Beam Dynamics Optimization for a High-brightness Photo Injector with various Photocathode Laser Pulse Shapes

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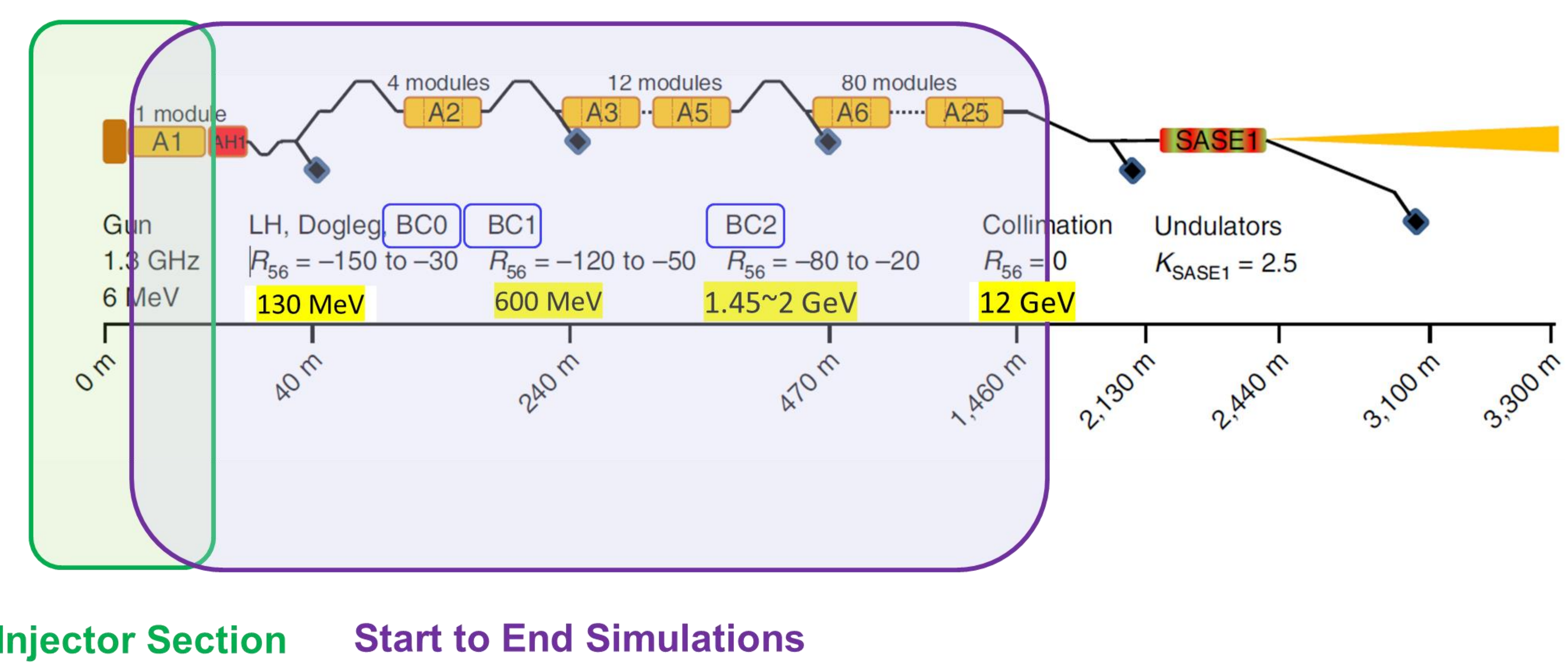
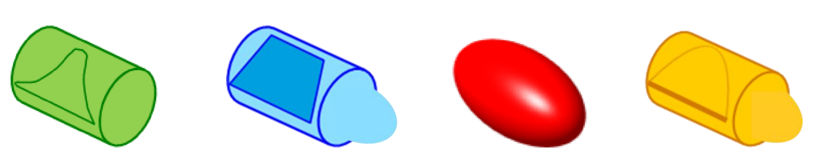
Abstract: At PITZ, a comprehensive study is conducted to analyse the factors influencing emittance growth in the European XFEL (EuXFEL) CW superconducting radio-frequency (SRF) setup. Emittance growth due to space charge effects can be mitigated using advanced photocathode laser pulse shapes. Multiobjective optimizations are reported with focus on minimizing emittance and maximizing brightness. The optimization is initially carried out for the CW SRF **injector section** planned for EuXFEL. The optimized cases are then further tracked through start-to-end (S2E) simulations to evaluate their behaviour in the compression stages of EuXFEL. A comparative analysis of G, FT, EL, and IP laser profiles is presented, assessing their efficiency not only in terms of emittance but also in 4D and 6D brightness before & after compression.

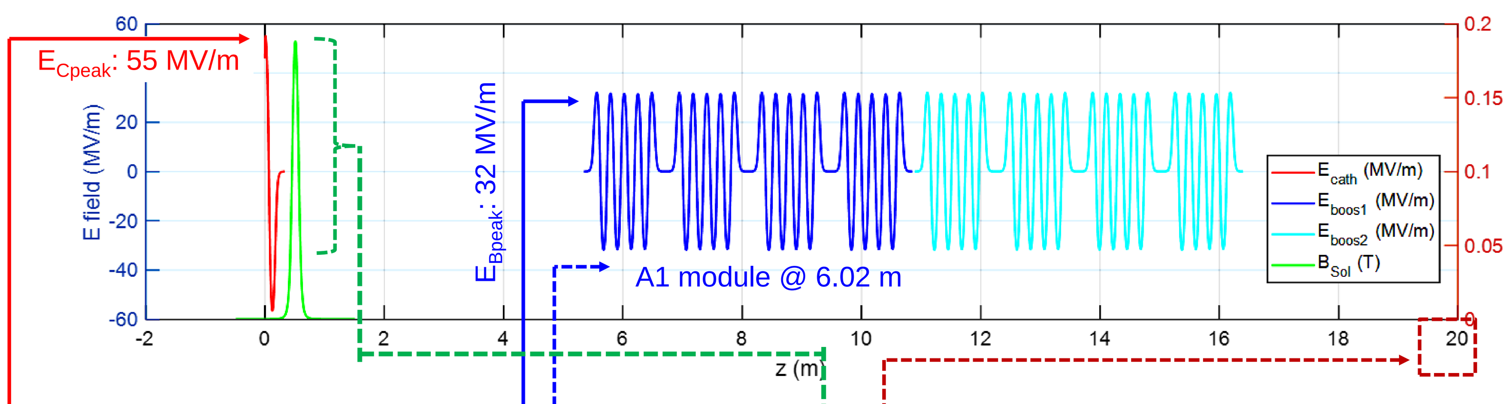
EuXFEL Superconducting CW Setup



Beam Dynamics at Injector: Multi-Objective Optimization for different Lasers Optimization

- Astra* based multi-objective optimizations
- Goal functions:
  - Projected emittance &
  - Electron rms bunch length



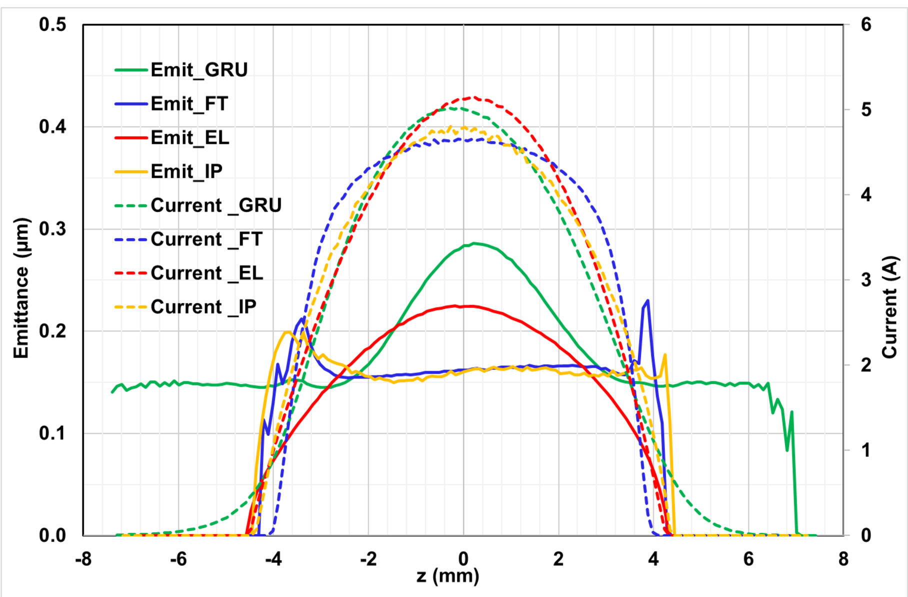


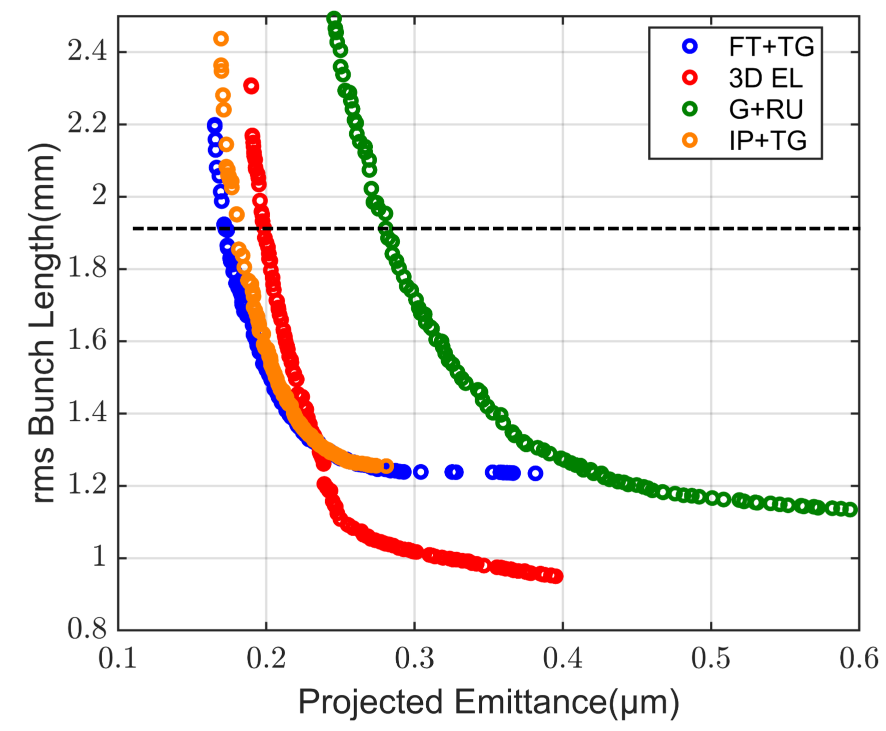
Fixed parameters during Optimization		Scanned parameters during Optimization
Parameters	Values	
$E_{cathode}$	55 MV/m	Laser long FWHM
A1: E_{peak}(1st ½)	32 MV/m	Laser transverse size
A1: E_{peak}(2nd ½)	32 MV/m	Gun Phase
A1 position	6.02 m	A1 Phase: (1st ½)
Bunch Charge	100 pC	A1 Phase (2nd ½)
Thermal Emit	1 µm/mm	Solenoid Field
Optimization at	20m	

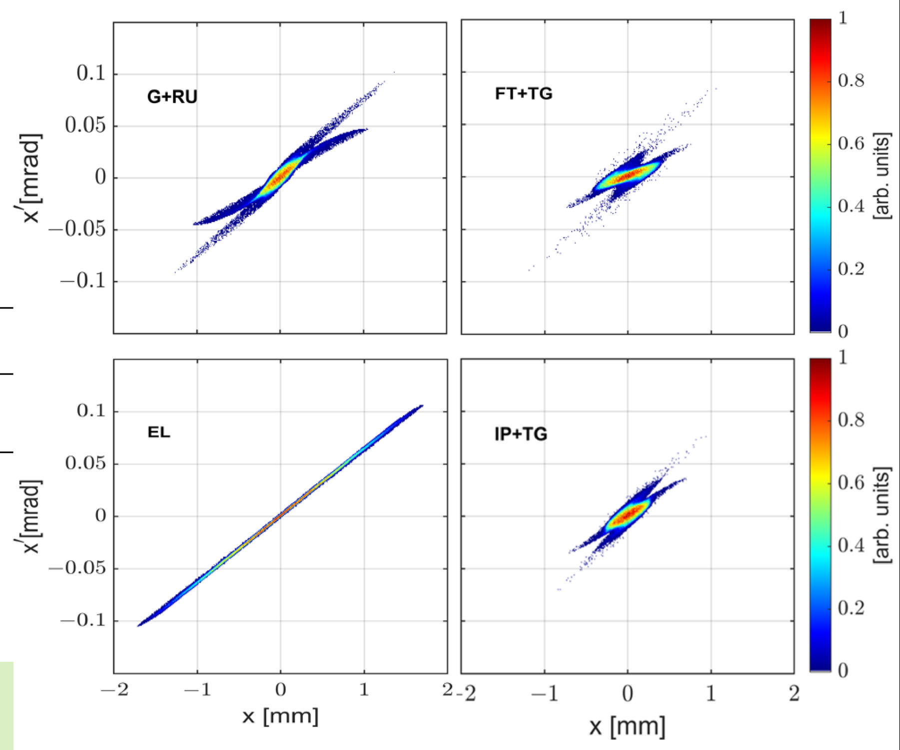
4D and 6D brightness comparison (a) after Injector and (b) after S2E simulations

$$\langle B_{4D}\rangle = \frac{1}{T}\int_{-T/2}^{T/2}\frac{I(t)}{\varepsilon_x(t)\varepsilon_y(t)}dt$$

$$\langle B_{6D}\rangle = \frac{1}{T}\int_{-T/2}^{T/2}\frac{I(t)}{\varepsilon_x(t)\varepsilon_y(t)\delta_E(t)}dt$$





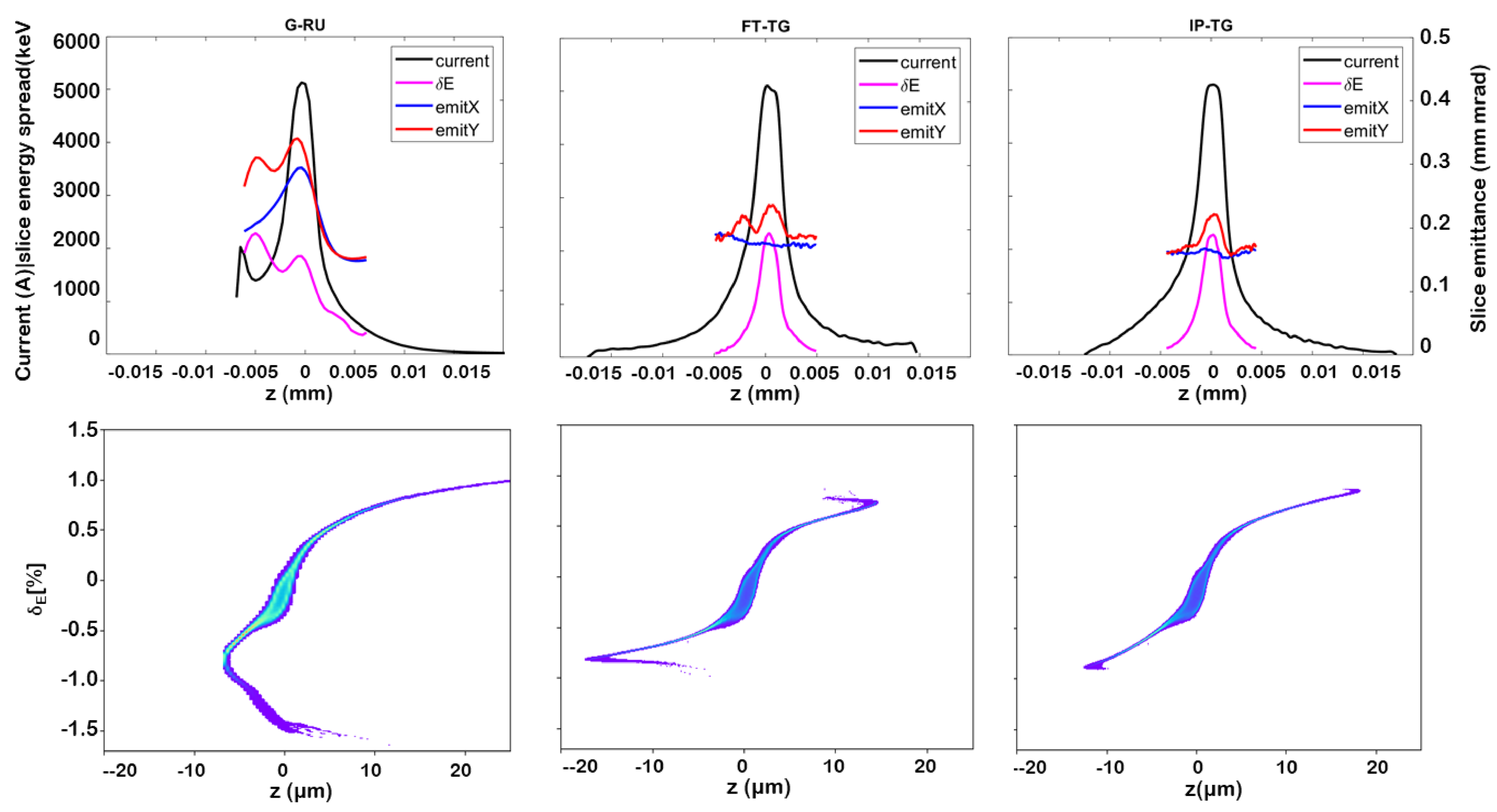


Best Cases for 2mm rms electron bunch length

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/µm²)	1231	1708	1983	2020

Start to End Simulations

- Propagation of e beam under collective effects: wakefield, space charge and CSR using Ocelot**
- Compression factors BC0: 3, BC1: 7.5
- BC2 was tuned → final peak current of 5 kA
- Laser heater tuning → energy spread 2 MeV → standard settings for all



* K. Flottmann, ASTRA particle tracking code, http://www.desy.de/~mpyflo
** https://ocelot.readthedocs.io/en/latest/index.html

Main Parameters after Start to End Simulations

	G+RU	FT+TG	IP+TG
I_{peak} (kA)	5.1	5.1	5.1
Proj emit $X_{(z=0)}$ (mm mrad)	0.33	0.19	0.18
Proj emit $Y_{(z=0)}$ (mm mrad)	0.29	0.24	0.22
Energy spread $dE_{(z=0)}$ (MeV)	1.8	2.2	2.2
Average 4D Bright $\langle B_{4D}\rangle$ (kA/µm²)	75.9	125	170
Average 6D Bright $\langle B_{6D}\rangle$ (kA/µm²/MeV)	75.3	245	303

Summary & Conclusion

- Optimization including A1 position → different optimized positions for different laser shapes
- The injector optimizations → FT+TG yields best emittance at the injector for A1 module's fixed/given position
- The IP+TG laser pulses are promising at **injector** & **after BC2**
- **IP → a better brightness achieving shape as compared to FT and comparable to EL → less technically challenging to realise**

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