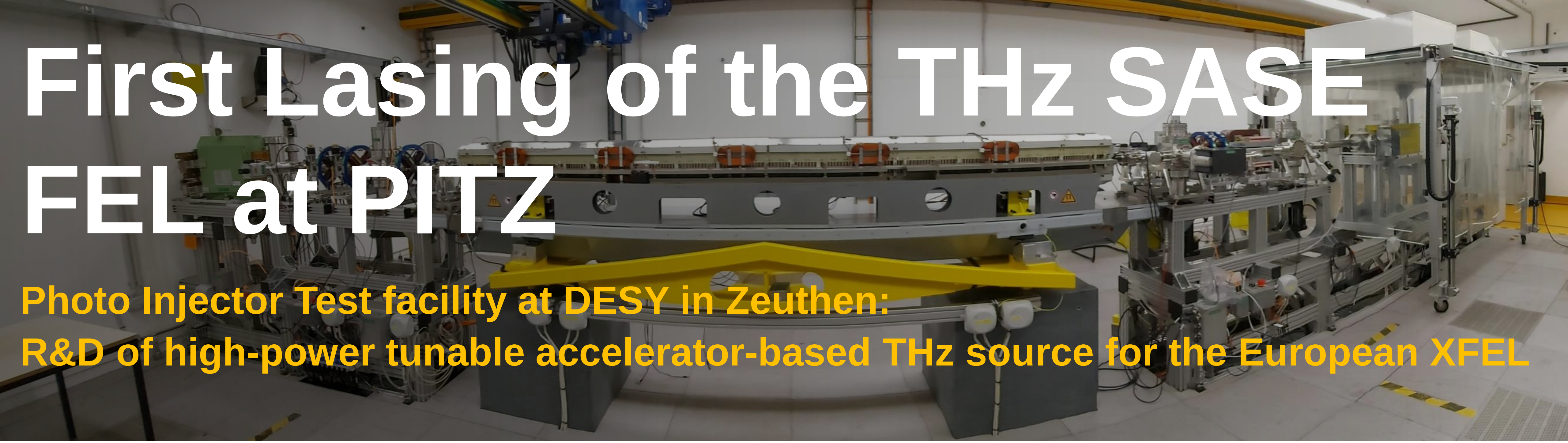


First Lasing of the THz SASE FEL at PITZ

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

Prach Boonpornprasert for the THz@PITZ Team
The 8th annual MT meeting, DESY Hamburg, 26-27.09.2022

Rehearsal in PPS 22.09.2022

HELMHOLTZ

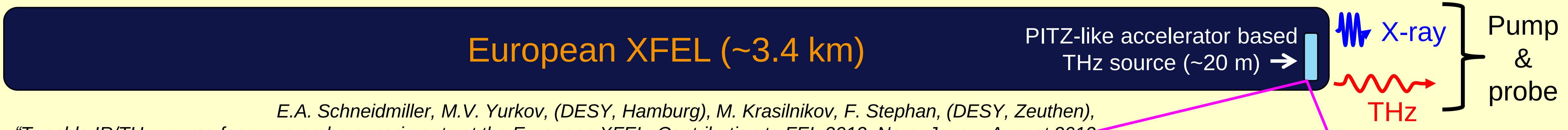
PITZ Photo Injector Test Facility Zeuthen

European XFEL

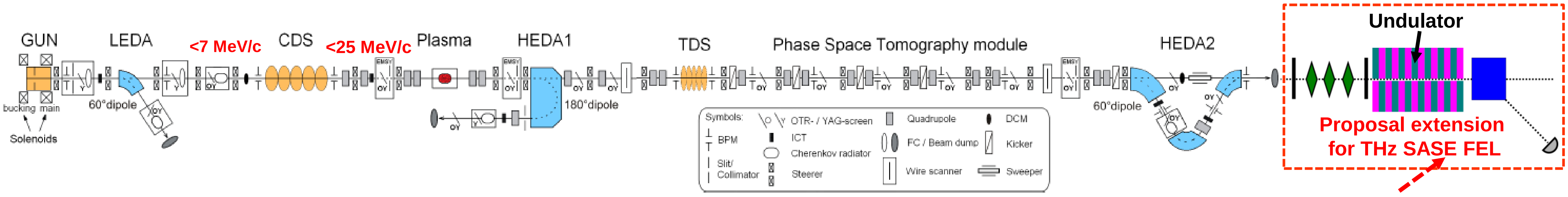
DESY.

THz SASE FEL source for pump-probe experiments at European XFEL

PITZ-like accelerator can enable high-power, tunable, synchronized THz radiation



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



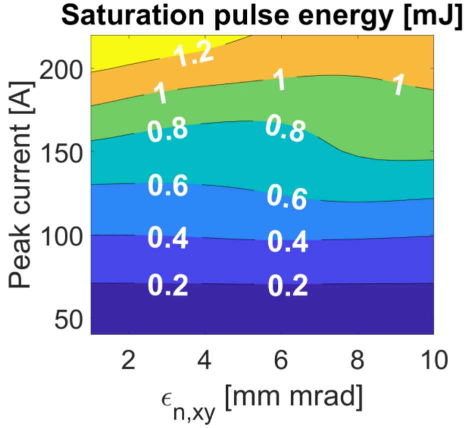
SASE FEL = Self Amplified Spontaneous Emission Free Electron Laser

Undulator for proof-of-principle experiment?

SASE FEL simulations assuming:

- Helical undulator with **λ_u=40 mm**
- Undulator length up to **5 m**
- **4 nC** electron beam with **15 MeV/c** and **~2 mm** rms bunch length

~mJ (sim) SASE FEL for $\lambda_{rad} \leq$ 100 µm (f ≥ 3 THz)



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

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

Some Properties of the LCLS-I undulator

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

λ_{rad}~100 µm → ~**17 MeV/c**

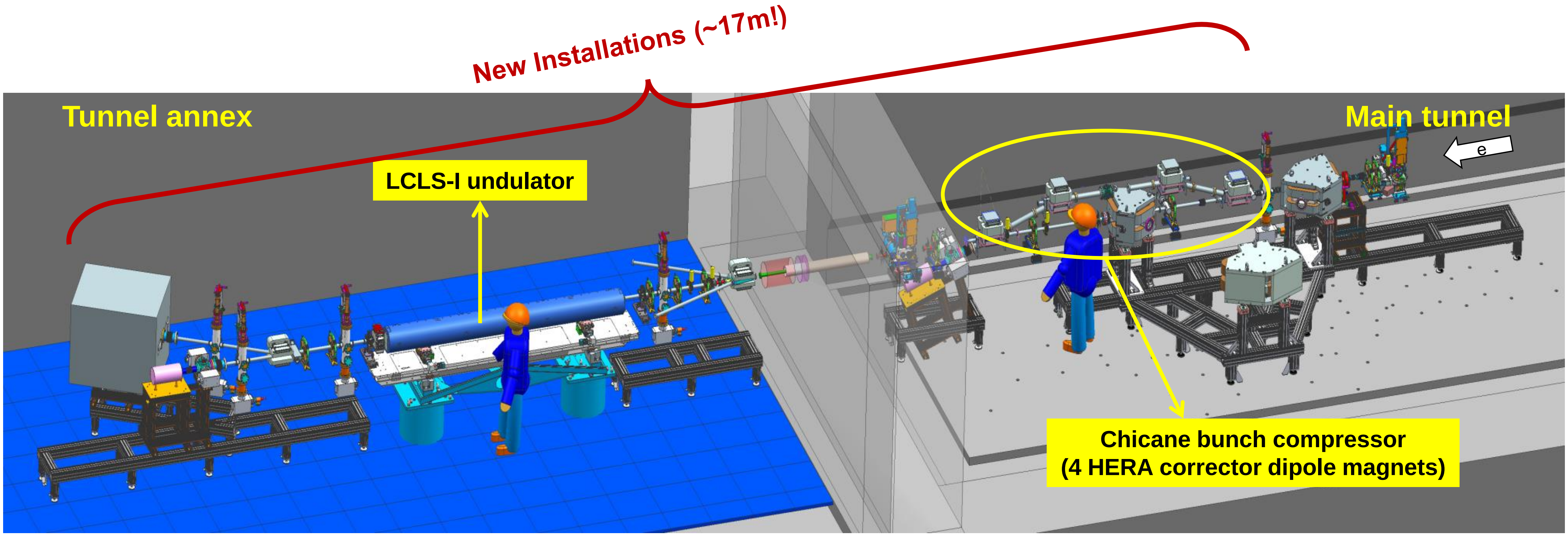
The project **"Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector"** was approved by **the European XFEL Management Board**

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

→ **Deliver the conceptual design report**

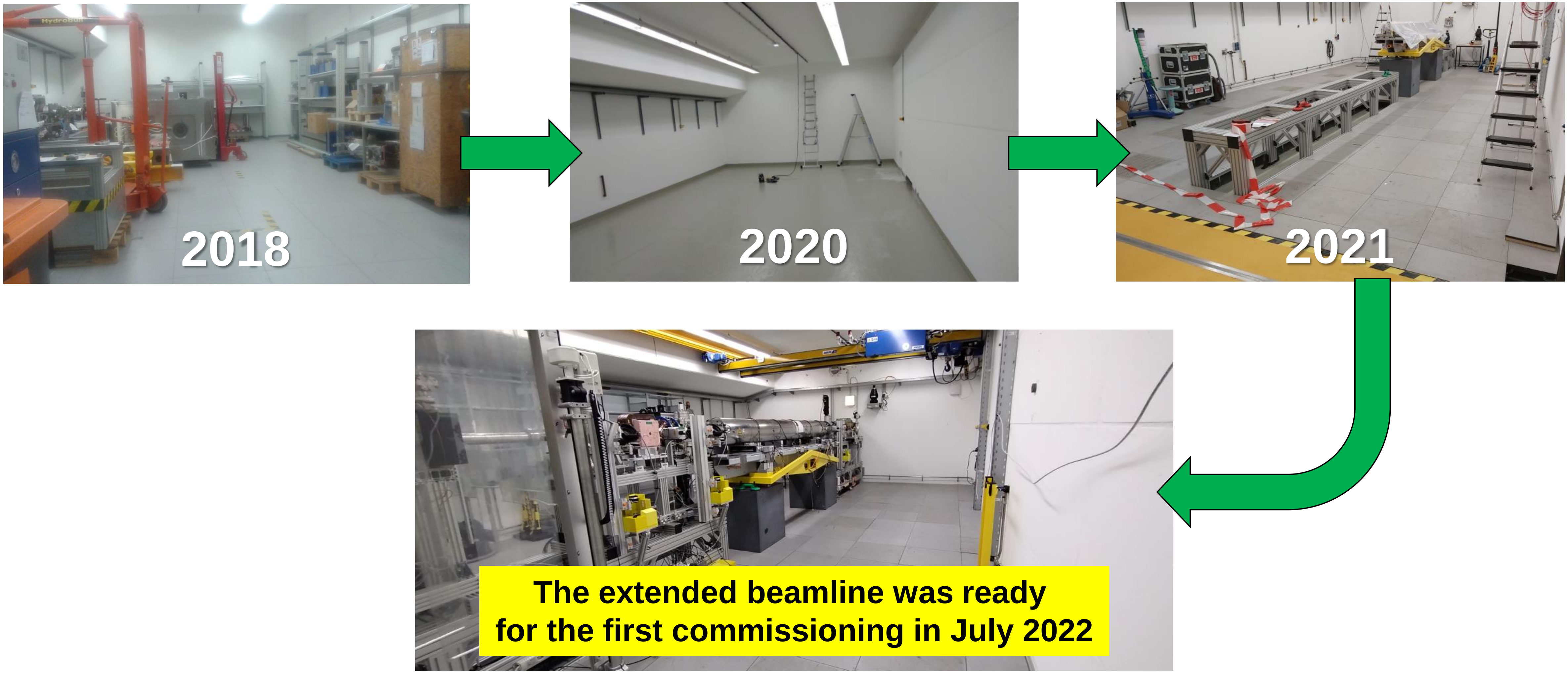
THz SASE FEL at PITZ: Beamline Extension

PITZ upgrade for the proof-of-principle experiment



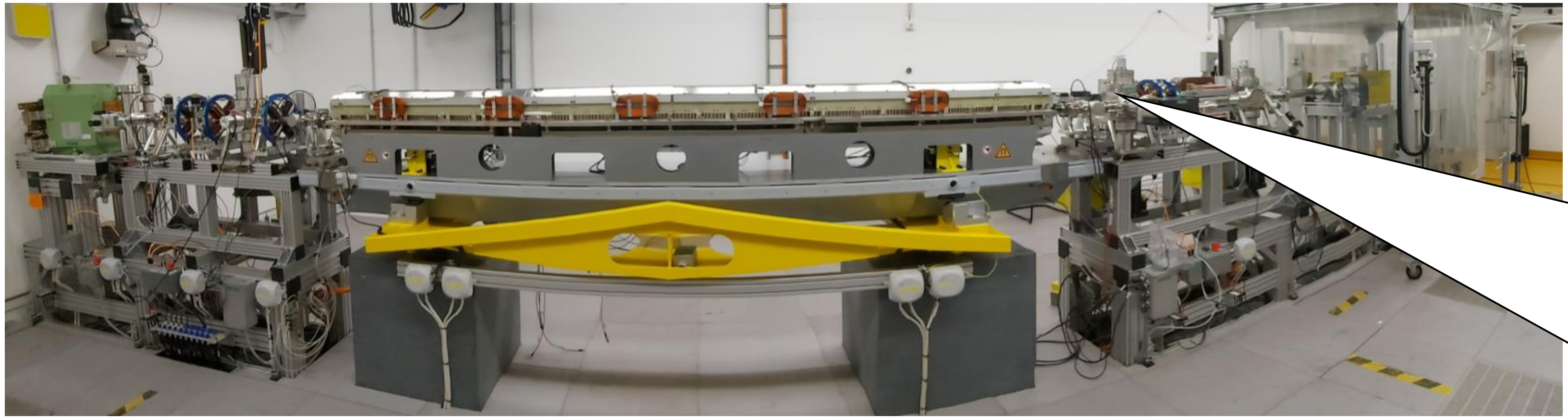
THz SASE FEL at PITZ: Construction and Installation

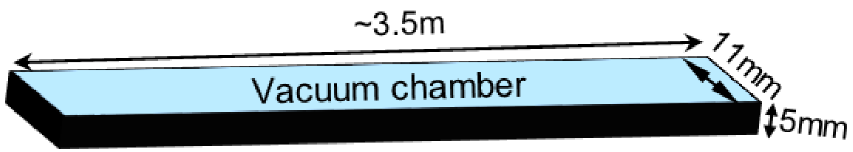
History of the tunnel annex

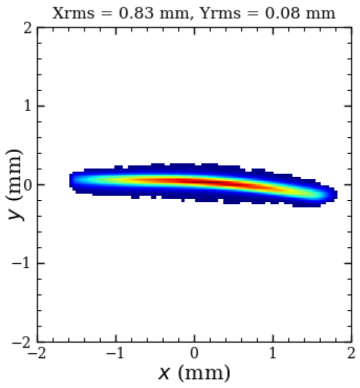


THz SASE FEL at PITZ: First Commissioning with E-Beam

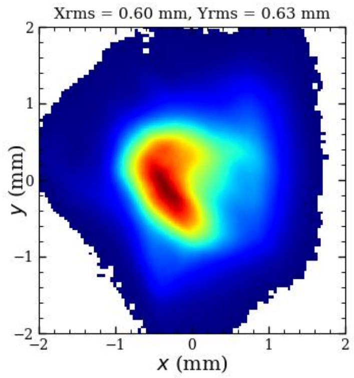
Transport and matching of e-beam with bunch charges of 100 pC ➔ 1 nC



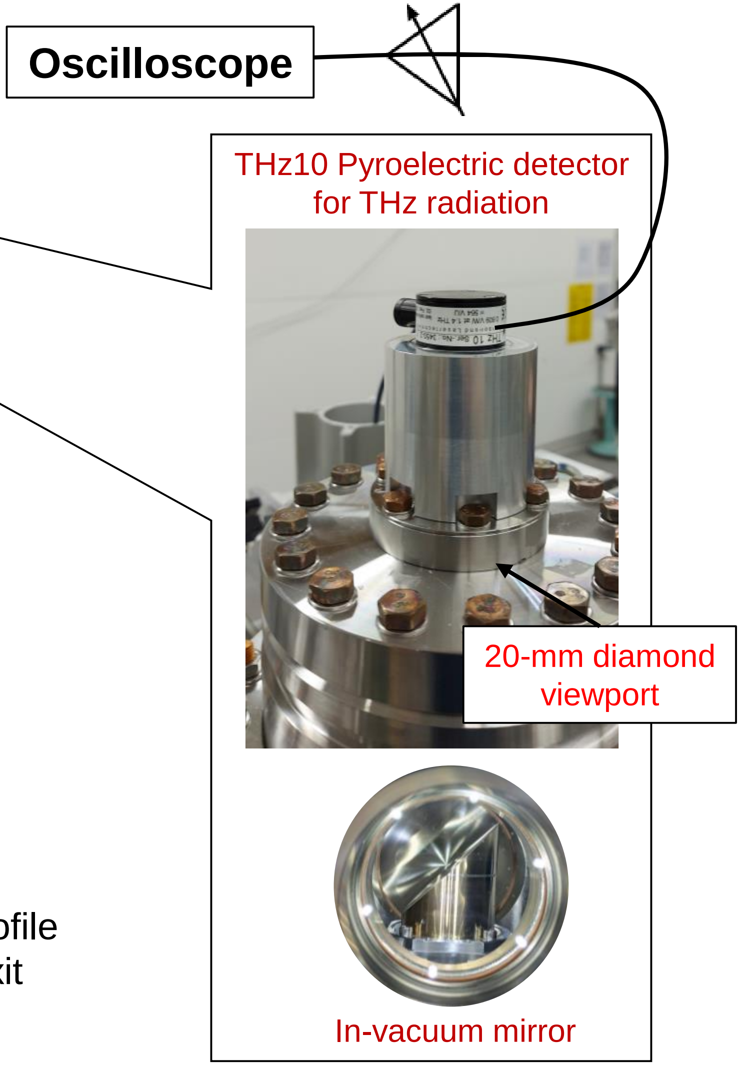




Measured transverse profile
Of **100 pC** beam at U.exit



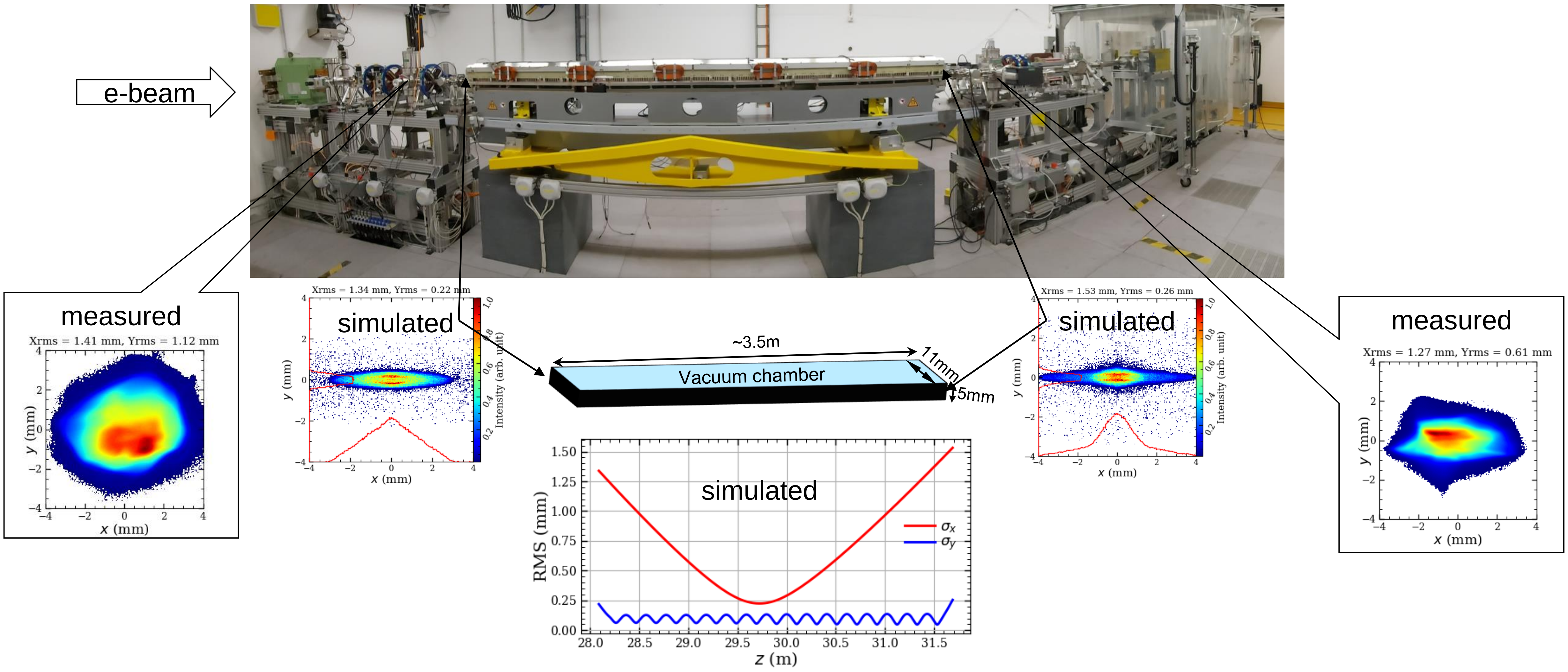
Measured transverse profile
Of **1 nC** beam at U.exit



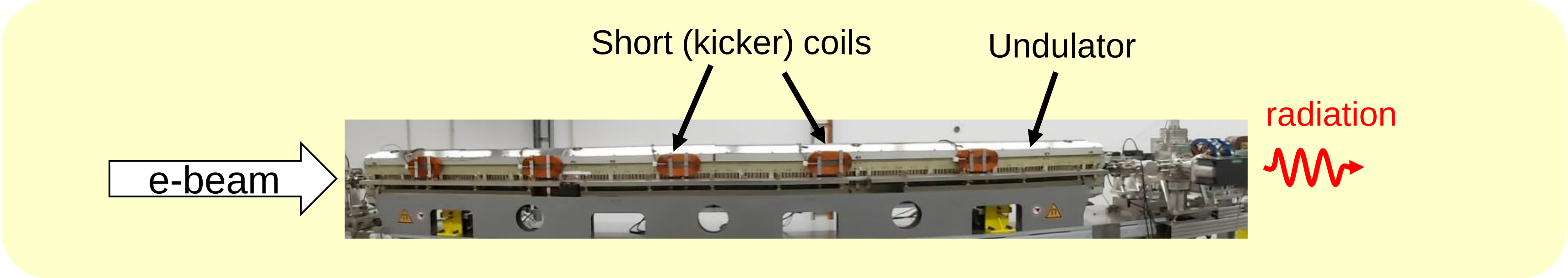
THz SASE FEL at PITZ: 1st Lasing from 1 nC Beam

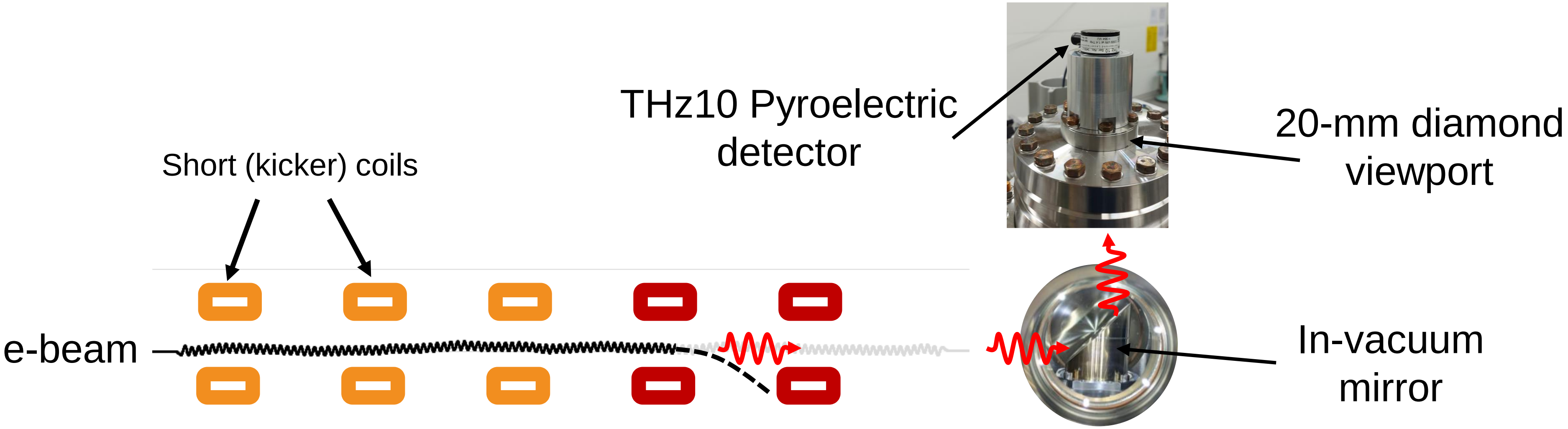
Pyrodetector signal from the oscilloscope (09.08.2022)

THz SASE FEL at PITZ: 2 nC Beam Transport and Matching



THz SASE FEL at PITZ: Gain Curve Measurement Setup

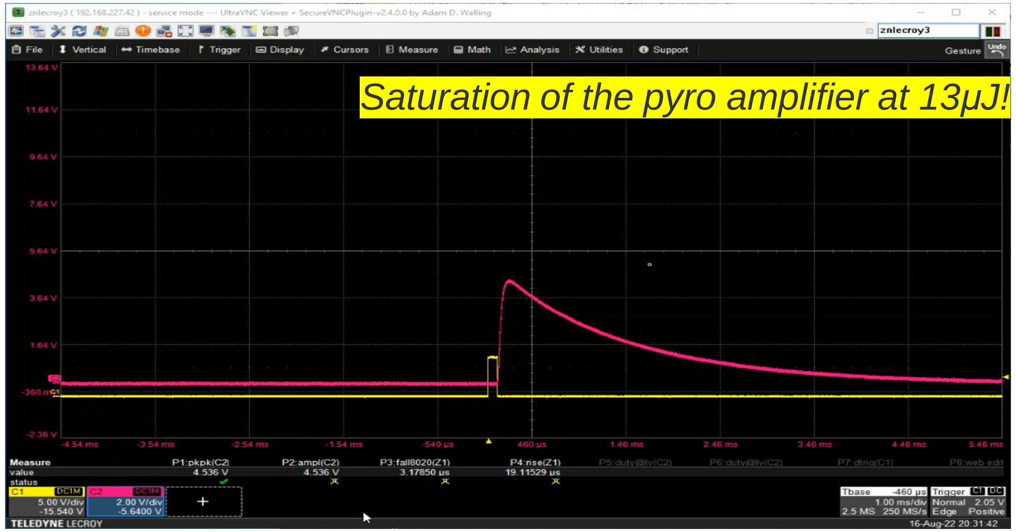




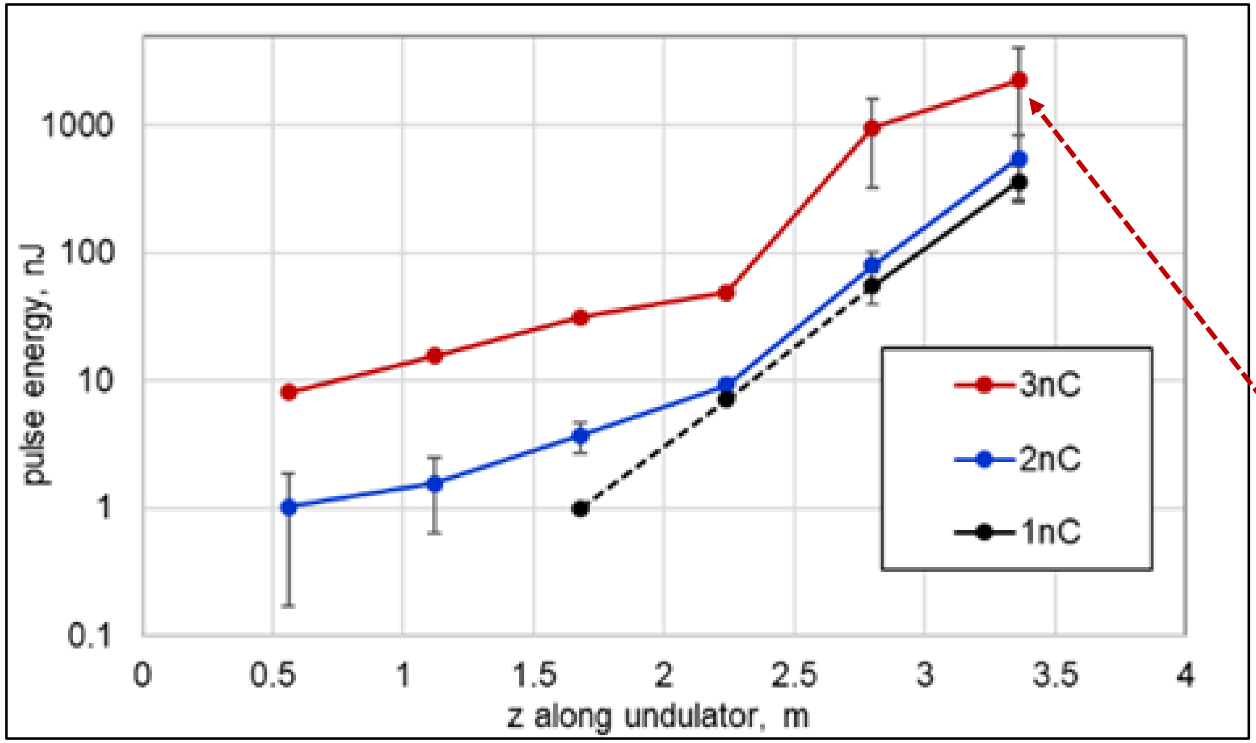
Simplified layout of the gain curve measurement setup

THz SASE FEL at PITZ: Gain Curves

First Characterization of FEL Gain Curves

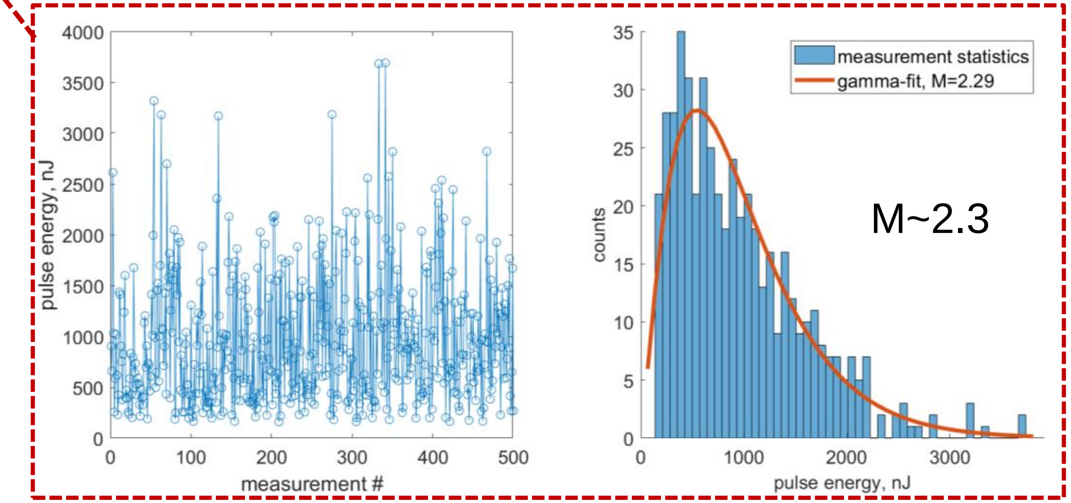


- **Lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**
- Gain curves at 1, 2 and 3nC



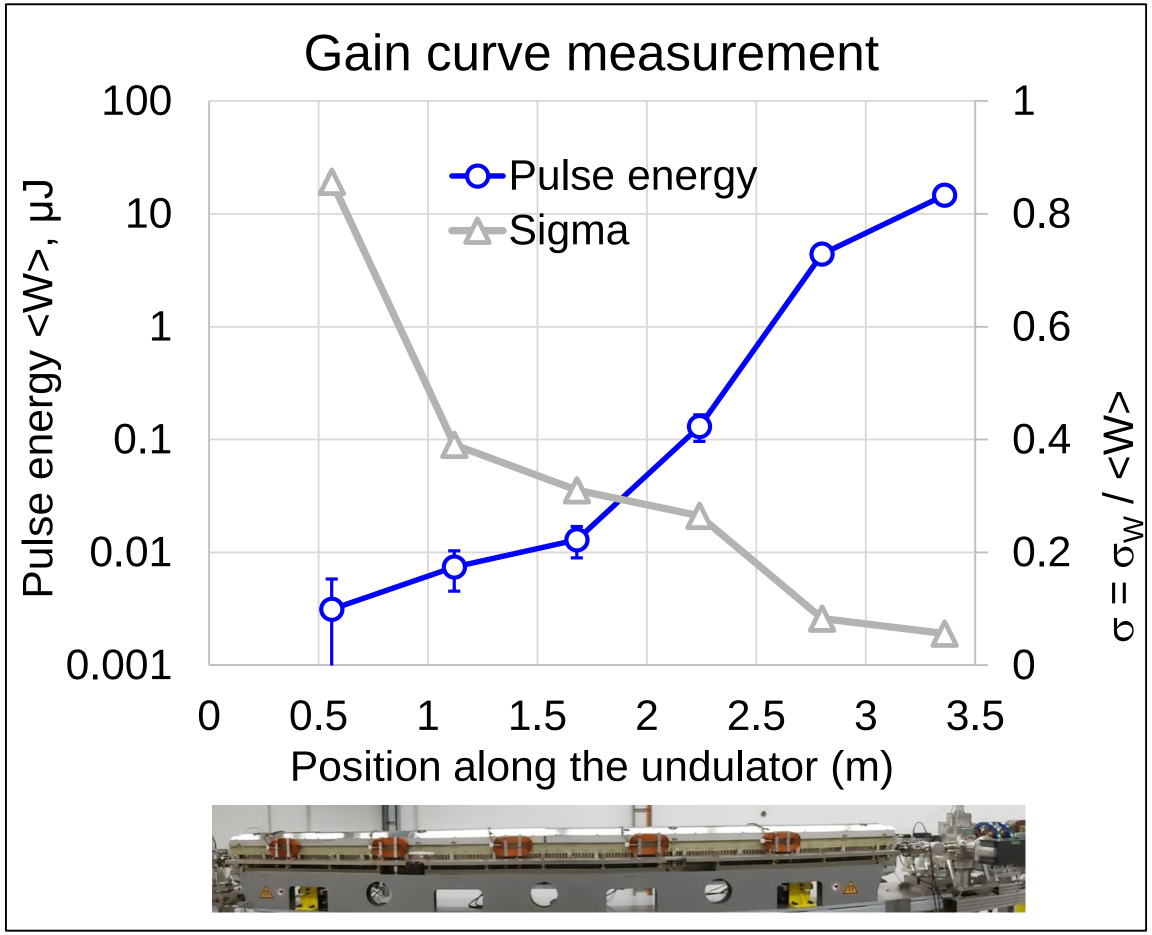
In linear model of SASE FEL, the probability distribution of the radiation energy can be described well by a gamma probability density function: $\rho(W) \propto \frac{M^M}{\Gamma(M)}\left(\frac{W}{\langle W\rangle}\right)^{M-1}\frac{1}{\langle W\rangle}\exp\left[-M\frac{W}{\langle W\rangle}\right]$

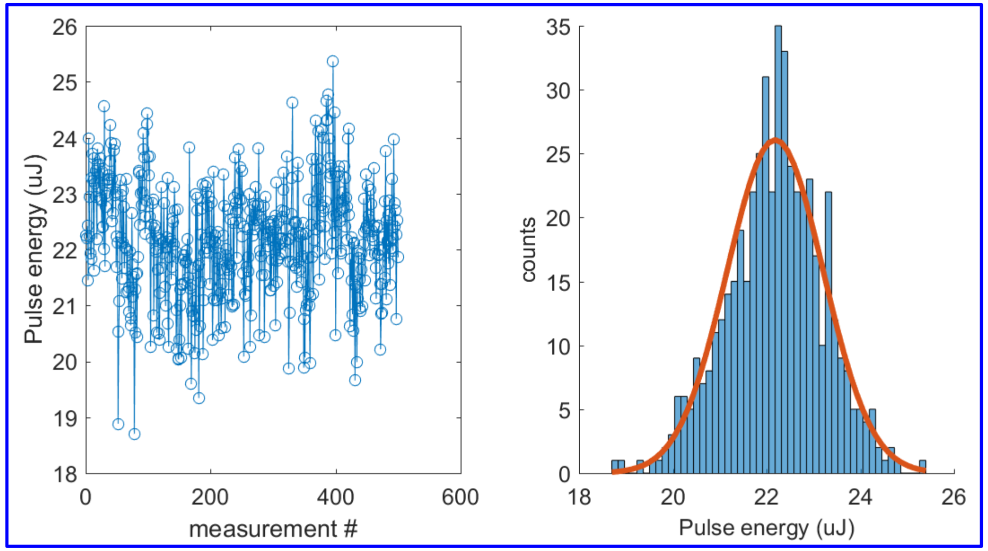
Reference: E.L. Saldin et al. NIM A 407 (1998)



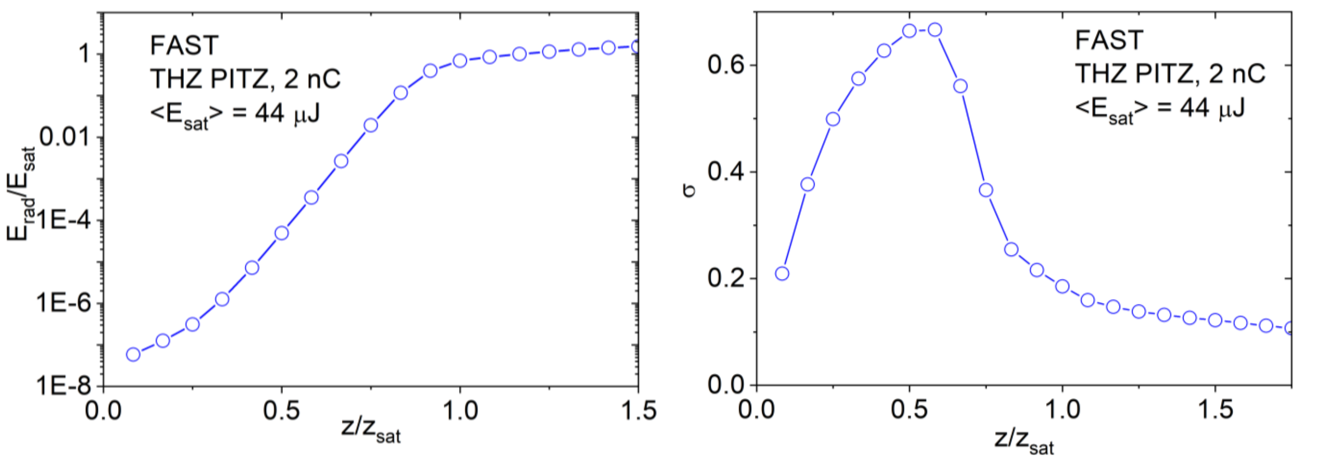
THz SASE FEL at PITZ: Further Tuning

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





FAST Simulations (M. Yurkov)

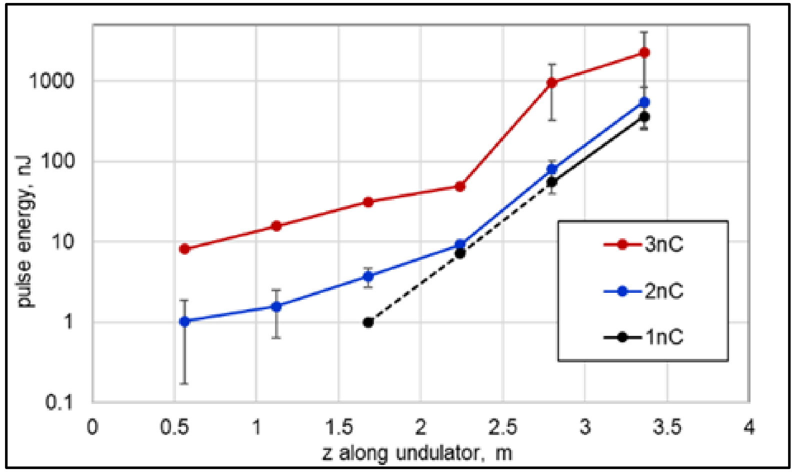


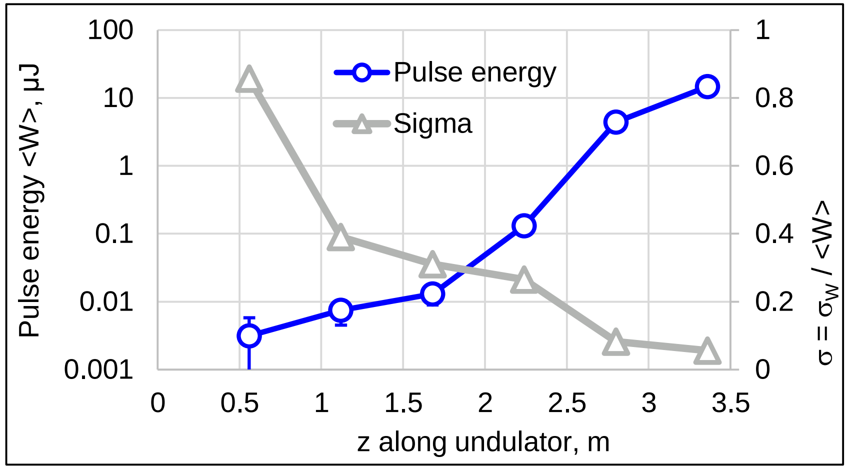
Conclusions

THz SASE FEL at PITZ

- Photo Injector Test facility at DESY in Zeuthen:
  - Develops high brightness electron beams sources and their applications
  - Prototype of accelerator based THz source for pump-probe experiments at the European XFEL

- Proof-of-principle experiment ongoing @PITZ (supported by E-XFEL):
  ➔ first electrons through the LCLS-I undulator → 22.07.2022
  ➔ 1st THz SASE FEL Lasing → beginning of August 2022
  ➔ High gain measured at ~ 3THz!
  ➔ Strong dependence on beam current and transport /matching,
  ➔ FEL saturation at >20µJ with 2nC (not fully optimized)
  High-gain THz SASE FEL at a PITZ-like accelerator ➔ **it works!!!**





- **Next steps:**
  - Detailed tuning of high-charge beam transport/matching
  - Setup full THz diagnostics (spectral characterization + BPF)
  - Other dedicated studies (bunch compressor, seeded THz FEL)

THz@PITZ Team and Collaboration

Many thanks and let's keep moving forward!

UHH
W. Hillert
J. Rossbach

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
- J.
- B. Krause
- M. Tischer
- P. Vagin

SLAC

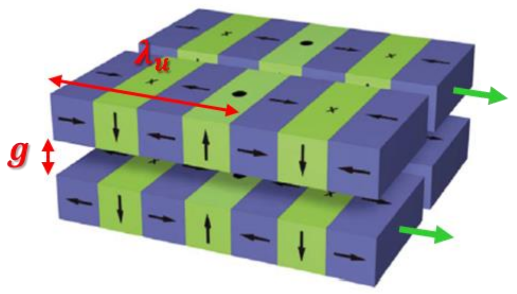
- A. Brachmann
- N. Holtkamp
- H.-D. Nuhn

Backup slides

THz SASE FEL at PITZ

Undulator and beam parameter space

APPLE- II Undulator*



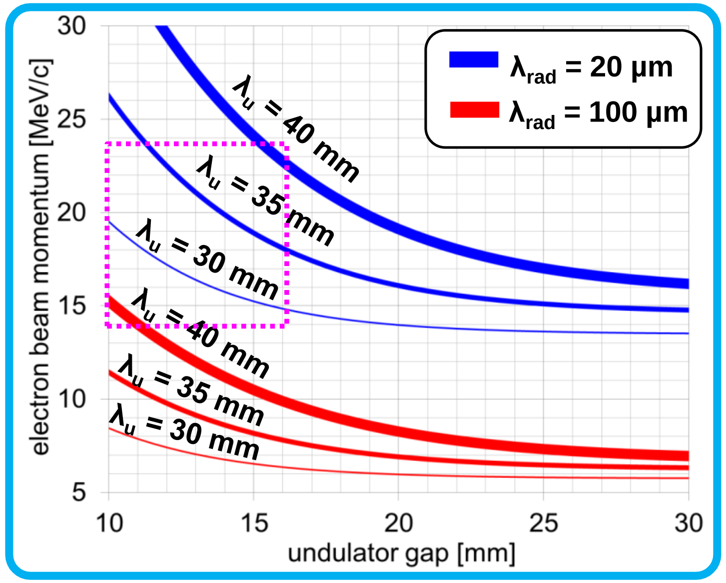
Radiation wavelength

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

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

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

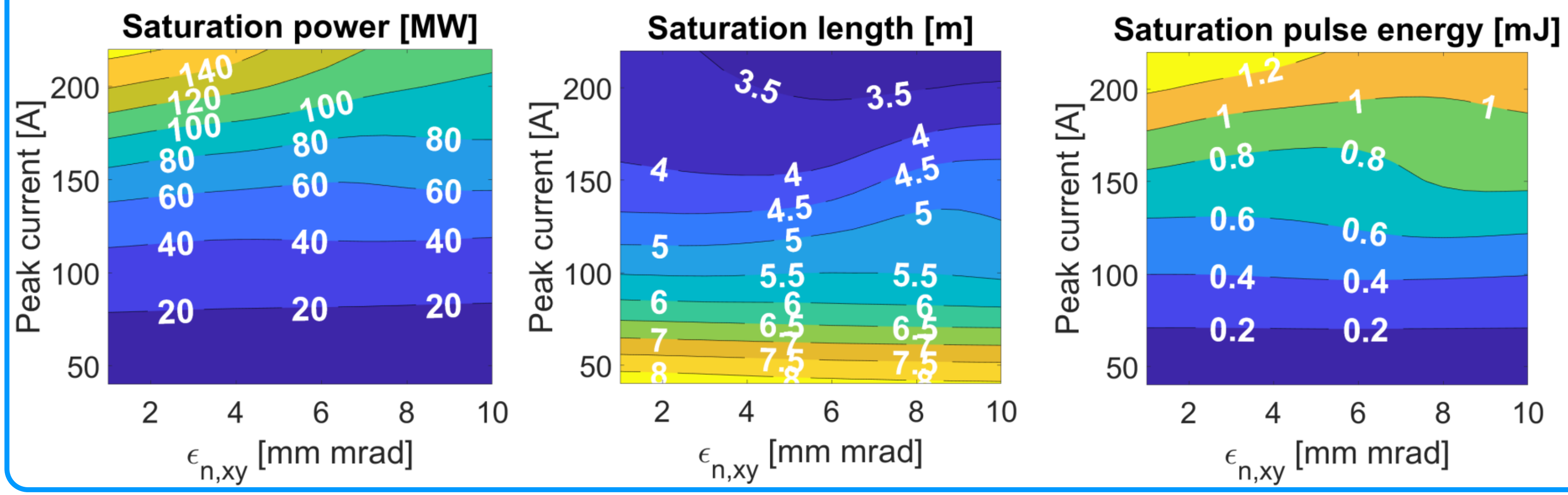
Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007



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:

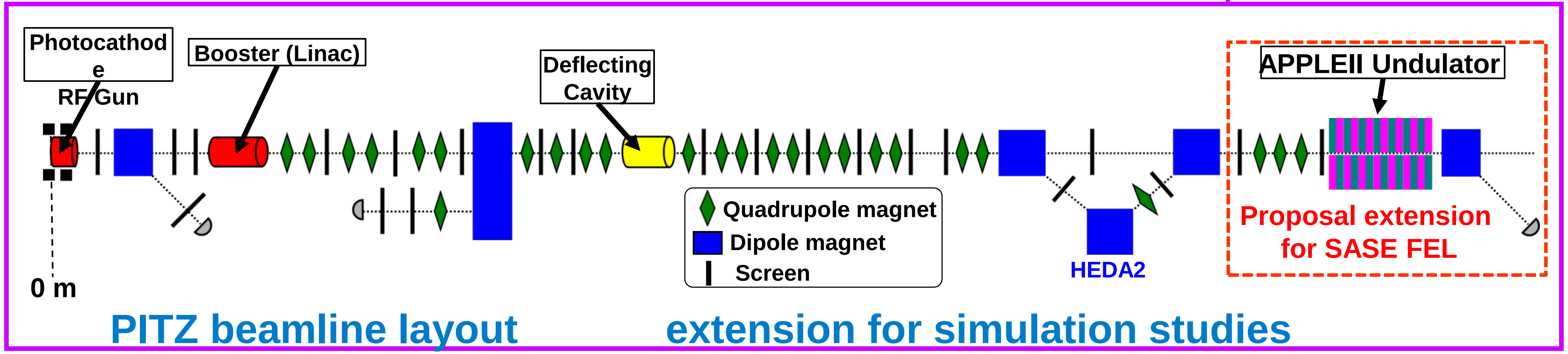
- Helical undulator with **λ_u=40 mm**
- **4 nC e**lectron beam with **15 MeV/c** and **~2 mm** rms bunch length

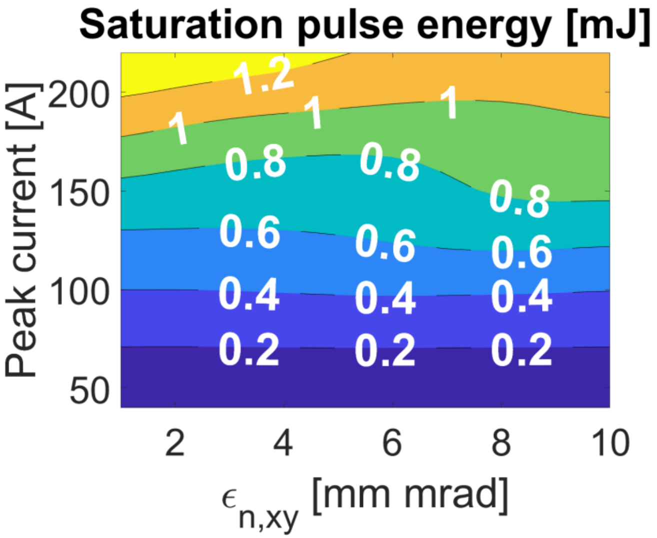
Preliminary conclusions:

- 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





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)

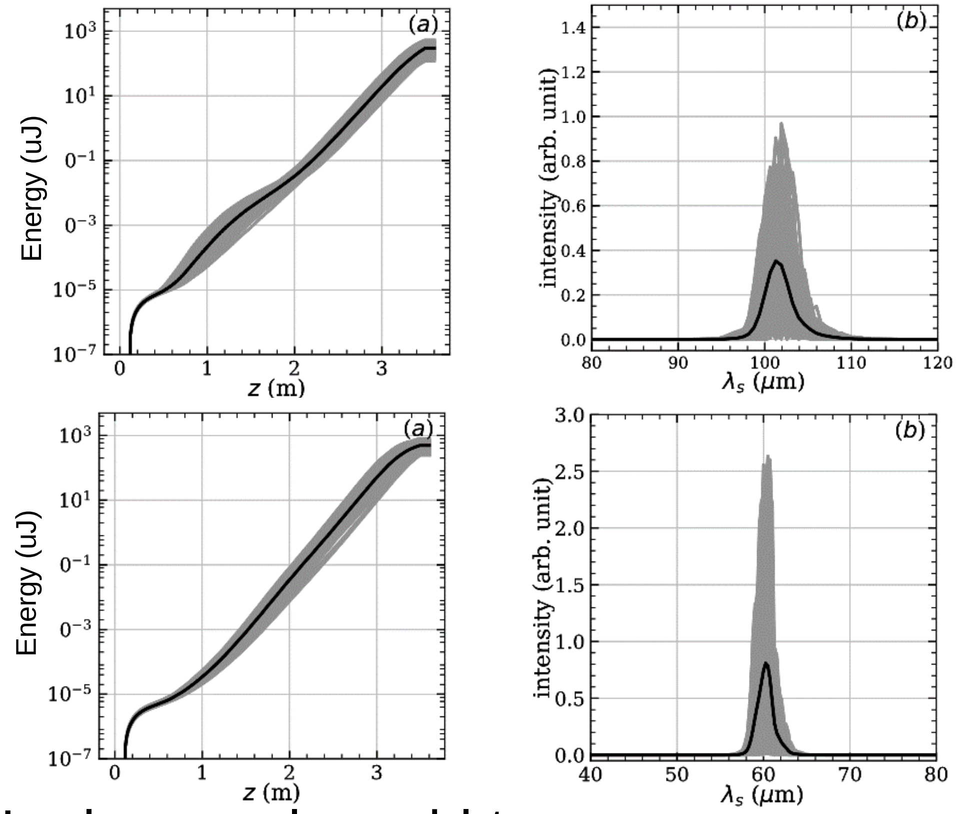
Start-to-end simulation

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

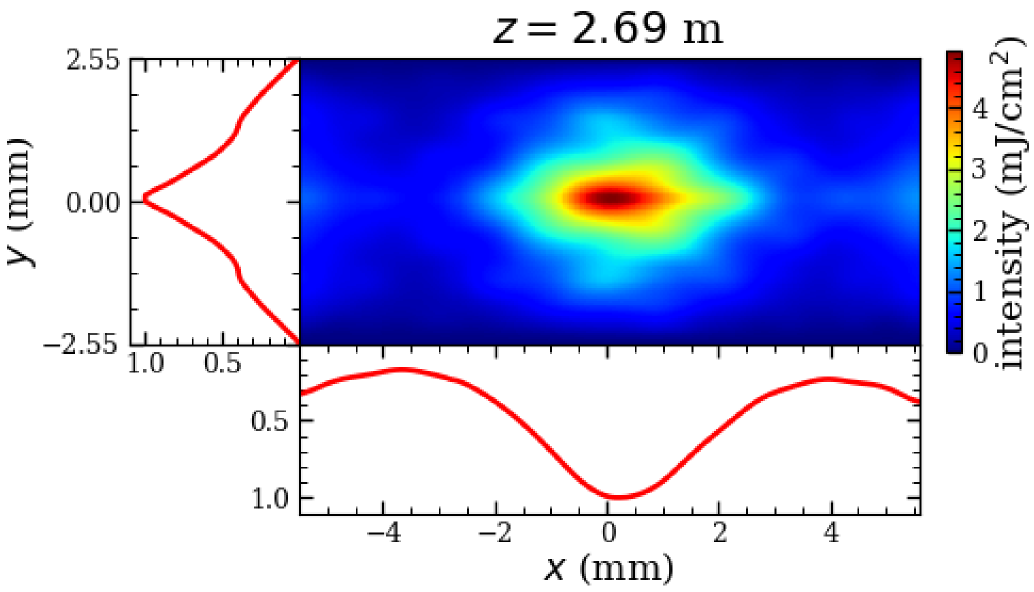
Summary of Genesis 1.3 simulation

Courtesy: X.-K. Li

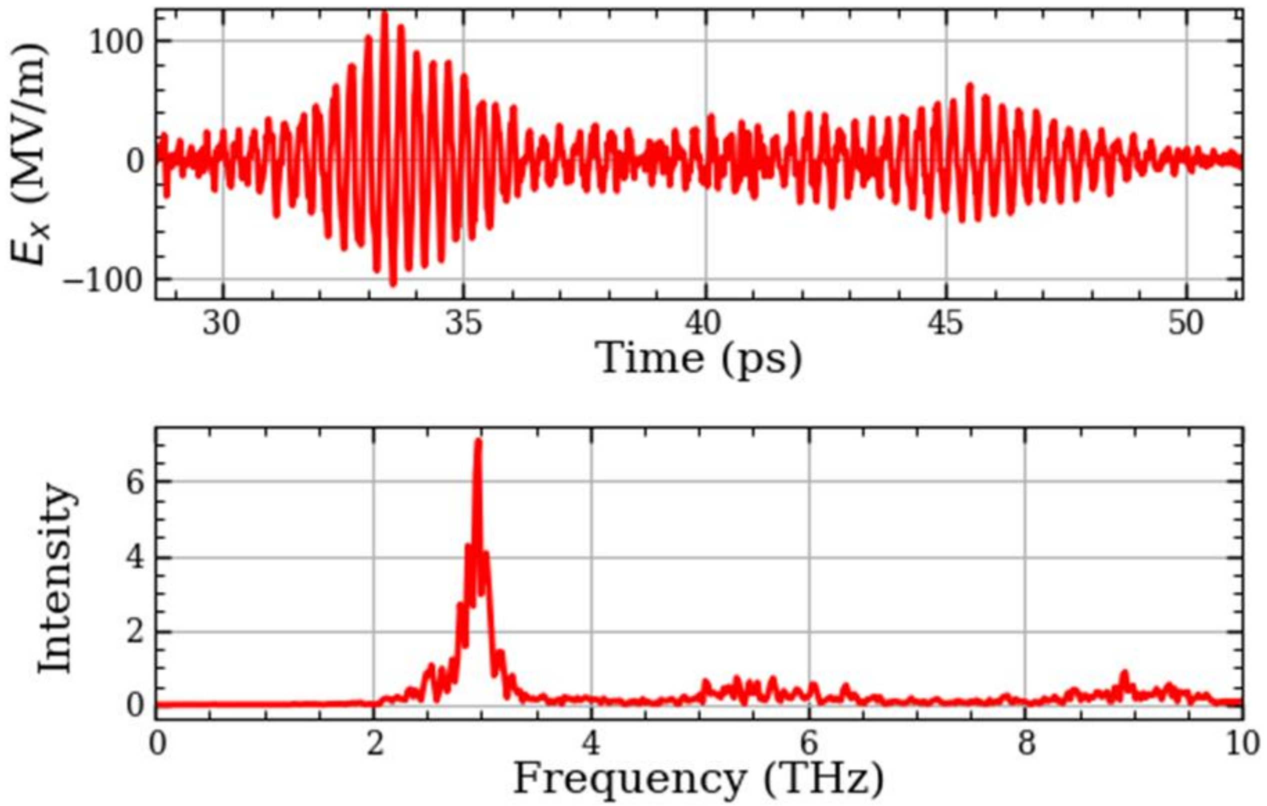
Start-to-end simulation

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

- Warp: Waveguide effect simulation (100um)



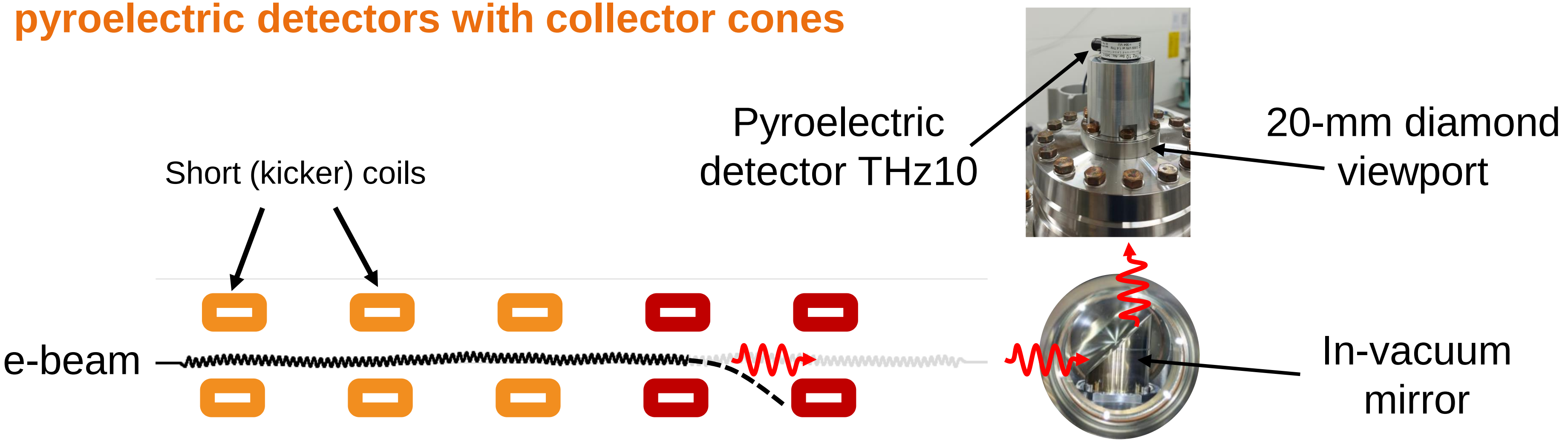
Particle-in-cell code;
Treat vacuum chamber (11x5 mm) as conducting boundaries



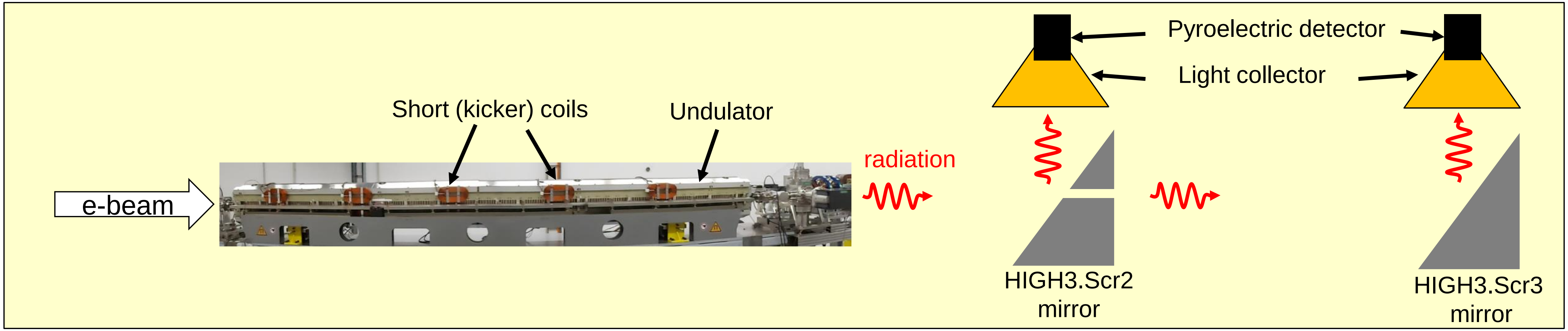
Courtesy: X.-K. Li

THz SASE FEL at PITZ: THz diagnostics setup

Startup: pyroelectric detectors with collector cones

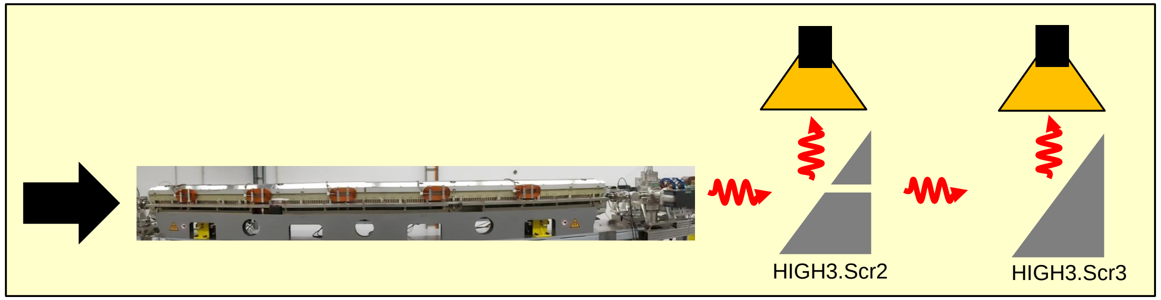


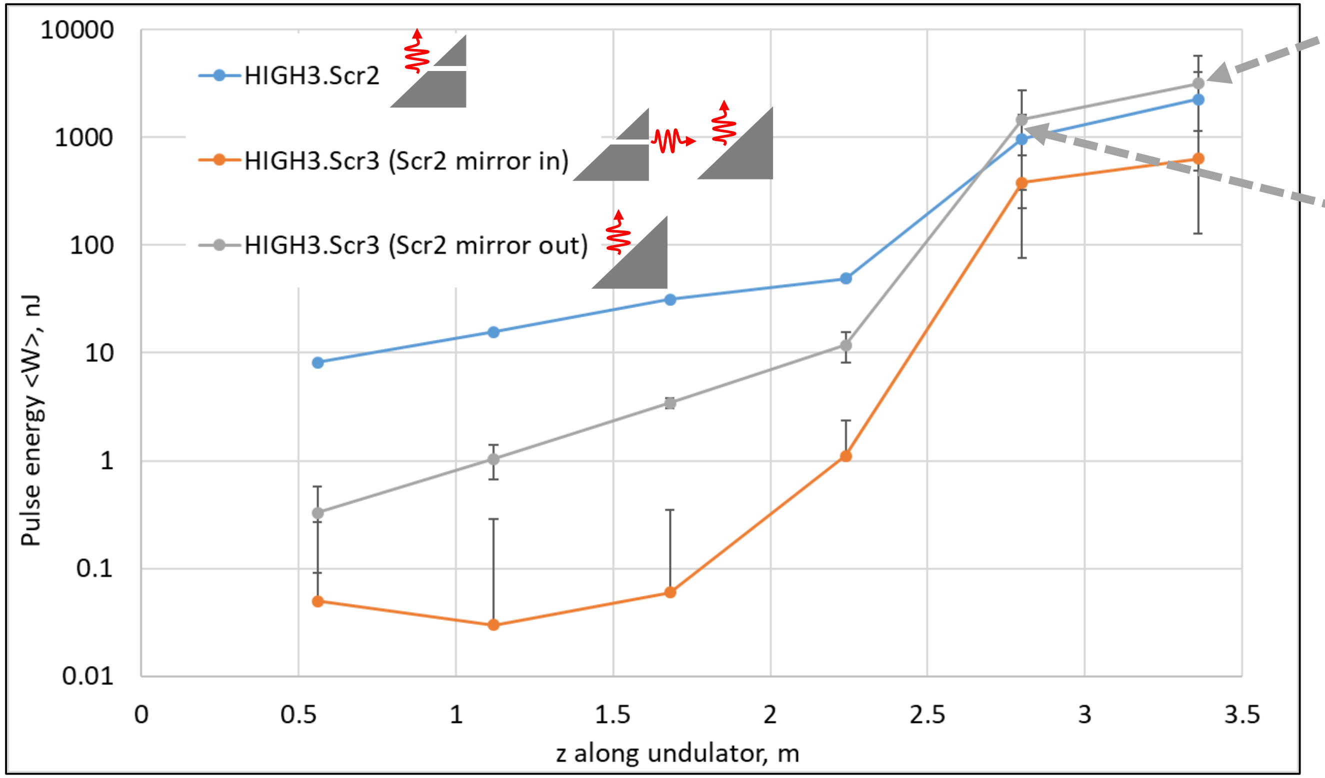
Simplified layout of the gain curve measurement setup

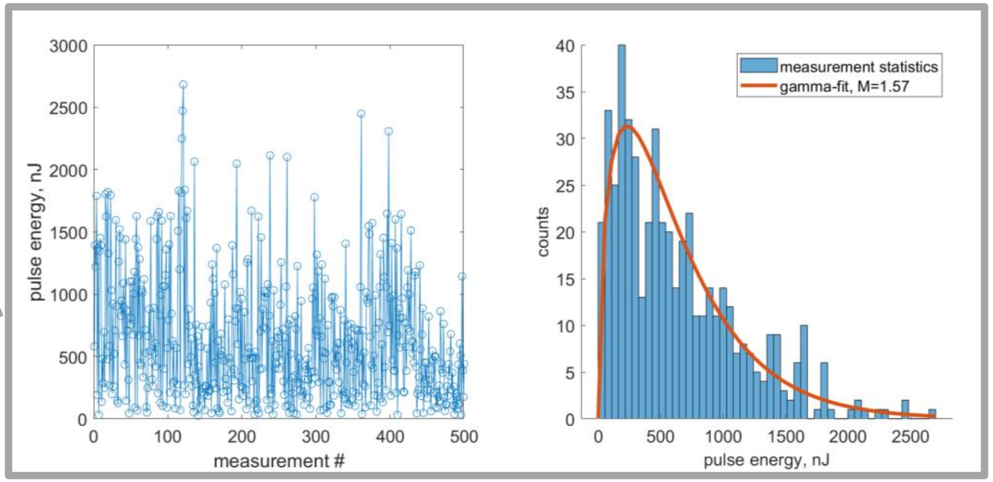


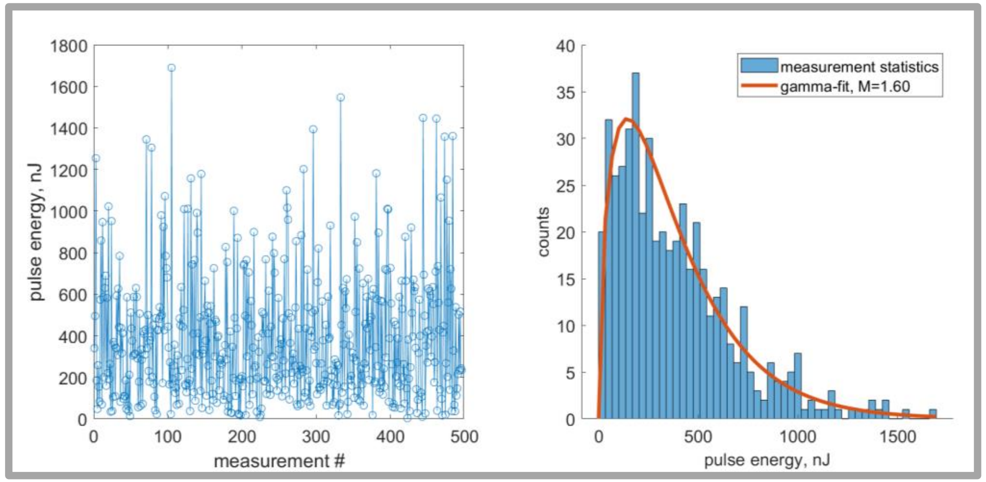
THz SASE FEL at PITZ: Gain Curves (3nC)

Measured pulse energy vs position along undulator for **different locations**



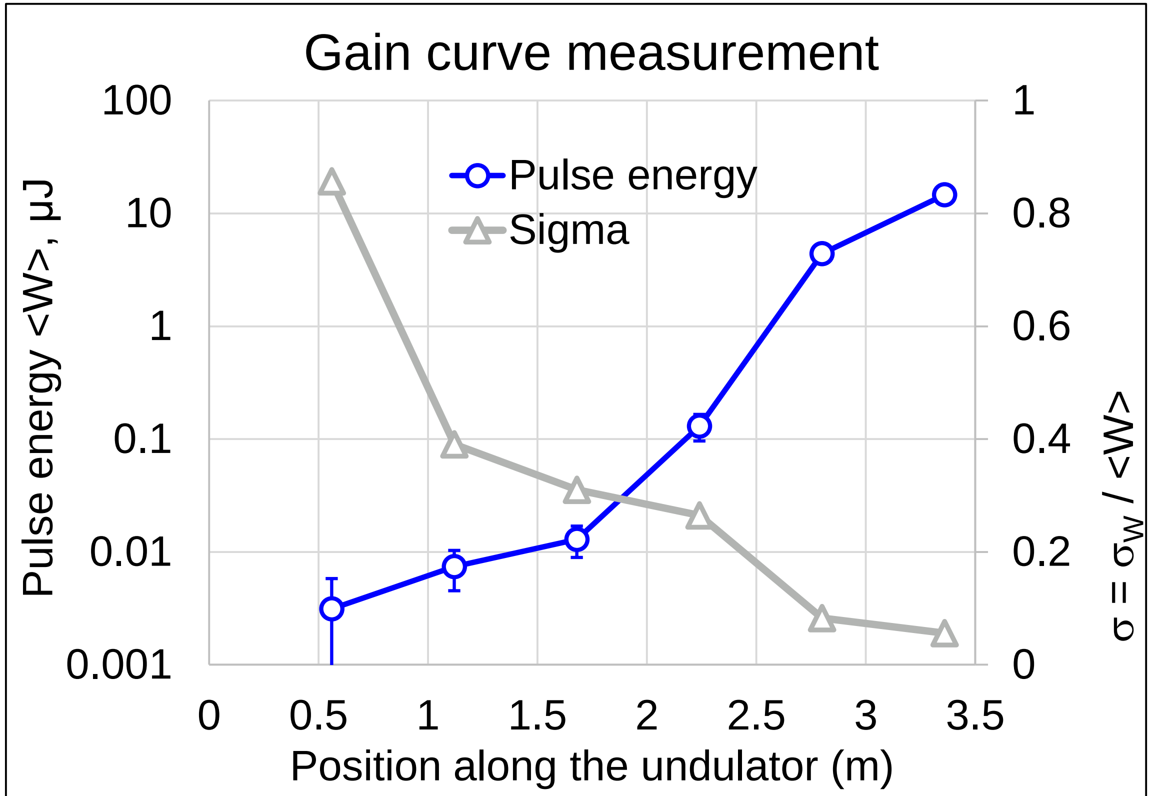


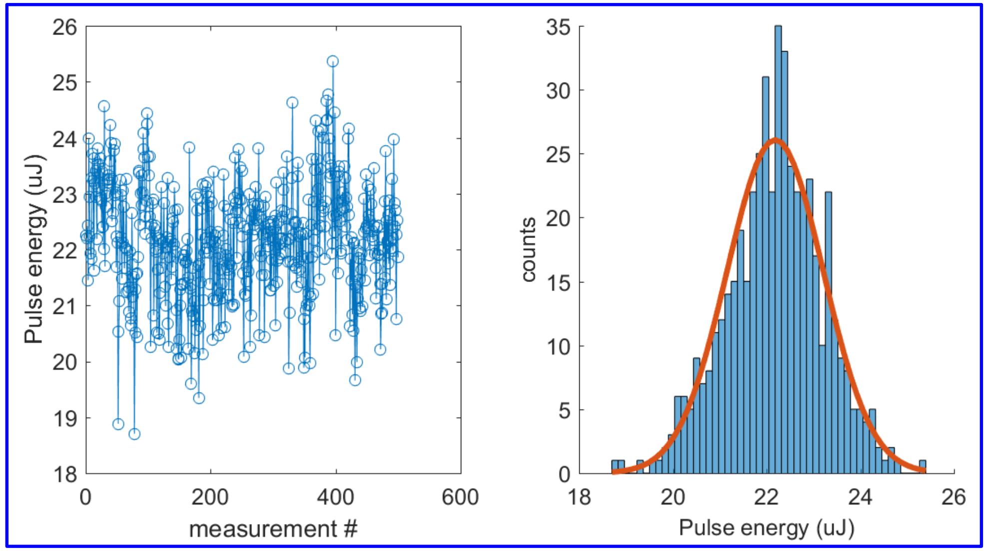




THz SASE FEL at PITZ: Further Tuning

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

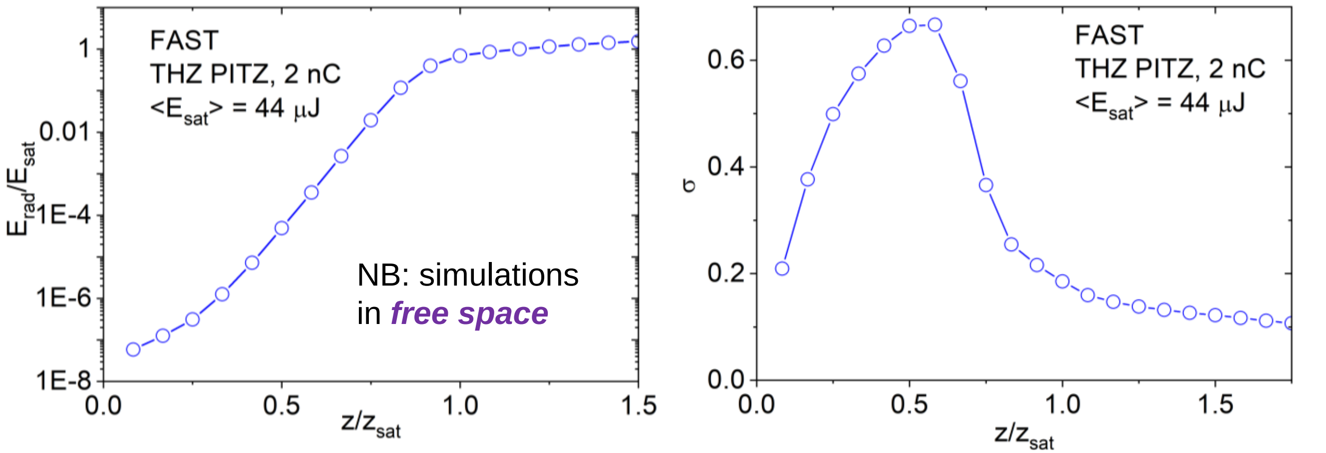




Photocathode laser spot (BSA=3.5mm)
from 3nC setup was applied for 2nC, not fully optimized

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

FAST Simulations (M. Yurkov)



THz SASE FEL source for pump-probe experiments at European XFEL

PITZ-like accelerator can enable high-power, tunable, synchronized THz radiation

European XFEL (~3.4 km)

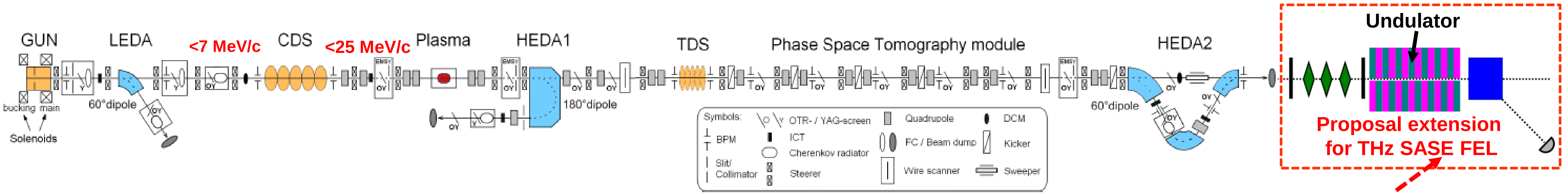
PITZ-like accelerator based THz source (~20 m) →

X-ray

THz

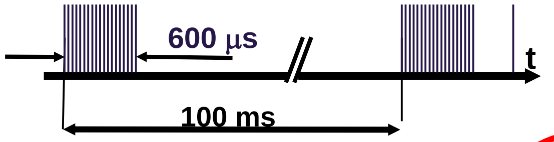
Pump & probe

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



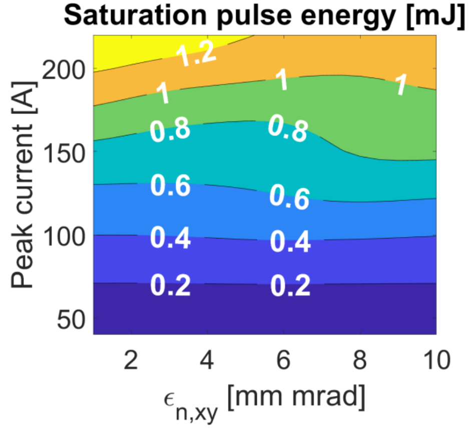
SASE FEL = Self Amplified Spontaneous Emission Free Electron Laser

PITZ Highlights:



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

Undulator for proof-of-principle experiment?



SASE FEL simulations assuming:

- Helical undulator with **λ_u=40 mm**
- Undulator length up to **5 m**
- **4 nC** electron beam with **15 MeV/c** and **~2 mm** rms bunch length

~mJ (sim) SASE FEL for λ_{rad} ≤ 100 μm (f ≥ 3 THz)

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

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

PITZ+ LCLS-I Undulator

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**

→ dedicated R&D activities at PITZ

→ **Proof-of-principle experiments (2019-2023)**

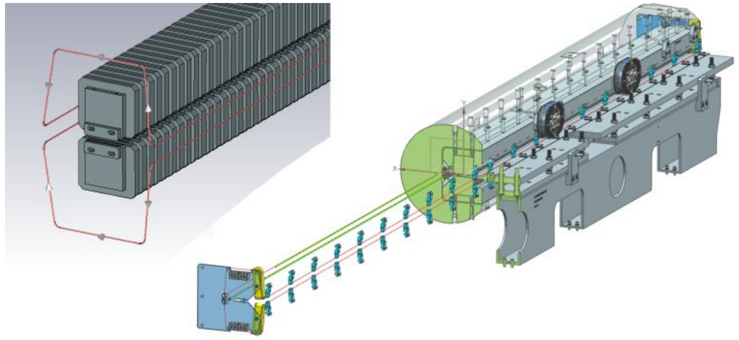
Some Properties of the LCLS-I undulator

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

λ_{rad}~100 µm → ~**17 MeV/c**

Main challenges:

- Space charge effect
- Waveguide effect
- Wakefields: geometric and conductive wall effects
- Strong undulator (vertical) focusing + horizontal gradient



Reference particle trajectories in the undulator with horizontal gradient