Optimizing EuXFEL Photoinjector Performance via Laser Shaping Approach

OPAL-FEL - Optimized Laser Pulses for Free-Electron-Lasers

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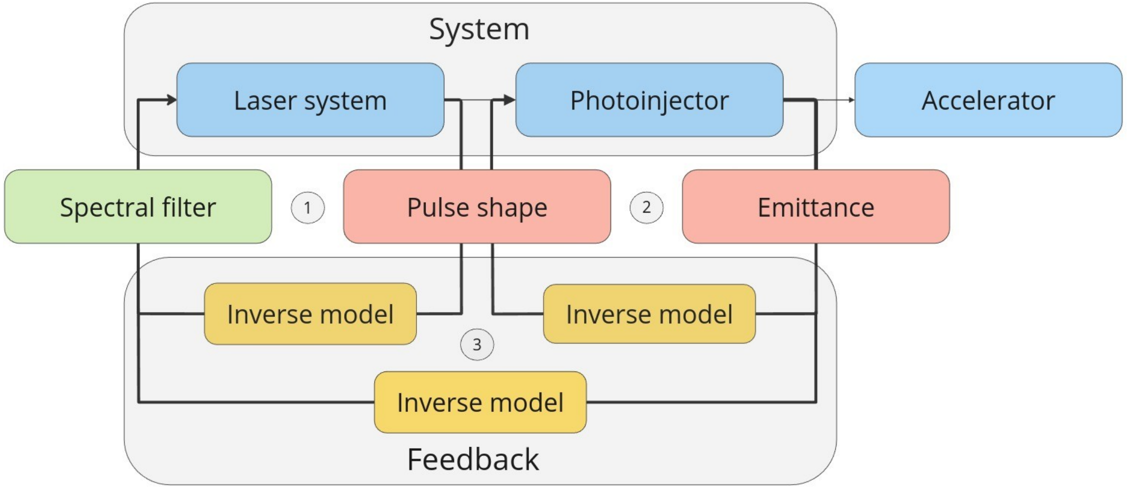
Project goal

Minimal emittance at higher photon energies (30+ keV) in the EuXFEL injector by temporal laser shaping and ML driven modeling



European XFEL
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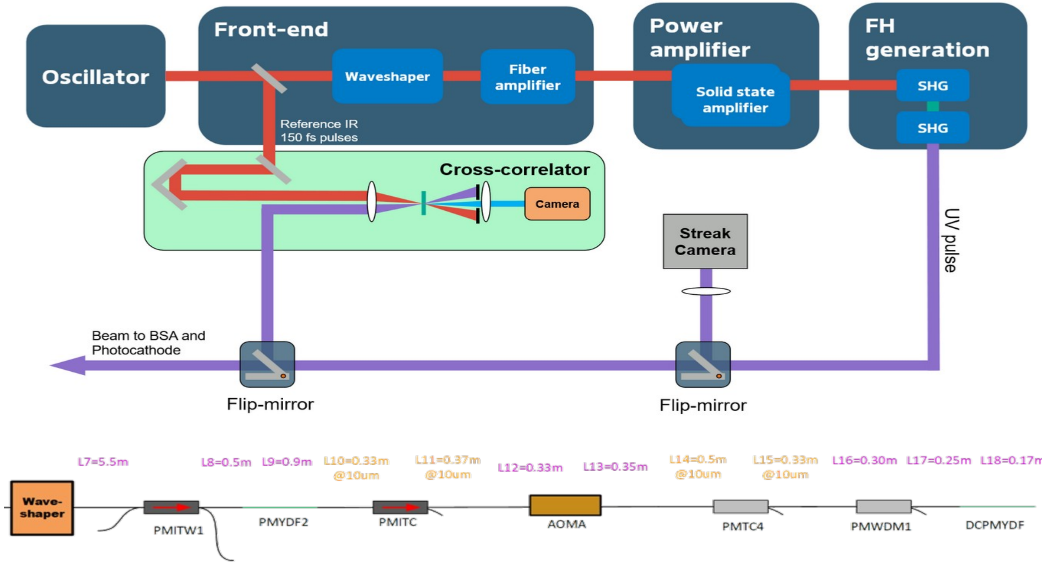
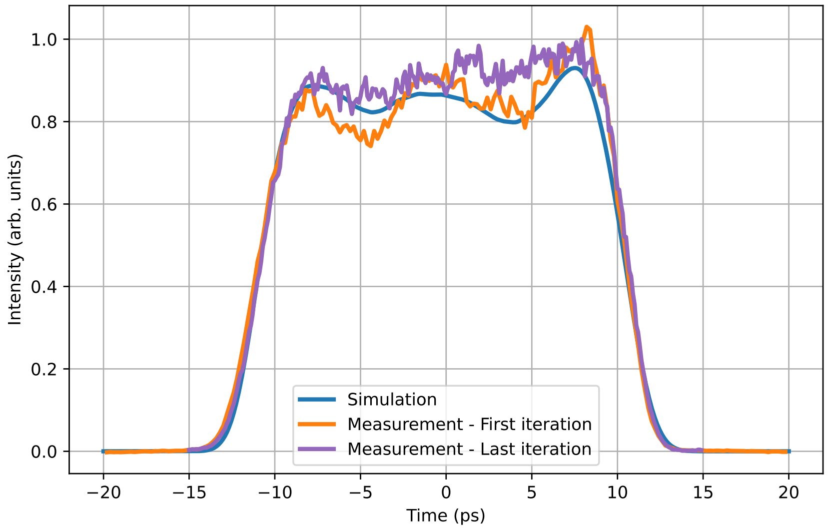
Photocathode Laser System Simulations and Experiments*





Results and Achievements

- Development of differentiable simulation software for nonlinear pulse propagation
- Gradient based shape optimization and transfer to the NEPAL laser system
- Successful operation of EuXFEL with flat-top temporal laser shape (1 week)

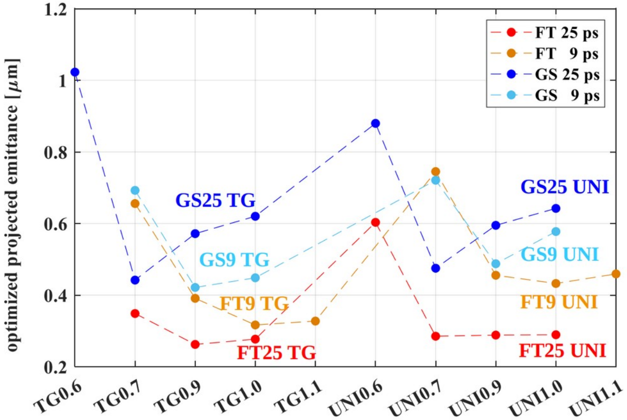
*Main work confined by D. Ilia (FS-LA)

Photoinjector Simulations and Experiments*

Simulation (1)

Simulation results indicating low emittance beam yielded by flat-top bunches of 25ps length

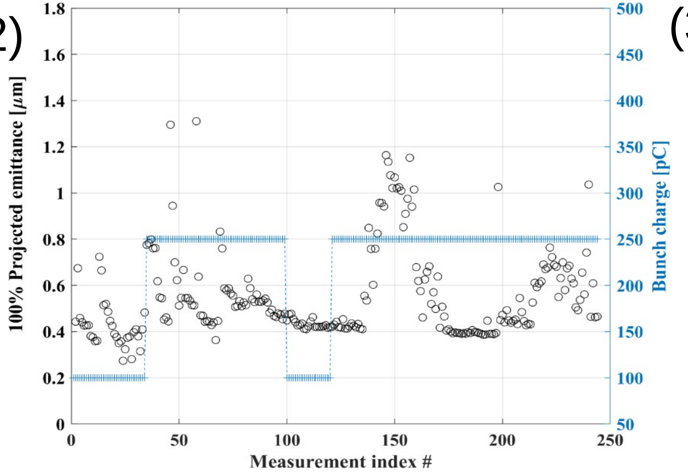
(1)



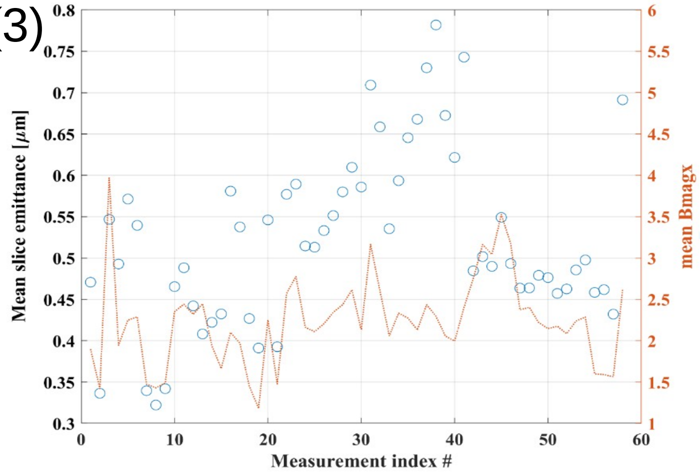
Experiments (2) + (3)

Best ever achieved (slice) emittance results for (250) 100pC at (0.32) 0.27µm

(2)



(3)

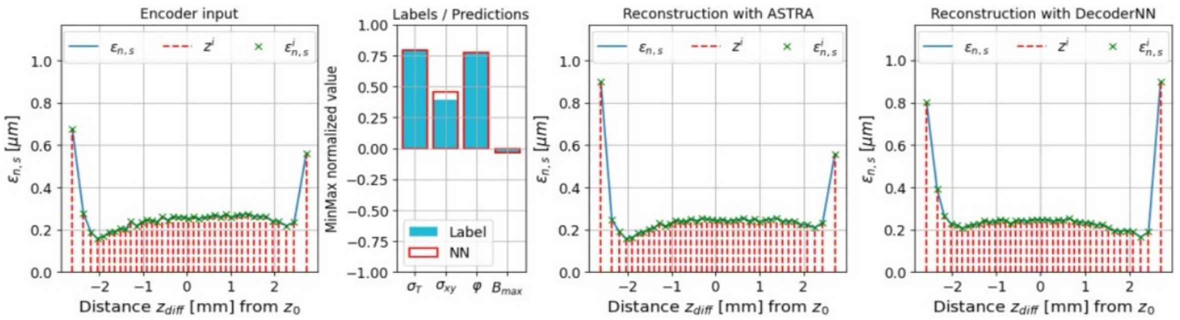


*Main work confined by Ye Chen and Meng Cai (MXL)

Machine Learning and Differentiable Simulations

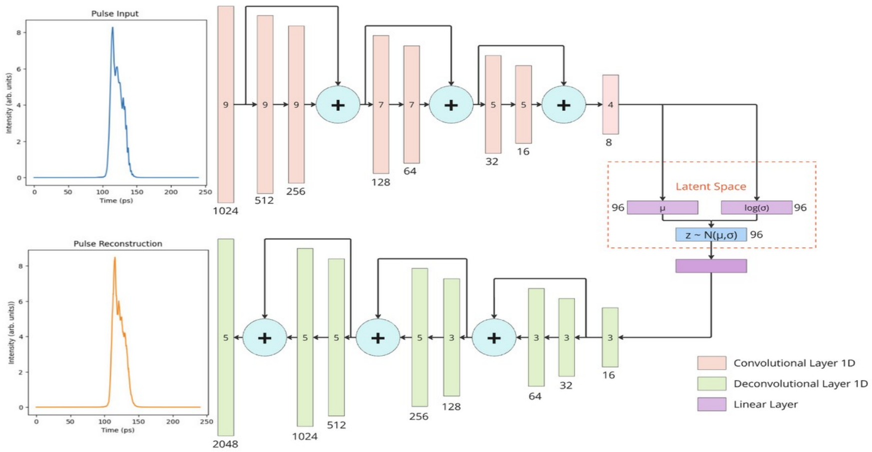
Inverse modeling for electron gun

Successful prediction of gun parameters from slice emittance and slice mismatch measurements on simulated data



Ongoing and future work

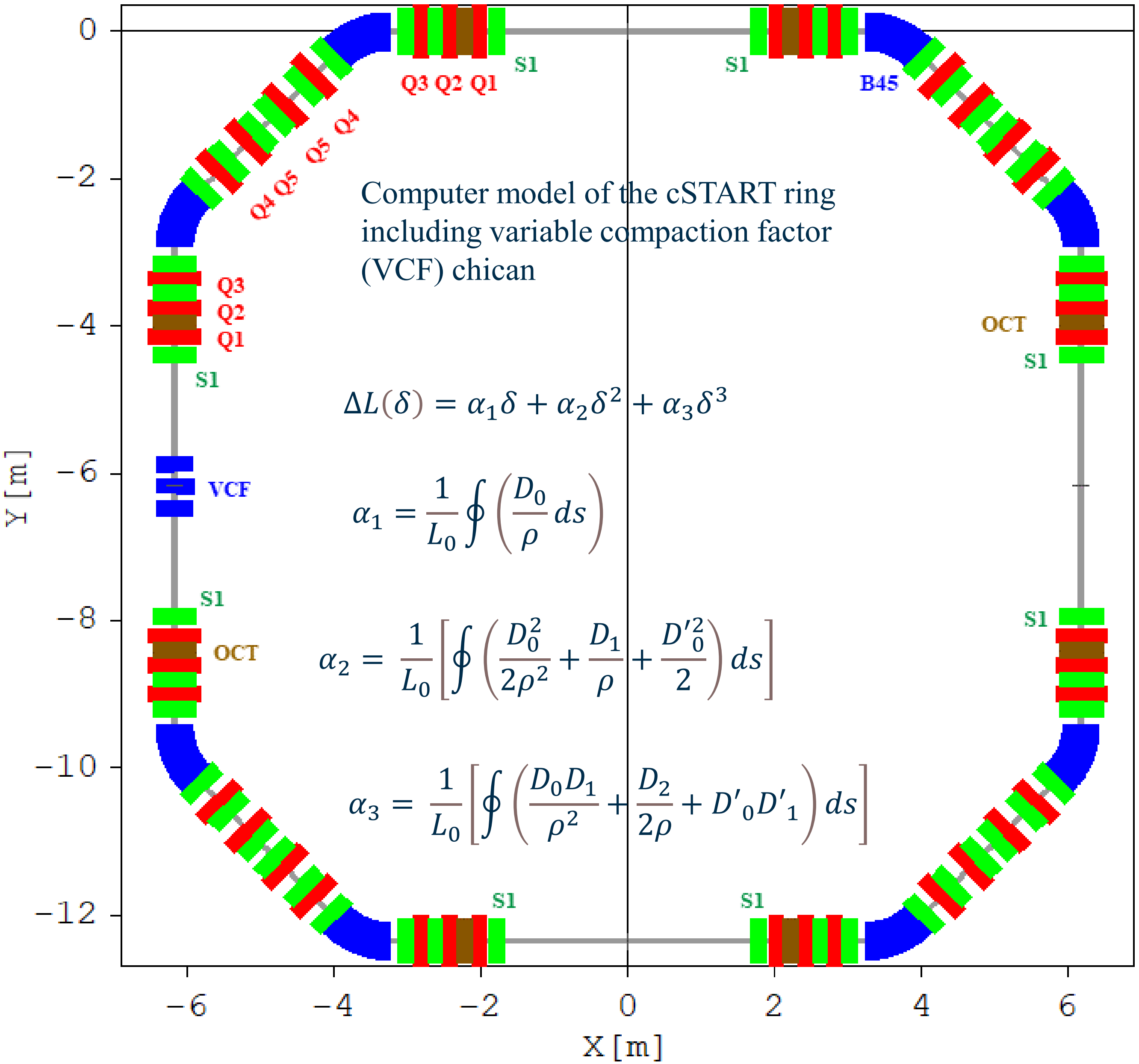
- Development of differentiable gun forward model to be used with Cheetah
- Generative ML modeling for pulse shaping



Quasi-isochronous conditions and high order terms of momentum compaction factor at the compact storage ring

A. I. Papash†, M. Fuchs, A.-S. Mueller, R. Ruprecht,
Karlsruhe Institute of Technology, Karlsruhe, Germany

- The **compact** storage ring project for accelerator research and technology (**cSTART**) is realized at the Institute for Beam Physics and Technology (**IBPT**) of the Karlsruhe Institute of Technology (KIT)
- **Flexible** lattice of a ring benefits variety of **operation modes**. Different physical experiments including **direct injection** and circulation of **Laser Plasma Accelerator** (LPA) electrons are planned at cSTART
- Deep **variation** of **momentum compaction factor** with simultaneous **control** of **high order terms** of alpha would demonstrate the capture and **storage** of **ultra-short bunches** of electrons in a circular accelerator
- Computer studies of linear and non-linear beam dynamics were performed with an objective to estimate arrangement and performance of dedicated **three pole chican** magnets to provide **quasi-isochronous** conditions for electrons
- Additonal families of so called "**longitudinal" sextupoles** and **octupoles** are included into a ring lattice to control **slope** and **curvature** of momentum compaction factor as function of energy offset of particles in a bunch.



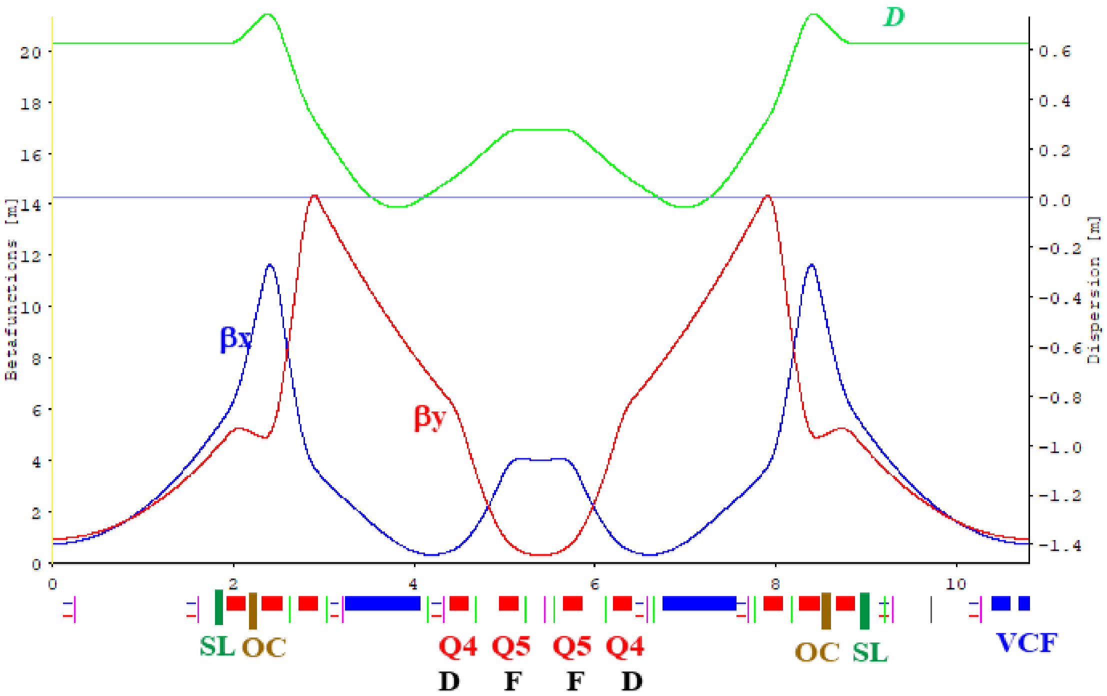
Computer model of the cSTART ring including variable compaction factor (VCF) chican

$$\Delta L(\delta) = \alpha_1 \delta + \alpha_2 \delta^2 + \alpha_3 \delta^3$$

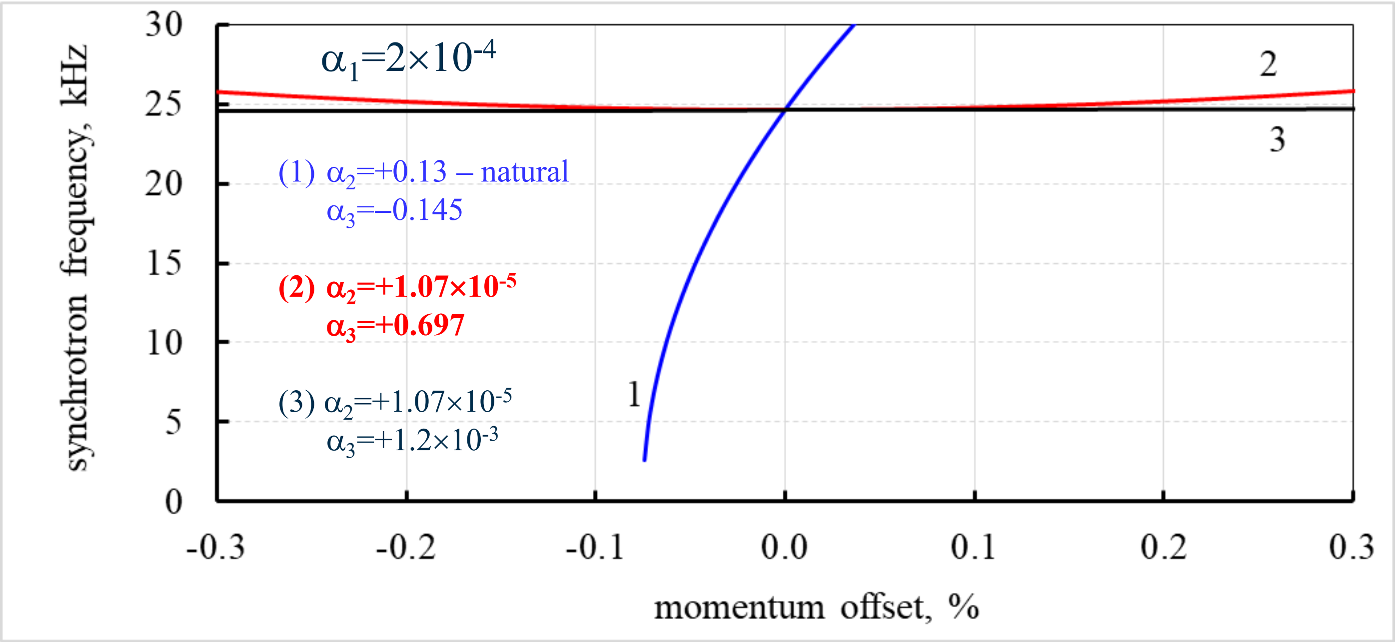
$$\alpha_1 = \frac{1}{L_0} \oint \left(\frac{D_0}{\rho} ds \right)$$

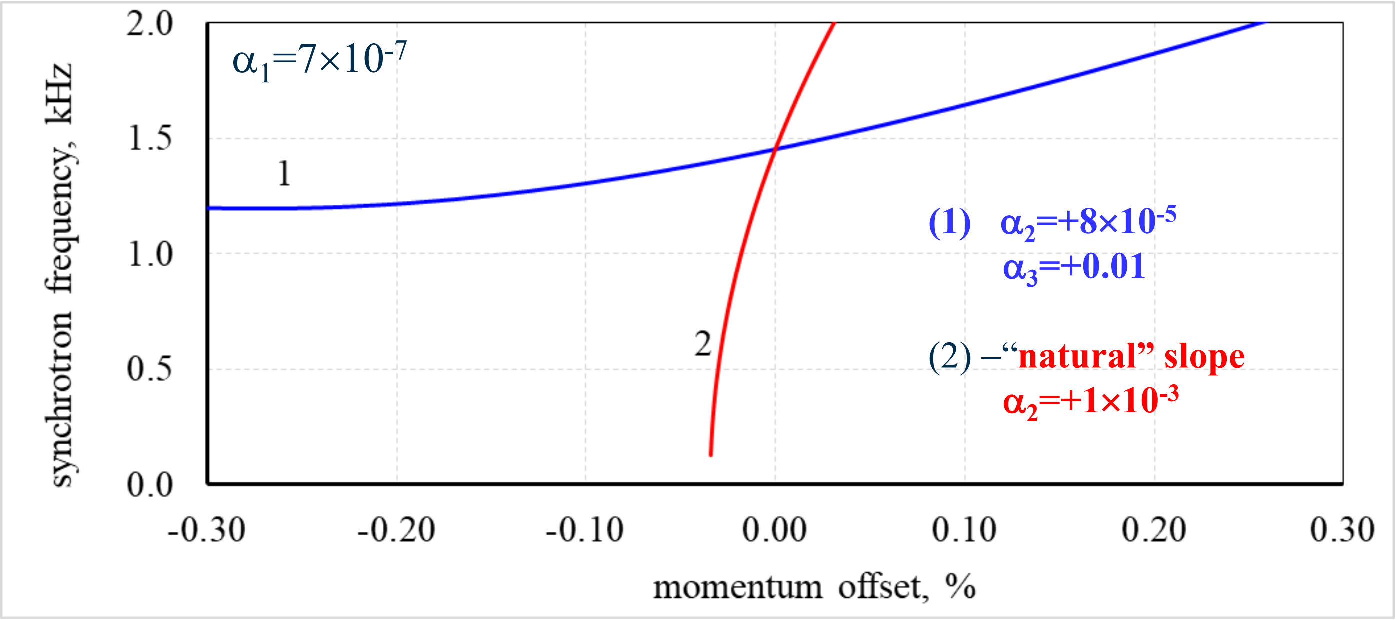
$$\alpha_2 = \frac{1}{L_0} \left[\oint \left(\frac{D_0^2}{2\rho^2} + \frac{D_1}{\rho} + \frac{D'^2_0}{2} \right) ds \right]$$

$$\alpha_3 = \frac{1}{L_0} \left[\oint \left(\frac{D_0 D_1}{\rho^2} + \frac{D_2}{2\rho} + D'_0 D'_1 \right) ds \right]$$

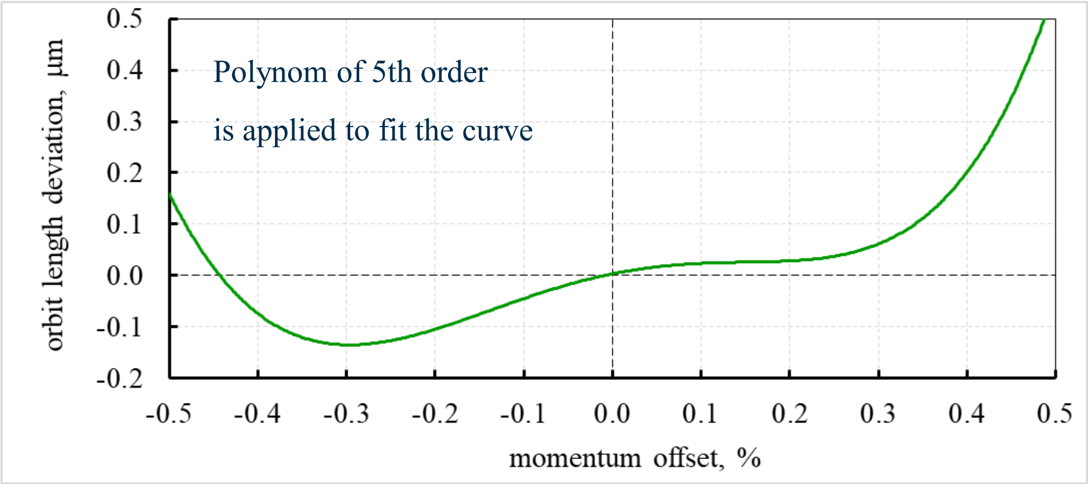


- Recent experiments with additional longitudinal sextupole at KARA ring provide "prove of principles" of dedicated set up with variable compaction factor chican at cSTART ring
- Ultrashort bunches of about 900 fs "zero current" bunch length (rms) have been received at KARA
- Flexible lattice with VCF chican at cSTART will benefit research program with ultrashort bunches





- Orbit length deviation for off-momentum particles at ultralow–α optics with $\alpha_1=7\cdot10^{-7}$
- High order terms are suppressed to minimize bunch length and provide sufficient momentum acceptance



Bunch elongation is less than 0.2 µm (0.7 fs) for particles at periphery of energy distribution $\delta_E=\pm0.3\%$ ($\delta_p=0.1\%$ rms)

S2E Simulation of THz FEL at PITZ with Bunch Compressor

Biaobin Li for THz group @ PITZ

ST3 meeting, 25.06.2025 to 27.06.2025

Content

- Ming-Xie Parameterization for THz SASE FEL
- Bunch compression for gaussian beam
- Genesis simulation results
- Summary

Ming-Xie Parameterization for THz SASE FEL

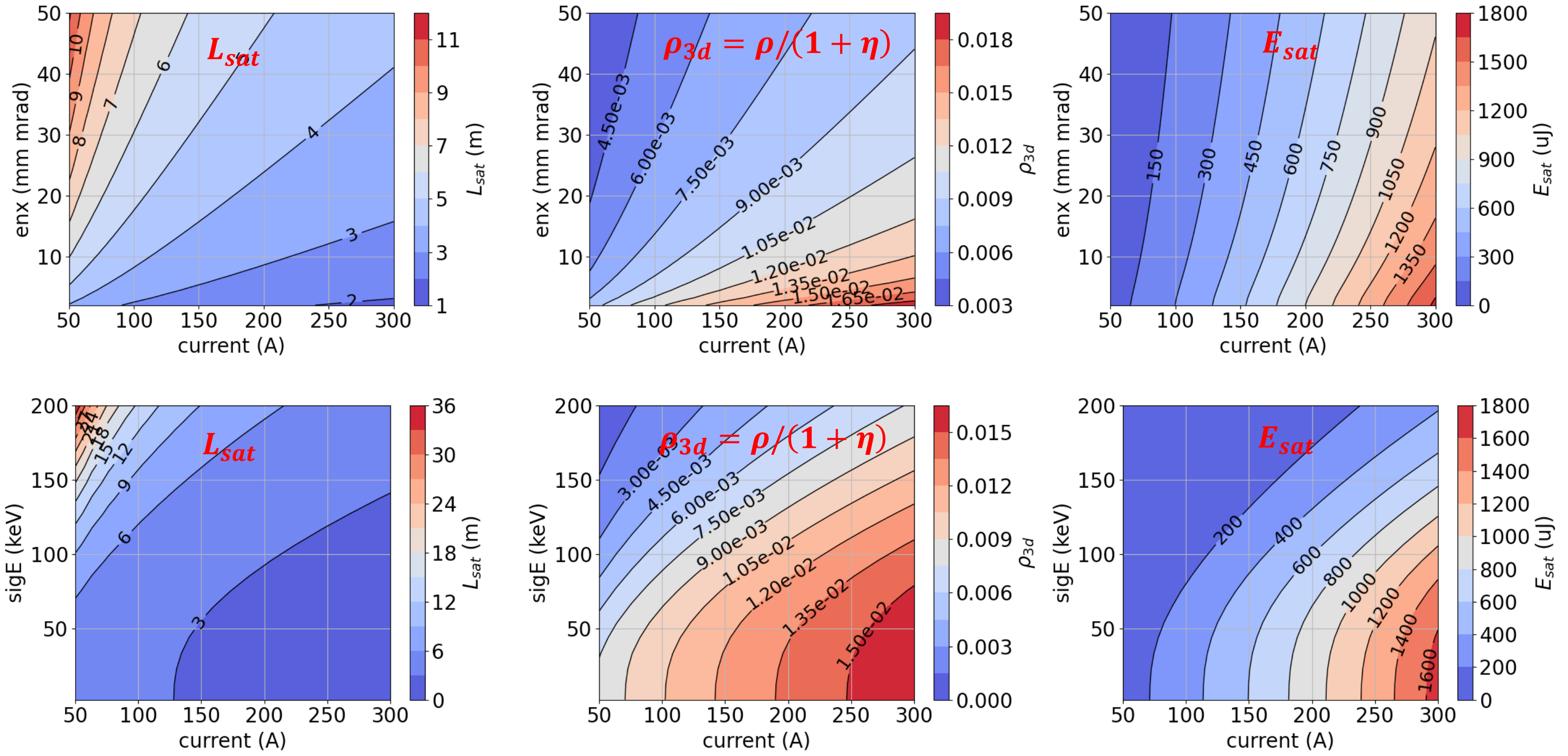
Electron beam for THz SASE FEL

Saturation length, pierce parameter and saturation power for SASE FEL can be given by Ming-Xie's 1D equations:

$$L_{sat} = L_g \ln\left(\frac{P_{sat}}{\alpha P_n}\right)$$

$$\rho = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_w A_w}{2\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma_0}\right)^3\right]^{1/3}$$

$$P_{sat} \approx 1.6\rho\left(\frac{L_{1d}}{L_g}\right)^2 P_{beam}$$



Results from scanning *beam current, emittance and energy spread* show that

- For ε_{xn}~5 um rad, σ_E~50 KeV, I~100 A:

  L_{sat}~3.5 m, ρ_{3d}~0.01, E_{sat}~300 μJ

- The output radiation energy is much more sensitive to beam current, not so sensitive to beam emittance & energy spread

  => Higher beam current from Bunch Compression !

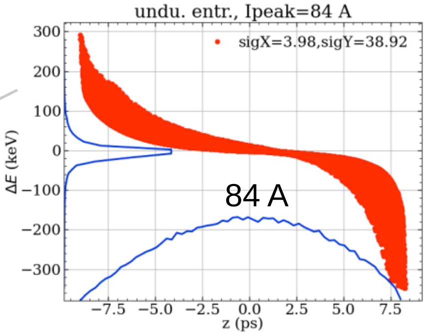
Beam and undulator parameters used in the scan:

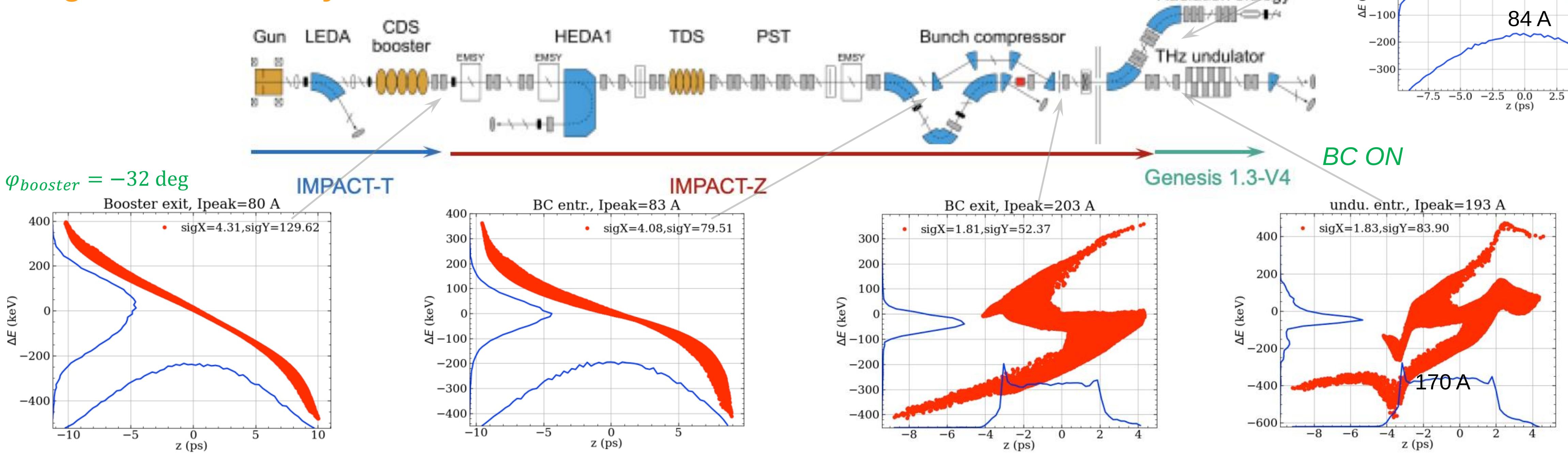
- E_{beam} = 16.7 MeV, σ_E = 50 keV
- ε_{xn} = 5 um rad, $\beta_{x,y}$ = 2 m, L_{beam} = 20 ps
- Planner undulator, K = 3.49, λ_w = 30 mm
- λ_s = 100 um

Xie, Ming, Proceedings Particle Accelerator Conference. Vol. 1. IEEE, 1995.

Bunch compression for gaussian beam

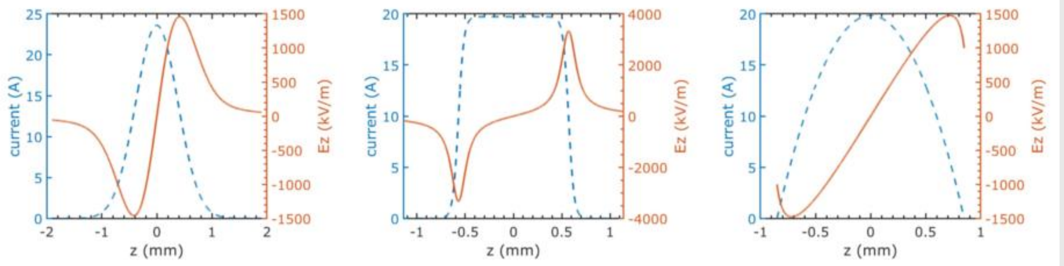
Longitudinal beam dynamics





- Electron beam $Q = 1\ \mathrm{nC}, \sigma_{x,y} = 0.83\ \mathrm{mm}\ (\mathrm{BSA} = 3.5\ \mathrm{mm}), \sigma_z = 2.97\ \mathrm{ps}$
- $R_{56} = 215\ \mathrm{mm}$ (fixed for the Chicane at PITZ), only booster phase is scanned: beam core section $I = 84\ \mathrm{A} \rightarrow\ 170\ \mathrm{A}$
- **Flattop & spike-at-tail current profile** can be obtained (due to the s-shape energy chirp from LSC)

LSC for different current profile



gauss, s-shape   flattop, z-shape   parabolic, s-shape

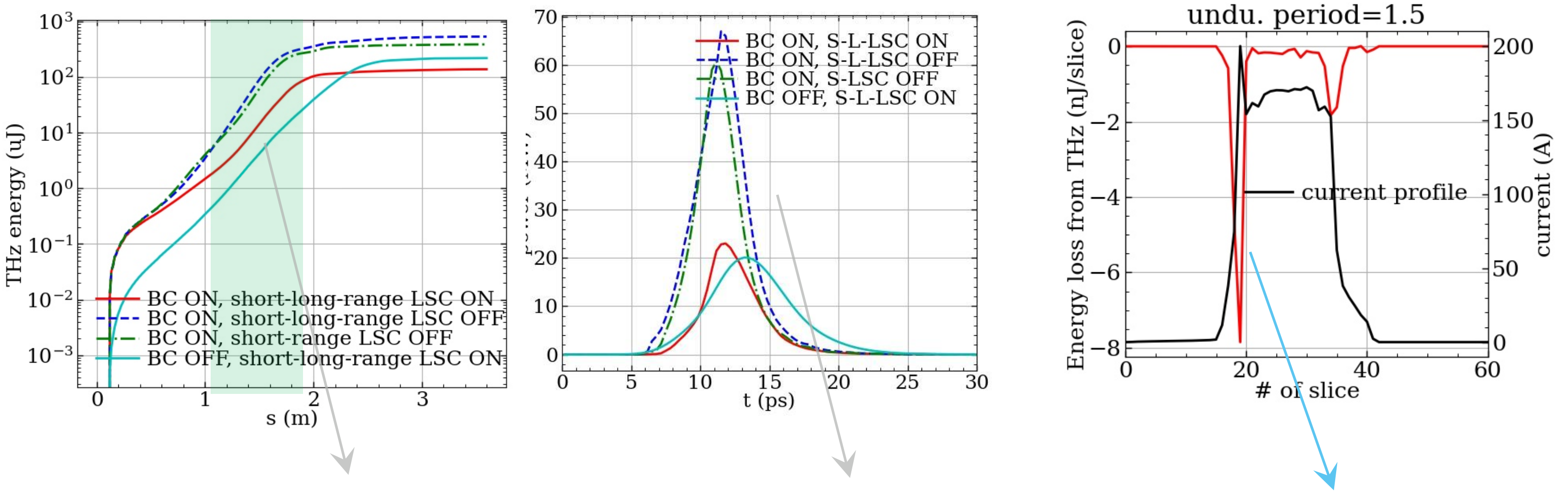
Coherent radiation from the sharp edge & spike of the current profile => SACSE FEL !

McNeil et al., Optics communications 165.1-3 (1999): 65-70.

Genesis simulation results for gaussian beam

Short-range LSC effects in high-gain region

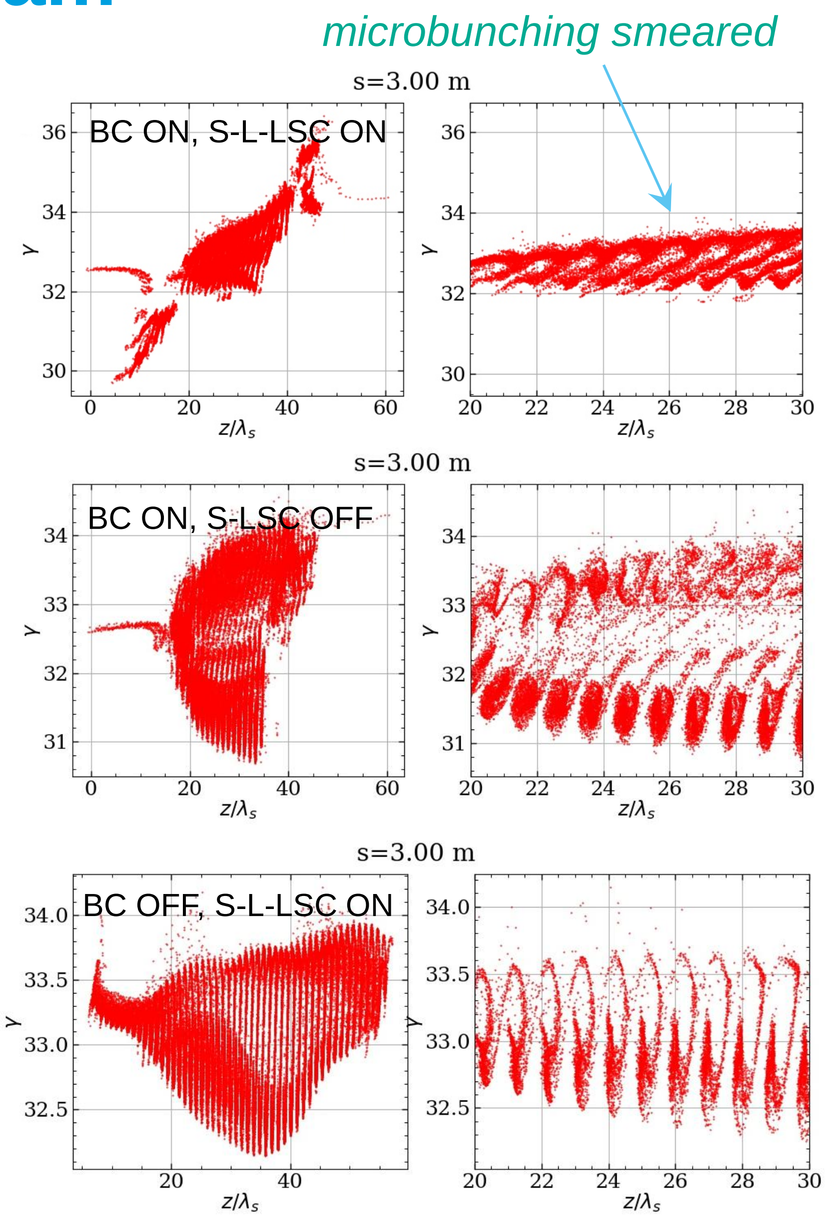
- ➢ The gain curve for BC ON **starts much faster**, and the final THz pulse is a little bit shorter than BC OFF
- ➢ Unfortunately, the **final THz energy is lower** even current is two times higher ($80\ \mathrm{A} \rightarrow 170\ \mathrm{A}$) with BC ON
- ➢ For higher current, **short-range LSC** is important during the bunching process, it tends to **smear out the micro-bunching** structures → lower output power



short-range LSC effects in high-gain section

higher peak power with S-LSC OFF

Strong seeding from the bunch tail



- ➢ *The bunch compressor seems limited improvement to THz FEL here*
- ➢ *For higher current, we need **higher beam energy**, or **larger beam size** inside the undulator to **mitigate** the **S-LSC** smearing effects!*

Summary

- For THz SASE FEL, the beam is **much more sensitive to beam current**, not so sensitive to beam emittance & energy spread => bunch compression for higher current
- **Flattop & spike-at-tail current profile** can be obtained using BC for gaussian beam, strong seeding from the coherent radiation of the beam tail is observed in the Genesis simulation
- For higher current, **short-range LSC** is important during the bunching process, it tends to smear out the micro-bunching structures => lower THz radiation energy

THANK YOU FOR YOUR ATTENTION !

Beam dynamics Optimization for a High-brightness Photoinjector with various Photocathode Laser Pulse Shapes

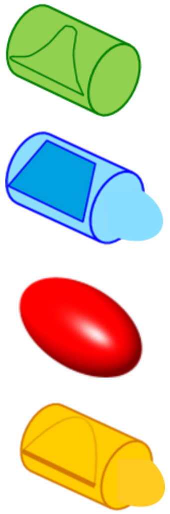
S. Zeeshan, M. Krasilnikov, X.-K. Li, D. Bazyl and I. Zagorodnov

Speed Talk- 13th MT ARD ST3 Meeting 2025 Zeuthen
27.06.2025

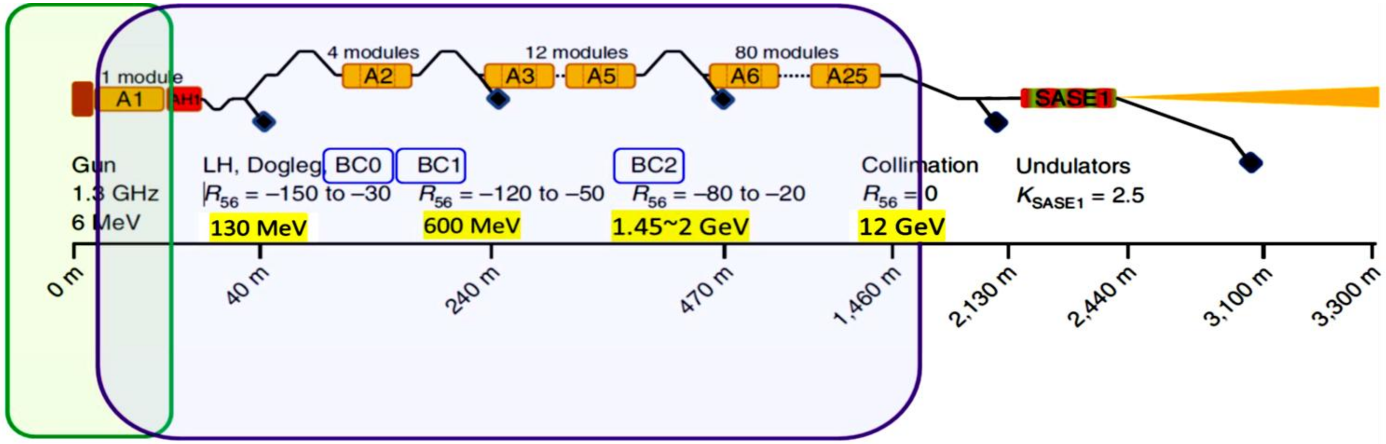
Beam Dynamics Optimization

EuXFEL CW SRF setup

- Using Multi-objective Genetic Algorithm (MOGA) based beam dynamic optimization with projected emittance and electron rms bunch length as goal functions
- A comparison of the performance of different photocathode laser profiles;
  - Longitudinal **G**aussian (G) with transverse **R**adial **U**niform (RU)
  - Longitudinal **F**lattop (FT) with transverse **T**runcated **G**aussian (TG)
  - 3D **EL**lipsoidal (3D EL)
  - Longitudinal **I**nverted **P**arabolic (IP) with transverse **TG** profiles
- Initial optimization for injector section @ 20m
- Best cases→ Prepared Monitors→ further tracked through S2E simulations



Parameters	Values
$E_{cathode}$	55 MV/m
A1: E_{peak}(1st ½)	32 MV/m
A1: E_{peak}(2nd ½)	32 MV/m
Bunch Charge	100 pC
Thermal emit	1um/mm
Optimization at	20 m

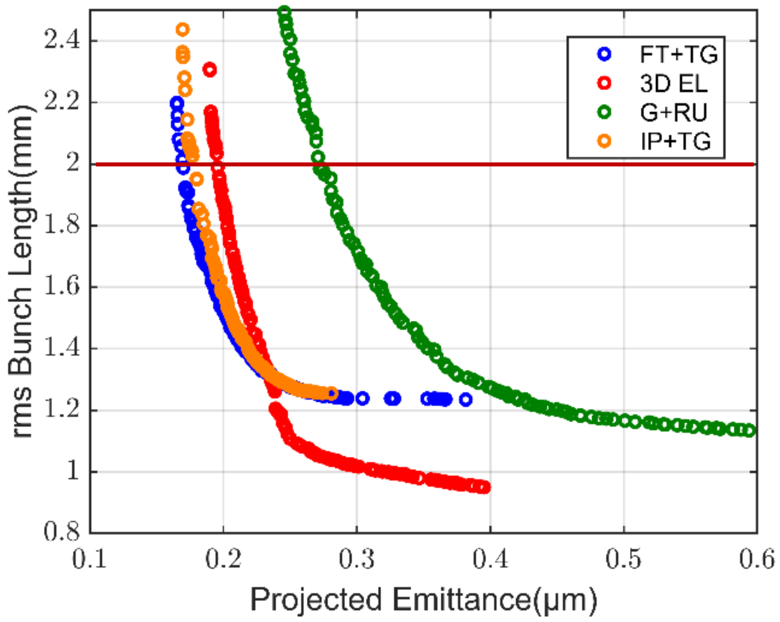


Injector Section **Start to End Simulations**

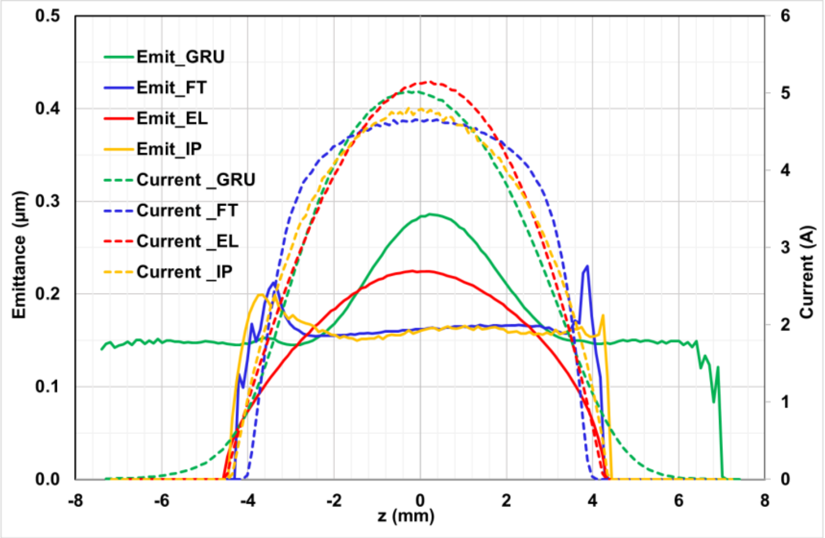
Optimization for Injector Section

Comparison of four Photoinjector Laser shapes

- Best cases for 2mm rms electron bunch length are compared
- This 2mm BL → corresponds to 5 kA peak current and it is sufficient to compress the beam at XFEL



Best Cases for 2mm rms electron bunch length				
Parameters	G+RU	FT+TG	EL	IP+TG
Proj emit (mm mrad)	0.26	0.17	0.19	0.18
Long emit (keV mm)	610	395	506	471
Energy spread (MeV)	0.56	0.36	0.27	0.76
Average 4D Bright ($A/\mu m^2$)	1231	1708	1983	2020



Slice emittance and slice current Optimized cases

Start to End Simulations

- Highest brightness at the end of injector for the IP+TG → further tracking for final evaluation as compared to other photocathode laser shapes
- S2E simulations to see the behaviour under compression under collective effects
- Multistage bunch compression involves
  - the mixing of longitudinal beam slices → local beam parameters as slice emittance & energy spread become critical
  - The shape of the photocathode laser → distribution of the slice parameters within the bunch

- The final estimation of 4D and 6D brightness at the end of S2E simulations reveal ?

Details on my poster

THANK YOU.

Contact

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Preliminary simulation of Terahertz superradiation generation at PITZ

Duo Xu
Zeuthen, 27/06/2025

HELMHOLTZ

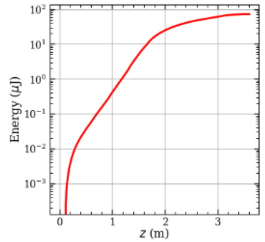
Parameter study for electron bunch at undulator entrance

with ideal 6D Gaussian distribution

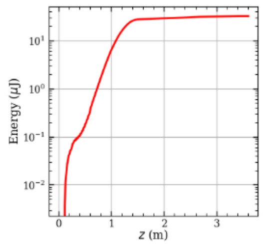
Initial beam parameters:

α_x	10	β_x	17.5 m	$\varepsilon_{x,n}$	2 μm
α_y	9.75	β_y	1.125 m	$\varepsilon_{y,n}$	2 μm
$\sigma_{E,cor}$	-85 keV	$\sigma_{E,uncor}$	8.5 keV	p_z	17 MeV/c

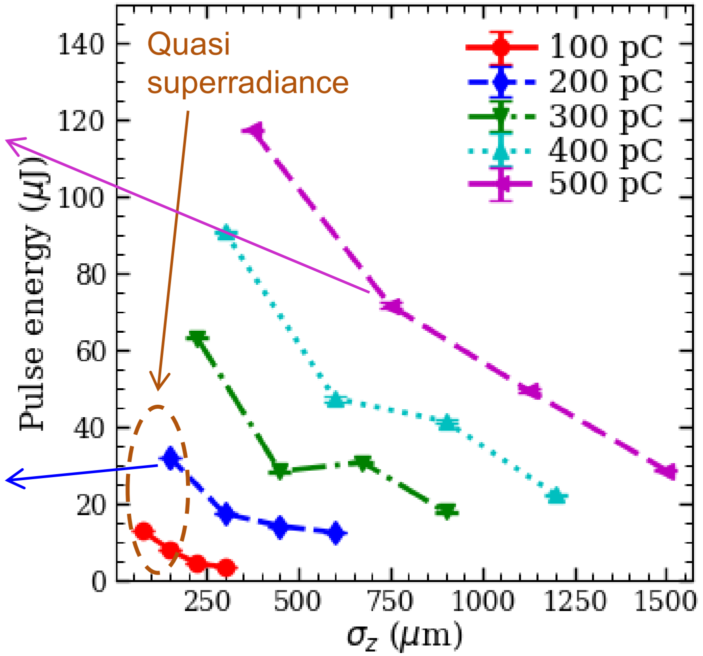
- The shortest rms bunch length was estimated according to previous studies of bunch compression at PITZ

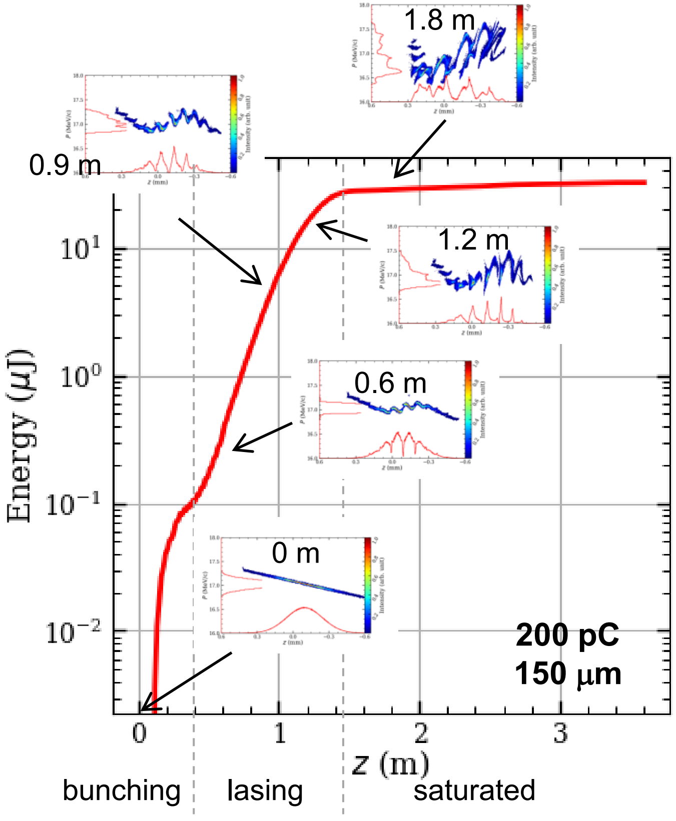


500 pC 750 μm

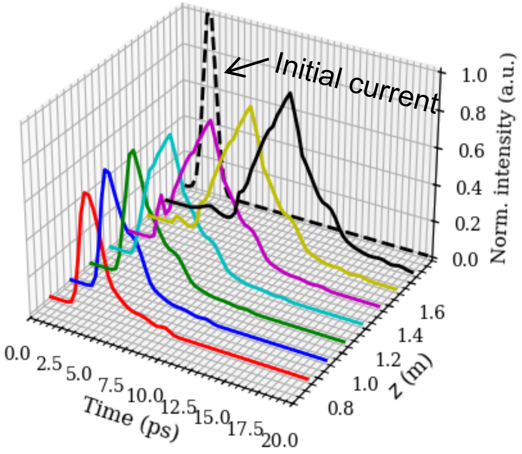


200 pC 150 μm





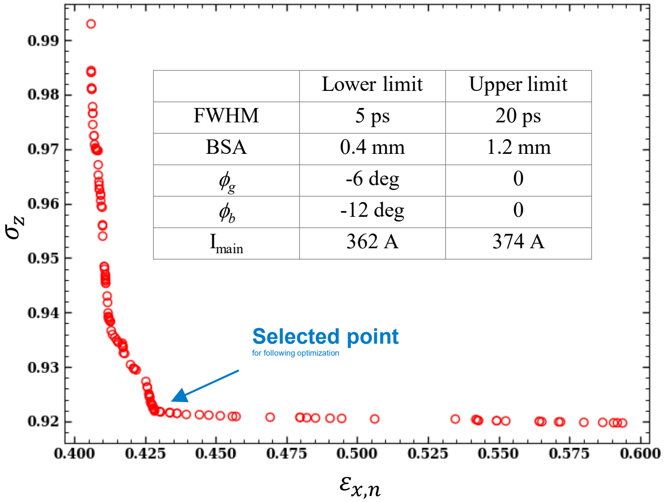
z (m)	FWHM (ps)	z (m)	FWHM (ps)
0.75	1.99	1.35	4.11
0.9	2.78	1.5	4.10
1.05	2.41	1.65	4.10
1.2	3.62		



Temporal profiles

Performance for the 200 pC 150 μm case:
Saturated undulator length **~1.4 m**
Saturated energy **~30 μJ**
THz pulse FWHM **4.1 ps**

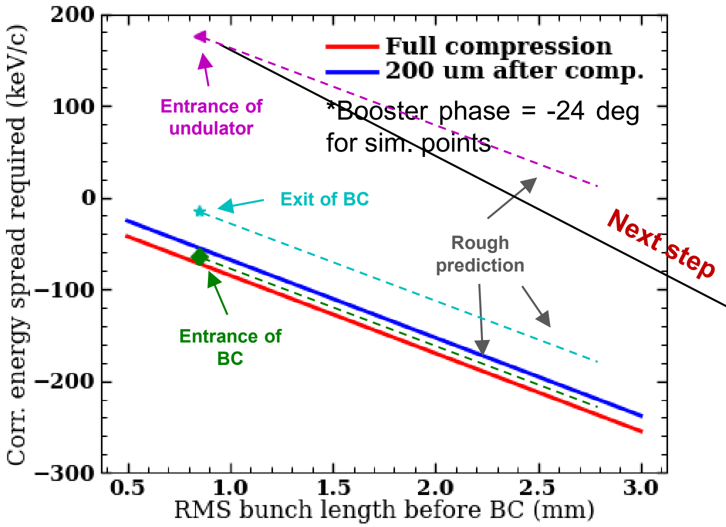
S2E simulation for generating desired electron bunch

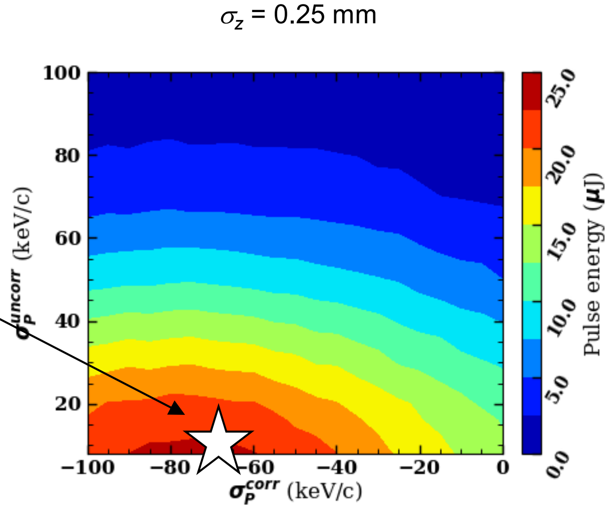


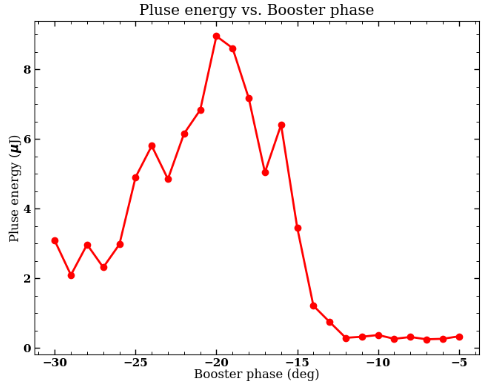
	Lower limit	Upper limit
FWHM	5 ps	20 ps
BSA	0.4 mm	1.2 mm
ϕ_g	-6 deg	0
ϕ_b	-12 deg	0
I_{main}	362 A	374 A

Optimized photoinjector parameters from minimizing bunch length and transversal emittance:

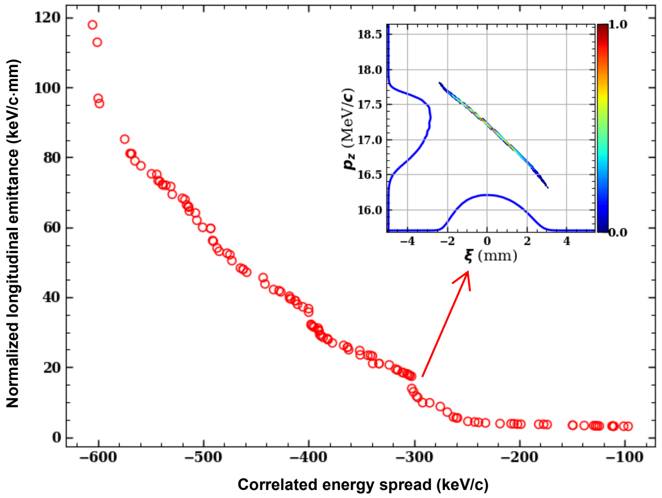
- **FWHM = 5 ps**
- **BSA = 1.2 mm**
- **ϕ_g = -5.73 deg**
- **I_{main} = 366.02 A**







Chirp flipped due to space charge effect -> bad FEL performance



Next steps for current PITZ facility:

1. Increase **laser length** and optimize **longitudinal phase space**;
2. Relax requirement for **target bunch length** step-by-step;
3. Reduce **charge**.

Suggestions for ideal machine design:

1. Increase **operating beam energy** to weaken space charge effect;
2. Shorten **drift space** after BC to prevent chirp flipping.

Thank you

Contact

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Nonlinear bunch compressors for DALI

Arthur Delan[1,2], U. Lehnert[1], A. Meseck[2], N. Mirian[1], R. Niemczyk[1], A. Wagner[1]

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[2] Johannes Gutenberg-Universität Mainz, Institute for nuclear physics

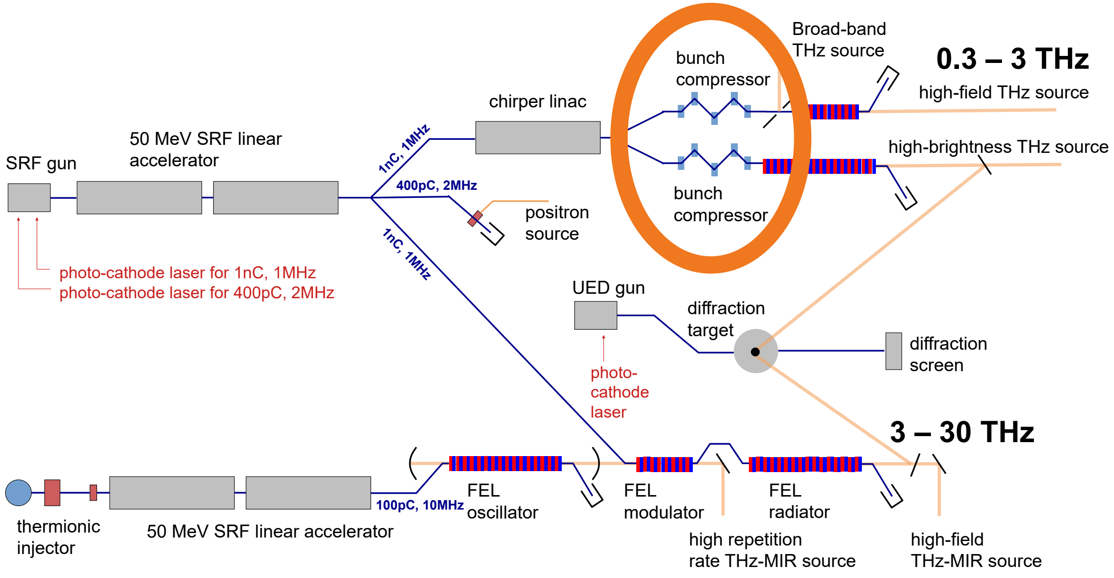
27th June 2025, 13th MT ARD ST3 meeting Zeuthen, DESY

Institute of radiation physics | ELBE | a.delan@hzdr.de | www.hzdr.de

Dresden Advanced Light Infrastructure

Successor to ELBE,

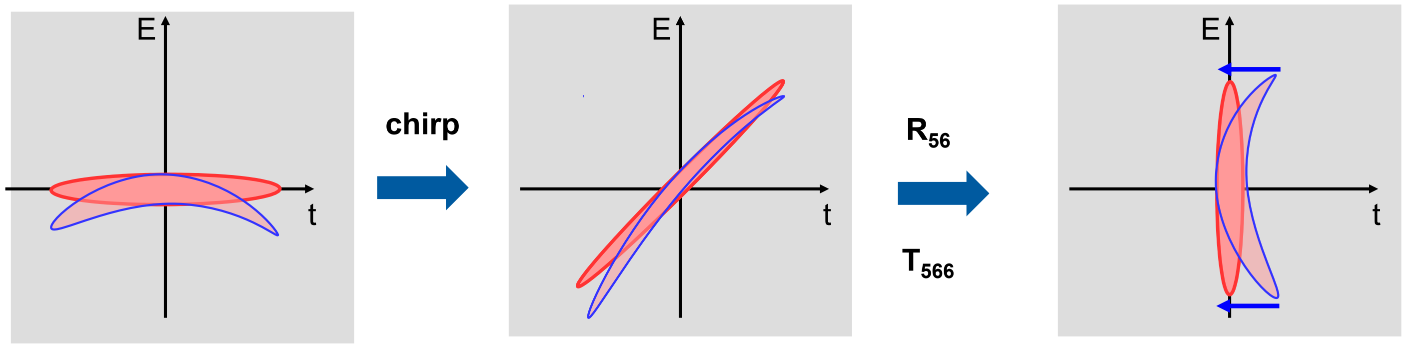
- increased bunch charge,
- energy
- tunable repetition rate
- sophisticated MIR generation scheme



THz sources require short bunches for superradiant emission

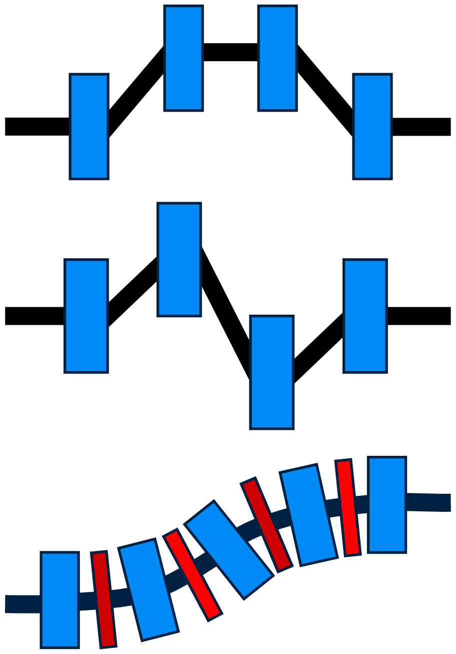
➢ compression by > 40, possible due to low energy spread of SRF gun

Bunch compression



- imprint corelated energy spread on bunch
- use energy dependent path length to transform energy deviation R_{56} into longitudinal shift

- limited by intrinsic energy spread and non-linearities in corelated energy spread
- use tailored higher order effects to compensate curvature



Structures to cause R_{56}:

- chicanes: T_{566} ~ -1.5 R_{56}
- arcs: T_{566} ~ 2 R_{56}
- using quadrupoles and sextupoles: arbitrary

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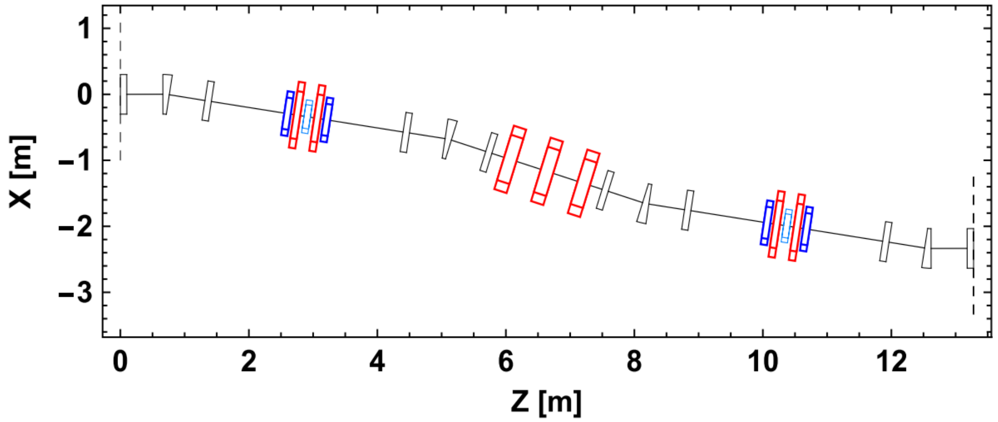
Checking options

multi bend achromat

plenty degrees of freedom allow for tuning of R_{56} and higher orders

limited footprint



Max IV layout of the inter storage ring bunch compressor
black: dipoles, red: quadrupoles

DOI: 10.1103/PhysRevAccelBeams.23.100701