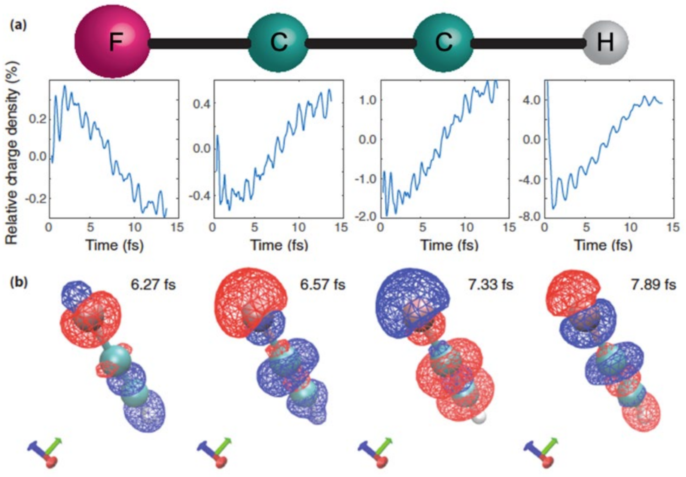
Beam dynamics related topics of the ASPECT project

AttoSecond Pulses with eSASE and Chirp/Taper

Jiawei Yan on behalf of the ASPECT team

Science Case

- X-ray imaging with attosecond pulses
- Charge migration in molecules after core ionization
- Direct multiphoton ionization



Science case by Daniel Rivas, Simon Dold, Tammaso Mazza, Michael Meyer
A. Picón et al., PRA 98, 043433 (2018)

RESEARCH

RESEARCH ARTICLE

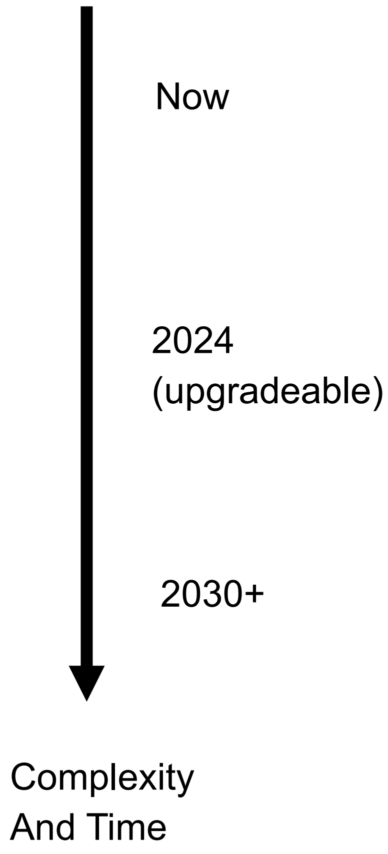
ATTOSECOND SCIENCE

Attosecond coherent electron motion in Auger-Meitner decay

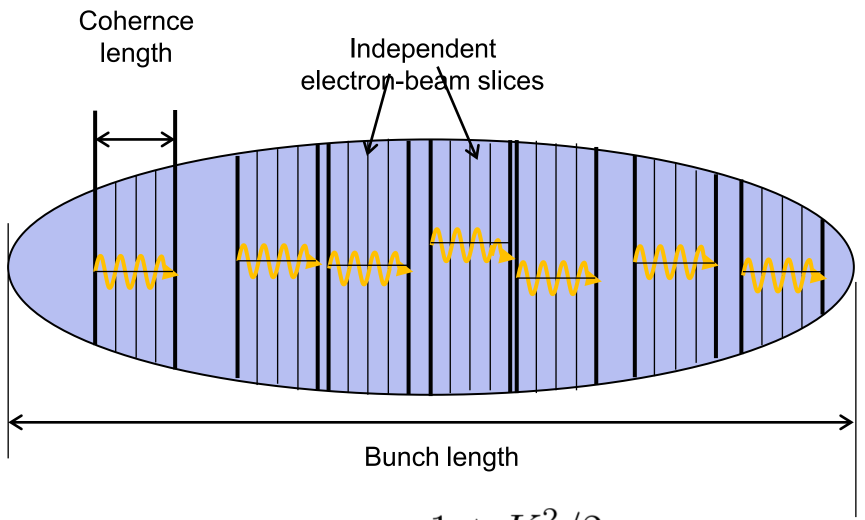
Siqi Li[1,2]†, Taran Driver[1,3,4]†, Philipp Rosenberger[1,3,5,6], Elio G. Champenois[3], Joseph Duris[1], Andre Al-Haddad[7], Vitali Averbukh[4], Jonathan C. T. Barnard[4], Nora Berrah[8], Christoph Bostedt[7,9],

Path to short pulse production at the European XFEL

- No or little hardware (some modes possible on User request – See FEL R&D talk):
  - Non-linear compression
  - Fresh-slice (now dispersion-based; best with dechirper to be installed this winter)
  - Low charge
  - Atto@harmonics
- Additional hardware (2025 shutdown)
  - Flexible (hard and soft)
  - Upgradeable
- Major facility upgrades (2nd fan….)
  - Beyond the current scope



Coherence time

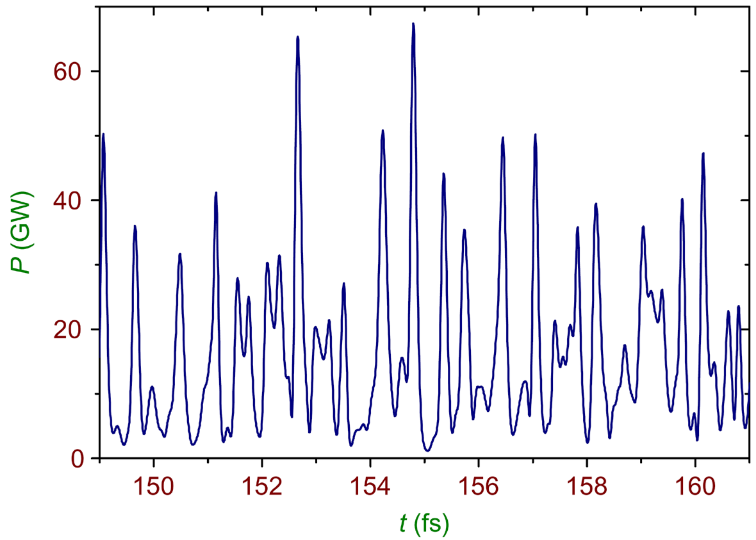


$$\lambda_1 = \lambda_u \frac{1+K^2/2}{2\gamma_1^2}$$

Radiation overtakes electron of one wavelength every undulator period

$$L_{g,\mathrm{power}} = \frac{\lambda_u}{4\pi\sqrt{3}\rho} \qquad \rho = \frac{\lambda_u}{4\pi}\left[\frac{4\pi^2}{\gamma_1^3}\frac{en_0}{I_A}\frac{K^2}{\lambda_u}\frac{A_{JJ}^2}{2}\right]^{1/3}$$

Overtaking length in L_g: $\frac{L_{g,\mathrm{power}}}{\lambda_u}\lambda_1 = \frac{\lambda_1}{4\pi\sqrt{3}\rho} = L_{coh}$



SASE FEL pulses usually much longer than coherence length → spikes in the time domain intensity profile (many independent modes)

Decreasing the lasing window implies a shorter X-ray pulse, same power level, less energy up to σ_z

$$\frac{\rho\omega\sigma_z}{c} \sim 1$$

HXR ~ fraction of fs

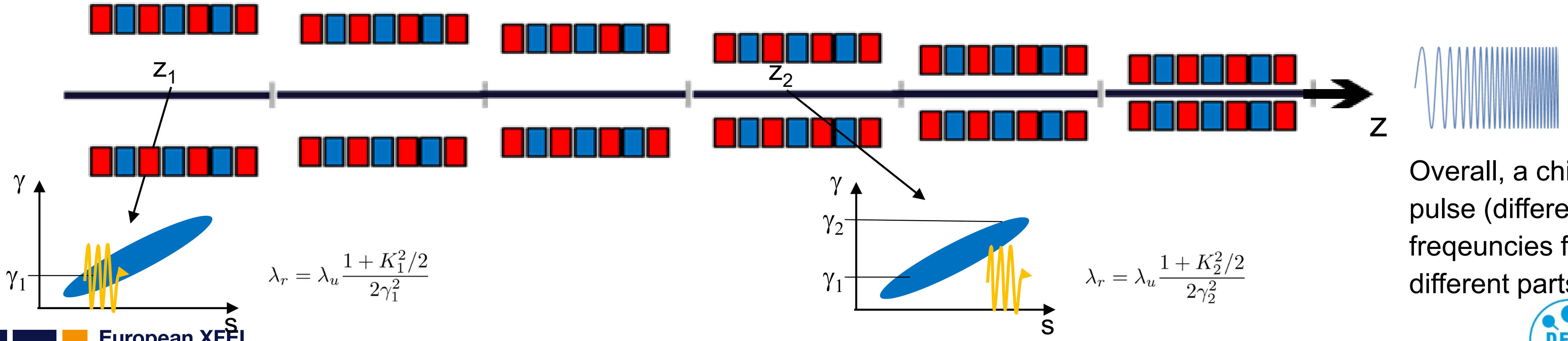
SXR ~ few fs level

Beyond the coherence time especially important for SXR

- Shorter X-ray pulses are easier at harder X-rays wavelengths!
- Need enhanced control and manipulation of the electron beam longitudinal phase space
- At European XFEL: we want short pulses both at HXR and SXR
- Two inter-related techniques:
  - Chirp/taper
  - eSASE
- Based on
  - Modulating the electron beam energy within a few tens of MeV at optical wavelength
  - Selecting short lasing window
    - Inverse taper
    - Transform energy modulation into density modulation and inverse taper
  - When needed (SXR): shorten the slippage (short radiator, wakes and increased current)

SASE process disruption with chirped beams

- Control of the lasing window can be achieved by energy chirp
- In fact lasing needs resonance along a gain length, i.e. within a coherence time
- When a linear energy chirp is imposed on an electron bunch, such that the relative energy deviation on the scale of a coherence time is larger than the FEL bandwidth, the FEL process is effectively disrupted $\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma\omega\rho^2}$ with modulus > 1
- But this effect can be roughly compensated by a taper $\frac{dK}{dz} = -\frac{(1+K^2/2)^2}{K}\frac{1}{\gamma^3}\frac{d\gamma}{c\,dt}$



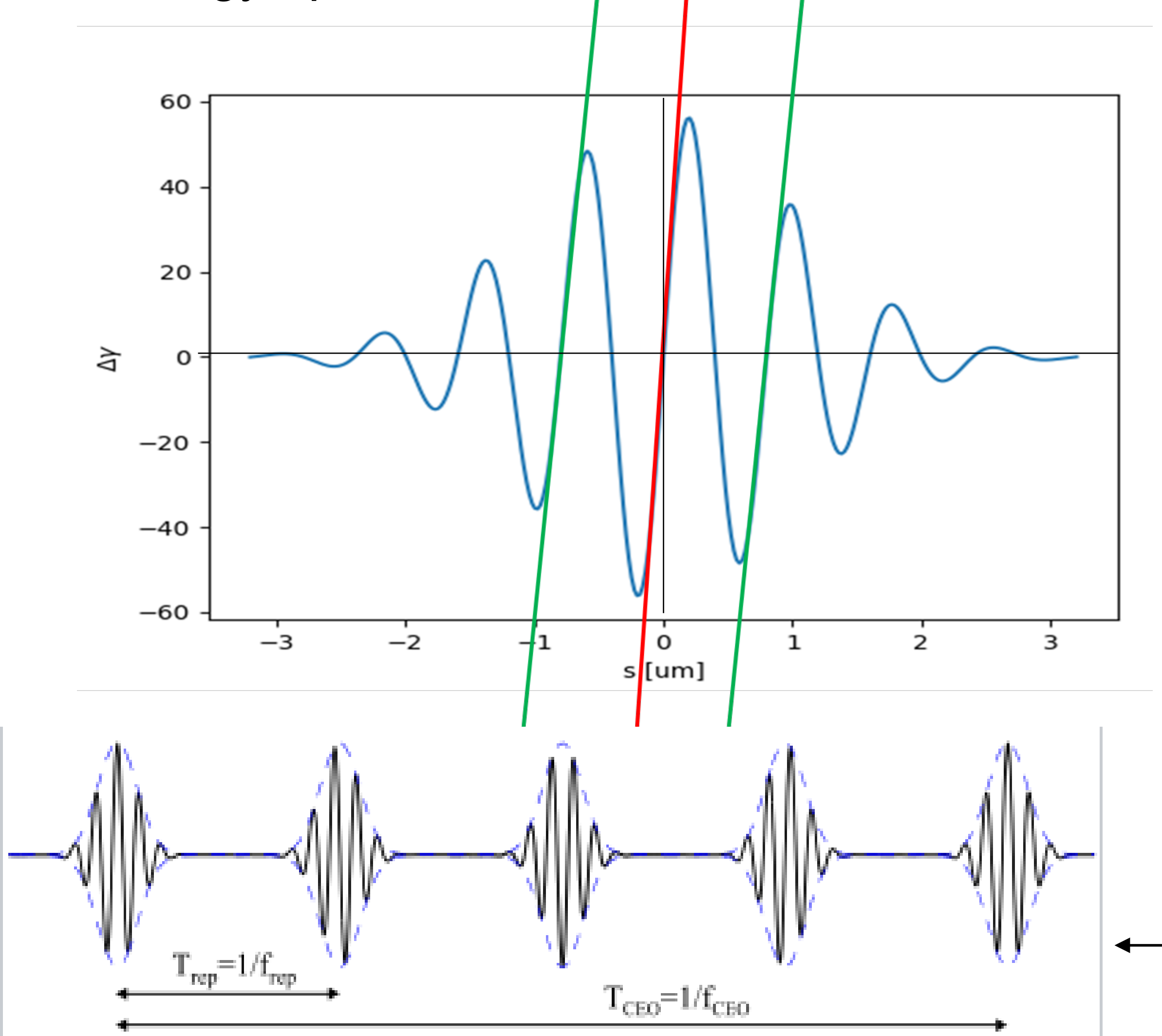
$\lambda_r = \lambda_u \frac{1+K_1^2/2}{2\gamma_1^2}$

$\lambda_r = \lambda_u \frac{1+K_2^2/2}{2\gamma_2^2}$

Overall, a chirped pulse (different freqeuncies from different parts)

Chirped electron beams by means of energy modulation

- Modulate the electron beam in energy e.g. by means of interaction with a few-cycle, high energy optical laser

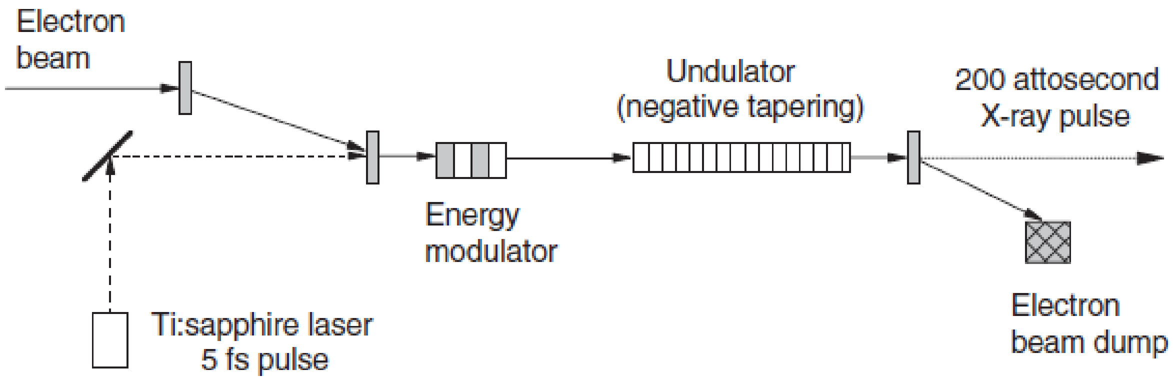


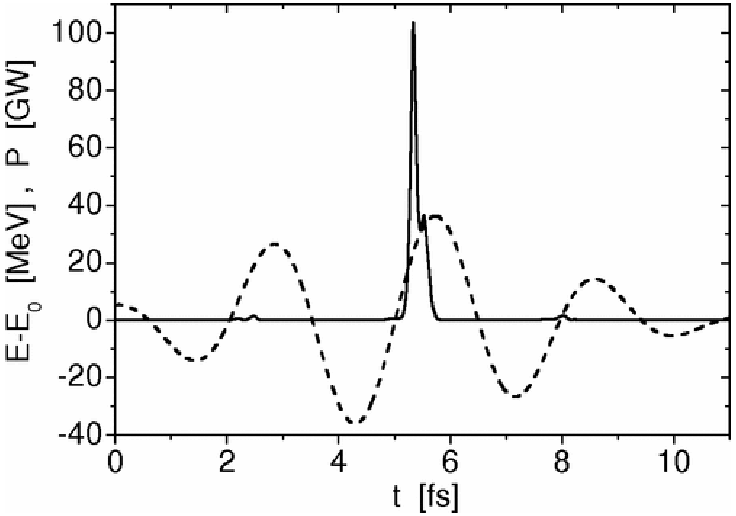
- Energy modulation induced on a 14 GeV bunch interacting in a two-period wiggler (70cm period) with a 800 nm/1030 nm pulse laser with 3mJ and 5fs FWHM duration, following [Zholents].
- It amounts to a sequence of positive and negative chirps
- Important parameters are:
  - magnitude of the gradient
  - ratio of gradients between peaks
- They must be large enough to avoid lasing everywhere except (upon taper correction) in the red part

← Carrier-envelope phase is clearly important as well (see later)

Chirp/Taper Scheme

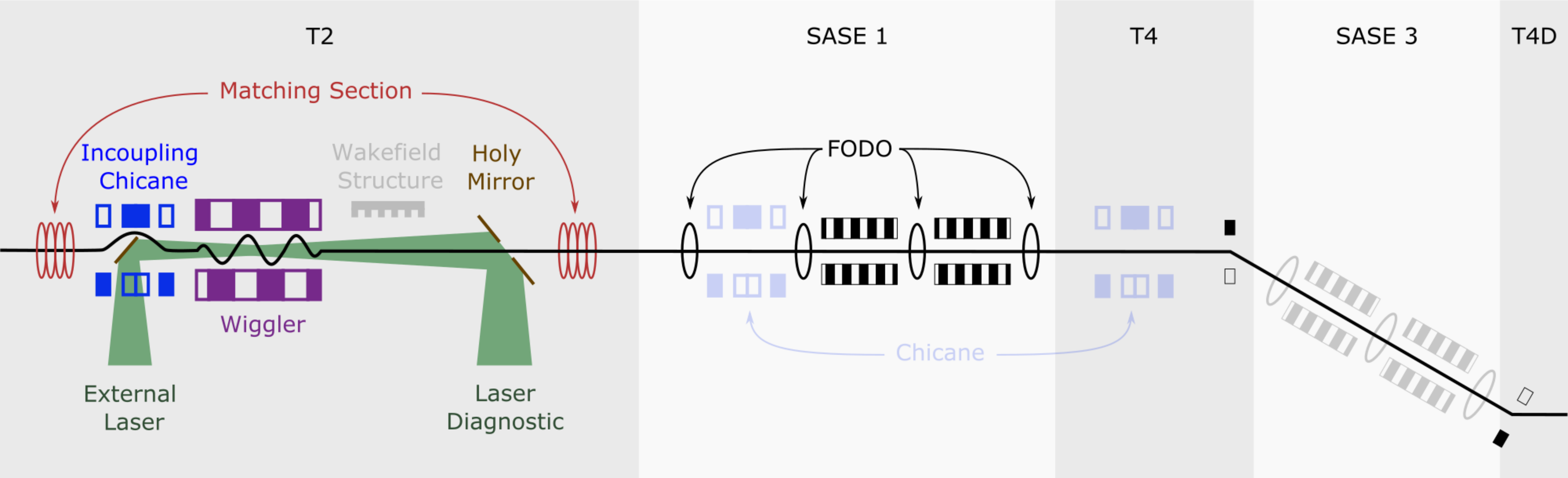
- Modulate the electron beam with external laser
- Reverse Taper to follow the energy chirp
- **HXR > 5keV**
  - Down to the coherence time, fraction of fs, larger than it. Limited by the lasing window.
- **SXR<5keV**
  - Issue, coherence time becomes longer than the lasing window, limited by the coherence time:
  - Suppress BKG by excessive reverse taper to bunch the beam
  - Use a short radiator



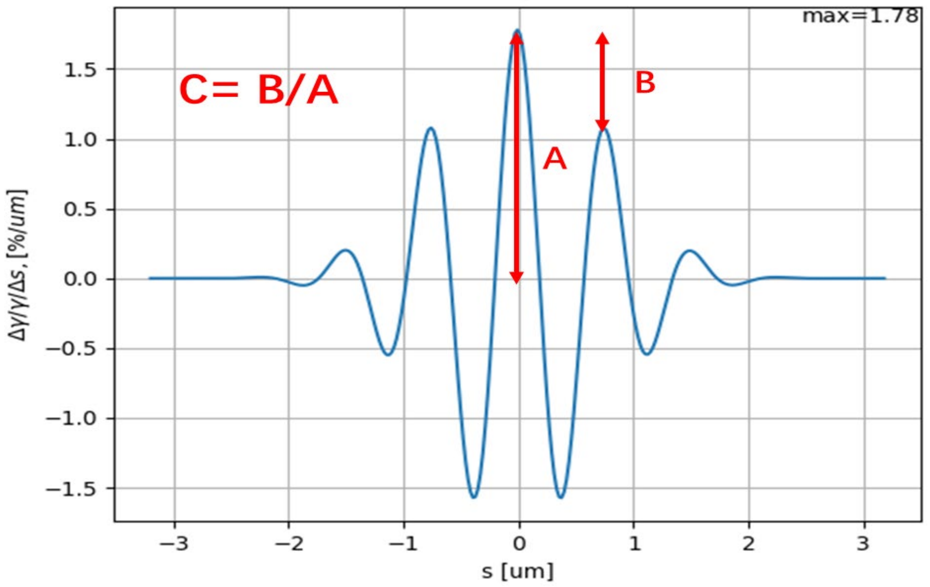


E. Saldin, et al. Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses. Doi: https://doi.org/10.1103/PhysRevSTAB.9.050702

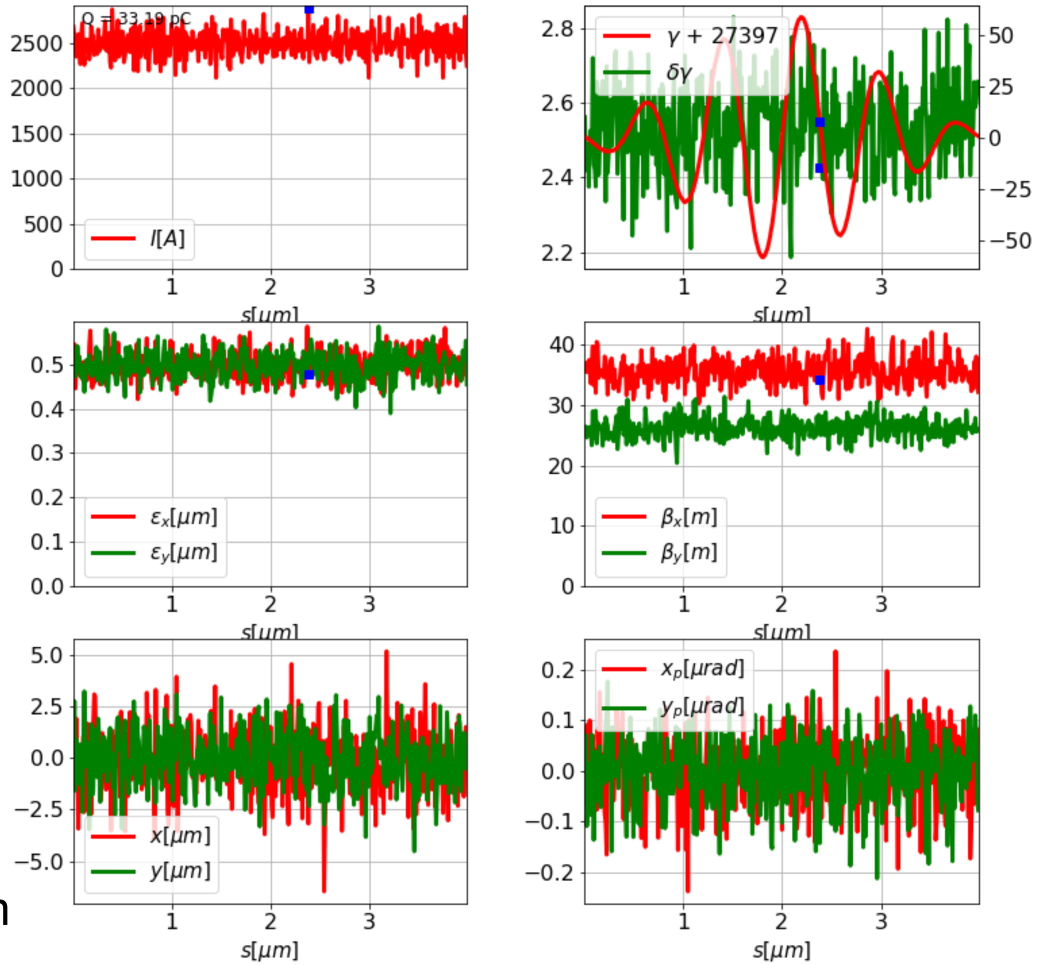
Possible realization at EuXFEL (Hard X-rays)



Simulations



Example at 800 nm, 3 mJ, 4fs



- There are two main Laser parameters
  - Magnitude of the gradient
  - Ratio of the gradient between peaks

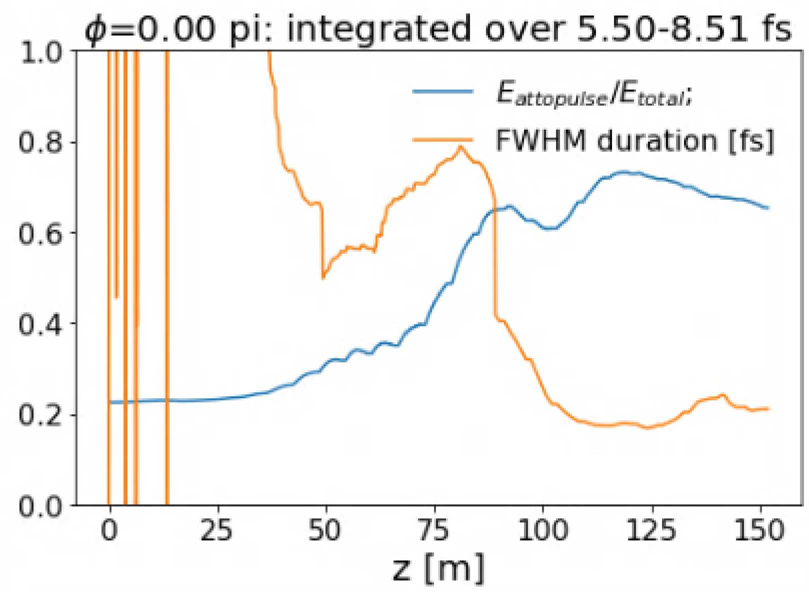
- Cases studied so far
  - Electron energy: 11.5 and 14 GeV
  - Laser Pulse: 4 – 5 fs and 2 – 5 mJ, 800nm and 1030 nm
    - ► What are the lower performance limits?

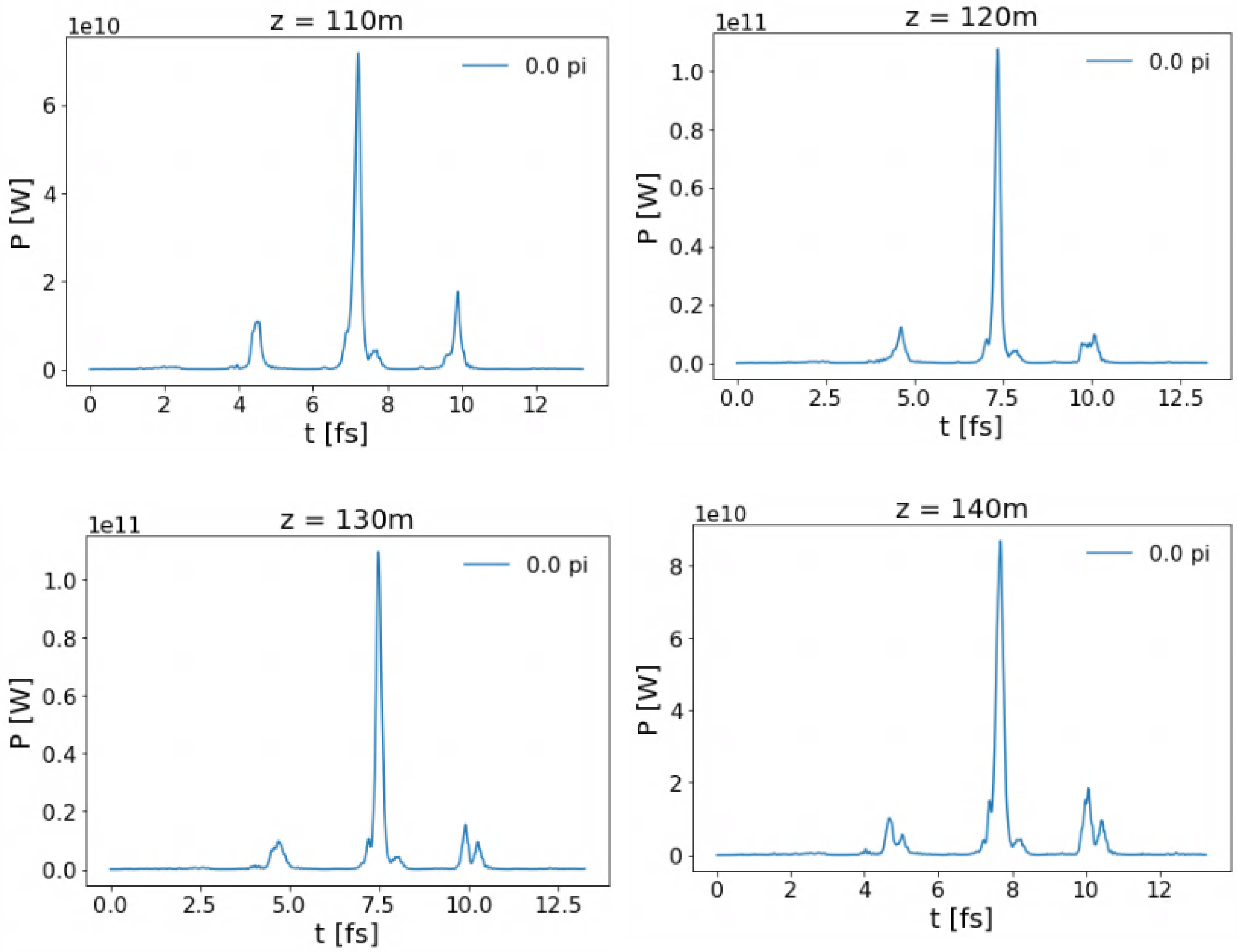
HXR simulations (example)

14 GeV, 6 keV

800 nm, 3 mJ, 4fs， dk/K/1m = 0.85e-4

A=1.41% B= 0.545%

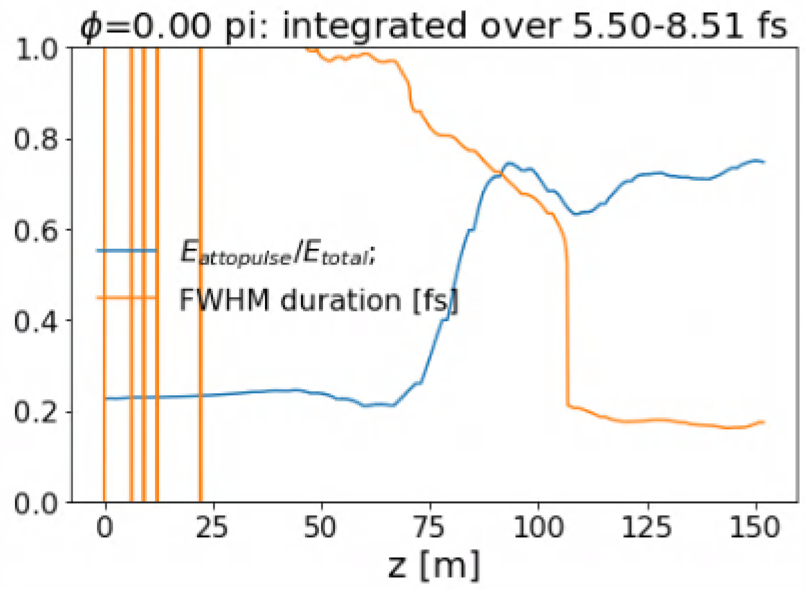


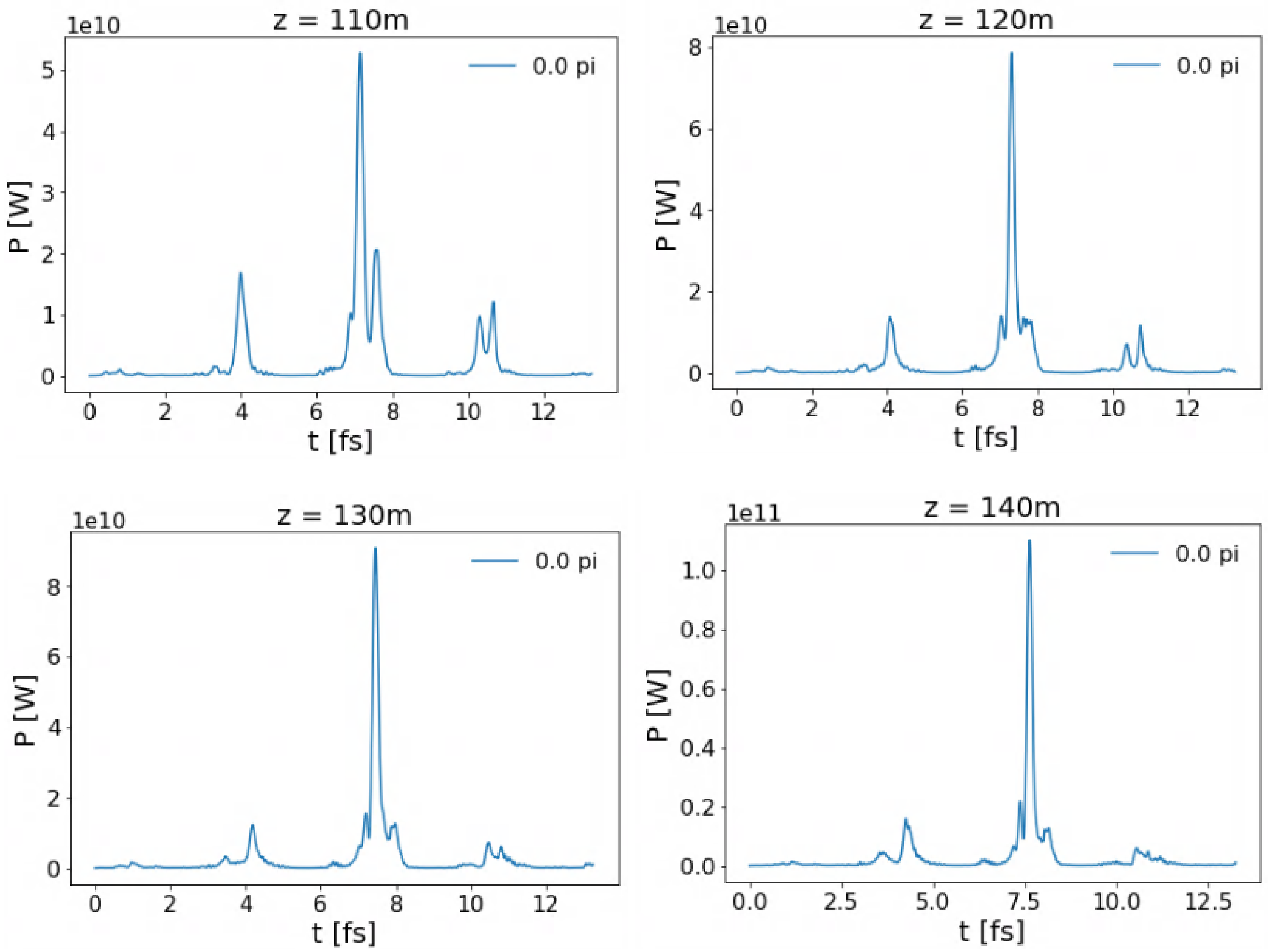


HXR simulations (example)

14 GeV, 6 keV
1030 nm, 4 mJ, 4fs， dk/K/1m = 0.7e-4

A=1.41% B= 0.545%





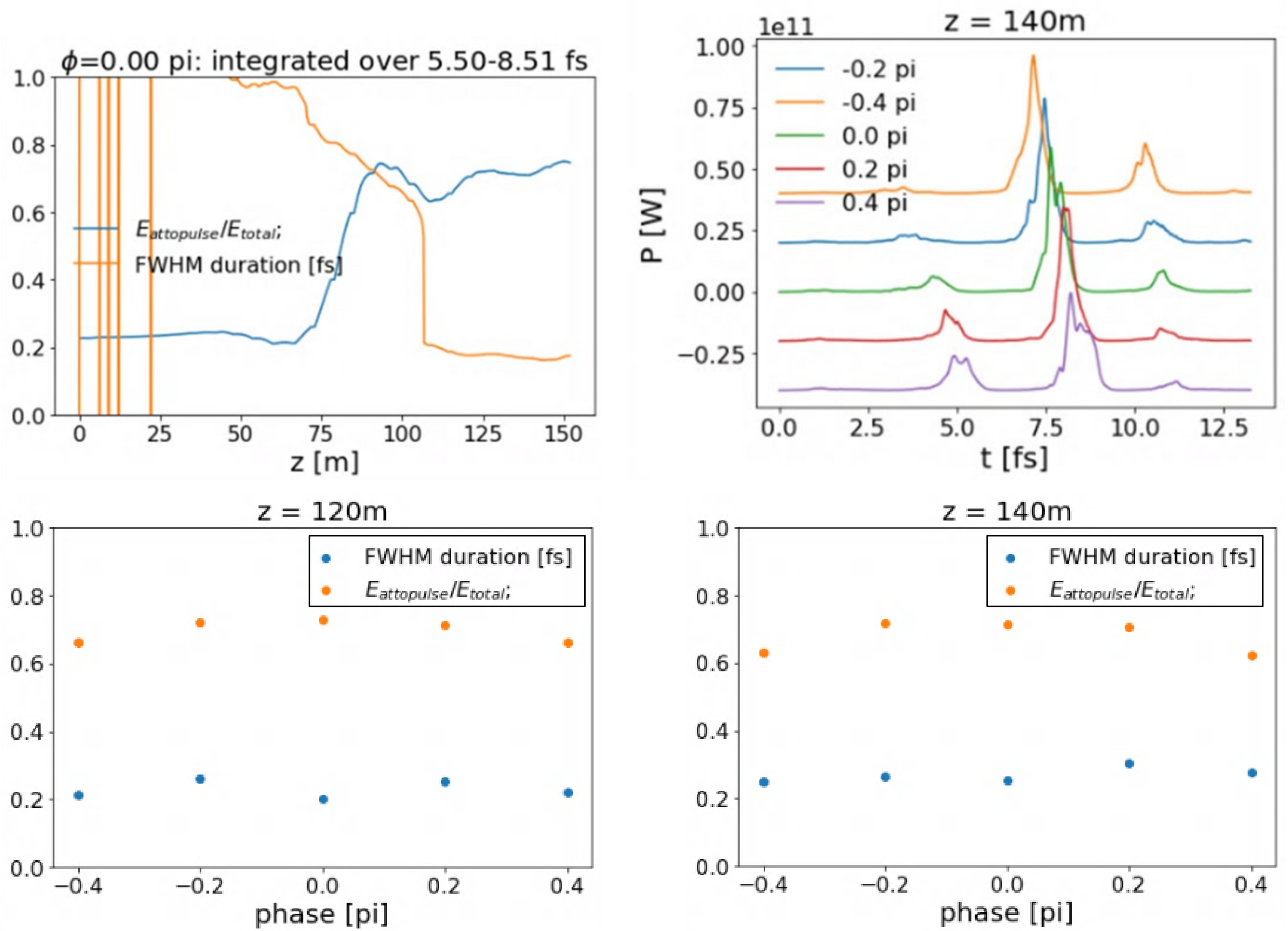
CEP Stability

14 GeV, 6 keV
1030 nm, 4 mJ, 4fs

CEP stability requirements ultimately depend on the experiment (what contrast can be tolerated)

Here we see that +/- 0.2π rad peak to peak keeps the contrast high for all pulses

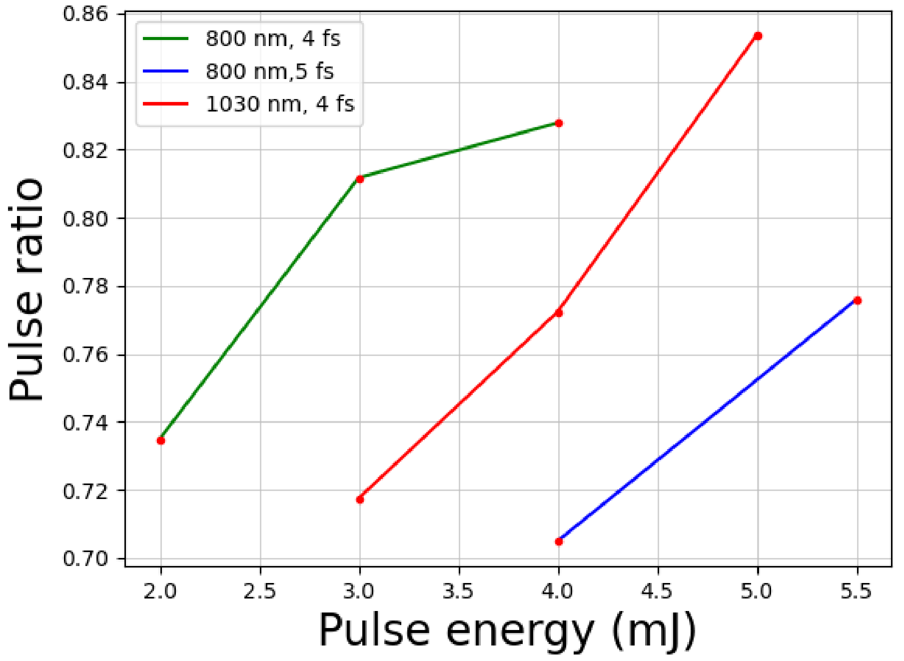
A reasonable requirement is then
400 mrad rms
(max: 600 mrad rms)



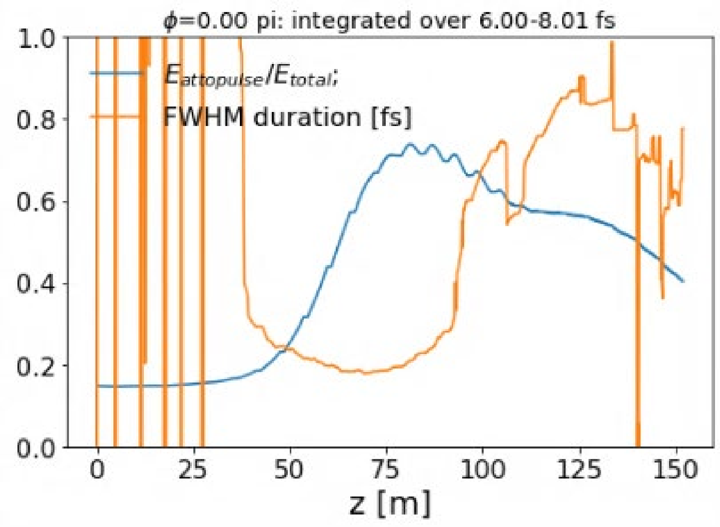
Summary of Laser Parameters

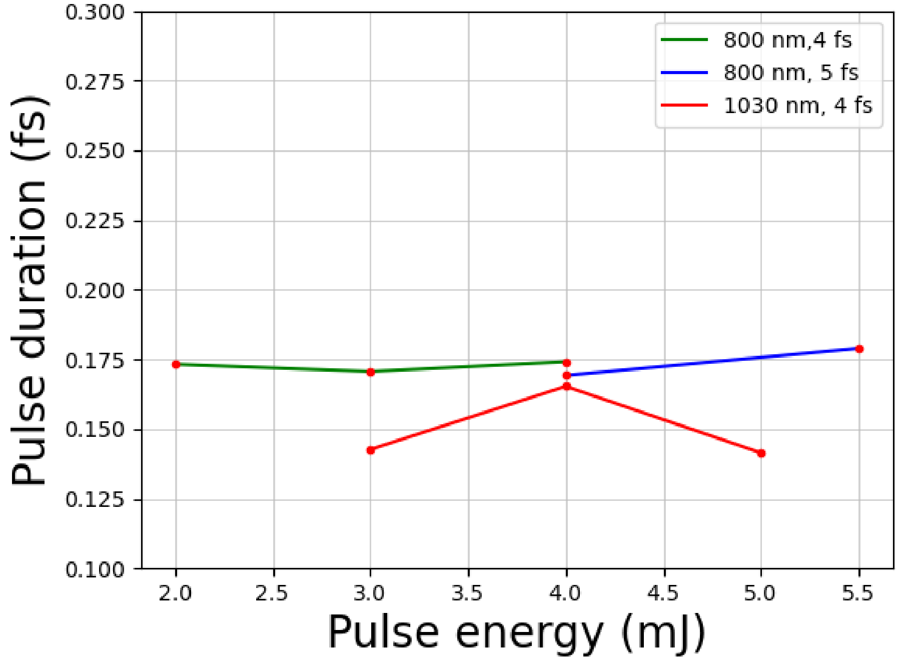
- Wavelengths
  - 512 nm – Lower peak power (2GW)
  - 800 nm - Good
  - 1030 nm - Good
- Electron energy
  - 11.5 and 14 GeV
- Laser Power
  - 4 – 5 fs and 2 – 5 mJ
- CEP Stability
  - 400 mrad rms

  (max 600 mrad rms)

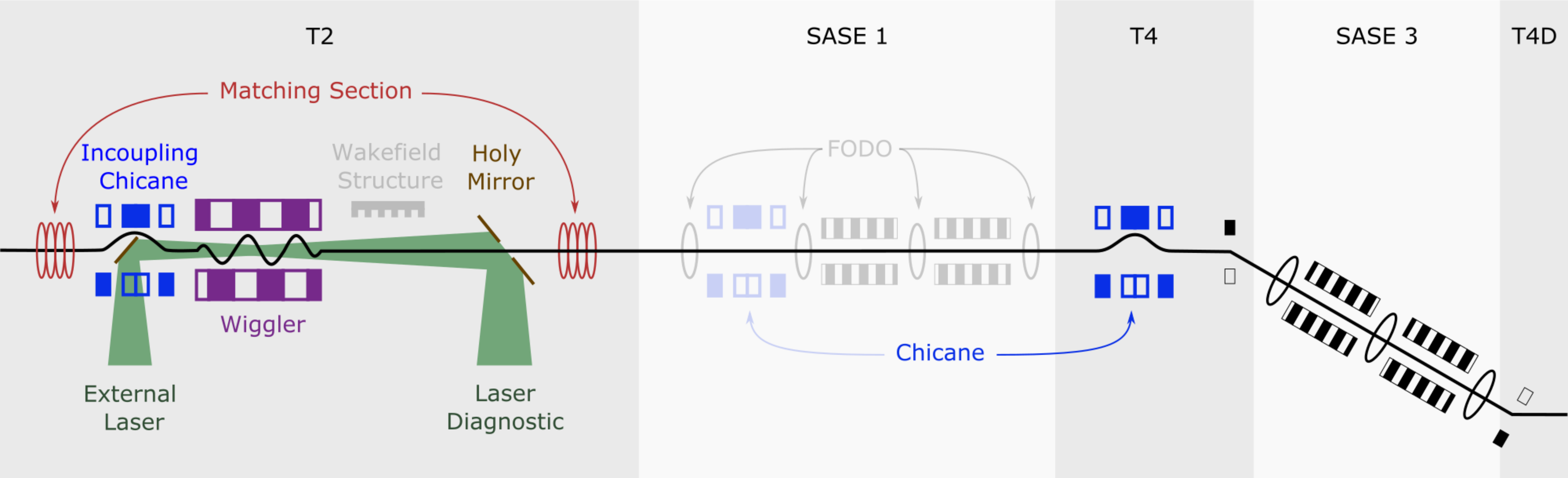


512 nm





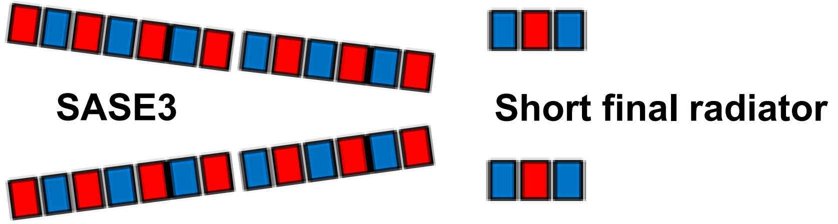
Possible realization at EuXFEL (Soft X-rays)

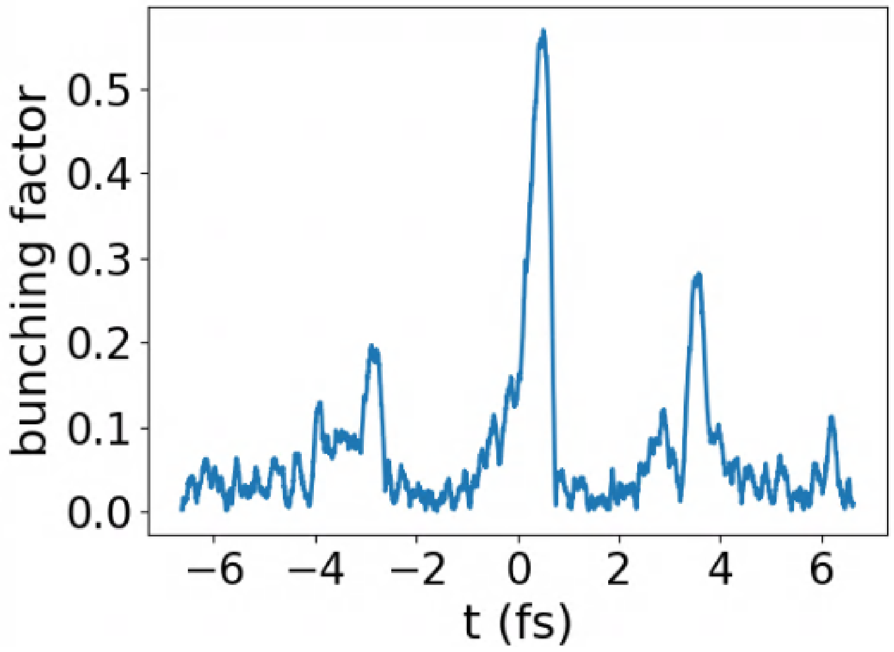


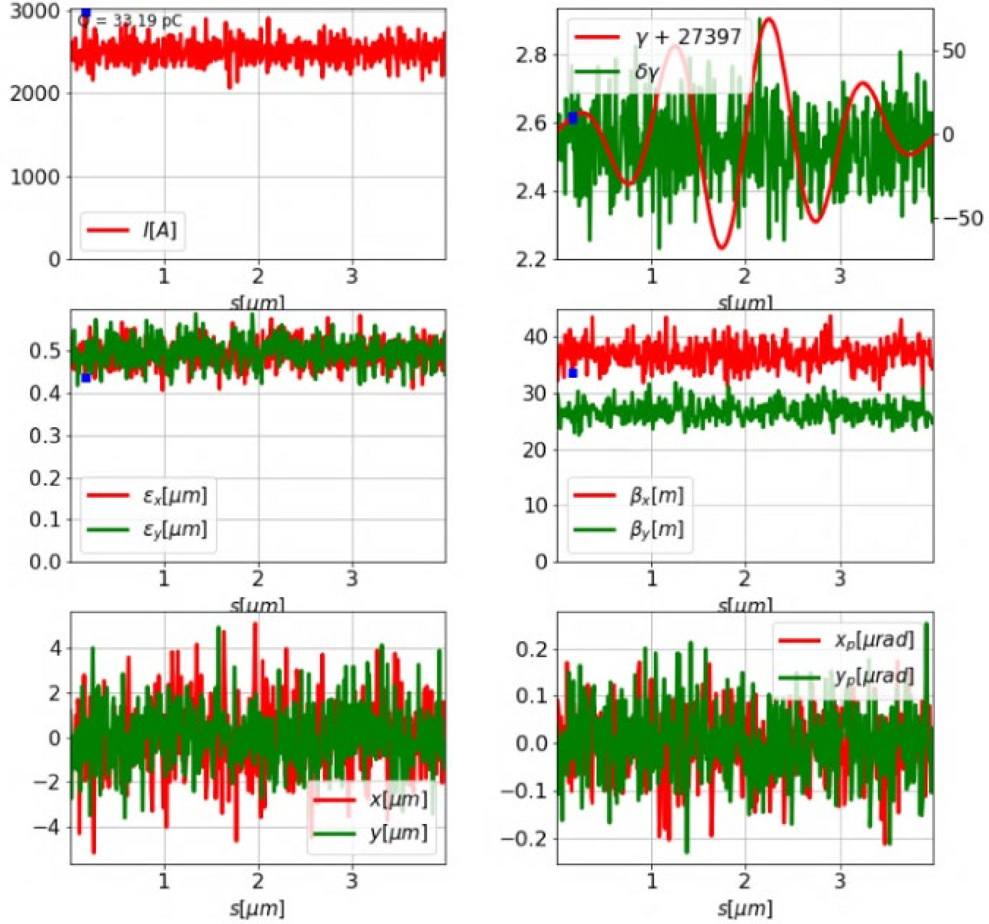
SXR simulations

- 1030 nm, 4 fs, 5 mJ
- 14 GeV, 2500 A, beta = 32 m, emittance= 0.5 mm mrad

Stage1 10 cell reverse taper
AW= 6.1727； +0.0185 per cell

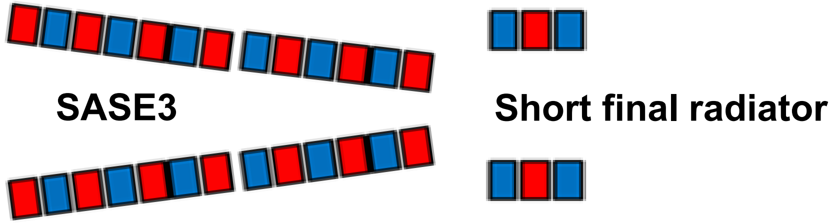




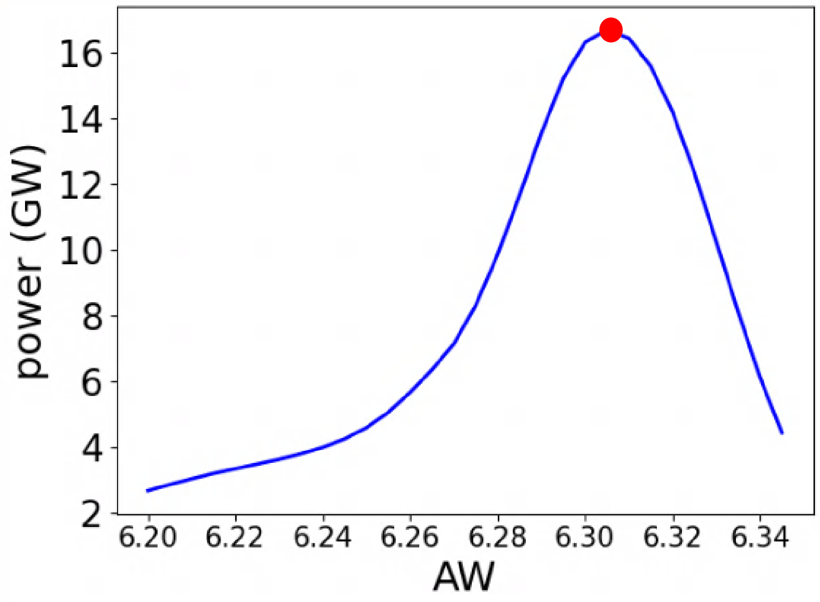


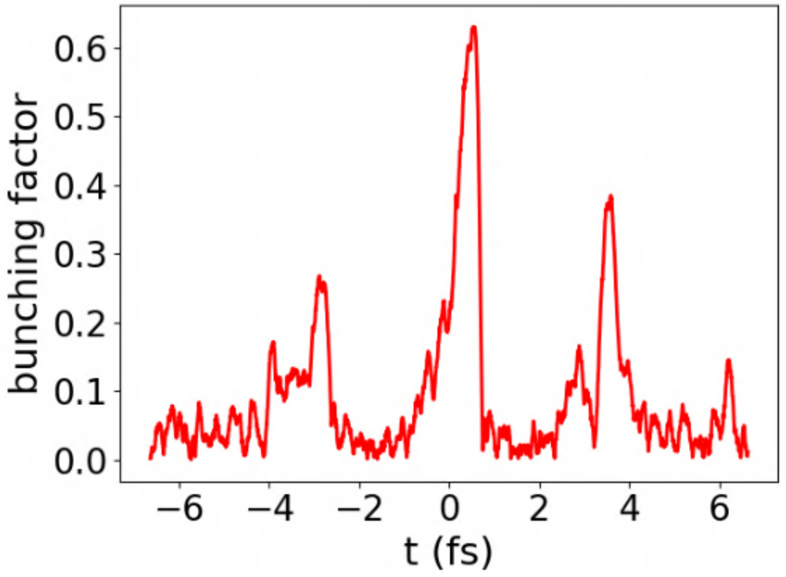
SXR simulations

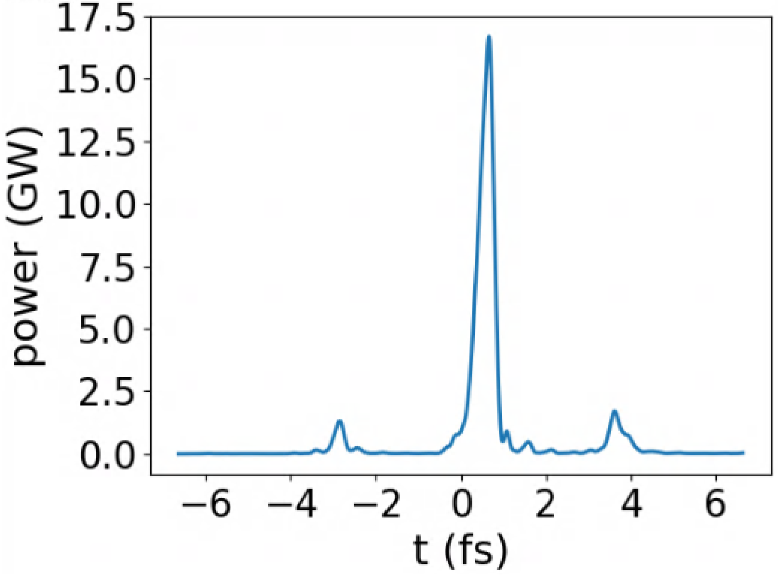
Stage2 1 cell



Contrast: ~ 82%
Pulse duration (FWHM): ~ 410 as



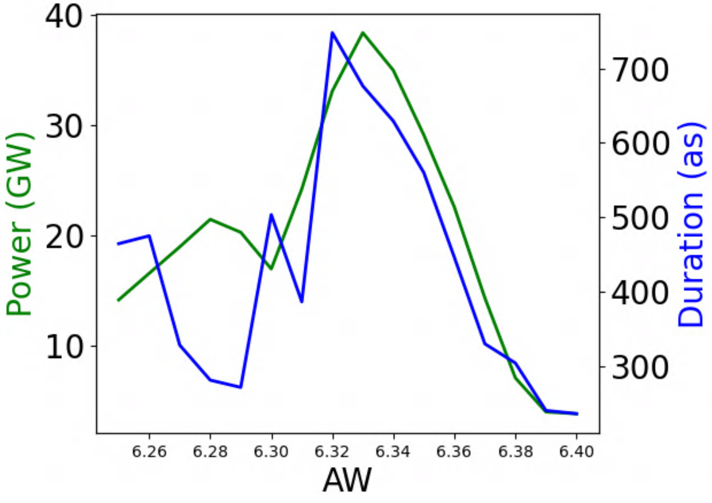


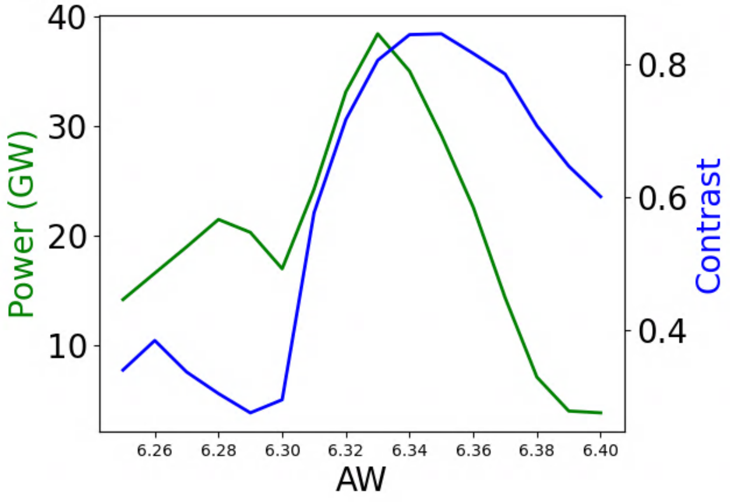


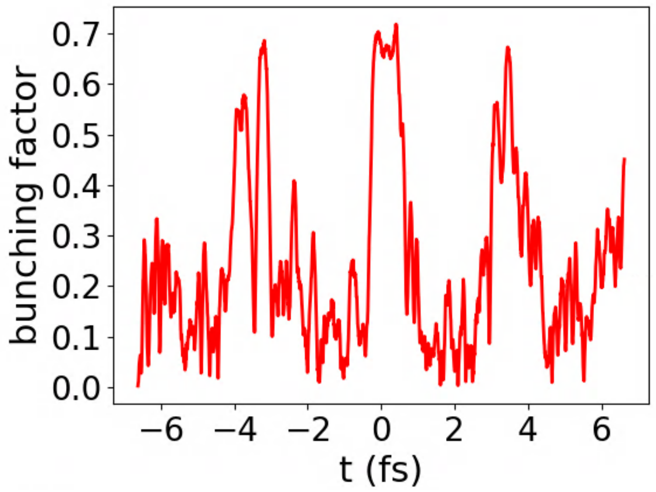
SXR simulations

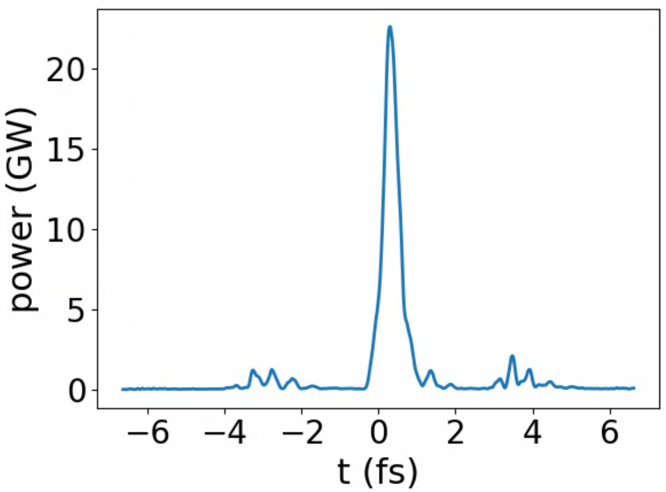
beta = 16 m, 10 cell reverse taper

Contrast: ~ 82%
Pulse duration (FWHM): ~ 446 as



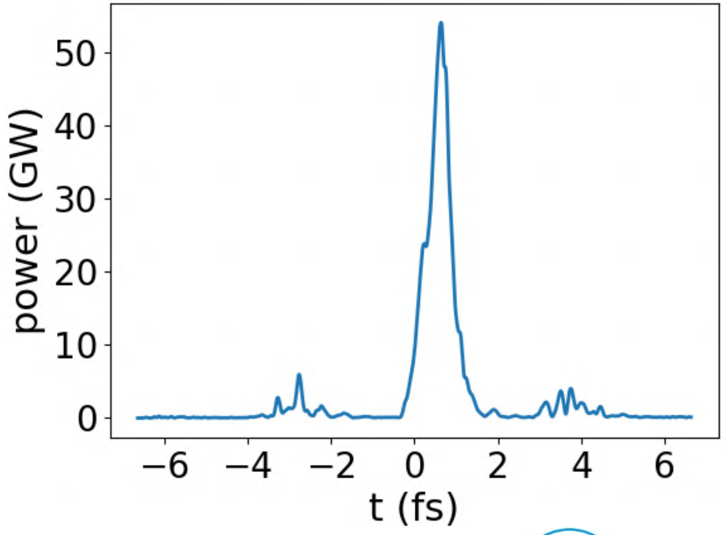






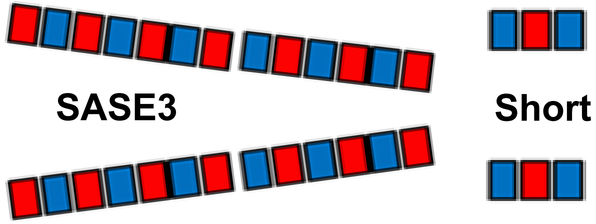
2 cells

Contrast: ~ 85.23%
Pulse duration (FWHM): ~ 516 as



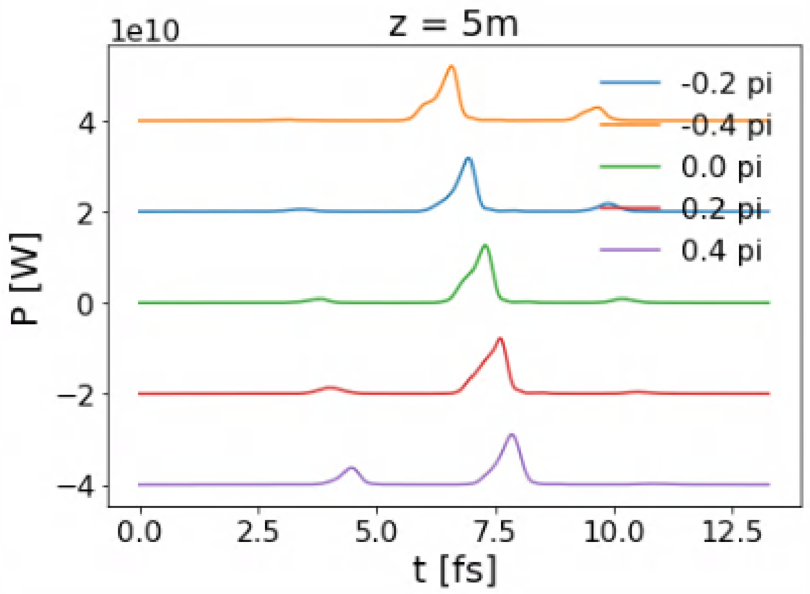
SXR simulations

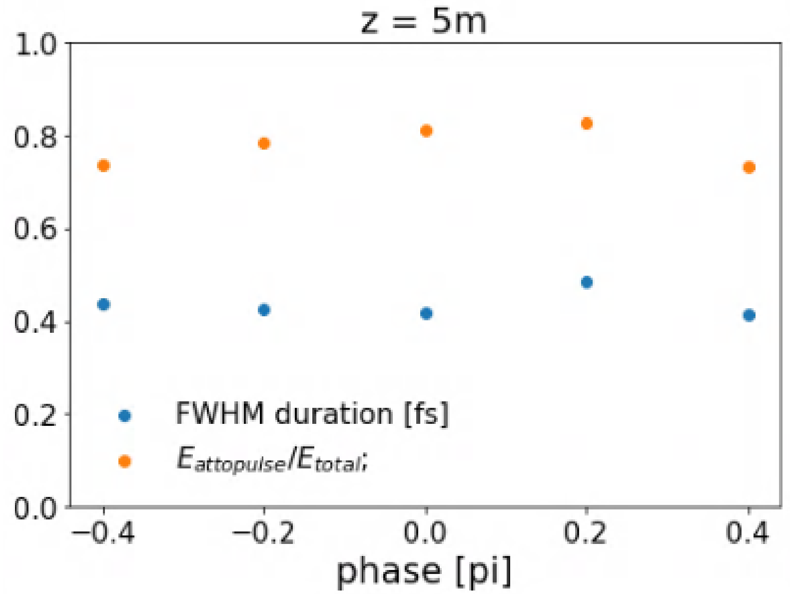
Stage2 1 cell



CEP Stability

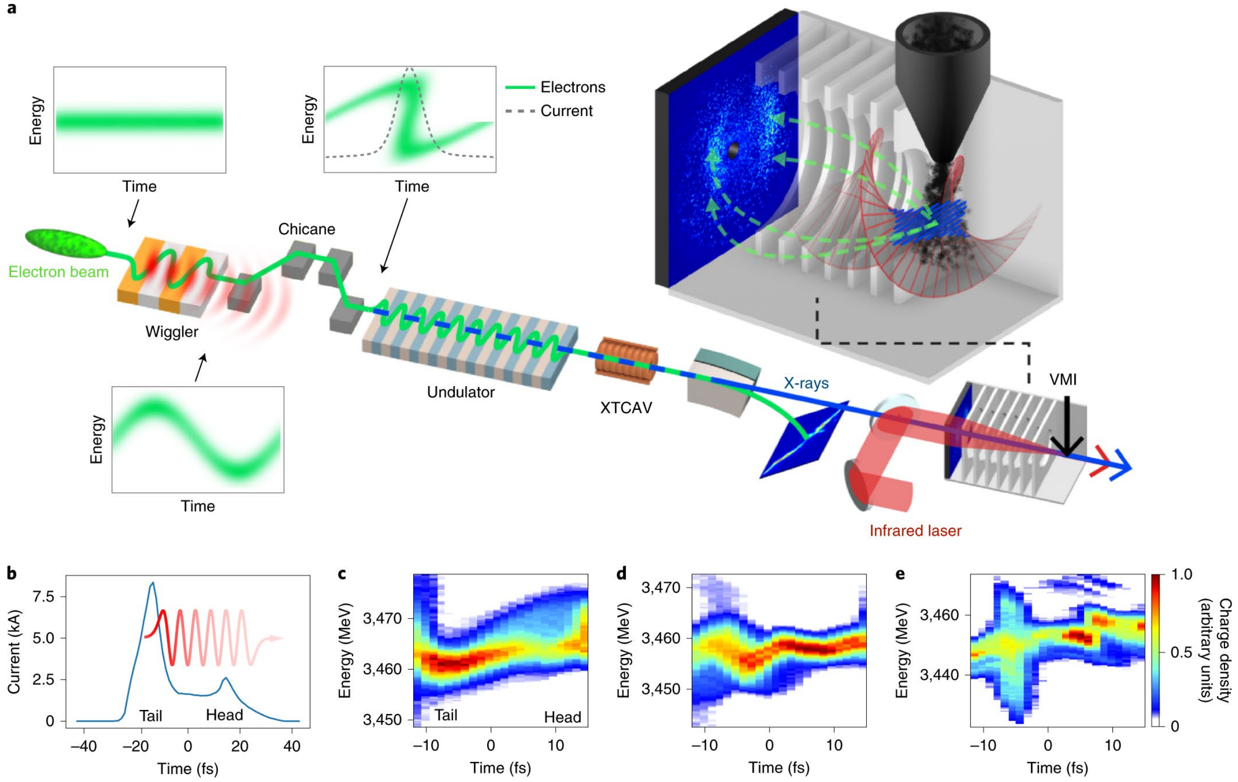
14 GeV, 700 eV
1030 nm, 5 mJ, 4fs





eSASE scheme at the LCLS

- Spike at the back of the bunch after compression
- Allows for self-modulation
- A chicane transforms the energy into a density modulation
- Creation of isolated high current peak
- Allows for
  - few-hundred as
  - GW peak power



J. Duris, et al. doi: [10.1038/s41566-019-0549-5](https://doi.org/10.1038/s41566-019-0549-5)

Summary

- We are currently investigating a chirp/taper and eSASE scheme for EuXFEL (ASPECT)
- Chirp/Taper simulations for both hard and soft x-rays are being performed
  - Simulated pulse durations of 200 as for HXR and 400 as for SXR
  - eSASE simulations come next
  - Explore other regimes
    - ► AppleX (polarization)
    - ► Two pulses
    - ► Chicane & third stage (superradiance)
- Investigation of space charge as a modulation source
- We plan to finish CDR this summer
- We plan to install major hardware in the long maintenance shutdown ´25