Towards attosecond SASE: generating photon pulse duration below the cooperation length

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Topical workshop on selected problems in FEL physics: from soft X-rays to THz,
Grado, Italy, 24.09.2025

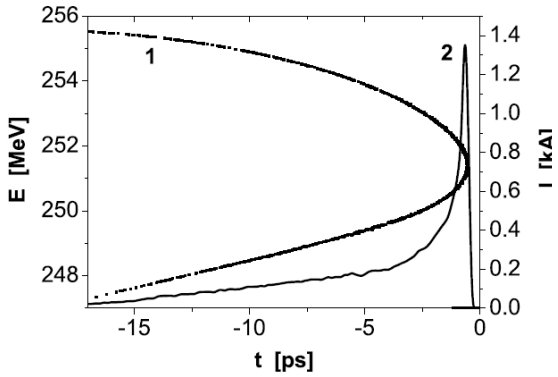
Single-mode lasing

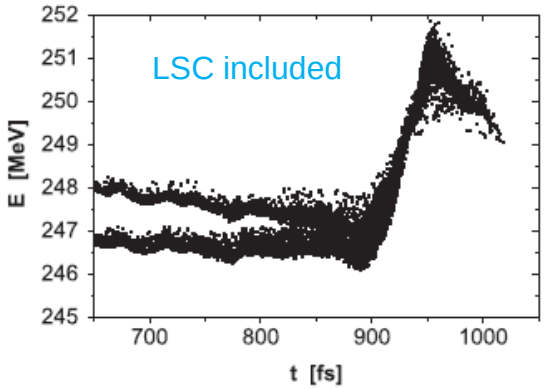
$$\ell_c = \lambda_s / 4\pi\rho$$ cooperation length

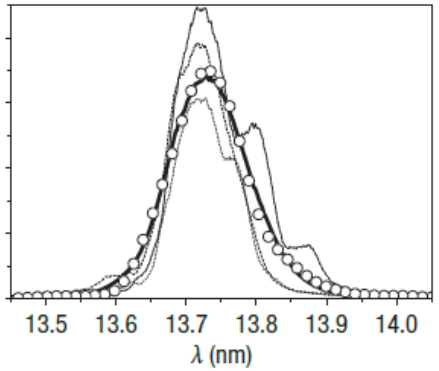
TTF1 FEL, FLASH: 2000-2009

Nonlinear compression

~ 10 fs for XUV



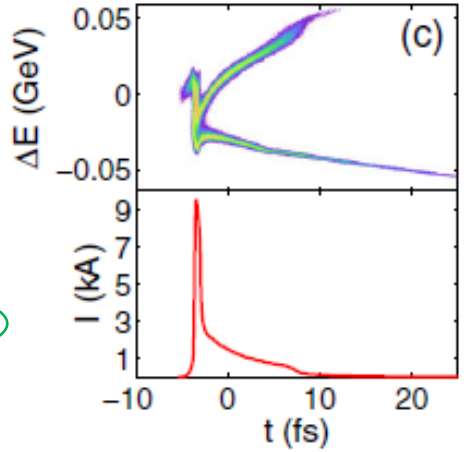


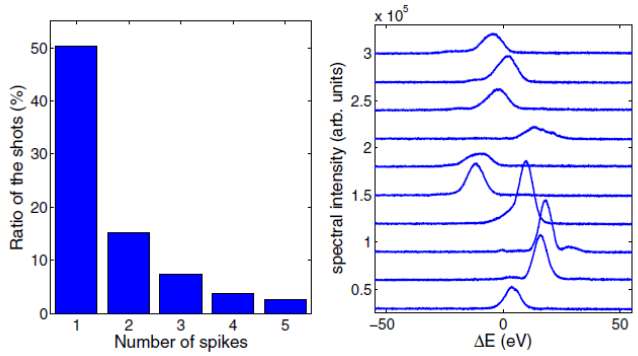


LCLS: 2017

First attosecond pulses from FELs

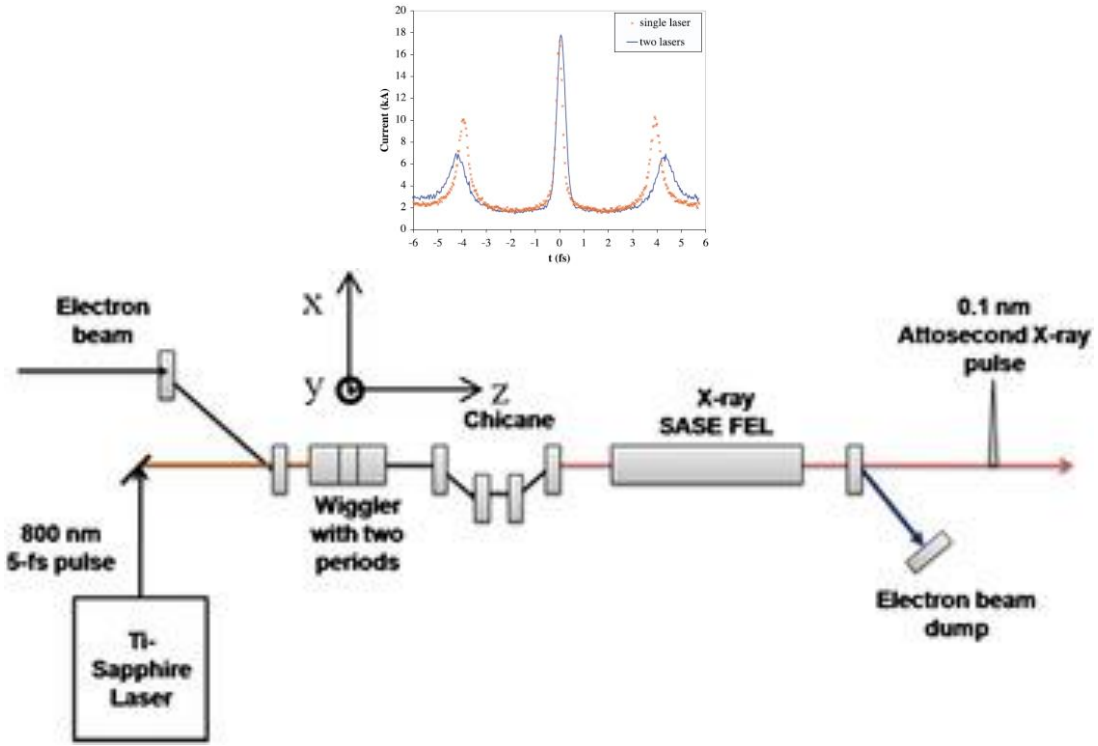
200 as for hard X-rays





S. Huang et al., PRL 119(2017)154801

eSASE

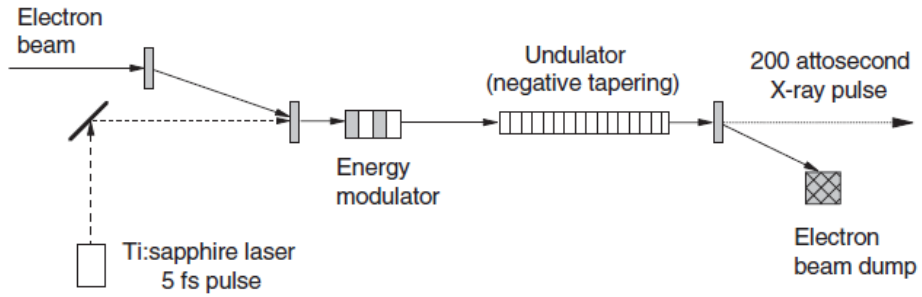


In the chicane the laser-induced energy modulations are converted into density modulations (current spikes). The spike with the highest current lases better (enhanced SASE).

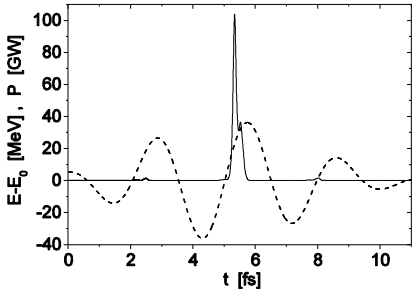
A. Zholents, Phys. Rev. ST-AB 8(2005)040701

A. Zholents and G. Penn, Phys. Rev. ST-AB 8(2005)050704

Chirp-Taper attosecond scheme



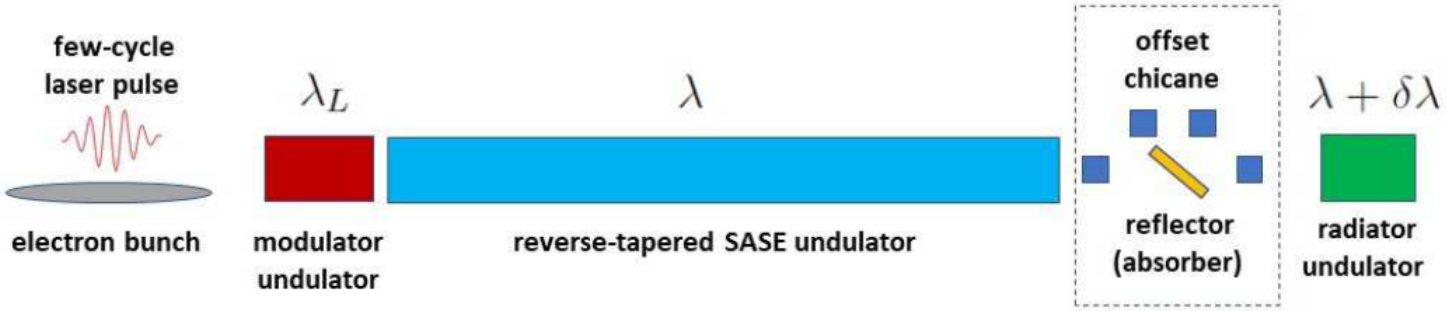
$$\frac{1}{H_{w0}}\frac{dH_w}{dz} = -\frac{1}{2}\frac{(1+K_0^2)^2}{K_0^2}\frac{1}{\gamma_0^3}\frac{d\gamma}{cdt}$$

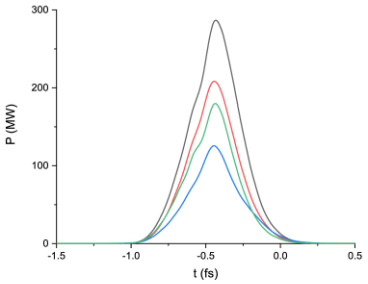


Undulator taper compensates for energy chirp within a short slice,
lasing in the rest of the bunch is suppressed by uncompensated taper.

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

Beating the FEL coherence time





~ 300 as at 4 nm

- Lasing slice is much shorter than coherence time
- Bunching distribution is narrow (<< coh. time); radiation pulse in the main undulator is ~ coh. time but is suppressed (separated) by
  - excessive reverse taper;
  - chicane with reflector or absorber;
  - kick with quadrupoles, achromatic bend, dogleg …
  - radiator can be tuned to a harmonic.
- Attosecond pulse is produced in a short radiator

E. Schneidmiller, Phys. Rev. Accel. Beams 25(2022)010701

Reverse taper for polarization control

Talks on Friday by
Suren and Juliane

reverse-tapered planar undulator (saturation)

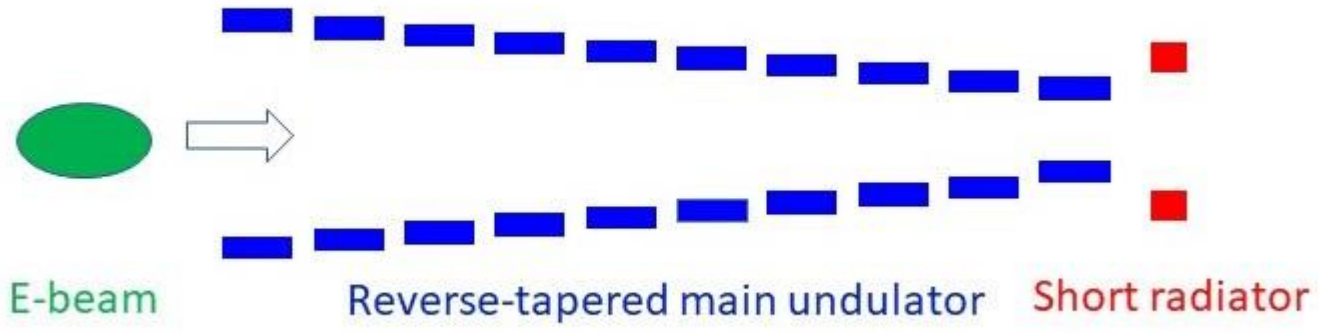
helical
afterburner

- Fully microbunched electron beam but strongly suppressed radiation power at the exit of reverse-tapered planar undulator
- The beam radiates at full power in the helical afterburner tuned to the resonance

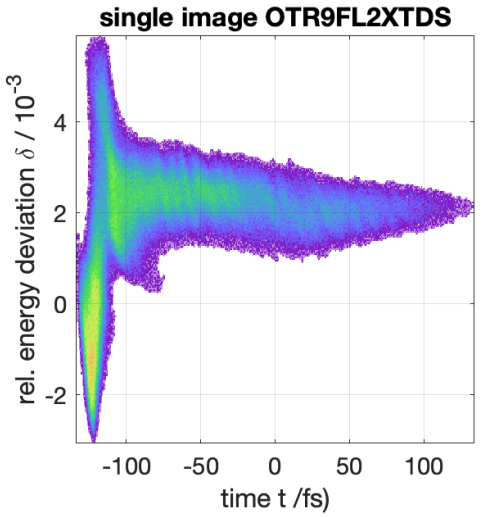
E. Schneidmiller and M. Yurkov, Phys. Rev. ST-AB 110702(2013)16

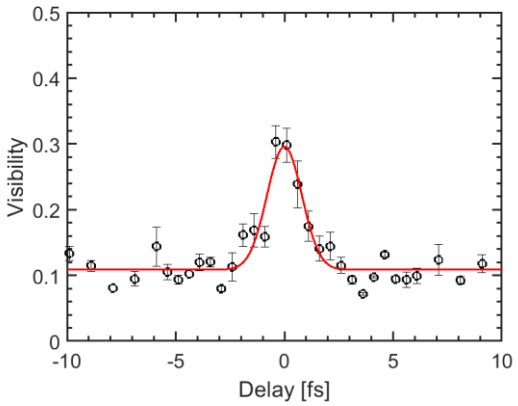
Short pulses with excessive reverse taper

- Apply linear or quadratic reverse taper to compensate for an energy chirp in the main undulator;
- Go to stronger reverse taper to suppress radiation while keeping microbunching;
- Use a short radiator (number of periods ~ number of cycles in microbunching).

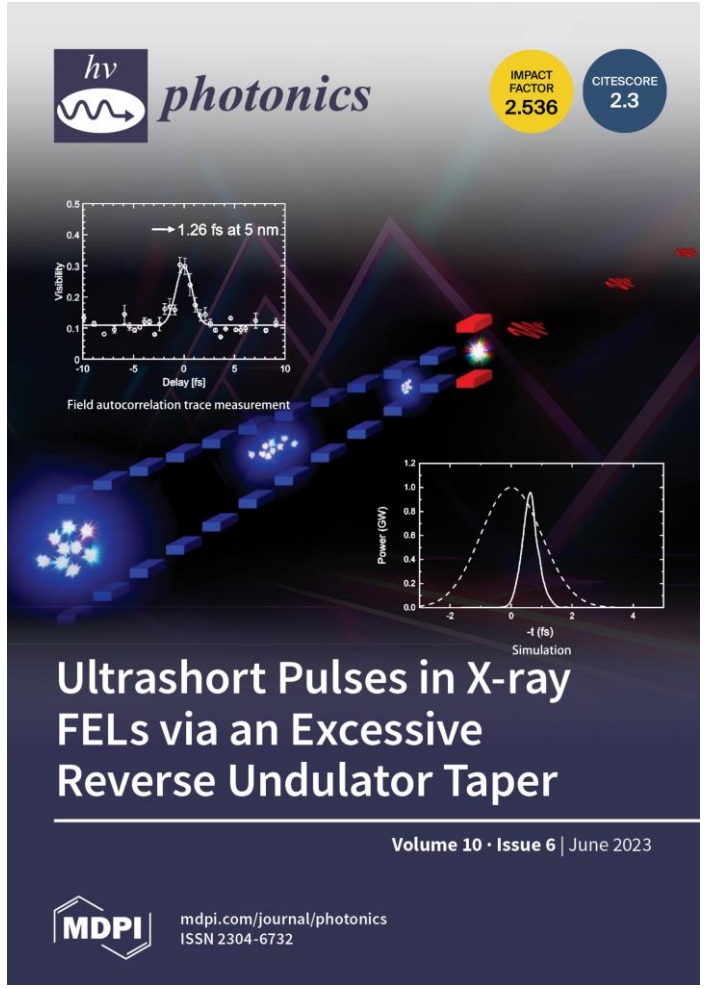


Experiment at FLASH2 (5 nm)





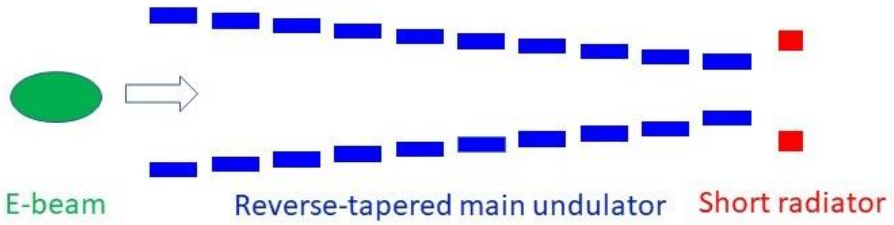
- Electron energy 1.2 GeV, wavelength 5 nm, charge 80 pC, nonlinear compression;
- Final compression in the chicane that is in front of the undulator;
- Strong energy chirp due to LSC in the undulator (~1%) across the current spike;
- Single-mode SASE regime established;
- Strongly reverse-tapered main undulator (eleven segments), the 12th is used as a radiator. To reduce its effective length, an ambient field correction coil was used to steer the beam inside the segment;
- The split-and-delay unit in FL24 is used to measure field autocorrelation: two beams create interference fringes; visibility depends on delay.
- Pulse energy is 1.5 uJ, pulse duration estimated at 1.2 fs.



E. Schneidmiller, M. Dreimann, M. Kuhlmann, J. Rönsch-Schulenburg, H. Zacharias, Photonics 10(2023)653

Prospects

- Few femtoseconds for XUV (FLASH at ~ 10-50 nm), short bunch from accelerator;
- Sub-femtosecond regime for FLASH at ~ 4 nm, short bunch from accelerator;
- eSASE for soft X-rays < 100 as;
- eSASE for hard X-rays: ~ 10 as with some refinements.



Conceptual limit: several cycles