

External Seeding Possibilities at the European XFEL and THz Addition



Takanori Tanikawa, European XFEL

Outline

- Design of external seeding (two-stage HGHG and EEHG) for the European XFEL
 - Introduction of external-laser seeding
 - Target wavelength and basic setup
 - Multi-parameters decision and radiation properties of two-stage HGHG and EEHG

- Concept of superradiant THz afterburner for the European XFEL
 - Introduction
 - Fixing undulator parameters and the target frequency
 - Superradiant THz properties
 - Synchronization between external-seeded FEL and superradiant THz

- Summary

Introduction of External-Laser Seeding

■ Property

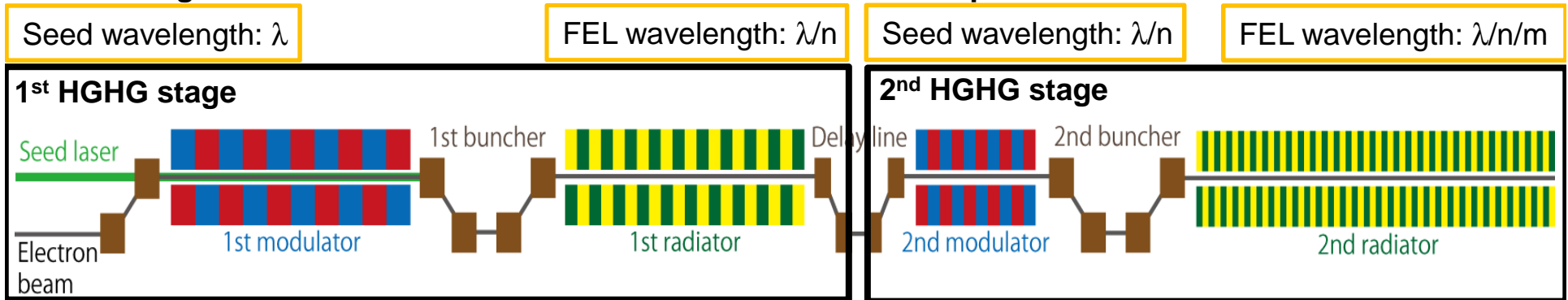
- High-coherent radiation (from UV to soft X-ray range)

■ Method

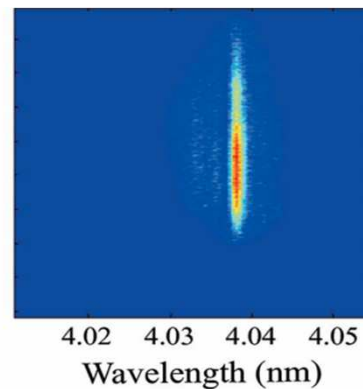
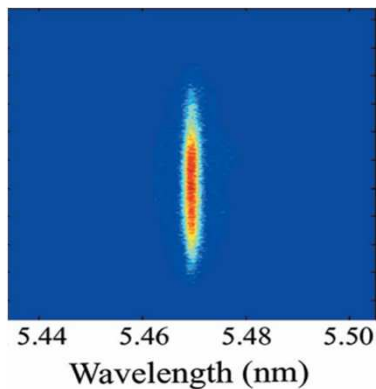
- Direct seeding
- High-gain harmonic generation (HG HG)
- Echo-enabled harmonic generation (EEHG)

Introduction of External-Laser Seeding

Two-stage HGHG: two-times harmonic conversion and then amplification



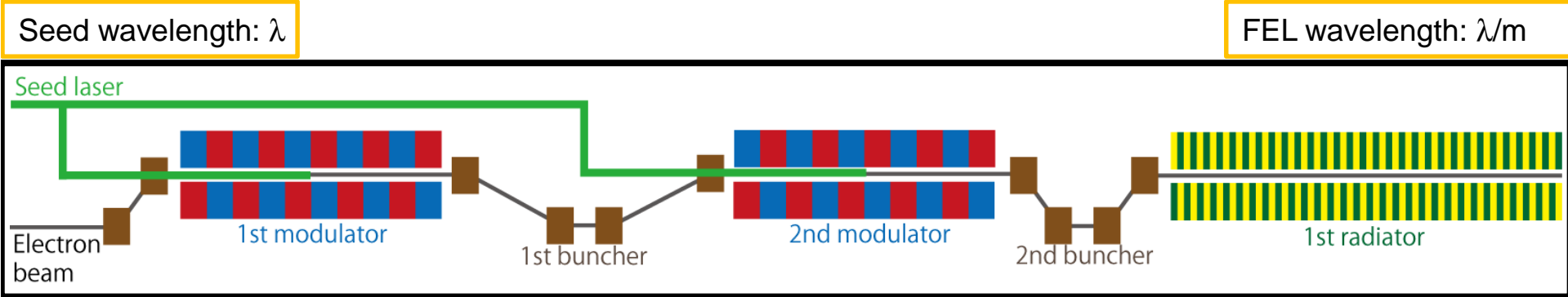
- ▶ FEL-2 undulator line at FERMI
 - 4 nm lasing ($\lambda=264$ nm, 66th harmonic ($n=6$, $m=11$))



E. Allaria, et. al,
J. Synchrotron Rad.
22 (2015) 485

Introduction of External-Laser Seeding

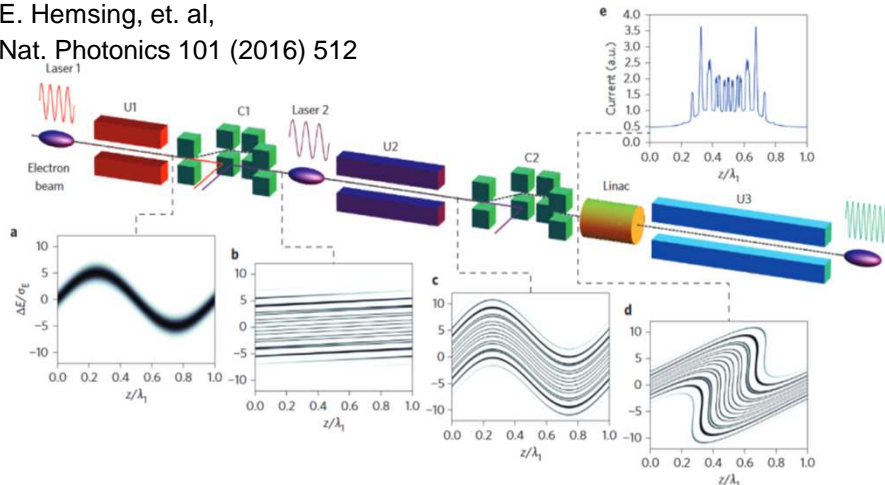
■ **EEHG: very high harmonic generation using strong bunching and then amplification**



► LCLS

- 32 nm lasing ($\lambda=2400$ nm, $m=75^{\text{th}}$ harmonic)

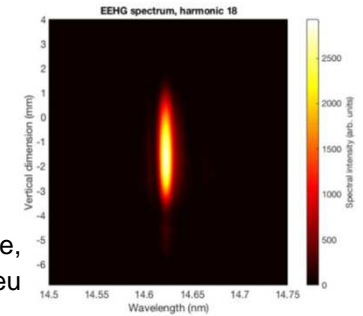
E. Hemsing, et. al, Nat. Photonics 101 (2016) 512



► FERMI

- 2018 May: 14 nm lasing ($\lambda=260$ nm, $m=19^{\text{th}}$ harmonic)

FELs of Europe, www.fels-of-europe.eu



- 2018 Sep: **5.8 & 5.9 nm** two-color lasing ($\lambda=265$ nm, $m=45^{\text{th}}, 46^{\text{th}}$ harmonic) : 2.6 nm CHG (no gain on undulator) ($\lambda=265$ nm, $m=101^{\text{st}}$ harmonic)

Speaker joined this experiment

Target Wavelength and Basic Setup for the European XFEL

■ Target wavelength

■ Below 2 nm (620 eV)

- (Ref) K-edge of C: 282 eV, N: 397 eV, O: 533 eV

■ Method

■ Direct seeding (ref. European XFEL Annual report 2016)

■ High-gain harmonic generation (HGHG)

■ Echo-enabled harmonic generation (EEHG)

Target Wavelength and Basic Setup for the European XFEL

Challenge

- ▶ In order to reach below 2 nm from optical seed wavelength, bunching factor at high harmonic is necessary
- ▶ But the $\Delta\gamma_{\text{modulation}}/\gamma_{\text{beam}}$ comes more difficult to get large value when electron beam energy goes higher
[ex. FLASH: 1.2 GeV, FERMI: 1.5 GeV, **European XFEL: 8.5 GeV!** (~17.5 GeV)]

$$F_h = |J_h^2(h\eta)| : h\text{-th bunching factor}$$

$$\eta \propto \Delta\gamma_{\text{modulation}}/\gamma_{\text{beam}} : \text{bunching phase}$$

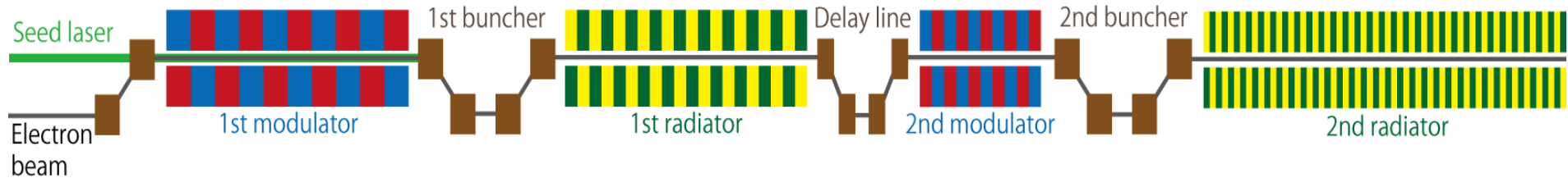
- ▶ Many parameters have to be properly designed

Reward

- ▶ Very high FEL peak power will be out !
(because of **high beam-energy and peak-current** electron beam at the European XFEL)

$$P_{FEL} = 1.6 * 10^3 * \rho_{FEL} * \left(\frac{L_{1Dgain}}{L_{3Dgain}}\right)^2 * \gamma_{beam} * I_{peak}$$

Multi-Parameters Decision for External Seeding



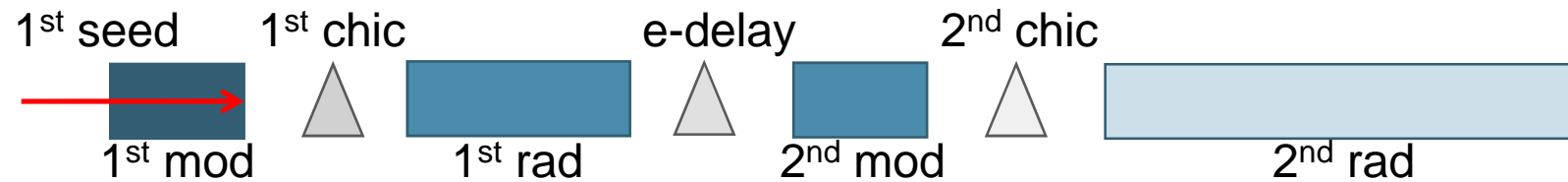
- Parameters to be kept as nominal
 - Electron beam quality
 - ▶ Flat-top beam current in addition to apply fresh-bunch technique
 - Driving laser specification (to prepare for seed laser)

- Free parameters (has to be decided from scratch)
 - Seed laser
 - ▶ Wavelength (harmonic number), peak power (incl. harmonic conversion efficiency), etc.
 - 1st modulator, 2nd modulator
 - ▶ Period length, number of period
 - 1st radiators, 2nd radiators
 - ▶ Harmonic number from modulators to radiate and be amplified
 - ▶ Period length, number of period, number of segment, FEL gain
 - 1st & 2nd bunchers, electron delay
 - ▶ R56 (energy modulation → density modulation)
 - ▶ R56 (applying fresh bunch technique)

Multi-Parameters Decision for Two-Stage HGHG

Two-stage HGHG setup

- 4 x different undulators (2 x modulators, 2 x radiators)
- 3 x magnetic chicanes (2 x bunchers, 1 x electron delay)
- 1 x seed laser injection



EEHG setup

- 3 x different undulators (2 x modulators, 1 x radiator)
- 2 x magnetic chicanes (2 x bunchers)
- 2 x seed laser injection



Multi-Parameters Decision for Two-Stage HGHG: Electron Beam

Flat-top beam

► Flat-top beam is very important for multi-stage HGHG

because multiple seeding requires different part of electron bunch (fresh bunch technique)

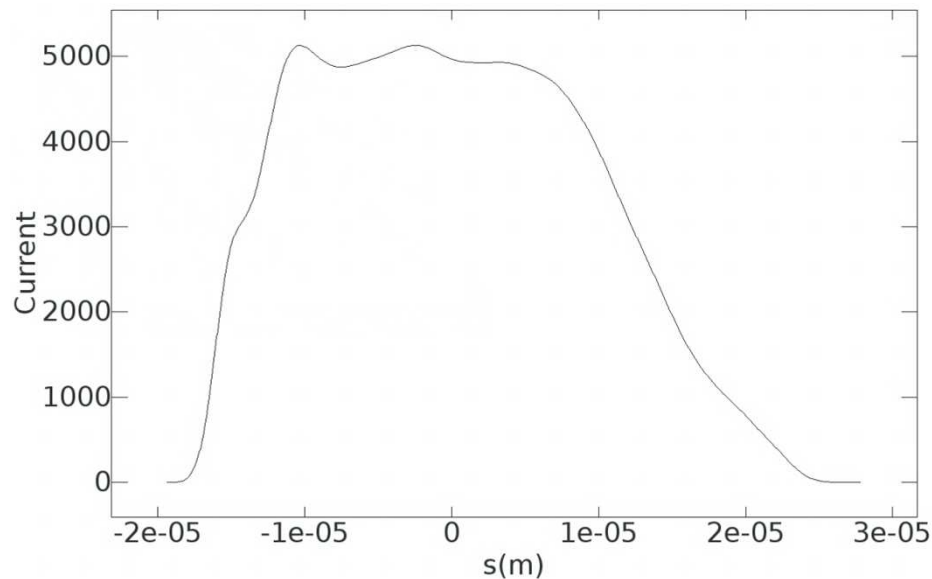
■ Energy: 8.5 GeV

■ Energy spread: $7e-5$

■ Emittance: 0.5 mm mrad

■ Peak current: 5 kA

■ Charge: 500 pC (necessity to have flat top)



S2E-simulated beam with 8.5 GeV
(courtesy: S. Liu)

Multi-Parameters Decision for Two-Stage HGHG: Driving Laser and Seed Laser

■ Driving laser (OPCPA)

- Wavelength: 750–820 nm (tunable!)
- Pulse energy, duration: 2.4 mJ, 15 fs
- Repetition rate: 100 kHz in burst
- Energy stability: 2 % energy stability

■ Seed laser

■ THG of driving laser

- ← concerning with harmonic conversion efficiency, conversion technique, pulse energy stability, etc.
- ▶ Measured efficiency: 3 % ← used in simulation
- ▶ More than 10% will be available ← concerning for transport loss by optics



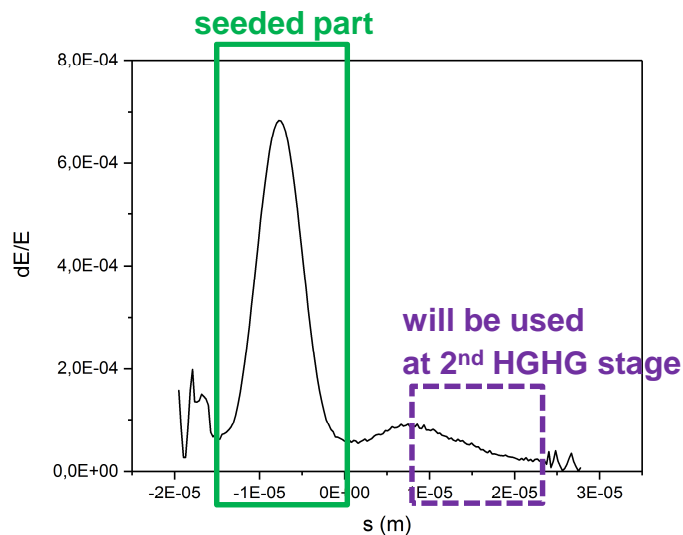
simulation, the 800 nm pulses had to be chirped to between 60 and 90 fs. In the future we intend to improve conversion efficiency to 3 – 5% by reducing the amount of dispersion in the fundamental beam path. Furthermore, there is a more elegant all-in-line configuration for THG, involving thin ($\approx 100\mu\text{m}$) delay compensator and wave plates. It enables substantially higher conversion efficiency ($>10\%$) at the shortest pulse durations [12] and will be the method of choice, once carrier-free crystal plates with our target clear aperture of 22mm or larger become technologically viable.

Multi-Parameters Decision for Two-Stage HGHG: 1st Modulator

Requirement

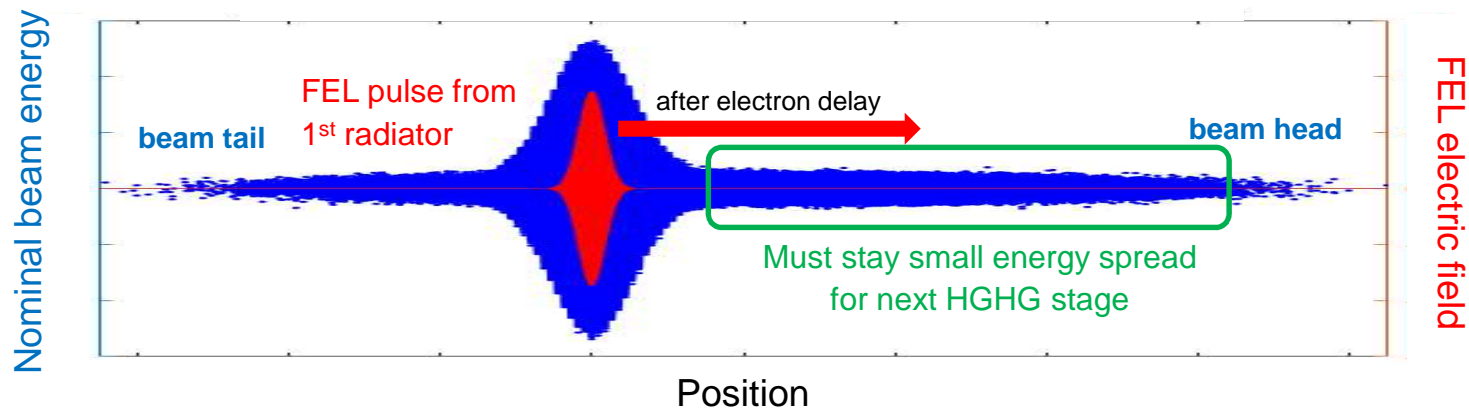
- Resonant wavelength: 250 – 273 nm (same with seed wavelength)
- Feasible peak magnetic field: below to 1.5 T
- Optimal number of period (accounting for slippage)

→ Period length: 26 cm, Number of period: 18



Multi-Parameters Decision for Two-Stage HGHG: 1st Radiator

- Choice of harmonic number & total length of 1st radiator
 - Necessary to reach 2 nm at last → as high harmonic number as possible
 - ▶ Highest harmonic number is limited by energy modulation after 1st modulator
 - Longer radiator length boosts higher FEL peak power output (will be second seed at 2nd HGHG stage)
 - ▶ But fresh bunch part is suffered if it's too long [**trade-off**]



Schematic drawing of phase space after 1st radiator

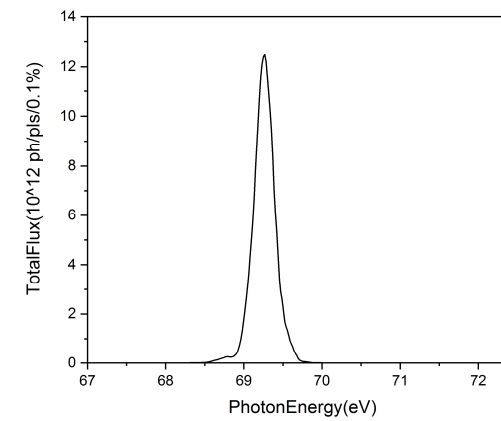
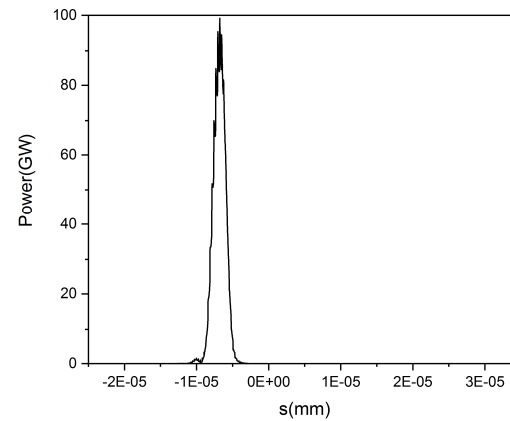
- ▶ Try several combination of harmonic number and radiator length
 - Result: 15th harmonic of 1st modulator (18 nm), 4 segments

Multi-Parameters Decision for Two-Stage HGHG: 1st Radiator

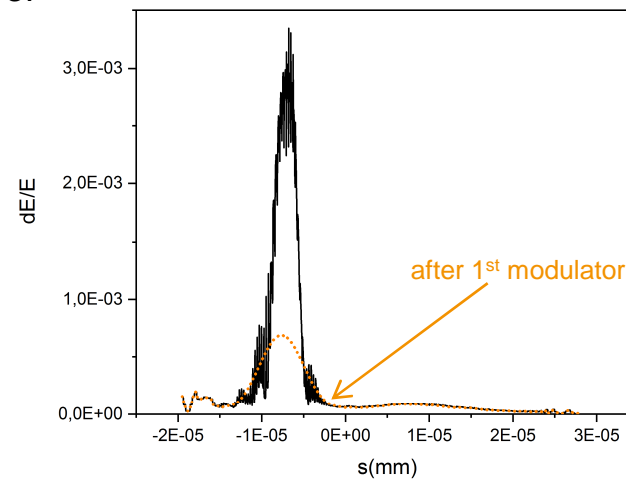
Parameters and results

Period length: 20 cm, number of period: 45, number of segment: 4

Radiation at 18 nm

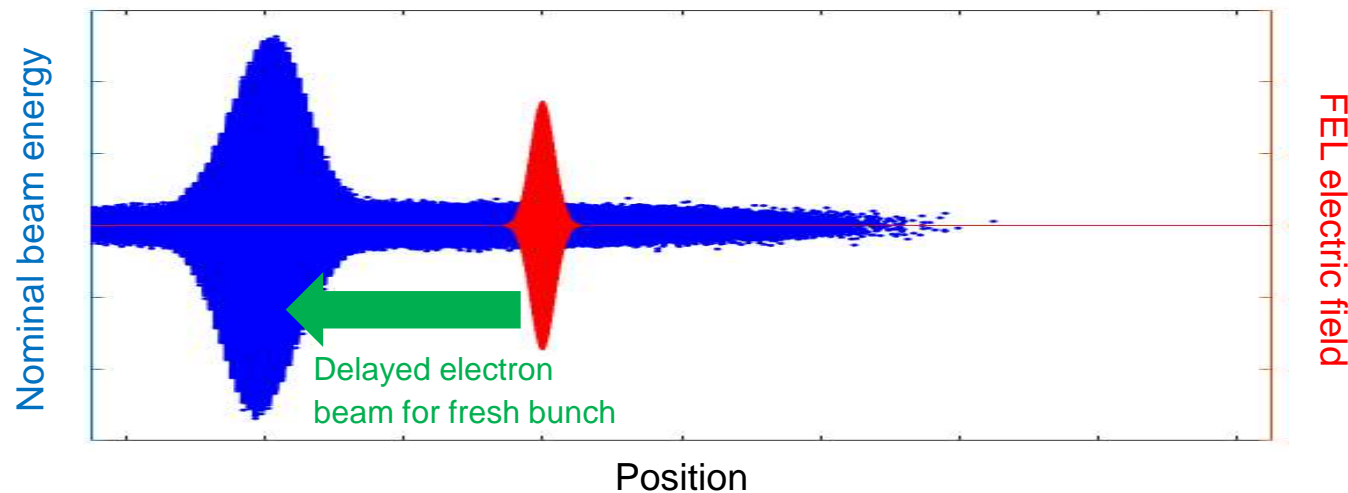


Energy spread of electron beam



Multi-Parameters Decision for Two-Stage HGHG: Electron Delay and 2nd Modulator

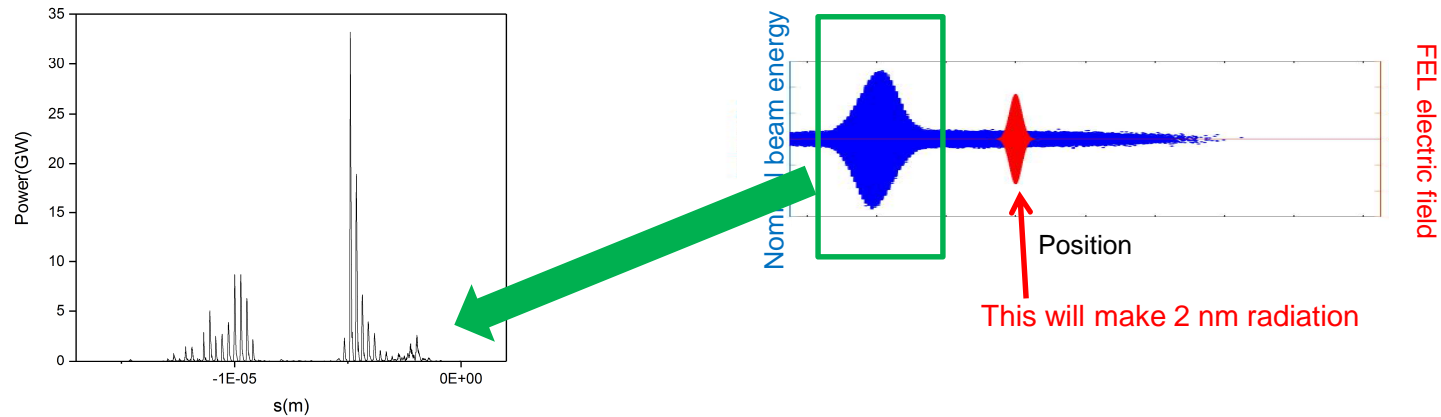
- Parameters of 2nd modulator: same with 1st radiator, 1 segment
- Electron delay to use fresh bunch technique
 - Delay electron bunch and seed the radiation from 1st radiator into fresh electrons part at 2nd modulator



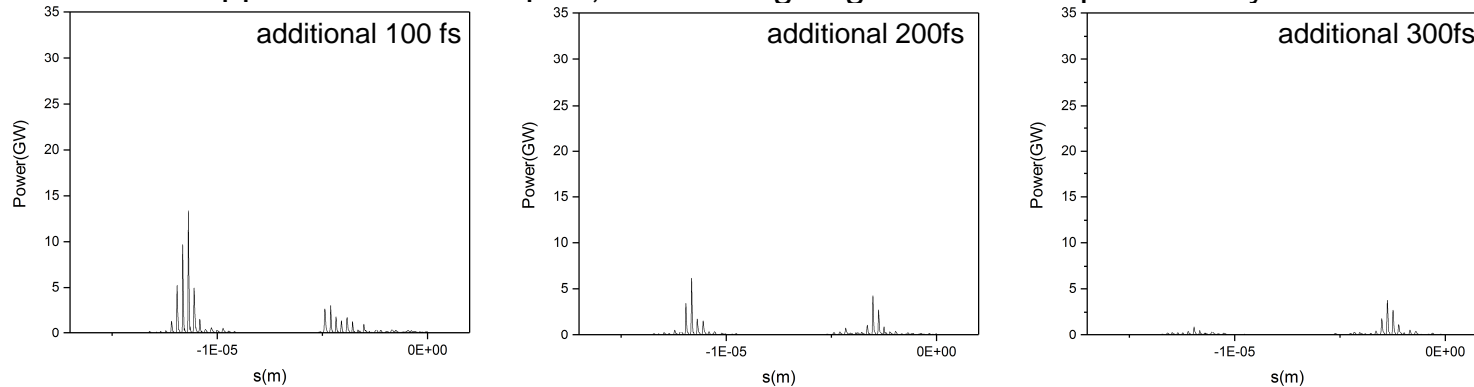
Schematic drawing of phase space after electron delay

Multi-Parameters Decision for Two-Stage HGHG: Electron Delay and 2nd Modulator

- Amount of delay using fresh bunch technique
- Electrons should be delayed at least far from 1st seeded part
- ▶ But this is not enough because 1st seeded part gets lasing at the end of 2nd HGHG stage



- ▶ In order to suppress 1st seeded part, introducing larger R56 and optical delay for 2nd seed



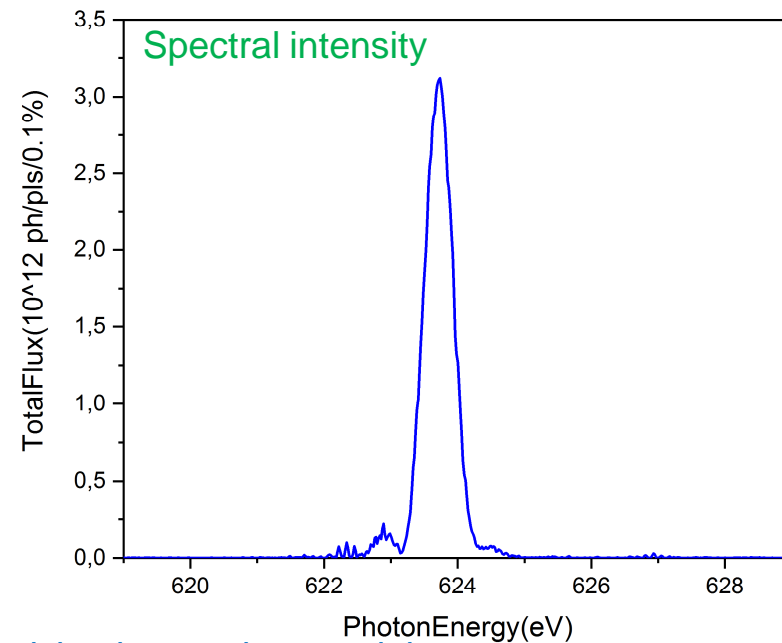
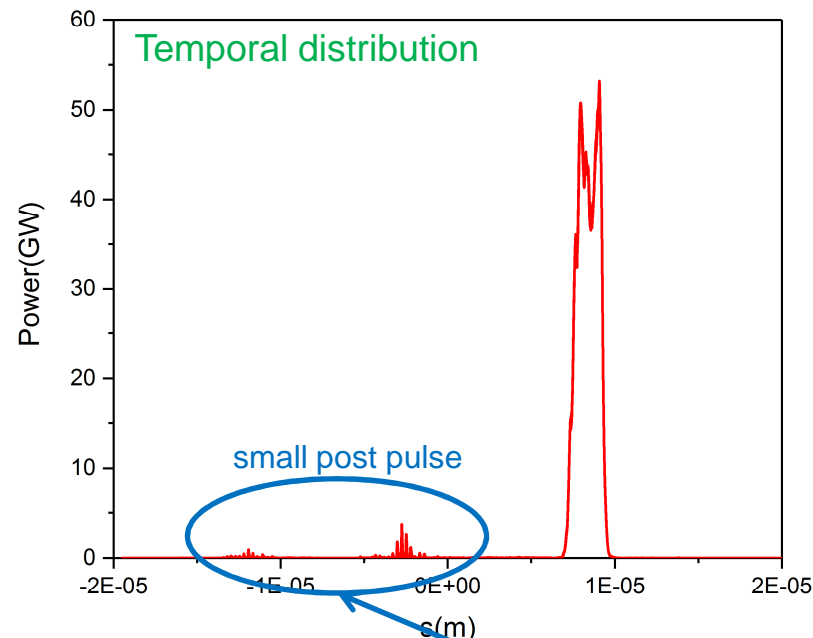
Results of Two-Stage HGHG for the European XFEL

- FEL wavelength: 1.99 nm (623 eV)
- Combination of 2-times harmonic conversion by FEL: 15 x 9
- 3 segments 2nd radiator case

Pulse properties:

[Note] FERMI: 0.5 GW @ 4 nm

- ▶ Peak power: up to 50 GW
(80 GW with larger post-pulse in case of 4 segments → with monochromator?)
- ▶ Pulse duration: 6 fs (FWHM)
- ▶ Bandwidth: 0.08 %



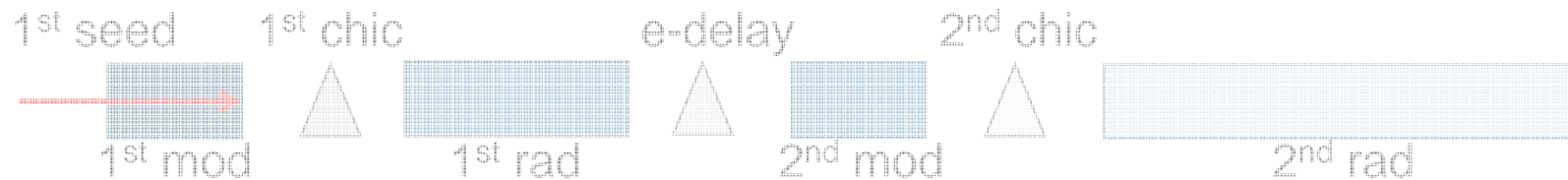
Can be reduced by applying larger electron delay
or applying spectral filter/monochromator

(or suppressed by implementing dechirper system: under study with S. Tomin)

Multi-Parameters Decision for EEHG

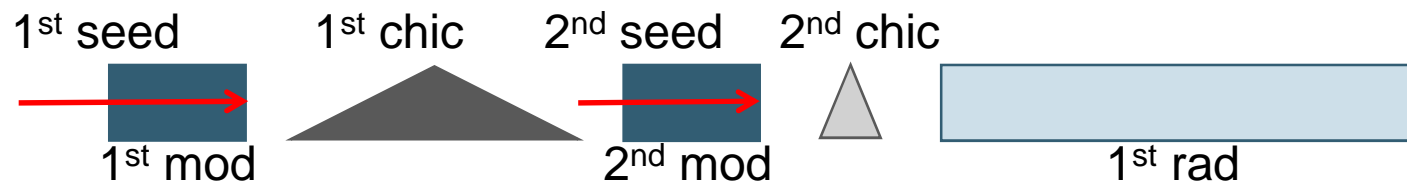
2-stage HGHG

- 4 x different undulators (2 x modulators, 2 x radiators)
- 3 x magnetic chicanes (2 x bunchers, 1 x electron delay)
- 1 x seed laser injection



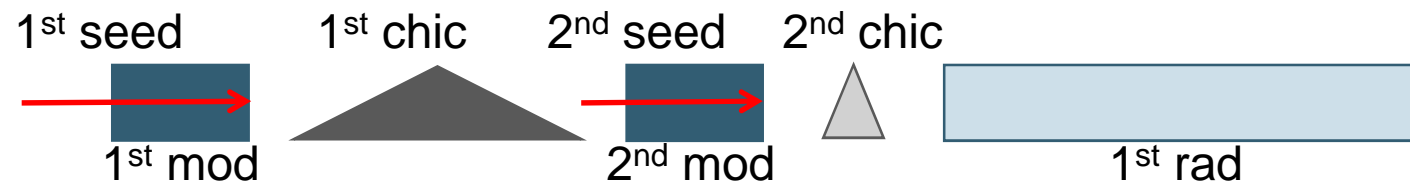
EEHG

- 3 x different undulators (2 x modulators, 1 x radiator)
- 2 x magnetic chicanes (2 x bunchers)
- 2 x seed laser injection



Multi-Parameters Decision for EEHG

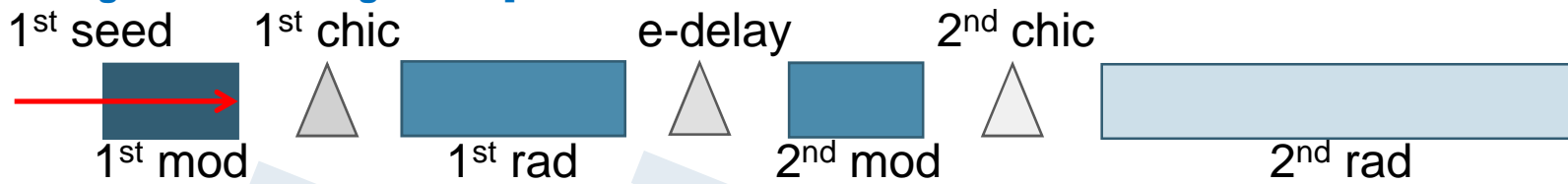
- Designing EEHG
 - Undulators parameters
 - How to manage 2 x seed laser injection
 - Different magnetic chicanes parameters for strong bunching technique



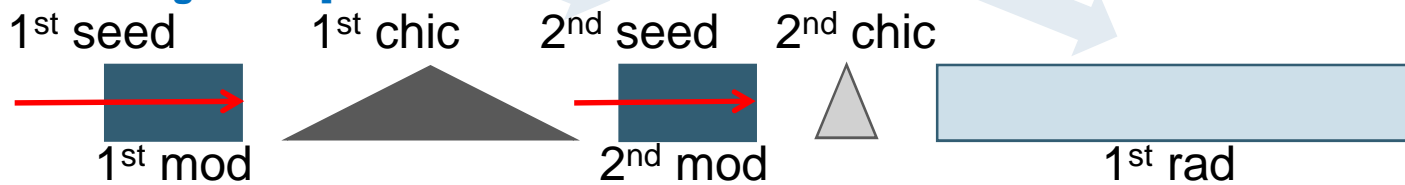
Multi-Parameters Decision for EEHG: Undulators

■ Undulators parameters

[Two-stage HGHG configuration]



[EEHG configuration]

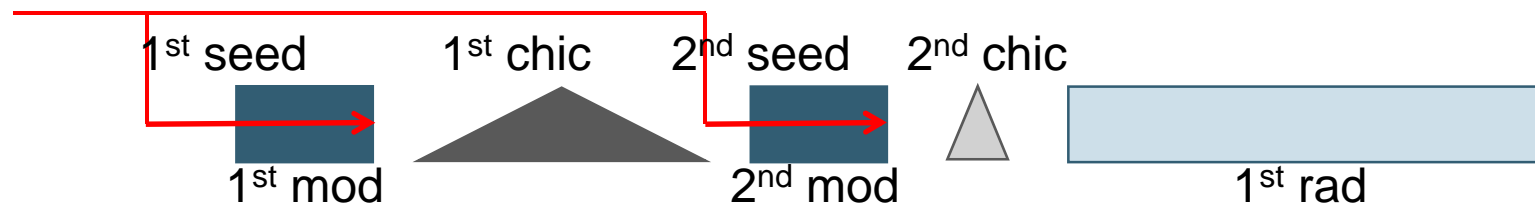


■ ■ ■ European XFEL

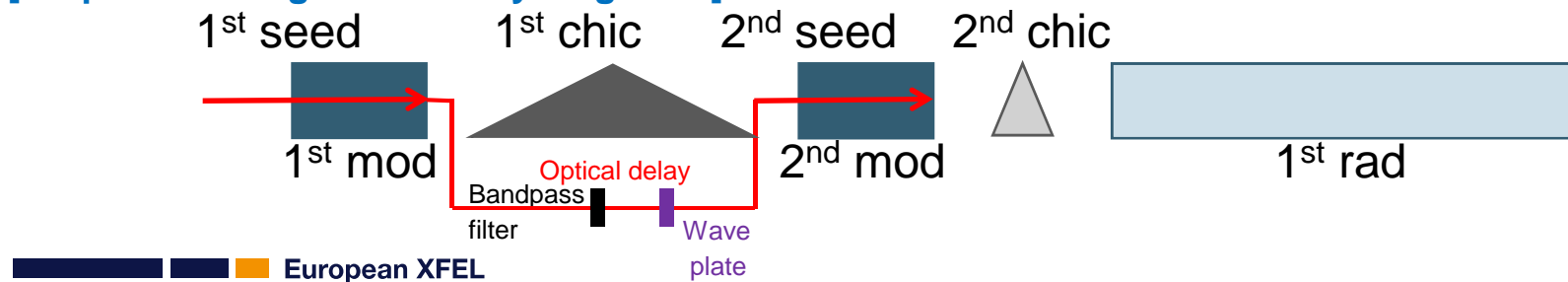
Multi-Parameters Decision for EEHG: Seeds

- How to manage 2 x seed laser injection

[Normal EEHG configuration: splitting seed]

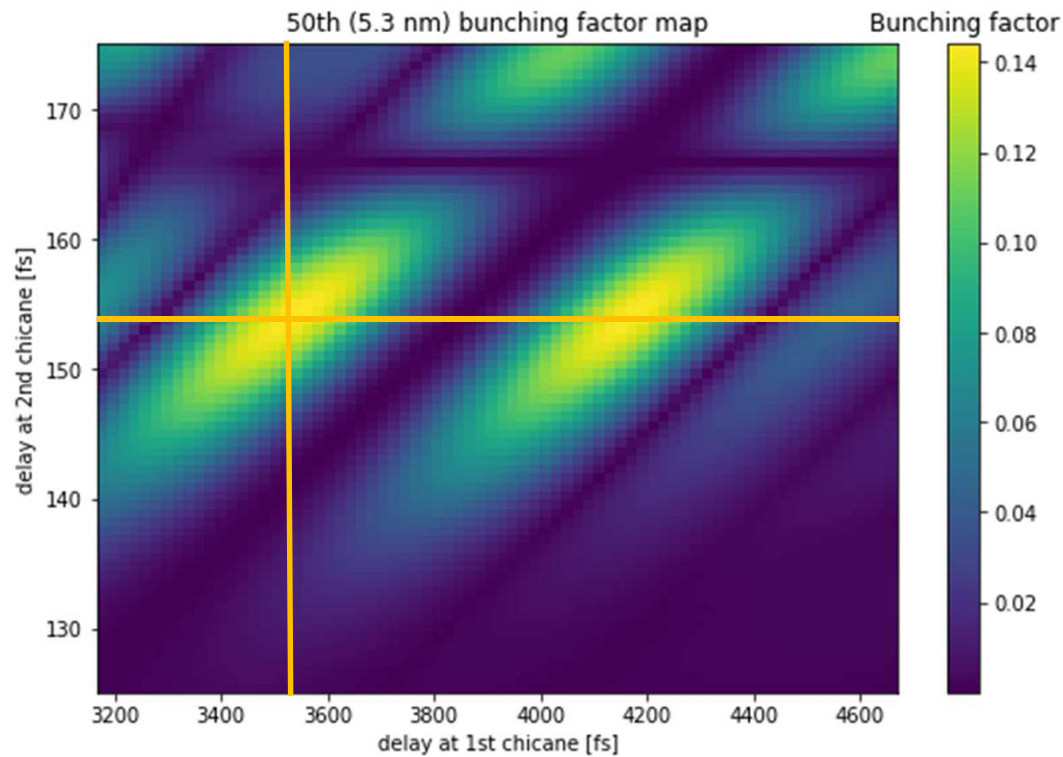


[Proposed configuration: recycling seed]

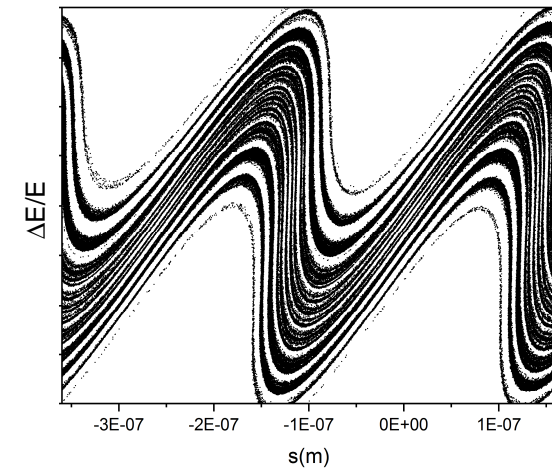


Multi-Parameters Decision for EEHG: Magnetic Chicanes

- Decision of 2 different seed powers and 2 different chicane strengths
(ex. 50th harmonic of 260 nm seed)



$n = -2$ case was chosen
(to avoid larger R56 in 1st chicane)



Electron beam phase space

Results of EEHG for the European XFEL

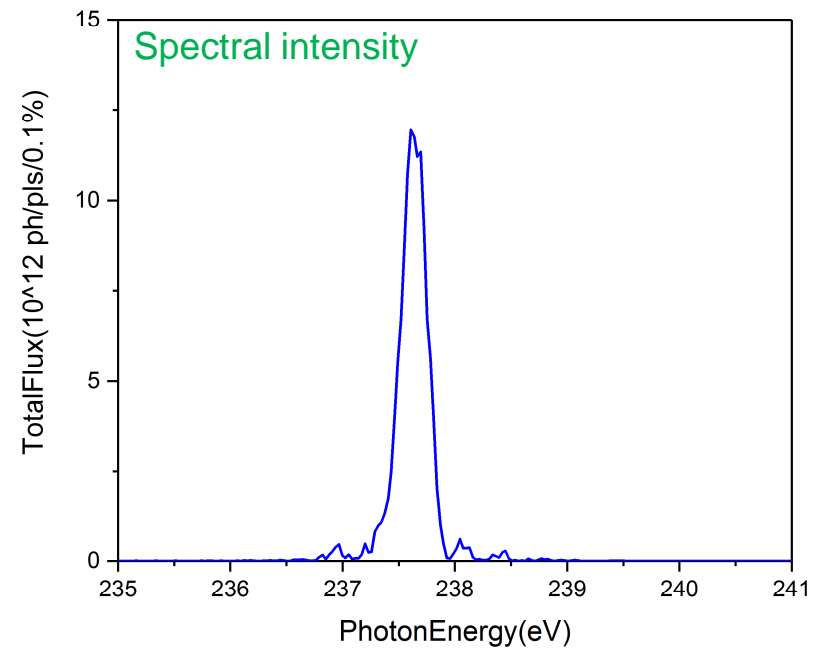
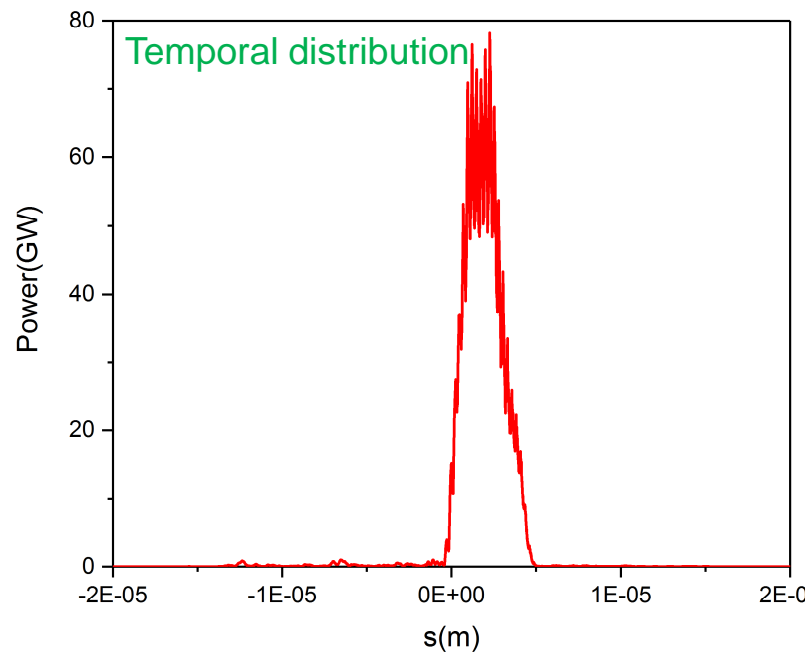
■ FEL wavelength: 5.36 nm (231 eV)

■ 50th harmonic amplification

[Note] FERMI: 0.2 GW @ 5.2 nm

■ Pulse properties:

- ▶ Peak power: up to 70 GW
- ▶ Pulse duration: 7.7 fs (FWHM)
- ▶ Bandwidth: 0.09 %

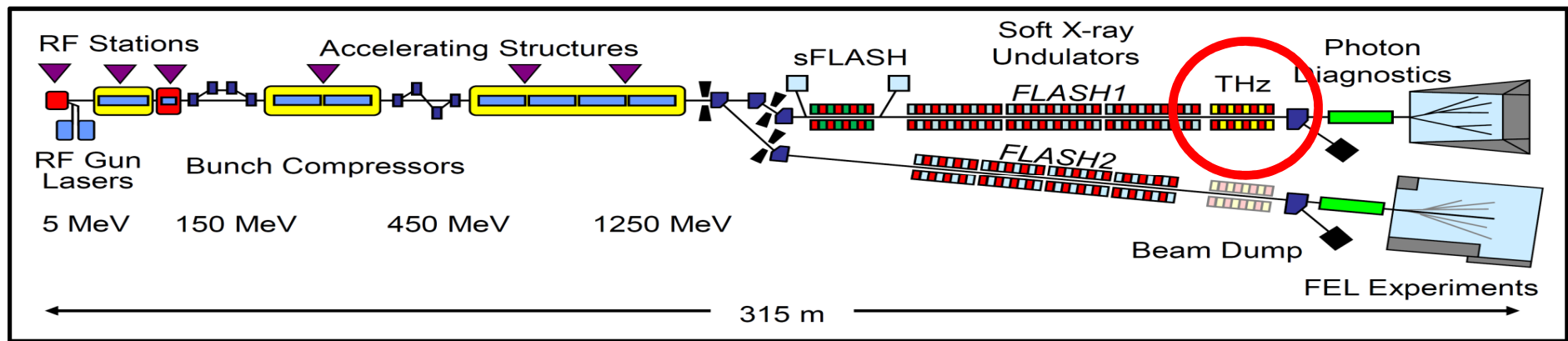


Let Us Dream Further: “High-Power” Soft X-Ray Probe & “Superradiant THz” Pump

- THz option for European XFEL
 - Discussed in a workshop
 - ▶ Laser-based source
 - ▶ Low-energy accelerator-based source
 - ... and
 - ▶ Third way: afterburner method like FLASH1

Study of THz undulator: independent project
 can be hosted any other FEL lines like SASE3

→ synergies with HGHG & EEHG must be considered !



Superradiant THz Radiation from THz Undulator

- In cooperation with
 - THz undulator:
 - S. Karabekyan (European XFEL)
 - S. Casalbuoni (KIT)
 - THz transport:
 - M. Gensch (HZDR)
 - S. Kovalev (HZDR)
 - N. Stojanovic (DESY)
 - Radiation simulation:
 - V. Asgekar (Pune Uni.)

Superradiant THz Radiation from THz Undulator

- European XFEL has advantage to generate higher THz Frequency
 - Because of ultra-short electron bunch
 - ▶ we can regard it as a “point” particle
 - high coherent THz (superradiant)

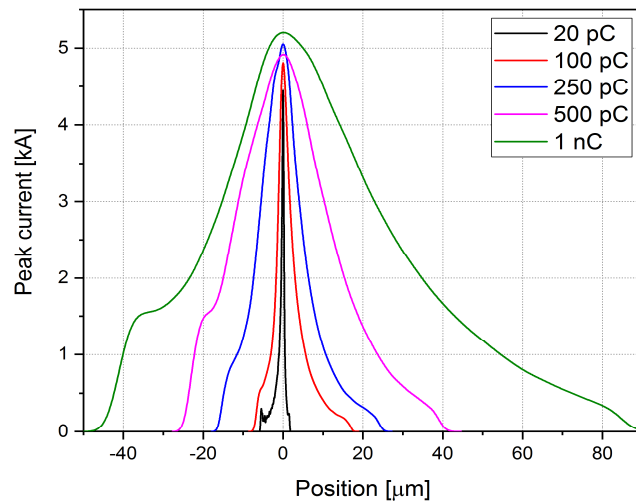
Photon flux of coherent radiation

$$P(\lambda) = N^2 f^2(\lambda) I(\lambda)$$

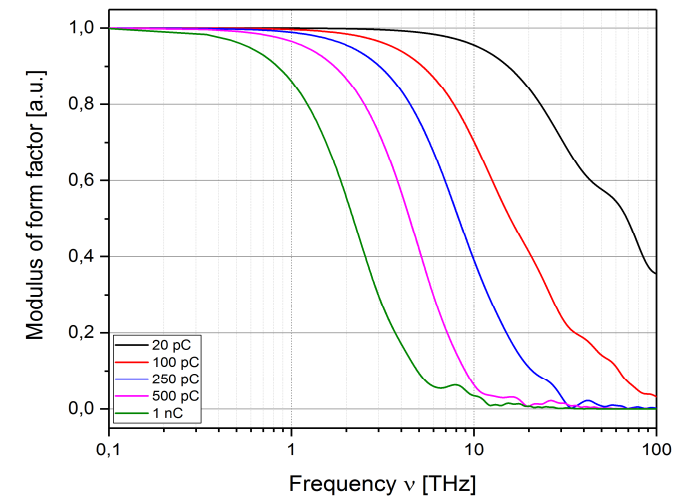
N : number of electrons

f : modulus of form factor

I : photon flux from single electron



Temporal distributions of electron bunch



Modulus of form factor calculated from temporal distributions

Fixing Parameters for THz Undulator

Technology

Permanent magnet case (example)

- ▶ To generate 3 THz
 - Period length 3 m (peak mag. field: 1.4 T)
 - Segment length: 30 m (10 periods considered)
 - Longer segment length requires larger gap size to let low frequency radiation pass through

$$\text{(source size } \approx \sqrt{\frac{\lambda}{2\pi} L_u})$$

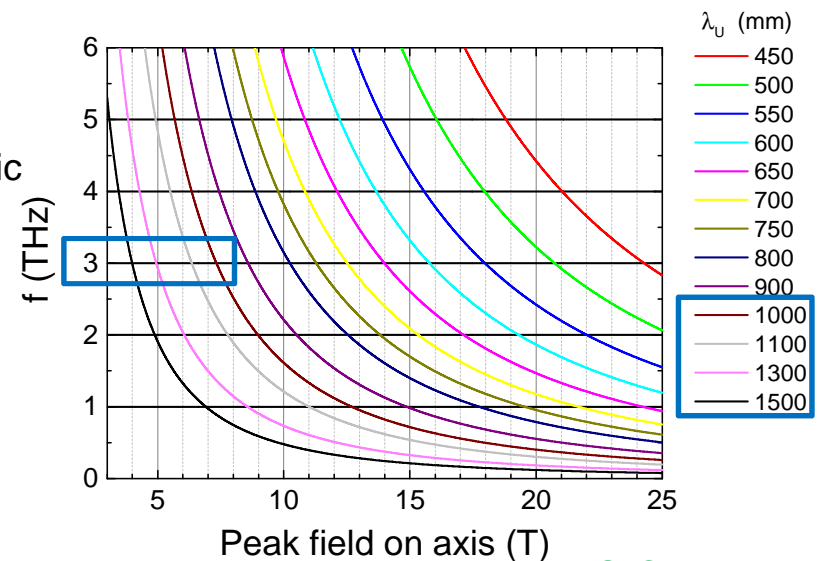
- ▶ Short period length
 - total length becomes smaller but higher magnetic field is required to generate low frequency

Well-studied technology up to 8 T

- ▶ Superconducting coil (Nb-Ti)

Multi-cycle THz field can be generated

- ▶ Depend on user demand



courtesy: S. Casalbuoni

Concept of Superconducting Superradiant (SC-SR) Undulator

Parameters

- Period length: 100 cm
- Number of periods: 10
- Number of segments: 1 (total: 10 m)
- Peak magnetic field: ~ 7.88 T
- Gap size: 50 mm

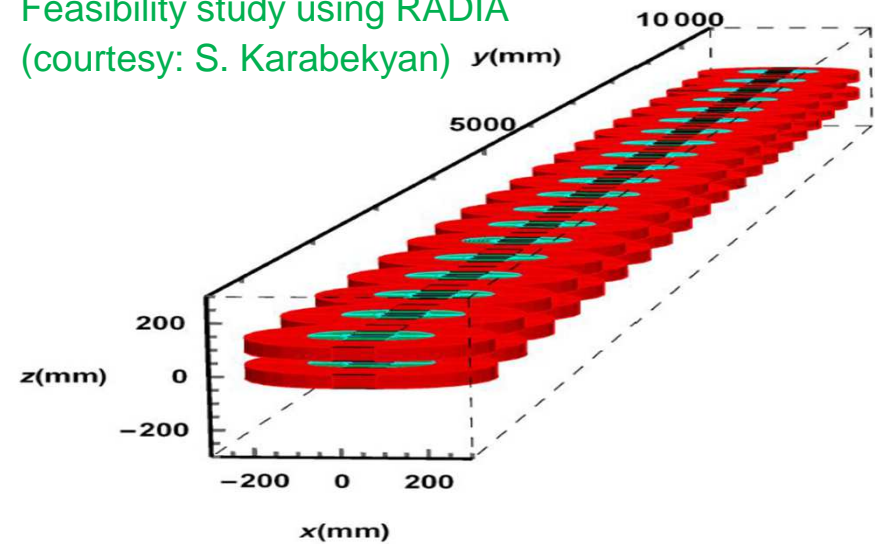
Target THz frequency

- 3THz \sim 50 THz

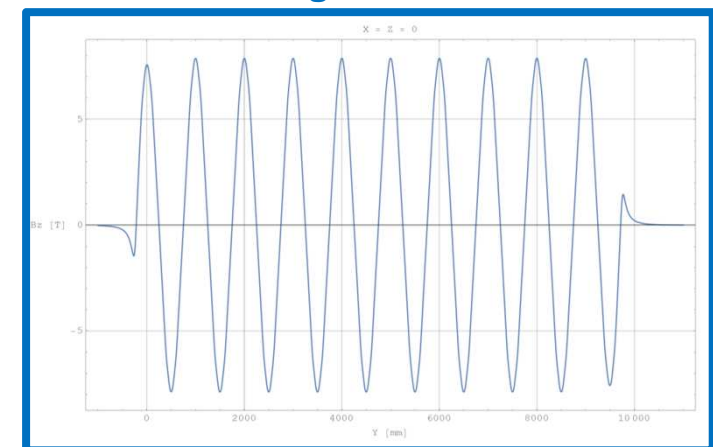
Operational electron beam energy

- Up to 17.5 GeV
- Spent e-beam after any FEL line can be used (afterburner concept)

Feasibility study using RADIA
(courtesy: S. Karabekyan)

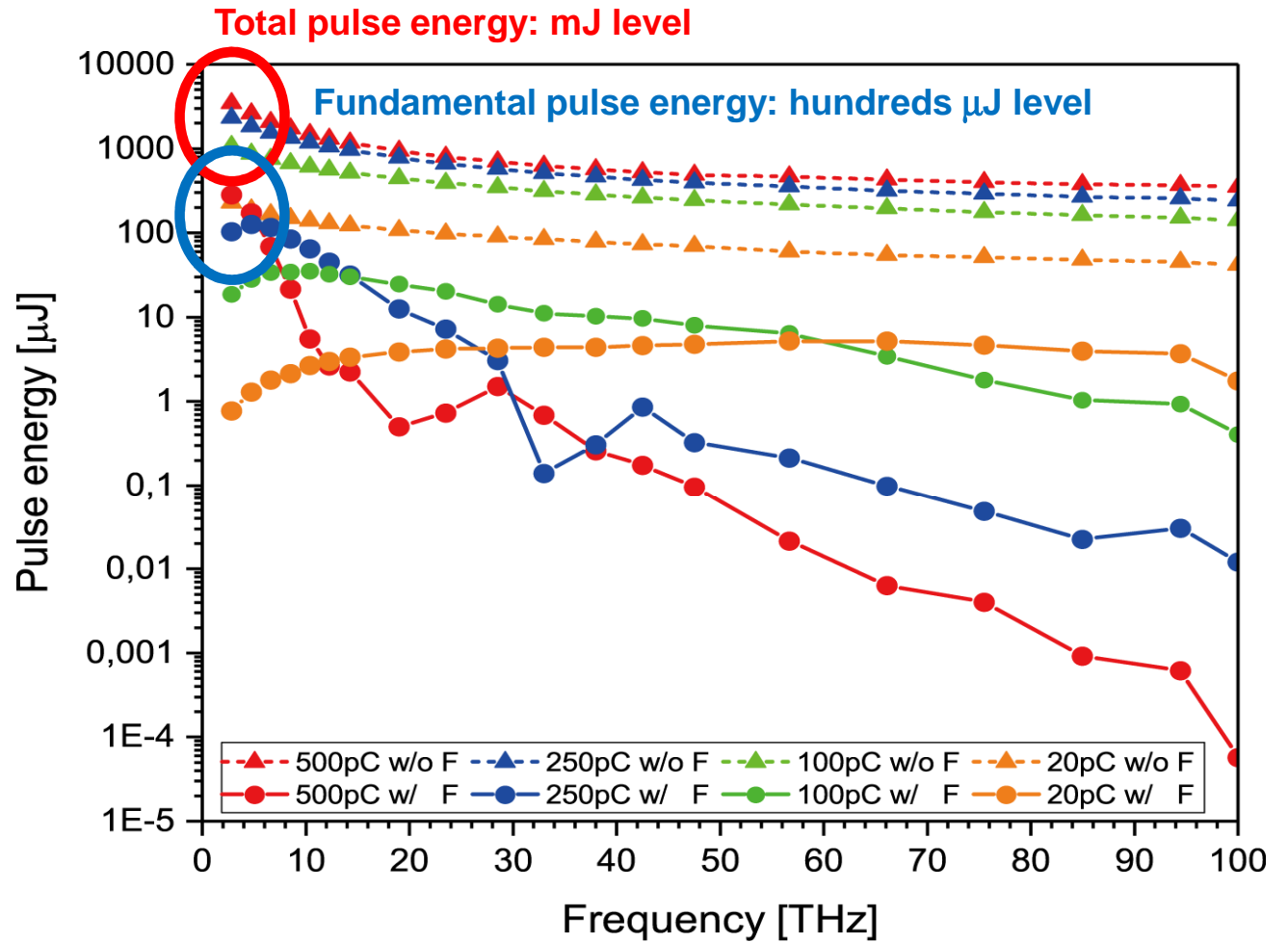


Magnetic field



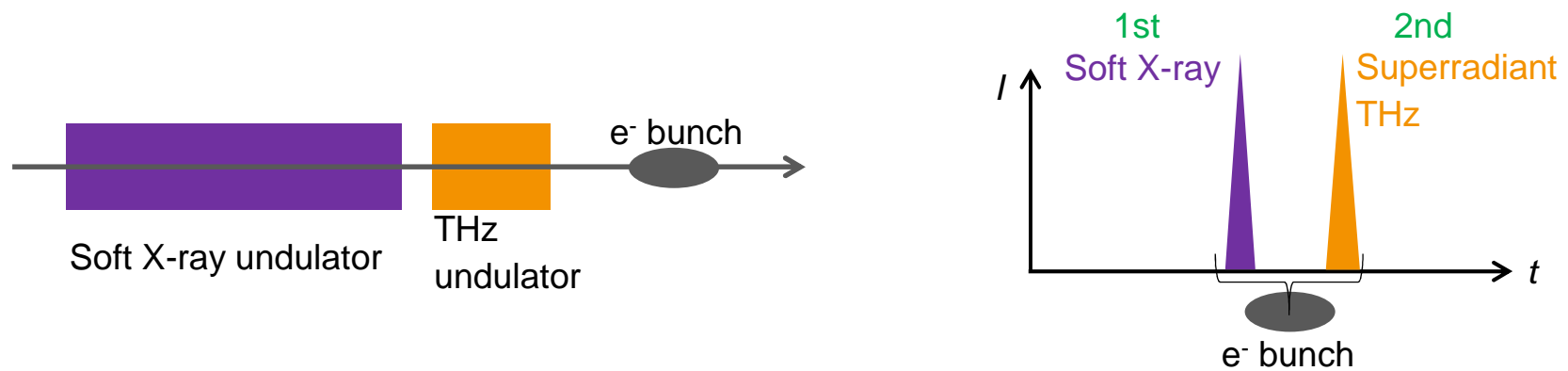
Superradiant THz Radiation Properties: Comparison with Different Fundamental Frequencies

- Different electron charge
- Without bandpass filter
- With 10% bandpass filter



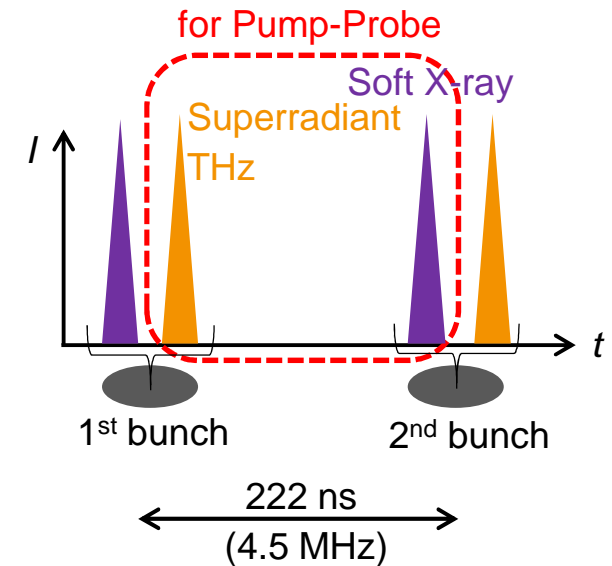
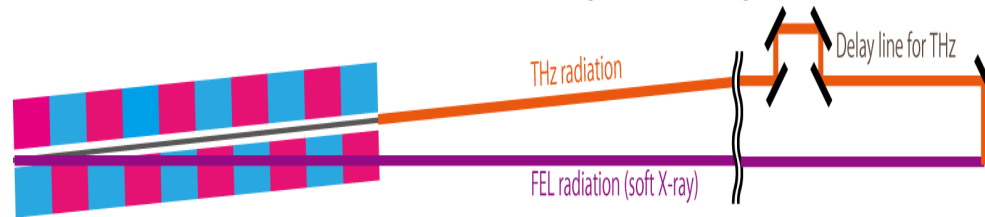
Synchronization between Superradiant THz & High-Power Seeded Soft X-ray

- Soft X-ray arrives earlier than THz using afterburner method



Synchronization between Superradiant THz & High-Power Seeded Soft X-ray

- Soft X-ray arrives earlier than THz using afterburner method
- Solution 2: THz delay line using following bunch

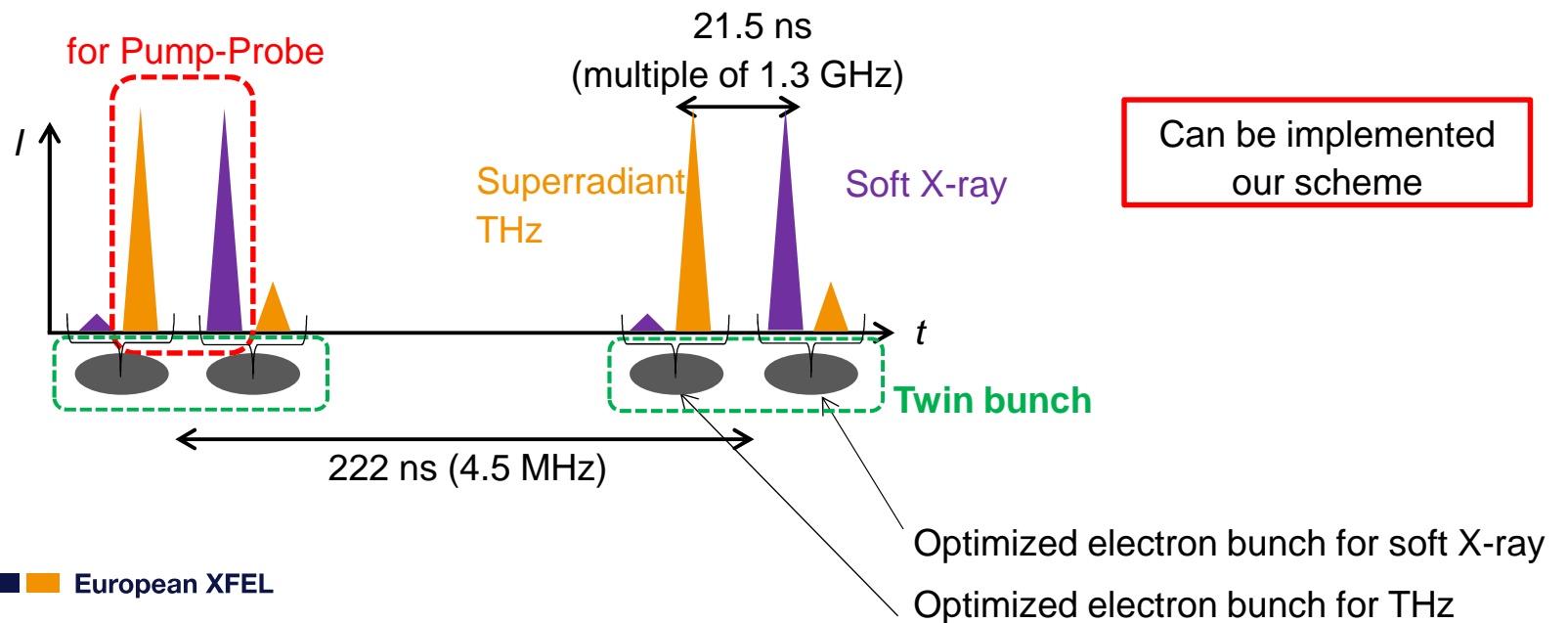


- ▶ SASE (soft X-ray) + THz case
 - Soft X-ray & THz repetition: up to 4.5 MHz
 - 222 ns interval between bunches
 - 33 m delay line

Synchronization between Superradiant THz & High-Power Soft X-ray

- Soft X-ray arrives earlier than THz using afterburner method
- Solution 3: THz delay line + “Twin bunch” technique
 - ▶ What FLASH was done in experiment
 - Generation of twin bunches in neighbor of electron bucket (RF frequency 1.3 GHz)

<Experimented condition at FLASH1 (ref: E. Zapolnova, J. Synchrotron Rad. 25 (2018) 39)>



Summary

Thanks to very powerful drive laser & high-quality electron beam from European XFEL, it will bring us:

- High-power coherent soft X-ray pulse (wavelength tunable)

- Two-stage HGHG case at 1.99 nm

- ▶ Peak power: up to 50 GW
- ▶ Pulse duration: 6 fs FWHM
- ▶ Bandwidth: 0.08 %

- EEHG case at 5.36 nm

- ▶ Peak power: up to 70 GW
- ▶ Pulse duration: 7.7 fs FWHM
- ▶ Bandwidth: 0.09 %

- Superradiant THz radiation

- Frequency: 3 ~ 50THz
- Pulse energy: up to 280 μ J (2.3 mJ without filter)
- THz cycles: up to 10
- High CEP stability

**Thank you for
your attention
&
Merry Christmas!**



(from www.facebook.com/EuropeanXFEL)