Experimental Slice Emittance Reduction at PITZ using Laser Pulse Shaping

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HELMHOLTZ

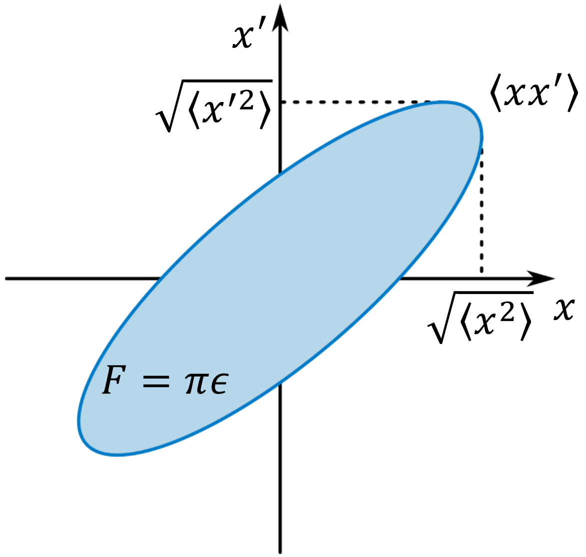
DESY.

Free-electron laser performance

Transverse emittance

- Volume in transverse phase space

$$\epsilon = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$



Emittance criterion: $\frac{\epsilon}{\beta\gamma} \leq \frac{\lambda_{\mathrm{rad}}}{4\pi}$ [1]

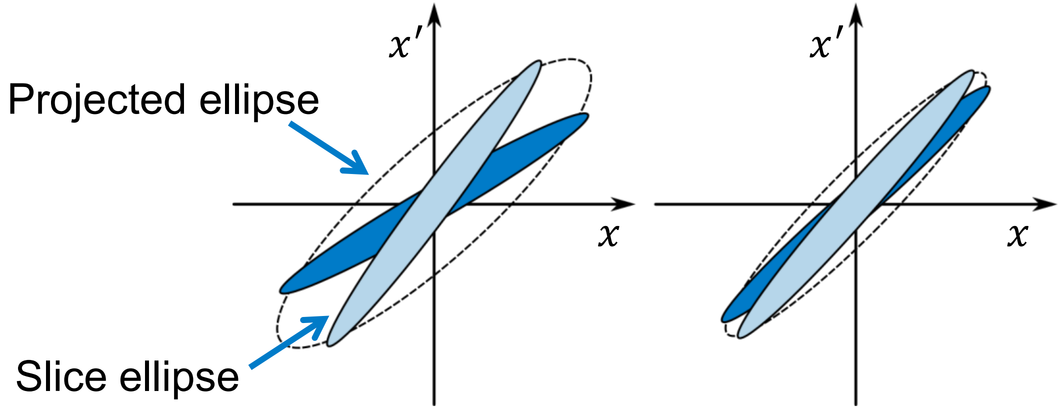
Beam phase space emittance

Radiation phase space volume

FEL process on fraction of bunch

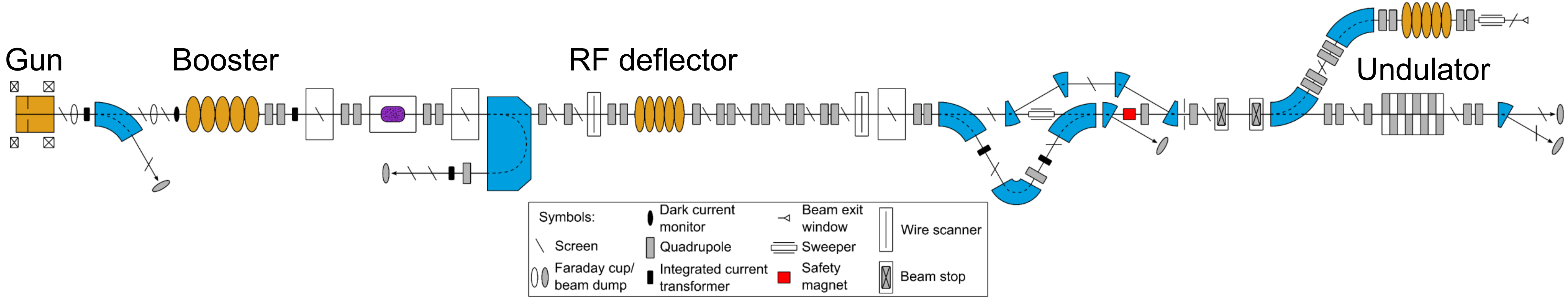
- Slice emittance important
- *Slice matching* determines projected emittance

→ Slice emittance measurement crucial



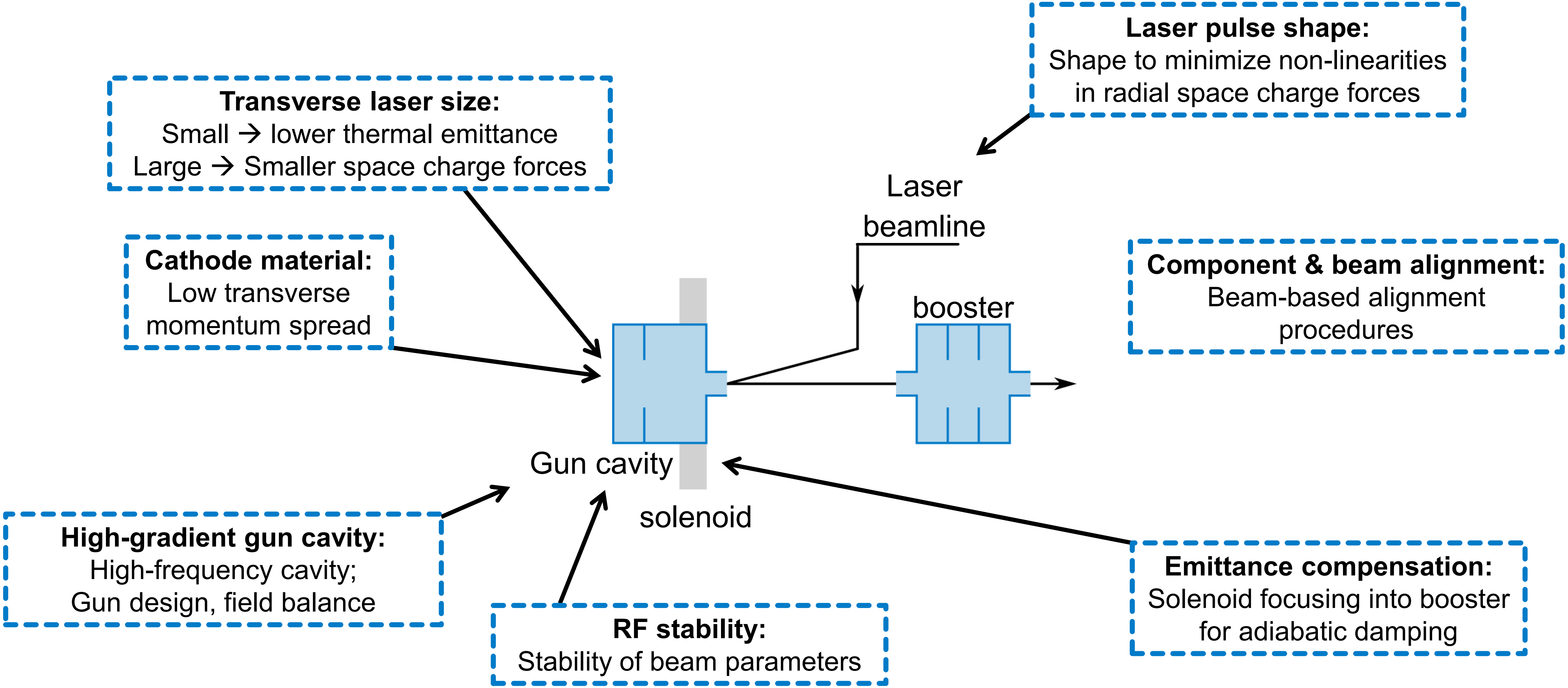
[1] P. Schmüser et al., Free-Electron Lasers in the Ultraviolet and X-Ray Regime, Springer (2014)

Photoinjector Test Facility at DESY in Zeuthen (PITZ)



- Test stand for photo electron guns of FLASH & European XFEL
- Beam energy ≤ 25 MeV
- High brightness
- Bunch charges up to 5 nC
- **Various diagnostics**
  - **Emittance**
  - **RF deflector (TDS)**
  - Longitudinal phase space
- **Flexible laser pulse shapes**

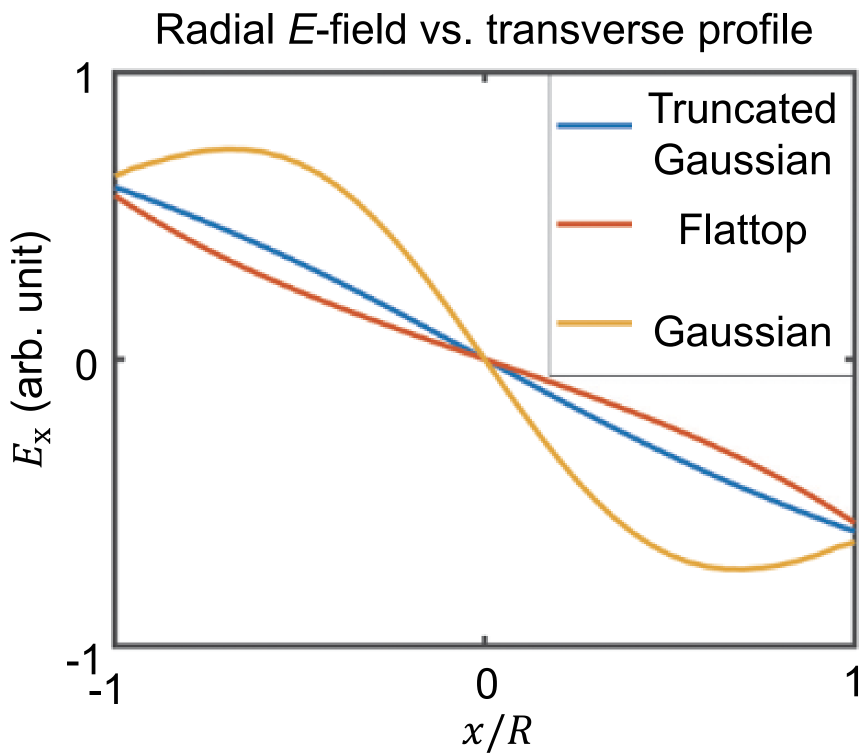
Emittance optimisation in photoinjectors



Emittance optimisation using laser pulse shaping

- Laser pulse shape determines bunch shape (near cathode)
- Bunch shape determines space charge forces
- Non-linear space charge forces lead to emittance growth

→ Photocathode laser pulse shaping = tool for emittance reduction

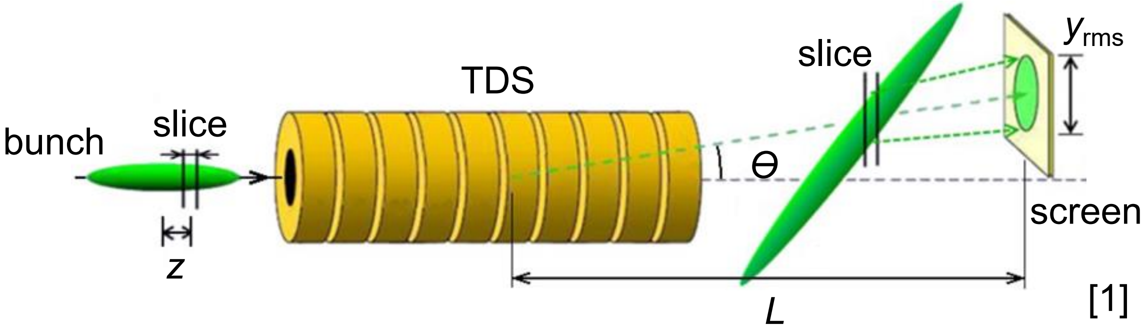


[2]

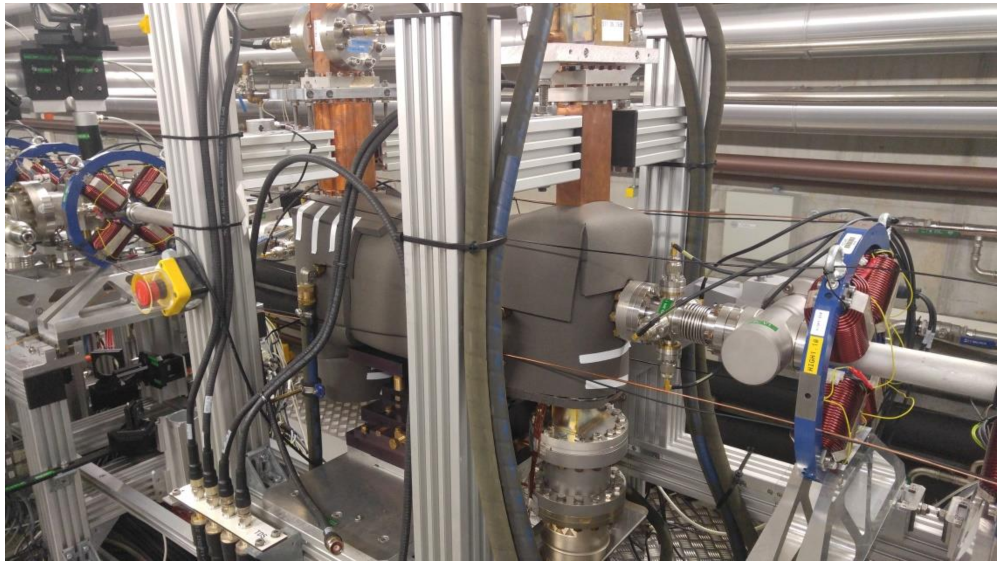
[1] F. Zhou et al., PR STAB **15**, 090701 (2012)
[2] H.Chen et al., PRAB **24**, 124402 (2021)
[3] M. Haenel, PhD thesis, Hamburg (2010)
[4] T. Plath et al., Proceeding IBIC2013, TUPC03

Transversely deflecting structure (TDS)

Mapping longitudinal to vertical coordinate
- Bunch profile
- Longitudinal phase space
- Time-resolved transverse phase space
  - **Slice emittance**

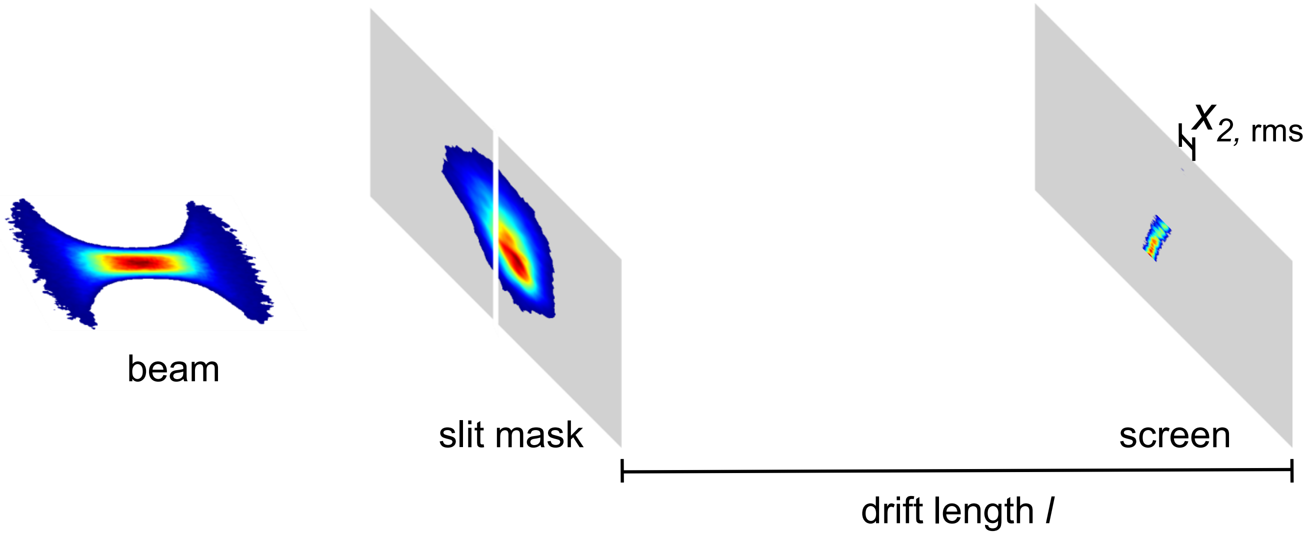


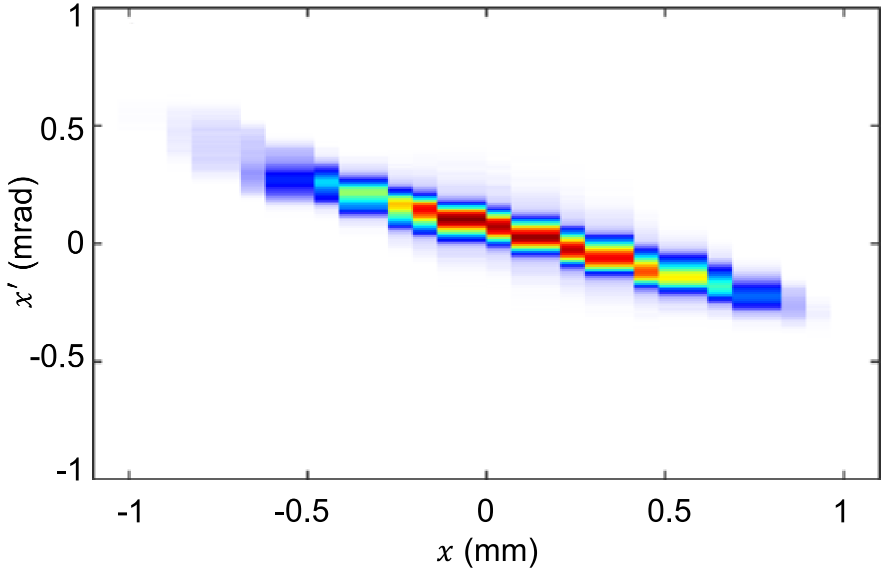
Properties
- European XFEL prototype
- 3 GHz (S band)
- Pulse length ≤ 3 μs
  - Deflection of up to 3 bunches
- Deflection voltage 1.7 MV
- Resolution ≥ 200 fs (typically)



[1] D. Malyutin, Ph.D. thesis, Universität Hamburg, (2014)

Projected emittance diagnostics



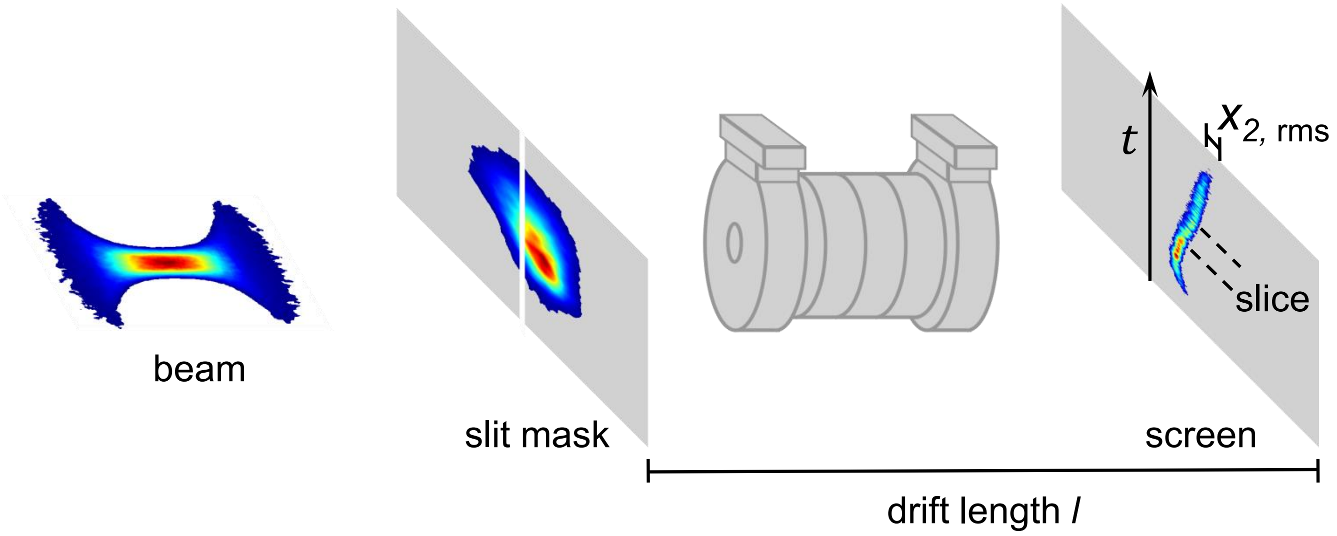


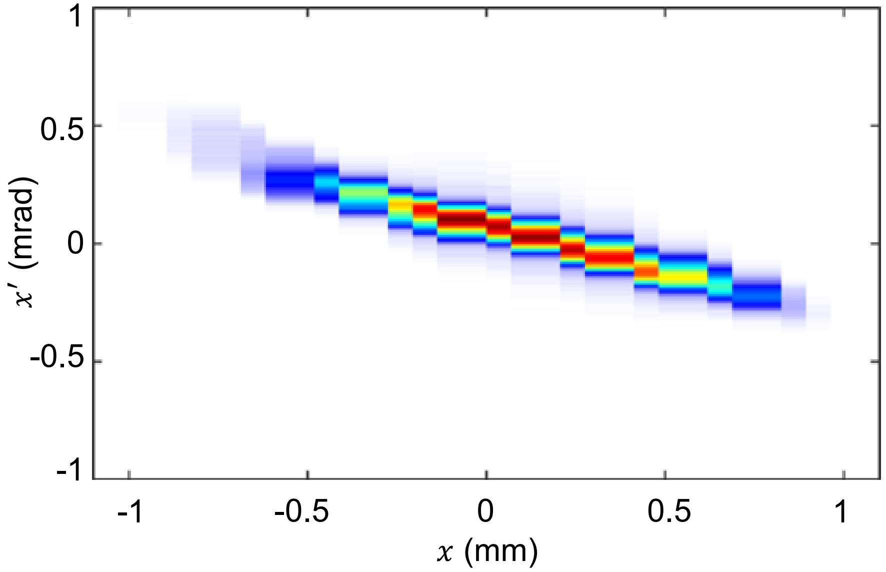
- Cut-out emittance-dominated beamlets from space charge-dominated beam with slit [1]
  - Mapping divergence to beam size: $x_1' \rightarrow x_2$
  - Measure **position, divergence, & intensity**

- Reconstruct phase space
  - Emittance calculation via $\epsilon = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$

[1] M. Krasilnikov et al., PR STAB **15**, 100701 (2012)

Slice emittance diagnostics





- Cut-out emittance-dominated beamlets from space charge-dominated beam with slit [1]
  - Mapping divergence to beam size: $x_1' \rightarrow x_2$
  - Measure **position, divergence, & intensity** and **time**

- Reconstruct phase space
  - Emittance calculation via $\epsilon = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$

[1] M. Krasilnikov et al., PR STAB **15**, 100701 (2012)

Challenges

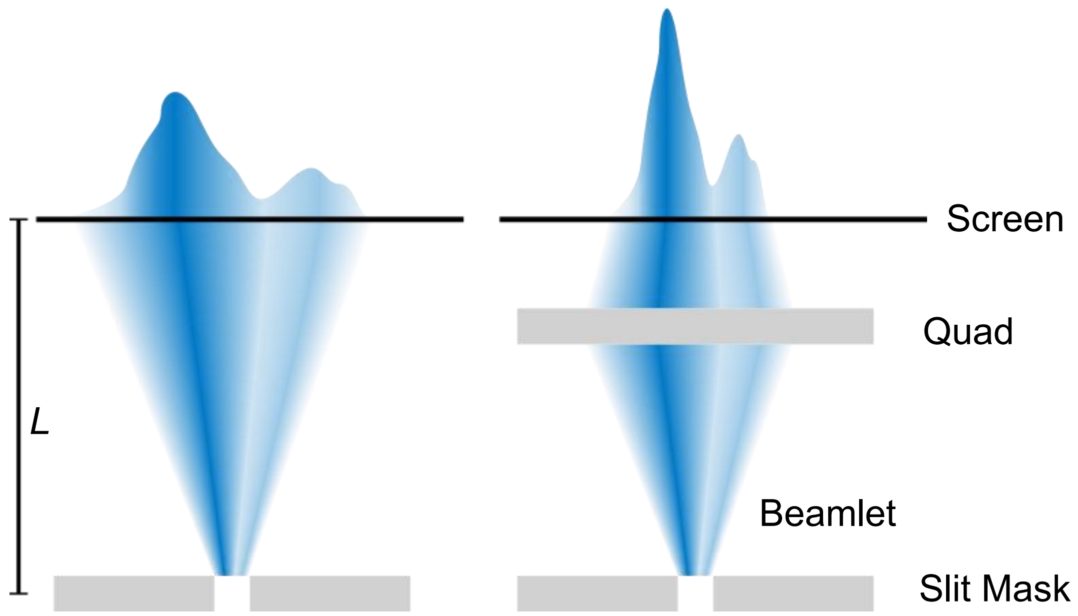
Obstacles

- Systematic error from *space charge effects*
- Low signal-to-noise ratio (SNR) due
  - Slit mask (reduces charge)
  - TDS deflection, 3 bunches max.
  - Long distance: Slit mask → Screen

Measures

- Use of high-sensitivity LYSO screen
- Screen station: Moved camera close to screen
- Use of quadrupole magnets behind slit mask
  - Reduce horizontal beam size
  - Increase SNR
  - Improve temporal resolution

$$\mathrm{SNR} = \frac{\text{maximum signal strength}}{\text{rms pixel value of background images}}$$

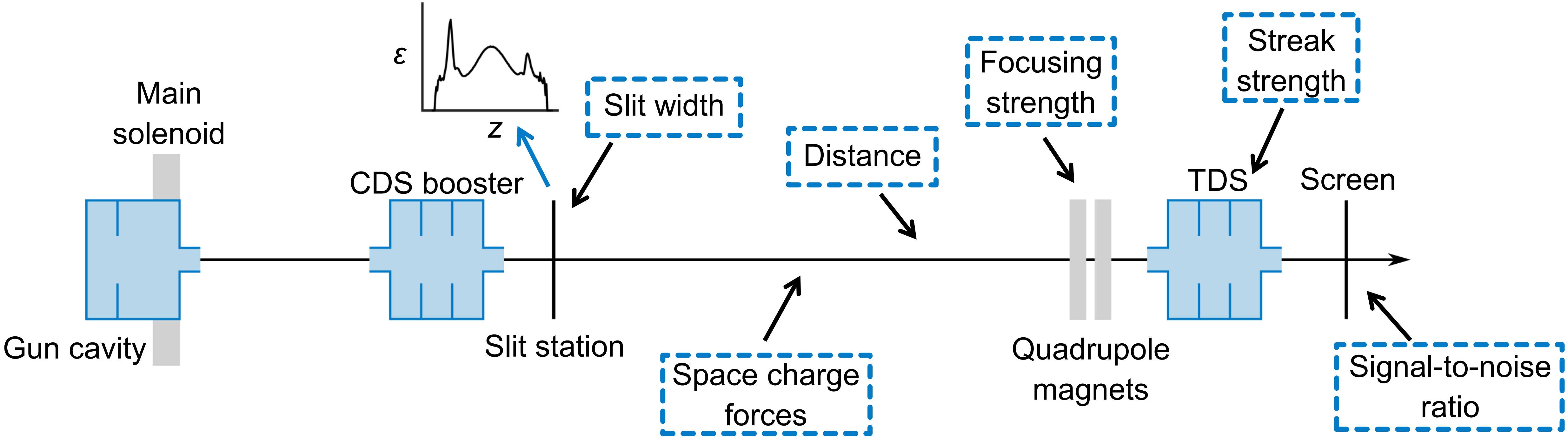


Systematic error estimation

Systematic error simulation studies

Generate standard beam

- Use PITZ standard conditions
- Optimise solenoid focusing strength
- Optimise transverse beam size @ cathode
  - Goal: Lowest projected emittance



Estimation of systematic error

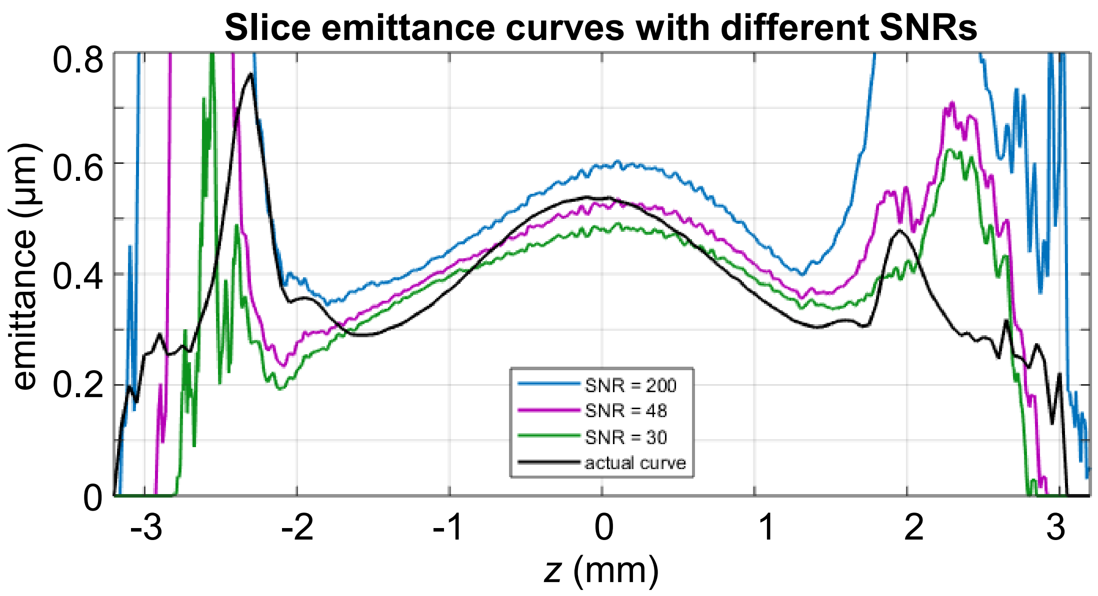
Slice emittance curve with finite SNR

- SNR > 200, slice emittance overestimation
  - Due space charge forces (mainly)
- SNR ~ 50, correct measurement
- SNR < 50, slice emittance underestimation
  - Low-intensity regions invisible

At PITZ

- SNR ~ 50

→ Only minor error

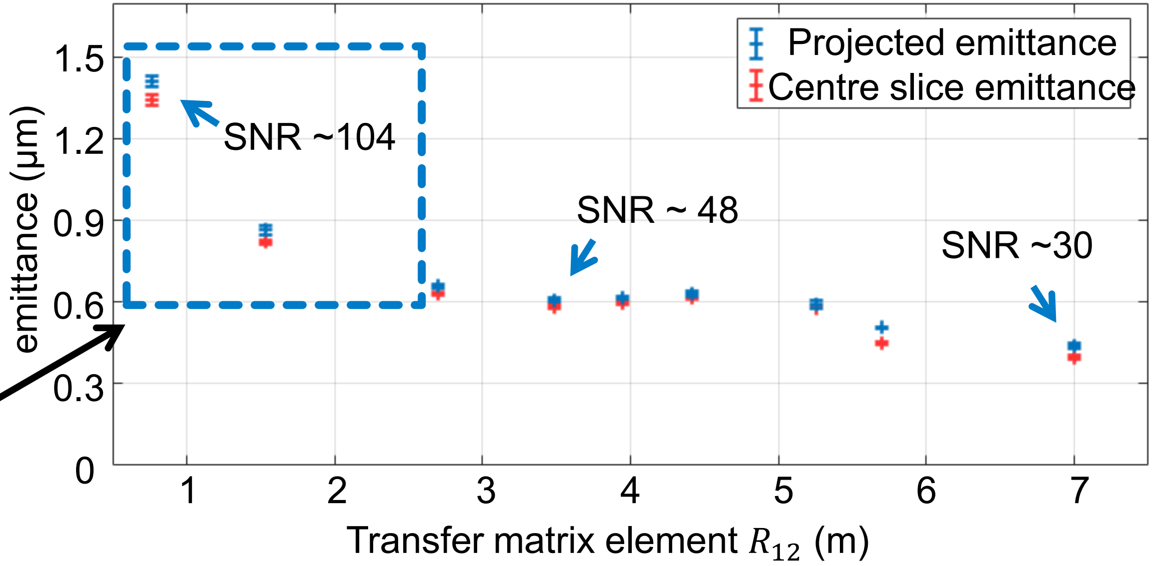


Estimation of systematic error

Scan of focusing strength (*R_{12}*)

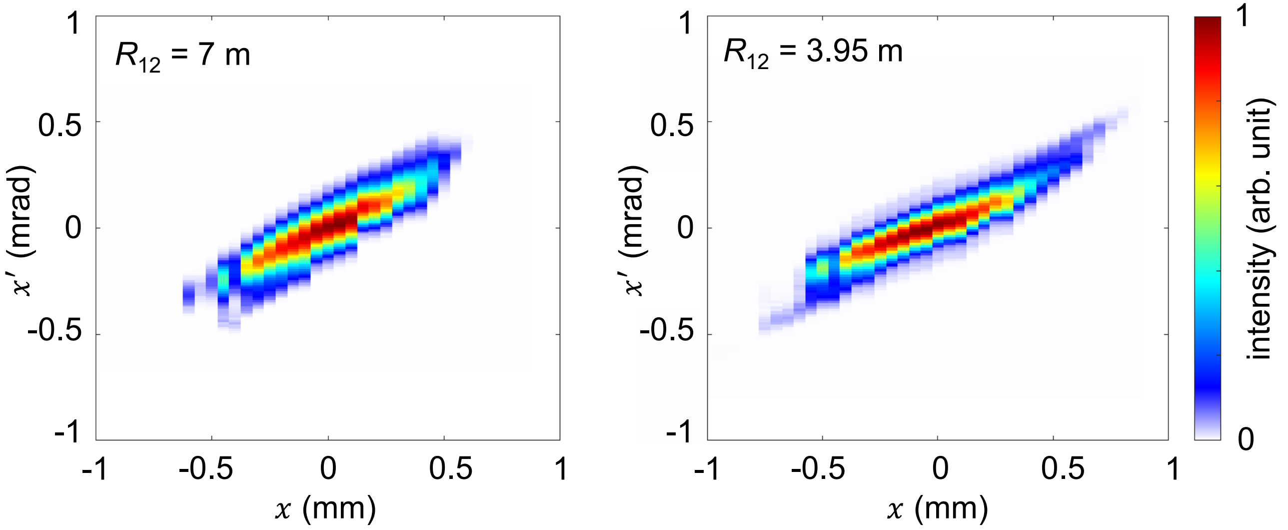
- Measured emittance growth due higher SNR
- Big error at small R_{12}'s (strong focusing)

Worsening angular resolution & Bigger space charge forces → Large error



Centre slice phase space

- With decreasing R_{12} SNR increases
- Higher sensitivity
- Low-signal areas become visible



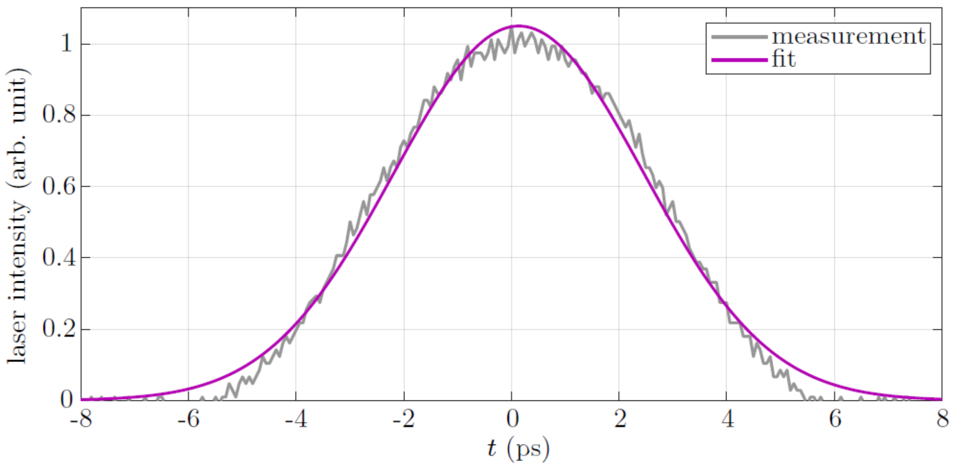
Beam characterisation

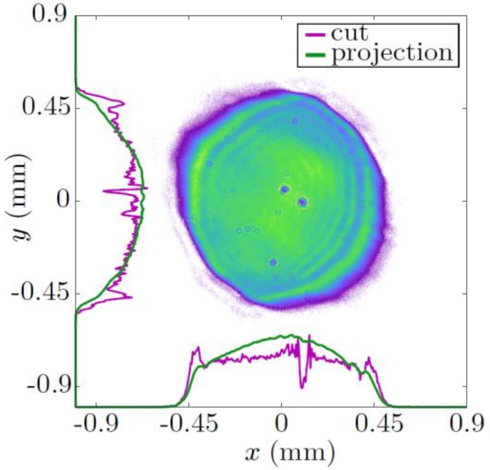
Laser pulse profile	
Temporal	Transverse
Gaussian	Flattop

Beam characterisation

Low-emittance beam at European XFEL conditions

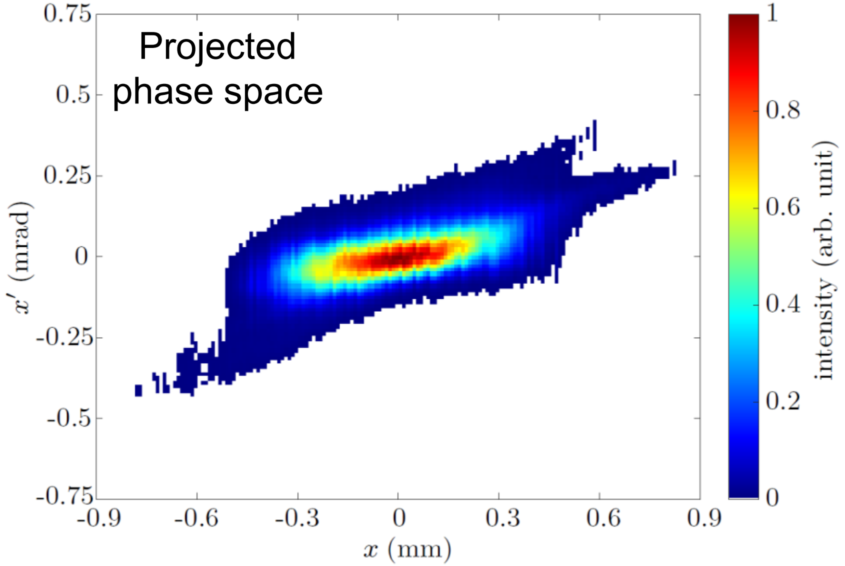
- Transverse flattop laser pulse profile
- Temporal Gaussian laser pulse shape
- 250 pC bunch charge
- Laser pulse length 6 ps (FWHM)





Solenoid scan for emittance optimisation

- Operation at optimum
- Proj. hor. emittance $\epsilon_x = 0.53^{+0.09}_{-0.08}$ (syst.) µm



Slice emittance measurement

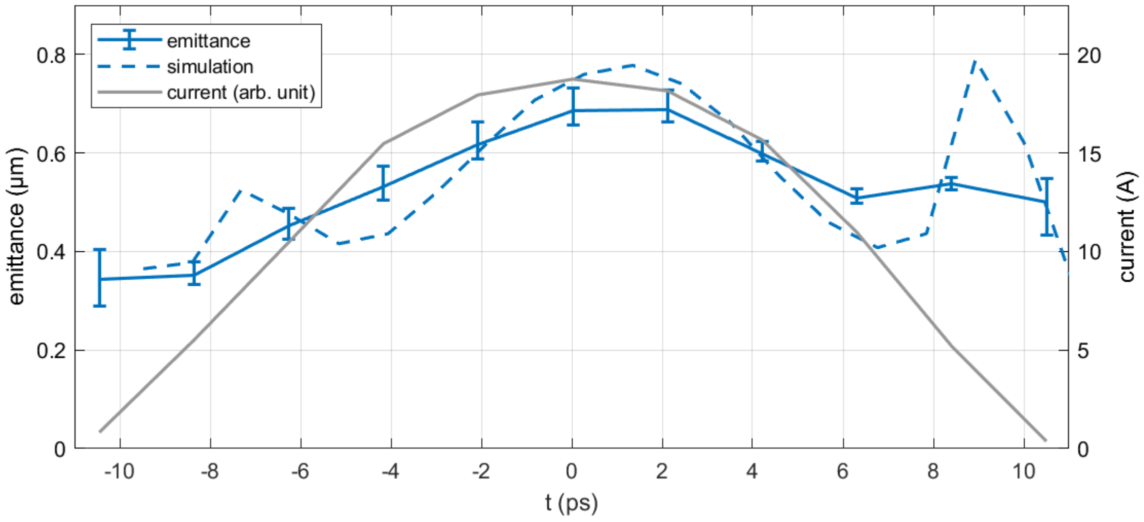
Temporal Gaussian
Transverse flattop

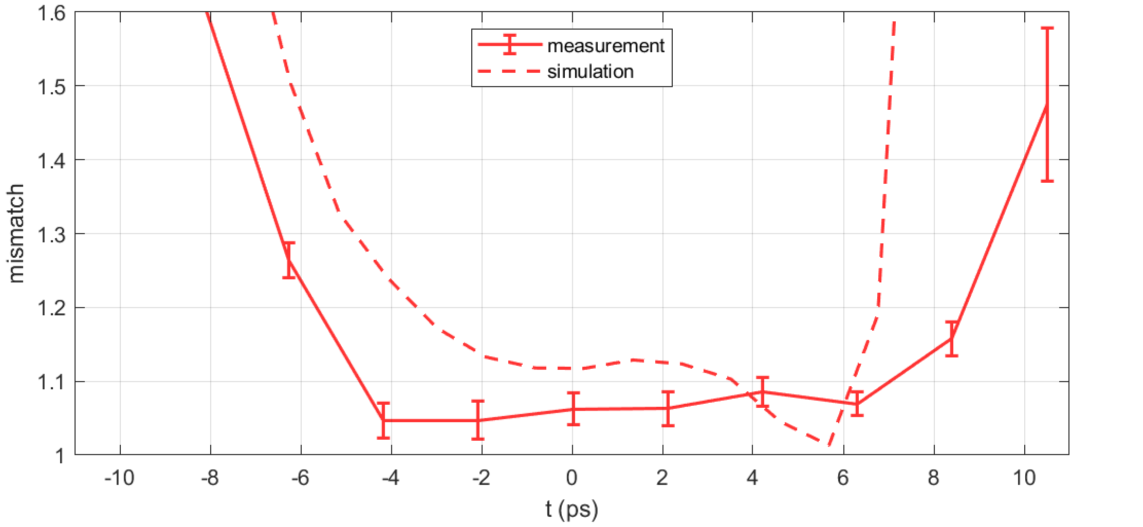
Emittance curve

- Higher emittance in centre
- Centre slice emittance $\epsilon_x = 0.69^{+0.05}_{-0.03}$ (stat.) µm
- Emittance reduces towards both tails
- Simulation curve agrees with measurement in centre

Mismatch

- Small mismatch in centre of bunch
- Large mismatch at both tails
- Simulation: Mismatch similar, but rises closer to centre





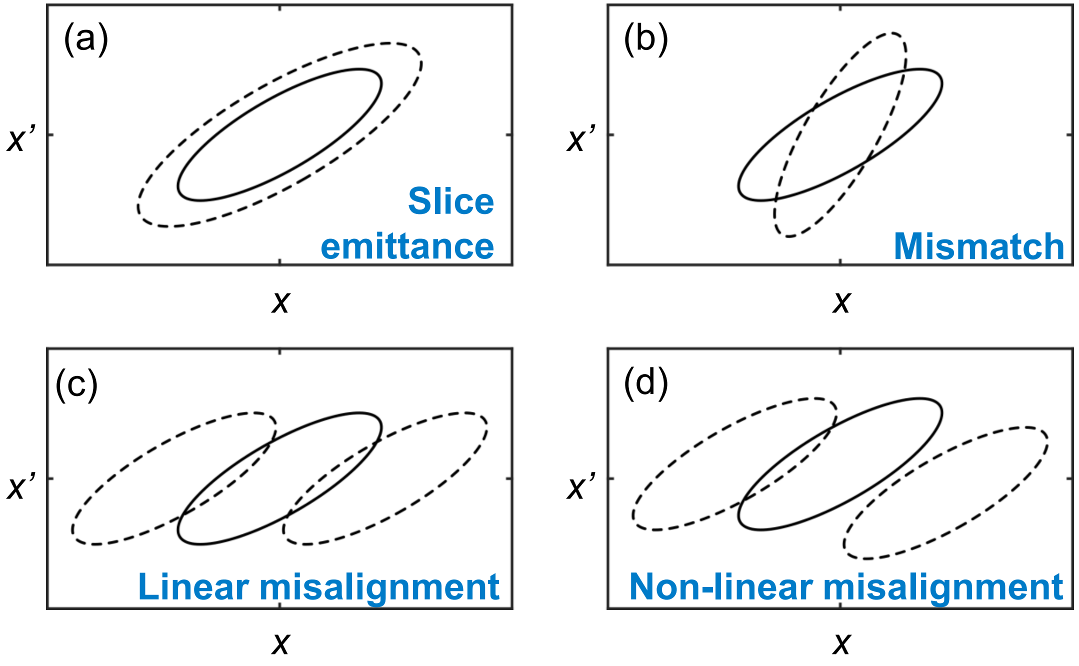
Emittance decomposition

Projected phase space results from slice phase space

Mismatch   Linear misalignment

Projected emittance[1]: $\varepsilon_x{}^2 = \varepsilon_\perp{}^2 + \varepsilon_{\mathrm{R}}{}^2 + \varepsilon_{\mathrm{int}}{}^2 + \varepsilon_\parallel{}^2$

Slice emittance   Non-linear misalignment



Emittance decomposition allows to identify significant emittance contributions

- High thermal emittance/non-linear radial space charge forces
- Longitudinal variation of transversely focusing forces
- Improper beam trajectory, leading to misalignment

→ Enables deeper insight into **beam quality optimisation**

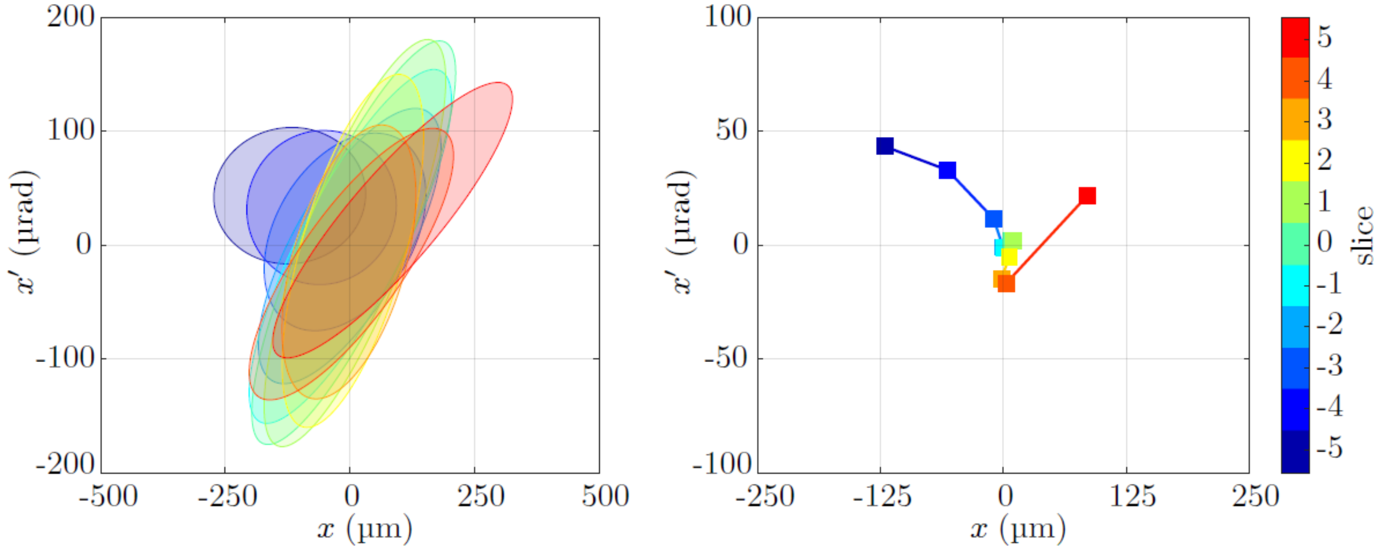
[1] C. Mitchell, *A General Slice Moment Decomposition of RMS Beam Emittance,* (2015).

Slice emittance measurement

Temporal Gaussian
Transverse flattop

Slice phase space ellipses & centroids

- Varying emittance & orientation visible
- (Mostly) linear misalignment visible as well



Emittance decomposition

- Slice emittance main contribution to projected emittance
- Moderate mismatch contribution
- Misalignment negligible

±FWHM/2	Measurement	Simulation
Projected emittance	0.68 µm	0.69 µm
Slice emittance	0.64 µm	0.60 µm
Mismatch emittance	0.25 µm	0.30 µm
Linear misalignment emittance	0.05 µm	0.01 µm
Non-linear misalignment emittance	< 0.01 µm	< 0.01 µm

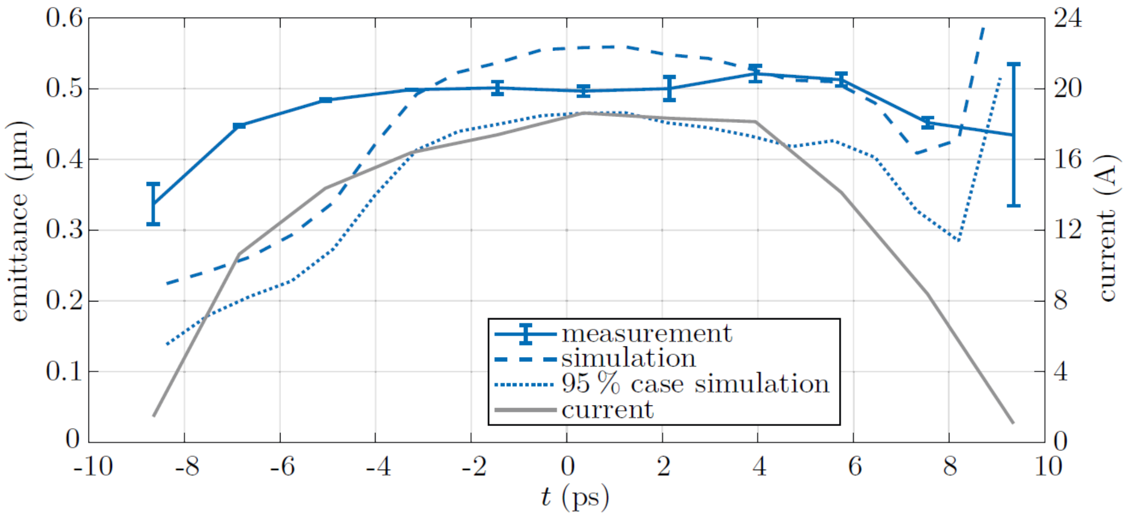
Beam characterisation

Laser pulse profile	
Temporal	**Transverse**
Gaussian	Flattop
Flattop	Flattop
Gaussian	Truncated Gaussian

Slice emittance measurement

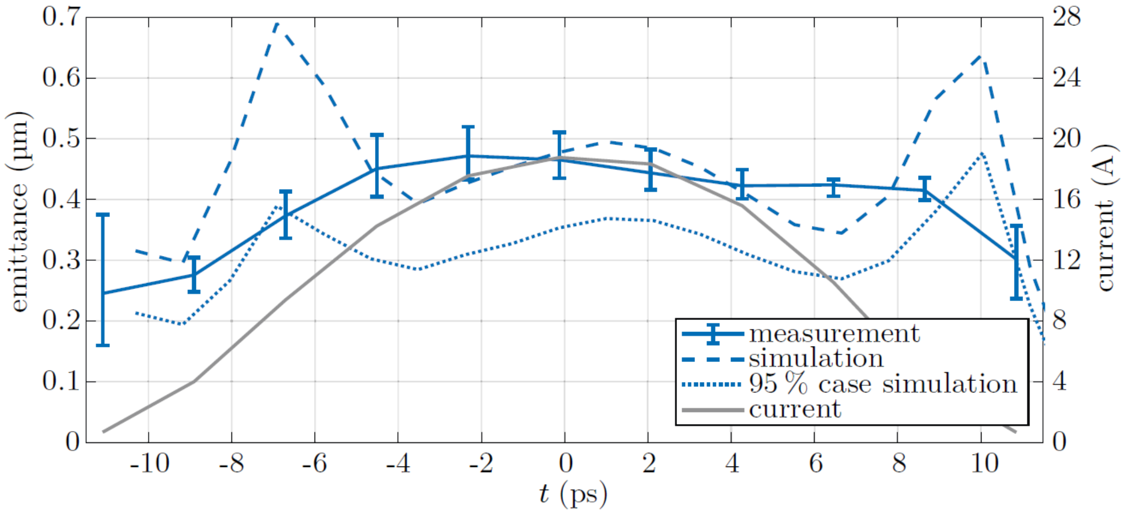
Temporal flattop
Transverse flattop

- Centre slice emittance $\epsilon_x = 0.50 \pm 0.01$ (stat.) µm
- Simulation curve agrees with measurement in centre



Temporal Gaussian
Transversely-truncated Gaussian

- Centre slice emittance $\epsilon_x = 0.47^{+0.05}_{-0.03}$ (stat.) µm
- High emittance at both tails

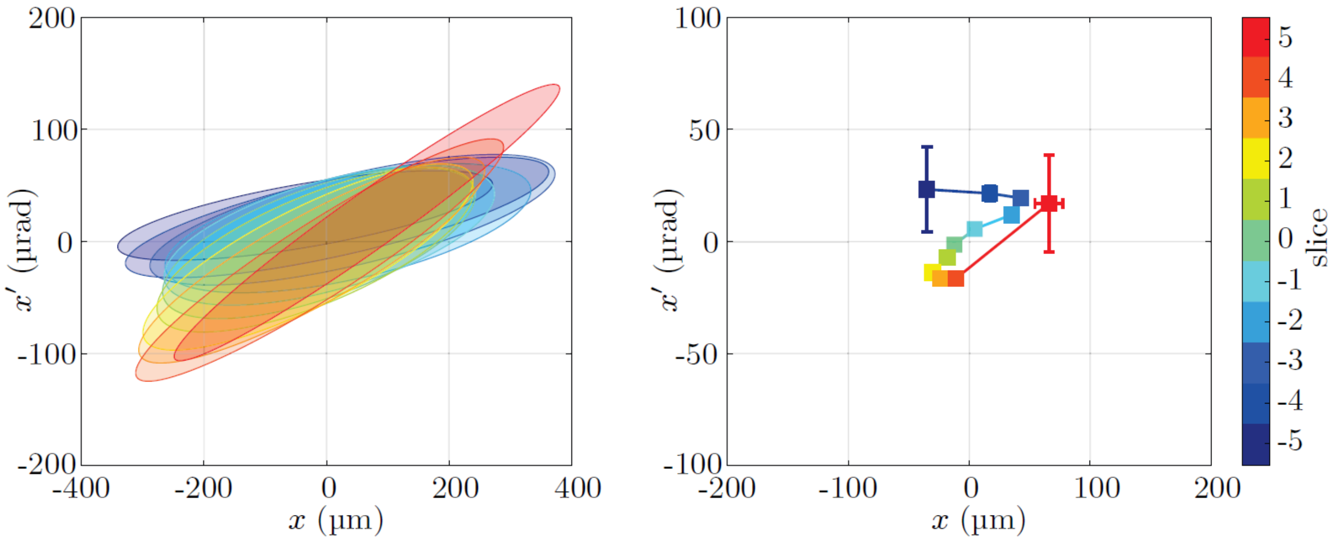


Slice emittance measurement

Temporal flattop
Transverse flattop

Slice phase space ellipses & centroids

- Varying tilt along z
  - Smaller/higher correlations in tails than in centre
- Shift in centroid positions
  - (Mainly) linear shift in centre



Emittance decomposition

- Good agreement of measurement & simulation

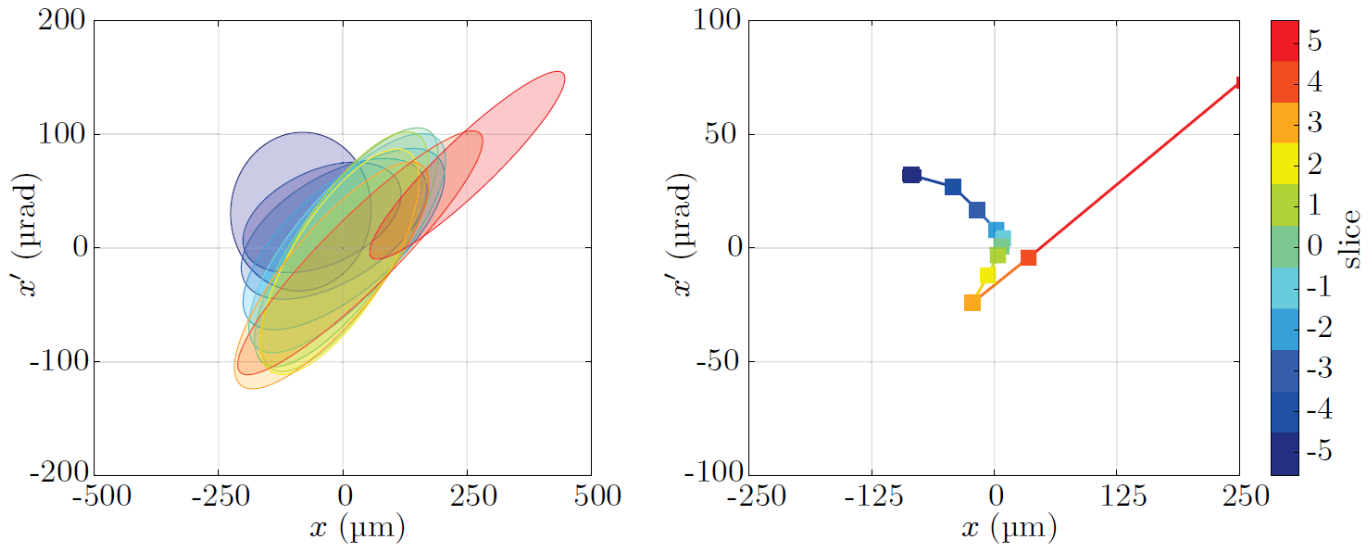
±FWHM/2	Measurement	Simulation
Projected emittance	0.57 µm	0.52 µm
Slice emittance	0.50 µm	0.49 µm
Mismatch emittance	0.23 µm	0.19 µm
Linear misalignment emittance	0.10 µm	0.01 µm
Non-linear misalignment emittance	< 0.01 µm	< 0.01 µm

Slice emittance measurement

Temporal Gaussian
Transversely-truncated Gaussian

Slice phase space ellipses & centroids

- Varying emittance & orientation visible



Emittance decomposition

- Mismatch emittance much larger in simulation

±FWHM/2	Measurement	Simulation
Projected emittance	0.47 μm	0.60 μm
Slice emittance	0.45 μm	0.45 μm
Mismatch emittance	0.13 μm	0.40 μm
Linear misalignment emittance	0.06 μm	0.01 μm
Non-linear misalignment emittance	< 0.01 μm	< 0.01 μm

Summary & outlook

Summary

Slit scan + TDS allows slice emittance measurement

- Systematic error acceptable
- Temporal resolution improved down to 200 fs with focusing

→ Reliable slice emittance calculation

Signal-to-noise ratio increased

- LYSO screens, optimised screen station, quadrupole focusing, wider slit opening
- Improved time resolution allows reduction of TDS voltage

→ For PITZ parameters: Syst. error ~ 4 %

Several beams characterized in experiment

- Emittance reduced by going from temporal Gaussian to flattop
- Emittance reduced by going from temporal Gaussian to Transversely-truncated Gaussian

Emittance	Laser pulse profile: Temporal	Laser pulse profile: Transverse
$\epsilon_x = 0.69^{+0.05}_{-0.03}$ (stat.) µm	Gaussian	Flattop
$\epsilon_x = (0.50 \pm 0.01)$ (stat.) µm	Flattop	Flattop
$\epsilon_x = 0.47^{+0.05}_{-0.03}$ (stat.) µm	Gaussian	Truncated Gaussian

Emittance decomposition

- Gives insight, how projected emittance can be reduced

Outlook.

Variability of SNR due LASER system & camera system

- New laser system for PITZ (NEPAL-P) in 2023
  - Higher repetition rate (1 MHz → 4.5 MHz)
- Upgrade camera
  - Electron-Multiplying CCD camera (EMCCD)
  - Lower noise improves SNR further

→ Narrower slit opening might be used

R&D program towards CW-operation of European XFEL

- Reduced gun gradient
- PITZ can characterize beams at cw-gun conditions
- Slice emittance optimisation by laser pulse shaping

Thank you

Contact

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