Attosecond Physics gets Nano

Marcelo Ciappina

ELI-Beamlines, Prague, Czech Republic

marcelo.ciappina@eli-beams.eu

XXX ICPEAC, Cairns, Australia, 01/08/17

Citius, Altius, Fortius

(Olympic motto, Pierre de Coubertin, 1894) Faster, Higher, Stronger

Memorial dedicated to the City of Cairns as Host City for the beginning of the 1956 Olympic Torch relay

Citissimus, Maximus, Brevissimus, Minimus

(Atto-nano-physics motto) Fastest, Highest, Shortest, Smallest

Citius, Altius, Fortius

(Olympic motto, Pierre de Coubertin, 1894) Faster, Higher, Stronger

Memorial dedicated to the City of Cairns as Host City for the beginning of the 1956 Olympic Torch relay

Citissimus, Maximus, Brevissimus, Minimus

(Atto-nano-physics motto) Fastest, Highest, Shortest, Smallest

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
    - Context
    - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
    - The physical picture: the three-step model
    - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
    - The (recent) past: the experiments, motivation
    - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
    - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
  - Context
  - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
  - The physical picture: the three-step model
  - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
  - The (recent) past: the experiments, motivation
  - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
  - The present: conclusions
- The (near) future: outlook & perspectives

Outline

- *Conventional* Strong Field phenomena (brief description)
    - Context
    - Above-threshold ionization (ATI) and high-order harmonic generation (HHG)
    - The physical picture: the three-step model
    - Typical numbers: the laser-ionized electron does not feel the spatial variation of the laser electric field
- Laser-matter processes driven by temporal and spatial synthesized laser fields
    - The (recent) past: the experiments, motivation
    - The (recent) past and present: the models (quantal, semiclassical and classical) & selected results
    - The present: conclusions
- The (near) future: outlook & perspectives

Conventional Strong Field phenomena
Context

- **What is strong/intense?** Electric field due to the attraction of an electron and a proton: $|E_H| = 5.14 \times 10^{11}$ V/m (51.4 V/Å). Intensity equivalent: $I = 3.51 \times 10^{16}$ W/cm^2. Laser pulses in an intensity regime between $10^{14} - 10^{16}$ W/cm^2 are routinely generated worldwide
- **What is short?** Classical period of an electron around a proton: $\tau = 152$ as, period of a light wave for a typical Titanium-Sapphire (Ti:Sa) laser ($\lambda = 800$ nm): 2.7 fs (1 fs = 10^{-15} s). Few-cycle laser pulses (less than 2-3 total optical cycles) are generated in several laboratories around the world
- **What is small?** Bohr radius: 0.0529 nm (0.529 Å), typical classical excursion of an electron in an oscillating electron field: 1-10s nm (10-100s Å). Engineering metal/dielectrics nanostructures down to a few tenths of nanometers is nowadays possible

For the first time we could combine attosecond time resolution with engineering at a nanometric scale: the Atto-nano-physics stage has just started!!!

- **What is strong/intense?** Electric field due to the attraction of an electron and a proton: $|E_H| = 5.14 \times 10^{11}$ V/m (51.4 V/Å). Intensity equivalent: $I = 3.51 \times 10^{16}$ W/cm^2. Laser pulses in an intensity regime between $10^{14} - 10^{16}$ W/cm^2 are routinely generated worldwide
- **What is short?** Classical period of an electron around a proton: $\tau = 152$ as, period of a light wave for a typical Titanium-Sapphire (Ti:Sa) laser ($\lambda = 800$ nm): 2.7 fs (1 fs = 10^{-15} s). Few-cycle laser pulses (less than 2-3 total optical cycles) are generated in several laboratories around the world
- **What is small?** Bohr radius: 0.0529 nm (0.529 Å), typical classical excursion of an electron in an oscillating electron field: 1-10s nm (10-100s Å). Engineering metal/dielectrics nanostructures down to a few tenths of nanometers is nowadays possible

For the first time we could combine attosecond time resolution with engineering at a nanometric scale: the Atto-nano-physics stage has just started!!!

- **What is strong/intense?** Electric field due to the attraction of an electron and a proton: $|E_H| = 5.14 \times 10^{11}$ V/m (51.4 V/Å). Intensity equivalent: $I = 3.51 \times 10^{16}$ W/cm^2. Laser pulses in an intensity regime between $10^{14} - 10^{16}$ W/cm^2 are routinely generated worldwide
- **What is short?** Classical period of an electron around a proton: $\tau = 152$ as, period of a light wave for a typical Titanium-Sapphire (Ti:Sa) laser ($\lambda = 800$ nm): 2.7 fs (1 fs = 10^{-15} s). Few-cycle laser pulses (less than 2-3 total optical cycles) are generated in several laboratories around the world
- **What is small?** Bohr radius: 0.0529 nm (0.529 Å), typical classical excursion of an electron in an oscillating electron field: 1-10s nm (10-100s Å). Engineering metal/dielectrics nanostructures down to a few tenths of nanometers is nowadays possible

For the first time we could combine attosecond time resolution with engineering at a nanometric scale: the Atto-nano-physics stage has just started!!!

Conventional Strong Field phenomena
Context

- **What is strong/intense?** Electric field due to the attraction of an electron and a proton: $|E_H| = 5.14 \times 10^{11}$ V/m (51.4 V/Å). Intensity equivalent: $I = 3.51 \times 10^{16}$ W/cm^2. Laser pulses in an intensity regime between $10^{14} - 10^{16}$ W/cm^2 are routinely generated worldwide
- **What is short?** Classical period of an electron around a proton: $\tau = 152$ as, period of a light wave for a typical Titanium-Sapphire (Ti:Sa) laser ($\lambda = 800$ nm): 2.7 fs (1 fs = 10^{-15} s). Few-cycle laser pulses (less than 2-3 total optical cycles) are generated in several laboratories around the world
- **What is small?** Bohr radius: 0.0529 nm (0.529 Å), typical classical excursion of an electron in an oscillating electron field: 1-10s nm (10-100s Å). Engineering metal/dielectrics nanostructures down to a few tenths of nanometers is nowadays possible

For the first time we could combine attosecond time resolution with engineering at a nanometric scale: the Atto-nano-physics stage has just started!!!

- **What is strong/intense?** Electric field due to the attraction of an electron and a proton: $|E_H| = 5.14 \times 10^{11}$ V/m (51.4 V/Å). Intensity equivalent: $I = 3.51 \times 10^{16}$ W/cm^2. Laser pulses in an intensity regime between $10^{14} - 10^{16}$ W/cm^2 are routinely generated worldwide
- **What is short?** Classical period of an electron around a proton: $\tau = 152$ as, period of a light wave for a typical Titanium-Sapphire (Ti:Sa) laser ($\lambda = 800$ nm): 2.7 fs (1 fs = 10^{-15} s). Few-cycle laser pulses (less than 2-3 total optical cycles) are generated in several laboratories around the world
- **What is small?** Bohr radius: 0.0529 nm (0.529 Å), typical classical excursion of an electron in an oscillating electron field: 1-10s nm (10-100s Å). Engineering metal/dielectrics nanostructures down to a few tenths of nanometers is nowadays possible

For the first time we could combine attosecond time resolution with engineering at a nanometric scale: the **Atto-nano-physics** stage has just started!!!

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. **91**, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. **45**, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))

Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

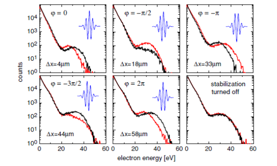
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

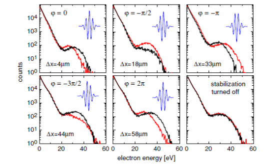
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

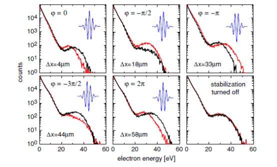
Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena
Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

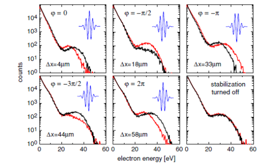
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

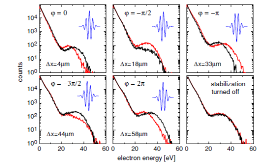
Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena
Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

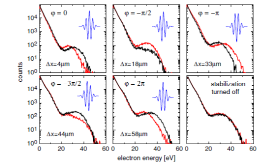
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)

Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

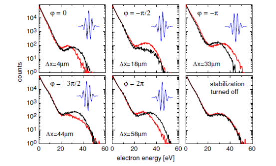
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

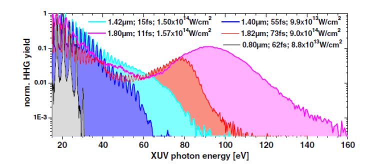
- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)



Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

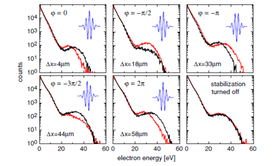
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

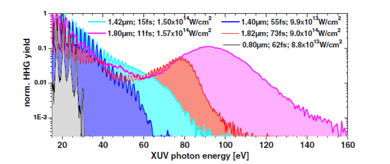
- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)



Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

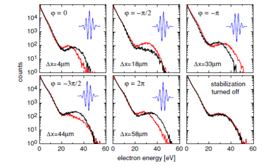
G. G. Paulus, et al. , Phys. Rev. Lett. **91**, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. **45**, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

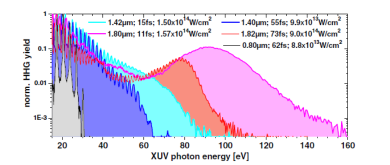
- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)



Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

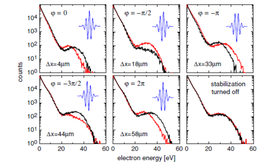
G. G. Paulus, et al. , Phys. Rev. Lett. 91, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. 45, 074008 (2012)

Conventional Strong Field phenomena

Brief description

Above-threshold ionization (ATI)

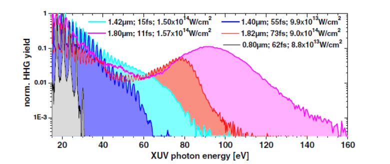
- Atomic or molecular bound electrons absorb many more photons than the minimum required to reach the continuum
- Excess energy converted to kinetic energy
- Production of direct and rescattered electrons
- Use as a few-cycle pulses characterization and molecular imaging (via laser-induced electron diffraction (LIED))



Typical photoelectron spectra (experiment)

High-order harmonic generation (HHG)

- Emission of the electron excess energy in the form of high-order harmonics of the fundamental laser field (HHG) (typically XUV photons)
- HHG spectra features: decay, plateau and cutoff
- Utilization as a source of coherent XUV radiation & attosecond pulses (key tools for molecular imaging)



Typical HHG spectra in atoms (experiment)

Main theoretical assumption: the laser electric field is spatially homogeneous

G. G. Paulus, et al. , Phys. Rev. Lett. **91**, 253004 (2003); B. E. Schmidt, et al. , J. Phys. B. **45**, 074008 (2012)

Conventional Strong Field phenomena
The physical picture

The three-step model (it is simple and works!!!!)

(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

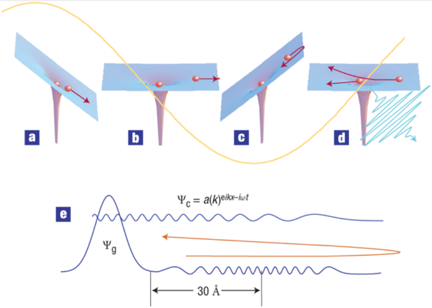
P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

The three-step model (it is simple and works!!!!)

(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

The three-step model (it is simple and works!!!!)



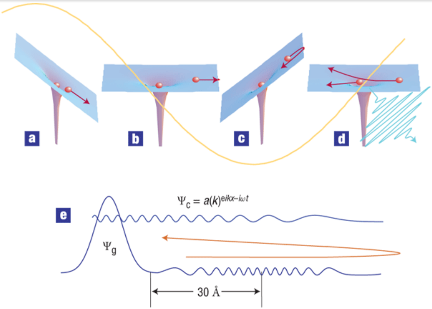
(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

Conventional Strong Field phenomena

The physical picture

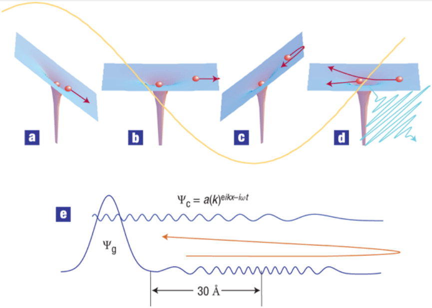
The three-step model (it is simple and works!!!!)



(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

The three-step model (it is simple and works!!!!)



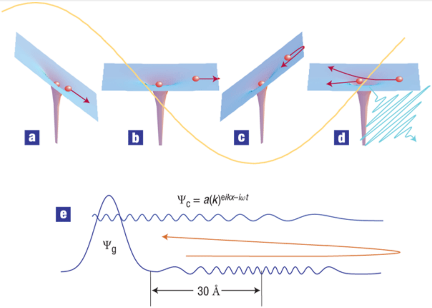
(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

Conventional Strong Field phenomena

The physical picture

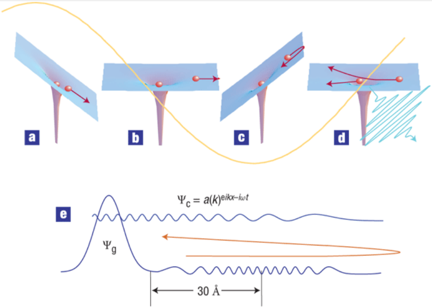
The three-step model (it is simple and works!!!!)



(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

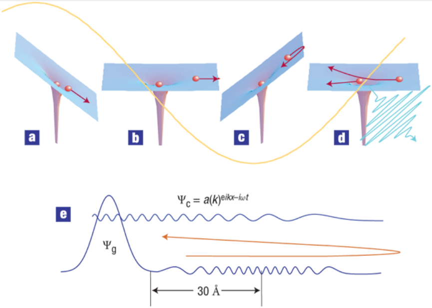
The three-step model (it is simple and works!!!!)



(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

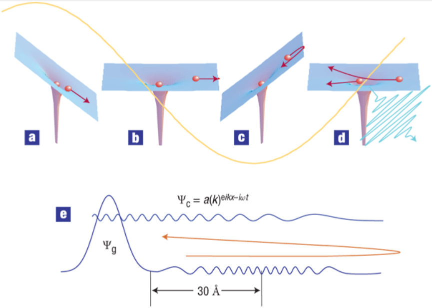
The three-step model (it is simple and works!!!!)



(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. 3, 381 (2007)

The three-step model (it is simple and works!!!!)



(a) an atomic or molecular electron is laser-ionized via tunneling; (b) it is pulled away from the atom; (c) it is driven back -when the laser electric field reverses its direction; (d) it can 'recollide' during a small fraction of time (sub-fs) and convert its kinetic energy into a high energy and 'ultrashort' photon -or it can rescatter, double ionize, etc.; (e) the quantum mechanical picture: split of the wavefunction in a bound and a continuum part, overlap after.

P. B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993); M. Lewenstein, et al., Phys. Rev. A **49**, 2117 (1994); P. B. Corkum & F. Krausz, Nat. Phys. **3**, 381 (2007)

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- $\mathrm{I} \approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- $\mathrm{I} \approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- $\mathrm{I} \approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- $\mathrm{I} \approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- $\mathrm{I} \approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- $\mathrm{I} \approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm

Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

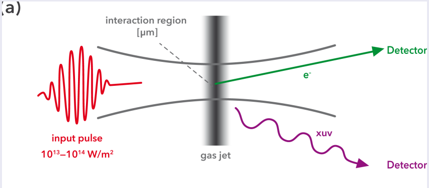
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm



Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Conventional Strong Field phenomena
Typical numbers

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

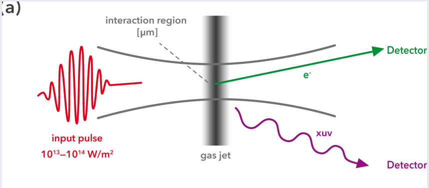
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm



Scheme of conventional strong field processes

Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

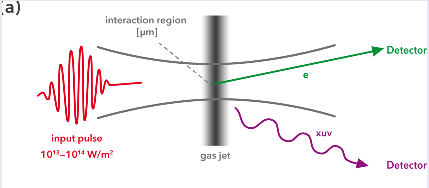
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

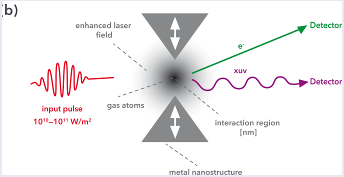
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm



Scheme of conventional strong field processes



Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

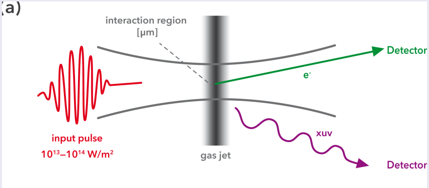
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

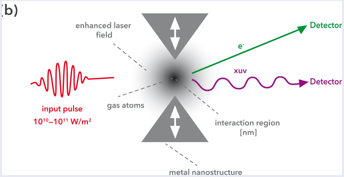
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm



Scheme of conventional strong field processes



Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical electron excursion in an oscillating electric field (quiver radius) $\alpha = E_0^2/\omega^2 = I/\omega^2$

@ 800 nm

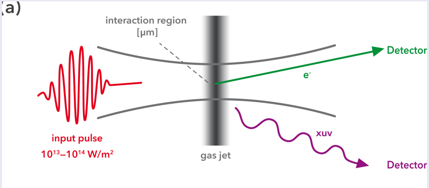
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.28$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 0.87$ nm

@ 1800 nm

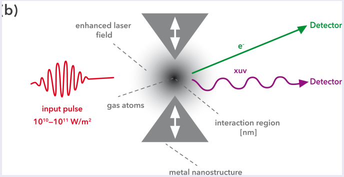
- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 1.5$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.5$ nm

@ 3.1 μm

- I $\approx 10^{13}$ W/cm^2 $\Rightarrow \alpha \approx \pm 4.1$ nm
- I $\approx 10^{14}$ W/cm^2 $\Rightarrow \alpha \approx \pm 13$ nm



Scheme of conventional strong field processes



Scheme of plasmonic-enhanced strong field processes

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past

Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)

HHG in gases driven by plasmonic fields II (2011)

HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past
Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)

HHG in gases driven by plasmonic fields II (2011)

HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past

Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)


Vol 453|5 June 2008|doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

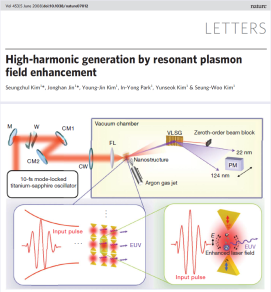
HHG in gases driven by plasmonic fields II (2011)

HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past
Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)


Vol 453|5 June 2008|doi:10.1038/nature07012

nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

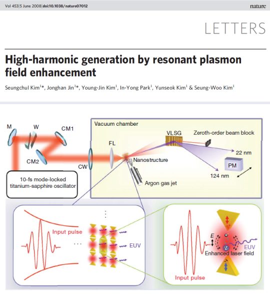
Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)

HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

HHG in gases driven by plasmonic fields I (2008)


Vol 453|5 June 2008|doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1]*, Jonghan Jin[1]*, Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)

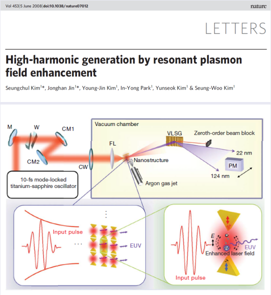
HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past

Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)



Vol 453|5 June 2008|doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1]*, Jonghan Jin[1]*, Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)

nature photonics LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.258

Plasmonic generation of ultrashort extreme-ultraviolet light pulses

In-Yong Park[1†], Seungchul Kim[1†], Joonhee Choi[1†], Dong-Hyub Lee[1], Young-Jin Kim[1], Matthias F. Kling[2], Mark I. Stockman[3] and Seung-Woo Kim[1]*

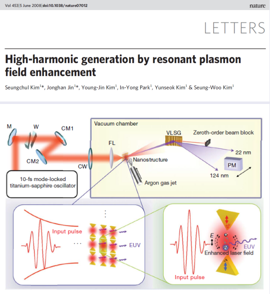
HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past

Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)



Vol 453 | 5 June 2008 | doi:10.1038/nature07012

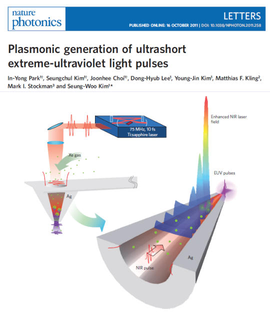
nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)



nature photonics

LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.258

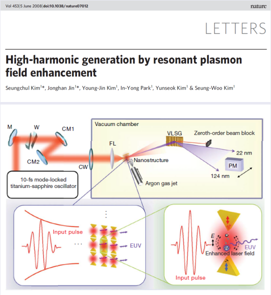
Plasmonic generation of ultrashort extreme-ultraviolet light pulses

In-Yong Park[1†], Seungchul Kim[1†], Joonhee Choi[1†], Dong-Hyub Lee[1], Young-Jin Kim[1], Matthias F. Kling[2], Mark I. Stockman[3] and Seung-Woo Kim[1*]

HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

HHG in gases driven by plasmonic fields I (2008)

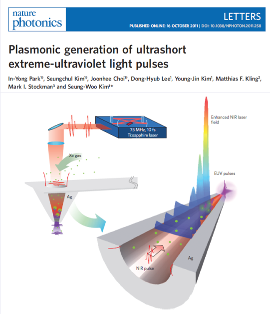

Vol 453 | 5 June 2008 | doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)


nature photonics LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.258

Plasmonic generation of ultrashort extreme-ultraviolet light pulses

In-Yong Park[1†], Seungchul Kim[1†], Joonhee Choi[1†], Dong-Hyub Lee[1], Young-Jin Kim[1], Matthias F. Kling[2], Mark I. Stockman[3] and Seung-Woo Kim[1*]

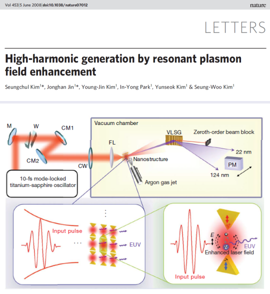
HHG in solids driven by plasmonic fields (2016)

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past

Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)

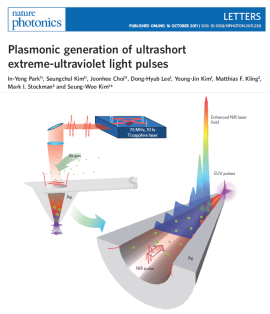

Vol 453 | 5 June 2008 | doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)

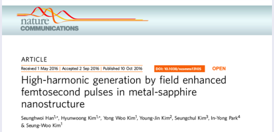

nature photonics LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.258

Plasmonic generation of ultrashort extreme-ultraviolet light pulses

In-Yong Park[1†], Seungchul Kim[1†], Joonhee Choi[1†], Dong-Hyub Lee[1], Young-Jin Kim[1], Matthias F. Kling[2], Mark I. Stockman[3] and Seung-Woo Kim[1*]

HHG in solids driven by plasmonic fields (2016)


nature COMMUNICATIONS

ARTICLE

Received 1 May 2016 | Accepted 2 Sep 2016 | Published 10 Oct 2016 DOI: 10.1038/ncomms13105 OPEN

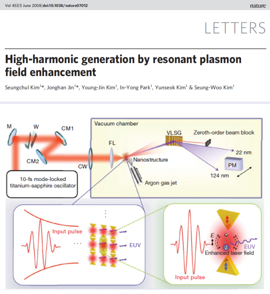
High-harmonic generation by field enhanced femtosecond pulses in metal-sapphire nanostructure

Seunghwoi Han[1,*], Hyunwoong Kim[1,*], Yong Woo Kim[1], Young-Jin Kim[2], Seungchul Kim[3], In-Yong Park[4] & Seung-Woo Kim[1]

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

The (recent) past
Motivation, the experiments I

HHG in gases driven by plasmonic fields I (2008)

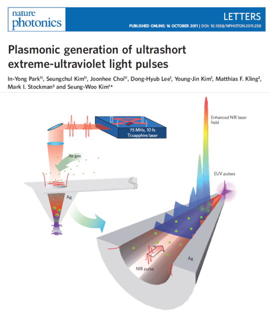

Vol 453 | 5 June 2008 | doi:10.1038/nature07012 nature

LETTERS

High-harmonic generation by resonant plasmon field enhancement

Seungchul Kim[1*], Jonghan Jin[1*], Young-Jin Kim[1], In-Yong Park[1], Yunseok Kim[1] & Seung-Woo Kim[1]

HHG in gases driven by plasmonic fields II (2011)

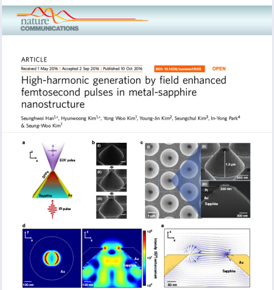

nature photonics LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.258

Plasmonic generation of ultrashort extreme-ultraviolet light pulses

In-Yong Park[1†], Seungchul Kim[1†], Joonhee Choi[1†], Dong-Hyub Lee[1], Young-Jin Kim[1], Matthias F. Kling[2], Mark I. Stockman[3] and Seung-Woo Kim[1*]

HHG in solids driven by plasmonic fields (2016)


nature COMMUNICATIONS

ARTICLE

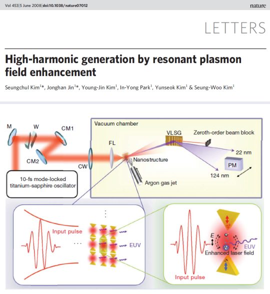
Received 1 May 2016 | Accepted 2 Sep 2016 | Published 10 Oct 2016 | DOI: 10.1038/ncomms13105 OPEN

High-harmonic generation by field enhanced femtosecond pulses in metal-sapphire nanostructure

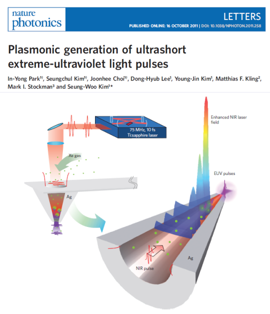
Seunghwoi Han[1,*], Hyunwoong Kim[1,*], Yong Woo Kim[1], Young-Jin Kim[2], Seungchul Kim[3], In-Yong Park[4] & Seung-Woo Kim[1]

S. Kim, et al., Nature 453, 757 (2008); I-Y. Park, et al., Nat. Phot. 5, 677 (2011); S. Han, et al., Nat. Commun. 7, 13105 (2016)

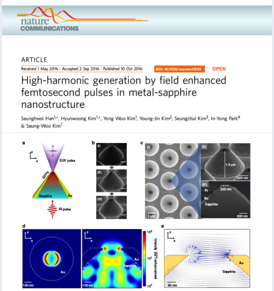
HHG in gases driven by plasmonic fields I (2008)



HHG in gases driven by plasmonic fields II (2011)



HHG in solids driven by plasmonic fields (2016)



S. Kim, et al., Nature **453**, 757 (2008); I-Y. Park, et al., Nat. Phot. **5**, 677 (2011); S. Han, et al., Nat. Commun. **7**, 13105 (2016)

The (recent) past
Motivation, the experiments II

Electron emission in nanospheres (2011)

Electron emission in nanotips I (2011)

Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

Electron emission in nanospheres (2011)

Electron emission in nanotips I (2011)

Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

Electron emission in nanospheres (2011)

Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]

Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

The (recent) past
Motivation, the experiments II

Electron emission in nanospheres (2011)

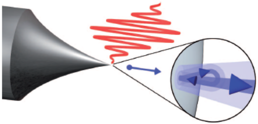
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]



Electron emission in nanotips II (2012)

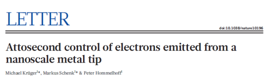
M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

The (recent) past

Motivation, the experiments II

Electron emission in nanospheres (2011)

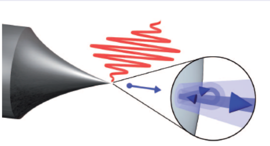
Electron emission in nanotips I (2011)


LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]



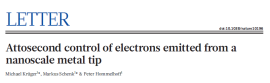
Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

The (recent) past

Motivation, the experiments II

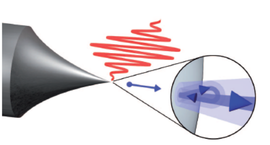
Electron emission in nanotips I (2011)


LETTER

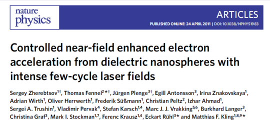
doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1*], Markus Schenk[1*] & Peter Hommelhoff[1]



Electron emission in nanospheres (2011)


nature physics

ARTICLES

PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3*] and Matthias F. Kling[1,8,9*]

Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

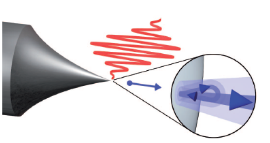
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]



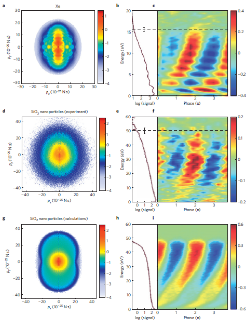
Electron emission in nanospheres (2011)

nature physics ARTICLES

PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3]* and Matthias F. Kling[1,8,9]*



Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

The (recent) past

Motivation, the experiments II

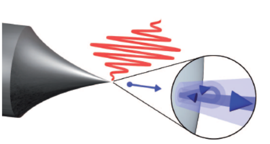
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]

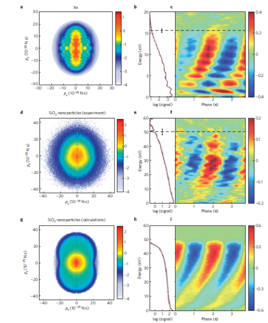


Electron emission in nanospheres (2011)

nature physics ARTICLES
PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3]* and Matthias F. Kling[1,8,9]*



Electron emission in nanotips II (2012)

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

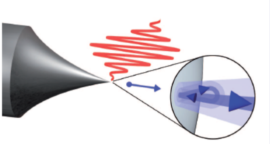
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1]*, Markus Schenk[1]* & Peter Hommelhoff[1]



Electron emission in nanospheres (2011)

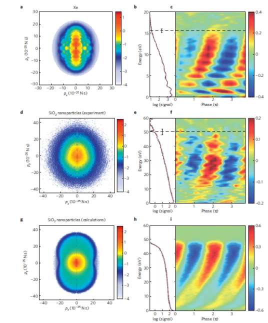
nature physics

ARTICLES

PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3]* and Matthias F. Kling[1,8,9]*



Electron emission in nanotips II (2012)

LETTER

doi:10.1038/nature10878

Field-driven photoemission from nanostructures quenches the quiver motion

G. Herink[1], D. R. Solli[1], M. Gulde[1] & C. Ropers[1]

M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

The (recent) past

Motivation, the experiments II

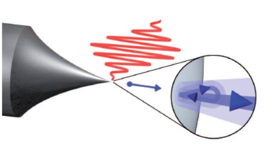
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1*], Markus Schenk[1*] & Peter Hommelhoff[1]

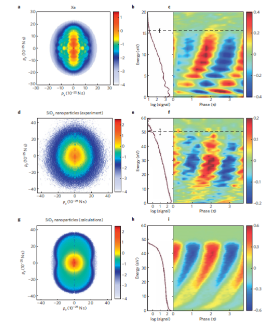


Electron emission in nanospheres (2011)

nature physics ARTICLES
PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3*] and Matthias F. Kling[1,8,9*]



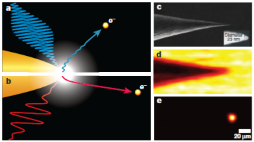
Electron emission in nanotips II (2012)

LETTER

doi:10.1038/nature10878

Field-driven photoemission from nanostructures quenches the quiver motion

G. Herink[1], D. R. Solli[1], M. Gulde[1] & C. Ropers[1]



M. Krüger, et al., Nature 453, 78 (2011); S. Zherebstov, et al., Nat. Phys. 7, 656 (2011); G. Herink, et al., Nature 483, 190 (2012)

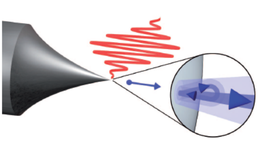
Electron emission in nanotips I (2011)

LETTER

doi:10.1038/nature10196

Attosecond control of electrons emitted from a nanoscale metal tip

Michael Krüger[1*], Markus Schenk[1*] & Peter Hommelhoff[1]



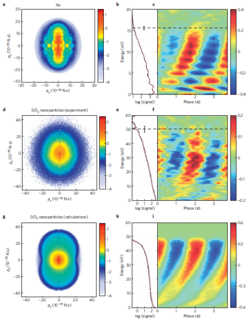
Electron emission in nanospheres (2011)

nature physics ARTICLES

PUBLISHED ONLINE: 24 APRIL 2011 | DOI: 10.1038/NPHYS1983

Controlled near-field enhanced electron acceleration from dielectric nanospheres with intense few-cycle laser fields

Sergey Zherebtsov[1†], Thomas Fennel[2*†], Jürgen Plenge[3†], Egill Antonsson[3], Irina Znakovskaya[1], Adrian Wirth[1], Oliver Herrwerth[1], Frederik Süßmann[1], Christian Peltz[2], Izhar Ahmad[1], Sergei A. Trushin[1], Vladimir Pervak[4], Stefan Karsch[1,4], Marc J. J. Vrakking[5,6], Burkhard Langer[3], Christina Graf[3], Mark I. Stockman[1,7], Ferenc Krausz[1,4], Eckart Rühl[3*] and Matthias F. Kling[1,8,9*]



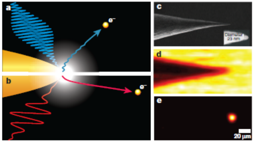
Electron emission in nanotips II (2012)

LETTER

doi:10.1038/nature10878

Field-driven photoemission from nanostructures quenches the quiver motion

G. Herink[1], D. R. Solli[1], M. Gulde[1] & C. Ropers[1]



M. Krüger, et al., Nature **453**, 78 (2011); S. Zherebstov, et al., Nat. Phys. **7**, 656 (2011); G. Herink, et al., Nature **483**, 190 (2012)

The (recent) past and present
Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present
Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present
Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (recent) past and present

Theoretical models

We treat spatially inhomogeneous fields by modifying the laser-electron coupling in the *conventional* theoretical models

Quantal

- The Time Dependent Schrödinger Equation (TDSE) 1D & 3D
- Numerical solution in a grid with absorbing boundaries
- ATI yield and HHG spectra obtained *postprocessing* the time propagated wavefunction
- Advantages & Drawbacks of each *flavor*

Semiclassical

- The Strong Field Approximation (SFA) or Lewenstein model
- The laser field does not affect the bound electron
- The residual Coulomb field does not affect the *continuum* electron
- Interpretation of ATI and HHG in terms of *quantum orbits*

Classical

- Newton-Lorentz equation (1D)
- Simple man's model prescriptions
- *Extraction* of the ionization and recombination times
- Electron kinetic energy calculations
- Excellent prediction of ATI yield (energy) and HHG spectra (harmonic order) limits

The three approaches give supplementary information

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\mathrm{atom}}(x)} + \boxed{V_{\mathrm{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- Advantages: low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- Drawbacks: finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. Attosecond physics at the nanoscale, Rep. Prog. Phys. 80, 054401 (2017)

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- time evolution of electron wf (1D)
- kinetic energy

$$\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t} = \left(-\frac{1}{2}\frac{d^2}{dx^2} + V_{\mathrm{atom}}(x) + V_{\mathrm{laser}}(x,t)\right)\Psi(x,t)$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\mathrm{atom}}(x)} + \boxed{V_{\mathrm{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\mathrm{atom}}(x)} + \boxed{V_{\mathrm{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t} = \left(-\frac{1}{2}\frac{d^2}{dx^2} + V_{\text{atom}}(x) + V_{\text{laser}}(x,t)\right)\Psi(x,t)$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial \Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\mathrm{atom}}(x)} + \boxed{V_{\mathrm{laser}}(x,t)} \right) \boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial \Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\text{atom}}(x)} + \boxed{V_{\text{laser}}(x,t)} \right) \boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models I

The Time Dependent Schrödinger Equation in reduced dimensions (TDSE-1D)

- time evolution of electron wf (1D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(x,t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\frac{d^2}{dx^2}} + \boxed{V_{\mathrm{atom}}(x)} + \boxed{V_{\mathrm{laser}}(x,t)}\right)\boxed{\Psi(x,t)}$$

- atomic potential
- laser-atom coupling
- electron wf (1D)

- Numerical solution in a grid using the Crank-Nicolson algorithm with absorbing boundary conditions (masks)
- HHG spectra calculated Fourier transforming the time-dependent dipole acceleration
- ATI yield calculated using the time propagated electron wavefunction via energy window techniques
- **Advantages:** low computational cost, allow general functional forms for the nonhomo field, excellent agreement with the classical predicted limits
- **Drawbacks:** finer details of HHG of ATI are missing, only allow energy analysis (ATI)

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling

- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- Advantages: excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI), real nonhomogeneous fields can be incorporated, modeling of complex atoms with high precision
- Drawbacks: high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. Attosecond physics at the nanoscale, Rep. Prog. Phys. 80 054401 (2017)

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial \Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)} \right) \boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\text{atom}}(r)} + \boxed{V_{\text{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling

- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t} = \left(-\frac{1}{2}\nabla^2 + V_{\mathrm{atom}}(r) + V_{\mathrm{laser}}(\mathbf{r},t)\right)\Psi(\mathbf{r},t)$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$i\frac{\partial \Psi(\mathbf{r},t)}{\partial t} = \left(-\frac{1}{2}\nabla^2 + V_{\mathrm{atom}}(r) + V_{\mathrm{laser}}(\mathbf{r},t) \right) \Psi(\mathbf{r},t)$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{i\frac{\partial \Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\rm atom}(r)} + \boxed{V_{\rm laser}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{i\frac{\partial\Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\text{atom}}(r)} + \boxed{V_{\text{laser}}(\mathbf{r},t)}\right)\boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Quantum models II

The Time Dependent Schrödinger Equation (TDSE-3D) in the Single Active Electron (SAE) approximation

- time evolution of electron wf (3D)
- kinetic energy

$$\boxed{\mathrm{i}\frac{\partial \Psi(\mathbf{r},t)}{\partial t}} = \left(\boxed{-\frac{1}{2}\nabla^2} + \boxed{V_{\mathrm{atom}}(r)} + \boxed{V_{\mathrm{laser}}(\mathbf{r},t)} \right) \boxed{\Psi(\mathbf{r},t)}$$

- atomic potential
- laser-atom coupling
- electron wavefunction (3D)

- $\Psi(\mathbf{r},t)$ is written in terms of angular momenta l
- For each l (typically several hundreds) we have a set of coupled partial differential equations for the radial variable r
- **Advantages:** excellent resolution for both the HHG spectra and ATI yield; it allows angular distributions calculations (ATI); real nonhomogeneous fields can be incorporated; modeling of complex atoms with high precision
- **Drawbacks:** high computational cost (in particular for longer laser pulses and longer wavelengths), up to date only spatially linear nonhomogeneous fields have been studied

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- time-dependent dipole moment
- recombination transition matrix

$$\begin{aligned}\mathbf{D}(t) &= -\mathrm{i}\int_0^t \mathrm{dt'} \int \mathrm{d}\mathbf{k}\, \langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle \\ &\times \langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle \exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]\end{aligned}$$

- ionization transition matrix
- classical action

M. Lewenstein et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina et al. Attosecond physics at the nanoscale, Rep. Prog. Phys. 80, 054401 (2017).

- time-dependent dipole moment
- recombination transition matrix

$$\boxed{\mathbf{D}(t)} = -\mathrm{i}\int_0^t \mathrm{dt}'\int \mathrm{d}\mathbf{k}\, \boxed{\langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle}$$
$$\times \boxed{\langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle}\ \boxed{\exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]}$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- time-dependent dipole moment
- recombination transition matrix

$$\boxed{\mathbf{D}(t)} = -\mathrm{i}\int_0^t \mathrm{dt}' \int \mathrm{d}\mathbf{k}\, \boxed{\langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle}$$
$$\times \boxed{\langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle}\ \boxed{\exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]}$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Semiclassical model I

The Strong Field Approximation (SFA) or Lewenstein model for HHG

- time-dependent dipole moment
- recombination transition matrix

$$\mathbf{D}(t) = -\mathrm{i}\int_0^t \mathrm{dt}'\int \mathrm{d}\mathbf{k}\,\langle\psi_0|-\mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle$$

$$\times\quad \langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle\ \exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- time-dependent dipole moment
- recombination transition matrix

$$\boxed{\mathbf{D}(t)} = -\mathrm{i}\int_0^t \mathrm{d}t' \int \mathrm{d}\mathbf{k}\, \boxed{\langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle}$$
$$\times \boxed{\langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle}\ \boxed{\exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]}$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- time-dependent dipole moment
- recombination transition matrix

$$\boxed{\mathbf{D}(t)} = -\mathrm{i}\int_0^t \mathrm{d}t' \int \mathrm{d}\mathbf{k}\, \boxed{\langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle}$$
$$\times \boxed{\langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle}\ \boxed{\exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]}$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A 49, 2117 (1994); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Semiclassical model I

The Strong Field Approximation (SFA) or Lewenstein model for HHG

- time-dependent dipole moment
- recombination transition matrix

$$\boxed{\mathbf{D}(t)} = -\mathrm{i}\int_0^t \mathrm{d}t' \int \mathrm{d}\mathbf{k}\, \boxed{\langle\psi_0| - \mathbf{r}|\mathbf{k}+\mathbf{A}(\mathbf{r},t)\rangle}$$

$$\times \quad \boxed{\langle\mathbf{k}+\mathbf{A}(\mathbf{r},t')|\mathbf{E}(\mathbf{r},t')\cdot\mathbf{r}|\psi_0\rangle} \; \boxed{\exp[-\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')]}$$

- ionization transition matrix
- classical action

M. Lewenstein, et al., Phys. Rev. A **49**, 2117 (1994); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- total probability amplitude

$$M_{\mathbf{p}}^{\mathrm{SFA}} = M_{\mathbf{p}}^{(\mathrm{d})} + M_{\mathbf{p}}^{(\mathrm{r})}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

D. B. Milošević, et al., J. Phys B 39, R203 (2006); M. F. Ciappina, et al., [illegible] the nanoscale, Rep. Prog. Phys. 80, 054401 (2017)

Semiclassical model II
The Strong Field Approximation (SFA) for ATI

- total probability amplitude

$$\boxed{M_{\mathbf{p}}^{\mathrm{SFA}}} = \boxed{M_{\mathbf{p}}^{(\mathrm{d})}} + \boxed{M_{\mathbf{p}}^{(\mathrm{r})}}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

D. B. Milošević, et al., J. Phys B 39, R203 (2006); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Semiclassical model II

The Strong Field Approximation (SFA) for ATI

- total probability amplitude

$$\boxed{M_{\mathbf{p}}^{\mathrm{SFA}}} = \boxed{M_{\mathbf{p}}^{(\mathrm{d})}} + \boxed{M_{\mathbf{p}}^{(\mathrm{r})}}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

D. B. Milošević, et al., J. Phys B 39, R203 (2006); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- total probability amplitude

$$\boxed{M_{\mathbf{p}}^{\mathrm{SFA}}} = \boxed{M_{\mathbf{p}}^{(\mathrm{d})}} + \boxed{M_{\mathbf{p}}^{(\mathrm{r})}}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

$$\boxed{M_{\mathbf{p}}^{(\mathrm{d})} = -\mathrm{i}\int_0^{T_p} \mathrm{d}t \langle \mathbf{p}+\mathbf{A}(\mathbf{r},t)|\mathbf{E}(\mathbf{r},t)\cdot\mathbf{r}|\psi_0\rangle \mathrm{e}^{\mathrm{i}S(\mathbf{p},\mathbf{r},t)}}$$

D. B. Milošević, et al., J. Phys B **39**, R203 (2006); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Semiclassical model II

The Strong Field Approximation (SFA) for ATI

- total probability amplitude

$$M_{\mathbf{p}}^{\mathrm{SFA}} = M_{\mathbf{p}}^{(\mathrm{d})} + M_{\mathbf{p}}^{(\mathrm{r})}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

$$M_{\mathbf{p}}^{(\mathrm{d})} = -\mathrm{i}\int_0^{T_p} \mathrm{d}t \langle \mathbf{p} + \mathbf{A}(\mathbf{r},t)|\mathbf{E}(\mathbf{r},t)\cdot\mathbf{r}|\psi_0\rangle \mathrm{e}^{\mathrm{i}S(\mathbf{p},\mathbf{r},t)}$$

$$M_{\mathbf{p}}^{(\mathrm{r})} = -\int_0^{T_p} \mathrm{d}t \int_t^{\infty} \mathrm{d}t' \int \mathrm{d}\mathbf{k}\; \mathrm{e}^{\mathrm{i}S(\mathbf{p},\mathbf{r},t')}\langle \mathbf{p} + \mathbf{A}(\mathbf{r},t')|V|\mathbf{k} + \mathbf{A}(\mathbf{r},t')\rangle$$

$$\times \mathrm{e}^{\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')}\langle \mathbf{k} + \mathbf{A}(\mathbf{r},t)|\mathbf{E}(\mathbf{r},t)\cdot\mathbf{r}|\psi_0\rangle$$

D. B. Milošević, et al., J. Phys B **39**, R203 (2006); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Semiclassical model II
The Strong Field Approximation (SFA) for ATI

- total probability amplitude

$$\boxed{M_{\mathbf{p}}^{\mathrm{SFA}}} = \boxed{M_{\mathbf{p}}^{(\mathrm{d})}} + \boxed{M_{\mathbf{p}}^{(\mathrm{r})}}$$

- direct electrons probability amplitude
- rescattered electrons probability amplitude

$$M_{\mathbf{p}}^{(\mathrm{d})} = -\mathrm{i}\int_0^{T_p} \mathrm{d}t \langle \mathbf{p} + \mathbf{A}(\mathbf{r},t) | \mathbf{E}(\mathbf{r},t)\cdot\mathbf{r} | \psi_0 \rangle \mathrm{e}^{\mathrm{i}S(\mathbf{p},\mathbf{r},t)}$$

$$M_{\mathbf{p}}^{(\mathrm{r})} = -\int_0^{T_p} \mathrm{d}t \int_t^{\infty} \mathrm{d}t' \int \mathrm{d}\mathbf{k}\, \mathrm{e}^{\mathrm{i}S(\mathbf{p},\mathbf{r},t')} \langle \mathbf{p} + \mathbf{A}(\mathbf{r},t') | V | \mathbf{k} + \mathbf{A}(\mathbf{r},t') \rangle$$

$$\times \mathrm{e}^{\mathrm{i}S(\mathbf{k},\mathbf{r},t,t')} \langle \mathbf{k} + \mathbf{A}(\mathbf{r},t) | \mathbf{E}(\mathbf{r},t)\cdot\mathbf{r} | \psi_0 \rangle$$

D. B. Milošević, et al., J. Phys B **39**, R203 (2006); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Classical approaches
Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\ddot{x}(t) = -\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is converted at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. Attosecond physics at the nanoscale, Rep. Prog. Phys. 80, 054401 (2017)

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \to$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \to$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\to$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \to$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \to$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\to$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\mathrm{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \to$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \to$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\to$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \to$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \to$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\to$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\ddot{x}(t) = -\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \rightarrow$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \rightarrow$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\rightarrow$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical approaches

Newton-Lorentz equation (1D) & simple man's model

- electron acceleration (1D)

$$\boxed{\ddot{x}(t)} = \boxed{-\nabla V_{\text{laser}}(x,t) = -\nabla[xE(x,t)]}$$

- force

- Initial conditions: $x(t_i) = 0$ & $\dot{x}(t_i) = 0$ ($t_i \to$ ionization time)
- Recollision condition $x(t_r) = 0$ ($t_r \to$ recollision time)
- The excess of energy is *converted* at recollision
- If the electron recombines and emits radiation $\to$ HHG
- HHG cutoff prediction $n_c = (3.17U_p + I_p)/\omega$ (experimentally confirmed)
- If the electron never return, $2U_p$ cutoff in ATI yield (direct electrons, experimentally confirmed)
- If the electron elastically rescatters, $10U_p$ cutoff in ATI yield (rescattered electrons, experimentally confirmed)

P. B. Corkum, Phys. Rev. Lett. **71**, 1994 (1993); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example

1D HHG spectra

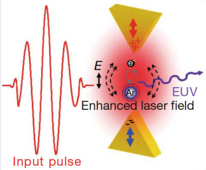
Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example



1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

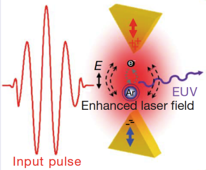
Selected Results - Episode I

The electron confinement menace

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example



1D HHG spectra

Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

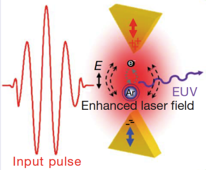
Selected Results - Episode I

The electron confinement menace

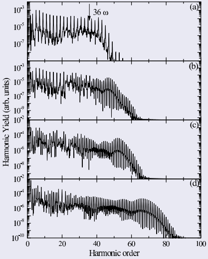
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example



1D HHG spectra



Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

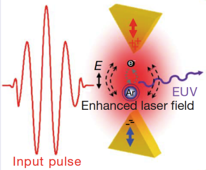
Selected Results - Episode I

The electron confinement menace

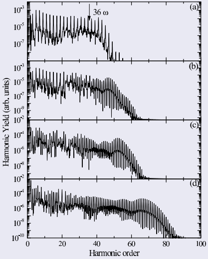
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

Setup example



1D HHG spectra



Time-analysis

M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

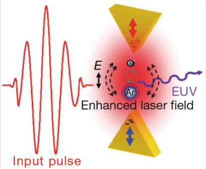
Selected Results - Episode I

The electron confinement menace

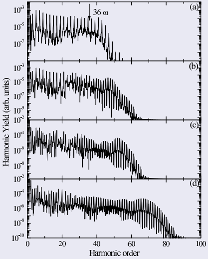
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

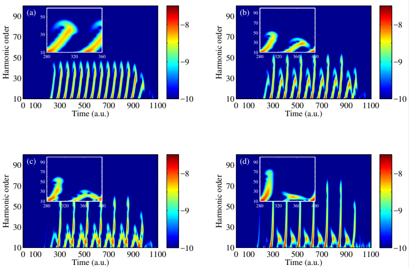
Setup example



1D HHG spectra



Time-analysis

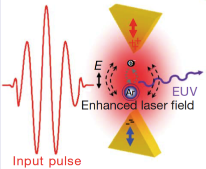


M.F. Ciappina, et al., Phys. Rev. A 85, 033828 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

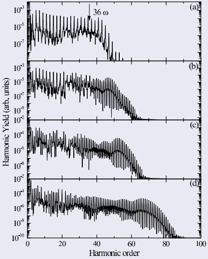
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- electron confinement (limited grid)
- tailoring trajectories (only short)
- HHG cutoff extension
- symmetry breaking

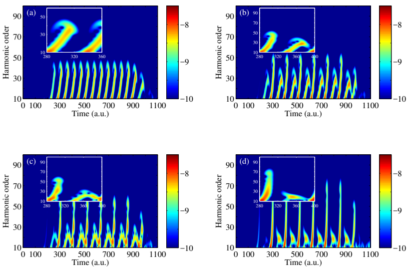
Setup example



1D HHG spectra



Time-analysis



M.F. Ciappina, et al., Phys. Rev. A **85**, 033828 (2012); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Selected Results - Episode II

Attacking the CEP determination

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Classical model

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode II

Attacking the CEP determination

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode II

Attacking the CEP determination

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode II

Attacking the CEP determination

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model

1D ATI for CEP #1

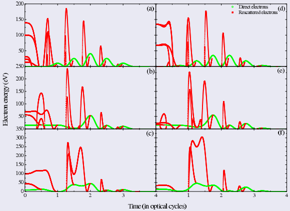
1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model



1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

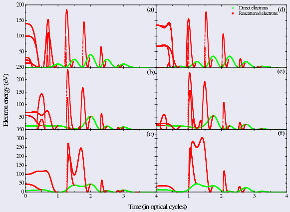
Selected Results - Episode II

Attacking the CEP determination

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model



1D ATI for CEP #1

1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

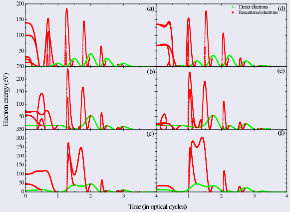
Selected Results - Episode II

Attacking the CEP determination

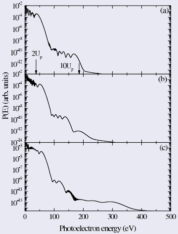
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model



1D ATI for CEP #1



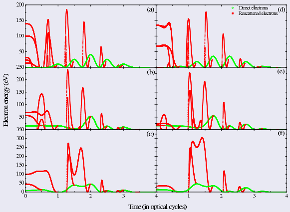
1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

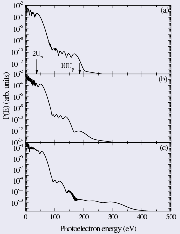
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

Classical model



1D ATI for CEP #1



1D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

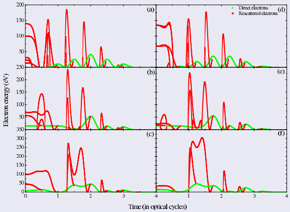
Selected Results - Episode II

Attacking the CEP determination

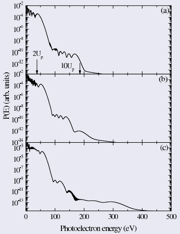
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

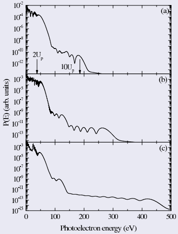
Classical model



1D ATI for CEP #1



1D ATI for CEP #2

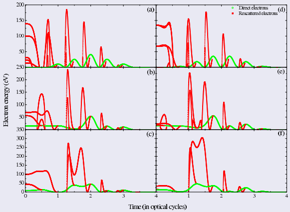


M.F. Ciappina, et al., Phys. Rev. A 86, 023413 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

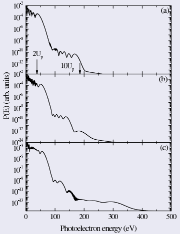
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (energy)
- high-energy electron production
- tailoring electron trajectories

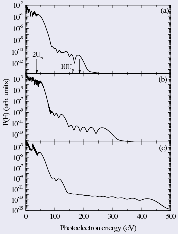
Classical model



1D ATI for CEP #1



1D ATI for CEP #2



M.F. Ciappina, et al., Phys. Rev. A **86**, 023413 (2012); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode III

The revenge of the CEP

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode III

The revenge of the CEP

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1

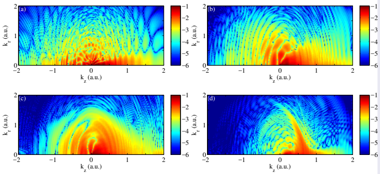
3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1



3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

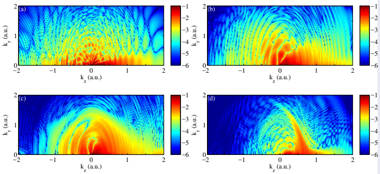
Selected Results - Episode III

The revenge of the CEP

Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1



3D ATI for CEP #2

M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

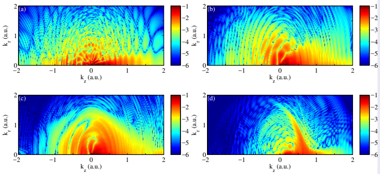
Selected Results - Episode III

The revenge of the CEP

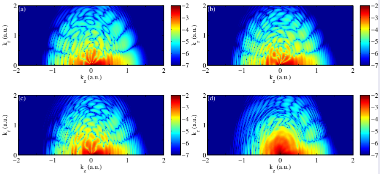
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1



3D ATI for CEP #2

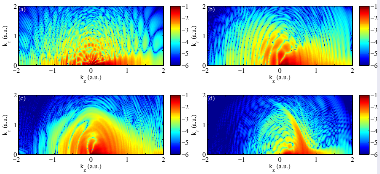


M.F. Ciappina, et al., Phys. Rev. A 87, 063833 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

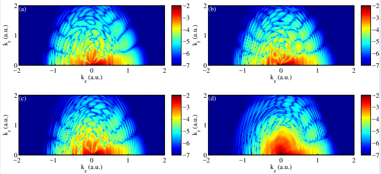
Rationale

- *caricature* of the plasmonic-enhanced field (linear dependence)
- strong CEP dependence (angular)
- tailoring electron trajectories
- directional electron bunches

3D ATI for CEP #1



3D ATI for CEP #2



M.F. Ciappina, et al., Phys. Rev. A **87**, 063833 (2012); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image

HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

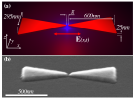
Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image



HHG (1D) & FDTD & real field #1

HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

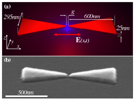
Selected Results - Episode IV

A new and improved model for the plasmonic field

Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image



HHG (1D) & FDTD & real field #1

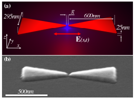
HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

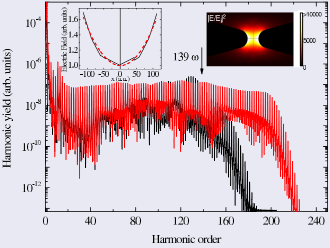
Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image



HHG (1D) & FDTD & real field #1



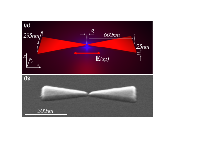
HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

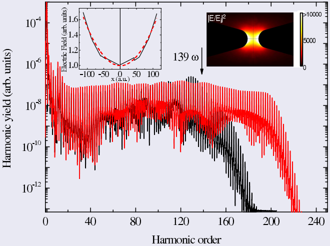
Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

Sketch & TEM image



HHG (1D) & FDTD & real field #1



HHG (1D) & FDTD & real field #2

M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

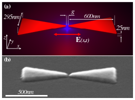
Selected Results - Episode IV

A new and improved model for the plasmonic field

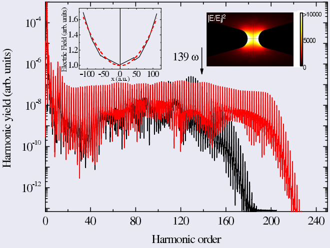
Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

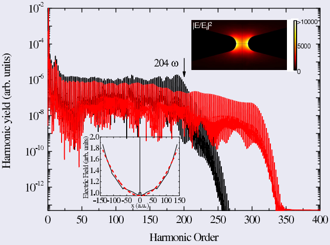
Sketch & TEM image



HHG (1D) & FDTD & real field #1



HHG (1D) & FDTD & real field #2



M.F. Ciappina, et al., Opt. Exp. 20, 26261 (2012); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

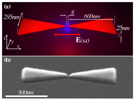
Selected Results - Episode IV

A new and improved model for the plasmonic field

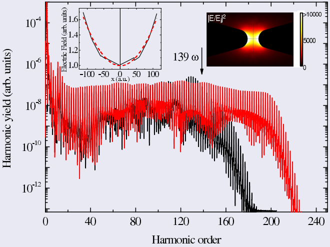
Rationale

- *real* plasmonic-enhanced field (FDTD)
- tailoring trajectories
- HHG cutoff extension
- symmetry breaking
- long wavelengths

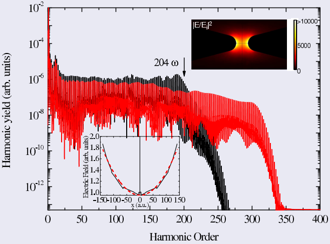
Sketch & TEM image



HHG (1D) & FDTD & real field #1



HHG (1D) & FDTD & real field #2



M.F. Ciappina, et al., Opt. Exp. **20**, 26261 (2012); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode V

The high energetic electron strikes back

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse

HHG in 3D (He)

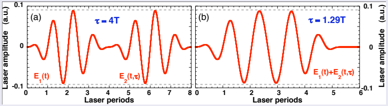
Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse



HHG in 3D (He)

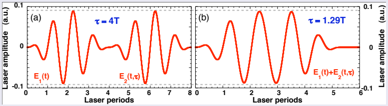
Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse



HHG in 3D (He)

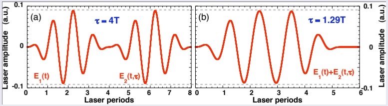
Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

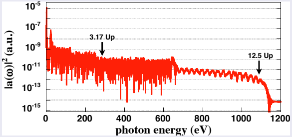
Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse



HHG in 3D (He)



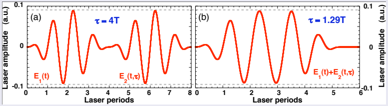
Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

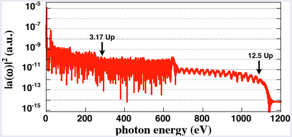
Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

Temporal synthesized pulse



HHG in 3D (He)



Time analysis & classical

J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

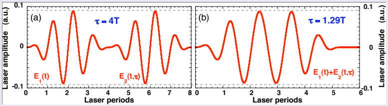
Selected Results - Episode V

The high energetic electron strikes back

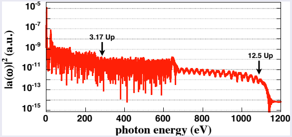
Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

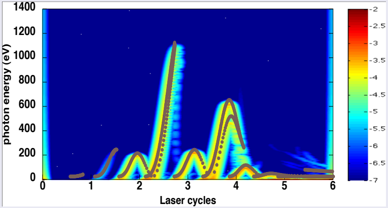
Temporal synthesized pulse



HHG in 3D (He)



Time analysis & classical

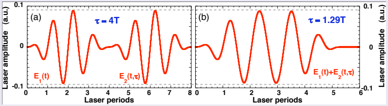


J. A. Pérez-Hernández, et al., Phys. Rev. Lett. 110, 053001 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

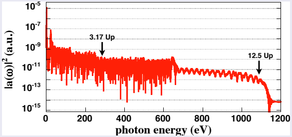
Rationale

- temporal synthesized field (experimentally tested)
- linear inhomogeneous field
- HHG cutoff extension
- interpretation via quantum vs. classical simulations
- supercontinuum generation (atto pulses)

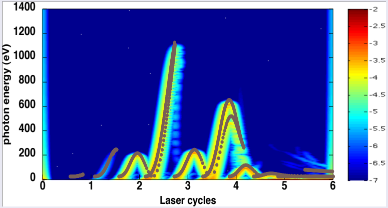
Temporal synthesized pulse



HHG in 3D (He)



Time analysis & classical



J. A. Pérez-Hernández, et al., Phys. Rev. Lett. **110**, 053001 (2013); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field

Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

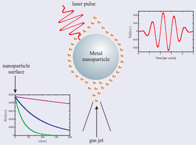
Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field



Electrons

Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

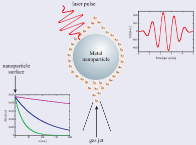
Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field



Electrons

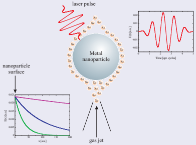
Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

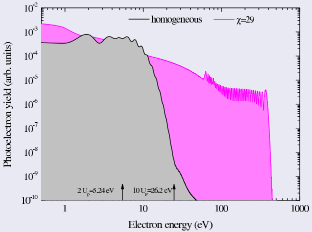
Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Proposed setup & near-field



Electrons



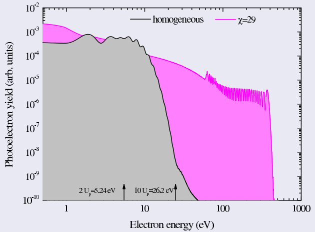
Photons

T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

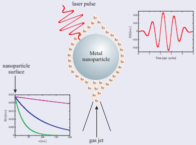
Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

Electrons



Proposed setup & near-field



Photons

T. Shaaran, et al., Phys. Rev. A **87**, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. **10**, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

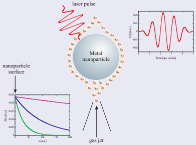
Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

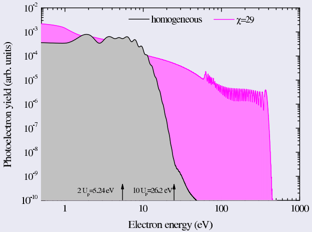
Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

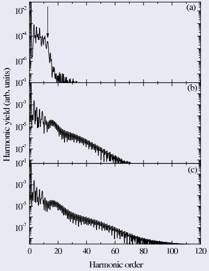
Proposed setup & near-field



Electrons



Photons



T. Shaaran, et al., Phys. Rev. A 87, 041402(R) (2013); M.F. Ciappina, et al., Las. Phys. Lett. 10, 105302 (2013); M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

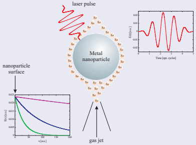
Selected Results - Episode VI

The return of ATI and HHG driven by plasmonic near-fields

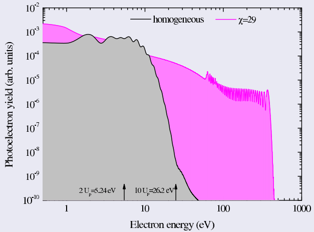
Rationale

- *near*-plasmonic-enhanced field (streaking)
- HHG cutoff extension
- high energetic electrons
- tailoring trajectories
- electron as a *probe* of plasmonic fields

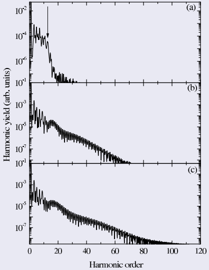
Proposed setup & near-field



Electrons



Photons



T. Shaaran, et al., Phys. Rev. A **87**, 041402(R) (2013); **M.F. Ciappina**, et al., Las. Phys. Lett. **10**, 105302 (2013); **M.F. Ciappina**, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)

CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

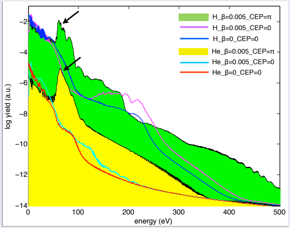
Selected Results - Episode VII

The high-energy structure (HES) awakens

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)



CTMC simulations

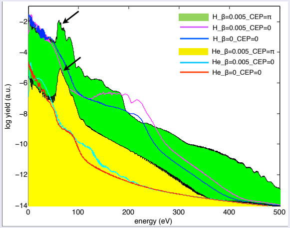
Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)



CTMC simulations

Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

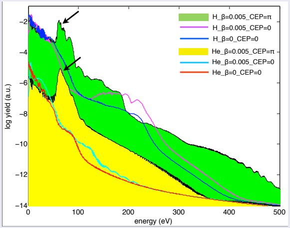
Selected Results - Episode VII

The high-energy structure (HES) awakens

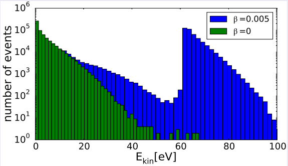
Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

3D TDSE (H and He)



CTMC simulations



Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

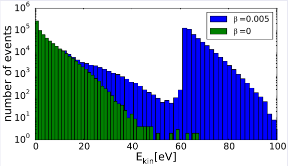
Selected Results - Episode VII

The high-energy structure (HES) awakens

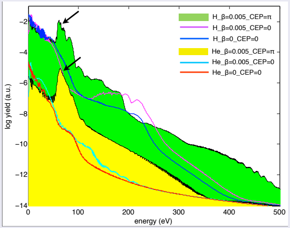
Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

CTMC simulations



3D TDSE (H and He)



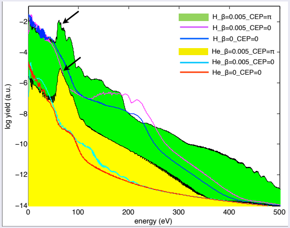
Ionization phase CTMC

L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

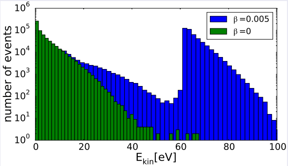
Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

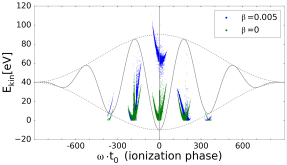
3D TDSE (H and He)



CTMC simulations



Ionization phase CTMC



L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

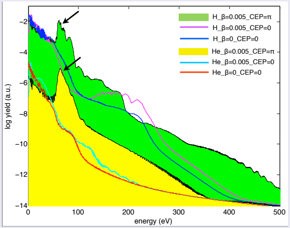
Selected Results - Episode VII

The high-energy structure (HES) awakens

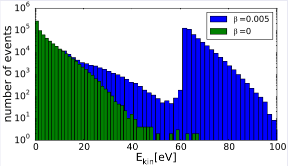
Rationale

- linear inhomogeneous field
- high-energy structure (HES)
- independent of the atom
- validated via CTMC simulations
- highly (temporally) localized electron bunches

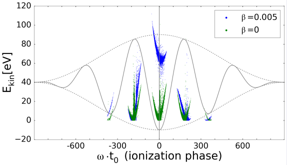
3D TDSE (H and He)



CTMC simulations



Ionization phase CTMC



L. Ortmann, et al. *Emergence of a higher energy structure in strong field ionization with inhomogeneous electric fields*, Phys. Rev. Lett. (in press) (2017).

Selected Results - Episode VIII
The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture

Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

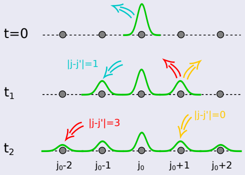
Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture



Comparison with Bloch-Bloch

Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

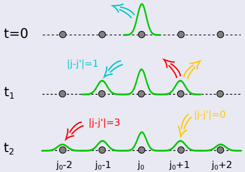
Selected Results - Episode VIII

The last recombination site

Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture



Comparison with Bloch-Bloch

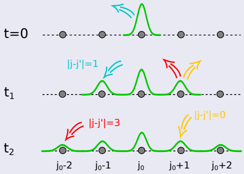
Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

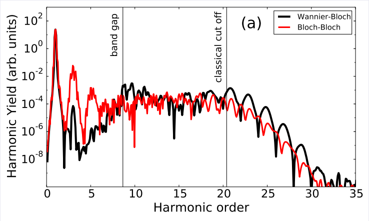
Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture



Comparison with Bloch-Bloch



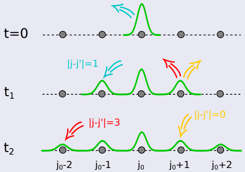
Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

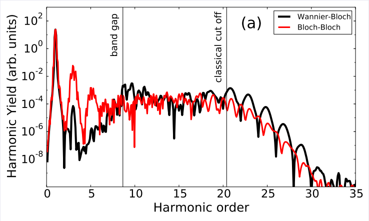
Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

Picture



Comparison with Bloch-Bloch



Localization study

E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

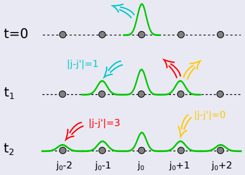
Selected Results - Episode VIII

The last recombination site

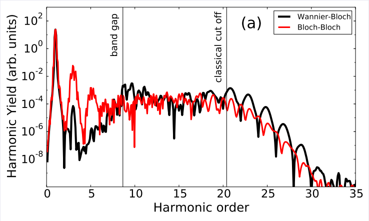
Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

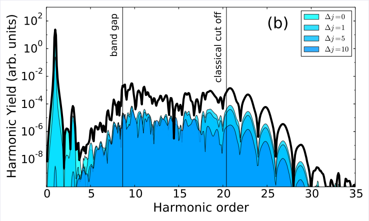
Picture



Comparison with Bloch-Bloch



Localization study



E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X 7, 027017 (2017).

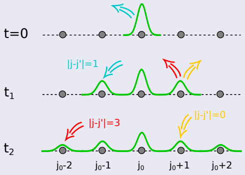
Selected Results - Episode VIII

The last recombination site

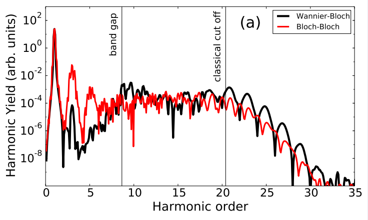
Rationale

- HHG in solids
- Wannier picture for the valence band (sites)
- Bloch picture for the conduction band (delocalized)
- atomic-like recombination picture (different sites contribution)
- other models comparison: advantages

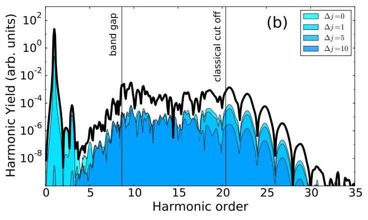
Picture



Comparison with Bloch-Bloch



Localization study



E. N. Osika, et al. *Wannier-Bloch approach to localization in high harmonics generation in solids*, Phys. Rev. X **7**, 027017 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- Studies of electron dynamics at its natural time and spatial scales
- Theoretical modeling of novel laser-matter processes: quantal, semiclassical & classical
- Reliability of the theoretical approaches and their predictions
- Prospect of table-top high repetition rates and strong laser sources using plasmonic fields: looking for experimental alternatives

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (near) future
Outlook, Perspectives & Challenges

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

The (near) future
Outlook, Perspectives & Challenges

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. 80, 054401 (2017).

- Extension of the theoretical approaches to more complex nonhomogeneous fields & macroscopic effects modeling (problem of incoherent radiation)
- Exploring (theoretical & experimentally) strong field related phenomena (above threshold photoemission, HHG in solids, electron emission and radiation from thin films, etc.)
- Strong field physics at nanometric scale (attosecond streaking of plasmonic fields, tailoring electron trajectories, molecular dynamics)
- Multielectronic processes driven by plasmonic fields: understanding the mechanisms

M.F. Ciappina, et al. *Attosecond physics at the nanoscale*, Rep. Prog. Phys. **80**, 054401 (2017).

Thank You

Thank you
for your attention !

Attosecond Physics at the Nanoscale

International Workshop

Scientific Coordinators:
Dr. Marcelo Ciappina (ELI-Beamlines, Czech Republic)
Prof. Seungchul Kim (POSTECH and Busan University, South Korea)
Prof. Young-Jin Kim (Nanyang Technological University, Singapore)

When: October 22-26, 2018 (Save the date!!!)
Where: Center for Theoretical Physics of Complex Systems (PCS), Daejeon, South Korea
Interested? Please write me: marcelo.ciappina@eli-beams.eu
Partial or total support provided

Stay Tuned!!!

Q & A

Questions & Answers