PSI Center for Accelerator Science and Engineering

Intrabeam Scattering and 6D Brightness

Modelling, Measurement, and the Road to a Brighter SwissFEL electron source

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Linear Accelerator Conference 2026, Daejeon, Korea

TH1A003

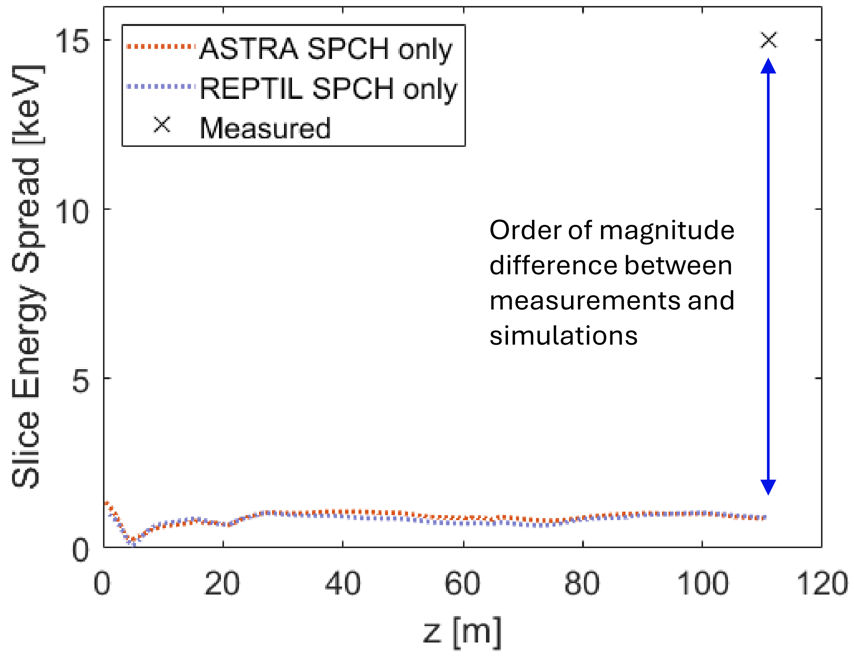
Contents

Contents

- **Overview of the History of Energy Spread in SwissFEL**
- Numerical and Analytical Modelling of Intrabeam Scattering
- Influence of IBS on electron sources
- Design of SwissFEL+ electron source in the Presence of IBS
- Summary

Early Observations and Studies (SwissFEL commissioning and Early Operation)

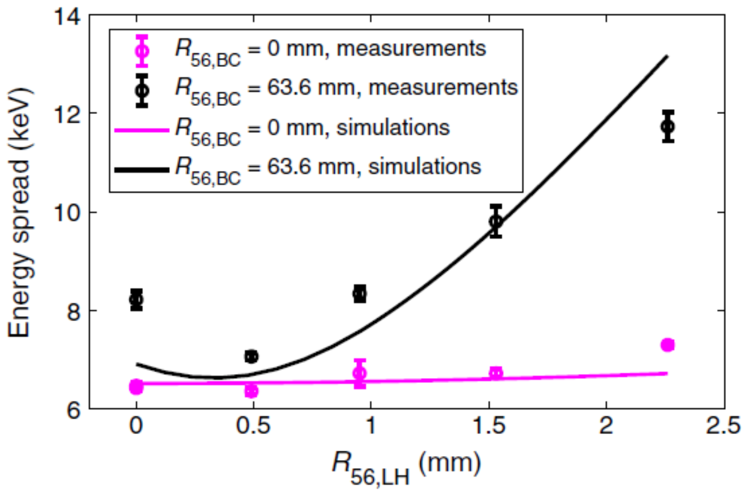
- Early measurements during the SwissFEL commissioning found an issue with bunch compression where the machine performance did not match the expectations of simulations.
- An expectation that this related to the slice energy spread (SES) led to measurements that were performed on the injector which **found SES values as large as 15 keV.**
- Simulations using **ASTRA and other codes predict values of ~1 keV** using the regular space-charge simulation.
- There was a suspicion here that the contribution to the slice energy spead may come from **intrabeam scattering and other effects** but to what extent of their contribution was unclear.

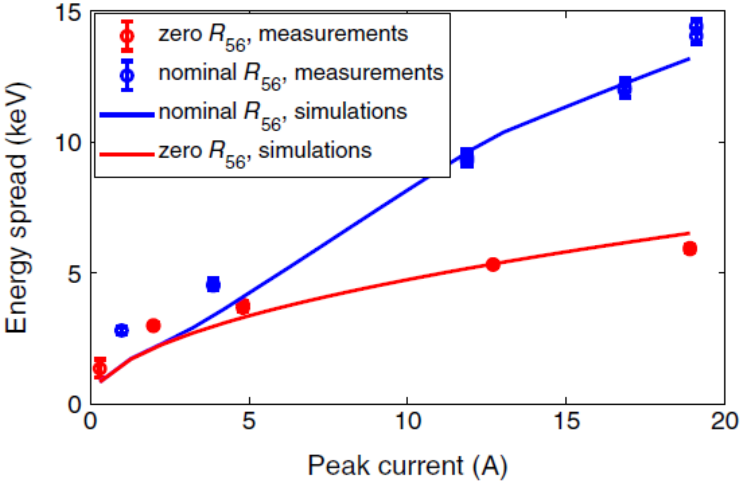


Reference: Prat, E., Dijkstal, P., Ferrari, E., Malyzhenkov, A., & Reiche, S. (2020). High-resolution dispersion-based measurement of the electron beam energy spread. *Physical Review Accelerators and Beams*, *23*(9), 090701.

Determination of Phenomena (~2022)

- Performed some measurements that disentangled the energy spread contributions:
  - ➢ Contribution 1: Microbunching instabilities = 13 keV
  - ➢ Contribution 2: IBS = 6 keV
- Early modelling of IBS used the Piwinski/Huang model.
- We also attempted to investigate new methods to model IBS through the use of Rutherford scattering and also using empirical models developed using one-to-one modelling using the Barnes-Hut Model (we were initially unsure if the Piwinski worked in this regime).
- We're initially unable to resolve a discrepancy between the model and measurements, and at first we added an arbitraty scalling factor to fit IBS data.





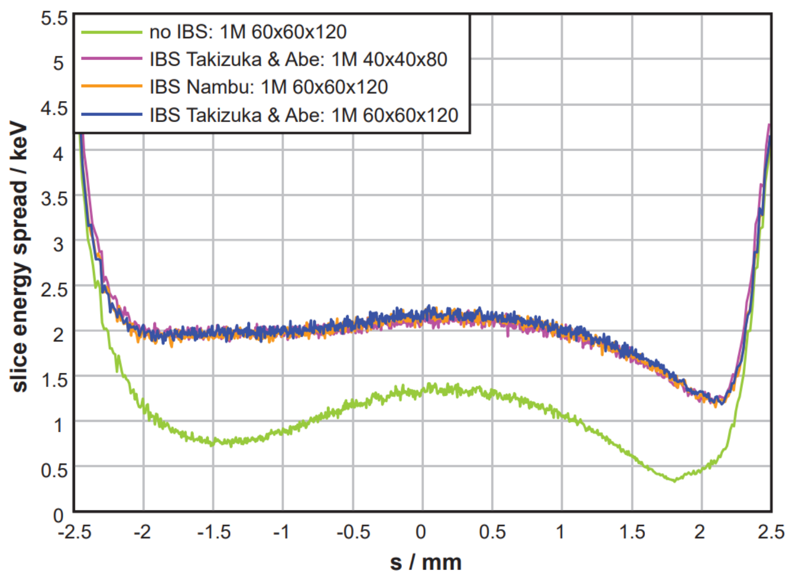
Reference: Prat, E., Craievich, P., Dijkstal, P., Di Mitri, S., Ferrari, E., Lucas, T. G., ... & Schietinger, T. (2022). Energy spread blowup by intrabeam scattering and microbunching at the SwissFEL injector. *Physical Review Accelerators and Beams*, *25*(10), 104401.

Contents

Numerical Modelling of IBS (2022-2025)

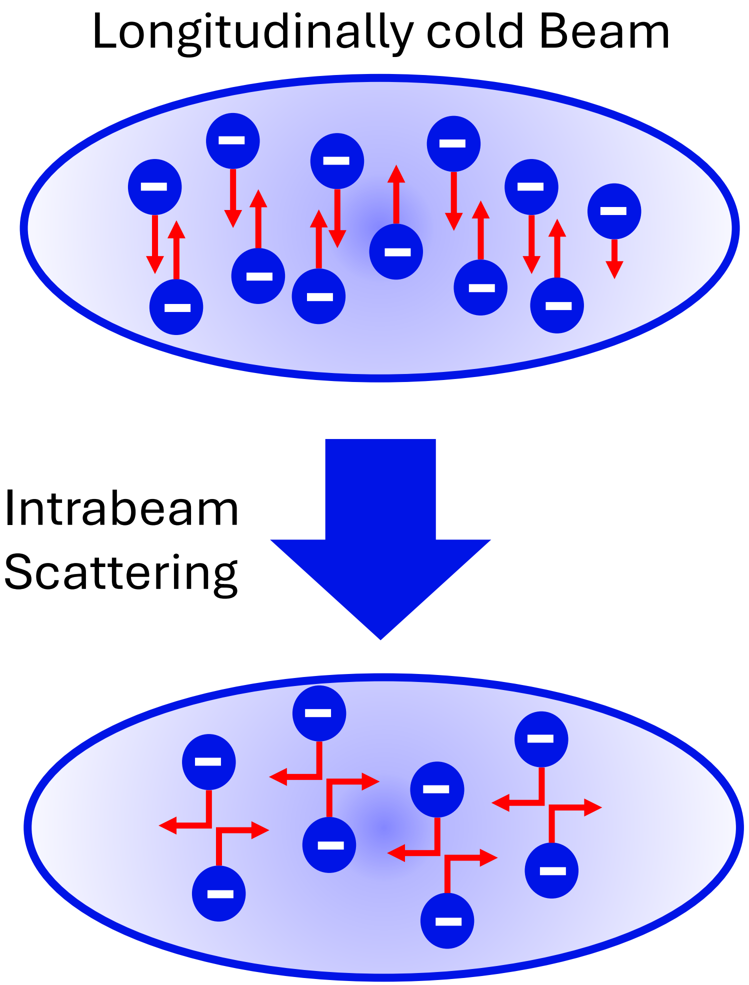
- Collaboration established after meeting at FEL22 in Trieste.
- A stochastic Monte Carlo model in the REPTIL tracking code.
- Based on Nanbu's cumulative binary collision method, where particles are grouped into spatial cells, and random pairs within each cell undergo effective Coulomb collisions.
- These collisions are ultimately modelled as momenta rotations in the centre-of-mass frame of the particle pair.
- This enables accurate IBS modelling for arbitrary distributions.

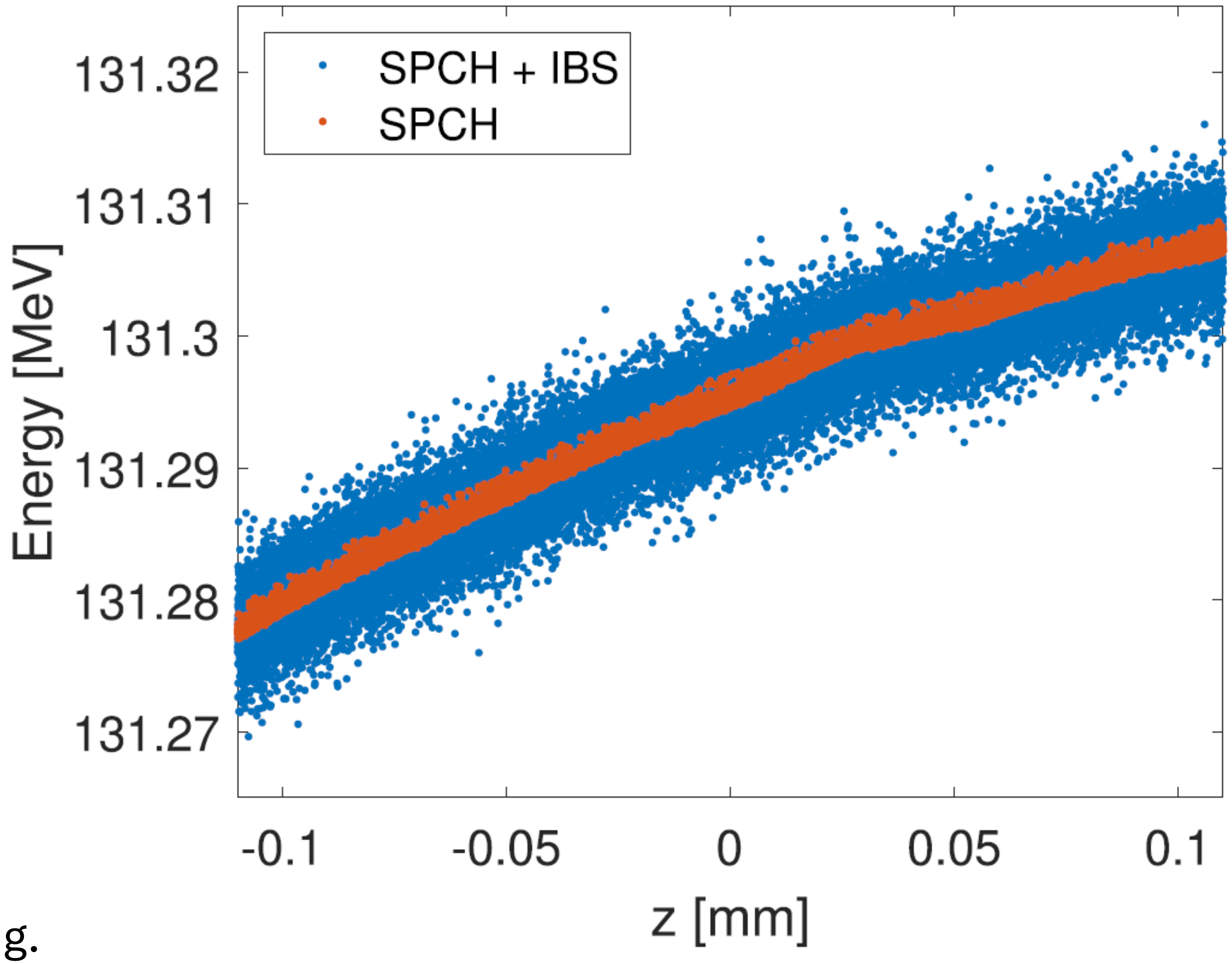
Reference: Gjonaj, E., De Gersem, H., Limberg, T. Intrabeam Scattering Effects in the Electron Injector of the of the European XFEL, Proceedings of the FEL2022, Trieste, Italy, WEP14, (2022).



A numerical method that could account for IBS-induced SES and we had measurements to compare it to.

What does IBS do in longitudinally cold electron sources?

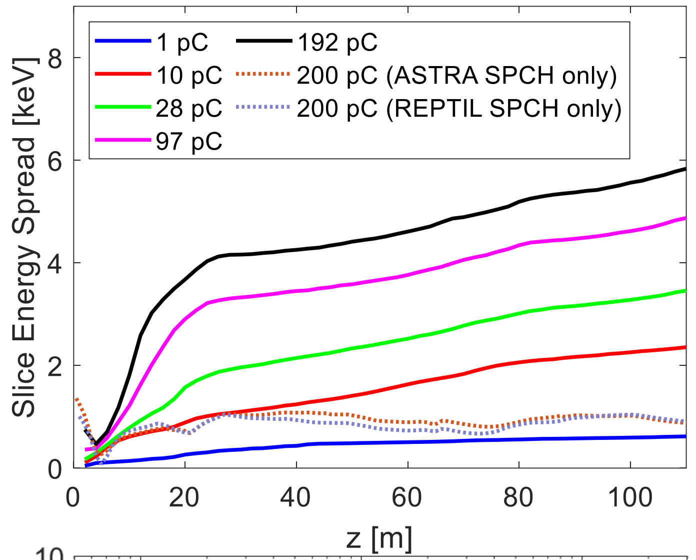


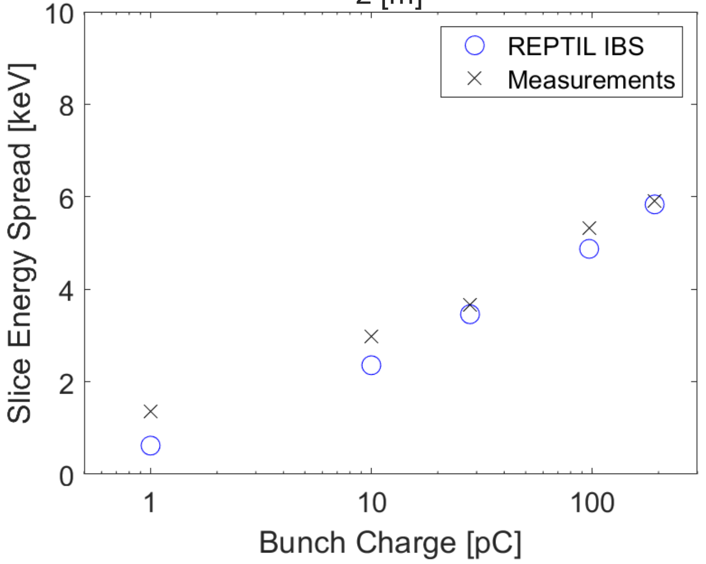


Most energy spread comes from Scattering.

Results of Numerical Modelling (2023)

- A model of the SwissFEL injector was initially made in ASTRA matching the optics of the machine and including the ‘switched-off’ laser heater and magnetic compressors.
- This was translated into the REPTIL code by E. Gjonaj and ran with and without IBS ‘switched on’.
- Comparison to the measured values illustrated strong agreement.
- We can now simulate IBS in injectors.





Reference: Lucas, T. G., Craievich, P., Prat, E., Reiche, S., & Gjonaj, E. (2026). Accurate modelling of intrabeam scattering and its impact on photoinjectors for free-electron lasers. *Scientific Reports*, *16*(1), 2629.

Development of Analytical Model

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- But of course numerical codes are slower than analytical calculations so we continued on this front.
- A natural extension of Piwinski and Huang models that took into account the relatively ‘cold’ nature of the longitudinal phase-space.
- Use of slice values to calculate the contribution.
- Model is made for **longitudinally cold photoinjectors** and may vary for other machines.
- Note that some models introduce correction factors to the original piwinski to account for energy spread but in the operational regime of our photoinjectors these are not observed.

$$\sigma_\gamma^2 = \sigma_{\gamma,0}^2 + \frac{r_e^2 N_b \Lambda_c}{4\sigma_x \epsilon_N \sigma_z}\Delta s,$$

$$N_b/\sigma_z = \sqrt{2\pi}\frac{q_s}{ce\Delta z_s} = \frac{\sqrt{2\pi} I_p}{ce}$$

2D motion in the reference frame of the bunch

$$\sigma_\gamma^2 = \sigma_{\gamma,0}^2 + \frac{\sqrt{2\pi} r_e^2 I_p \Lambda_c}{4ce\sigma_{r,s}\epsilon_{N,s}}\Delta s.$$

$$\Lambda_c = \ln\left(\frac{\Delta\gamma_{\max}}{\Delta\gamma_{\min}}\right), \quad \Delta\gamma_{\max} = \gamma^2\sigma_{r',s}, \quad \Delta\gamma_{\min} = \frac{r_e}{\sigma_{r,s}\sigma_{r',s}}.$$

Reference: Lucas, T. G., Craievich, P., Prat, E., Reiche, S., & Gjonaj, E. (2026). Accurate modelling of intrabeam scattering and its impact on photoinjectors for free-electron lasers. *Scientific Reports*, *16*(1), 2629.

Results of Numerical and Analytical Modelling

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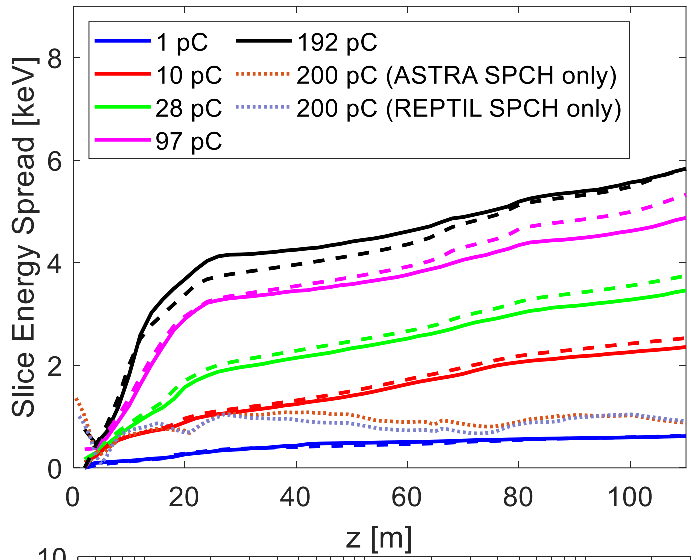
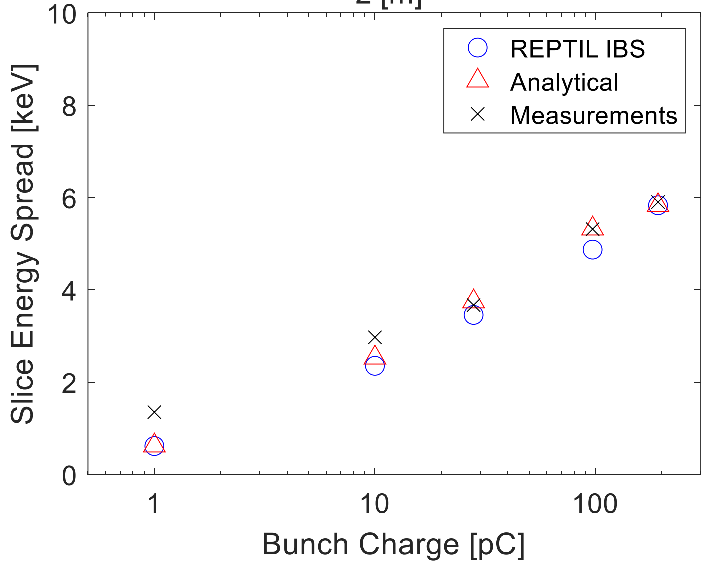
- Updated the Piwinski model and compared to the numerical model.
- Our small change in the interpretation is found to have strong agreement with the measurements.
- We can use the analytical model for optimisation studies as it is quick. However, numerical models remain vital to account for bunch distributions and other beam parameters that may not match our assumptions for photoinjectors.





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Contents

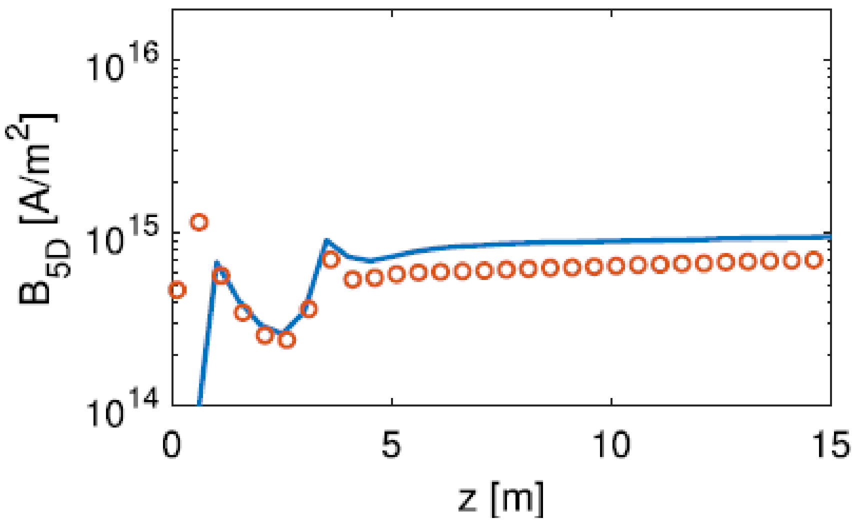
What do these results mean?

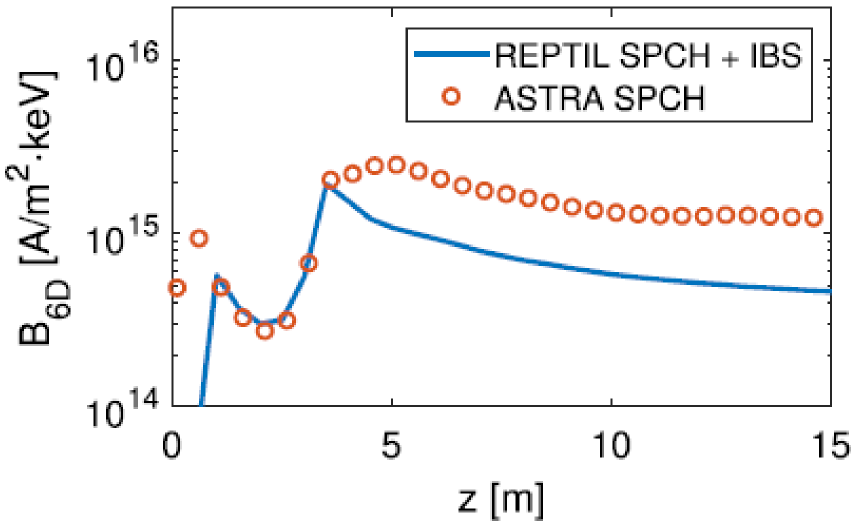
Conventional wisdom

- 5D brightness is largely locked in after reaching relativistic energies. Emittance compensation ensures good slice mismatch.

New paradigm

- IBS-induced SES leads to a decay in 6D brightness over z.





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How does this impact FEL design and operation?

Conventional 1D FEL Theory

$$\rho = \frac{1}{\gamma}\left[\left(\frac{K f_c}{4 k_u \sigma_x}\right)^2 \frac{I_p}{2 I_A}\right]^{1/3} \quad \Rightarrow \quad \rho \propto B_{5D}^{1/3}$$

However, in the machine's setup, we:

1. Compress as much as possible: $$\rho \approx \frac{\sigma_\gamma}{\gamma}$$
2. Have strong focusing in the undulator: $$\rho \approx \frac{\epsilon_N \lambda_u}{4\lambda\gamma\beta}$$

With some of algebra, you find: $$\rho \propto \frac{I_p}{\epsilon_N^2 \sigma_\gamma} = B_{6D}$$

Reference: Lucas, T. G., Craievich, P., Prat, E., Reiche, S., & Gjonaj, E. (2026). Accurate modelling of intrabeam scattering and its impact on photoinjectors for free-electron lasers. *Scientific Reports*, *16*(1), 2629.

How does this directly influence electron source and injector design?

1. If possible, start with higher current bunches to mitigate the requirement of compression:

We now know that IBS contributes to the performance of an XFEL:

How do we having enough final peak current while minimising SES from IBS and compression:

$$SES \propto \sqrt{I_p}$$

$$SES \propto C$$

2. Shorten the machine, and if you must compress, do so early (low z)

We now know that IBS contributes to the performance of an XFEL:

$$SES \propto \sqrt{z}$$

Concepts for the Electron Sources

We've now included the modelling of IBS in our electron source simulations. If we optimise for 6D brightness, rather than 5D brightness, does this change our operational point?

Optimisation using Surrogate optimiser. We find that the optimised operational points are very similar.

-> The requirements for emittance compensation dominate the requirements.

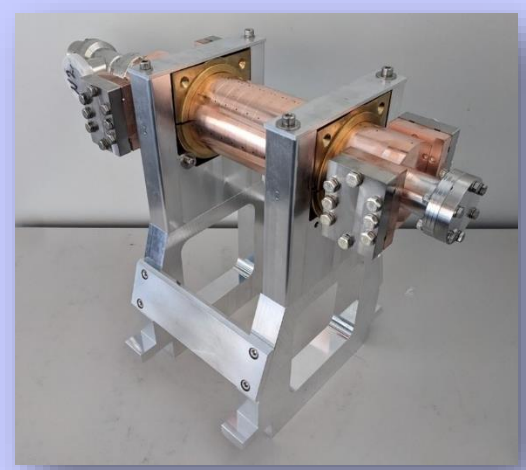
Note: that this is not the case for a linac where one can relax the optics to reduce IBS (*illustrated by Prat et al in Energy spread blowup by intrabeam scattering and microbunching at the SwissFEL injector*).

Parameter	Optimizing on B_{5D}	Optimizing on B_{6D}
5D Brightness$[A/m^2]$	$9.16 \cdot 10^{14}$	$\mathbf{9.02 \cdot 10^{14}}$
6D Brightness $[A/m^2 keV]$	$5.54 \cdot 10^{14}$	$\mathbf{5.58 \cdot 10^{14}}$
Peak Current[A]	19.77	**19.87**
Projected emittance[mm mrad]	0.3298	**0.3311**
Slice emittance [mm mrad]	0.2078	**0.2102**
Mismatch avg	1.4963	**1.4174**

Contents

Electron source upgrade approaches

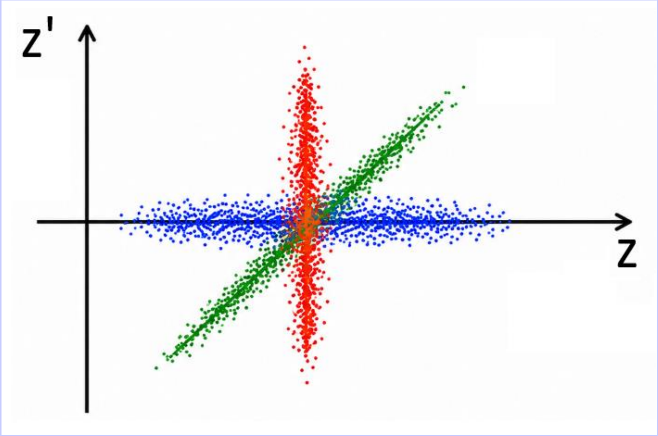
Approach 1: High Gradient Guns



Using a high accelerating gradient on the cathode and a high output energy, one can achieve reduce the impact of space-charge on the beam degradation and consequently start with bunches at higher densities.

Travelling-Wave RF Photogun: From Back-of-the-Envelope Concept to High-Power Operation
Presented as a poster Monday (MOPO013)

Approach 2: Beam manipulation



Compressing the bunch within the electron source can significantly boost the peak current and mitigate the detrimental effects of compression downstream.

This Talk -> Expect publication soon.

Electron source upgrade approaches

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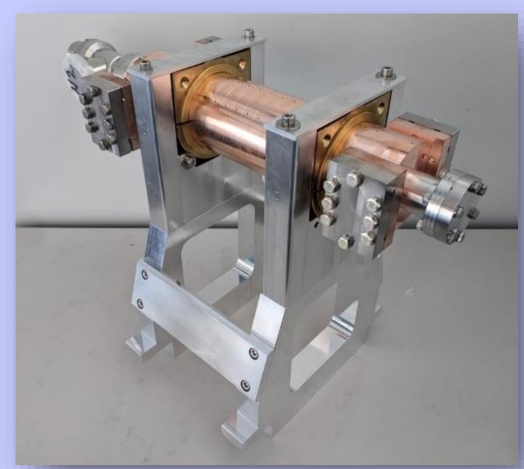

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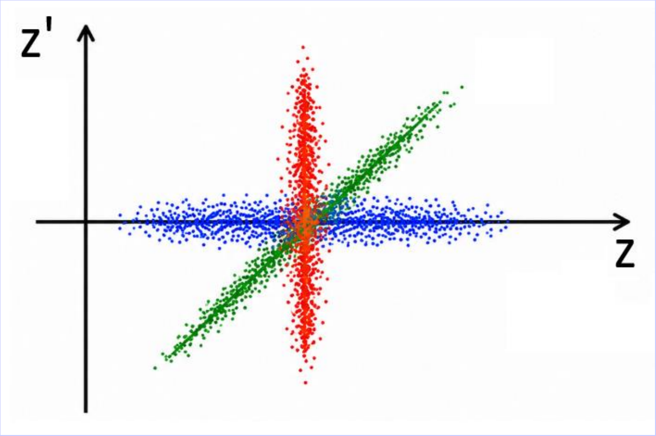

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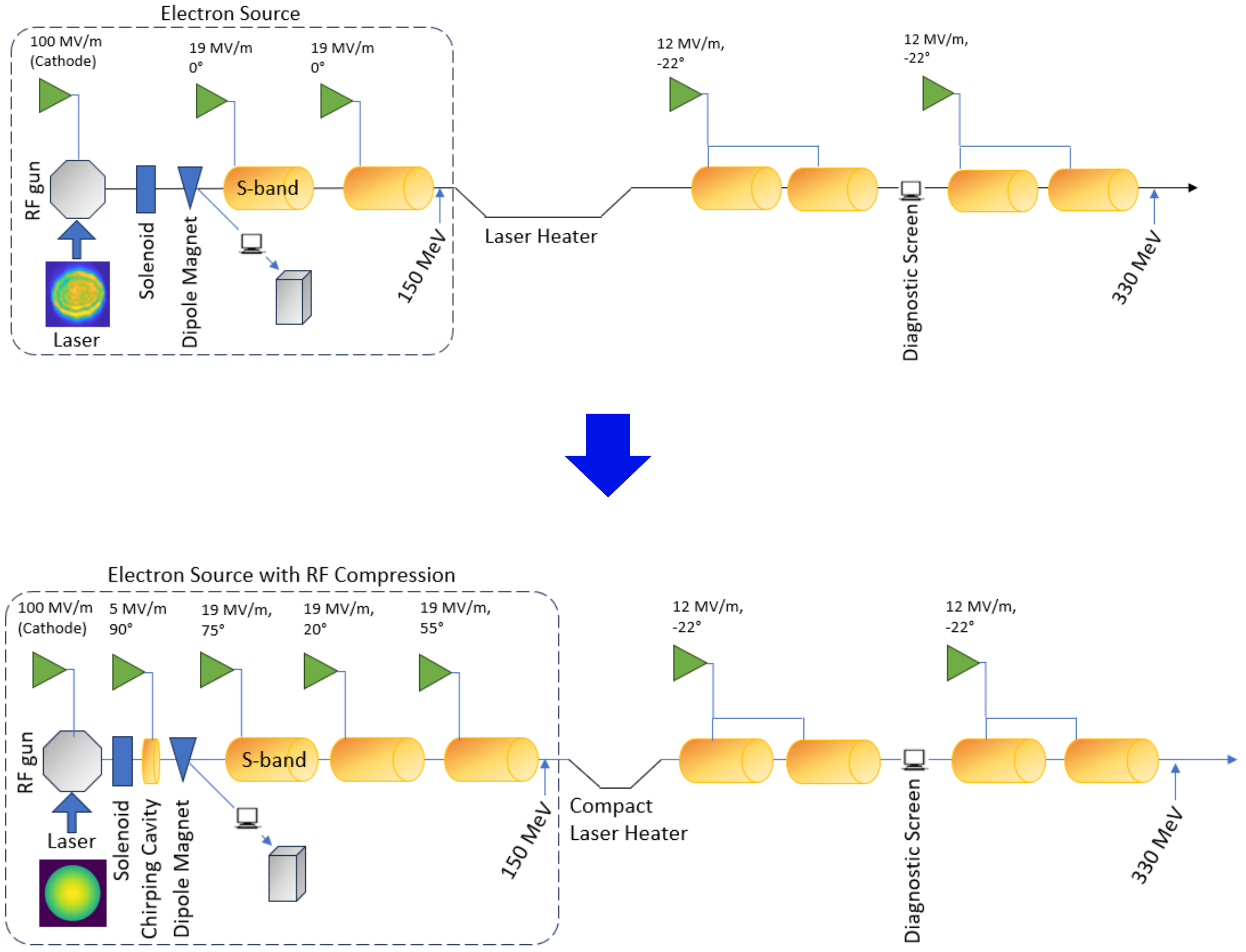
Concepts for the New Electron Source for SwissFEL+

The SwissFEL+ electron source will be made up of two main upgrades:

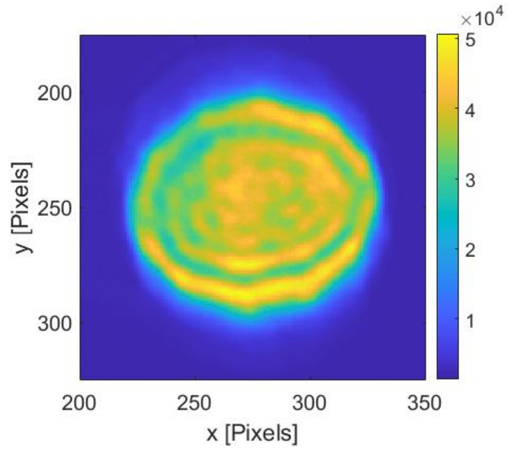
1. **Velocity/ballistic bunching in electron source:** Addition of a chirping cavity and operating the gun and structures slightly off-crest to induce ballistic and velocity bunching.

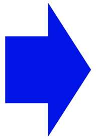
2. **Transverse Photocathode Laser Shaping:** The longitudinal profile is chosen as a gaussian as this microbunching was found when trying to flatten. Optimising the transverse distribution finds a cut-gaussian nearly completely linearises space-charge forces.

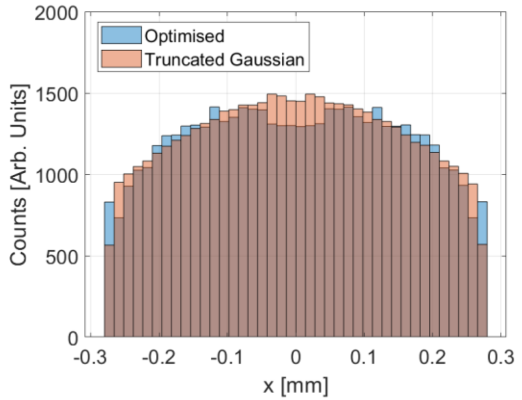


Technological challenges: Photocathode Shaping

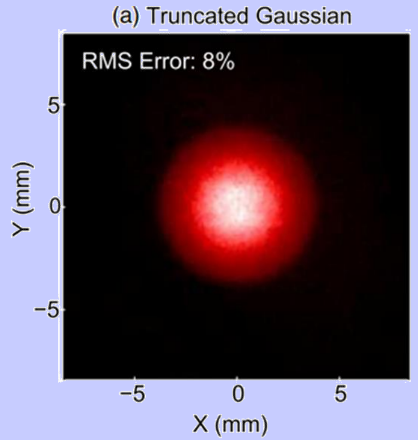
We need to transform this to a truncated gaussian.





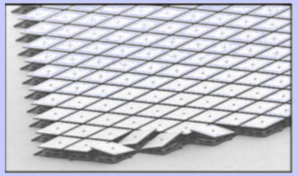


Technologies we've investigating for this Concept

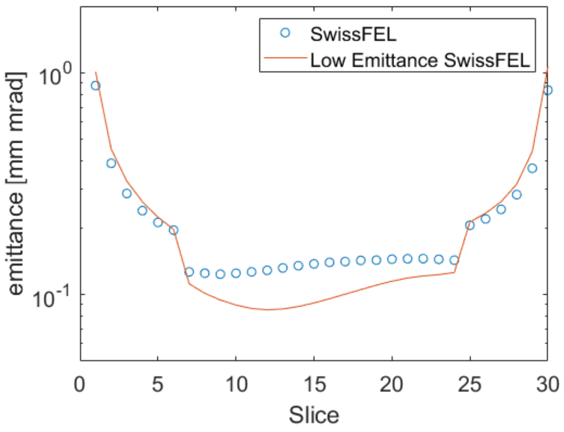


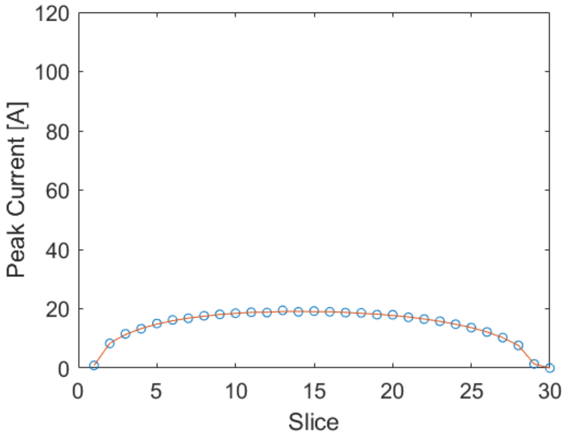
Spatial Light Modulator

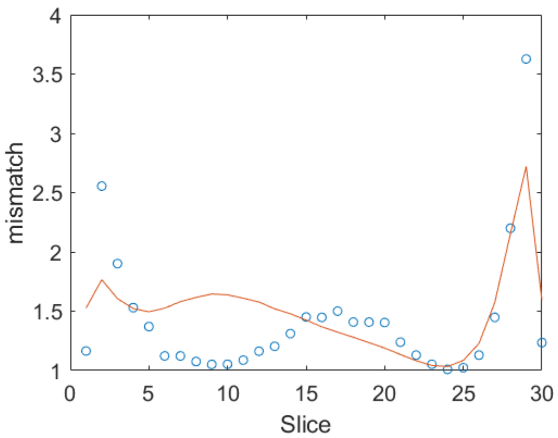
Deformable mirrors

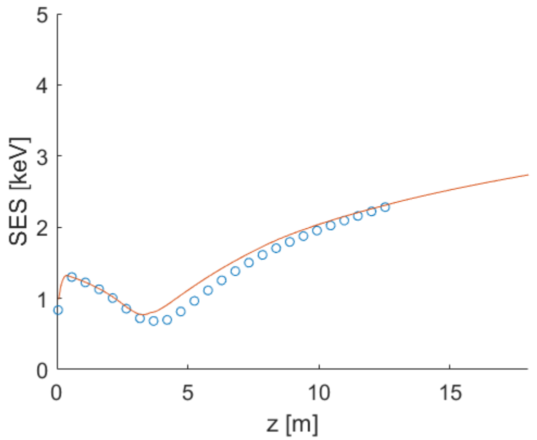


Digital Micromirrors



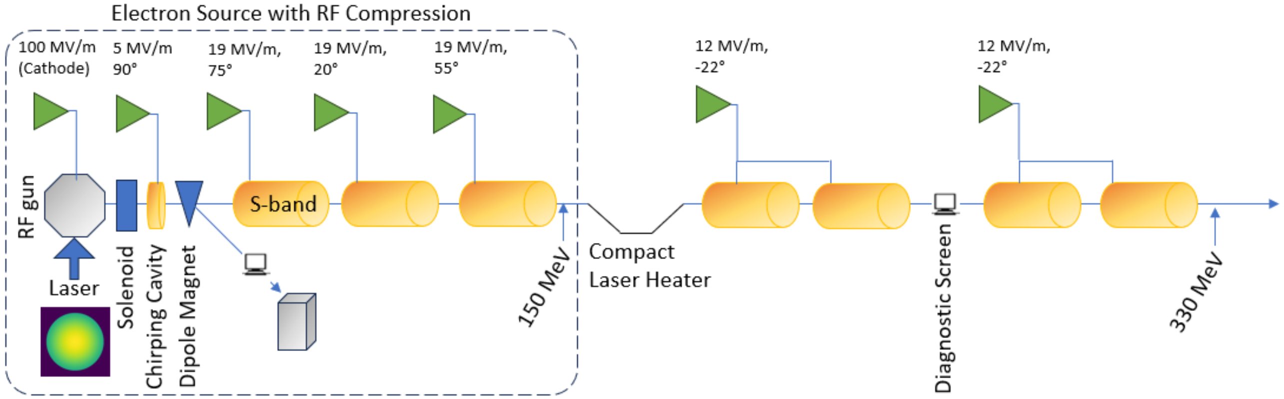




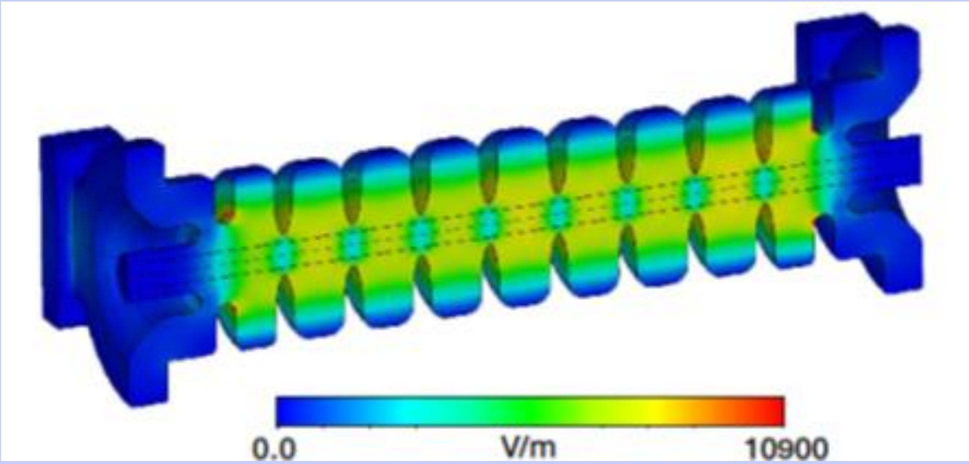


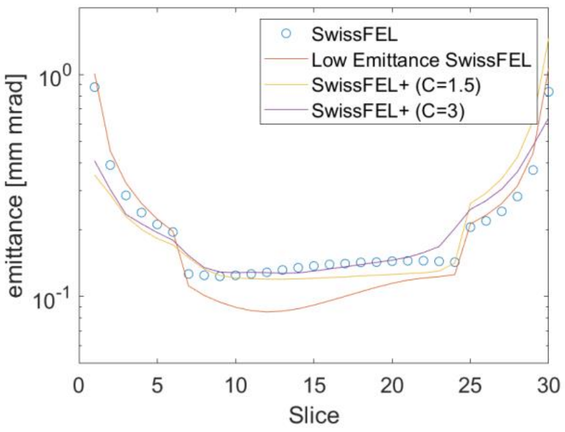
https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.18.023401

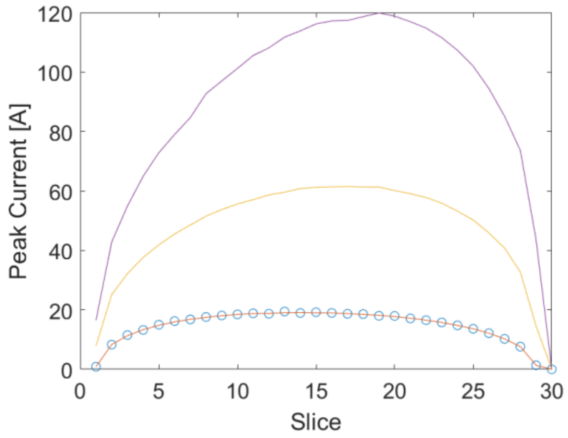
Technological challenges: RF Compressor with Radially Large Beams

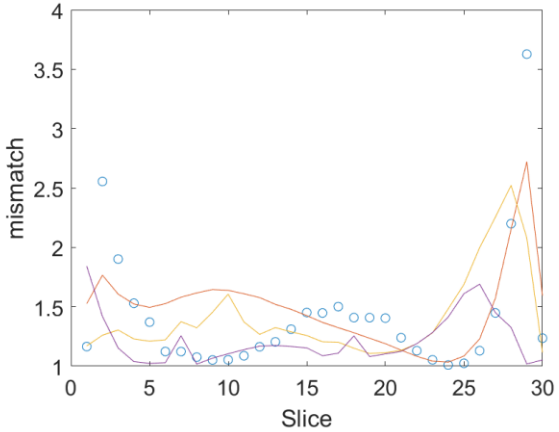


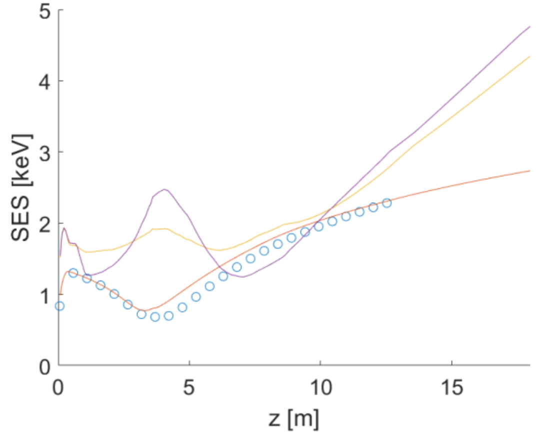
Multipole Reduction with Coaxial











Decay of 6D brightness

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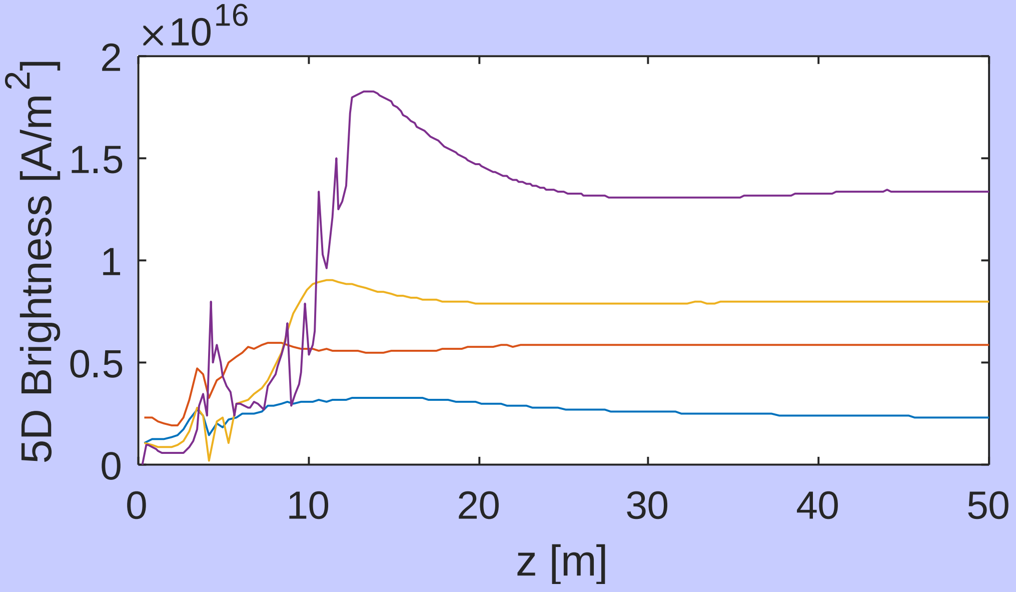
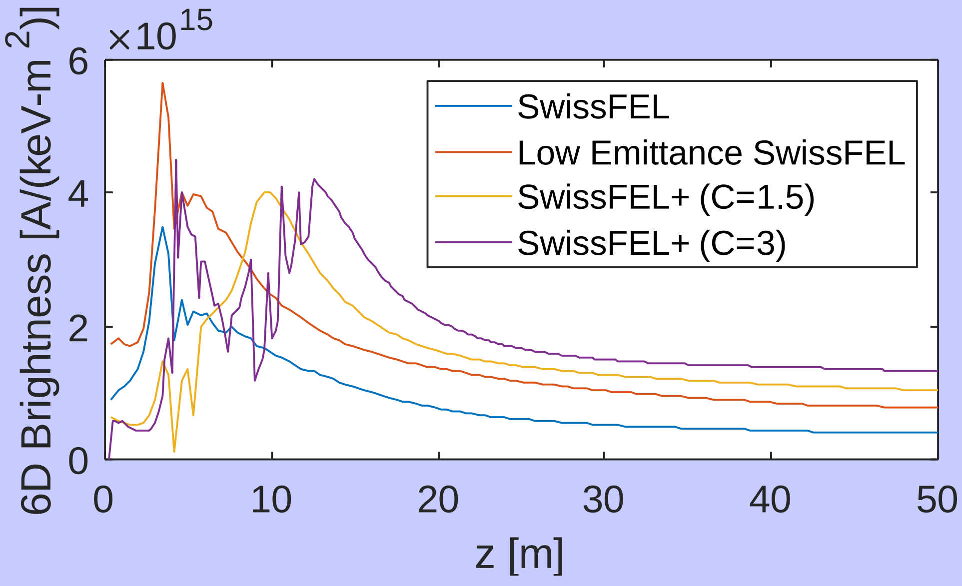
Five-Dimensional Brightness

We see that there's no decay in 5D brightness as the emittance and peak current are largely conserved in the absence of compression and in the presence of IBS (assuming it is longitudinally cold compared to transverse plane).



Six-Dimensional Brightness

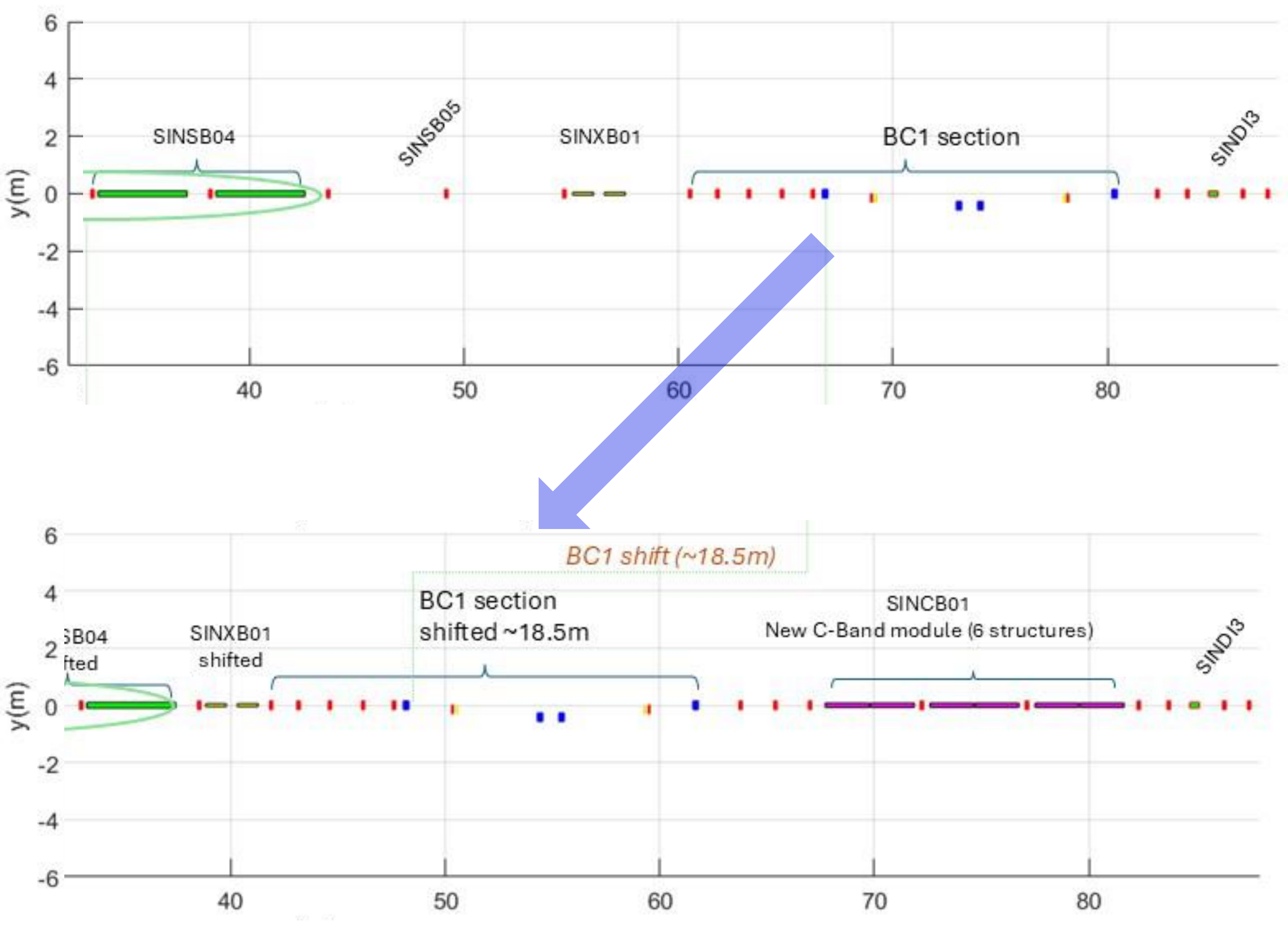
The 6D brightness decays as the transverse motion couples to longitudinal in the form of SES growth.



Bunch Compressor Location

In line with the concept that IBS grows with z, part of the SwissFEL+ concept is shifting the bunch compressor upstream.

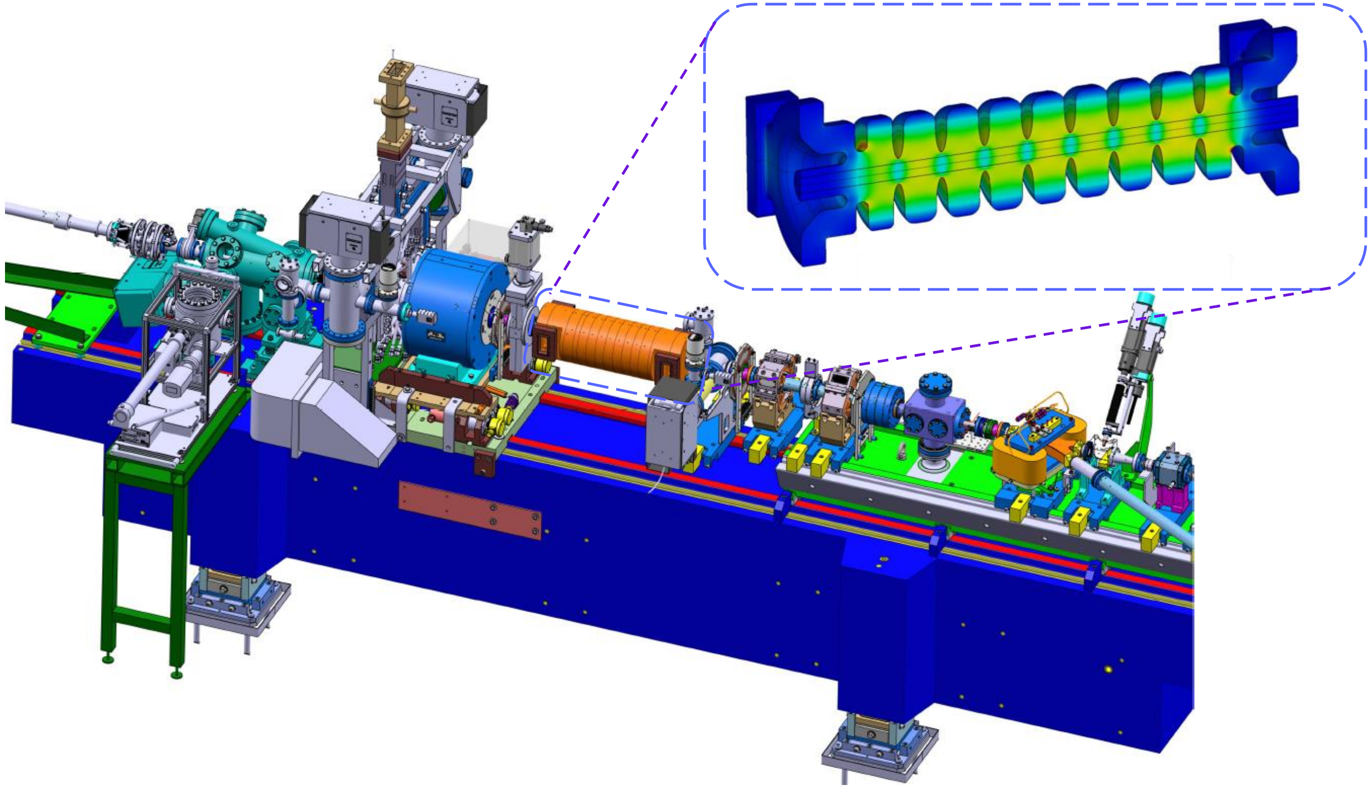
The impact of this is not as impactful as starting with a higher charge but does contribute to an overall brightness gain.



Contents

Future Work: An Electron Source Test Stand at PSI

- Next steps in our journey is demonstration of these new techniques in an electron source.
- We're developing a new electron source test stand at PSI where concepts for SwissFELplus can be tested.
- The test stand will have a replica of the SwissFEL electron gun with the newly realised chirping cavity and new photocathode laser.
- We'll test laser shaping techniques using deformable mirror, Spatial Light Modulators and apertures.



Summary

- Intrabeam scattering has been found to be the culprit in the significant slice energy spread growth in electron sources.
- Modelling of the injector with newly developed numerical and analytical methods have demonstrated excellent agreement with measurements.
- With this knowledge, we find that IBS causes a degradation of six-dimensional beam brightness over the machine leading to the conclusion that two important changes could enhance SwissFEL operation
    1. *Generating higher bunch charges from the electron source to reduce compression downstream.*
    2. *Moving the bunch compressor upstream to mitigate IBS growth.*
- SwissFELplus will employ beam shaping and RF compression to boost the brightness of the current SwissFEL electron source. Critical to this is the identification and design of technologies to implement these strategies.
- A new test stand will be commissioned at PSI to test these concepts before their eventual implementation in SwissFEL.

Acknowledgements

I would like to thank all those that contributed to the work on IBS and the design of the SwissFEL+ electron source:

Eduard Prat, Sven Reiche, Erion Gjonaj, and Paolo Craievich, Alejandra Ocampo Duque and Mariia Zykova.

If you’d like to collaborate in improving the accuracy of your electron source through improved simulations techniques or including IBS, I’m open. Contact me at: thomas.lucas@psi.ch