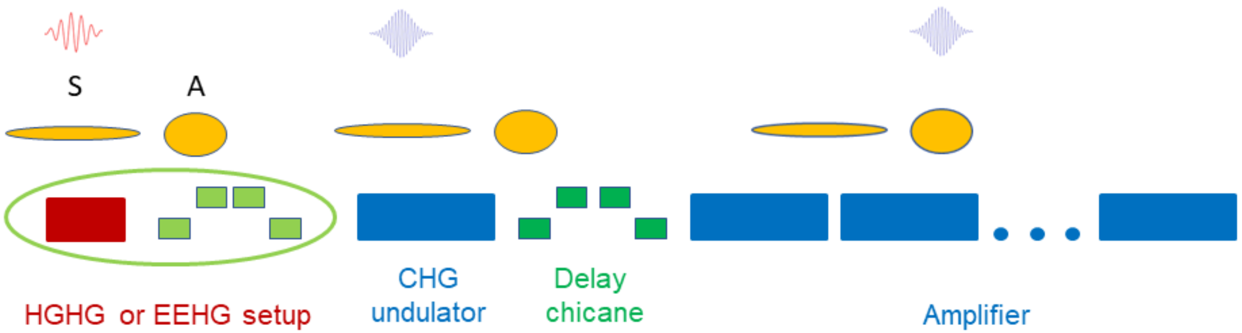
Two-bunch seeding of soft X-ray free electron lasers



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Beam Dynamics Seminar

DESY, Hamburg

November 5, 2024

Outline

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- The concept of two-bunch seeding
  - The seeding scheme
  - Beam dynamics aspects
  - FEL operation
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Motivation

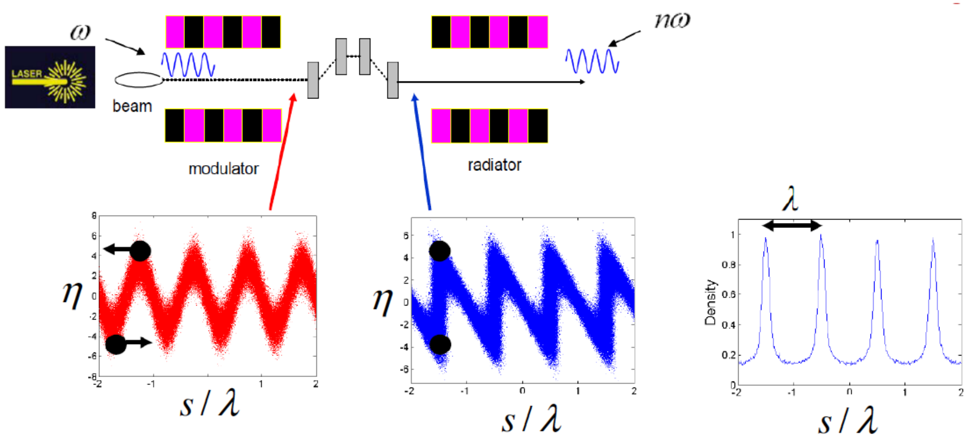
- Implementation of seeding schemes in high-gain short-wavelength FELs promises **exceptionally bright output radiation with stable properties**.
- There are two main seeding schemes that have been proposed and tested: High-Gain Harmonic Generation (**HGHG**) and Echo-Enabled Harmonic Generation (**EEHG**).

[1] L.-H. Yu, Generation of intense UV radiation by subharmonically seeded single-pass free-electron lasers, Phys. Rev. A 44, 5178 (1991).

[2] G. Stupakov, Using the beam-echo effect for generation of short-wavelength radiation, Phys. Rev. Lett. 102, 074801 (2009).

Motivation

High-gain harmonic generation (HGHG)



- ❑ energy modulation with frequency ω
- ❑ conversion in density modulations
- ❑ coherent radiation with frequency nω in radiator section

❑ In order to generate density harmonic number *n* in the modulator-chicane system, one should impose the energy modulation ΔΕ that is significantly larger than uncorrelated energy spread in the electron beam σ_E

$$\frac{\Delta\mathcal{E}}{\sigma_{\mathcal{E}}} > n \qquad \frac{\Delta\mathcal{E}}{\mathcal{E}} < \rho$$

❑ Another problem is that the required laser power (for a given uncorrelated energy spread) scales as the square of harmonic number

$$P_L \propto (\Delta\mathcal{E})^2 \propto n^2$$

❑ **In typical systems for a single-stage HGHG the harmonic number n is limited to n < 20.**

Motivation

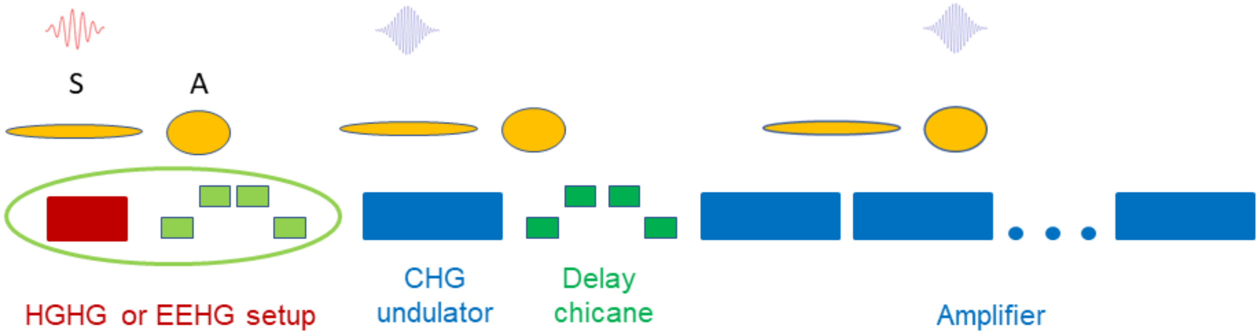
High-gain harmonic generation (HGHG)

- Uncorrelated **energy spread** is small in the gun, but then it **increases proportionally to a peak current** in bunch compression systems. High peak current is needed for a successful operation of the FEL amplifier at short wavelengths.
- **The same bunch** with a high current and a relatively large uncorrelated energy spread **is used to generate harmonics** in modulator-chicane system**,** and then **to produce the radiation** at a harmonic in the amplifier.
- We propose to **separate these functions** by generation of two bunches in the accelerator that drives the FEL: a weakly compressed bunch to be used in the modulator-chicane system, and a strongly compressed bunch to amplify the radiation produced by a weakly compressed bunch.

Echo-enabled harmonic generation (EEHG)

- Although the previous condition on harmonic number is not applied to EEHG case, the required energy modulations by lasers are still proportional to uncorrelated energy spread, i.e. EEHG method can also strongly profit from two-bunch concept.

The concept of two-bunch seeding



- **Two bunches are extracted from the RF gun** and then compressed in a different way. They propagate in the same RF backet and arrive at the entrance of seeded FEL such that the **low-current bunch** (S-bunch) is behind the **high-current bunch** (A-bunch).
- The **S-bunch** with low uncorrelated energy spread is modulated by a seed laser with a subsequent conversion of energy modulation into density modulation (HGHG scheme). It **produces coherent radiation at a harmonic** in a relatively short undulator (Coherent Harmonic Generation, or CHG).
- In the following delay chicane, both bunches are delayed with respect to the radiation **pulse** which **is parked on the A-bunch and is amplified** to saturation in a long amplifier.
- The bunching in the S-bunch is smeared in the chicane, so that this bunch can only produce SASE in the amplifier but due to its low current the gain is low, and the generated background is negligible (the same refers to the radiation produced by A-bunch in a short CHG undulator).

The concept of two-bunch seeding

The photoinjector

- The photoinjector laser system can be upgraded by adding a split-and-delay unit, Thus, two pulses with the same length but different intensities and a controllable delay are generated. The cathode of the RF gun is illuminated by two pulses, and two electron bunches with equal or different charges are produced. **The RF phases in the gun of two pulses can differ significantly what potentially might be a challenge because emittances and Twiss parameters of these bunches can be essentially different**.
- Some FEL facilities like FLASH and European XFEL are equipped with two photoinjector lasers allowing to produce two pulses with different properties and controllable delay.

The concept of two-bunch seeding

Bunch compression

- Typical bunch compression system consists of **one or two chicanes** operated at different energies.
- To linearize compression process, a **high harmonic RF cavity** is typically used (3rd harmonicin case of FLASH).
- When optimizing compression of two bunches, we came to the conclusion that **it is better to use overcompression regime**. In particular, it means that the two bunches change their relative positions: S-bunch leaves the gun first but arrives at the FEL setup last.
- Since **S-bunch** is only weakly compressed, its properties are expected **to be stable**, and this will guarantee high **spectral stability** of the output FEL radiation.

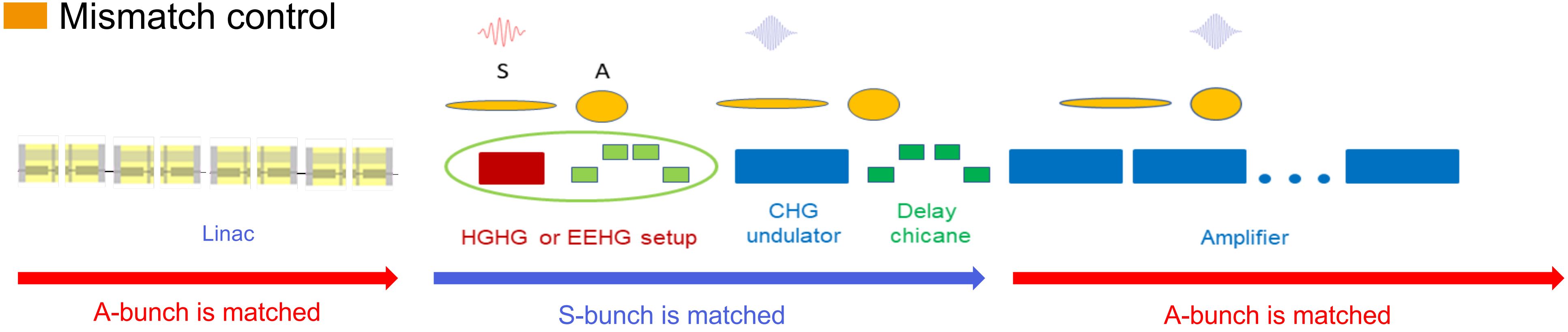
The concept of two-bunch seeding

Collective effects

- **Operation of seeding schemes is sensitive to the collective effects** in the beam formation and transport systems. Collective effects like space charge, coherent synchrotron radiation (CSR), geometrical wakefields in a linac lead to a degradation of beam quality, and the **degradation is more significant for strongly compressed bunches**.
- In our simulations, the most important collective effects are properly included but **we do not see any essential deterioration of the longitudinal phase space of the S-bunch** because it is weakly compressed.
- At the same time, **the action of A-bunch on S-bunch is weak**, as we see in numerical simulations.
- The properties of the longitudinal phase space (LPS) of the S-bunch define the spectral quality of the output radiation so that it can be kept almost ideal.

The concept of two-bunch seeding

Mismatch control



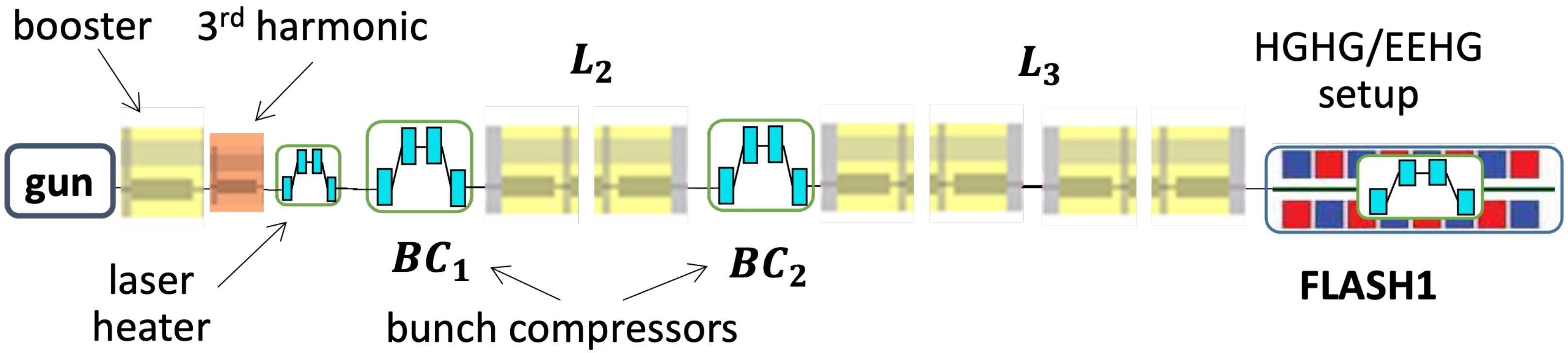
- One of the possible issues with the proposed scheme might be a **strong difference in properties of the transverse phase spaces** (characterized by Twiss parameters) of the two bunches. The reason is that they are formed and evolve under the action of very different transverse forces from RF fields as well as from collective fields (mainly space charge), especially in the injector.
- **The problem is solved by introducing two additional matching points in the machine** (assuming that the A-bunch is matched in the linac). The first one is in front of the FEL setup where the S-bunch is matched. The second one, for the A-bunch, is between the CHG undulator and the amplifier where the matching can be done by quadrupoles before and after the delay chicane.

The concept of two-bunch seeding

HGHG, EEHG and two-bunch seeding

- It is hard to overcome harmonic number 20 in the single-stage HGHG. There is a consensus among FEL physicists that **seeding at high harmonic numbers should be done with EEHG** scheme.
- **EEHG requires a chicane with a relatively large R56** in the first stage which can create serious problems. The most significant issue is that appearance of this chicane results in one more amplification cascade for the **microbunching instability**.
- Another problem is a distortion of the longitudinal phase space in this chicane due to **Coherent Synchrotron Radiation** (CSR) that can result in a reduced bunching factor [26].
- In addition, **Intra-Beam Scattering** (IBS) effects can deteriorate the process of generation of a large bunching factor at high harmonic numbers.
- **The two-bunch seeding concept mitigates the mentioned issues due to a low current of the S-bunch**.
- Moreover, the concept makes it possible to generate high harmonics in a relatively simple HGHG configuration. In this case the required R56 is typically by two orders of magnitude smaller than in the case of the first stage of EEHG. Thus, such effects as additional microbunching instability gain or CSR in dipoles of the chicane do not play a significant role anymore.
- **In this talk we concentrate on HGHG** case leaving EEHG for future studies.

Simulations of beam dynamics in FLASH accelerator



- We perform numerical simulations of beam dynamics in FLASH accelerator with the **goal to find a good solution** for our two-bunch seeding scheme.
- FLASH is the first free-electron laser for XUV and soft X-ray radiation. It covers a **wavelength range from 4 nm to about 90 nm** with GW peak power and pulse durations between a few fs and 200 fs.
- The electron bunches with **maximum energy of 1.35 GeV** are distributed betweenthe two branches, FLASH1 and FLASH2.

Simulations of beam dynamics in FLASH accelerator

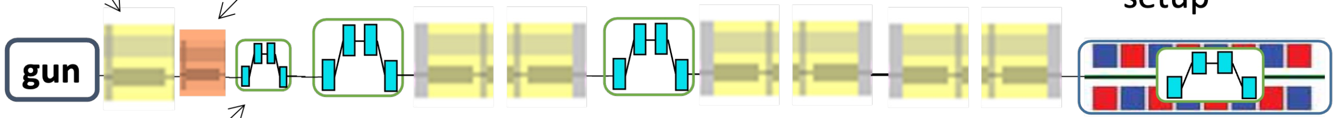


TABLE I: Maximal accelerating voltage in RF sections.

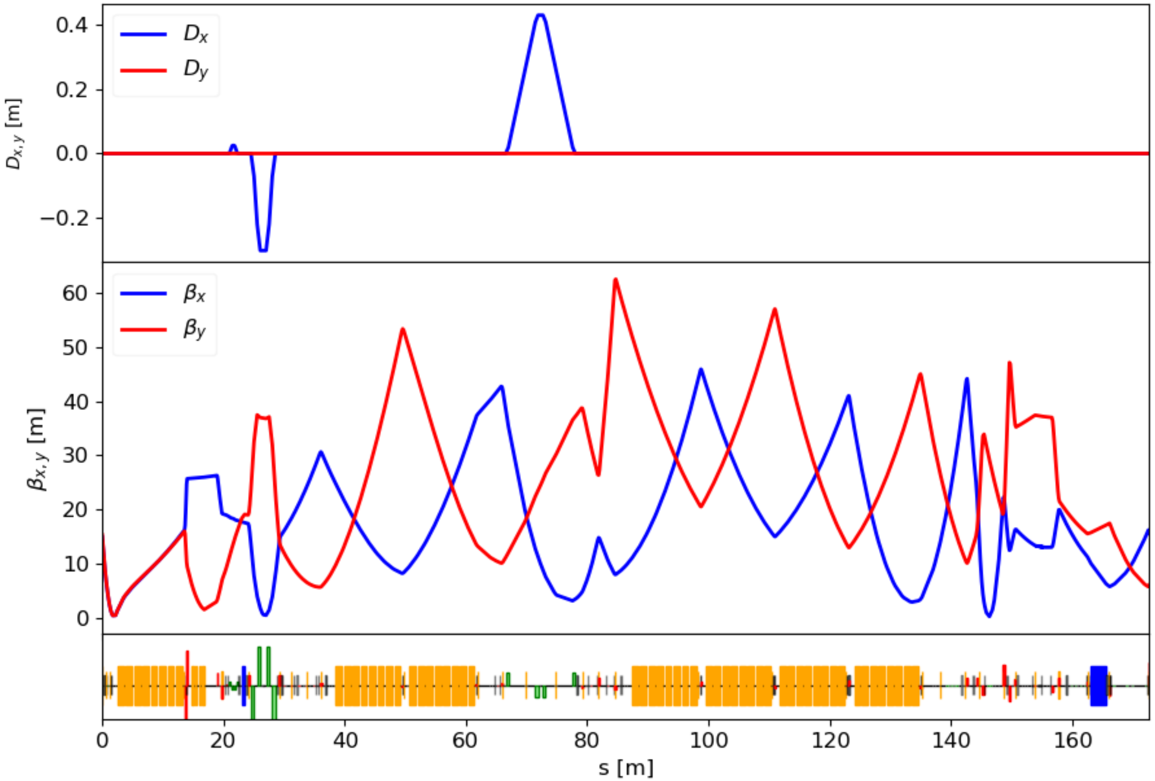
section name	booster	3^{rd}harm.	L_2	L_3
maximal voltage, MV	170	22.5	440	800

TABLE II: Range of momentum compaction factors in the bunch compressors.

section name	BC_1	BC_2
$\lvert R_{56}\rvert$, mm	120 - 250	0 - 105

- In order to compress the beam to a high peak current the electron beam line incorporates **two horizontal bunch compressors of C-type**.
- **The maximal accelerating voltages at different sections of the accelerator** (as it was assumed in the simulations) are listed in Table I. The ranges for the compression compaction factors are presented in Table II .

Simulations of beam dynamics in FLASH accelerator



The design optics of FLASH1.
The bottom plot presents an outline of different elements:
quadrupoles (in red),
dipoles (in green),
RF modules (in orange).

Simulations of beam dynamics in FLASH accelerator

The properties of the two bunches at distance z = 2.6 m from the cathode of RF gun.

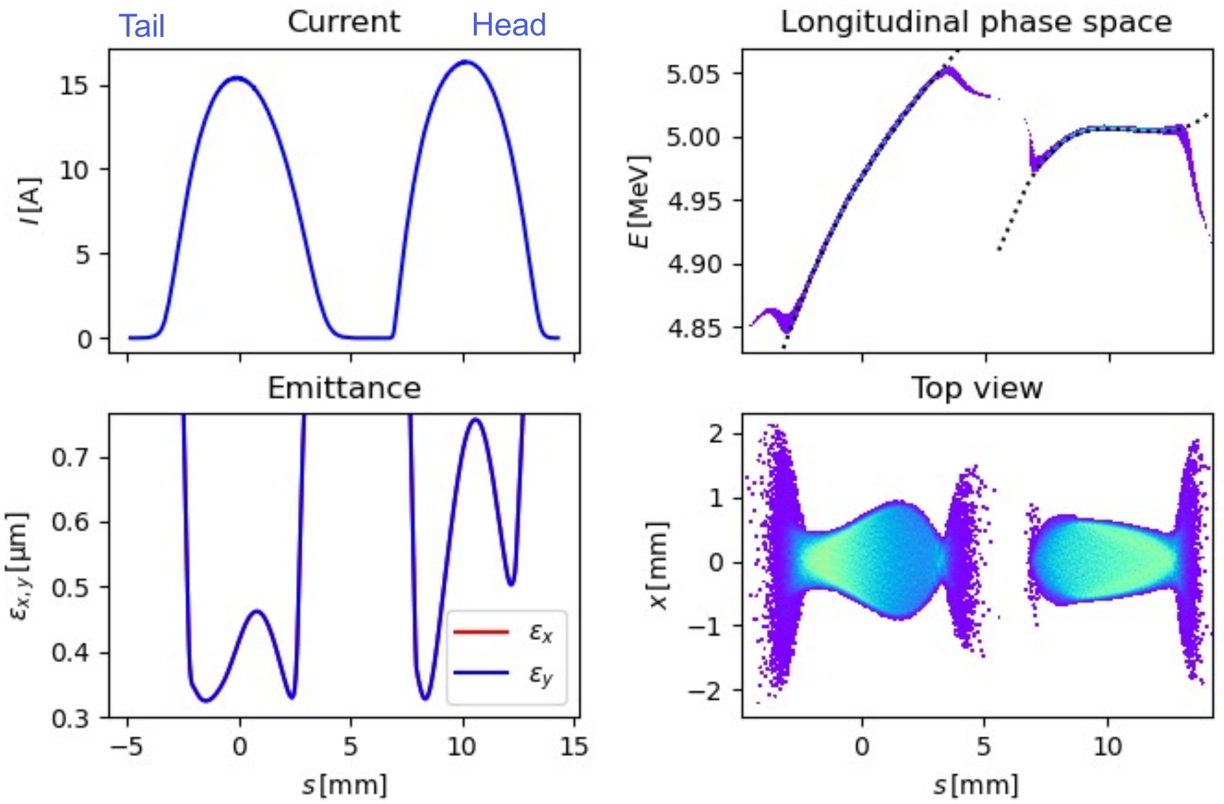


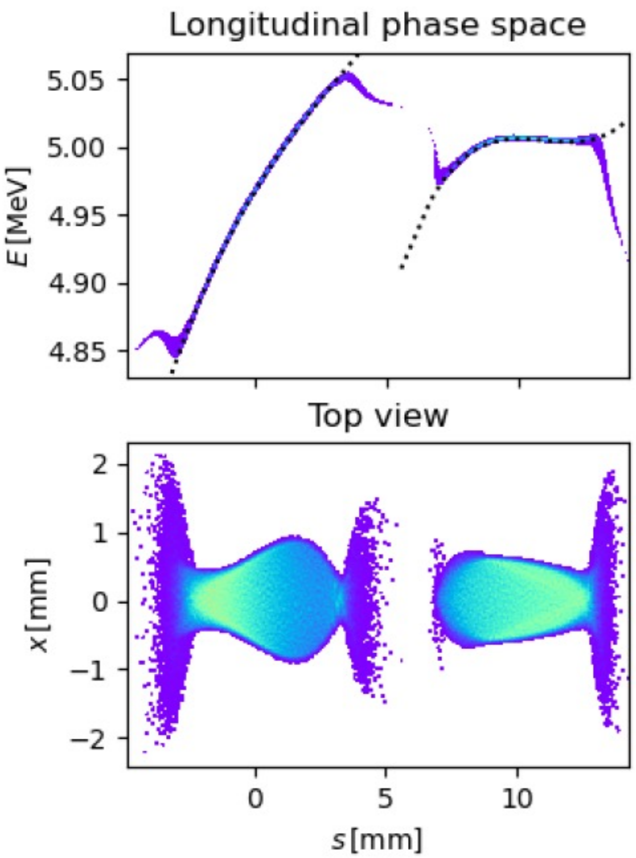
TABLE III: The injector parameters.

subsection	parameter	A-bunch	S-bunch
laser	rms length, ps	4	4
	apperture diameter, mm	1.15	1.15
RF cavity	frequency, GHz	1.3	1.3
	maximal field on cathode, MV/m	45	45
	relative phase, degree	- 10	10
solenoid	Magnetic field, T	0.172	0.172

- The simulations are done with code ASTRA. In our simulations we use $2{\times}10^6$ macroparticles per bunch.

K. Floettmann, ASTRA: A Space Charge Tracking Algorithm, DESY, 2017.

Simulations of beam dynamics in FLASH accelerator



- The dotted line in the longitudinal phase space corresponds to Eq.(*)

$$E_0(s) = \begin{cases} E_0^A(s), & s \le 0.0055\text{m}, \\ E_0^S(s), & s > 0.0055\text{m}, \end{cases}$$

$$E_0^A(s) = E_0^{ref,A}(1 + \zeta_1^A s + \zeta_2^A s^2 + \zeta_3^A s^3),$$

$$E_0^S(s) = E_0^{ref,S}(1 + \zeta_1^S (s - 0.01\text{m}) + \zeta_2^S (s - 0.01\text{m})^2 + \zeta_3^S (s - 0.01\text{m})^3)$$

parameter	A-bunch	S-bunch
E_0^{ref}, MeV	4.97	5.01
ζ_1, 1/m	6.42	-0.14
ζ_2, 1/m/m	-420	-390
ζ_3, 1/m/m/m	38590	140748

Simulations of beam dynamics in FLASH accelerator

$$\Delta E_{11} = eV_{11}\cos(ks + \varphi_{11}),$$
$$\Delta E_{13} = eV_{13}\cos(3ks + \varphi_{13}),$$
$$\Delta E_2 = eV_2\cos(ks + \varphi_2),$$
$$s_i = s_{i-1} - (R_{56i}\delta_i + T_{566i}\delta_i^2 + U_{5666i}\delta_i^3), \quad i = 1, 2.$$

The relative energy deviations in the reference points after the bunch compressors

$$\delta_1 = \frac{(1+\delta_0)E_0^{ref} + \Delta E_{11} + \Delta E_{13}}{E_1^{ref}} - 1,$$
$$\delta_2 = \frac{(1+\delta_1)E_1^{ref} + \Delta E_2}{E_2^{ref}} - 1,$$

For the fixed values of RF parameters and momentum compaction factors we define the compression functions in each bunch compressor:

$$C_i(s) = \frac{1}{Z_i(s)}, \quad Z_i(s) = \frac{\partial s_i(s)}{\partial s}, \quad i = 1, 2.$$

- The introduced one dimensional model of the longitudinal beam dynamics neglects the collective effects and the velocity bunching. In order to find the RF parameters of the accelerating modules we use the analytical solution published in

I. Zagorodnov and M. Dohlus, Semianalytical modeling of multistage bunch compression with collective effects, Phys. Rev. ST Accel. Beams 14, 014403 (2011).

Simulations of beam dynamics in FLASH accelerator

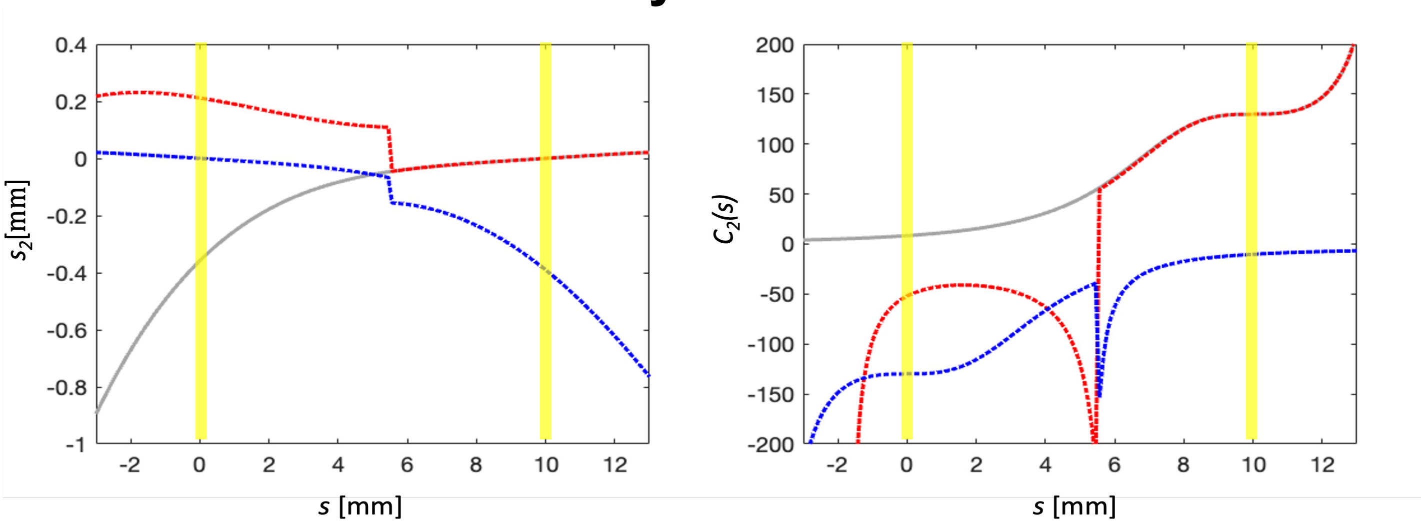
The energies at the beam compressors are fixed by design studies and are listed in Table V. The global compression C_2 comes from the requirement on the peak current value of 2 kA.

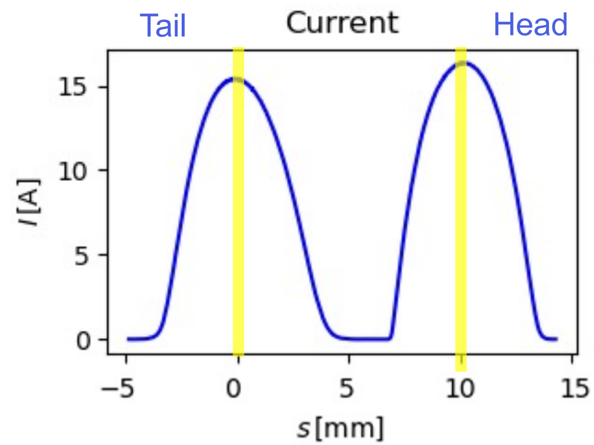
TABLE V: The longitudinal dynamics parameters.

E_1^{ref}	$(R_{56})_1$,	C_1	E_2^{ref}	$(R_{56})_2$	C_2	C_2'	C_2''
MeV	mm		MeV	mm		1/m	1/m/m
130	-122	3	550	-104	-130	0	0

The first and the second derivatives of the global compression are special parameters which allow to tune the flatness and the symmetry of the current profile. We put them to zeros. It means that we would like to have a flat current profile at the vicinity of the reference position.

Simulations of beam dynamics in FLASH accelerator

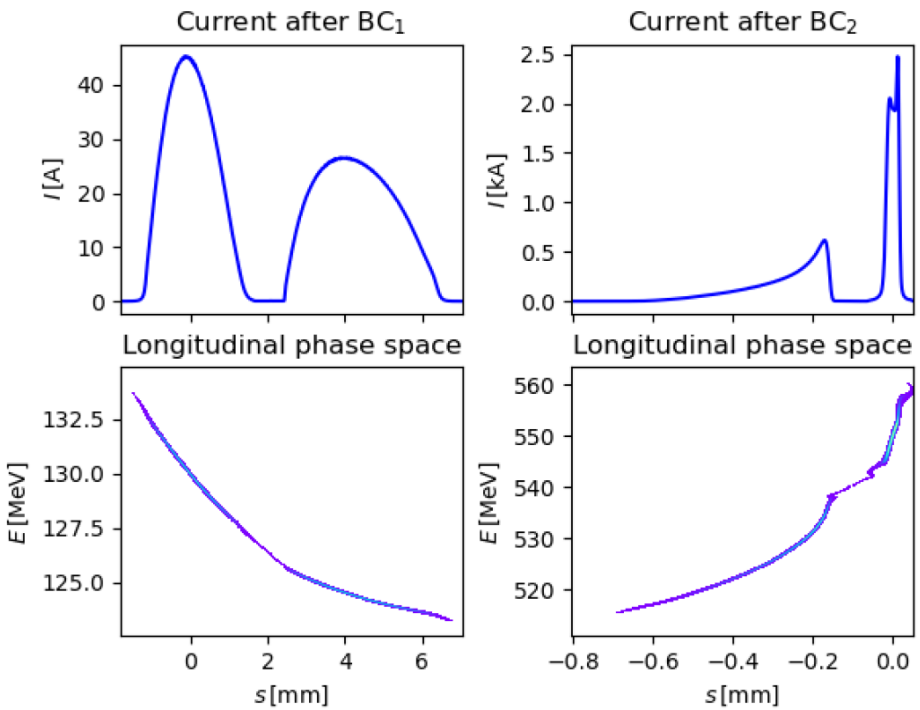




The position (on the left) and the compression (on the right) curves of the longitudinal dynamics without collective effects.

- ❑ The grey solid curve describes the position (on the left plot) and the compression (on the right plot) for the ideal beam without energy spread.
- ❑ The dashed curves present the position and the compression for the longitudinal phase space approximated by Eq. (*). The red curves correspond to the hypothetical situation when A-bunch leaves the gun first.
- ❑ The blue curves correspond to the simulated case, when the S-bunch leaves the gun first and then the bunches exchange their relative positions during the bunch compression.

Simulations of beam dynamics in FLASH accelerator



The current and the longitudinal phase space after bunch compressor BC1 (on the left) and after bunch compressor BC2 (on the right).

- The above results are confirmed with the **particle tracking in Ocelot with the collective effects included.** The RF parameters for this case are listed in the second raw of Table VI.

TABLE VI: The RF parameters.

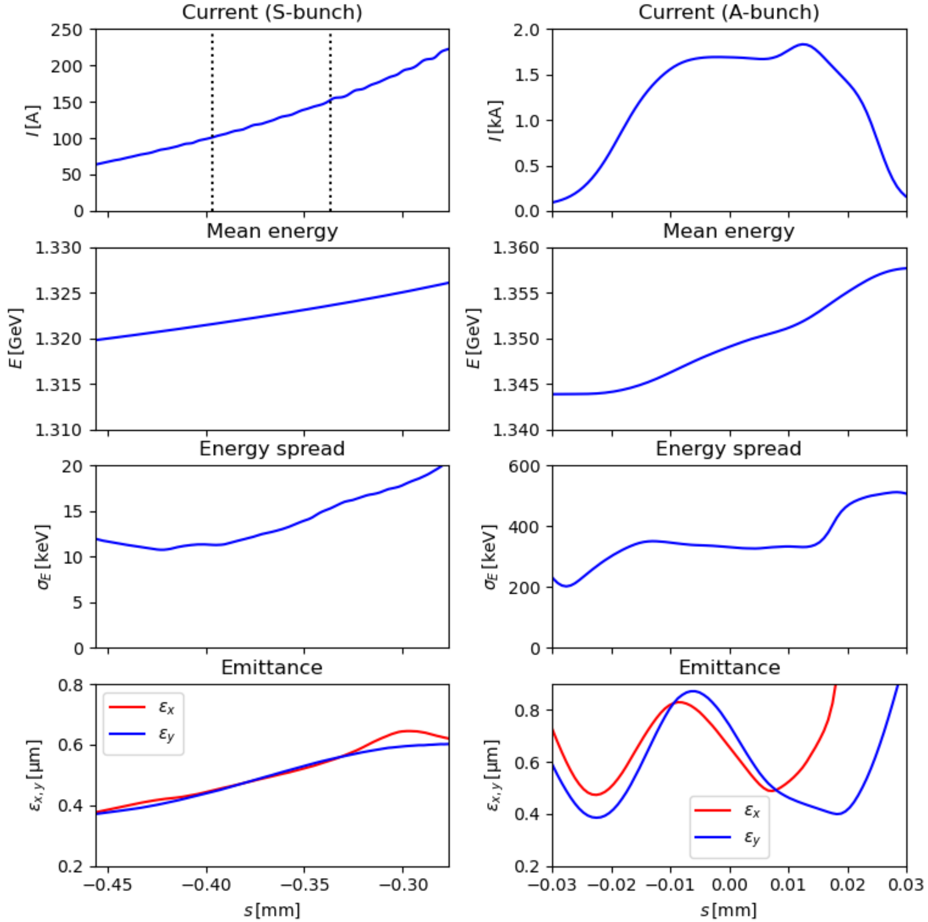
	V_{11} MV	φ_{11} deg	V_{13} MV	φ_{13} deg	V_2 MV	φ_2 deg	V_3 MV	φ_3 deg
analytical	146.4	5.66	21.0	168.53	436.8	15.95	800	0
with self-fields	144.8	-2.35	22.5	150.42	438.8	16.23	800	0

Simulations of beam dynamics in FLASH accelerator

- The physical models and the **numerical algorithms of code Ocelot** [1] are described shortly in Appendix B of paper [2].
- The numerical modeling of the accelerator beam dynamics presented in this paper includes the wake functions of the accelerating modules in the form described in [3]. We have tested with the direct numerical solution of Maxwell equations [4], that this form **of the wake functions describes accurately the wakefields in the second bunch as well**.

[1] S. Tomin, I. Agapov, M. Dohlus, I. Zagorodnov, Ocelot as a framework for beam dynamics simulations of X-ray sources, in Proceedings of the International Particle Accelerator Conference (IPAC), Copenhagen, Denmark, 2017, WEPAB031.
[2] I. Zagorodnov, M. Dohlus, and S. Tomin, Accelerator beam dynamics at the European X-ray freeelectron laser, Phys. Rev. Accel. Beams 22, 024401 (2019).
[3] I. Zagorodnov, S. Tomin, Y. Chen, and F. Brinker, Experimental validation of collective effects modelling at injector section of X-ray free-electron laser, Nucl. Instrum. Methods Phys. Res., Sect. A 995, 165111 (2021).
[4] I. Zagorodnov and T. Weiland, TE/TM field solver for particle beam simulations without numerical Cherenkov radiation, Phys. Rev. ST Accel. Beams 8, 042001 (2005).

Simulations of beam dynamics in FLASH accelerator

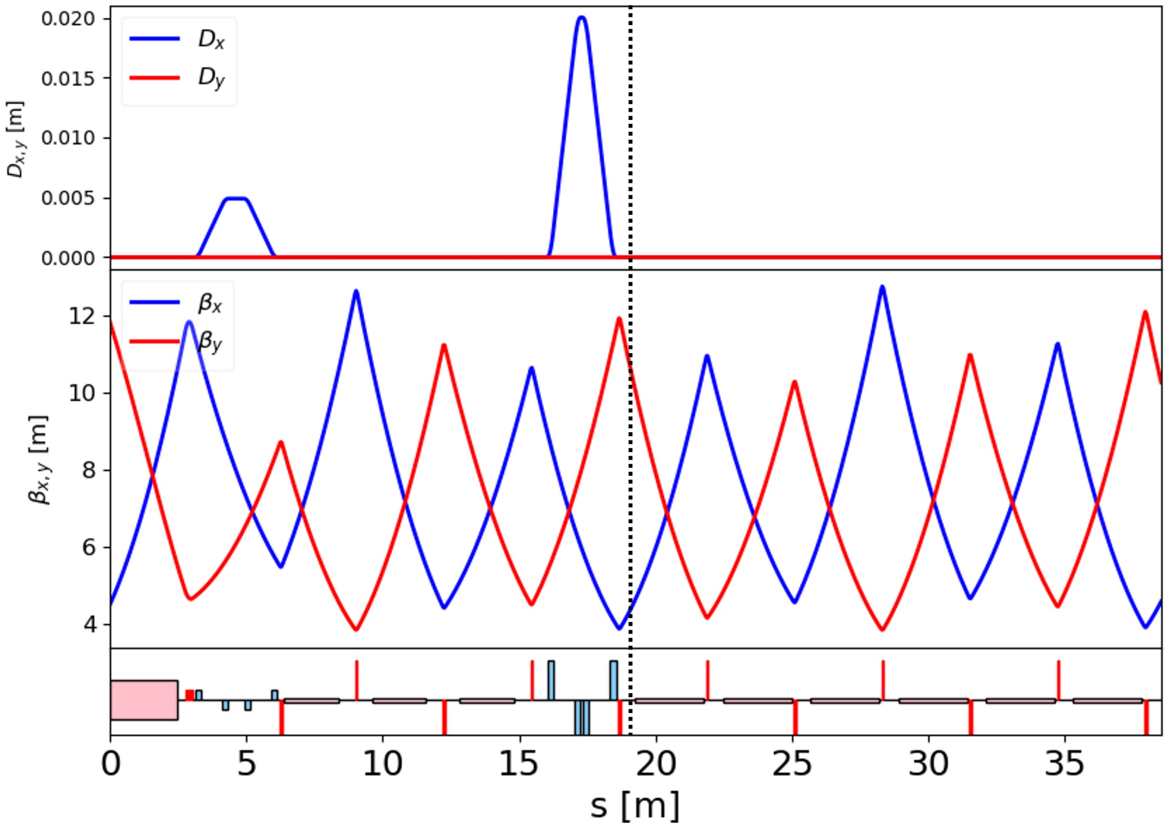


The current, the mean slice energy, the slice energy spread and the slice emittance of the seed bunch before the modulator (on the left) and of the lasing bunch before the amplifier (on the right). The dotted lines on the left current plot outline the simulation window used in the FEL modeling.

- The slice parameters of each bunch are shown for the **simulation window of 60 um** used in the FEL.
- The **peak current** of the A-bunch **is reduced** by approximately 15 % **in the delay chicane** before the amplifier due to the strong energy chirp in the A-bunch.
- One can notice a relatively **small uncorrelated energy spread** of S-bunch, about 10 keV at the current of 100 A.
- We checked that **our scheme works even if the energy spread is significantly larger**, see simulations below.

FEL simulations

at the 75th harmonic (wavelength 4 nm)



The design optics of the seeding setup.
The bottom plot presents an outline of different elements:
quadrupoles (in red),
dipoles (in green),
undulators (in blue).
The dotted vertical line shows the rematching position for the lasing bunch.

FEL simulations

at the 75th harmonic (wavelength 4 nm)

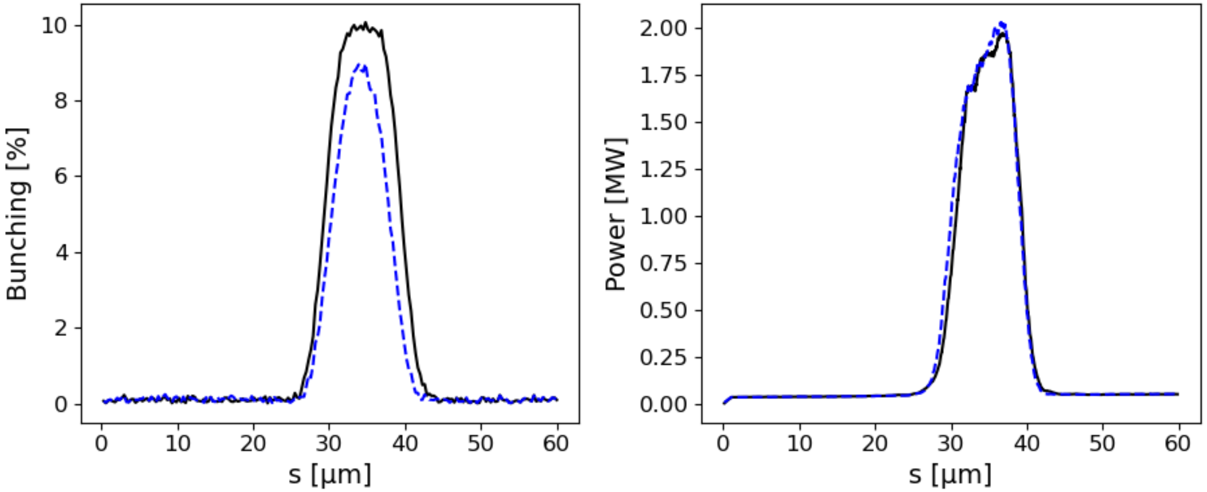
- The main parameters used in FEL simulations are presented in Table VII.
- The **CHG undulator is planar and consists of three segments** followed by the delay chicane.
- **The amplifier** is place behind the chicane and **consists of six segments** with variable polarization.
- We simulate two cases: **linear and circular polarization of the amplifier undulator**.
- In the latter case only a half of the radiation power from CHG undulator is coupled to the amplifier (linearly polarized beam can be decomposed into left and right circularly polarized beams), so that we introduce the reduction by a factor of two in our simulations.

TABLE VII: The parameters of FEL simulations.

subsystem	**parameter**	**Value**
Laser	Laser pulse duration (FWHM) , fs	33
	Laser wavelength, nm	300
	Laser power, MW	100
Modulator	Undulator period, cm	8.26
	Number of periods	30
	Undulator parameter K_{rms}	6.9117
Chicane	R56, μm	52
Radiator	Number of modules	3
	Undulator period, cm	3.15
	Number of periods in one module	63
	Undulator parameter K_{rms}	0.8400
Delay chicane	R56, μm	740
Amplifier	Number of modules	6
	Undulator period, cm	3.5
	Number of periods in one module	72
	Undulator parameter K_{rms}	0.7725

FEL simulations

at the 75th harmonic (wavelength 4 nm)

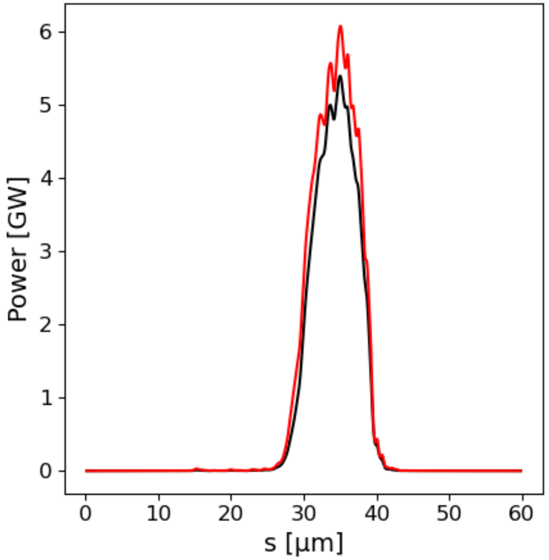


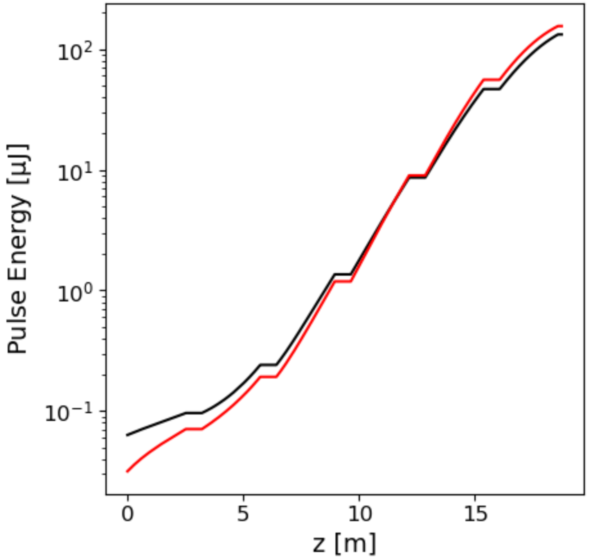
The left plot shows the bunching factor at the seeding bunch after the CHG radiator. The right plot presents the FEL power profile after the radiator. The black curves are simulated for beam parameters from previous Fig. while the dashed blue curves are simulated for the case when the uncorrelated energy spread of the S-bunch is artificially increased to 30 keV.

- One can notice a **relatively high value of the bunching factor** (nearly 10% at the 75th harmonic of the laser despite its moderate peak power). This is possible due to the small uncorrelated energy spread in the corresponding part of S-bunch, about 10 keV.
- To prove that our results do not critically depend on the uncorrelated energy spread, **we artificially increased it to 30 keV**. Obviously, in this case one needs a higher laser power and a lower R56 of the chicane.
- **We could get a similar distribution of power at the exit of CHG radiator** (shown as blue dash curve). The laser power in this simulation was 650 MW, and the R56 was 15.4 um.

FEL simulations

at the 75th harmonic (wavelength 4 nm)



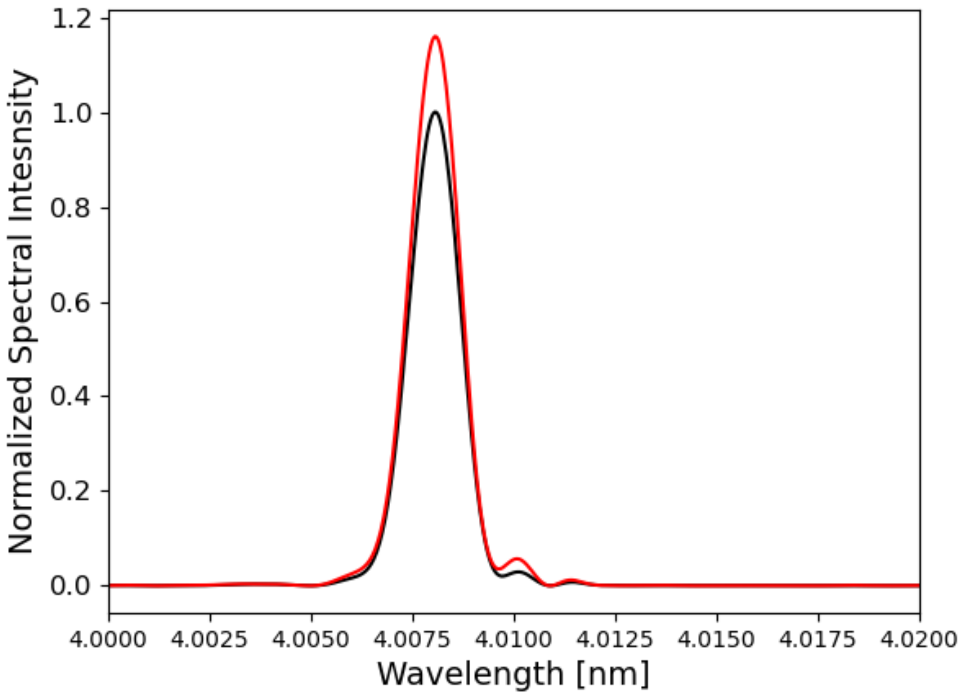


The left plot shows the output FEL power profiles of planar (black curve) and helical (red curve) undulators. The right plot presents the gain curves of planar (black curve) and helical (red curve) undulators.

- Pulses energies at the undulator end are about 150 uJ, pulse durations about 25 fs.
- Despite in the circularly polarized case the effective input power is lower, the FEL gain and the output power are somewhat higher due to a better coupling between the electron motion and the electromagnetic field.
- If the undulator was longer, a higher radiation power could be produced with some post-saturation taper.

FEL simulations

at the 75th harmonic (wavelength 4 nm)



Output FEL spectra of planar (black curve) and helical (red curve) undulators.

- Despite the slight distortions, one can notice a relatively high quality of spectra at the high harmonic number considered in this paper.
- The relative spectrum width is about 3.4×10^{4} (FWHM), and the **time-bandwidth product exceeds Fourier limit for a Gaussian pulse by only 40%**.

Summary

- We proposed two-bunch seeding concept and demonstrated its validity in start-to-end simulations.
- We showed that nearly Fourier-limited multi-gigawatt pulses can be generated at the wavelength of 4 nm in HGHG configuration with the compact undulator design of FLASH.
- Some aspects (EEHG case, specific matching optics, sensitivity studies, lasing at even shorter wavelengths, reduction of the required laser power at moderate harmonic numbers) will be studied in future works but already now we can conclude that **the concept promises enormous improvements with respect to the traditional seeding scenarios**.

Acknowledgments

The authors would like to thank M. Vogt, J. Zemella and S. Tomin for providing the optical layout of FLASH, G. Paraskaki for the help with the Genesis 1.3 simulations.