PSI Center for Accelerator Science and Engineering

Slice Energy Spread in FELs

LEDS-Workshop 2024

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Outline

- Impact of Energy Spread on FEL Performance
- Projected, Intrinsic and Slice Energy Spread
- SASE vs Seeded FEL
- Sources of Energy Spread:
  - Intra-Beam Scattering
  - Microbunching Instability
- Conclusion

Landau Damping

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Landau Damping is the process that any coherent structure (here microbunching) is smeared out due to runtime differences for different energies.

Landau Damping counteracts the formation of the microbunching of the FEL process.

Thus there is a guideline that the energy spread must be small:

$$\frac{\sigma_\gamma}{\gamma} \ll \rho$$

← *FEL Parameter*

Since rho depends indirectly on the energy spread,

where is the actual optimum point?

Optimizing Compression for Shortest Gain Length

FEL theory gives a correction factor to the FEL gain length L_g as:

$$L_g = \frac{\sqrt{3}}{2}\frac{\lambda_u}{4\pi\rho}\left[1+\left(\frac{\sigma_\gamma}{\rho\gamma}\right)^2\right]$$

With the definition of the FEL parameter ρ:

$$\rho = \frac{1}{\gamma}\left[\left(\frac{f_c K}{4k_u\sigma_x}\right)^2\frac{I}{2I_A}\right]^{\frac{1}{3}}$$

λ_u:	undulator period
K:	undulator parameter
f_c:	coupling factor (~ 1)
K_u:	undulator wavenumber
σ_γ:	beam size
γ:	beam energy
I:	current
I_A:	Alfven current (~17 kA)

Since peak current and energy spread scales roughly with the compression factor, there is an optimum compression point between:

- Energy Spread is negligible, but FEL parameter is too small
- FEL parameter is large but Landau damping reduces efficiency of FEL process

Optimizing Energy Spread

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Scaling current and energy spread by same factor to find shortest gain length

Aramis parameters:

- Current: 2 kA
- Energy Spread: 1 MeV
- Energy : 6 GeV

Normalized Energy Spread

$$\frac{\sigma_E}{\rho E} = 0.35$$

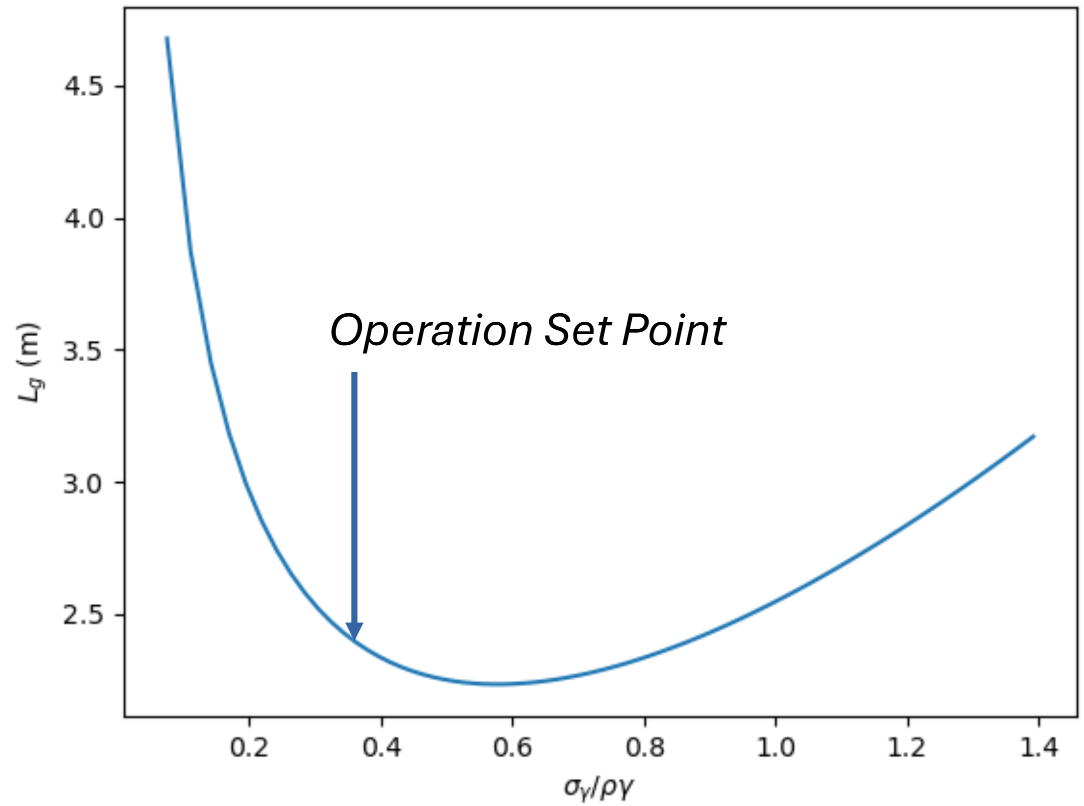
Athos parameters:

- Current: 2 kA
- Energy Spread: 1 MeV
- Energy : 3 GeV

Normalized Energy Spread

$$\frac{\sigma_E}{\rho E} = 0.17$$

Aramis Compression Scan



Aramis is close to the optimum compression while Athos would benefit from higher current. However collective effects (CSR, Wakefields) in beam transport favor reduced compression

FEL Performance at Full Optimization

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Energy Spread Optimization:

$$\frac{\sigma_\gamma}{\gamma} \approx 0.5\rho \quad \Rightarrow \quad \rho^2 \frac{\sigma_\gamma}{\gamma} \approx 0.5\rho^3$$

$$\Rightarrow \quad \rho^2 \frac{\sigma_\gamma}{\gamma} \approx \frac{1}{I_A \gamma^3} \left(\frac{f_c K}{8 k_u}\right)^2 \frac{I}{\sigma_x^2}$$

$$\Rightarrow \quad \rho^2 \frac{\sigma_\gamma}{\gamma} \approx \frac{1}{I_A} \left(\frac{f_c K}{8 \gamma k_u}\right)^2 \frac{I}{\epsilon_N \beta}$$

$$\Rightarrow \quad \rho \approx \frac{1 + K^2/2}{I_A} \left(\frac{f_c K}{8 \gamma k_u}\right)^2 \boxed{\frac{I}{\epsilon_N^2 \sigma_\gamma}}$$

6D beam brilliance

Focusing Optimization:

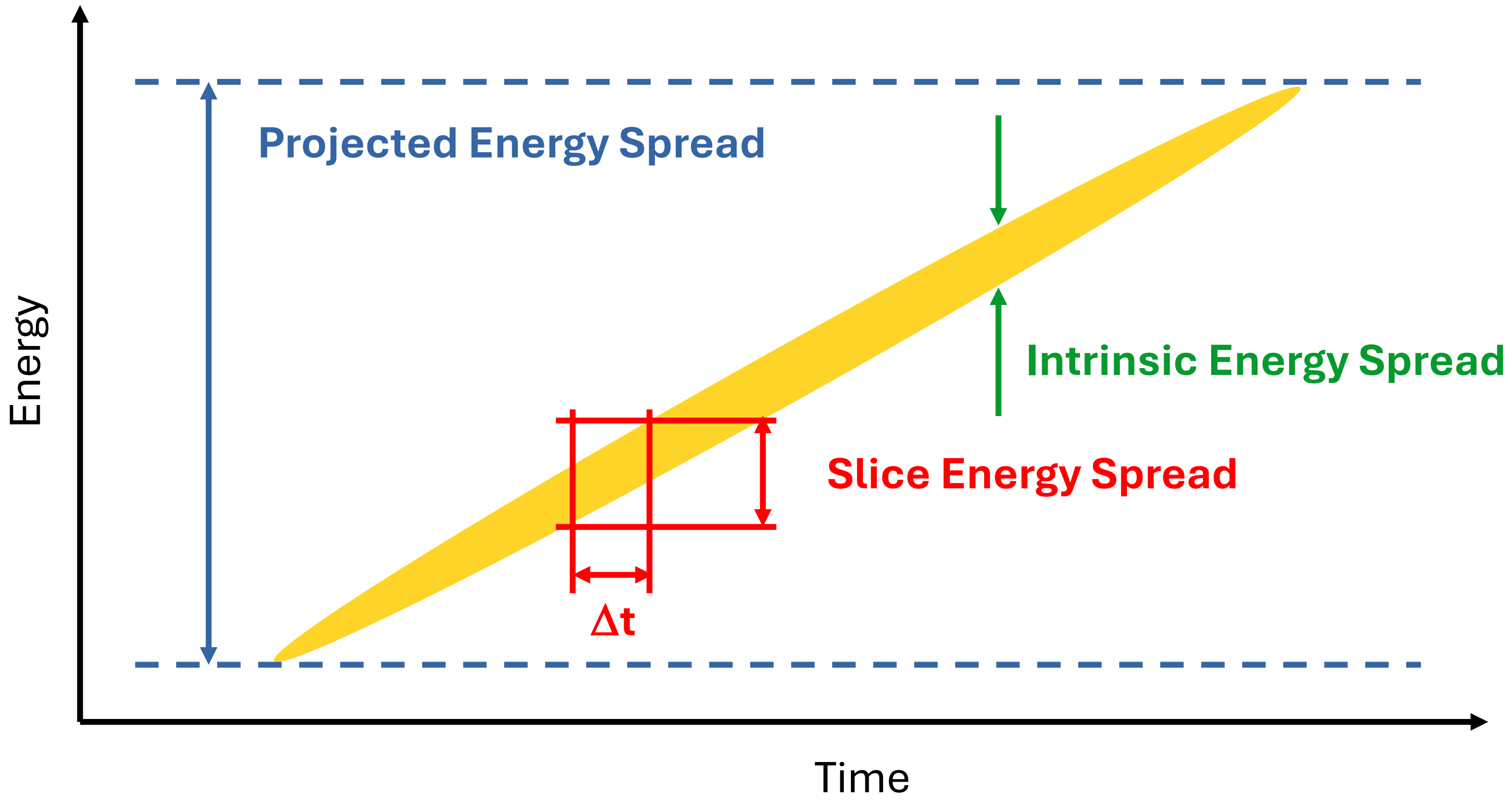
Stronger focusing will push more kinetic energy into the betatron oscillation thus modulating the longitudinal velocity in full analogy to energy spread)

$$\frac{\lambda_u}{4\lambda\gamma} \frac{\epsilon_n}{\beta} \approx 0.5\rho$$

betatron-function

For source development 6D brilliance can be more important than 5D Brightness.
Keep an eye on the energy spread!!!

Longitudinal Phase Space Distribution and Various Energy Spreads



Instead of **Projected** and **Intrinsic** energy spread, the terms **Correlated** and **Uncorrelated** energy spread can be used.

They are almost interchangeable beside a subtle difference that the intrinsic energy spread can vary along the bunch while the uncorrelated energy spread is the projection of the intrinsic energy spread.

Slice energy spread depends on the slice duration Δt and is often in context to a characteristic scale in the system (e.g. cooperation length of FEL, resolution of streaker)

FEL and Slice Energy

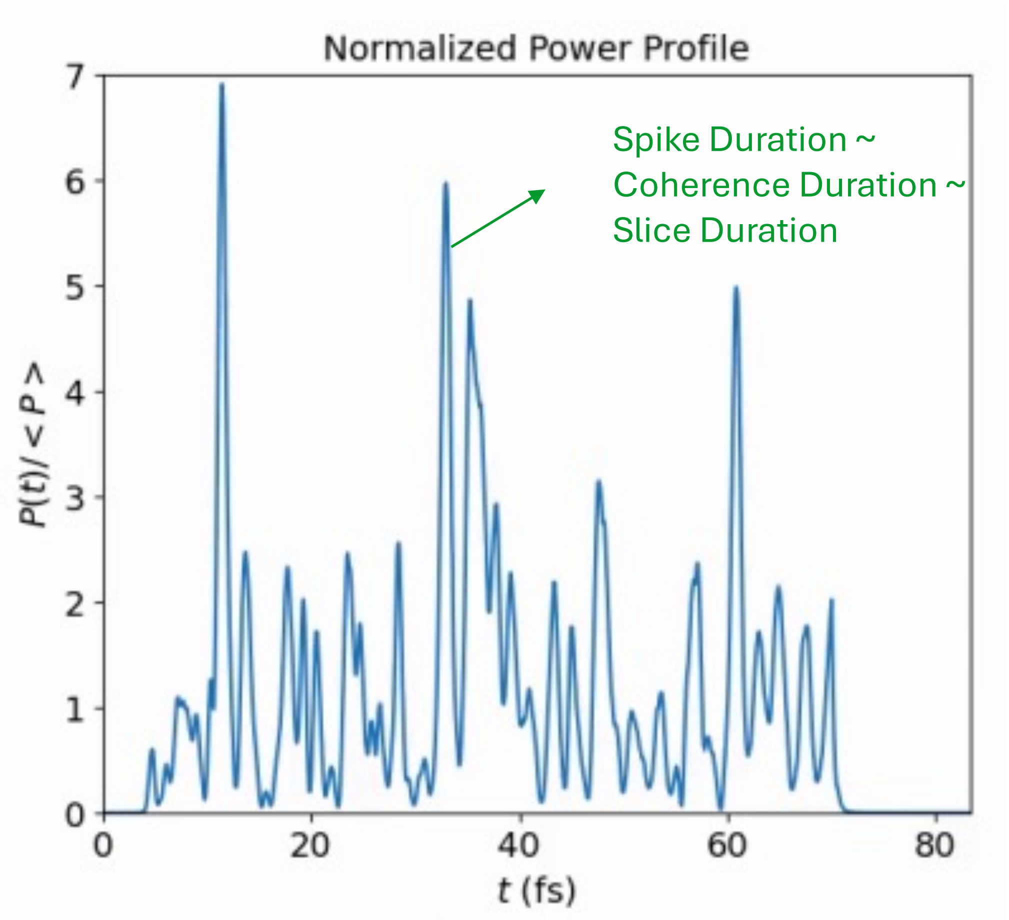
In FEL the field advances one radiation wavelength per undulator period. The total distance is called slippage length

Athos: about 800 nm at 1 nm wavelength

Over the duration of the slippage the radiation field 'samples' the variation in the beam parameter such as emittance, mean energy and energy spread. Thus, it is the logical time duration for evaluating the slice parameters. (*Athos: about 2.6 fs*)

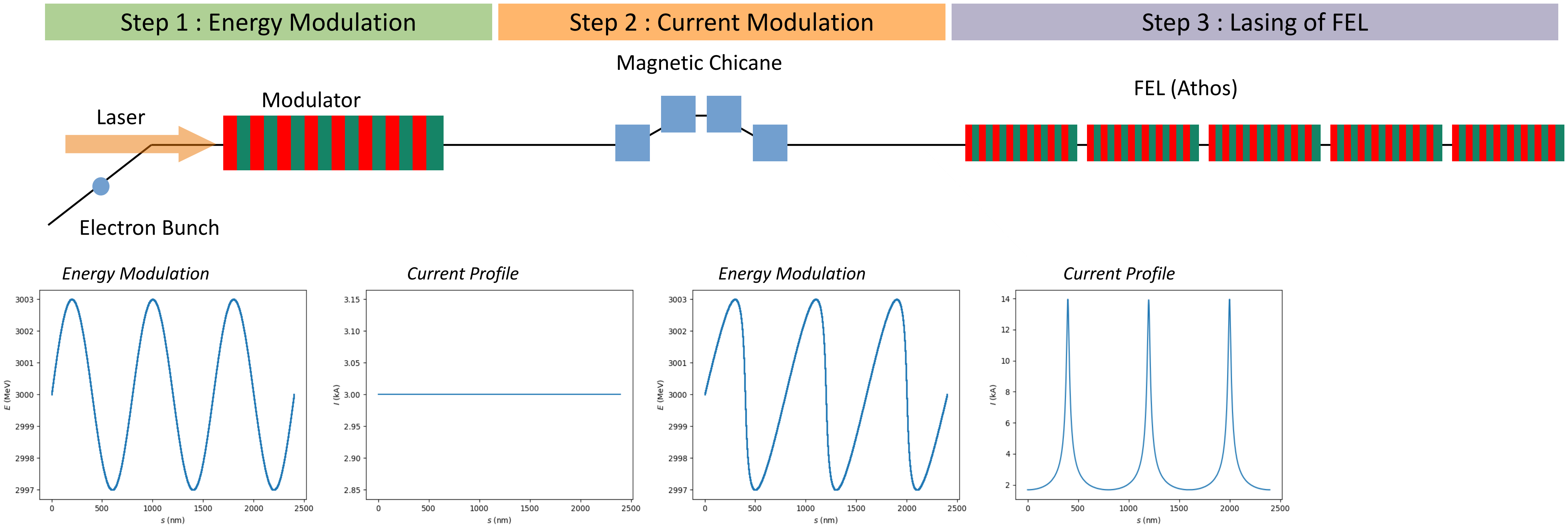
Regions of the beam, separated by more than the slice duration, have no interaction and amplify the radiation independently (and possibly differently) in SASE operation

SASE Pulse at Athos



External Seeding (HGHG and EEHG)

In HGHG/EEHG an external laser modulates the beam in energy. The dispersion of a chicane converts it into current spikes with length shorter than the radiation wavelength. The beam emits coherently in the undulator.



The drawback is that the electron beam gains an energy modulation, which is seen on the ‘slice’-level as an increase of energy spread.

External Seeding and Energy Spread Increase

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High-Gain Harmonic Generation (HGHG):

A single energy modulation which scales with the harmonic number

$$A = \frac{\Delta E}{\sigma_E} > h$$

Slice energy spread:

$$\hat{\sigma}_E = \sigma_E \sqrt{1 + \frac{1}{2} A^2}$$

Intrinsic energy spread from machine

Slice energy spread seen by FEL process

Echo-Enabled Harmonic Generation (EEHG):

Two modulation stations but with moderated energy modulation requirement:

$$A_1 \approx 3 \quad A_2 \approx 0.5 - 3$$

Slice energy spread:

$$\hat{\sigma}_E = \sigma_E \sqrt{1 + \frac{1}{2}[A_1^2 + A_2^2]}$$

For good performance seeded FELs need lower intrinsic energy spread.

In soft X-ray FEL the trade-off can be made in the emittace or current.

Energy Spread in Injectors

The injector is characterized by the 6D brilliance and is at best preserved in a single pass machine.

However, non-linear processes can degrade the energy spread and – with that – the brilliance.

At SwissFEL there are two main mechanisms, driving the energy spread growths at long the machine:

- Intra-Beam Scattering (IBS)
- Microbunch-Instability (uBunch) at high frequencies.

Intra-Beam Scattering

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Simple Model [Piwinski in Proc. Of Int. Conf. High-energy Accelerators, SLAC, 1974]

Compression → $\frac{I_f}{I_0}$

Intra-Beam Scattering → $\int_0^L \frac{\sqrt{8\pi}r_e}{I_A}\frac{I_0}{\bar{\sigma}_\perp\bar{\epsilon}_N}dz$

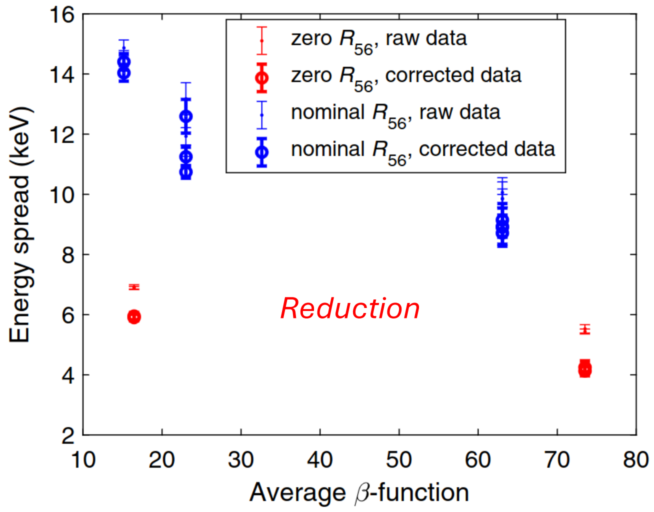
$$\sigma_E = \frac{I_f}{I_0}\sqrt{\int_0^L \frac{\sqrt{8\pi}r_e}{I_A}\frac{I_0}{\bar{\sigma}_\perp\bar{\epsilon}_N}dz}$$

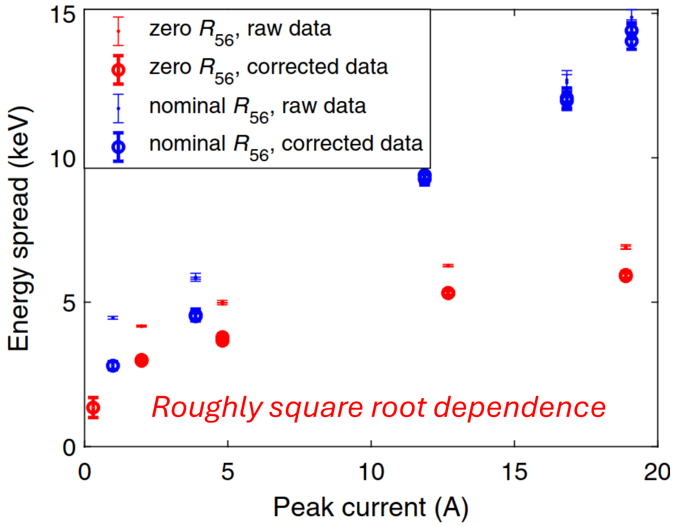
- I_f: *Reduced Final Current*
- I_0: *More current from the gun and less compression*
- L: *More compact Injector*
- $\bar{\sigma}_\perp$: *Large beam size along machine (new optics)*

Measurement at SwissFEL Injector:

[Prat et al, PRAB 25, 104401(2022)]

Large optics and reduced current increases the intrinsic energy spread of **uncompressed** beam.





Means of Mitigating Intra-Beam Scattering

I. Higher Current from the RF Gun

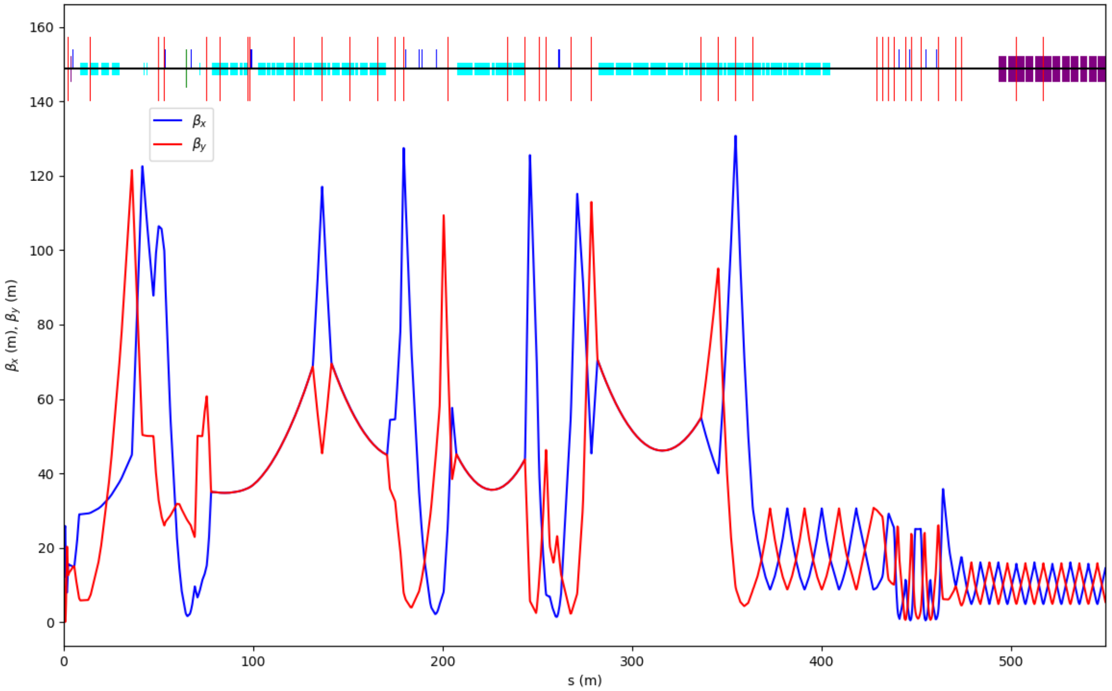
For SwissFEL we can reduce the laser pulse duration but increase the transverse size to increase the current from 20 A to 40 A, but at the cost of an increased emittance.

A 40 A beam from the SwissFEL gun has been demonstrated by Anastasiia Riabchikova and Eduard Prat last week!

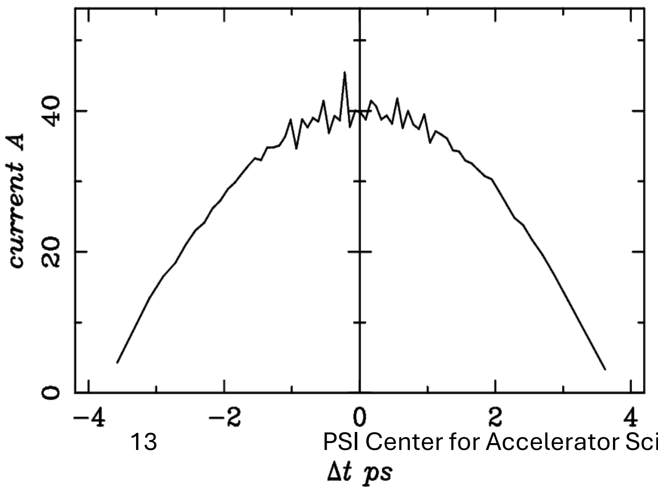
II. Relaxed Optics

Linac sections are mostly free drifts with some central triplet focusing. Betafunction increases from 10/20 m to about 40 m.

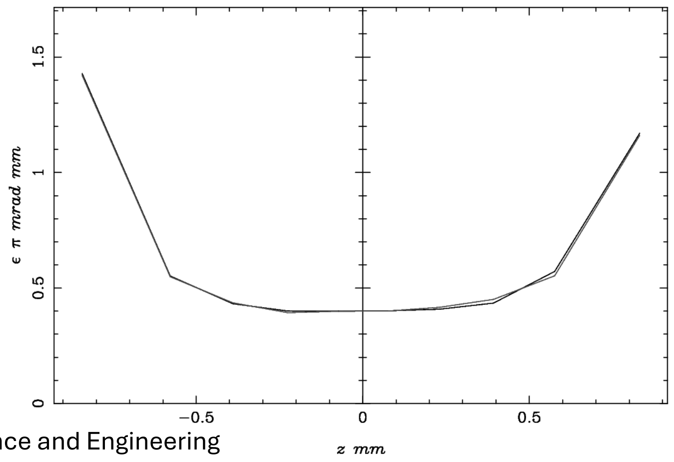
New Optics for Main Linac



Current Profile



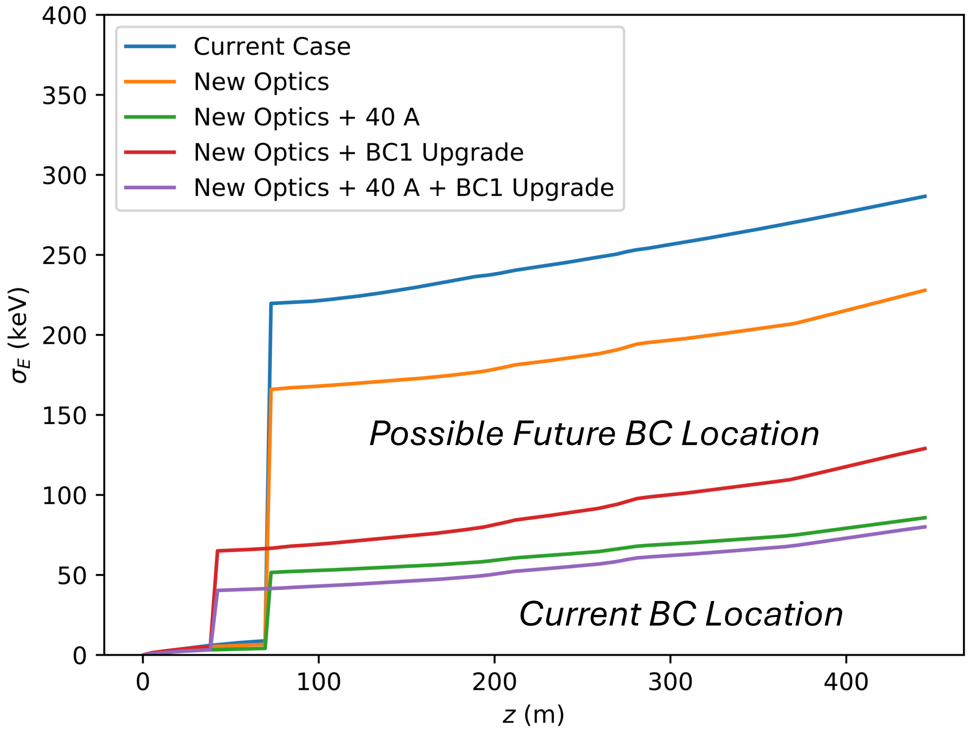
Slice Emittance



Putting it Together for IBS

Using the Intra-Beam Scattering model to estimate the effect of higher current, relaxed optics and a possible reduction in injector length (*might be feasible with a future energy upgrade of SwissFEL*).

Reference case is a peak current of 500 A, used for the demonstration of EEHG at Athos.



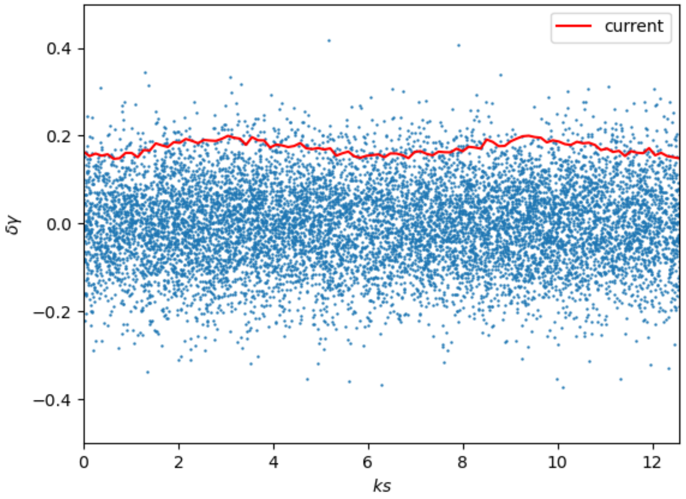
- Strong improvement by combination of higher current and relaxed optics.
- Injector upgrade (years from now) not essential for lower energy spread but a single/strong compression in first bunch compressor is mandatory.
- Improvement of factor 3 and more, which allows for more compression (e.g. 1 kA, 150 keV energy spread).
- Current priority is to verify the scaling at SwissFEL and to study the impact of micro bunching.

Beam brilliance is rather defined by the entire machine than the injector alone.

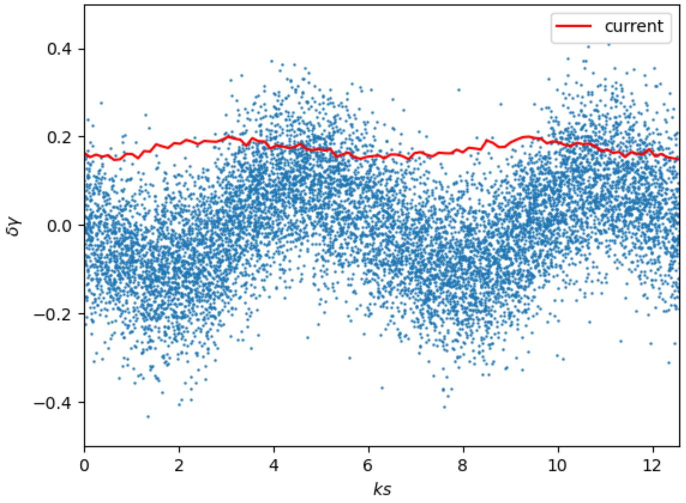
Micro-Bunch Instability

Instability works similar to optical klystron effect in FELs:

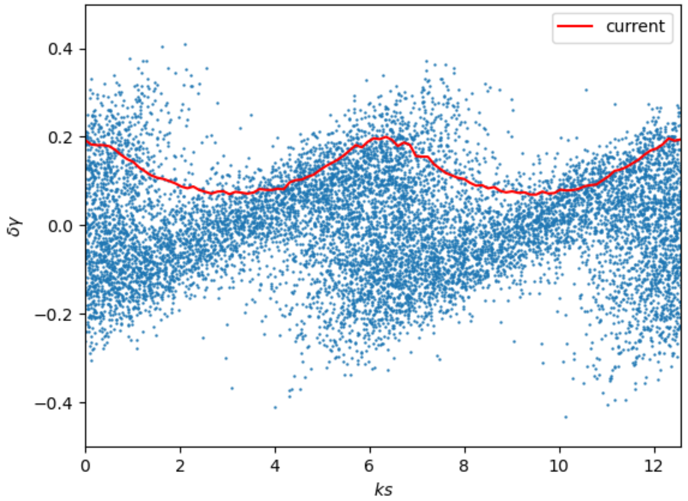
Bunching ***b*** *(Ripple in Beam Current)*



Space-charge induces energy modulation $\delta\gamma$



R56 of Chicane concerts energy modulation to stronger ripple



$$\delta\gamma_{j+1} = \delta\gamma_j - \frac{I}{e\pi I_A}\frac{Z_j(k)\Delta z}{Z_0} b_j$$

$$b_{j+1} = \left[b_j - i\frac{kR_{56}}{\gamma}\delta\gamma_j \right] e^{-\frac{1}{2}(kR_{56}\frac{\sigma_\gamma}{\gamma})^2}$$

For free drift ($R_{56} = \Delta z/\gamma$^2) the bunching factor ***b*** oscillates : ***Plasma oscillation***

Current end energy modulation are 90 degree apart (Impedance Z(k) has pure imaginary value)

Micro Bunching Instability: High-Frequency Limit

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High frequencies components with a length scale shorter than the slice length are added up to incoherent energy spread.

To compare with measurement at the injector we use a simple two step model:

Gun section → ***Laser Heater Chicane*** → ***Rest of Injector***

The bunching after laser has a dependence on R56!

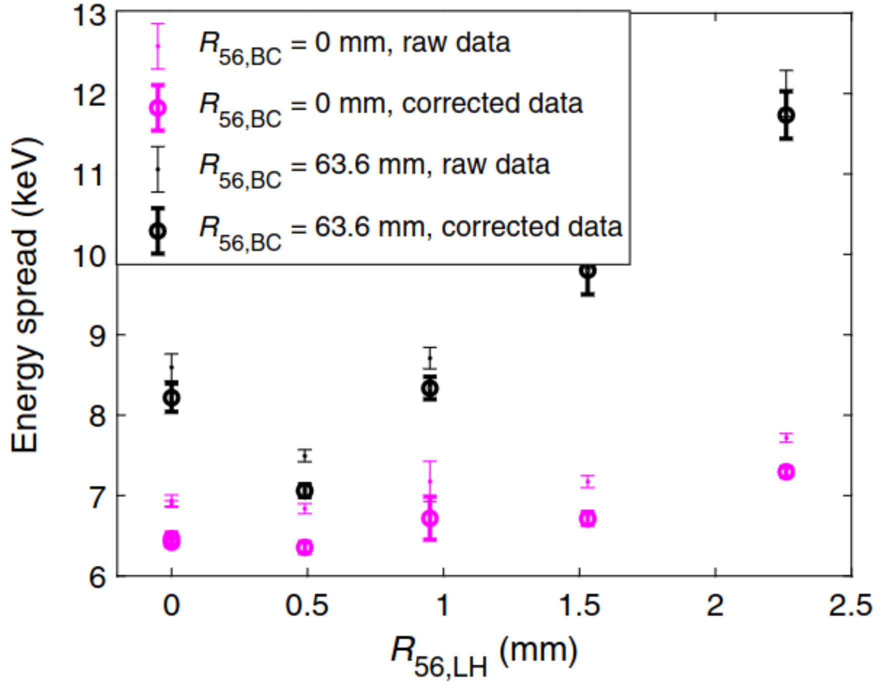
$$b_{j+1} = \left[1 + i\frac{kR_{56}}{\gamma}\frac{I}{e\pi I_A}\frac{Z_j(k)L_{gun}}{Z_0}\right] e^{-\frac{1}{2}(kR_{56}\frac{\sigma_\gamma}{\gamma})^2} b_j$$

Bunching is influenced by:

- Landau damping (driven by IBS!)
- By a proper choice of R56 for a given frequency

(Impedance Zj(k) has imaginary value!!!)

[Prat et al, PRAB 25, 104401(2022)]



Modelling of IBS and uBunch Instability in the Gun

Modelling both effects in the gun is very challenging since it requires the correct physics of Coulomb interaction of few particles at short distance. Most codes have a shielding or filtering mechanism to exclude numerical noise at short distances.

The qualitative behaviour of IBS can be approximated by the Piwinski model though it has the parameter of the natural logarithms of the maximum and minimum impact parameter of the Coulomb scattering.

Similar is the low-gain uBunch model to reproduce the general dependence on machine parameter. However, for high frequencies the Landau damping is dropping the bunching factor below the shot noise level in this model, which is not physical.

Conclusion

Energy spread limits the peak current of an electron beam, driving the FEL amplification. The lower the energy spread the more the beam can be compressed.

In seeded FELs the requirement for the energy spread are more stringent since the seeding process increases the slice energy spread.

Injectors, driving hard X-ray FELs are optimized for smallest emittance on the cost of increased energy spread. Soft X-ray FELs, in particular seeded ones, are rather optimized for energy spread. Not clear if one injector can drive both beamline.

Intra-Beam Scattering and Microbunching Instability are the driving process to define the energy spread (at least at SwissFEL). Some measures are studied to reduce the impact of those two processes.