External Seeding Possibilities at the European XFEL

Takanori Tanikawa, European XFEL

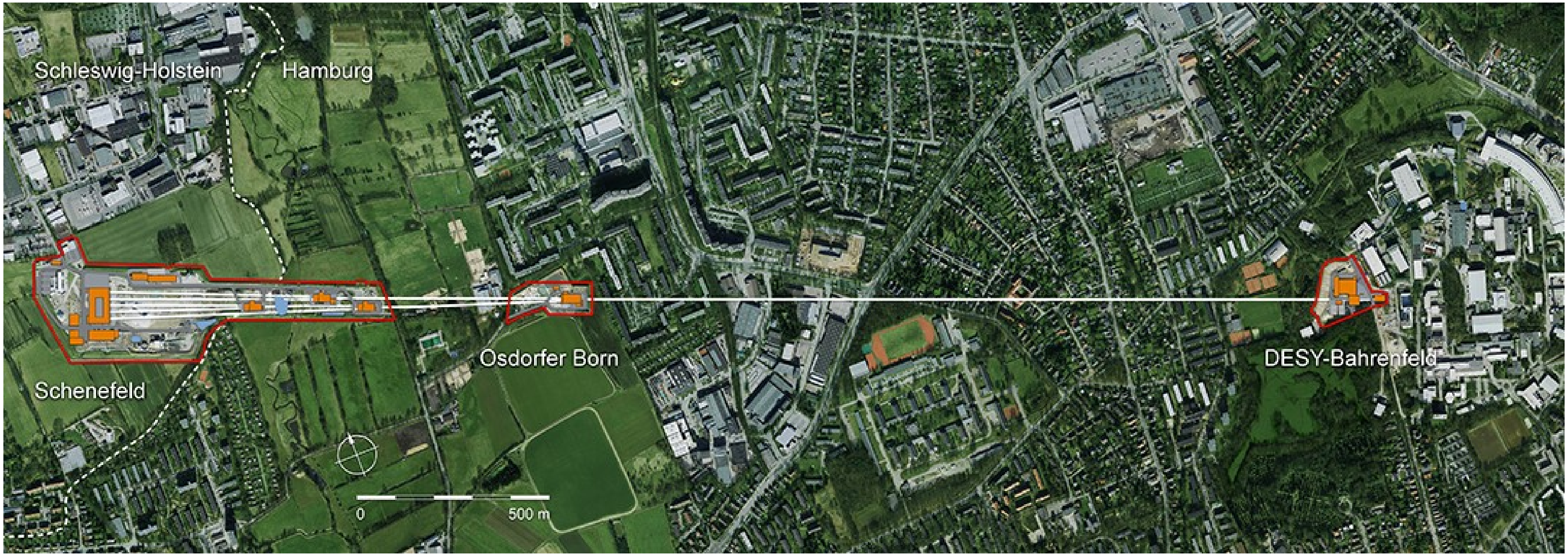
Future of Seeded free Electron lasers workshop
Trieste, Italy, December 10-11th, 2019

Outline

- Introduction about European XFEL
- Background and requirement to external seeding for the European XFEL
- Two-stage HGHG option for the European XFEL
- EEHG option for the European XFEL
- Summary

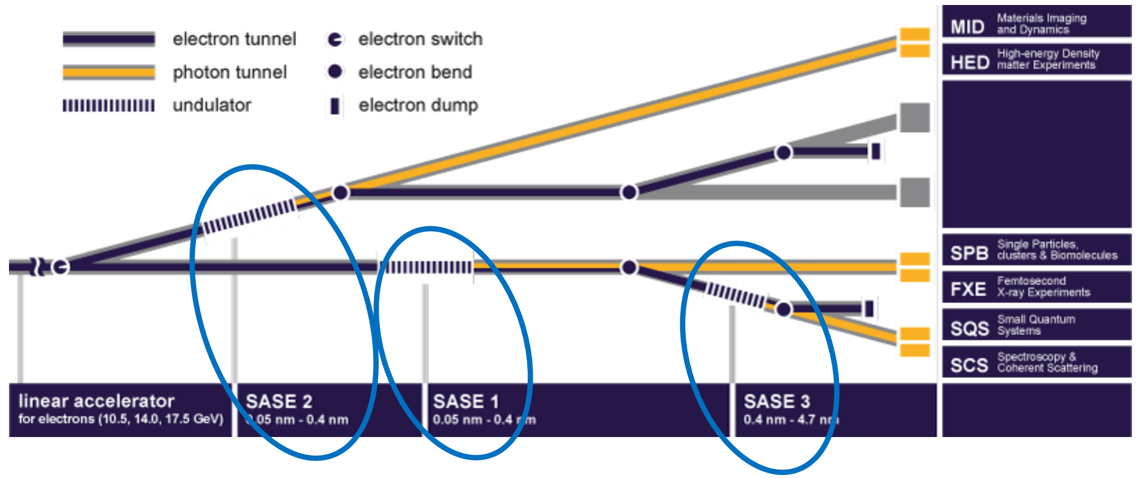
European XFEL

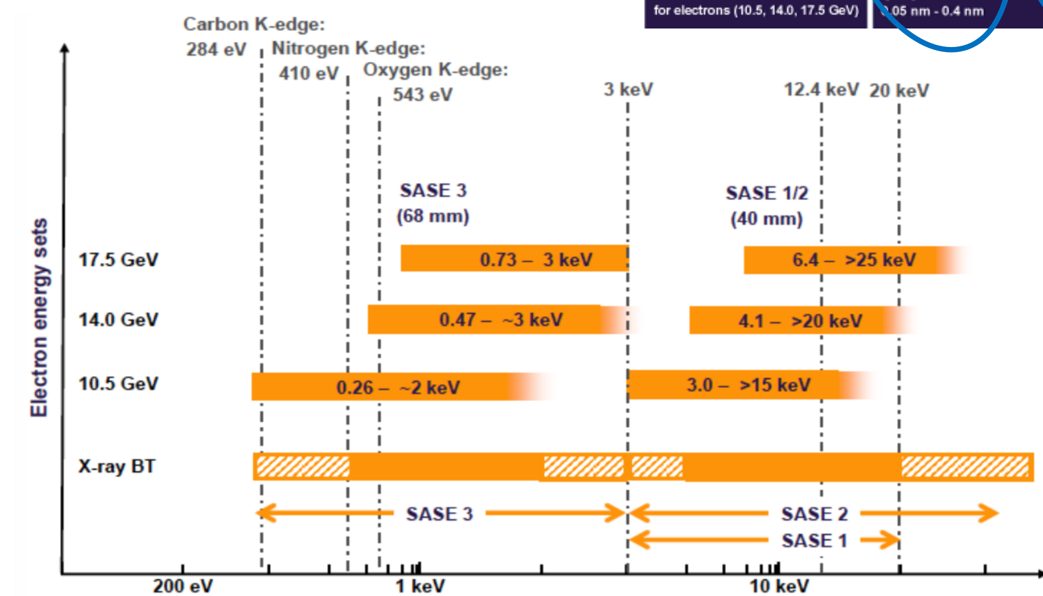
- Superconducting accelerator (total: 3.4 km long)
- Electron beam energy: 8.5 GeV up to 17.5 GeV
- Beam charge: 20 pC up to 1000 pC (2 – 100 fs)
- 4.5 MHz burst-mode pulse (10 Hz macro pulse)



European XFEL

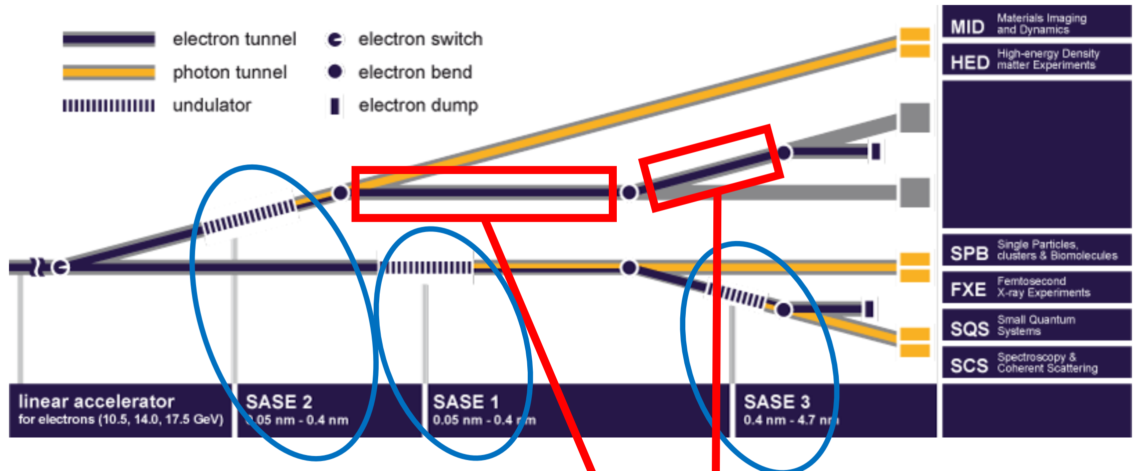
- First lasing in 2017
- Now simultaneous operation
  - SASE1 & 2: hard X-ray FEL
  - SASE3: soft X-ray FEL

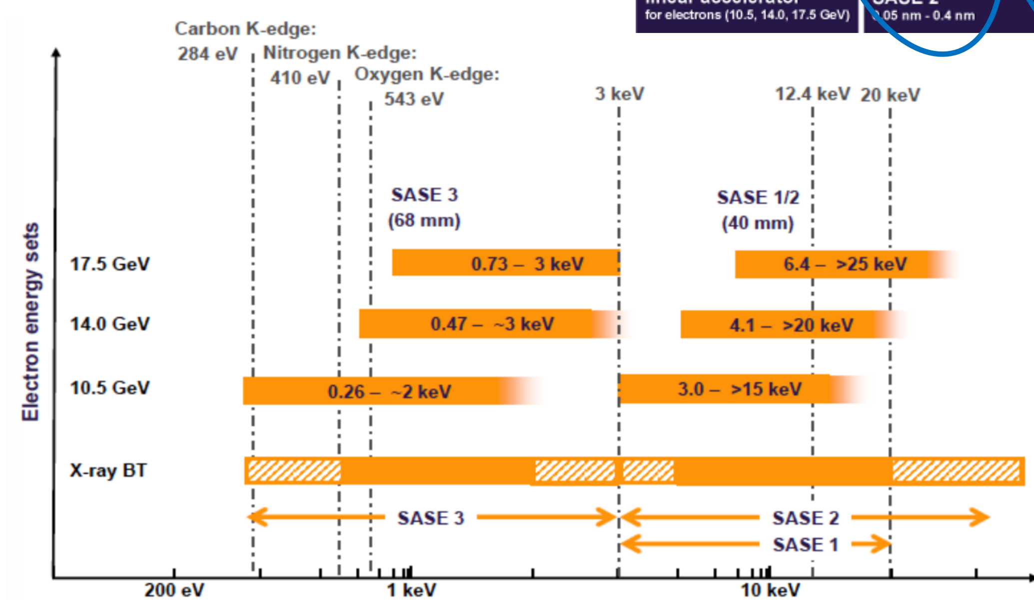




SASE 4 & 5 at the European XFEL

- Simultaneous operation
  - SASE1 & 2: hard X-ray FEL
  - SASE3: soft X-ray FEL

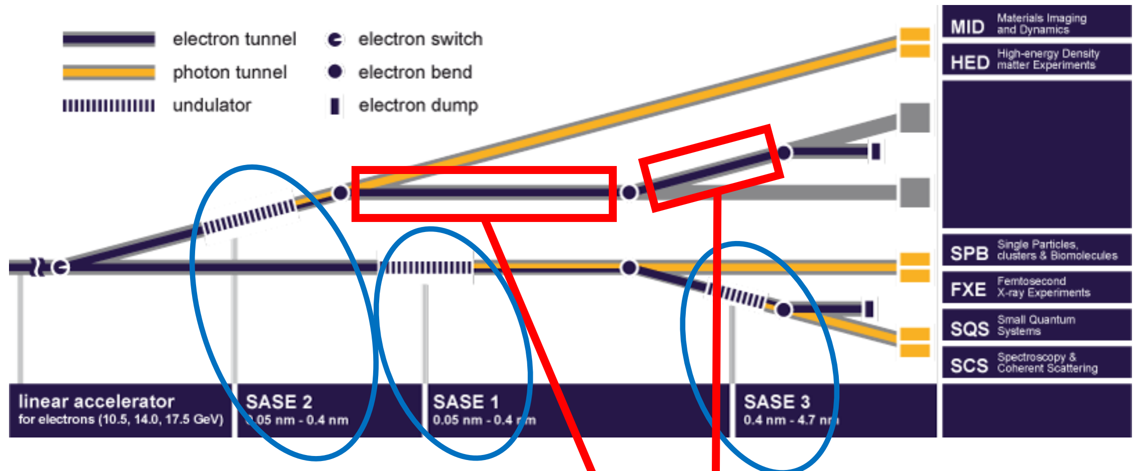


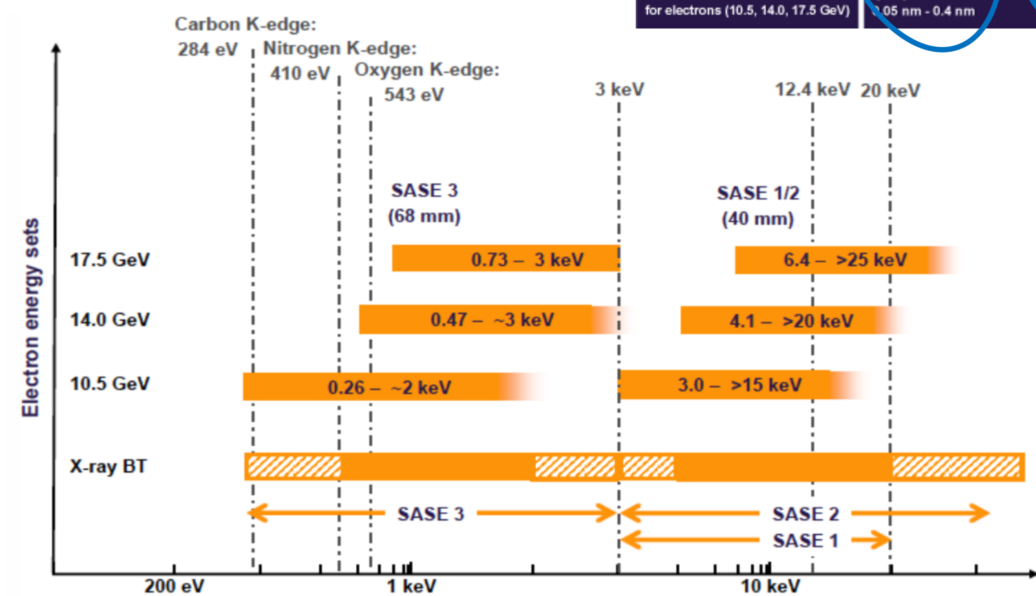


Two empty FEL tunnels "SASE 4 & 5"
* (super) hard X-ray line
* soft X-ray line
(under consideration)

External Seeding Option for the European XFEL

- Simultaneous operation
  - SASE1 & 2: hard X-ray FEL
  - SASE3: soft X-ray FEL





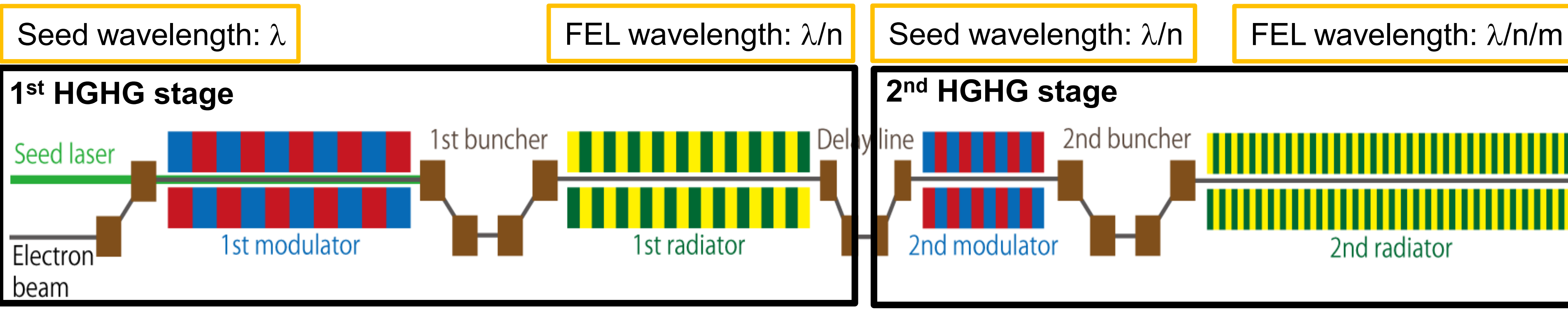
European XFEL

- Two empty FEL tunnels “SASE 4 & 5”
  - * (super) hard X-ray line
  - * **soft X-ray line**

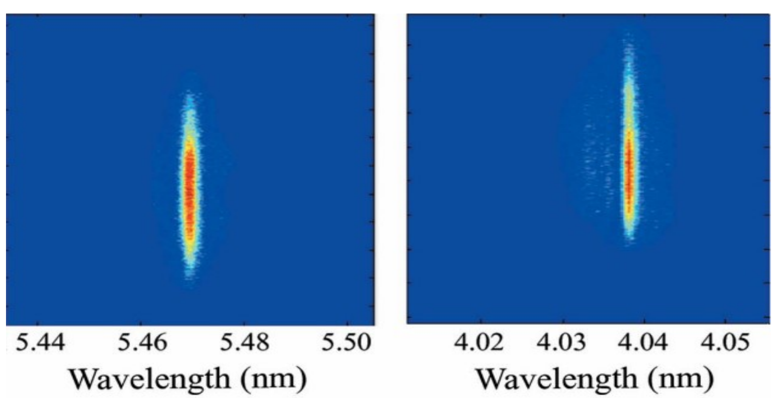
  (under consideration)

How about implementing external seeding??

Look Back Recent Seeding Research: Two-Stage HGHG at FERMI



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

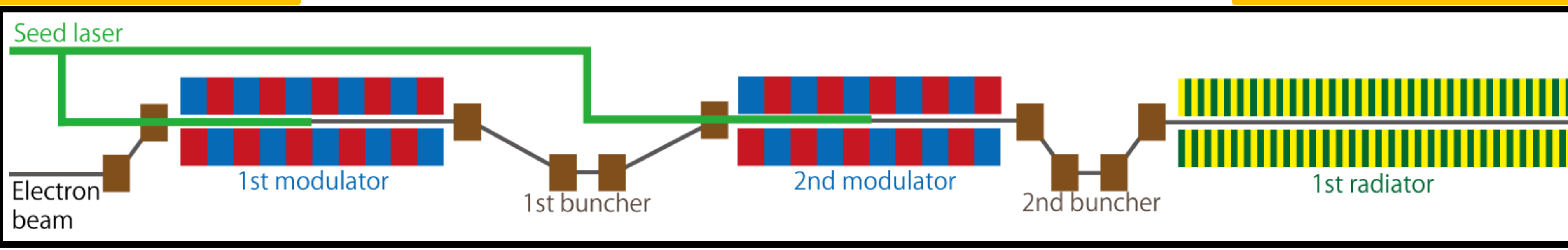


E. Allaria, et. al,
J. Synchrotron Rad.
22 (2015) 485

Look Back Recent Seeding Research: EEHG at LCLS & FERMI

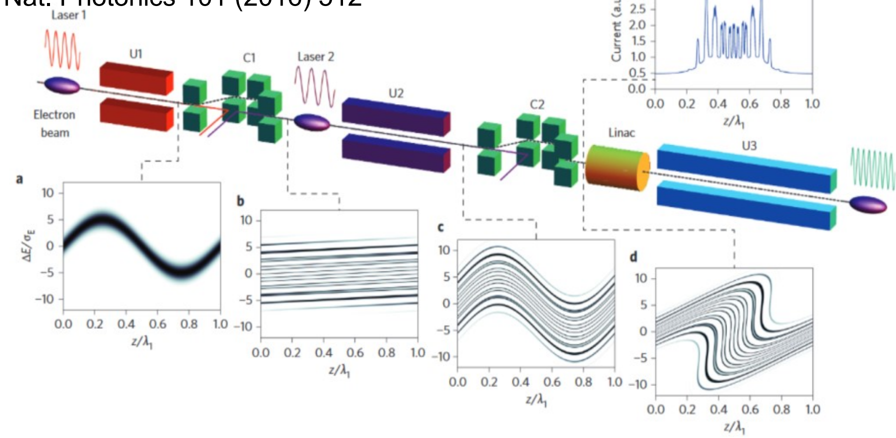
Seed wavelength: λ

FEL wavelength: λ/m

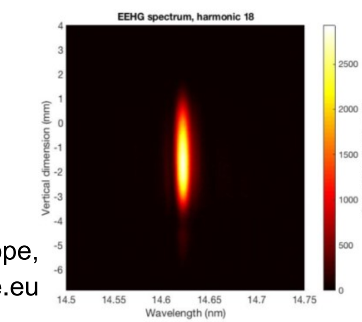


- ▶ LCLS
  - 32 nm lasing
    (λ=2400 nm, m=75th harmonic)

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



- ▶ FERMI
  - 2018 May: 14 nm lasing
    (λ=260 nm, m=19th harmonic)



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

  - 2018 Sep: **5.8 & 5.9 nm**
    two-color lasing
    (λ=265 nm, m=45th,46th harmonic)
    : 2.6 nm CHG (no gain on undulator)
    (λ=265 nm, m=**101st** harmonic)

P.R. Ribic, et. al,
Nat. Photonics 13 (2019) 555-561

Requirement to External Seeding Option for the European XFEL

- Requirement
  - Target wavelength
    - ▶ **Below 2 nm (620 eV)**
      - (ref) K-edge of C: 282 eV, N: 397 eV, O: 533 eV
  - Electron beam
    - ▶ nominal beam used for operation
      → beam energy: more than **8.5 GeV**, peak current: **5 kA**
  - Repetition rate
    - ▶ > 100 kHz (preferably same rep. rate with machine (4.5 MHz))
  - Total system length
    - ▶ Below 200 m (to be filled in an empty tunnel "SASE4/5")

- What is possible scheme of external seeding?
  - Direct seeding using HHG source (ref. European XFEL Annual report 2016)
  - **Two-stage high-gain harmonic generation (HGHG)**
  - **Echo-enabled harmonic generation (EEHG)**

Challenge and Reward to External Seeding at the European XFEL

- Challenge
  - Energy modulation induced by seed laser

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

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

- ▶ Very high harmonic conversion (from optical to below 2 nm seed)
- ▶ Large energy modulation is required to obtain high bunching factor at target wavelength
- ▶ $\Delta\gamma_{modulation}/\gamma_{beam}$ comes more difficult to get large value when electron beam energy is high [ex. Beam energy at FERMI: 1.5 GeV, at EuXFEL: 8.5 GeV]

  - Competition with shot noise
    - ▶ Since beam energy and peak current are high at European XFEL, high shot noise power is generated (FEL gain ρ is very high) [ex. Peak current at FERMI: ~750 A, at EuXFEL: 5000 A]

Challenge and Reward to External Seeding at the European XFEL

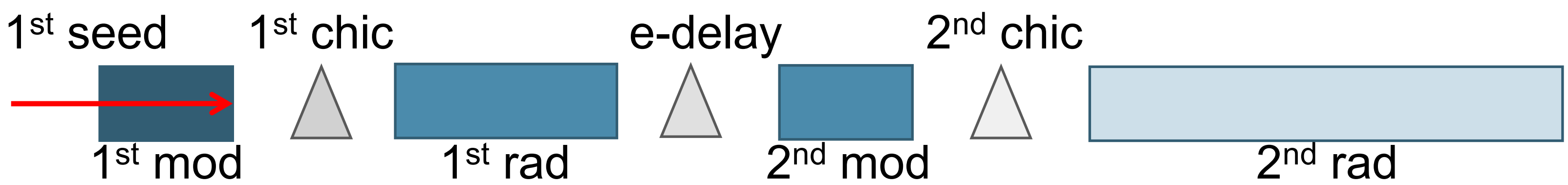
- Reward
  - If everything is managed well, very high FEL peak power will be out !
    (because of high beam-energy and peak-current electron beam at European XFEL)

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

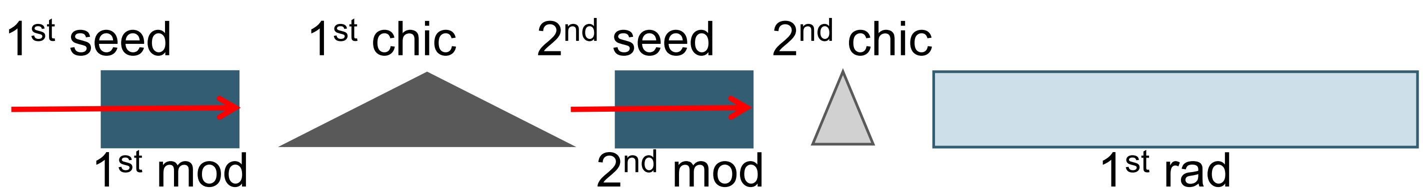
Ok, let's try!

Multi-Parameters Decision for External Seeding

- 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 Scheme

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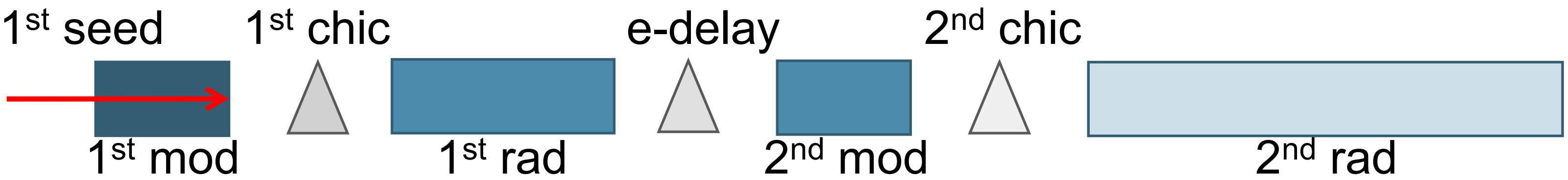
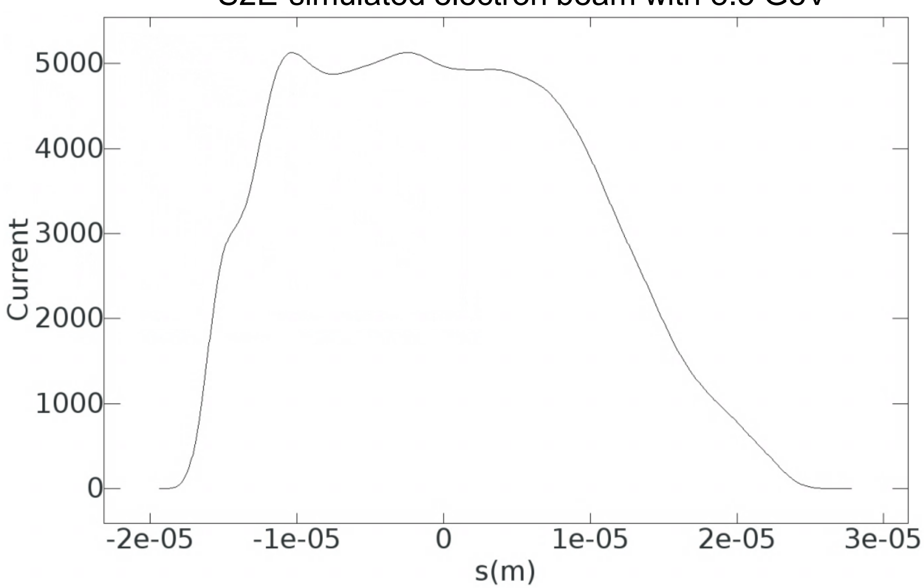


Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Beam

- Flat-top beam
  - ► very important for multi-stage HGHG (fresh bunch technique)
  - Energy: 8.5 GeV
  - Peak current: 5 kA
  - Energy spread: 8e-5*
  - Charge: 500 pC (necessity to have flat top)

S2E-simulated electron beam with 8.5 GeV

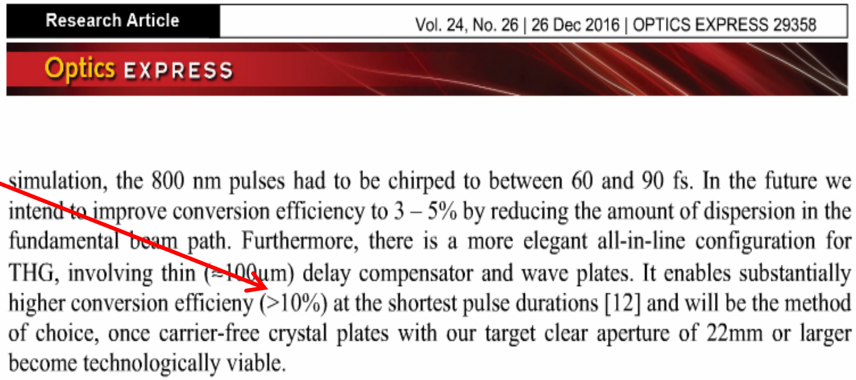


* The value was obtained by S2E simulation and used for following simulations but recently larger value was observed experimentally

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

- Driving laser (OPCPA): used for pump-probe experiment at EuXFEL
  - 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



Research Article | Vol. 24, No. 26 | 26 Dec 2016 | OPTICS EXPRESS 29358

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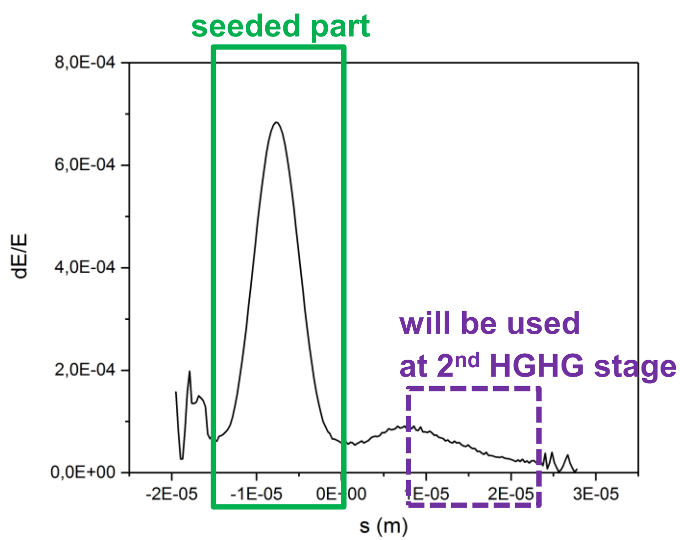
simulation, the 800 nm pulses had to be chirped to between 60 and 90 fs. In the future we intend to improve conversion efficiency to 3 – 5% by reducing the amount of dispersion in the fundamental beam path. Furthermore, there is a more elegant all-in-line configuration for THG, involving thin (≈100μm) delay compensator and wave plates. It enables substantially higher conversion efficieny (>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.

(ref) M. Pergament et. al, 24 (2016) Opt. Express 29349

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

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

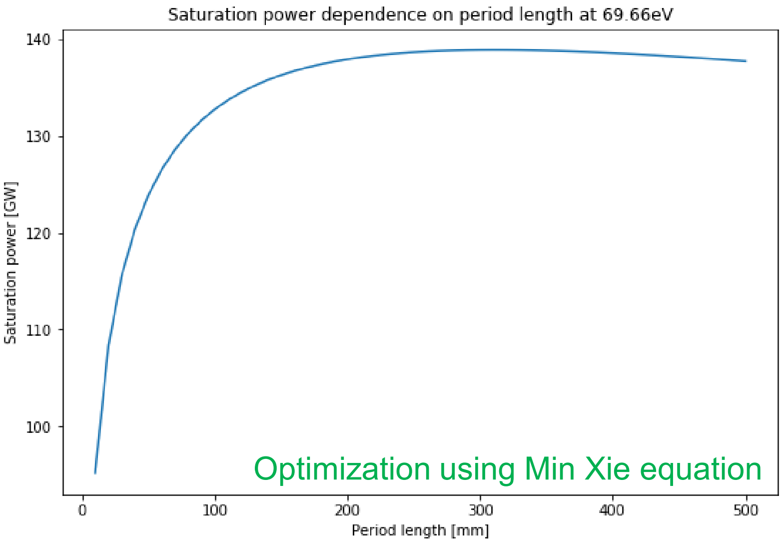
→ Period length: 26 cm, Number of period: 18



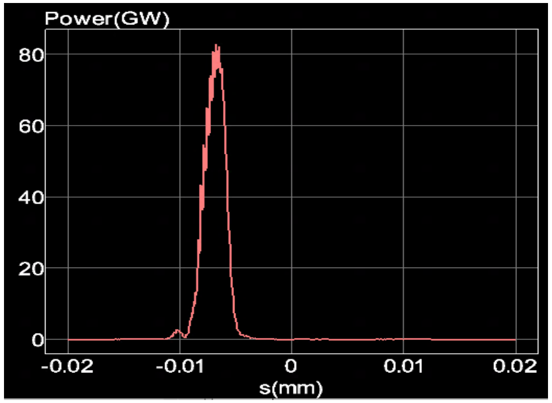
Energy modulation induced by seed laser after 1st modulator

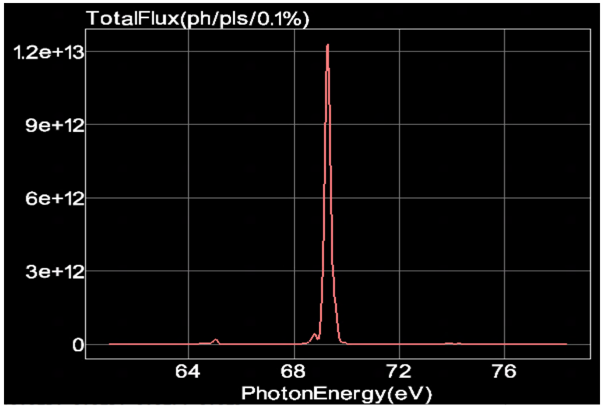
Multi-Parameters Decision for Two-Stage HGHG Scheme: 1st Radiator

- Parameters
  - Radiates 18 nm
    (15th harmonic from 1st modulator)
    ► Period length: 15 cm
    number of period: 45
    number of segment: 4



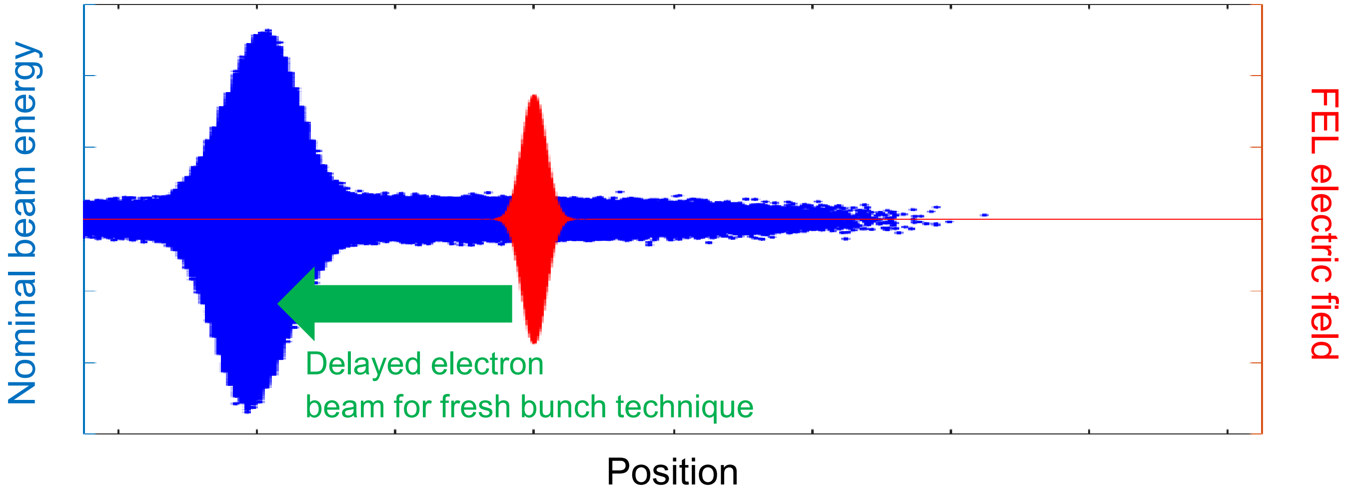
  - Output property of 18 nm seeded from 1st radiator (will be another seed for 2nd modulator)





Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

- Electron delay for 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 Scheme: Electron Delay

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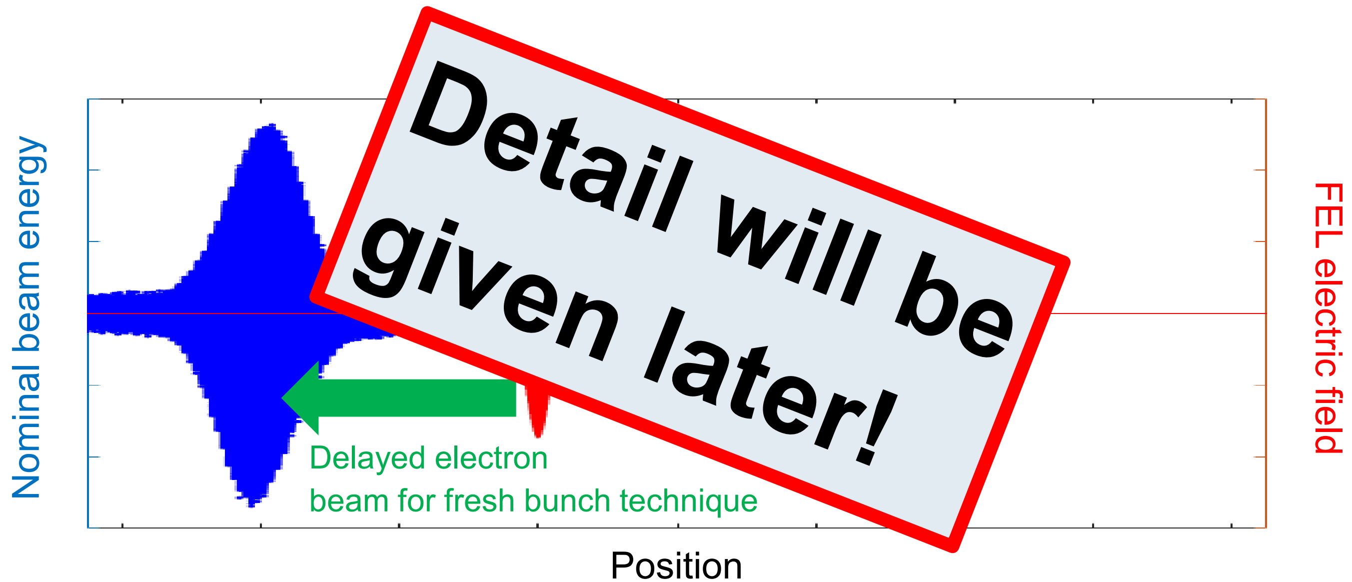
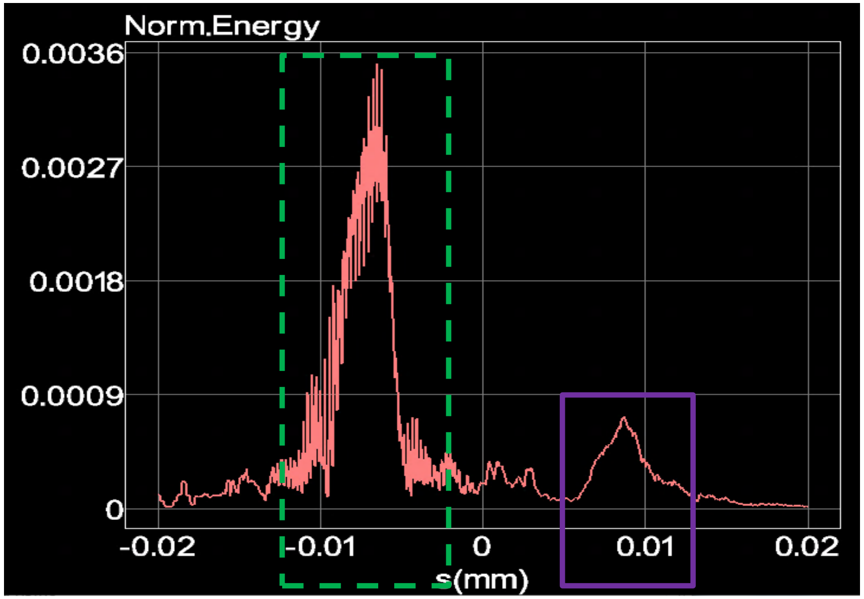


Schematic drawing of phase space after electron delay

Multi-Parameters Decision for Two-Stage HGHG Scheme: 2nd Modulator

- Radiation from 1st radiator generates another energy modulation on head part of bunch
  - In order to obtain high harmonic at 2nd HGHG stage
    - ► Energy spread shouldn't be increased by FEL process at 1st radiator and 2nd modulator
    - ► Giving large energy modulation in order to compete shot noise at 2nd radiator [ex. Shot noise power at FERMI: ~20 W @5.2 nm, EuXFEL: ~1000 W@2 nm]

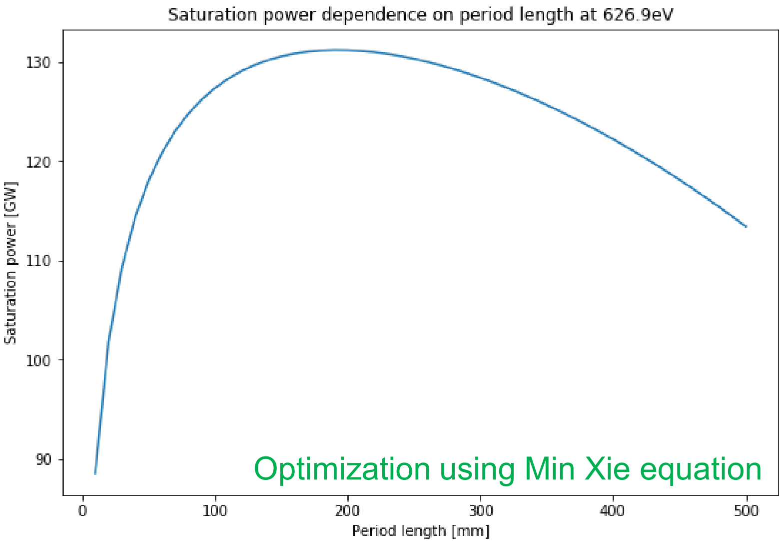


Induced at 1st HGHG stage

Induced at 2nd modulator

Multi-Parameters Decision for Two-Stage HGHG Scheme: 2nd Radiator

- Parameters
  - Radiates 2 nm
    (9th harmonic from 2nd modulator)
    - ► Period length: 13 cm
      number of period: 36
      number of segment: up to 7



Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

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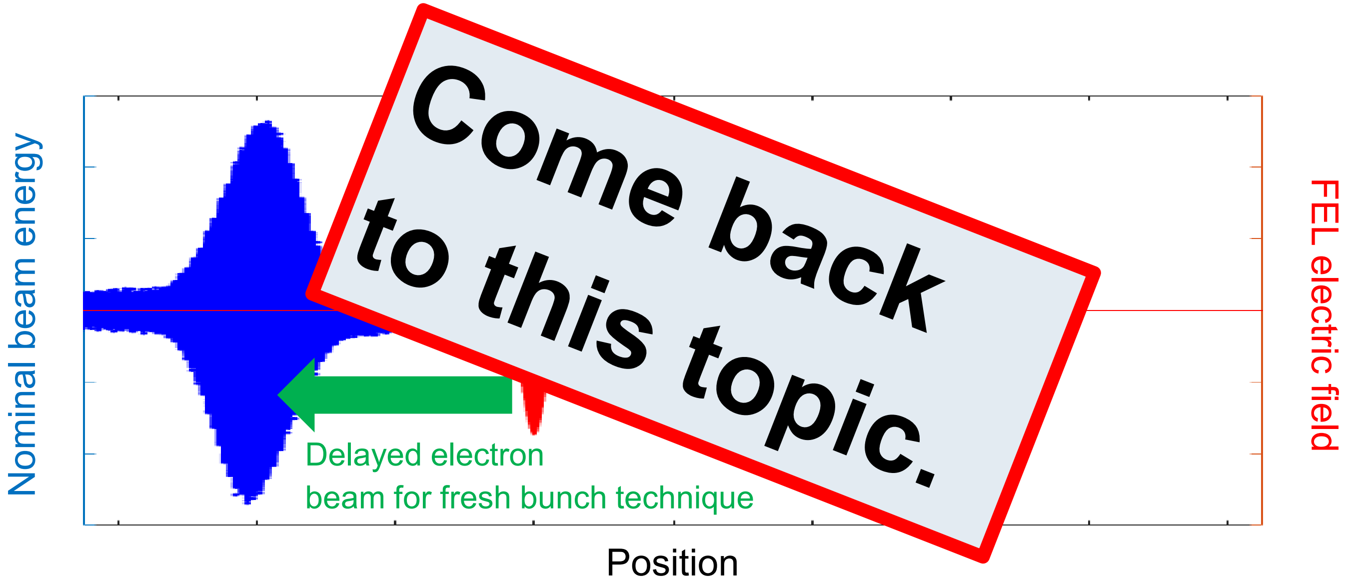
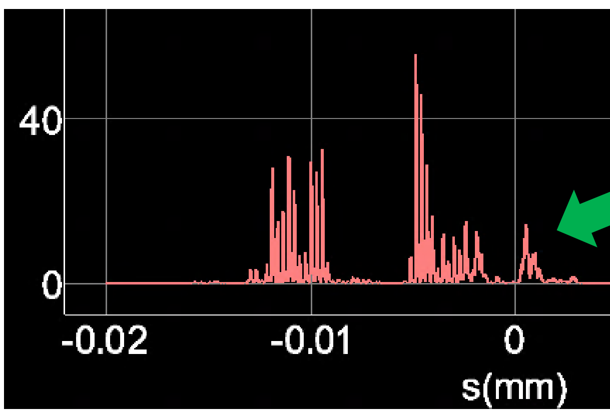
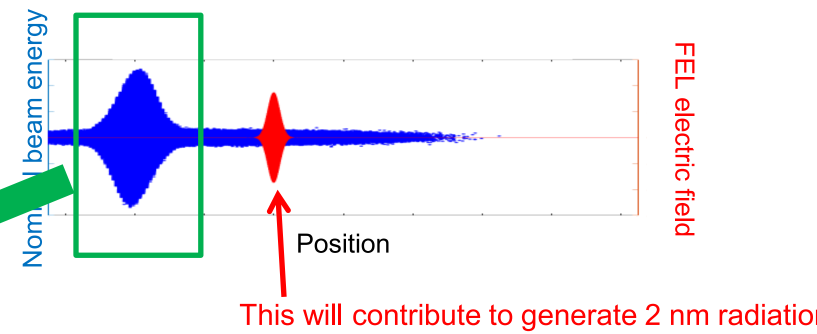


Schematic drawing of phase space after electron delay

Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

- Problem
  - ► Because of short electron bunch, micro bunch induced at 1st HGHG stage cannot be spoiled enough and contribute to generate undesirable radiation at 2nd HGHG stage
    [ex. Bunch length at FERMI: ~ 1 ps beam, at EuXFEL: 70 fs]





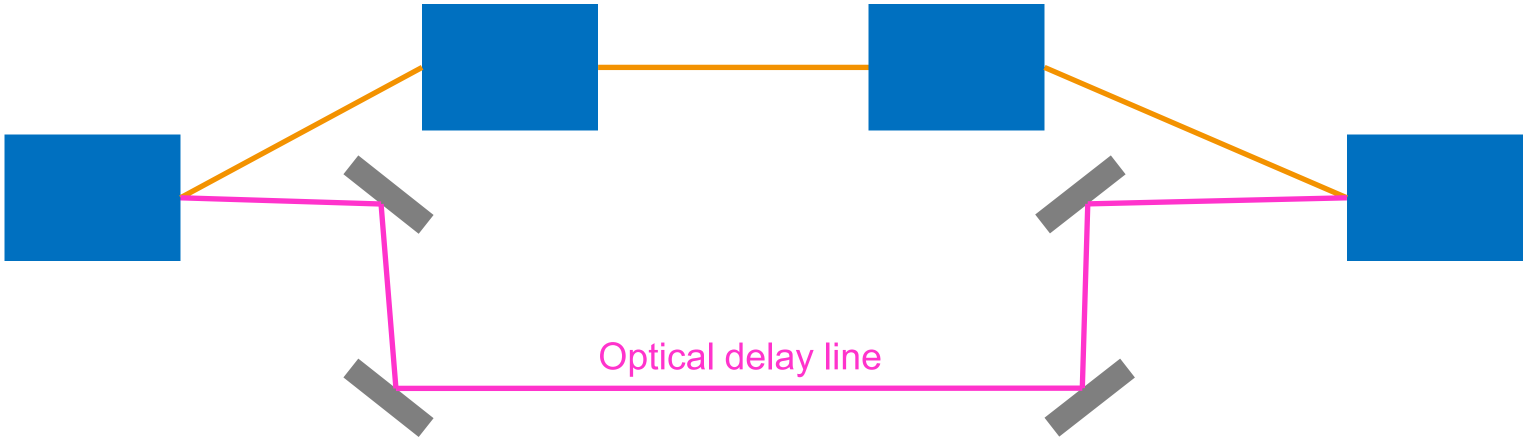
Radiation from 2nd radiator after applying 50 fs delay for fresh bunch technique

Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

- Solution to suppress undesirable radiation from electron bunch tail
  - (1) Larger R56 and optical delay
  - (2) implement corrugated structure and kick the electron beam tail

Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

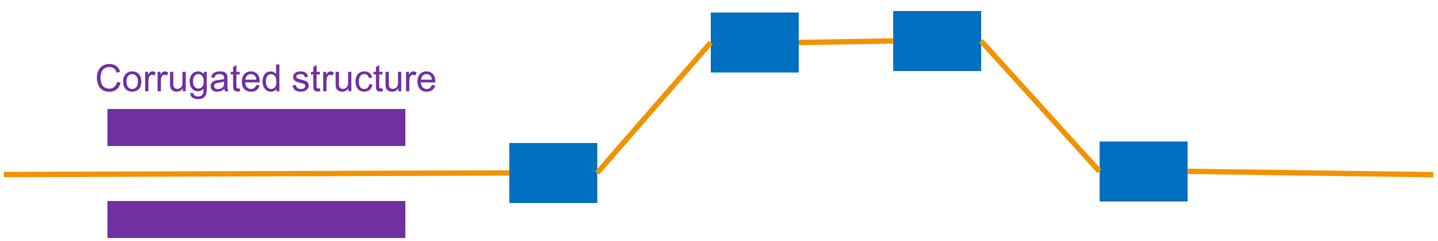
- Solution to suppress unwanted radiation from electron bunch tail
  - (1) Larger R56 and optical delay

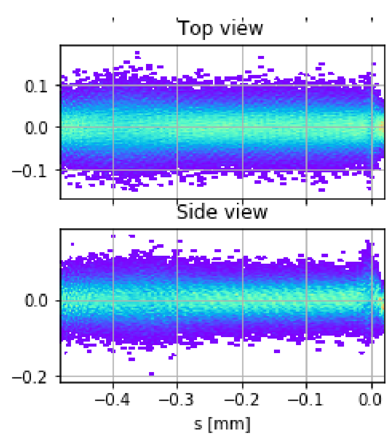


► Introducing large R56 but need to compensate by optical delay

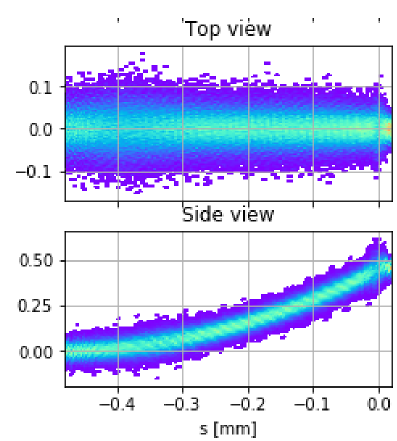
Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

- Solution to suppress unwanted radiation from electron bunch tail
  - (2) implement corrugated structure and kick the electron beam tail
    - ► Spoil the tail part of electron beam and let it not contribute to lase at 2nd HGHG stage





Before corrugated structure

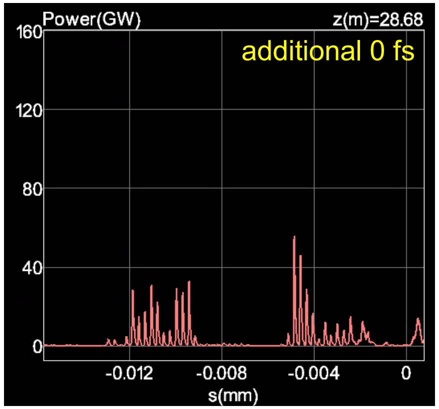


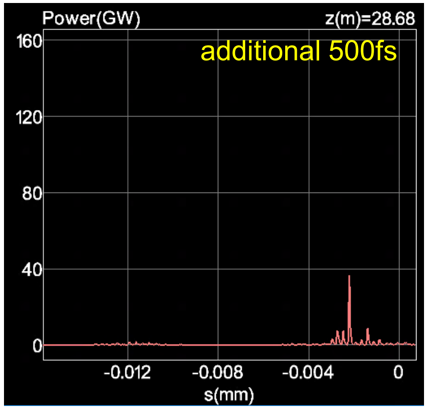
After corrugated structure

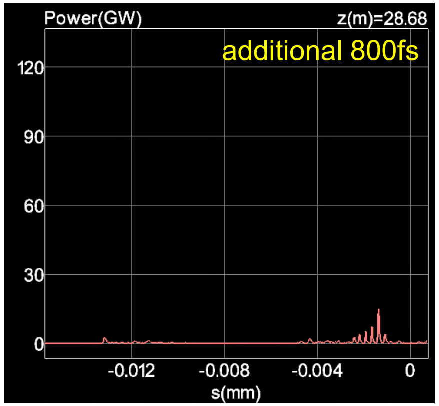
*parameters of corrugated structure is under study

Multi-Parameters Decision for Two-Stage HGHG Scheme: Electron Delay

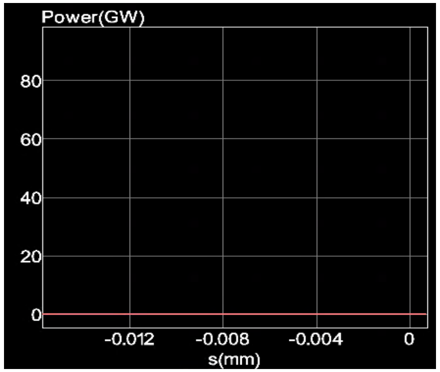
- Solution to suppress unwanted radiation from electron bunch tail
  - (1) Larger R56 and optical delay (power distribution at tail part after 2nd HGHG stage)







  - (2) implement corrugated structure and kick the electron beam tail (only transverse kick)



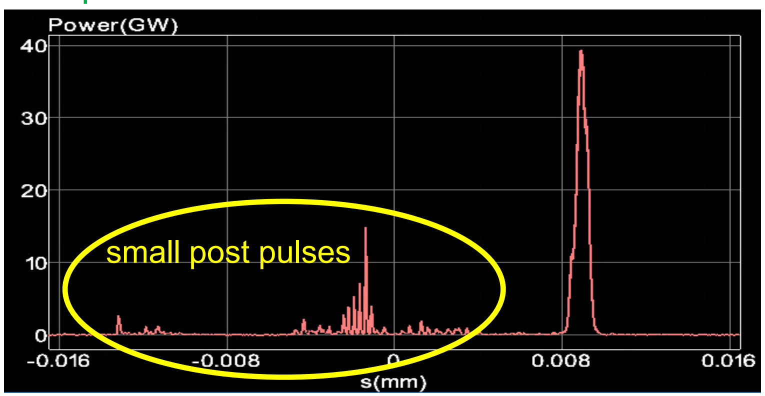
Results of Two-Stage HGHG for the European XFEL

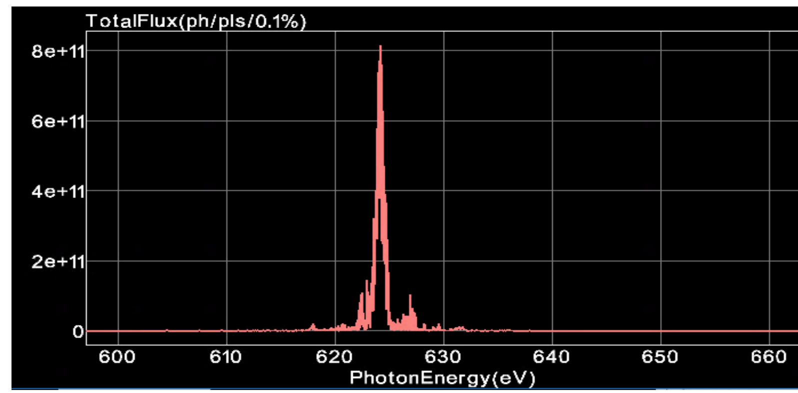
- FEL wavelength: 1.99 nm (623 eV)
  - Combination of 2-times harmonic conversion by FEL: 15 x 9
- Pulse properties:
  - ▶ Peak power: up to 110 GW
  - ▶ Pulse duration: 5 fs (FWHM)

Temporal distribution

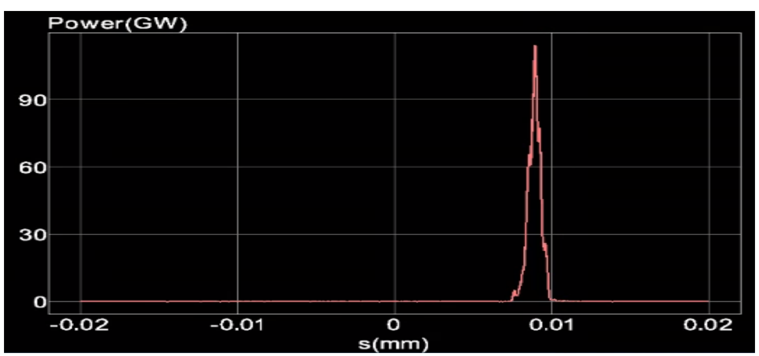
Spectral intensity

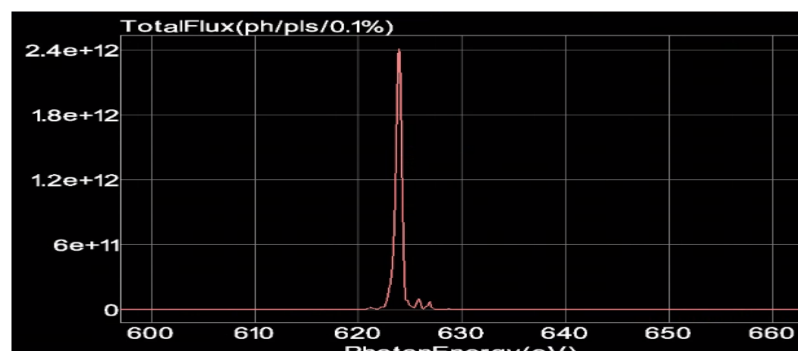
Large R56 electron delay case



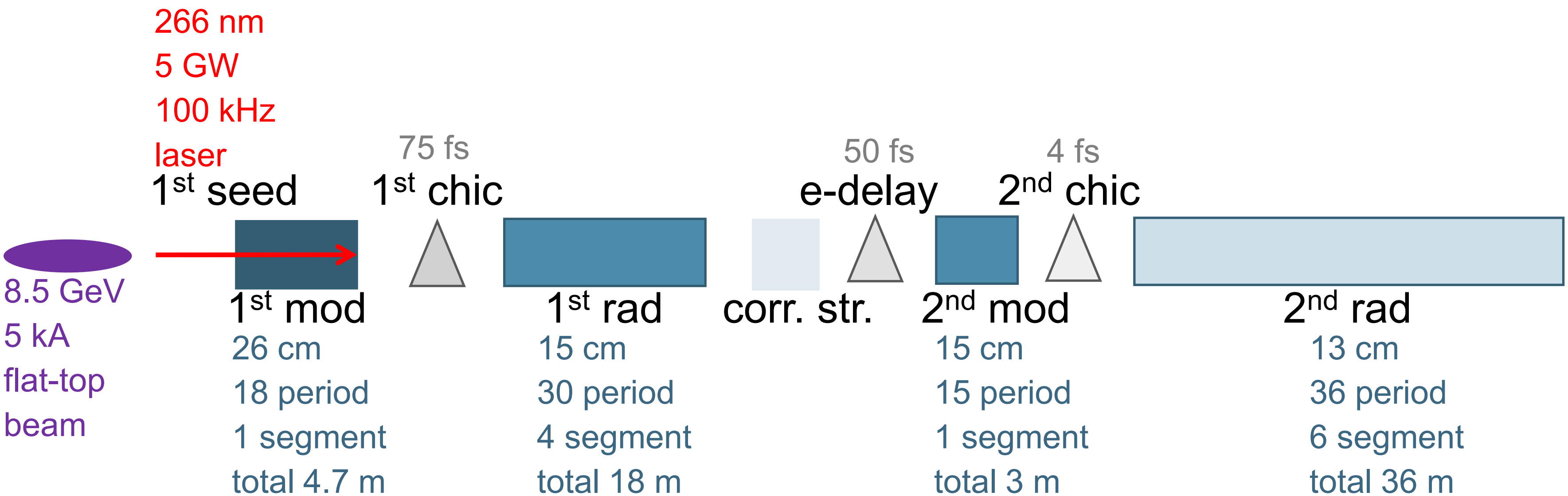


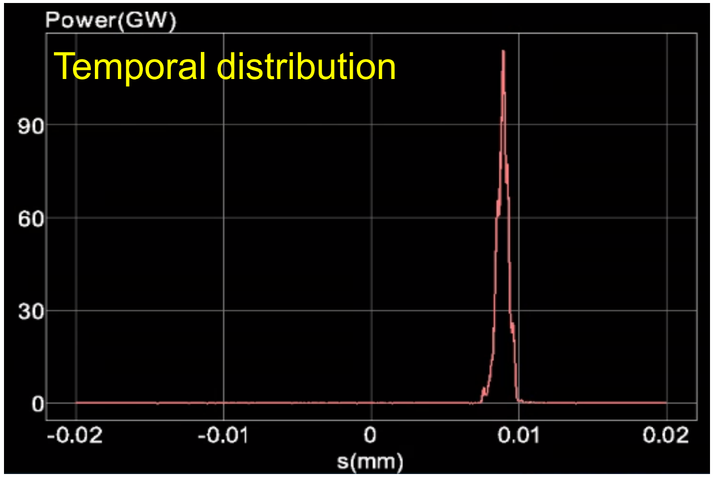
Corrugated structure case

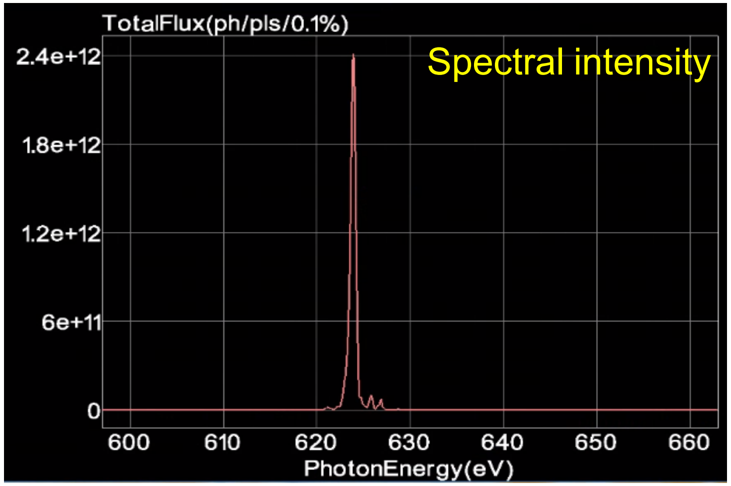




Summary of Two-Stage HGHG for the European XFEL

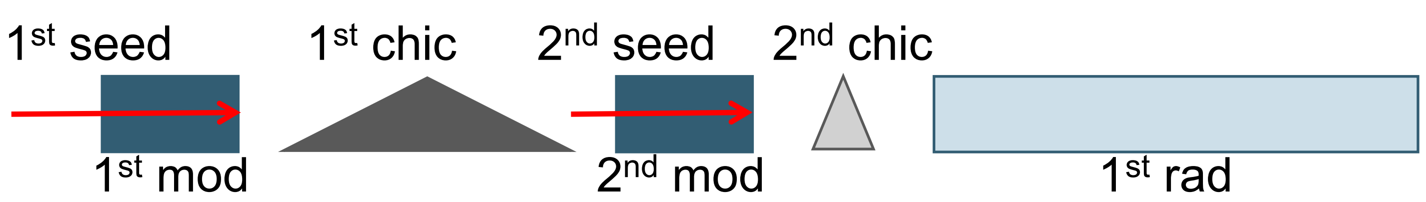






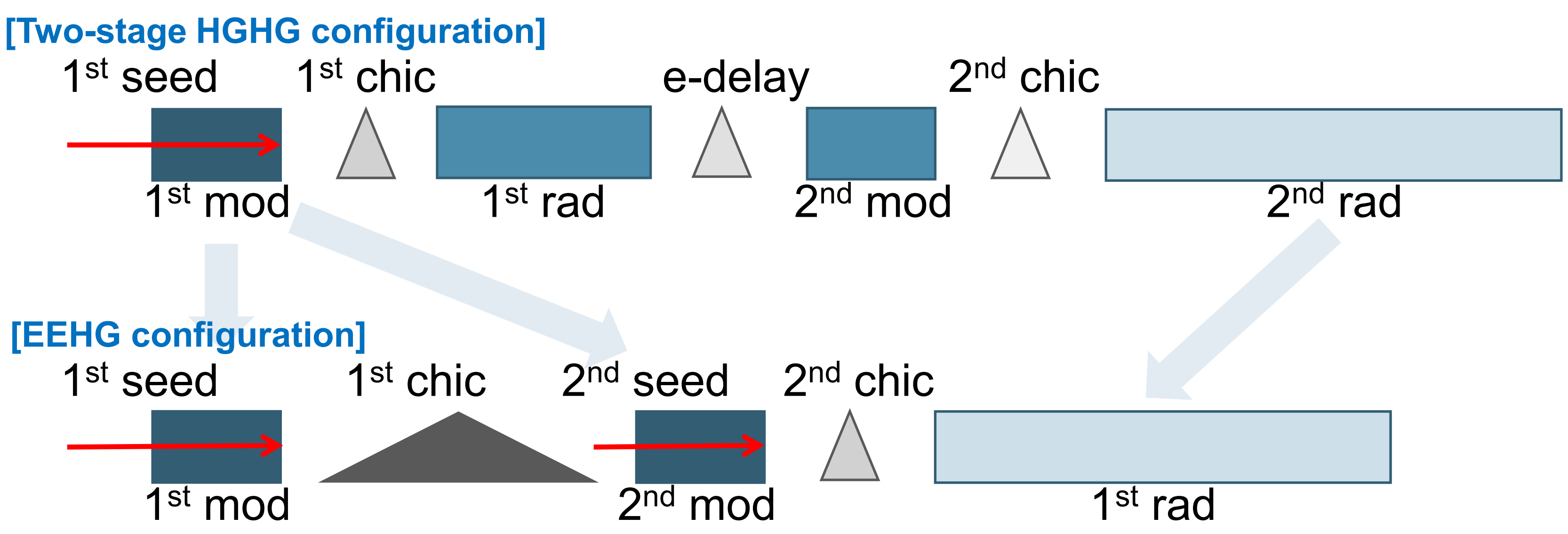
Multi-Parameters Decision for EEHG Scheme

- 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 Scheme: Undulators Parameters

- Undulators parameters



Multi-Parameters Decision for EEHG Scheme: Energy Modulations and Magnetic Chicanes

- Decision of 2 different seed powers and 2 different chicane strengths

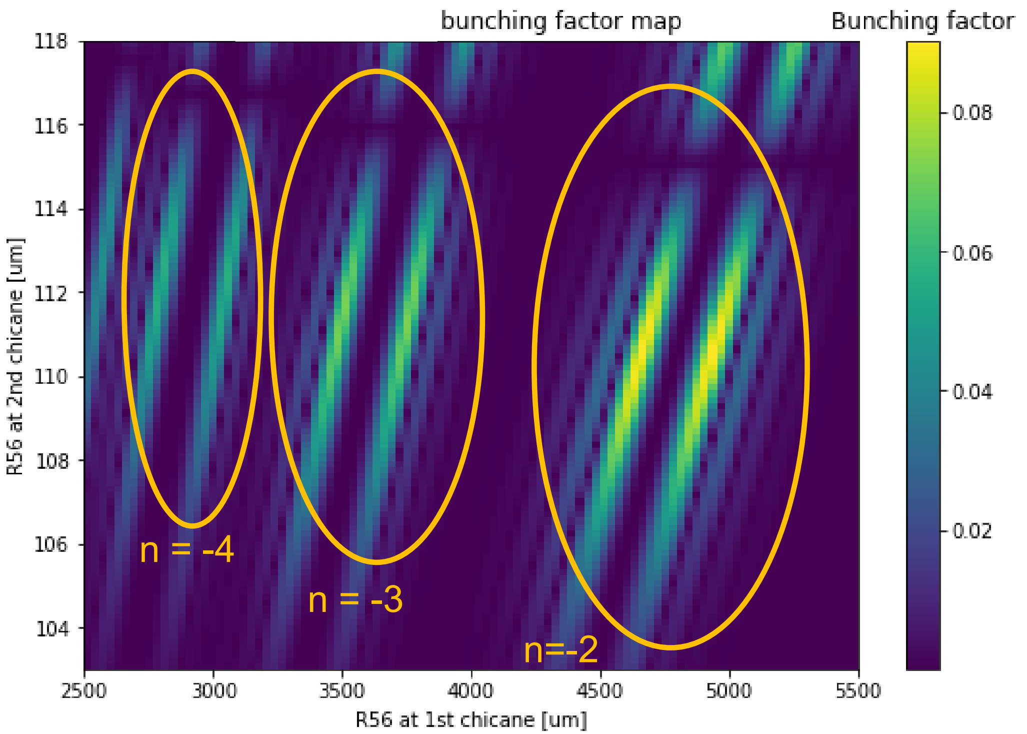
$$b_a = 2\left|\sum_{m=-\infty}^{\infty} e^{im\varphi} J_{-m-n}\{A_1[(m+a)B_1 + aB_2]\} J_m(aA_2B_2) e^{-(1/2)[(m+a)B_1+aB_2]^2}\right|$$

b_a: a-th bunching factor
m: positive or negative integer
A_1, A_2: amount of 1st and 2nd energy modulation
B_1, B_2: 1st and 2nd chicane strength

$$k_{echo} = ak_1 = nk_1 + mk_2$$

k_{echo}: wave number of radiation
n: positive or negative integer
k_1, k_2: wave number of seed

[ref. G. Stupakov, PRL 102 (2009) 074801]



Simulation parameters requires a bit different from analytical for very higher harmonic…

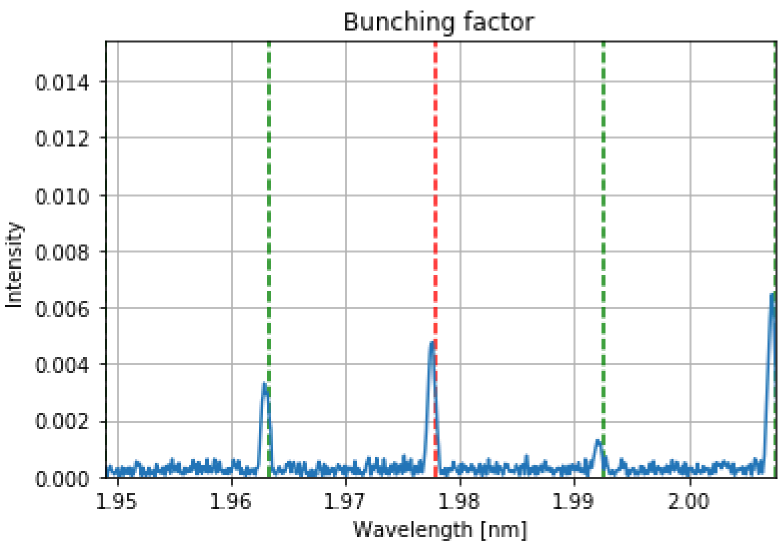
Considerable reason 1

- Less bunching factor and strong shot noise
  - To obtain 2 nm from THG of 800 nm seed laser
    - ▶ Two-stage HGHG case: 15 x 7
      - If the radiation power from 1st stage is sufficient, conversion factor is just 7 (high bunching factor)
    - ▶ EEHG case: 135
      - The higher harmonic number is, the less bunching factor is obtained (e.g. HHG spectrum)
        → This bunching factor has to compete with strong shot noise from European XFEL

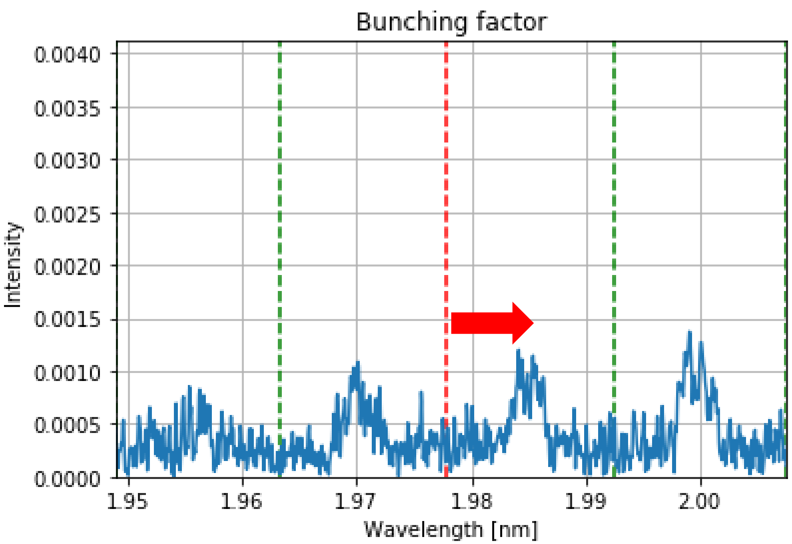
Considerable reason 2

- Spectral shift of signal caused by “very-short” seed pulse
  - Large shift happens at very high harmonic and less bunching intensity
    - ► Resonant wavelength of radiator is not any more harmonic wavelength of seed laser

54 fs seed case



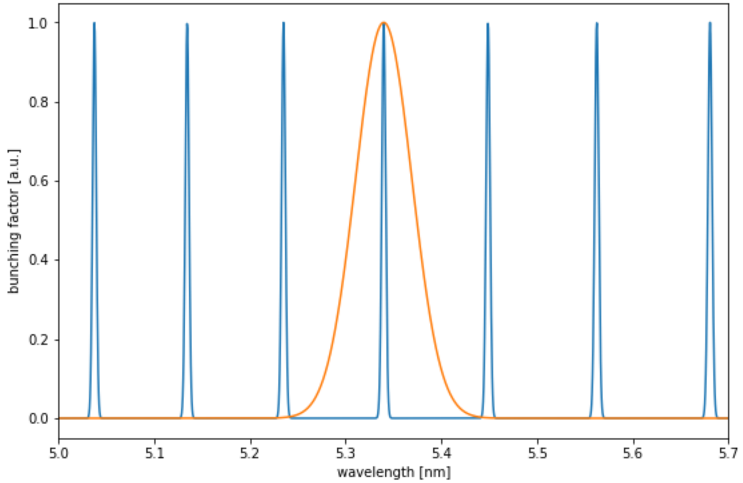
12 fs seed case



Considerable reason 3

Bunching is now OK. But at the radiator…..

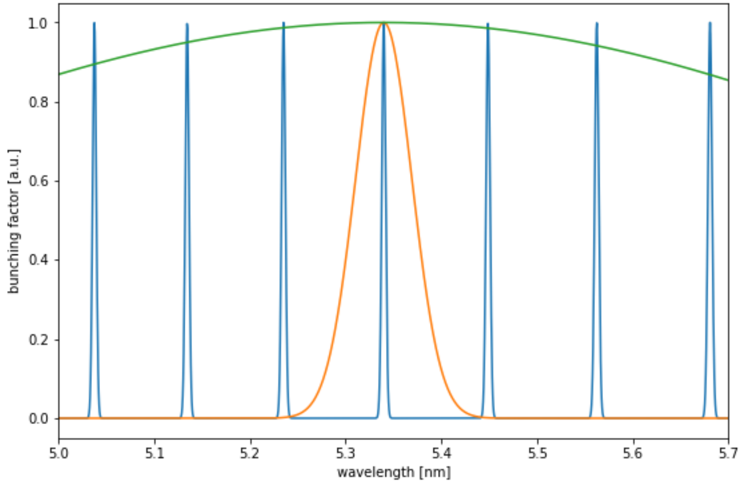
- Spectrum selection with high FEL gain
  - Radiator works as spectral filtering and amplifier
    - ► When FEL gain is high, filtered bandwidth is also wide



[Schematic drawing]
blue: EEHG signal
orange: FELMI radiator case

Considerable reason 3

- Spectrum selection with high FEL gain
  - Radiator works as spectral filtering and amplifier
    - ► When FEL gain is high, filtered bandwidth is also wide
      → multiple harmonics are chosen to be amplified → non-single mode

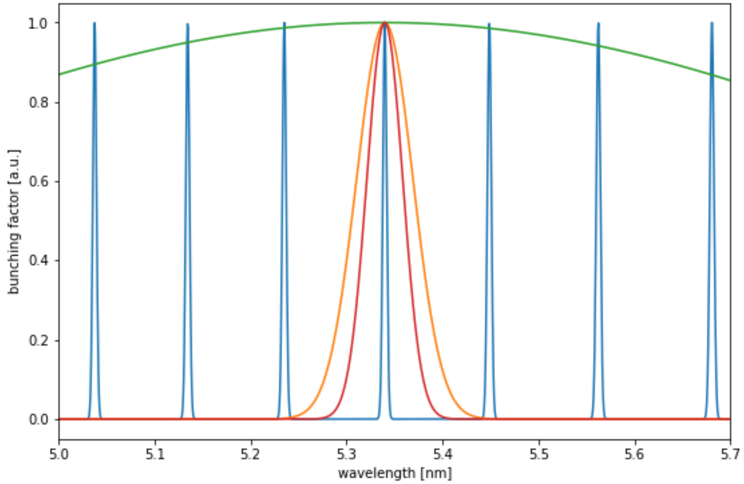


[Schematic drawing]
blue: EEHG signal
orange: FERMI radiator case
green: EuXFEL radiator case with high gain

Considerable reason 3

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

- Spectrum selection with high FEL gain
  - Radiator works as spectral filtering and amplifier
    - ► When FEL gain is high, filtered bandwidth is also wide
    - ► Reduction of FEL gain by
      - decreasing peak current → output will drop in terms of gain and beam power
      - increasing Beta function → output will drop in terms of gain



[Schematic drawing]

blue: EEHG signal

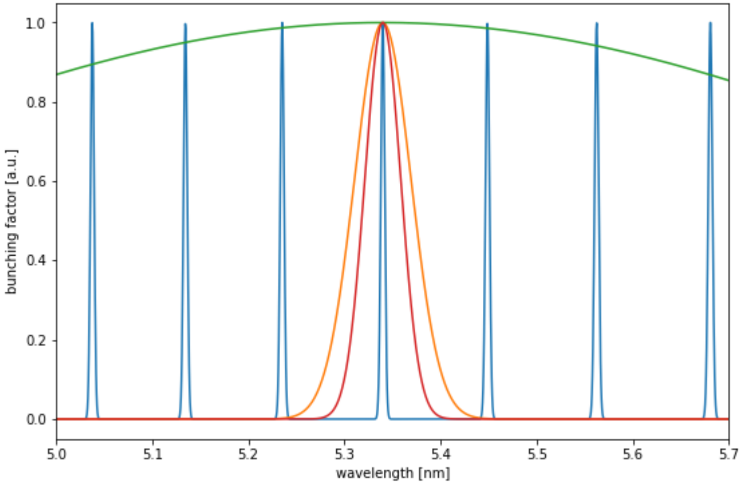
orange: FELMI radiator case

green: EuXFEL radiator case with high gain

red: EuXFEL radiator case with middle gain

Considerable reason 3

- Very high gain at European XFEL
  - Radiator works as spectral filtering and amplifier
    - ► When FEL gain is high, filtered bandwidth is also wide
      → multiple harmonics are chosen to be amplified → non-single mode
    - ► On the other hand….
      - With high gain mode → atto second pulse train



[Schematic drawing]
blue: EEHG signal
orange: FELMI radiator case
green: EuXFEL radiator case with high gain
red: EuXFEL radiator case with middle gain

Considerable reasons

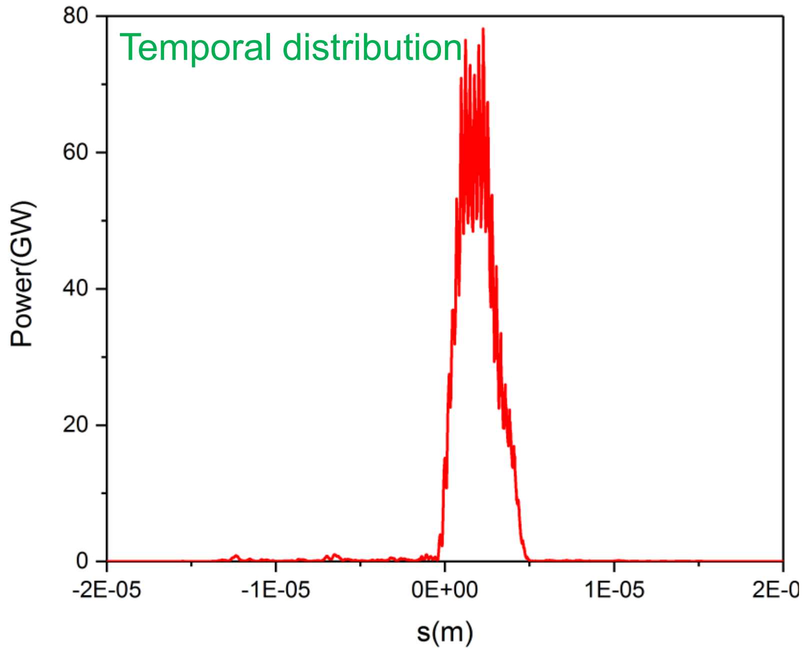
- Less bunching factor and strong shot noise
- Spectral shift of signal caused by very short seed pulse
- Spectrum selection with high FEL gain

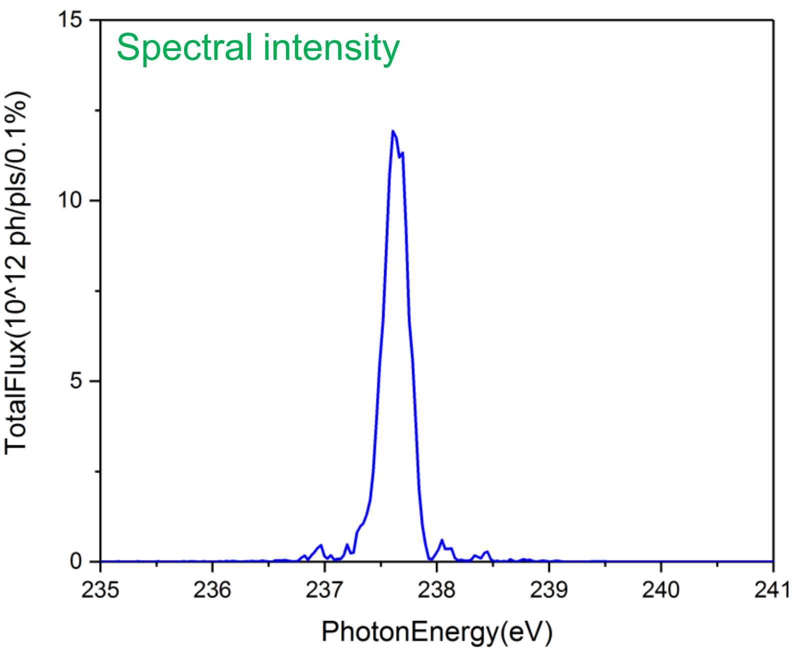
→ All effects must be included to generate and amplify EEHG signal for European XFEL case!

Results of EEHG for the European XFEL

- FEL wavelength: 5.36 nm (231 eV)
  - 12 fs seed injection (short pulse)
  - 50th harmonic amplification
  - Single bandwidth mode

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



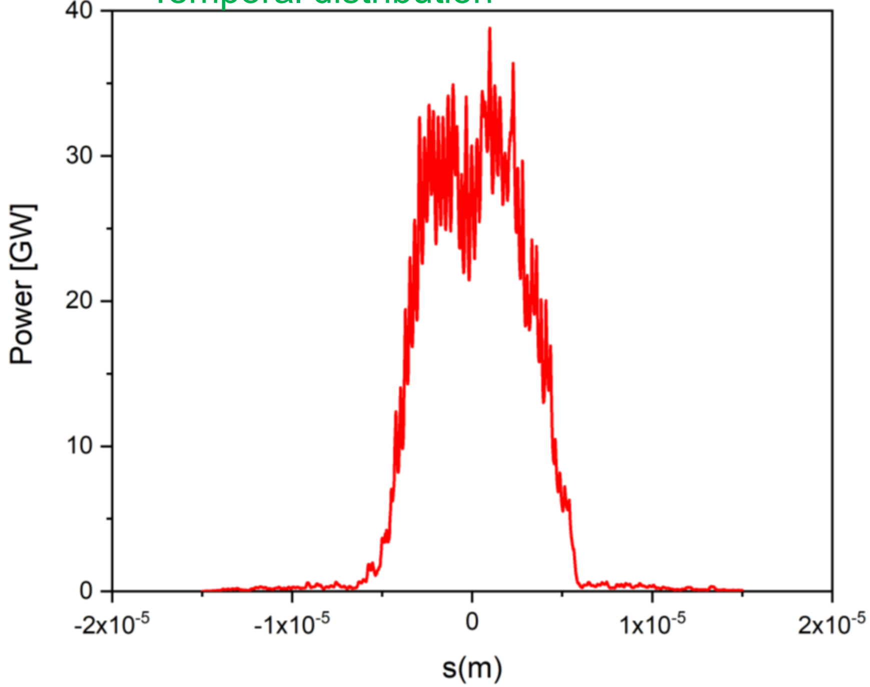


Results of EEHG for the European XFEL

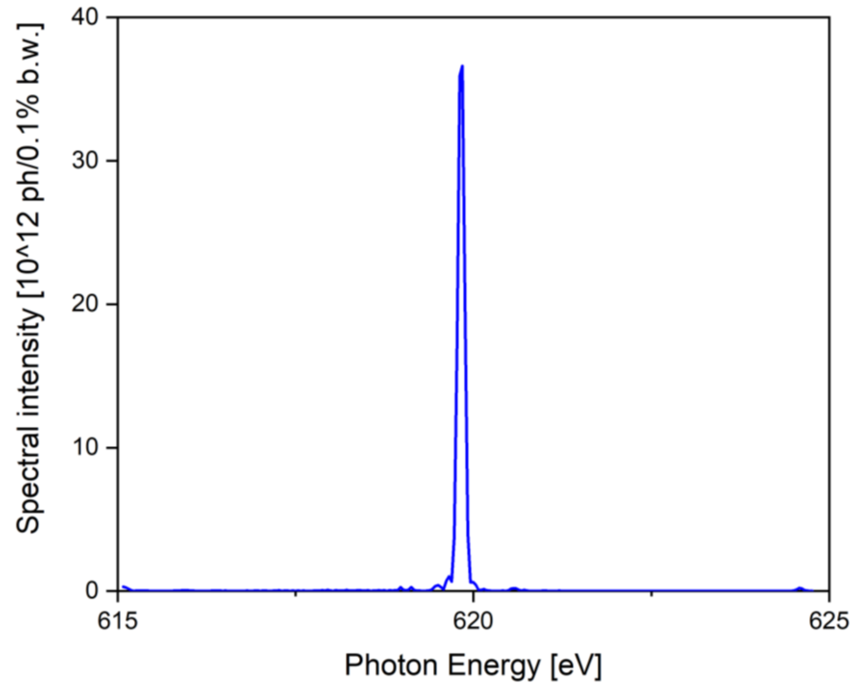
- FEL wavelength: 2 nm (620 eV)
  - 54 fs seed injection (long pulse)
  - 135th harmonic amplification
  - Single band mode

- Pulse properties:
  - ► Peak power: up to 30 GW
  - ► Pulse duration: 17 fs (FWHM)

Temporal distribution



Spectral intensity

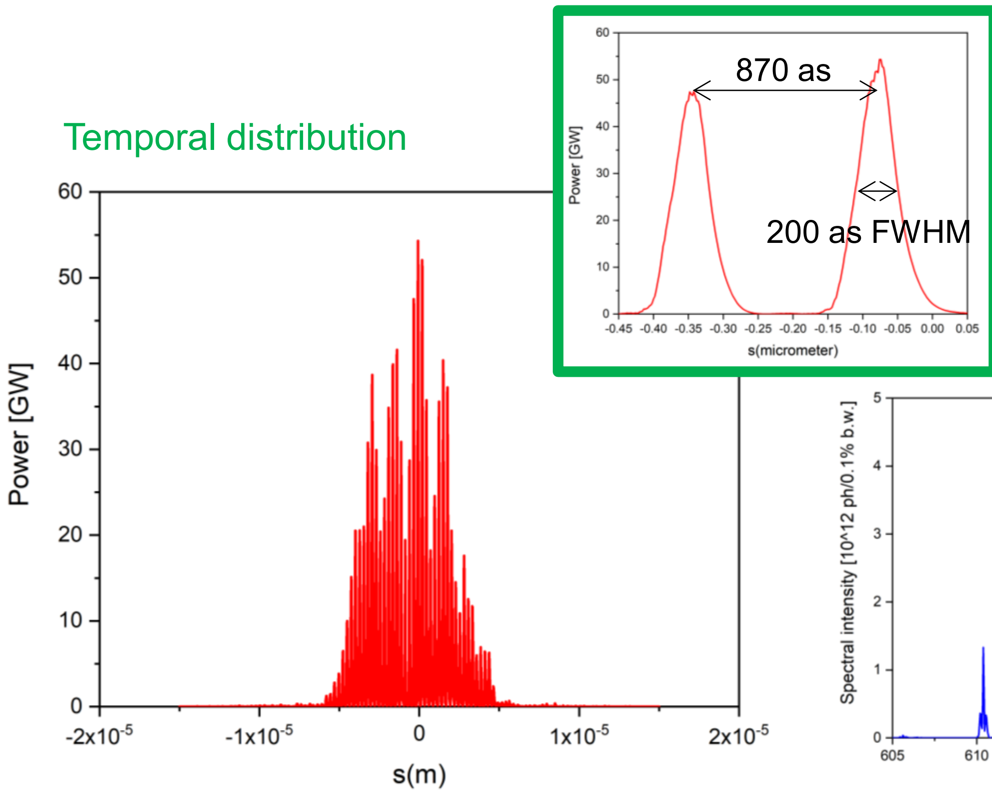


Results of EEHG for the European XFEL

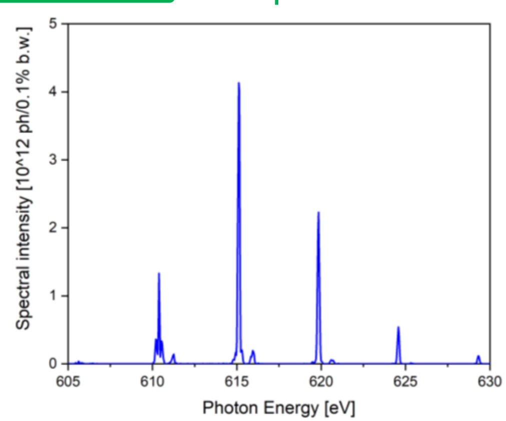
- FEL wavelength: 2 nm (620 eV)
  - 54 fs seed injection (long pulse)
  - 135th harmonic amplification
  - Attosecond mode

- Pulse properties:
  - ▶ Peak power: up to 40 GW
  - ▶ Single pulse duration: 200 as (FWHM)
  - ▶ Pulse separation: 870 as

Temporal distribution



Spectral intensity



Summary of EEHG for the European XFEL

260 nm
1 GW long
100 kHz
laser

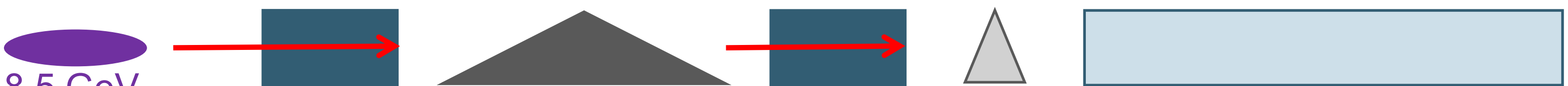
1st seed

~ 6 mm
1st chic

260 nm
1 GW long
100 kHz
laser

2nd seed

~ 120 µm
2nd chic

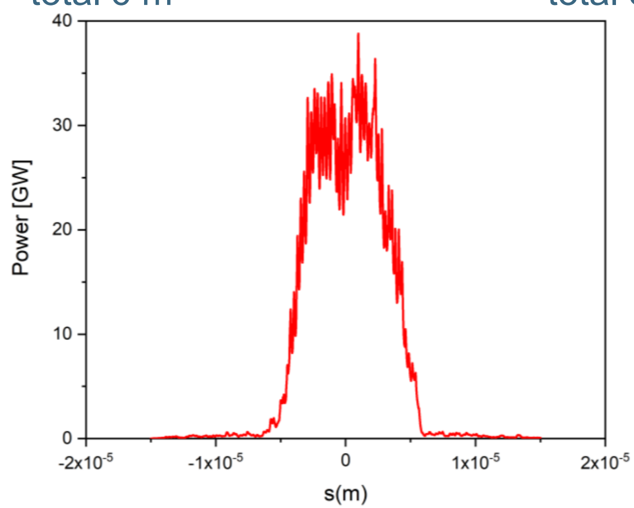


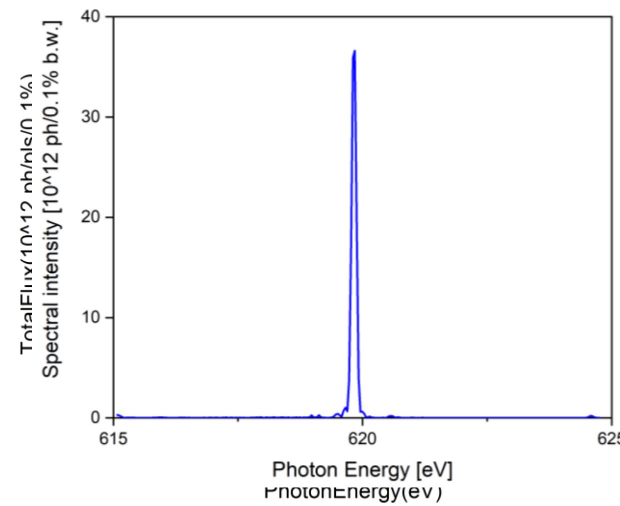
8.5 GeV
5 kA
flat-top
beam

1st mod
26 cm
18 period
1 segment
total 6 m

2nd mod
26 cm
18 period
1 segment
total 6 m

1st rad
15 cm
30 period
13 segment
total 78 m





Summary

Both high electron beam energy and peak current case was never studied for the feasibility of HGHG and EEHG schemes. But thanks to very powerful drive laser & XFEL-class electron beam, it will bring us:

- Two-stage HGHG scheme
  - Peak power: 110 GW
  - Pulse duration: 5 fs FWHM
  - Corrugated structure will help to suppress undesirable post pulse instead of using large R56 and optical delay

- EEHG scheme
  - Control of amplification bandwidth by changing FEL gain (mild gain → single band mode, high gain → atto second pulse)
  - Peak power: 30 GW (single band mode), 50 GW (attosecond mode)
  - Pulse duration: 17 fs FWHM (single band mode), 200 as (attosecond mode)
  - Choice of desirable seed pulse duration
  - Detrimental effects are under study

Thank you for your attention