Experimental Slice Emittance Reduction at PITZ using Laser Pulse Shaping

Raffael Niemczyk
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Bangkok, 16.06.2022

HELMHOLTZ

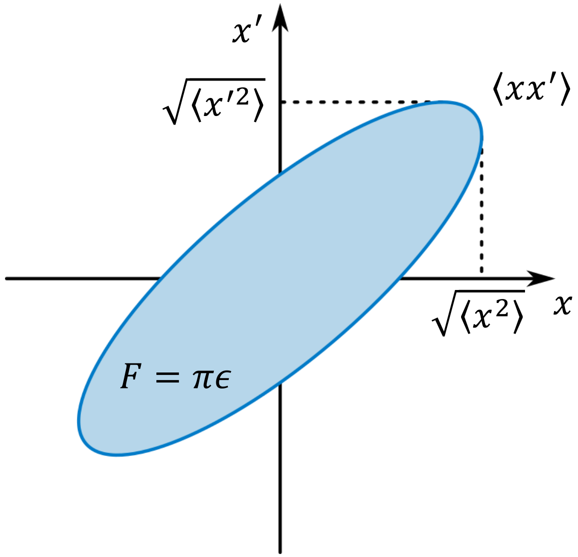
DESY.

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: $\epsilon \leq \frac{\lambda_{\text{rad}}}{4\pi}$ [1]

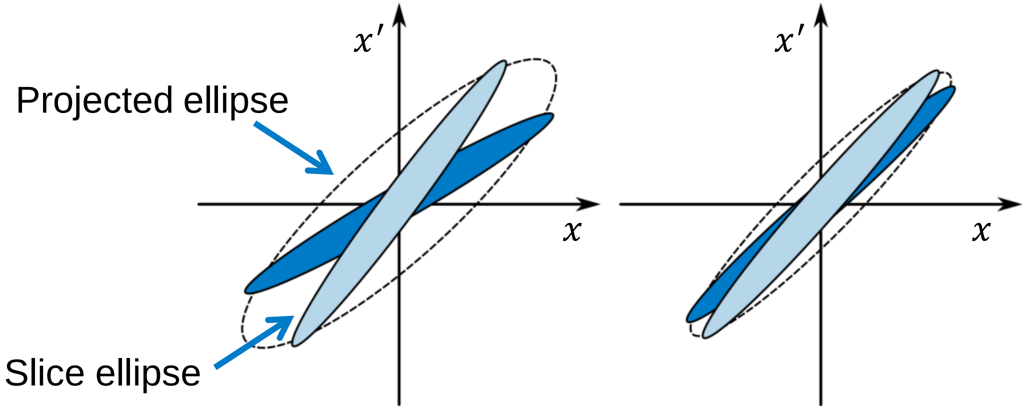
Beam phase space emittance

Radiation phase space volume

FEL process on fraction of bunch

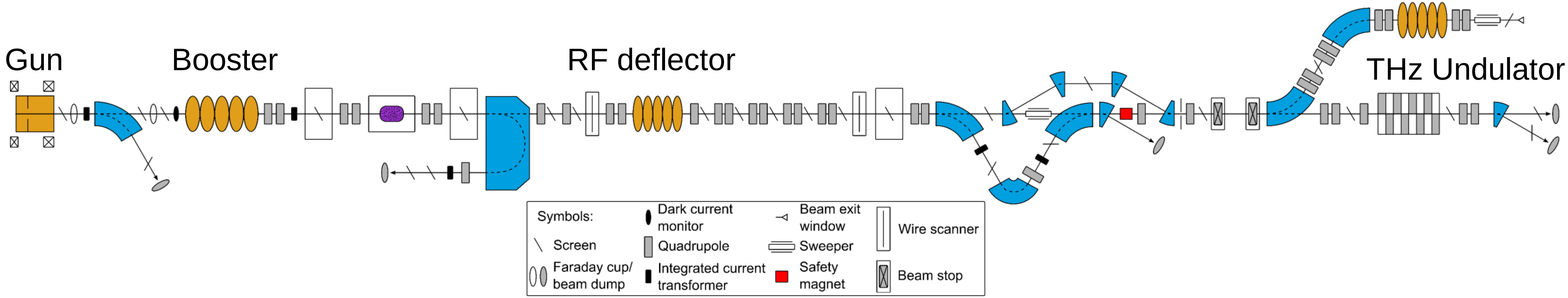
- Slice emittance important
- *Slice matching* determines projected emittance

→ 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)



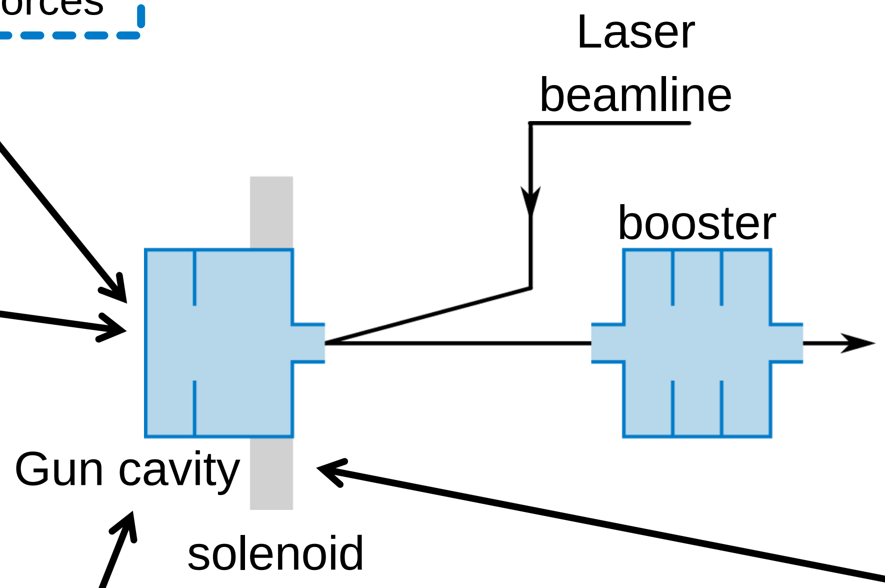
- Test stand for photo electron guns of FLASH & European XFEL
- Beam energy ≤ 25 MeV
- High brightness
- Main bunch charges 1 pC – 4 nC
- **Various diagnostics**
  - **Emittance**
  - **RF deflector (TDS)**
  - Longitudinal phase space
- **Flexible laser pulse shapes**

Emittance Optimisation in Photoinjectors

Laser pulse shape:
Shape to minimize non-linearities in radial space charge forces

Transverse laser size:
Small → lower thermal emittance
Large → Smaller space charge forces

Cathode material:
Low transverse momentum spread



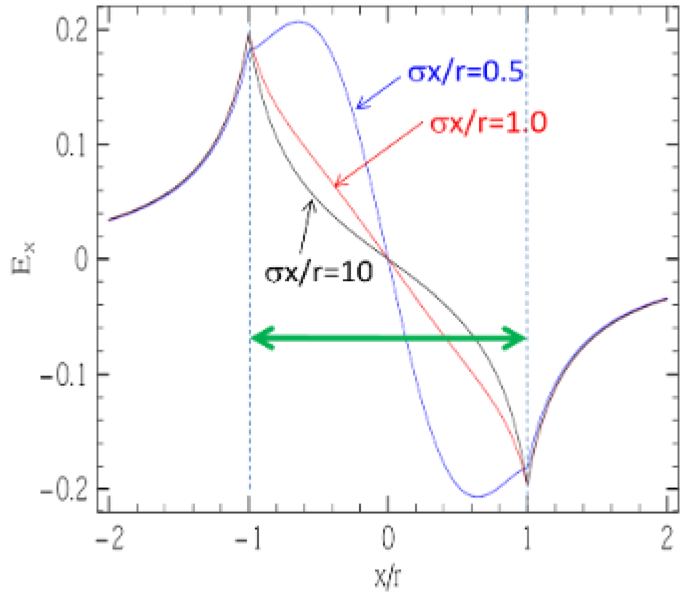
Component & beam alignment:
Beam-based alignment procedures

High-gradient gun cavity:
High-frequency cavity;
Gun design, field balance

RF stability:
Stability of beam parameters

Emittance compensation:
Solenoid focusing into booster for adiabatic damping

Emittance optimization using Laser Pulse Shaping

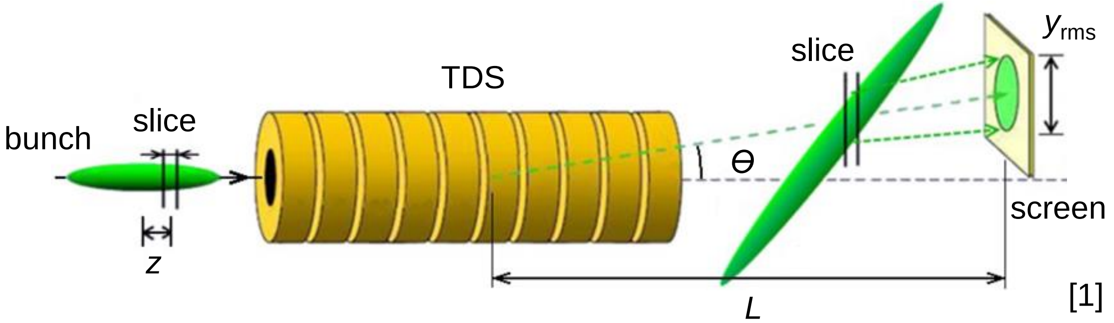


Phys. Rev. ST Accel. Beams 15, 090701 (2012)

Transversely Deflecting Structure (TDS)

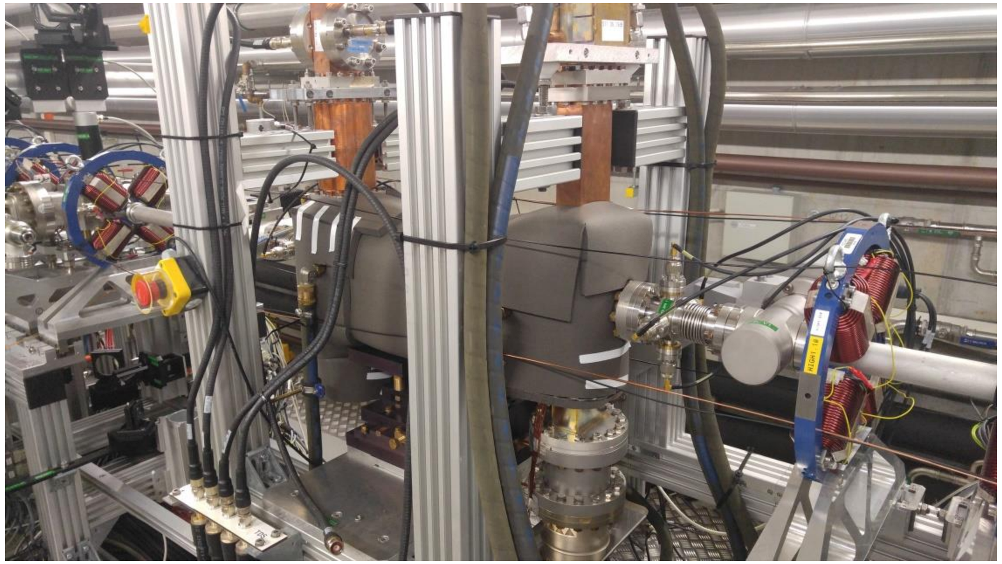
Mapping longitudinal to vertical coordinate

- Bunch profile
- Longitudinal phase space
- Time-resolved transverse phase space
  - **Slice emittance**



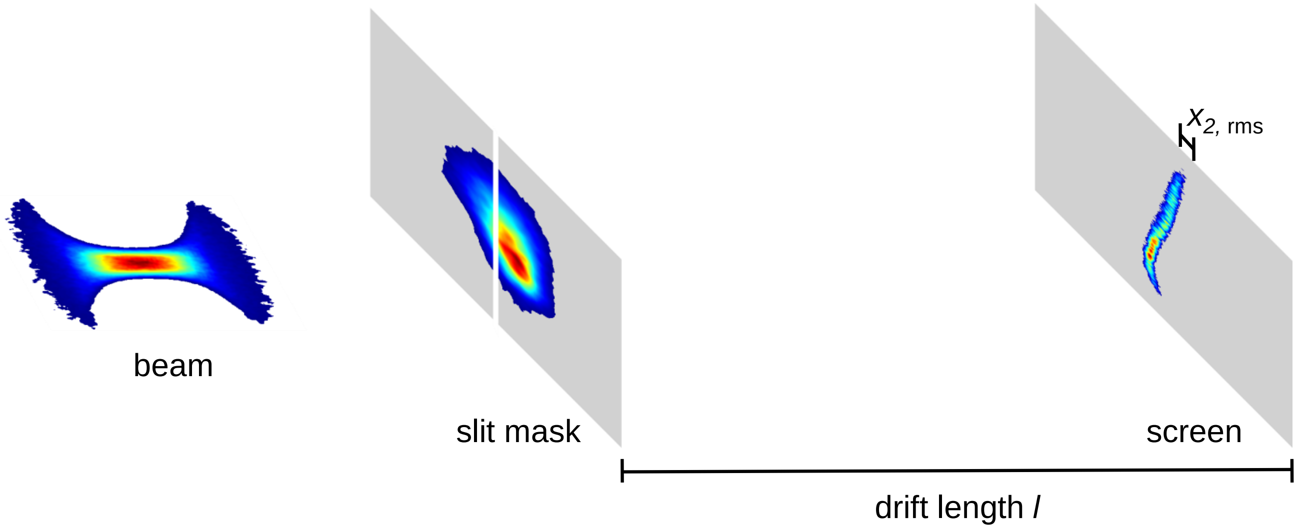
Properties

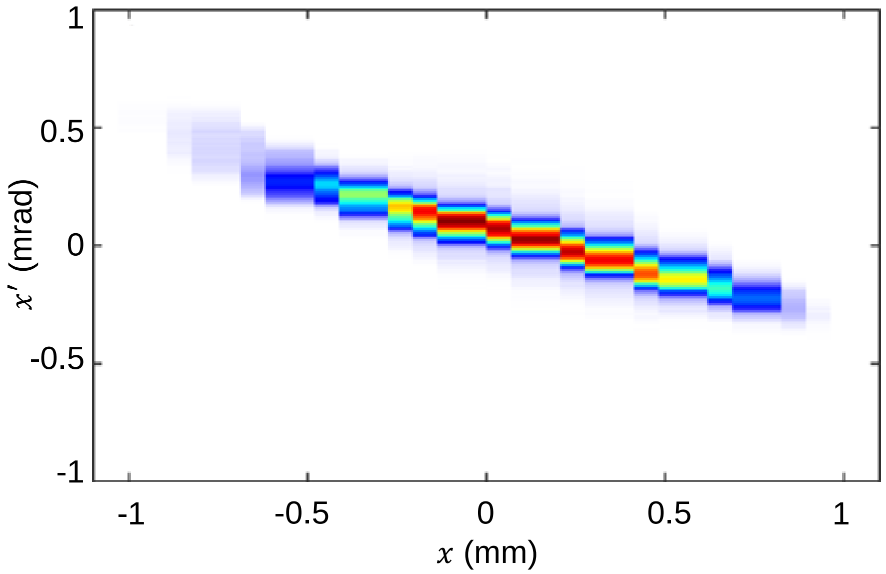
- European XFEL prototype
- 3 GHz (S band)
- Pulse length ≤ 3 μs
  - Deflection of up to 3 bunches
- Deflection voltage 1.7 MV
- Resolution ≥ 200 fs (typically)



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

Projected emittance diagnostics



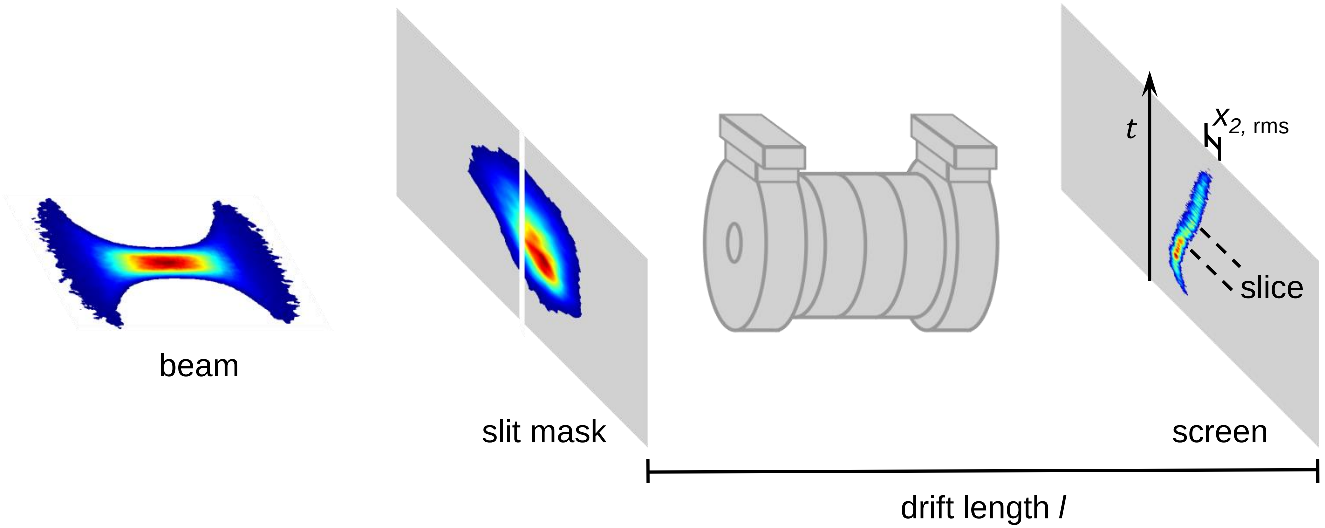


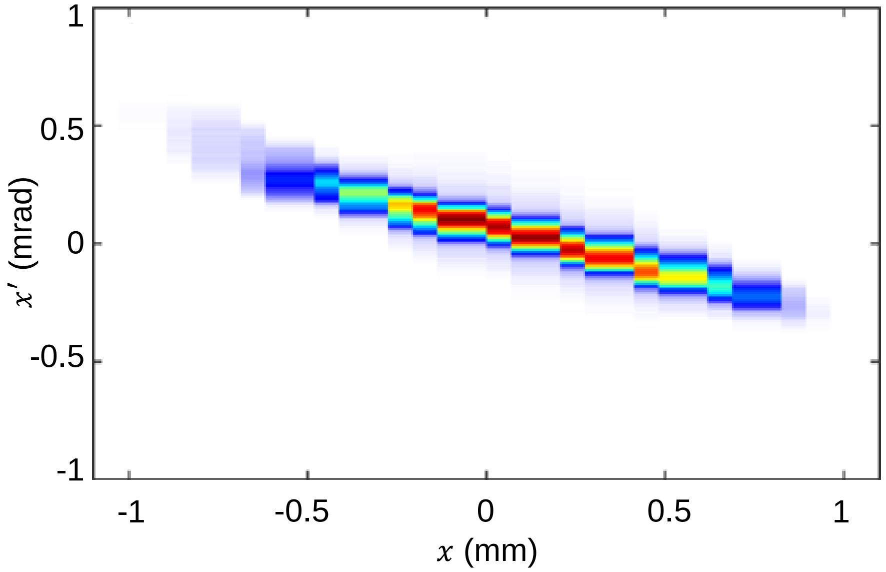
- Cut-out emittance-dominated beamlets from space charge-dominated beam with slit [1]
  - Mapping divergence to beam size: ***x_1' → x_2***
  - Measure **position, divergence, & intensity**

- 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)

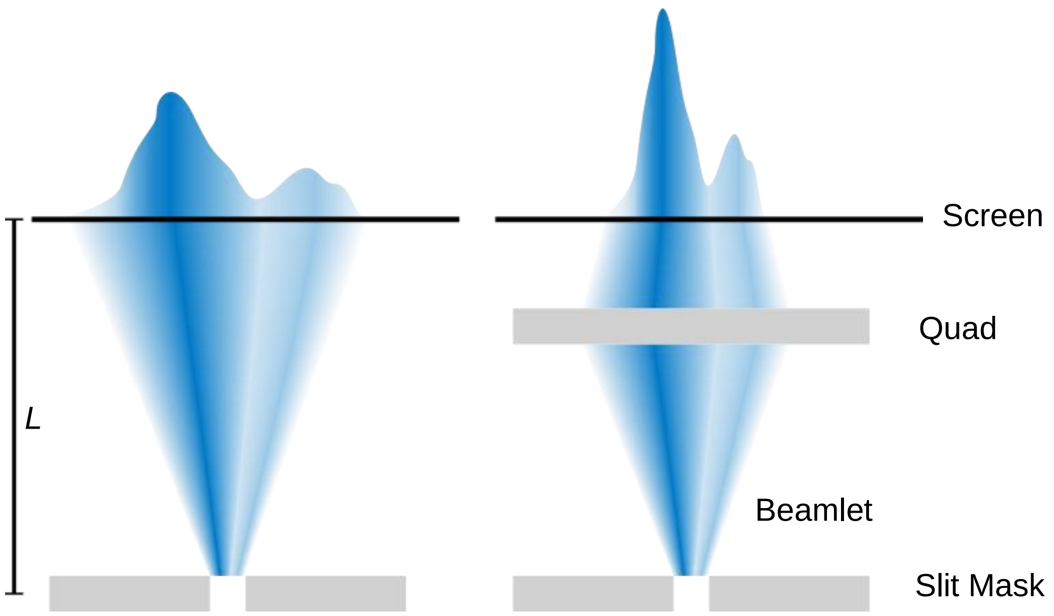
Challenges

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

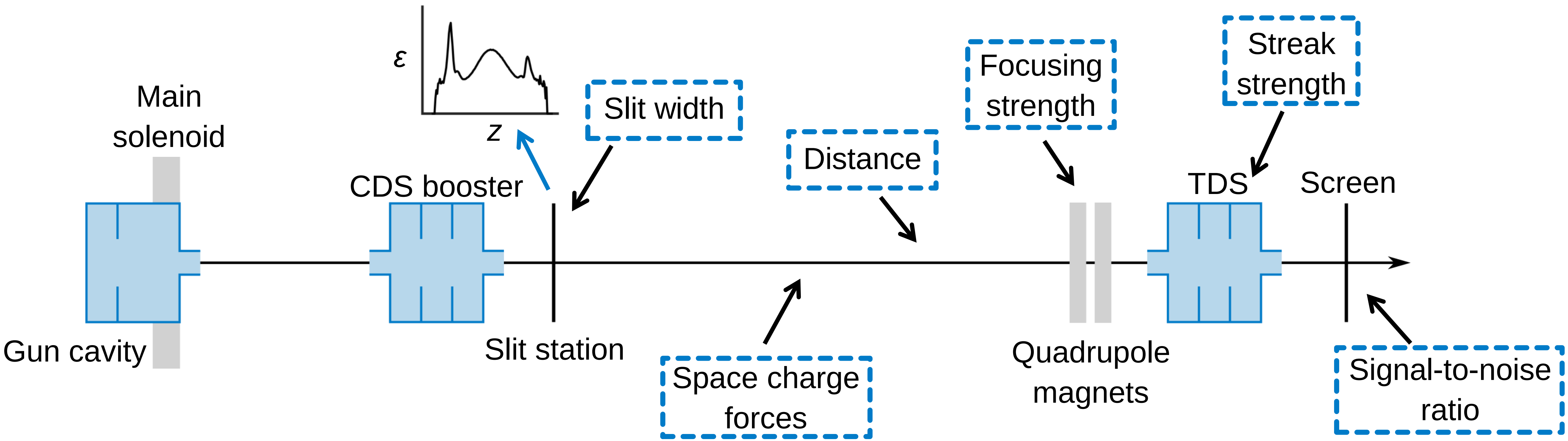


Systematic error estimation

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

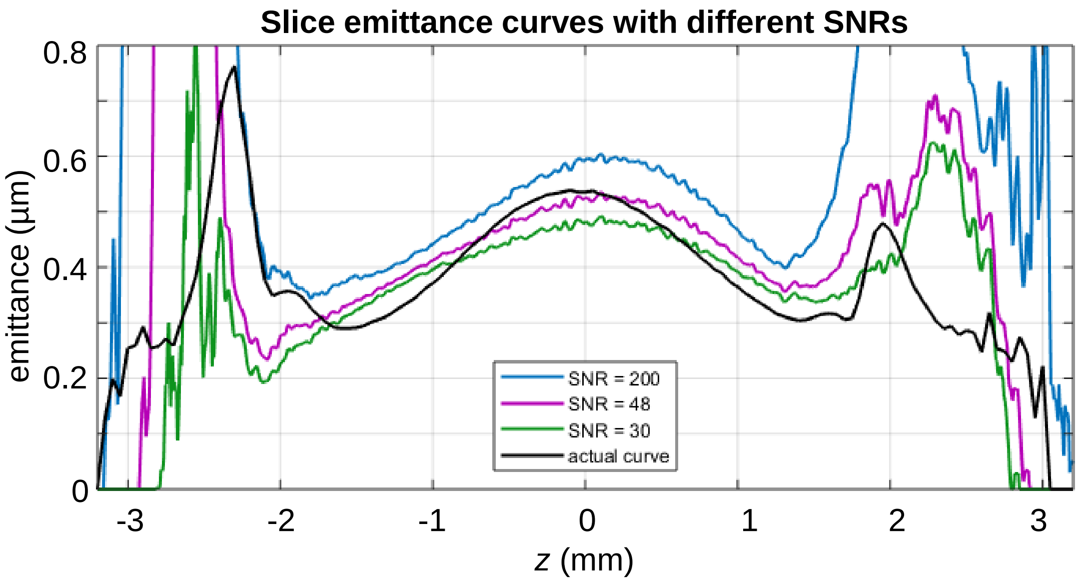
Slice emittance curve with finite SNR

- SNR > 200, slice emittance overestimation
- SNR ~ 50, correct measurement
- SNR < 50, slice emittance underestimation

At PITZ

- SNR ~ 50

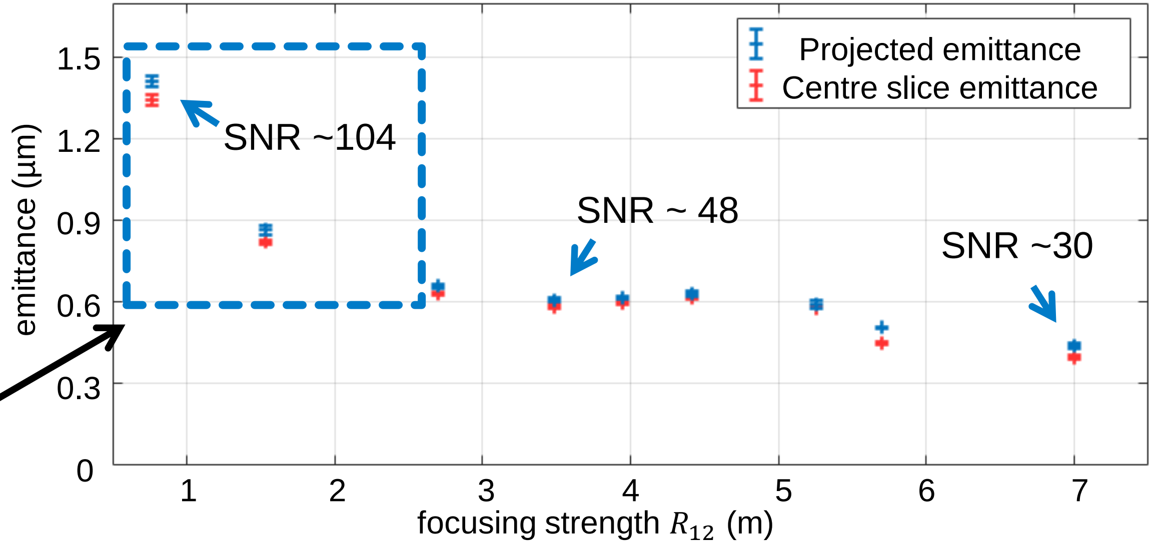
→ Only minor error



Estimation of systematic error

Scan of focusing strength (R_{12})

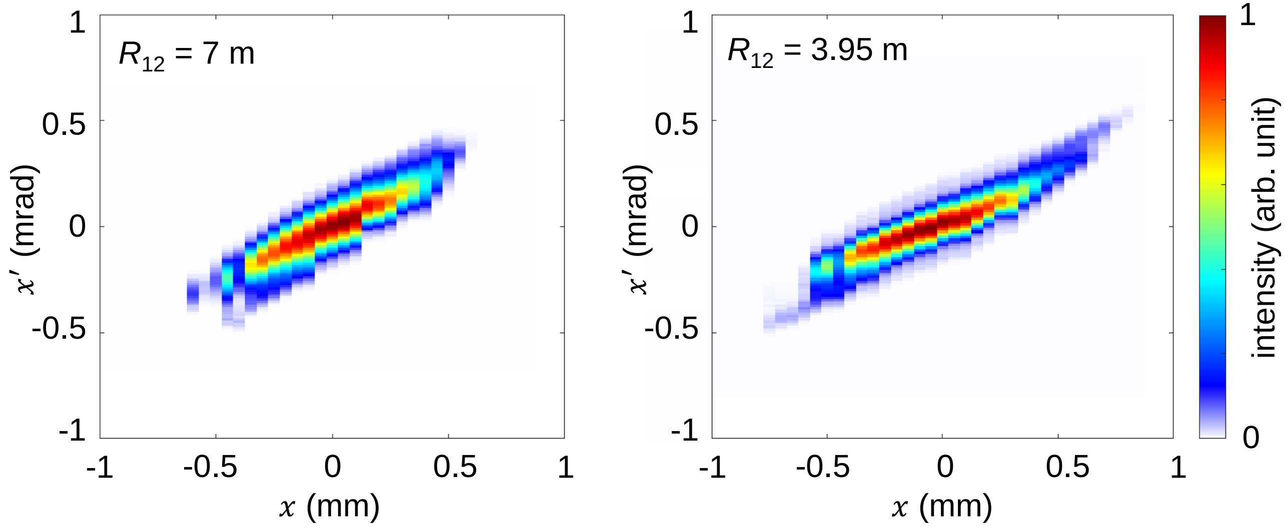
- Measured emittance growth due higher SNR
- Big error at small R_{12}'s (strong focusing)



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

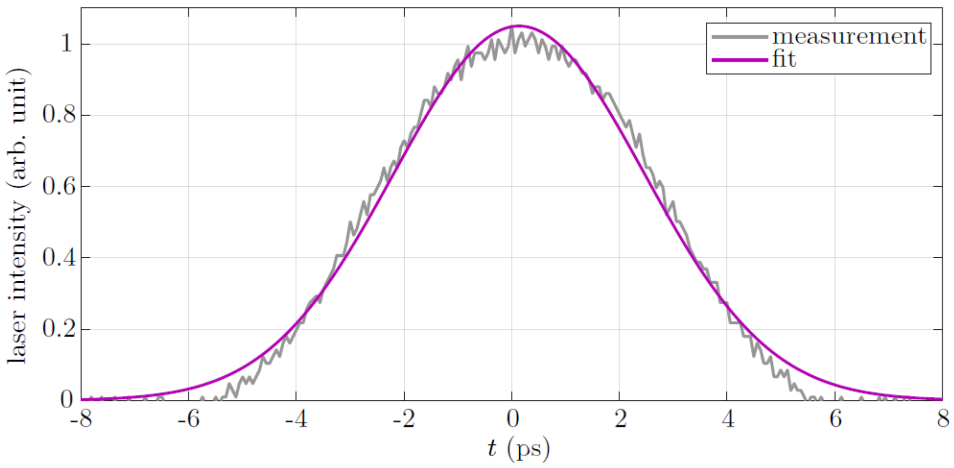
Laser pulse profile	
Temporal	Transverse
Gaussian	Flattop

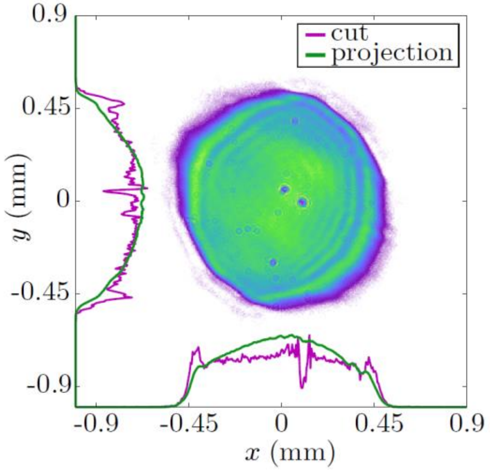
Beam characterisation

Temporal Gaussian
Transverse flattop

Low-emittance beam at EuXFEL conditions

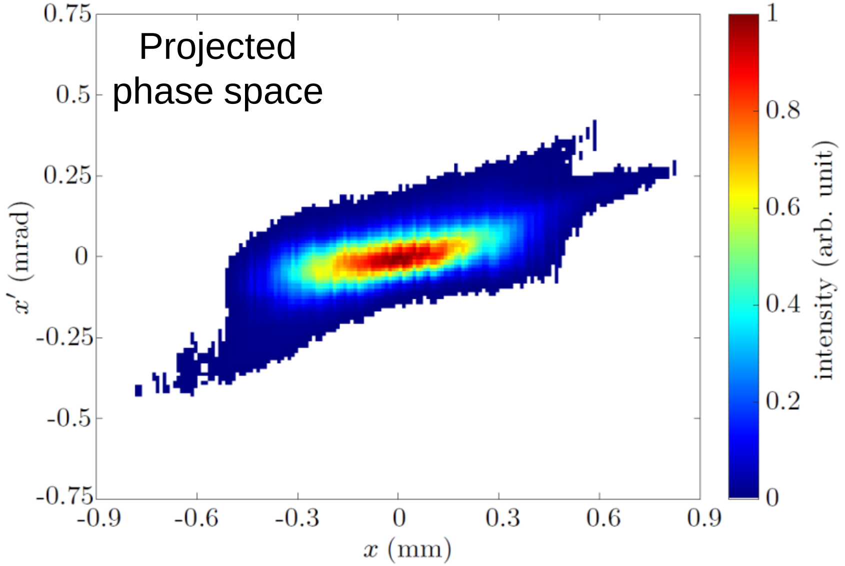
- Transverse flattop laser pulse profile
- Temporal Gaussian laser pulse shape
- 250 pC bunch charge
- Laser pulse length 6 ps (FWHM)





Solenoid scan for emittance optimisation

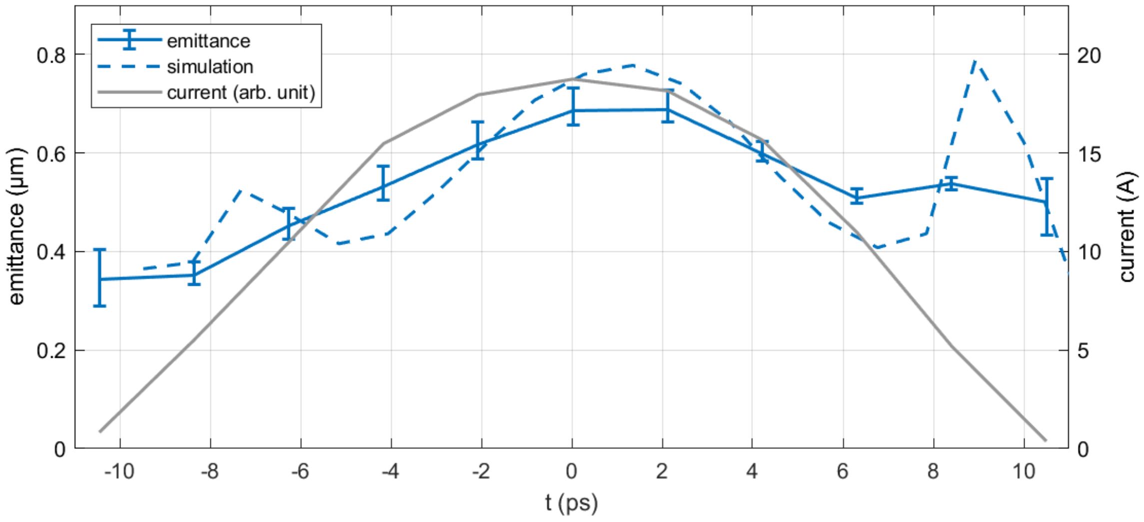
- Operation at optimum
- Proj. hor. emittance $\epsilon_x = 0.53^{+0.09}_{-0.08}$ (syst.) µm



Slice emittance measurement

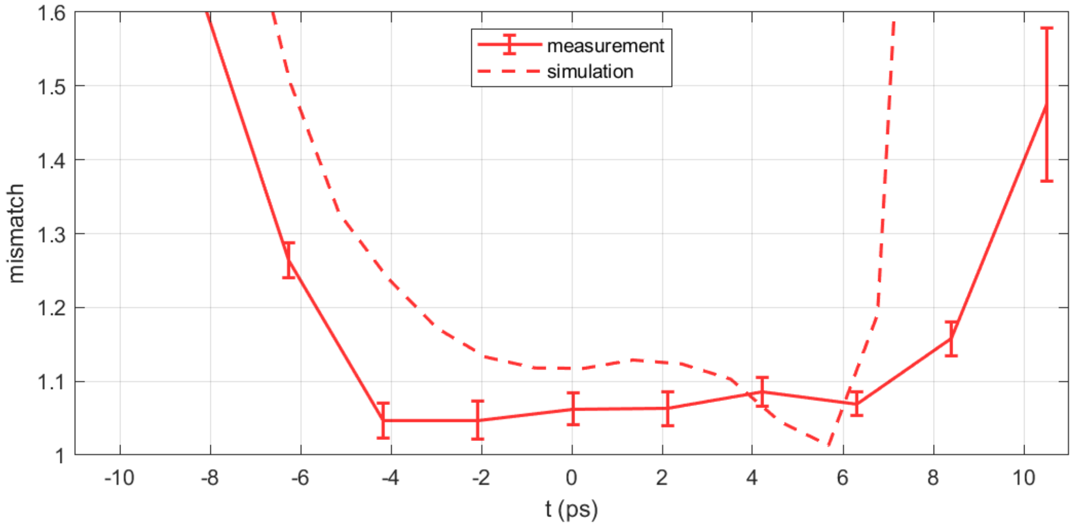
Emittance curve

- 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



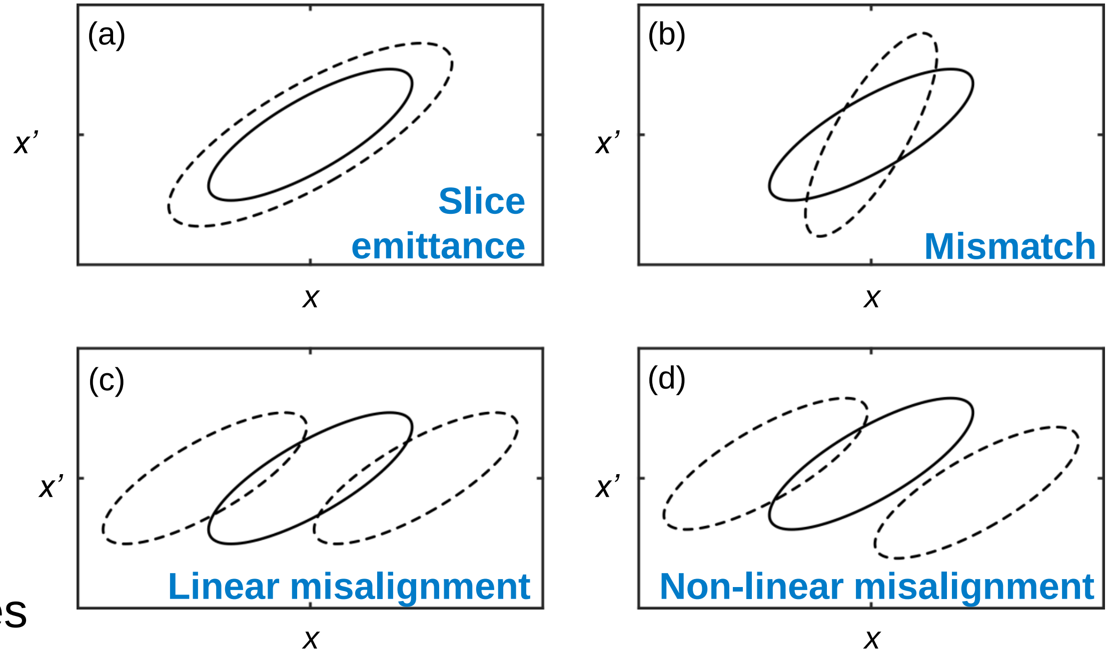
Emittance decomposition

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**

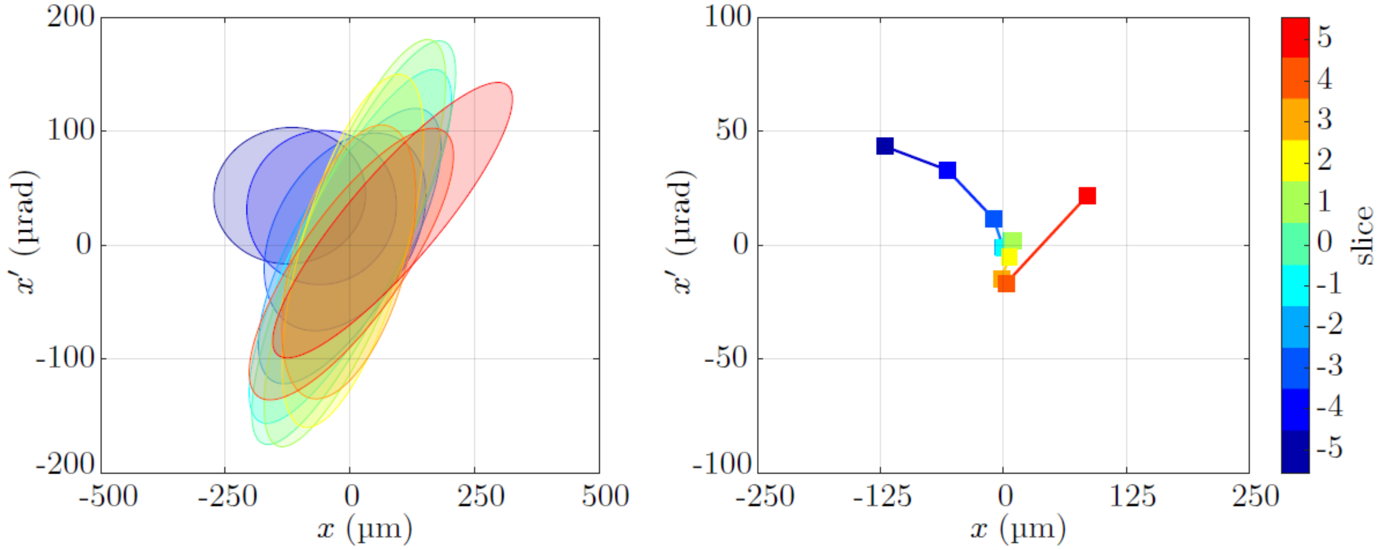
[1] C. Mitchell, *A General Slice Moment Decomposition of RMS Beam Emittance,* (2015).

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

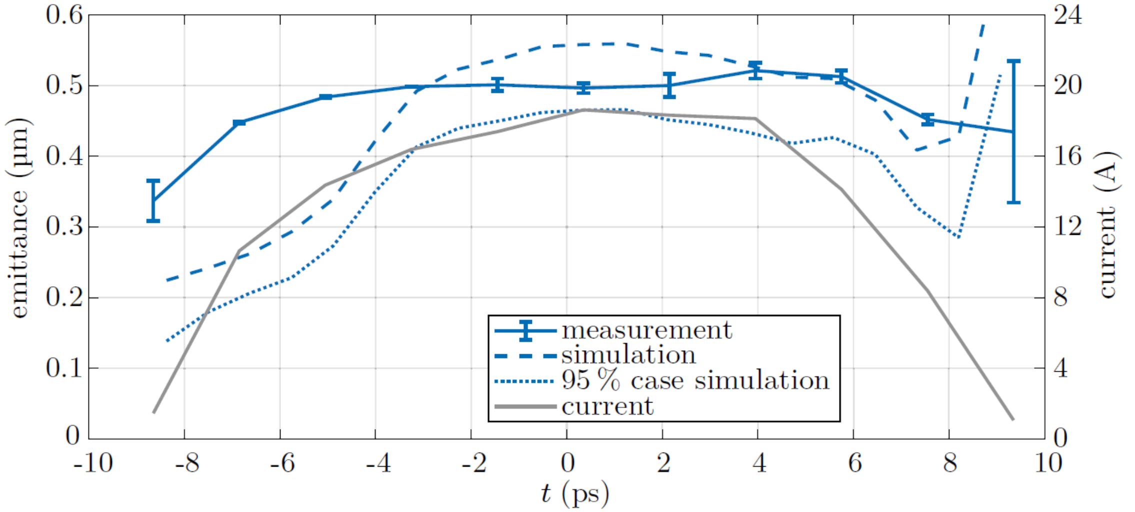
Laser pulse profile	
Temporal	Transverse
Gaussian	Flattop
Flattop	Flattop
Gaussian	Truncated Gaussian

Slice emittance measurement

Temporal flattop

Transverse flattop

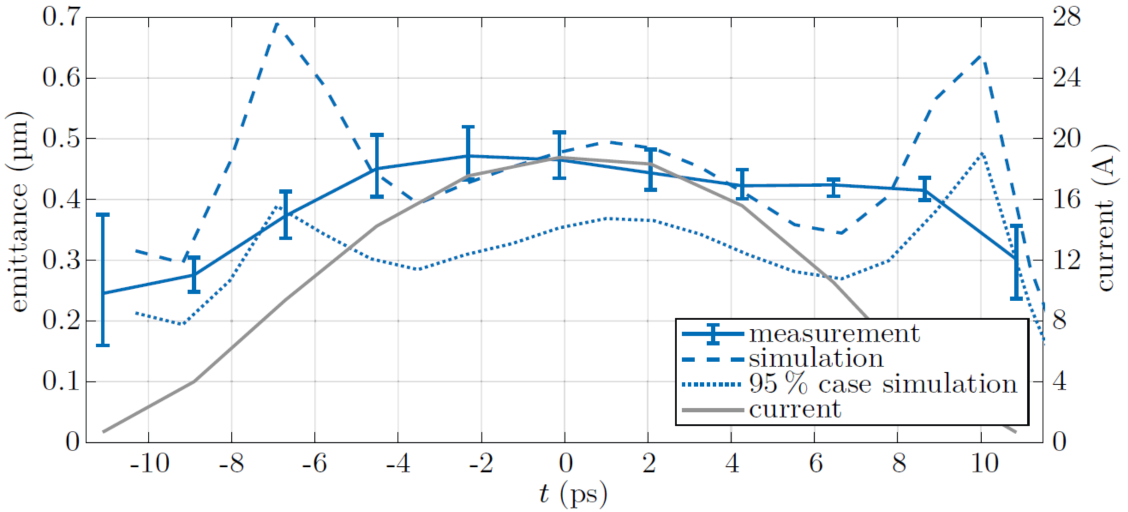
- Centre slice emittance $\epsilon_x = 0.55 \pm 0.01$ (stat.) µm
- Simulation curve agrees with measurement in centre



Temporal Gaussian

Transversely-truncated Gaussian

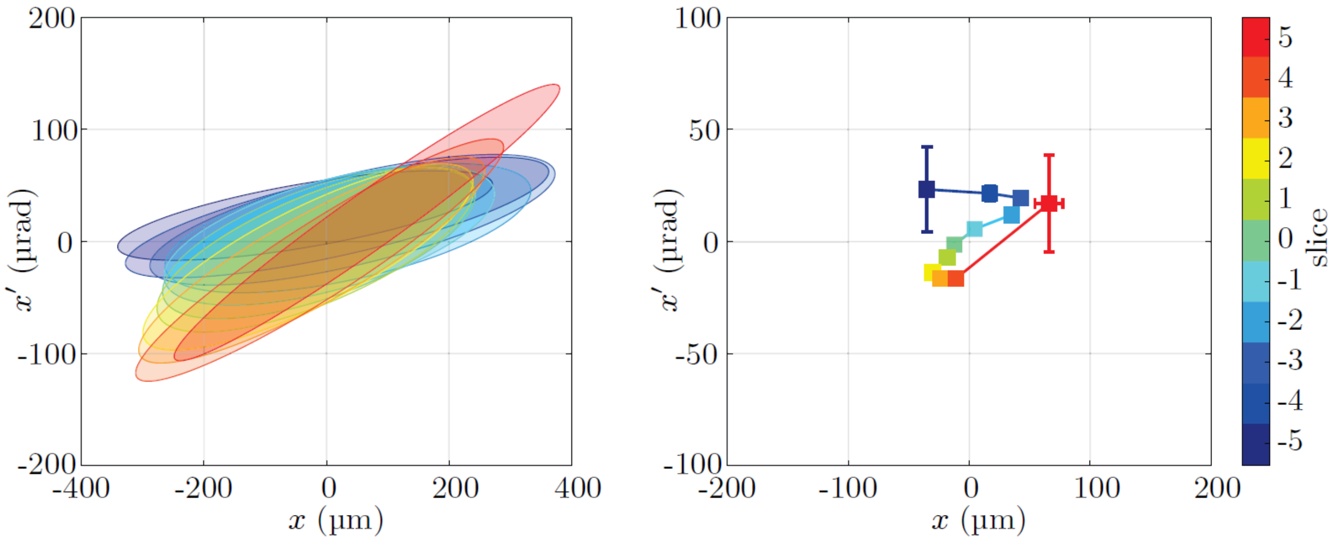
- Centre slice emittance $\epsilon_x = 0.47^{+0.05}_{-0.03}$ (stat.) µm
- High emittance at both tails



Slice emittance measurement

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

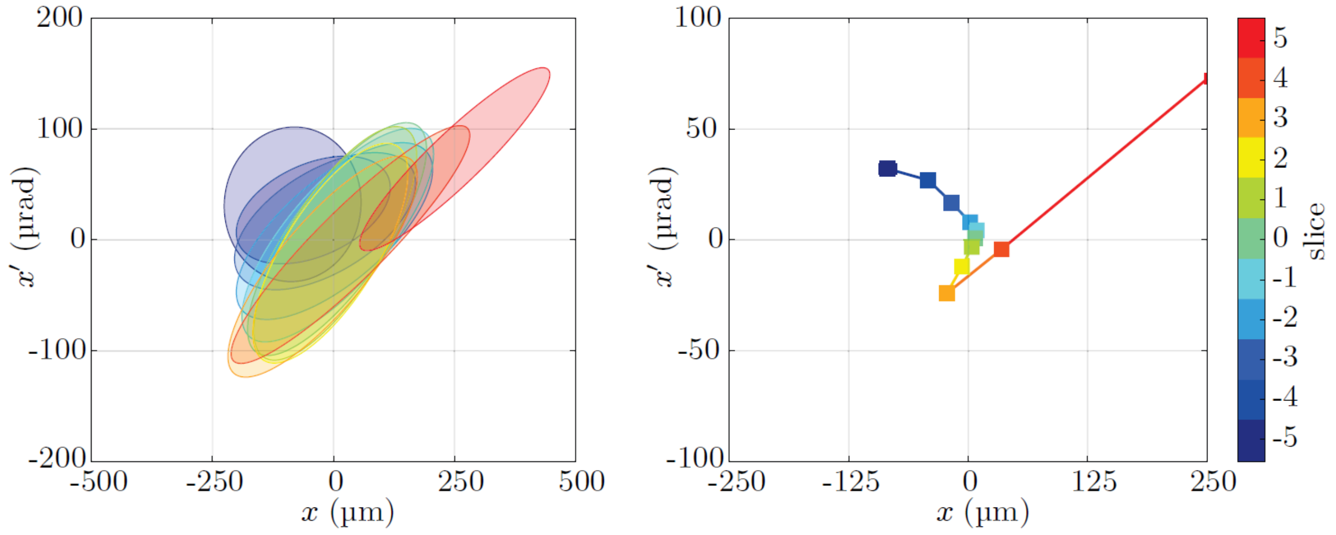
±FWHM/2	Measurement	Simulation
Projected emittance	0.57 µm	0.52 µm
Slice emittance	0.50 µm	0.49 µm
Mismatch emittance	0.23 µm	0.19 µm
Linear misalignment emittance	0.10 µm	0.01 µm
Non-linear misalignment emittance	< 0.01 µm	< 0.01 µm

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 with focusing to 200 fs

→ 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 characterised

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

Emittance decomposition

- Gives insight, how projected emittance can be reduced

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

Outlook.

New laser system for PITZ (NEPAL-P) in 2023

- Higher repetition rate (1 MHz → 4.5 MHz)
- Increase of SNR by factor ~4

→ Narrower slit opening might be used

Upgrade camera

- Electron-Multiplying CCD camera (EMCCD)
- Lower noise improves SNR further

R'n'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

PITZ Photo here

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Raffael Niemczyk
PITZ Group
raffael.niemczyk@desy.de
+49 33762/7-7280

Backup slides

Estimation of systematic error from finite SNR

Add time profile, detailed PITZ informations

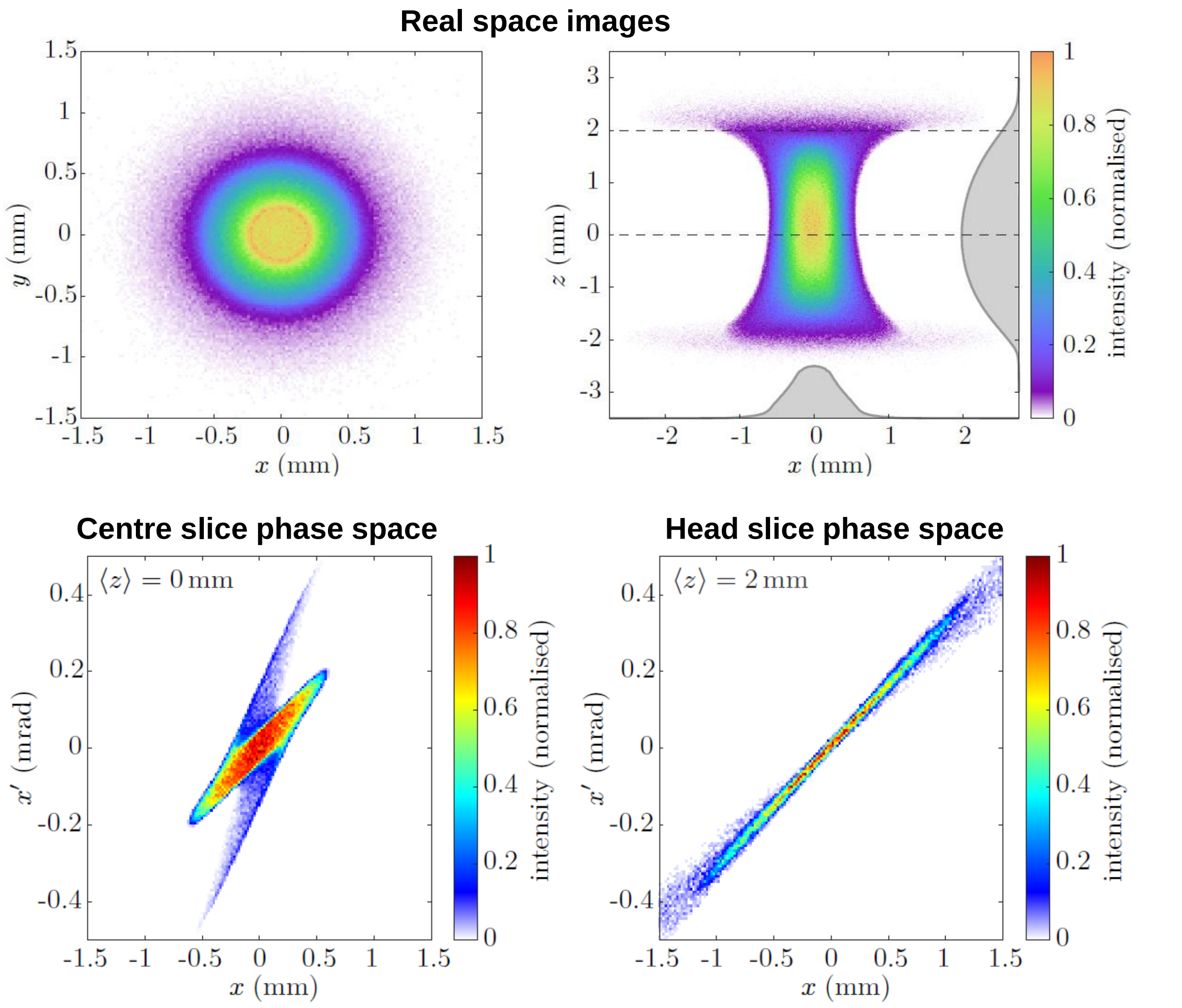
Laser systems (photos + key properties)

Add time profile, detailed PITZ informations

Estimation of systematic error

Start-to-end simulation in ASTRA[1]

Beam parameters and results	
Bunch charge	250 pC
Laser pulse length	6 ps (FWHM)
Solenoid current	366 A
Gun momentum	6.32 MeV/*c*
Beam momentum	19.29 MeV/*c*
Beam size at EMSY1	0.37 mm
Projected emittance	0.61 µm



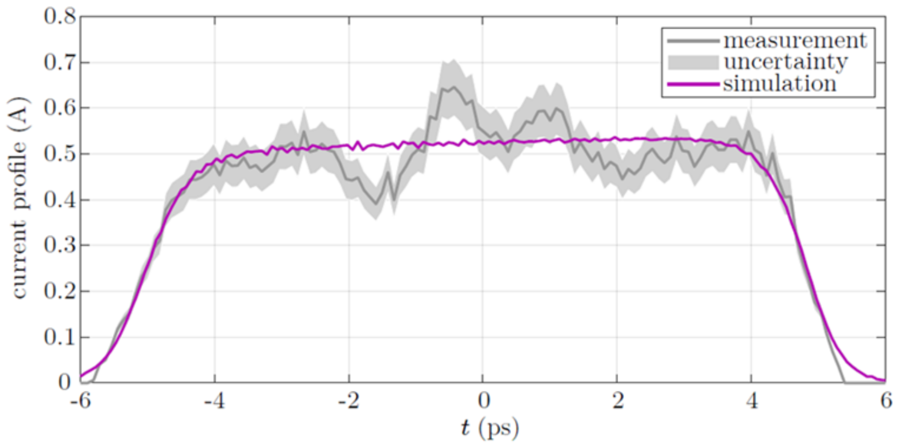
[1] Astra, https://www.desy.de/~mpyflo/

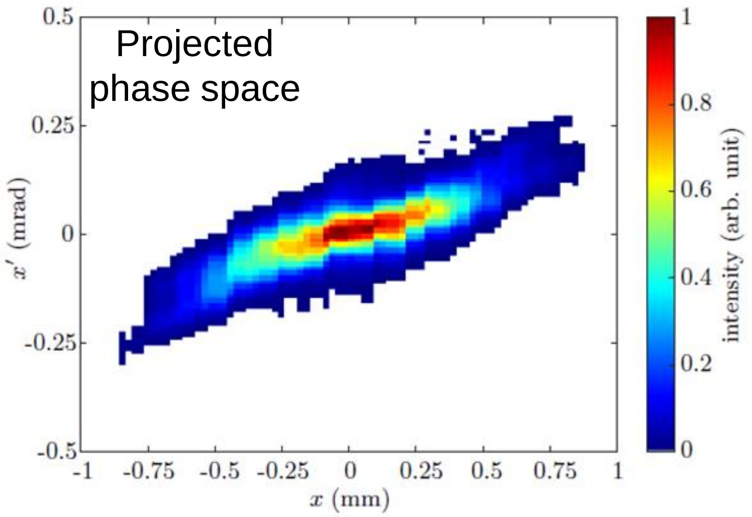
Beam characterisation

Temporal flattop
Transverse flattop

Low-emittance beam at Eu-XFEL conditions

- Transverse flattop laser pulse profile
- Temporal flattop laser pulse shape
- 250 pC bunch charge



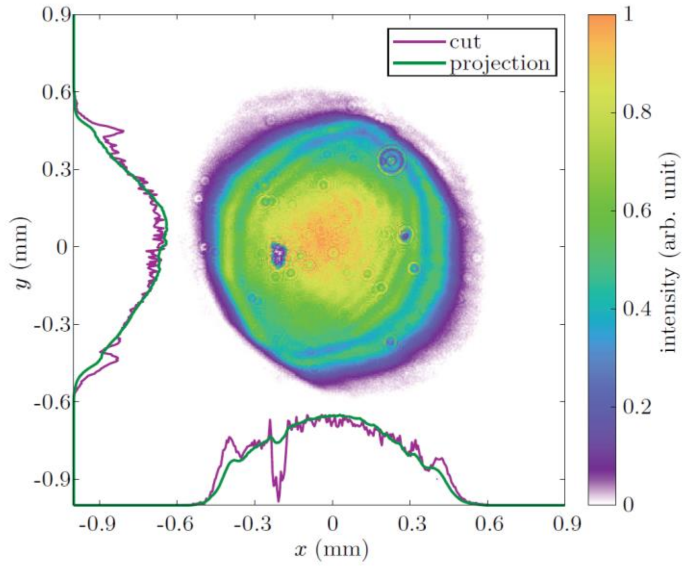


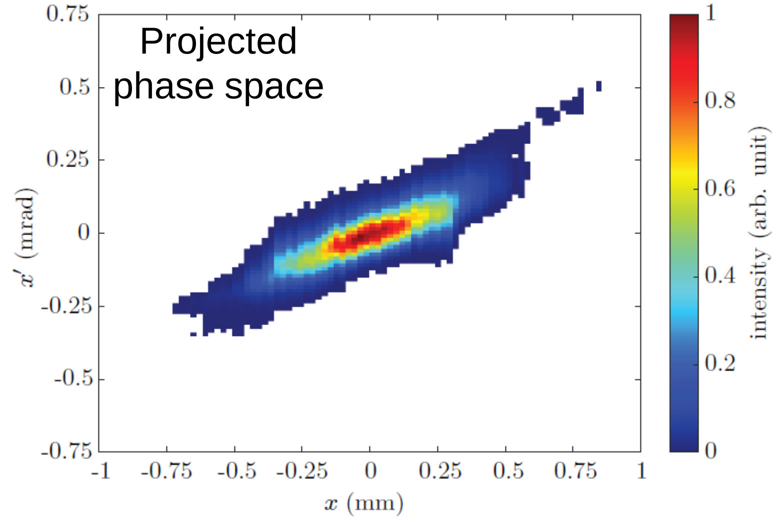
Beam characterisation

Temporal Gaussian
Transversely-truncated Gaussian

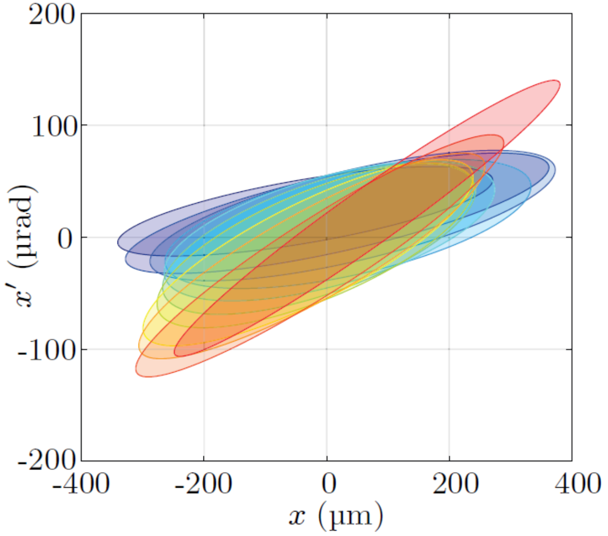
Low-emittance beam at Eu-XFEL conditions

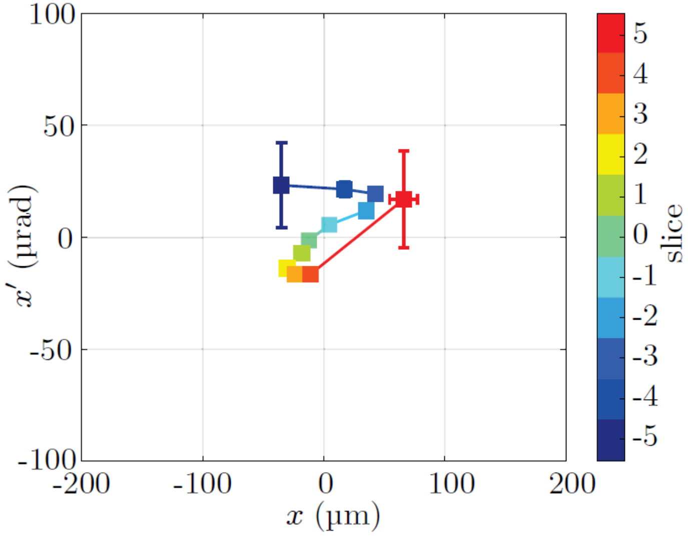
- Transversely-truncated Gaussian laser pulse profile
- Temporal Gaussian laser pulse shape
- 250 pC bunch charge





Slice emittance measurement





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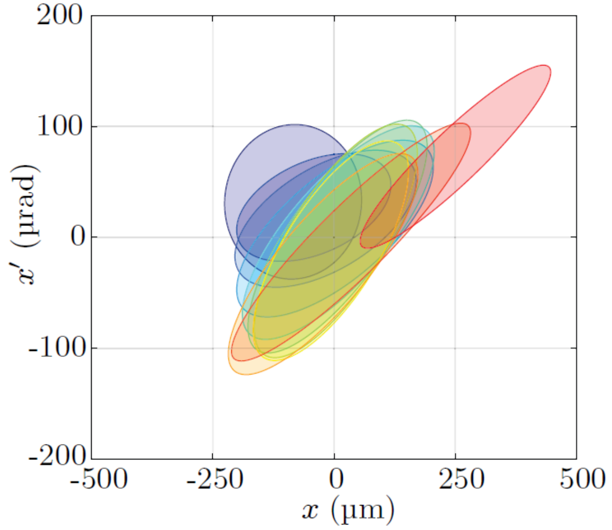

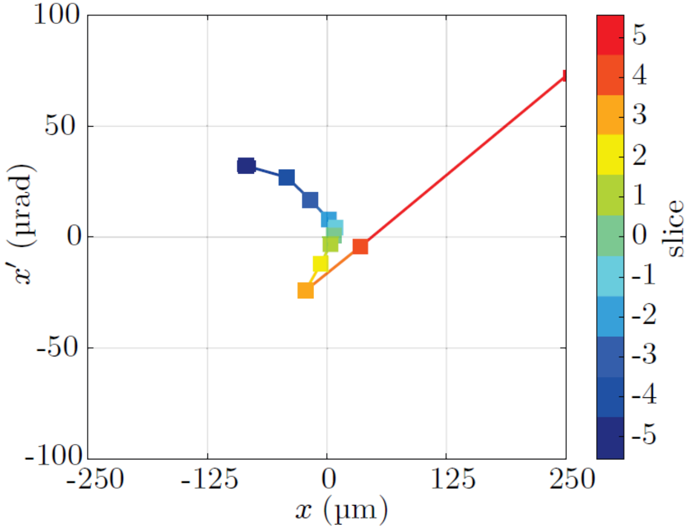

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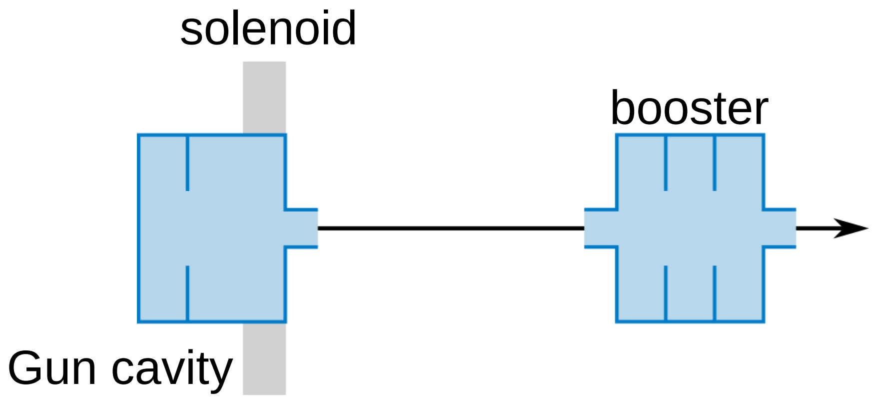
Emittance reduction in injector

Reduce emittance

- Low thermal emittance (from cathode)
  - Low transverse momentum spread
  - Small laser spot size
- Low space charge emittance
  - Reduce SC non-linearities
    - Laser pulse shaping
    - Lower bunch charge
- Gun design
  - High cathode field with gun design (field balance)
  - Pulsed gun
  - High frequency
- Emittance compensation
  - Solenoid focusing into booster entrance
  - Slice PS overlap
- RF stability
  - Emittance measurements are multi-shot



Info’s for me:

General info’s for me

Subheading, optional

01 Talk length

- 20 min presentation
- 5 min questions

02 Frank Stephan

- Not only my thesis, but message from PITZ facility

03 Check abstract

- What did I tell I would cover?

04 Check abstract

- Font size: 14

General info’s for me

Subheading, optional

Speaker: Raffael Niemczyk **Paper ID**

Author(s) Raffael Niemczyk, Zakaria Aboulbanine, Gowri Dulanjalee Adhikari, Namra Aftab, Prach Boonpornprasert, Georgi Zhivkov Georgiev, James David Good, Matthias Gross, Christian Koschitzki, Xiangkun Li, Osip Lishilin, David Melkumyan, Sandeep Kumar Mohanty, Anne Oppelt, Houjun Qian, Seyd Hamed Shaker, Guan Shu, Frank Stephan, Tobias Weilbach (DESY Zeuthen, Zeuthen), Maria Elena Castro Carballo, Mikhail Krasilnikov, Grygorii Vashchenko (DESY, Hamburg), Wolfgang Carl Albert Hillert (University of Hamburg, Hamburg)

Abstract Free-electron lasers in the X-ray regime require a high-brightness electron beam, i.e. an electron beam with high current and low transverse emittance. At the Photo Injector Test facility at DESY in Zeuthen (PITZ) high-brightness electron sources are optimized for the use at FLASH and European XFEL. A low transverse emittance of the electron beam's central part, which is assumed to be the lasing slices, is of particular interest for the efficient FEL operation. Over the past years a slice emittance measurement scheme has been developed at PITZ which employs an rf deflector and additional quadrupole magnets along the beamline to the standard measurement procedure for the projected emittance (single-slit scan). It allows measuring the slice emittance in a high-brightness photo injector. Transversely flat-top shaped laser pulses of different temporal distributions (Gaussian and flat-top) have been used to emit electrons, as well as transversely-truncated Gaussian laser pulses with temporal Gaussian shape. The paper shows that the lowest slice emittance in the injector is reached with a temporal flattop shape, or when using a transversely-truncated Gaussian shape.

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Abstract key points

- Paper shows that lowest emittance is achieved when using flattop or transversely-truncated Gaussian profile

- How to progress: Check content first, then polish slides (fontsize etc.)