Beam dynamics studies for Emittance and Brightness Optimization using Photocathode laser Pulse shaping for SRF XFEL Injector

Sumaira Zeeshan

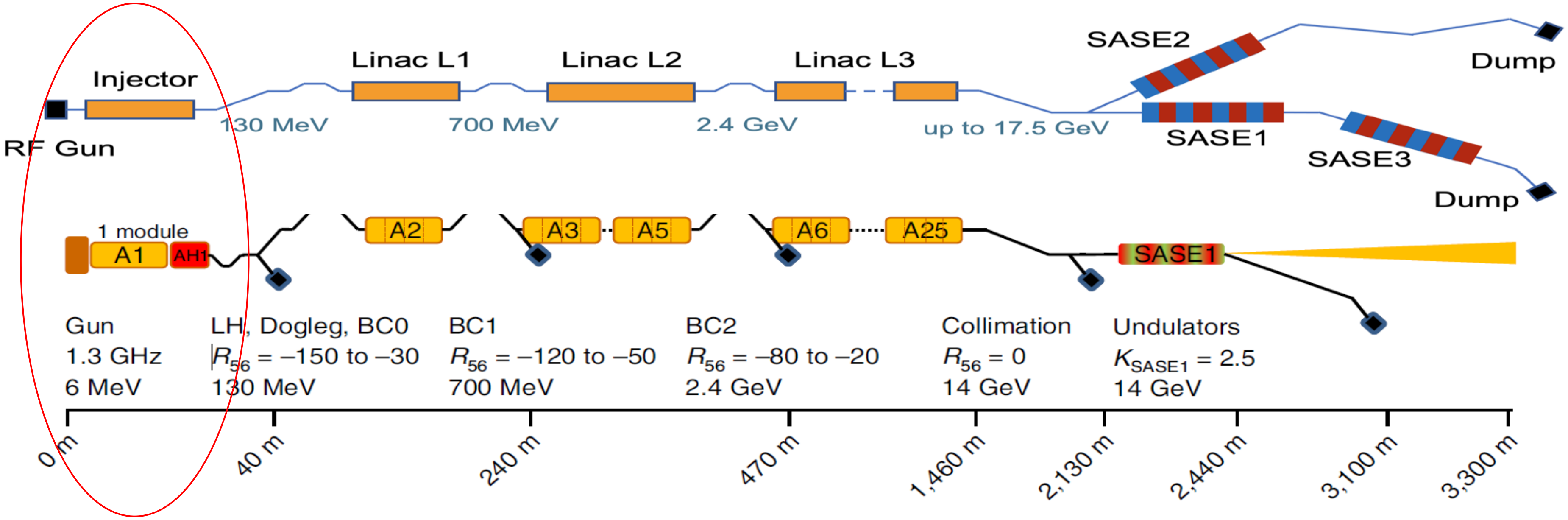
3.12.2024

Optimization Studies for XFEL

Injector Optimization for Start to End Simulations

Dmitry Bazyl

- Parameter optimization at Injector
- Preparation of monitors for start to end simulations to be done at Hamburg



Parameters Provided
Bunch Charge: 100 pC Laser Longitudinal Shape: Flattop, Ellipsoidal, Gaussian Laser Transverse shape: Truncated Gaussian
Goal to compare Projected emittance for different laser shapes @ 15m

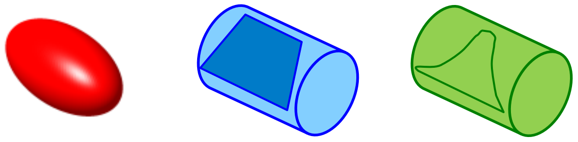
$E_{cathode}$: 55 MV/m (further steps: dependence on ?)

A1: E(1st ½) : Optimized (24-32) MV/m

E(2nd ½) : 32 MV/m

Multi Objective Optimization for XFEL

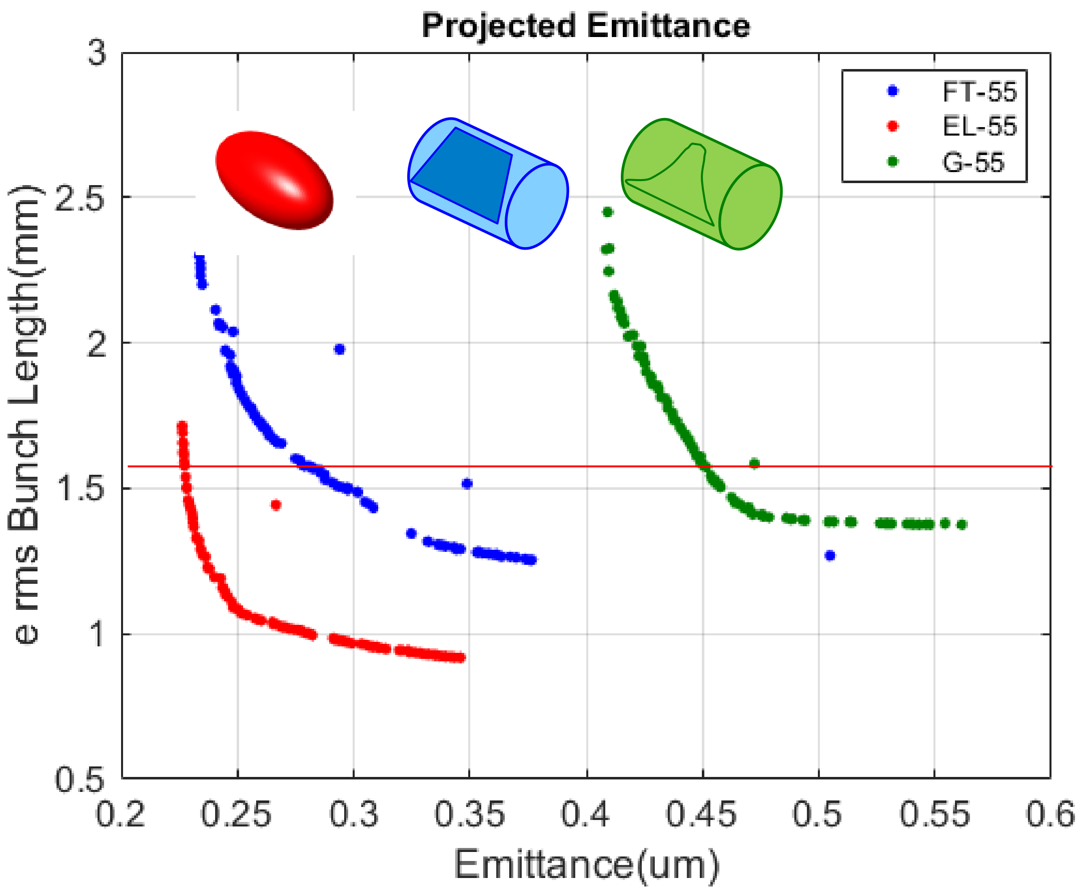
Optimization with updated data of Field profiles of RF cavity , Solenoid and solenoid position (provided by Dmitry Bazyl)

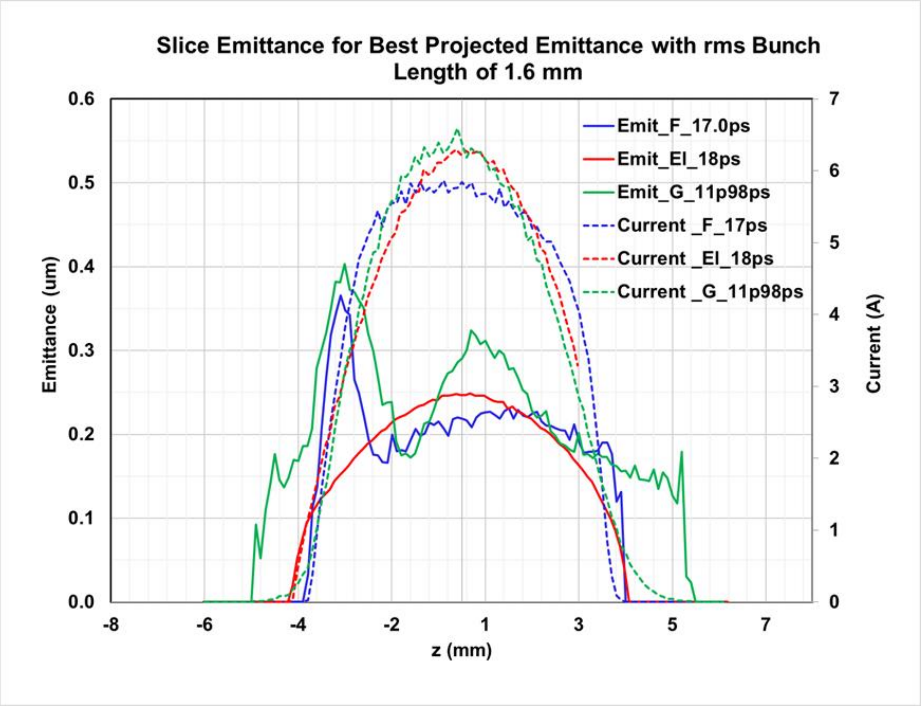


- Thermal emittance : ~ 1um/mm (Ekin = 0.75), Bunch charge: 100pC, E_{cath} : 55 MV/m
- Laser setting:
  - Long.→ Gaussian, Flattop,
  - Trans.→ Truncated Gaussian
  - **New: 3D Ellipsoidal**
- Variables:
  - Laser long FWHM
  - Laser transverse size
  - Gun and Booster phase
  - Booster ½ Gradient : Optimized (24-32) MV/m
  - Solenoid Field
- Goal functions:
  - Projected Emittance & rms BL(Pareto fronts)
  - Longitudinal core emittance(±σ & ±1.5 σ) & e BL (Pareto fronts)
  - Brightness (Integral & long Core)

Multi Objective Optimization for XFEL: Laser shaping

Flattop, Ellipsoidal and Gaussian





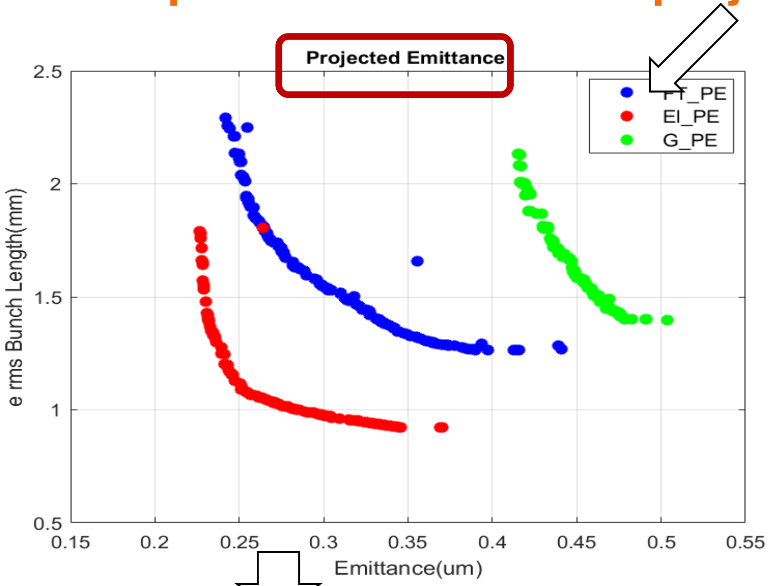
Emittance Optimization Strategy

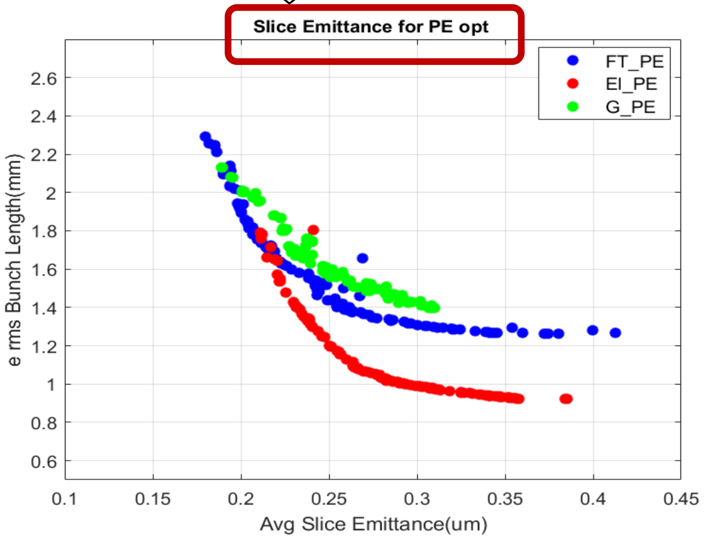
Define a strategy on emittance optimization

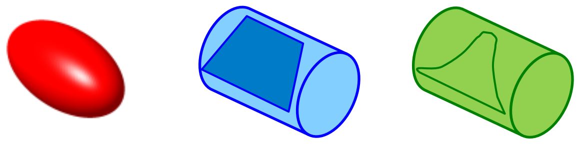
- Figure of merit for the emittance optimization?
  - *Projected* emittance as a ***rough upper*** limit
  - *Projected* emittance of the *longitudinal core* – ***realistic*** (?)
  - Integral brightness 4D & 6D

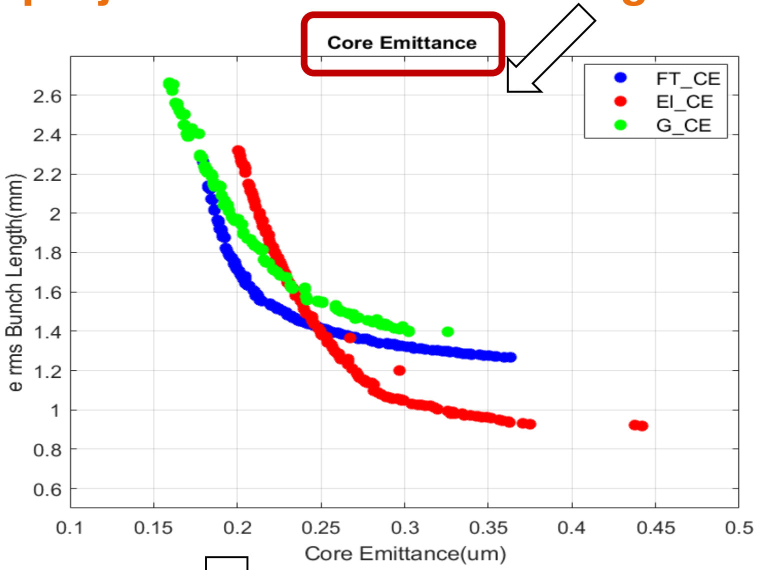
Emittance Optimization Strategy

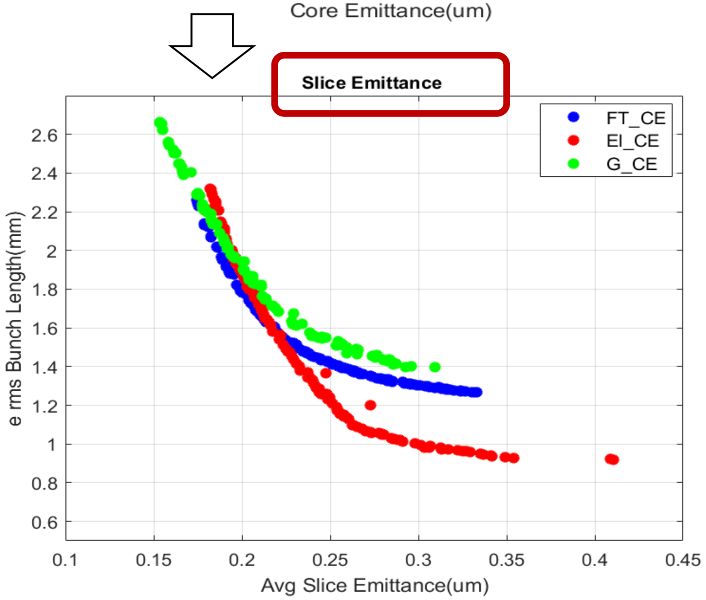
2 different optimizations: one for projected emittance and other for projected emittance of longitud. core





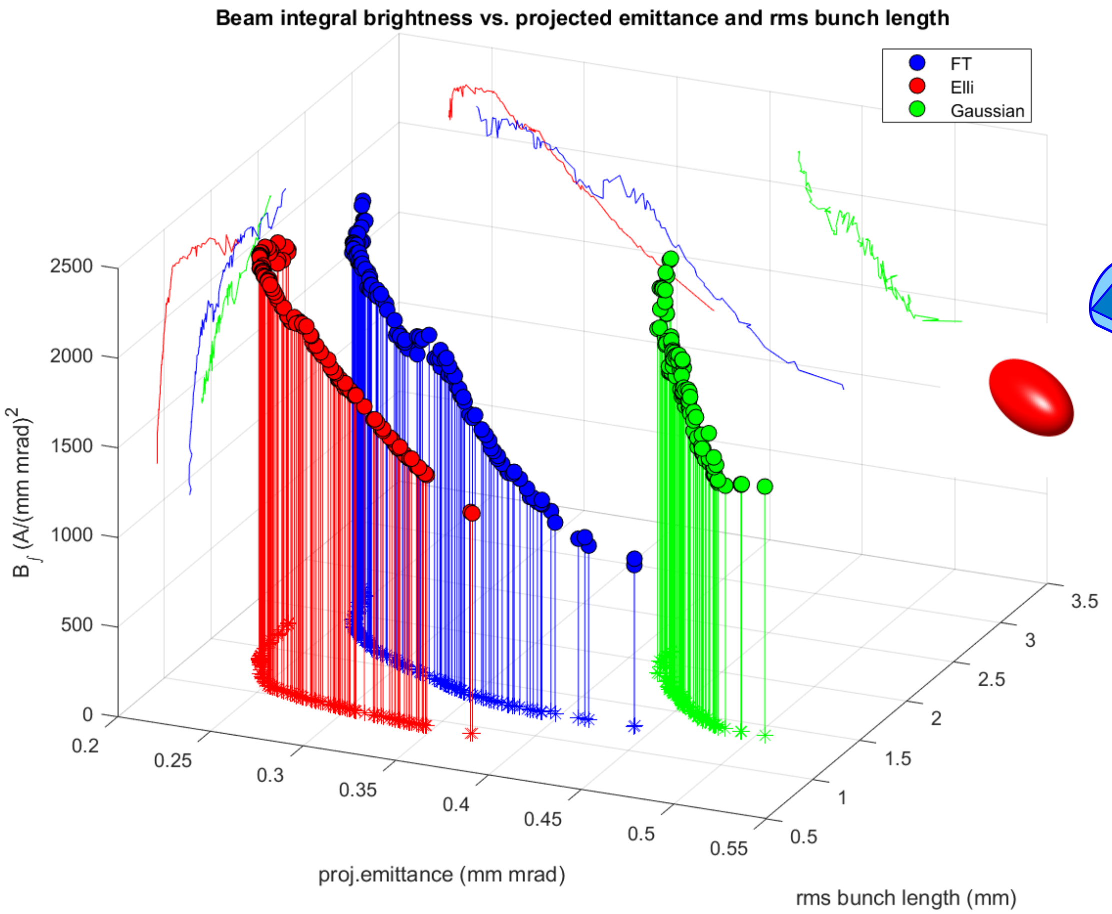


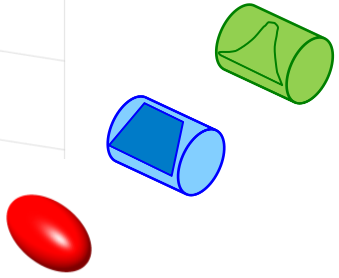




Beam Brightness

Emittance or Brightness the right Parameter to Optimize





$$Integral\ 4D\ Brightness = \int_{-T}^{T} \frac{I(t)dt}{\varepsilon_x(t)\varepsilon_y(t)}$$

T can be:

- ∞
- 1.5 σ
- σ

Courtesy M. Krasilnikov

Longitudinal Phase Space (LPS) Nonlinearity Correction

Evaluation of the LPS quality from the injector

Given the primary accelerating cavity operates at fundamental frequency f_1, and the third harmonic cavity operates at $f_3 = 3f_1$, the total energy modulation experienced by the beam after passing through both cavities can be written as:

$$\Delta E = E_0 \cdot \left\{ \sin[\varphi - \varphi_0] + \frac{V_3}{V_1} \cdot \sin[3 \cdot (\varphi - \varphi_0) + \psi_0] \right\},$$

where:

- E_0 is the energy of the particle before the modulation,
- $(\varphi - \varphi_0)$ is the phase offset of the particle in the fundamental cavity,
- V_1 is the voltage of the fundamental cavity,
- V_3 is the voltage of the third harmonic cavity,
- ψ_0 is the relative phase between the fundamental and third harmonic cavities.

M . Krasilnikov

Practical formula: $p_{z,fit} = p_{z,0} + A \cdot \{\sin[\varphi - \varphi_0] + V_r \cdot \sin[3 \cdot (\varphi - \varphi_0) + \psi_0]\}$, where $\varphi = \frac{2\pi f_1 z}{c}$, $\psi = \frac{2\pi 3 f_1 z}{c}$

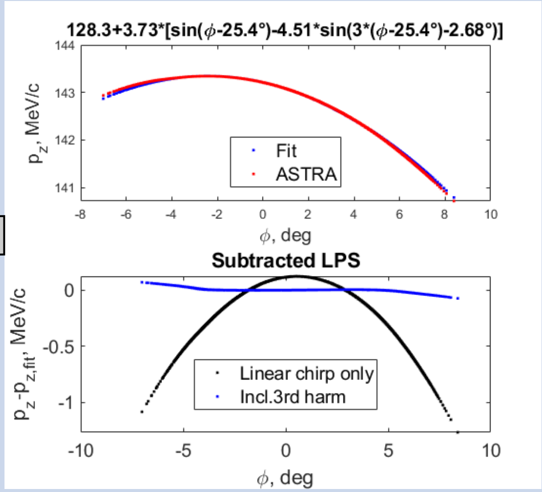
Fit parameters: $\{p_{z,0}; A; \varphi_0; V_r; \psi_0\}$

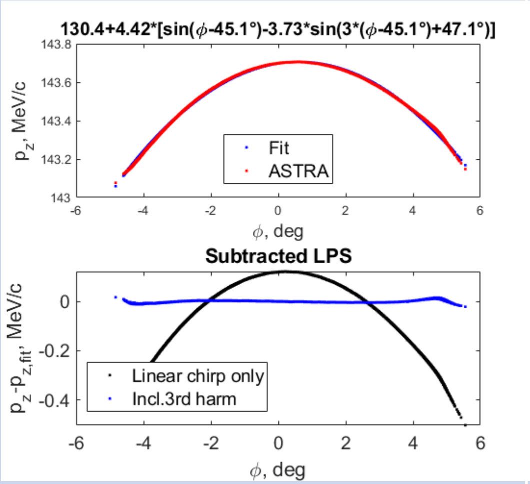
LPS Nonlinearity Correction for various Pulse Shapes

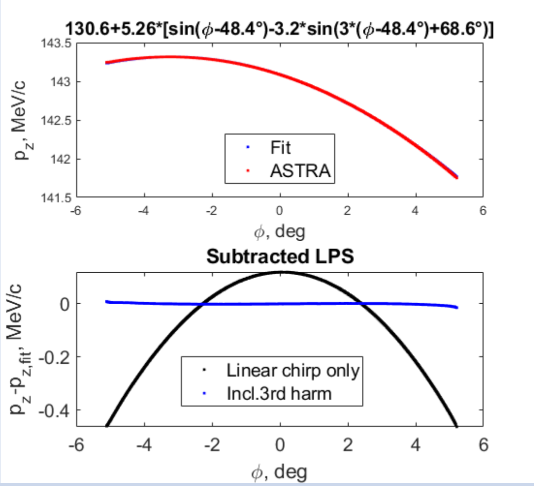
M. Krasilnikov

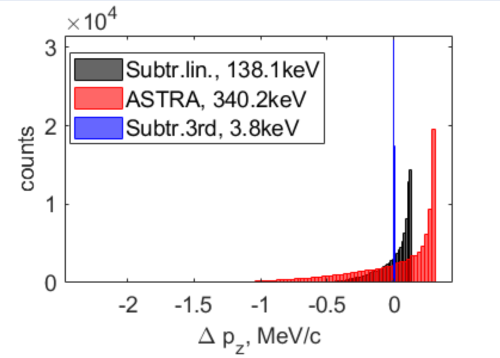
Evaluation of the LPS quality from the injector

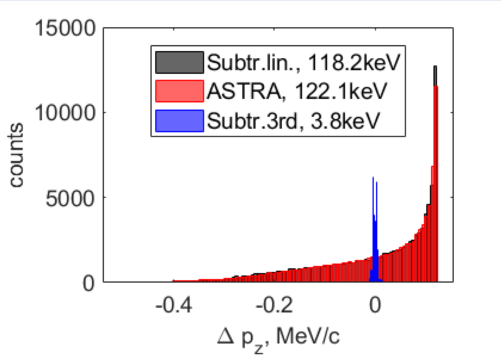
$$p_{z,fit} = p_{z,0} + A \cdot \{sin[\varphi - \varphi_0] + V_r \cdot sin[3 \cdot (\varphi - \varphi_0) + \psi_0]\}$$

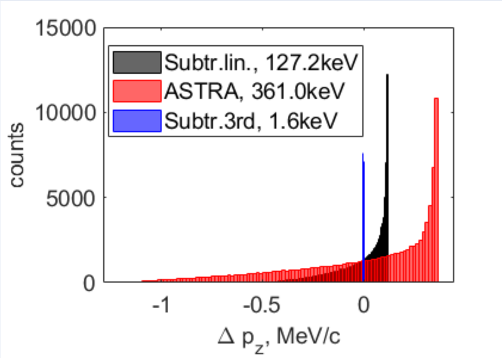
<table>
<tr><th>PC Laser→</th><th>Gaussian</th><th>Flattop</th><th>Ellipsoid</th></tr>
<tr><td>LPS</td><td>


</td><td>


</td><td>


</td></tr>
<tr><td>Pz-projection</td><td>


</td><td>


</td><td>


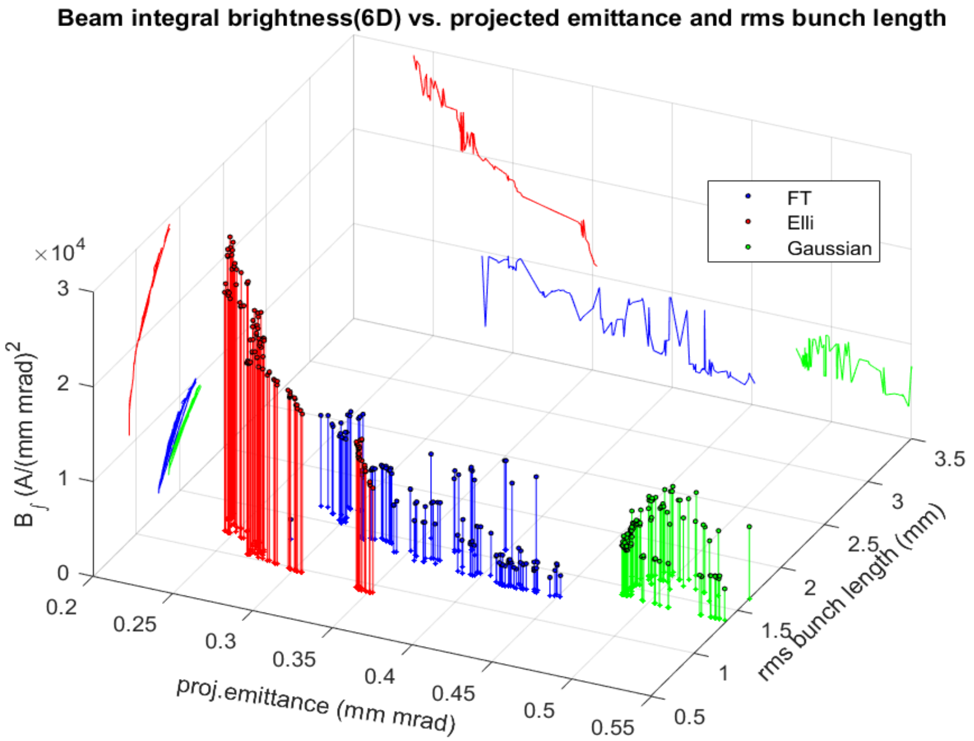
</td></tr>
<tr><td>PZrms (proj / linear / 3rd harm), keV/c</td><td>340.2 / 138.1 / 3.8</td><td>122.1/ 118.2/ 3.8</td><td>361.0 / 127.2/ 1.6</td></tr>
</table>

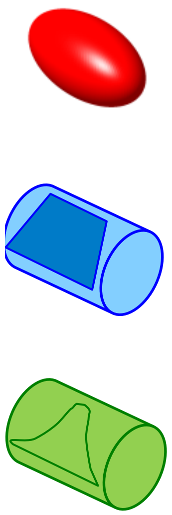
6D Brightness as the goal function in MOGA

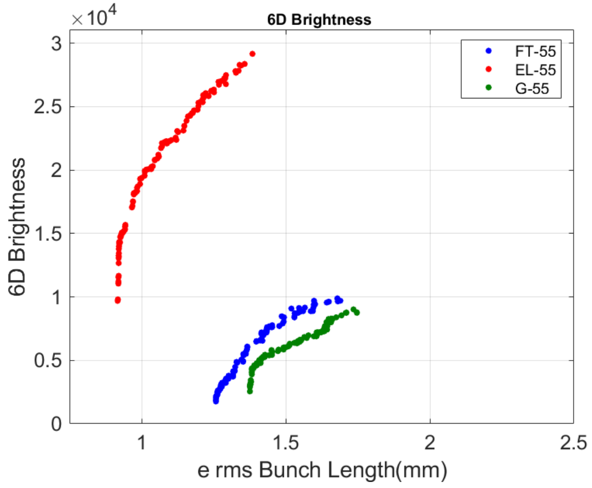
Including energy spread

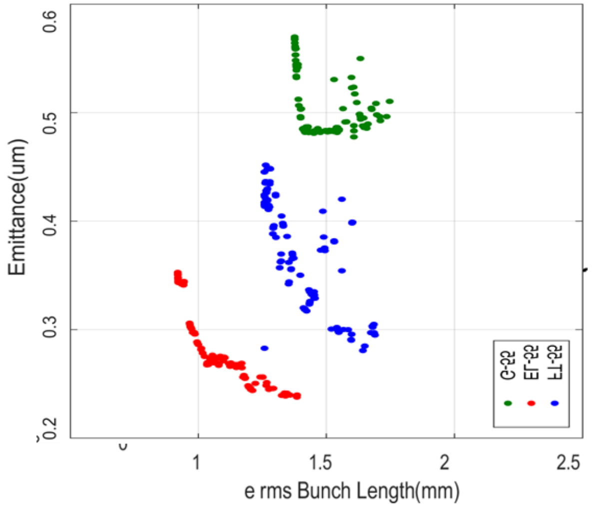
4(5?)D integral brightness: $\langle B_{4D} \rangle = \int_{T_1}^{T_2} \frac{2I(t)dt}{\varepsilon_{x,n}(t)\cdot\varepsilon_{y,n}(t)} \approx \sum_{i=1}^{N} \frac{2Q_i}{\varepsilon_{x,n}(i)\cdot\varepsilon_{y,n}(i)}$

6D brightness: $B_{6D}^{*} = \frac{\langle B_{4D} \rangle}{\delta_{pz}^{*}}$, where δ_{pz}^{*} - RMS momentum spread with subtracted 1st and 3rd harmonic cavity contributions









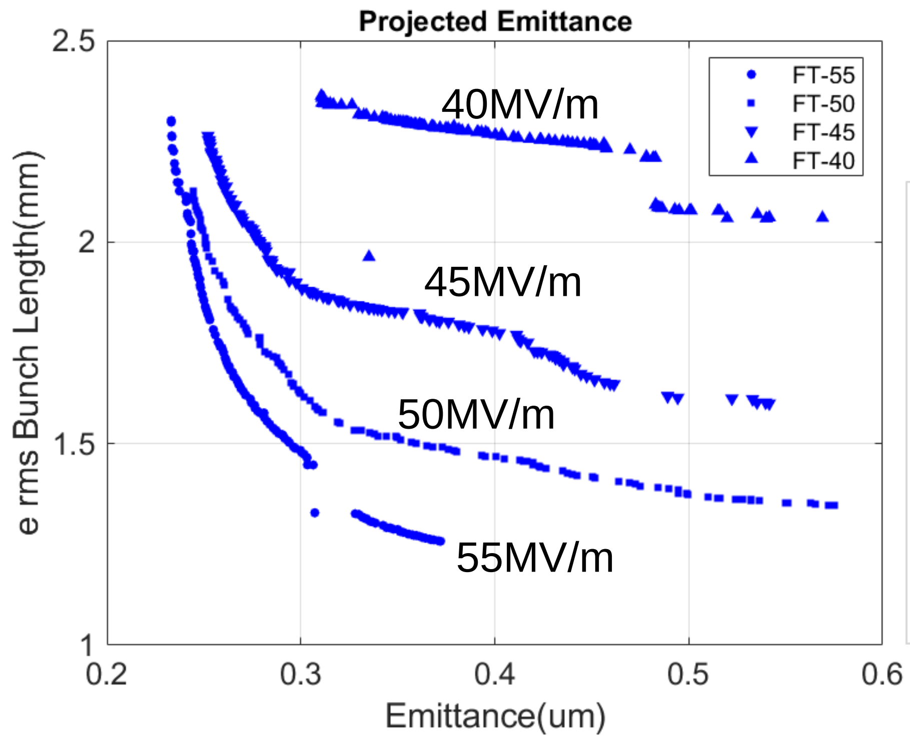
Gradient Optimization

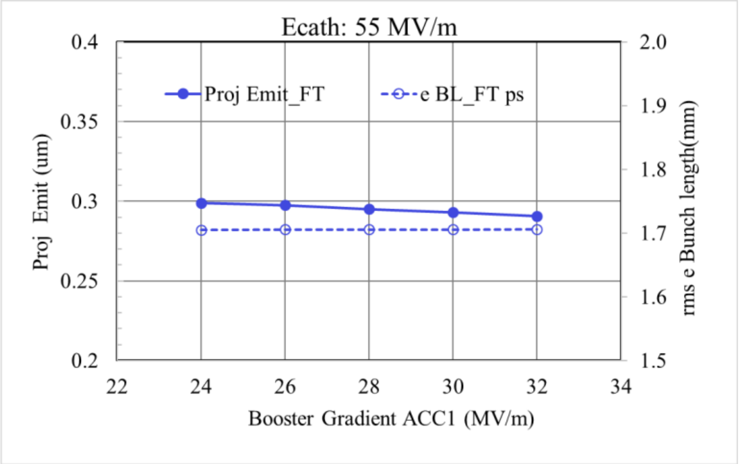
Ecath and E(1st ½)

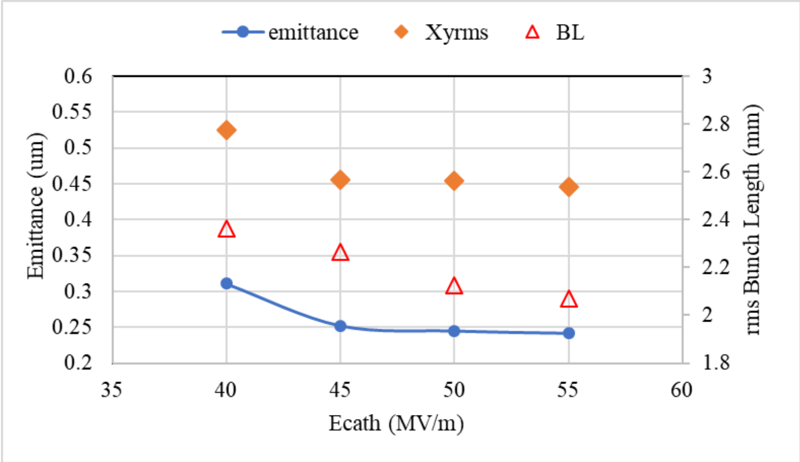
$E_{cathode}$: 40 & 55 MV/m
A1: E(1st ½) : 24-32 MV/m
E(2nd ½) : 32 MV/m

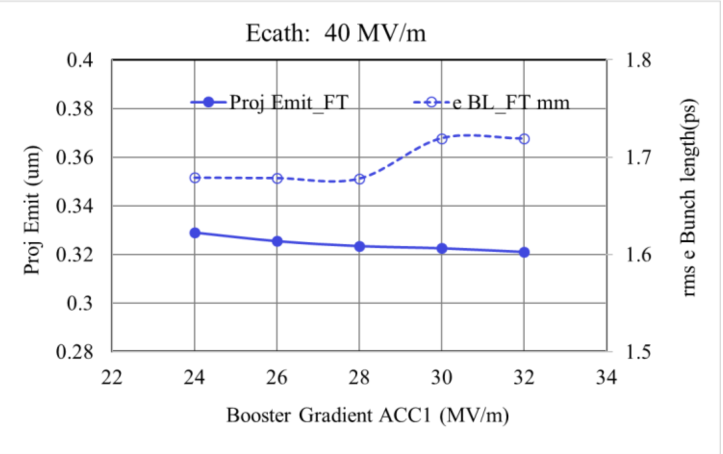
E_{kin} : 0.75 eV

Parameters Provided
Bunch Charge: 100 pC
Laser Longitudinal Shape: Flattop
Laser Transverse shape: Truncated Gaussian
Compare Minimum Projected emittance achieved for different laser shapes @ 15m



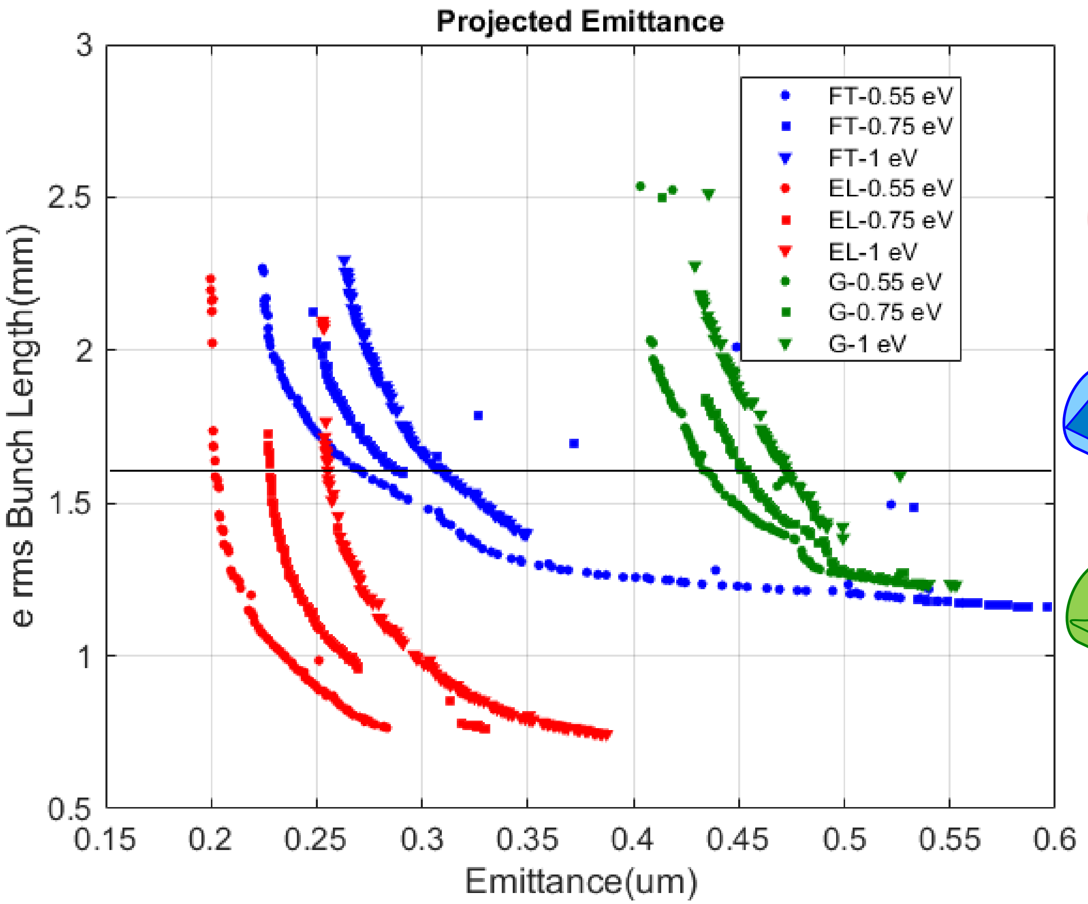


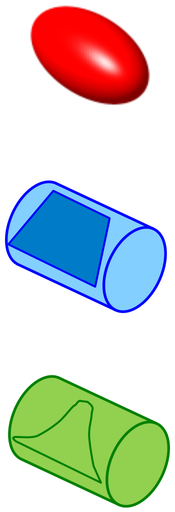


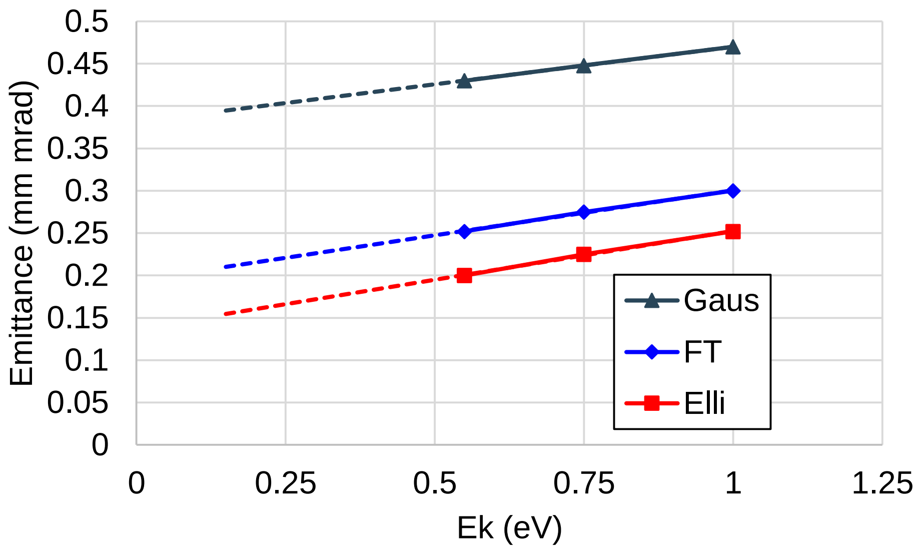


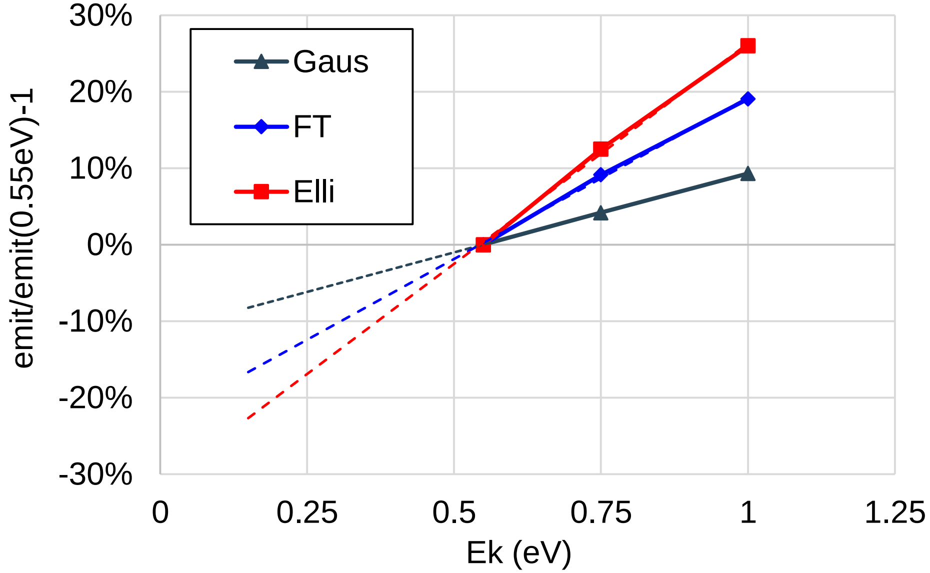
Projected Emittance for different Cathode E_{kin}: 0.55, 0.75 and 1eV

Thermal Emittance









Bench Marking: Need further Optimization

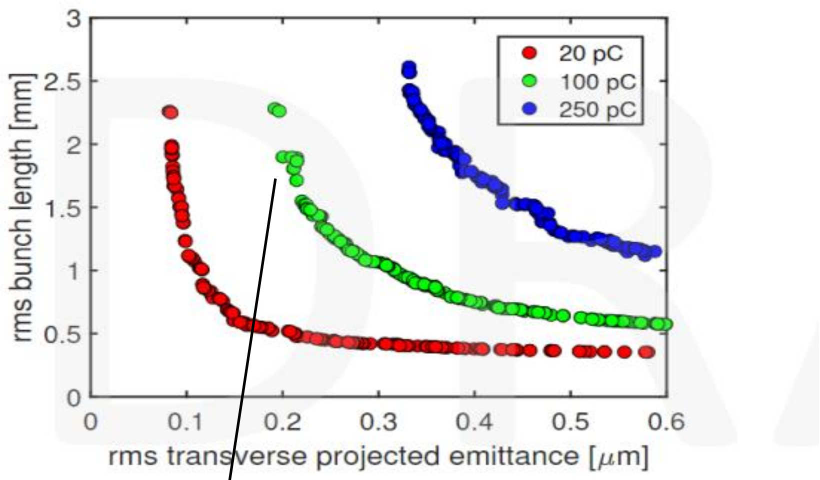
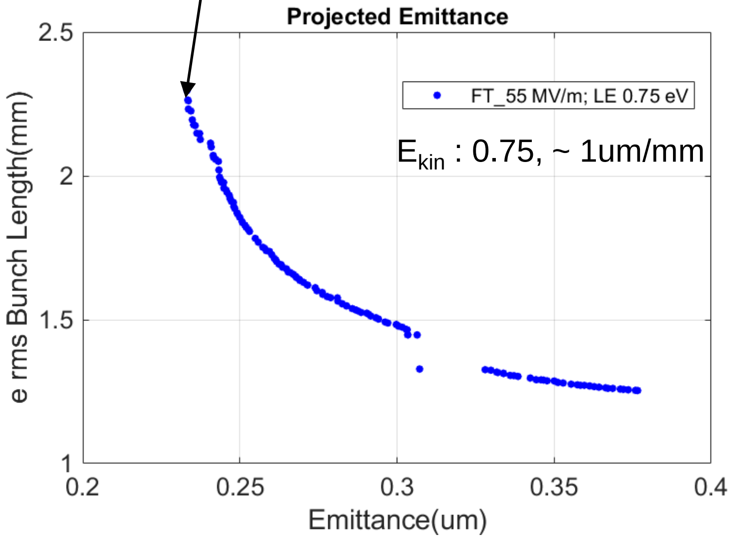
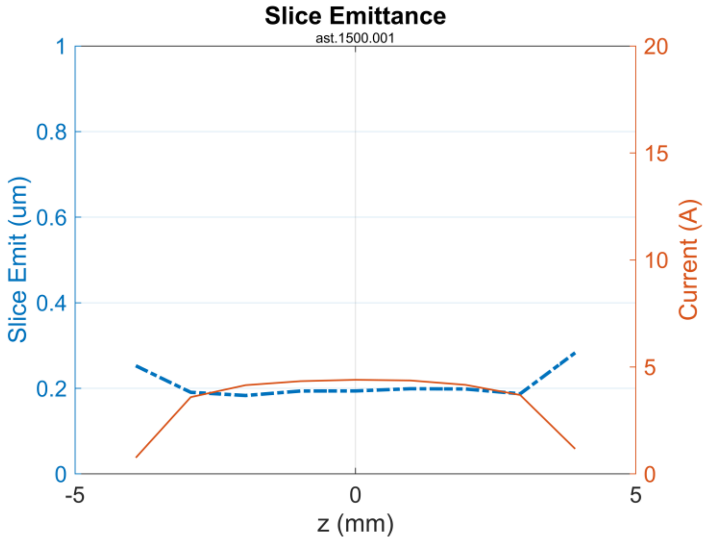
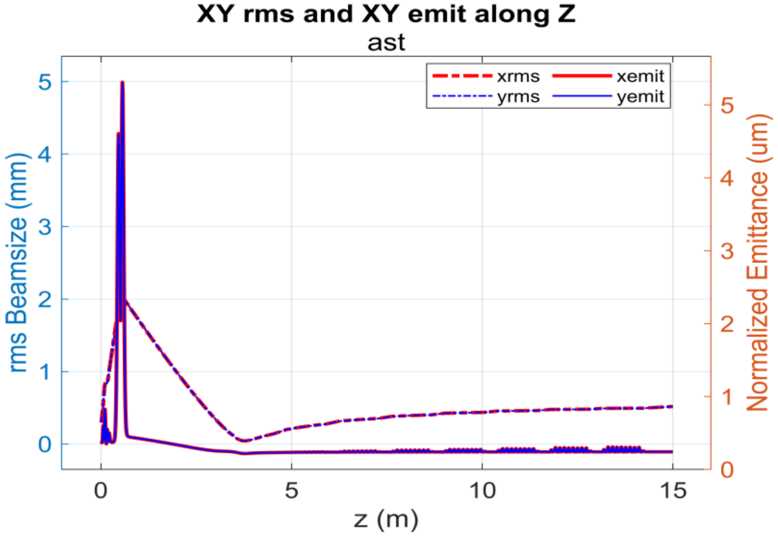


FIG. 6. Results of optimization for various charges for 1 um / mm thermal emittance.







Summary and Outlook

- Beam Dynamics optimizations for Photo Injector performance vs Photocathode laser pulse shape for the updated SRF Photo Injector setup of XFEL
  - dependencies on Ecath, Ekin
- Optimization studies for for current PITZ and XFEL setup in plan
- Develop a figure of merit for the PI optimization including bunch shape into consideration (long. core emittance,
  - 4D/ 6D integral brightness to find a single point along the Pareto front
  - For the 6D brightness → optimize 6D brightness and emittance both as goal functions in Multiobjective algorithms
- Interface with start-to-end simulations including bunch compression for the three laser shapes
- Longitudinally 2D + 1D Gaussian truncation would be explored in the future for comparison