Cathode thermal emittance measurements for OPAL-FEL

Meng Cai

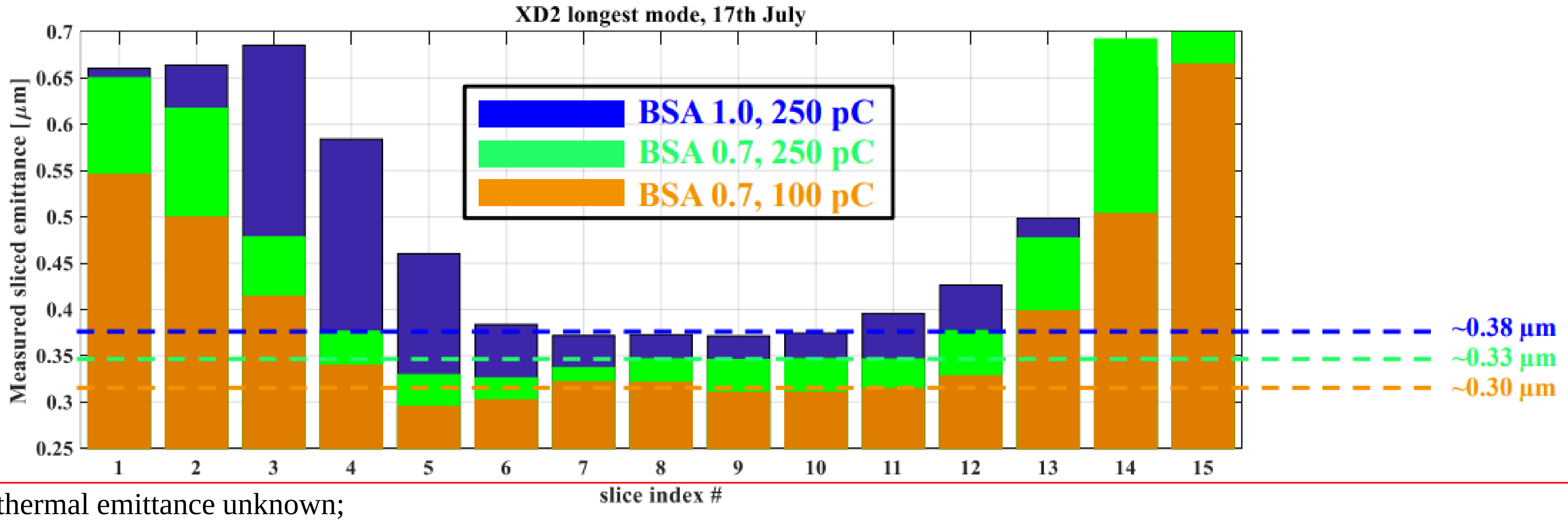
14.01.2025

Motivation

Key driver:

Thermal emittance from photoemission is the dominant factor affecting the final injector emittance.

It sets a fundamental lower limit on the achievable emittance



Measured thermal emittance unknown;
If assuming **~1.1** μm/mm rms & trans. Uni. distribution, thermal emittance **~ 0.275** μm at BSA1.0;
Under this assumption, the best measured central slice emittance at 250 pC higher than thermal emittance by **~17%** (e.g. simulations by **10%**).

Motivation

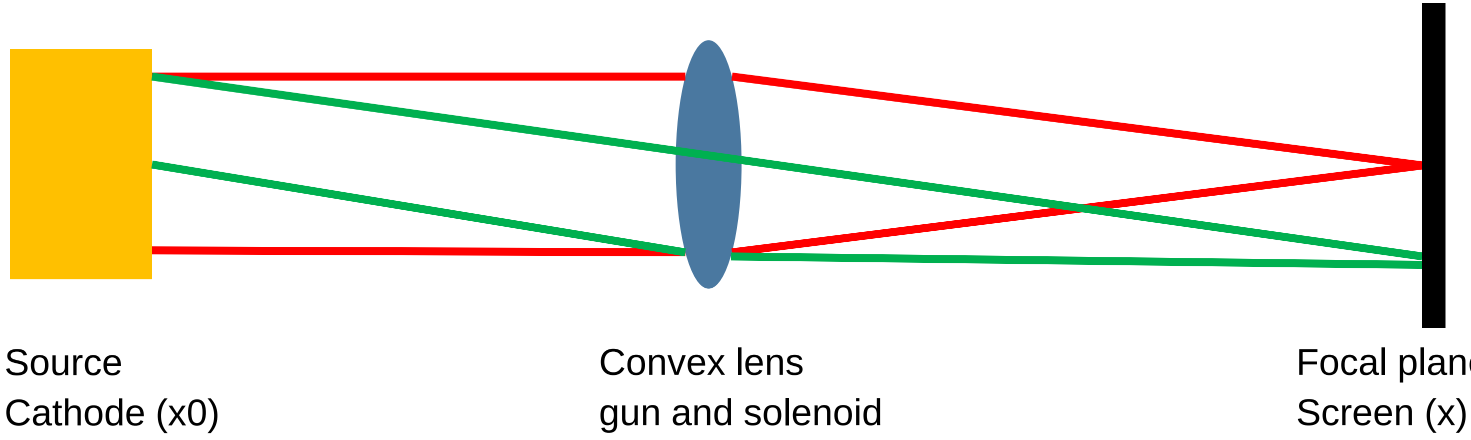
- **Laser impact** on cathode emission:

Cathode properties including thermal emittance evolve dynamically with laser characteristics. (pulse length, temporal shape, transverse size).

- Need for **routine** thermal emittance measurements.
- **Challenge**: Conventional methods (solenoid scan) require extensive data collection, making them time-consuming and impractical for frequent diagnostics.

Methodology

Huang, Peng-Wei, et al. "Single shot cathode transverse momentum imaging in high brightness photoinjectors."



- Transfer matrix formalism: $\begin{pmatrix} x \\ \frac{p_x}{m_0 c} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ \frac{p_{x0}}{m_0 c} \end{pmatrix}$

- To achieve momentum imaging: $M_{11} = 0,\ x = M_{12} * \frac{p_{x0}}{m_0 c}$

$$\frac{\varepsilon_{th}}{\sigma_{x0}} = \frac{\sigma_{p_{x0}}}{m_0 c} = \frac{\sigma_x(L)}{M_{12}}$$

ε_{th} : thermal emittance; σ_{x0}: laser spot size;

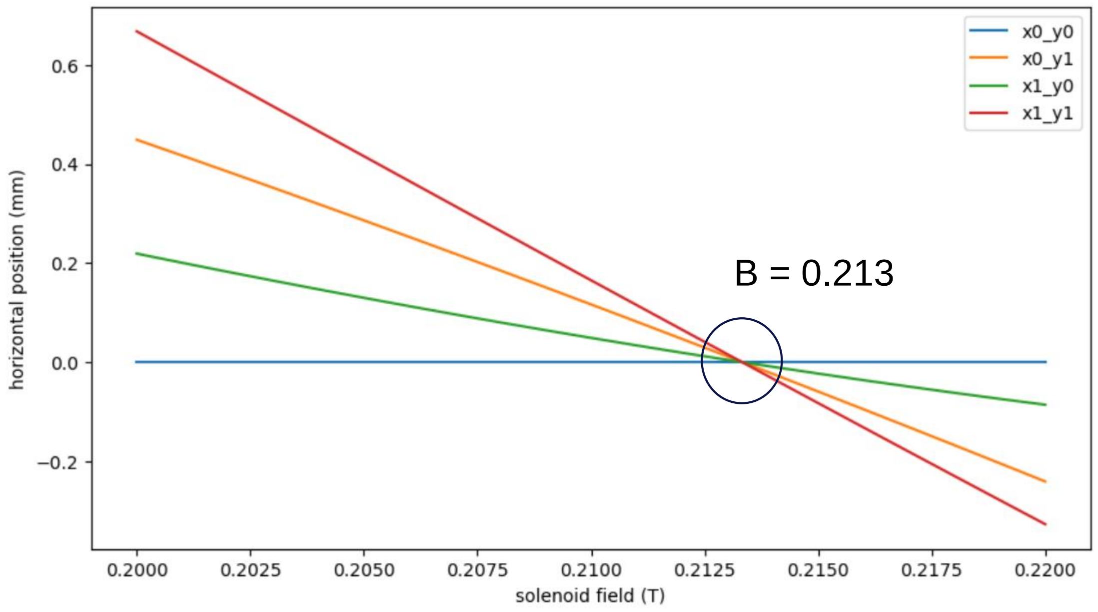
$\sigma_{p_{x0}}$: rms transverse momentum; $\sigma_x(L)$: rms spot sizes at the screen; M_{12}: obtained from ASTRA simulations

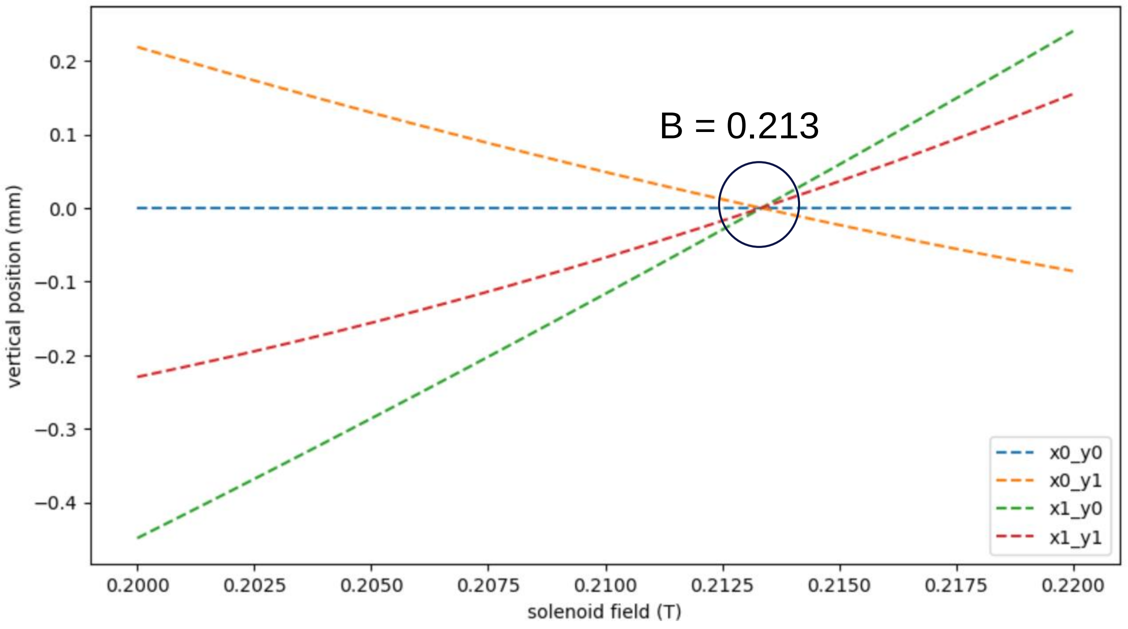
Simulation parameter	Value
L1 (distance from gun exit to solenoid)	0.276 m
L2 (distance from the solenoid to screen)	0.924 m
peak electric field	56 MV/m
pulse length	6 ps
transverse spot size	1 mm
charge	100 fC
distribution model	isotropic

Simulations using parameters of European XFEL

- The beam position on the screen as a function of solenoid field strength

At the correct solenoid field strength, the imaging condition $M_{11} = 0$ is satisfied, and beams originating from different cathode positions converge to the same position on the screen.

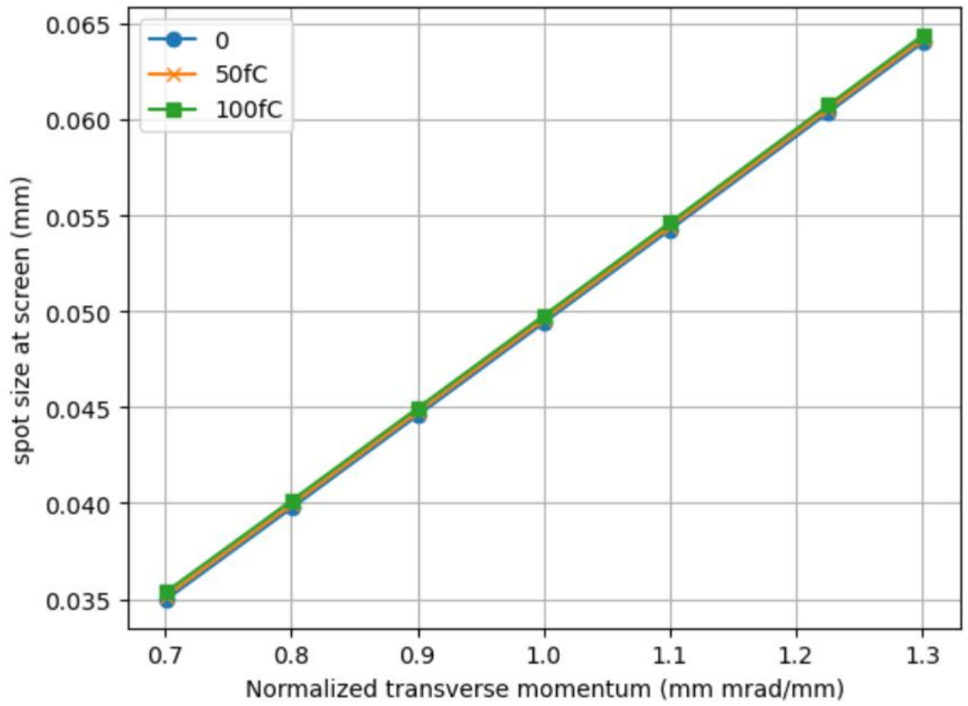




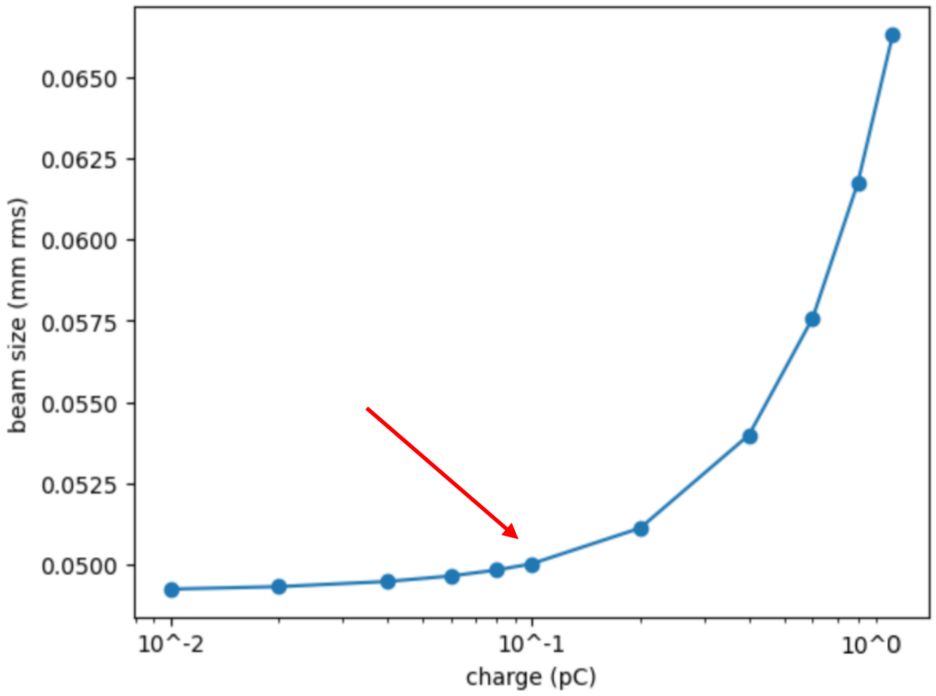
Beam size varies with normalized transverse momentum (with and without space charge)

At $M_{11} = 0$, there is a linear relation between the rms cathode transverse momentum and beam size at screen

Fitted: $M_{12} = 0.0484$;   theoretical value: 0.0620



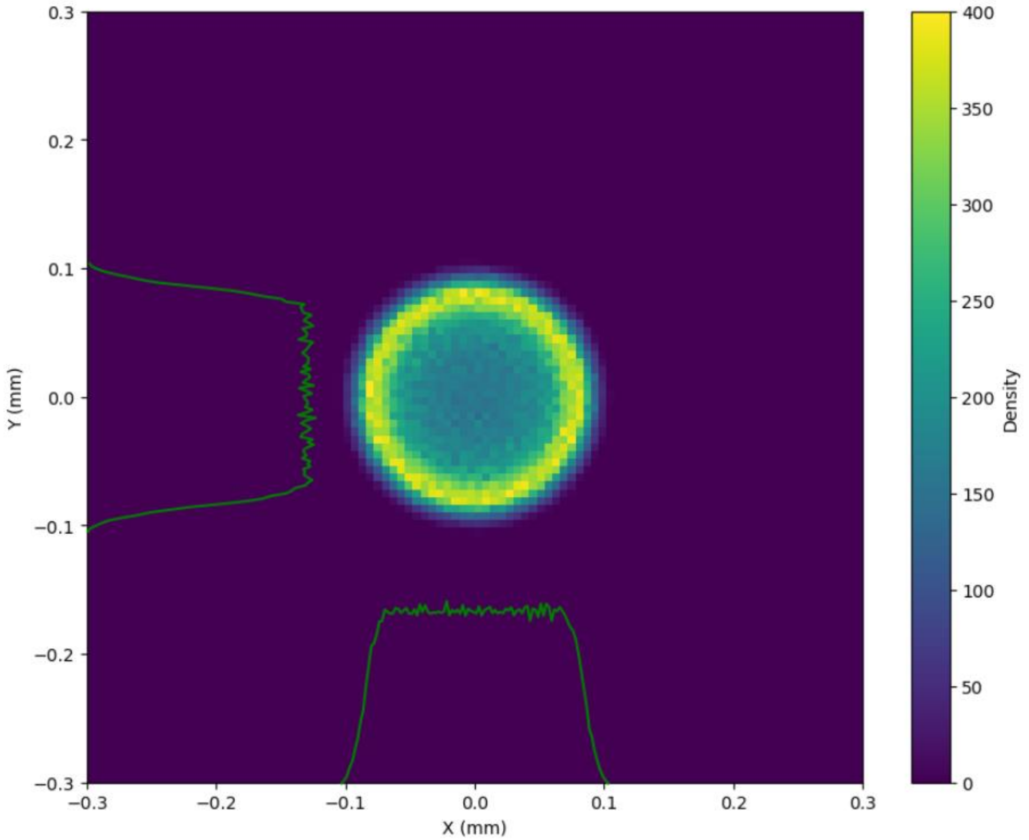
Beam size variation with charge



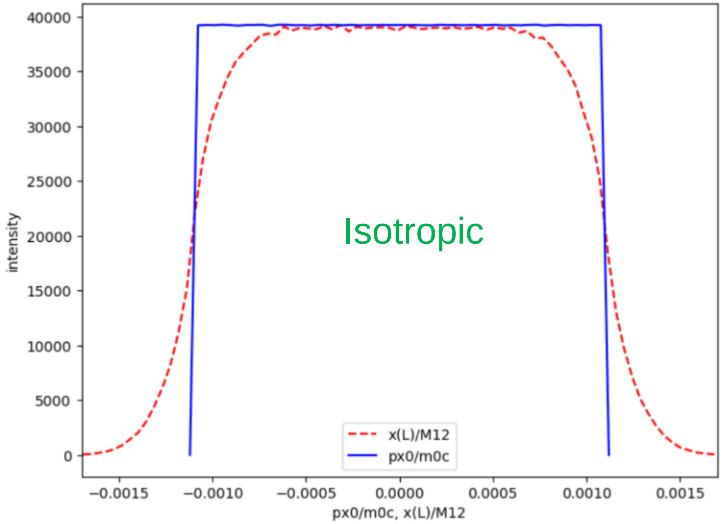
A typical image with proper imaging condition and bunch charge

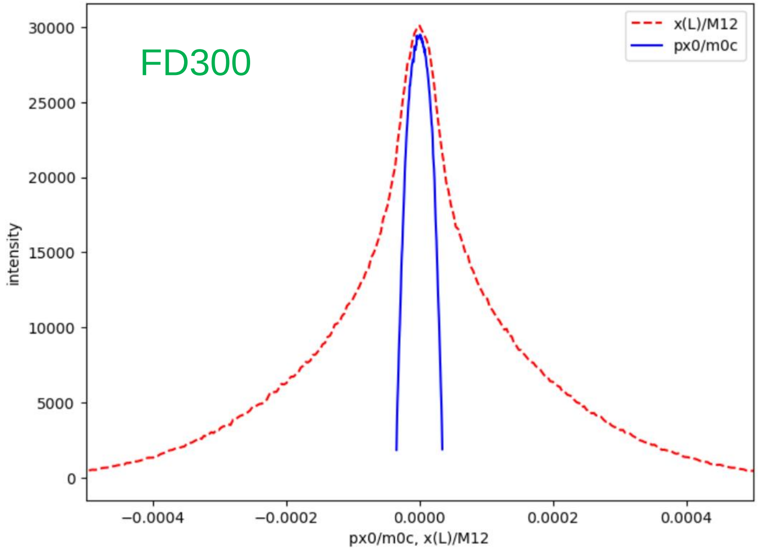
Rms spot size: 0.05 mm;

Initial momentum: 1.03 mm mrad/mm ($\frac{\sigma_x(L)}{M_{12}}$) vs. 1.00



Comparison between cathode transverse momentum and beam projection at the screen





Next steps:

- Sources of error in the calculation of M_{12}
- Robustness analysis:

Evaluate sensitivity to experimental conditions and beam parameters

- Quadrupole field influence:

Study quadrupole field effects on beam convergence and develop correction strategies.

Key Points for Work Package Alignment:

- Main achievements:

Numerical optimization using a combined “1D + 2D” laser shaping approach with parameters provided by the Denis.

Brightness model development for Eu-XFEL, integrated with machine learning techniques with Alex.

Collaboratively conducted 3 experiments on the generation of flattop-shaped laser pulses with contributions from all teams.

Single-shot cathode emittance simulations. (will be implemented and validated in future experiments.)

- Future plan

- Validate single-shot thermal emittance simulation with experiments
- Extend brightness model for more injector configurations.
- Complete ML optimization from laser parameters to injector output.