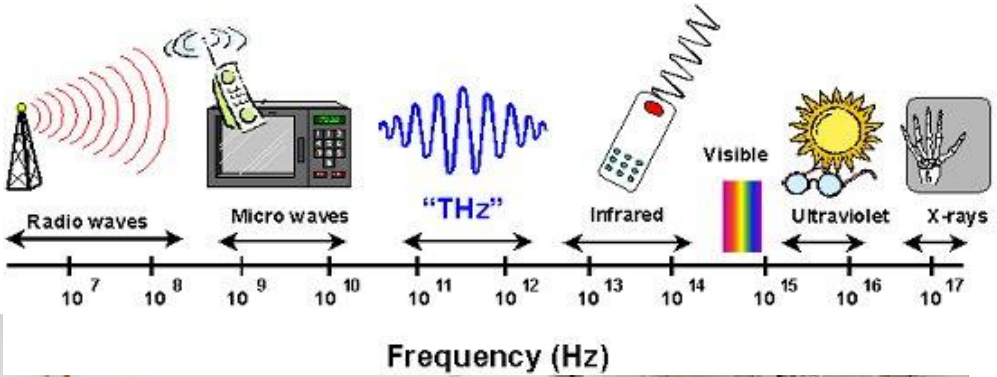
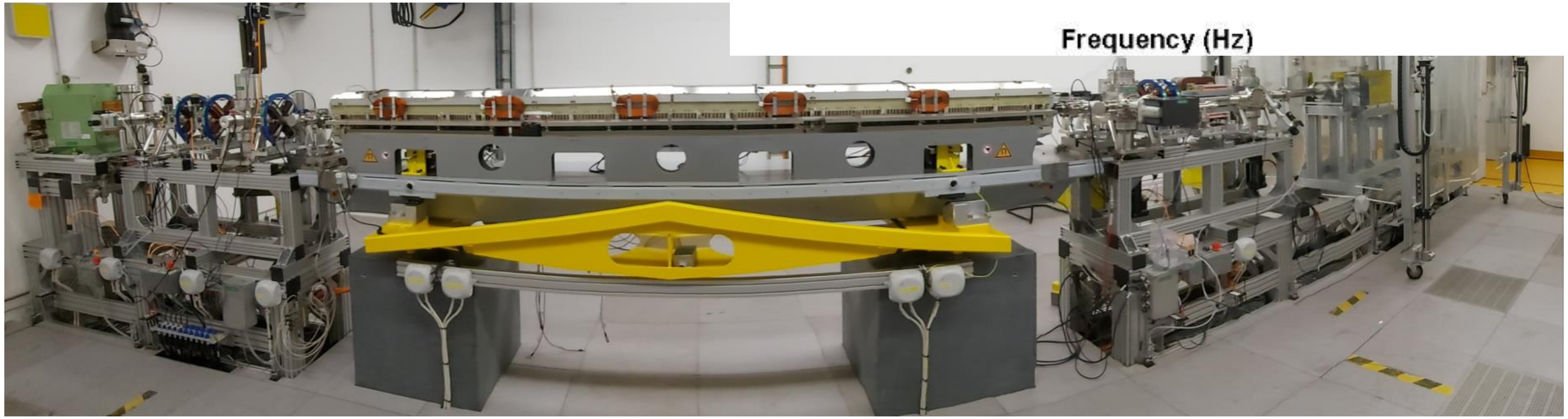
THz SASE FEL at PITZ: Results from first lasing runs

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

➔Proof-of-Principle experiment

Mikhail Krasilnikov for the THz@PITZ Team
DESY-TEMF meeting, Darmstadt, 20.10.2022





HELMHOLTZ

DESY.

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)

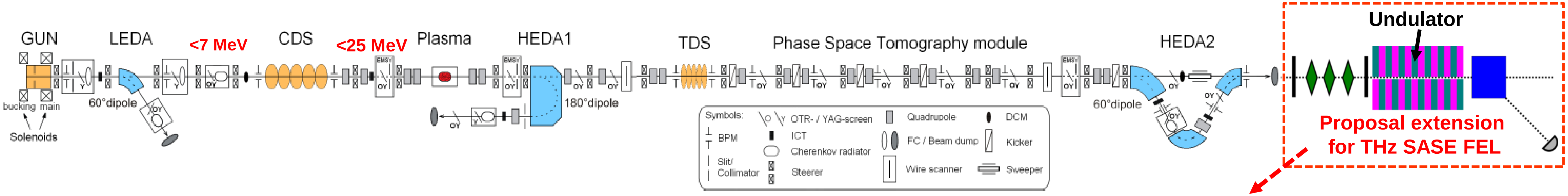
PITZ-like accelerator based THz source (~20 m)

X-ray

THz

Pump & probe

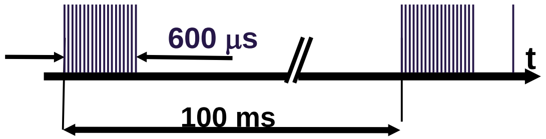
E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012



THz SASE FEL =
Self Amplified Spontaneous Emission Free Electron Laser

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

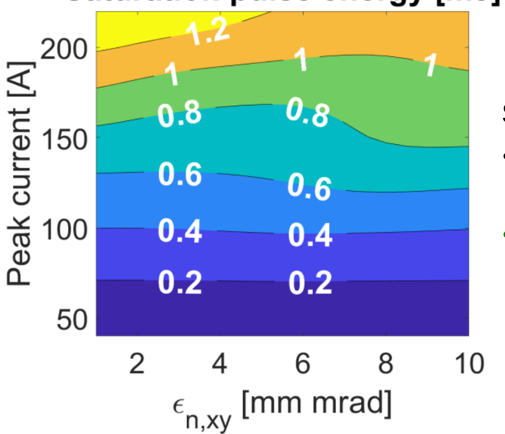
PITZ Highlights:



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

Undulator for proof-of-principle experiment?

Saturation pulse energy [mJ]



SASE FEL simulations assuming:

- Helical undulator with λ_u=40 mm, gap g ≥ 10 mm, L~5m
- **4 nC e**lectron beam with **15 MeV/c** and **~2 mm** rms bunch length (flattop profile)

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

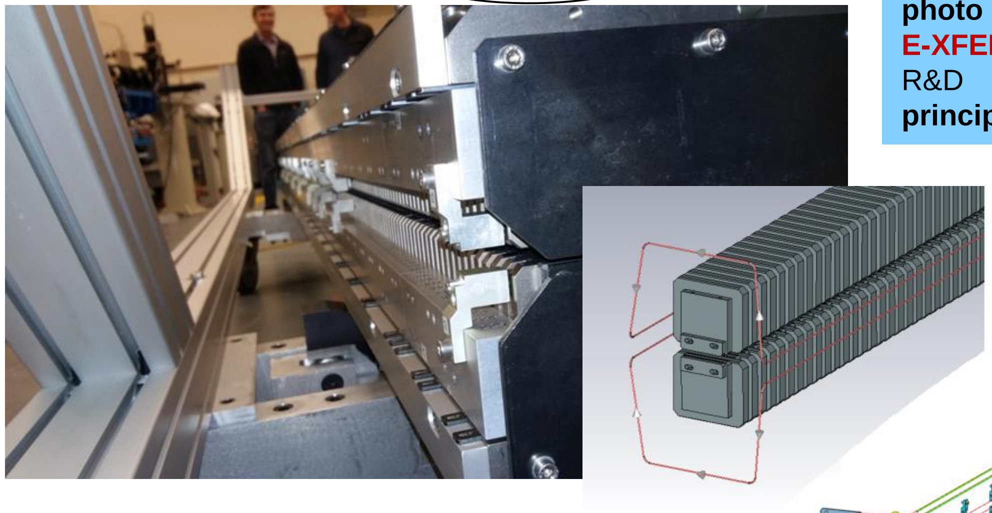
Using LCLS-I undulators (available on loan from SLAC)

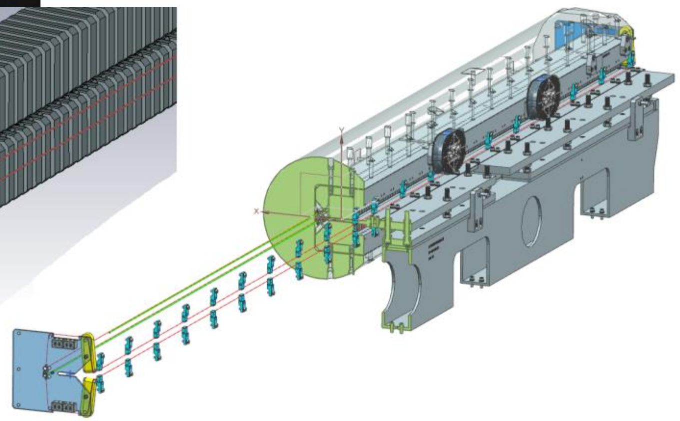
PITZ+ LCLS-I Undulator

Proposal **“Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector”** has been supported by the **E-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

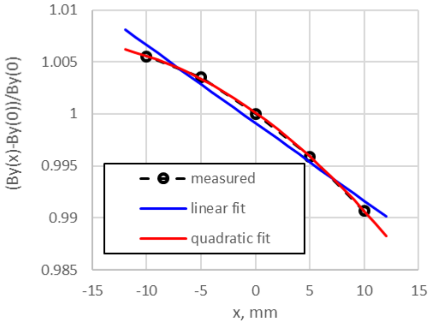




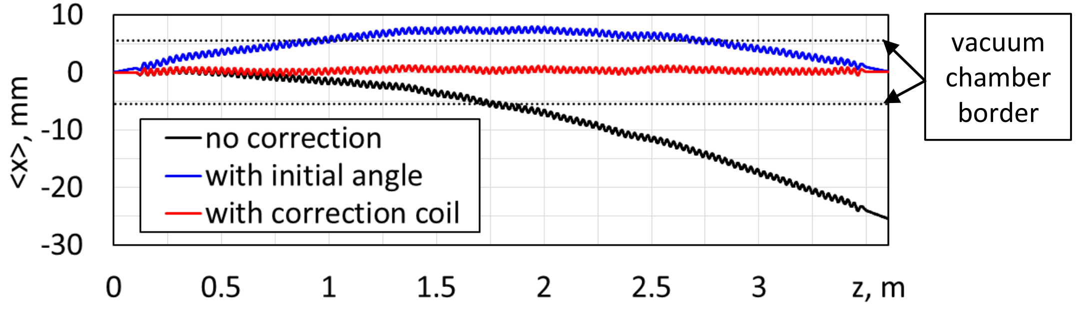
λ_{rad}~100μm → **~17MeV/c**

Main challenges:

- Space charge effects
- Strong undulator (vertical) focusing
  + horizontal gradient
- “Full physics” might have to be considered
- Waveguide effect
- Wakefields: geometric and resistive wall effects



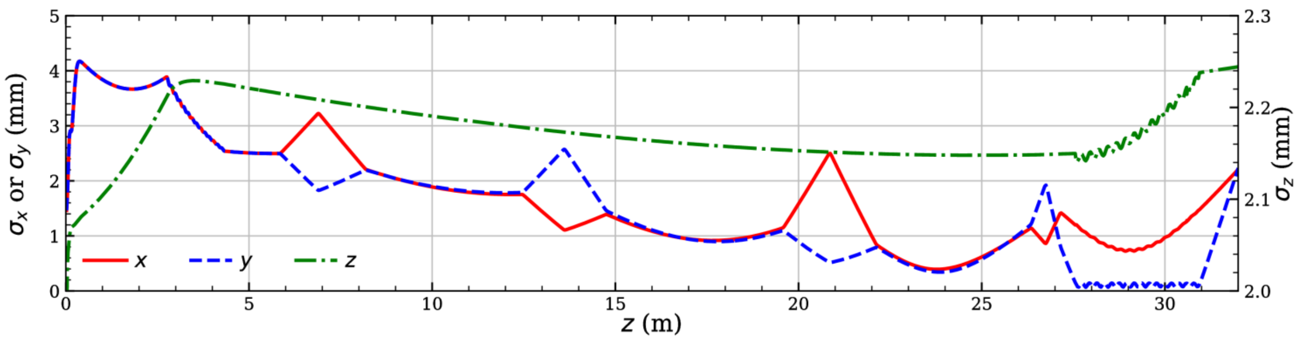
Reference particle trajectories in the undulator with horizontal gradient



Start-to-end simulation

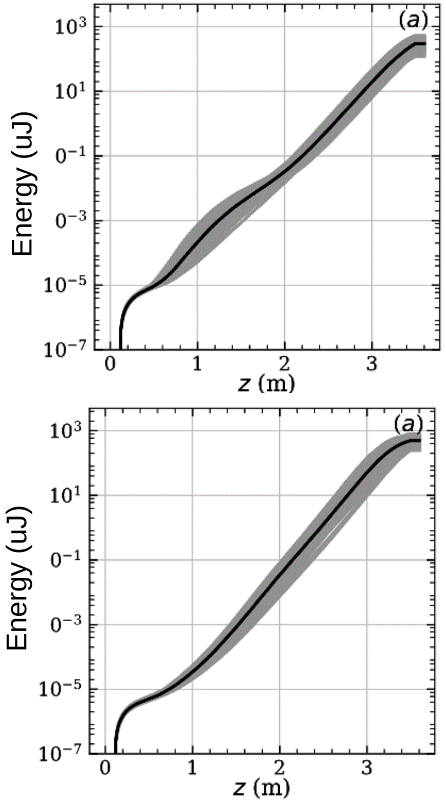
Proof-of-principle experiment on THz SASE FEL at PITZ

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

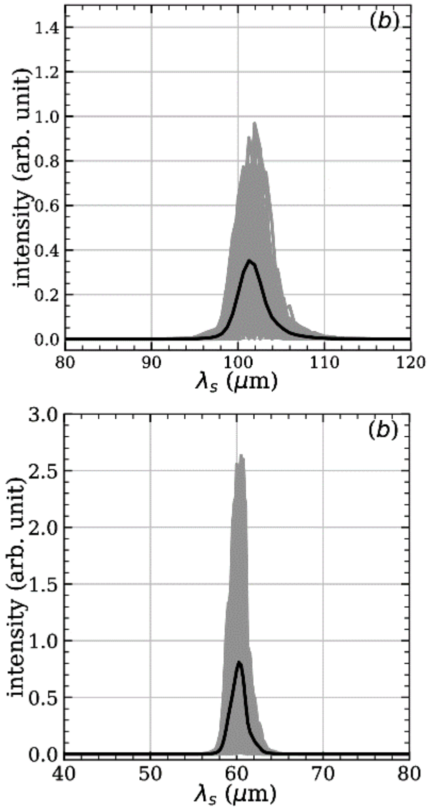


~100 um

~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

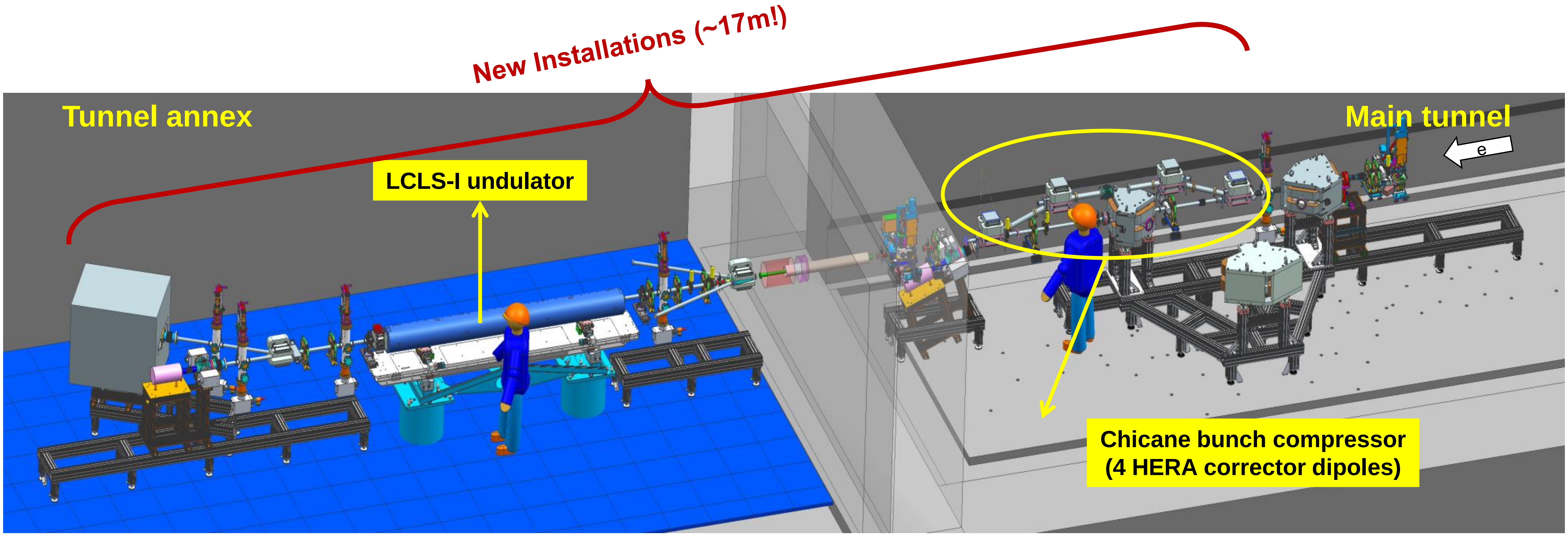
Summary of Genesis 1.3 simulation

Courtesy: X.-K. Li

NB: Genesis simulations in free space, no vacuum chamber (waveguide effect neglected)

THz SASE FEL at PITZ: Realization

PITZ upgrade for the proof-of-principle experiment



Procedure for beam matching into the LCLS-I undulator

X. Li et al., “Matching of a Space-Charge Dominated Beam into the Undulator of the THz SASE FEL at PITZ”, in Proc. 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, pp. 3244-3247.

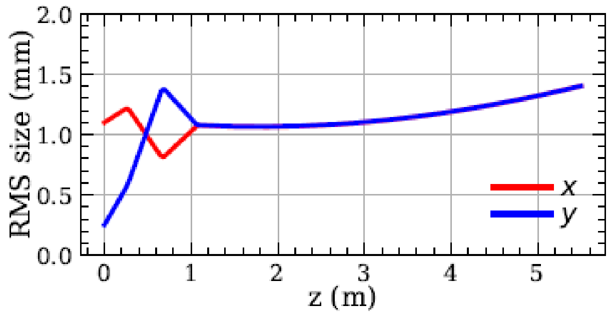


Figure 4: Backward tracking of the electron bunch starting from the undulator entrance.

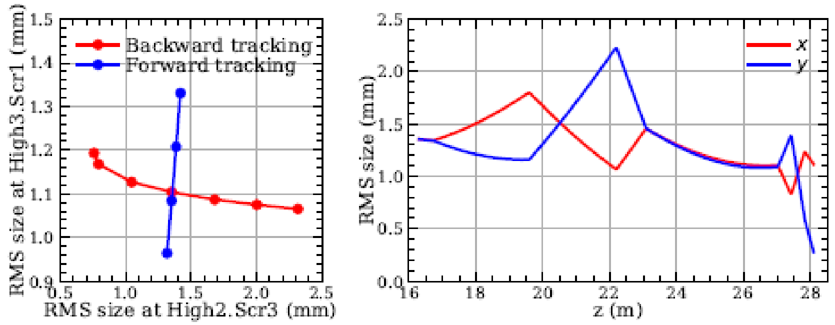
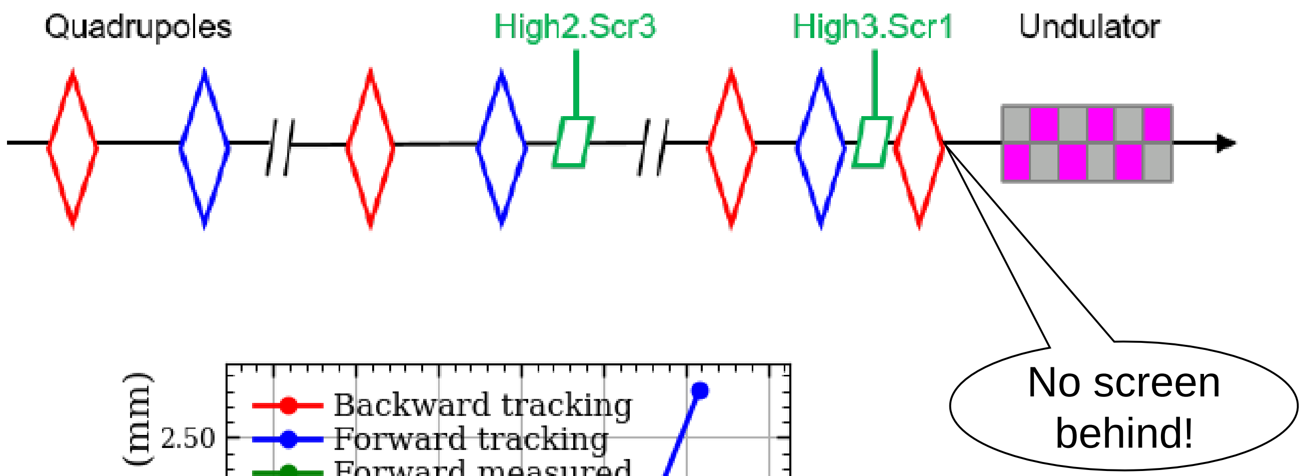
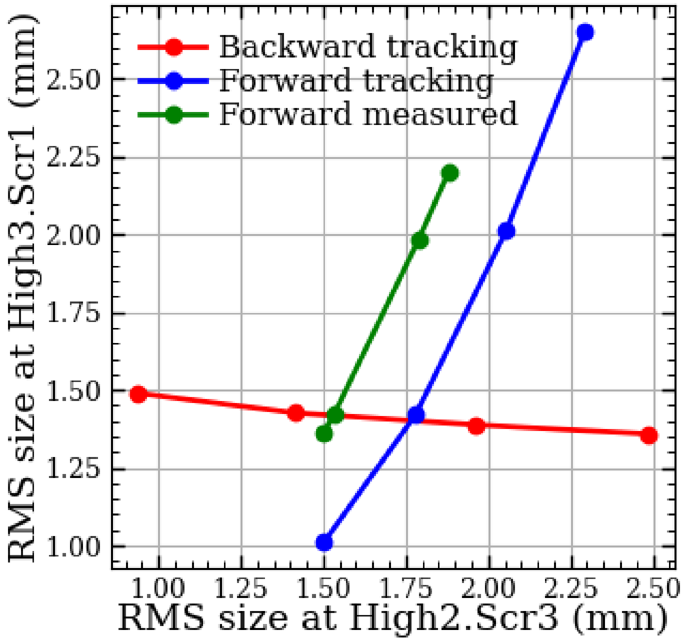


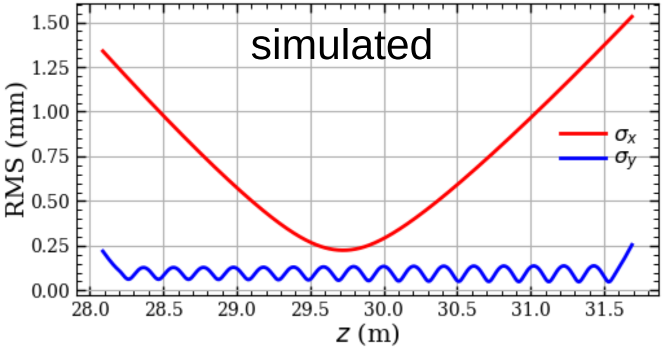
Figure 5: Matching procedure (left) and transport of the electron bunch under the matching condition (right).

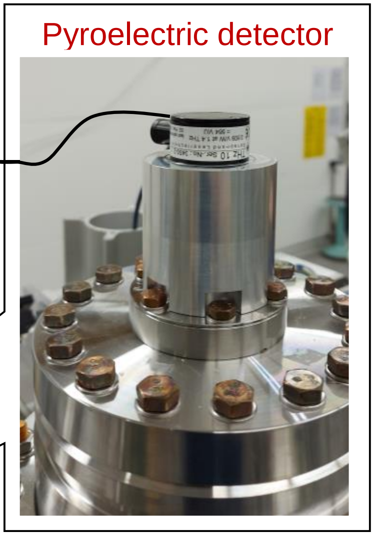


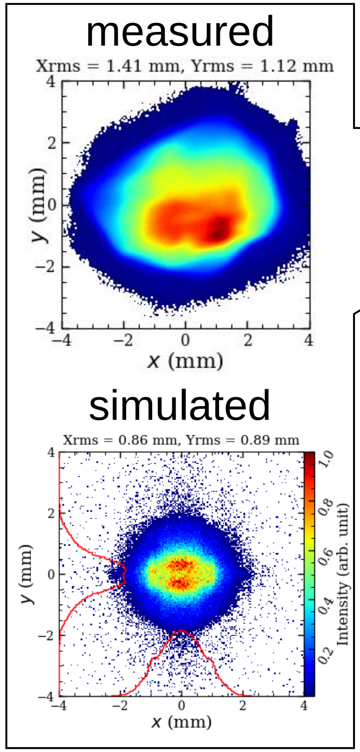


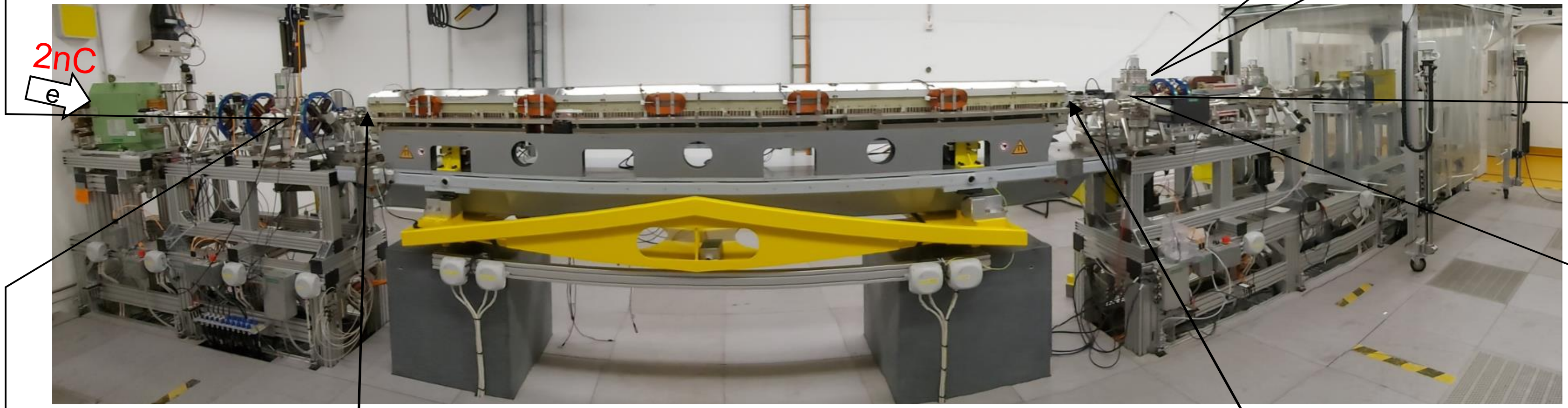
THz SASE FEL at PITZ

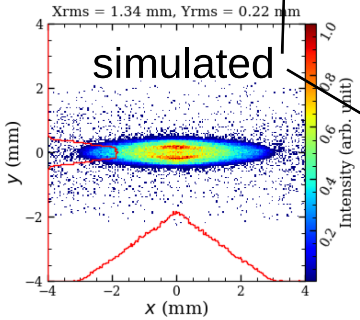
Electron beam matching for lasing

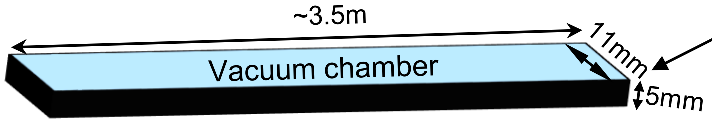


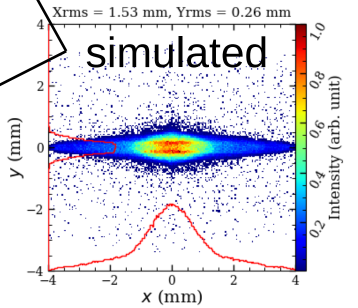


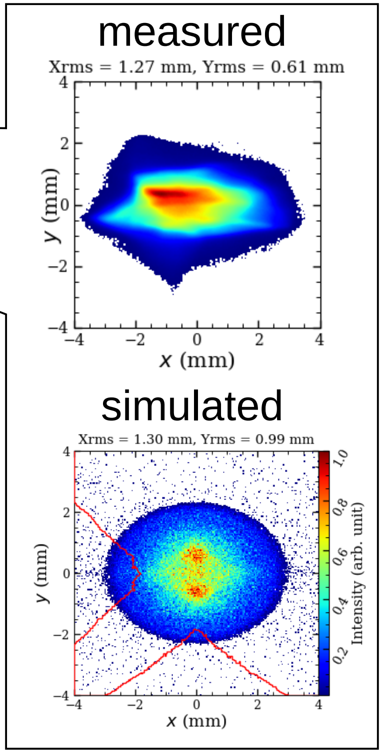






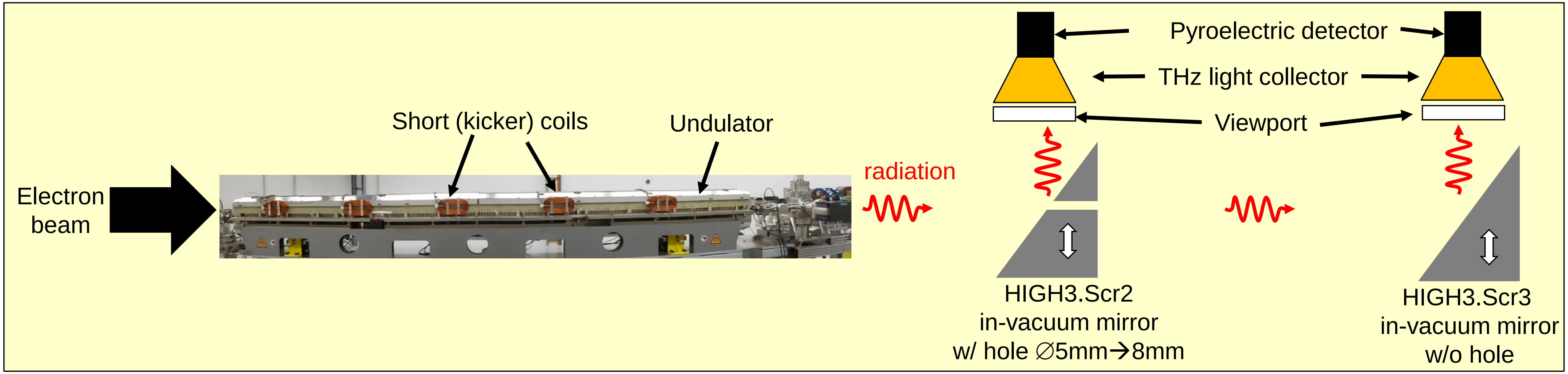


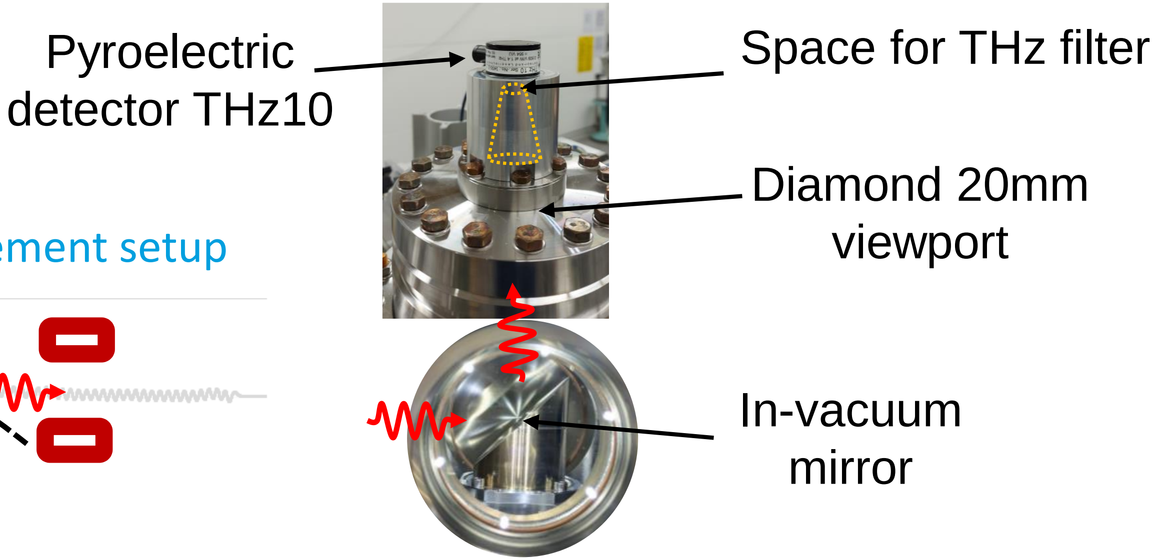




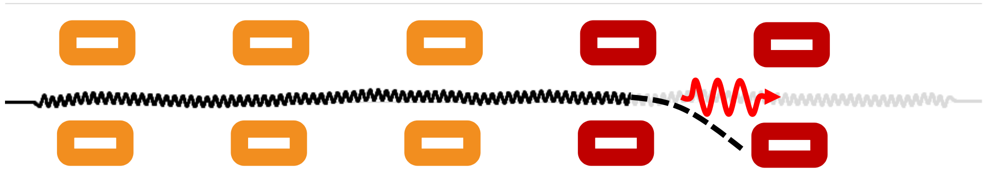
THz SASE FEL at PITZ: THz diagnostics setup for gain curve

Startup: pyroelectric detectors with collector cones





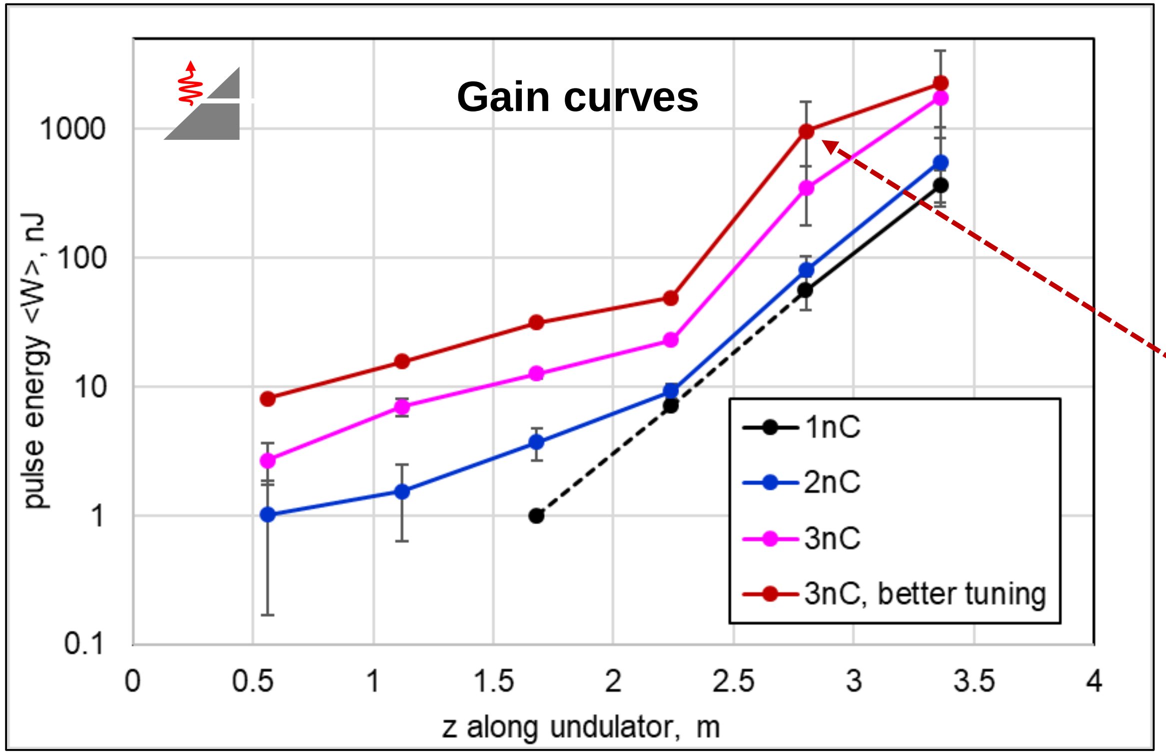
Simplified layout of the gain curve measurement setup

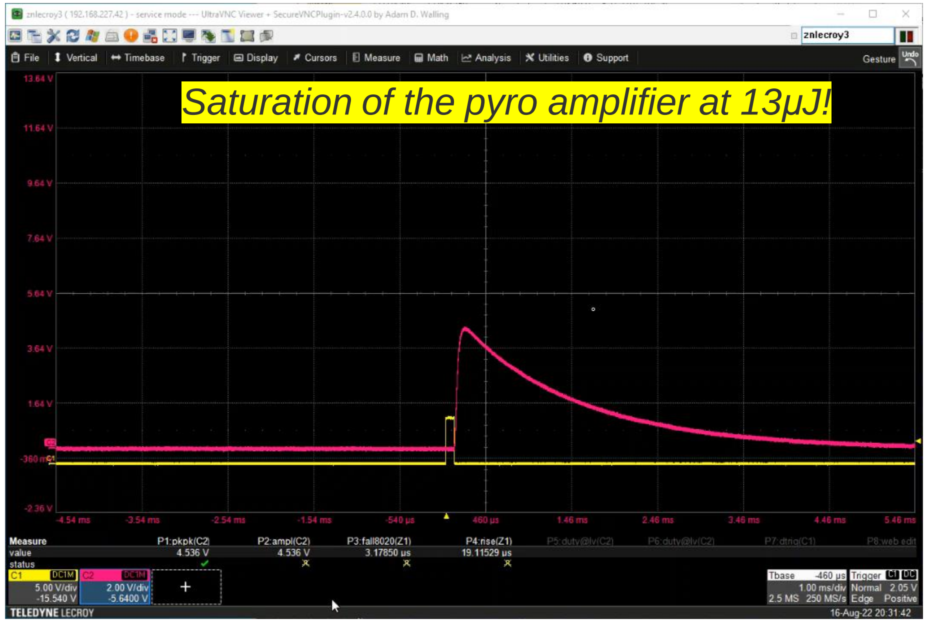


THz SASE FEL at PITZ: Gain Curves

First Characterization: FEL Gain Curves with HIGH3.Scr2 mirror

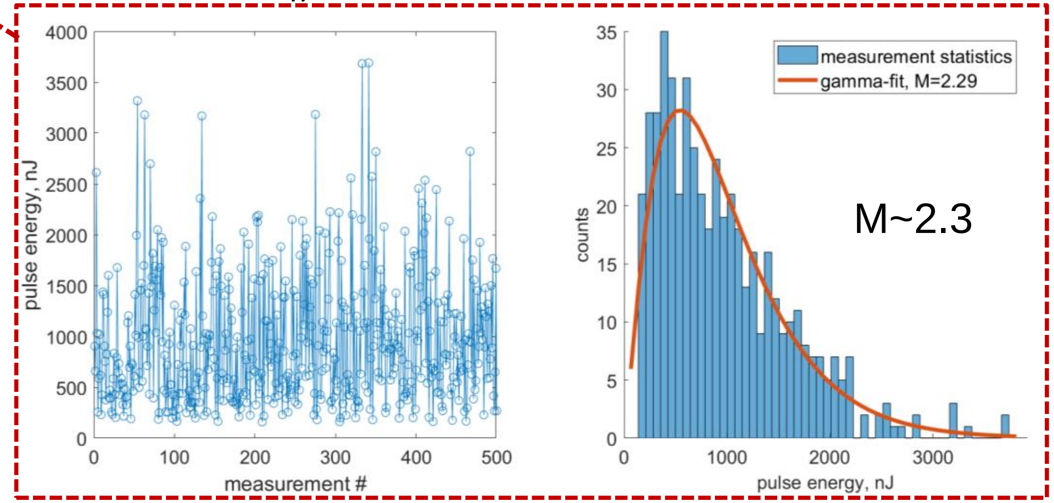
- **Lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**
- Gain curves at 1, 2 and 3nC





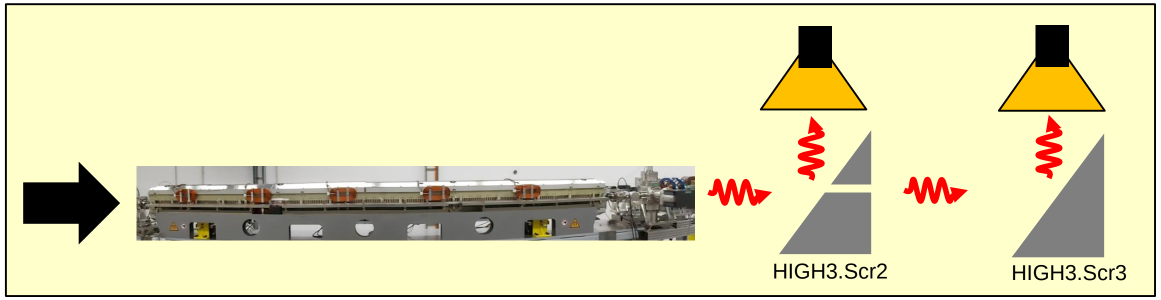
$$\rho(W) \propto \frac{M^M}{\Gamma(M)}\left(\frac{W}{\langle W\rangle}\right)^{M-1}\frac{1}{\langle W\rangle}\exp\left[-M\frac{W}{\langle W\rangle}\right],$$

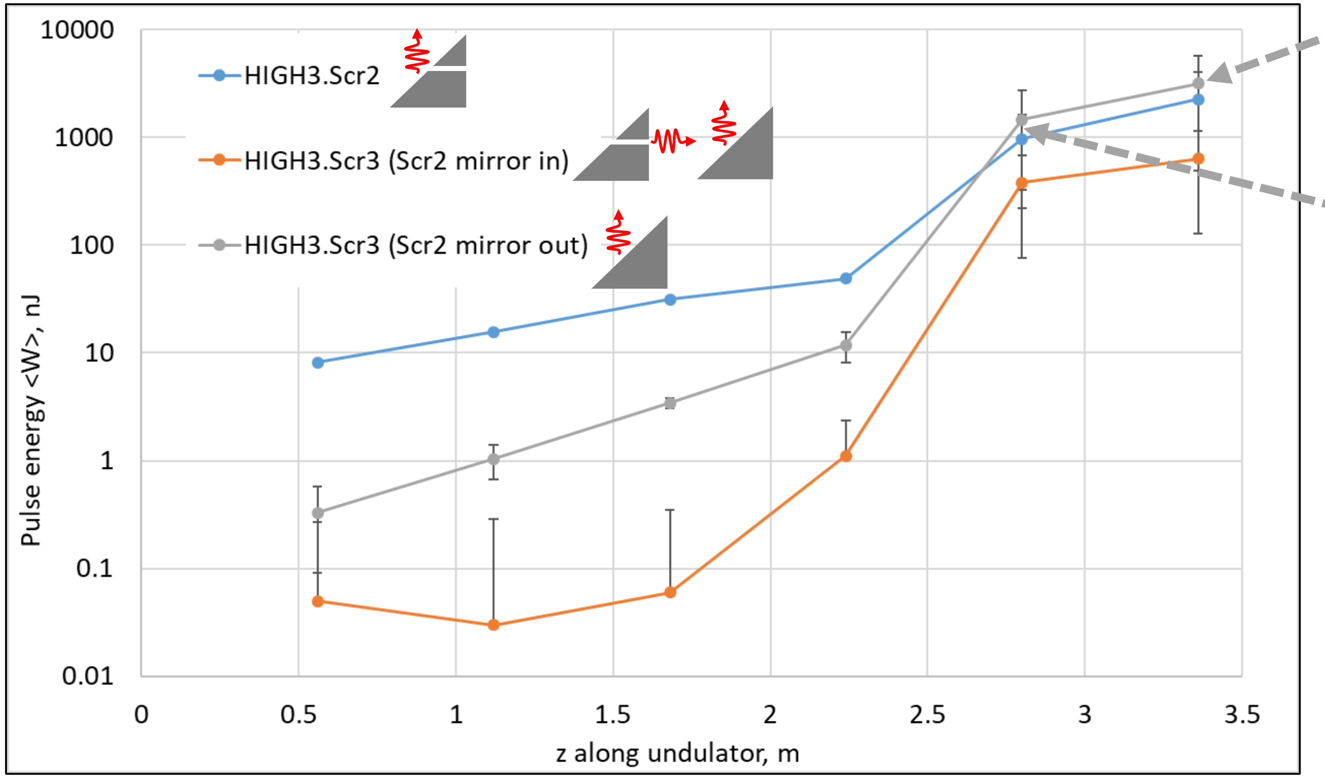
where $M = \frac{\langle W\rangle^2}{\sigma_W^2}$ is number of modes in the radiation pulse

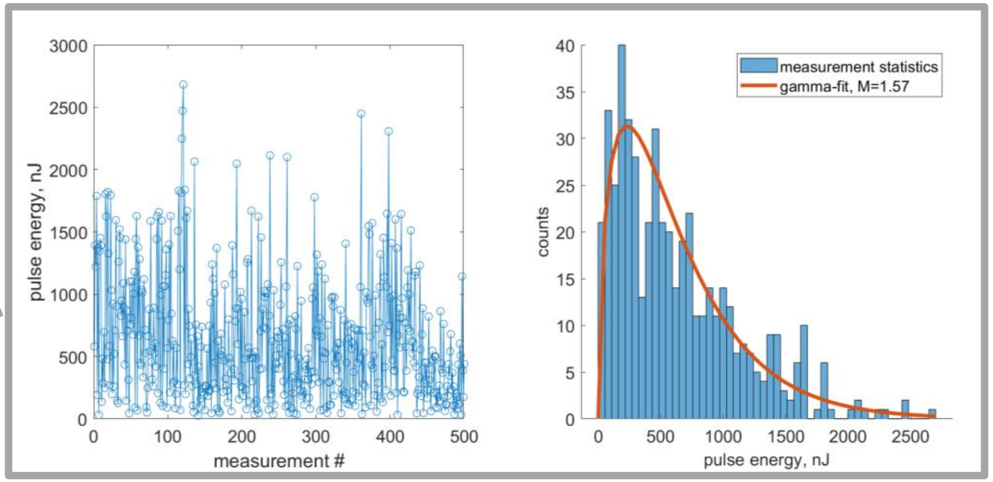


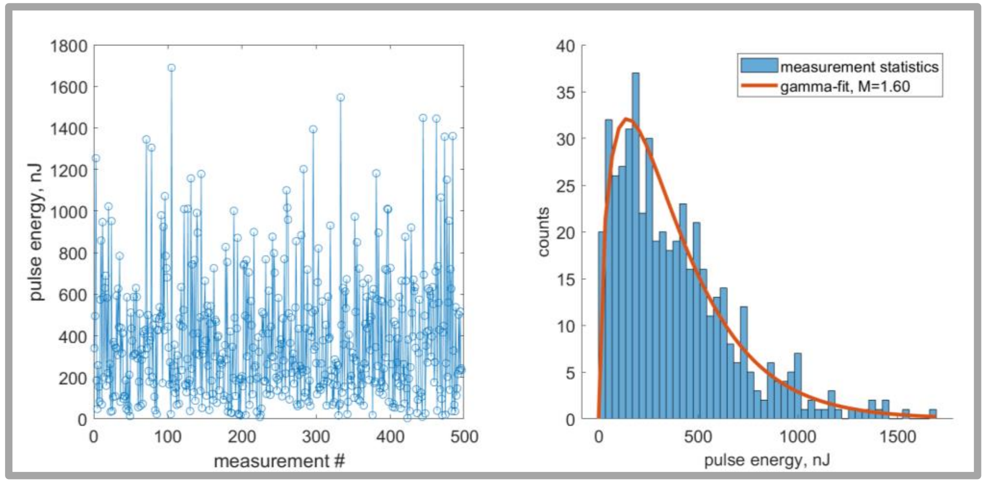
THz SASE FEL at PITZ: Gain Curves (3nC)

Measured pulse energy vs position along undulator for different locations



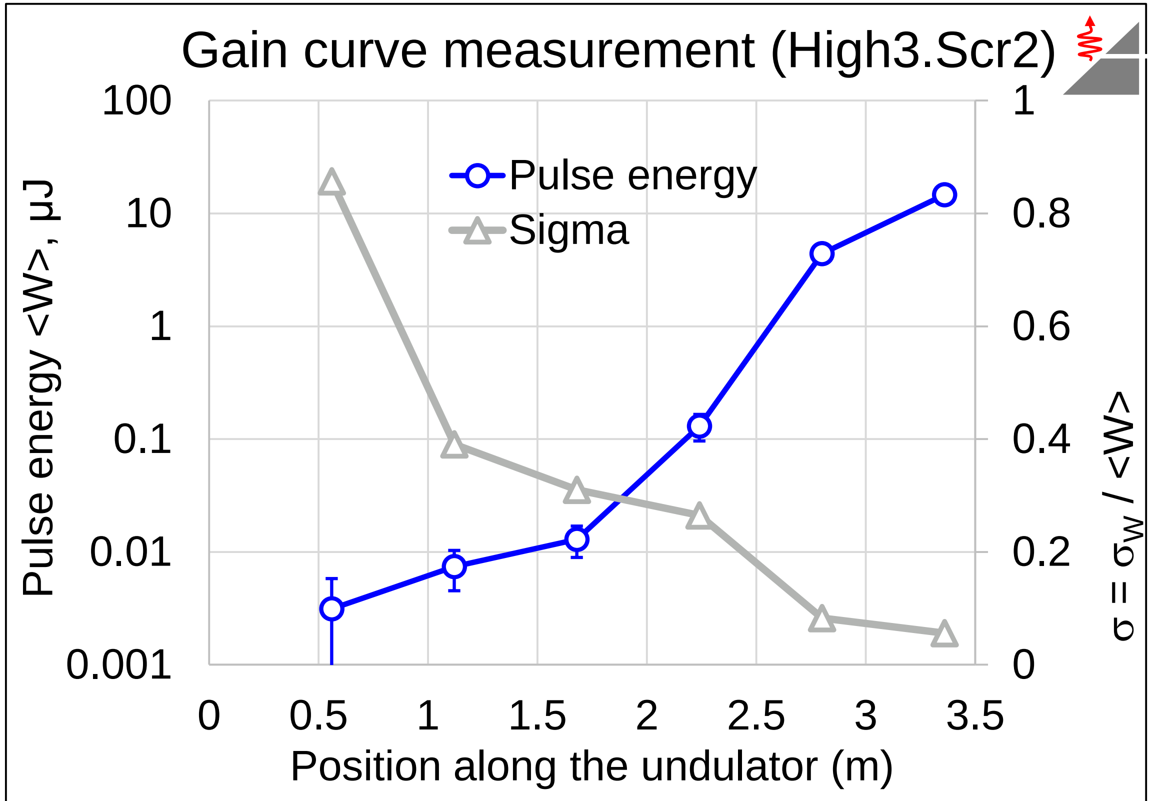


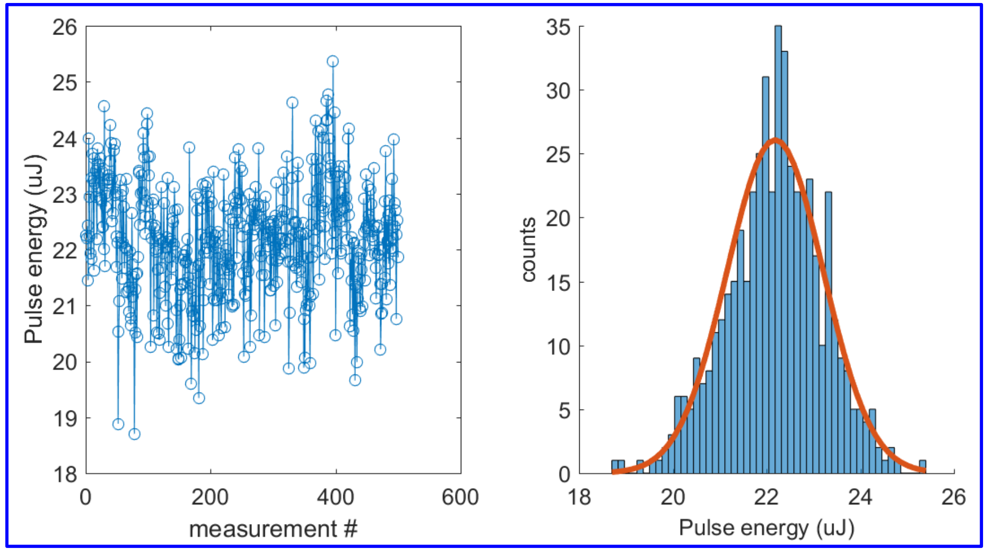




THz SASE FEL at PITZ: Further Tuning

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

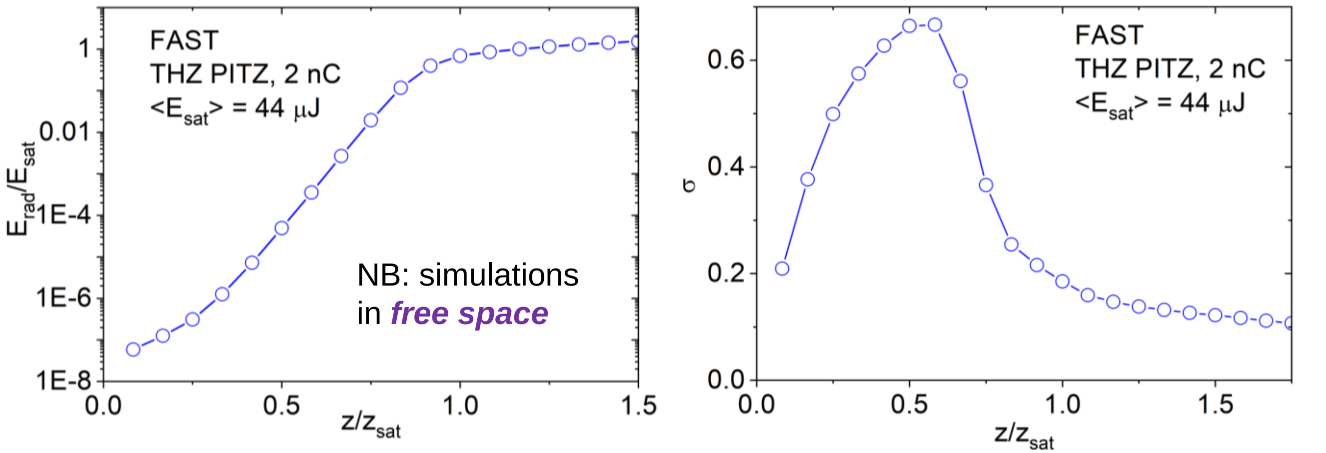




Photocathode laser spot (BSA=3.5mm)
from 3nC setup was applied for 2nC, not fully optimized

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

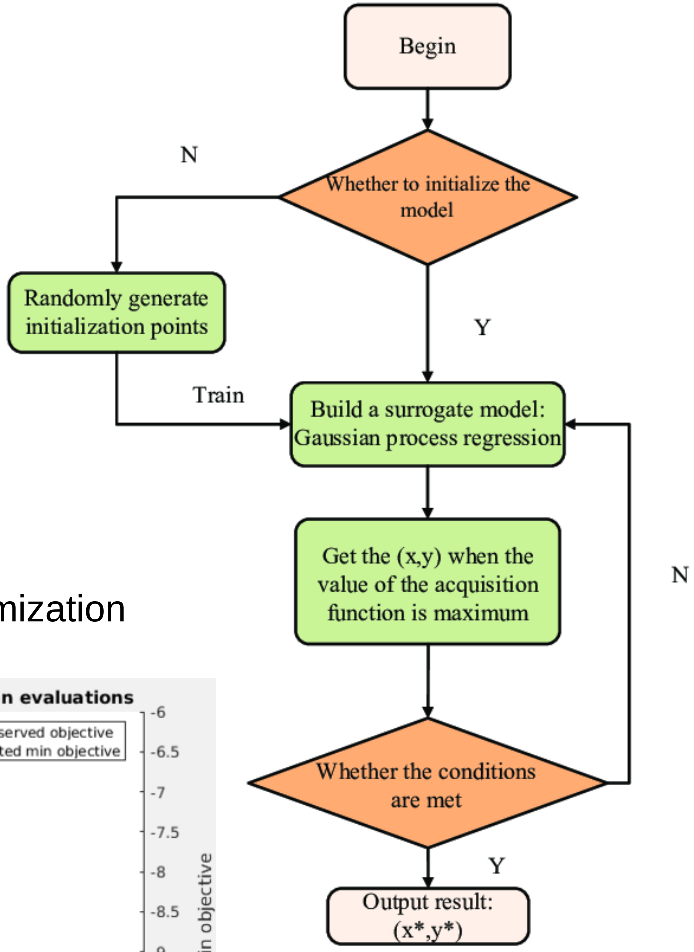
FAST Simulations (M. Yurkov)

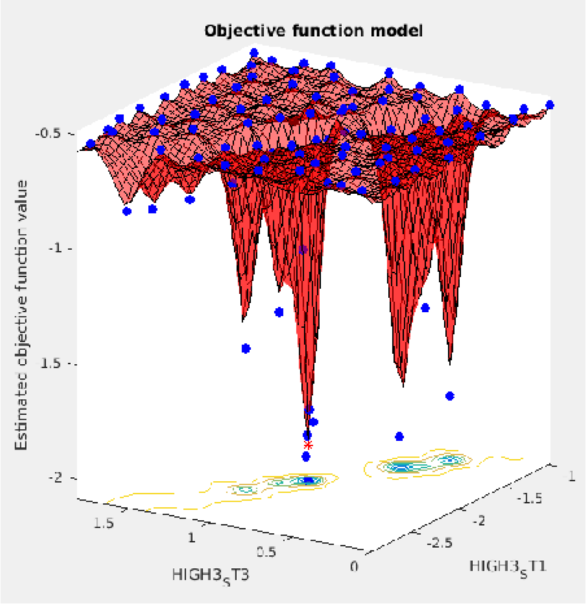


Bayesian optimization for THz SASE FEL

Tuning machine parameters to maximize pyrodetector signal

- Best-suited for optimization over continuous domains of less than 20 dimensions
- **bayesopt** - **MATLAB function** for finding the global minimum of a function using Bayesian Optimization
  - Online monitoring of the optimization status
  - Allows to resume optimization from a previous run
- **BayesianOpt_test.m – Script** for THz SASE optimization
  - Using a config file to setup the magnets (later also others) to be optimized
  - All intermediate machine settings and measurement data are saved for later analysis
  - Hysteresis can be reduced by loading the saved machine settings following the history of the optimization



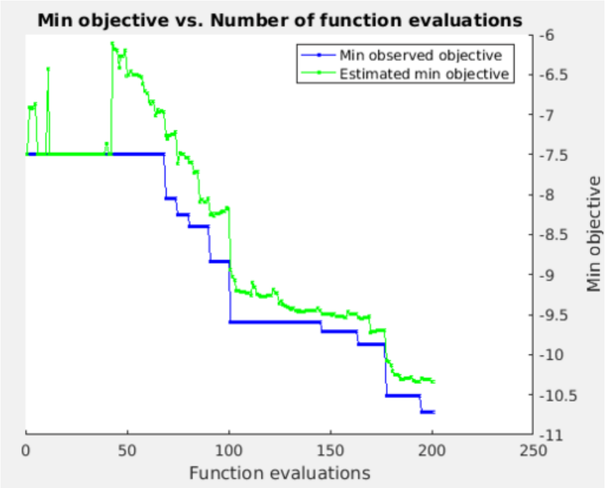


config.txt | BayesianOpt_test.m

```
% From left to right are magnet
% Always start the magnets from
HIGH3.ST1    0    0.8    0.2   1
HIGH3.ST2    -0.5   0.3  0.2  1
HIGH3.ST3   -0.2   0.6   0.2   1
HIGH2.ST5   -0.8  0  0.2  1
HIGH3.Q1  -2  -0.9  0.2  1
HIGH3.Q2    3   5  0.2  1
HIGH3.Q3  -2.7  -2.1  0.2  1
```

Example of input file

From left to right:
magnet, **lower limit**, **upper limit**, **relative change** and **0/1**



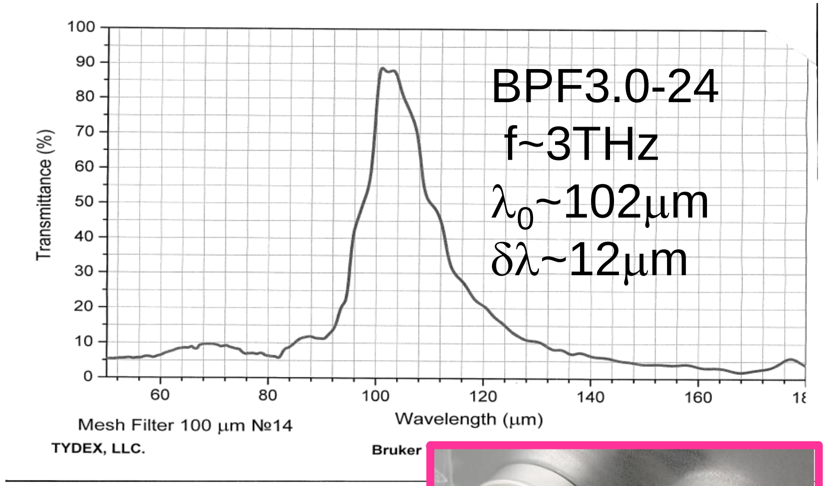
Optimization status

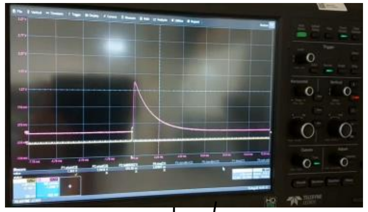
Li, Y.; Zhang, Y.; Cai, Y. A, New Hyper-Parameter Optimization Method for Power Load Forecast Based on Recurrent Neural Networks. Algorithms **2021**, 14, 163.

THz SASE FEL: Update for better characterization

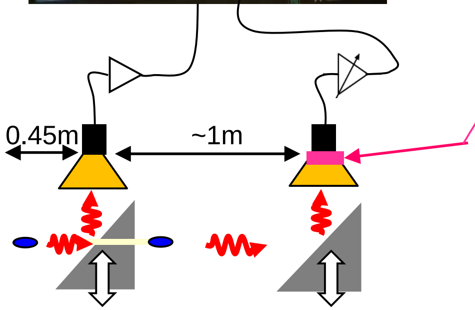
Since 09.10.2022A

- 7 x SCCs (+2)
- Main optimization at HIGH3.Scr3:
  - Whole THz mirror (w/o hole)
  - Band-Pass Filter BPF 3THz
  - Pyro detector THz10 with remotely controllable amplifier





Undulator

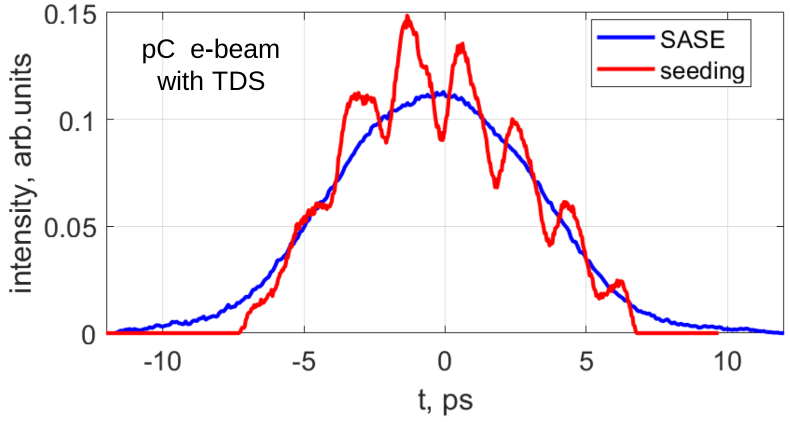


	High3.Scr2	High3.Scr3
Estimated transmission	49%	63%

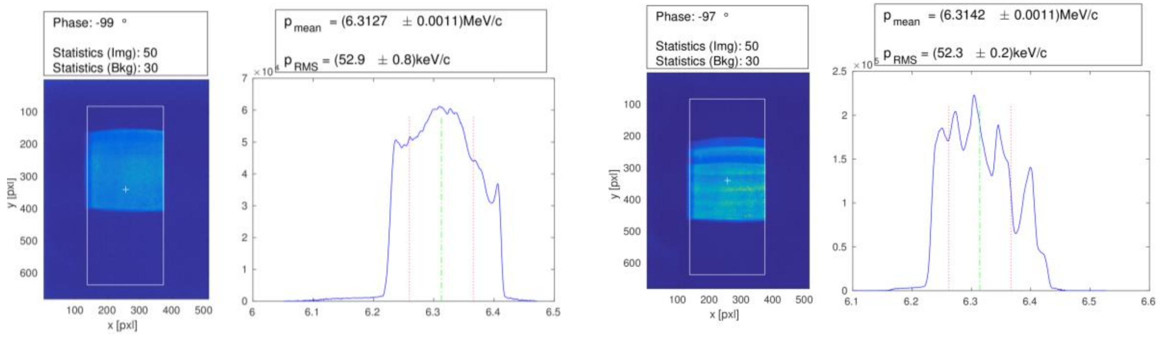
THz radiation with BPF at HIGH3.Scr3 (THz mirror w/o hole)

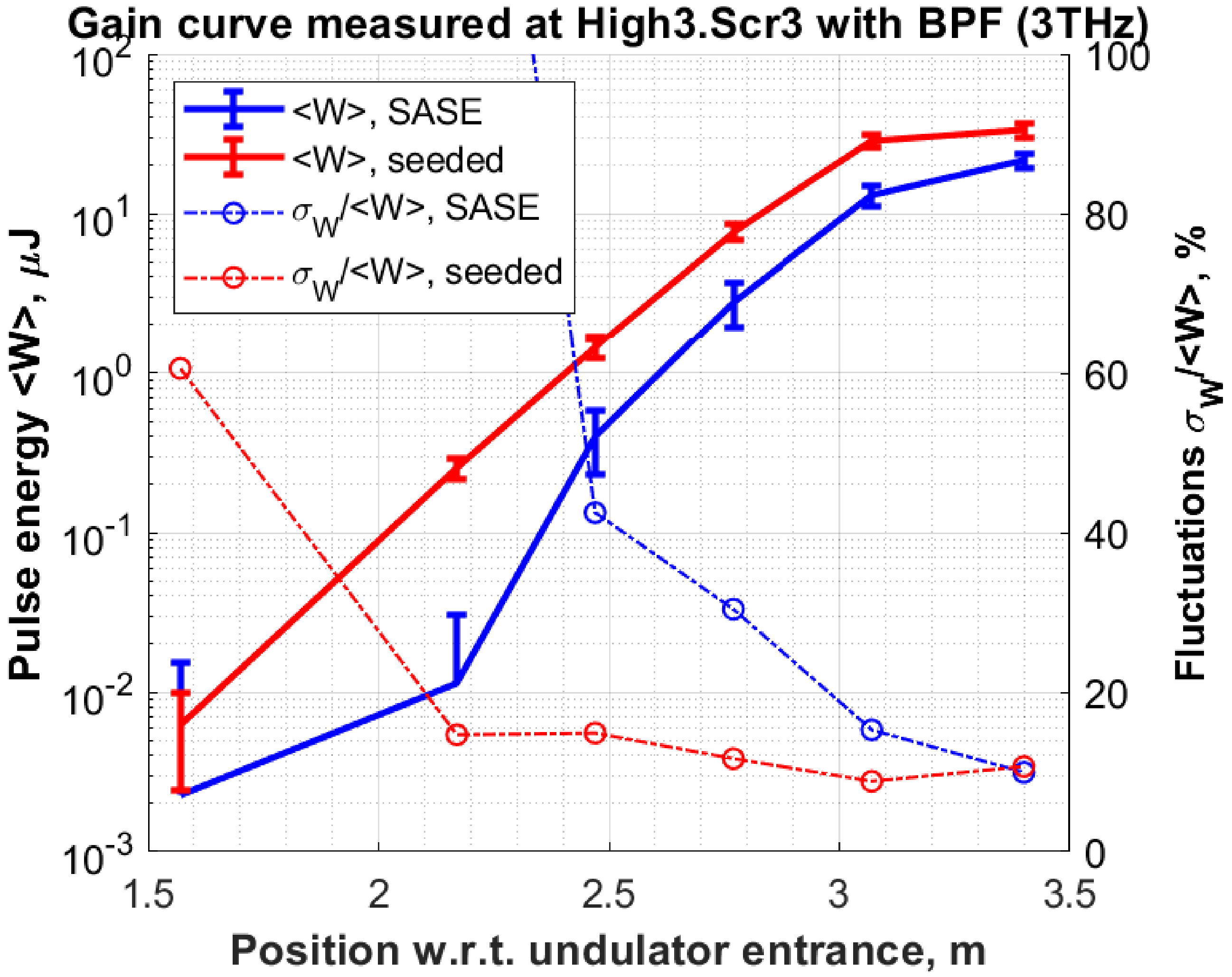
SASE vs. seeded with modulated photocathode pulse (preliminary results)

- THz FEL Seeding experiments (**2nC** e-beam with modulated photocathode laser pulse): <W>→ **33μJ** vs **21μJ** from SASE



P_z-distributions of e-beam (2nC) after gun (LEDA)





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 EXFEL):

→ LCLS-I undulator

➔ first electrons through the undulator → 22.07.2022

➔ 1st THz SASE FEL Lasing → beginning of August 2022

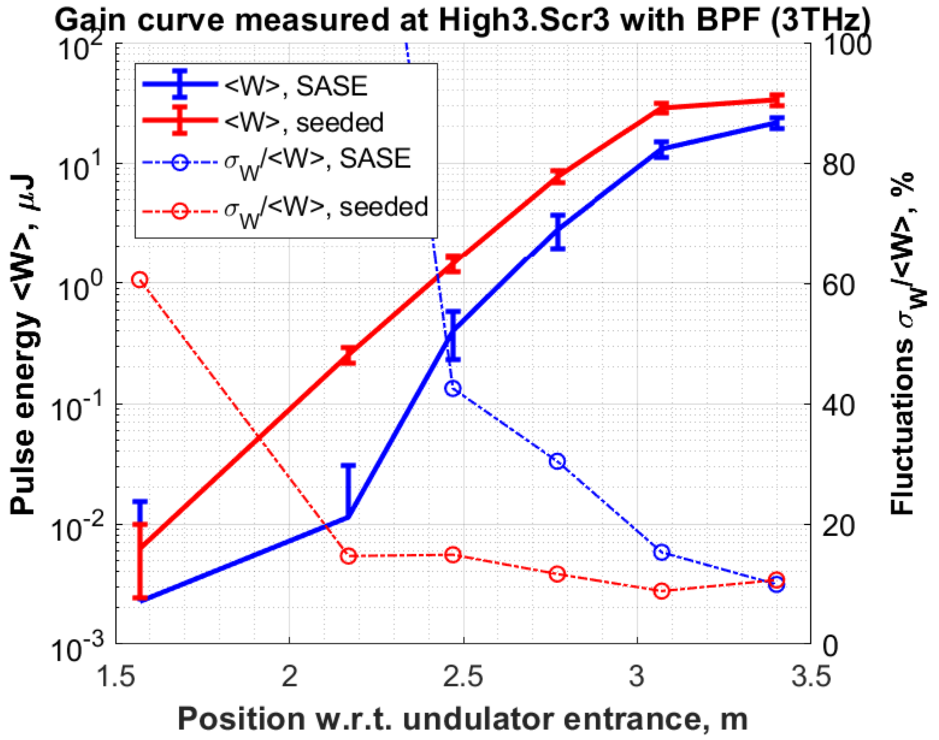
➔ High gain measured !

➔ Strong dependence on beam current and transport /matching

➔ Saturation at >20μJ with 2nC (not fully optimized)

➔ First seeding experiments >30μJ with 2nC modulated beams

High-gain THz SASE FEL at a PITZ-like accelerator → **it works!!!**



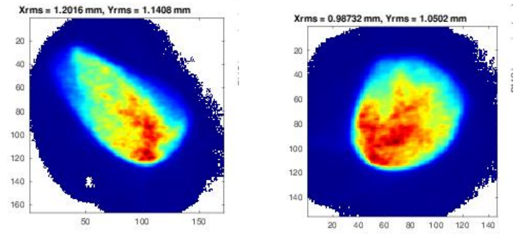
- **Next steps:**
  - Detailed tuning of high-charge beam transport/matching (trajectory model)
  - Setup full THz and e-beam diagnostics (spectral information, THz camera)
  - Other dedicated studies (BC, seeded THz FEL, SUR)

Outlook

Physics and Computational challenges for proof-of-principle experiments on THz FEL at PITZ

- High bunch charge (beam current)
  → 1-4nC (~200A)
- Moderate beam energy
  → 16-20MeV/c
- Long transport (~30m) of space charge dominated beams
- Extremely tight matching (esp. vertical) of the beam trajectory / envelope into the LCLS-I undulator
- Narrow vacuum undulator chamber (Al)
- Alternative beam transport (e.g., "flat beams"?) and further tuning knobs (gun phase, solenoid) to improve the THz output

3nC beam at PST.Scr1:
tuning beam trajectory through TDS



- Wakefields (geometric + resistive):
  - TDS
  - Collimator 6-20mm
  - Undulator vacuum chamber
  - Other beam line elements?
- THz generation:
  - Waveguide effect
  - Seeding (NoP, comp T)
  - Superradiant with short bunches
  - THz radiation transport
- Bunch compressor:
  - Space charge
  - CSR
  - Wakefields
- …

Currently not well understood:

- Best tuning 3nC → 2nC
- Long compensation coil current is by 20-30% lower than simulated
- Band-Pass Filter (BPF3.0): beam energy is by ~0.6-0.8MeV higher than calculated (K?)
- THz fluctuation rate along the undulator

? "Full physics simulations" including:

- Waveguide effect
- Wakefield (geometric+resistive) effects
- Space charge including MB
- Undulator: 3D field including end cells and horizontal gradient
- Long compensation coils
- No WPA approximation?
- Higher harmonics?
- THz transport to detector
- Initial (shot?) noise
- Imperfections