THz Activities at PITZ

PITZ studies towards an accelerator driven high power, tunable THz source for pump-probe experiments at European XFEL

Prach Boonpornprasert for the PITZ team

1st ARD Alliance Meeting
DESY Hamburg, 5.9.2018

Outline of the Talk

- **Photo Injector Test facility at DESY, Zeuthen site (PITZ)**
- **A proposal for Accelerator based THz source for P&P at E-XFEL**
- **IR/THz Options at PITZ:**
  - High-gain SASE FEL
  - Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation (CDR)

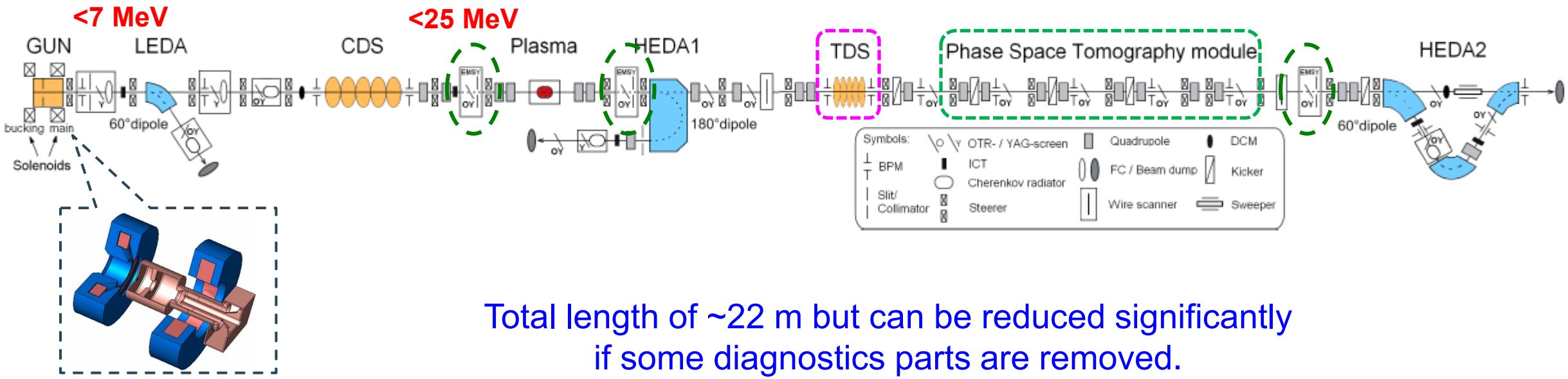
} **Topic of my PhD thesis**

- **SASE FEL based on PITZ accelerator and LCLS-I undulators**
- **LUSIA proposal** (**A**ttosecond **SI**ngle-cycle **U**ndulator **L**ight ➔ Horizon2020 FETOPEN call)

Photo Injector Test facility at DESY, Zeuthen site (PITZ)

Development, test and optimization of high brightness e-sources for SC linac driven FELs + applications:

- test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning, characterization and optimization of gun cavities and photo injector subsystems, e.g. photocathode laser)
- **high brightness → small transverse emittance (projected and slice)**
- further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …
  → applications like **THz**, plasma acceleration, UED, …



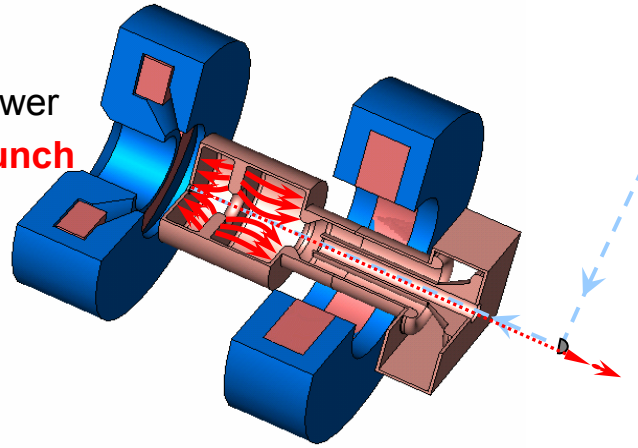
Total length of ~22 m but can be reduced significantly
if some diagnostics parts are removed.

PITZ "engine": RF-Gun and Photocathode Laser

Highlights of the facility

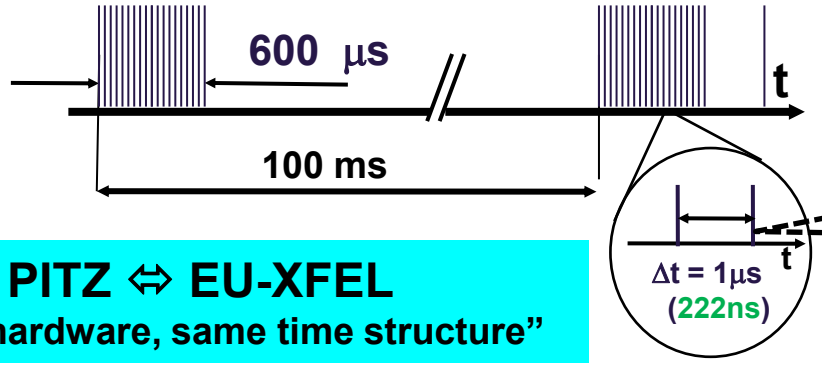
RF gun

- L-band (1.3 GHz) 1.6-cell copper cavity
- Ecath>~60MV/m → **7MeV/c** e-beams
- 650us x 10Hz → up to **45 kW** av. RF power
- Cs_2Te PC (QE~5-10%) → **up to 5nC/bunch**
- LLRF control for amp&phase stability
- Solenoids for emittance compensation



Pulse Train Time Structure:

PITZ and **EXFEL** trains with up to 600 (**2700**) laser pulses



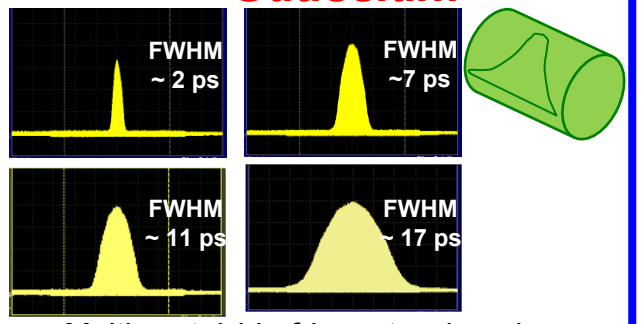
PITZ ⇔ EU-XFEL

"Same hardware, same time structure"

Photocathode laser(s) (UV)

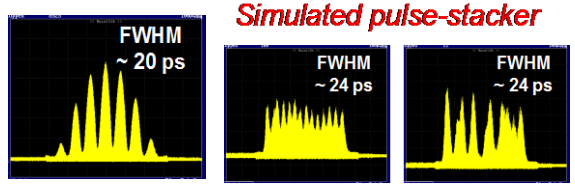
Default laser system
(Max-Born-Institute, Berlin)

Gaussian:

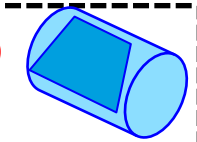


Multicrystal birefringent pulse shaper containing 13 crystals

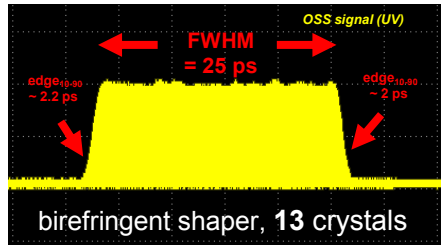
Simulated pulse-stacker



Flattop



Cathode laser pulse: temporal profile



Institute of Applied Physics of the Russian Academy of Sciences

New laser system

3D ellipsoidal

Pulse shapers:
- Spatial Light Modulator (SLM) based
- Upgrade with Volume Bragg Grating (VBG)

Oscillator upgrade – Pharos-20W-1MHz frontend
Pulse length 0.25-10ps+

Different lasers

➔ Possible to use **simultaneously**

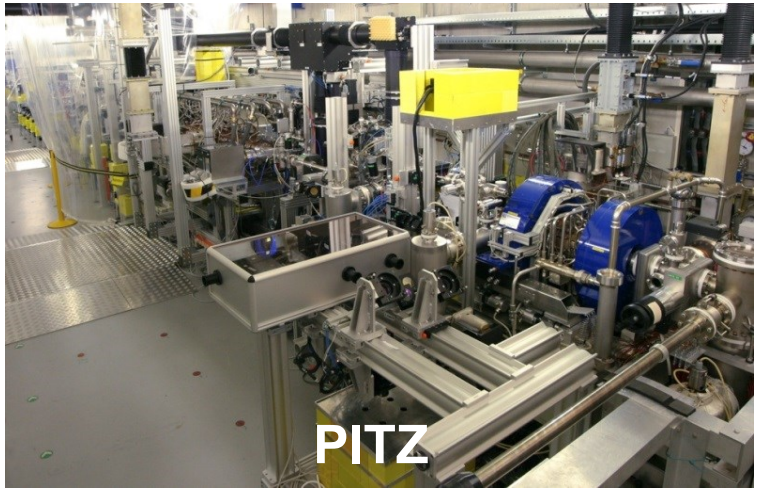
➔ various **THz options**

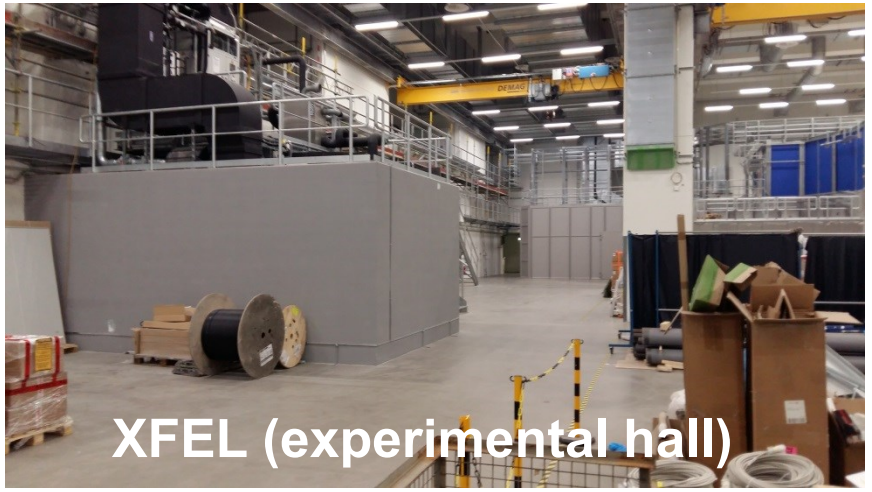
Accelerator based tunable IR/THz source for P&P at E-XFEL

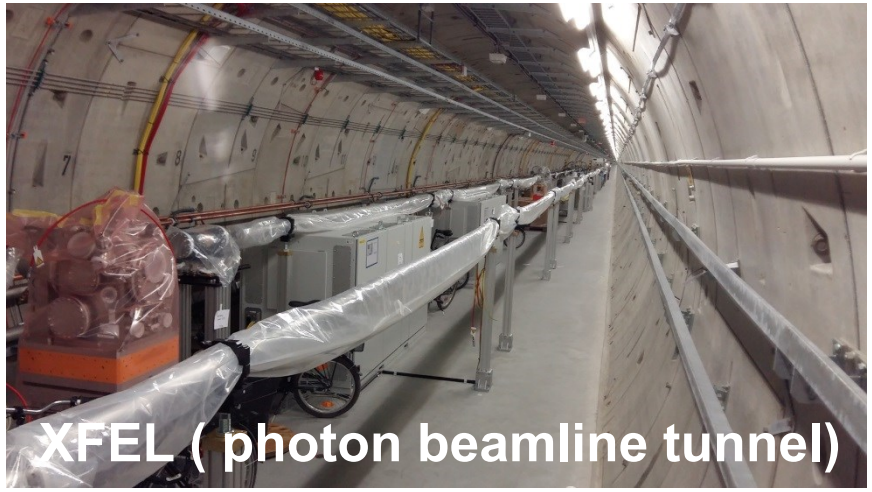
PITZ can be used as a prototype!

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

- Accelerator based IR/THz source meets all requirements for pump-probe experiments (e.g., the same pulse train structure!).
- Construction of a radiation shielded annex (reduced copy of PITZ facility) is possible close to user experiments at the European XFEL.
- Prototype of the accelerator already exists. → **PITZ** facility at DESY in Zeuthen.


PITZ

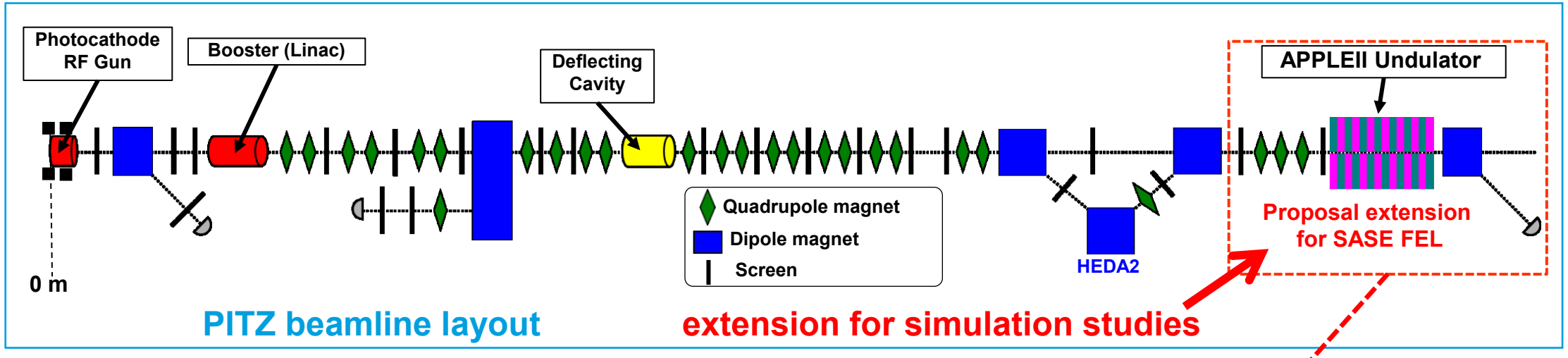

XFEL (experimental hall)


XFEL (photon beamline tunnel)

→ PITZ can be used for proof of principle and optimization!

IR/THz Options at PITZ: High-gain SASE FEL

Case studies of generating THz radiation by PITZ electron beam



PITZ Highlights:

- Pulse train structure
- **High charge feasibility (4 nC)**
- **Advanced photocathode laser shaping**
- E-beam diagnostics
- Available tunnel annex
- …

► **SASE FEL for $\lambda_{rad} \leq 100$ µm ($f \geq 3$ THz)**

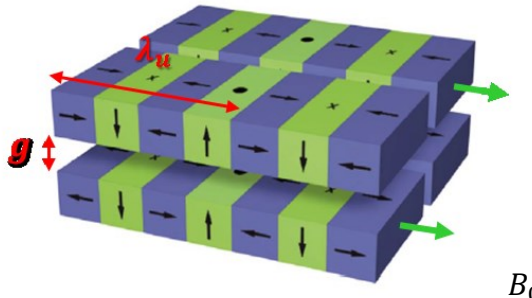
Current PITZ "boundary conditions":

- 22-25 MeV/c max
- No bunch compressor
- No undulator (yet…)
- …

THz SASE FEL at PITZ

Undulator and beam parameter space

Example: APPLE- II Undulator*



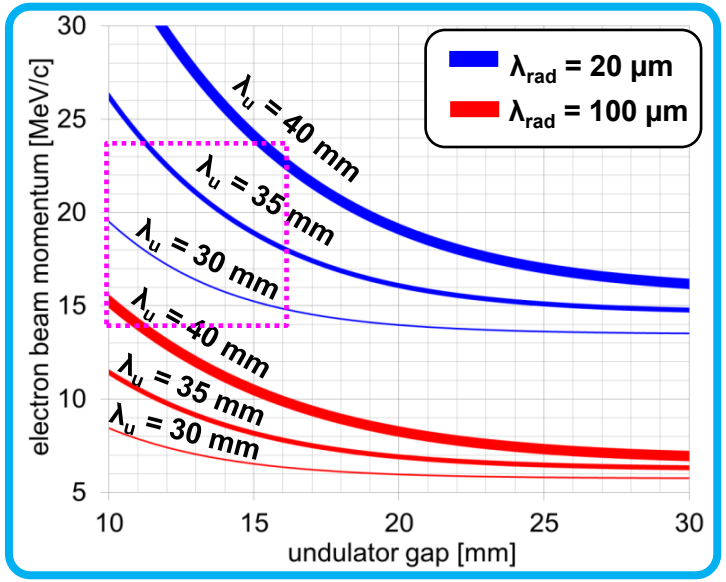
Radiation wavelength

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

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

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

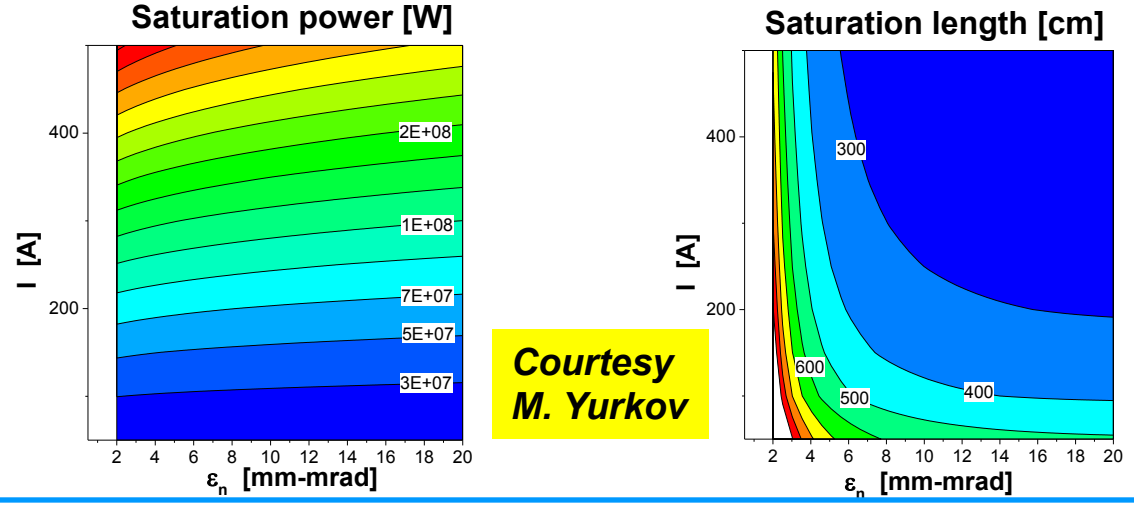
Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007



Conditions :
λ_{rad} of 20 – 100 μm
Max P_z ~ 22 MeV/c
gap $g \geq 10$ mm

Selections :
λ_u of 40 mm
22 MeV/c for 20 μm
15 MeV/c for 100 μm

FEL Parameter Space with FAST code (λ_{rad} = 100 μm)



Courtesy M. Yurkov

SASE FEL simulations assuming:

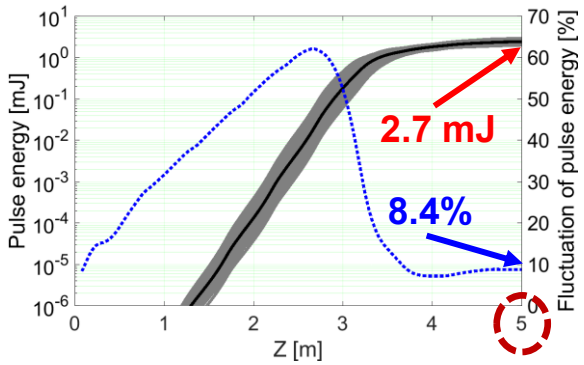
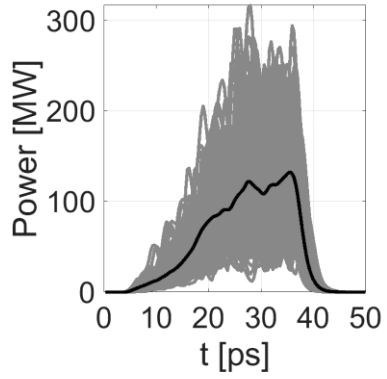
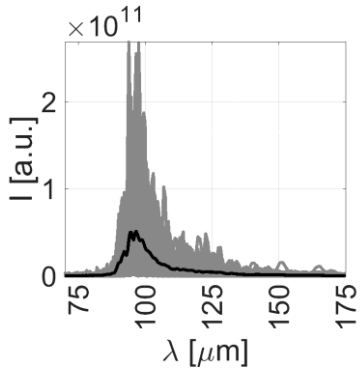
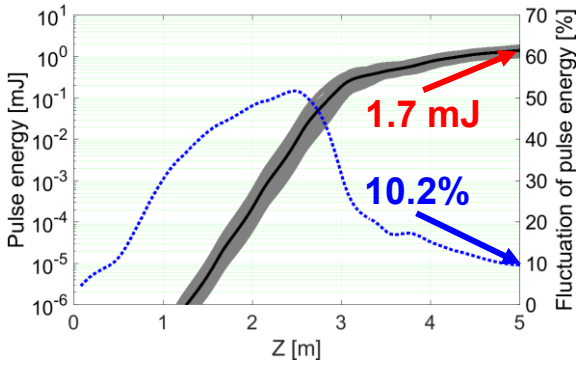
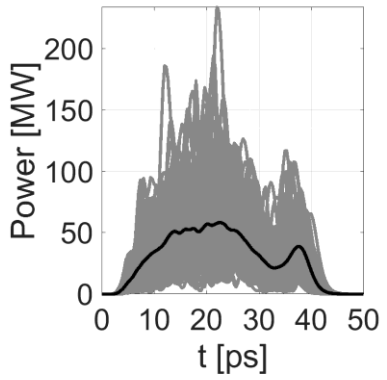
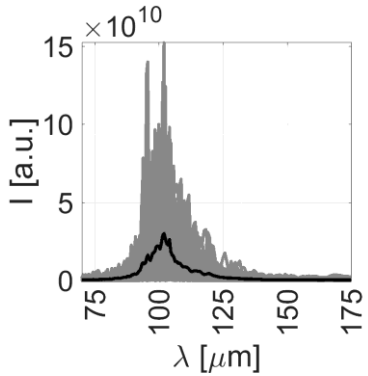
- Helical undulator with period length of **40 mm**
- Electron beam with **15 MeV/c** momentum, **4 nC** bunch charge, **~2 mm** rms bunch length

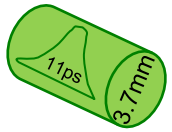
Preliminary conclusions:

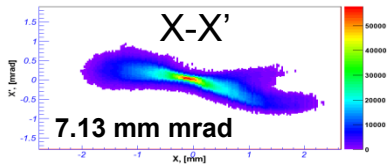
- Transverse normalized emittance ε_n has almost no impact on saturation power
- Higher ε_n ➔ lower saturation length
- Beam **peak current** (charge) → most impact

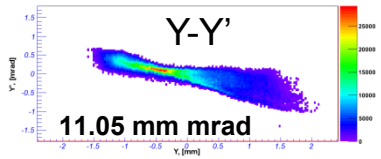
THz SASE FEL: Beam Dynamics Simulations and Experiments

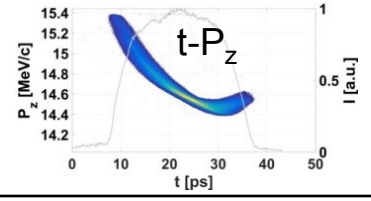
λ_{rad} = 100 µm (3 THz)

Setup: **4nC** → I_{peak}~200A, ~15MeV/c, λ_u=40 mm, K=1.8, L_u=5m	FEL pulse energy (average and rms fluct.)	FEL radiation pulse at undulator exit	
		temporal profiles	spectral profiles
Start-to-end: ASTRA→GENESIS1.3 • Photocathode laser: ∅5mm, flattop 2/20\2ps • Gun and booster phases and main solenoid optimized for high I_{peak} and small δE			
E-beam from **experiment**→ GENESIS1.3 • Photocathode laser: ∅3.7mm, Gaussian 11ps FHWM • Phase spaces → from measurements			



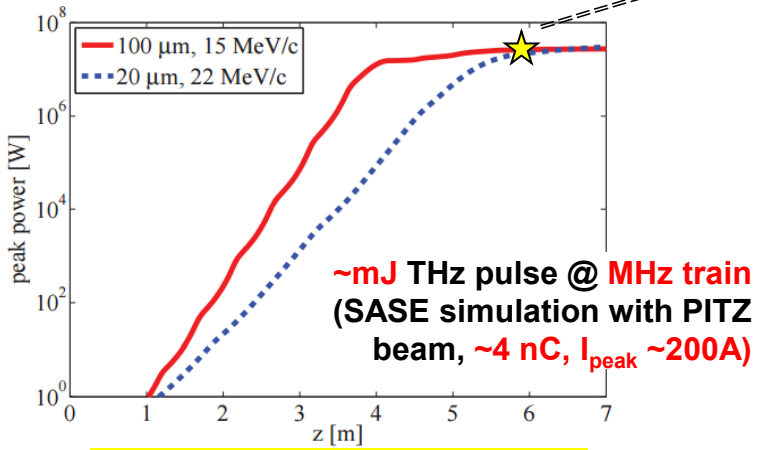






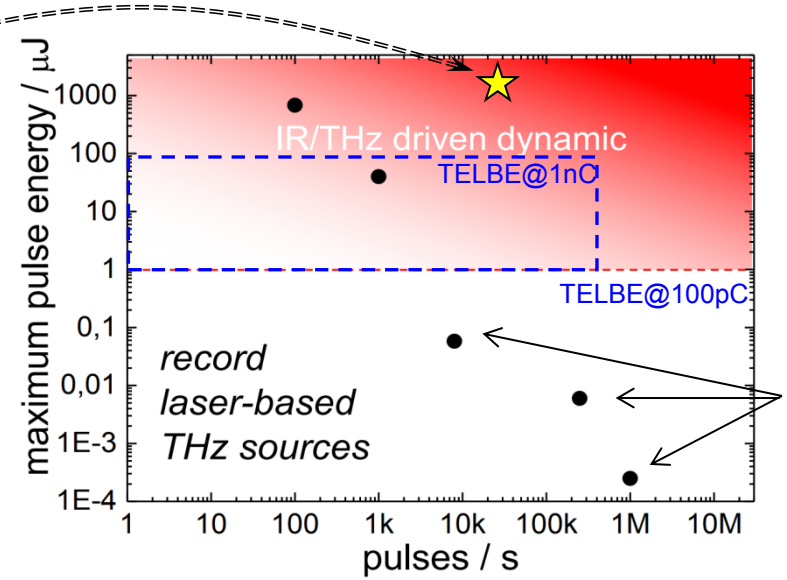
THz SASE FEL: Comparison with laser-based THz sources

PITZ-like accelerator can produce ~mJ THz pulses (λ_{rad}=20-100μm) matching time structure to XFEL X-ray pulses.



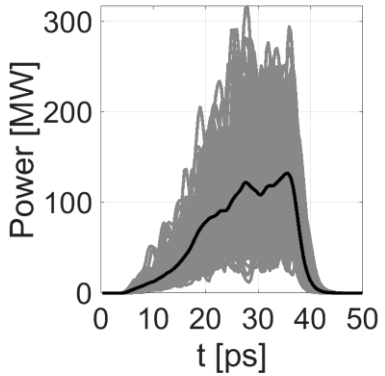
~mJ THz pulse @ MHz train (SASE simulation with PITZ beam, ~4 nC, I_{peak} ~200A)

P.Boonpornprasert, et al. MOP055, FEL2014, Basel, Switzerland



Laser based THz pulse energy is limited at high repetition rate

*Plot based on talk of **M. Gensch** "Follow up on THz Radiation" at ARD-ST3 Annual Workshop 19-21.07.2017,DESY, Zeuthen and paper **B. Green**,. et al. High-Field High-Repetition-Rate Sources for the Coherent THz Control of Matter. Sci. Rep. 6, 22256; doi: 10.1038/srep22256 (2016).*

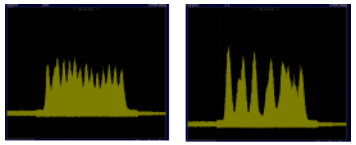


But still SASE (starting from the shot noise) ...

?How to improve stability (CEP= carrier envelope phase)?

Options to improve THz radiation stability

Pre-bunching → "Seeding"

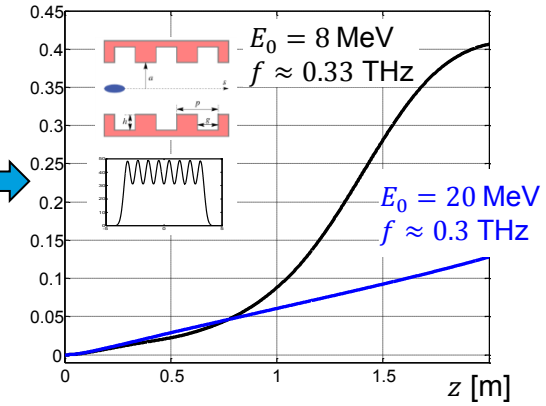


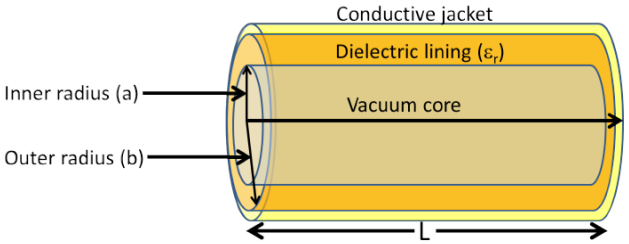
- Photocathode laser pulse temporal modulation
- Using IR laser, modulator and BC for E or δE modulations
- Using CDR from short seeding bunch
- **Using corrugated structures**
- **Using Dielectric Lined Waveguides - DLW (first experiments)**

Pipe radius a, mm	2
Pipe length L, m	0.5-2
Corrugation depth h, mm	0.05
Corrugation period p, mm	0.04
Corrugation gap g, mm	0.02
Gaussian bunch rms σ, mm	0.1-0.3(*8)

ΔE[mJ]

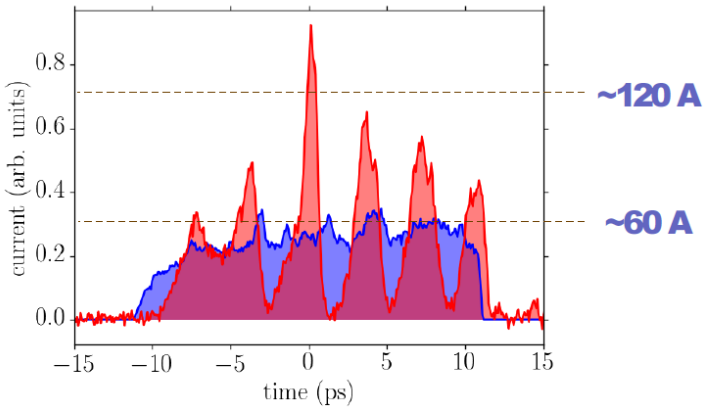
***Courtesy** I. Zagorodnov*



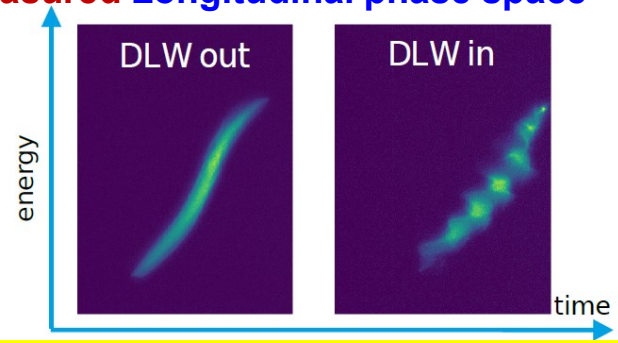


Measured e-beam current profile

without (blue trace) with DLW (red trace), λ=1.03 mm; The peaks are consistent with the wavelength of the structure 3.3 ps.



Measured Longitudinal phase space



In collaboration with CFEL (F. Lemery) and APC FNAL (P. Piot)

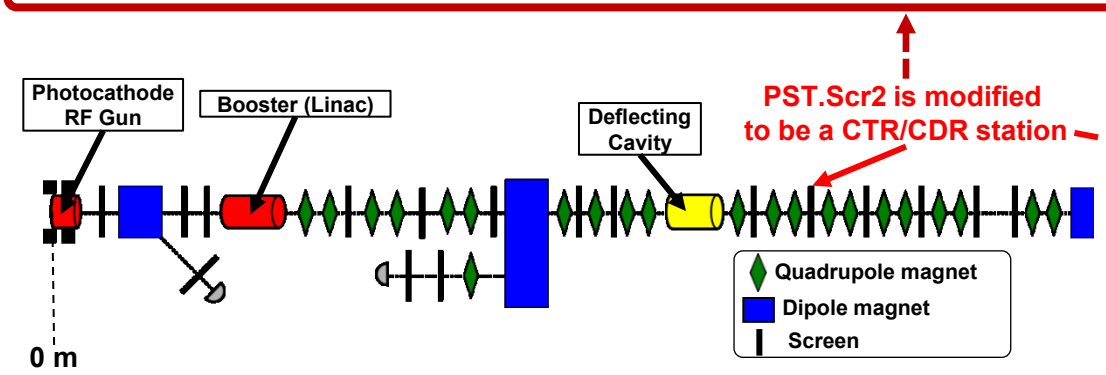
F. Lemery et al., Experimental demonstration of ballistic bunching with dielectric-lined waveguides at PITZ, IPAC 2017, WEPAB122

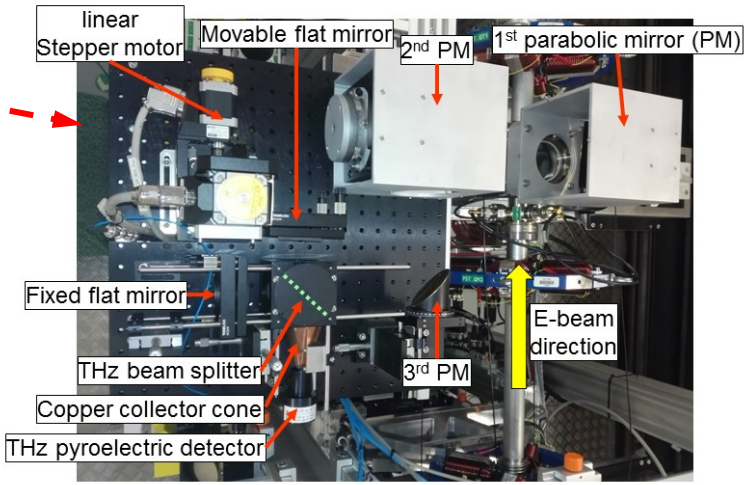
Future topics for PhD research at PITZ

First THz Radiation Generated at PITZ

CTR/CDR for THz generation

Coherent Transition / Diffraction Radiation (CTR/CDR) for $\lambda_{rad} \geq 100$ µm ($f \leq 3$ THz)





PITZ Highlights:

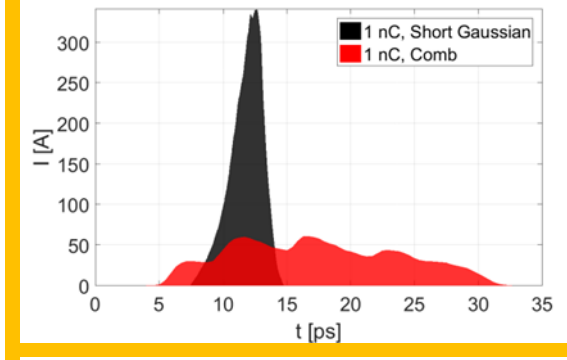
- Pulse train structure
- High charge feasibility (4 nC)
- **Advanced photocathode laser shaping**
- E-beam diagnostics
- Available tunnel annex
- …

Current PITZ "boundary conditions":

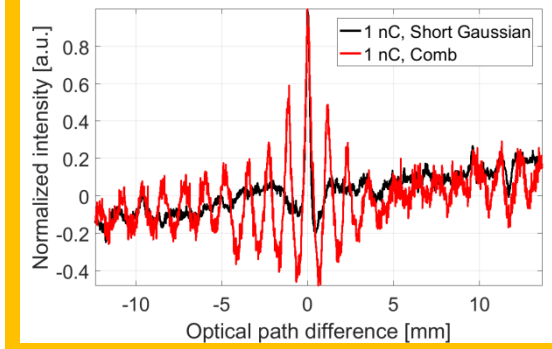
- 22-25 MeV/c max
- No bunch compressor
- …

1st experiments with CTR/CDR THz generation

Measured electron beam temporal profiles



THz Michelson interferometer measurements of CTR



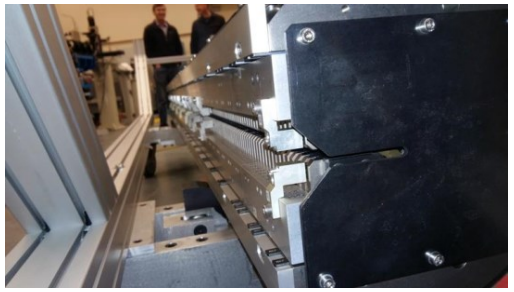
SASE FEL based on PITZ accelerator and LCLS-I undulators

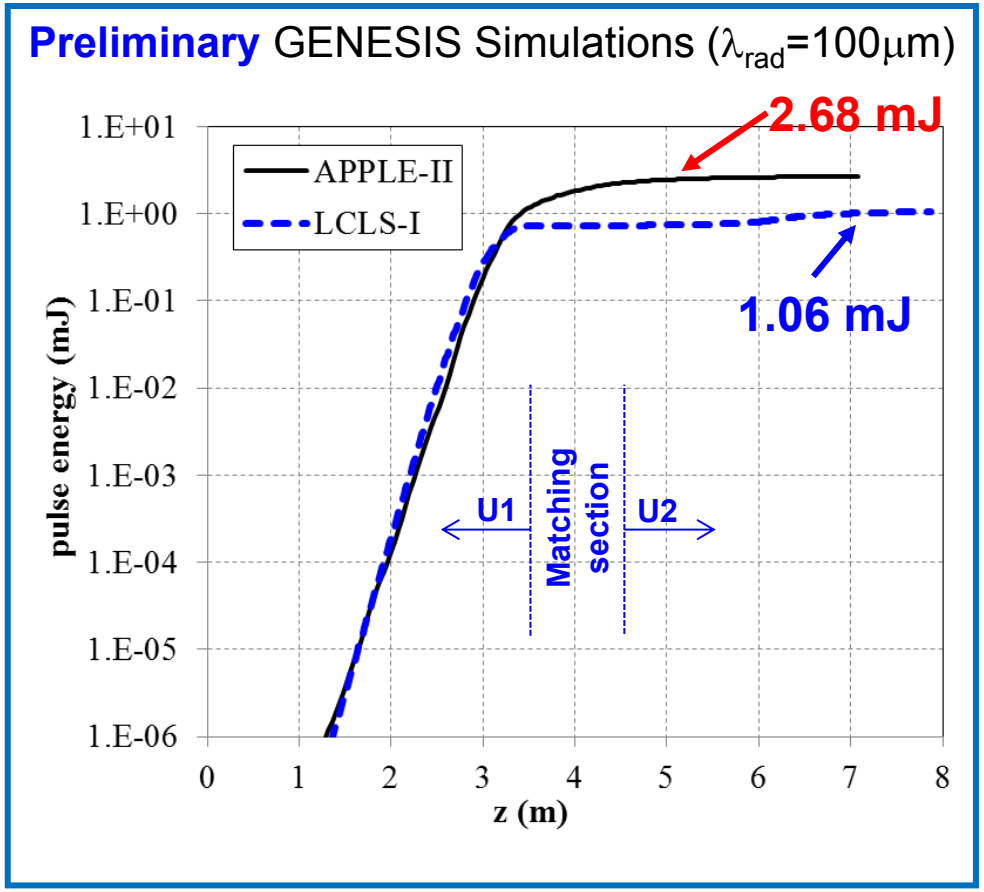
LCLS-I undulators (available on loan from SLAC) → under study and negotiations

Some Properties of the LCLS-I undulator

Properties	Details
Type	**planar hybrid** (NdFeB)
K-value	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

Reference: LCLS conceptual design report, SLAC-0593, 2002.





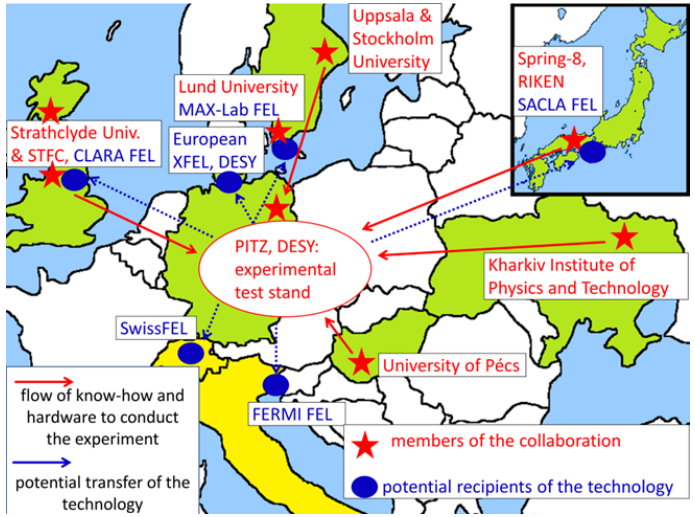
Preliminary conclusions on LCLS-I undulators at PITZ:

- Not such extremely high performance as for the APPLE-II, but is clearly proper for **the proof-of-principle experiment!**
- 4 nC electron beam transport through the vacuum chamber needs efforts, but seems to be feasible.

Single Cycle THz Pulse Generation from Undulator

European Commission funding
Horizon2020
FETOPEN 2018-2020

Participation in the LUSIA proposals (Attosecond SIngle-cycle Undulator Light on the horizon)



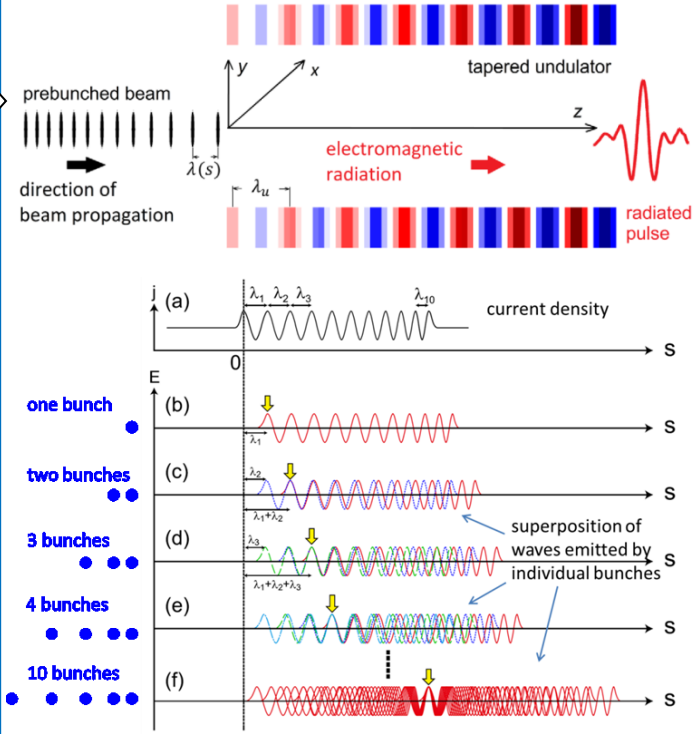
Develop a new technology to generate *isolated **attosecond** single-cycle μJ-level X-ray pulses*

*proof-of-principle in the terahertz (**THz**) regime at **PITZ**.*

1st experiment

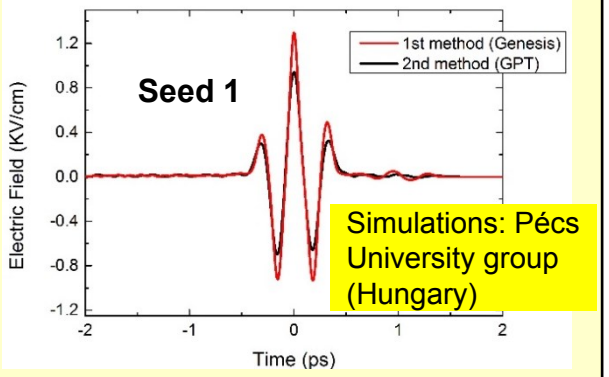
2nd experiment

Manipulated undulator radiation:
coherent emission from a chirped microbunched beam passing through strongly tapered undulator



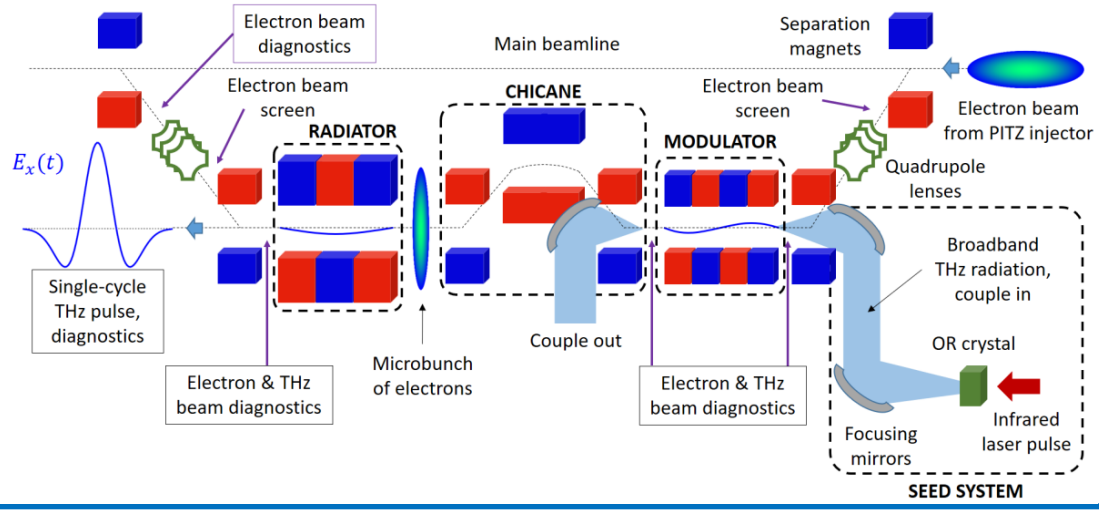
T. Tanaka. "Proposal to Generate an Isolated Monocycle X-Ray Pulse by Counteracting the Slippage Effect in Free-Electron Lasers." Phys. Rev. Lett.114.4 (2015): 044801

THz pulse calculated after the radiator undulator



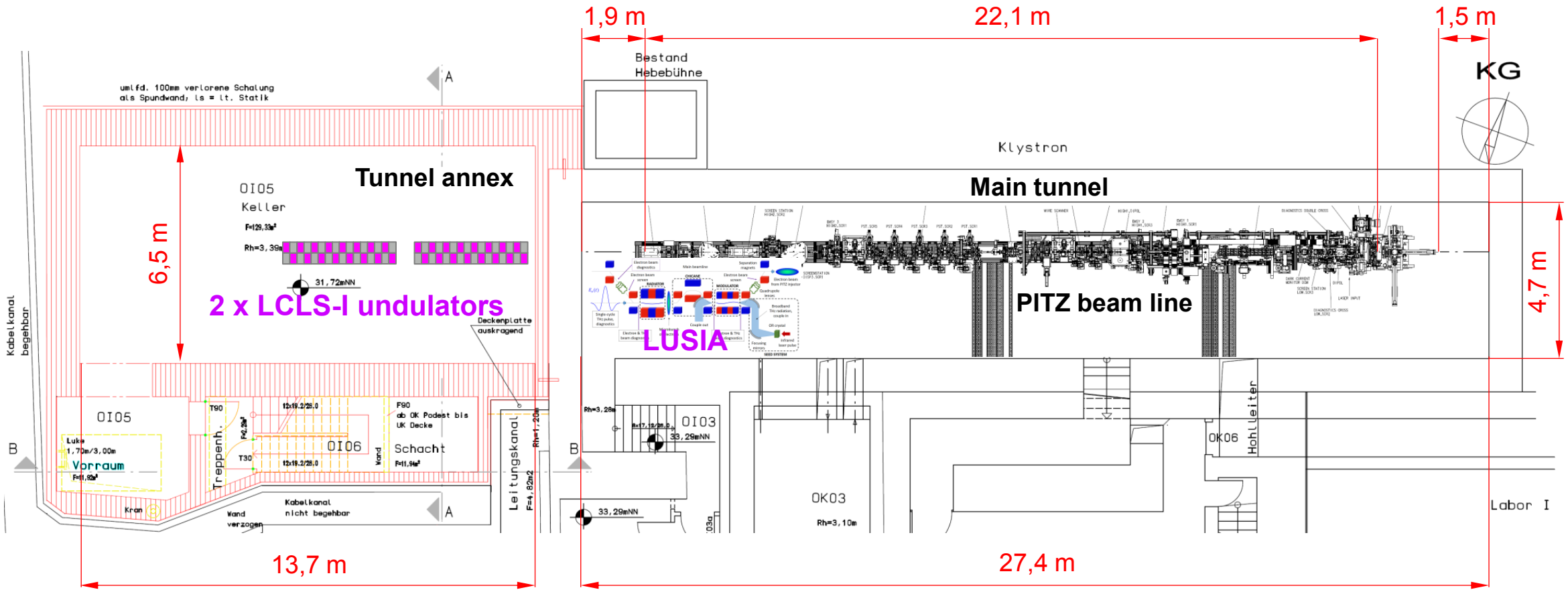
Energy (1st method):	**73.4 nJ**
Energy (2nd method):	**113.4 nJ**

Undulator radiation from microbunch seeded by short IR laser pulse



Install LCLS-I Undulators and LUSIA in PITZ Tunnel + Annex

Will be used for proof-of-principle experiments at PITZ



Currently improving radiation shielding and preparing for operation permission for tunnel annex

Summary & Outlook

Studies on the tunable accelerator-based THz source (for P&P at EU-XFEL) are ongoing at PITZ

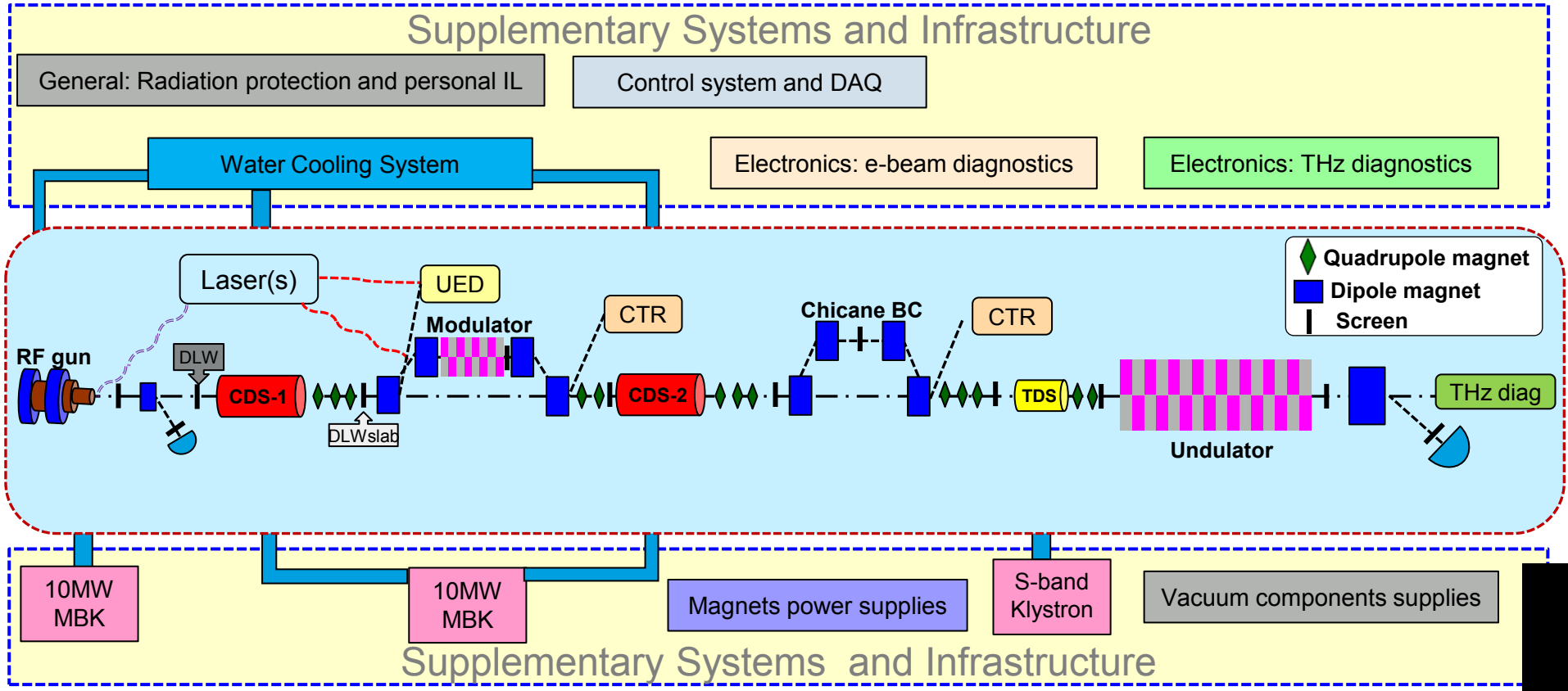
➔ SASE FEL (~mJ@100µm), CTR&CDR

- **Short-term (1-2 years)**
  - Continue CTR/CDR experimental studies
  - Detailed simulations for THz SASE FEL with LCLS-I undulators
- **Mid-term (1-5 years)**
  - Installation and commissioning of 2 LCLS-I undulators in the PITZ tunnel annex, electron beamline
  - THz SASE FEL experiments with LCLS-I undulators
  - Studies on seeding options to improve CEP stability
  - Single cycle undulator THz radiation (LUSIA proof-of-principle experiments 1 and 2)
- **If funded by EU-XFEL: Long-term (3-7+X years)**
  - APPLE-II undulator or other modern undulators
  - Realization of the seeding option
  - THz facility optimization (BC, layout, etc.)
  - Delivery knowhow/hardware for acc.-based THz source for the pump-probe experiments

Backup slides

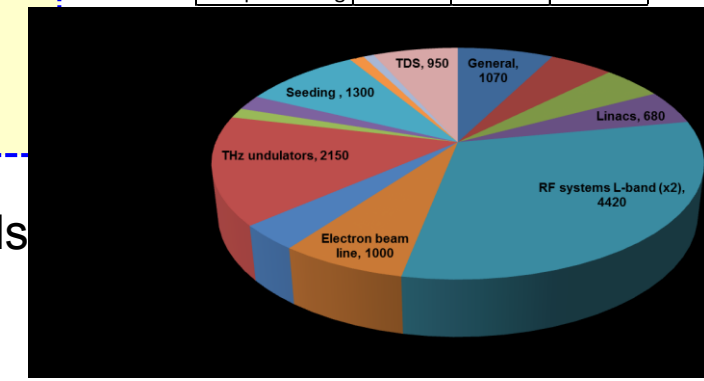
Outlook: Possible "PITHz" Layout

"all options" included
reduction in size and costs possible



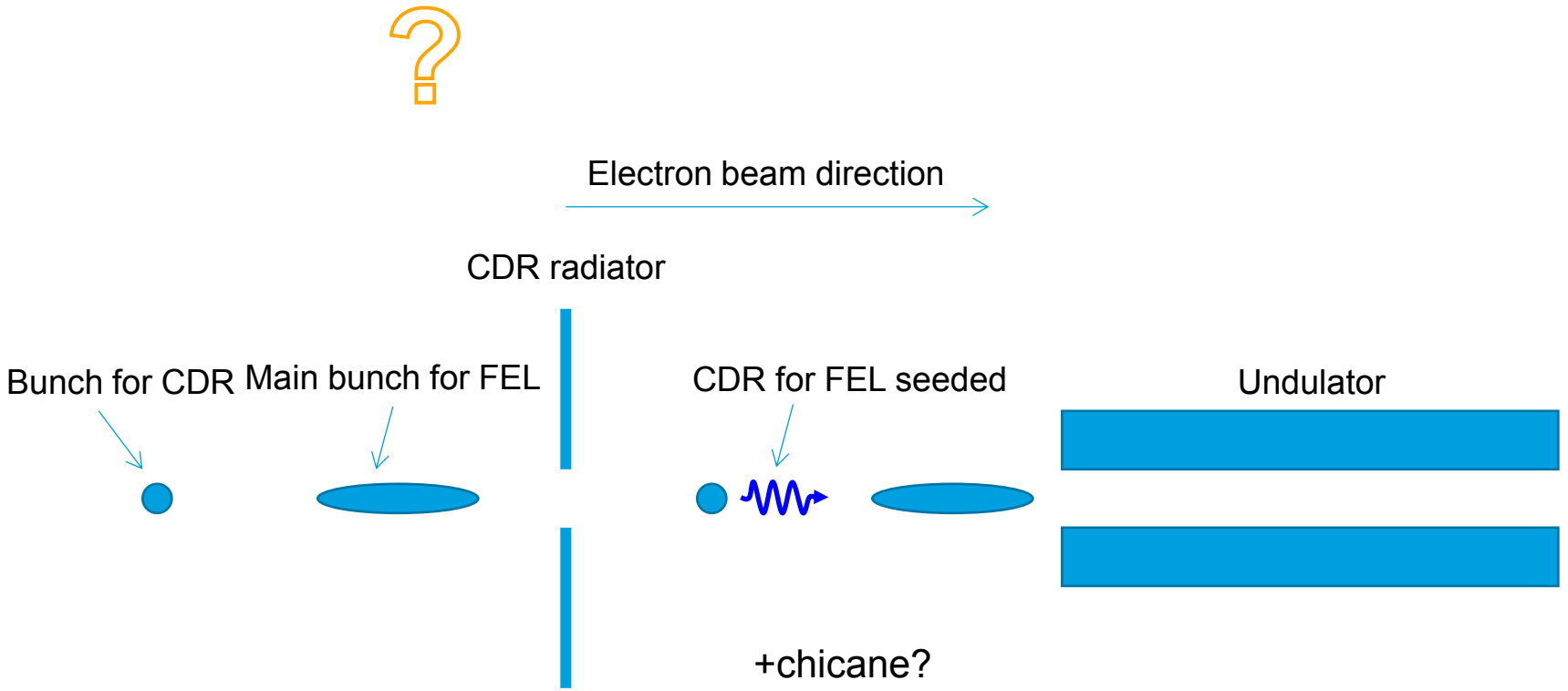
Hardware costs:
VERY rough estimations

Section	length	startZ	endZ
PC system	2	0	2
gun	1	2	3
LE	2	3	5
CDS-1	2	5	7
matching	1	7	8
modulator	2	8	10
matching	1	10	11
CDS-2	2	11	13
matching	1	13	14
BC	2	14	16
matching	1	16	17
TDS	1	17	18
matching	1	18	19
undulator	6	19	25
Dump&THzdiag	2	25	27



~14M€, full option, can be reduced according to needs

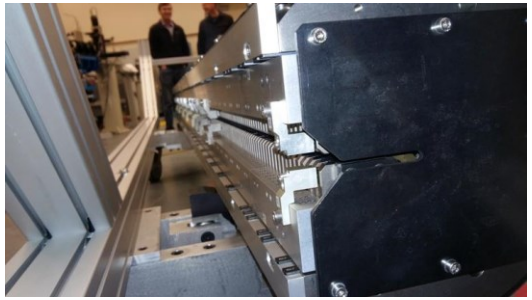
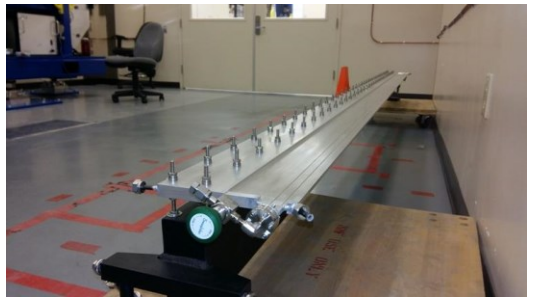
CDR as seeding



Use of LCLS I undulators for THz studies at PITZ

THz SASE FEL at PITZ as proof-of-principle for accelerator based THz source for pump-probe experiments at XFEL

- Contact with Heinz-Dieter Nuhn (HDN, SLAC) about current LCLS I undulators
- During visit at SLAC beginning of May 2018 HDN showed undulator components:
  - 3.4 m long modules, Ø = 30 cm (titanium), weight ~1 ton
  - Vacuum chamber
  - Support structure


- Norbert Holtkamp (SLAC) was asked if PITZ could have a long term loan of 2 undulator segments:
  → very positive reply → request should be content of a letter from H. Dosch
  → should be agreed at next DESY/SLAC directorate meeting in autumn 2018

- Components that are NOT re-used at LCLS II (and might be on loan)
  - undulators
  - the girder beneath the undulator
  - the motors for sliding the undulator in and out of the beam path
  - the vacuum chamber (outside: 6mm, inside: racetrack shape with **5mm height**)
  - cavity BPM and electronics for the BPM

Motivation for accelerator based tunable IR/THz source for pump probe experiments at the European XFEL

Requirements to the pump source

General:

- **Time structure** of IR/THz source → time structure of x-ray pulses
- IR/THz source should have wide **tunability** range
- IR/THz source → wide possibilities for generation of **different temporal and spectral patterns, polarization**. (i.e. strong single-cycle pulses, narrow band radiation)
- Many applications require high peak power (field strength) or **high pulse energy**.
- **Time jitter** of pump and probe pulses should be small enough for resolving time-dependent phenomena

Specific for the European XFEL:

- EXFEL → burst mode: 10Hz x 0.6 ms x 4.5 MHz = =**27000 pulses** per sec
- Current **range** of interest:

	from	to
λ, μm	6 - **20**	**100** - 1000
f, THz	50 - **15**	**3** - 0.3
$h\nu$, *meV*	207 - **62**	**12.4** - 1.24

- **Pulse energy spans** a lot: μJ → hundreds of μJ → **mJ**
- **Time jitter**: 2 types of experiments:
  - **I. field** driven dynamics where temporal resolution ~few fs → →**CEP stability**
  - **II."intensity"** driven dynamics where temporal resolution ~longest pulse duration (e.g. if THz pulse is 3 ps than the timing only need to be 3 ps).

Generation of IR/THz radiation by relativistic electron beams

Attractive features are:

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

Methods of generation:

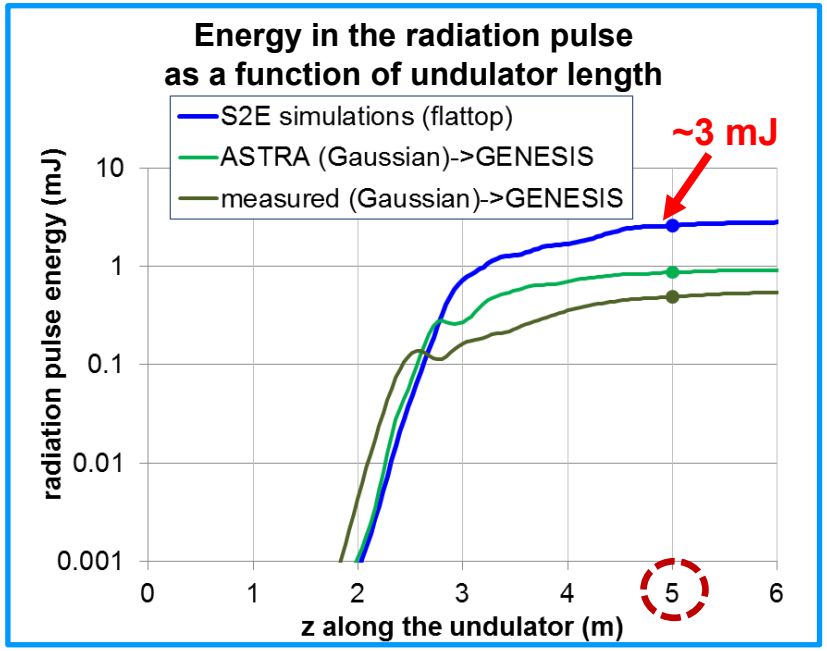
- radiation in a bend magnet
- undulator radiation
- transition radiation (i.e., crossing metallic foil)
- diffraction radiation (i.e. passing through an aperture)
- …

THz SASE FEL: Beam Dynamics Simulations and Experiments

λ_{rad} = 100 µm (3 THz)

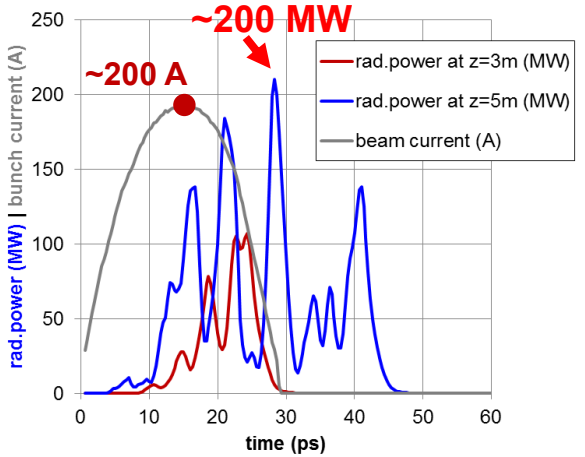
Simulation Tools:

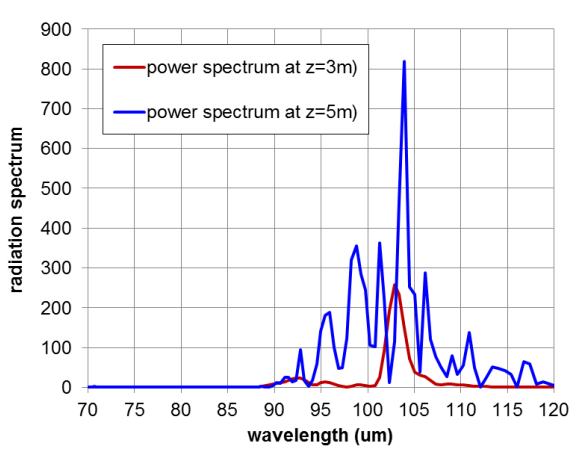
- **ASTRA code** →goals of the beam transport (0→22.5m):
  - **<P_z> ~ 15 MeV/c** at the undulator entrance
  - Symmetric transverse beam sizes and emittances at the undulator entrance
  - Bunch charge **4 nC**
  - PC laser: ∅5mm, flattop 2/20\2ps
  - Gun and booster phases and main solenoid optimized for high I_{peak} and small δE
- **GENESIS 1.3 code (Version 2) for SASE FEL:**
  - Time-dependent mode, space-charge calculation included.
  - Helical undulator with λ_u=40 mm
  - SASE FEL, λ_{rad}≈100 µm (3 THz)

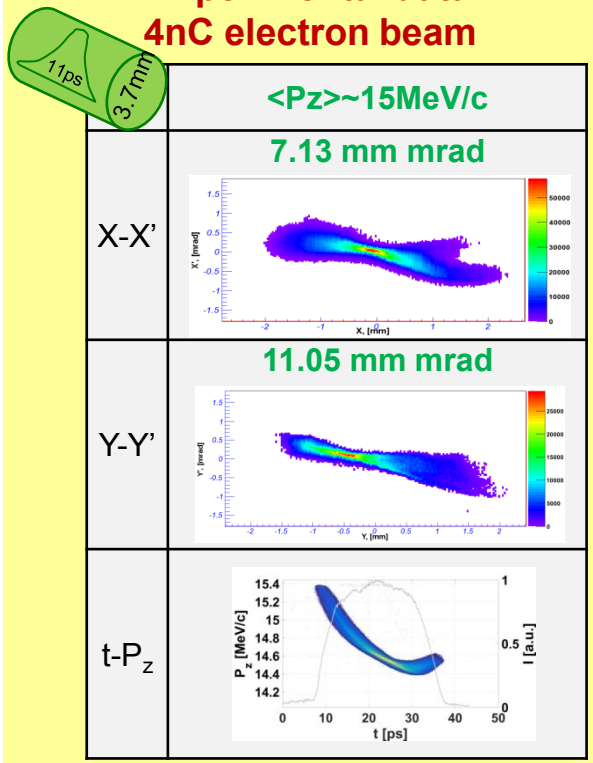


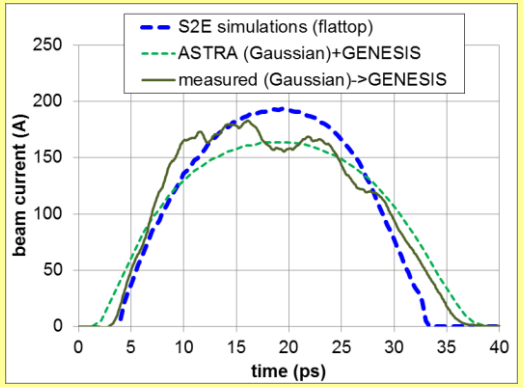
- I_{peak}~200A
- E_{pulse}~3mJ
- L_{und}~5m
- BW~5-10%

P. Boonpornprasert









THz-related PITZ publications and talks

2012-2018

Papers and conference proceedings

1. E.A. Schneidmiller, M.V. Yurkov, M. Krasilnikov, F. Stephan “Tunable IR/THz source for pump probe experiments at the European XFEL”, Proceedings of the 34th International Free Electron Laser Conference, Nara, Japan, 2012, WEPD55.
2. E. Syresin, S. Kostromin, R. Makarov, N. Morozov, D. Petrov, M. Krasilnikov “Possibility of Application of THz Wiggler in Low Energy FEL for Measurements of Electron Bunch Longitudinal Structure”, IPAC2014, 2177–2179 (2014).
3. E. Syresin, S. Kostromin, M. Krasilnikov, R. Makarov, N. Morozov, D. Petrov “THZ wiggler applied for measurements of electron bunch longitudinal structure in FEL”, Physics of Particles and Nuclei Letters, 2015, Vol. 12, No. 1, pp. 118–121.
4. P. Boonpornprasert, M. Krasilnikov, F. Stephan , B. Marchetti, DESY, “Numerical Simulations of a Sub-THz Coherent Transition Radiation Source at PITZ”, Proceedings of the 37th International Free Electron Laser Conference, Daejeon, Korea, 2015, MOP033
5. P. Boonpornprasert, Y. Chen, J.D. Good, H. Huck, I.I. Isaev, D.K. Kalantaryan, M. Krasilnikov, X. Li, O. Lishilin, G. Loisch, D. Melkumyan, A. Oppelt, H.J. Qian, Y. Renier, T. Rublack, F. Stephan, G. Asova, C. Saisa-ard, Q.T. Zhao, “Experimental Optimization and Characterization of Electron Beams for Generating IR/THz SASE FEL Radiation with PITZ”, Proceedings of IPAC2017, Copenhagen, Denmark, WEPAB033
6. F. Lemery, G.A. Amatuni, B. Grigoryan, P. Boonpornprasert, Y. Chen, J.D. Good, M. Krasilnikov, O. Lishilin, G. Loisch, S. Philipp, H.J. Qian, Y. Renier, F. Stephan, P. Piot, “Experimental Demonstration of Ballistic Bunching with Dielectric-Lined Waveguides at PITZ”, Proceedings of IPAC2017, Copenhagen, Denmark, WEPAB122
7. P. Boonpornprasert, M. Krasilnikov, F. Stephan, “Calculations for a THz SASE FEL Based on the Measured Electron Beam Parameters at PITZ”, Proceedings of the 38th International Free Electron Laser Conference FEL 2017, Santa Fe, New Mexico, USA, WEP004

Talks and posters

1. P. Boonpornprasert “Simulation of Undulator Radiation for the THz Source Project at PITZ”, talk at DPG-Frühjahrstagung, Dresden: 30. März - 4. April 2014
2. P. Boonpornprasert, M. Khojoyan, M. Krasilnikov, F. Stephan, B. Marchetti, E. Schneidmiller, M. Yurkov, S. Rimjaem, “Start-to-end simulations for ir/thz undulator radiation at PITZ”, Proceedings of the 36th International Free Electron Laser Conference, Basel, Switzerland, 2014, MOP055.
3. P. Boonpornprasert et al., “Start-to-End Simulations for a 100 µm SASE FEL at PITZ”, talk at DPG-Frühjahrstagung, Wuppertal, Germany, March 9–13, 2015
4. P. Boonpornprasert, M. Krasilnikov, B. Marchetti, F. Stephan, “Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)”, talk and poster at 3rd ARD ST3 Workshop, Karlsruhe, Germany: July 15–17, 2015
5. P. Boonpornprasert “Simulations of the IR/THz Options at PITZ (High-gain FEL and CTR)”, talk at DESY Beschleuniger Ideenmarkt, Hamburg: September, 2015
6. P. Boonpornprasert et al., “First Experimental Characterization of Electron Beams for THz Options at PITZ”, poster at 2nd Annual MT Meeting, Karlsruhe: 8 - 10 March 2016
7. P. Boonpornprasert et al., “First Characterizations of a 4 nC Electron Beam for THz Options at PITZ”, talk at DPG-Frühjahrstagung (Spring Meeting), Darmstadt: 14 - 18 March 2016
8. P. Boonpornprasert et al., “Electron Beam Characterizations for Generating THz Radiation with PITZ”, poster at 3rd Annual MT Meeting, GSI, Darmstadt: 31 January 2017 to 02 February 2017
9. P. Boonpornprasert et al., ”Experimental Optimization of Electron Beams for Generating THz Coherent Transition and Diffraction Radiations with PITZ”, DPG-Frühjahrstagung (DPG Spring Meeting), Dresden, 19 - 24 of March 2017
10. M. Krasilnikov, “Tunable IR/THz source based on PITZ (-like) accelerator for pump probe experiments at the European XFEL”, Terahertz Science at European XFEL, 1-2 June 2017, Schenefeld
11. P. Boonpornprasert et al., ”Experimental Optimization and Characterization of Electron Beams for Generating IR/THz SASE FEL Radiation with PITZ”, 5th ARD-ST3 workshop 19-21 July 2017, Zeuthen.
12. M. Krasilnikov, “Update on THz studies at PITZ”, LUSIA project meeting, 27.11.2017, Szentágothai Research Centre, Pécs, Hungary