THz SASE and seeded FEL at Photo Injector Test facility at DESY in Zeuthen (PITZ)

PITZ developments on THz source for pump-probe experiments at the European XFEL

Mikhail Krasilnikov for THz@PITZ team
LEDS2023, ENEA Frascati, 03.10.2023

THz@PITZ Team and Collaboration

Proof-of-principle experiment on high power THz source

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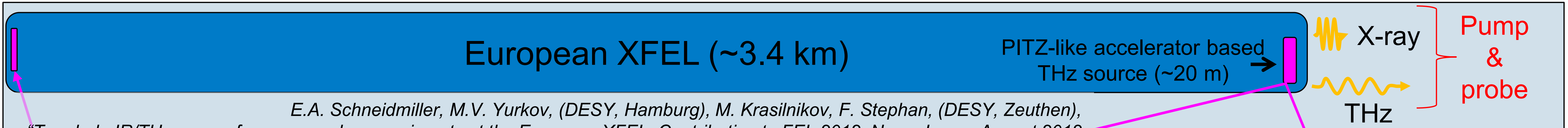
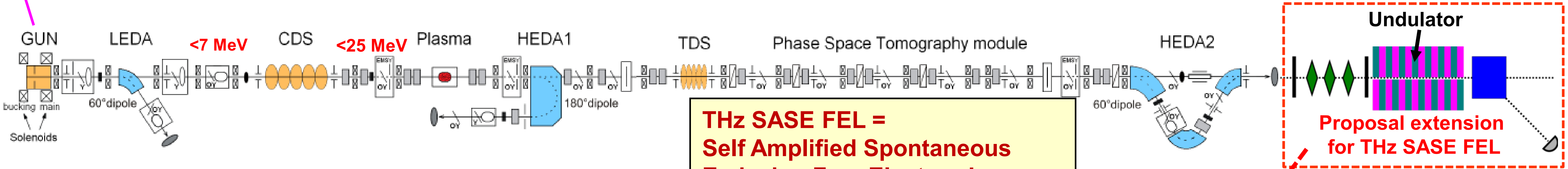
THz SASE FEL source for pump-probe experiments at European XFEL

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

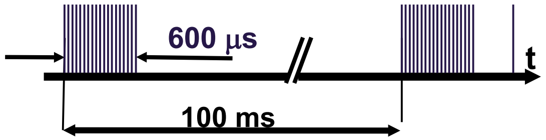


THz SASE FEL =
Self Amplified Spontaneous Emission Free Electron Laser

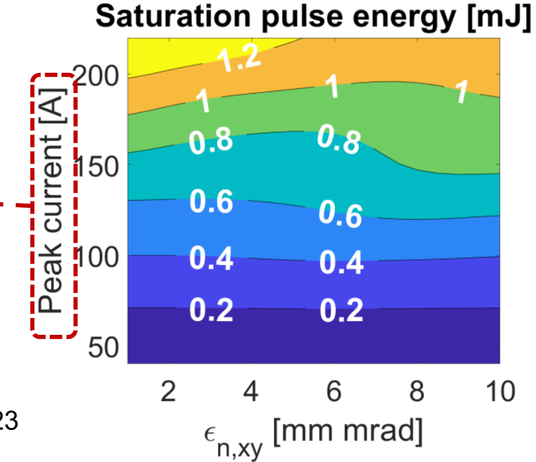
for λ_{rad} > 100 µm (f < 3 THz) → CTR / CDR / SUR?

~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**



SASE FEL "ideal" simulations assuming:

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

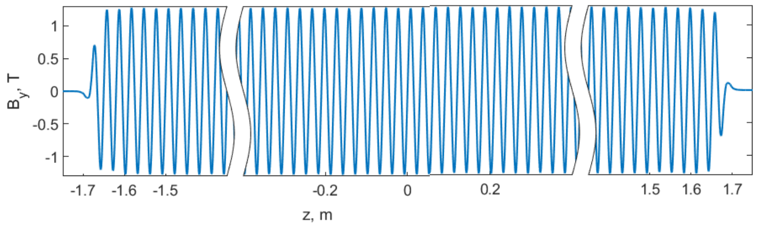
Undulator for proof-of-principle experiment?

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

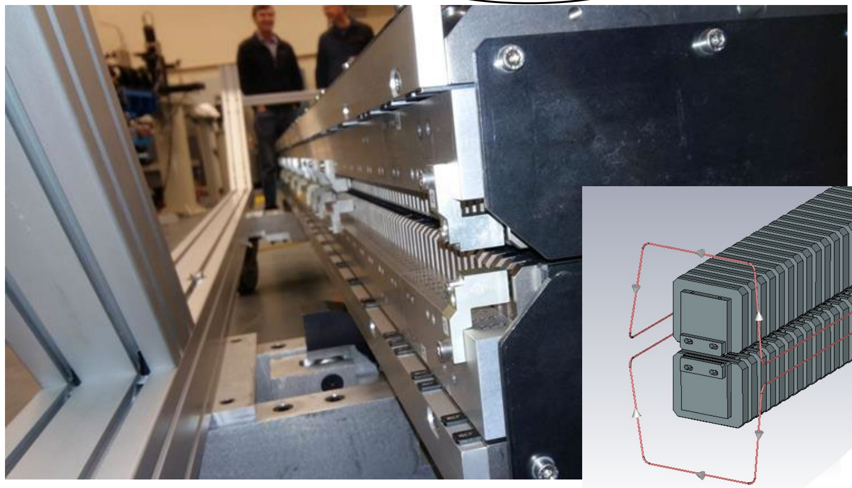
Using LCLS-I undulators (available on loan from SLAC)

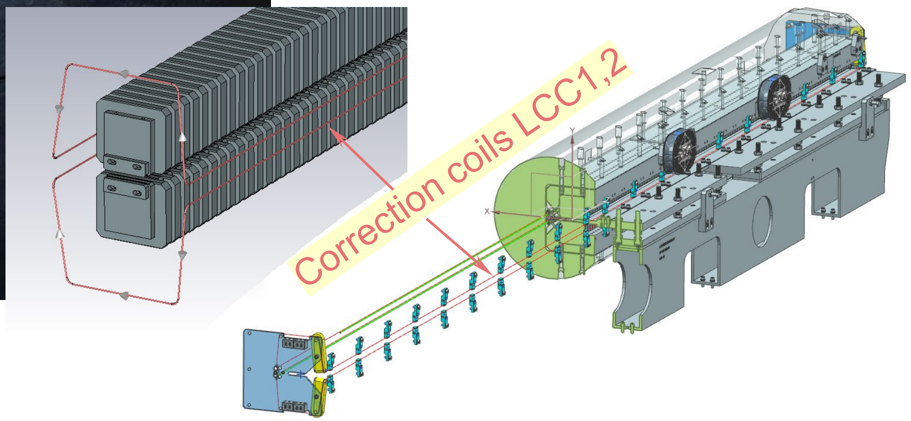
Some Properties of the LCLS-I undulator

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** **W**
Period length	30 mm
Periods / a module	113 periods



PITZ+ LCLS-I Undulator





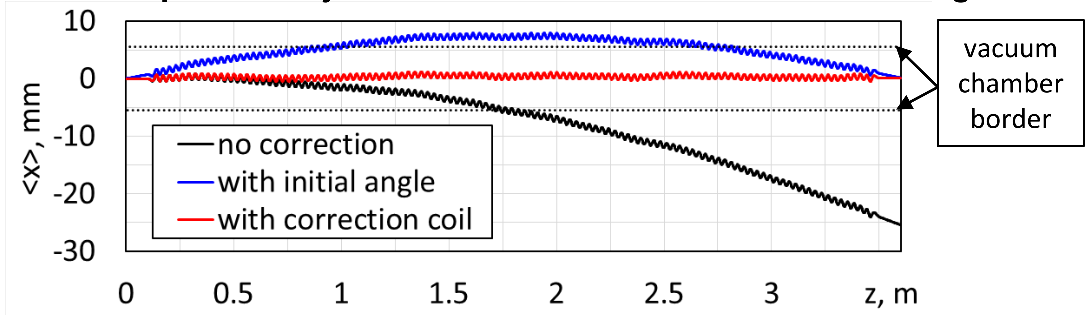
λ_{rad}~100μm → ~**17MeV/c**

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)**

<u>Main challenges:</u>

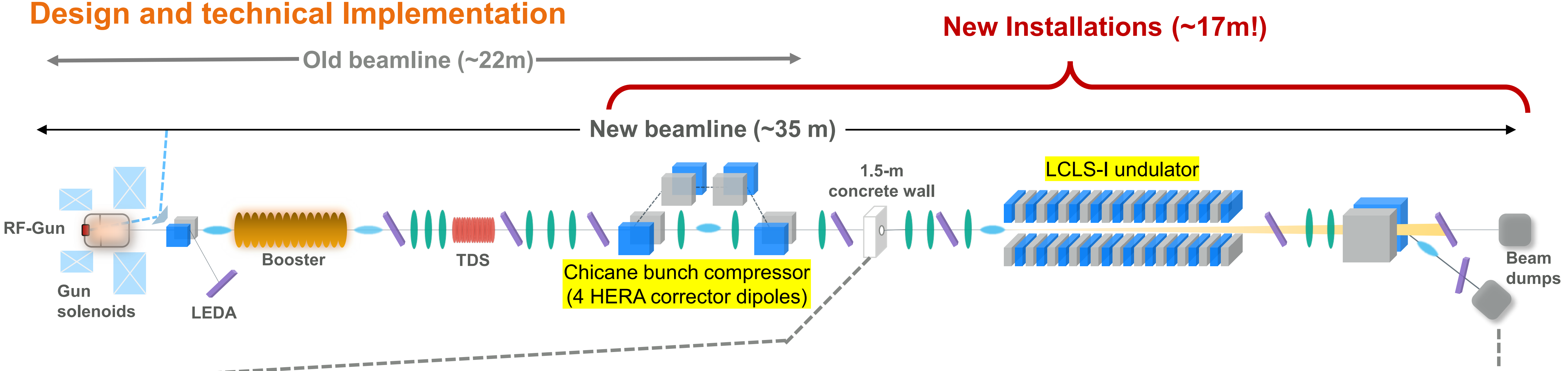
- Space charge effect
- Strong undulator (vertical) focusing + horizontal gradient
- "Full physics" might have to be considered
- Waveguide effect **W**
- Wakefields: geometric and conductive wall effects

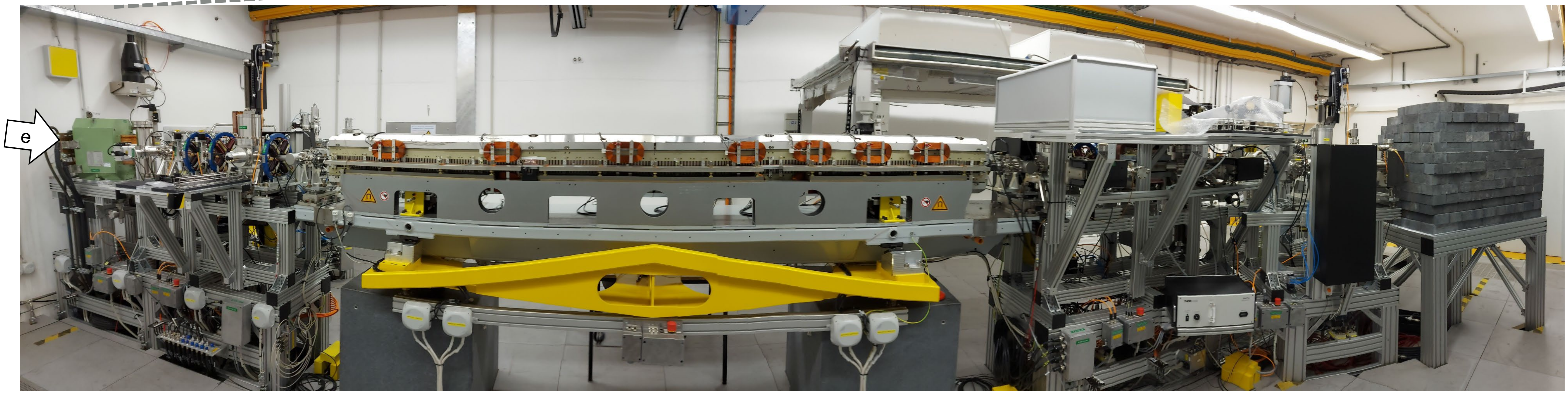
Reference particle trajectories in the undulator with horizontal gradient



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

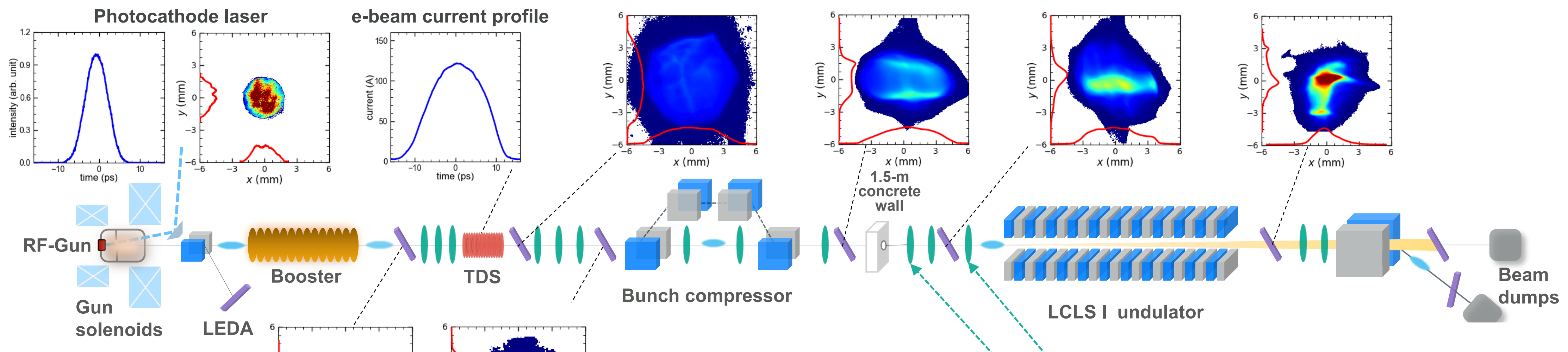
Design and technical Implementation

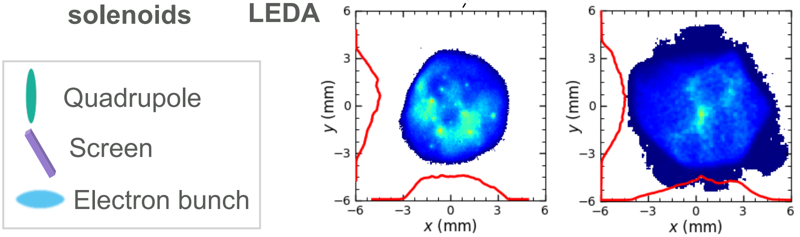


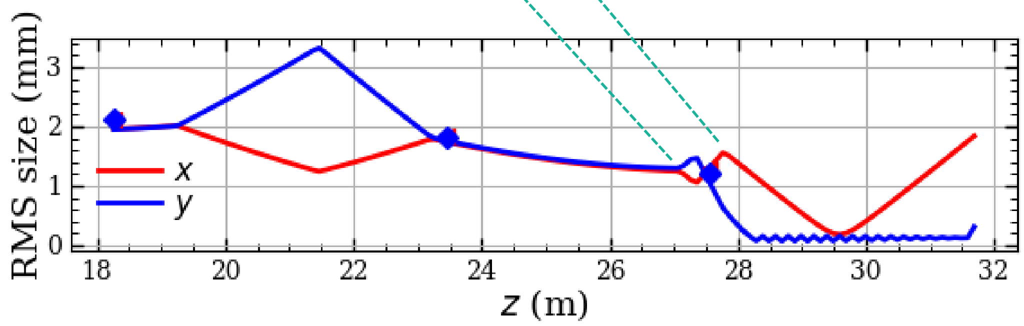


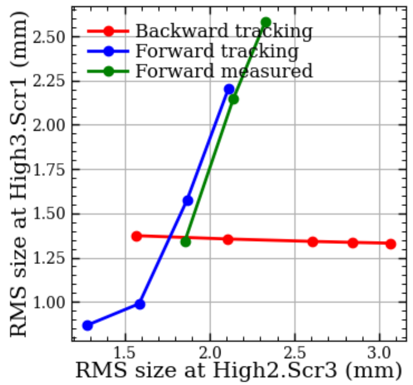
THz SASE FEL at PITZ, $\lambda_{rad} = 100\mu m$

Space charge dominated electron beam transport over ~27m, 2nC, 17MeV/c









Main challenges:

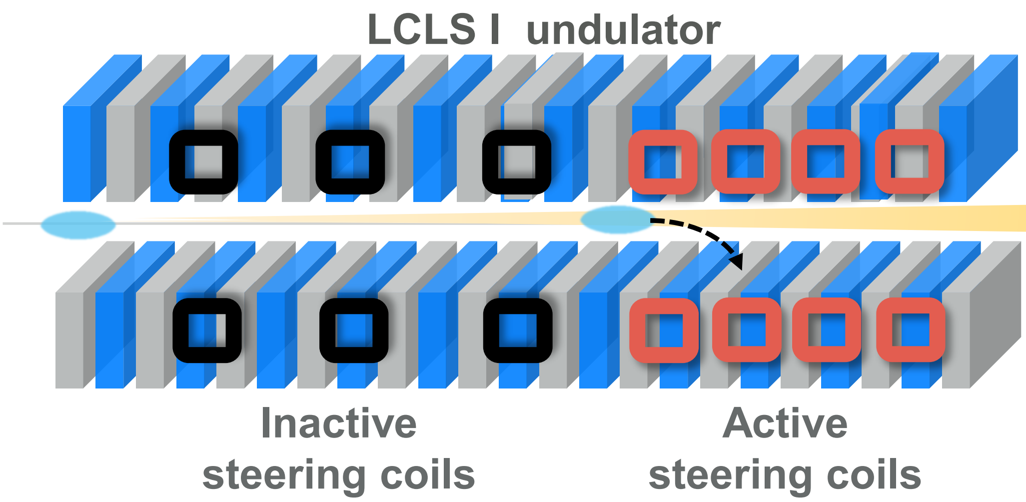
- Space charge effect
- Geometric wakefields (apertures)
- Matching into the LCLS-I undulator:
  - Narrow vacuum chamber
  - Strong vertical focusing
  - Lattice constrains

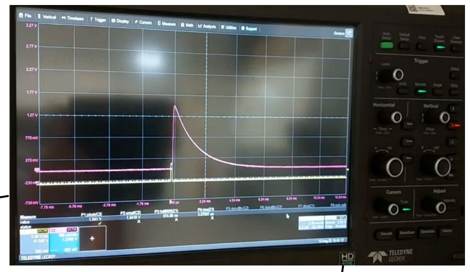
X.-K. Li et al., "Matching of a space-charge dominated beam into the undulator of the THz SASE FEL at PITZ," in 12th Int. Particle Acc. Conf., IPAC2021, Campinas, 2021.

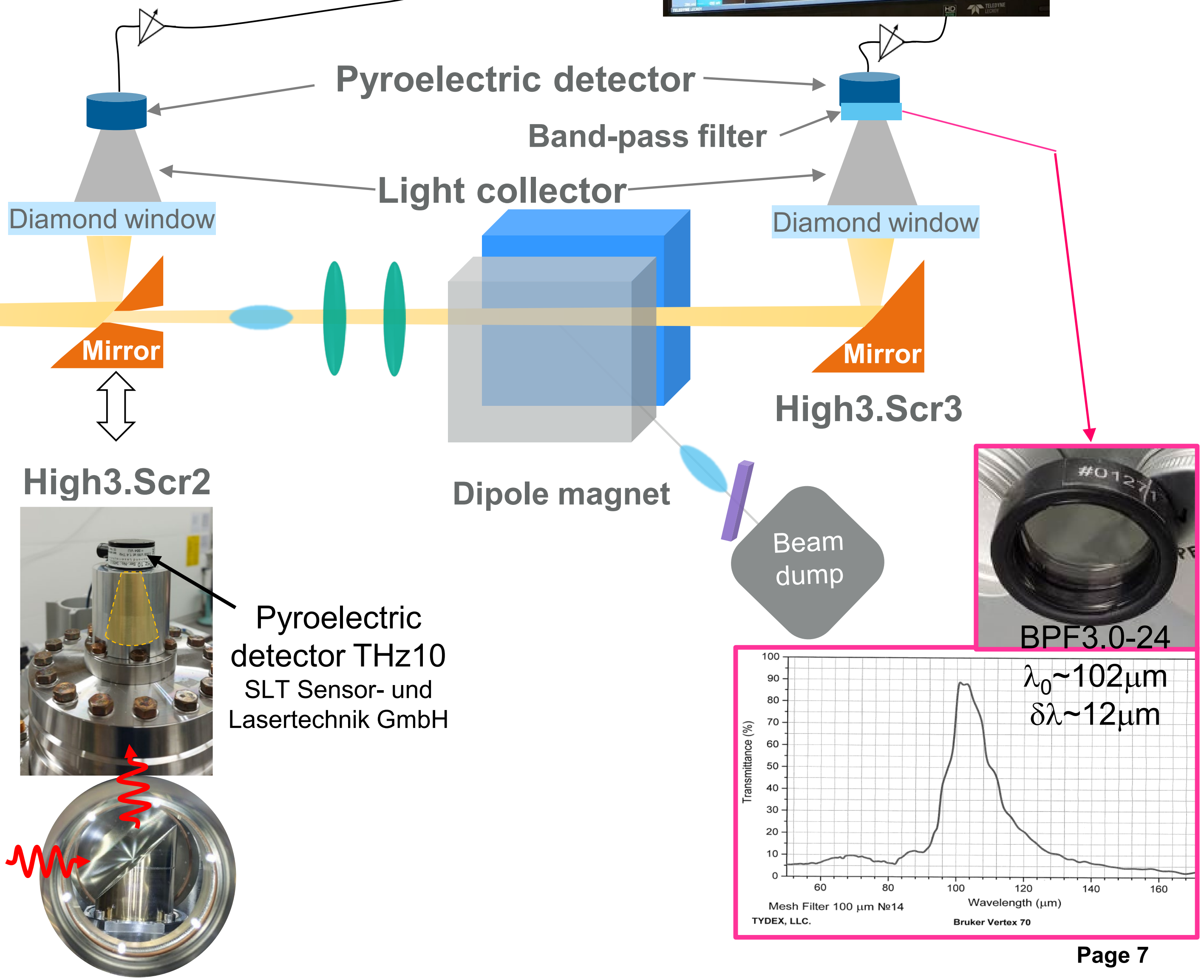
THz SASE FEL at PITZ: THz diagnostics setup

Startup: pyroelectric detectors with collector cones

Simplified layout of the gain curve measurement setup



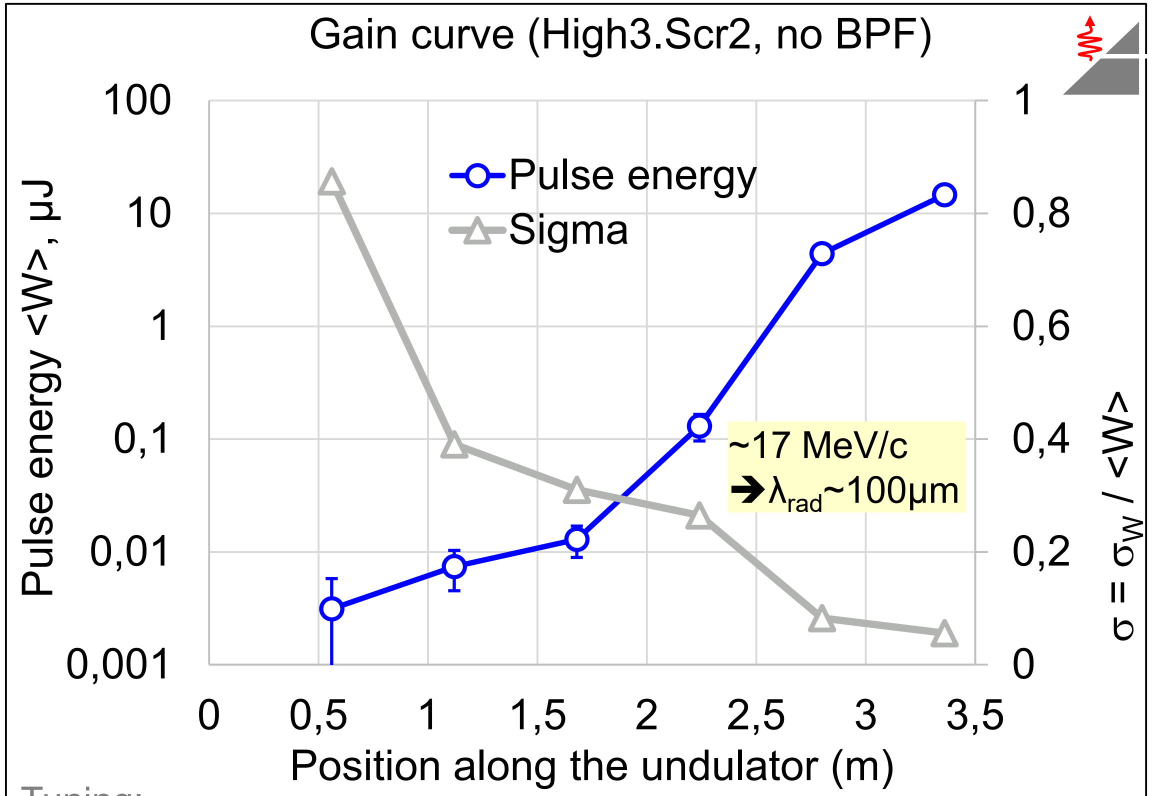




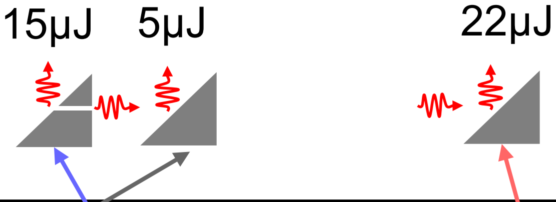
	High3.Scr2	High3.Scr3
Estimated transmission	49%	63%

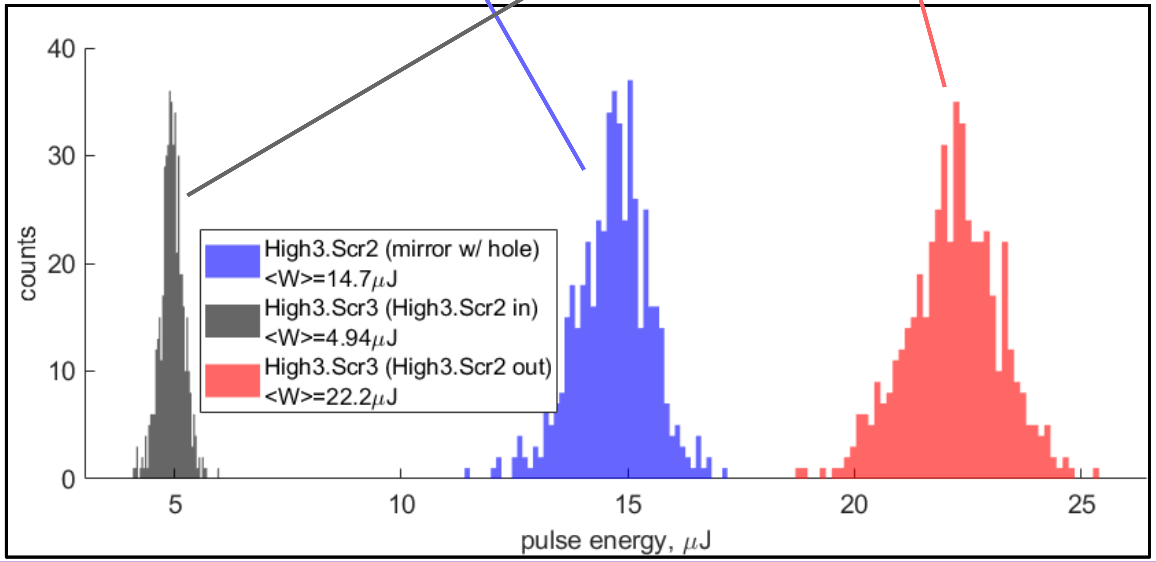
THz SASE FEL at PITZ

Saturation observed for 2nC: max pulse energy~22μJ at High3.Scr3

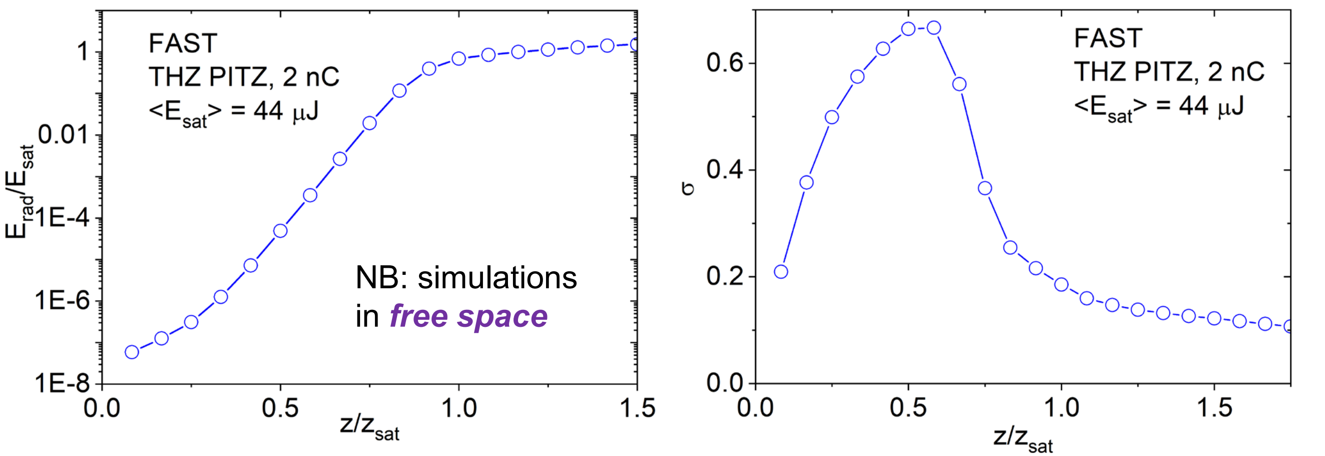


Tuning: started from 3nC!





FAST Simulations (M. Yurkov)



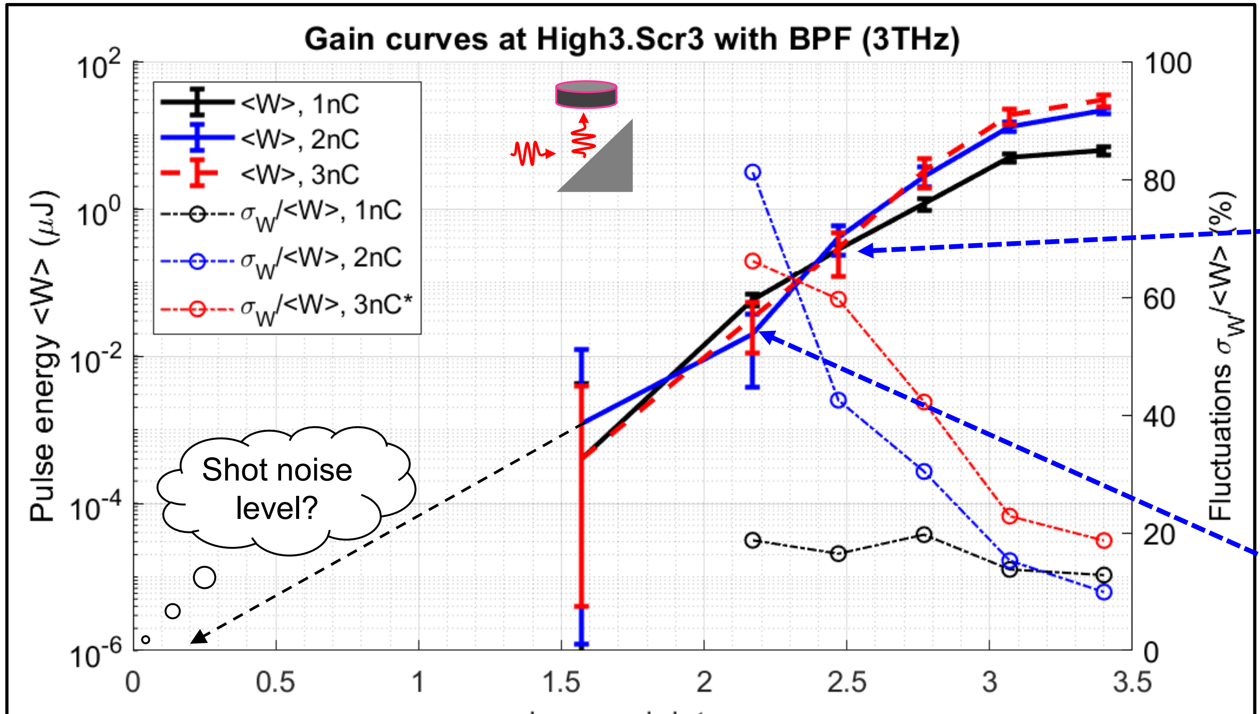
NB:
- Strong ***waveguide regime*** of SASE FEL **W**
- WARP (PIC) simulations with vacuum chamber border yield ×2-3 higher THz pulse energy

THz SASE FEL at PITZ: Gain Curves

High gain (~10^6) THz SASE FEL characterization

Gain curves for 1nC, 2nC and 3nC measured at HIGH3.Scr3:

- in-vacuum mirror without hole
- band-pass filter (BPF3.0-24) applied

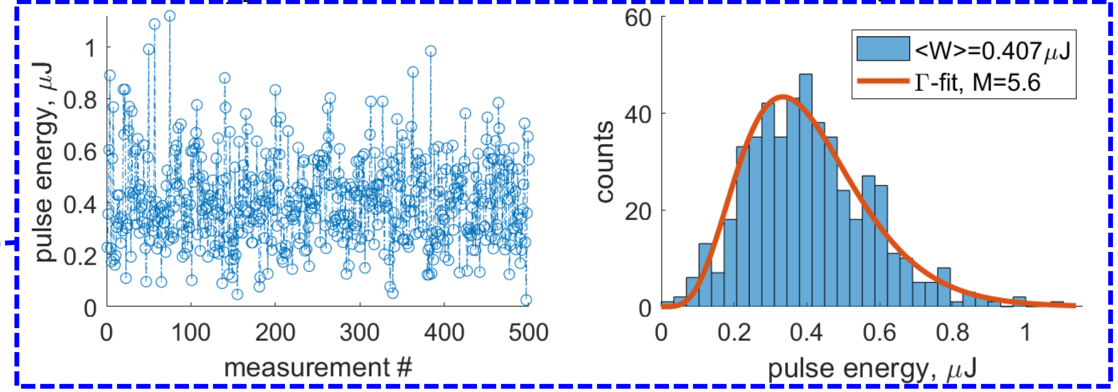


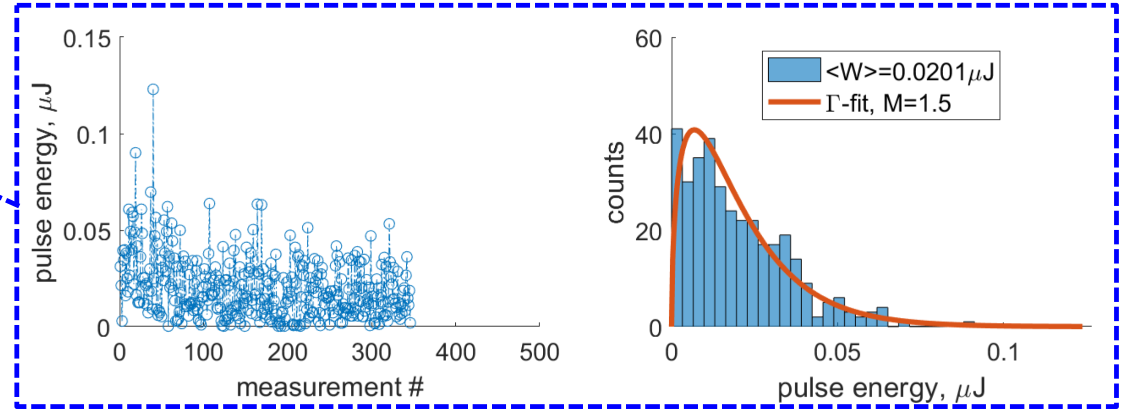
*not fully optimized (3nC)

Probability distribution of the radiation pulse energy from SASE FEL operating in the high gain linear regime follows gamma distribution**:

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

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



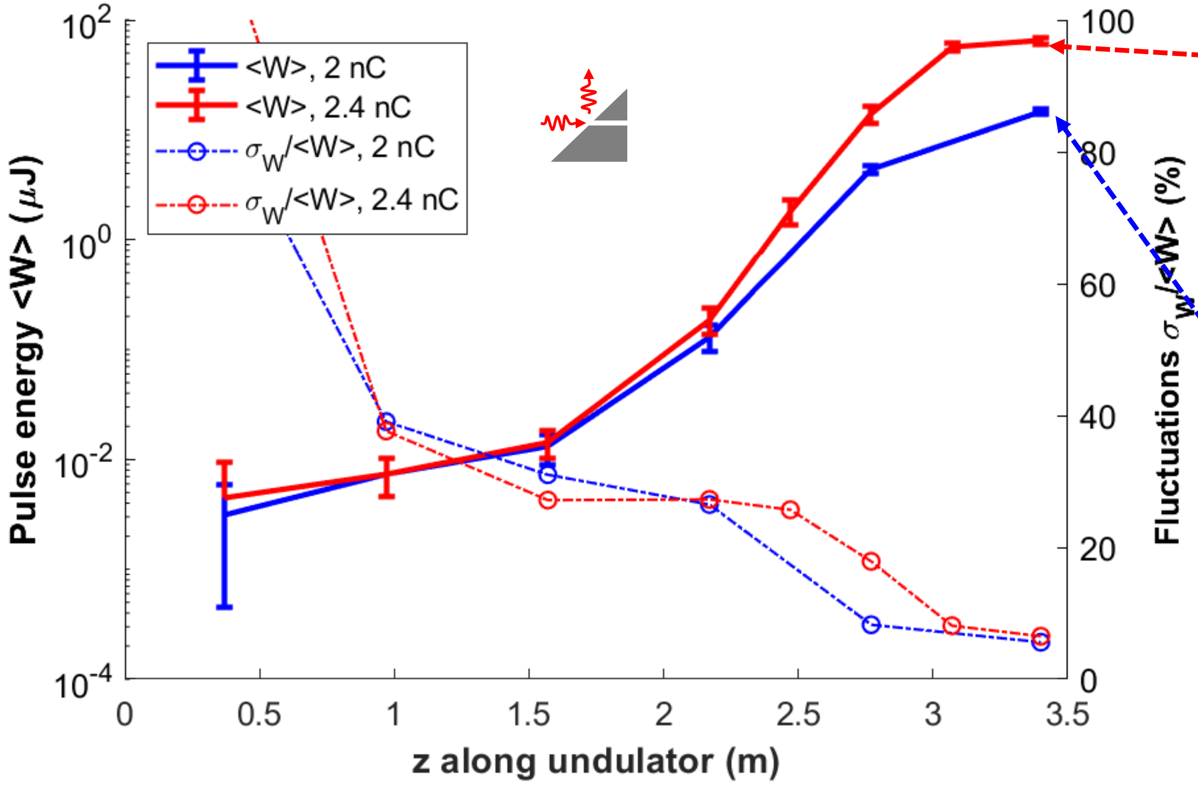


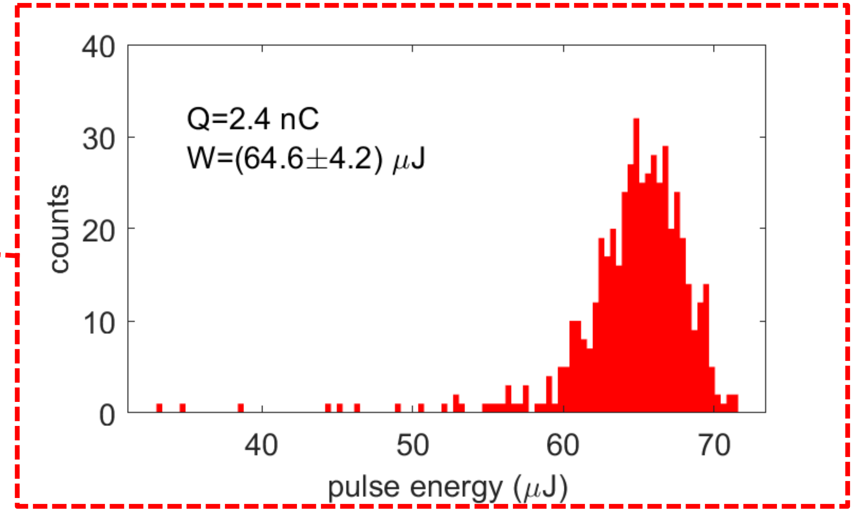
**E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, "Statistical properties of radiation from VUV and X-ray free electron laser", Opt. Commun., vol. 148, p. 383, March 1998. doi:10.1016/S0030-4018(97)00670-6

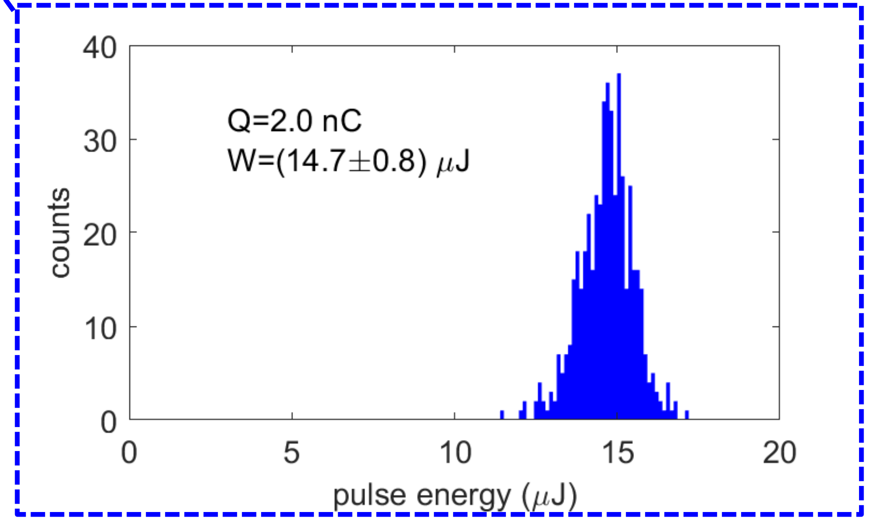
THz SASE FEL at PITZ: Further Optimization

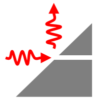
High gain THz SASE FEL characterization

- Gain curves for 2 and 2.4nC at HIGH3.Scr3:
  - in-vacuum mirror with hole
  - No band-pass filter applied









Estimated transmission ~50%

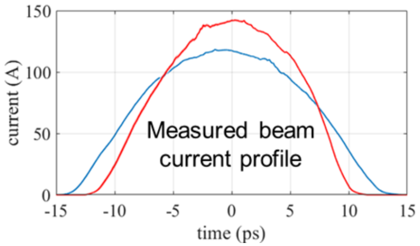
>100µJ generated

Reference case: 2nC

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

e-beam

parameter	value
Energy, E_0	~17MeV
γ	34
$<\sigma_x>$	0.75mm
$<\sigma_y>$	0.2mm
$<\sigma_r>$	0.55mm
charge	2nC
I_{peak}	125A
$\varepsilon_{n,x,y}$	5 mm mrad
σ_E	~10keV (slice)



FEL radiation

parameter	value
λ_{rad}	~90µm
Q	0.429
A_{JJ}	0.745
θ_l	0.10
γ_l	12.6
Γ	$(0.237\text{m})^{-1}$

$$\lambda_{rad} = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$Q = \frac{K^2}{4+2K^2}$$

$$A_{JJ} = J_o(Q) - J_1(Q)$$

$$\theta_l = K/\gamma$$

$$\frac{1}{\gamma_l^2} = \frac{1}{\gamma^2} + \frac{\theta_l^2}{2}$$

$$\Gamma = \sqrt{\frac{I_{peak}A_{JJ}^2\omega^2\theta_l^2}{2I_A c^2\gamma_l^2\gamma}}$$

FEL dimensionless

Parameter	Value
Diffraction B	~0.1
SC $\hat{\Lambda}_p^2$	0.9
FEL ρ	0.01
EnSpread $\hat{\Lambda}_T^2$	0.003
Waveguide $\Omega*$	5.3

$$B = \frac{2\Gamma\sigma_r^2\omega}{c}$$

$$\hat{\Lambda}_p^2 = \frac{4c^2}{[\theta_l\sigma_r\omega A_{JJ}]^2}$$

$$\rho = \frac{\gamma_l^2\Gamma}{\omega/c}$$

$$\hat{\Lambda}_T^2 = \frac{\sigma_E^2}{[E_o\rho]^2}$$

$$\Omega = \Gamma R_{eff}^2\omega/c$$

undulator system

parameter	value
λ_u	30mm
K	3.34 (3.47)
Vacuum chamber R_{eff}	4.2mm

$$E_x(z) \propto \exp(\Lambda \cdot z)$$

Reference: Saldin E.L., Schneidmiller E.A., Yurkov M.V. “The physics of free electron lasers” - Berlin et al.: Springer, 2000.

Reference case: 2nC

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

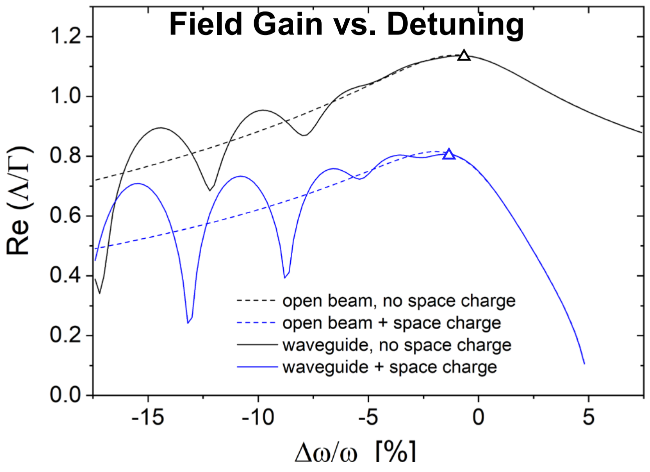
The gain parameter of the FEL amplifier

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

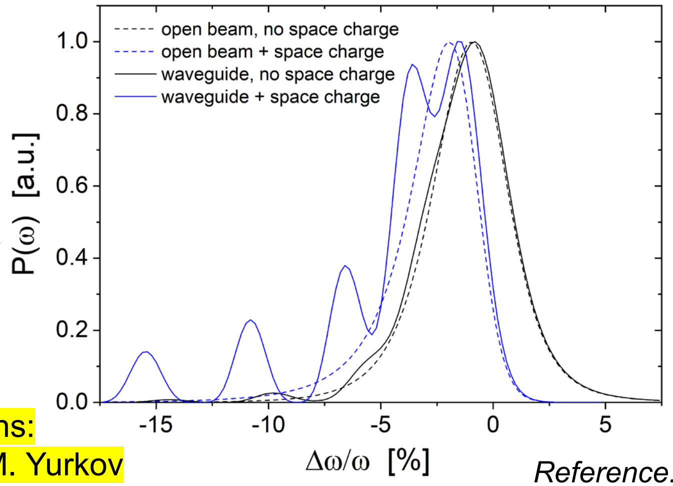
Parameter		Value
Diffraction	B	~0.1
SC	$\hat{\Lambda}_p^2$	0.9
FEL	ρ	0.01
EnSpread	$\hat{\Lambda}_T^2$	0.003
Waveguide	$\Omega*$	5.3

Eigenvalue problem → beam radiation modes

$E_x(z) \propto \exp(\Lambda \cdot z)$, Λ → field gain ($\mathrm{Re}\Lambda$)

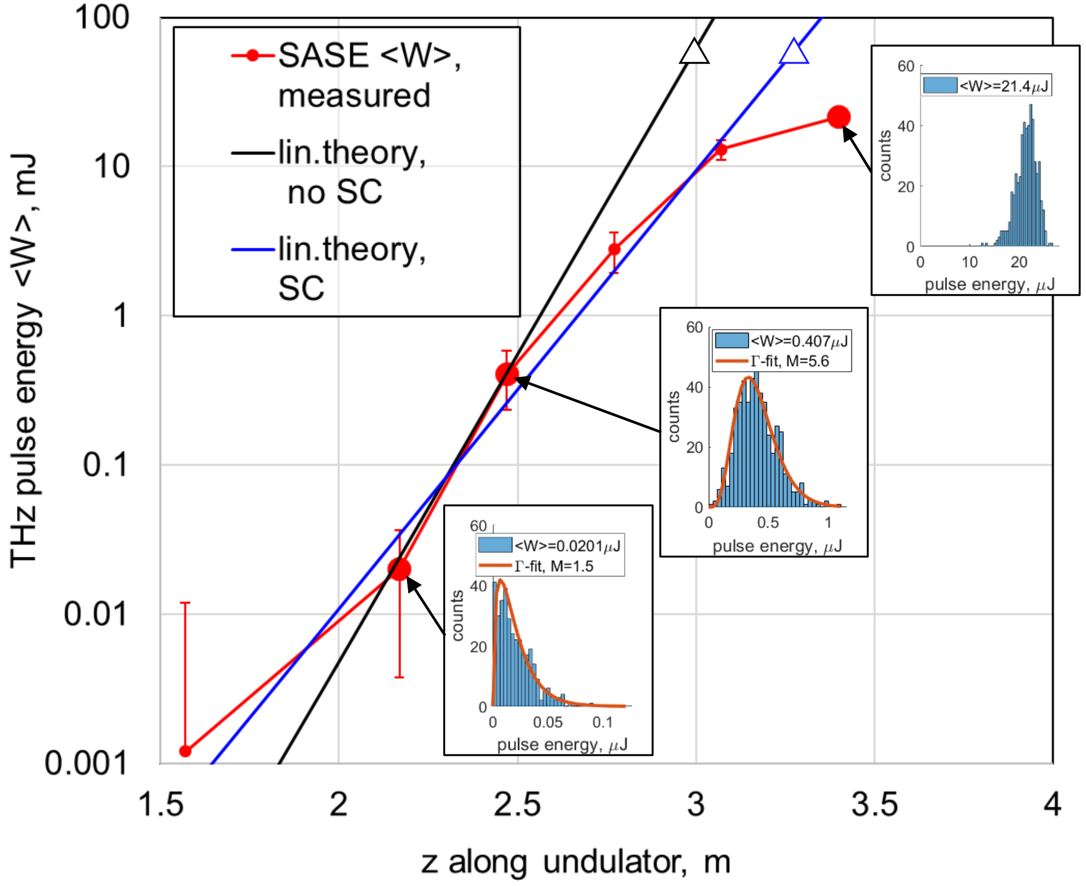


Expected power spectrum (the high gain regime at the onset of saturation)



Calculations: courtesy M. Yurkov

SASE 2nC: Linear theory versus measurements

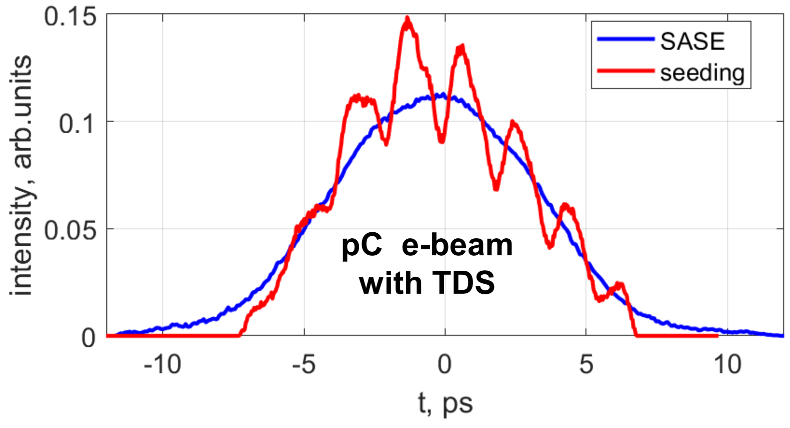


Reference: E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, "On a theory of an FEL amplifier with circular waveguide and guiding magnetic field", Nucl. Instr. Meth. A 375, p. 241, 1996.

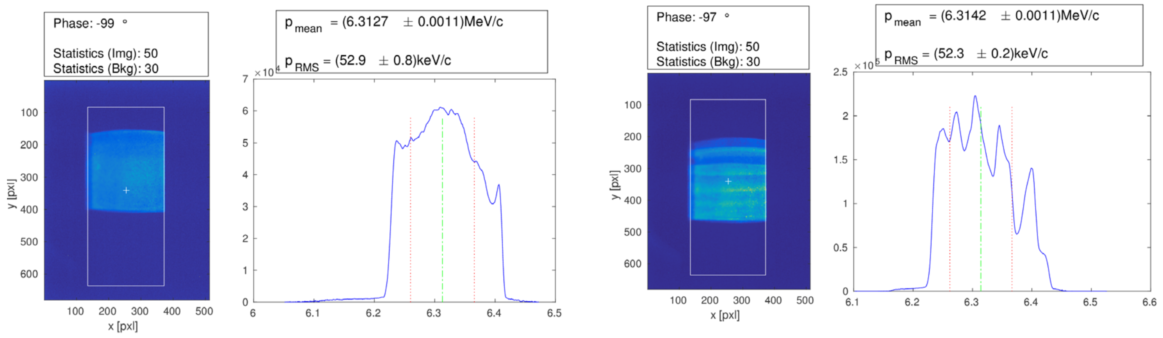
First Seeding Experiments

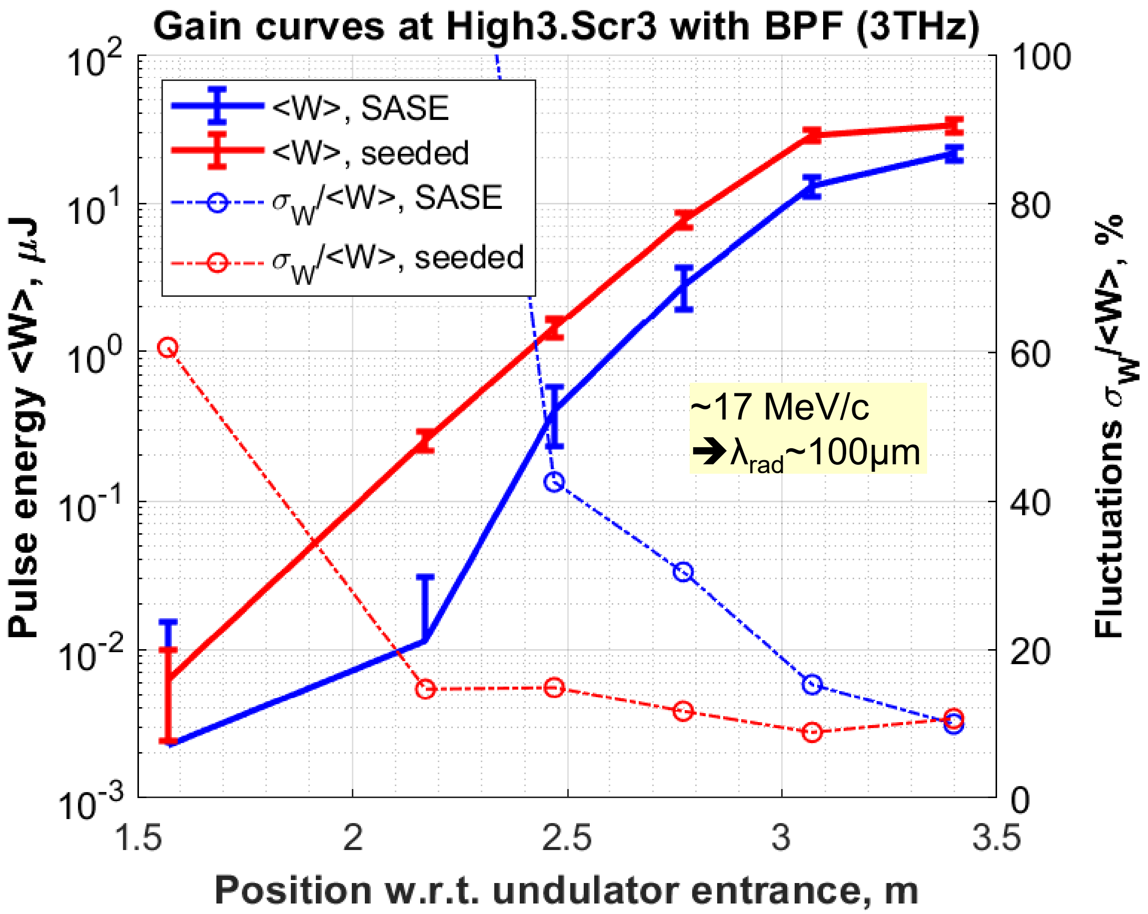
SASE vs. seeded THz FEL with modulated photocathode pulse (preliminary results)

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

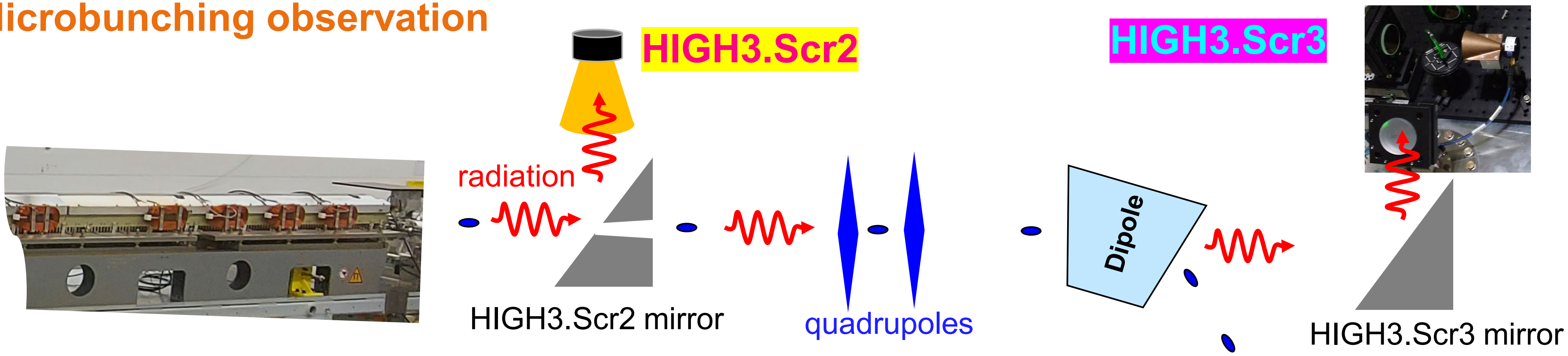


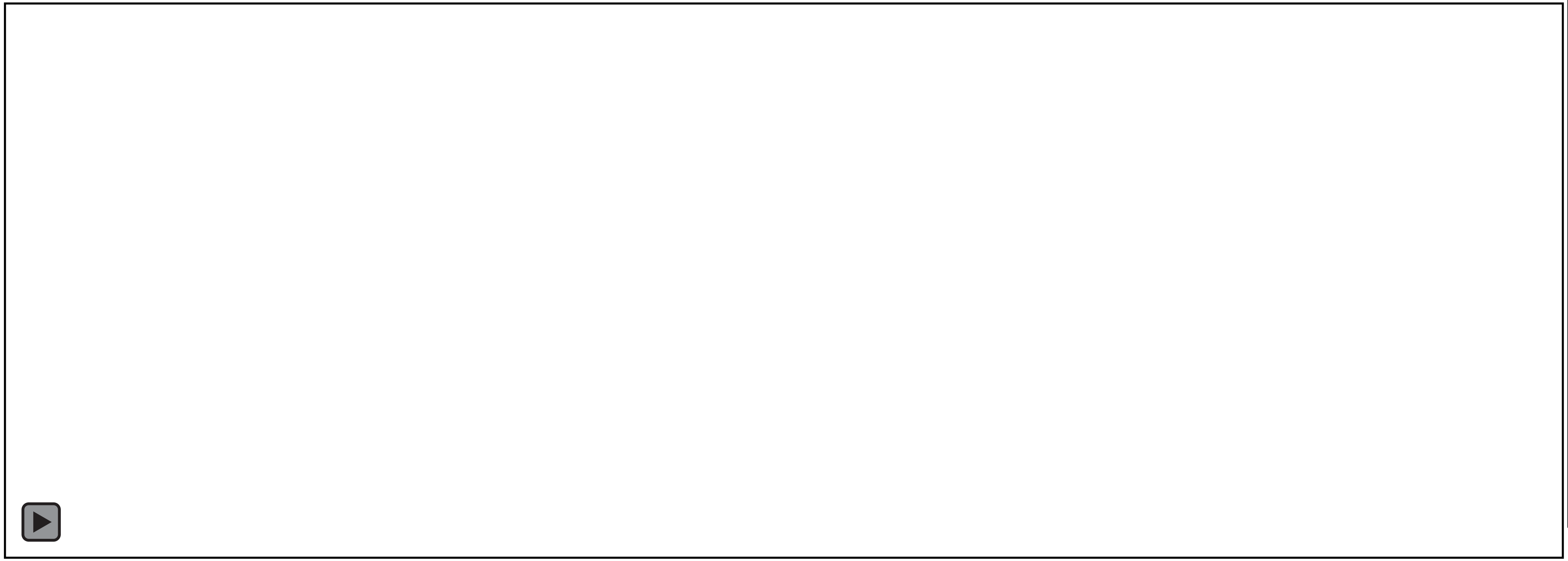


Seeded THz FEL gain curve:
- higher energies + earlier start
- better stability

Electron beam in dispersive section and pyrodetectors signals

Microbunching observation

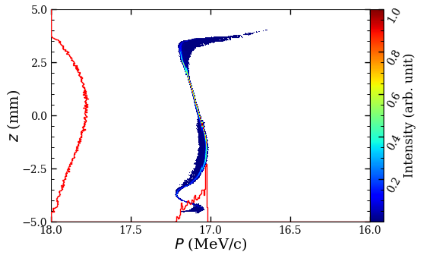




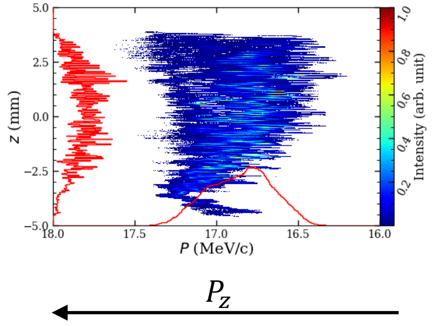
WARP simulations

Longitudinal Phase Space

Before undulator



After undulator

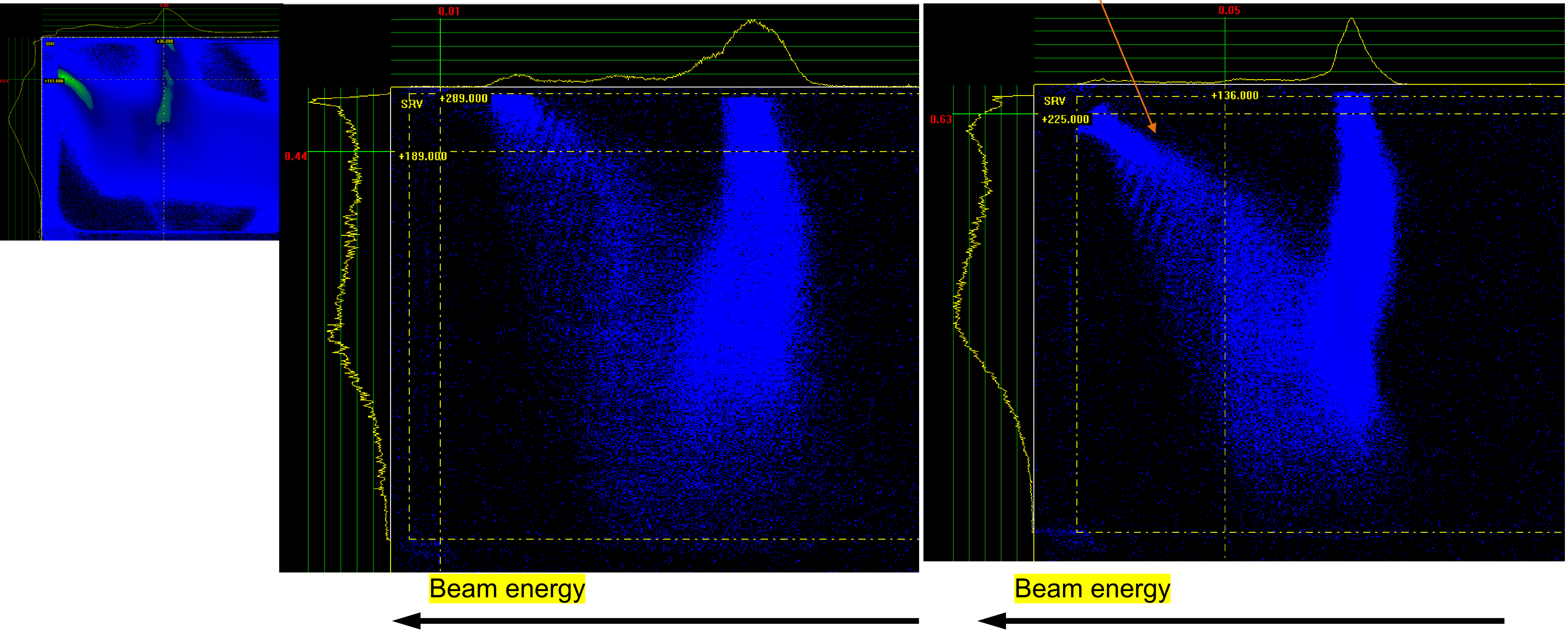


Simulations: X.-K. Li

Disp4.Scr1

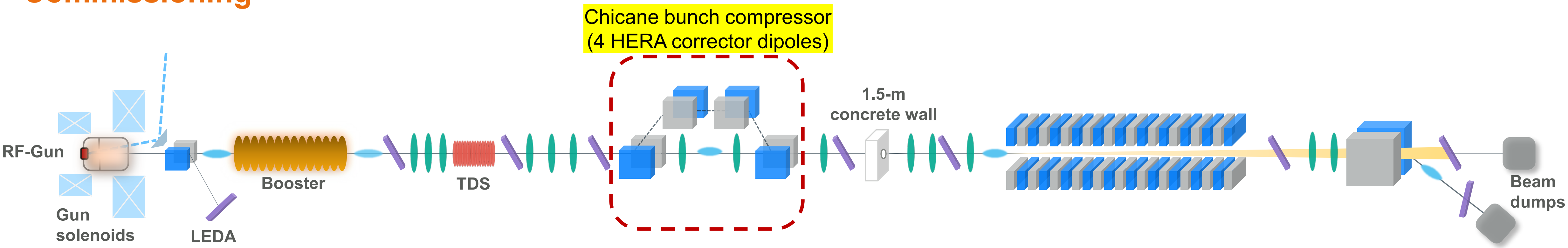
(After-)Lasing beam in horizontal dispersive arm

Microbunching?



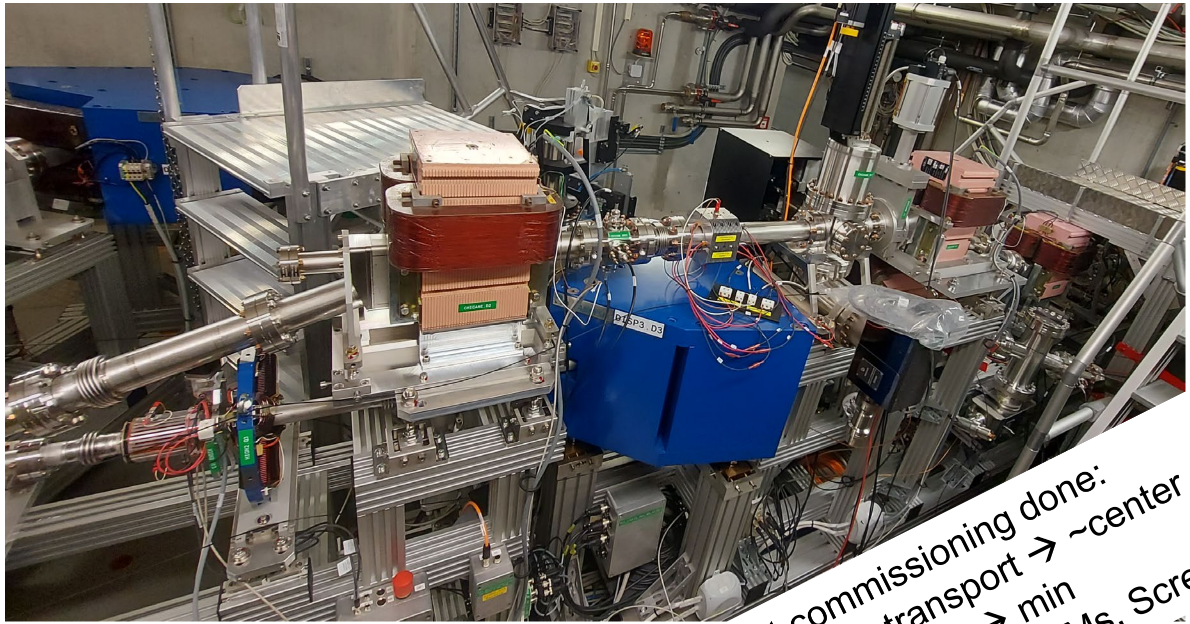
PITZ Bunch Compressor

Commissioning



The bunch compressor is designed to optimize e-beam for:

- SASE FEL
  - > 5ps FWHM, I_{peak} ~ 200 – 400 A
- Coherent radiation from ultra-short bunch (SUR, CTR, CDR)
  - < 1ps FWHM, bunch charge < 400pC
- Support tuning of FEL seeding (using PC laser pulse modulation, DLW, slit technique, etc.)

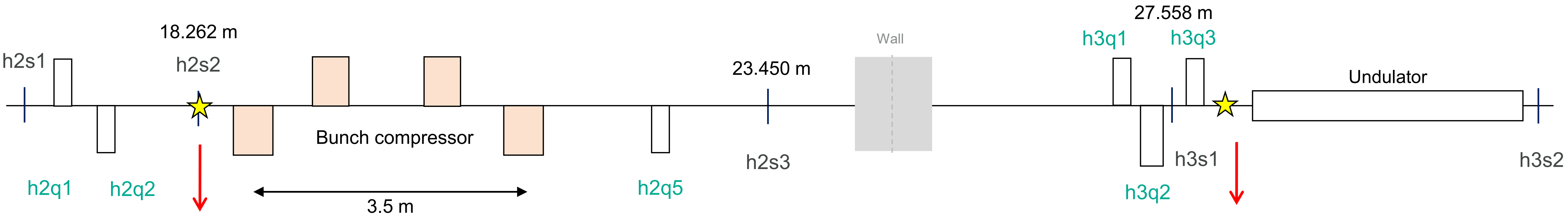


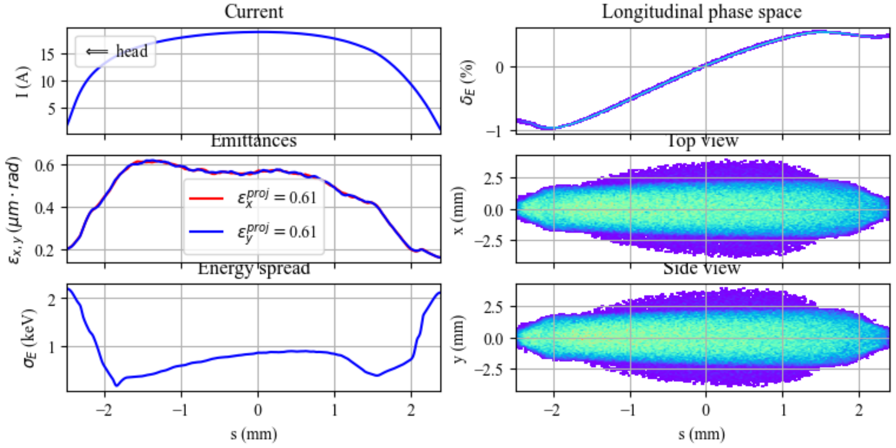
First commissioning done:

- Beam transport → ~center
- Dispersion → min
- Diagnostics (BPMs, Screens, CTR)

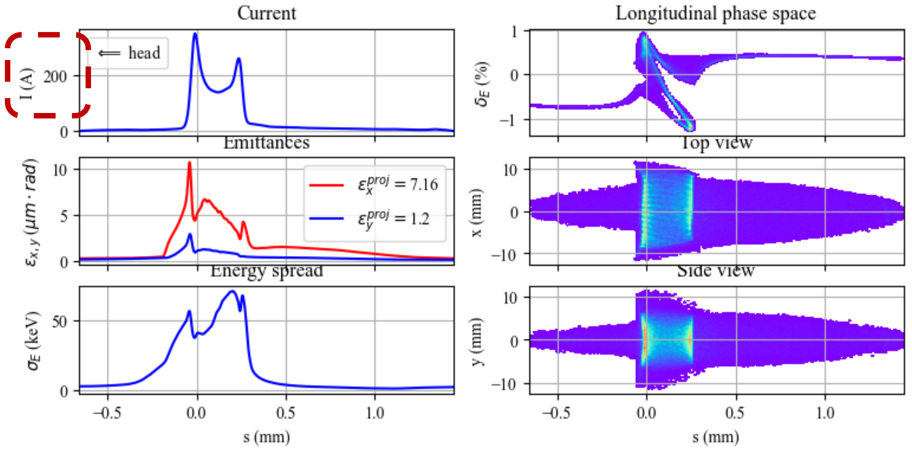
PITZ Bunch Compressor

250pC bunch compression (s2e)





Before BC at HIGH2.Scr2



After compression from BC before undulator magnet

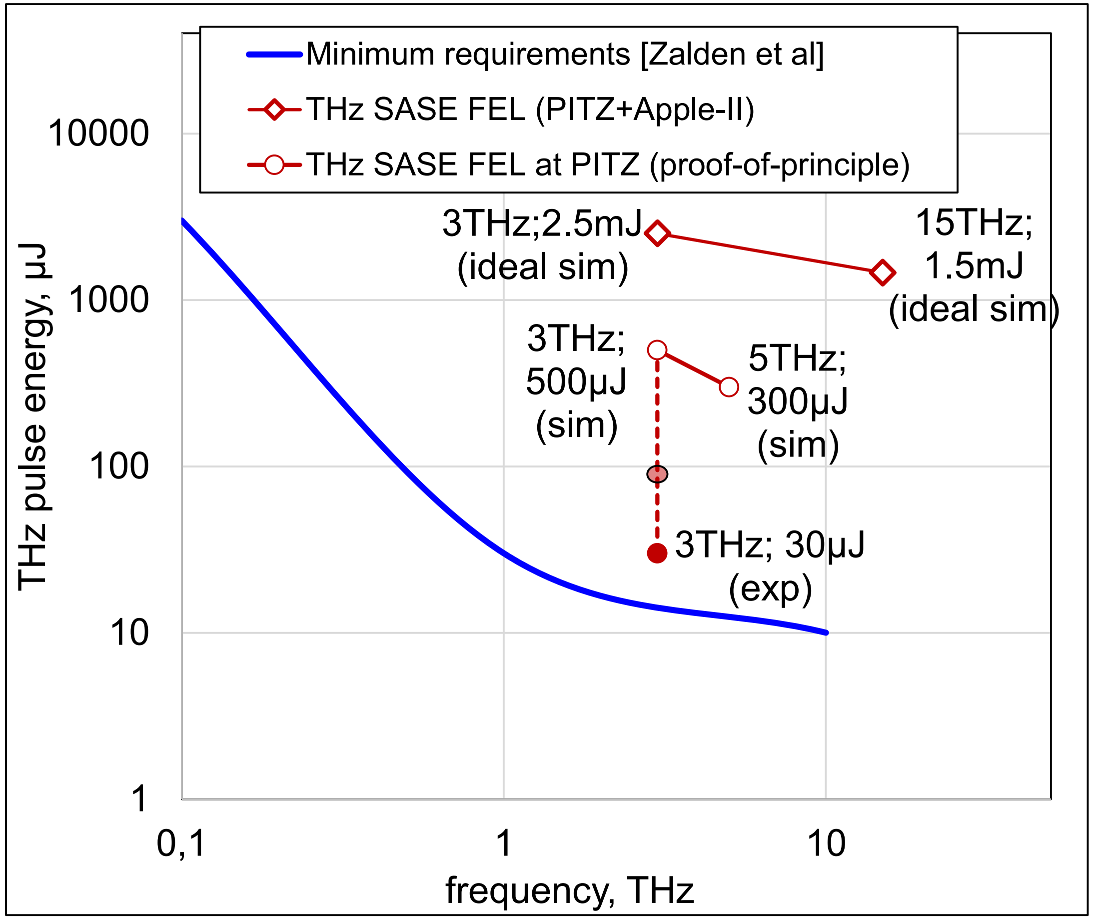
- BSA : 1 mm
- Gun main solenoid : 340 A
- Average beam momentum : 17.02 MeV/c
- Energy spread : 0.523 %

- Bunch charge : **250 pC**
- Phase of acceleration ~ -20 deg. w.r.t. MMMG phase
- R_{56} ~ 0.244 m (before compression in the 1st order)

Courtesy of E. Kongmon

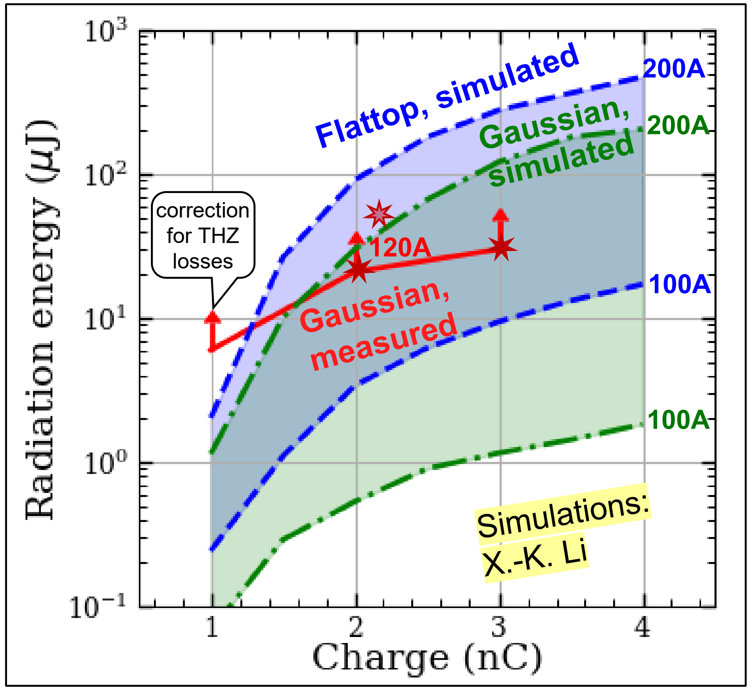
Proof-of-principle Experiment on THz Source at PITZ

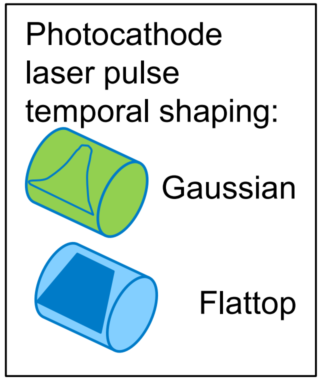
Where we are now and the way to go



parameter	Min. requirements [1]	PITZ (experiment)
Bandwidth	1…0.05	~0.02
f [THz]	0.1…**3…20**…30	**3…5**
Pulse energy	3mJ@0.1THz; 30μJ@1THz; 10μJ@10THz	**30..65μJ@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





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."

Conclusions and Outlook

THz SASE FEL prototype based on high brightness photo injector

- PITZ e-source = EXFEL and FLASH e-sources → *same pulse train structure!*
- Developments on high (peak- and average-) power tunable accelerator-based THz source for *pump-probe* experiments at the European XFEL:
  - Proof-of-principle experiment ongoing @PITZ (supported by EXFEL):
    → LCLS-I undulator (challenging parameters for 1-3nC and 17MeV/c)
    → 1st THz SASE FEL Lasing at $\lambda_{rad} = 100\mu m$ → 09.08.2022
    → High gain (~10^6) measured !
    → Strong dependence on beam *current* and transport /matching
    → Saturation at **>20μJ** (BPF) with 2nC
    →Recently **>65μJ** (w/o BPF) with ~2.4nC
    → First seeding experiments **>30μJ** (BPF) with 2nC modulated beams

- High-gain THz SASE FEL at a PITZ-like accelerator **it works!!!**
- Electron bunches with long bunch length (>>λ_{rad}) = source of high THz pulse energy!
- Proper undulator choice (design) → ~mJ?

Outlook:

- Further THz SASE FEL studies (laser flattop, BC, tunability, etc.)
- Further studies on seeding options for stabilization
- Explore PITZ BC usage for THz generation (+SUR, seeding tuning)
- More THz diagnostics (spectrum, EOS, stability, etc.)

Thank you!

Contact

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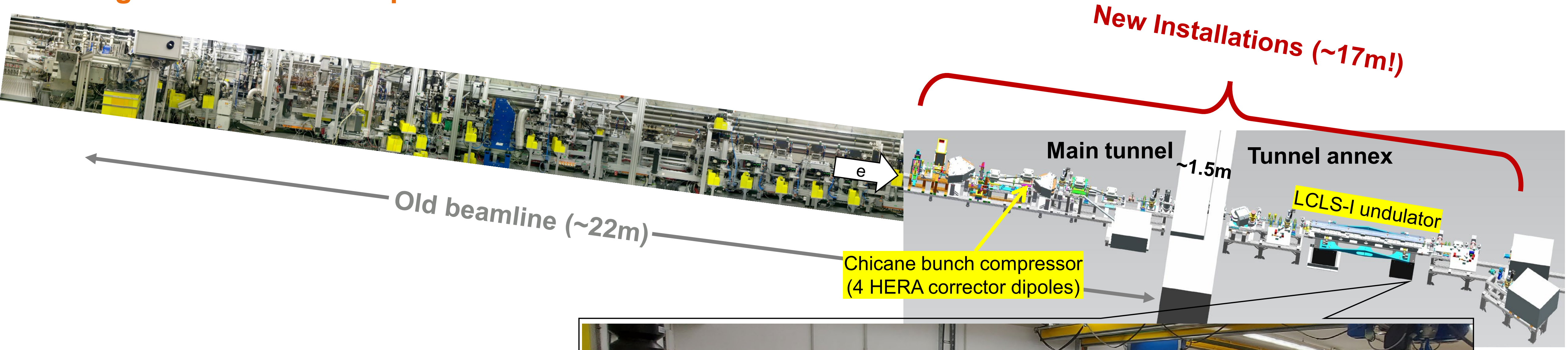
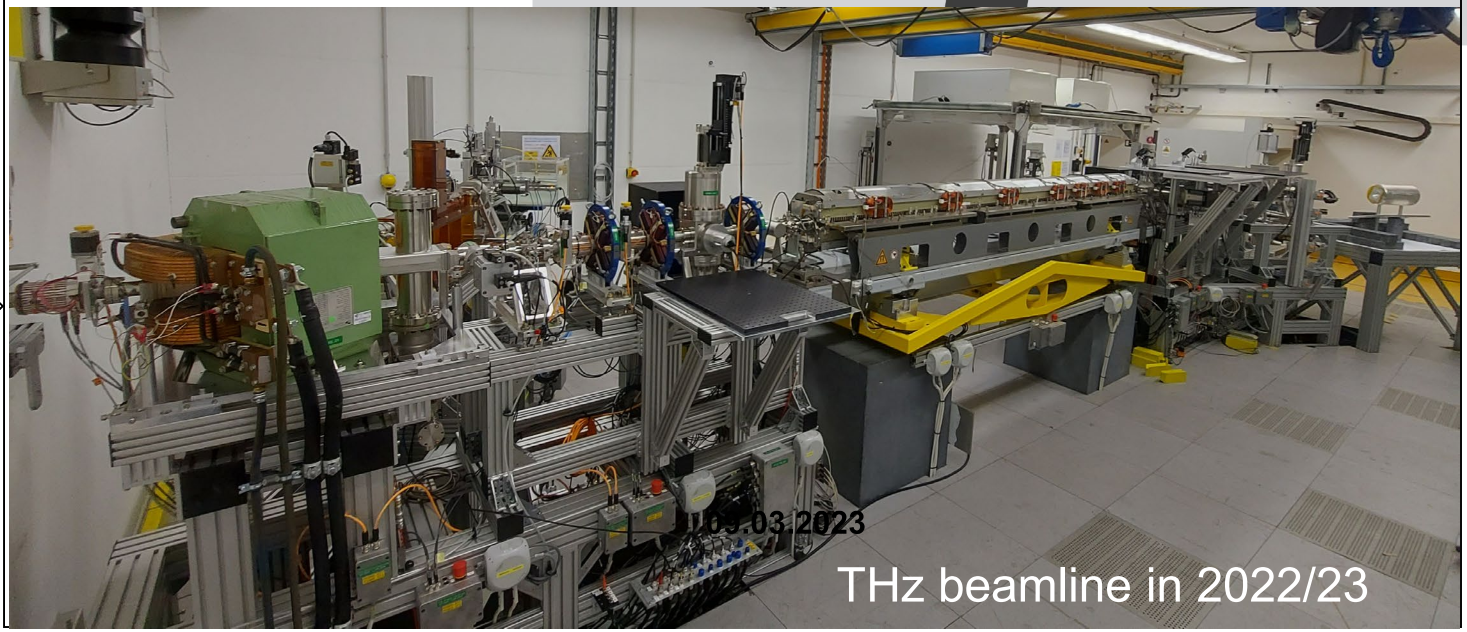
Backup slides

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

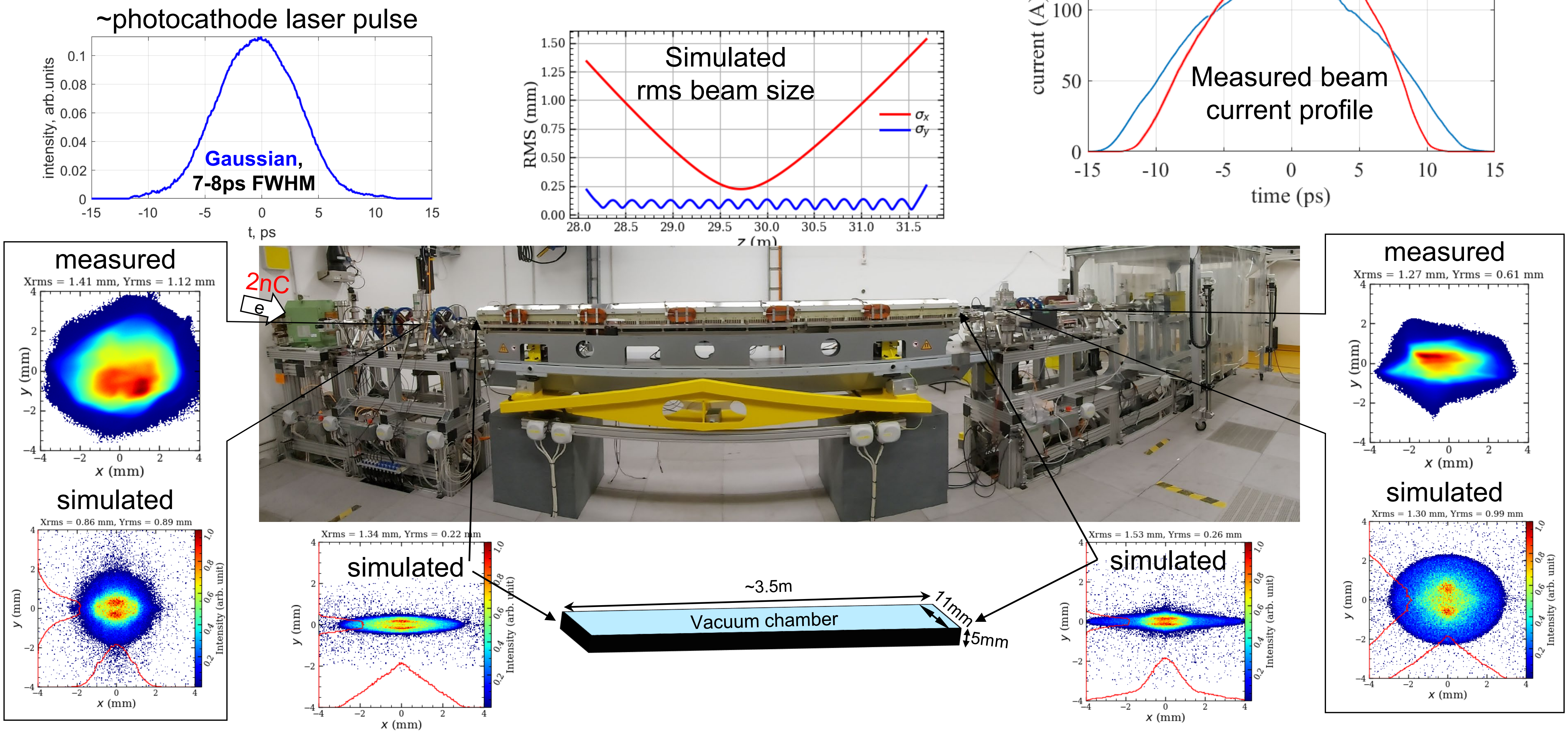
Design and technical Implementation





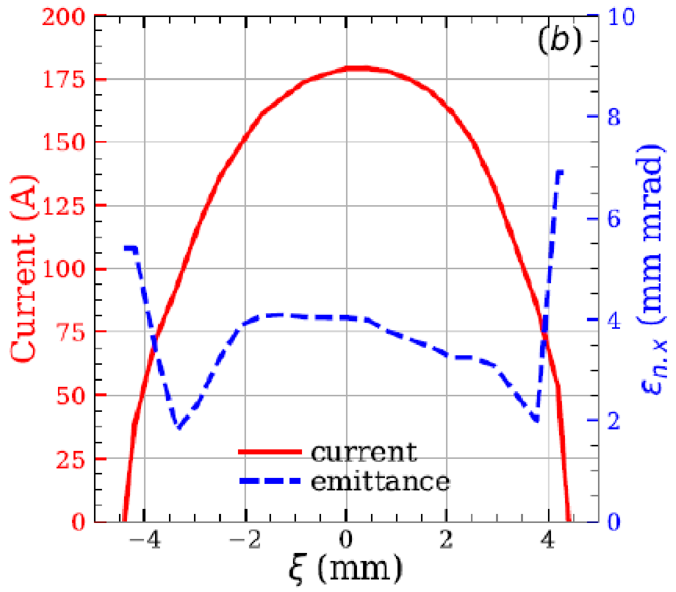
THz SASE FEL at PITZ

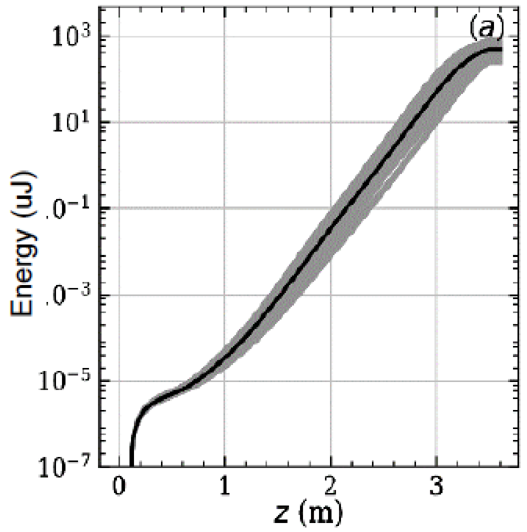
Electron beam matching (2nC) for lasing



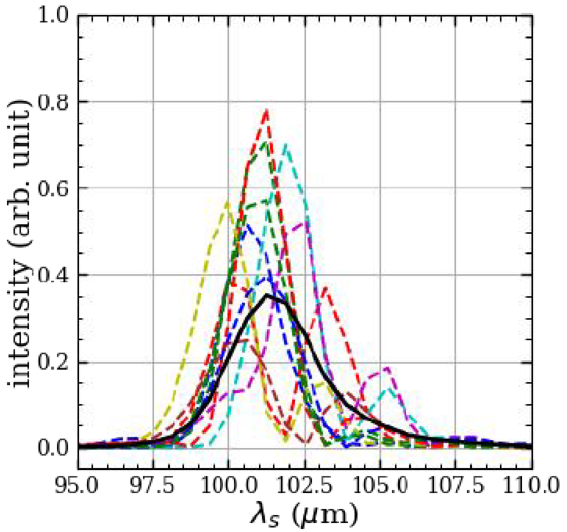
Astra+Genesis1.3 simulation
Nominal case

- Input beam for Astra: **4 nC**, flattop 22 ps laser pulse
- Beam momentum: 17 MeV/c → **100 um, 3 THz**

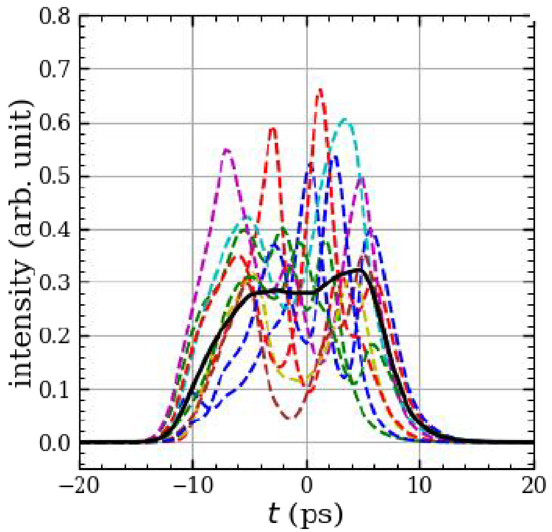




THz pulse energy in undulator



Spectrum



THz pulse profile

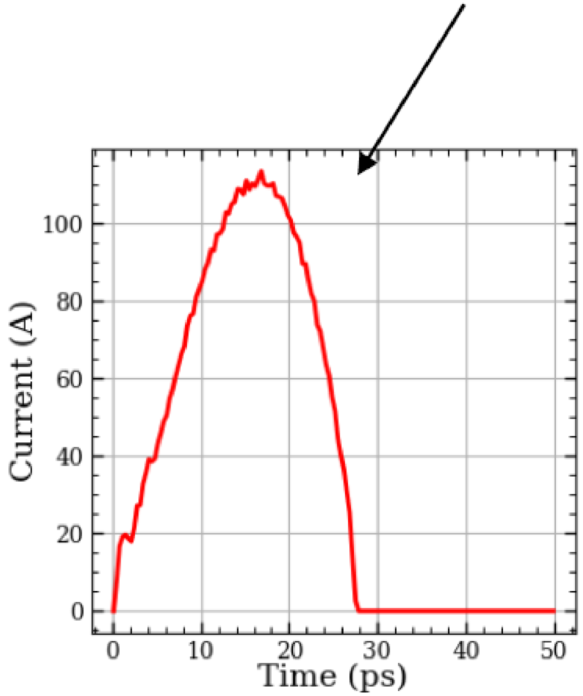
Case	100 um	Unit
Electron momentum	17	MeV/c
THz pulse energy	493.1± 109.8	µJ
Arrival time jitter	1.5	ps
Center wavelength	101.8± 0.7	µm
Spectrum width	2.0±0.4	µm

Courtesy: X.-K. Li

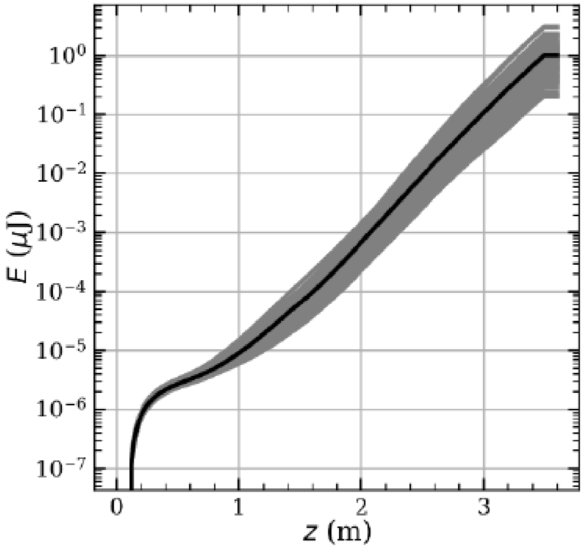
Astra+Genesis1.3 simulation

2 nC as used in experiments

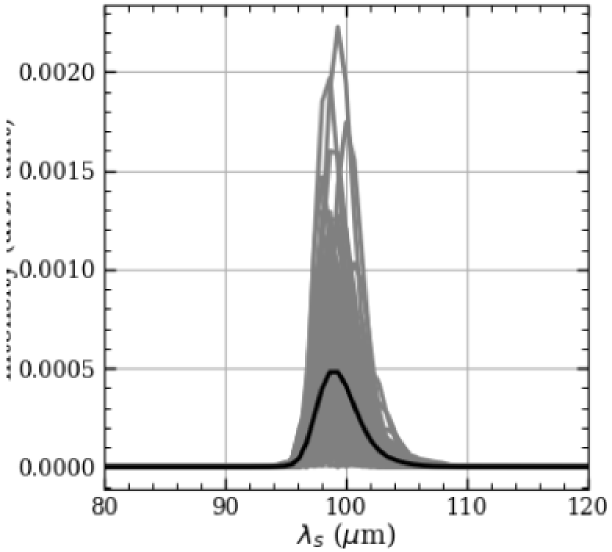
- Input beam for Astra: **2 nC**, MBI laser (6-7 ps Gaussian) → only **1 μJ**



Bunch profile in front of undulator (Astra simulation)



THz pulse energy in undulator

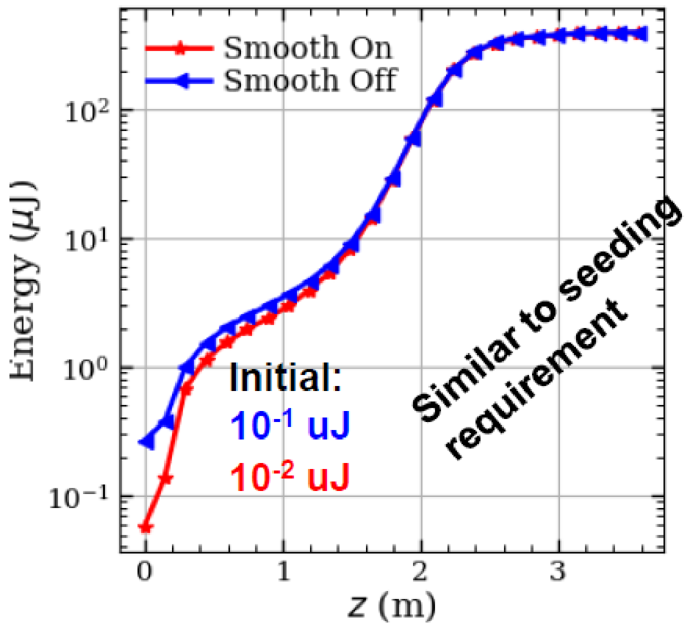


Spectrum

Courtesy: X.-K. Li

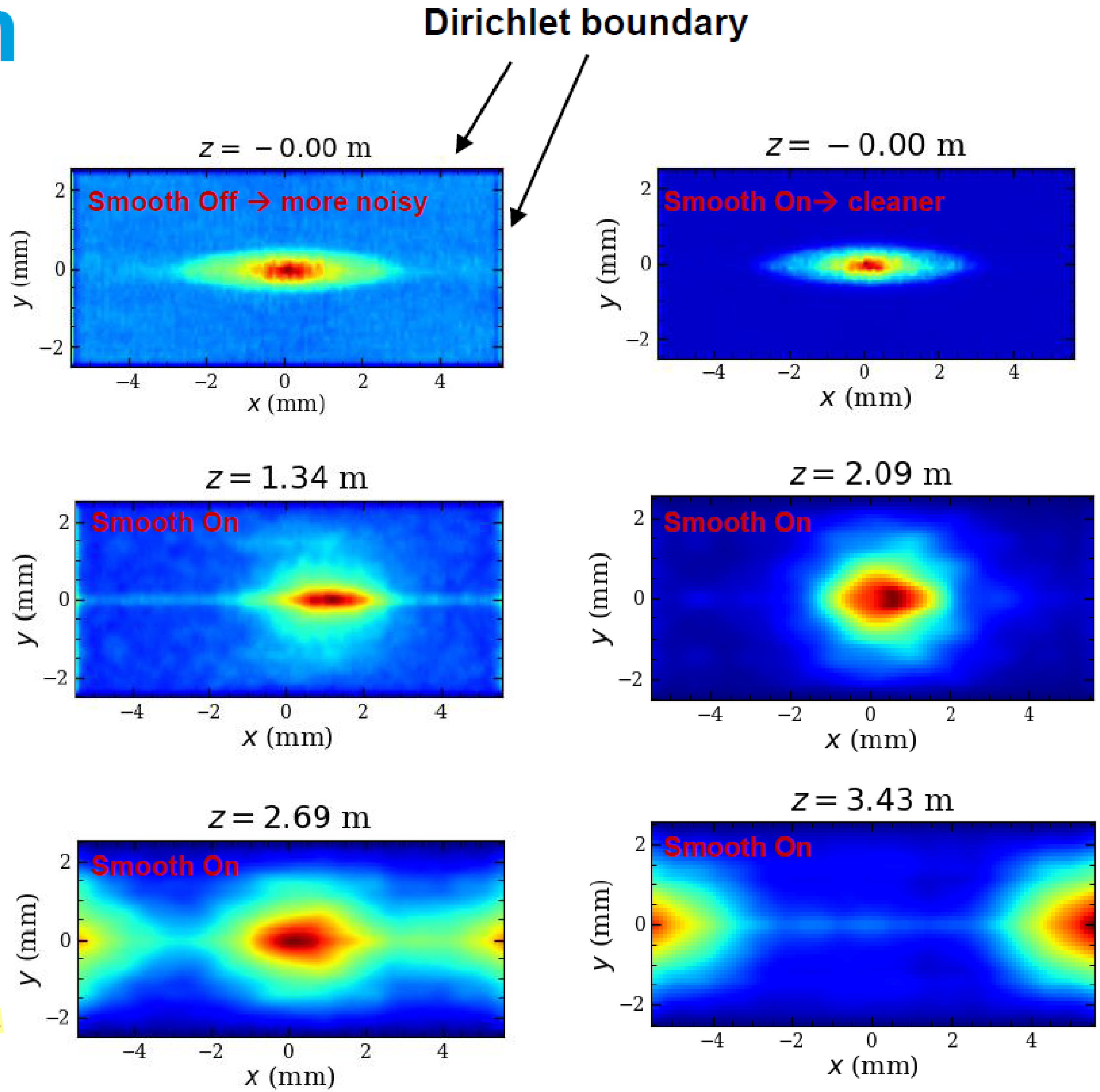
Astra+Warp simulation

- Input: **2 nC** beam from Astra simulation, **1 M** macro particles (**10^4** less than electrons)
- **Smoothing** of charge/current for EM solver switched ON to suppress noise



To do:
- **Shot noise** implementation
- Initial noise compared to theoretical estimation
- **THz profile** measurement

Courtesy: X.-K. Li



TE01 + TE21?

LCLS-I undulator

Vacuum chamber and coils