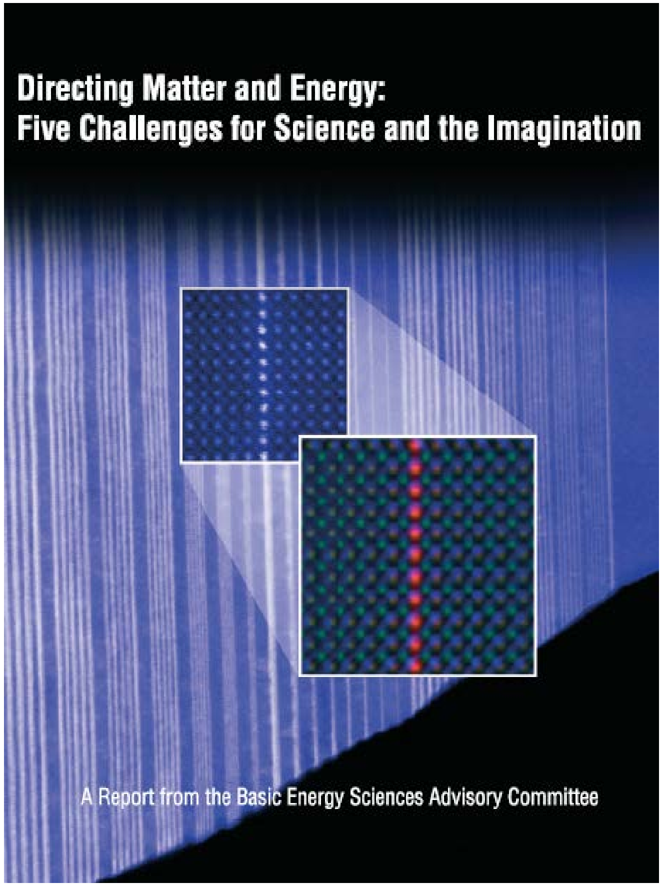
A. Zholents

Towards a 5th Generation Light Source, October 1 -2, 2010

… all great discoveries in science come on heels of innovations in technology and experimental tools

Attosecond x-ray pulses is a powerful tool for addressing Grand Challenges in Science and BES Research Needs



- *How do we control materials and processes at the level of electrons?*
- *How do we design and perfect atom-and energy-efficient synthesis of new forms of matter with tailored properties?*
- *How do remarkable properties of matter emerge from complex correlations of atomic and electronic constituents and how can we control these properties?*
- *Can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living systems?*
- *How do we characterize and control matter away—especially very far away—from equilibrium?*

Attosecond XUV pulses had been obtained

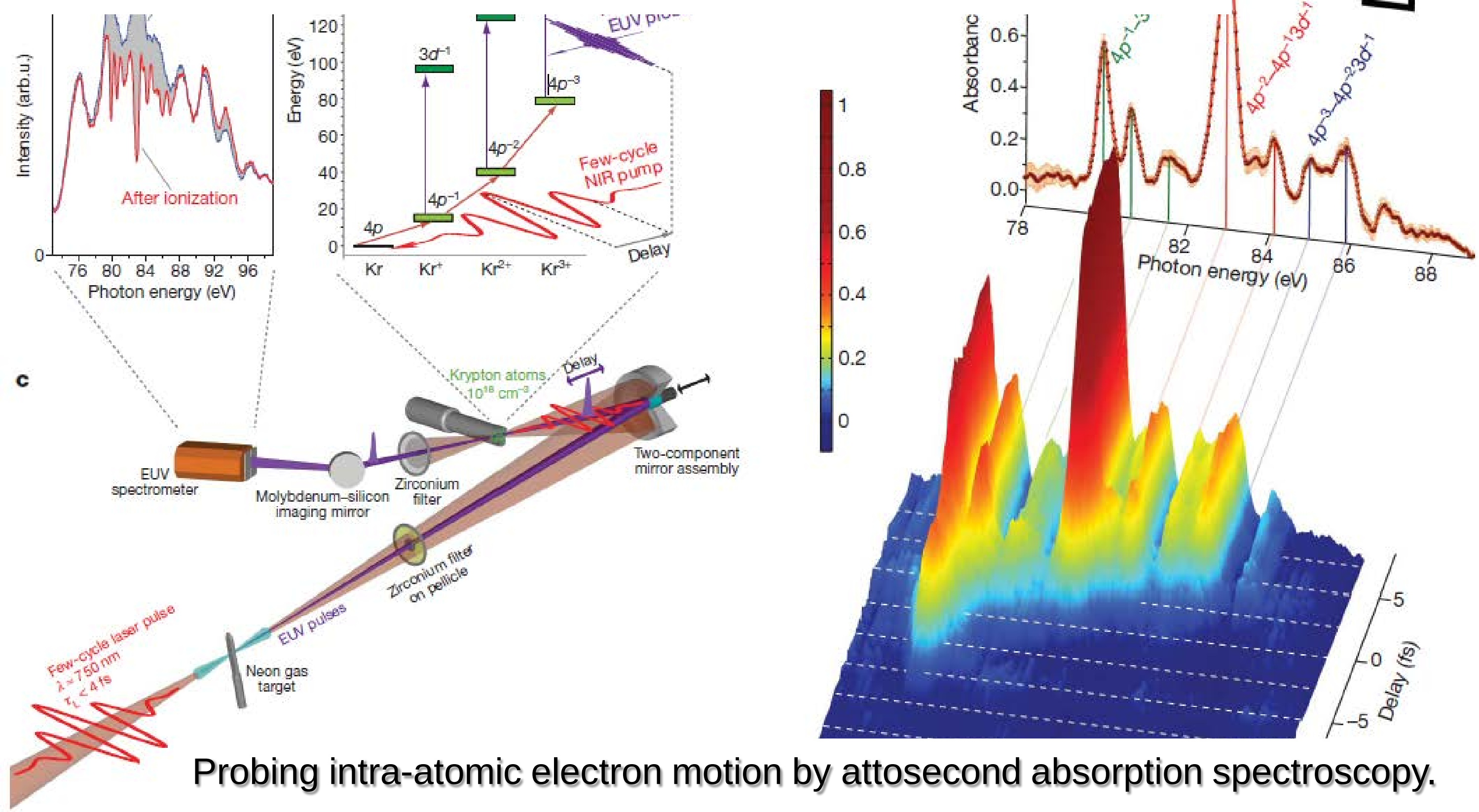
June 19, 2008

Joint PRESS RELEASE of
***M**ax **P**lanck Institute of **Q**uantum Optics*
and
***M**unich Centre for **A**dvanced **P**hotonics*

Ultrafast Look into Atoms and Molecules

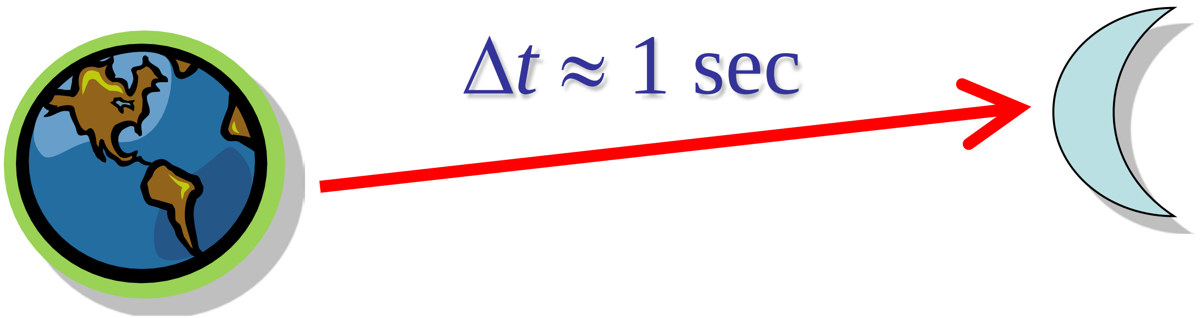
New record in ultrafast metı … Quantum Optics and the
Ludwig-Maximilians-Un … pulses lasting only 80

80 attoseconds !



Probing intra-atomic electron motion by attosecond absorption spectroscopy.

E. Goulielmakis et al., Nature, 466, 739(2010).



c x 80 attoseconds --> 24 nm !

α x c x 80 attoseconds --> 2 Å !

Electron beam-based sources of ultrashort x-ray pulses

- Where we are?
  - State-of-the-art for a short x-ray pulse generation using FELs
- Where we are going?
  - Generation of attosecond x-ray pulses

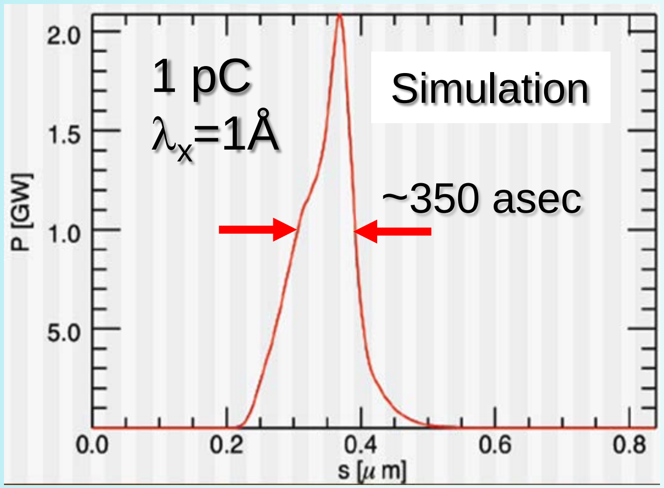
- Short EUV/x-ray pulses are routinely produced at FLASH (10 – 70 fs), SCSS (~ 30 fs) , LCLS (<10 – 80 fs)
- All future x-ray FEL projects consider ultra-short x-ray pulse capabilities

Simple thoughts

- Short electron bunch radiates short x-ray pulse
- For a given peak current short bunch holds a low charge
- With low charge one may expect better 6D electron bunch brightness[1]

$$B = \frac{2Q}{\gamma^3 \varepsilon_x \varepsilon_y \varepsilon_z}$$

- Nearly FTL pulses from SASE[1]



LCLS

$Q = 1$ nC — B= 0.3 nC/μm³

$\gamma\varepsilon_{x,y} \approx 1\mu$m

$\gamma\varepsilon_z \approx \sigma_z(3\text{ keV})/mc^2 = 6.5\ \mu$m

$Q = 0.02$ nC — B= 4.5 nC/μm³

$\gamma\varepsilon_{x,y} \approx 0.15\mu$m

$\gamma\varepsilon_z \approx \sigma_z(1\text{ keV})/mc^2 = 0.4\ \mu$m

P. Emma, LBNL workshop, 08/2010

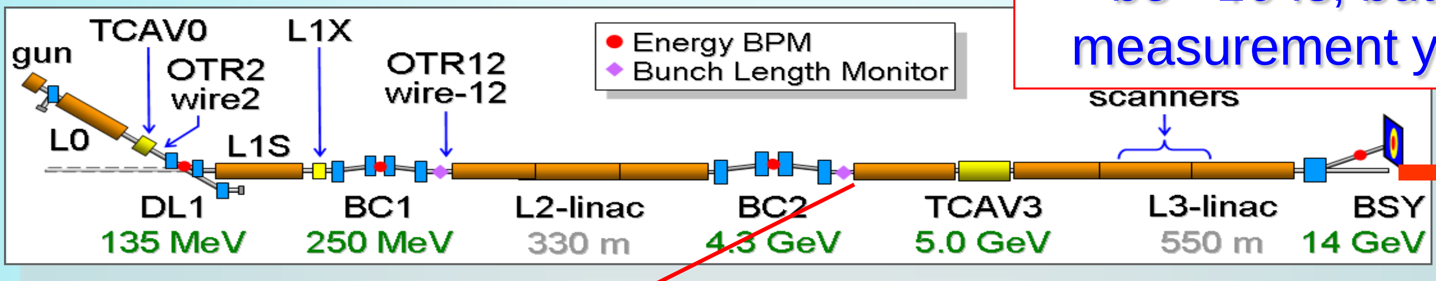
Brightness defines the gain length

$$1/L_G \sim B$$

1) S. Reiche, P. Musumeci, C. Pellegrini, J.B. Rosenzweig, Nucl. Instr. and Meth. A 593 (2008) 45

20-pC bunch operation at LCLS[1]

X-ray pulse duration should be <10 fs, but no direct measurement yet possible



soft x-ray
hω=840 eV

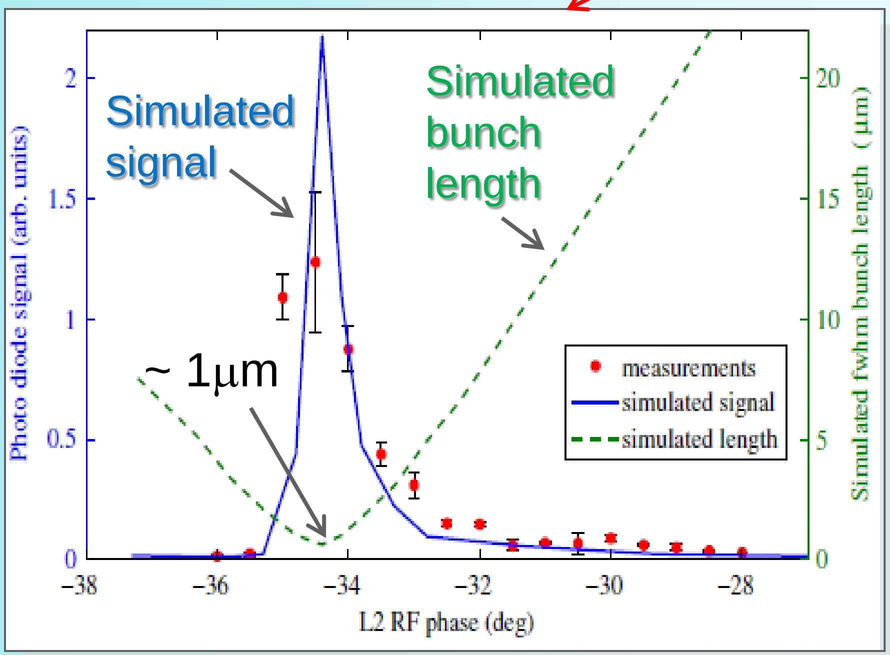
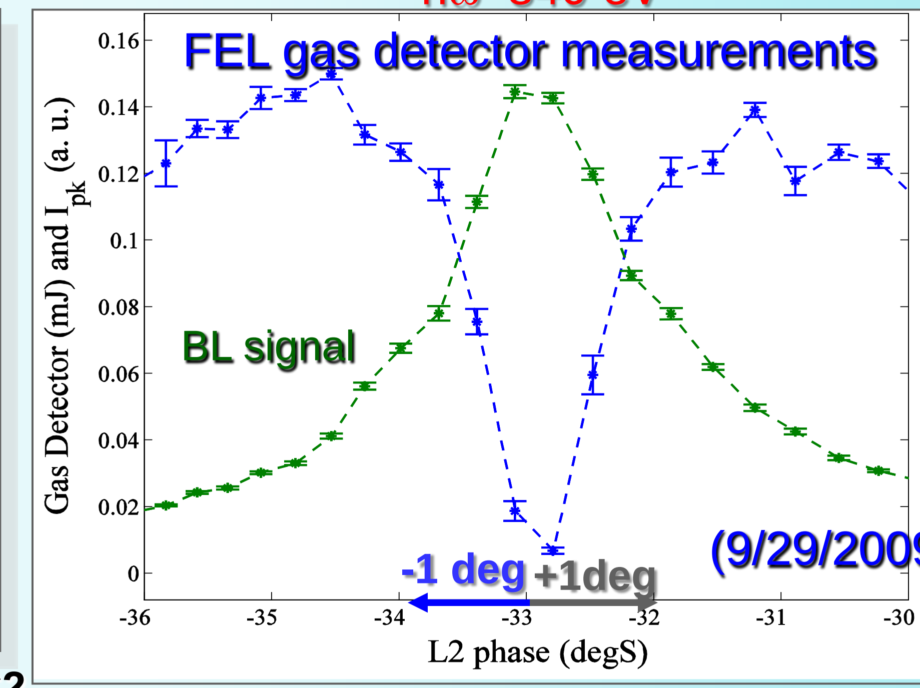


Photo-diode signal on OTR screen after BC2

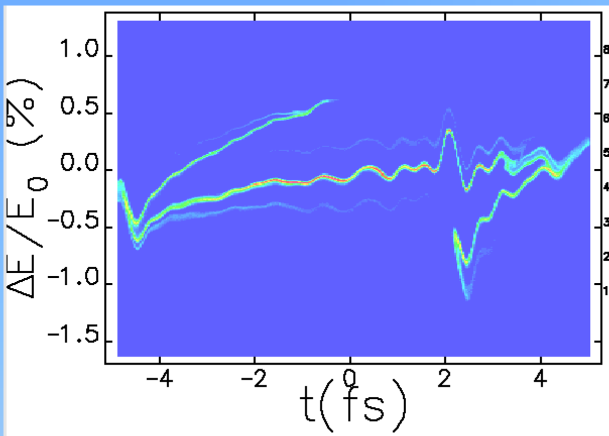


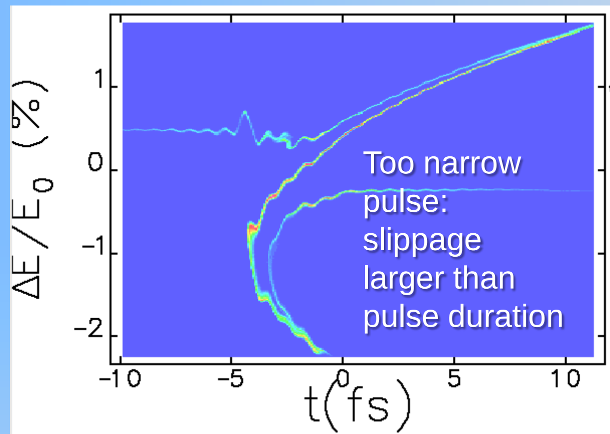
1) Y. Ding et. al, PRL 2009

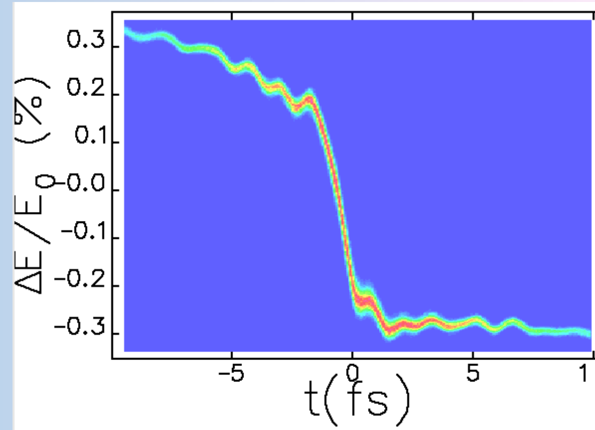
Soft x-rays at 1.5 nm (simulations for LCLS)[1]

1) Y. Ding ,LBNL workshop, 08/2010

At undulator entrance, 4.3 GeV, Laser heater off



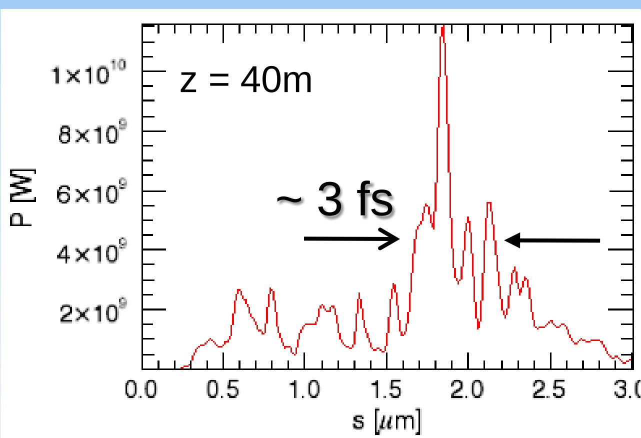


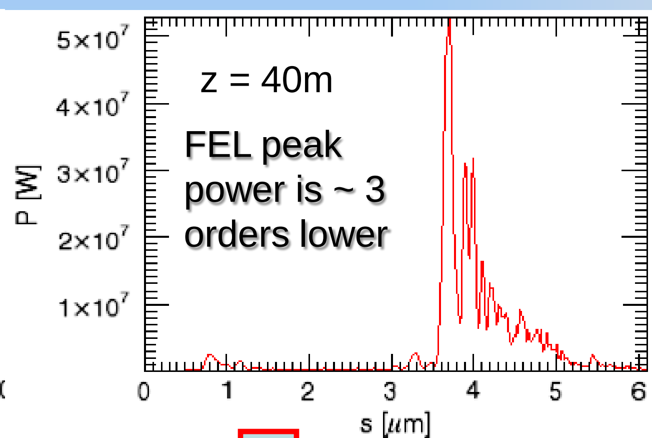


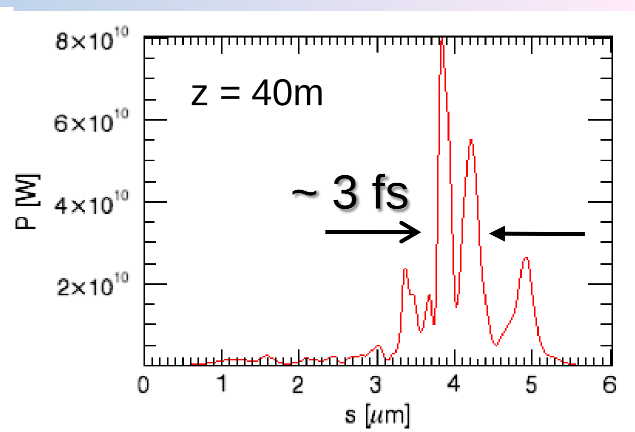
Under-compression: +1 deg off

Full-compression

Over-compression: -1 deg off



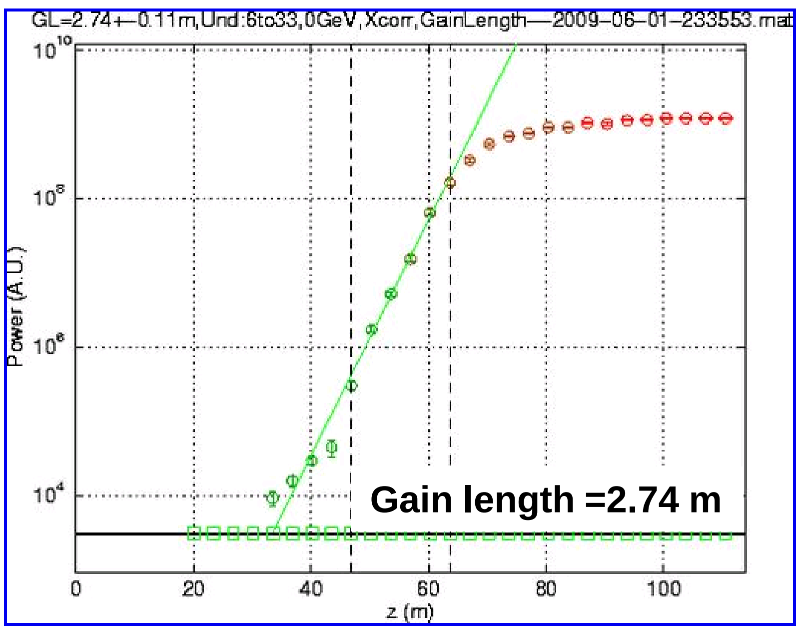


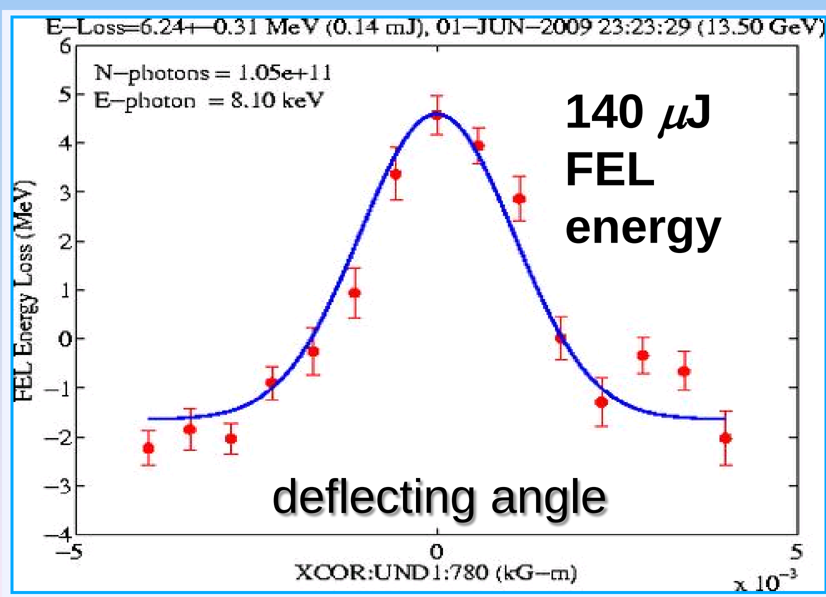


Actual measurements qualitatively confirm simulations.
Direct measurement of ultra-short x-ray pulse duration remains to be difficult.

At 1.5 Å FEL performs well at full compression (slippage just right)

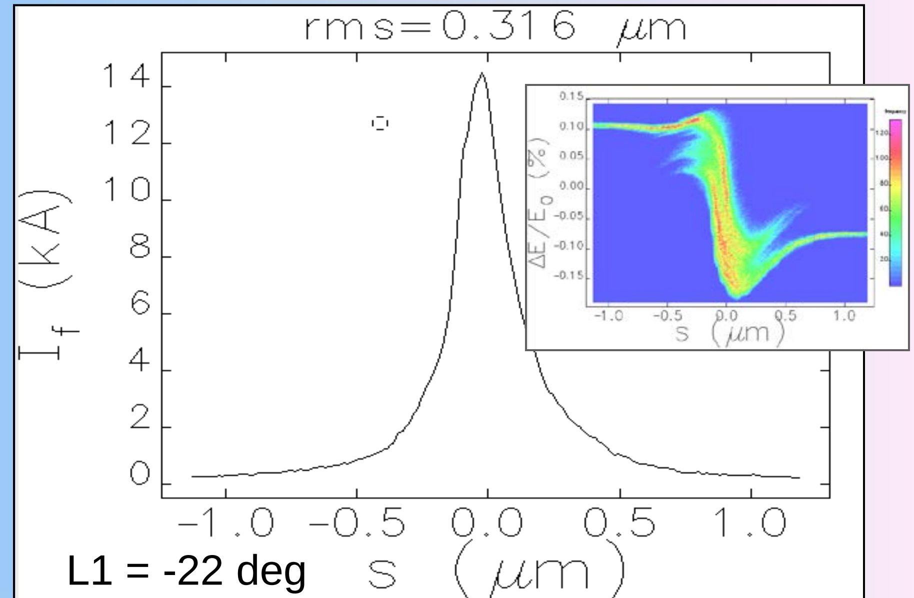
Measurement

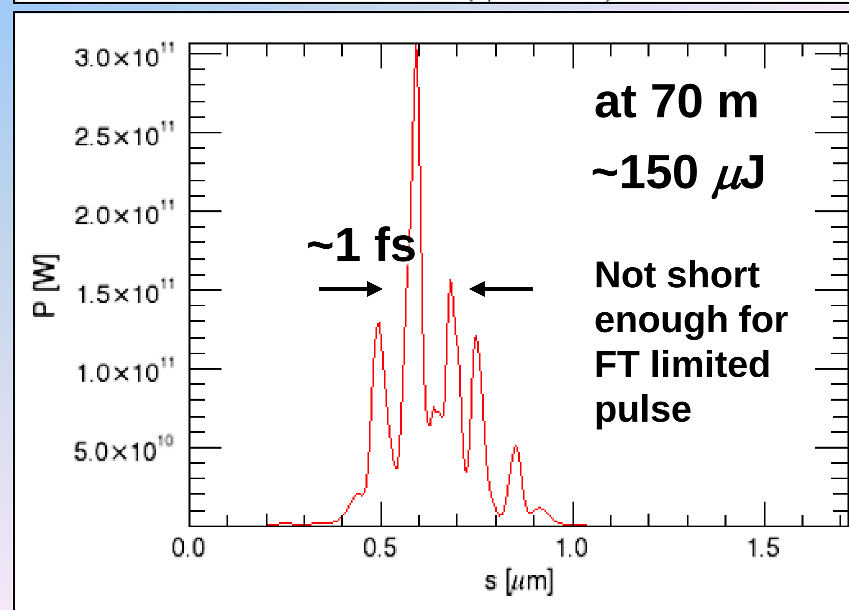




J. Frish et. al., talk at FEL'09

Simulation at 13.6 GeV

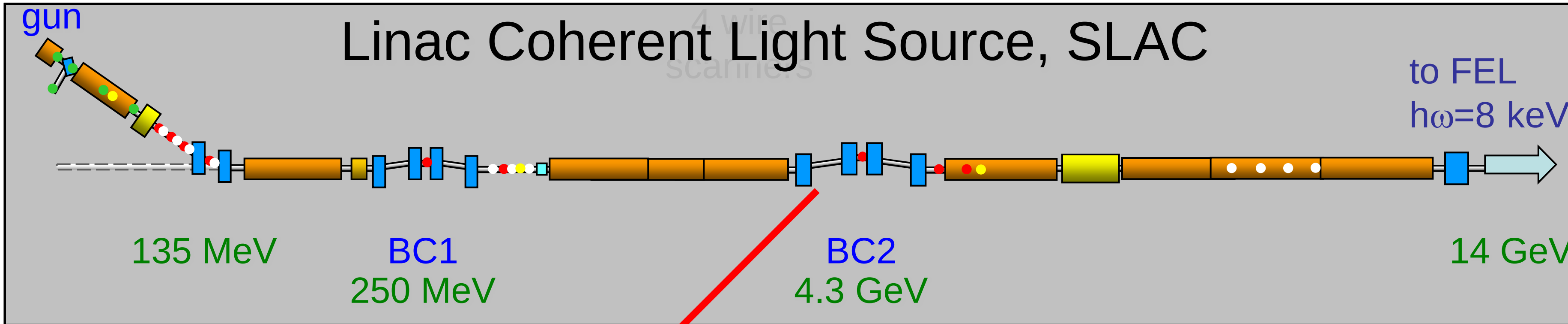


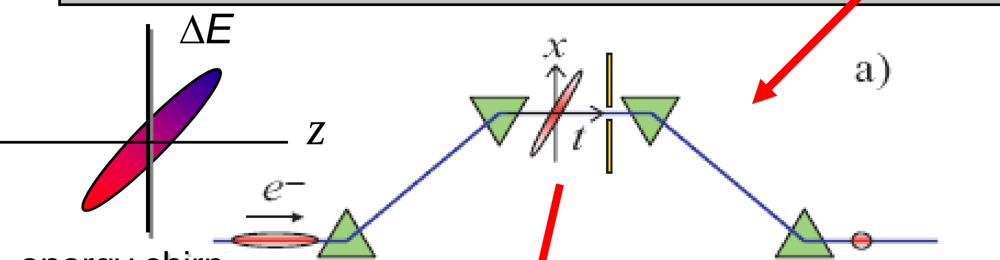


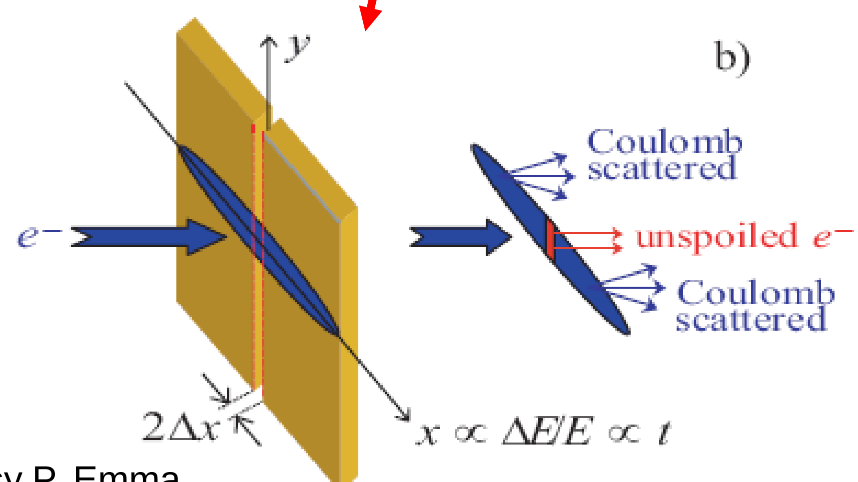
Y. Ding ,LBNL workshop, 08/2010

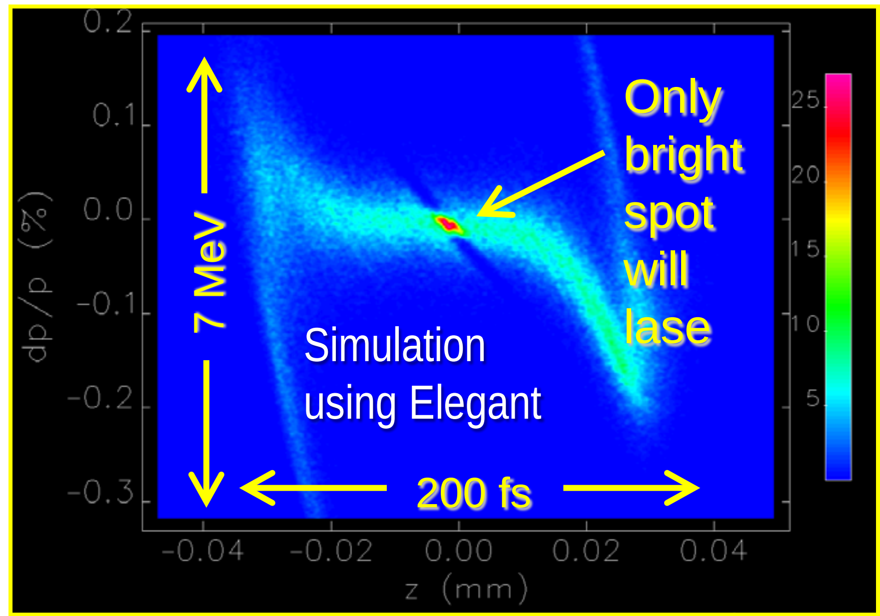
SUB-FEMTOSECOND X-RAY PULSES USING THE SLOTTED FOIL METHOD

P. Emma, M. Cornacchia, K. Bane, Z. Huang, H. Schlarb ,G. Stupakov, D. Walz , PRL, 2004





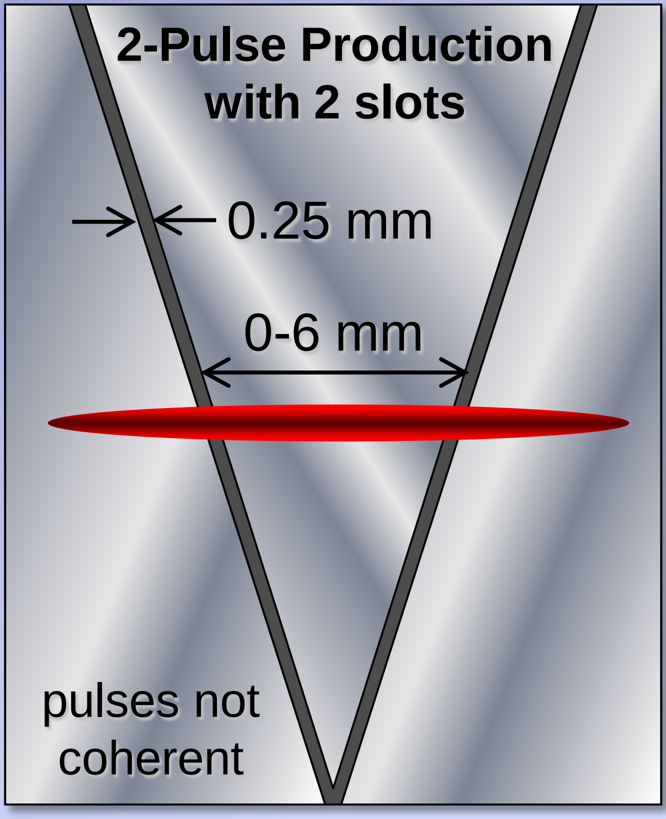


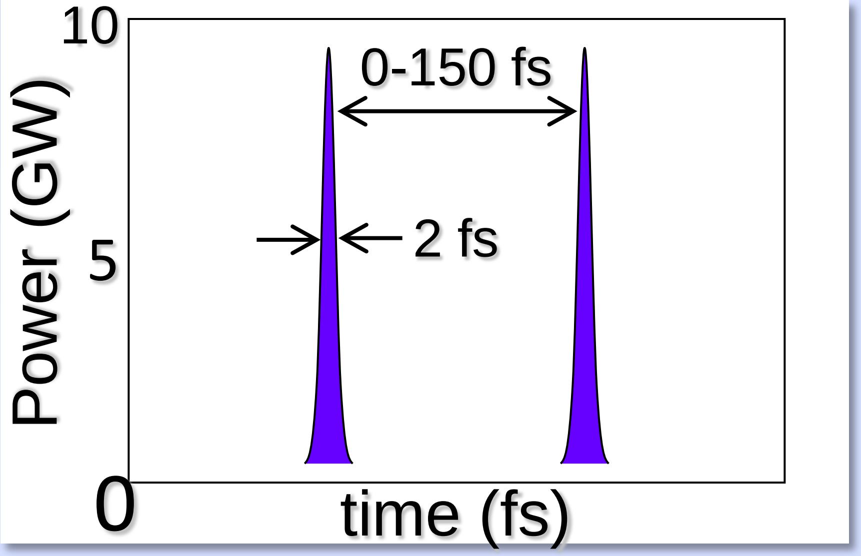


X-ray pulse width ~ 400 asec
Bunch arrival time jitter ~ 50 fs
~ 10^9 photons/pulse -> 7 GW

Courtesy P. Emma

Double X-Ray Pulses from a Double-Slotted Foil





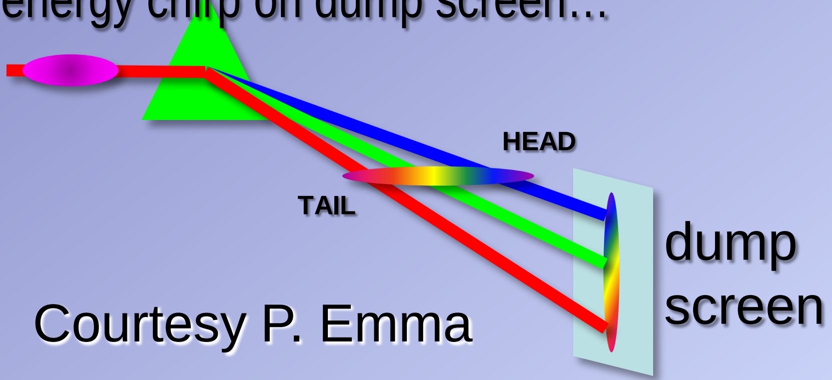
FEMTOSECOND X-RAY PULSES IN THE LCLS USING THE SLOTTED FOIL METHOD

Precise controlled time delay between x-ray pump and x-ray probe pulses

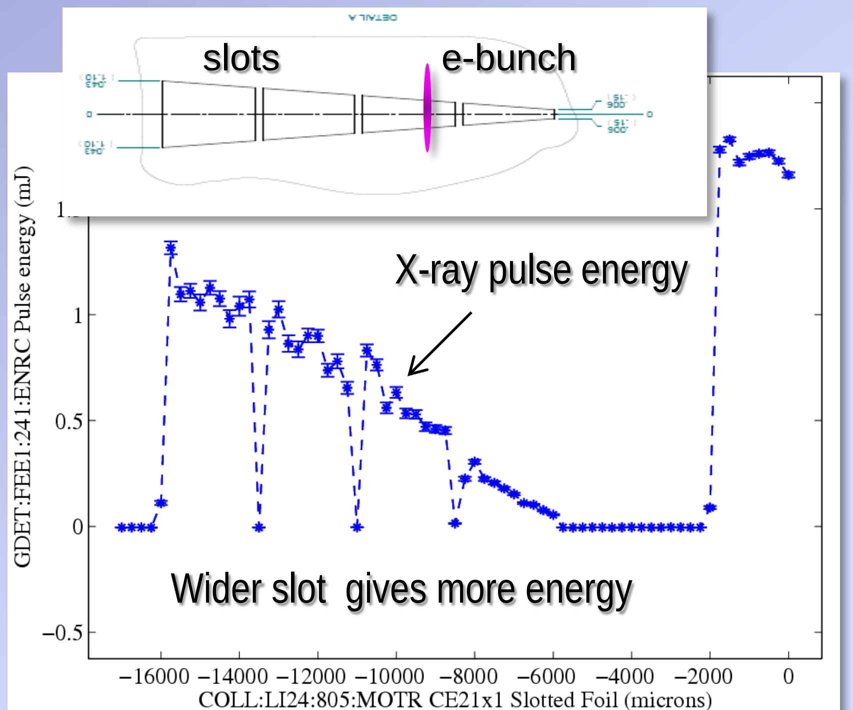
Courtesy P. Emma

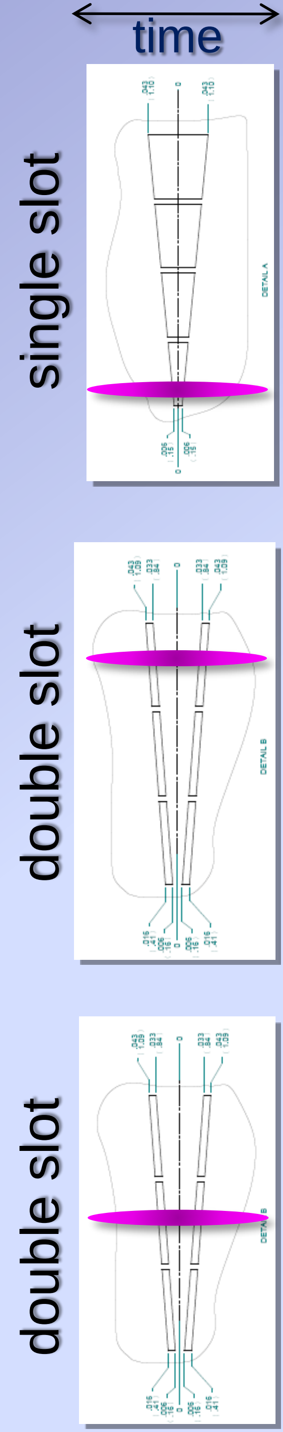
Initial results (very preliminary), June 17, 2010

Over-compressed bunch introduces e⁻ energy chirp on dump screen…

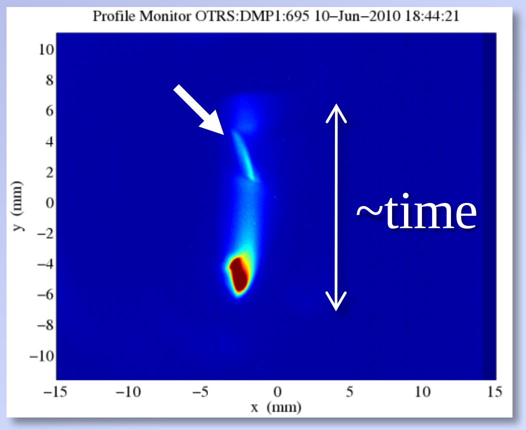


Courtesy P. Emma

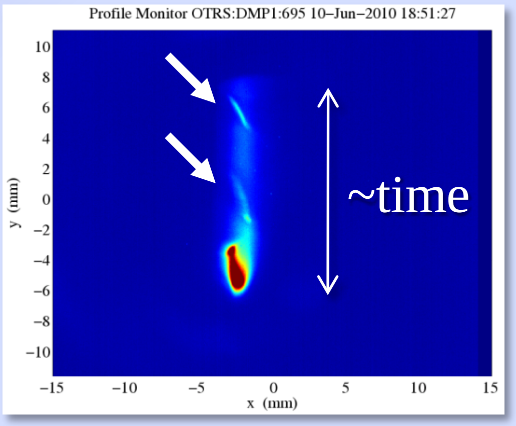




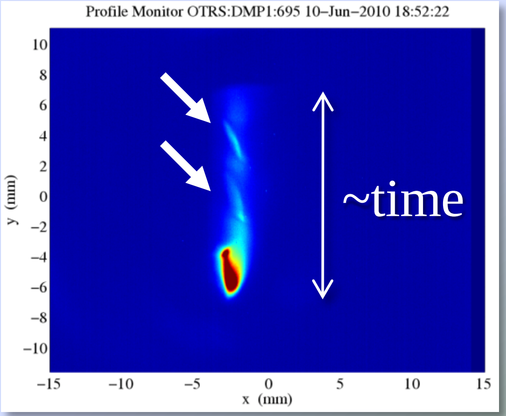
Slotted Foil in at -6000 um



Slotted Foil in at -37000 um

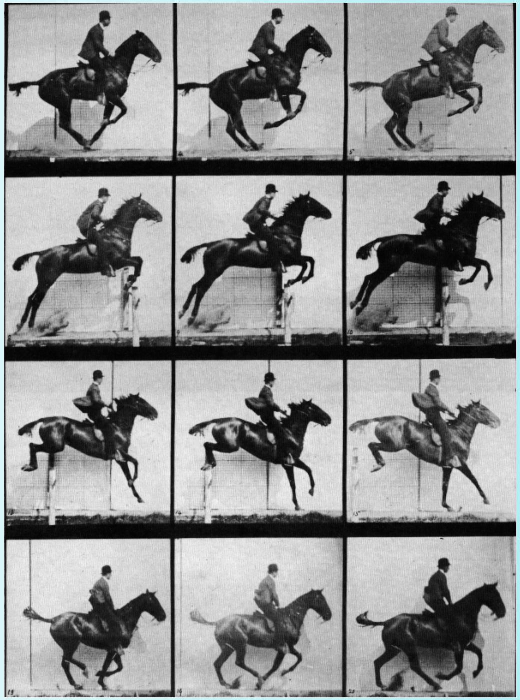


Slotted Foil in at -34000 um

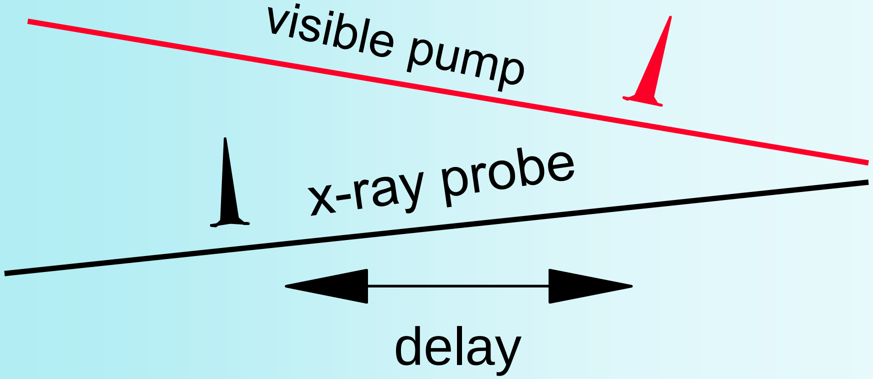


Pump – probe studies using ultra-fast x-ray pulses

Pellet hits a strawberry

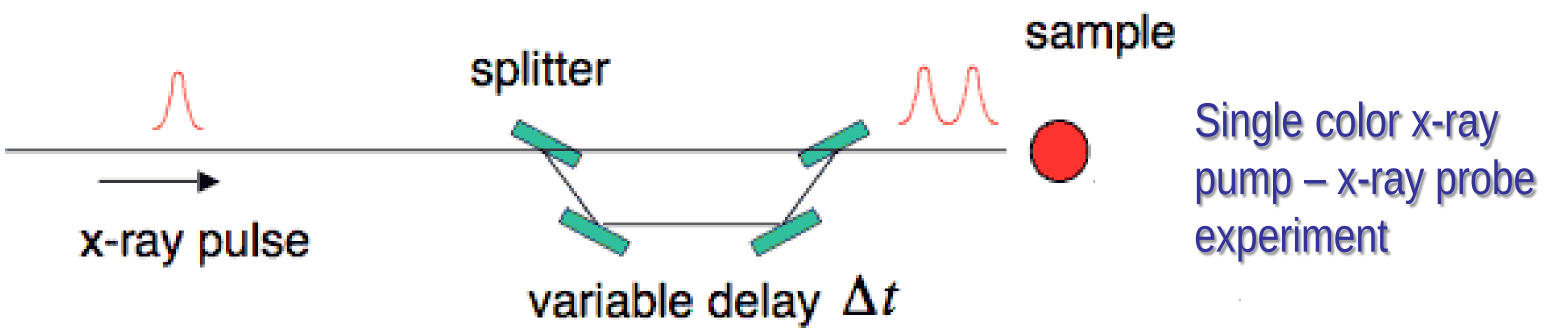


Stop-motion photography
E. Muybridge, 1878

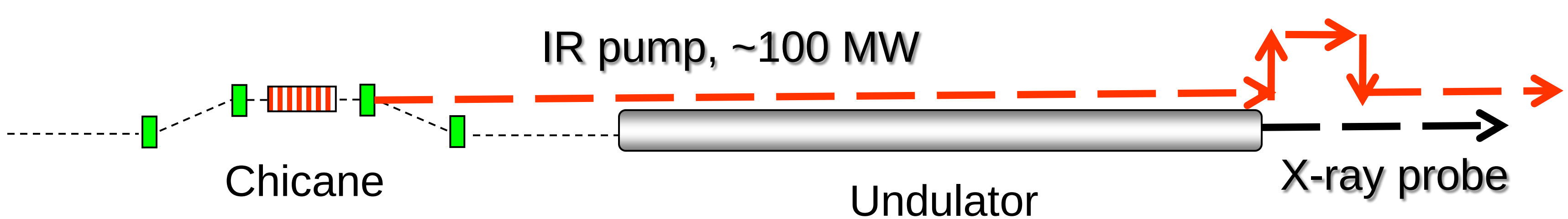


Options for experiment utilizing synchronized pump and probe signals when electron bunch arrival time has a "large" jitter

- Use double slotted foil
- Split single x-ray pulse into two and adjust delay



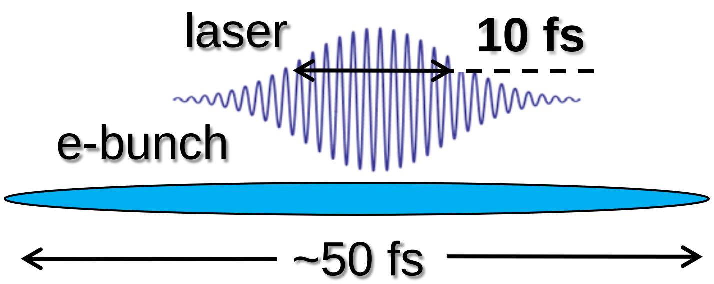
- Create pump signal using cohrent undulator radiation and adjust delay[1] (in case of an ultra-short e-bunch, ~ 1 fs)



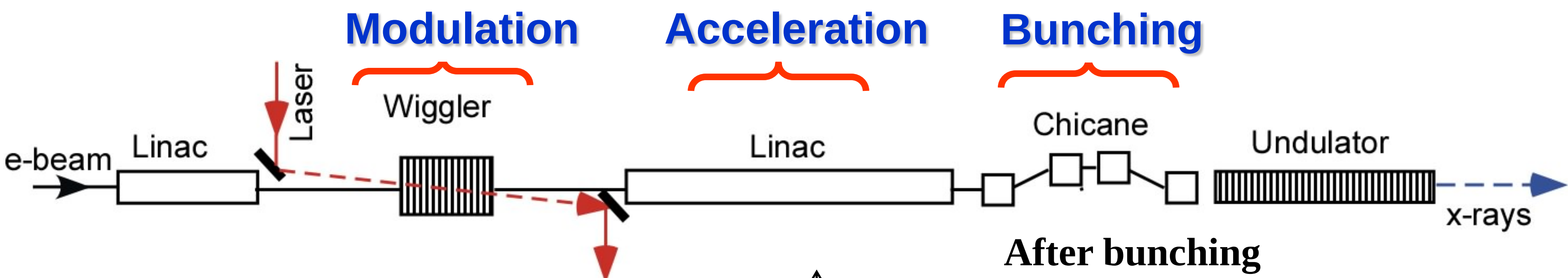
1) U. Fruhling *et al*., *Nature Photonics*, **3**, 523(2009); also considered by UCLA group

Precision synchronization of pump and probe pulses

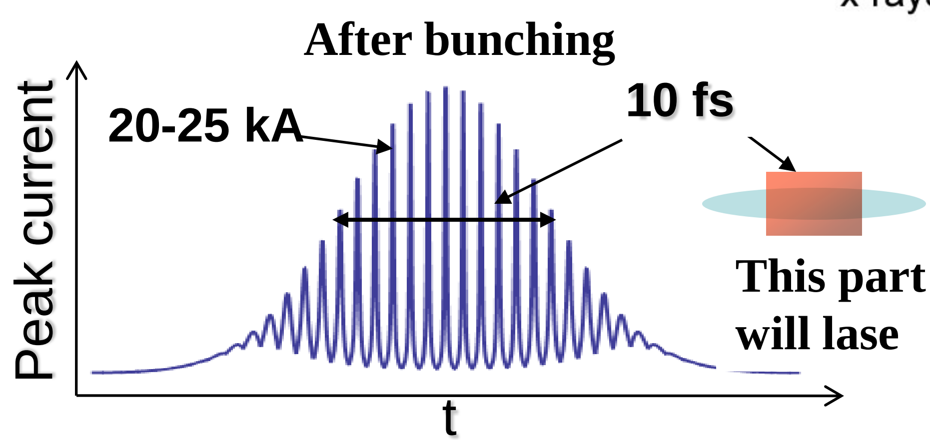
- Seeded FELs naturally posses precise synchronization
  - if electron bunch length > laser pulse + jitter



- Current-enhanced SASE FEL --> same conclusion

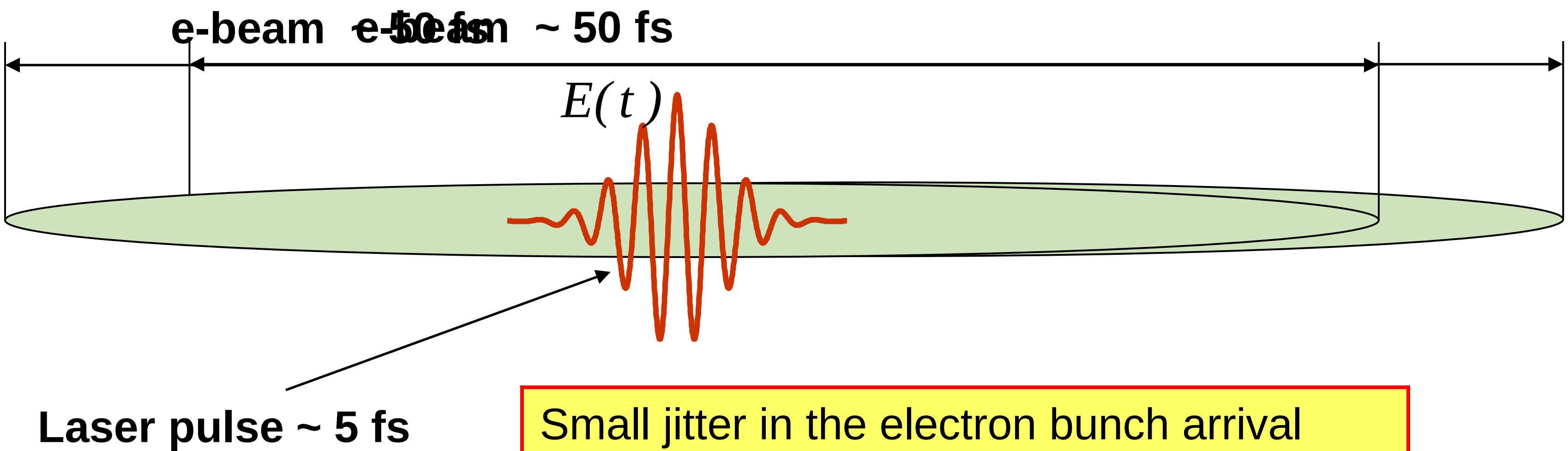


Require synchronization of the seed and pump lasers, 10 fs is state of the art *)



*) J. Kim *et. al*., *Nature Photonics*, **2**, 733, 2008; R. Wilcox, *Opt. Lett*. **34**, 3050, 2009

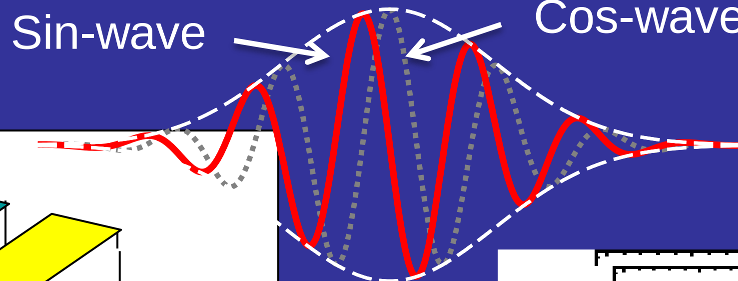
Attosecond pulse generation via electron interaction with a few cycle carrier-envelop phase stabilized laser pulse



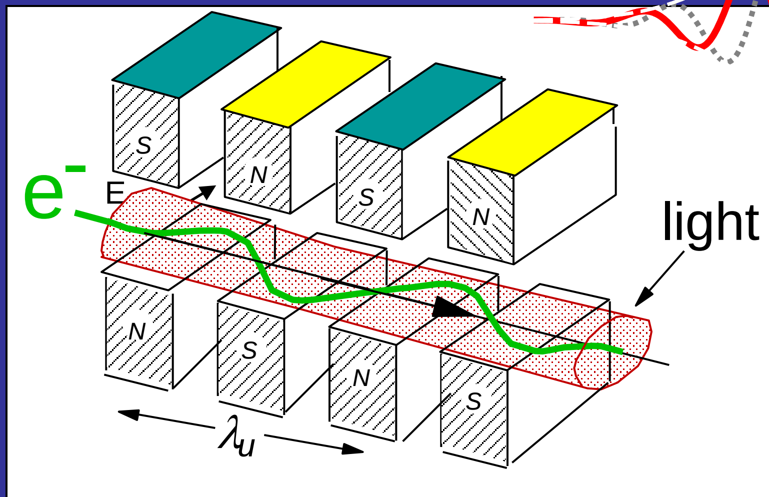
Small jitter in the electron bunch arrival time is not important – good for pump-probe experiments using variety of pump sources derived from initial laser signal

Basic idea:
Take an ultra-short slice of electrons from a longer electron bunch to produce a dominant x-ray radiation

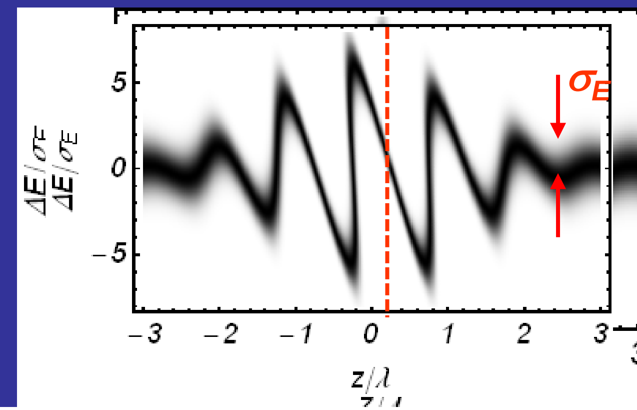
Light interaction with relativistic electron



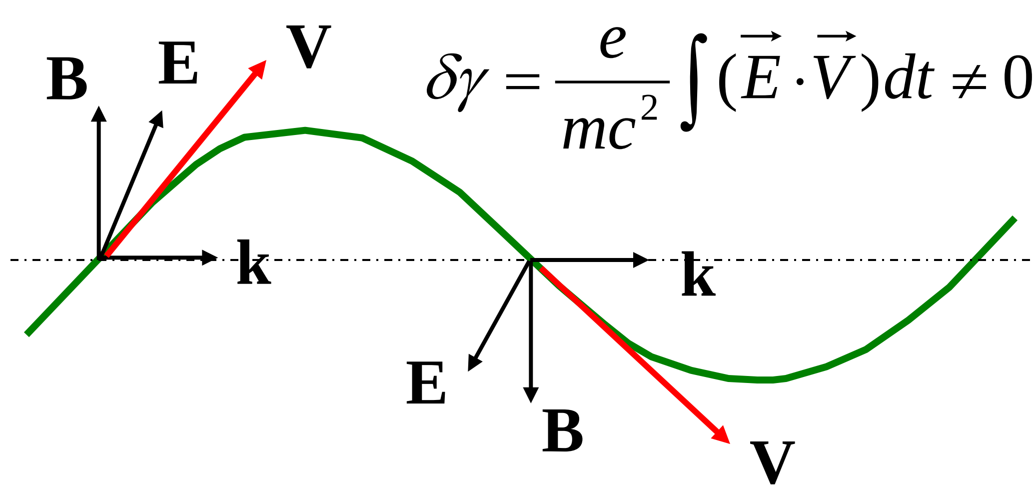
Laser pulse:
1 mJ, 5-fs
at 800 nm wave length
with CEP stabilization



Electron trajectory through undulator



Fragment of the electron bunch



$$\delta\gamma = \frac{e}{mc^2}\int(\vec{E}\cdot\vec{V})dt \neq 0$$

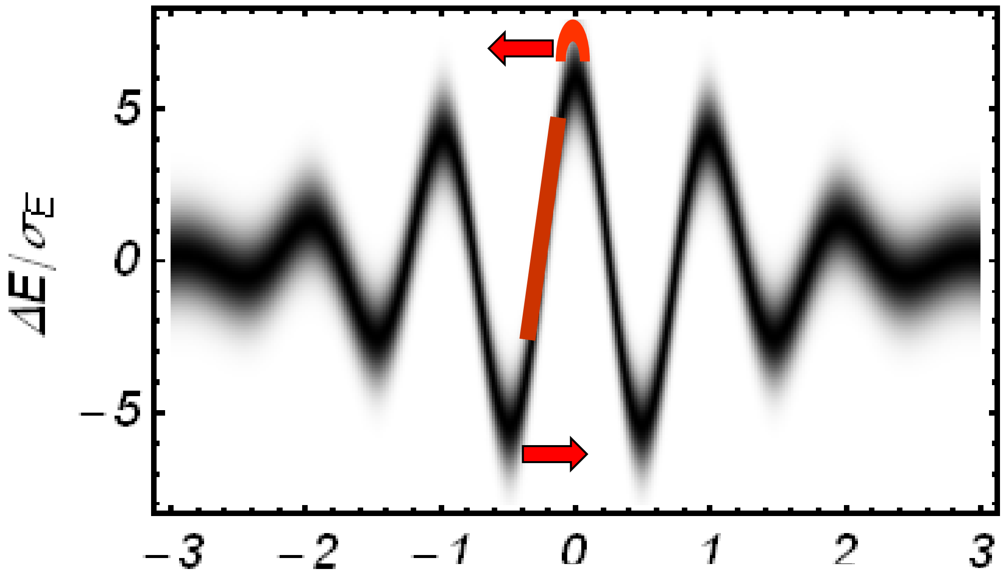
Laser wavelength

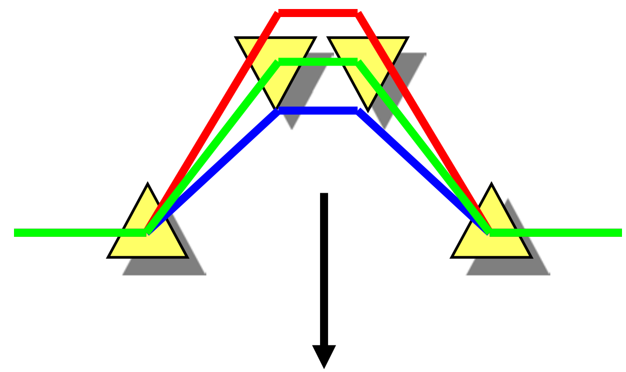
$$\lambda_L = \lambda_u(1+K^2/2)/2\gamma^2$$

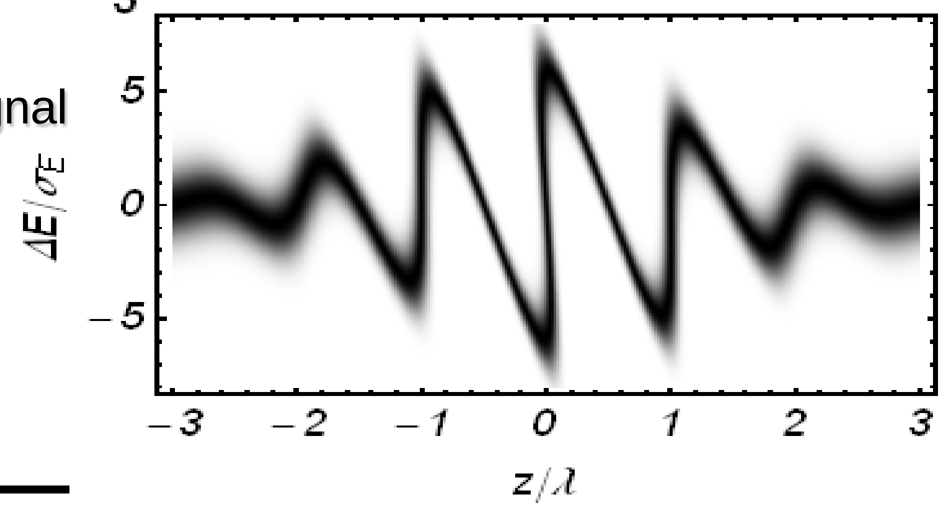
Undulator period

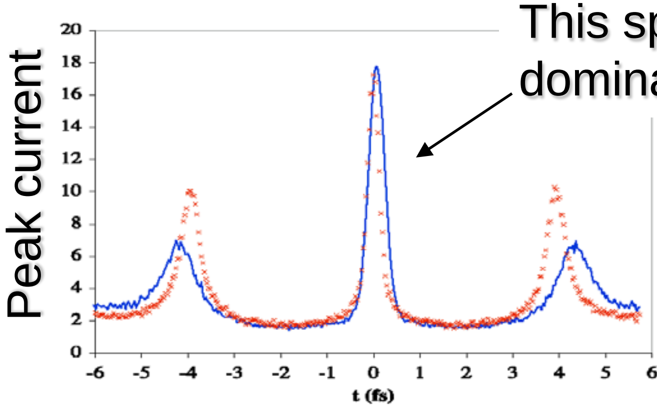
While propagating one undulator period, the electron is delayed with respect to the light on one optical wavelength

Energy modulation induced in the electron bunch during interaction with a ~1 mJ, 5 fs, 800 nm wave length laser pulse in a two period wiggler magnet with *K* value and period length matched to FEL resonance at 800 nm





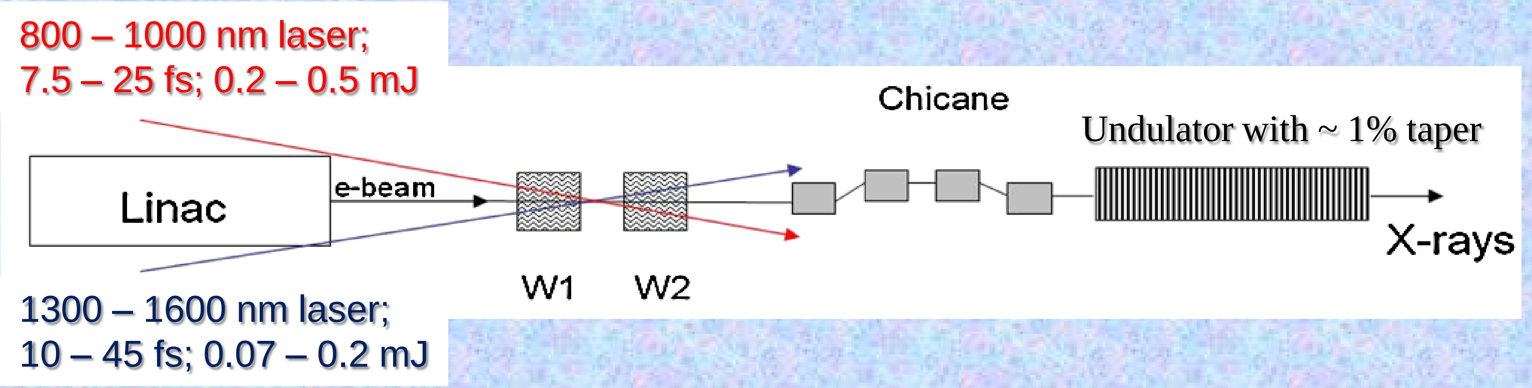


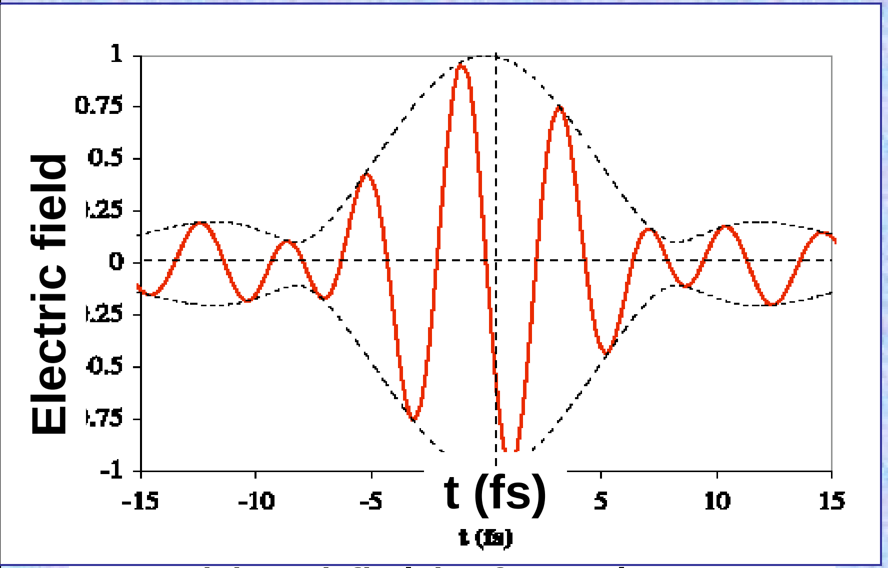


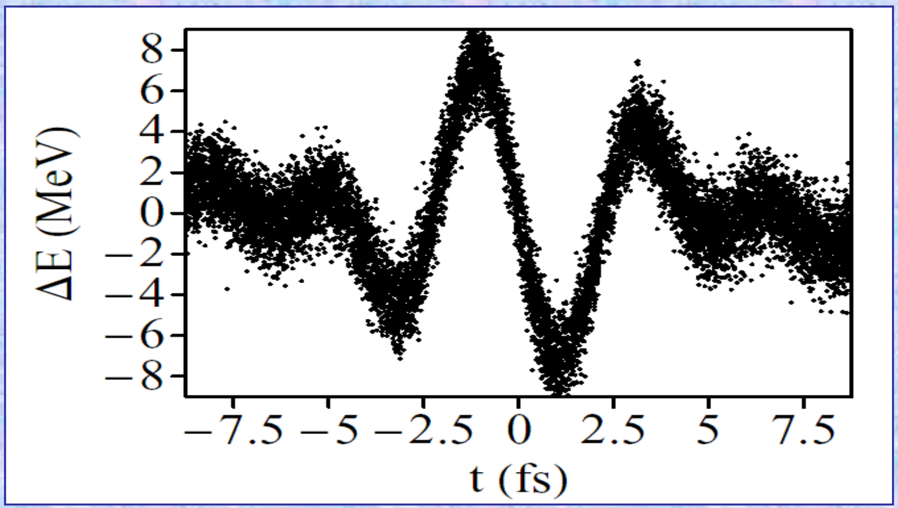
This spike gives a dominant x-ray signal

Current enhancement

Current enhancement method *)





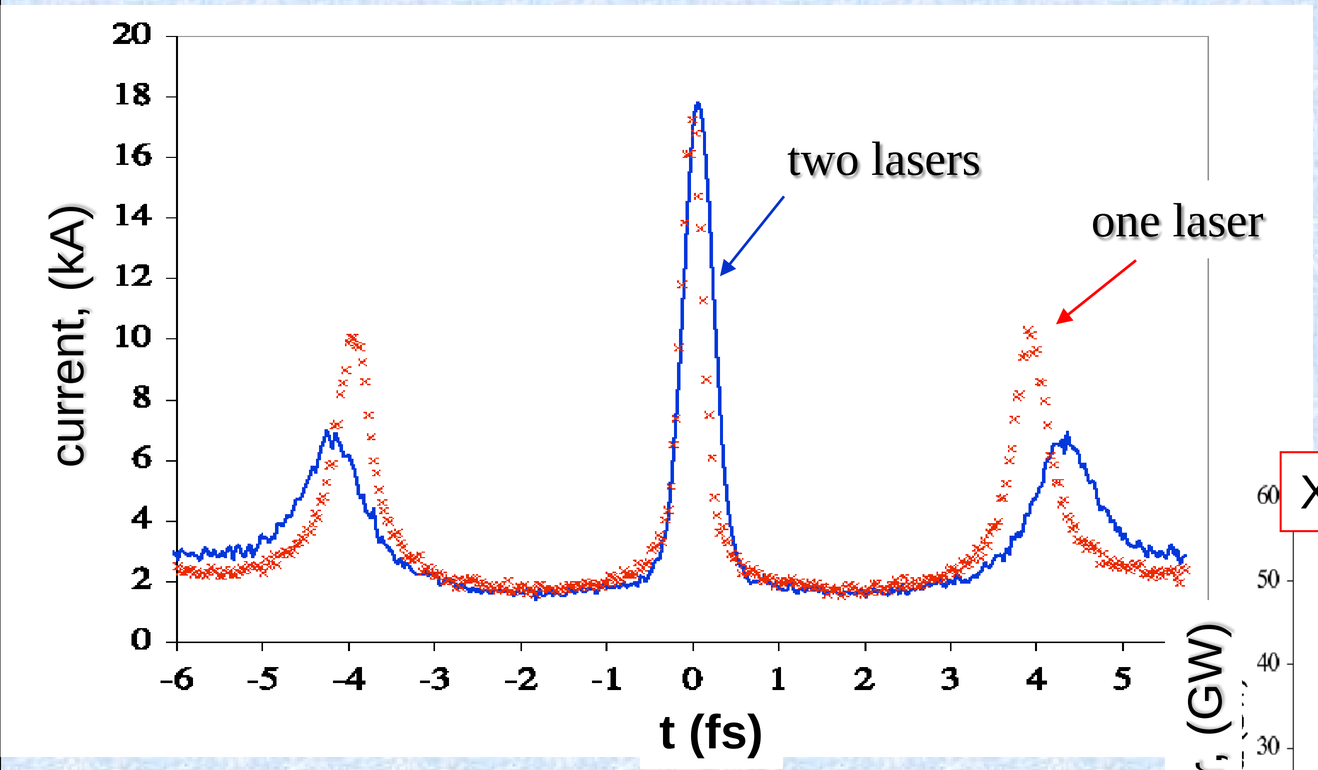


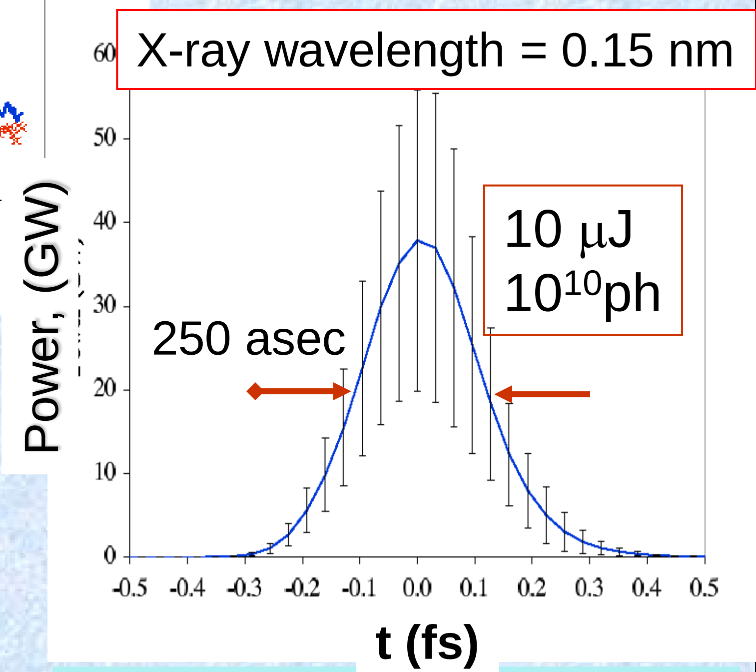
Combined field of two lasers: increases one laser bandwidth

Energy modulation of electrons produced in interaction with two lasers

*) Zholents, Penn, PRST-AB, 8, (2005);
Y. Ding et al., Phys. Rev. ST-AB, 12, (2009).

Current enhancement method (2)





Selection of attosecond x-ray pulse: regions with higher peak current reach saturation earlier

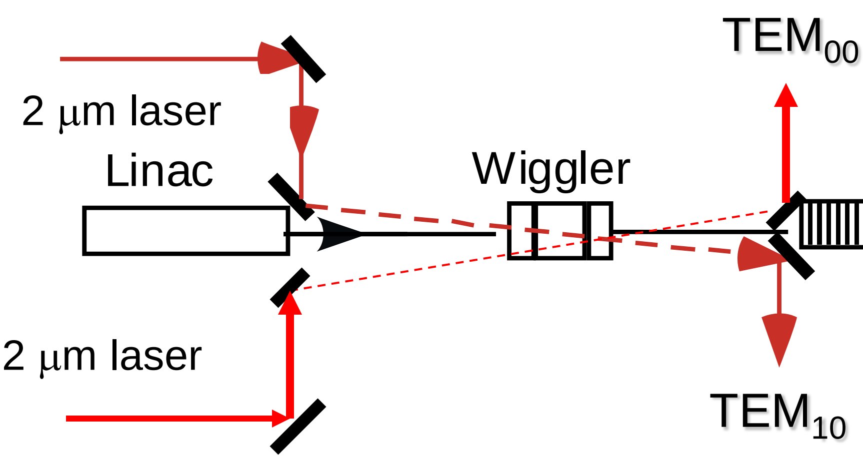
Contrast ≈ 1 (assuming 100 fs long bunch)

Nearly Fourier transform limited pulse

Publications exploring generation of attosecond x-ray pulses using a few-cycle laser pulse with a carrier envelop phase stabilization:

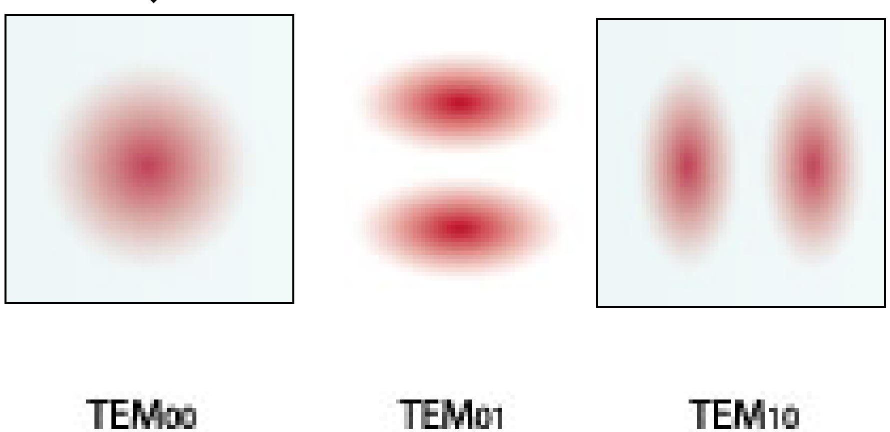
[1] A. A. Zholents and W. M. Fawley, Phys. Rev. Lett. 92, 224801 (2004).
[2] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Commun. 237,153 (2004).
[3] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Commun. 239,161 (2004).
[4] A. A. Zholents and G. Penn, Phys. Rev. ST-AB 8, 050704 (2005).
[5] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST-AB 9, 050702 (2006).
[6] A. A. Zholents and M.S. Zolotorev, New J. Phys. 10, 025005 (2008).
[7] W.M. Fawley, Nucl. Inst. and Meth. A 593, 111(2008).
[8] Y. Ding, Z. Huang, D. Rather, P. Bucksbaum, H. Maerdji, Phys. Rev. ST-AB 12, 060703 (2009).
[9] D. Xiang, Z. Huang, G. Stupakov, Phys. Rev. ST-AB 12, 060701 (2009).
[10] A. A. Zholents and G. Penn, Nucl. Inst. and Meth. A 612, 254(2010).

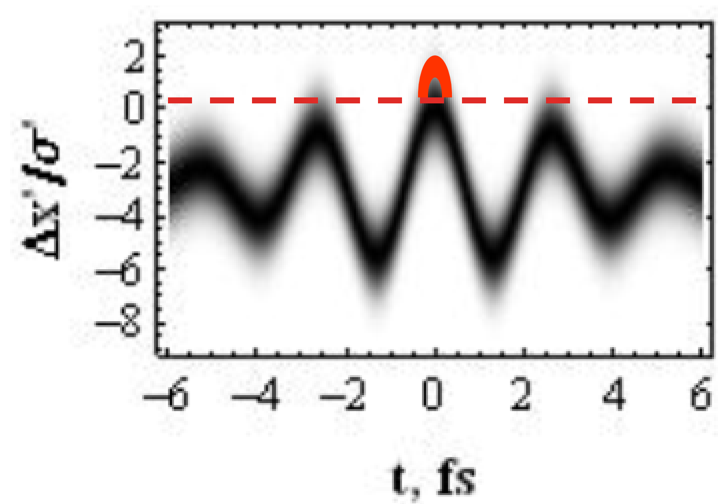
Selection of attosecond x-ray pulses via angular modulation of electrons*)



$$\Delta E(z) = \Delta E_0 \sin(kz)$$

$$\Delta x'(z) = \Delta x'_0 \cos(kz)$$

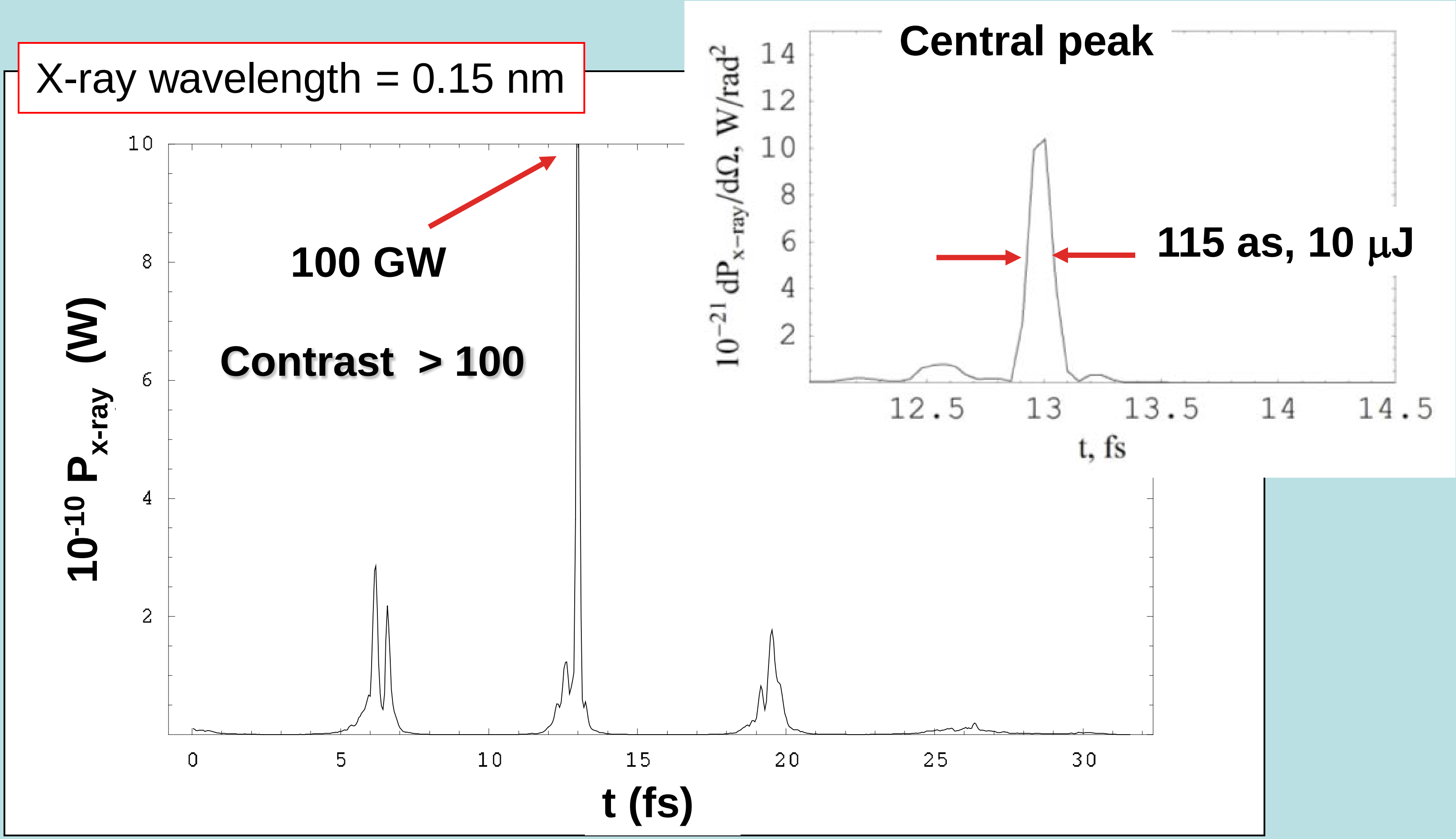




Hermite-Gaussian laser modes

*) Zholents, Zolotorev, New Journal of Physics, 10, 025005 (2008).

Combining angular and energy modulations for improved contrast of attosecond x-ray pulses

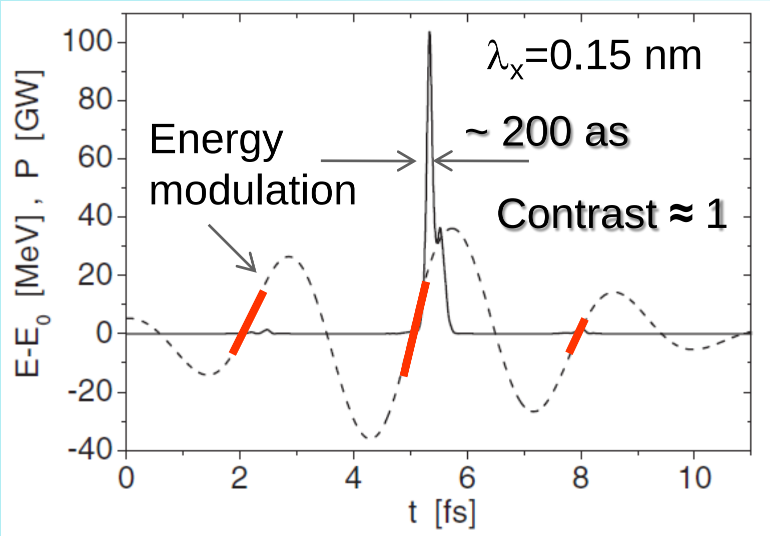


X-ray peak power as a function of time

Tapered undulator method*

Hard x-rays

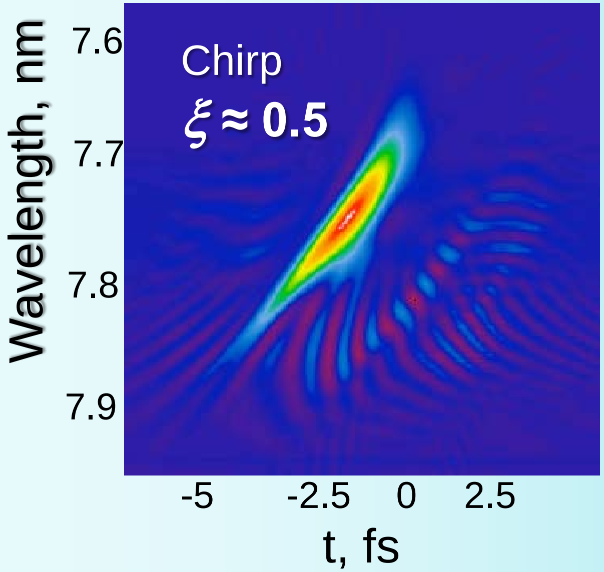
Energy chirp is compensated by the undulator taper in the central slice



$$\frac{d\ln K}{dz} = -\frac{\lambda_x}{\lambda_u}\frac{1+K^2/2}{K^2/2}\frac{d\ln\gamma}{cdt}$$

Soft x-rays

Wigner transform of the on-axis far field



Frequency chirp definition $\varphi = \xi(t/\sigma_t)^2$

Fourier transform limited pulse ~ 1.5 fs (FWHM)

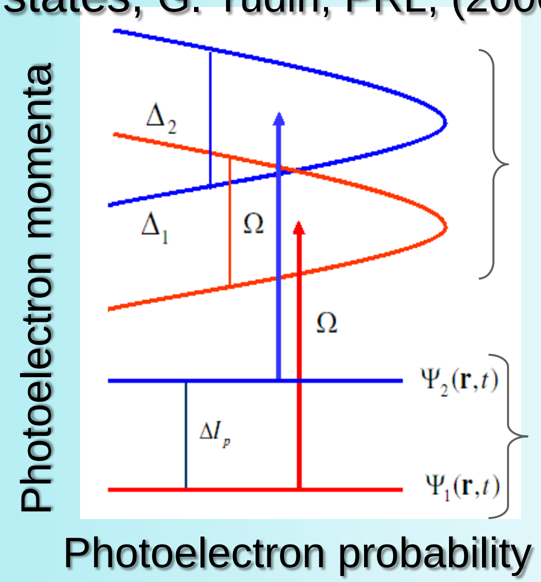
W.M. Fawley, Nucl. Inst. and Meth. A 593, 111(2008).

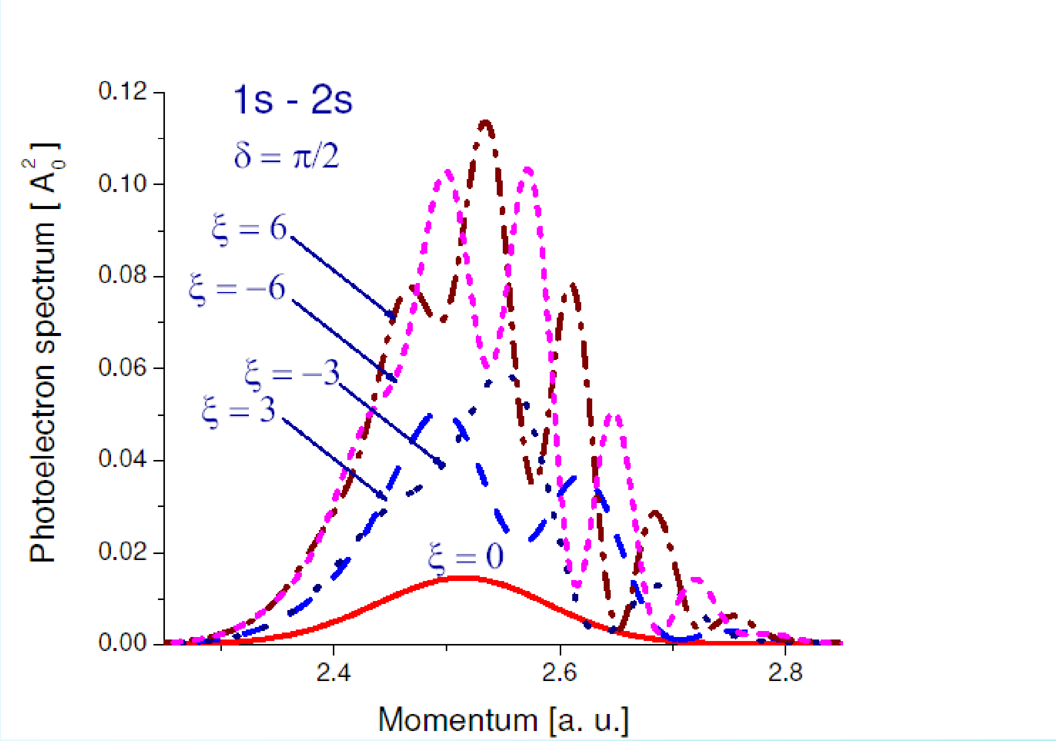
With two laser one can manipulate the energy chirp and, thus, the frequency chirp

*) E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. ST-AB 9, 050702 (2006).

The figure-of-merit is broad bandwidth of attosecond pulses

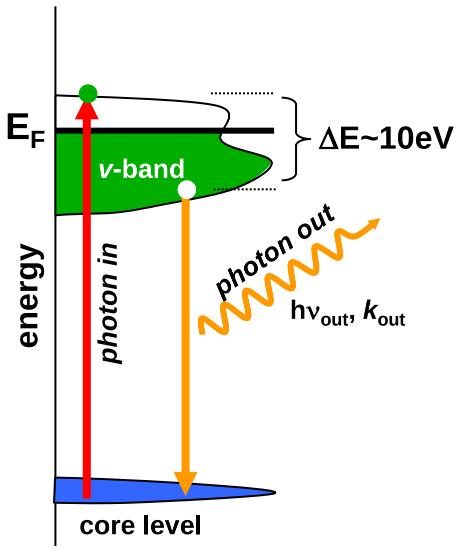
"Sudden" photoionization creates a coherent superposition of electronic states, G. Yudin, PRL, (2006)

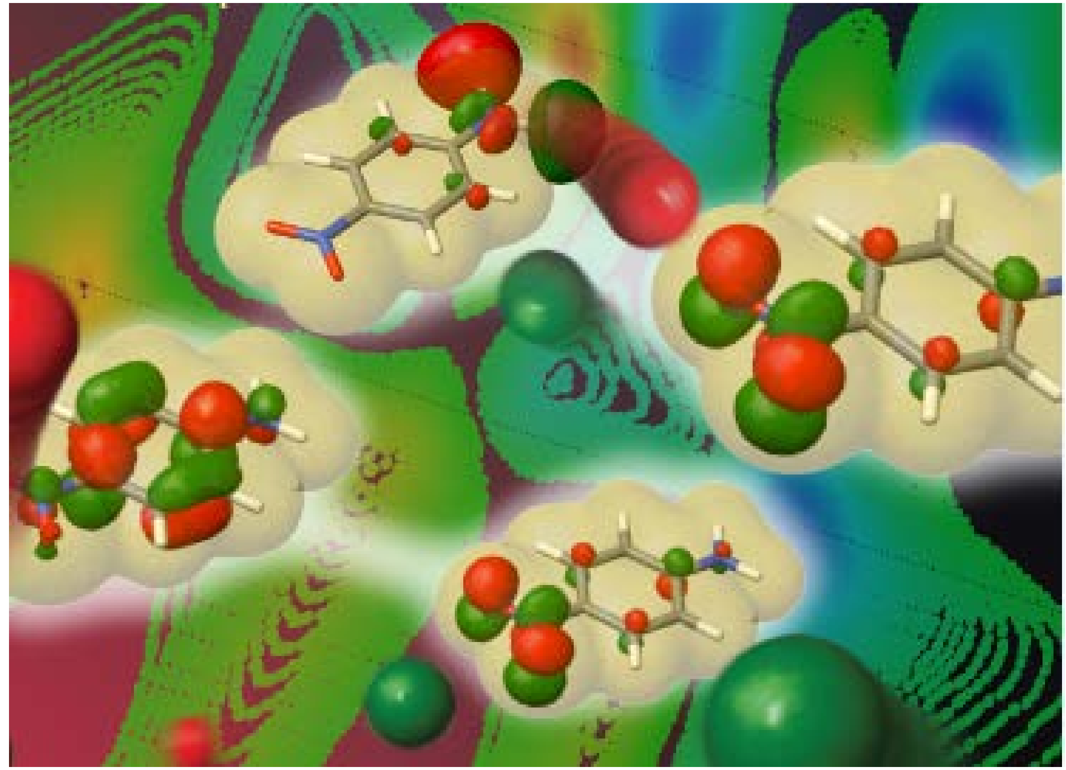




Intense attosecond x-ray pulses from FELs provide the opportunity to probe the matter on atomic scale in space and time

Stimulated X-ray Raman spectroscopy *)
X-ray pump, X-ray probe;
element specific





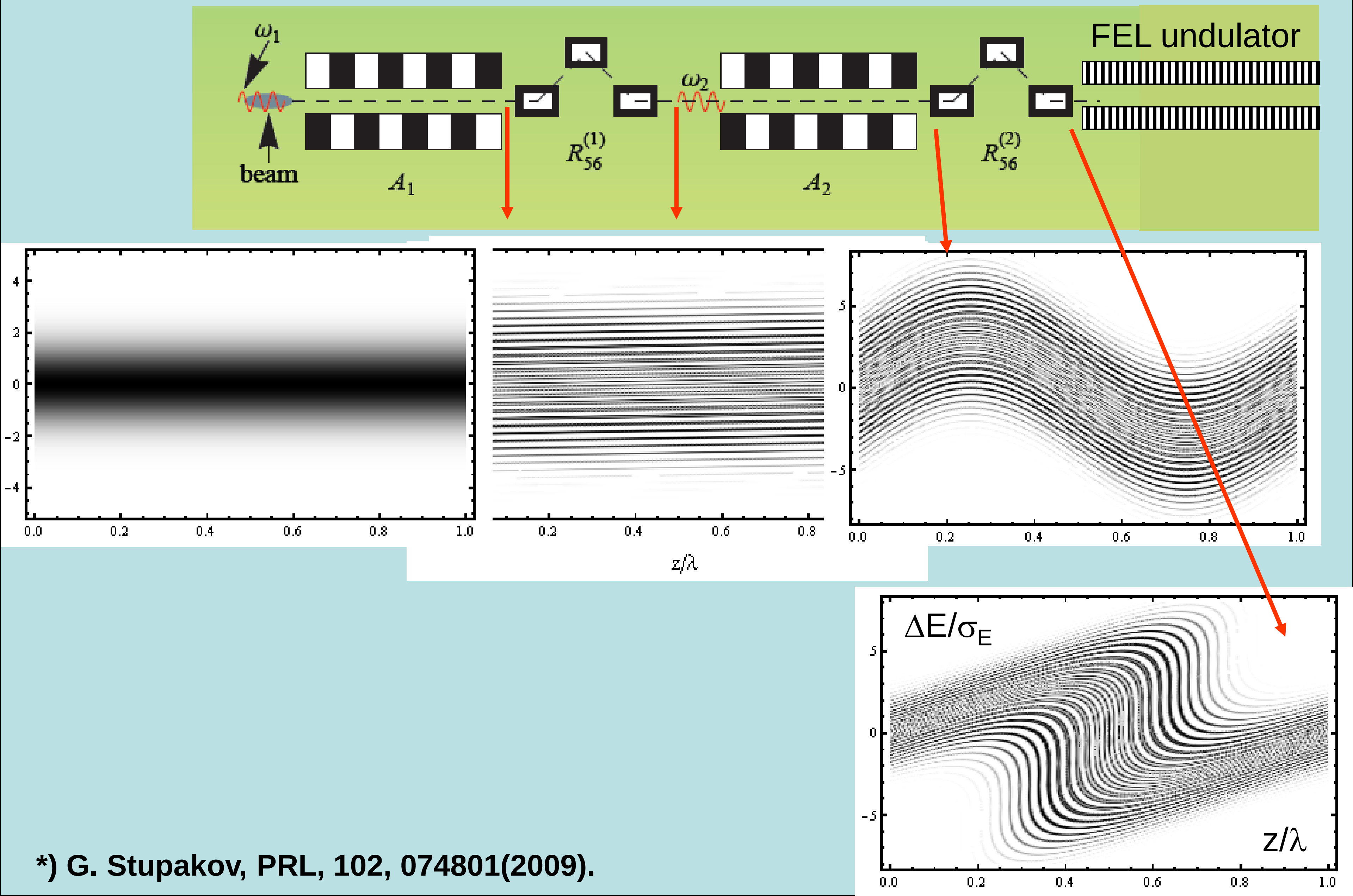
Artist's (Denis Han) view of excited electron wavepackets in molecule created by core excitation with attosecond x-ray pulses (courtesy S. Mukamel)

300 asec -> 6 eV, i.e. "sudden" excitation reveals multi-electron dynamics

In molecules all electrons move in a combined potential of ion core and other electrons

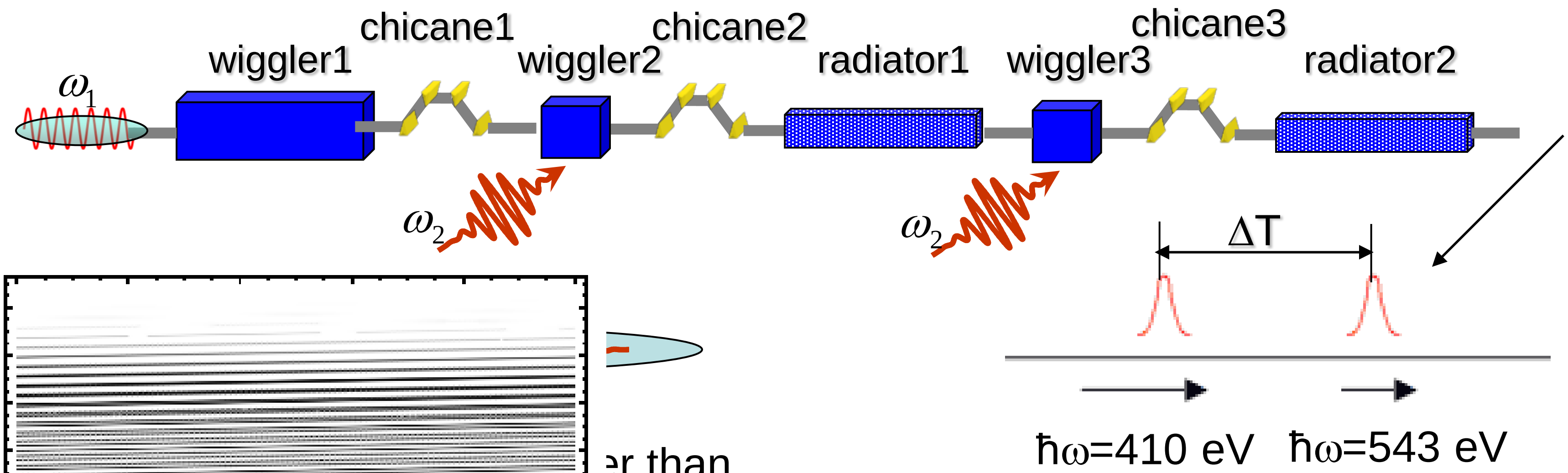
*) Schweigert, Mukamel, Phys. Rev. A 76, 012504 (2007)

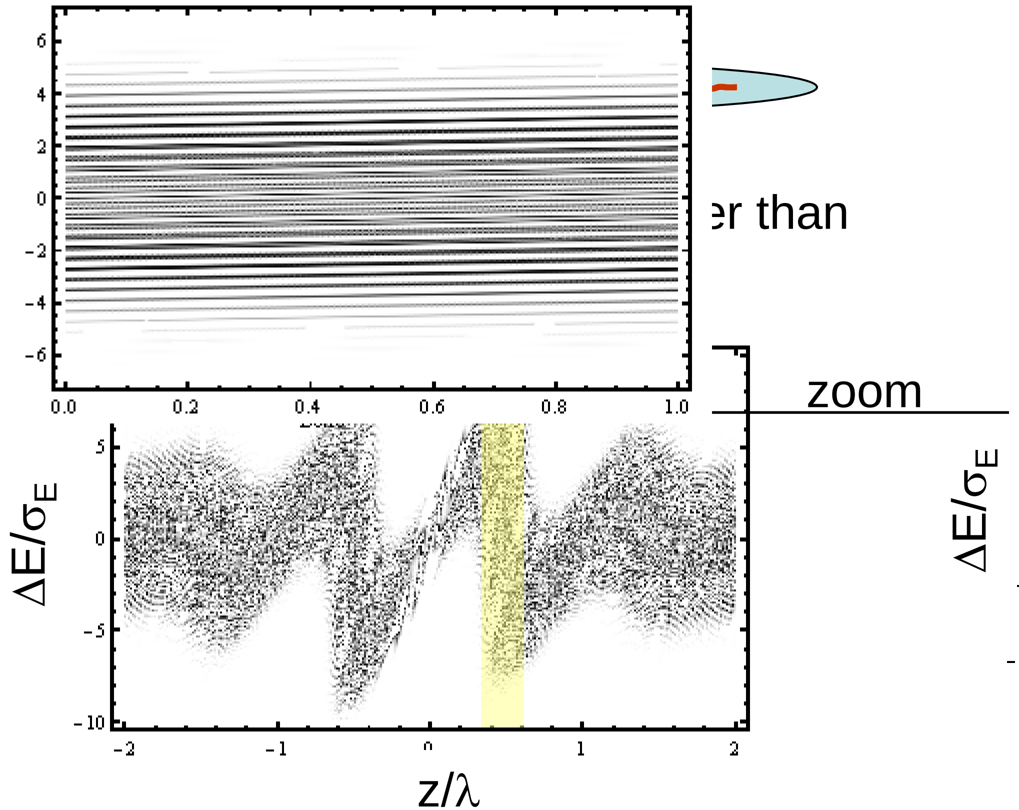
Echo effect for harmonic generation of x-rays*)



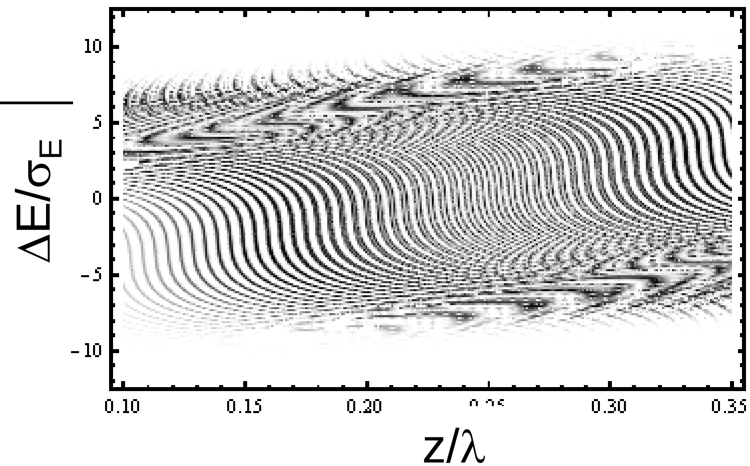
*) G. Stupakov, PRL, 102, 074801(2009).

Two color attosecond pump and attosecond probe x-ray pulses*)





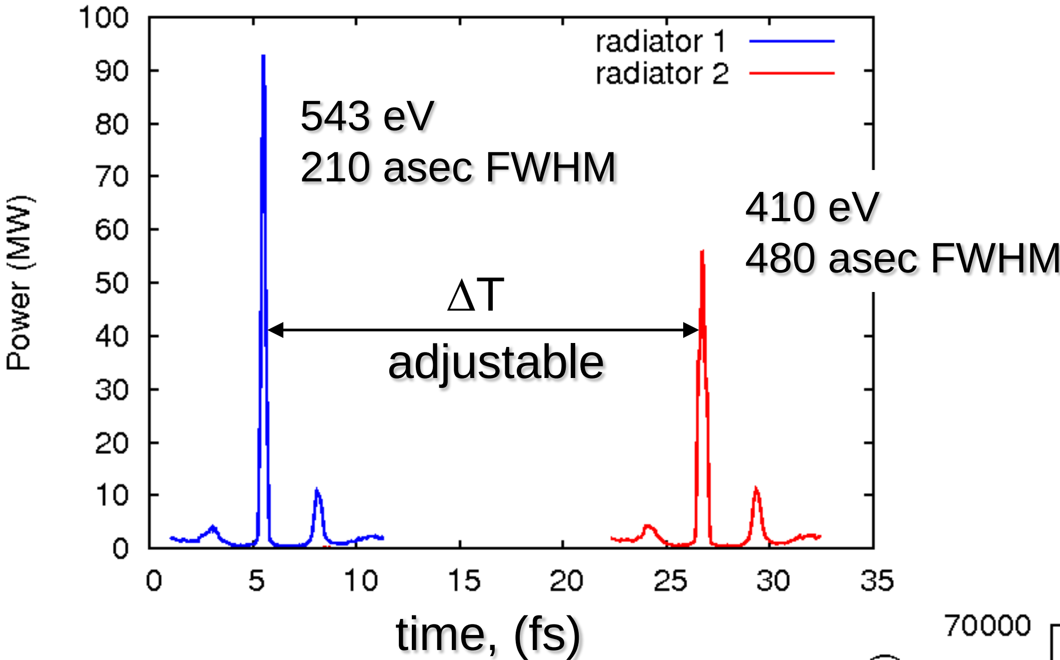
Fragment of the longitudinal phase space

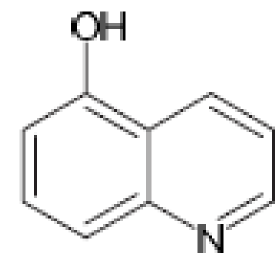


Zoom into the main peak shows microbunching at 2.28 nm

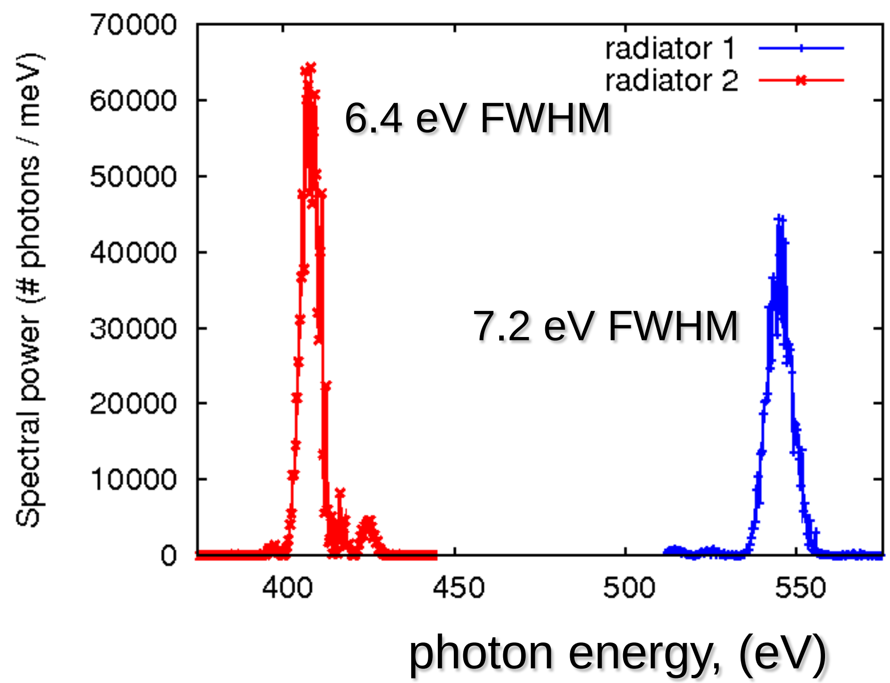
*) Zholents, Penn, Nucl. Inst. and Meth. A 612, 254(2010).

Simulation results using 1D code and GENESIS for two color scheme



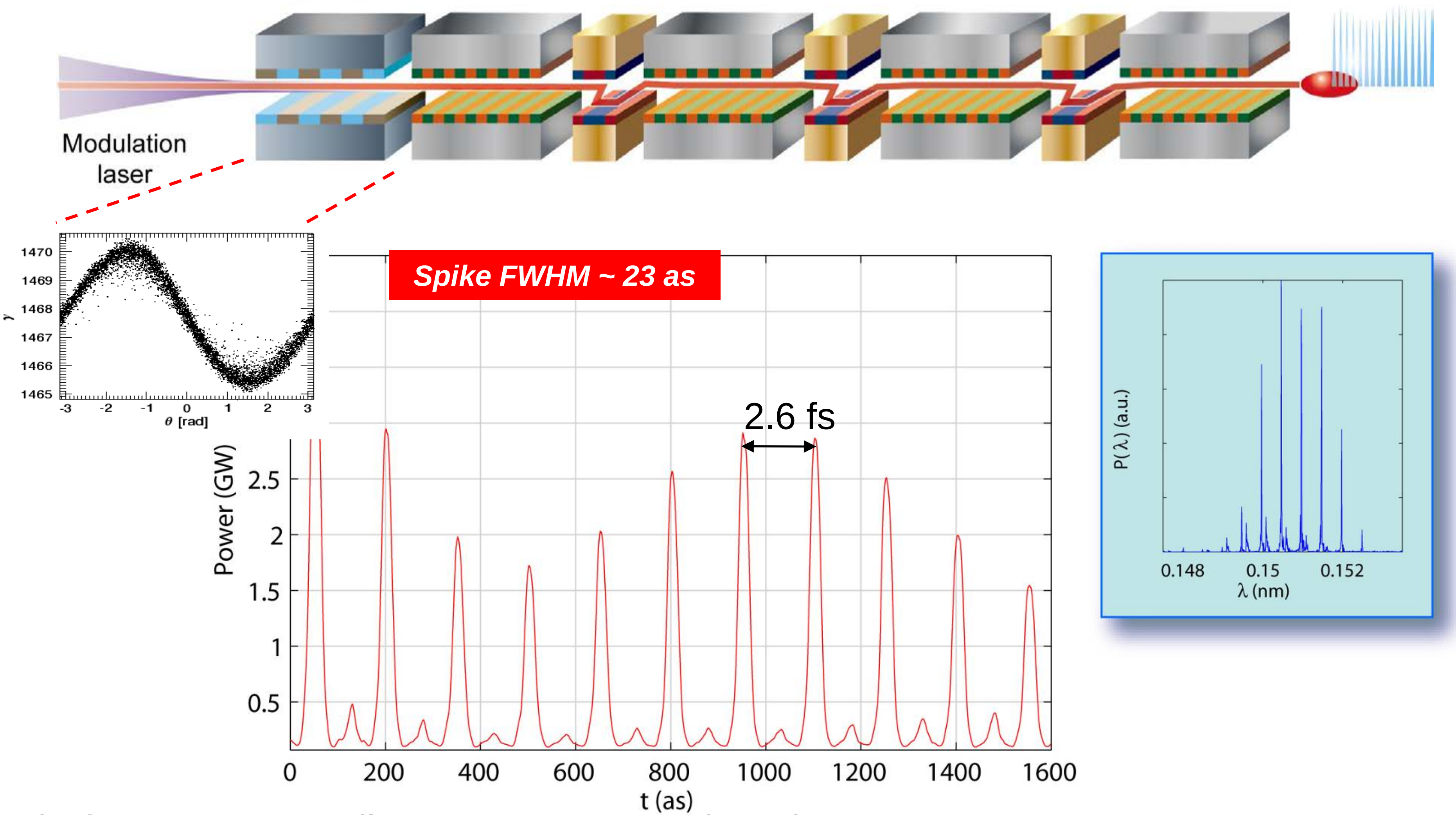


Molecule structure of 5-quinolinol



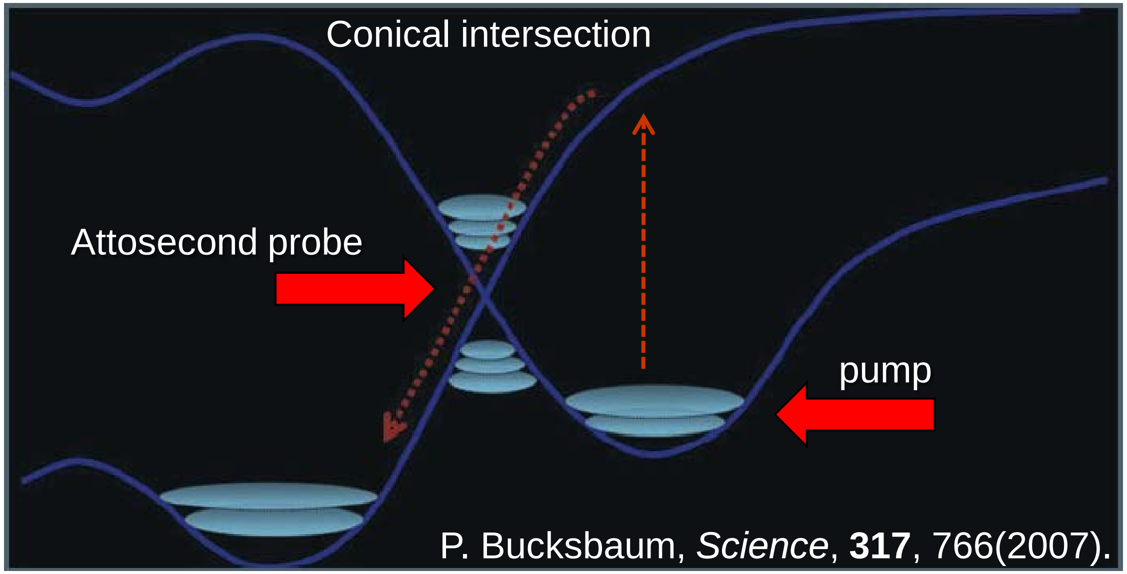
X-ray SASE FEL amplifier with mode-locking produces a train of attosecond pulses*

courtesy B. McNeil



*) Thompson, McNeil, PRL, 100, 203901(2008);
Kur, Dunning, McNeil, Wurtele, Zholents, New Journal of Phys. 063012(2011).

Summary: FELs – the light fantastic



Million times brighter and thousand times shorter than anything spontaneous emission can do

- **We are at the threshold of a new era of science, where for the first time, the new instruments, the x-ray FELs, are capable to study the matter with a single atom time and space resolution.**
- **FLASH, SCSS and LCLS routinely work with ultra-short XUV/x-ray pulses. SACLA and FERMI are getting ready.**
- **Remarkably, adding attosecond x-ray pulse capabilities to existing FELs require rather modest modifications – in most cases a three pole wiggler and a carrier-envelope stabilized laser.**

Thank you for your attention