Broadband isolated attosecond XUV pulses

E. Mével

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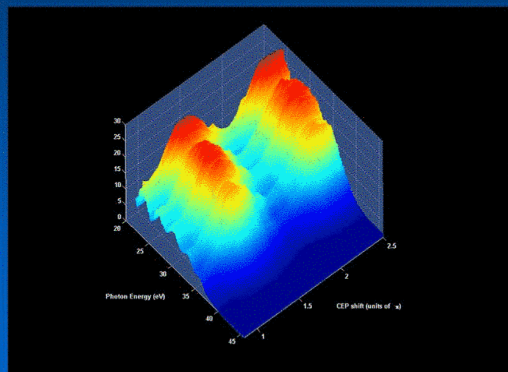

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Outline

Ultrashort reminder on the 3 step model

Isolation of a single attosecond pulse

Experimental confinement in Argon and Neon

Conclusions and perspectives

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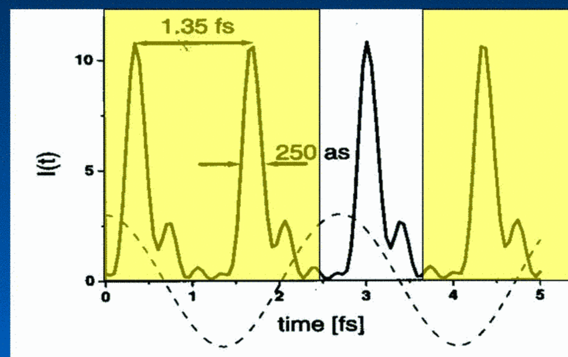
HHG as a source of as pulse train

$T_0/2$



P. M. Paul et al., Science ***292****, 1689 (2001)*

How to select a single pulse from a train ?
Or
How to produce only a single pulse ?

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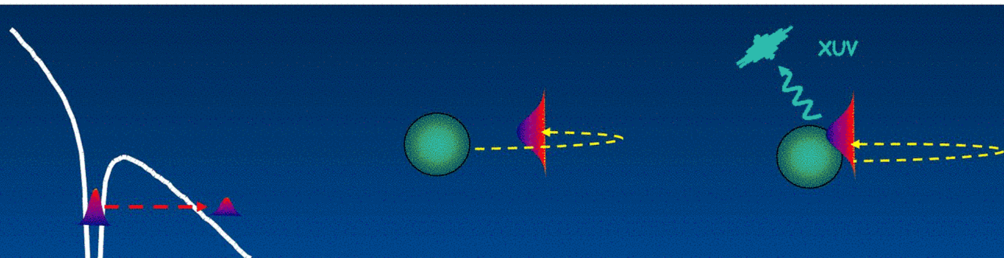
Three-step model



1: Ionisation

2: Oscillation Gain E_k

3: recombination XUV emission $h\nu = I_p + E_k$

Recombination times < $T_0/2$ =1.3 fs : attosecond pulse

Periodicity : train of attosecond pulses

Key : one recolliding EWP ⟹ one attosecond XUV pulse

P. B. Corkum, PRL ***71****, 1994 (1993)*

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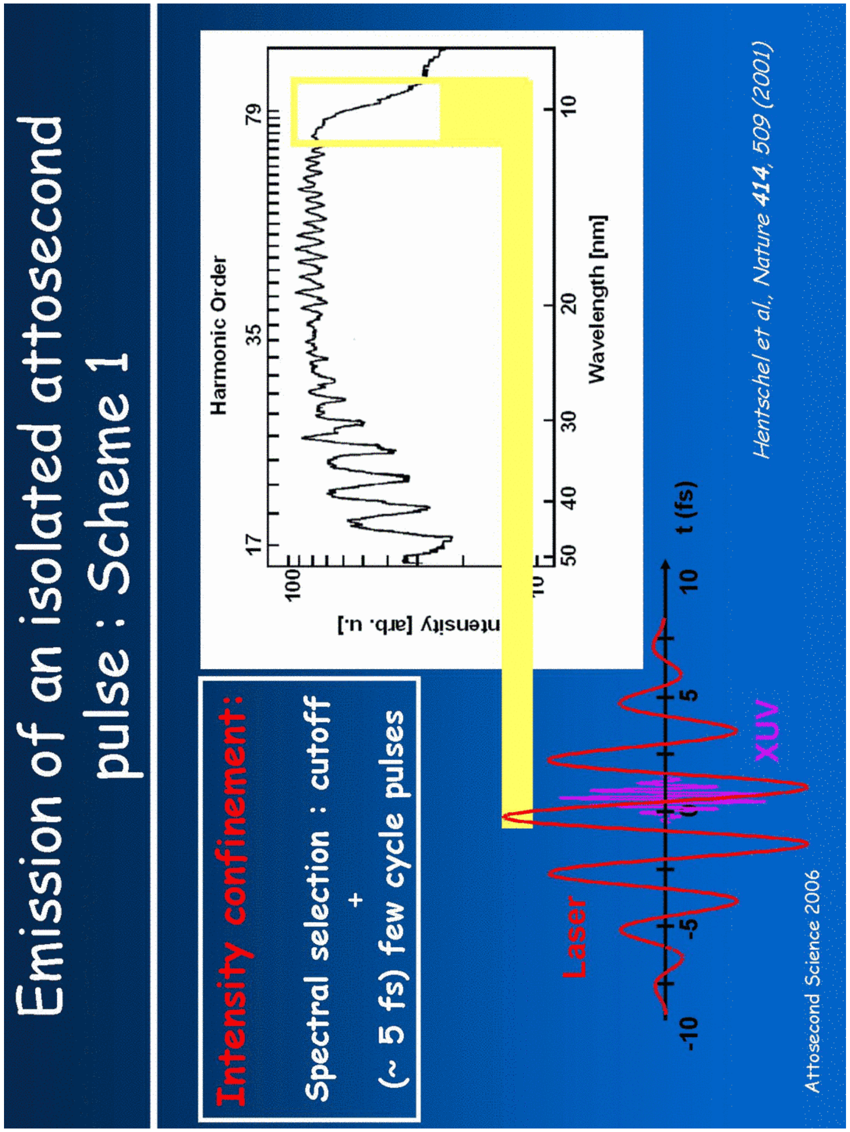
Emission of an isolated attosecond pulse : Scheme 1
Intensity confinement:
Spectral selection : cutoff
+
(~ 5 fs) few cycle pulses
Harmonic Order
17
35
79
Intensity [arb. u.]
100
10
Wavelength [nm]
50
40
30
20
10
Laser
XUV
t (fs)
-10
-5
0
5
10
Hentschel et al., Nature 414, 509 (2001)
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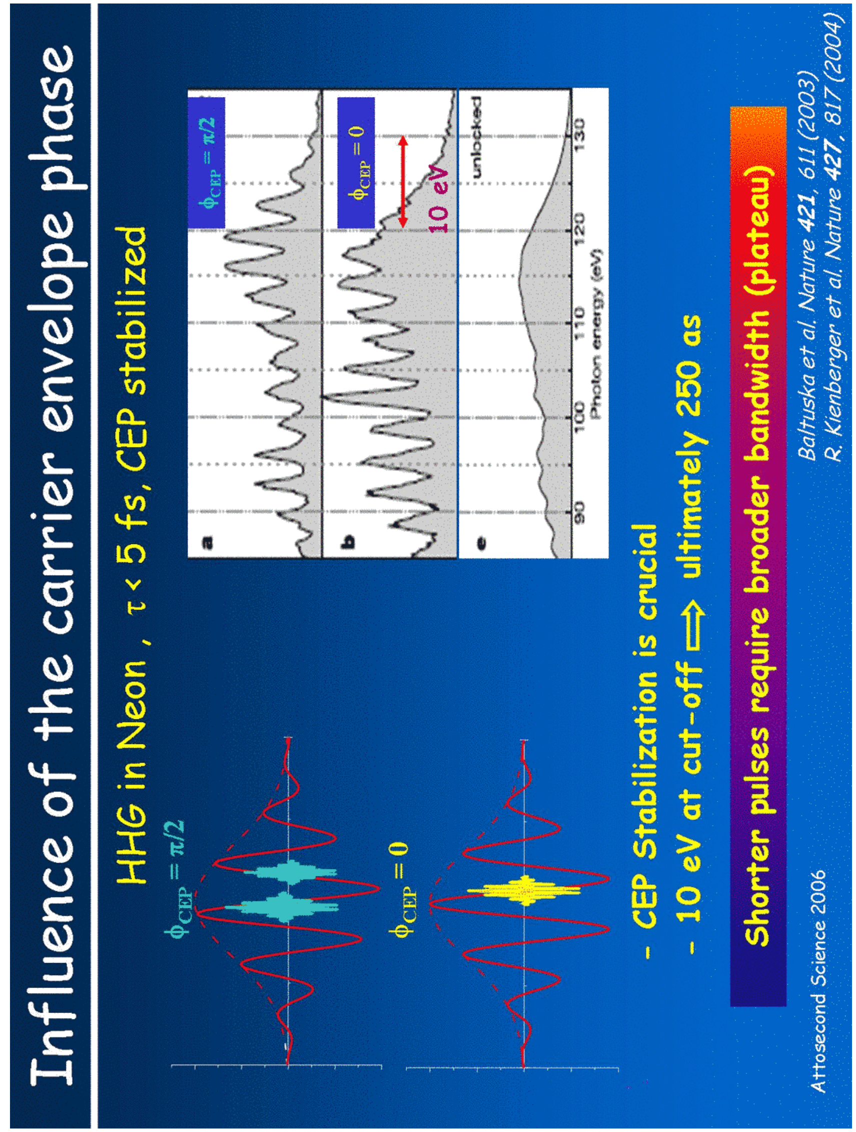
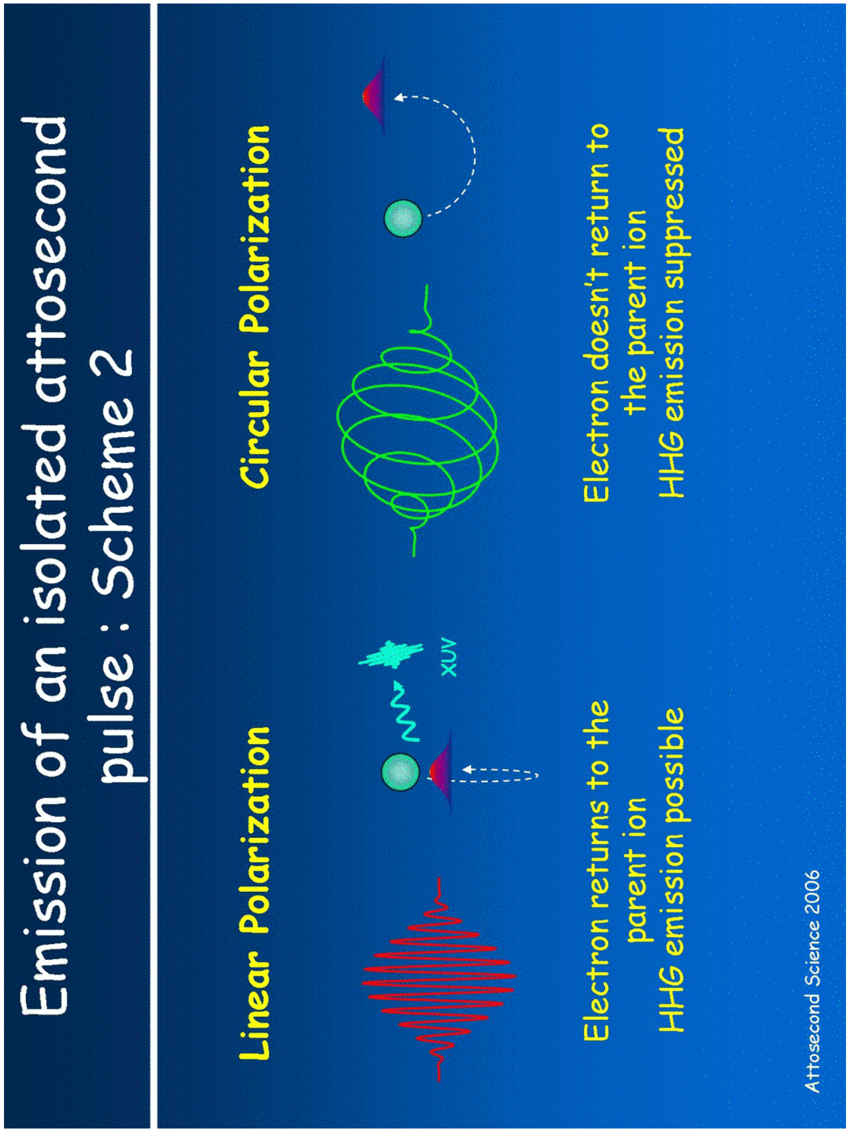
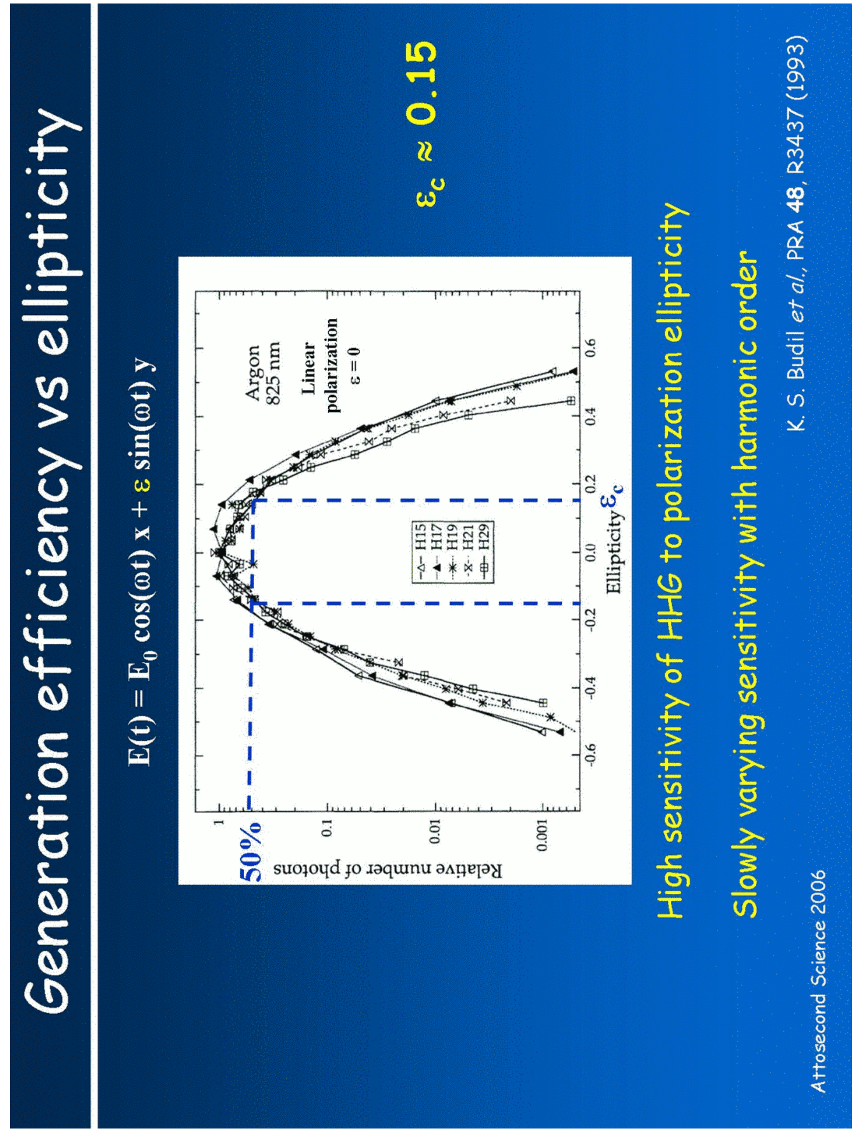
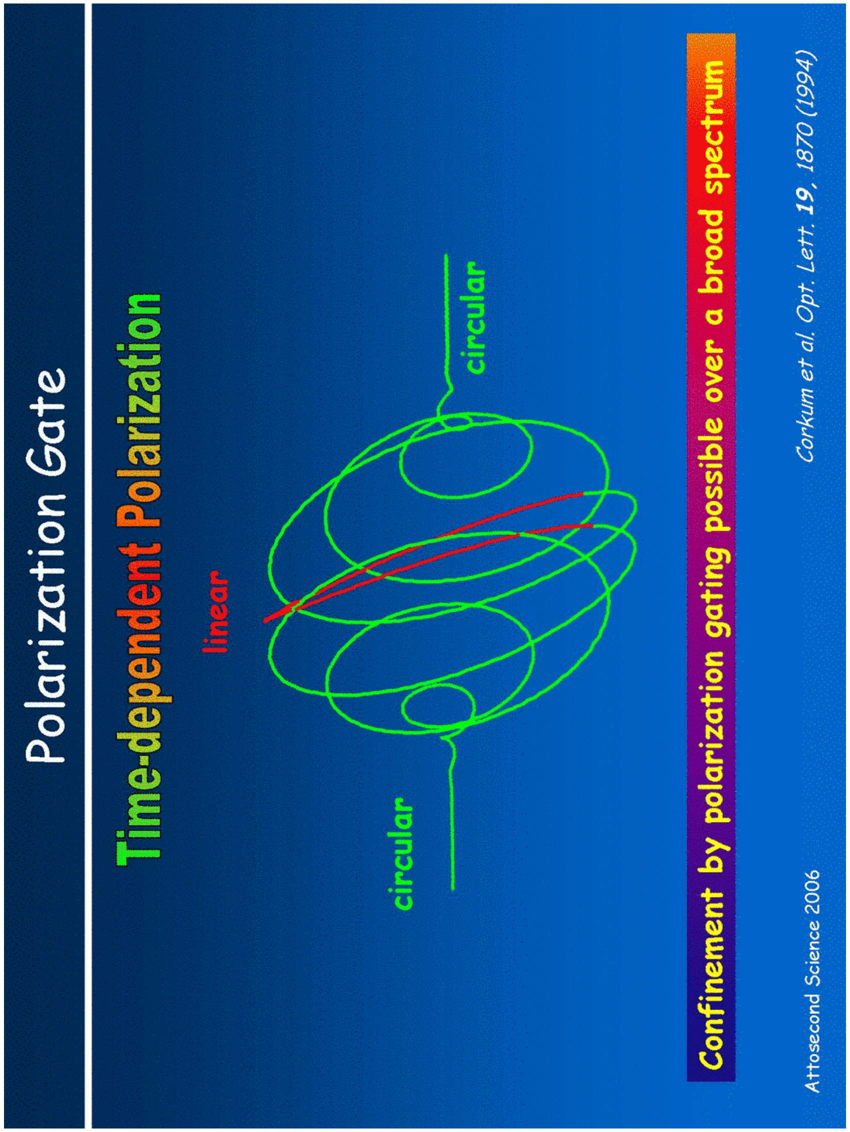
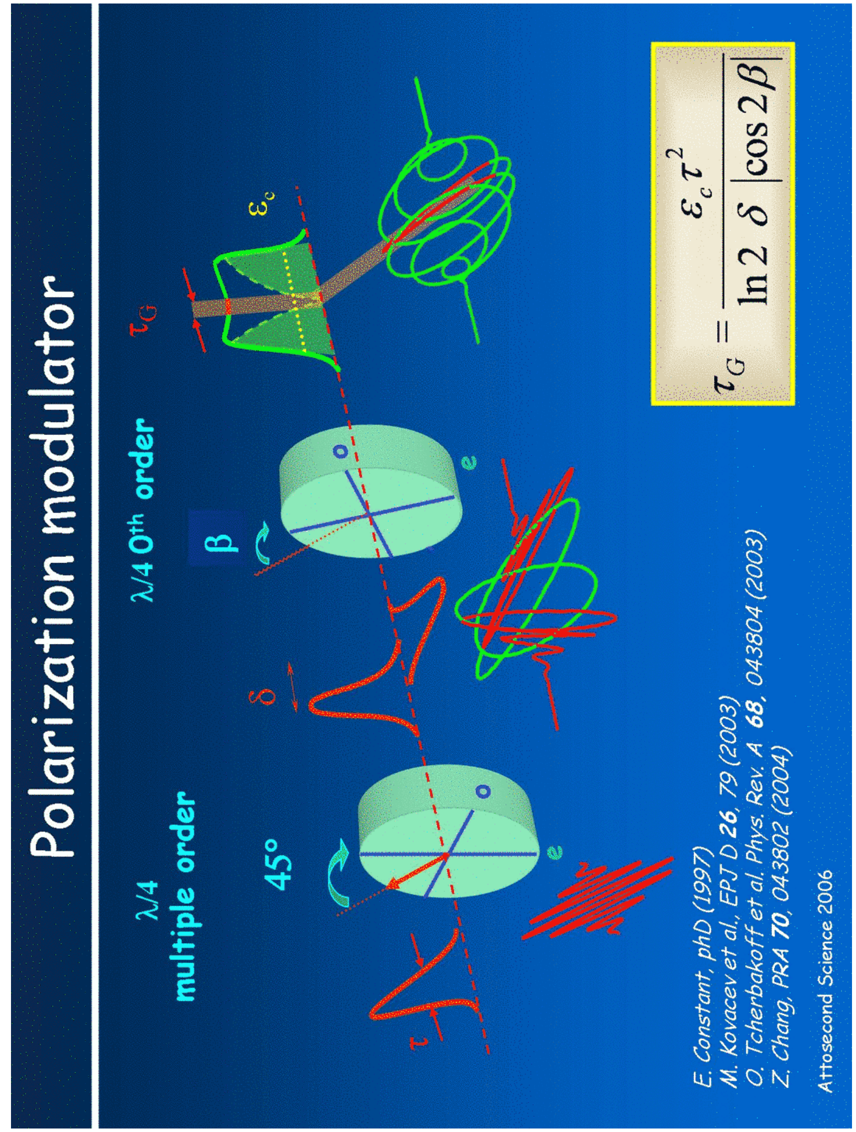
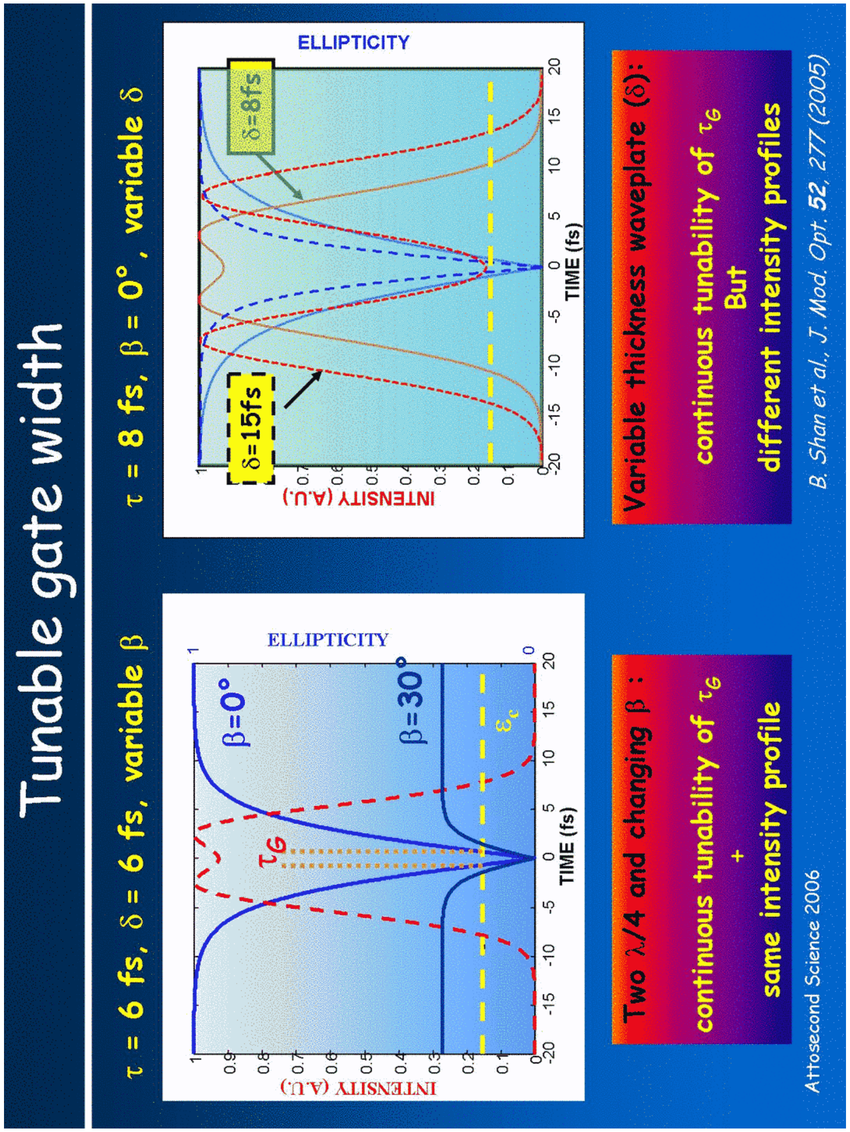

Influence of the carrier envelope phase
HHG in Neon , τ < 5 fs, CEP stabilized
φCEP = π/2
φCEP = 0
φCEP = π/2
φCEP = 0
10 eV
unlocked
Photon energy (eV)
90
100
110
120
130
- CEP Stabilization is crucial
- 10 eV at cut-off ⟹ ultimately 250 as
Shorter pulses require broader bandwidth (plateau)
Baltuska et al. Nature 421, 611 (2003)
R. Kienberger et al. Nature 427, 817 (2004)
Attosecond Science 2006

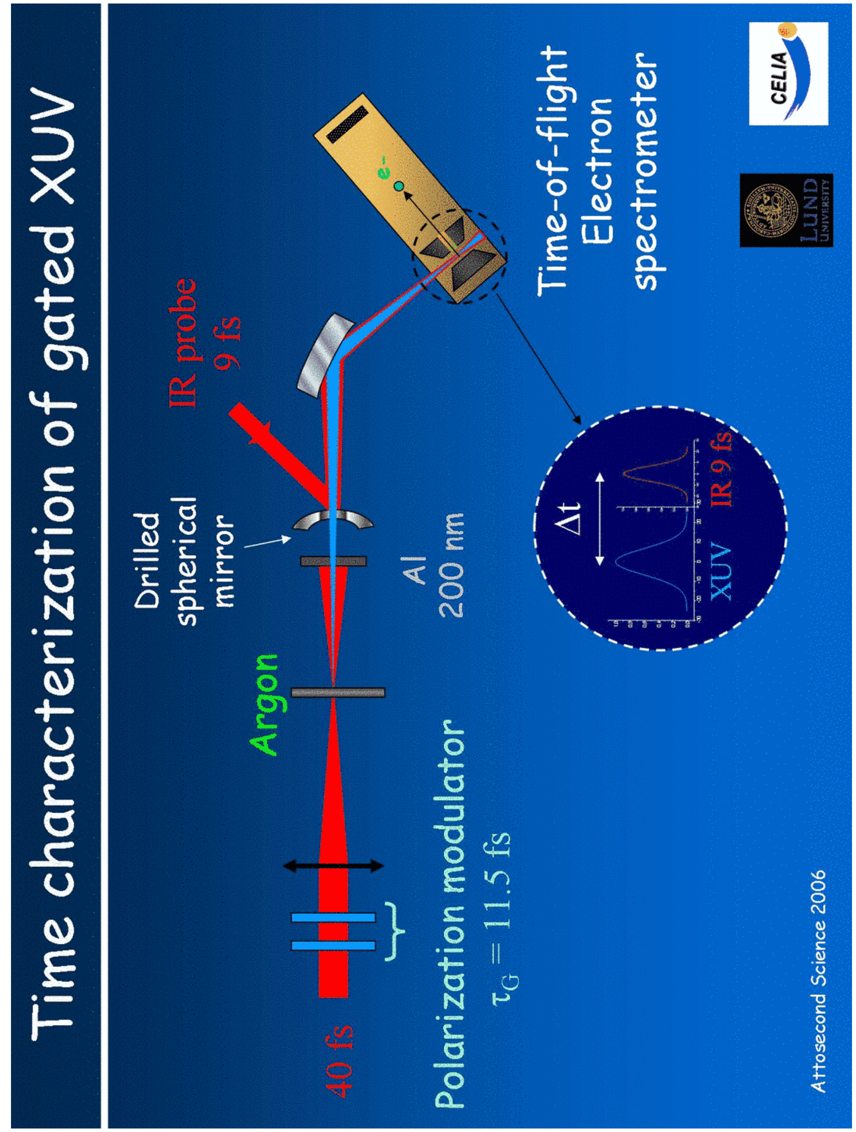

Emission of an isolated attosecond pulse : Scheme 2
Linear Polarization
Circular Polarization
XUV
Electron returns to the parent ion
HHG emission possible
Electron doesn't return to the parent ion
HHG emission suppressed
Attosecond Science 2006

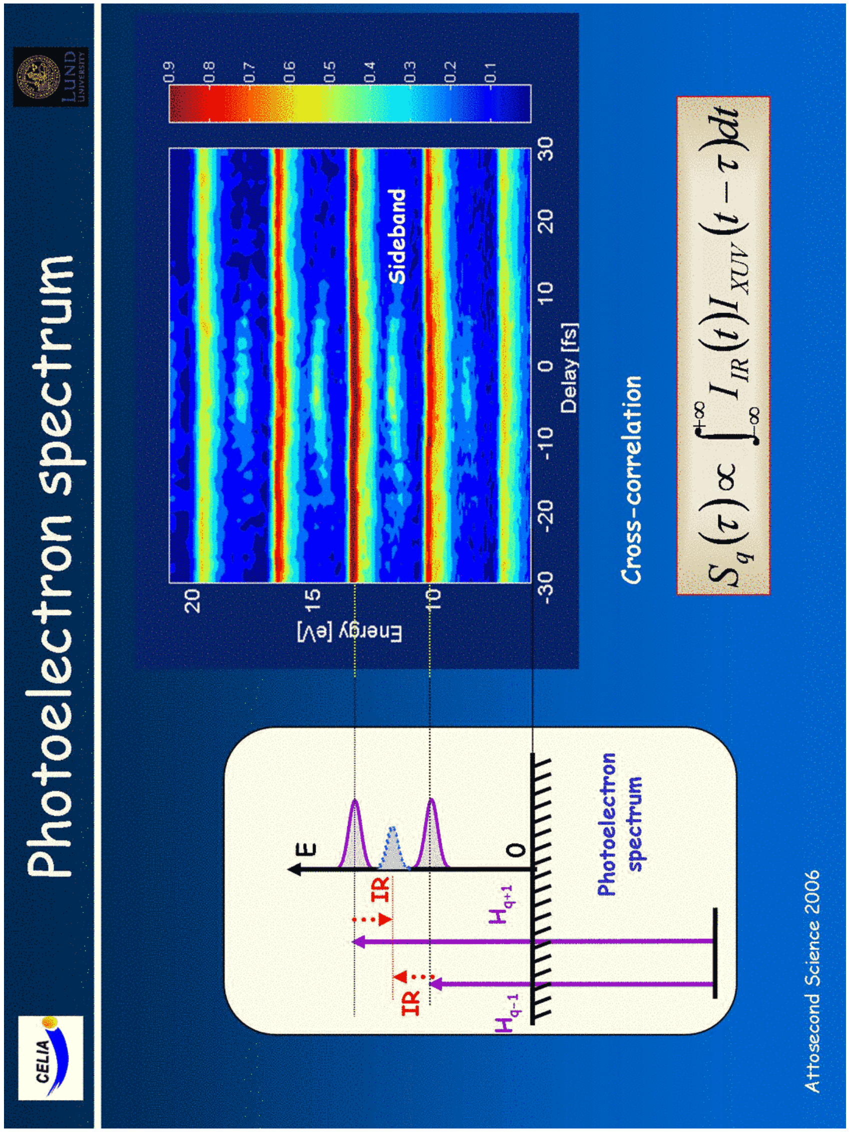

Generation efficiency vs ellipticity
E(t) = E0 cos(ωt) x + ε sin(ωt) y
Argon
825 nm
Linear polarization
ε = 0
H15
H17
H19
H21
H29
Relative number of photons
50%
Ellipticity
εc
εc ≈ 0.15
High sensitivity of HHG to polarization ellipticity
Slowly varying sensitivity with harmonic order
K. S. Budil et al., PRA 48, R3437 (1993)
Attosecond Science 2006


Polarization Gate
Time-dependent Polarization
linear
circular
circular
Confinement by polarization gating possible over a broad spectrum
Corkum et al. Opt. Lett. 19, 1870 (1994)
Attosecond Science 2006


Polarization modulator
λ/4
multiple order
45°
λ/4 0th order
β
τ
δ
τ_G
ε_c
o
e
o
e
$\tau_G = \frac{\varepsilon_c \tau^2}{\ln 2 \ \delta \ |\cos 2\beta|}$
E. Constant, phD (1997)
M. Kovacev et al., EPJ D 26, 79 (2003)
O. Tcherbakoff et al. Phys. Rev. A 68, 043804 (2003)
Z. Chang, PRA 70, 043802 (2004)
Attosecond Science 2006


Tunable gate width
τ = 6 fs, δ = 6 fs, variable β
τ = 8 fs, β = 0°, variable δ
ELLIPTICITY
INTENSITY (A.U.)
TIME (fs)
β=0°
β=30°
τ_G
ε_c
δ=15fs
δ=8fs
Two λ/4 and changing β :
continuous tunability of τ_G
+
same intensity profile
Variable thickness waveplate (δ):
continuous tunability of τ_G
But
different intensity profiles
Attosecond Science 2006
B. Shan et al., J. Mod. Opt. 52, 277 (2005)


Time characterization of gated XUV
40 fs
Polarization modulator
τ_G = 11.5 fs
Argon
Drilled spherical mirror
Al
200 nm
IR probe
9 fs
e-
Time-of-flight Electron spectrometer
Δt
XUV
IR 9 fs
CELIA
LUND UNIVERSITY
Attosecond Science 2006



Photoelectron spectrum
E
0
IR
IR
H_{q+1}
H_{q-1}
Photoelectron spectrum
Sideband
Energy [eV]
Delay [fs]
Cross-correlation
$S_q(\tau) \propto \int_{-\infty}^{+\infty} I_{IR}(t) I_{XUV}(t-\tau)dt$
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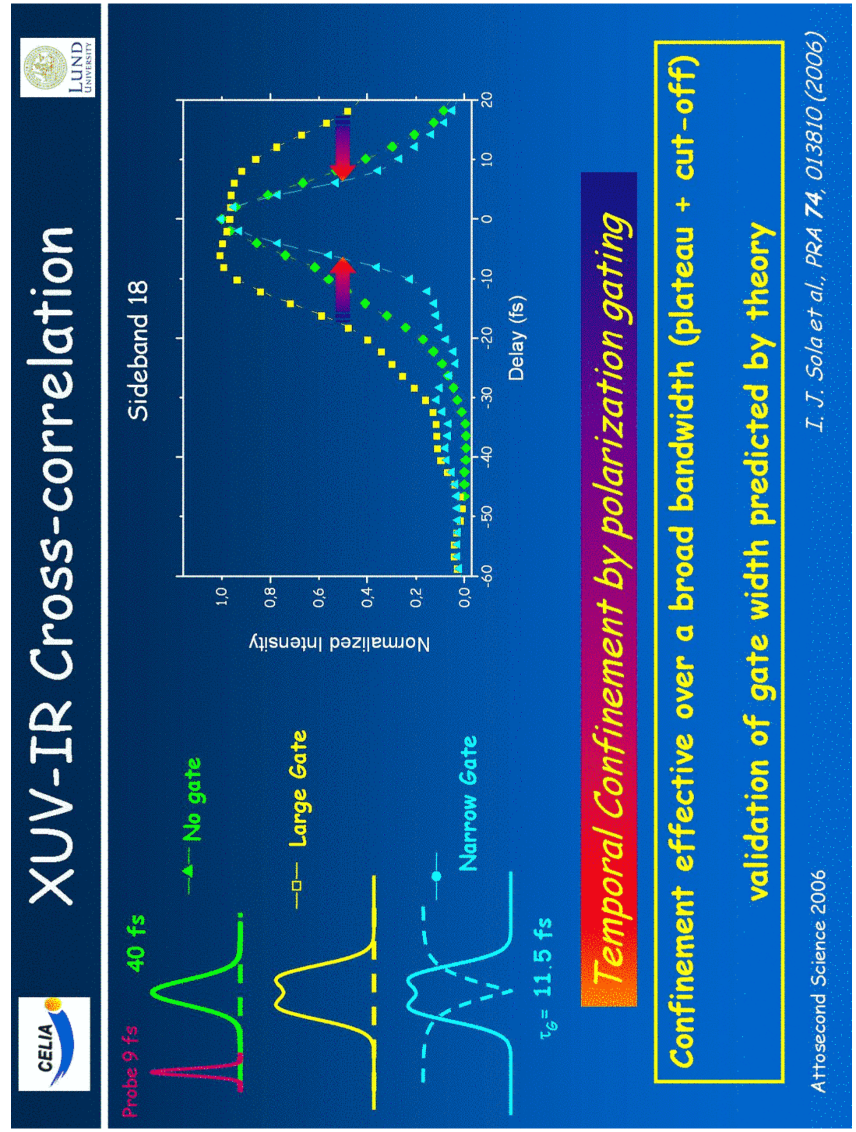
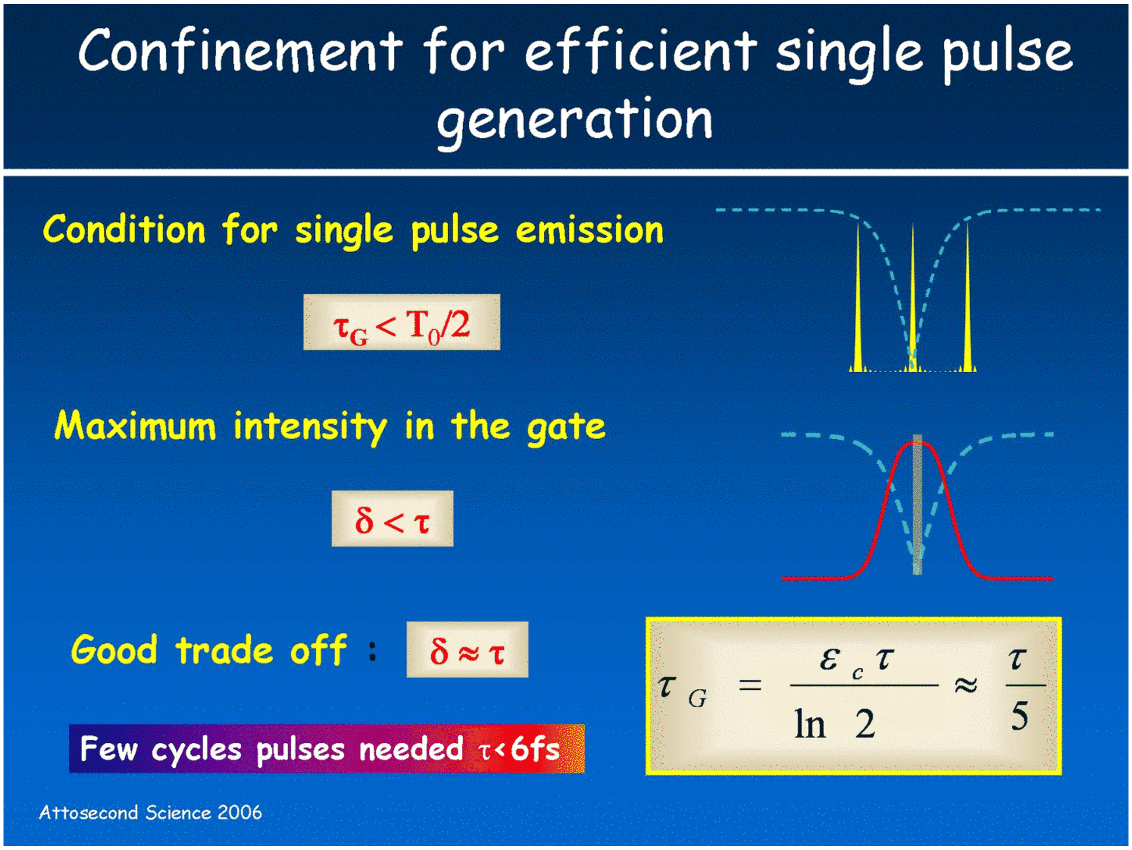
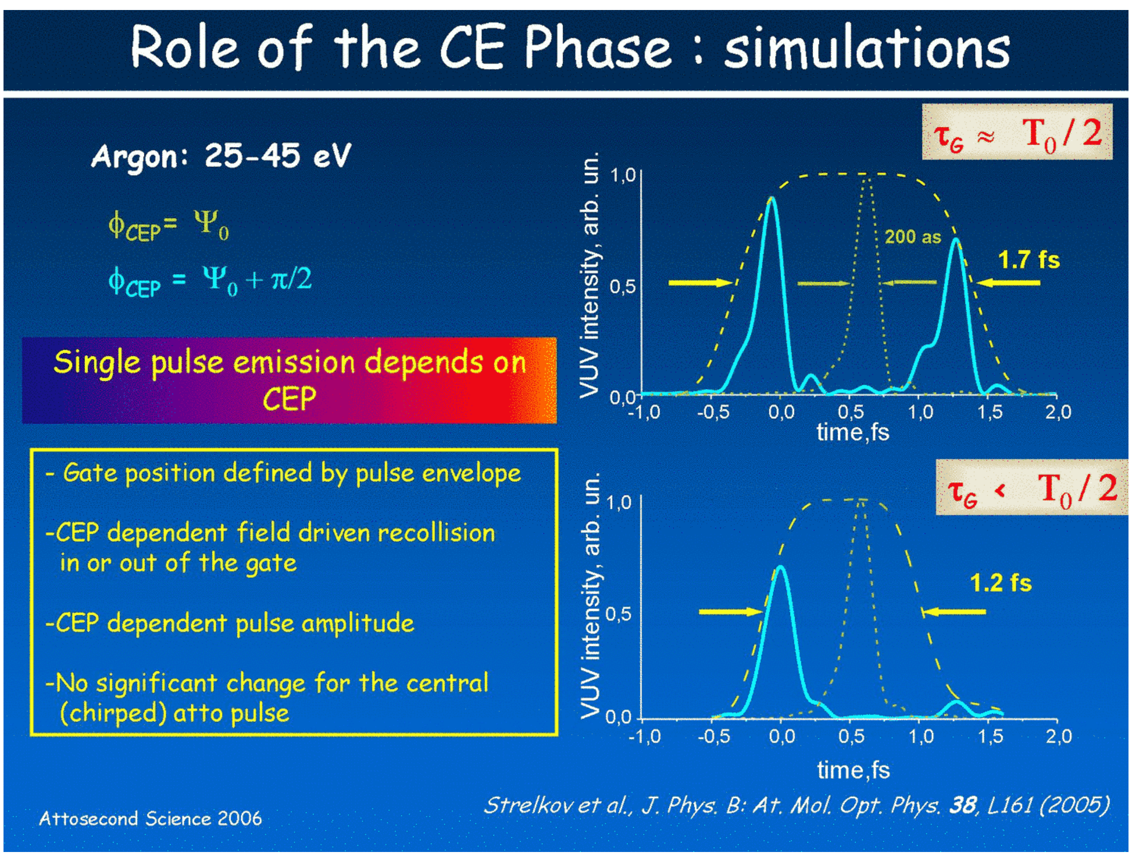
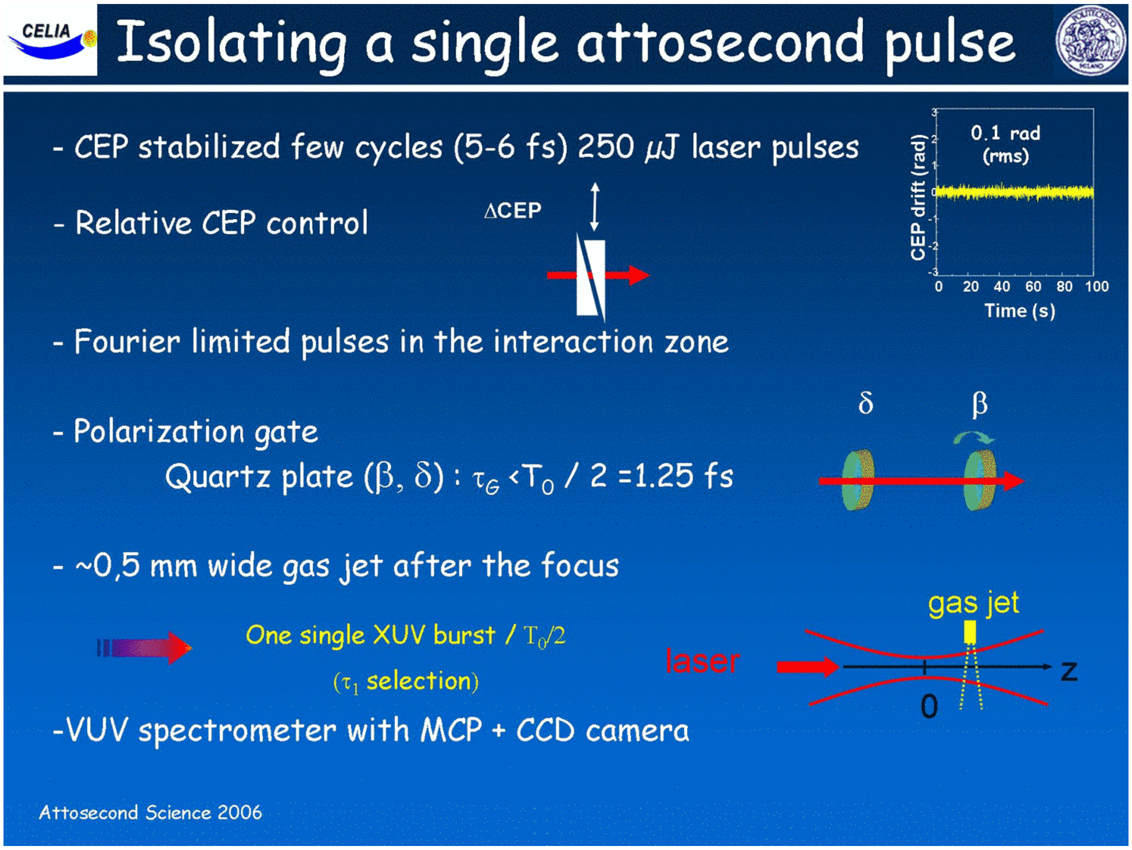


XUV-IR Cross-correlation
Probe 9 fs
40 fs
No gate
Large Gate
Narrow Gate
τ_G = 11.5 fs
Sideband 18
Normalized Intensity
Delay (fs)
Temporal Confinement by polarization gating
Confinement effective over a broad bandwidth (plateau + cut-off)
validation of gate width predicted by theory
I. J. Sola et al., PRA 74, 013810 (2006)
Attosecond Science 2006


Confinement for efficient single pulse generation
Condition for single pulse emission
$\tau_G < T_0/2$
Maximum intensity in the gate
$\delta < \tau$
Good trade off : $\delta \approx \tau$
Few cycles pulses needed τ<6fs
$\tau_G = \frac{\varepsilon_c \tau}{\ln 2} \approx \frac{\tau}{5}$
Attosecond Science 2006


Role of the CE Phase : simulations
Argon: 25-45 eV
$\phi_{CEP} = \Psi_0$
$\phi_{CEP} = \Psi_0 + \pi/2$
Single pulse emission depends on CEP
- Gate position defined by pulse envelope
-CEP dependent field driven recollision in or out of the gate
-CEP dependent pulse amplitude
-No significant change for the central (chirped) atto pulse
$\tau_G \approx T_0/2$
$\tau_G < T_0/2$
VUV intensity, arb. un.
time,fs
200 as
1.7 fs
1.2 fs
Strelkov et al., J. Phys. B: At. Mol. Opt. Phys. 38, L161 (2005)
Attosecond Science 2006


CELIA
Isolating a single attosecond pulse
- CEP stabilized few cycles (5-6 fs) 250 μJ laser pulses
- Relative CEP control
ΔCEP
0.1 rad (rms)
CEP drift (rad)
Time (s)
- Fourier limited pulses in the interaction zone
- Polarization gate
Quartz plate (β, δ) : $\tau_G < T_0 / 2 = 1.25$ fs
δ
β
- ~0,5 mm wide gas jet after the focus
One single XUV burst / $T_0/2$
(τ_1 selection)
laser
gas jet
z
0
-VUV spectrometer with MCP + CCD camera
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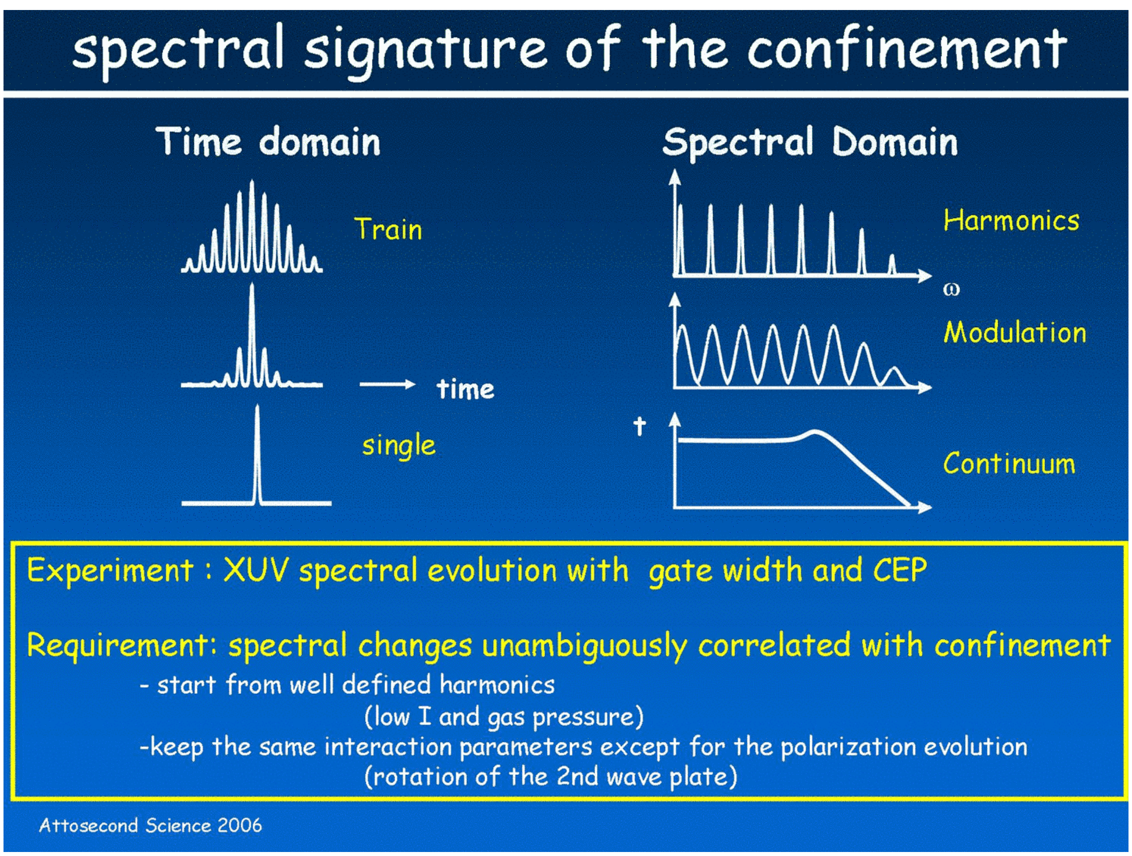
spectral signature of the confinement
Time domain
Train
time
single
Spectral Domain
Harmonics
ω
Modulation
Continuum
Experiment : XUV spectral evolution with gate width and CEP
Requirement: spectral changes unambiguously correlated with confinement
- start from well defined harmonics
(low I and gas pressure)
-keep the same interaction parameters except for the polarization evolution
(rotation of the 2nd wave plate)
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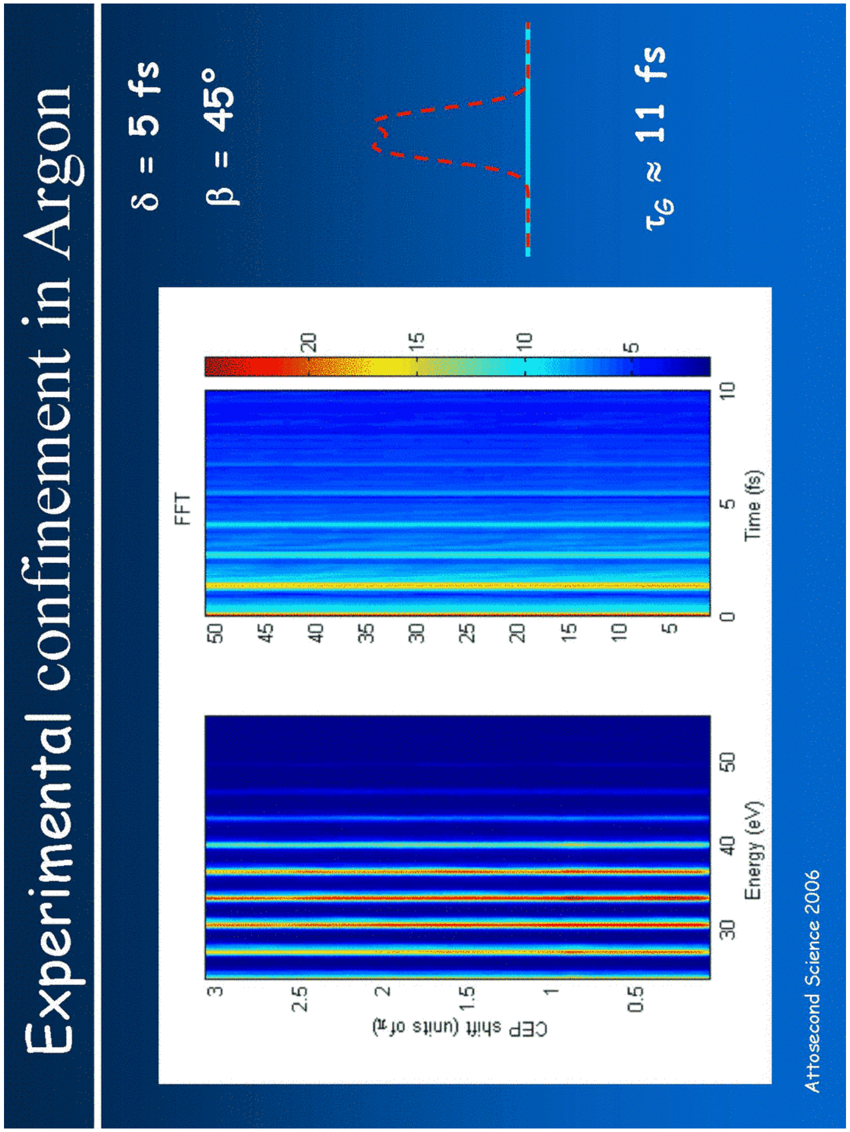
Experimental confinement in Argon
δ = 5 fs
β = 45°
τG ≈ 11 fs
CEP shift (units of π)
Energy (eV)
FFT
Time (fs)
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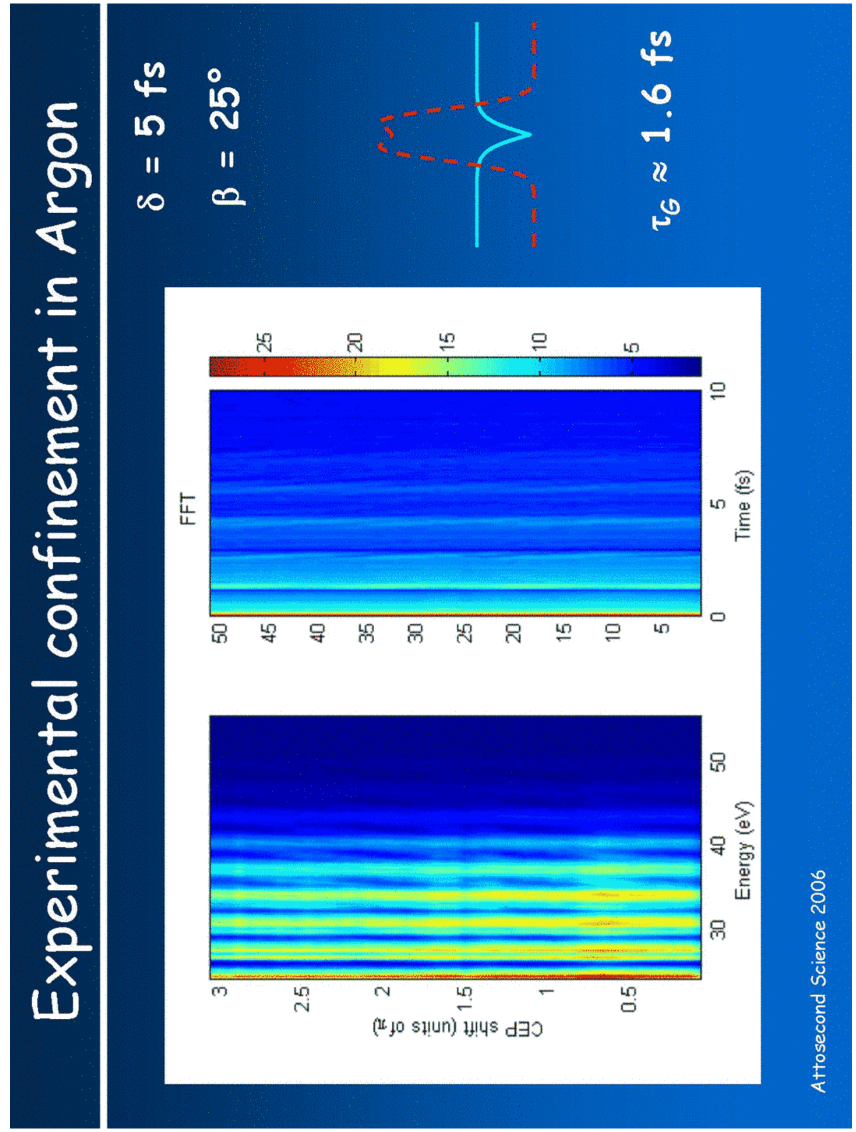
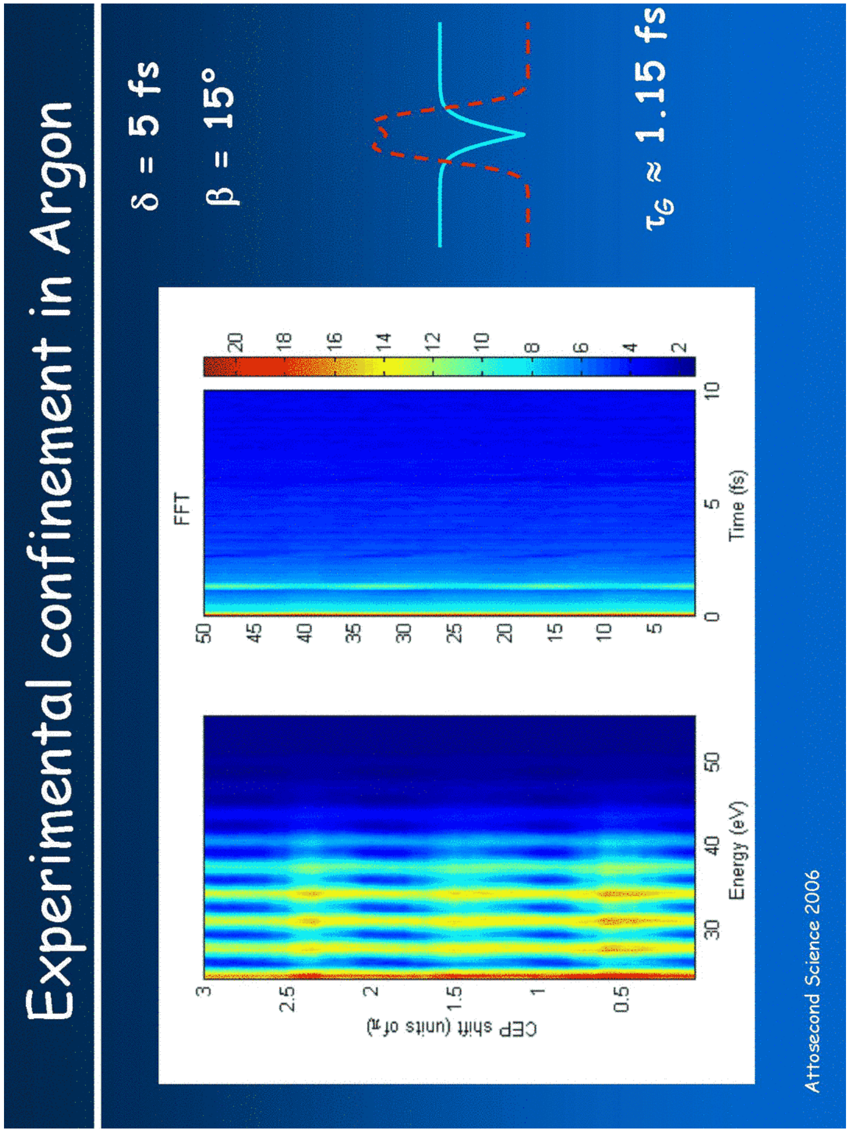
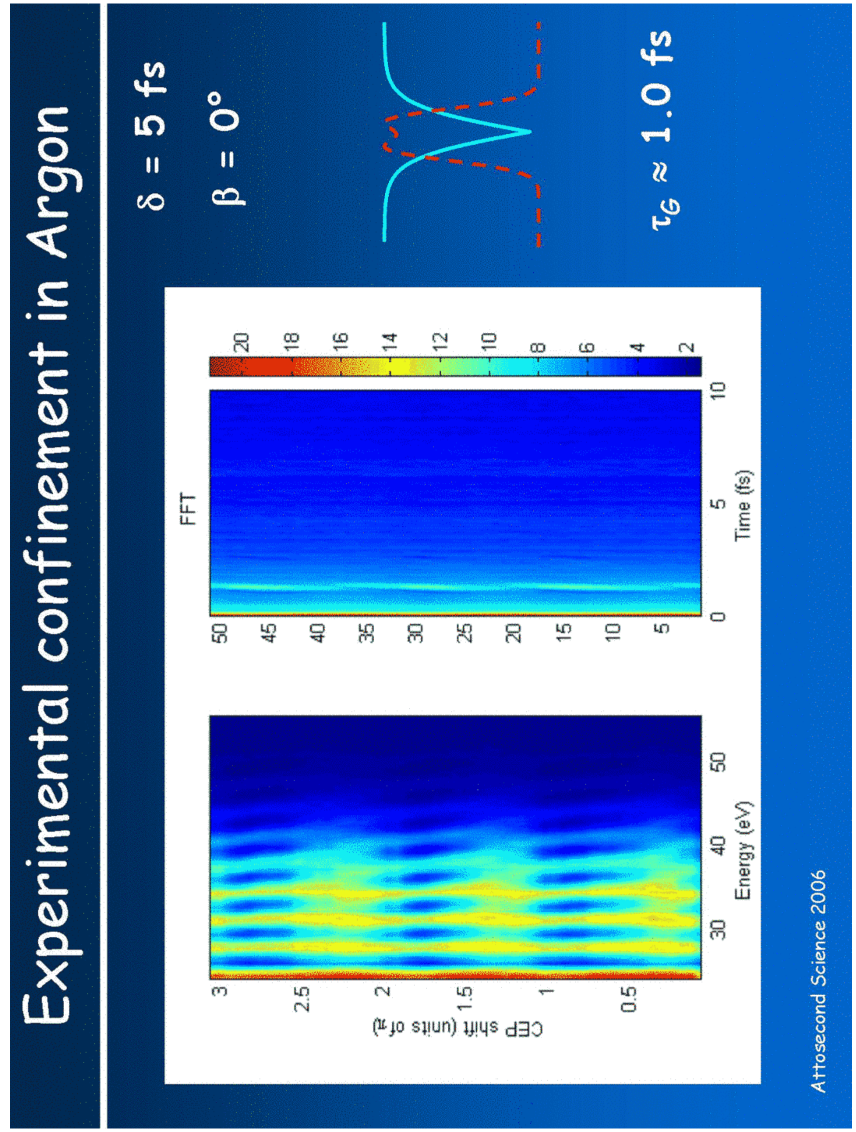

Experimental confinement in Argon
δ = 5 fs
β = 25°
τG ≈ 1.6 fs
CEP shift (units of π)
Energy (eV)
FFT
Time (fs)
Attosecond Science 2006


Experimental confinement in Argon
δ = 5 fs
β = 15°
τG ≈ 1.15 fs
CEP shift (units of π)
Energy (eV)
FFT
Time (fs)
Attosecond Science 2006


Experimental confinement in Argon
δ = 5 fs
β = 0°
τG ≈ 1.0 fs
CEP shift (units of π)
Energy (eV)
FFT
Time (fs)
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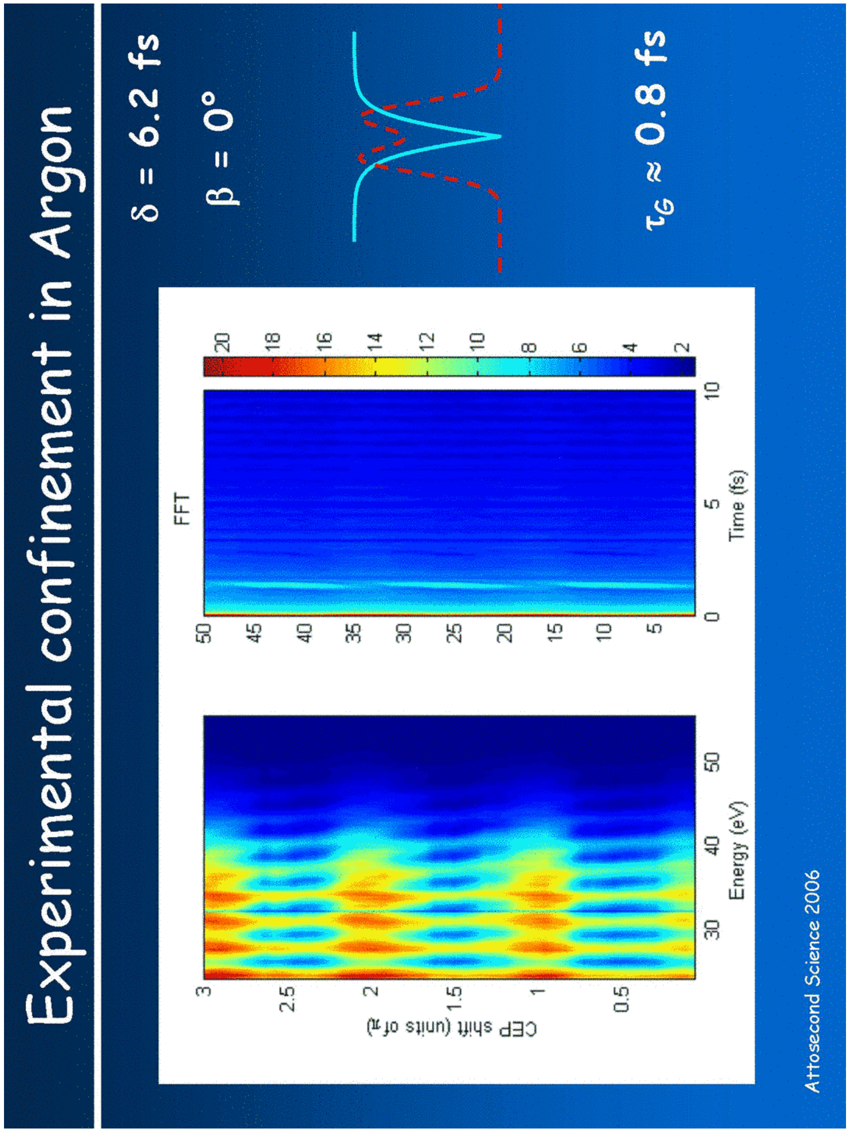
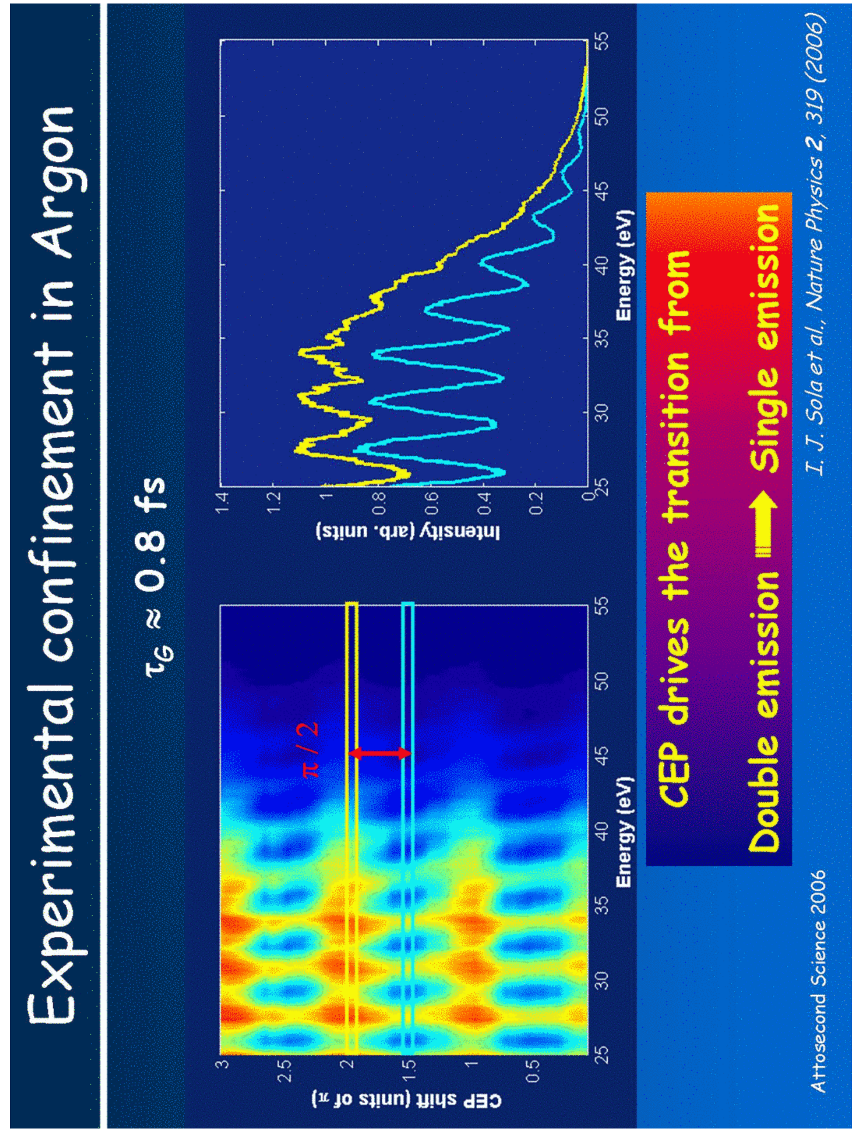

Experimental confinement in Argon
δ = 6.2 fs
β = 0°
τ_G ≈ 0.8 fs
FFT
CEP shift (units of π)
Energy (eV)
Time (fs)
Attosecond Science 2006


Experimental confinement in Argon
τ_G ≈ 0.8 fs
π / 2
CEP shift (units of π)
Energy (eV)
Intensity (arb. units)
CEP drives the transition from
Double emission ⟹ Single emission
I. J. Sola et al., Nature Physics 2, 319 (2006)
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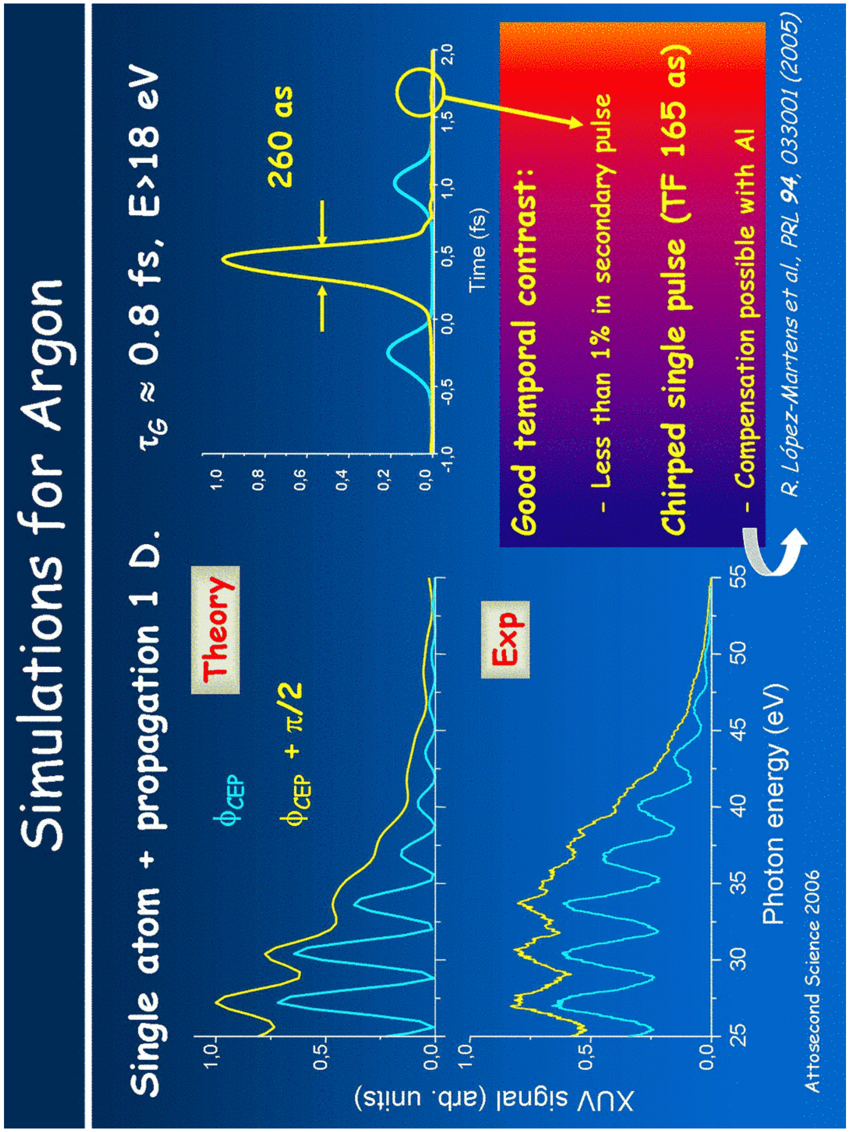
Simulations for Argon
Single atom + propagation 1 D.
$\tau_G \approx 0.8$ fs, E>18 eV
Theory
Exp
ϕ_{CEP}
$\phi_{CEP} + \pi/2$
XUV signal (arb. units)
Photon energy (eV)
260 as
Time (fs)
Good temporal contrast:
- Less than 1% in secondary pulse
Chirped single pulse (TF 165 as)
- Compensation possible with Al
R. López-Martens et al., PRL 94, 033001 (2005)
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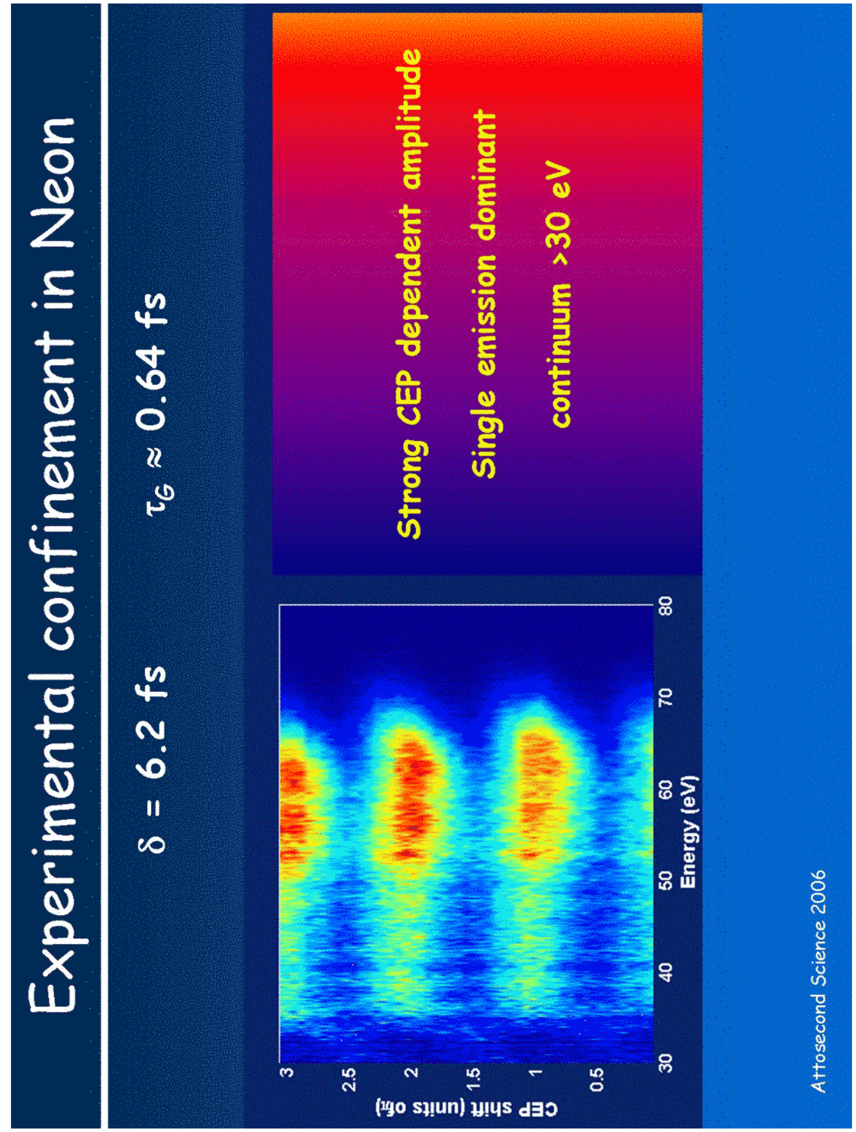
Experimental confinement in Neon
δ = 6.2 fs
$\tau_G \approx 0.64$ fs
CEP shift (units of π)
Energy (eV)
Strong CEP dependent amplitude
Single emission dominant
continuum >30 eV
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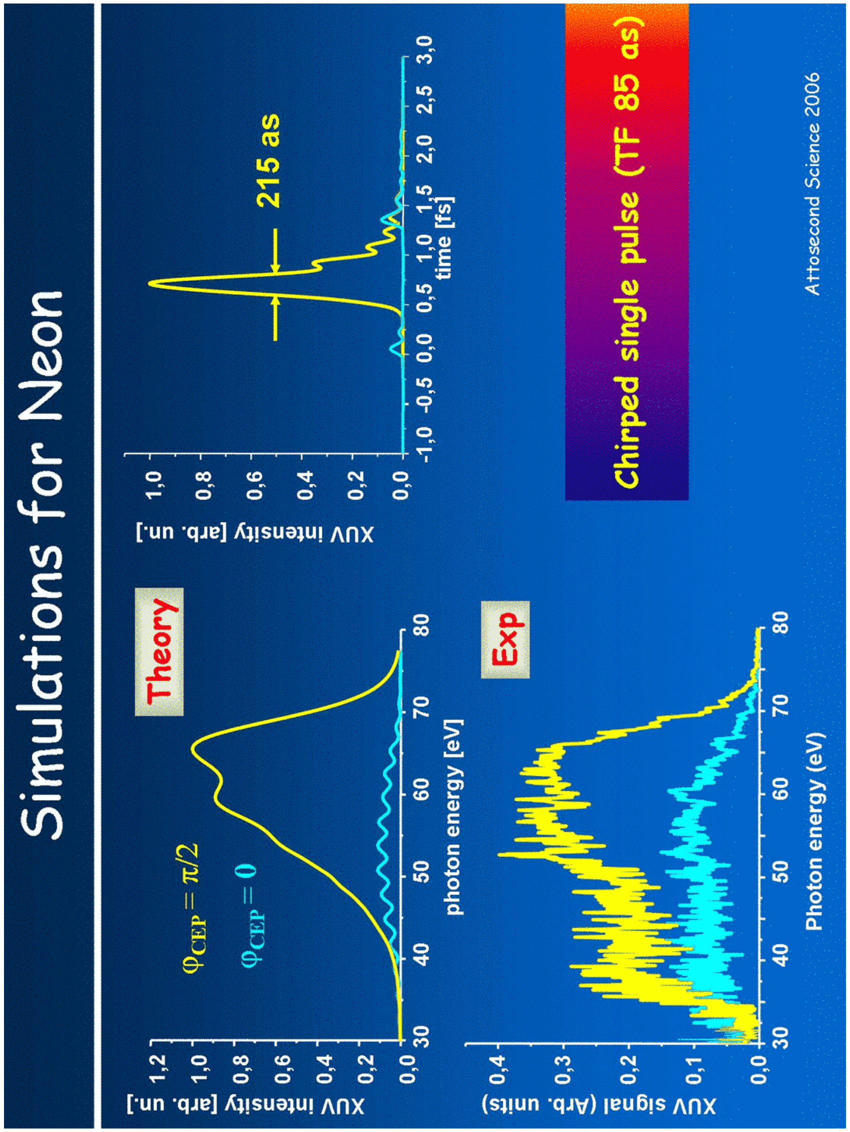
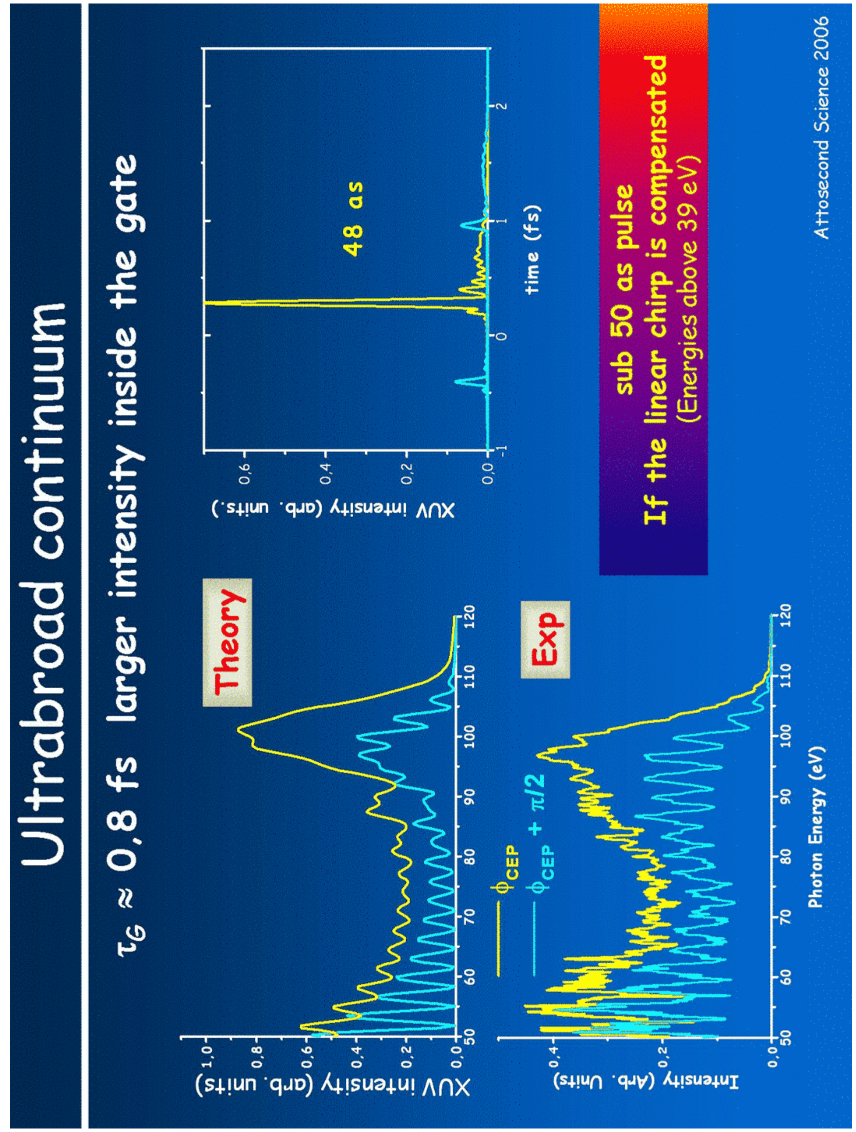

Simulations for Neon
Theory
φCEP = π/2
φCEP = 0
XUV intensity [arb. un.]
photon energy [eV]
Exp
XUV signal (Arb. units)
Photon energy (eV)
215 as
time [fs]
Chirped single pulse (TF 85 as)
Attosecond Science 2006


Ultrabroad continuum
τG ≈ 0,8 fs larger intensity inside the gate
Theory
XUV intensity (arb. units)
Exp
φCEP
φCEP + π/2
Intensity (Arb. Units)
Photon Energy (eV)
48 as
XUV intensity (arb. units.)
time (fs)
sub 50 as pulse
If the linear chirp is compensated
(Energies above 39 eV)
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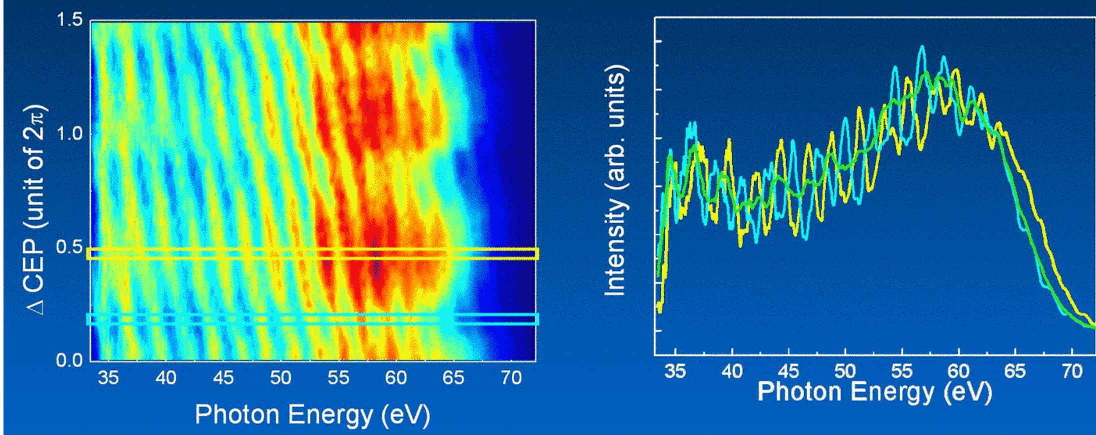
CEP and averaging effects

$\tau_G \approx 0{,}9$ fs



CEP averaging leads to an apparent continuum

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Conclusions

- **Continuous Attosecond control of EWP**
  control of the nb of recolliding EWP
- **Broadband & Tunable single attosecond emission**
  Argon (25 - 40 eV)
  Neon (35 - 70 eV, 50 - 100 eV)
- **New temporal domain now accessible: sub 100 as**
- **About 0.1 nJ/isolated attosecond pulse … BUT**
  - *High energy (few mJ) few cycle pulse now available*
  - *Polarization gating + ω-2ω field synthesis with 12 fs pulses*
    T. Pfeifer *et al.*, Opt. Lett. **31**, 975 (2006)
  - *Other (albeit more complicated) schemes of polarization gating for more efficient HHG with 20 fs pulses*
    D. Oron *et al.*, Rev. A **72**, 063816 (2006)

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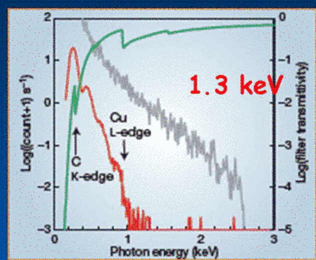
Perspectives : Isolated attosecond XUV pulses



J. Seres *et al.*, Nature **433**, 596 (2005)

Energetic (>1mJ) few cycle pulses, $\lambda \sim 1.6$ - 3 μm

Cut-off $\propto I \lambda^2 > 1$ keV

Supercontinuum >100 eV

few attosecond pulse

➡ **Probing multielectron relaxation at the atomic unit time scale (Auger, direct double ionization)**

Tunable sub-fs XUV pulse

➡ **Selective studies from excited to low lying orbitals dynamics in molecules. Mapping out H_2+ vibrational wave packet (14 fs)**

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Challenges

Spectral filtering and chirp compensation ?

- Spectral reshaping through re-absorption + confinement
- Metallic filters (specific bandwidth)
- Chirped XUV mirrors (low reflectivity)
  A. S. Morlens et al., Opt. Lett. 30, 1554 (2005)
- Plasma dispersion
  see poster from Kyung Taec Kim (KAIST)
- Limited intrinsic atto chirp
  HHG with 2 & 4 μm (Lou DiMauro)

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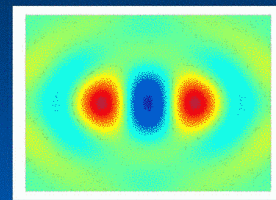
Perspectives:
Single recolliding electron wave packet

Tomography of stationary orbitals *J. Itatani et al, Nature 432, 867 (2004)*



Long pulses:

Identical recolliding EWP probe the orbital

Time resolved Tomography

Time resolved tomography of non stationary orbitals
- -Broad EWP energy spectrum required
- -Attosecond temporal resolution (provided the chirp is known)

G.L. Yudin et al., Phys. Rev. Lett. ***96****, 063002 (2006)*

Does the time dependent polarization twist the EWP ?

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Collaborations and Aknowledgments

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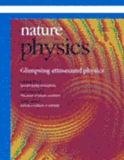
General Physics Institute of Russian academy of Sciences, Moscow (Russia)

EU networks ATTO et XTRA | Laserlab JRA FOSCIL | Région Aquitaine

Looking for summer reading.... ?



Sola et al., Nature Physics ***2****, 319 (2006)*

And more...