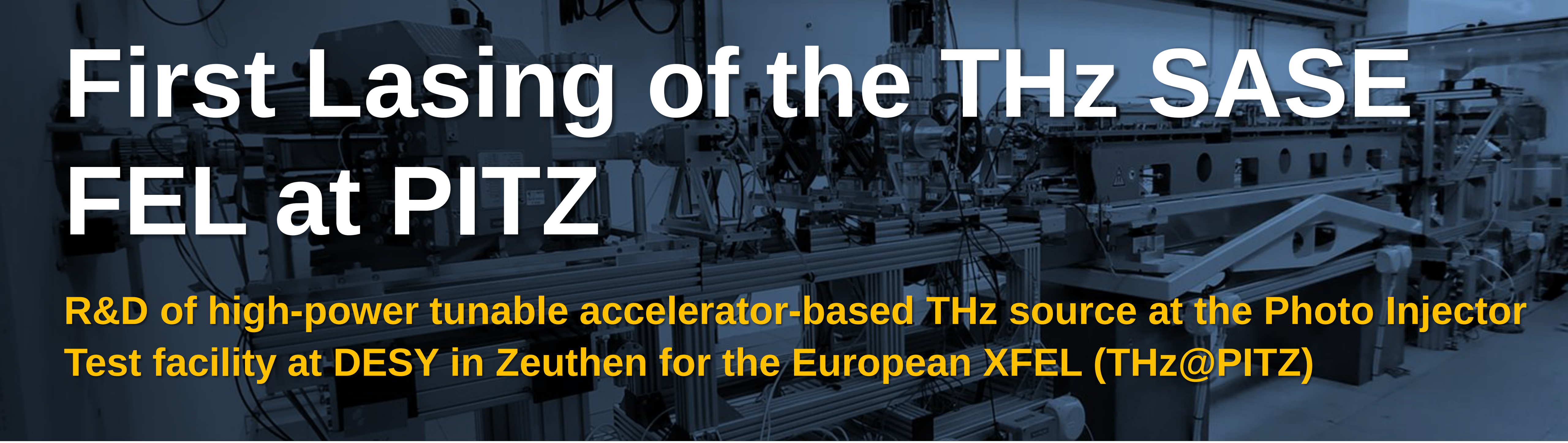


First Lasing of the THz SASE FEL at PITZ

R&D of high-power tunable accelerator-based THz source at the Photo Injector Test facility at DESY in Zeuthen for the European XFEL (THz@PITZ)

Prach Boonpornprasert for the THz@PITZ Team

The 8th annual MT meeting, DESY Hamburg, 26-27.09.2022

HELMHOLTZ

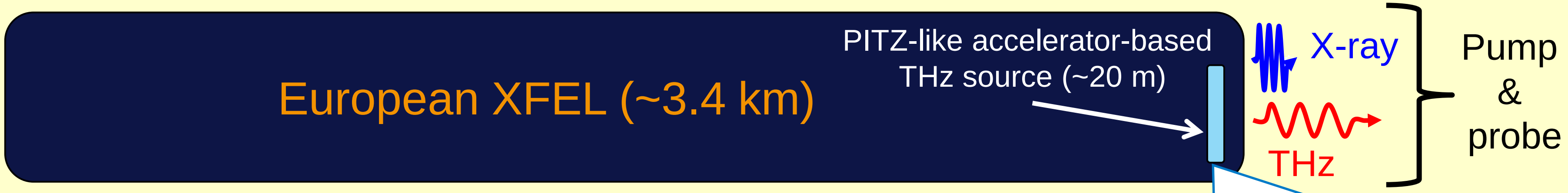
PITZ Photo Injector Test Facility Zeuthen

European XFEL

DESY.

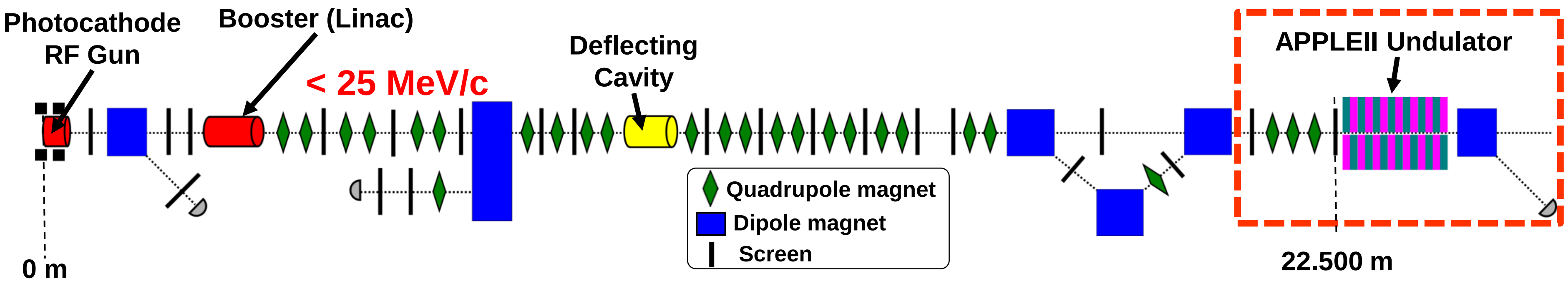
Background

Prototype THz source for pump-probe experiments at European XFEL



Reference: E. Schneidmiller, M. Yurkov, M. Krasilnikov, and F. Stephan, in Proc. FEL2012, paper WEPD55.

THz pulses from PITZ-like accelerator
- High-power
- Tunable
- Synchronization with X-ray pulses

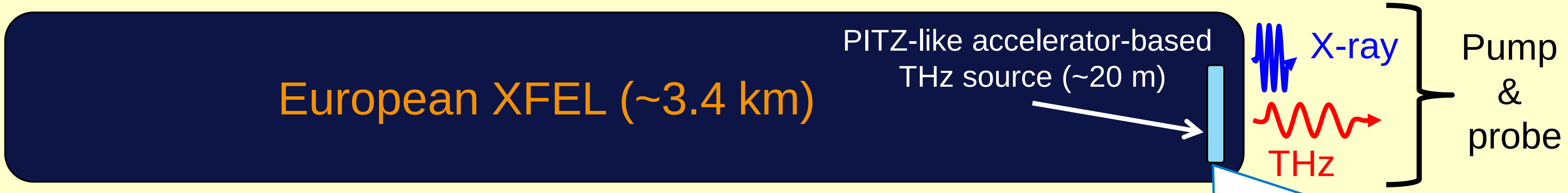


PITZ beamline layout (2014) including an extension for SASE FEL simulations (in red-dashed box)

Reference: P. Boonpornprasert, PhD thesis, University of Hamburg, 2020.

Background

Prototype THz source for pump-probe experiments at European XFEL



Reference: E. Schneidmiller, M. Yurkov, M. Krasilnikov, and F. Stephan, in Proc. FEL2012, paper WEPD55.

THz pulses from PITZ-like accelerator

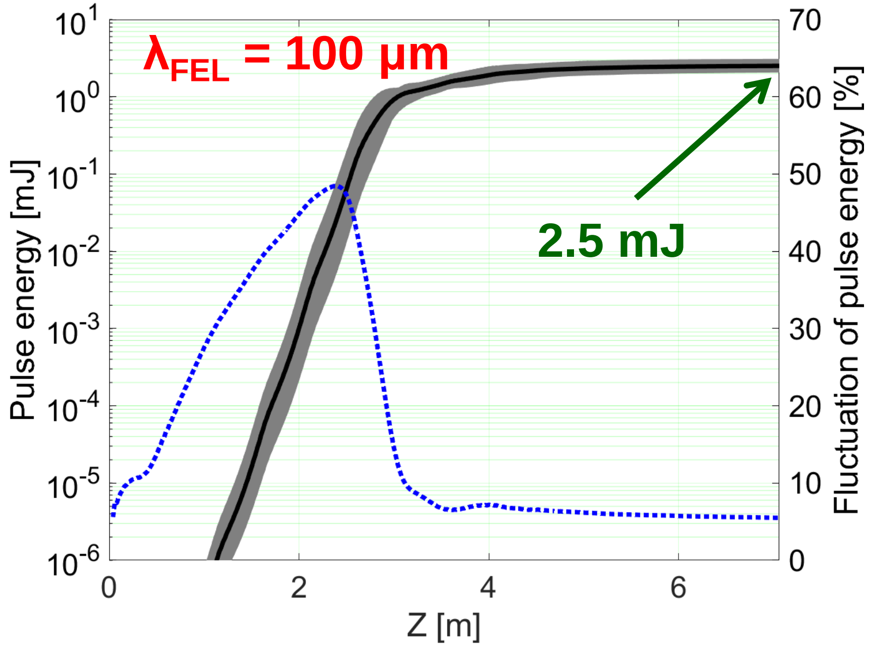
- High-power
- Tunable
- Synchronization with X-ray pulses

PITZ Highlights:

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

SASE FEL simulations

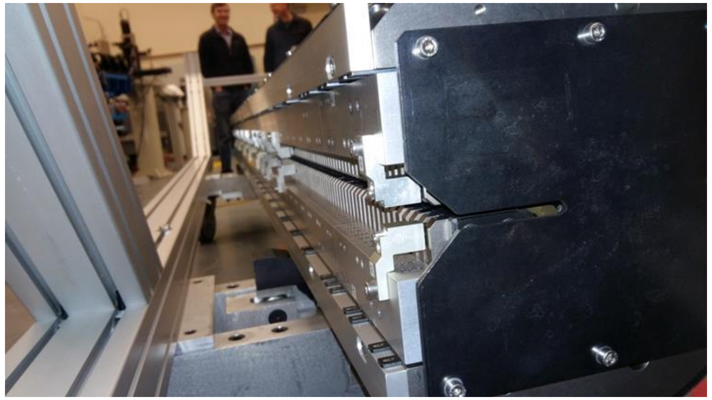
- Genesis 1.3 code
- Helical undulator with **λ_u = 40 mm**
- Electron beam with
  - Momentum of **15 MeV/c**
  - RMS bunch length of ~2 mm
  - Bunch charge of **4 nC**
  - Peak current **~200 A**



Reference: P. Boonpornprasert, PhD thesis, University of Hamburg, 2020.

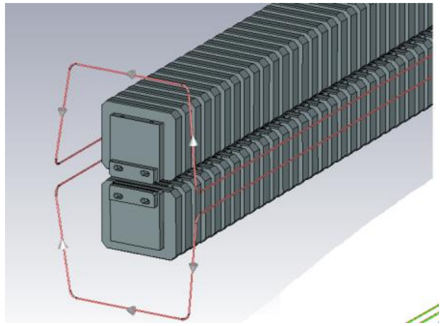
Proof-of-principle experiment on THz SASE FEL at PITZ

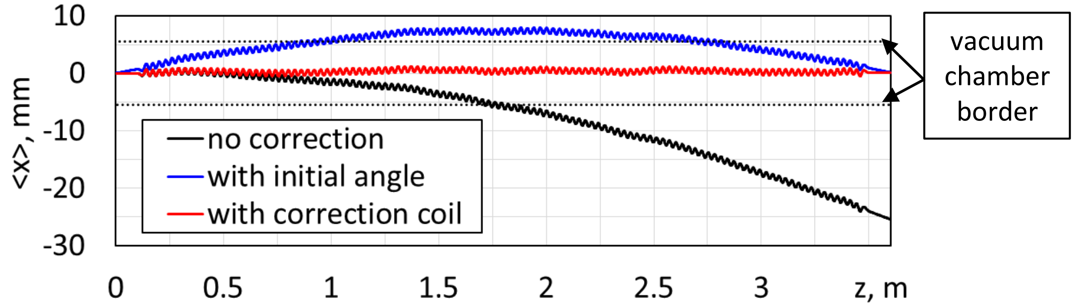
Using LCLS-I undulators (available on loan from SLAC, USA)



Main challenges:

- Space charge effect
- Waveguide effect
- Wakefields effect
- Strong horizontal gradient





Reference particle trajectories in the undulator with horizontal gradient

Some Properties of the LCLS-I undulator

Properties	Details
Type	**planar hybrid** (NdFeB)
K-value	3.585 (3.49)
Period length	30 mm
Periods / a module	113 periods
Total length	3.4 m
Vacuum chamber size	11 mm x 5 mm

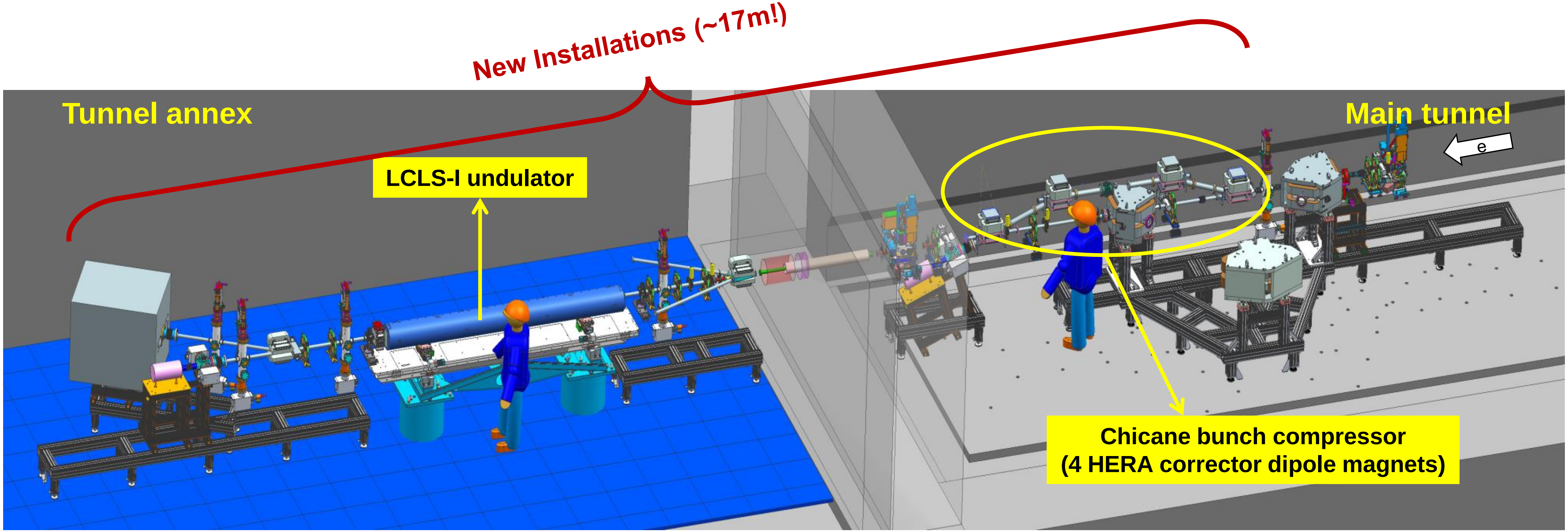
~17 MeV/c ➔ λ_{rad}~100 µm

The project **"Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector"** was approved by **the European XFEL Management Board**

→ **PITZ + LCLS-I undulator for Proof-of-principle experiments (2019-2023)**

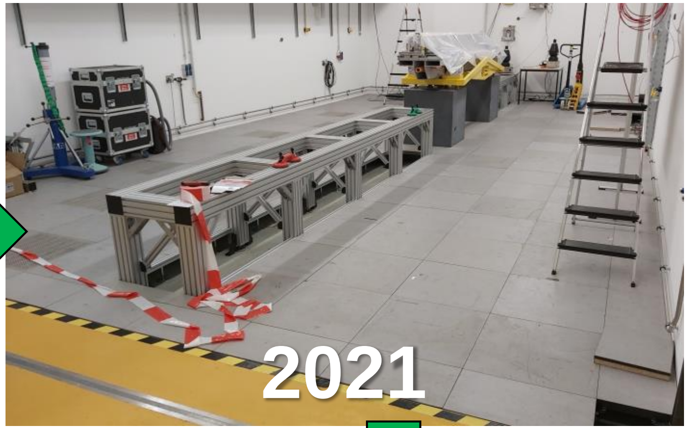
Beamline Extension

PITZ upgrade for the proof-of-principle experiment



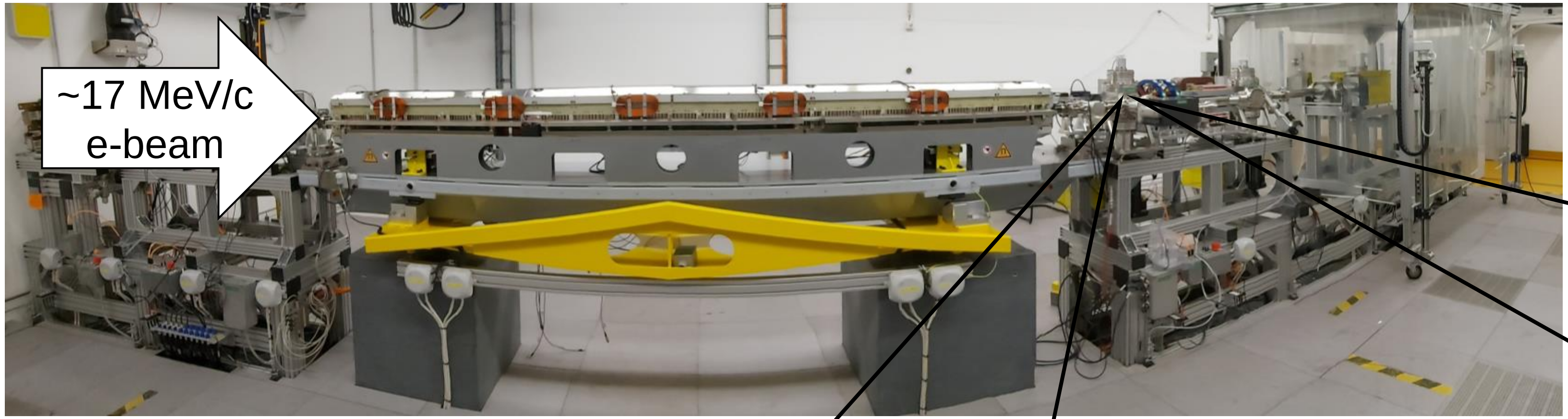
Construction and Installation

History of the tunnel annex

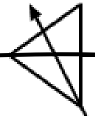


First Commissioning with E-Beam

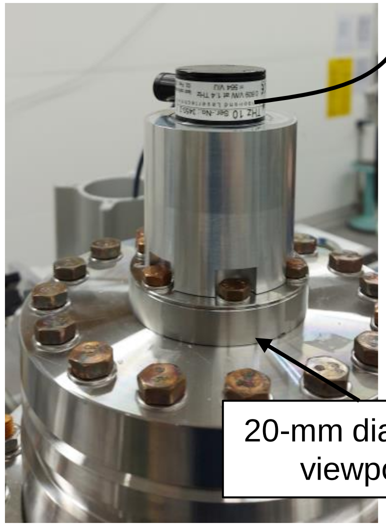
Transport and matching of e-beam with bunch charges of 100 pC ➔ 1 nC (end of July 2022)



Oscilloscope

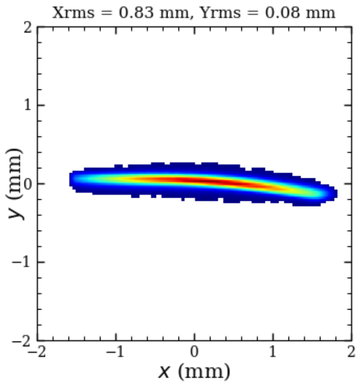


THz10 Pyroelectric detector for THz radiation

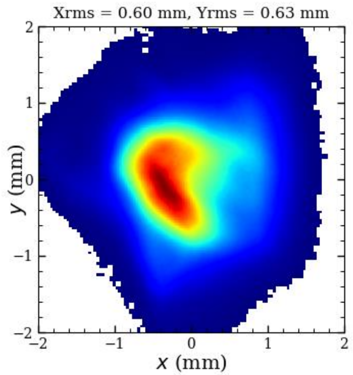


20-mm diamond viewport

In-vacuum mirror



Measured transverse profile of **100 pC** beam



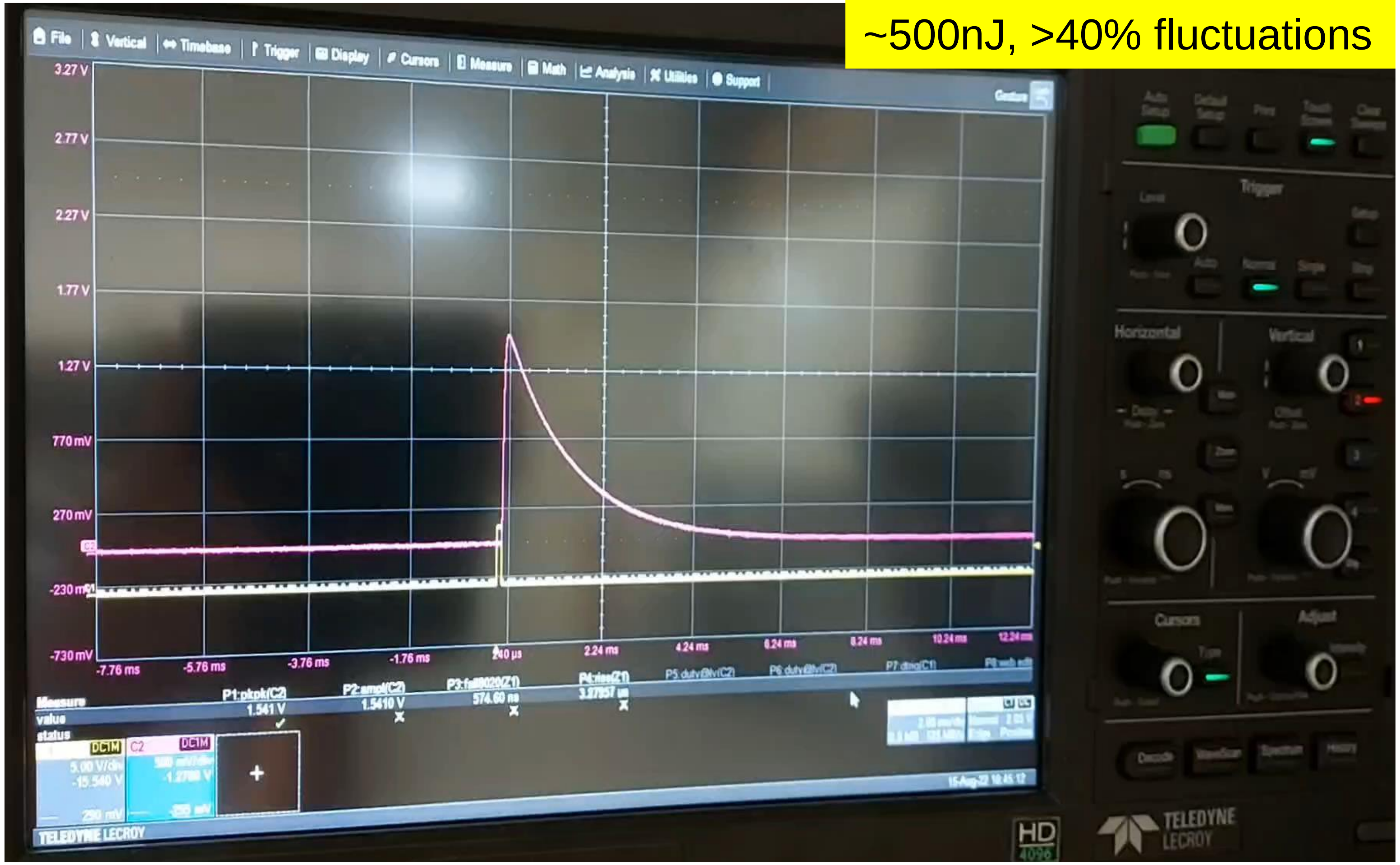
Measured transverse profile of **1 nC** beam

Advanced approach of space-charge dominated beam matching was used.

Reference: X-K. Li et al., in Proc. IPAC2021, paper WEPAB257.

1st Lasing from 1 nC Beam

Pyroelectric detector signal from the oscilloscope (beginning of August 2022)



~500nJ, >40% fluctuations

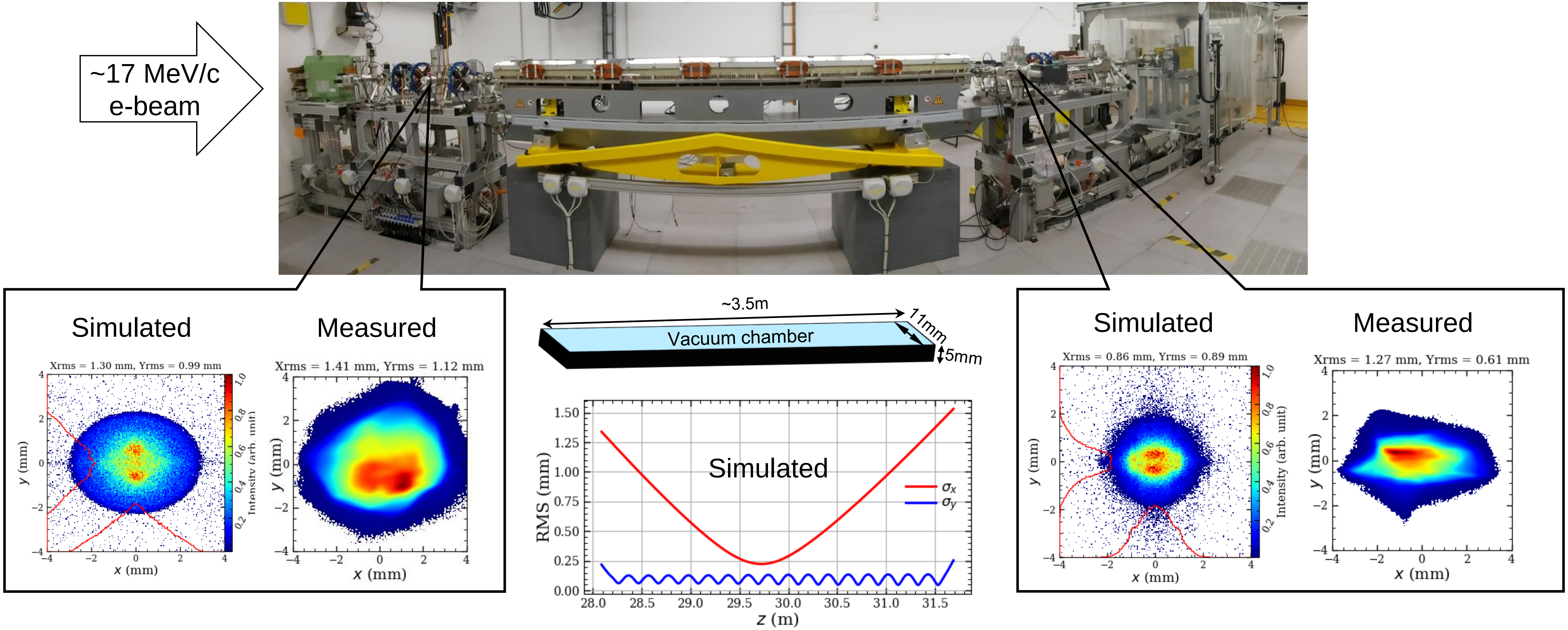
~17 MeV/c ➔ λ_{rad}~100 µm

Next steps to confirm SASE FEL

- Go to higher bunch charges
- Measure energy gain curves
- Analyze probability distribution of measured pulse energy
  ⇐ Probability distribution of SASE FEL in linear regime is a gamma distribution
  (Reference: E.L. Saldin et al. NIM A 407 (1998), 291-295.)

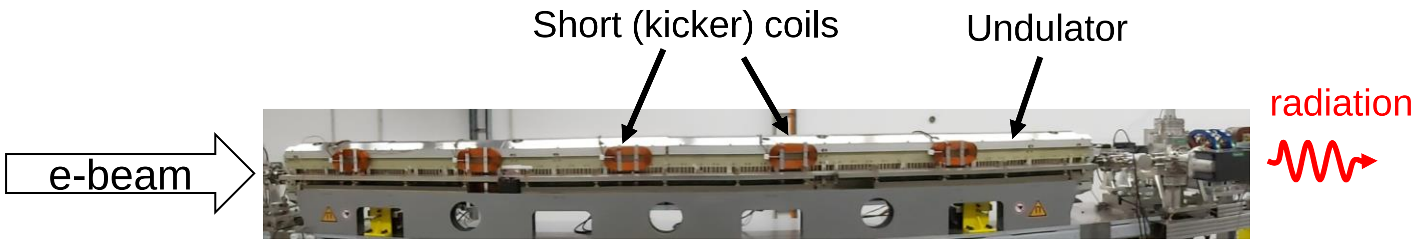
2 nC Beam Transport and Matching

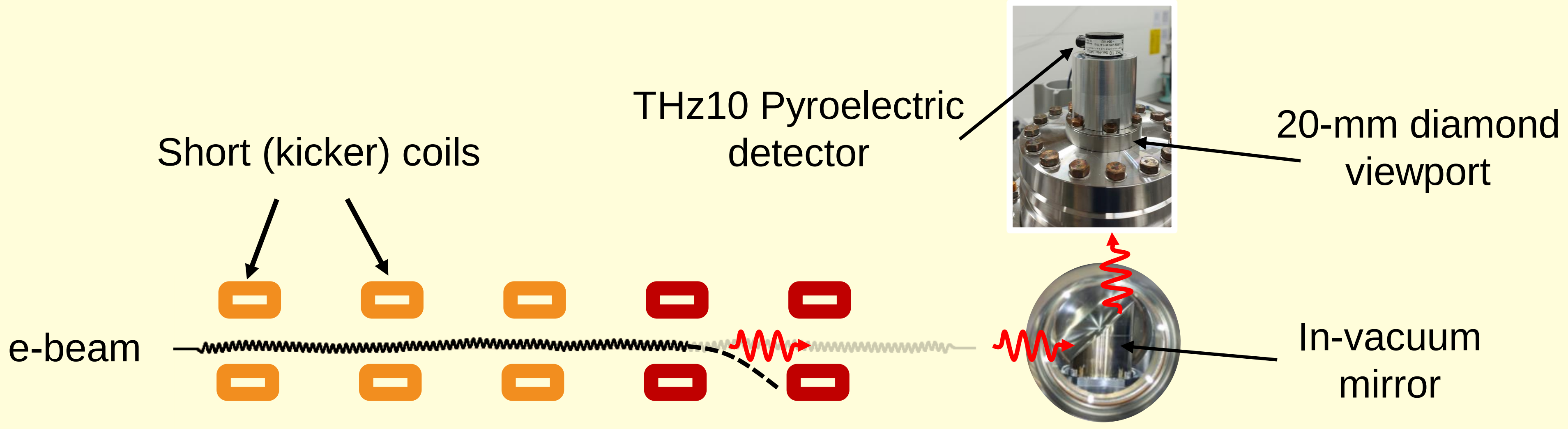
Comparison with simulations



Gain Curve Measurement Setup

Using kicker coils to change **“effective length”** of the undulator

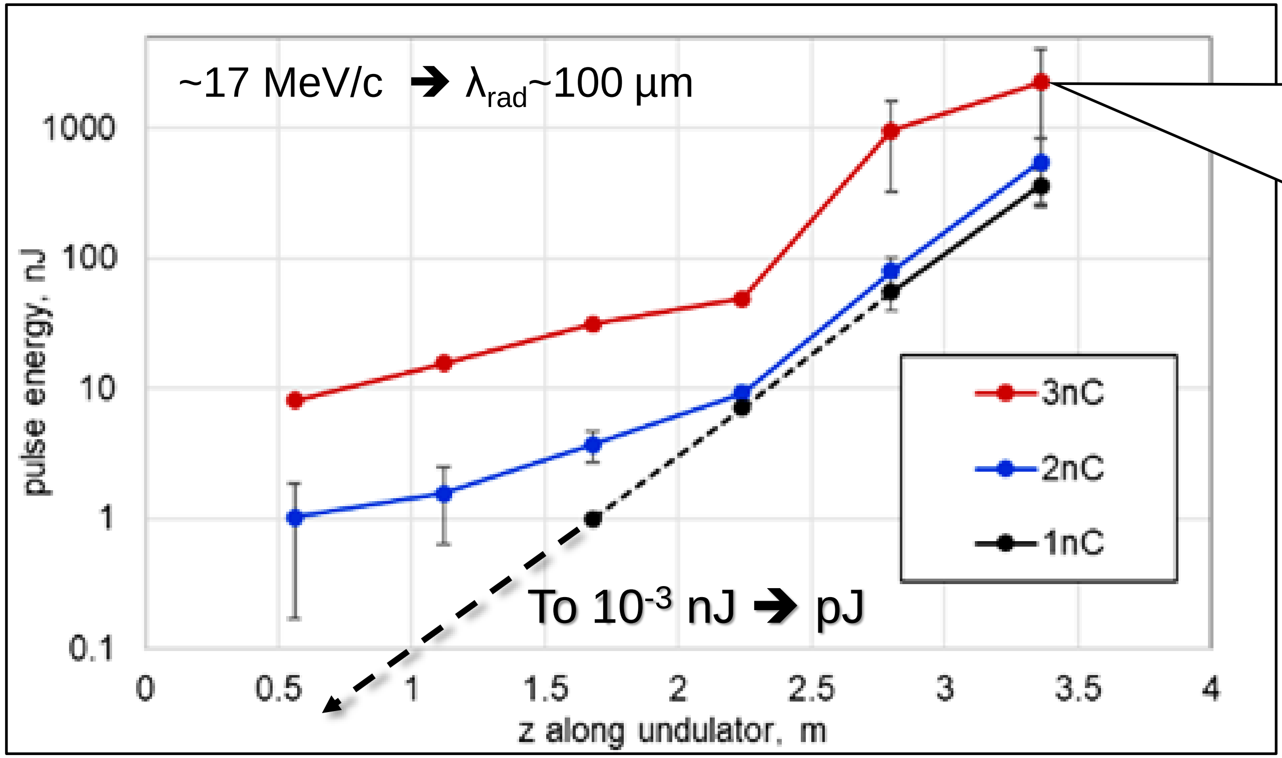




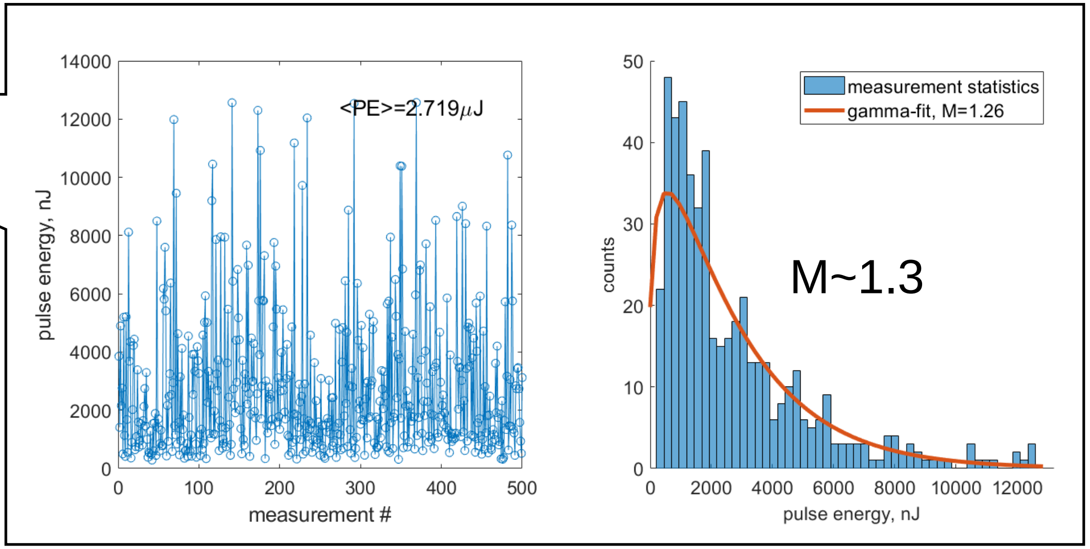
Simplified layout of the gain curve measurement setup

Gain Curve Measurements

First Characterization of FEL Gain Curves at 1, 2 and 3 nC



Energy gain pJ to µJ in 3.5 m
➔ high gain FEL at PITZ!



Gamma probability distribution

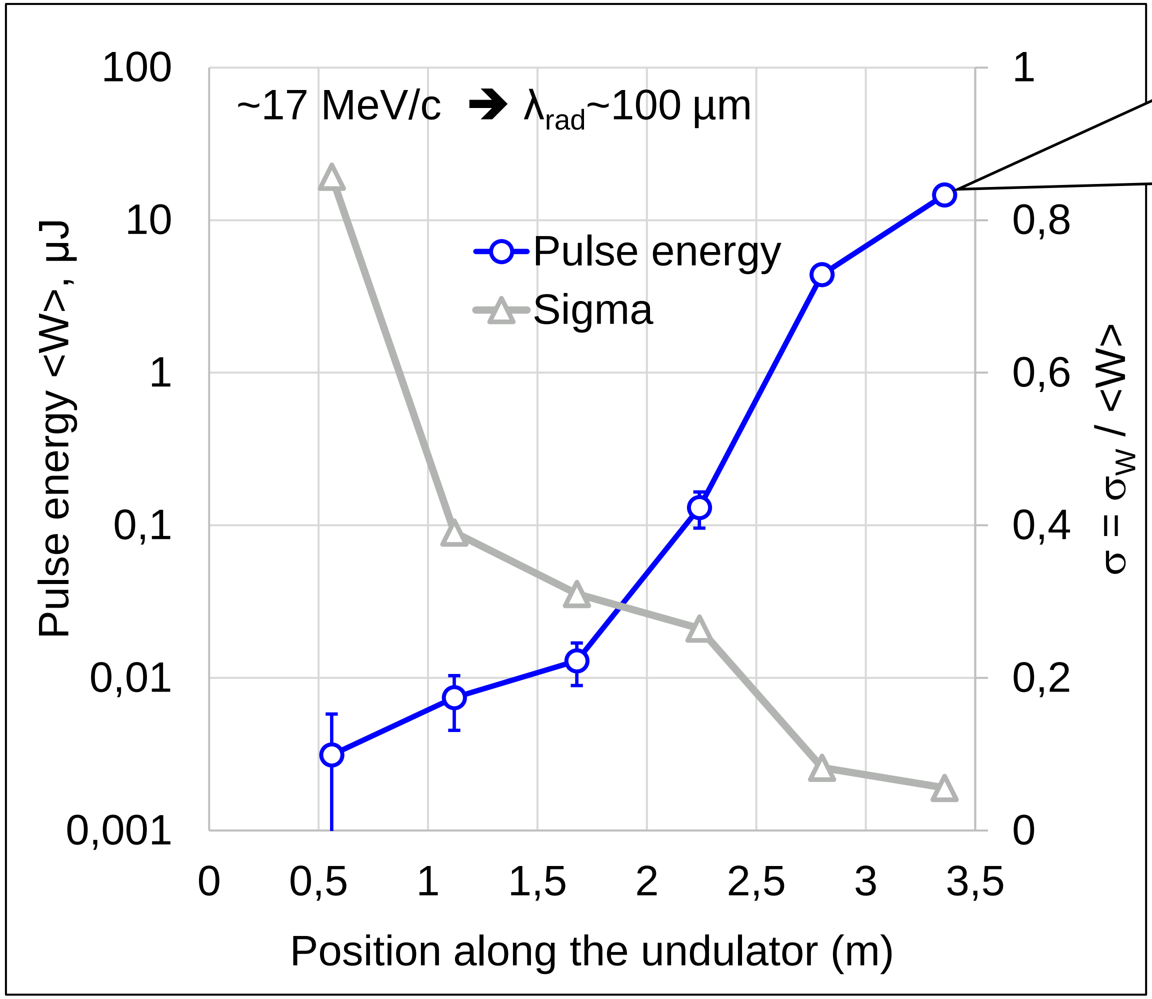
➔ **SASE FEL** in linear regime

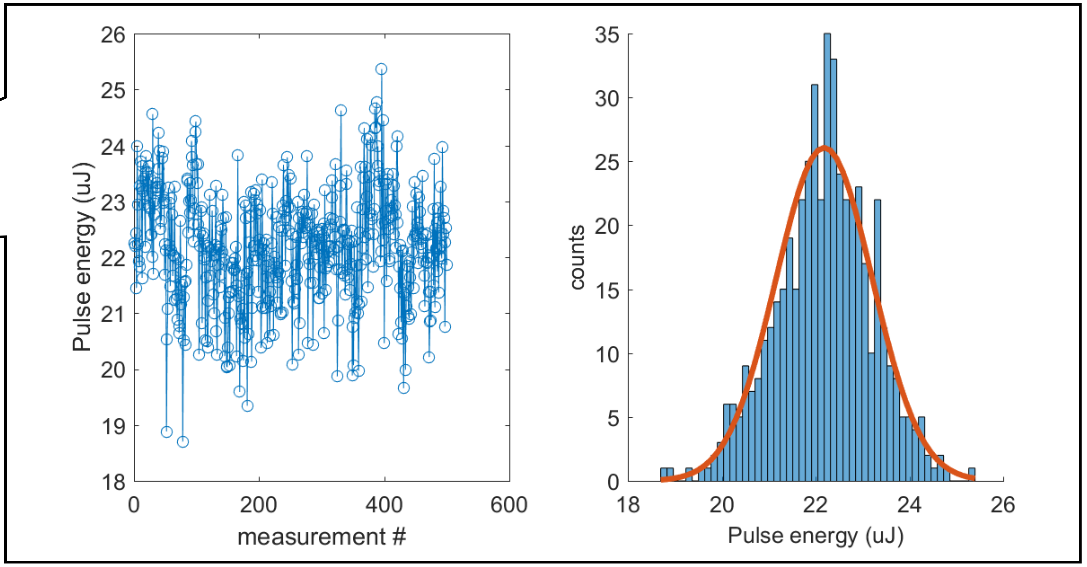
Remark: Strong dependence of measured pulse energy on beam current and beam transport/matching

Reference: M. Krasilnikov et al. presented in FEL2022, MOA08.

Further Tuning

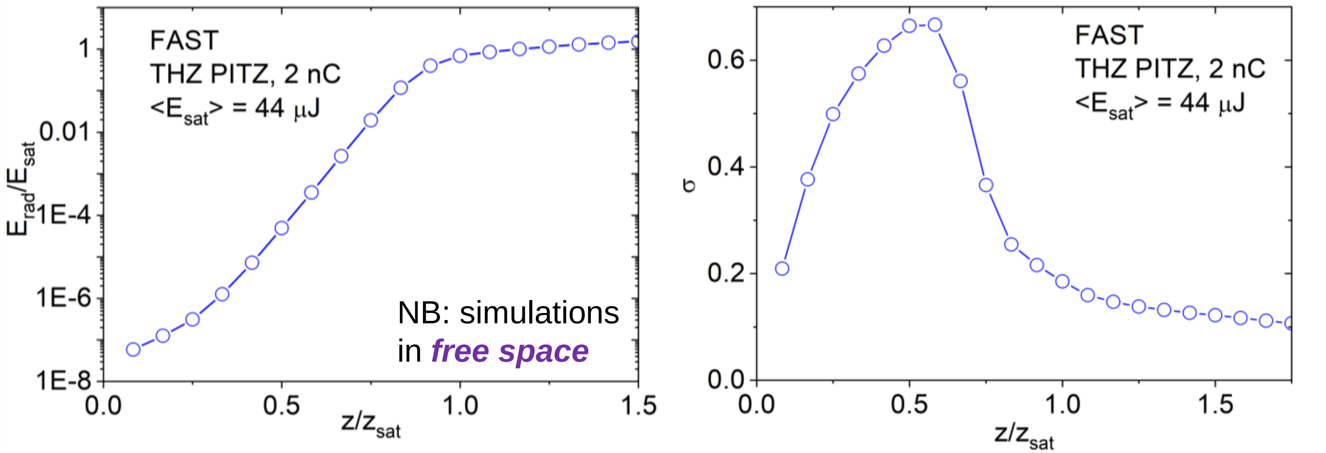
Saturation observed for 2 nC: max <W> ~ 22 µJ





NB: strong ***waveguide regime*** of SASE FEL

FEL Simulation using FAST (M. Yurkov)



Summary and Outlook

THZ SASE FEL at PITZ

- Proof-of-principle experiment of THz SASE FEL is ongoing @PITZ (supported by E-XFEL):
  ➔ first electrons through the LCLS-I undulator ➔ End of July 2022
  ➔ 1st THz SASE FEL Lasing ➔ Beginning of August 2022
  ➔ High gain FEL measured at ~ 3THz!
  ➔ Strong dependence on beam current and transport /matching
  ➔ FEL saturation at > 20 μJ with 2 nC
- THz SASE FEL was demonstrated experimentally at PITZ
- The concept of PITZ-like accelerator-based THz FEL is working
- **Next steps:**
  - Detailed tuning of high-charge beam transport/matching
  - Setup full THz diagnostics (spectral characterization and band pass filters)
  - Other dedicated studies (bunch compressor, seeded THz FEL)

Acknowledgements

THz@PITZ Team and Collaboration

DESY Zeuthen

- Z. Aboulbanine
- G. Adhikari
- N. Aftab
- P. Boonpornprasert
- G. Georgiev
- J. Good
- M. Gross
- A. Hoffmann
- M. Krasilnikov
- X.-K. Li
- A. Lueangaramwong
- R. Niemczyk
- A. Oppelt
- H. Qian
- C. Richard
- F. Stephan
- G. Vashchenko
- T. Weilbach
- R. General
- L. Heuchling
- M. Homann
- L. Jachmann,
- D. Kalantaryan
- W. Köhler
- G. Koss
- S. Maschmann
- D. Melkumyan
- F. Müller
- R. Netzel
- B. Petrosyan
- S. Philipp
- M. Pohl
- C. Rüger
- A. Sandmann-Lemm
- M. Schade
- E. Schmal
- J. Schultze
- S. Weisse

DESY Hamburg

- E. Schneidmiller
- M. Yurkov
- B. Krause
- M. Tischer
- P. Vagin

Universität Hamburg

- W. Hillert
- J. Rossbach

SLAC, USA

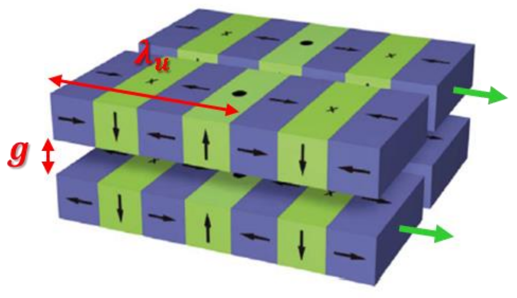
- A. Brachmann
- N. Holtkamp
- H.-D. Nuhn

Backup slides

THz SASE FEL at PITZ

Undulator and beam parameter space

APPLE- II Undulator*



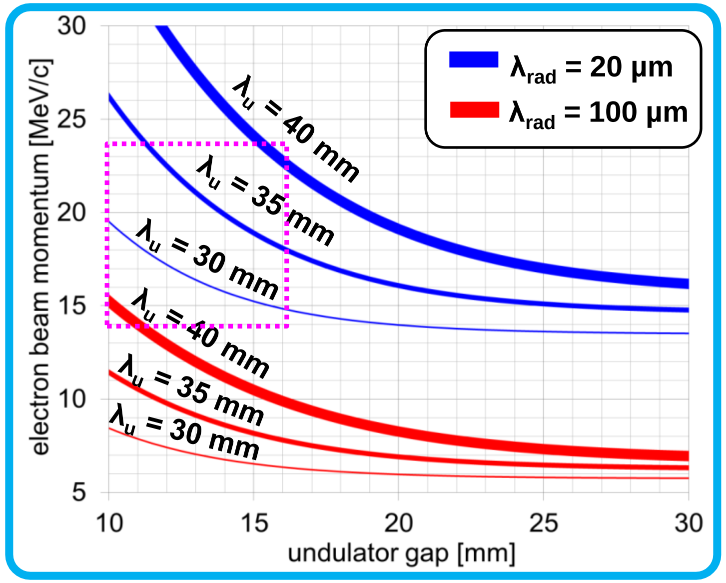
Radiation wavelength

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + K_{rms}^2\right)$$

$$K_{rms} = 0.66 \cdot B_0[T] \cdot \lambda_u[cm]$$

$$B_0 = 1.54 e^{\left(-4.46\frac{g}{\lambda_u} + 0.43\left(\frac{g}{\lambda_u}\right)^2\right)}$$

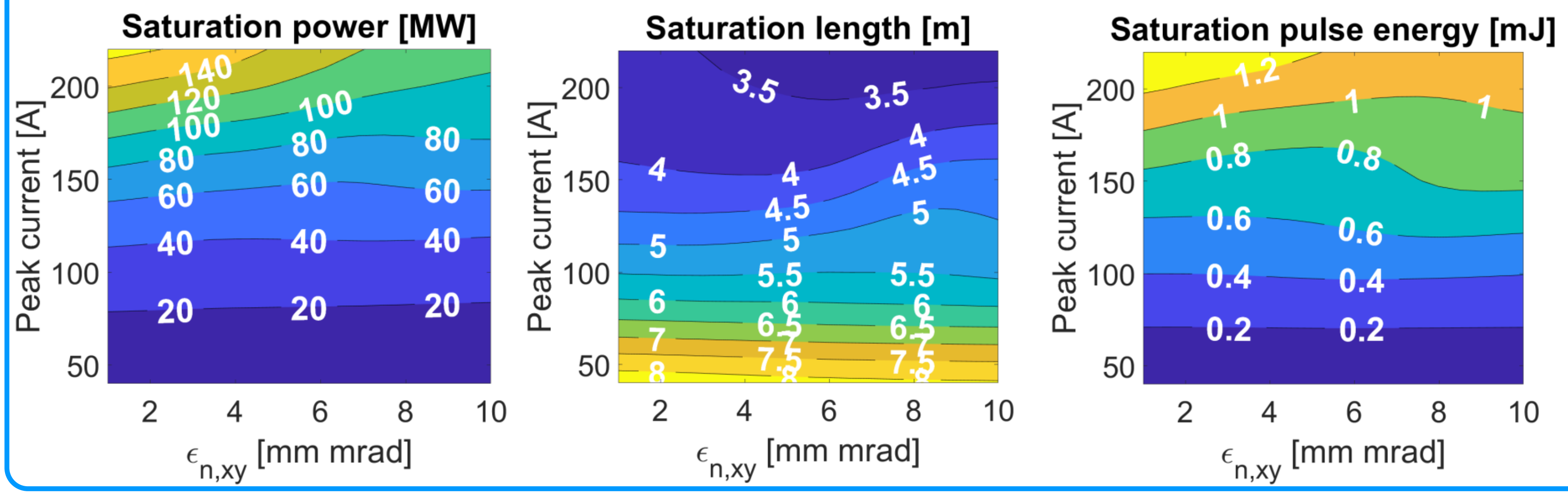
**Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007*



Conditions :
λ_{rad} of 20 – 100 μm
Max P_z ~ 22 MeV/c
gap $g \geq$ 10 mm

Selections :
λ_u of 40 mm
22 MeV/c for 20 μm
15 MeV/c for 100 μm

THz SASE FEL Parameter Space with GENESIS (λ = 100 μm)



SASE FEL simulations assuming:

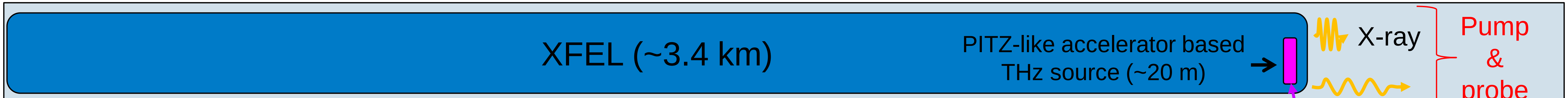
- Helical undulator with λ_u=40 mm
- 4 nC electron beam with 15 MeV/c and ~2 mm rms bunch length

Preliminary conclusions:

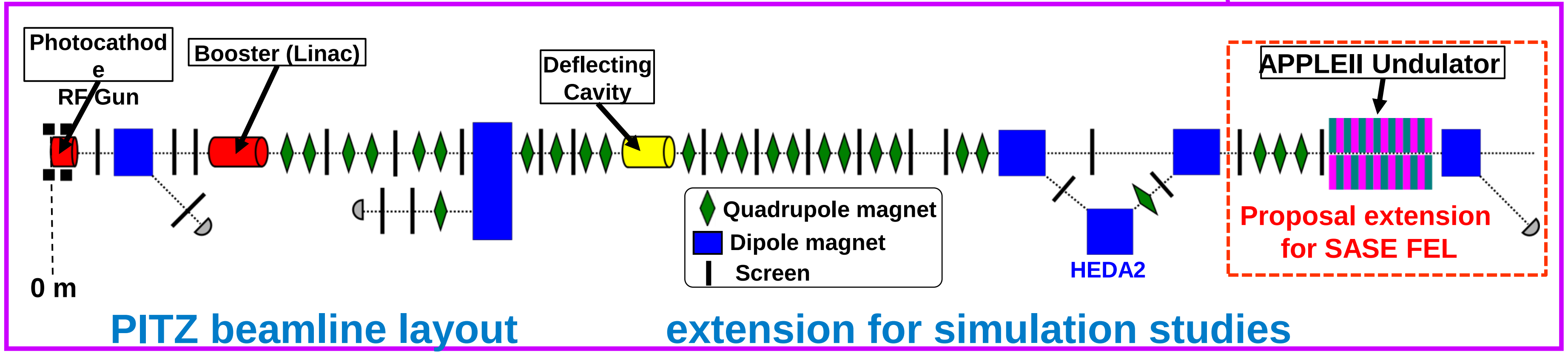
- Beam **peak current** (charge) → most impact
- Transverse normalized emittance ε_n has almost no impact on saturation power

THz@PITZ: original proposals (2018)

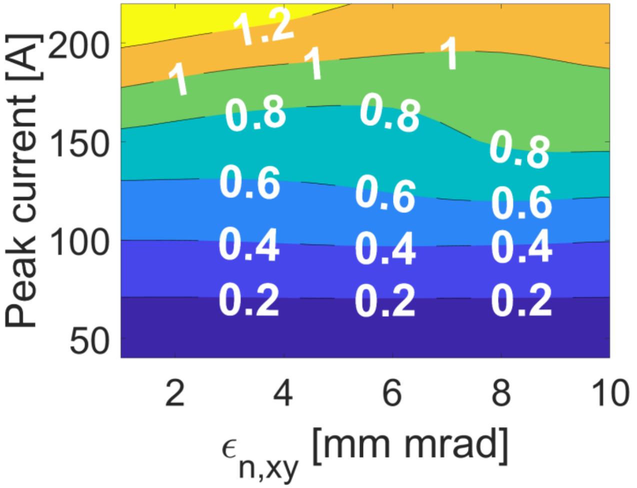
PITZ as prototype for an accelerator based tunable THz source for pump-probe experiments at the European XFEL



E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012



Saturation pulse energy [mJ]



Peak current: 50 to **200 A**
Emittance: 1 to 10 mm mrad

FEL properties from Start-to-End (S2E) simulations

Property	Detail
Central wavelength	106.4 µm
Saturation length	2.94 m
Pulse energy at saturation & U.exit	0.78 mJ & **2.51 mJ**
Peak power at saturation & U.exit	95 MW & 188.7 MW
Radiation pulse duration	18 ps (FWHM)
Spectral width	10 µm (9.4%)

Properties of the APPLE-II undulator used in simulations

Property	Detail
Undulator type	Helical
K-value	1.82
Period length & total length	40 mm & 7 m (175 periods)

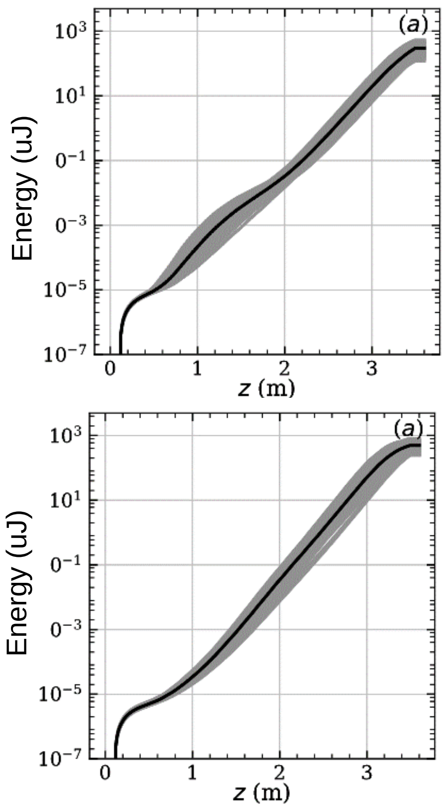
Start-to-end simulation

Proof-of-principle experiment on THz SASE FEL at PITZ

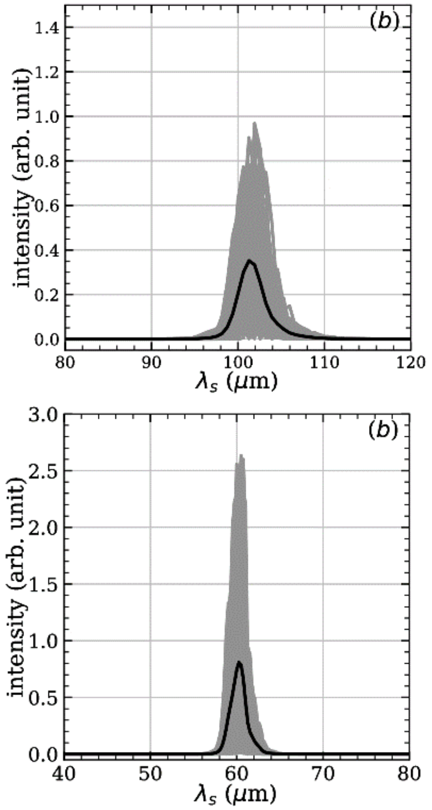
- Astra: Photocathode to Undulator entrance
- Genesis 1.3: FEL simulation (input from Astra)

~100 um

~60 um



THz pulse energy along undulator



Spectrum

Case	100 um	60um	Unit
Momentum	17	22	MeV/c
Pulse energy	**493.1±109.8**	**294.8±83.8**	μJ
Arrival time jitter	1.5	1.1	ps
Center wavelength	**101.8±0.7**	**60.3±0.3**	μm
Spectrum width	2.0±0.4	1.0±0.2	μm

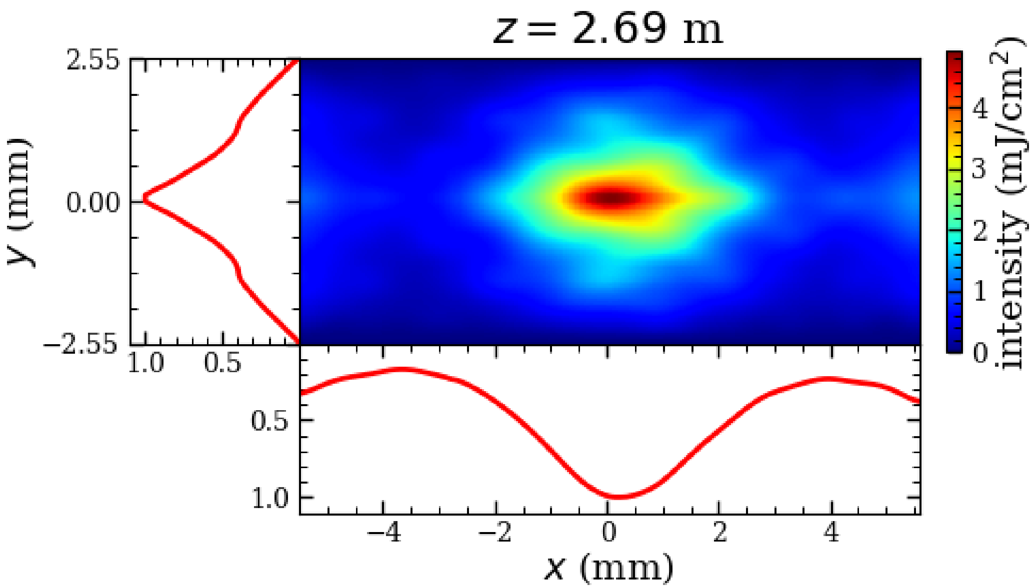
Summary of Genesis 1.3 simulation

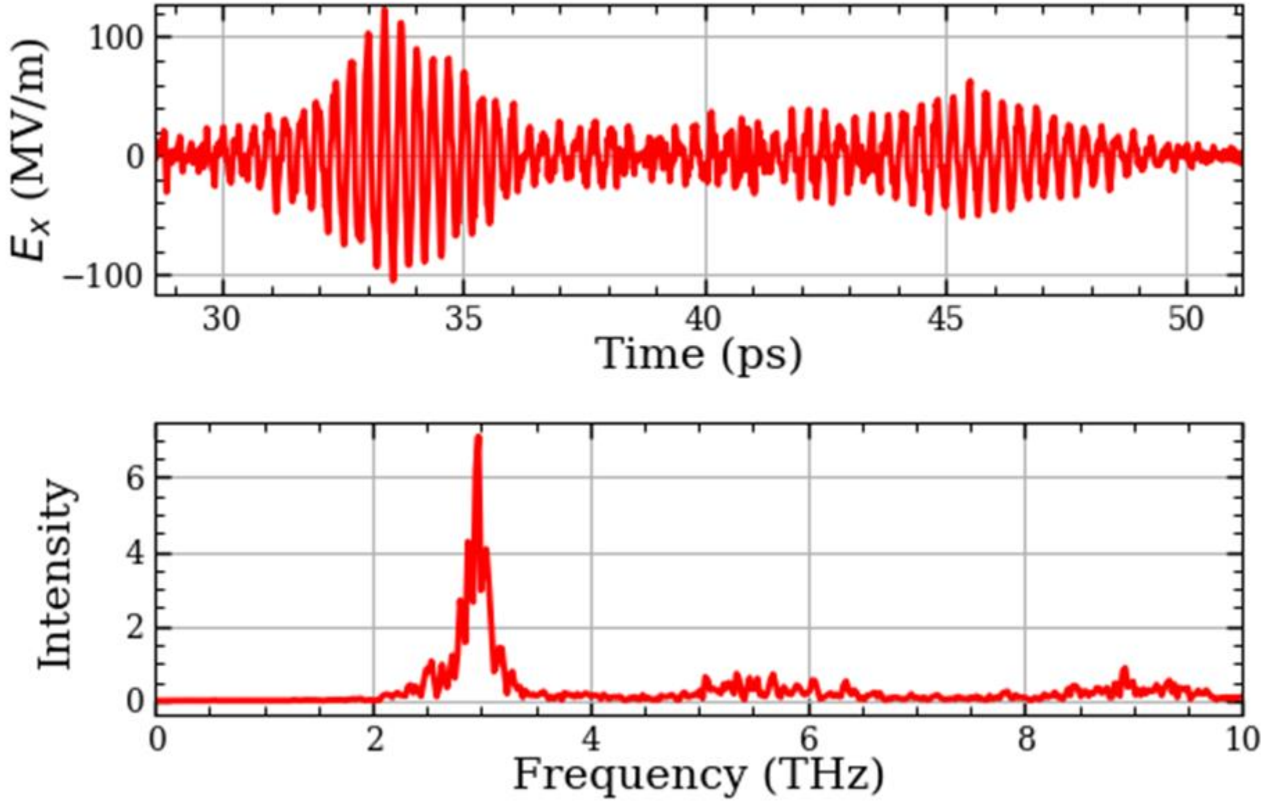
Courtesy: X.-K. Li

Start-to-end simulation

Proof-of-principle experiment on THz SASE FEL at PITZ

- Warp: Waveguide effect simulation (100 μm)



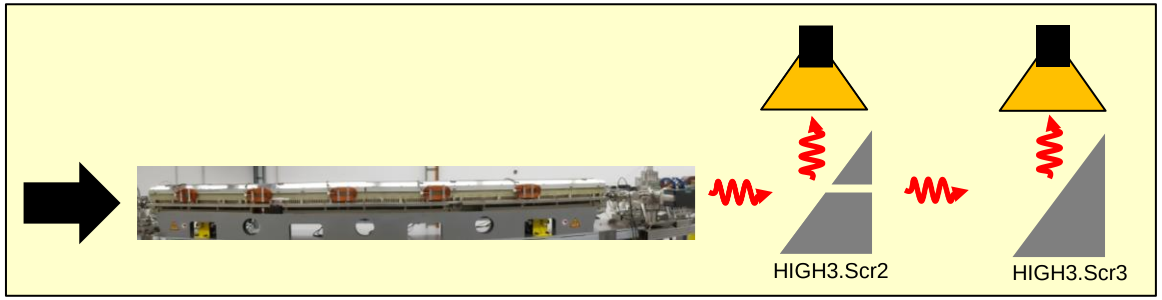


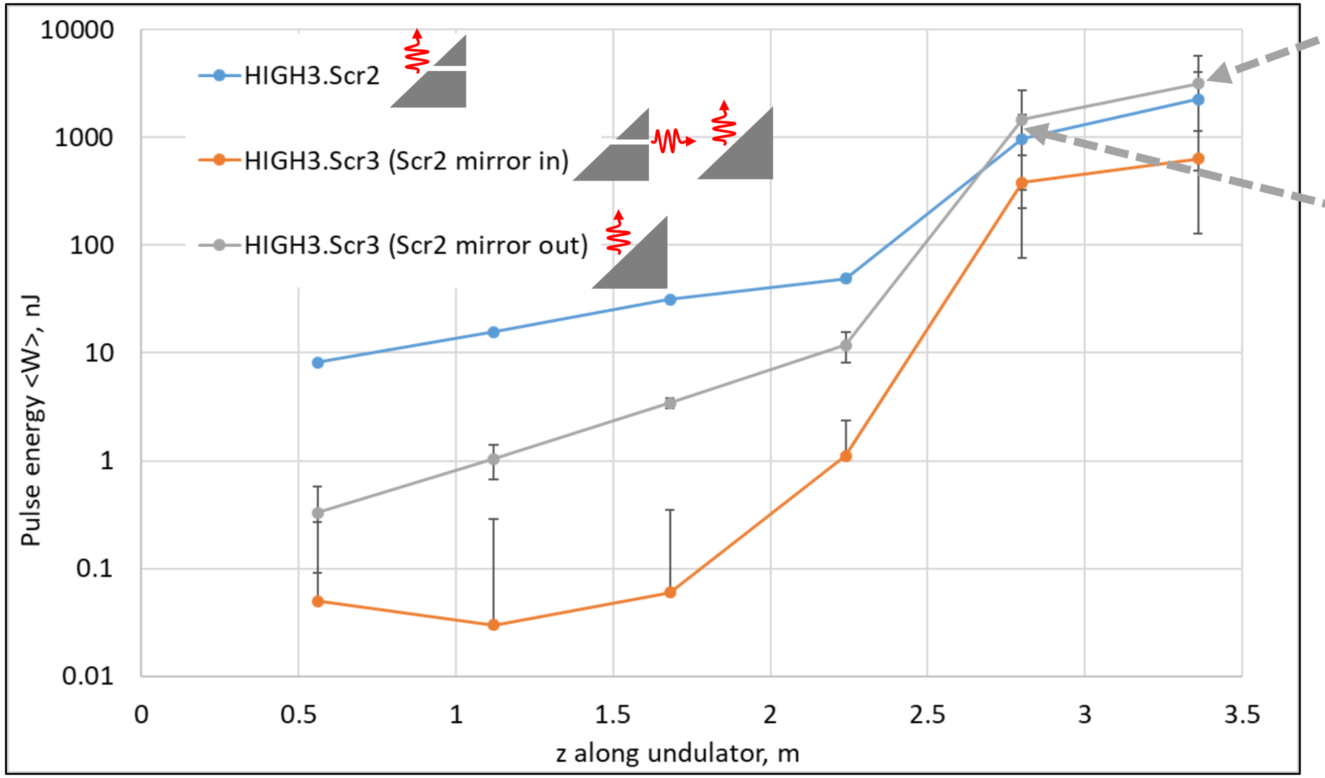
Particle-in-cell code; Treat vacuum chamber (11x5 mm) as conducting boundaries

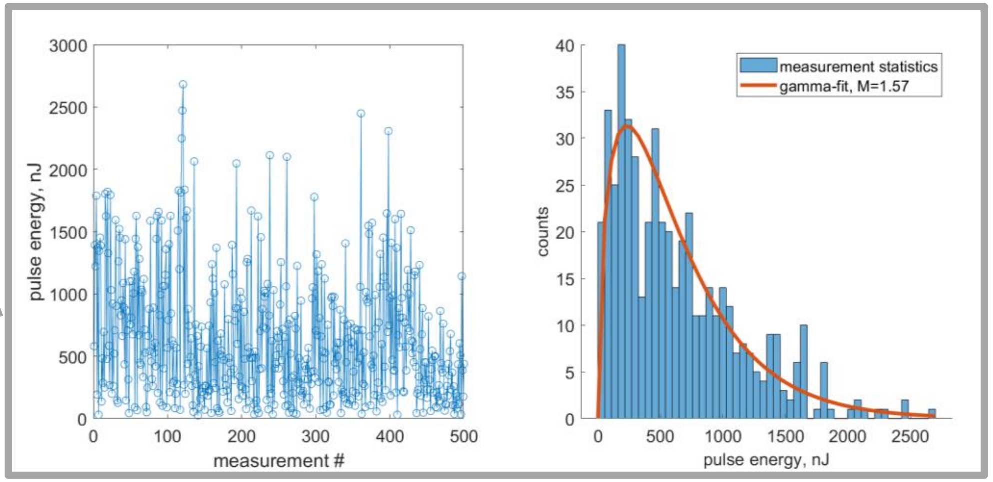
Courtesy: X.-K. Li

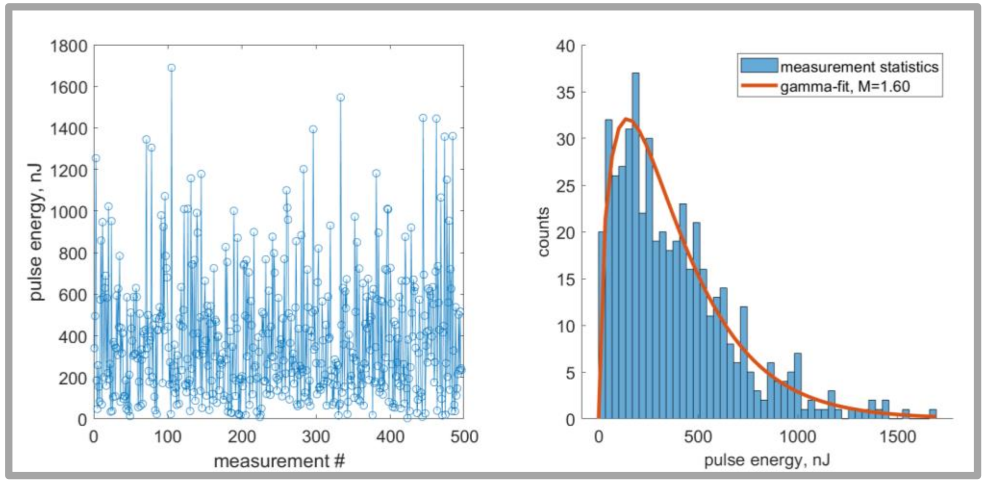
Gain Curve Measurements (3nC)

Measured pulse energy vs position along undulator for different locations

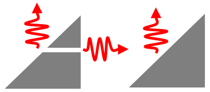




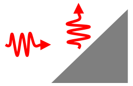




2.3μJ 0.6μJ

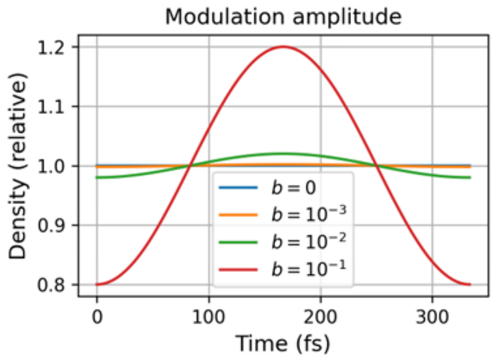


3.1μJ



Simulation of Seeding Option for THz FEL at PITZ

G. Georgiev et al., Presented in FEL2022, TUP40.



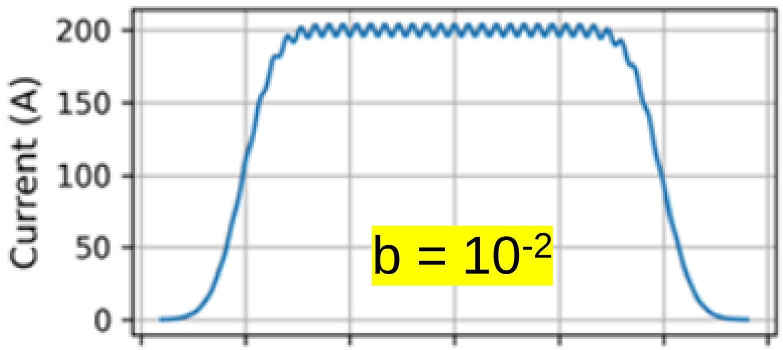


Figure 2: Electron beam current modulation along the duration of one period for different bunching values.

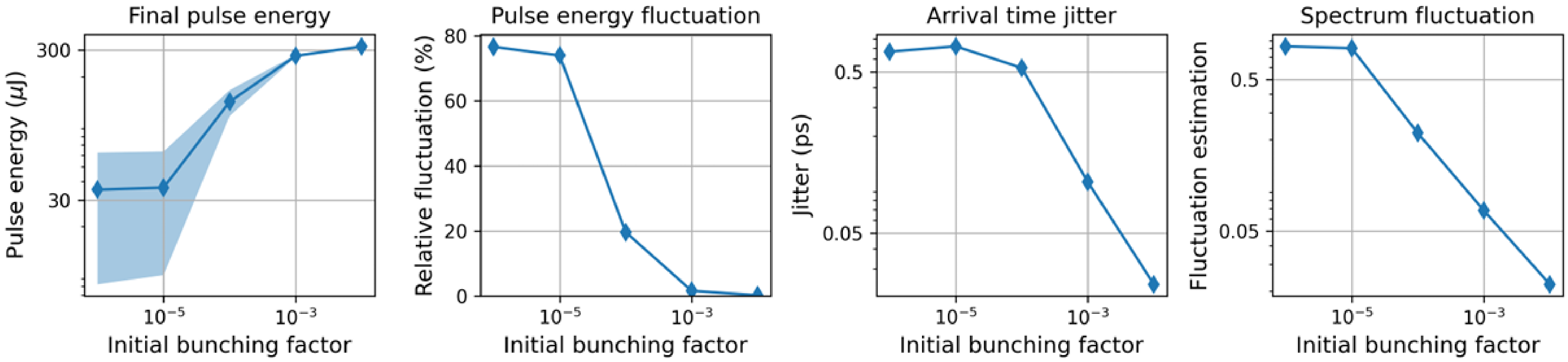


Figure 4: Summary of simulation results with pre-bunched electron beam. The bunching factor varies from 10^{-6} to 10^{-2}.