Task 4.5 Photogun prototype and beam diagnostics

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Photo Injector Test facility at DESY in Zeuthen (PITZ)

- EURIZON Annual Meeting 2023 – WP4 Meeting
- 9 February 2023 – GSI, Darmstadt

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
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Task 4.5: Photogun prototype and beam diagnostics

CREMLIN+ → EURIZON

European network for developing new horizons for Ris, WP4 Collaboration with X-ray light sources in Europe

CREMLIN+ (until 02/2022) - Photogun prototype, its beam diagnostics and RF systems:

· New models for beam dynamics simulation in photoguns (new photoemission models for high charge)

· Beam dynamics and electrodynamics for USSR photogun

· Training of young staff at Zeuthen (as far as it will possible…)

→ EURIZON - Photogun prototype and beam diagnostics

The Photo Injector Test facility at DESY in Zeuthen (PITZ) is working successfully for more than 20 years. The PITZ gun is able to produce **high brightness** bunches (with **high charge** and **low emittance**) which after acceleration to the required beam energy could also be injected into a storage ring if wanted. The detailed **diagnostics** of the electron beam produced from the photo injector in a large range of bunch charges is critical for the further acceleration and application of these beams. This task will focus on developing diagnostic tools for a wide range of bunch charges based on PITZ experience, in particular on an **accurate and reliable transverse phase space measurement procedure**.

- Deliverable 4.5.1 (M48, DESY) Report on an optimized procedure for precise and reliable phase space measurements at high brightness photoinjectors
- M 4.5.1 (M48, DESY) - Optimized procedure for precise and reliable phase space measurements at high brightness photoinjectors established, release of software.

Development of new photoemission model

27th Russian Particle Acc. Conf. RuPAC2021, Alushta, Russia JACoW Publishing
ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-THC03

NUMERICAL SIMULATIONS OF SPACE CHARGE DOMINATED BEAM DYNAMICS IN EXPERIMENTALLY OPTIMIZED PITZ RF PHOTOGUN *

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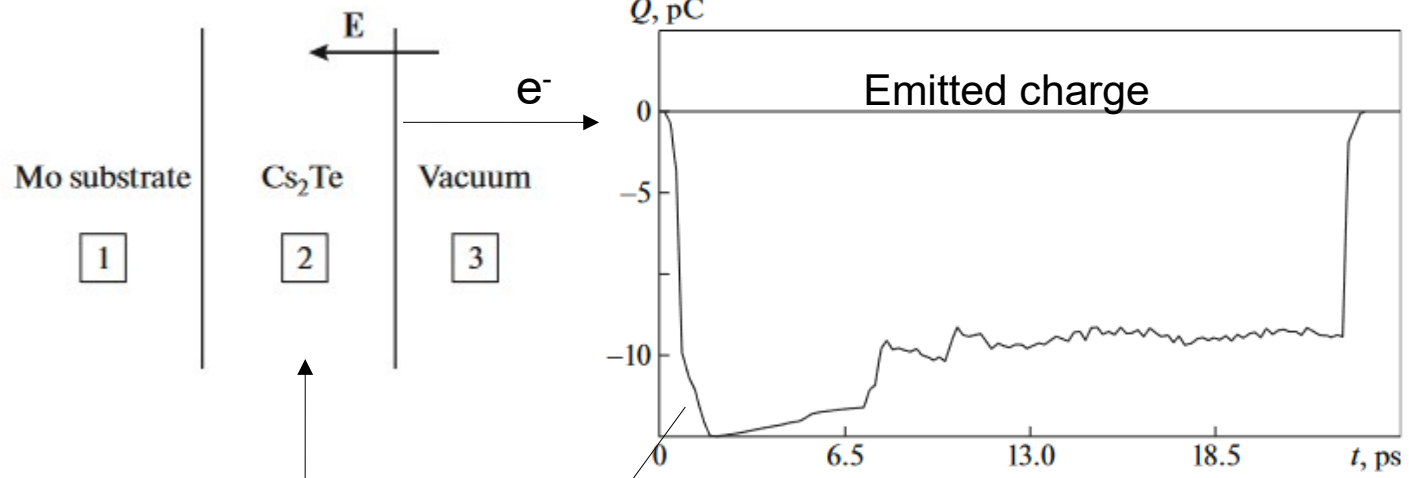
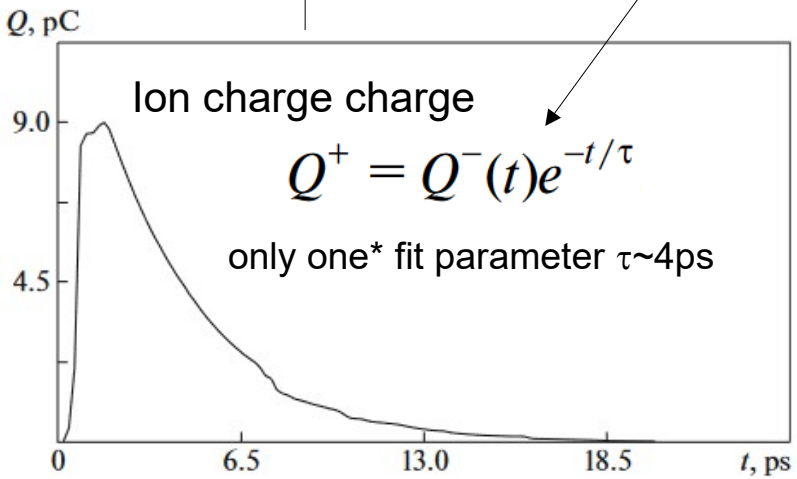
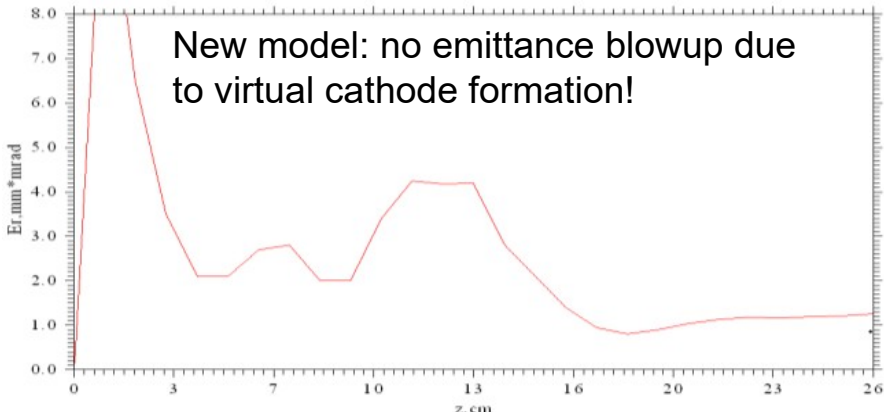
PITZ authorship was withdrawn because the conference at Crimea as well as for the next 2 paper because of war in Ukraine

CREMLIN+ (2021)

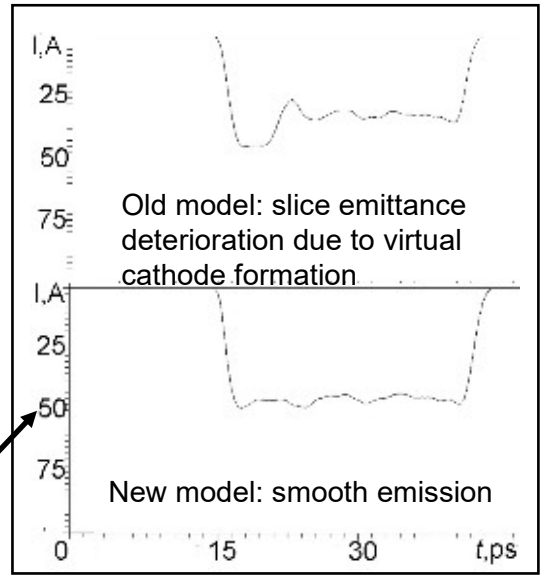
Cathode model







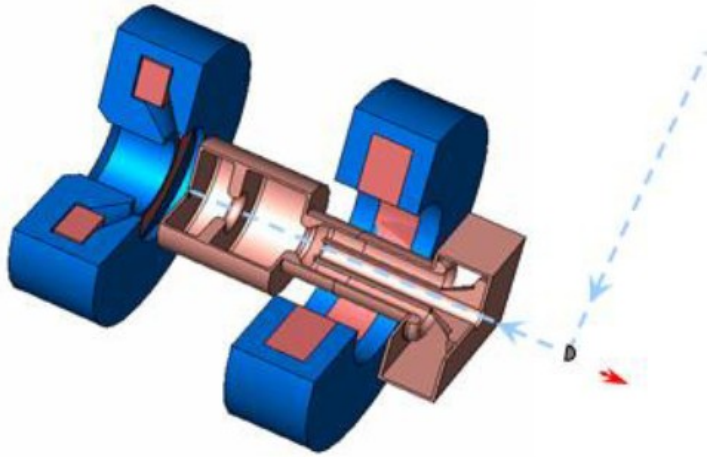
- Improvement to space charge dominated emission in SUMA code
- Account for positive ion inflow within Ce2Te layer
- Increase of positive charges increases the space charge limit of the emission current



Beam current profiles after emission from flattop photocathode laser pulses (21.5ps fwhm), 1nC case

Comparison with experiments at PITZ

CREMLIN+ (2022)

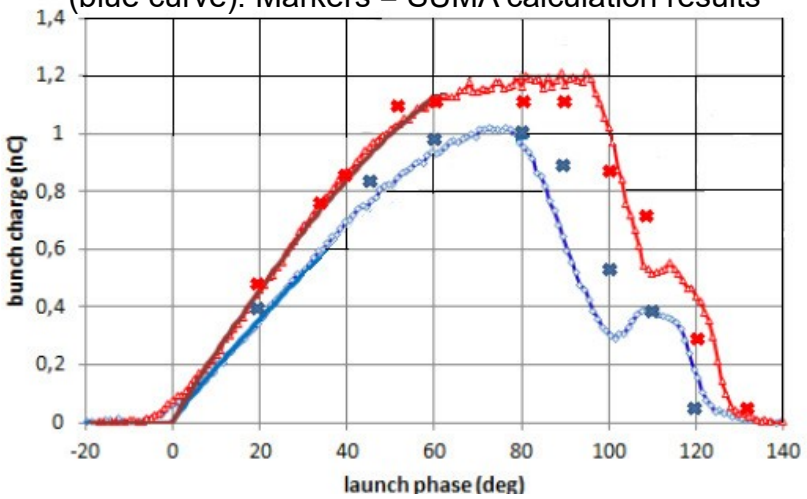


PITZ RF gun scheme

- ASTRA photoemission simulations (without ion influx) deviates from measured emission curves in space charge dominated regions
- SUMA (with ion influx) can be tuned to match the measured emission curves and Schottky scans

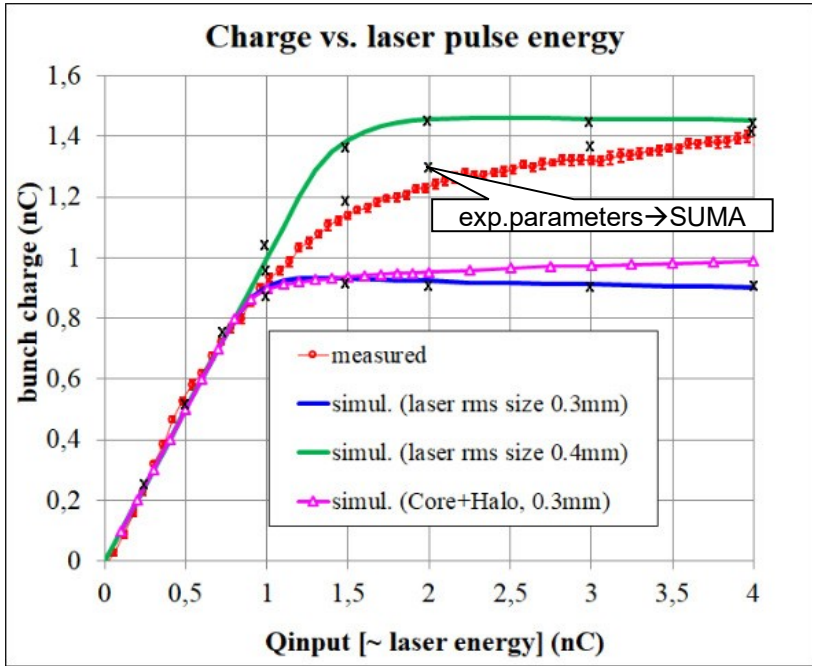
Schottky scans

PITZ measurements (PRSTAB paper 2012 data): Ecath.=62 MV/m (red curve) and Ecath=47.6 MV/m (blue curve). Markers = SUMA calculation results



Emission curves

measured at PITZ (red curve) compared to ASTRA results (green,blue and magenta curves) and corresponding SUMA results (crosses).

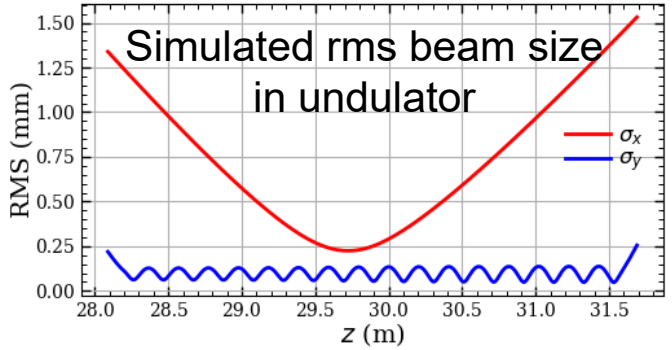


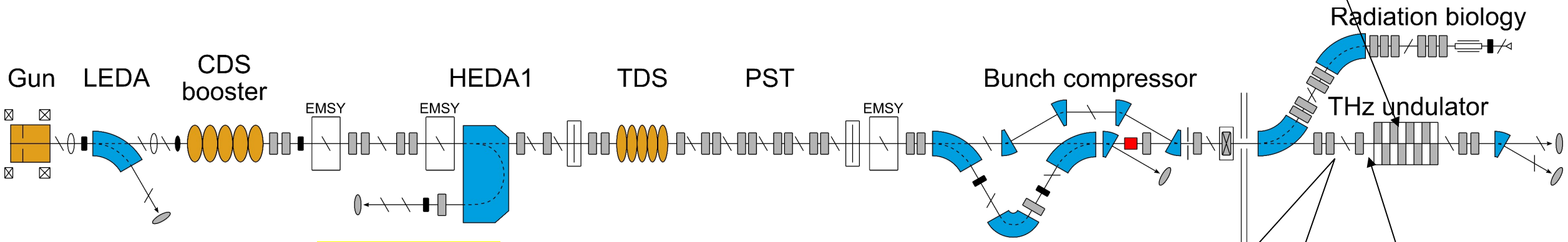
High **charge** production!

THz SASE FEL source at PITZ

PITZ-like accelerator can produce high-power, synchronized THz radiation

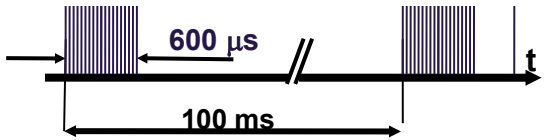
Developments of the prototype for accelerator-based tunable high-power THz source for pump-probe experiments at European XFEL



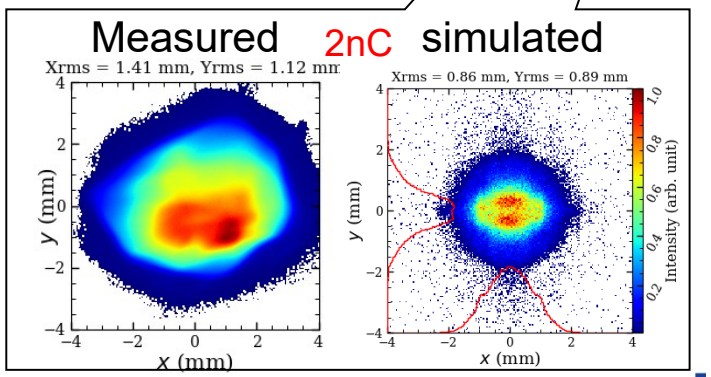


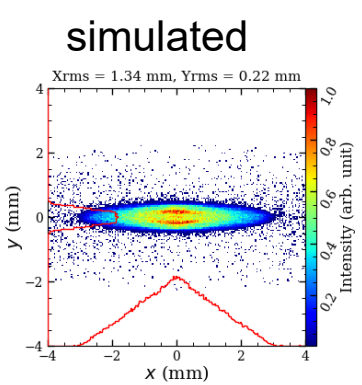
THz SASE FEL =
Self Amplified Spontaneous Emission Free Electron Laser

PITZ Highlights:



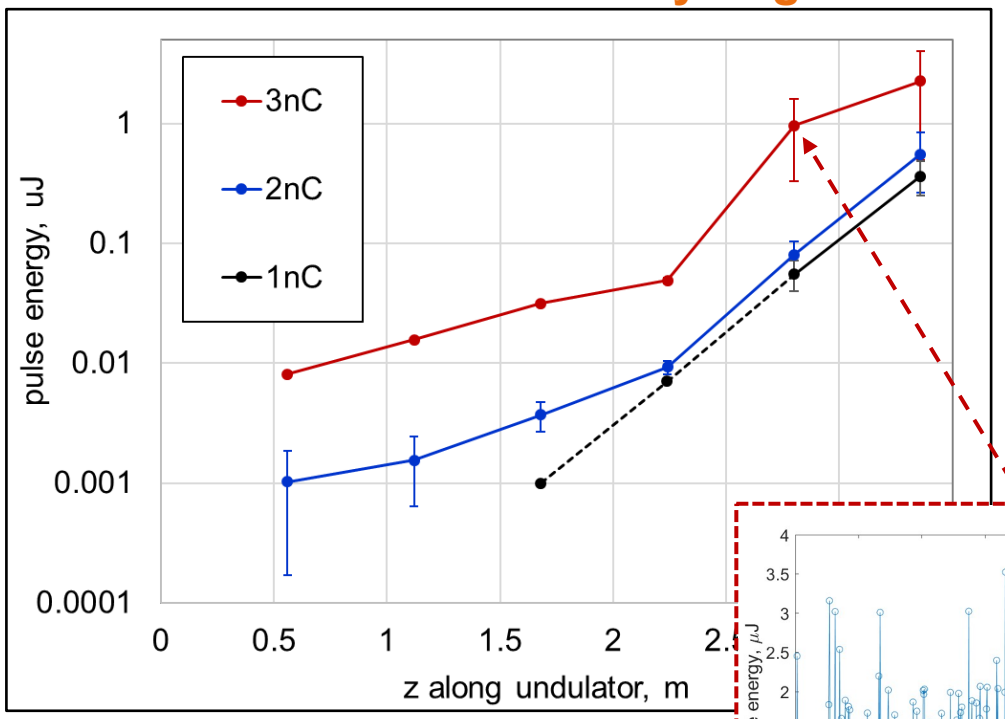
- Pulse **train** structure
- High **charge** feasibility (up to 6 nC), high QE photocathodes
- Advanced photocathode laser pulse **shaping**

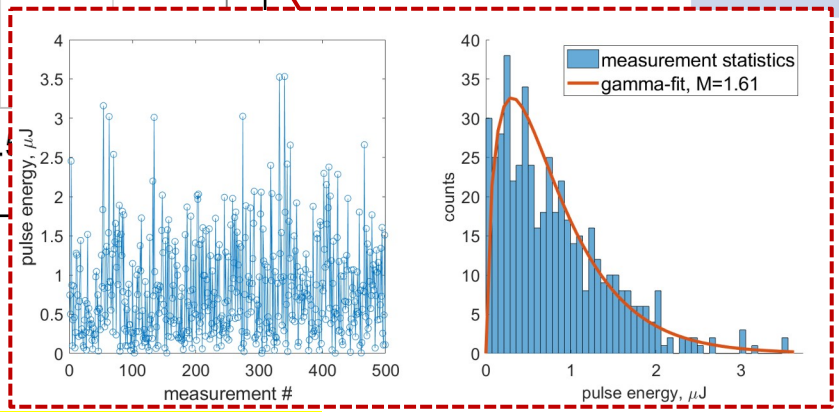




Proof-of-principle Experiment on THz Source at PITZ

Where we are now and the way to go

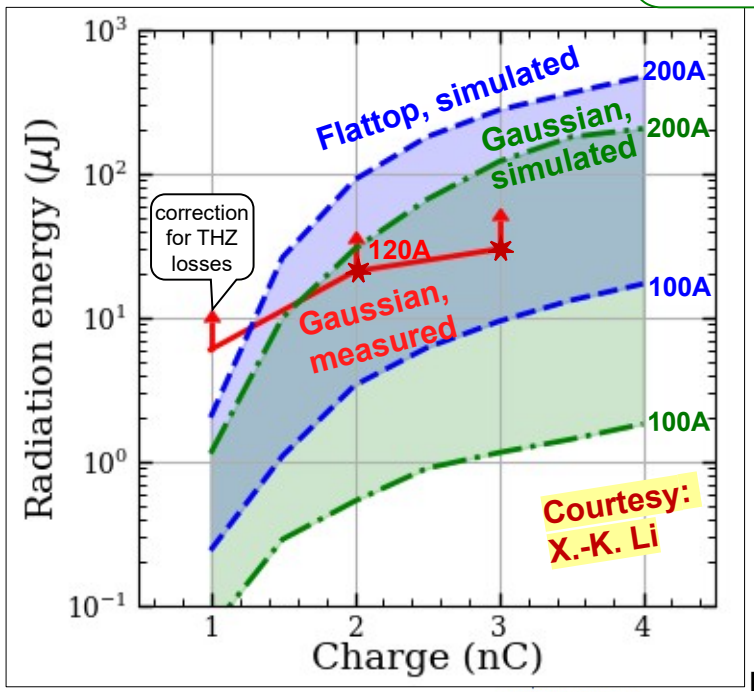




parameter	Min. requirements [1]	PITZ (exp)
Bandwidth	1…0.05	~0.02
f [THz]	0.1…**3…20**…30	**3…5**
Pulse energy	3mJ@0.1THz; 30μJ@1THz; 10μJ@10THz	**30μJ@3THz**
CEP	yes	no*
Rep.Rate (burst)	0.1MHz…4.5MHz	1MHz*
Synchronization	<0.1/f	challenge
Polarization	optional	yes

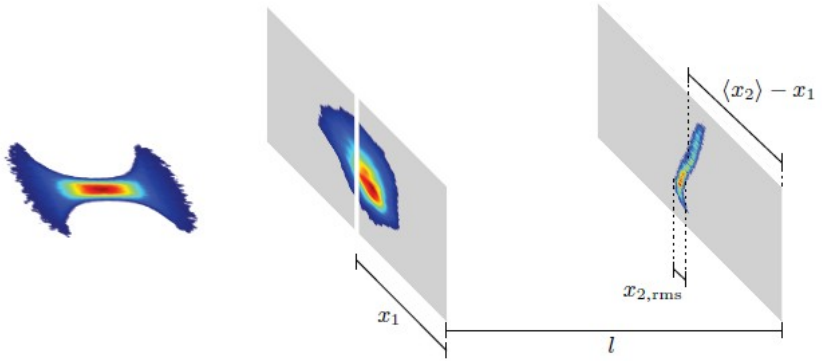
Gaussian photocathode laser, **2-3 nC** bunch charge

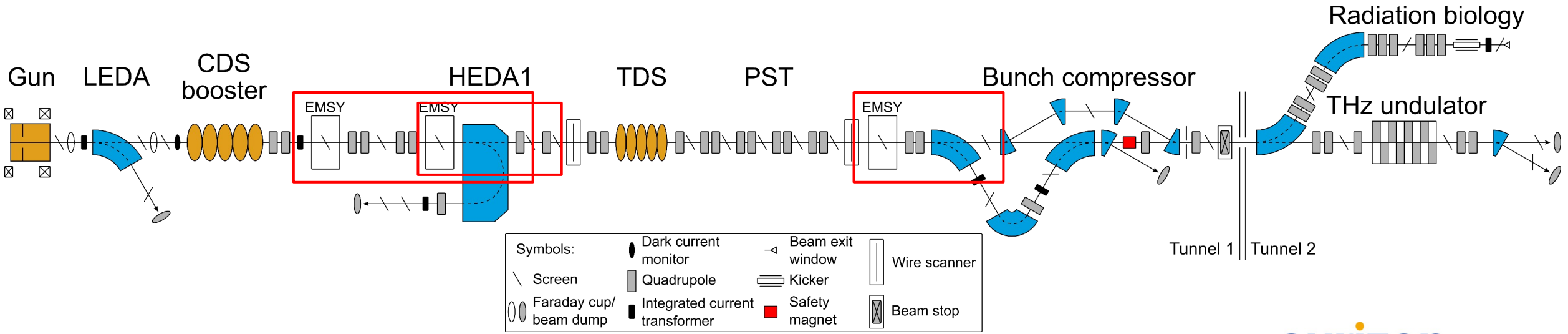
- Gain curves at 1nC, 2nC and 3nC
- Lasing at ~100μm
  ➔ worldwide first high gain THz SASE FEL at PITZ!
- Further development requires high charge and better matching into the undulator
  - **Interest at PITZ for continued development of transverse phase space diagnostics and modeling space charge dominated beams**



Transverse Emittance Measurement SYstem (EMSY) at PITZ

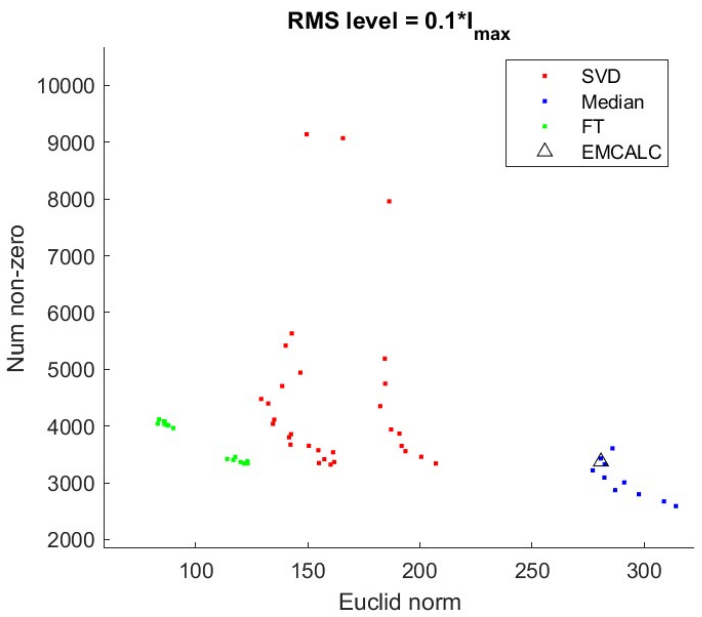
- Three EMSY stations using slit-screen method
  - Typical use first station with parameters: 3.133 m drift, 10 or 50 um slit, 0.035 px/mm camera resolution
- Systematic errors have been estimated, but not removed
  - Requires further study to fully understand and correct systematic errors
- Measurement software is antiquated and challenging to update
  - Requires rewriting from scratch → allows for updating of image processing

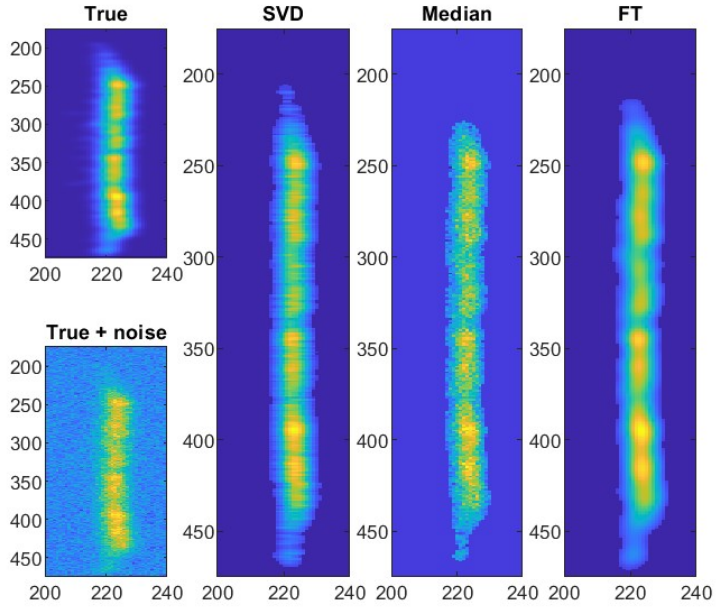


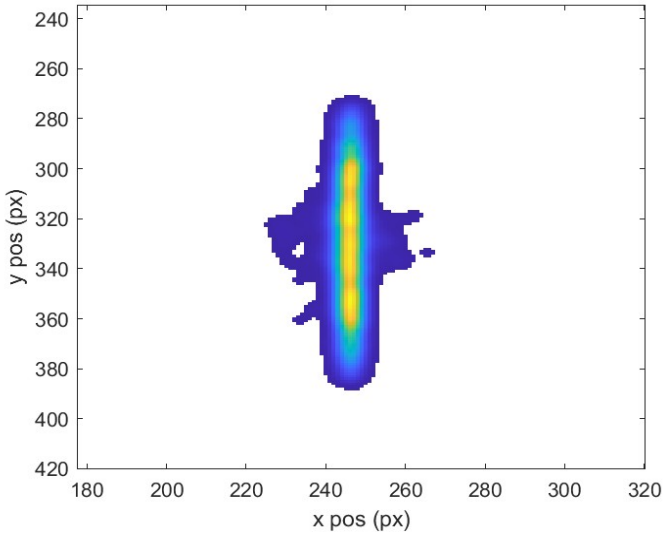


Updated noise filtering

- Previous filter (EMCALC)
  - Based on applying cuts and masks to the images. Results in bias to the right due to the mask shape
- Singular Value Decomposition (SVD) filter
  - Reduces processing to 1D problem → easy to adapt
  - Better reconstructed signal even at low SNR







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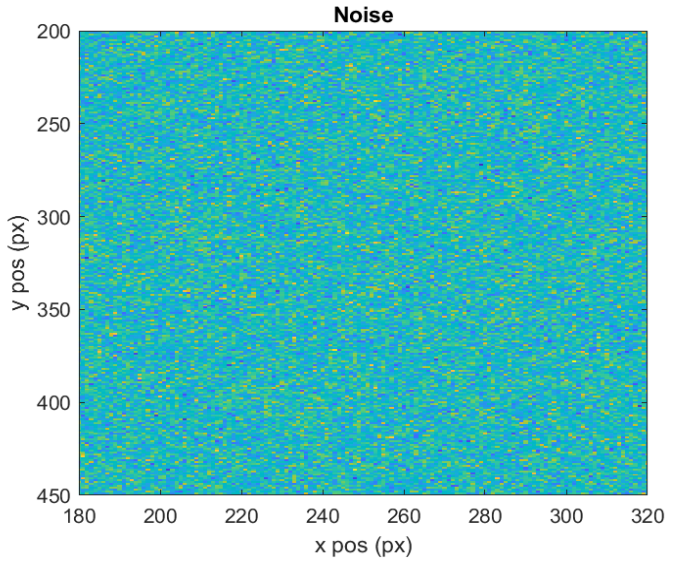

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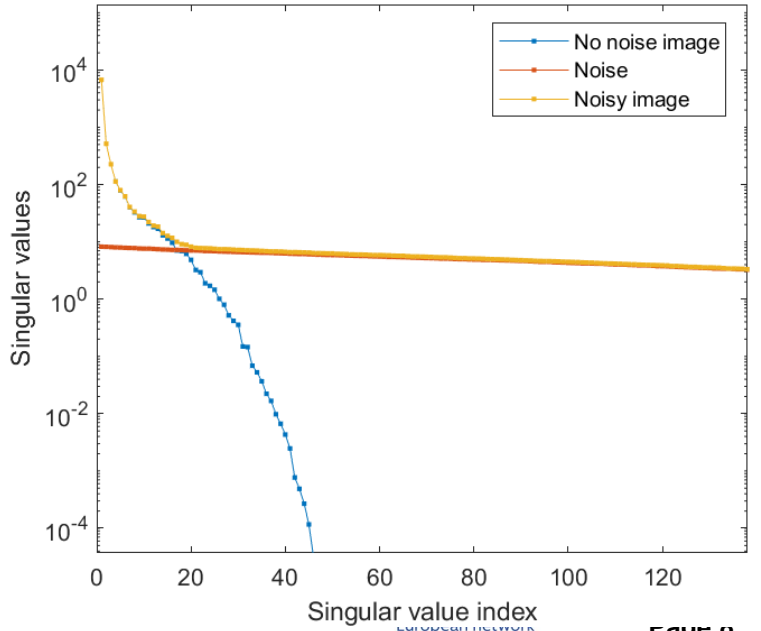
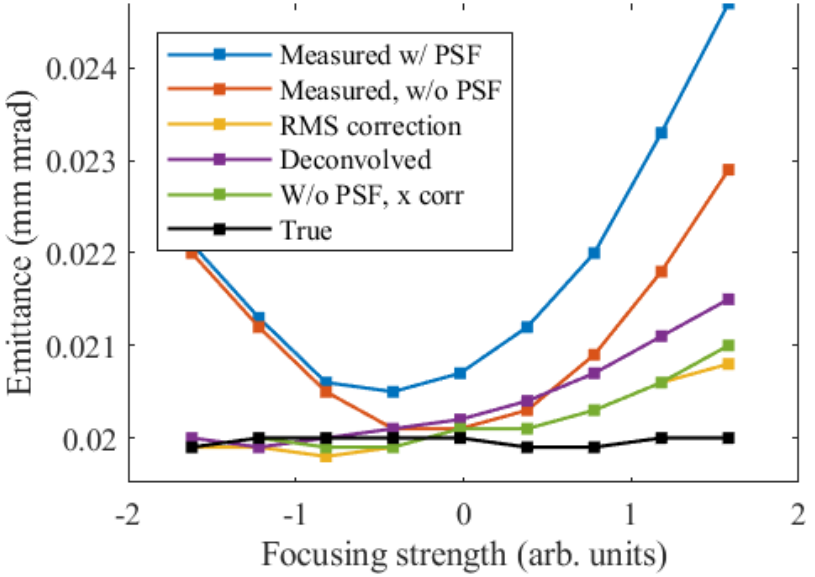
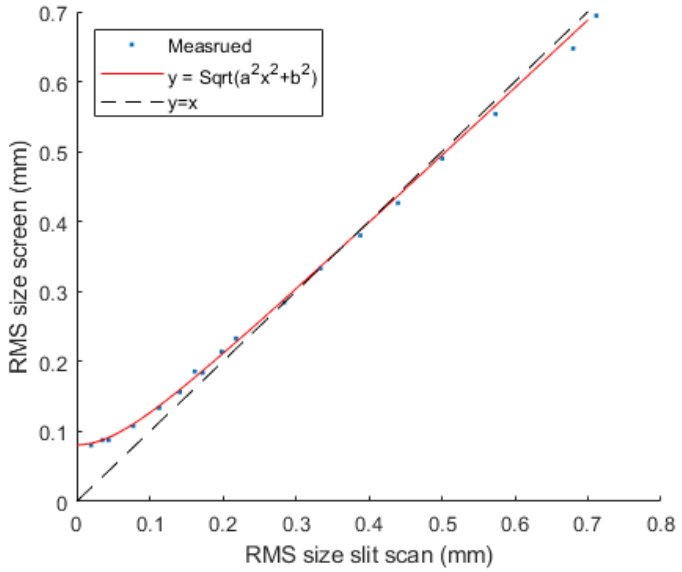
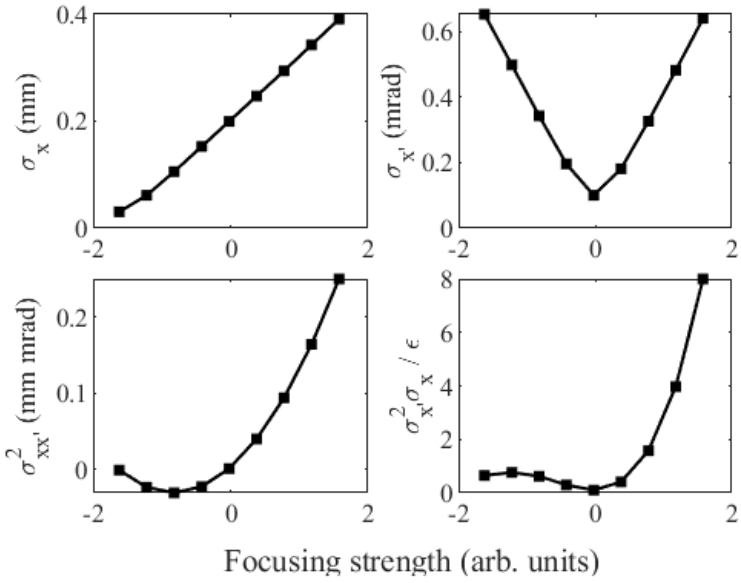


Slit and camera resolution effects

- Measure beamlets selected by a slit and imaged using a scintillator screen
  - Slit size is non-zero → measure convolution of slit opening and beam size
  - Camera resolution is non-zero → measure convolution of the camera PSF and beamlet images $\sigma^2_{bl,m} = \sigma^2_{bl,t} + \sigma^2_p$
- Effect on rms size and angle can be small but lead to significant changes in the rms emittance if the beam is strongly coupled
- Measure camera resolution by comparing rms beam size from slit scan and screen at same location
  - Expected: y = sqrt(1.00x^2 + 0.073^2)
    - camera res = 0.0347 mm/px
  - Measured: y = sqrt(0.97^2 x^2 + 0.080^2)
    - camera res = 0.0377 mm/px

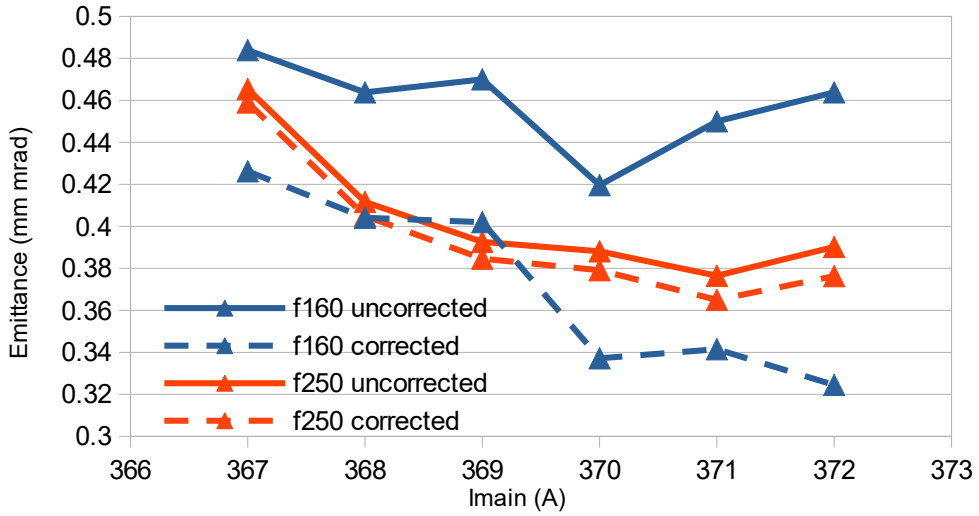


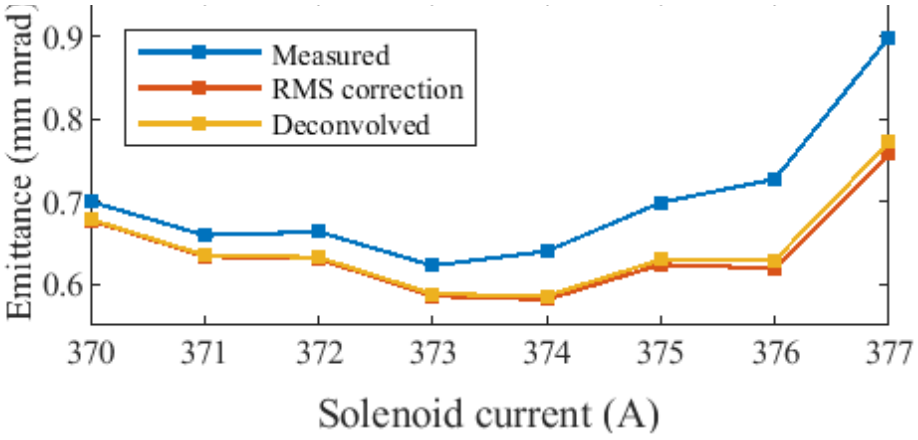




Correcting camera resolution

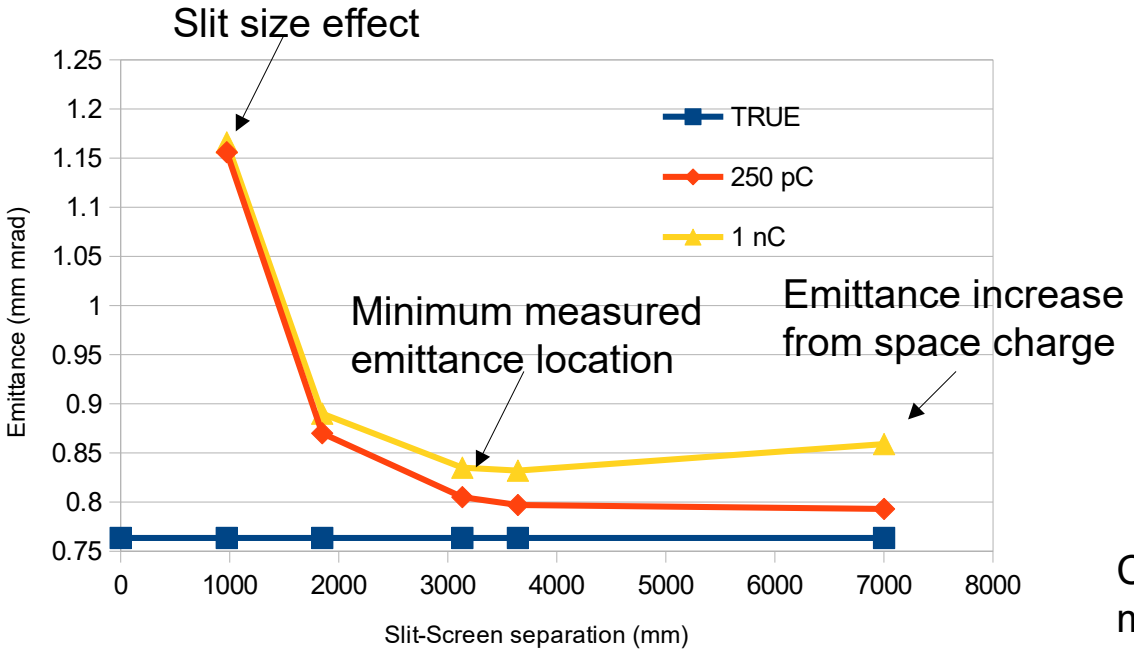
- True correction: Deconvolve the measured images with the camera PSF
  - Challenging to minimize artifacts especially for low SNR
- Correct beamlet images by scaling axes by the ratio of the PSF size to the measured size
  - $\exp\left(-\frac{x^2}{2(\sigma_b^2+\sigma_p^2)}\right) \approx \exp\left(-\frac{x^2}{2\sigma_b^2}\left(1-\frac{\sigma_p^2}{\sigma_b^2}\right)\right) \equiv \exp\left(-\frac{\overline{x}^2}{2\sigma_b^2}\right)$ Assumes the PSF << beamlet size
  - Improves agreement between measurements taken with different camera lenses (i.e. different PSFs)
- This correction can impact tuning for minimum transverse emittance

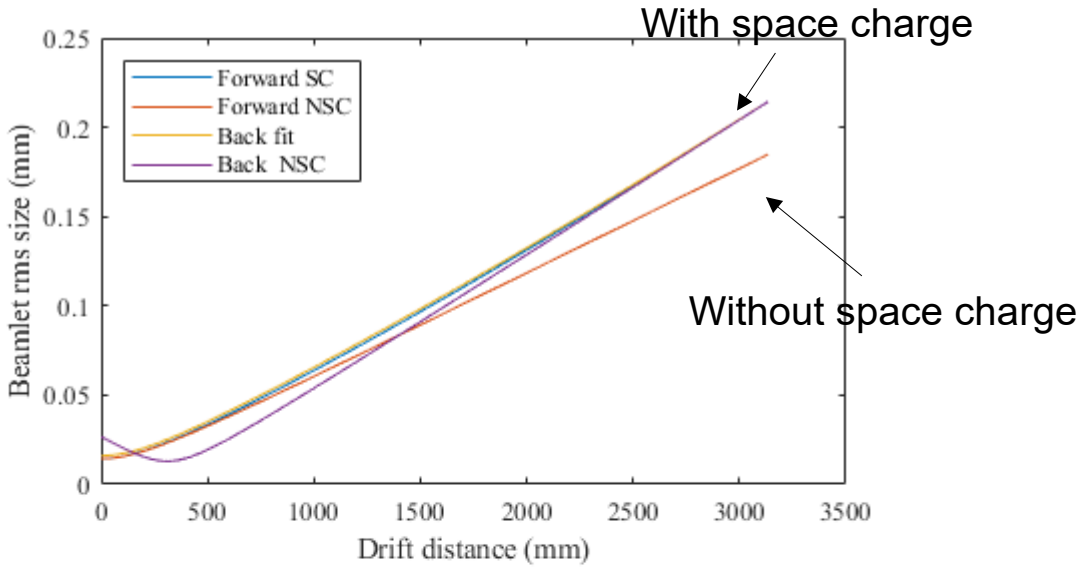


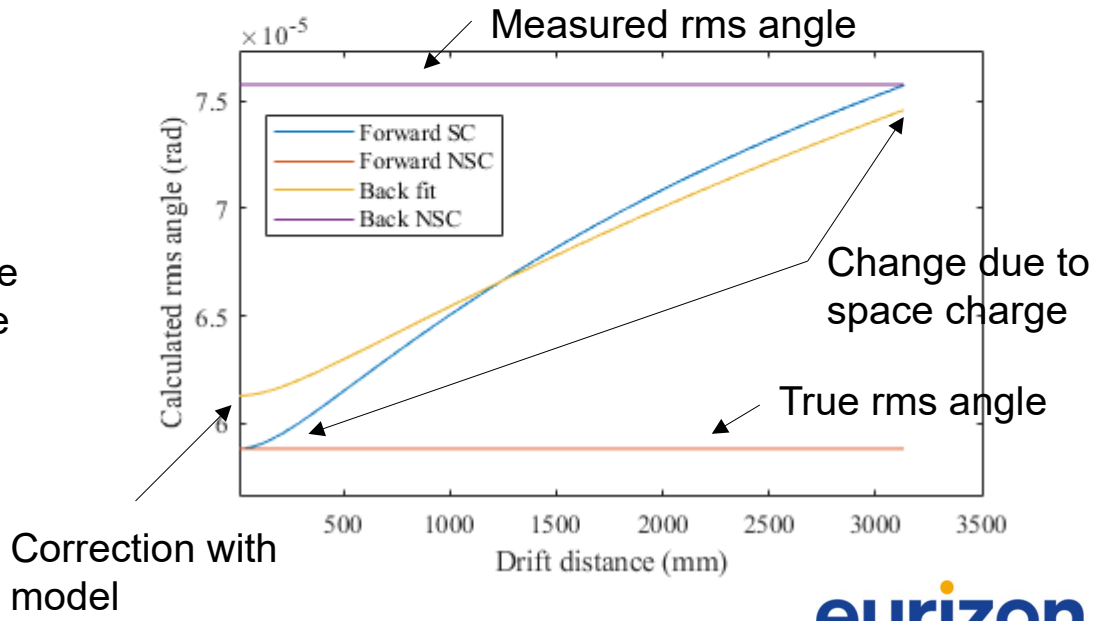


Space charge effects

- Standard analysis: $\sigma_{x'} = \sigma_{x,\mathrm{beamlet}} / L_{\mathrm{drift}}$
  - But space charge effects cause the beamlet sizes to increase further → overestimate emittance
- Can result in >~10% increase in measured emittance for 1 nC beam
- In development: rms space charge model to corrected measured beamlet sizes







EURIZON Task 4.5 Photogun prototype and beam diagnostics

Status 01/2023

- The content of Task 4.5 was updated as part of the transition from CREMLIN+ to EURIZON, and work is progressing well under the revised content, which focuses on improving the accuracy of the transverse emittance measurements.
  - Training of young staff from NRC KI at Zeuthen
    - Postponed then canceled due to end of collaboration
  - Development of new photoemission models → frozen, but there is an interest from PITZ.
    - Positively charged ions were added to SUMA code improving the agreement with measurements
    - DESY authorship withdrawn from relevant papers
  - Transverse emittance measurements
    - Improved by accuracy of measurements by accounting for slit size and camera resolution
    - Corrections for space charge effects are in development
- The work within Task 4.5 is in line with the main activities at PITZ (DESY): high brightness electron beams (production and precise diagnostics) and their applications (e.g. developments of the prototype for accelerator-based tunable high-power THz source for pump-probe experiments at European XFEL)