# High-power single-pass THz FEL at PITZ in operation

**Photo Injector Test facility at DESY in Zeuthen (PITZ):**
**Proof-of-Principle experiments on THz source for the European XFEL**

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Ultrafast Beams and Applications

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HELMHOLTZ

# Motivation for THz R&D at PITZ

## Accelerator based THz source for pump-probe experiments at the European XFEL

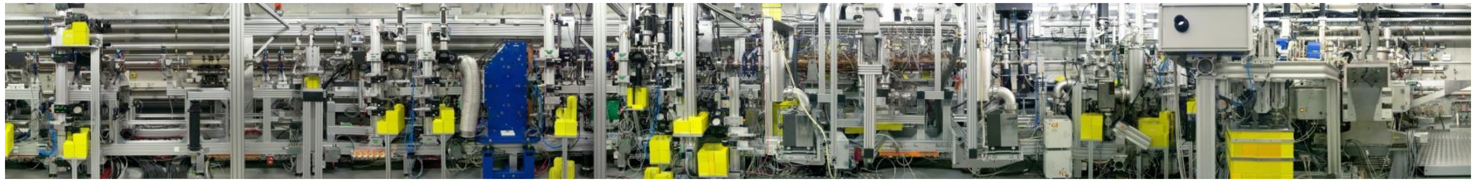
THz source requirements *(P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0):*

- **Tunable** → $f = 0.1 \ldots 20\, THz$ ($\lambda_{rad} = 3mm \ldots 15\mu m$)
- Various temporal and *spectral* patterns, polarization - ideally **narrow-band** → $\Delta W / W \sim 0.1 \ldots 0.01$
- Time jitter → from CEP (few fs) *stable* for field driven to "intensity" driven dynamics (~longest pulse duration) → $\sigma_t \sim 0.1/f$
- **High pulse energy** $W > 10\mu J$ ($\mu J$ - hundreds of $\mu J$ - $mJ$, depending on $f$)
- **Repetition rate** to follow European XFEL → $(600\mu s \ldots 900\mu s) \times (0.1 \ldots 4.5MHz) \times 10Hz = 27000 \ldots 40500\, pulses/s$

Generation of THz radiation by relativistic electron beams

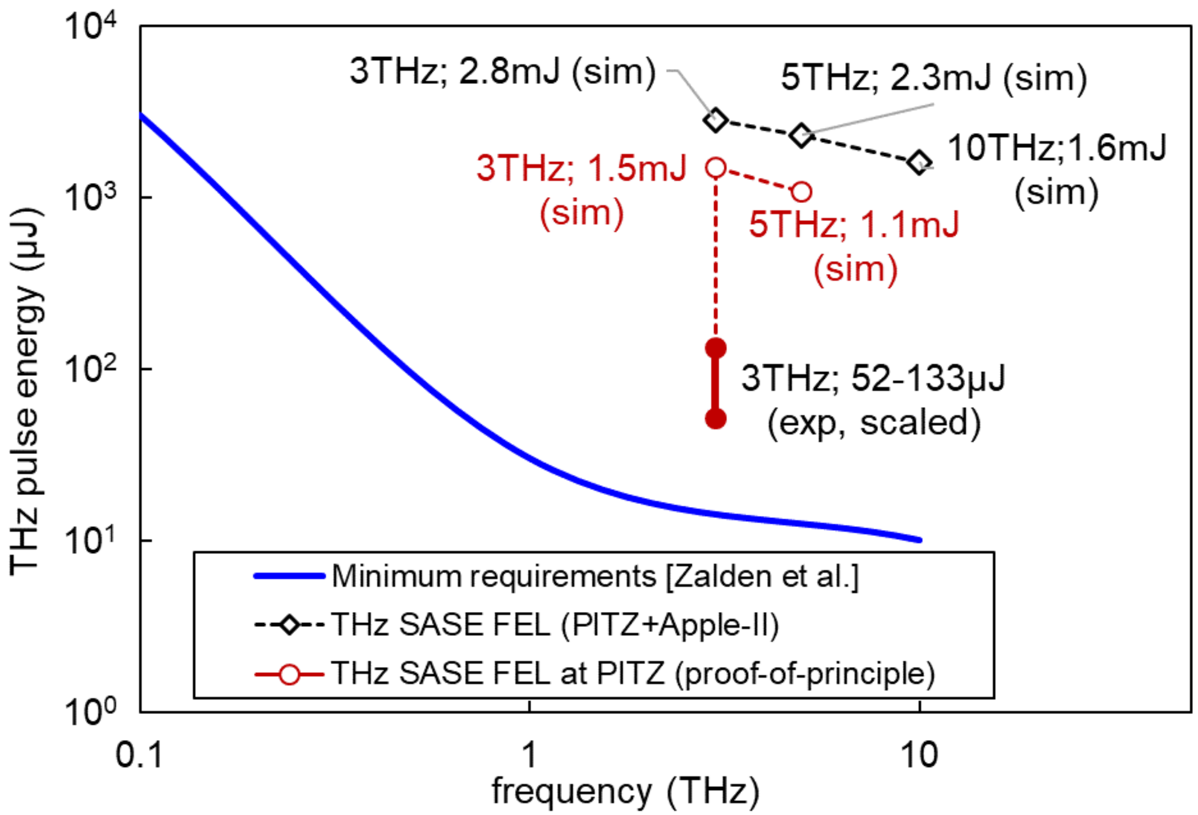
| Attractive features: | Methods of generation: |
| --- | --- |
| • clean in-vacuum radiation production | • bend magnet |
| • tunability (electron beam manipulation) | • **undulator** |
| • potential to provide high power (high field) | • **transition radiation** |
| • polarization control | • diffraction radiation |
| | • Cherenkov radiation (DLW) |

Photo Injector Test facility at DESY in Zeuthen (PITZ)



# Proof-of-principle Experiment on THz Source at PITZ

## Where we are now




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)**

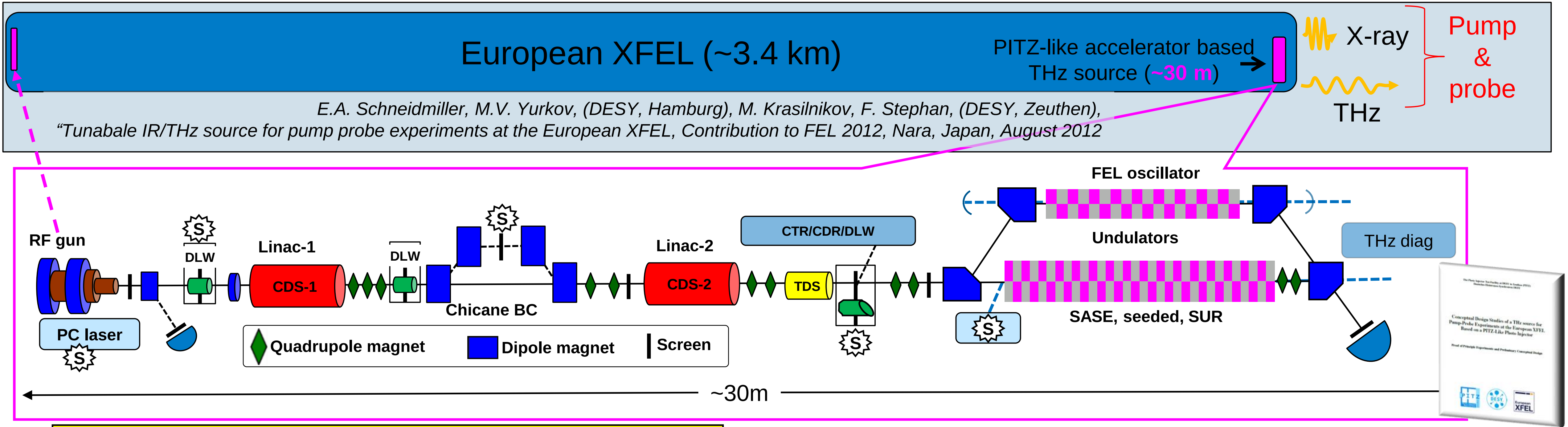
| parameter | Min. requirements [1] | PITZ (exp) |
|---|---|---|
| Bandwidth | 1…0.05 | ~0.02 |
| f [THz] | 0.1…**3…20**…30 | **3…5** |
| Pulse energy | 3mJ@0.1THz;<br>30μJ@1THz;<br>10μJ@10THz | **30..65μJ@3THz** |
| CEP | yes | To be studied |
| Rep.Rate (burst) | 0.1MHz…4.5MHz | 1MHz…4.5MHz |
| Synchronization | <0.1/f | To be investigated |
| Polarization | optional | yes |

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

Scientific requirements:
[1] P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0
"..3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies."

# 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),*
*“Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012*

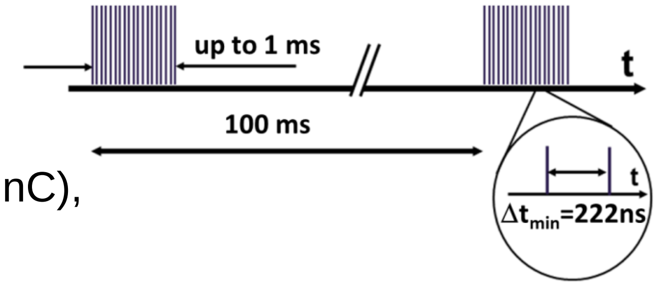
**THz SASE FEL =**
**Self Amplified Spontaneous Emission Free Electron Laser**

**$I_{peak}$~200A (4nC) for ~mJ (sim) SASE FEL for $\lambda_{rad}$ ≤ 100 µm (f ≥ 3 THz)**

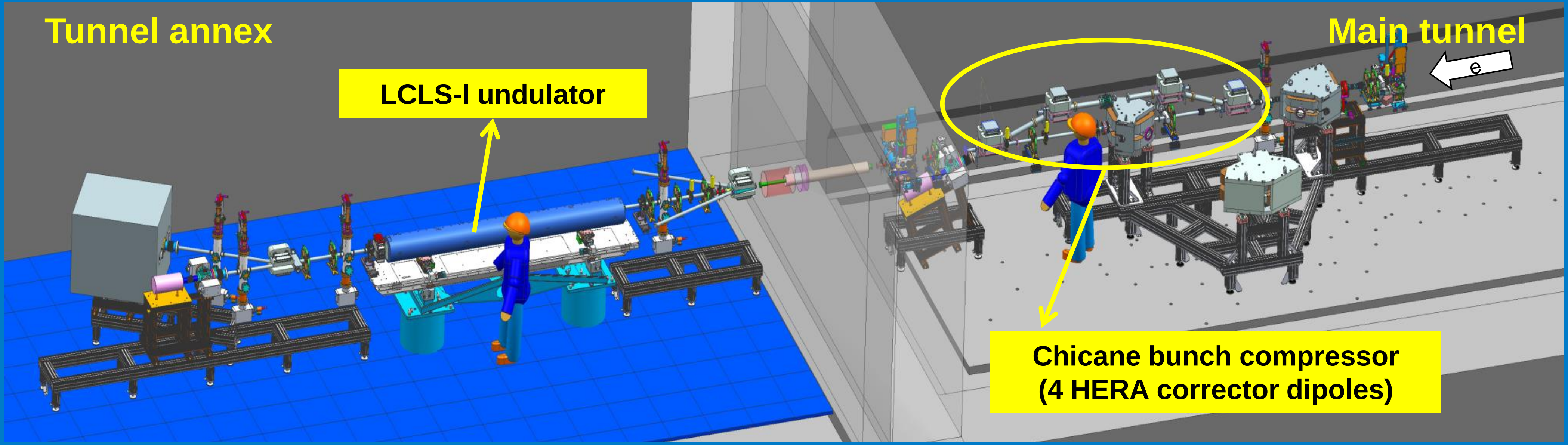
**for $\lambda_{rad}$ > 100 µm (f < 3 THz) → CTR / CDR / SUR?**

**PITZ Highlights:**

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

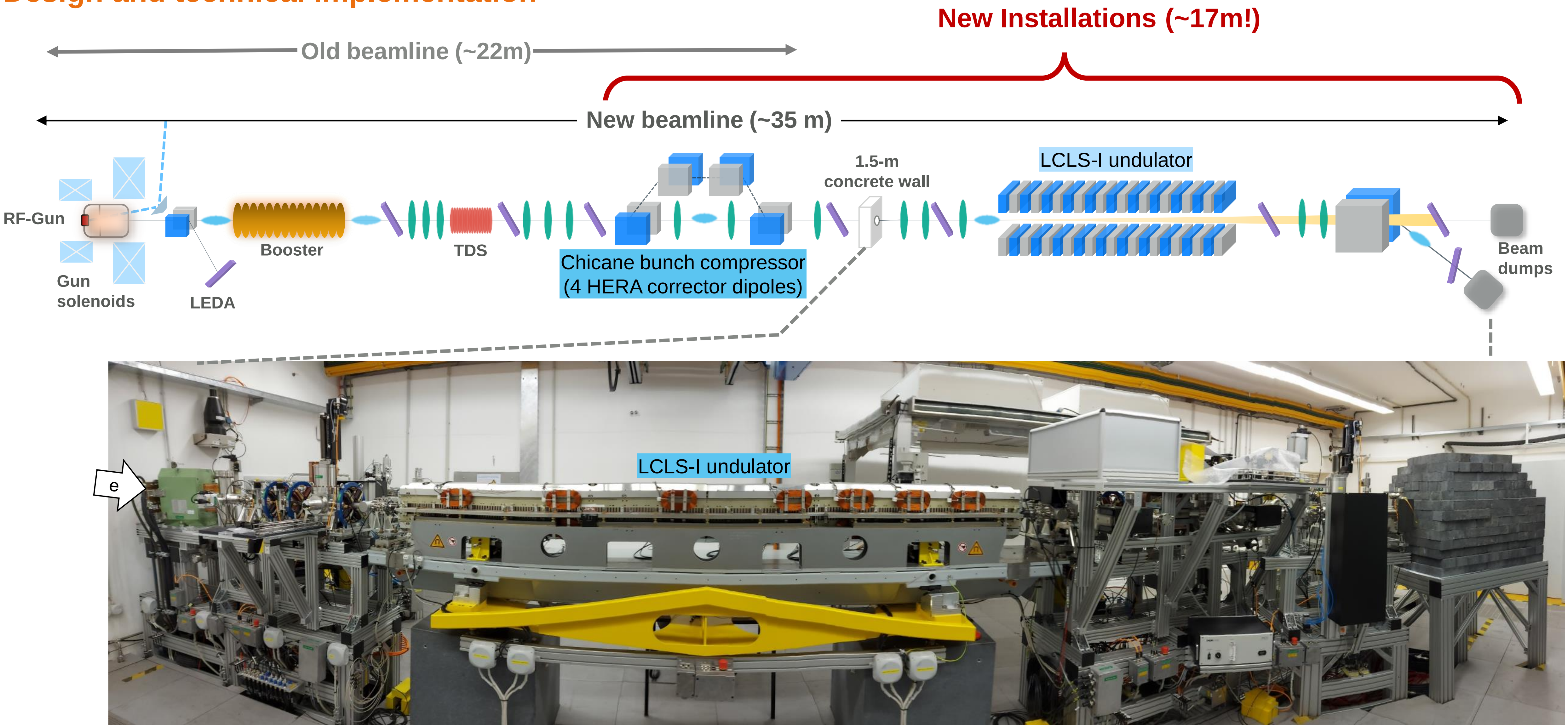


# Proof-of-Principle Experiments on THz SASE FEL at PITZ: Technical Realization



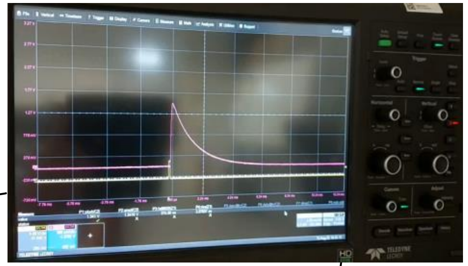
# PITZ upgrade for the proof-of-principle experiment on THz source

## Design and technical Implementation

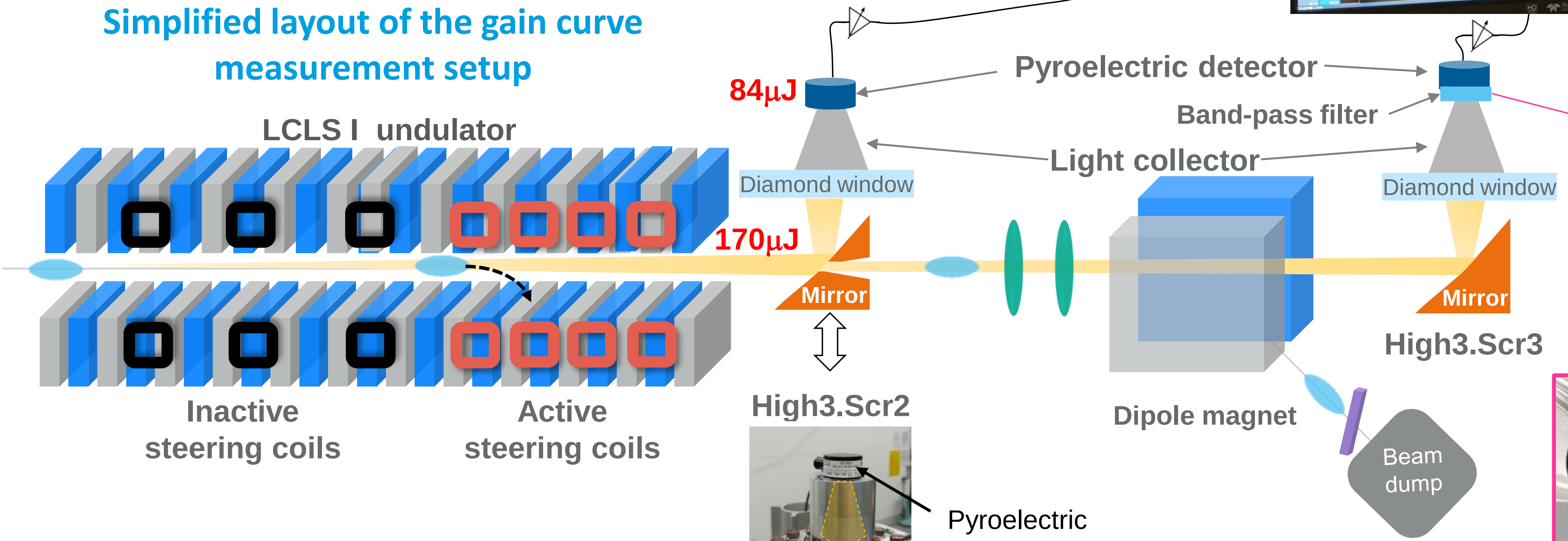


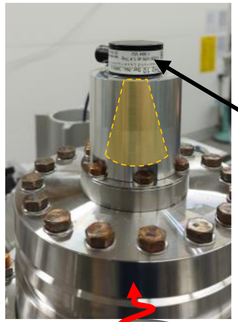
# THz SASE FEL at PITZ: THz diagnostics setup

## Startup: pyroelectric detectors with collector cones

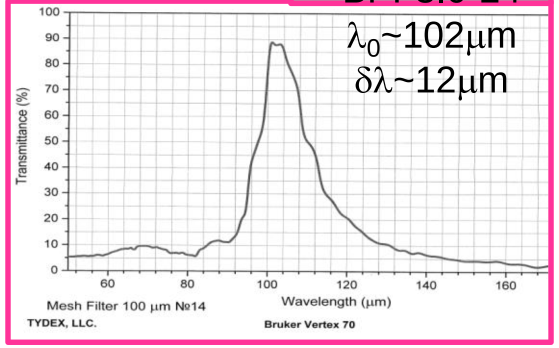


### Simplified layout of the gain curve measurement setup



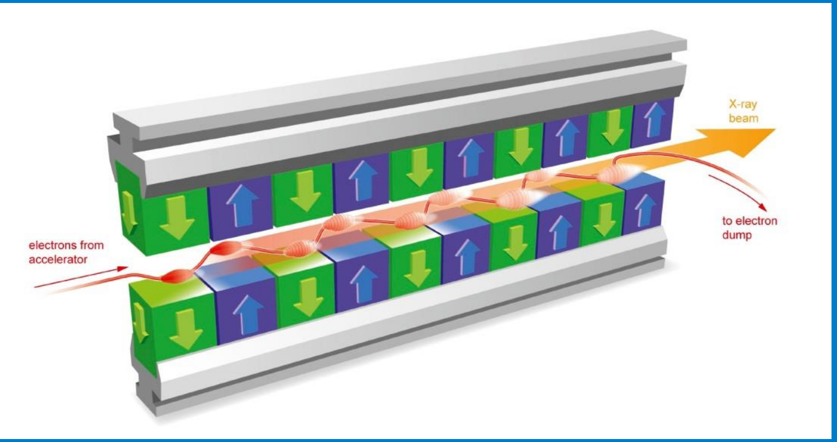



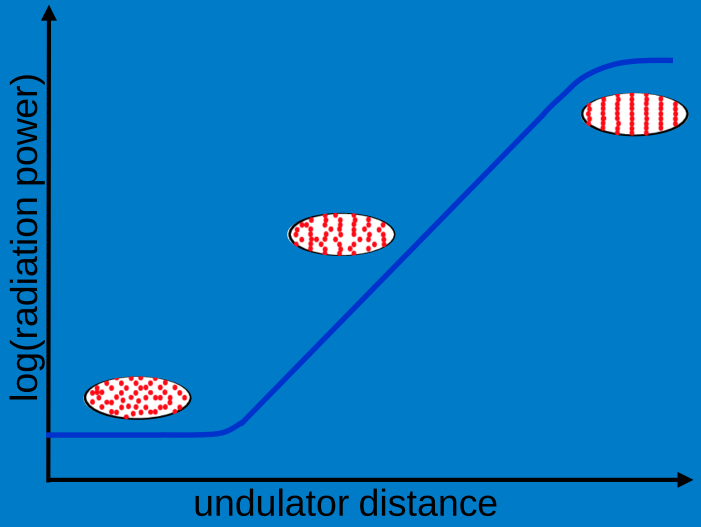





| | High3.Scr2 | High3.Scr3 |
|---|---|---|
| Estimated transmission | 49% | 63% |

# THz SASE FEL at PITZ: Electron Beam Transport and FEL Lasing Tuning

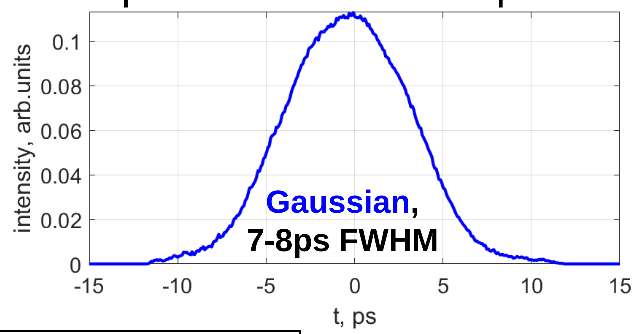


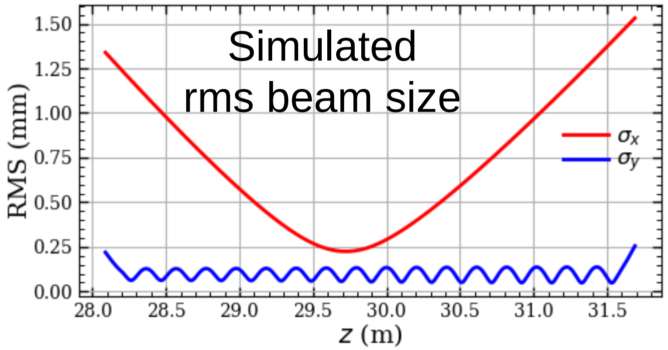



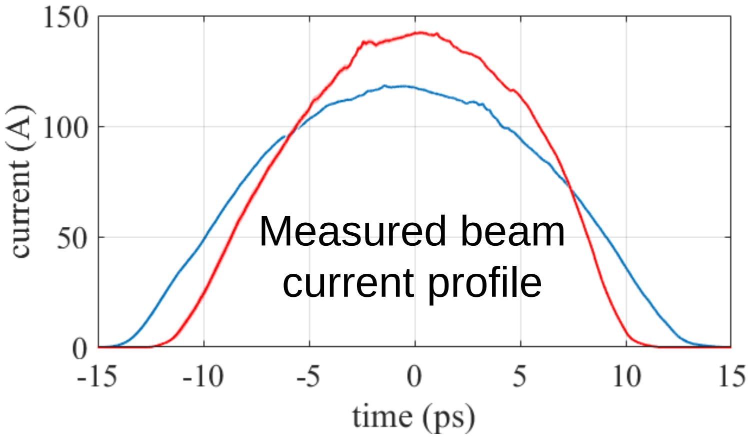
# THz SASE FEL at PITZ

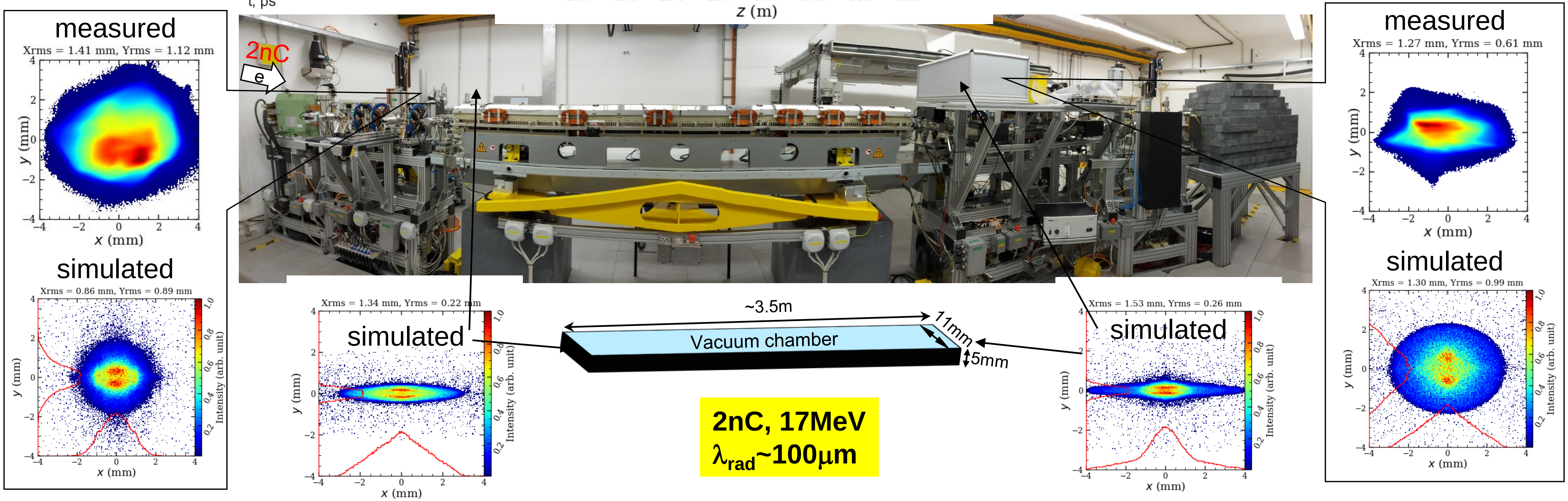
## Main challenge: electron beam matching (2nC, 17MeV/c) for lasing

~photocathode laser pulse



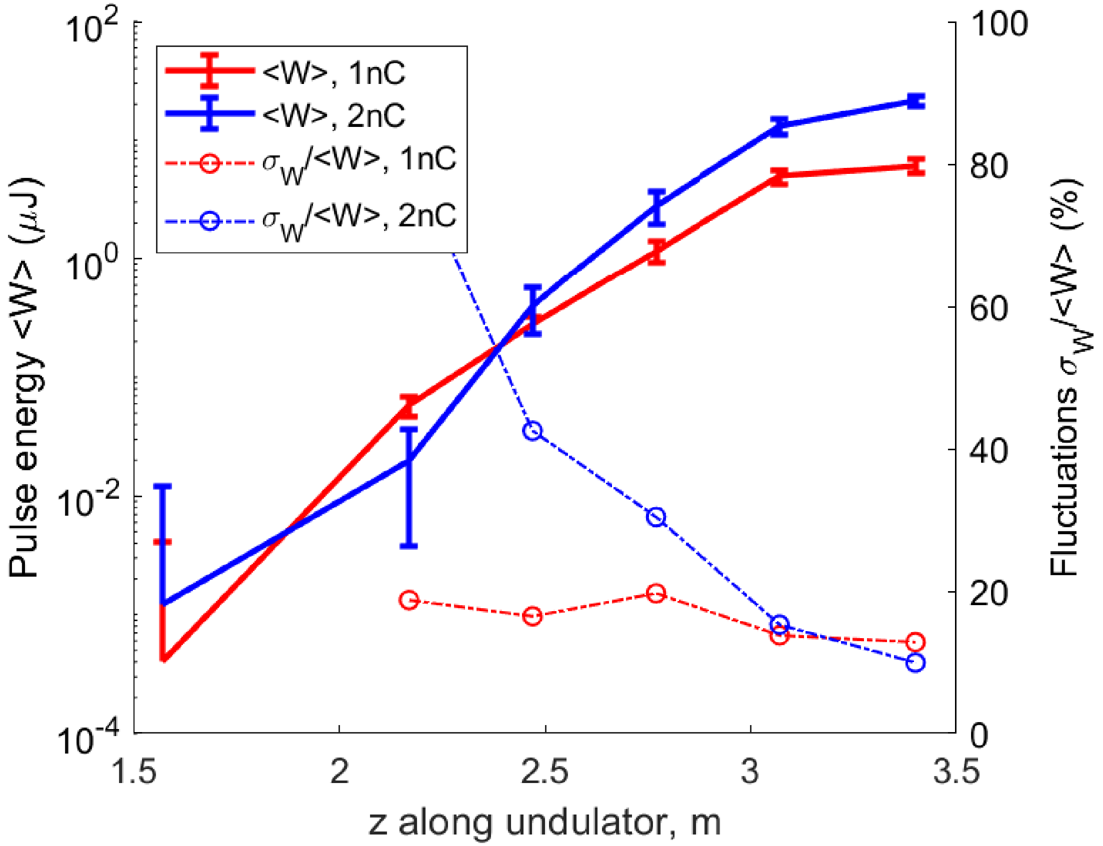



# SASE Gain Curves at High3.Scr3 with BPF

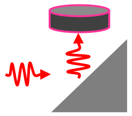
## In-vacuum mirror without hole + 3THz Band-pass filter



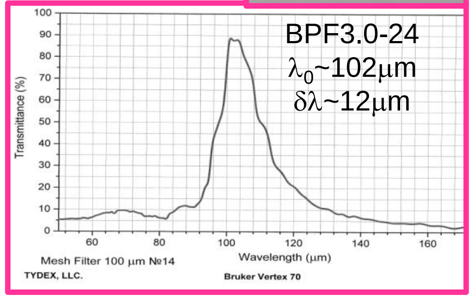

*Using **Gaussian** photocathode laser pulses 7-8ps FWHM*

**Optimization progress**
**<pulse energy> (fluctuations)**

**High3.Scr2 vs High3.Scr3**



| Bunch charge | 1st lasing, no BPF | Tuning, BPF |
|---|---|---|
| 1nC | 0.36 uJ (32%) | 6.12uJ (13%) |
| 2nC | 0.55uJ (52%) | 21.44uJ (10%) |



# Reference case: 2nC, 3THz

## Cross-check with linear theory of FEL amplifier with diffraction effects

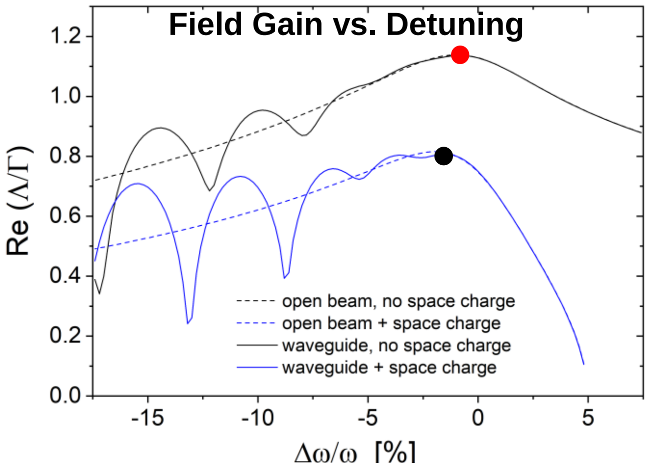
The gain parameter of the FEL amplifier

$$\Gamma = \sqrt{\frac{I_{peak} A_{JJ}^2 \omega^2 \theta_l^2}{2 I_A c^2 \gamma_l^2 \gamma}} = (0.237m)^{-1}$$

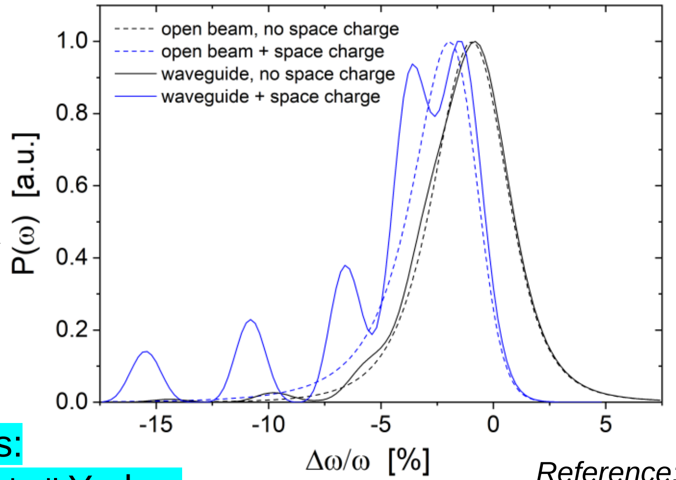
| Parameter | Value |
|---|---|
| Diffraction $B$ | $\sim 0.1$ |
| SC $\hat{\Lambda}_p^2$ | 0.9 |
| *FEL* $\rho$ | 0.01 |
| E-spread $\hat{\Lambda}_T^2$ | 0.003 |
| *Waveguide* $\Omega*$ | 5.3 |

Eigenvalue problem →beam radiation modes

$E_x(z) \propto \exp(\Lambda \cdot z)$, $\Lambda$ → field gain (Re$\Lambda$)

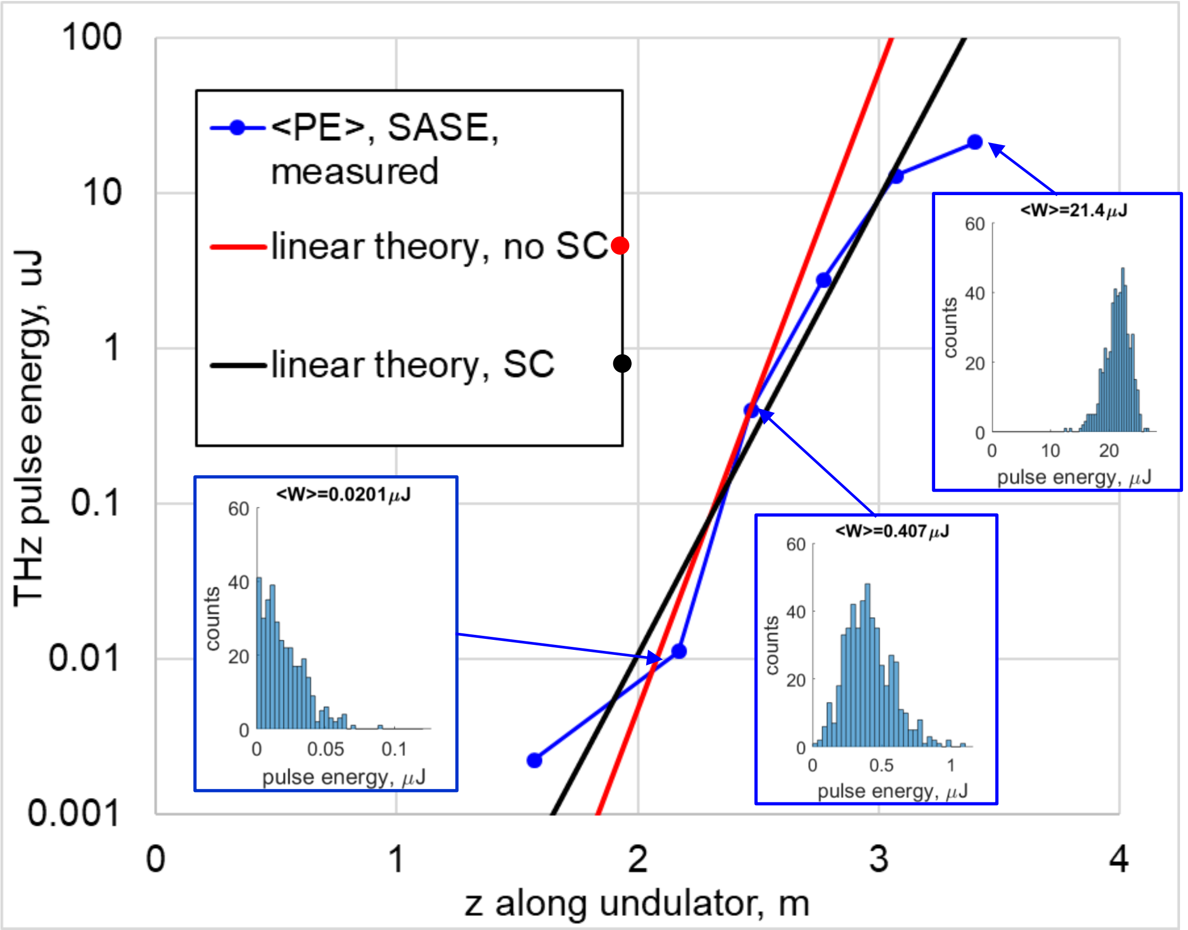



**Expected power spectrum (the high gain regime at the onset of saturation)**




Calculations:
courtesy Mikhail Yurkov

**SASE 2nC: Linear theory versus measurements**

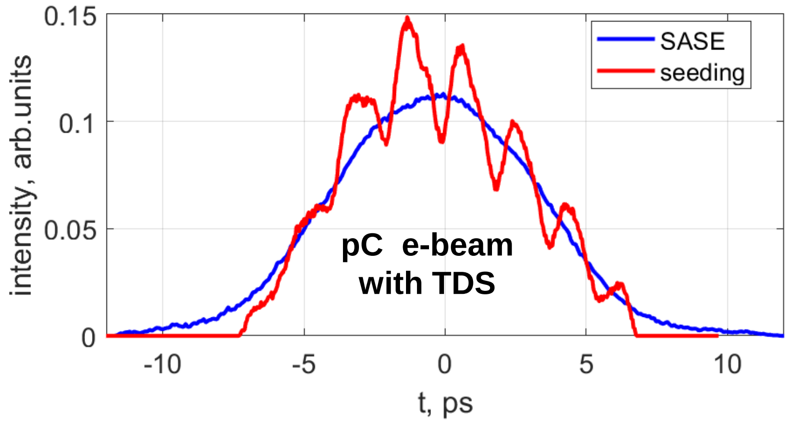


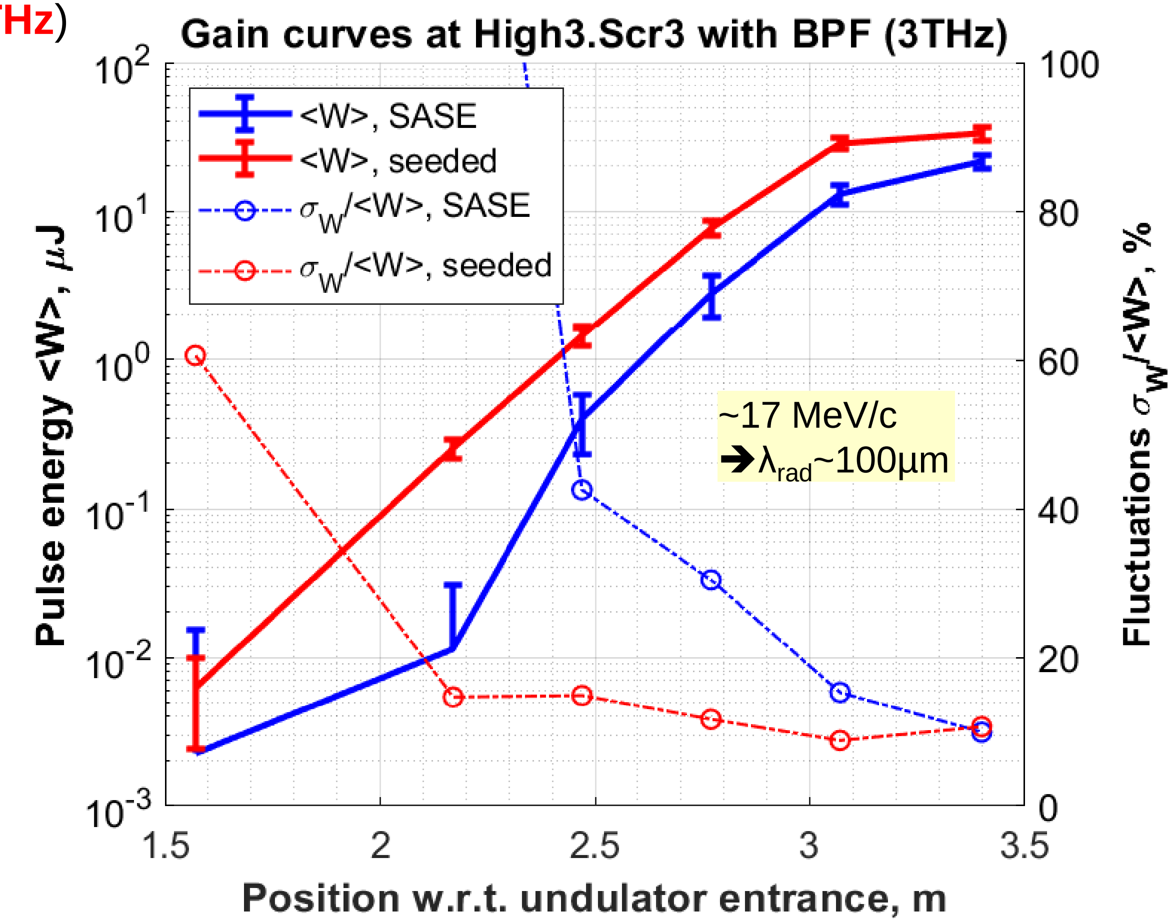

*Reference: E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, "On a theory of an FEL amplifier with circular waveguide and guiding magnetic field", Nucl. Instr. Meth. A 375, p. 241, 1996.*

# First Seeding Experiments

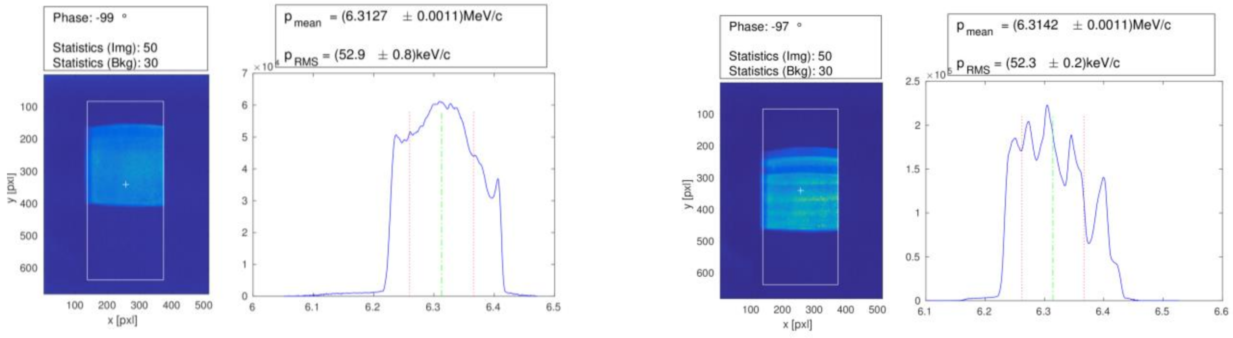
## SASE vs. seeded THz FEL with modulated photocathode pulse (preliminary results)

- Gain Curves at HIGH3.Scr3 (THz mirror w/o hole) with BPF (**3THz**)
- 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)




Seeded THz FEL gain curve:
- Higher energies + earlier start
- Better stability

# Simulations Challenges

## Shot (intrinsic) noise accurate modeling

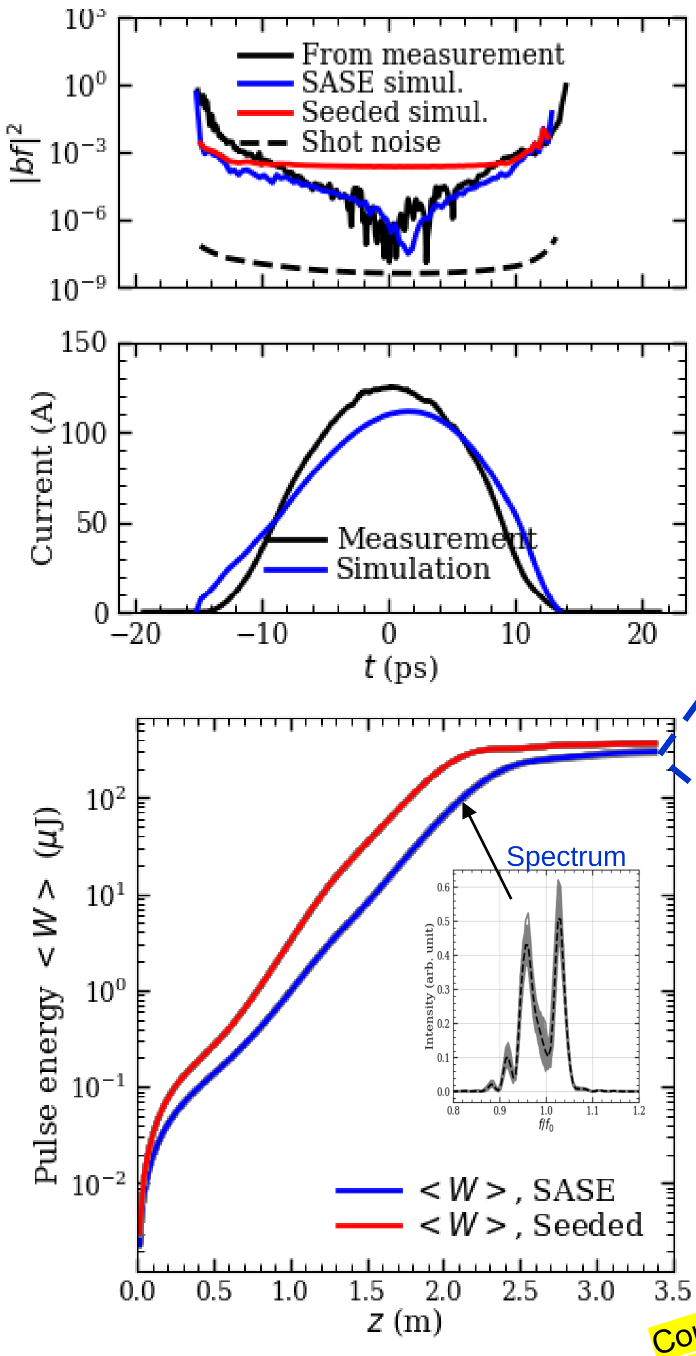
- The bunching factor

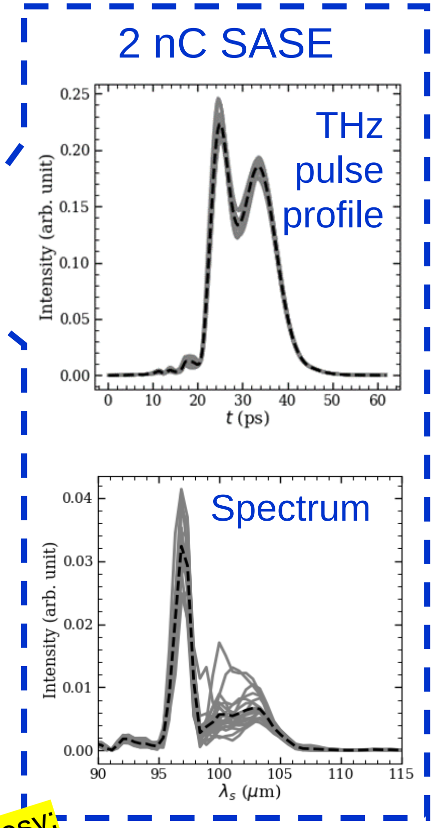
$$bf(\lambda,t) = \frac{1}{N_t} \sum_{n \in N_t}^{c|t_n - t| \le \lambda/2} e^{2\pi i \frac{c t_n}{\lambda}}.$$

- For random distribution, the square of bunching factor (or the shot noise) follows exponential distribution and we have $\langle |\boldsymbol{bf}(\boldsymbol{\omega})|^2 \rangle = \frac{\mathbf{1}}{\boldsymbol{N_e}}$, where $N_e$ is the number of electrons within one radiation wavelength,
  e.g., $I_{peak} = 2\text{ kA}, \lambda_s = 0.1\text{ nm}$ for XFEL and $I_{peak} = 200\text{ A},\ \lambda_s = 100\ \mu\text{m}$ for THz : Ne(THz)/Ne(XFEL) = **$10^5$ !**

- But, due to the longer wavelength of THz, the radiations actually see a density slope within one wavelength

- There are other possible reasons for an increased noise level at THz wavelengths (emission from cathodes, Boersch effect, etc.)



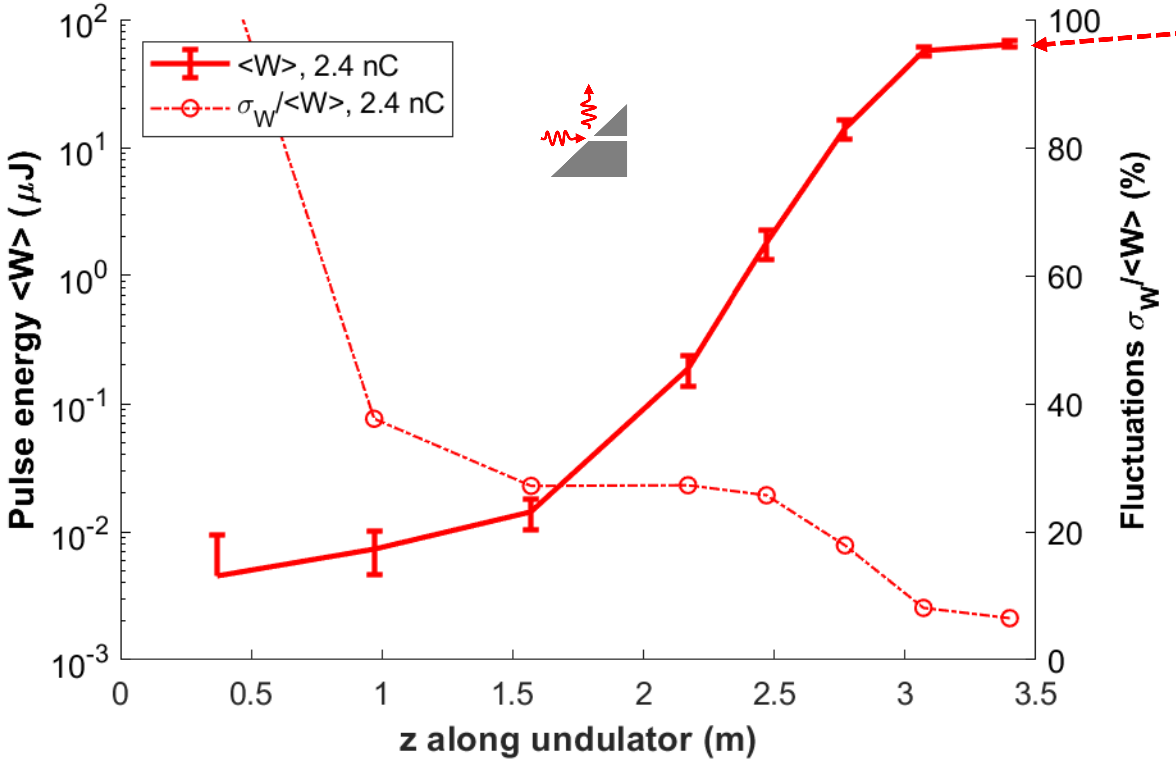



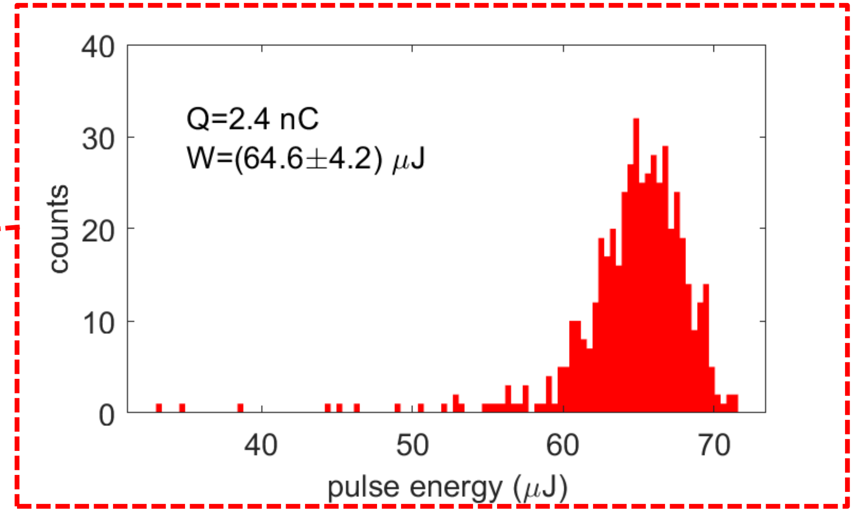

Courtesy: X.-K. Li

# THz SASE FEL at PITZ: Further Optimization

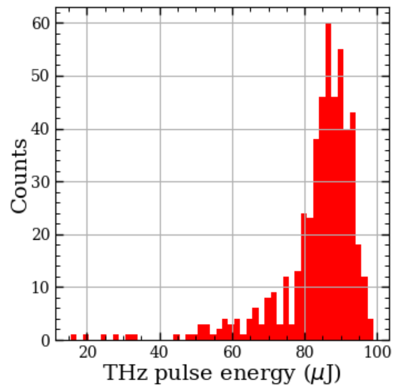
## High gain THz SASE FEL (~3THz) characterization

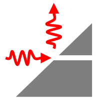
- Gain curves for 2.4nC at HIGH3.Scr2:
  - in-vacuum mirror with hole
  - No band-pass filter applied




**Currently max 3THz pulse energy at best setting:**
**$(83.8 \pm 13.3)$ μJ**
Q=2.4nC



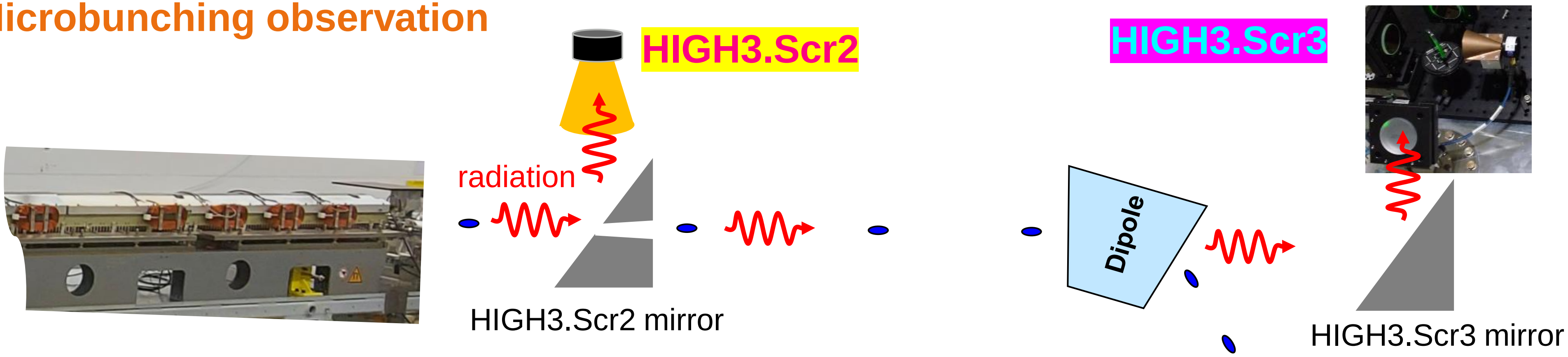



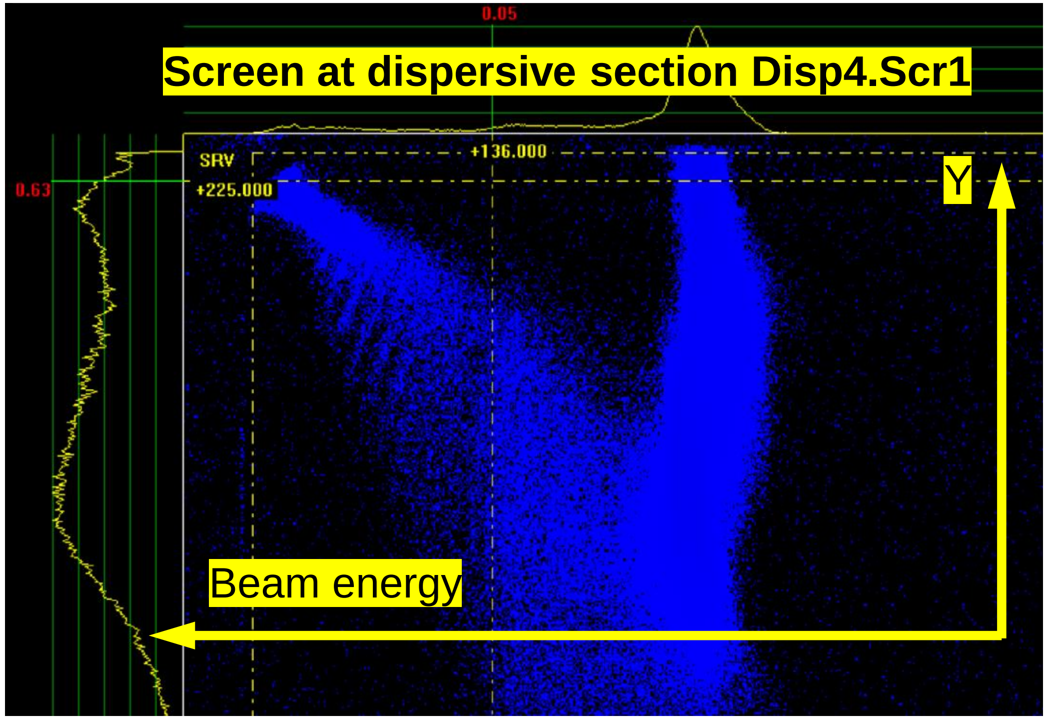
Estimated transmission ~50%

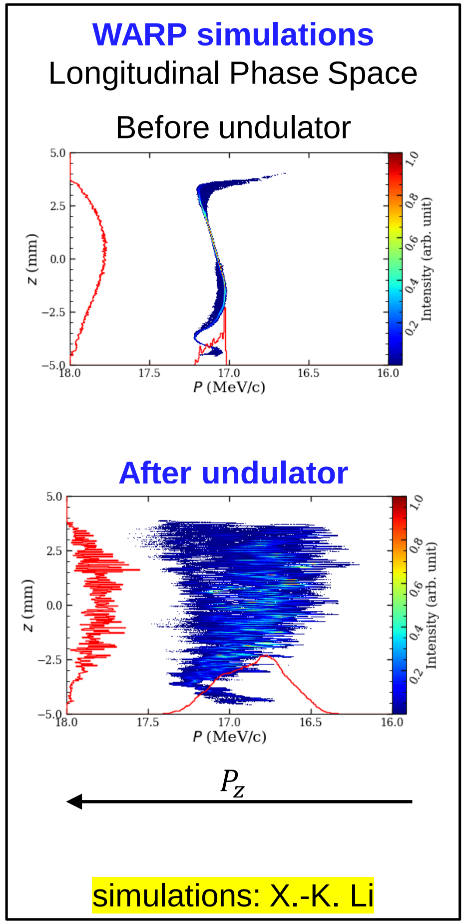
**>100μJ generated**

# Electron beam in dispersive section and pyrodetectors signals

## Microbunching observation

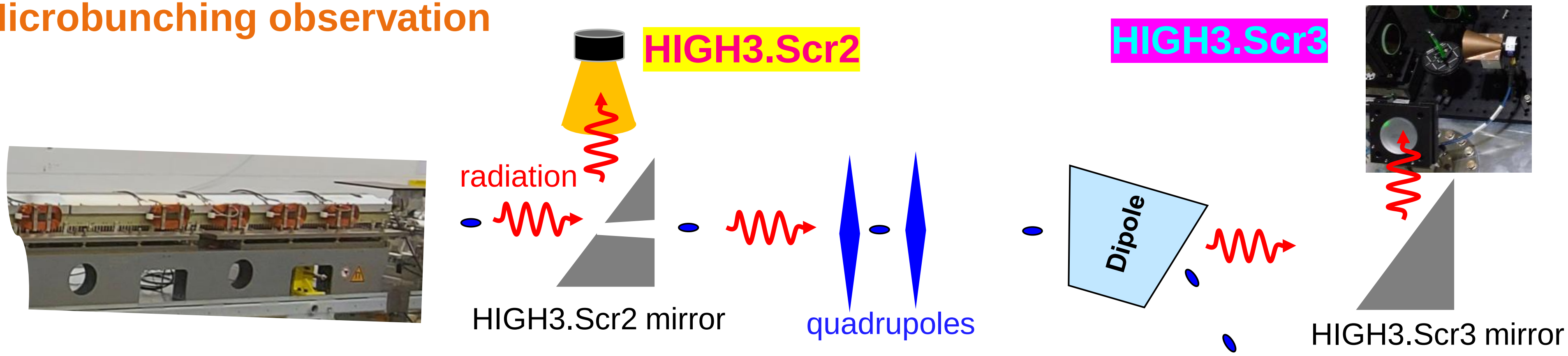


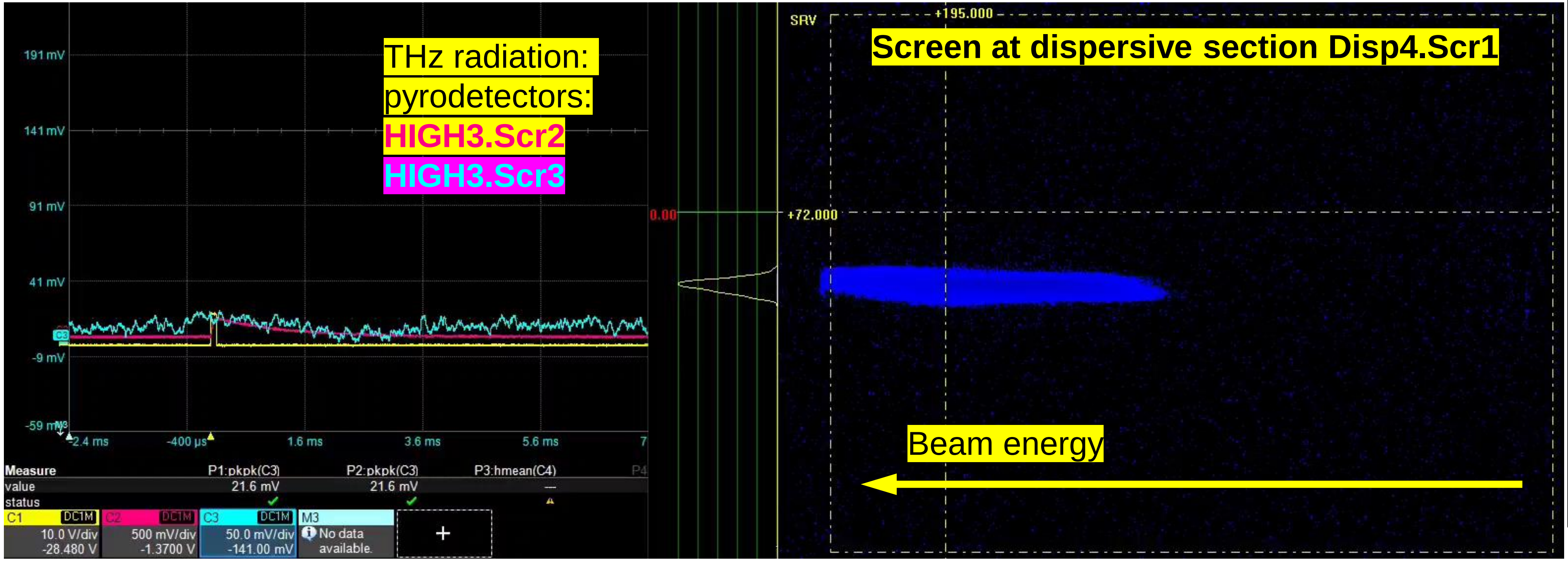



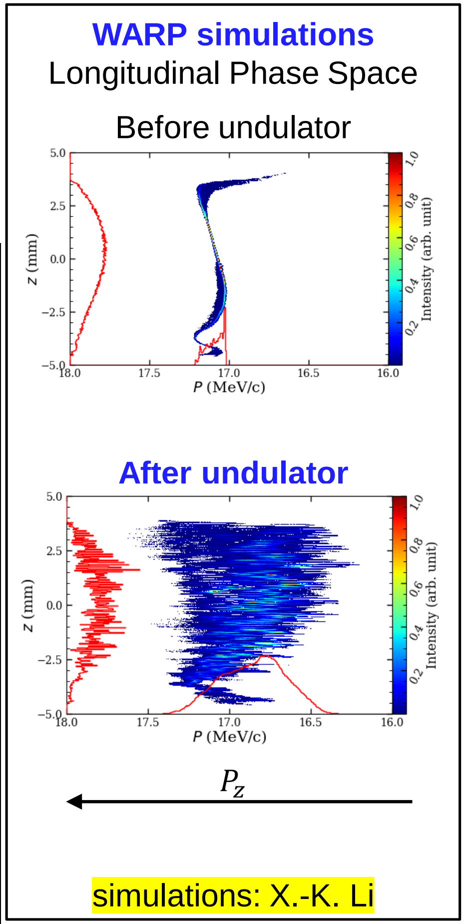



# Electron beam in dispersive section and pyrodetectors signals

## Microbunching observation



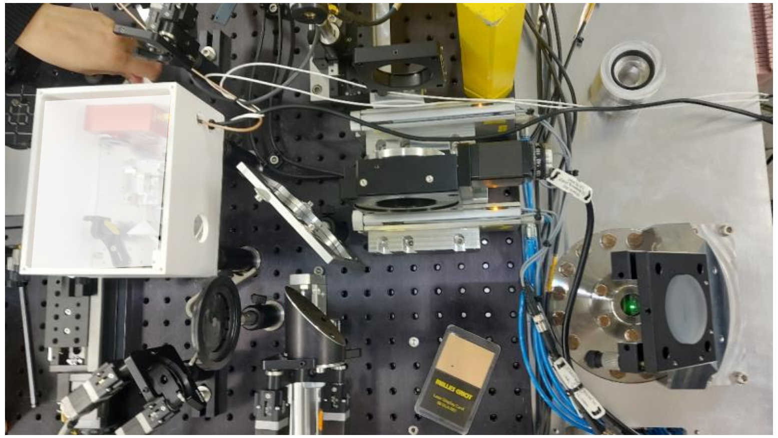



# THz FEL Spectrum Measurements at TD3 (High3.Scr3)

## 11.04.2024N, FTIR spectrometer measurements (with E. Zapolnova, FS-FLASH-B)

- TD3 with a compact broadband THz spectrometer
  based on the reflective lamellar grating, reference signal from the PITZ pyro
- Central wavelength ~ 2.82 THz ($\lambda rad$ ≈ 106.5 μm)



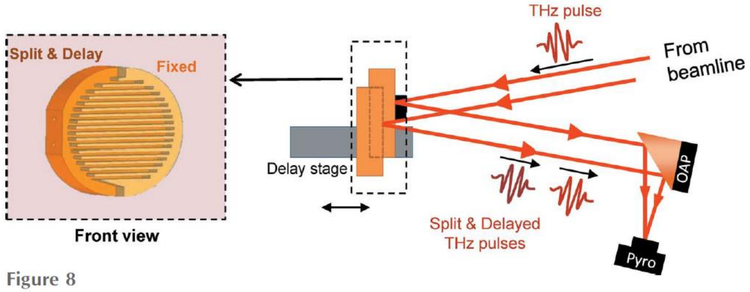
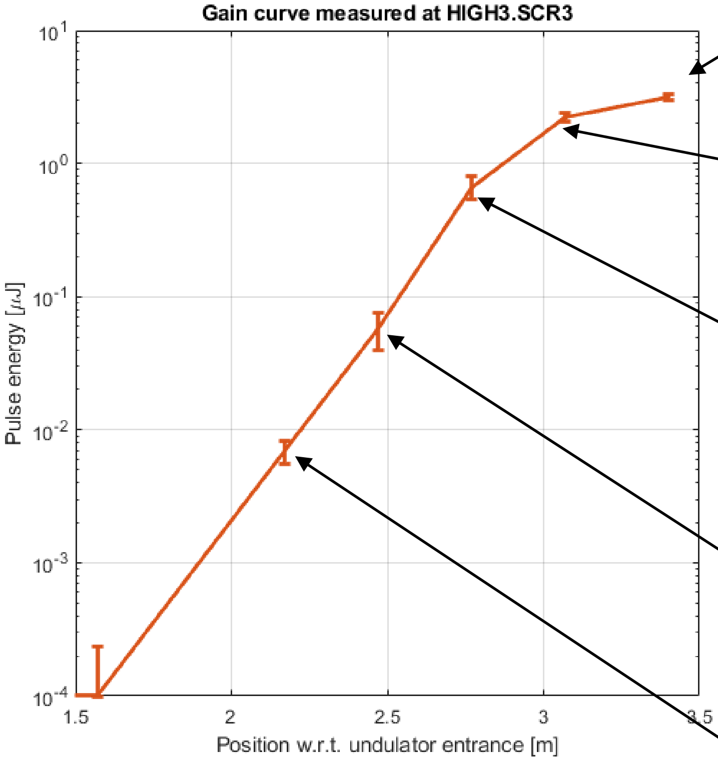
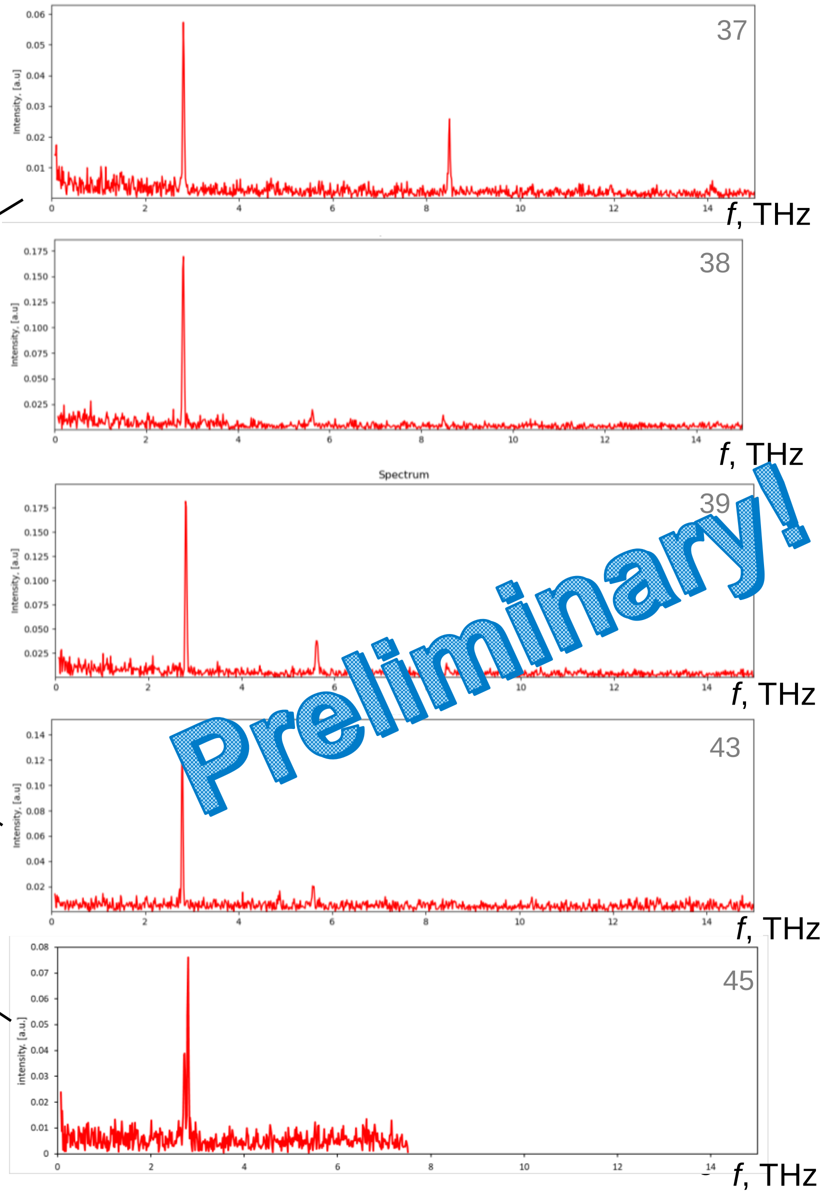



Figure 8
Scheme of the lamellar grating interferometer. OAP: off-axis parabolic mirror.

*R. Pan, E. Zapolnova, T. Golz, et al., (2019). Photon diagnostics at the FLASH THz beamline. J. Synchrotron Rad. 26, 700-707*



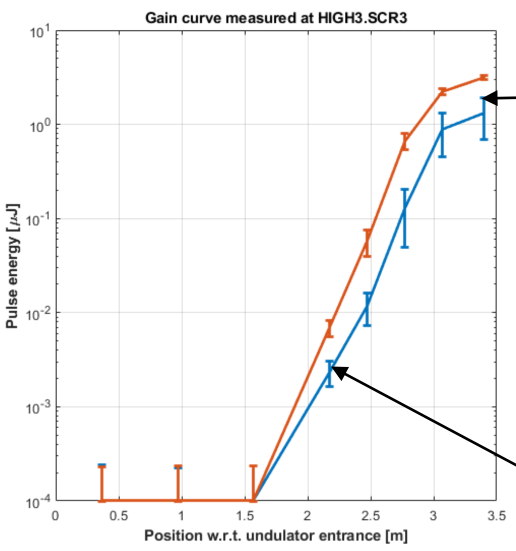



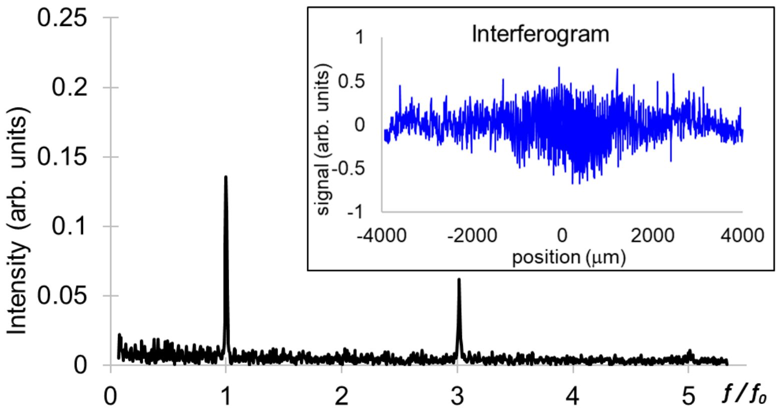

- **Narrow bandwidth demonstrated**
- **Harmonics observed**

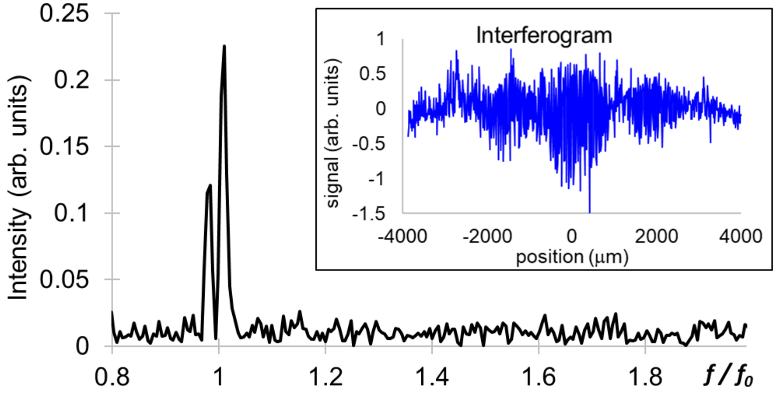
# THz FEL Spectrum Measurements at TD3 (High3.Scr3)

## 11.04.2024N, FTIR spectrometer measurements vs. simulations

- 2nC, central frequency around 2.82 THz (106.5 μm), reference signal - from PITZ pyro



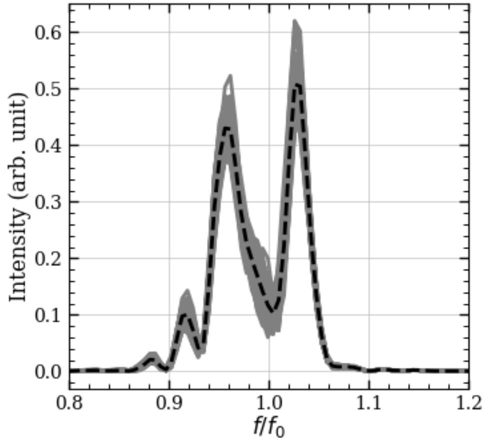




Preliminary!

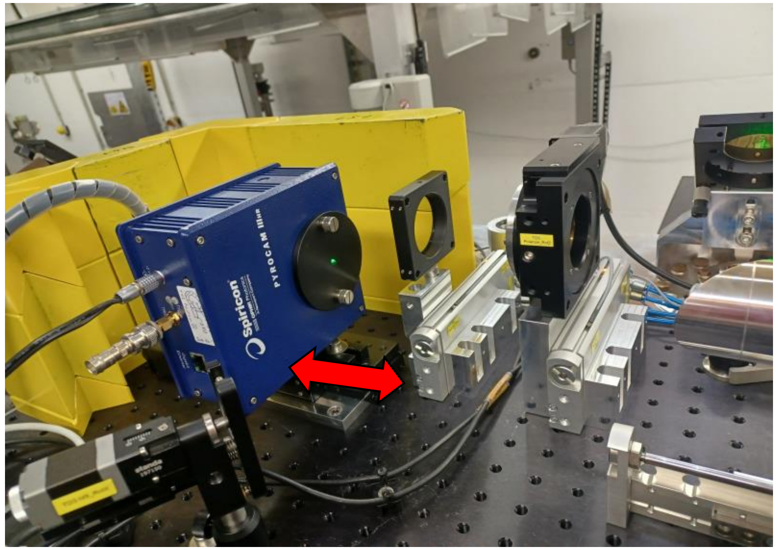
- Narrow bandwidth
- High harmonics
- Spectrum shape in linear regime

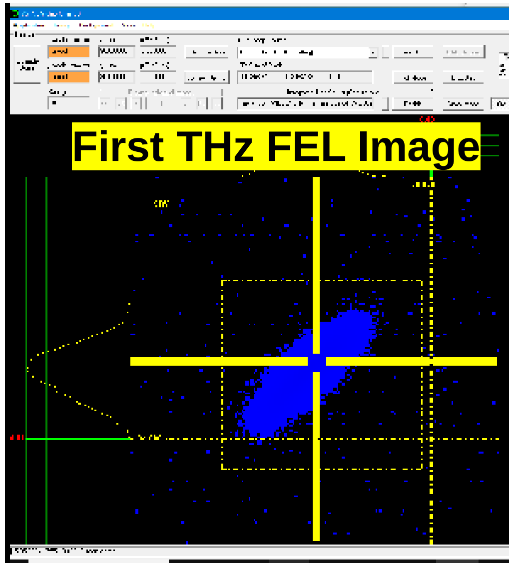
vs. GENESYS1.3 simulations

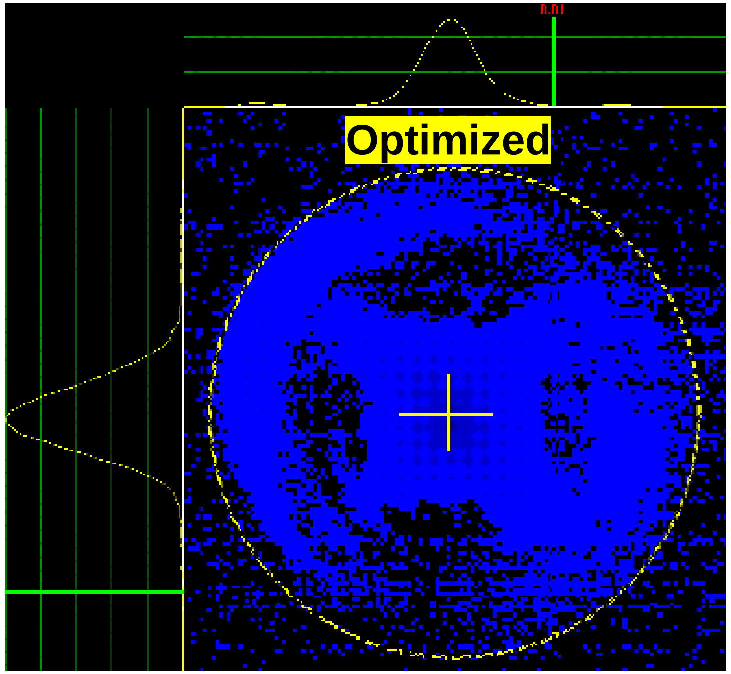


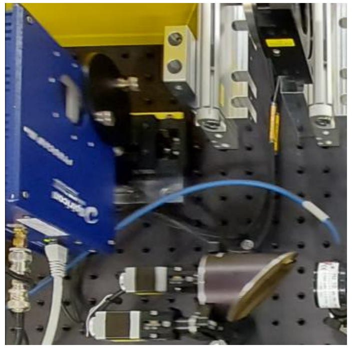
# First THz imaging with Pyro Camera

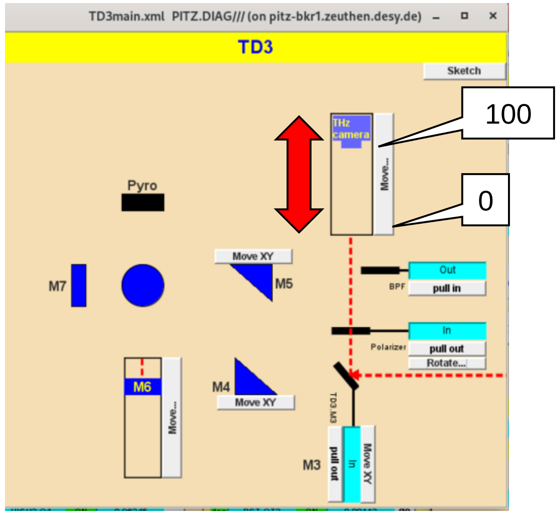
## Pyrocam IIIHR

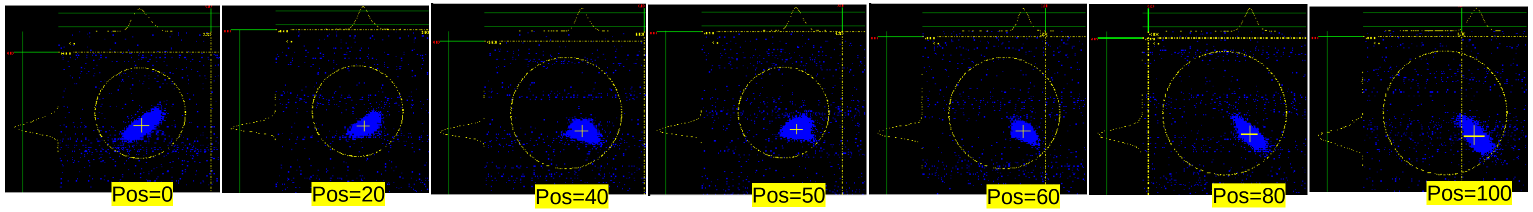


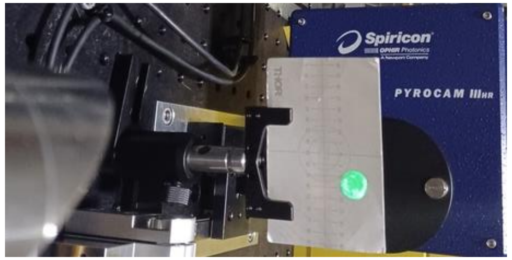





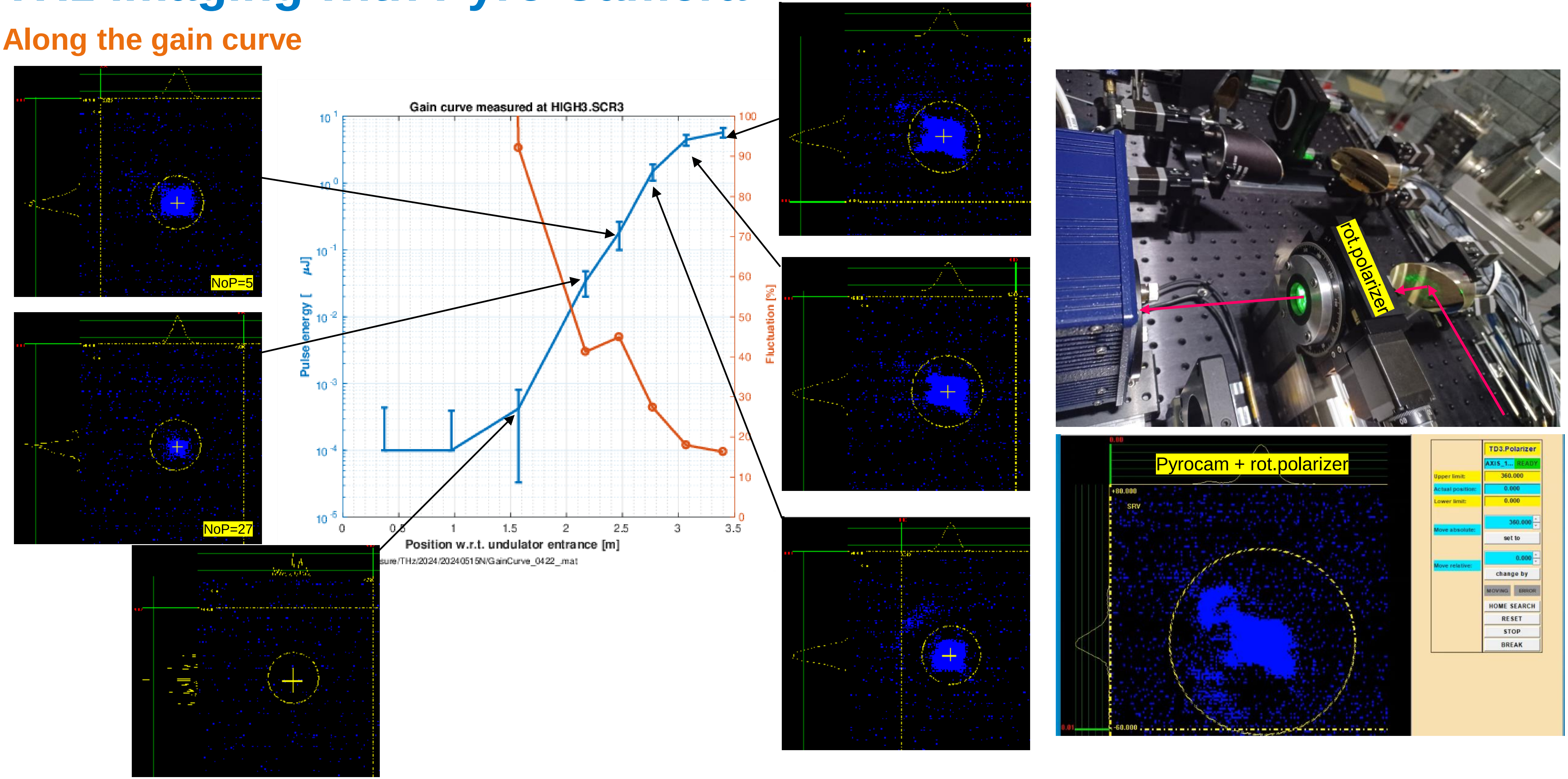




Recent alignment (TD3.M3 roll)



# THz imaging with Pyro Camera

## Along the gain curve



# Conclusions

## THz R&D at PITZ

- PITZ-like accelerator → **high-power tunable accelerator-based THz source** for pump-probe experiments at the European XFEL → **identical pulse train structure** + high (~2-4nC) bunch charge

### **Proof-of-principle experiments** at PITZ (supported by EuXFEL)

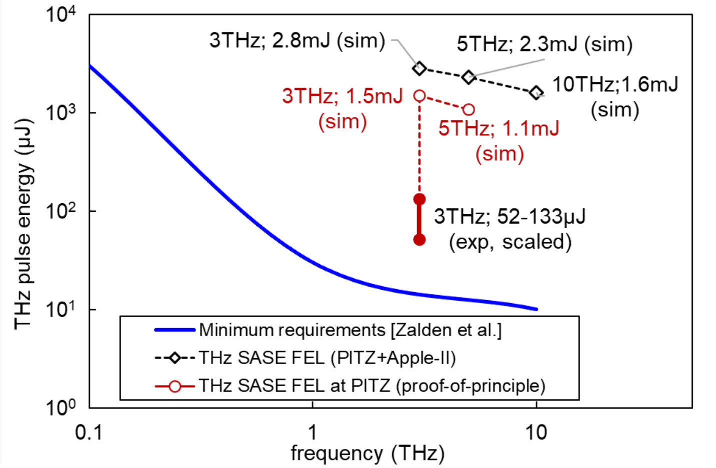
**Key findings / experiences gained / lessons learned** :

- **17m** new THz beamline at PITZ with *LCLS-I* undulator, including *BC*
- ***SC*** dominated beam transport and matching procedures
- Detailed FEL *simulations* → impact of the **bunching factor**
- Beam dynamics and FEL ***simulations*** for *THz@PITZ* and for the proposed *ideal machine (CDR studies)*

**Experimentally demonstrated**:

- **High-gain** THz FEL **lasing** at ~**3THz** with ~17MeV/c, 2nC *Gaussian* beams, **more than 100μJ generated,** THz pulse energy fluctuations ~6-10%
- 1st **seeding** with modulated PC laser pulses
- Narrow **bandwidth** (1st FTIR measurements)
- 1st THz radiation imaging

| Still to demonstrate | Current limitations, risks |
|---|---|
| More tunability – 5THz, 1THz(?) | Beam time (stable gun), supporting simulations (ongoing), finalization of special experimental procedures |
| Further seeding studies (e.g., DLW, 2 bunches) | |
| Use BC to explore the parameter space | |
| Spectral studies (FTIR and MIF) | Complete fabrication / installation of the THz diagnostics stations |
| Transverse distribution with Pyrocam | |
| Flattop PC laser pulses | Full performance of the NEPAL-P |



# THz@PITZ Team and Collaboration

## Proof-of-principle experiment on high power THz source

**DESY Zeuthen**

Physicists:
- Z. Aboulbanine*
- G. Adhikari*
- *N. Aftab*
- *P. Boonpornprasert**
- *G. Georgiev**
- J. Good
- M. Gross
- A. Hoffmann
- E. Kongmon*
- *M. Krasilnikov*
- *X.-K. Li*
- *A. Lueangaramwong**
- R. Niemczyk*
- A. Oppelt
- H. Qian*
- C. Richard
- F. Stephan
- G. Vashchenko
- T. *Weilbach**
- *X. Zhang*

* → left PITZ for other lab

Special thanks to CANDLE colleagues participated in THz commissioning and lasing shifts!

Engineers and Technicians:
- 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

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

**DESY Hamburg**
- E. Schneidmiller
- M. Yurkov
- B. Krause
- M. Tischer
- P. Vagin

**Uni Hamburg**
- J. Rossbach
- W. Hillert

Thank you!

# Radiation Biology at PITZ: FLASH RT Studies

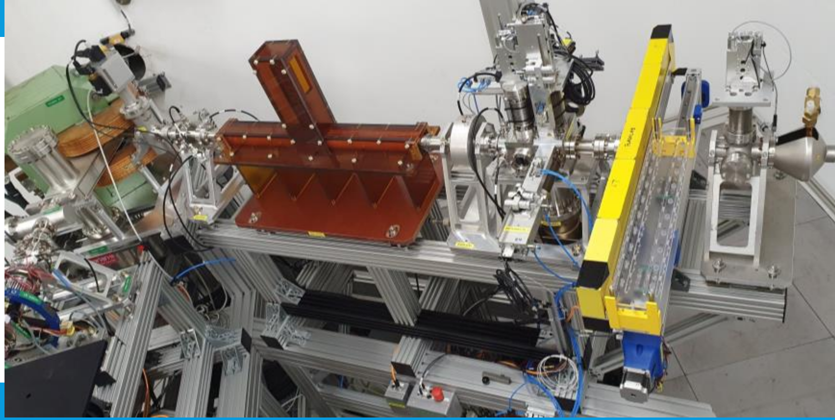
*courtesy S. Gohari*

## FLASH*lab*@PITZ

## DESY

## Zeuthen, Germany

Frank.Stephan@desy.de
https://pitz.desy.de/
https://pitz.desy.de/research_and_development/flashlabpitz/



| Particle type | Electrons |
|---|---|
| Source / accelerator | Photoinjector with Linac |
| Energy (min. max.) [MeV] | 6 – 22 |
| Dose rate (min. max.) Gy/s | 0.05 – $10^6$ (pulse) – $10^{12}$(peak) |
| Beam time structure | Pulsed, adjustable # bunches |
| **Homogeneous application:** | |
| Field size (max.) [mm x mm] | 20 x 20, > at longer distance |
| **Minibeam application:** | |
| Beam size [µm] | 20 – 300 @exit window |
| Beam production | focusing or collimation poss. |
| Beam application | scattering or scanning poss. |

**Sample environment:**

Startup beam line: experimental area with water bath or with moving stage (10 samples, 10-300 µL)
Full beam line (installation planned to start summer 2024): experimental area with robotic arm, online dosimetry and moving water bath (up to 27 samples, planned 10-300 µL)

**Experimental environment:**

*in vitro* experiments: chemistry, 2D and 3D cell culture, sample prep and analysis
*in vivo* experiments: animal biolab under prep for zebrafish embryo and mice (to be operational in 2024)

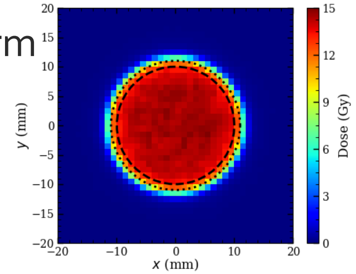
**Facility access:**

To apply for beam time:
https://pitz.desy.de/research_and_development/flashlabpitz/beam_time_request

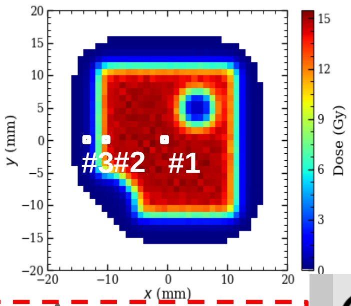
F. Stephan, et al. Physica Medica 104 (2022): 174-187.

# ONGOING CONSTRUCTION & UPGRADE for FLASHlab@PITZ

- Wide and uniform irradiation with **scatterer and/or collimator**

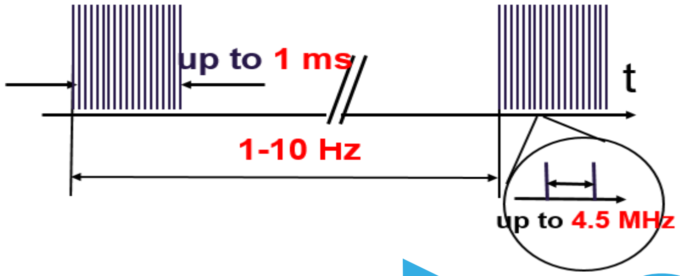


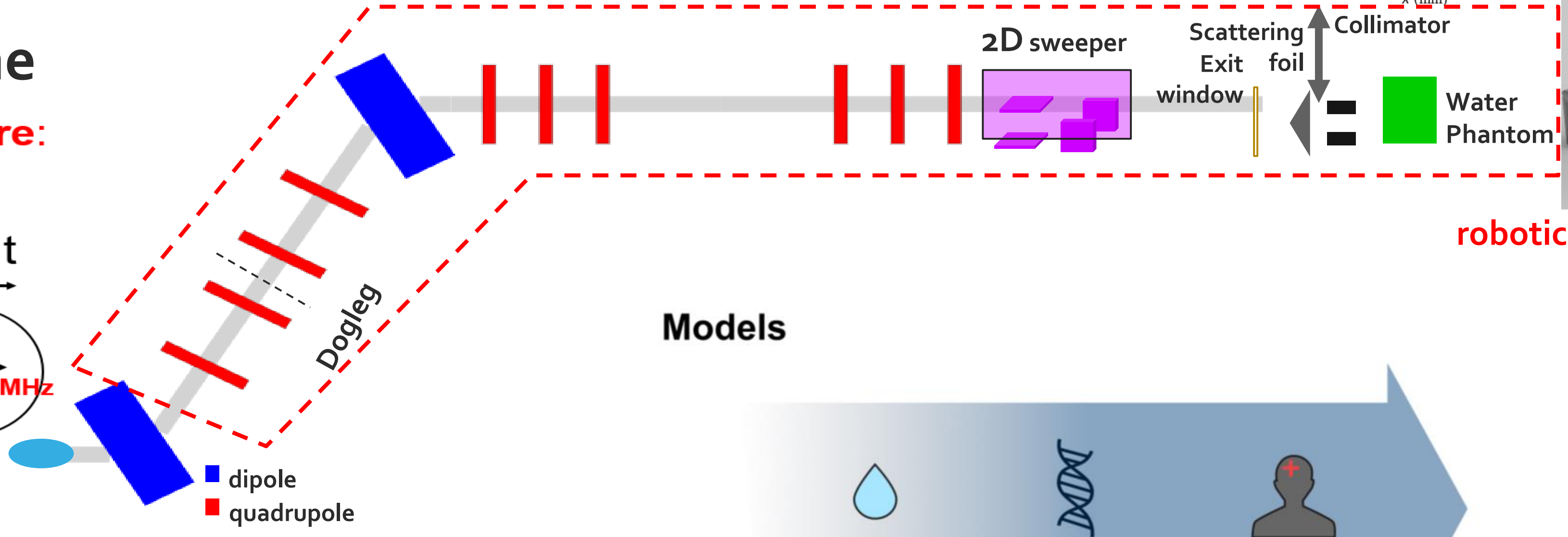

- Arbitrarily distributed target with **2D sweeper**




- **Full FLASH-beamline**

**Pulse Train Time Structure:**



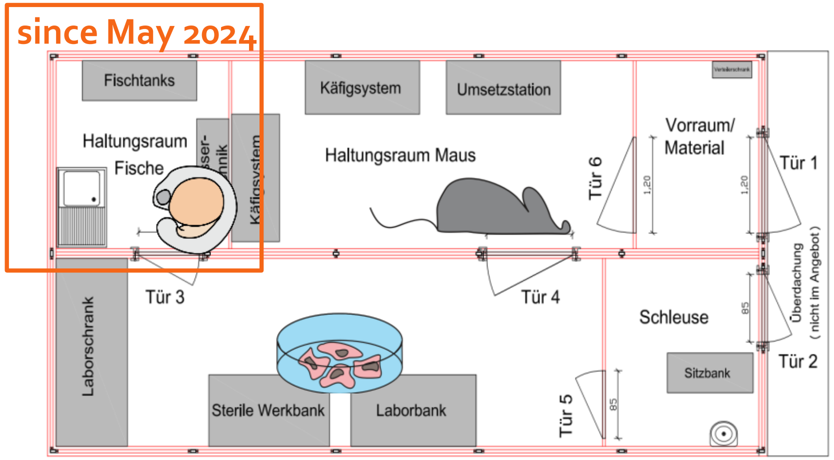





Property of Dr. Pierre Korysko

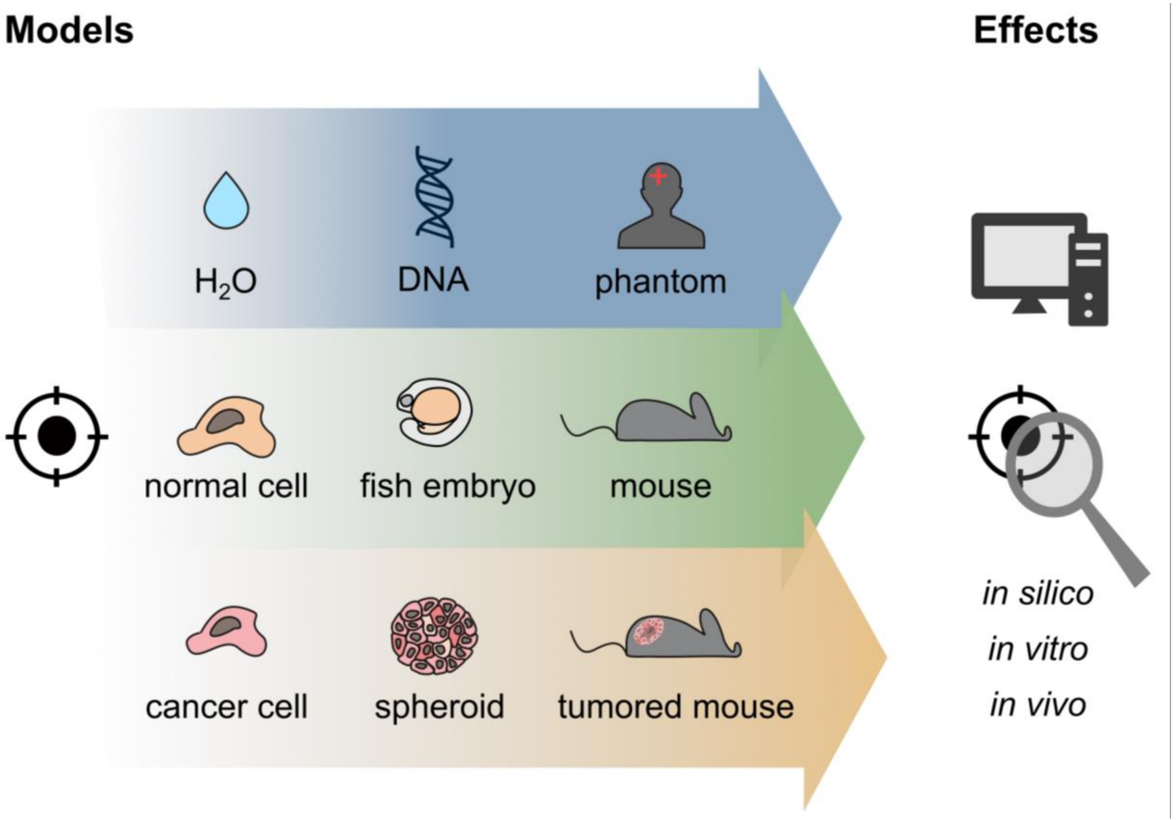
robotic experimental area

- **Animal biolab under prep**




MDC MAX DELBRÜCK CENTER FOR MOLECULAR MEDICINE IN THE HELMHOLTZ ASSOCIATION

DIfE Deutsches Institut für Ernährungsforschung Potsdam-Rehbrücke



# Thank you!