Attosecond pulse shaping using quasi-phase matching

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Imperial College London

Outline

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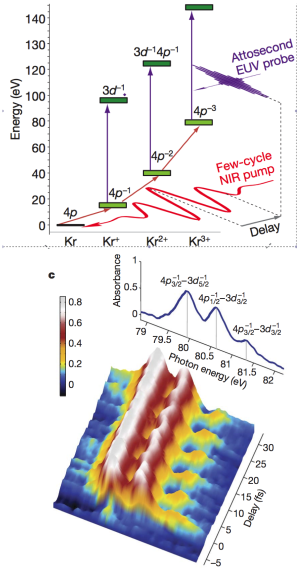
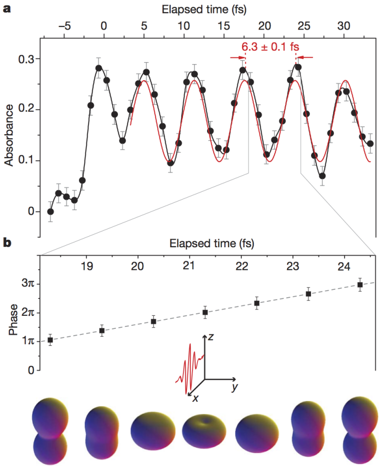
- Propose new method: chirped quasi-phase matching
- Simulations: transform-limited pulses and chirp control
- Simulations: shaping of attosecond pulse sequences
- Conclusion

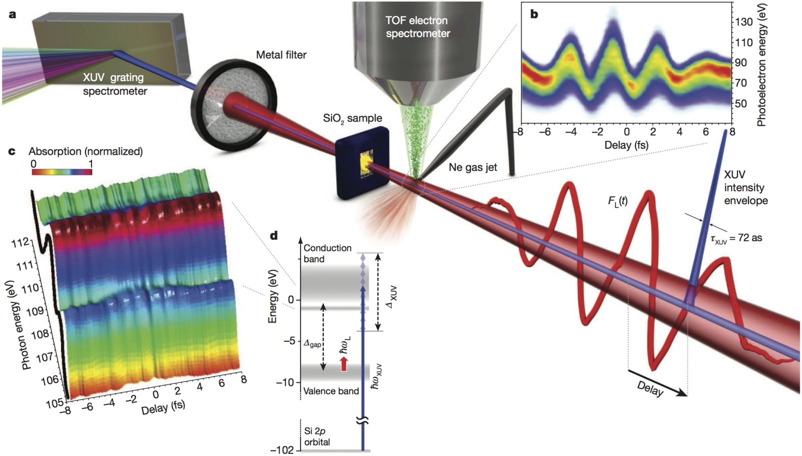
Transient absorption — probe of valence electron motion





Goulielmakis *et al.* (2010)

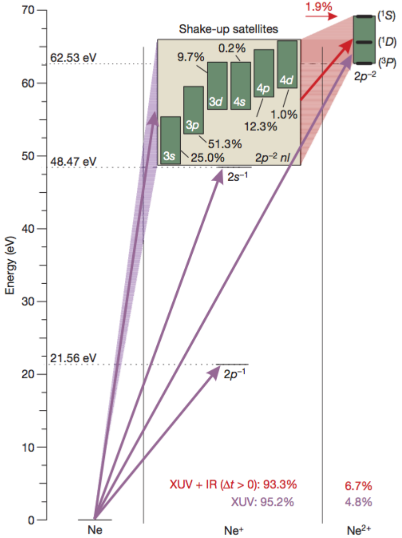
Transient absorption — probe of ultrafast change of material properties

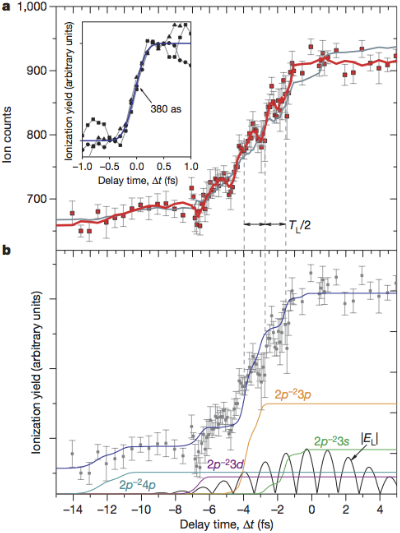


Schultze *et al.* (2013)

Creation of excited ionic states

Probed with optical field ionization

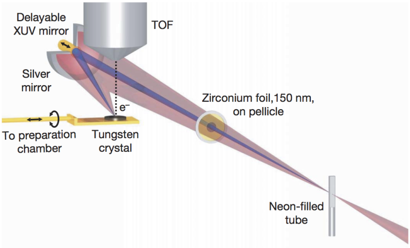


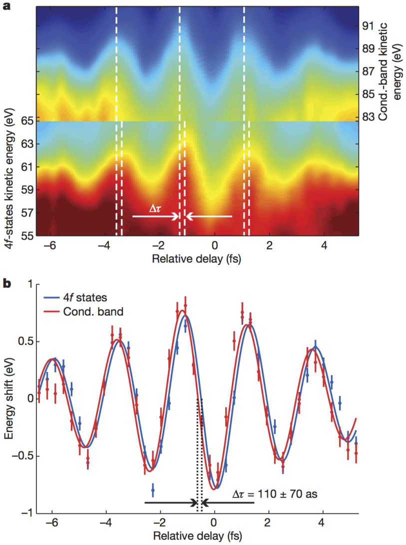


Uiberacker *et al.* (2007)

Launching electron motion in a solid

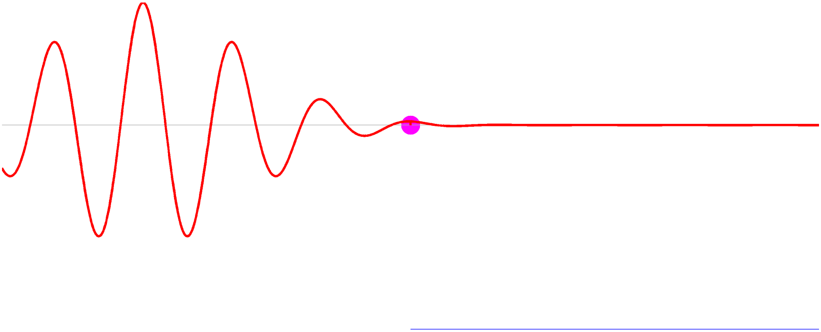
Probed with photoelectron streaking





Cavalieri *et al.* (2007)

Production with HHG



$$\omega = \mathsf{KE} + Ip$$

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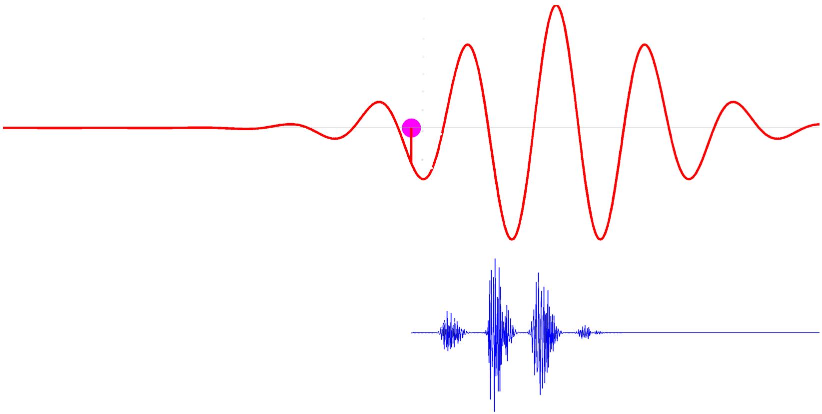

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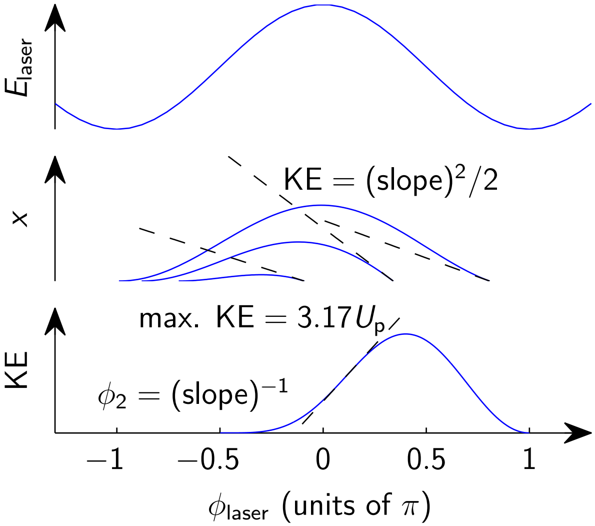
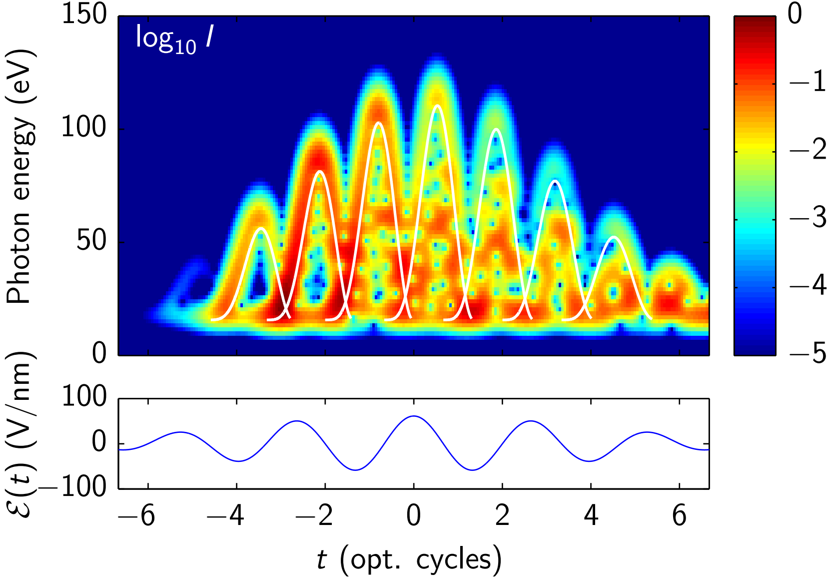
Structure of an attosecond burst



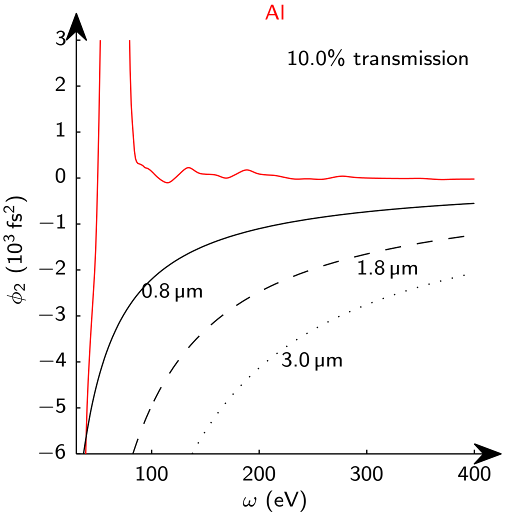
$$Up = EL^2/\omega L^2$$

Classical versus quantum



Attosecond dispersion control

- 50-300 nm metal films: Zr,Si,Al,...
  Goulielmakis *et al.* (2008);
  López-Martens *et al.* (2005)
  < 150 eV



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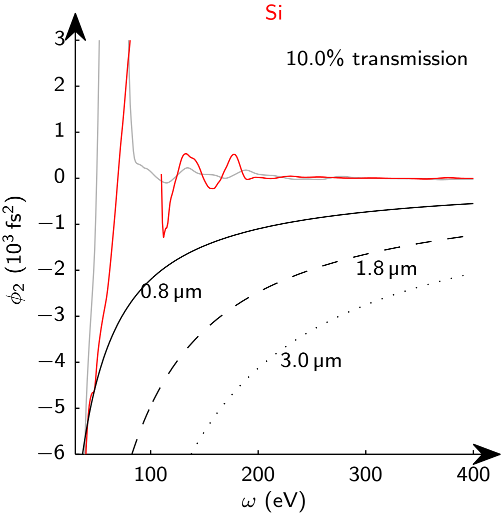

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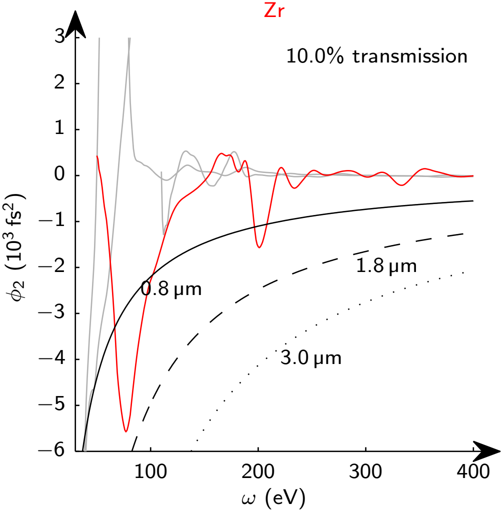

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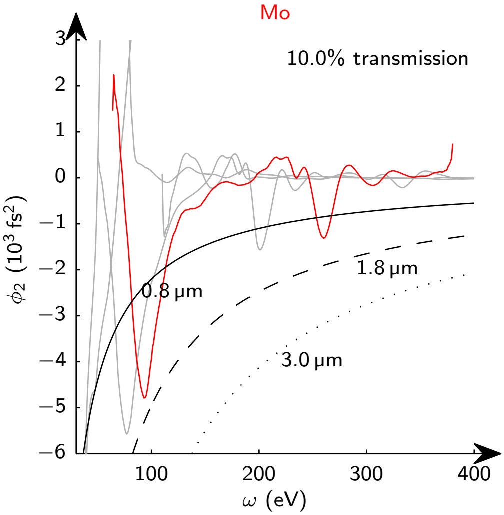

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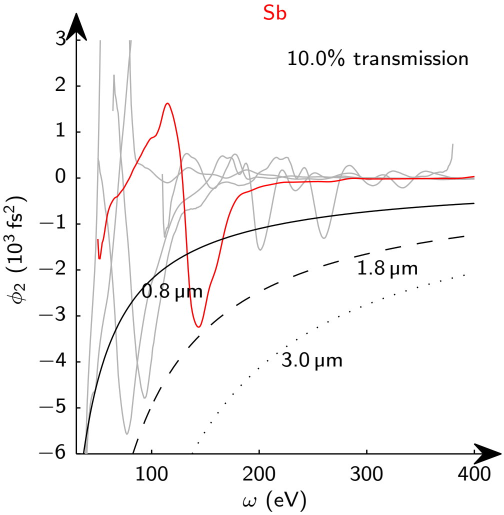

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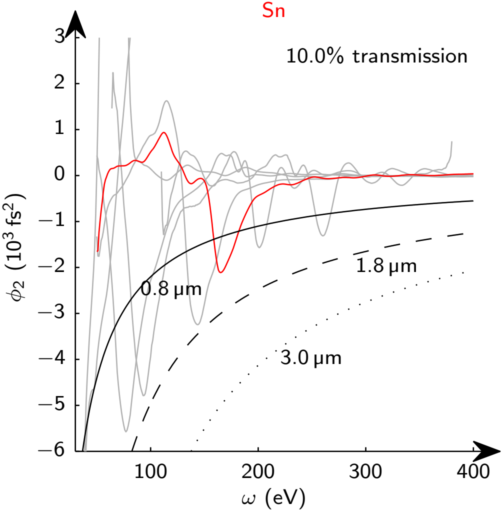

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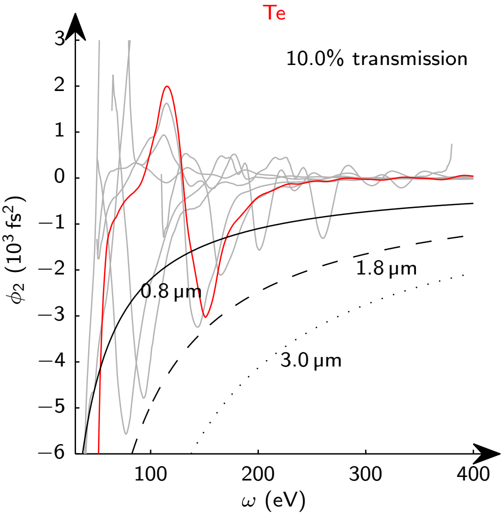

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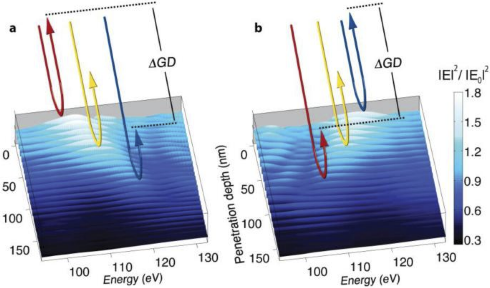

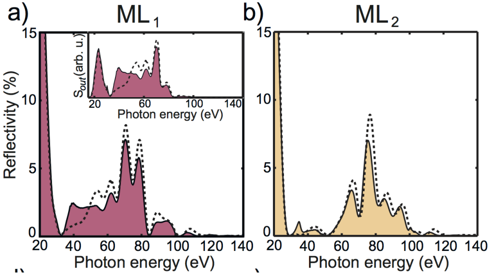

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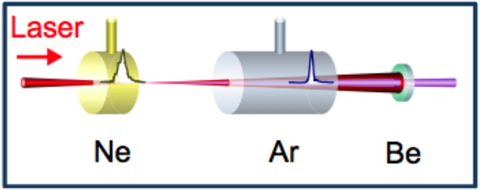

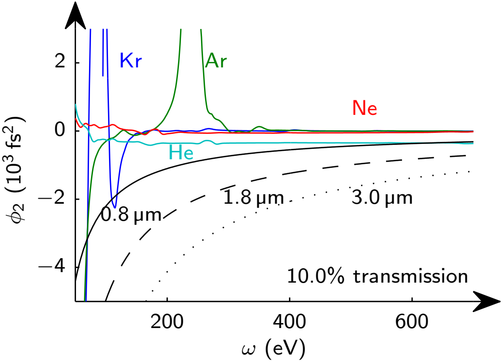

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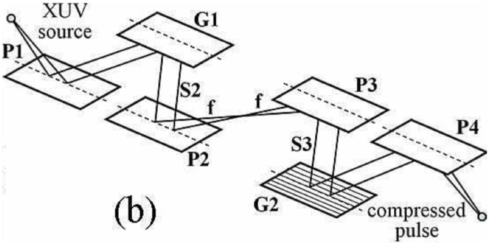
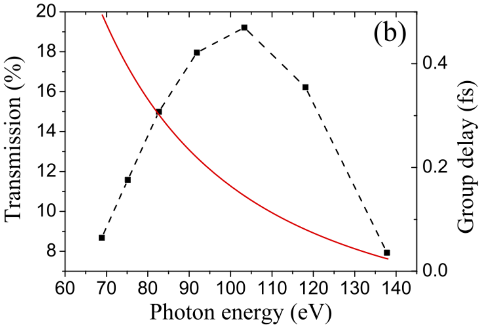
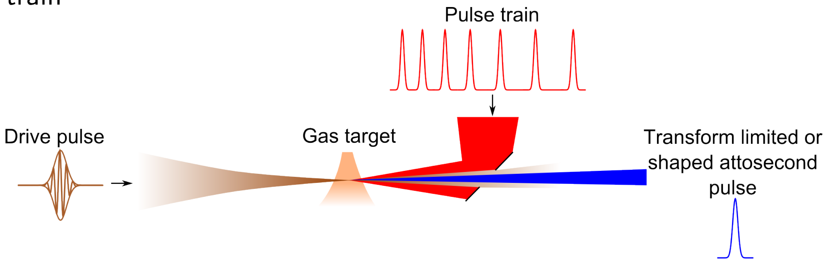
- Grating compressor
  Mero *et al.* (2011)





Proposal

Quasi-phase matching with a *chirped* counterpropagating pulse train



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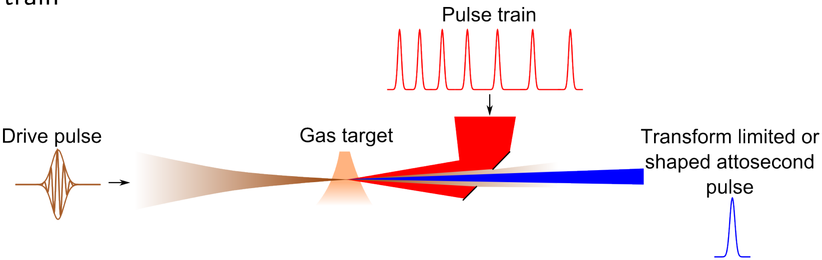

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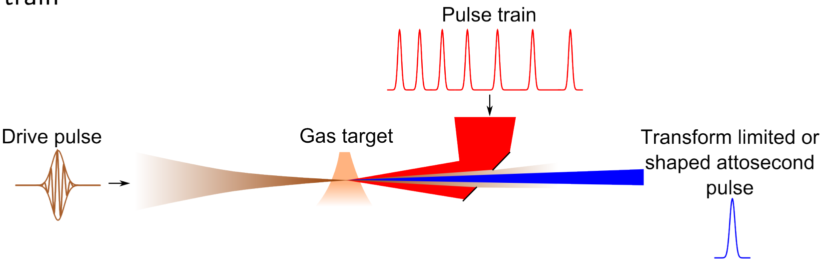
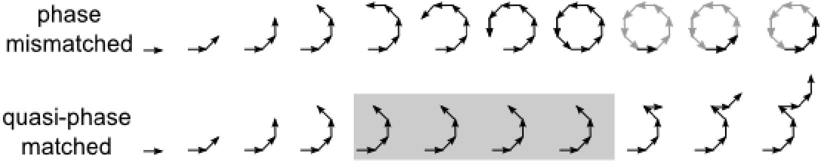


- No spectral range limitations
- Maps XUV pulse shaping onto optical pulse shaping — programmable

Quasi-phase matching

Single frequency picture:

$$\frac{E(\omega)}{z} = e^{i\Delta kz} D(\omega)$$



$$K = \Delta k$$

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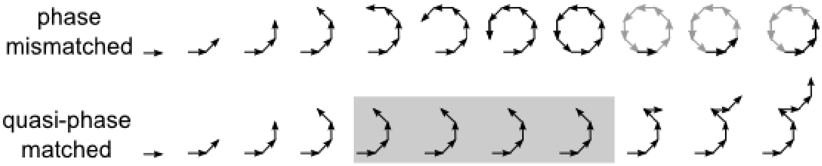


$$K = \Delta k$$

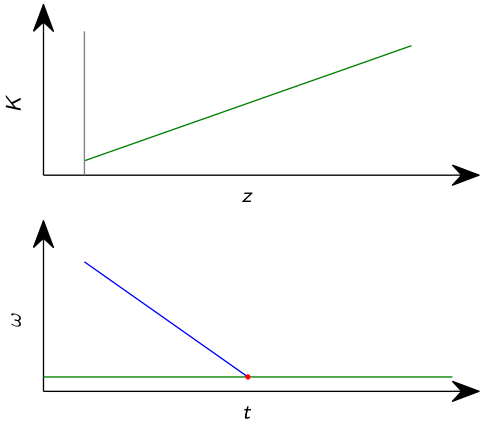
Refractive index mismatch: $\Delta k = \Delta n \omega / c$

$$\frac{E(t)}{z} = D(t - \Delta n z / c)$$

$$\omega = \frac{cK}{\Delta n}$$

Dynamic quasi-phase matching

chirped source D, generated field E, quasi-phase matching K



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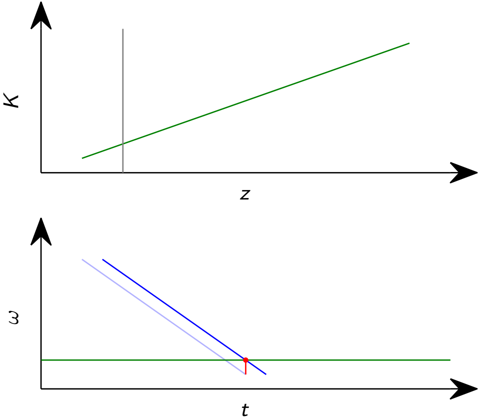

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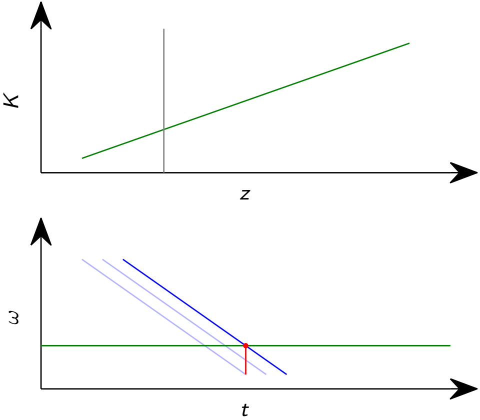

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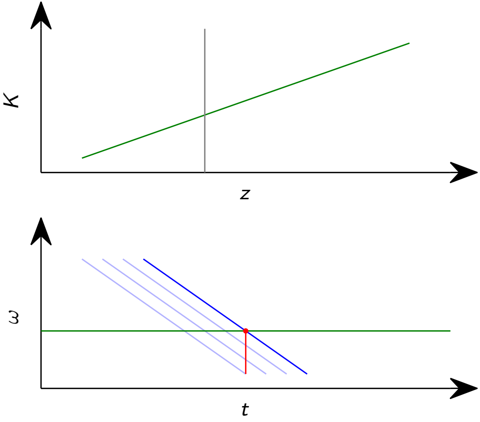

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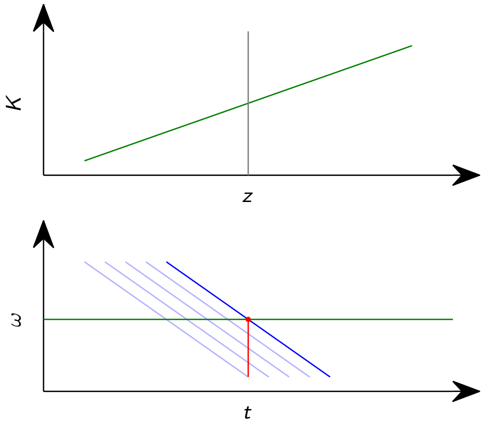

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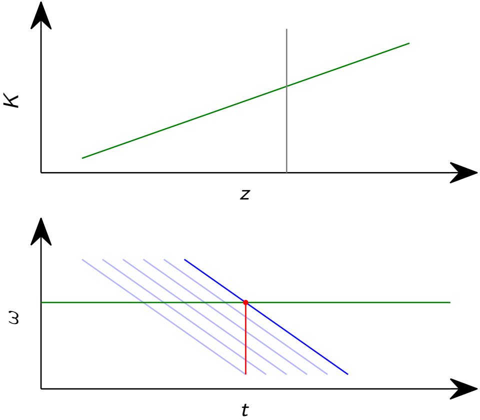

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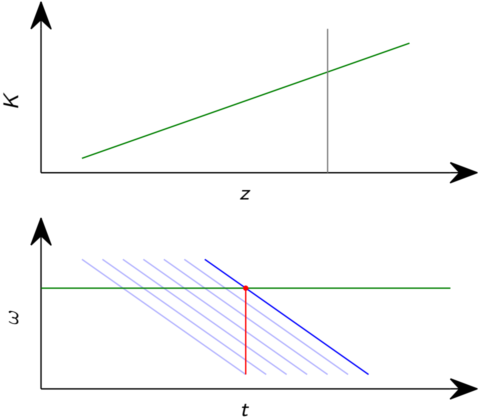

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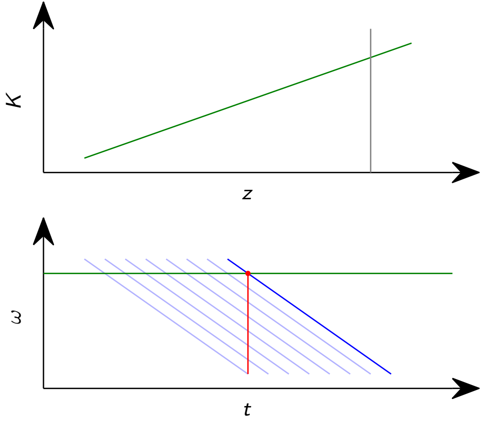

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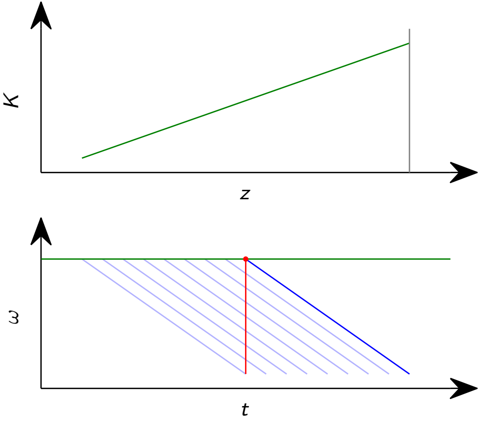
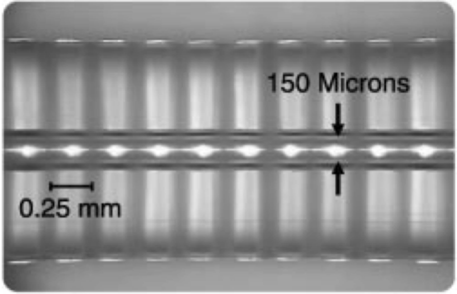


Quasi-phase matching in HHG

- Modulated waveguide
  Gibson *et al.* (2003)



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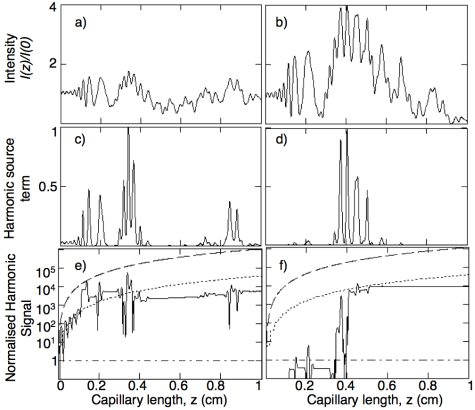

Quasi-phase matching in HHG

- Modulated waveguide
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- Counter-propagating pulse train
  Zhang *et al.* (2007);
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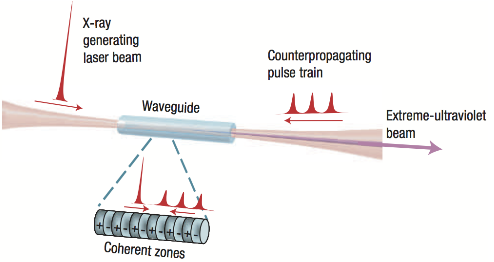
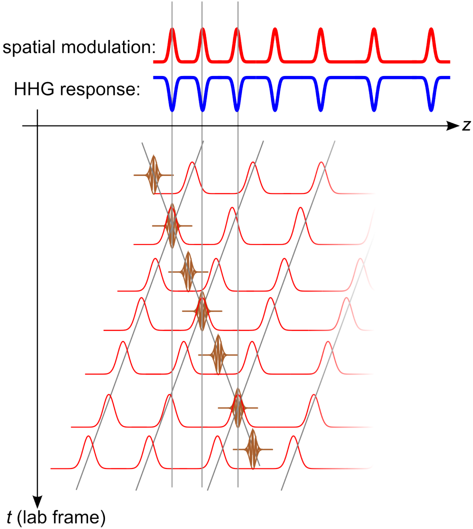
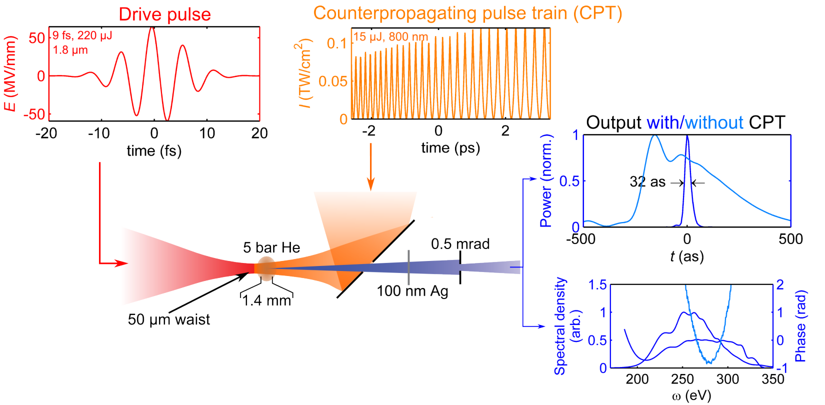


Counterpropagating pulse train



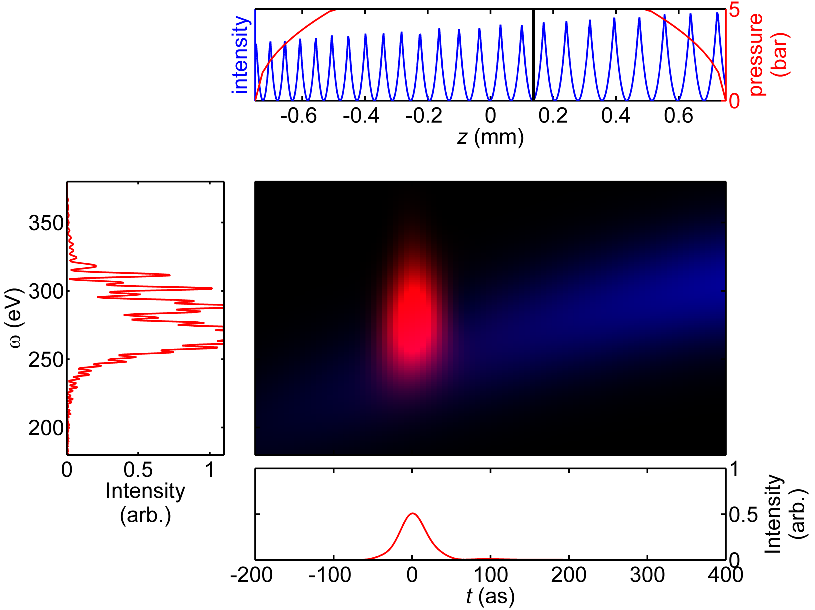
$$t_{CPP} = \frac{2z}{c}$$

Transform-limited pulse generation



Simulation details
Laser pulse propagation: 3D with cylindrical symmetry, neutral dispersion, diffraction, Kerr, ADK ionization rate, plasma absorption and loss.
Single-atom response: strong-field approximation with stationary-phase approximation over momentum and birth time, ADK ionization rate, photorecombination cross sections: Austin & Biegert (2012); Gordon & Kärtner (2005).
XUV propagation: diffraction, dispersion, absorption, spectral and spatial filtering.

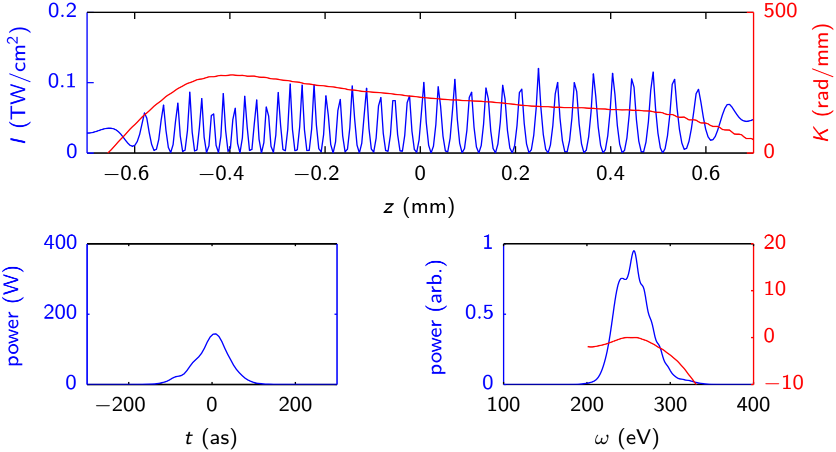
Dynamic spectrogram



Tunability

Linearly varying QPM spatial frequency: $K(z) = K_0 + K_1$.

Applied quadratic spectral phase: $\phi_2 = \left(\frac{\Delta n}{c}\right)^2 \frac{1}{K_1}$.



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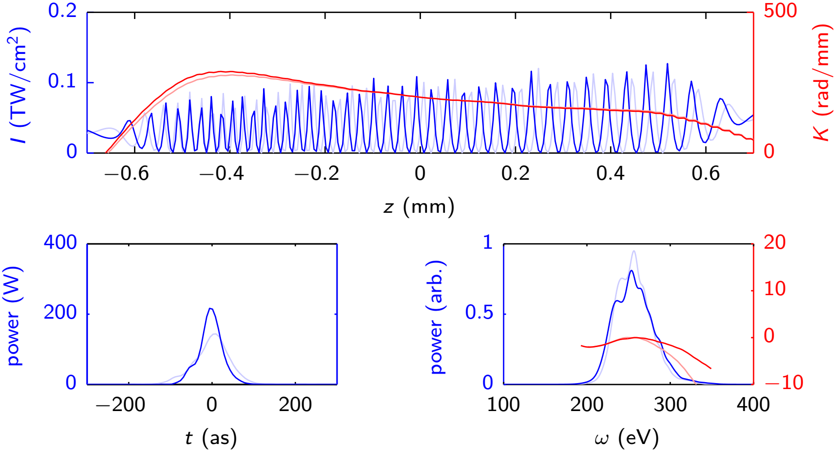

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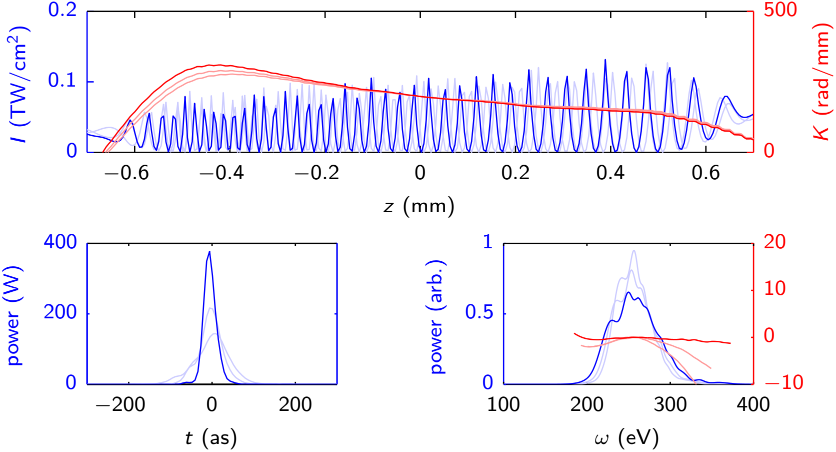

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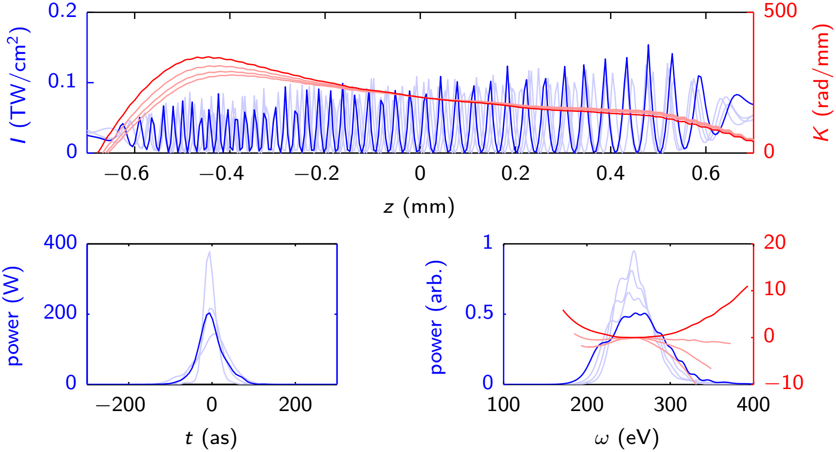

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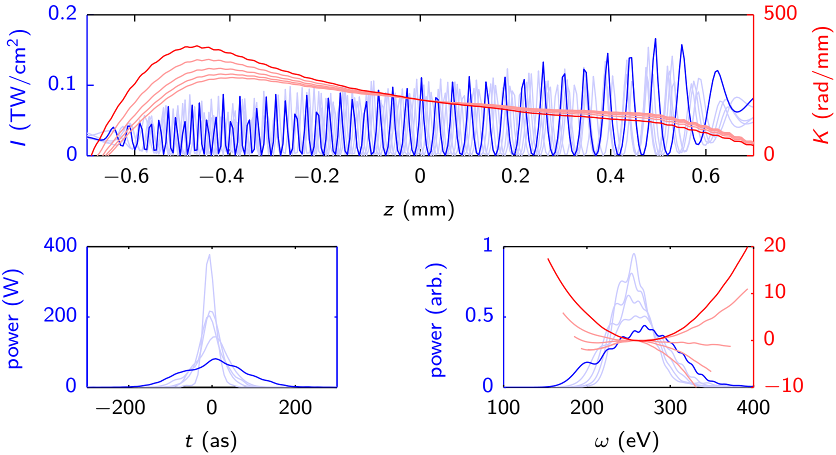
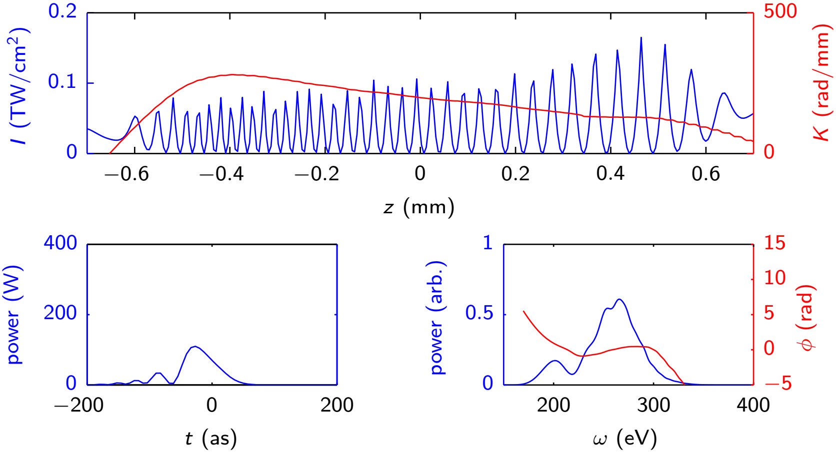


Third-order phase

Quadratic variation in *K* gives *cubic* spectral phase



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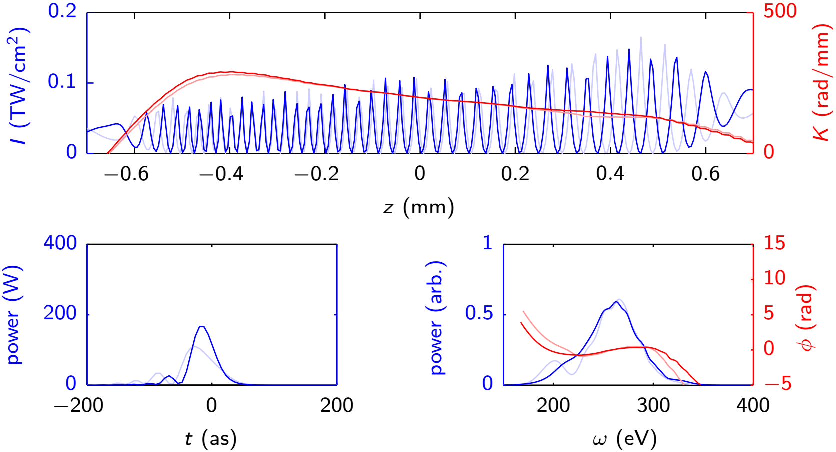

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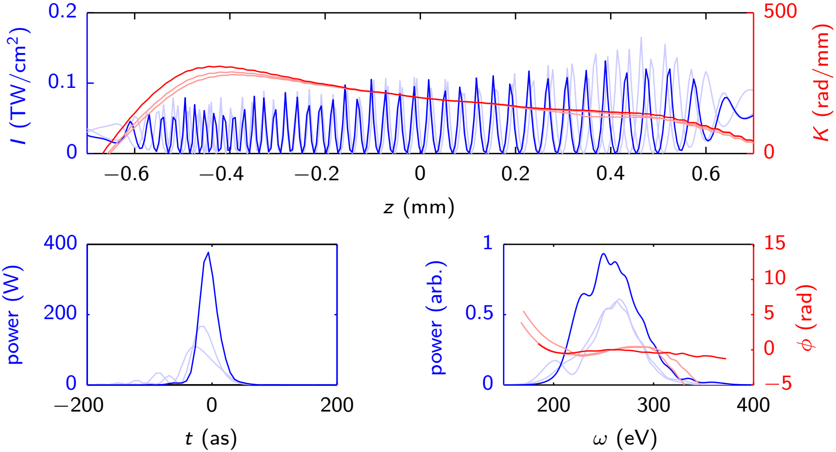

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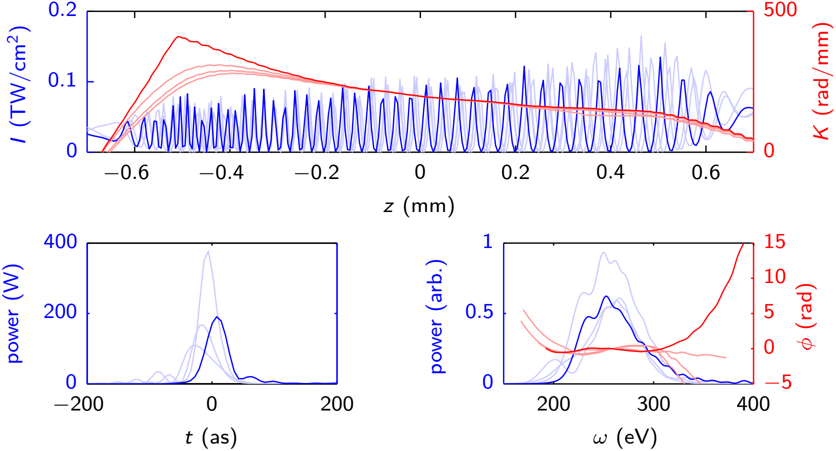

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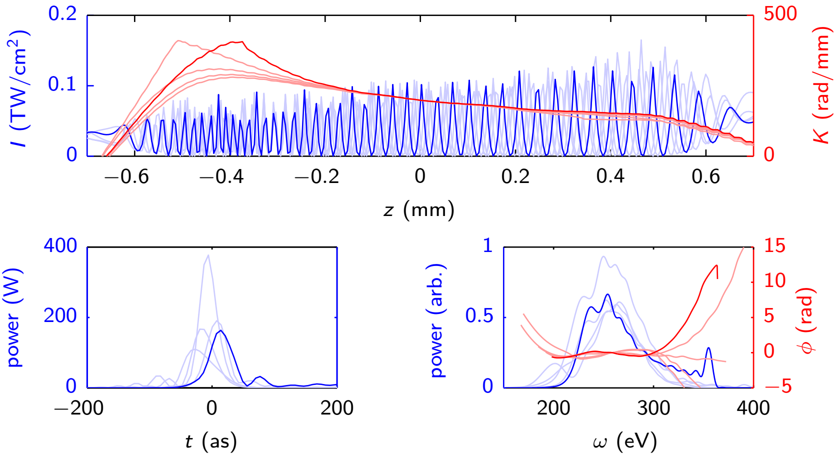
Quadratic variation in K gives *cubic* spectral phase



Attosecond pulse shaper

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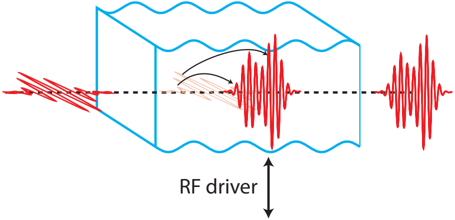
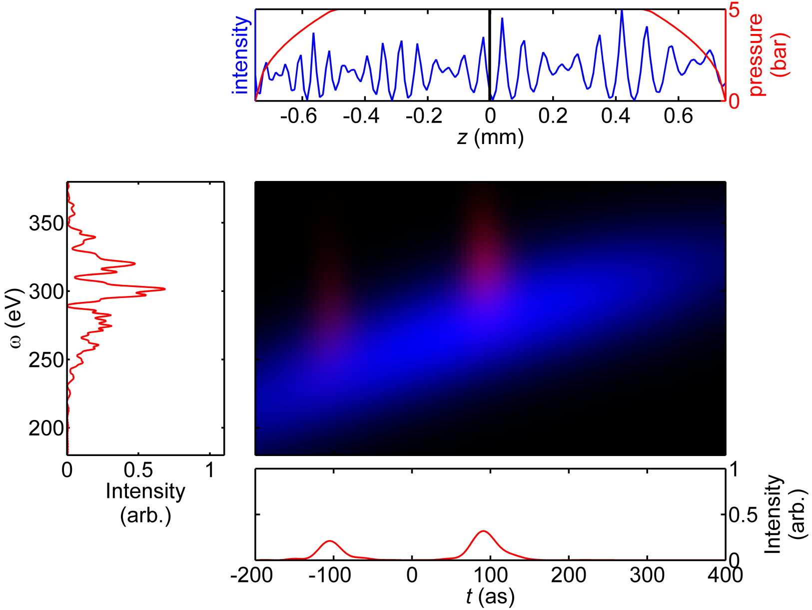
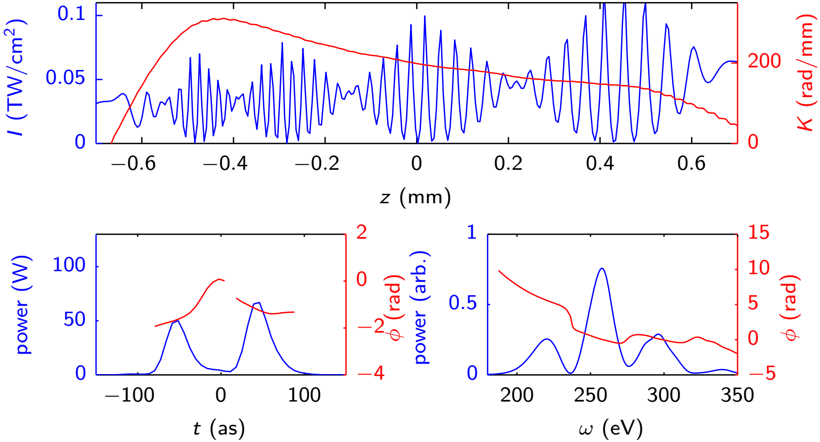
- Analogous to acousto-optic programmable dispersive filter



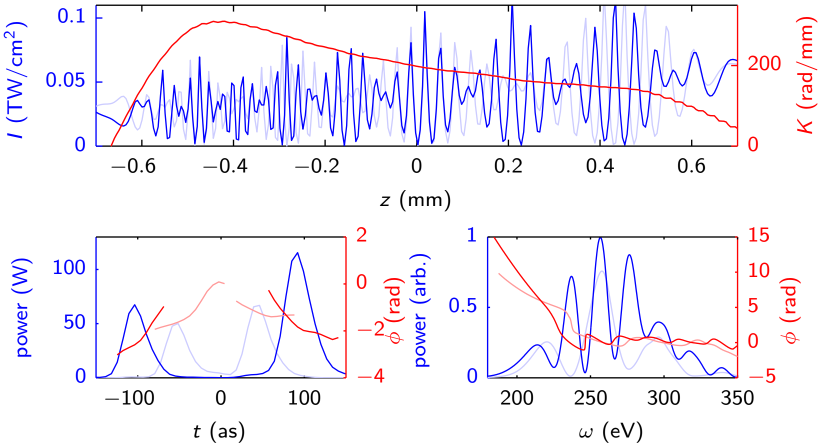
Double attosecond pulse



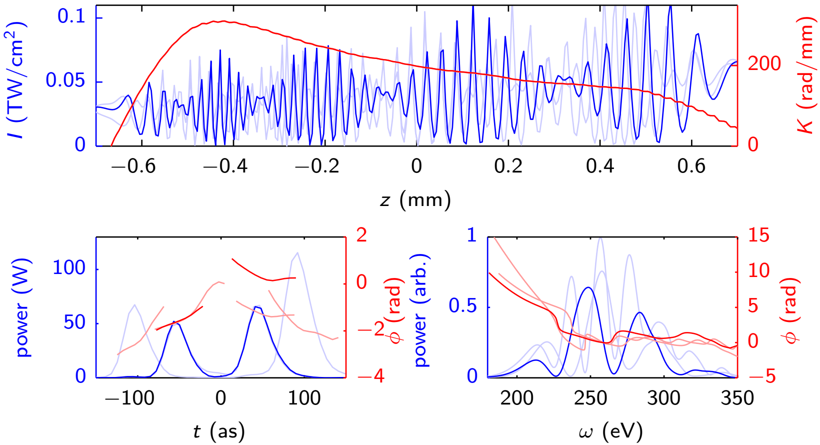
Delay and relative phase control



Delay and relative phase control



Delay and relative phase control



Conclusion

- Refractive index mismatch + longitudinally varying quasi-phase matching = phase control

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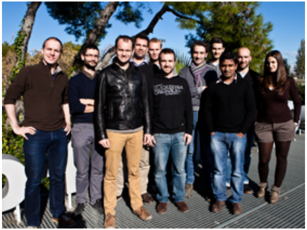
With thanks to. . .



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