Options for generation of attosecond x-ray pulses at the European XFEL

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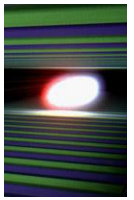
FEL R&D Meeting, October 14, 2020

Why we need short radiation pulses?



Radiation sources with ultrashort pulse duration (down to attosecond time scale) are required for studying dynamical process in the matter:

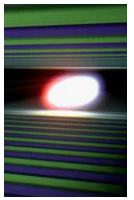
- Phase transitions in solids.
- Surface dynamics.
- Making and braking of bonds during chemical reactions.
- Chemical dynamics in proteins.
- Correlated behavior of electrons in complex solids .

…. And many others.

Temporal scale depends on physical phenomena under investigation. Typical atomic time scale is in a few tens of attosecond range; vibration period between the two hydrogen atoms in a hydrogen molecule is about 8 fs; 1Å / (speed of sound) ~ 100 fs.

Typical experiment for studying time-dependent phenomena involves two radiation pulses (pump-probe technique) when the first pulse triggers some physical process, and the second pulse is used for probing state of the system at prescribed moment of time. Pulse duration and synchronization accuracy are key parameters for achieving temporal resolution.

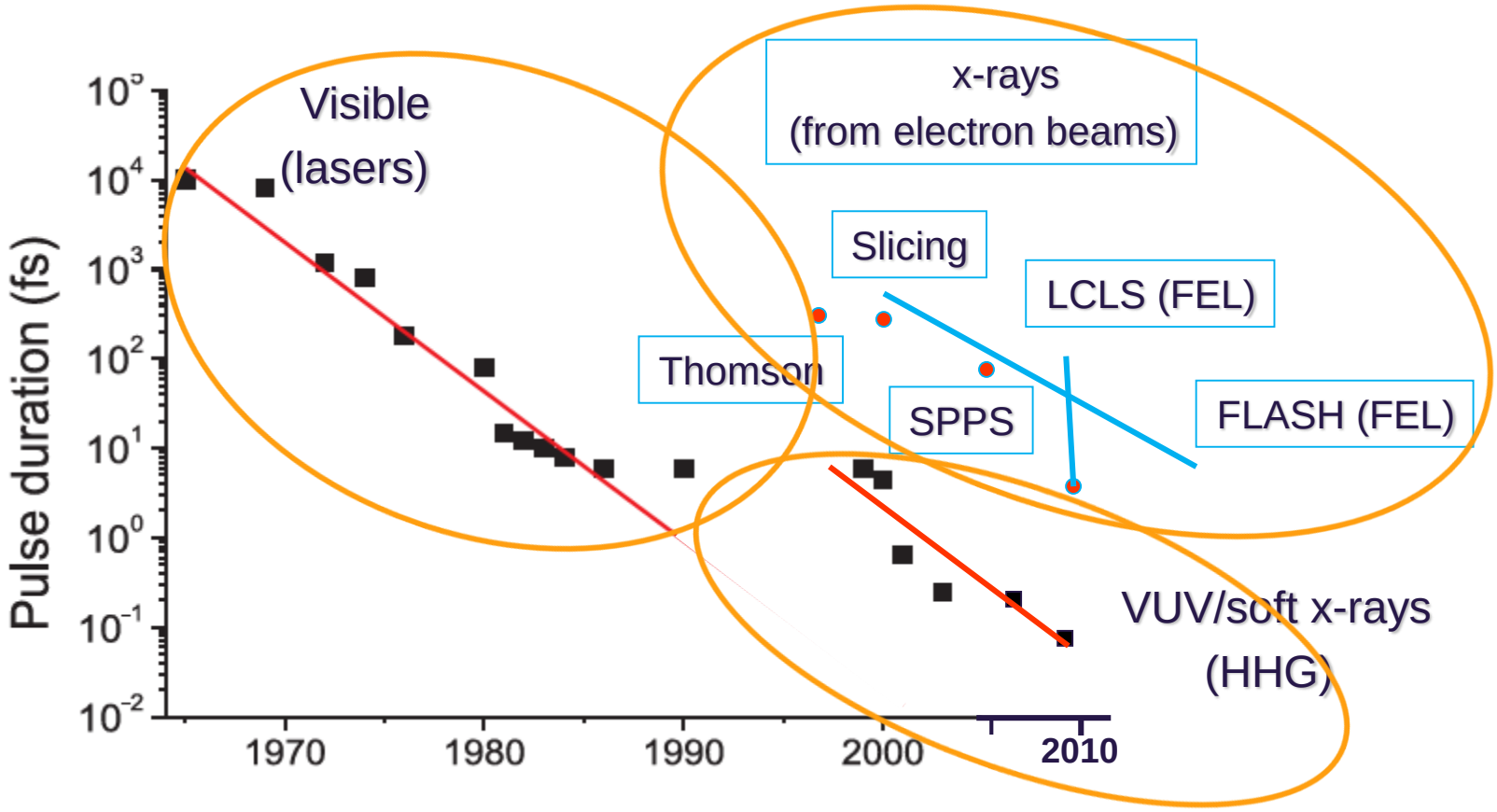
Requirements to the radiation source



Scope of requirements to the radiation source:

- Photon energy range;
- Temporal, spectral and polarization properties;
- Intensity (photons per pulse);
- Repetition rate;
- Synchronization with an external laser or other x-ray pulse (pump-probe experiments);
- Stability (intensity, position, temporal);
- Contrast of an ultrashort (e.g., attosecond) pulse wrt background (radiation pedestal);
- Photon beam transport to a sample;
- Need in a monochromator (intensity reduction and radiation damage).

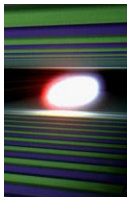
Status of ultrashort pulses production



J. Levesque and P.B. Corkum, Canadian Journal of Physsics, 84(2006)1

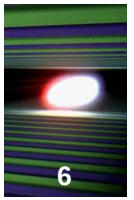
A. Zholents, Proc. FEL2010 Conf.

Production of ultrashort radiation pulses by electron beams



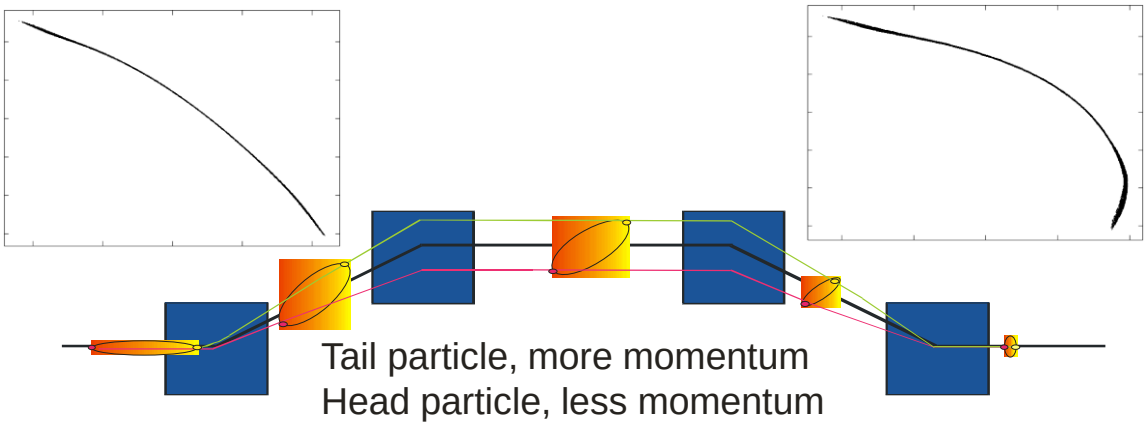
- Production of ultrashort electron pulses which then generate ultrashort radiation pulses.
- Slicing of electron bunches aiming local change of electron beam properties at a short time scale.
- Then different techniques (based on physical effects as well as technical tricks) are used to derive ultrashort radiation pulse.
- Coherent enhancement of the radiation intensity is an essential issue.

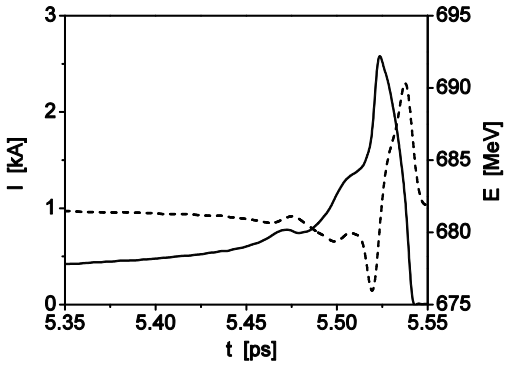
Some examples of ultrashort pulse generation

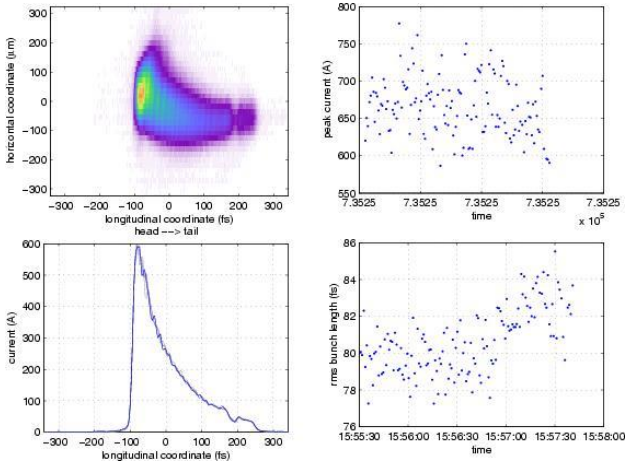


- “Simple” schemes (not involving external lasers)
  - Statistical selection
  - Slotted foil
  - Low charge
  - LCLS experience (nonlinear compression and XLEAP)
- (Some of the) schemes using few-cycle laser pulse
  - Chirp and taper
  - Current enhancement

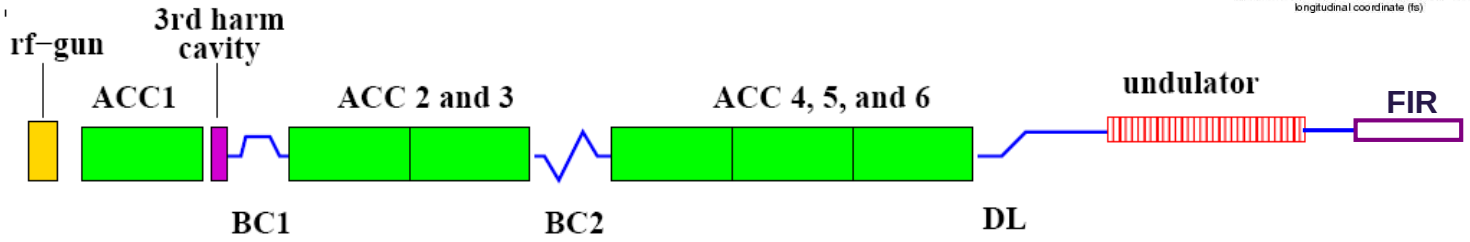
Formation of ultrashort bunches in linear accelerators (x-ray FELs, linear colliders)







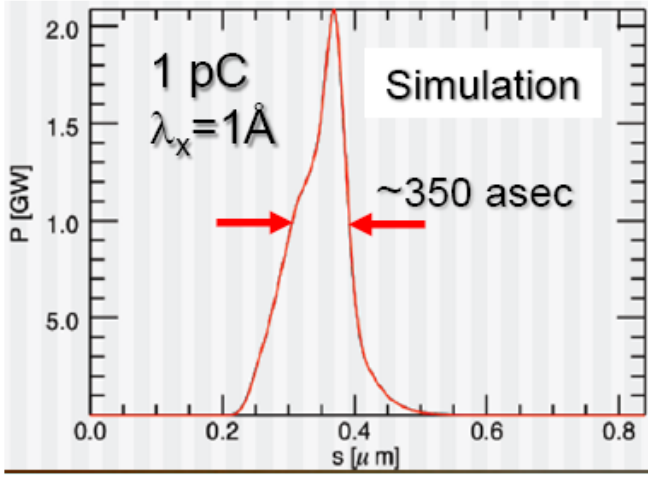
- Application of several stages of bunch compression. Electron beam gains energy chirp in acceleration section which then is transformed into spatial compression in magnetic chicane.
- Strongly nonlinear compression can produce very sharp features of the electron beam /W. Ackermann et al, Nature Photonics 1(2007)336/.
- Linearization of compression scheme with higher harmonics rf cavities allows to compress significant fraction of the electron bunch.

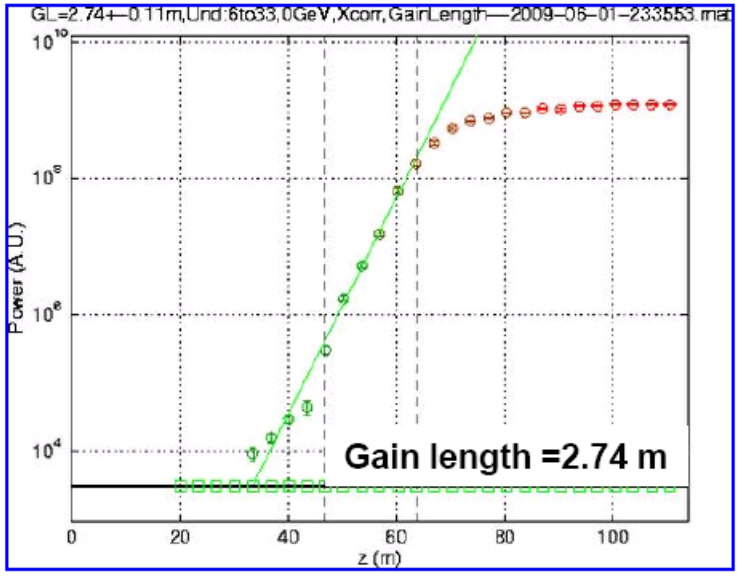


Direct production (low charge)

S. Reiche et al., NIM A593(2008)45

1 pC case simulated





LCLS operates at 20 pC, few fs x-rays

Y. Ding et al., PRL 102(2009)254801

Talk by Z. Huang

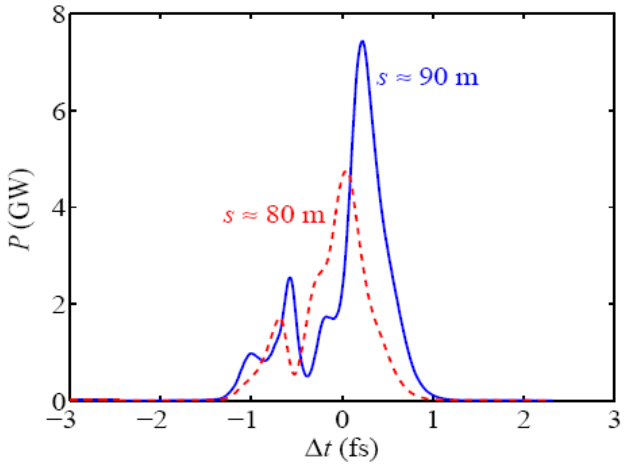
Slotted foil method

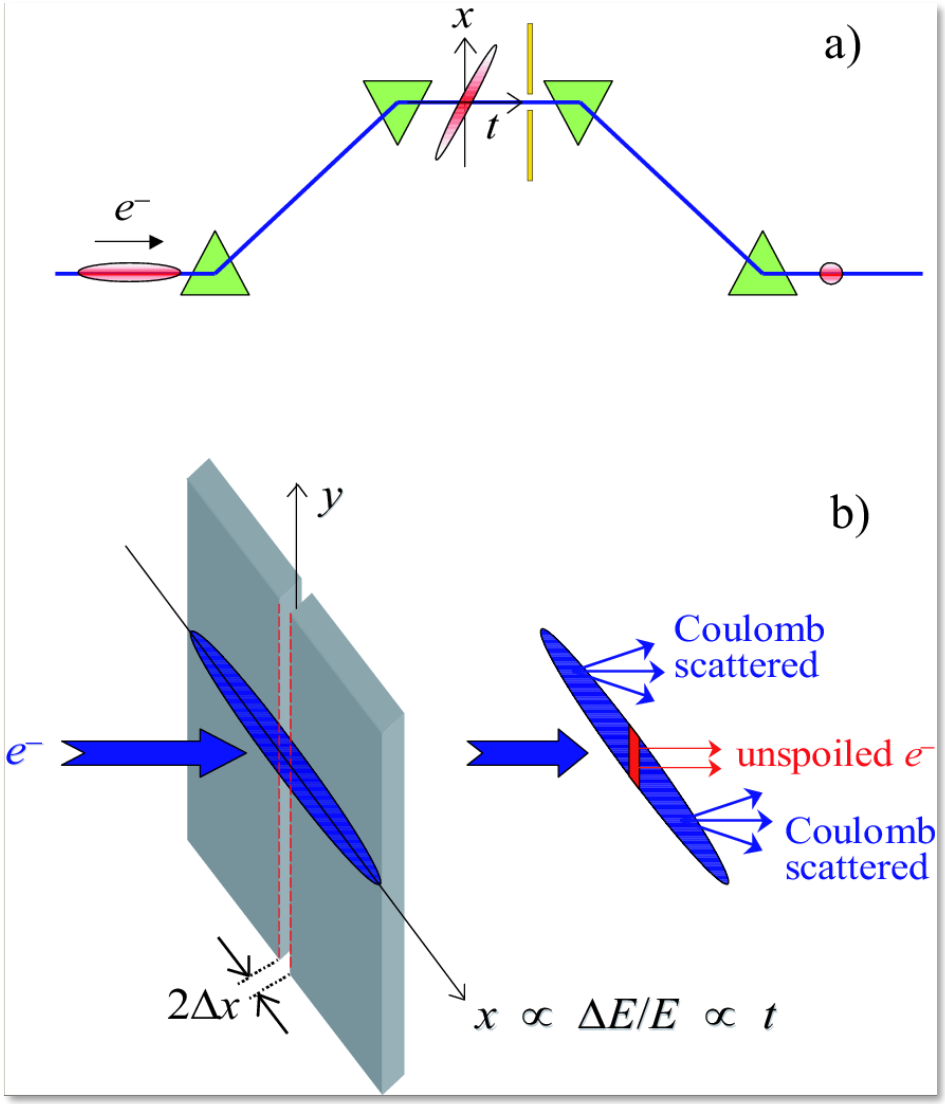
P. Emma et al., *PRL* **92**, 074801 (2004)

(femtoseconds)

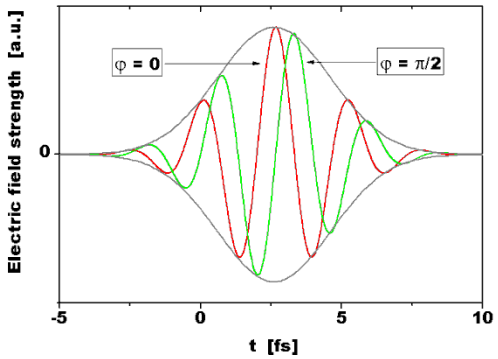
P. Emma, Z. Huang, M. Borland, FEL'2004

(attoseconds)

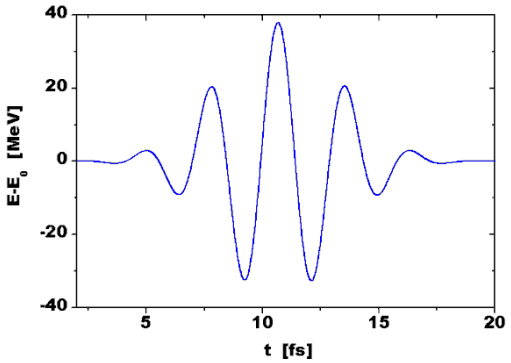




Methods using few-cycle laser pulse



Two-period undulator



Laser pulse with carrier-envelope phase (CEP) stabilization (~ 1 mJ)

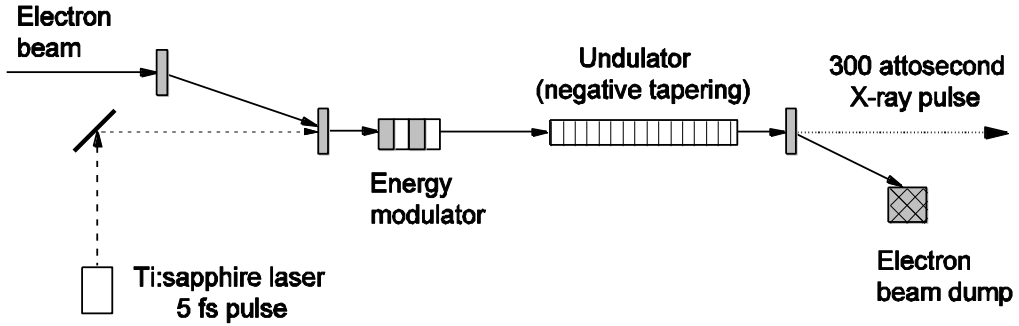
Energy modulation of electron beam

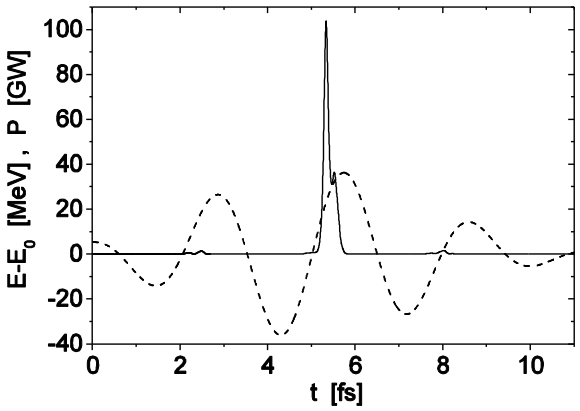
A. Zholents and W. Fawley, PRL 92(2004)224801
E. Saldin, E. Schneidmiller and M. Yurkov, Opt. Comm. 237(2004)153
E. Saldin, E. Schneidmiller and M. Yurkov, Opt. Comm. 239(2004)161
A. Zholents and G. Penn, PRST-AB 8(2005)050704
E. Saldin, E. Schneidmiller and M. Yurkov, PRST-AB 9(2006)050702
A. Zholents and M. Zolotorev, New J. Phys. 10(2008)025005
Y. Ding et al., PRST-AB 12(2009)060703
D. Xiang, Z. Huang and G. Stupakov, PRST-AB 12(2009)050702

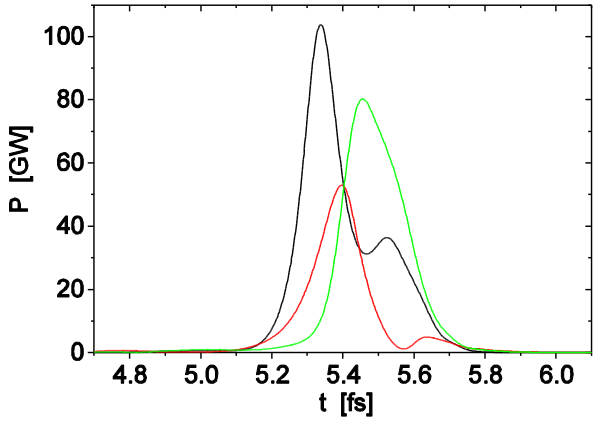
Energy chirp and undulator taper

Energy chirp is perfectly compensated for by undulator taper

$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{cdt}$$



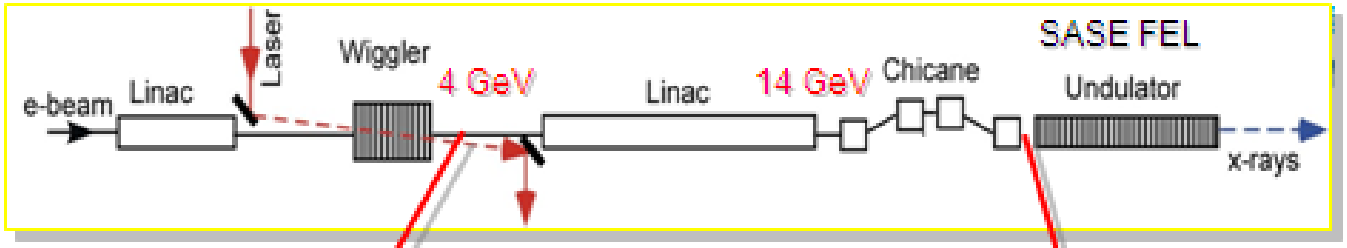


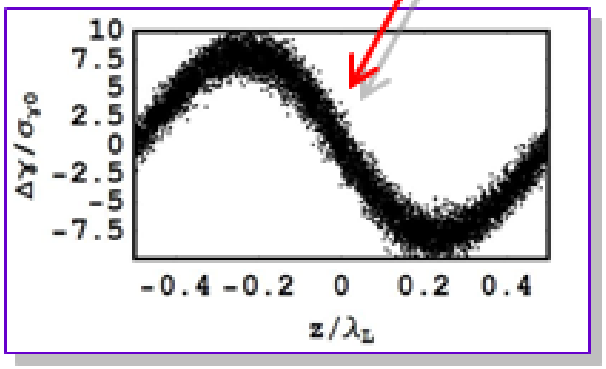


High power, high contrast attosecond pulses

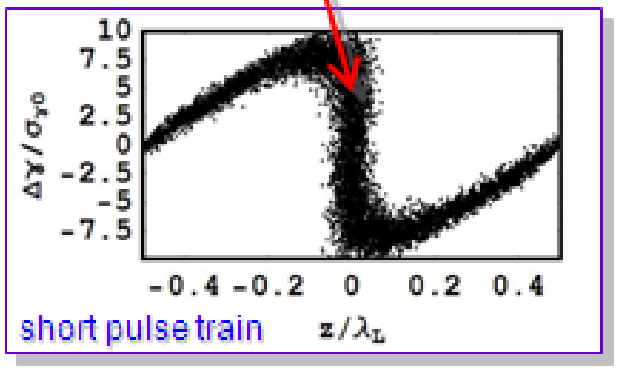
E. Saldin, E. Schneidmiller and M. Yurkov, PRST-AB 9(2006)050702

Current enhancement



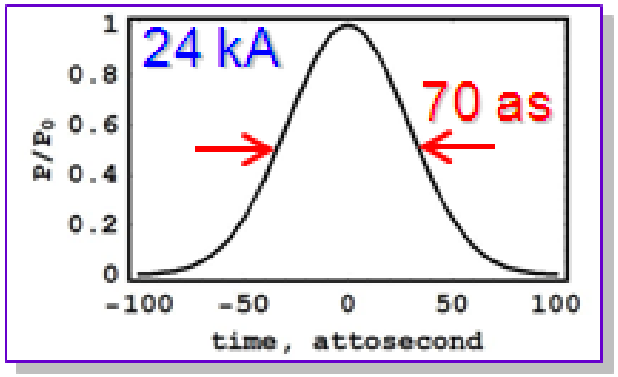


800-nm modulation (few GW)



Allows synchronization between laser pulse and x-ray pulse

E-SASE (applied to *LCLS*)



Take care of LSC in the undulator! (G.Geloni et al., NIM A583(2007)228)

A. Zholents , PRST-AB 8(2005)040701; A. Zholents et al., FEL2004

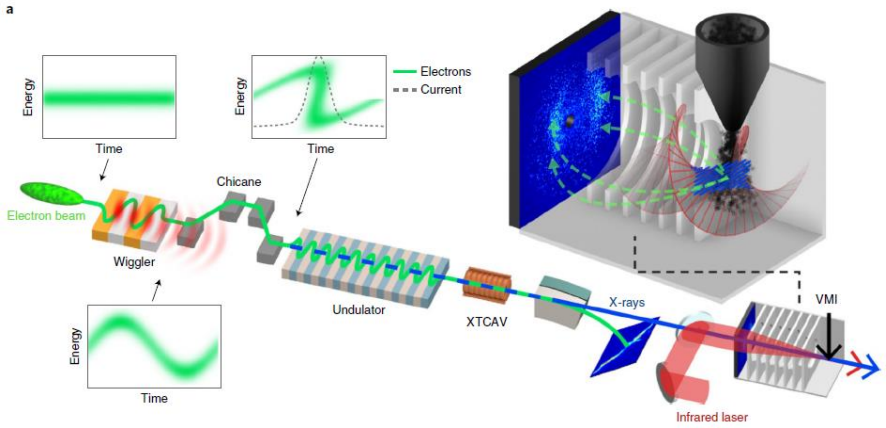
Recent LCLS experiments

- Nonlinear compression + LSC + undulator taper: worked in hard X-ray regime

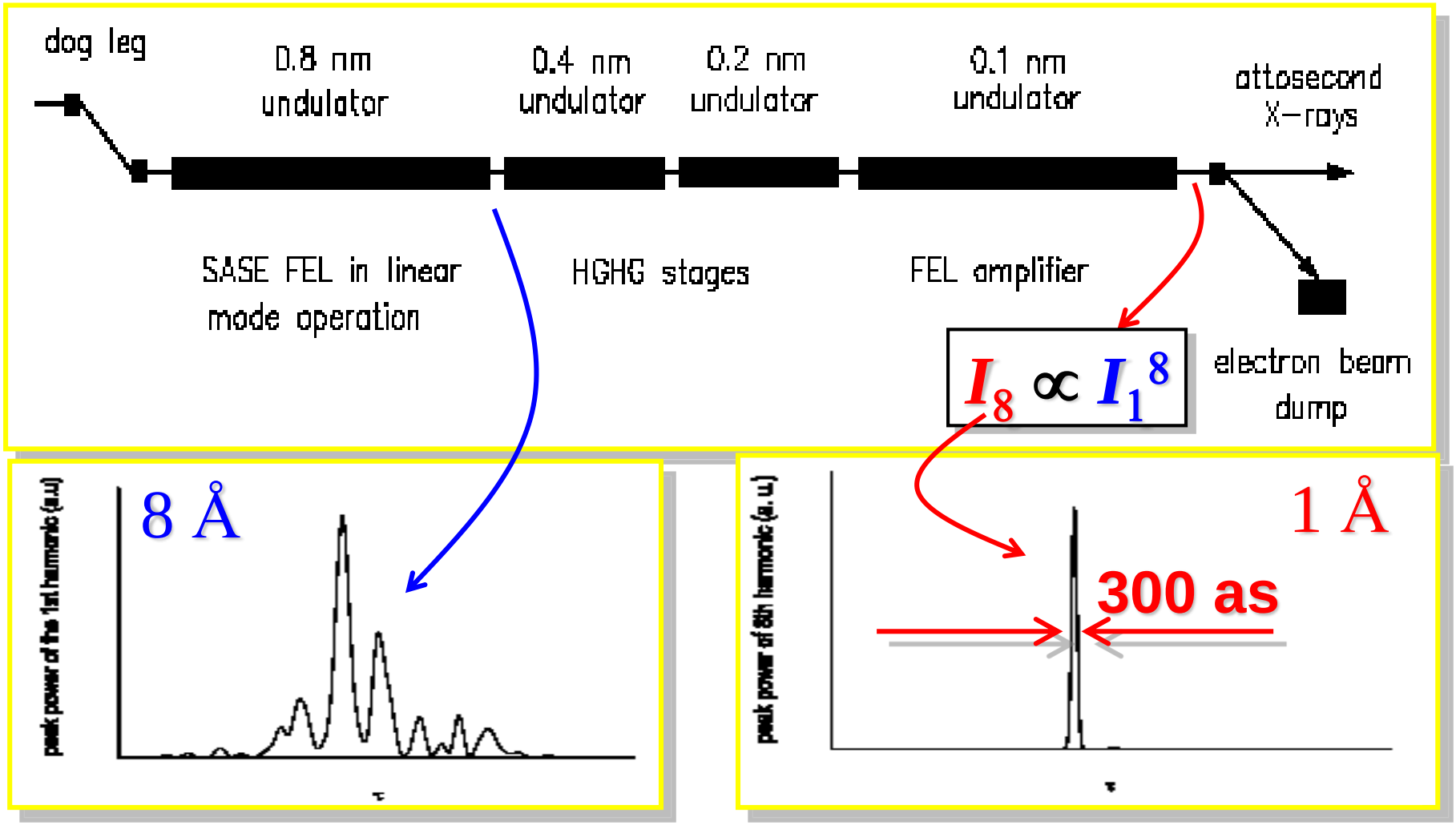
  S. Huang et al., Phys. Rev.Lett.119(2017)154801

- XLEAP (“XCHEAP”): self-modulation of beam in the wiggler + compression of a short slice + LSC + taper: sucsessfully worked in soft X-ray regime

  J. Duris et al.,
  Nat. Photon.1430(2020)6



Statistical selection of a single spike



E. Saldin, E. Schneidmiller, M. Yurkov, *Opt. Comm.* 212(2002)377

Options for EuXFEL

- Nonlinear compression and/or low charge (~ 1 fs): studies by Bolko and colleagues.
- The same but in combination with harmonic cascade/statistical selection in SASE3: attosecond pulses. For example: 700 eV – 2.1 keV – 4.2 keV. Can be tried out in the near future.
- Slotted foil is of limited applicability at the European XFEL – does not survive at high repetition rate (high average power).
- XLEAP-like approach (with a wiggler for self-modulation) can be studied but we need to accumulate a culture of bunch shape manipulation (stable and reproducible horn)
- Laser-based attosecond schemes should be seriously considered. Synchronization on 10 fs scale is state-of-the-art (combination with slotted foil a la LCLS is not required). Modulator undulator and chicane are simple and inexpensive but the laser transport and infrastructure require a lot of efforts.