Development of a high-power tunable photoinjector-based THz source at PITZ: results and possible next steps

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

Mikhail Krasilnikov for the THz@PITZ team,
Internal THz workshop, EuXFEL
05.03.2024

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** $W > 10\mu J$ (μJ - hundreds of μJ - 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

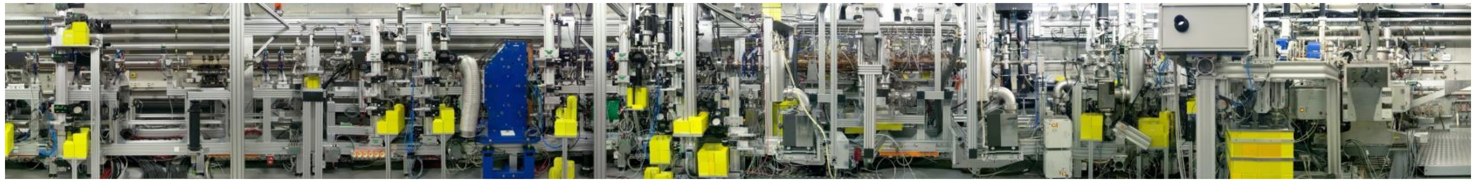
Attractive features:

- clean in-vacuum radiation production
- tunability (electron beam manipulation)
- potential to provide high power (high field)
- polarization control

Methods of generation:

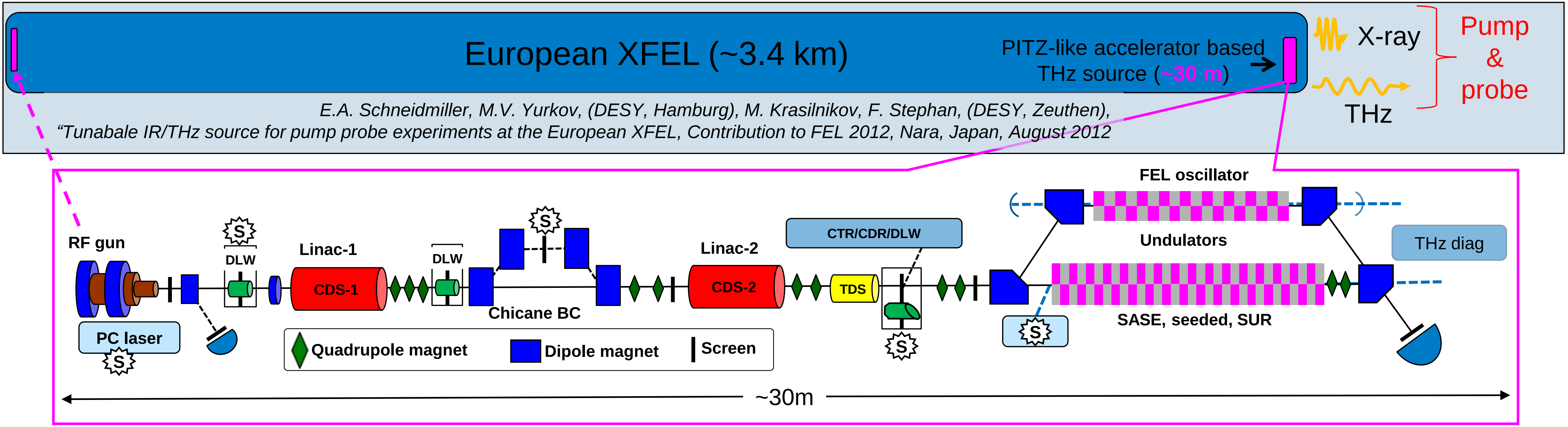
- bend magnet
- **undulator**
- **transition radiation**
- diffraction radiation
- Cherenkov radiation (DLW)

Photo Injector Test facility at DESY in Zeuthen (PITZ)



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

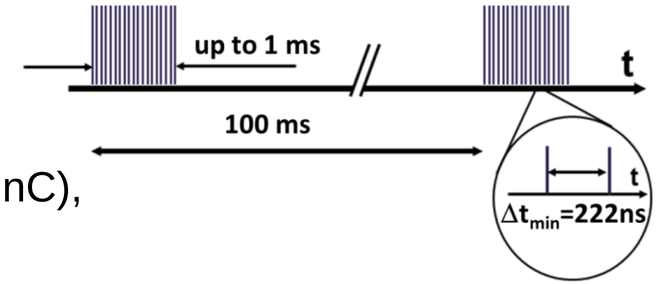
THz SASE FEL =
Self Amplified Spontaneous Emission Free Electron Laser

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

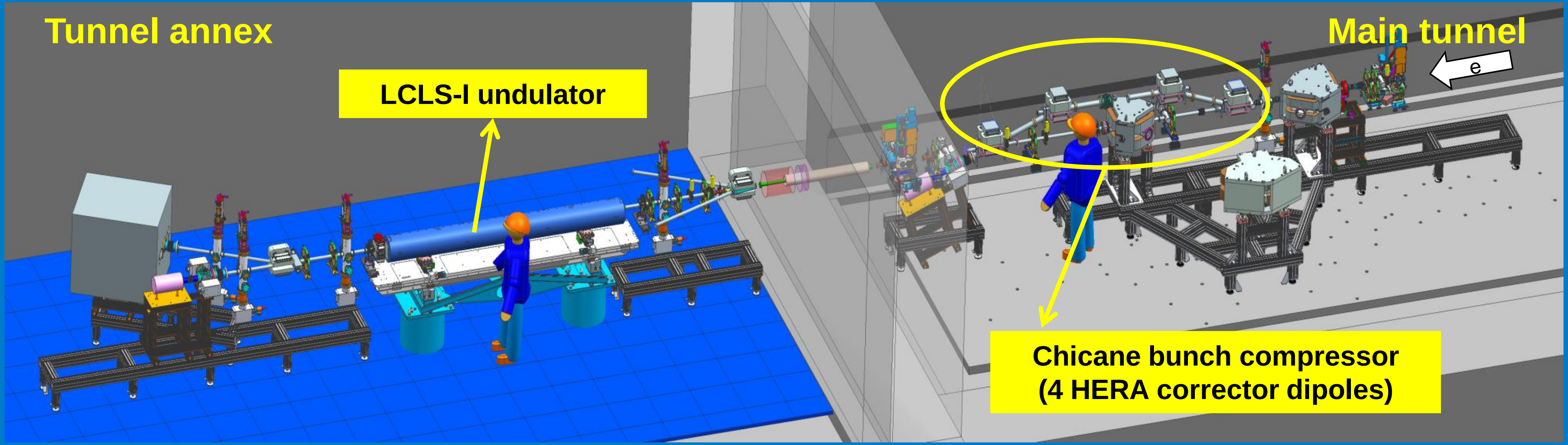
for $\lambda_{rad} >$ 100 μm (f < 3 THz) → CTR / CDR / SUR?

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



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

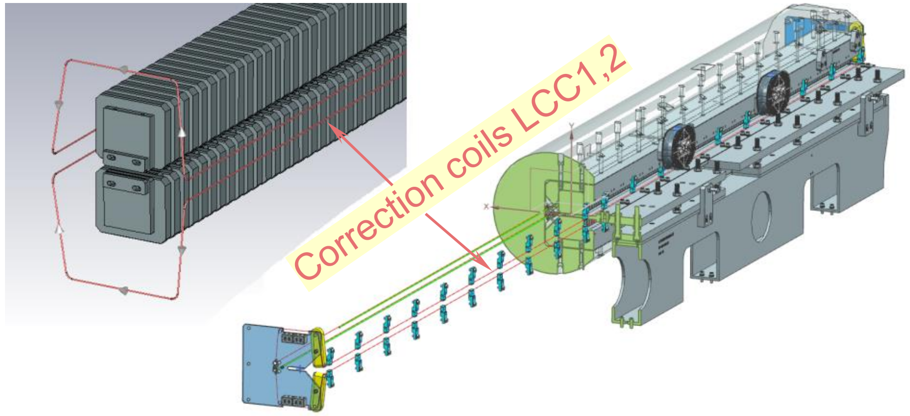
Proposal **“Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector”** has been supported by the **E-XFEL Management Board** → dedicated R&D activities at PITZ → **Proof-of-principle experiments (2019-2023)**

Position	**R&D**	**+ ~x2 more from PITZ (DESY) own resources**
Personnel	**1PD+1PhD**	
Invest	**200k**	
Operation	**3weeks/year**	

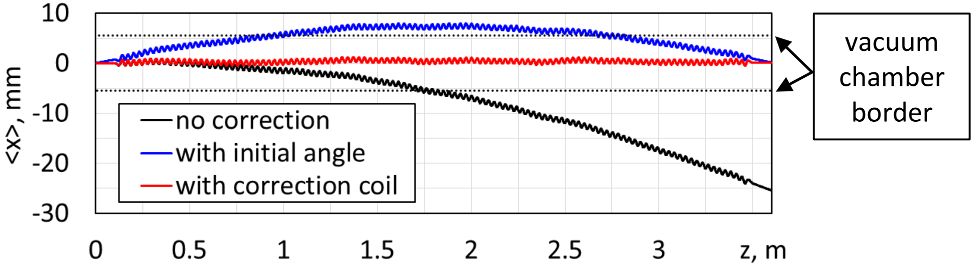
$\lambda_{rad}\sim 100\mu m$ → <Pz>~**17MeV/c**

Main challenges:

- Space charge effect
- Strong undulator (vertical) focusing + horizontal gradient
- FEL parameter is not very small
- Bunching factor impact?
- Waveguide effect
- Wakefields: geometric and conductive wall effects

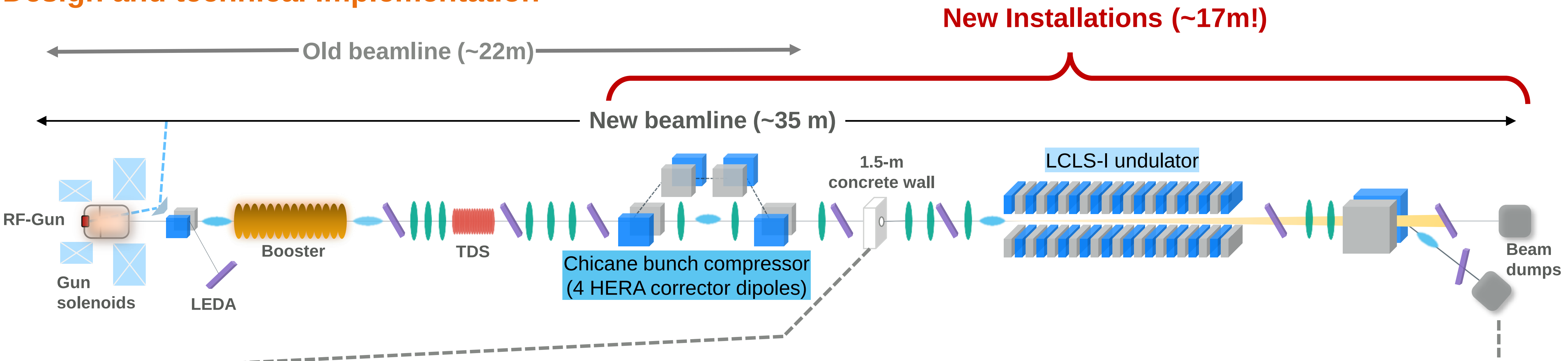


Reference particle trajectories in the undulator with horizontal gradient



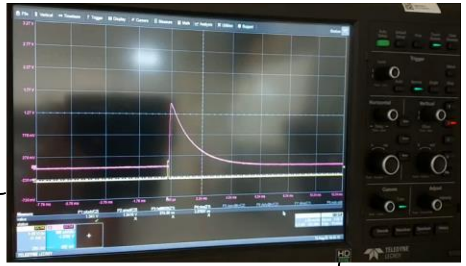
PITZ upgrade for the proof-of-principle experiment on THz source

Design and technical Implementation

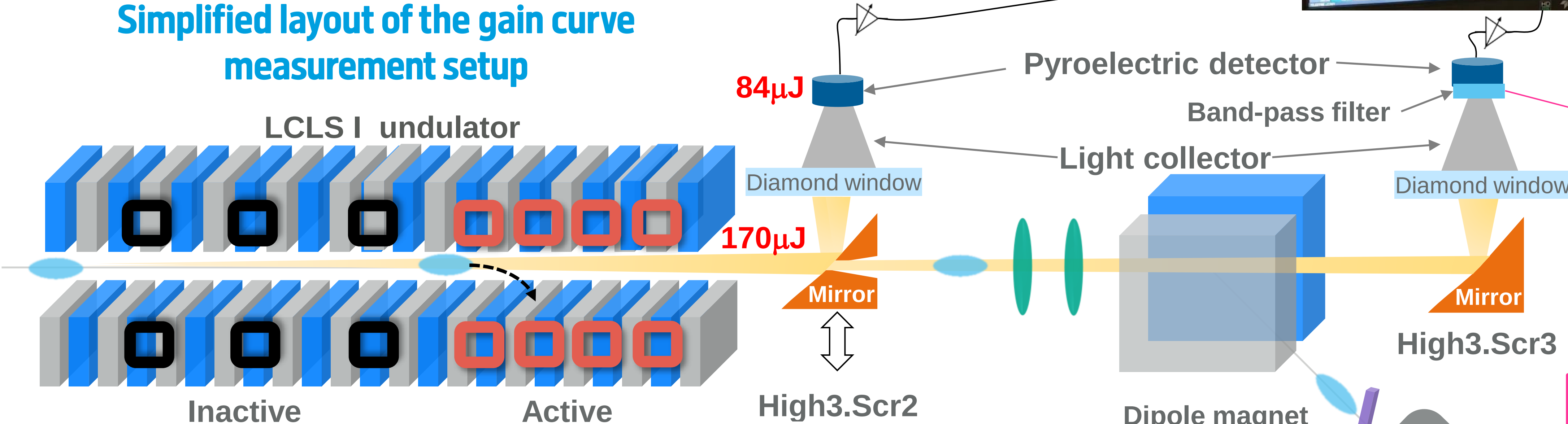


THz SASE FEL at PITZ: THz diagnostics setup

Startup: pyroelectric detectors with collector cones



Simplified layout of the gain curve measurement setup



Inactive steering coils

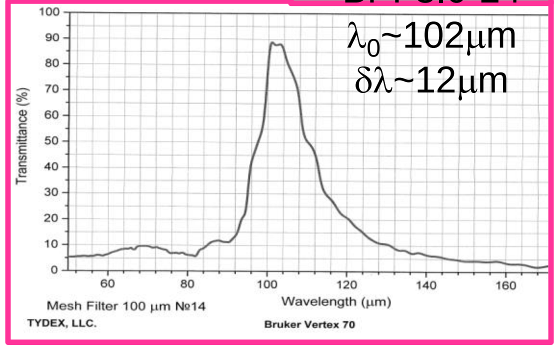
Active steering coils

High3.Scr2

Beam dump

Pyroelectric detector THz10
SLT Sensor- und Lasertechnik GmbH

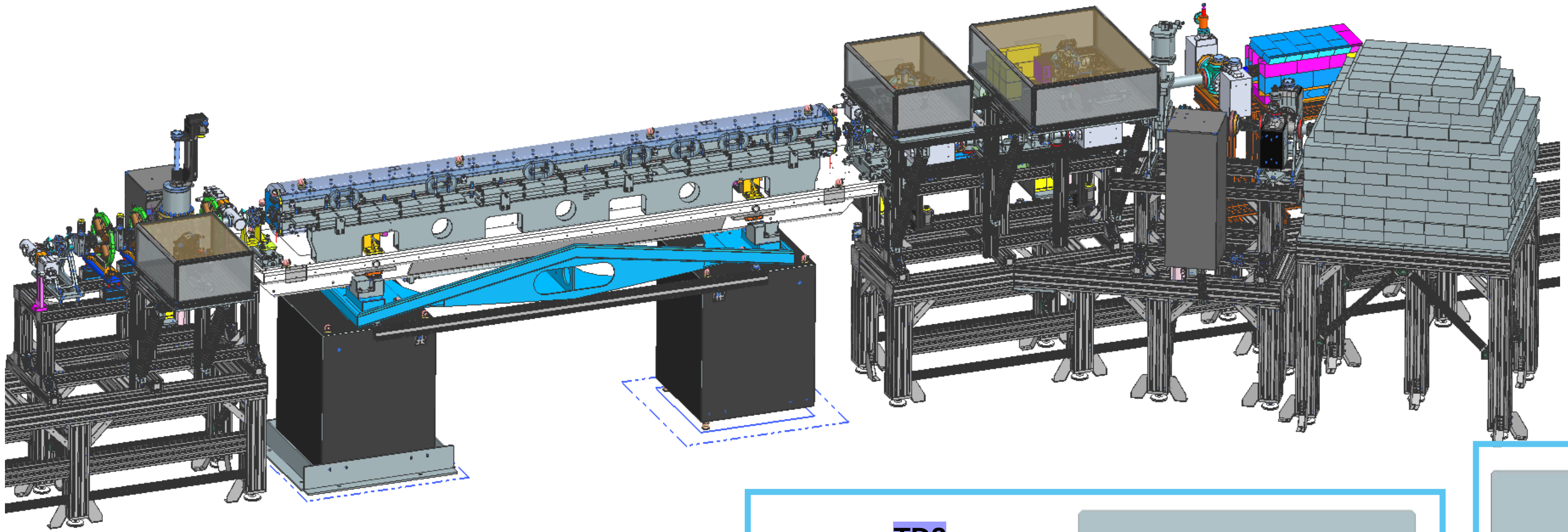
BPF3.0-24
λ_0~102μm
$\delta\lambda$~12μm



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

THZ Diagnostics at PITZ

3 stations in the second tunnel

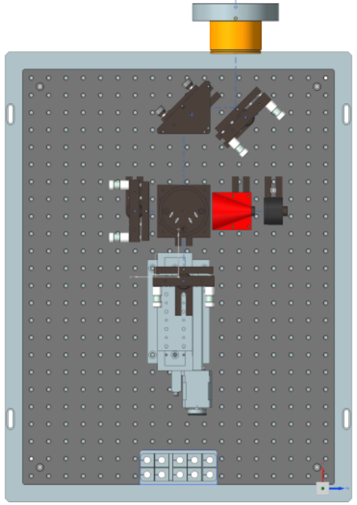


Enclosed system

Pure air circulator unit (Thorlabs) for air purification and humidity reduction.

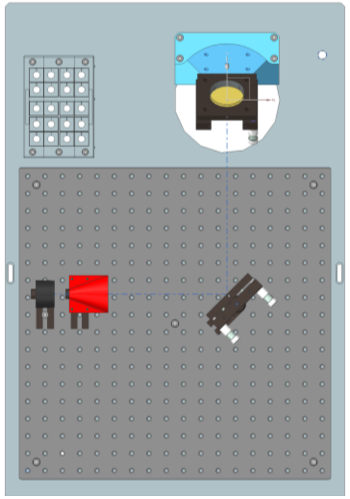
TD1:

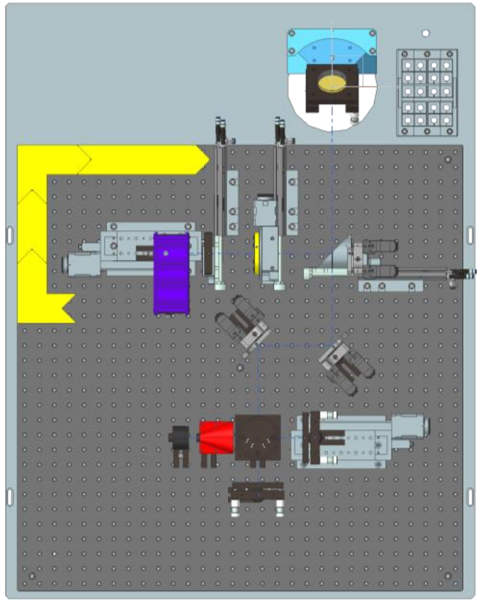
- Pulse energy using pyroelectric detector
- THz spectrum using a Michelson interferometer
- Quartz vacuum window
- ~0.2 m transport in vacuum, ~0.5 m transport in air
- Focusing by using 90° off-axis ellipsoidal and parabolic mirrors
- 1 motorized linear stage



TD2

- Pulse energy using pyroelectric detector
- Diamond vacuum window
- ~0.8 m transport in vacuum, ~0.5 m transport in air
- Focusing by using 90° off-axis ellipsoidal mirror

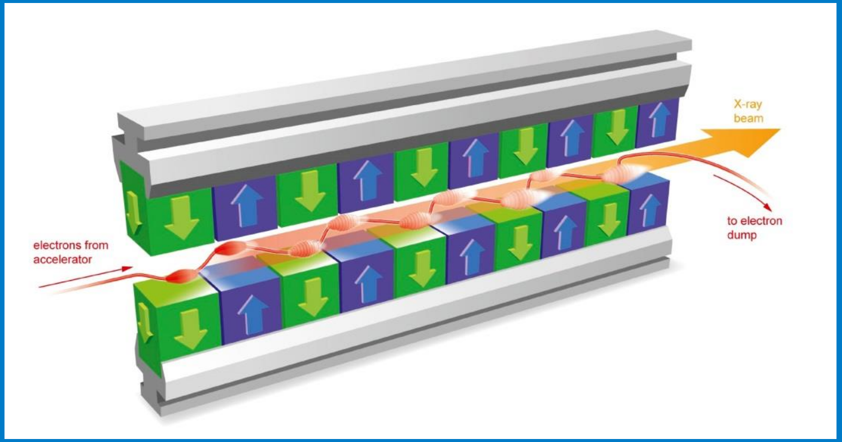


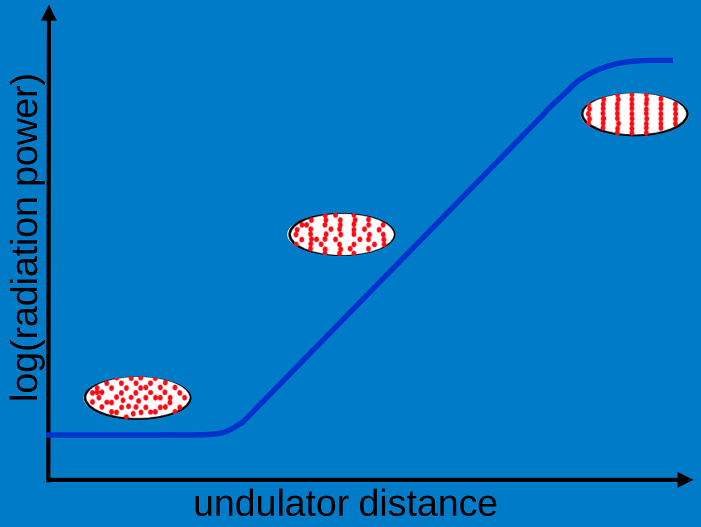


TD3:

- Pulse energy using pyroelectric detectors
- Transverse profile using a THz camera
- Polarization using a THz polarizer
- THz spectrum using a Michelson interferometer
- Diamond vacuum window
- ~1.8 m transport in vacuum, 1-1.5 m transport in air
- Focusing by using 90° off-axis ellipsoidal and parabolic mirrors
- 3 pneumatic actuators, 3 motorized mirror adjusters, 2 motorized linear stages

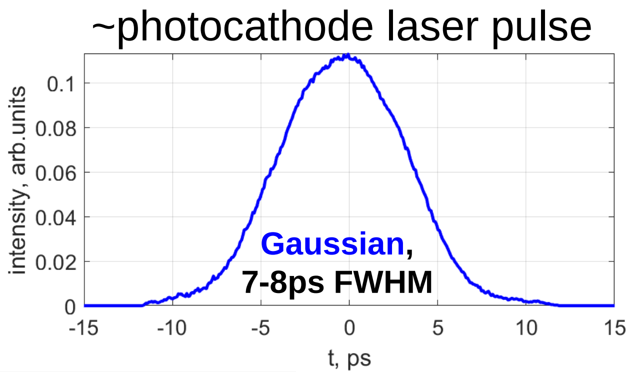
THz SASE FEL at PITZ: Electron Beam Transport and FEL Lasing Tuning

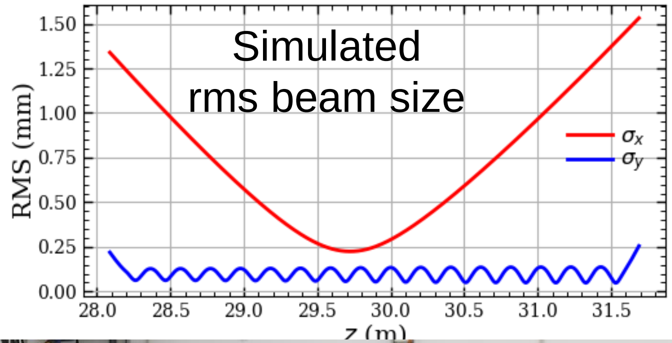


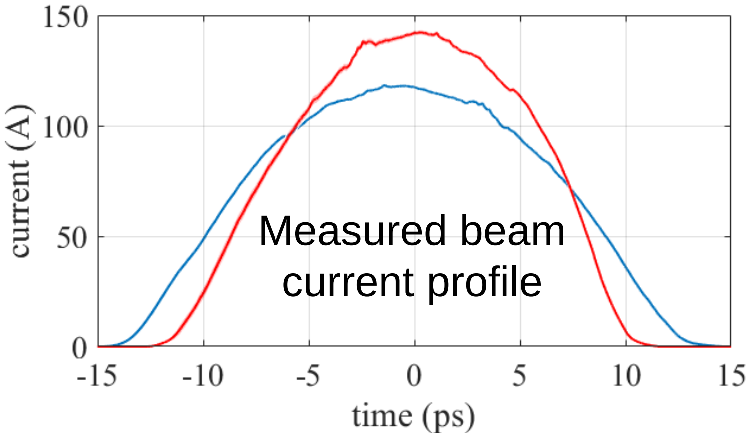


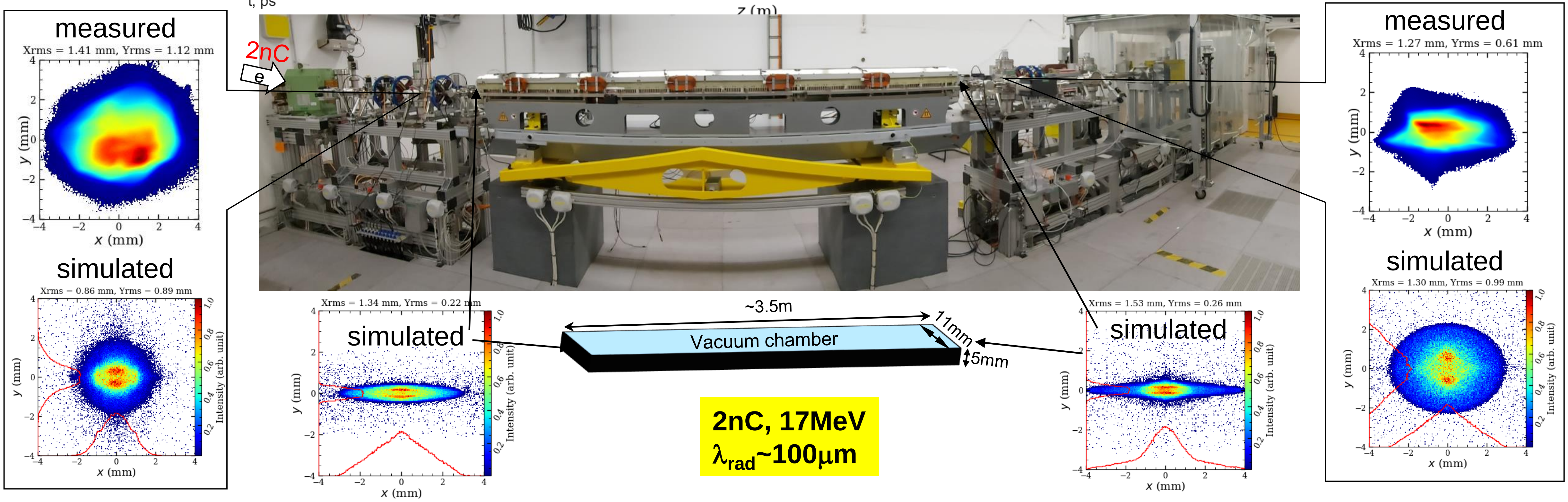
THz SASE FEL at PITZ

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





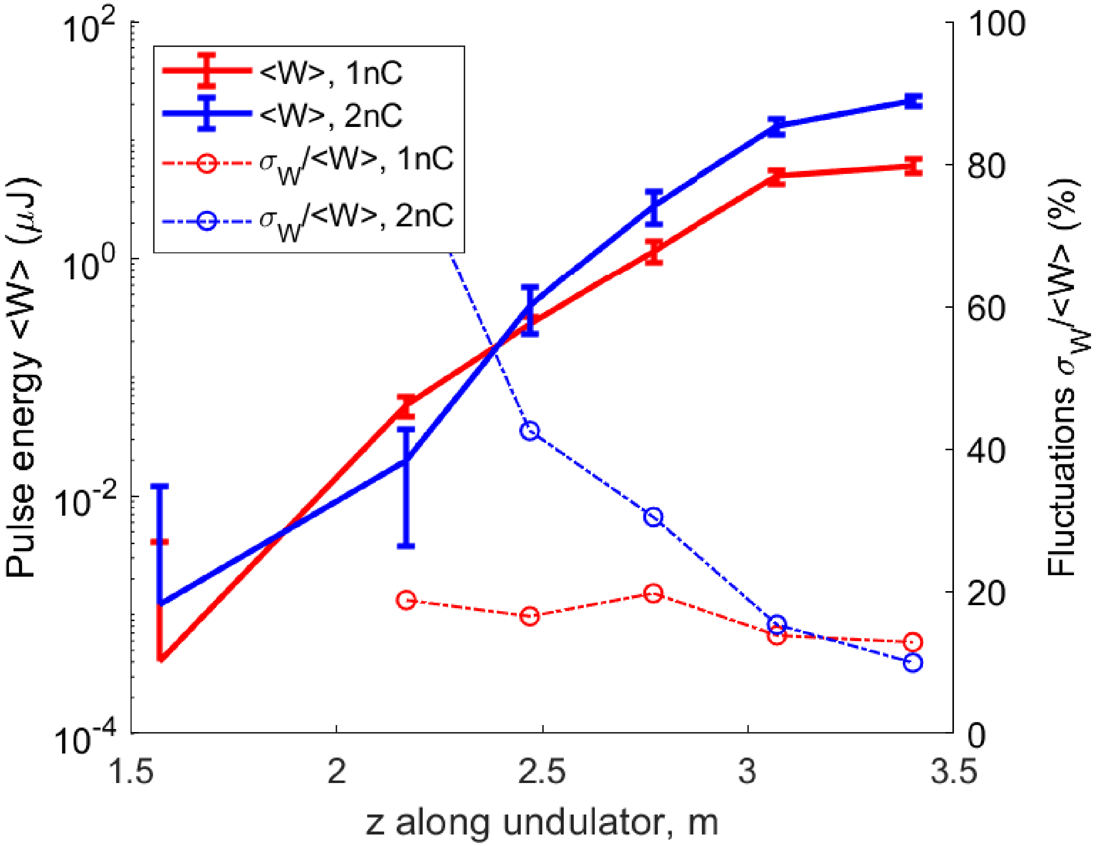




2nC, 17MeV
λ_{rad}~100μm

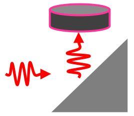
SASE Gain Curves at High3.Scr3 with BPF

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

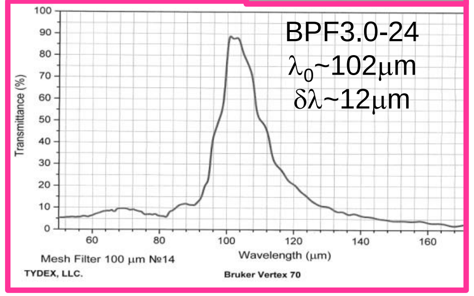


*Using **Gaussian** photocathode laser pulses 7-8ps FWHM*

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%)



BPF3.0-24
λ_0~102μm
$\delta\lambda$~12μm

Reference case: 2nC, 3THz

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

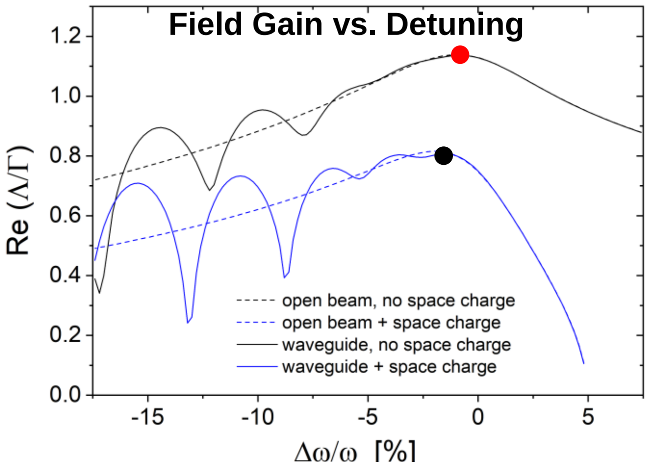
The gain parameter of the FEL amplifier

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

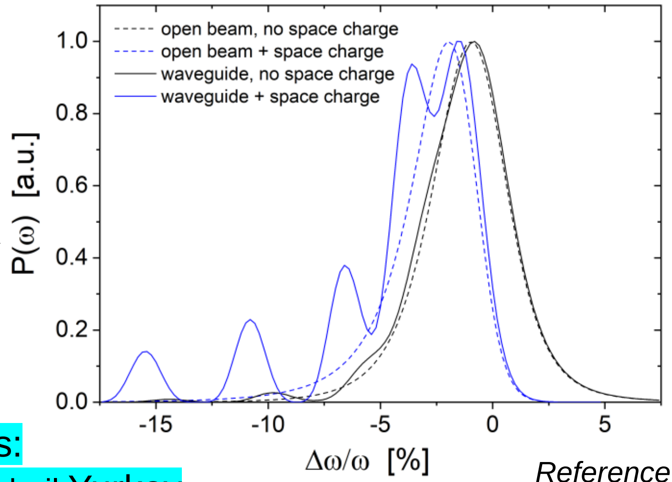
Parameter	Value
Diffraction B	~0.1
SC $\hat{\Lambda}_p^2$	0.9
FEL ρ	0.01
E-spread $\hat{\Lambda}_T^2$	0.003
Waveguide $\Omega*$	5.3

Eigenvalue problem →beam radiation modes

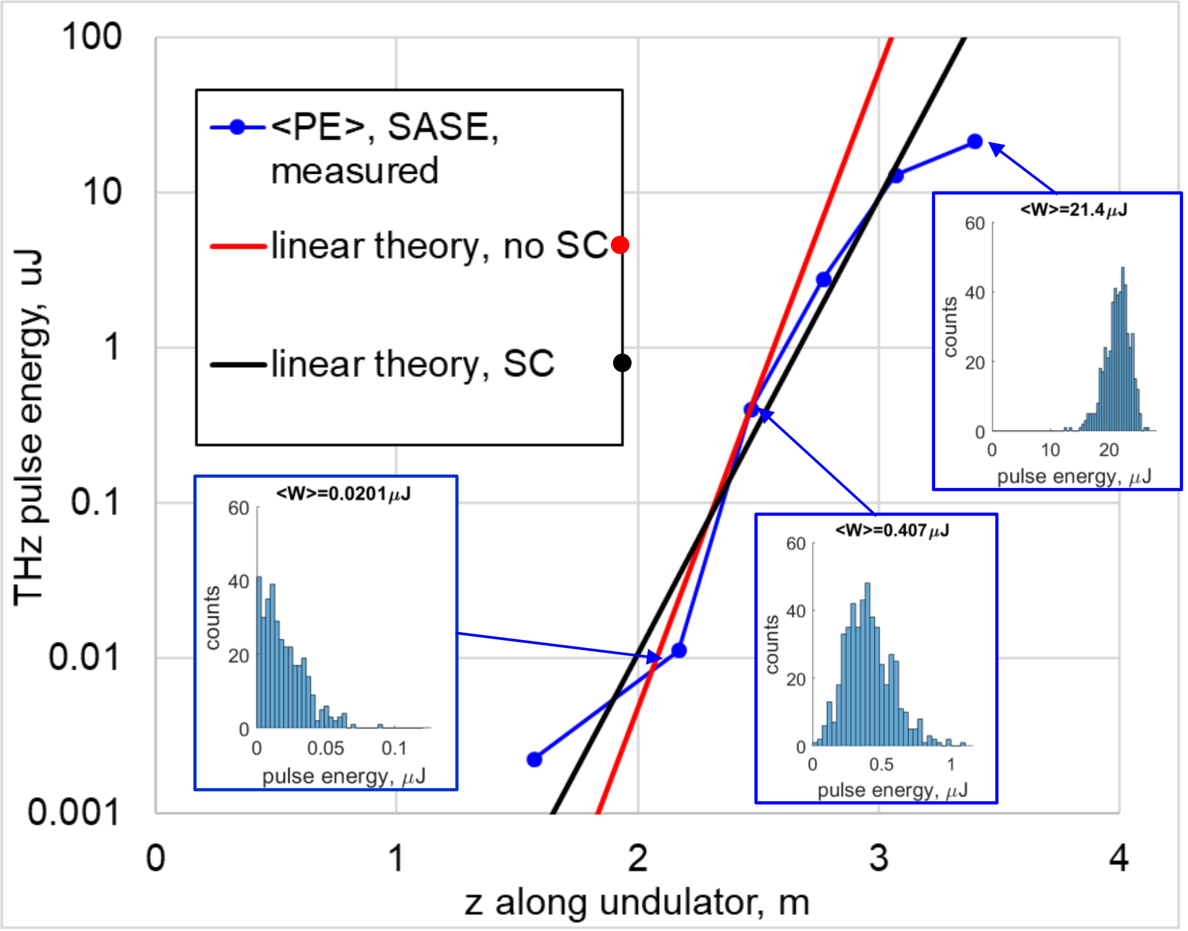
$E_x(z) \propto \exp(\Lambda \cdot z)$, Λ → field gain ($\mathrm{Re}\Lambda$)



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



SASE 2nC: Linear theory versus measurements



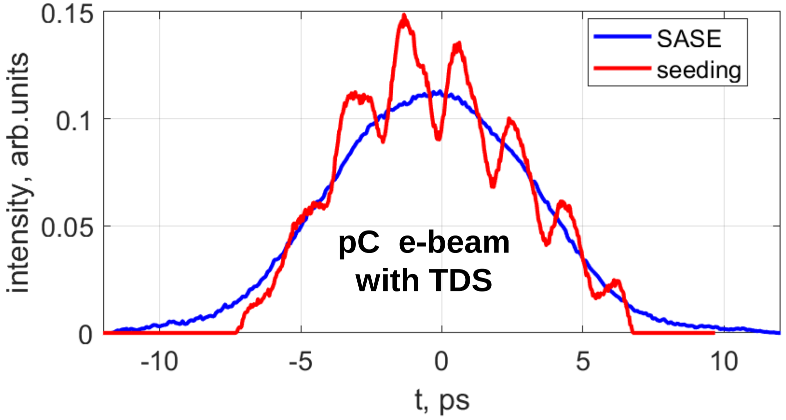
Calculations:
courtesy Mikhail Yurkov

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.

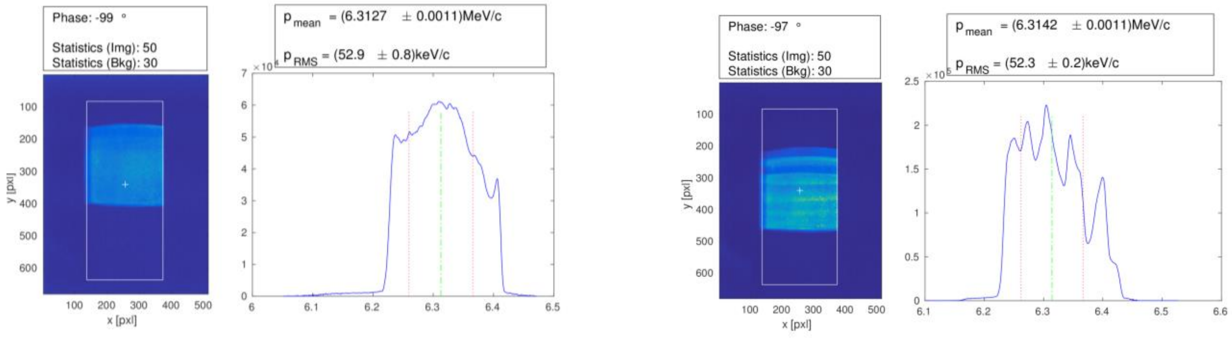
First Seeding Experiments

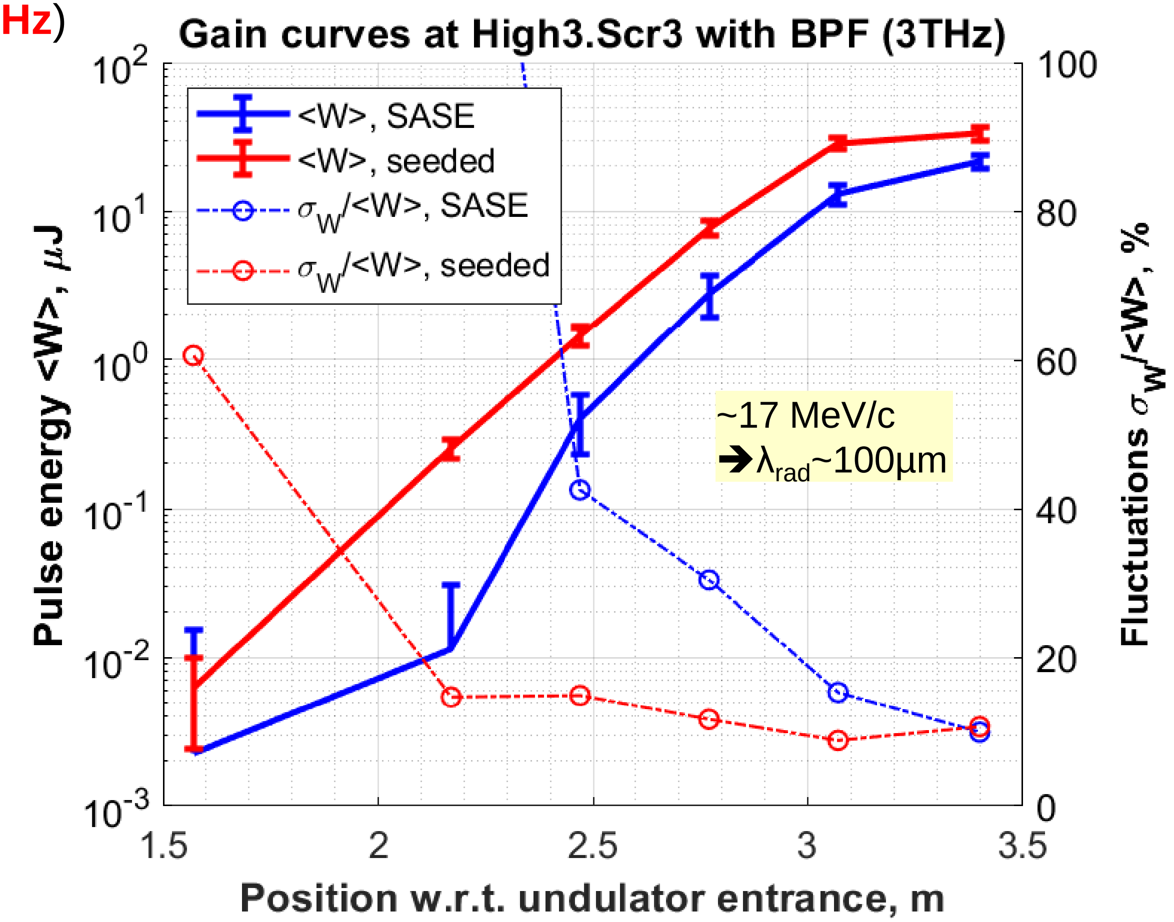
SASE vs. seeded THz FEL with modulated photocathode pulse (preliminary results)

- 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

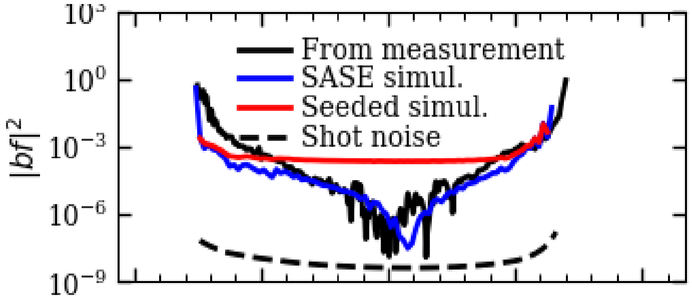
- The bunching factor

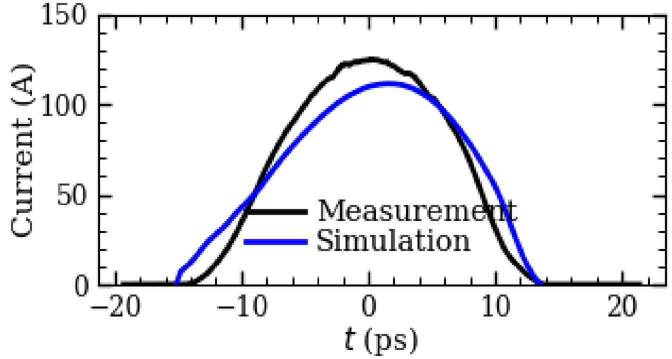
$$bf(\lambda,t) = \frac{1}{N_t}\sum_{n\in N_t}^{c|t_n-t|\le\lambda/2} e^{2\pi i\frac{ct_n}{\lambda}}.$$

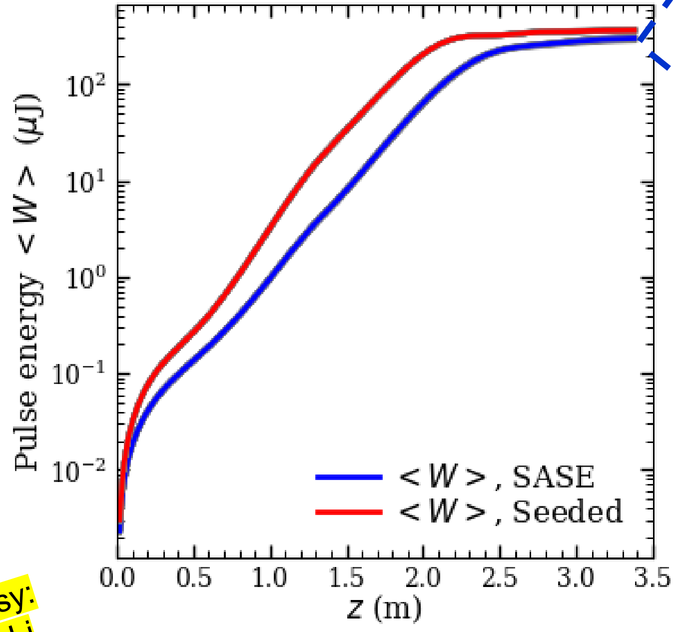
- For random distribution, the square of bunching factor (or the shot noise) follows exponential distribution and we have $\langle|\boldsymbol{bf}(\boldsymbol{\omega})|^2\rangle = \frac{\mathbf{1}}{\boldsymbol{N_e}}$, where N_e is the number of electrons within one radiation wavelength,
  e.g., $I_{peak}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

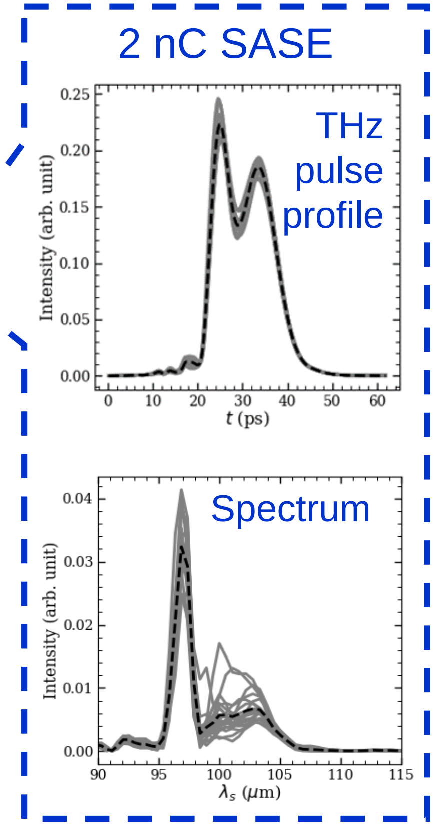
- But, due to the longer wavelength of THz, the radiations actually see a density slope within one wavelength

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







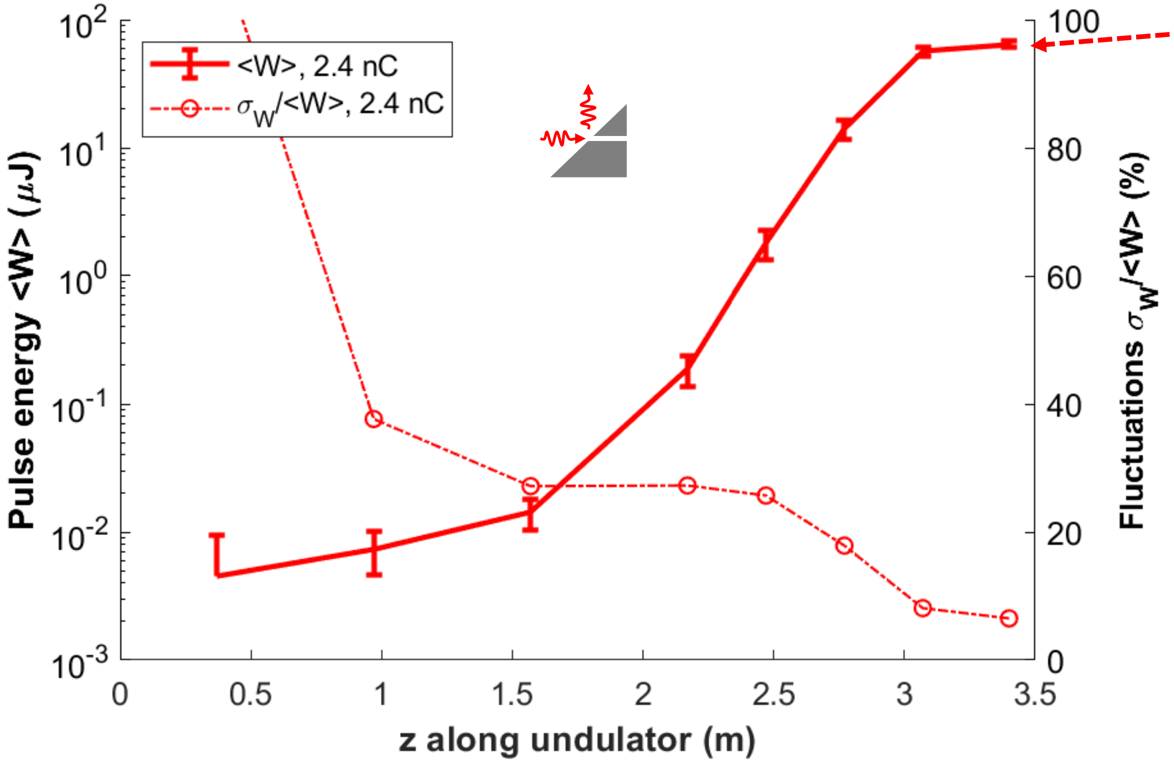


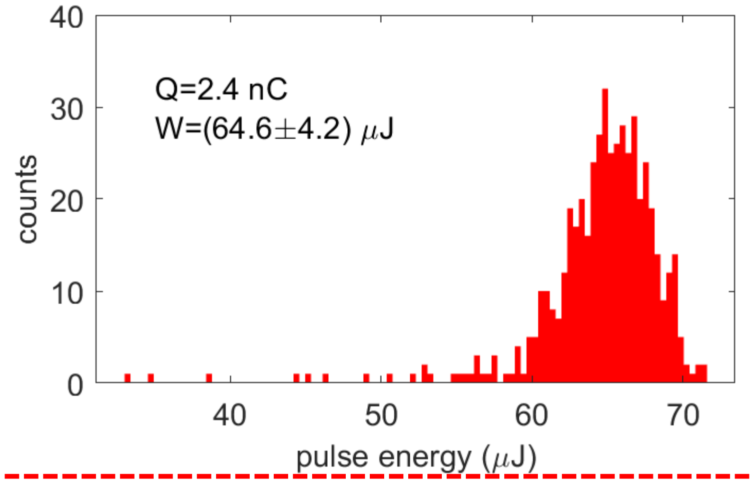
Courtesy: X.-K. Li

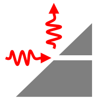
THz SASE FEL at PITZ: Further Optimization

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







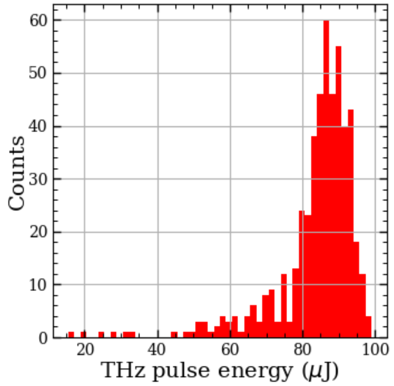
Estimated transmission ~50%

>100µJ generated

Currently max 3THz pulse energy at best setting:

(83.8 ± 13.3) µJ

Q=2.4nC



First Direct THz FEL Spectrum Measurements

28.02.2024N, FTIR spectrometer measurements (with E. Zapolnova, FS-FLASH-B)

- 2nC, central wavelength around 2.57 THz (110 μm)

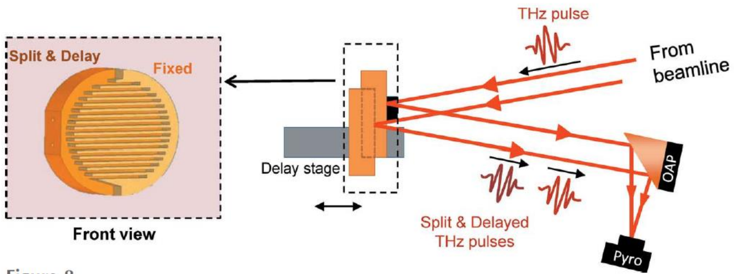
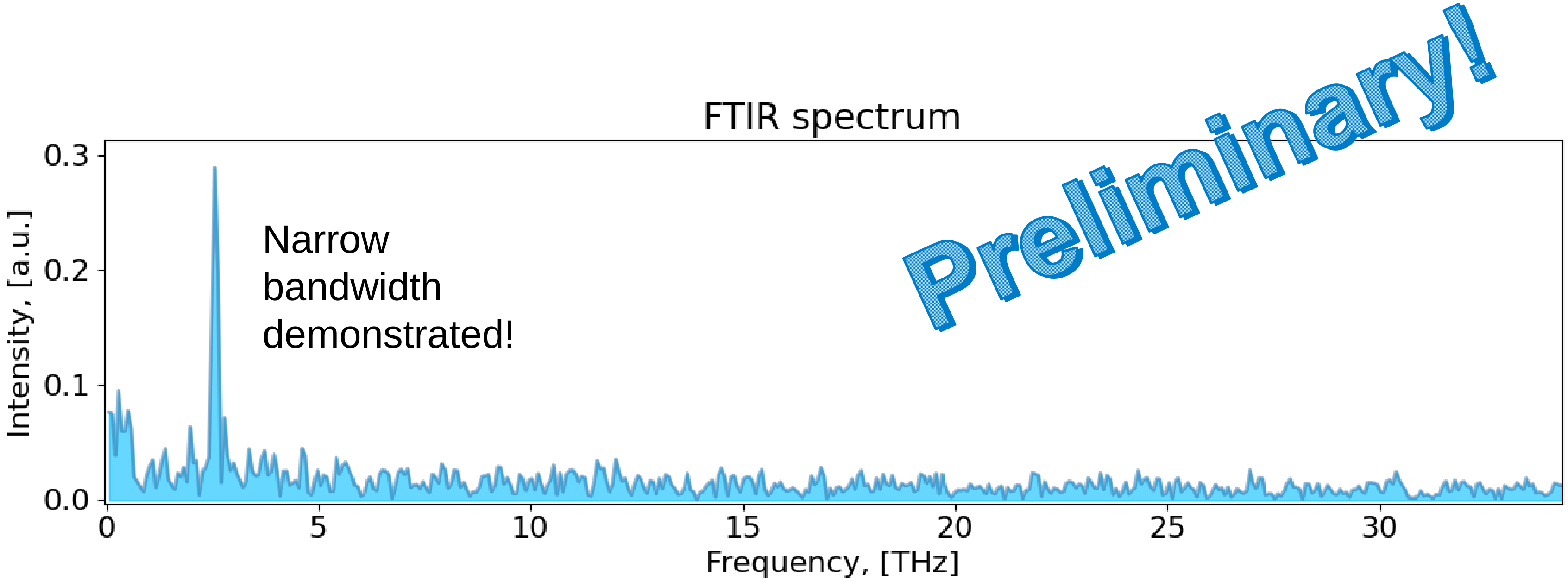


Figure 8
Scheme of the lamellar grating interferometer. OAP: off-axis parabolic mirror.



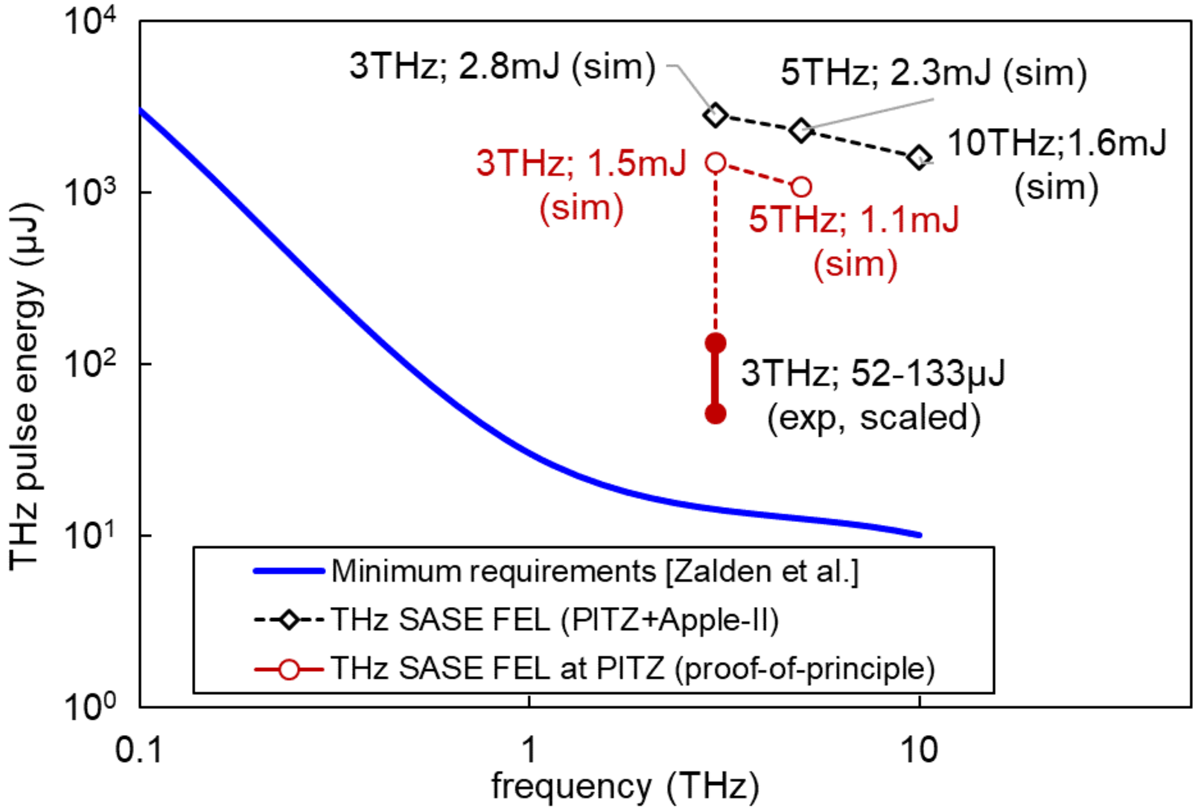
Narrow bandwidth demonstrated!

Preliminary!

Pan, R., Zapolnova, E., Golz, T., Krmpot, A. J., Rabasovic, M. D., Petrovic, J., Asgekar, V., Faatz, B., Tavella, F., Perucchi, A., Kovalev, S., Green, B., Geloni, G., Tanikawa, T., Yurkov, M., Schneidmiller, E., Gensch, M. & Stojanovic, N. (2019). Photon diagnostics at the FLASH THz beamline. J. Synchrotron Rad. 26, 700â€07.

Proof-of-principle Experiment on THz Source at PITZ

Where we are now and the way to go



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; 30µJ@1THz; 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

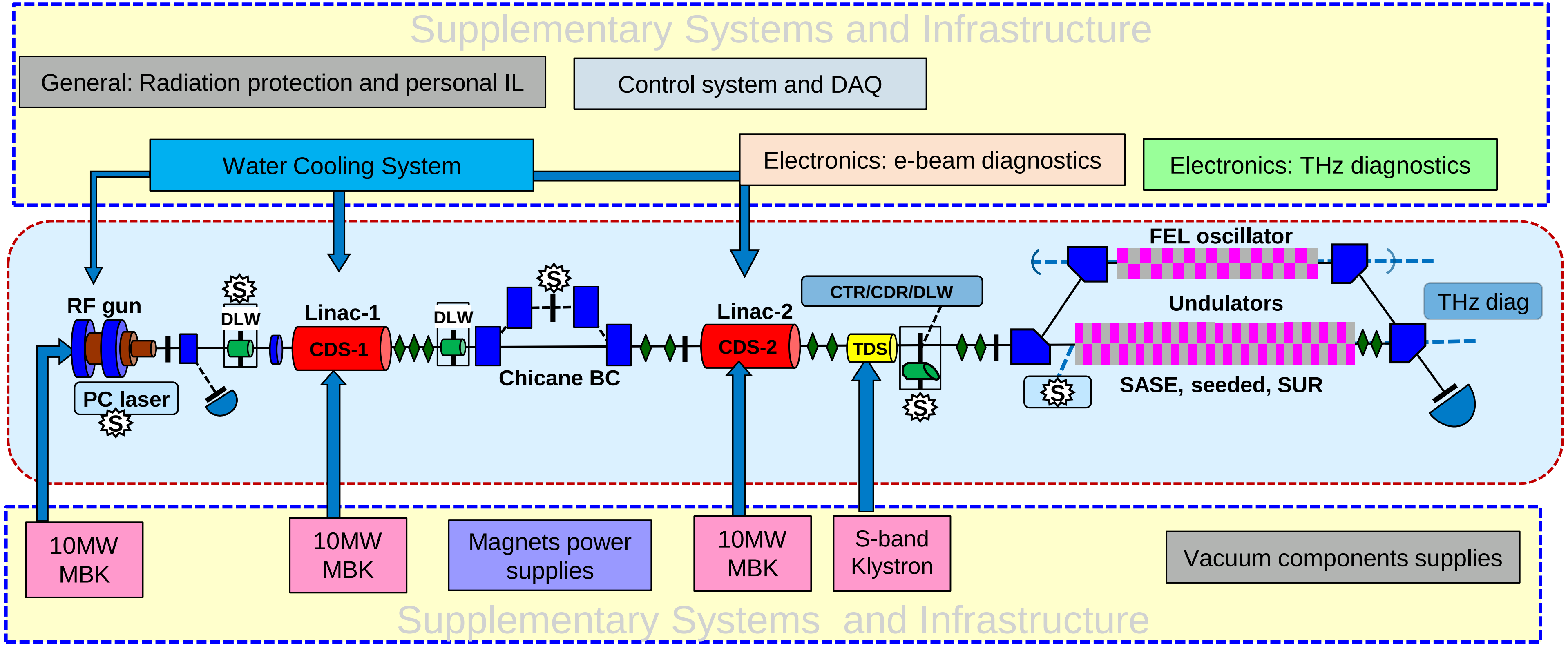
Gaussian photocathode laser, **2-3 nC** bunch charge

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.”

Conceptual Design of THz source based on PITZ-like accelerator

Zero-order CDR



Supplementary Systems and Infrastructure

General: Radiation protection and personal IL

Control system and DAQ

Water Cooling System

Electronics: e-beam diagnostics

Electronics: THz diagnostics

10MW MBK

10MW MBK

Magnets power supplies

10MW MBK

S-band Klystron

Vacuum components supplies

Supplementary Systems and Infrastructure

The Photo Injector Test Facility at DESY in Zeuthen (PITZ)
Deutsches Elektronen-Synchrotron DESY

Conceptual Design Studies of a THz source for Pump-Probe Experiments at the European XFEL Based on a PITZ-Like Photo Injector

Proof of Principle Experiments and Preliminary Conceptual Design

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*

Experimentally demonstrated:

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

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)	
Use BC to explore/extend the parameter space	
Spectral studies (FTIR and Michelson interferometer)	Complete fabrication / installation of the THz diagnostics stations
Transverse distribution with Pyrocam	
Flattop PC laser pulses + 4nC to increase the THz pulse energy	Full performance of the NEPAL-P

THz@PITZ: next steps

Topics for THz R&D 2024+, “Reduced list”

WP1: Exploration of THz parameter space at PITZ

- SASE (+bf studies)
- Seeded FEL (using modulated e-beams)
- ~~"Tapering studies with LCLS-I undulator?"~~

WP2: E-beam generation for THz seeding

- "PC laser pulse modulation with new methods + e-beam generation"
- Two-beam scheme
- DLW?
- ~~"Other methods: external source, etc."~~
- THz radiation w/ DLW?

WP3: THz diagnostics

- **EOS**
- Spectrometry
- ~~Martin-Puplett Interferometer (MPI)~~
- ~~Other advanced (fast) tools~~

?WP4: TDR on THz source for EuXFEL

- Project management
- "Ideal" THz facility layout refinement
- “Ideal” THz undulator design
- “Ideal” BC for THz machine

WP#	Topic	Our view on preferred priority (1-3)	Challenges	Expected delivery	Start date	Duration years	Investments		Operation			Manpower										Total costs on DESY site (rough estimate)	Risks		Possible collaborations	Remarks
							Componenets	Rough estimate in kEuro	weeks/year	weeks total	costs, kEuro	PD/year	PD total	PhD/year	PhD total	Tech/year	Tech total	All FTEs/year	All FTE*year total	PD (Hamburg) total	Ing. (Hamburg) total		level	details		
1	**Exploration of THz parameter space at PITZ**				**2024**	**3**		**150**	**4**	**12**	**480**	**0.5**	**1.5**	**1**	**3**	**0.5**	**1.5**	**2**	**6**			**1018.5**				
	SASE	1	tunability check, presice trajectory model understanding waveguide effect	updated diagnostics, realistic			Beam arrival cavity (BAM), e-beam diagnostics improvements?	100	1.5	4.5	180	0.25	0.75	0.5	1.5	0.25	0.75	1	3			**507.75**	low / medium	accelerator componenets failures	MPY	
	Seeded FEL (using modulated e-beams)	1	control of the input signal properties, BC setup	seeding procedure, BC tuning			Update of CTR/CDR station for seeding tuning	50	2.5	7.5	300	0.25	0.75	0.5	1.5	0.25	0.75	1	3			**510.75**	low / medium	accelerator componenets failures	MPY	
	~~Tapering studies with LCLS-I undualtor?~~	~~2-3~~	~~independent and safe undulator motors control~~	~~system in operation~~			~~SPS or similar?~~																~~medium/ high~~	~~mechanical constrains, movement range is not sufficient~~	~~SLAC?~~	
2	**E-beam generation for THz seeding**				**2024**	**3**		**80**	**5**	**15**	**600**	**0.5**	**1.5**	**1**	**3**	**0.5**	**1.5**	**2**	**6**			**1021.5**				
	PC laser pulse modulation with new methods + e-beam	1	Laser system modification / extension, presice and reliable control of modulation	system in operation			Laser components (optics, gratings, etc	70	4	12	480	0.25	0.75	0.5	1.5	0.25	0.75	1	3			**515.25**	medium / high	stablity, routine opreration?	FS-LA	
	Two-beam scheme	1-2	Laser beamline update, synchronization	system in operation			Laser beam line components	10	1	3	120	0.25	0.75	0.5	1.5	0.25	0.75	1	3			**506.25**	low / medium			
	~~Other methods: DLW, external source, etc.~~	~~2-3~~	~~space charge, emittance dilution, apperture issues~~	~~system in operation~~			~~New DLW (tunable?)~~																~~medium / high~~	~~see challenges~~	~~CFEL~~	
	~~THz radiation w/ DLW~~	~~2-3~~	~~Modification of High3 stations~~	~~proof-of-principle~~			~~DLW w/ Vlasov antenna at High3.Scr1,3?~~																~~medium / high~~	~~see challenges~~	~~CFEL (F. Lemery)?~~	
3	**THz diagnostics**		**SASE fluctuations, long multicycle pulses, arival time jitter, towards CEP, THz transport**		**2024**	**3**		**395**	**5.5**	**10.5**	**420**	**1**	**3**	[illegible]	[illegible]	[illegible]	**3**	**3.25**	**9**			**1625**				
	EOS	1	+single shot	EOS design for THz SASE/seeded FEL at PITZ			diag.laser or diode pump for Pharos (50k+150k?), pectrometer/. spectrum analyzer - camera (2 channel, high resolution) 100k?, fibers, BL components+controls 50k?	350	3	9	360	1	[illegible]	[illegible]	2.25	1	3	2.75	8.25			**1467.5**	high	fluctuations of the THz signals, long THz pulses, sensitivity of the spectrometer, diagnostic laser transport	Univ. de Lille (S. Bielawski) FLASH (B. Steffen), CFEL (N. Matlis?)	Spectrometer/camera could be on load from DESY HH?
	Spectrometry	1-2	+sigle shot, narrow band, resolution, 3rd and 5th harmonics	Spectrometry setup is in operation at PITZ			Lamellar Grating Spectrometer Echelon mirrors, band-pass filtes	40	2	[illegible]	0	[illegible]	0	0.25	0.75	0.25	0	0.5	0.75			**92.5**	high	no experience at PITZ, resolution issue due fluctuations (pointing jitter)?	FLASH (E. Zapolnova)	
	~~Martin-Puplett Interferometer (M~~	~~1-2~~	~~alignment~~	~~MPI commissioned and in operation~~			~~new design, 2 pyro~~																~~low~~	~~alignment issues?~~	~~HZDR (TELBE)?~~	
	~~Other advanced (fast) tools~~	~~2-3~~	~~fast detector, calibration, integration into PITZ control system, DAQ~~	~~THz pulse train measurements~~			~~Fast DESY-pyro?, 1MHz resolved~~																~~medium~~	~~cross-talk, electronic noise?~~	~~FLASH (B. Steffen)?~~	
	Transverse distribution	2-3	proper THz camera setup, new 2D detectors	Transverse modes characterization, coherency studies			Consumables (filter, polarizers, etc) New 2D detector (Hamamtsu) XXk?	5	0.5	1.5	60											**65**	medium	stability, THz camera damage?		
SUM (WP1-3)								**625**			**1500**	**2**	**6**	**3**	**9**	**2.25**	**6**	**7.25**	**21**	**0**	**0**	**3665**				
4	**TDR on THz source for EuXFEL**		**to be coordinated with EuXFEL!**	**TDR on THz source**	**2025**	**2**						**2**	**4**			**1**	**2**	**3**	**6**	**1**	**2**	**600**	**medium**			**Who will lead / coordinate the project at DESY (HH or Zeuthen)?**
	Project management	1	Overall coordination (HH-Z), costs estimations	TDR								1	2			1	2	2	4	0.75	1.5	**400**		coordination Hamburg-Zeuthen-EuXFEL		Also manpower from EuXFEL? (1FTE for on-site planing?)
	"Ideal" THz faclity layout refinement	1	realistic s2e simulations	beamline design, budget estimate								0.5	1					0.5	1			**100**		realistuic simulations, space constraints		Accelerator layout refinement for a dedicated (multiple) THz source, oscillator (optical cavity) at 4.5MHz?
	“Ideal” THz undulator design	1	combine several options, variable tapering, strength, period?	THz undulator design								0.25	0.5					0.25	0.5	0.25	0.5	**50**		prototype for proof-of-principle	FS-US DESY HH (M. Tischer, P. Vagin)	? Prototype fabrication (not included)
	“Ideal” BC for THz machine	1-2	multipurpose, dispersion management, space charge, CSR	optimized BC design								0.25	0.5					0.25	0.5			**50**		prototype for proof-of-principle		Really multipurpose for ultimate performance
SUM (WP1-4)								**625**			**1500**	**4**	**10**	**3**	**9**	**3.25**	**8**	**10.3**	**27**	**1**	**2**	**4265**				

proposal

THz@PITZ Team and Collaboration

Proof-of-principle experiment on high power THz source

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Thank you!