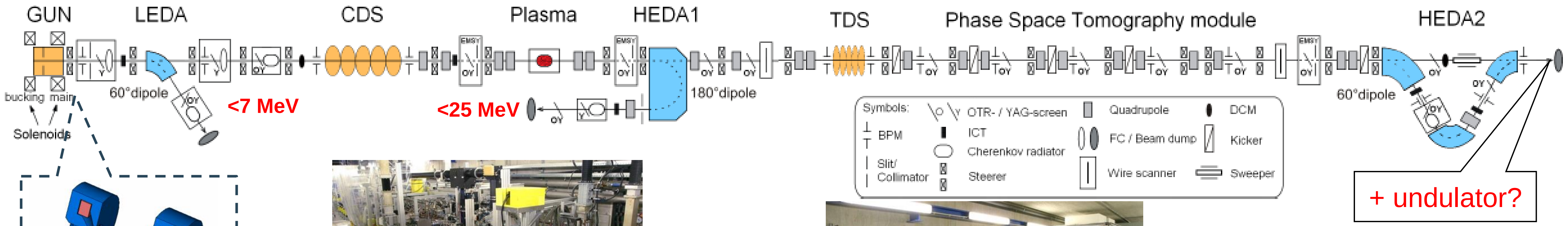
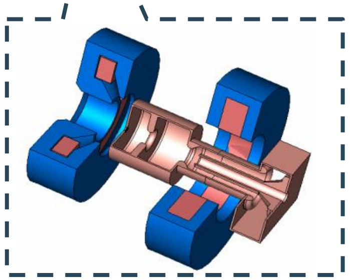
A THz Facility for the European XFEL

M. Krasilnikov for PITZ (PITHz) team

Workshop "Shaping the Future of the European XFEL: Options for the SASE4/5 Tunnels“,
6-7 December 2018, European XFEL

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





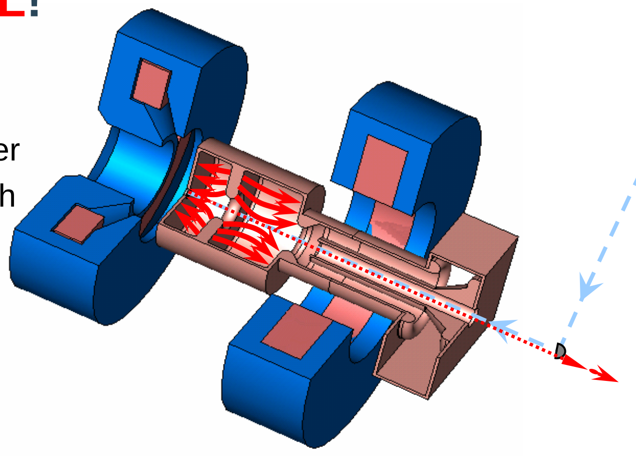
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

PITZ "engine": RF-Gun and Photocathode Laser

Highlights of the facility

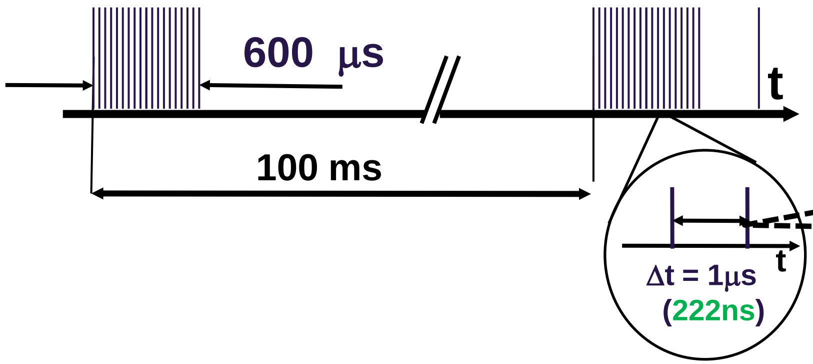
RF gun = for European XFEL!

- 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:

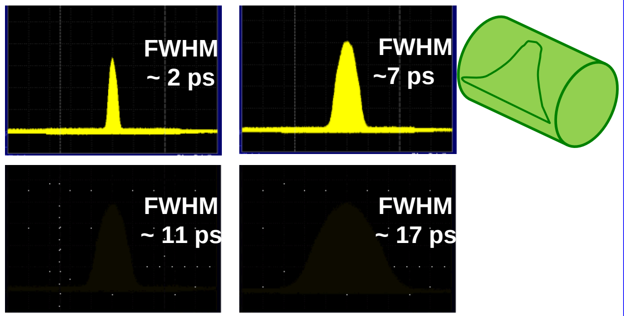
PITZ and EXFEL trains with up to 600 (2700) laser pulses



Photocathode laser(s) (UV)

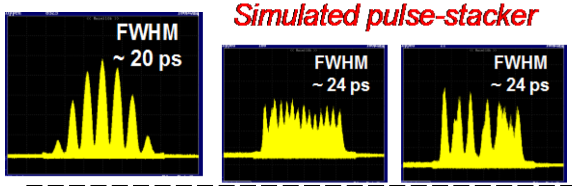
Default laser system
(Max-Born-Institute, Berlin)

Gaussian:



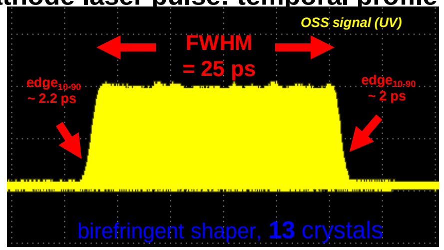
Multicrystal birefringent pulse shaper containing 13 crystals

Simulated pulse-stacker



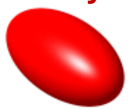
Flattop

Cathode laser pulse: temporal profile



Institute of Applied Physics of the Russian Academy of Sciences

New laser system



3D ellipsoidal pulse shaper:
- Spatial Light Modulator (SLM) based
- Upgrade with Volume Bragg Grating (VBG)

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

Different lasers

→ various **THz options**

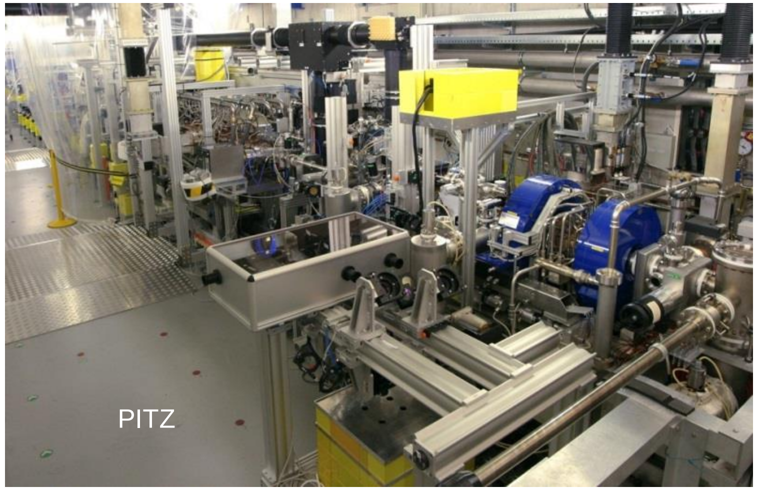
→ possibility of **simultaneous** usage

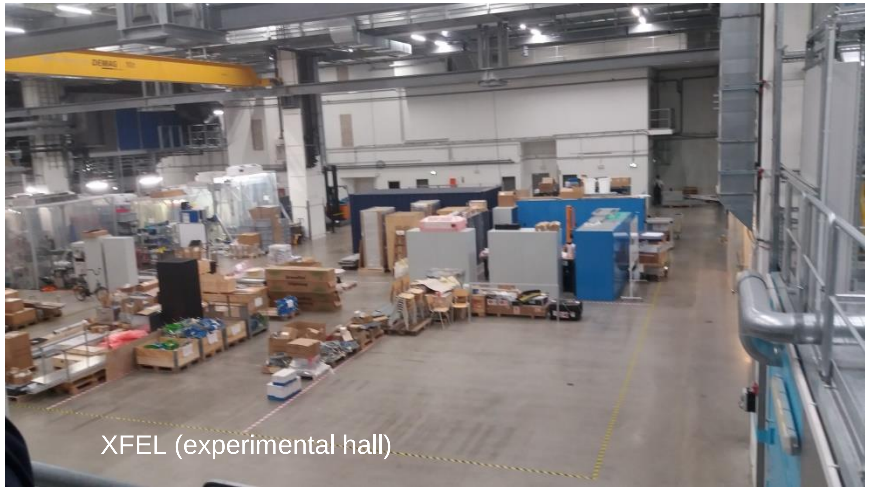
Accelerator based tunable IR/THz source for P&P at E-XFEL

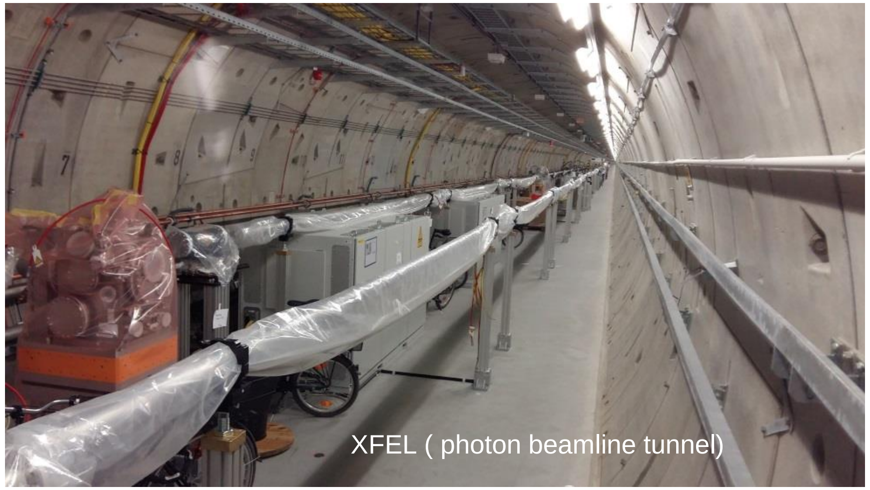
PITZ can be used as a prototype!

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

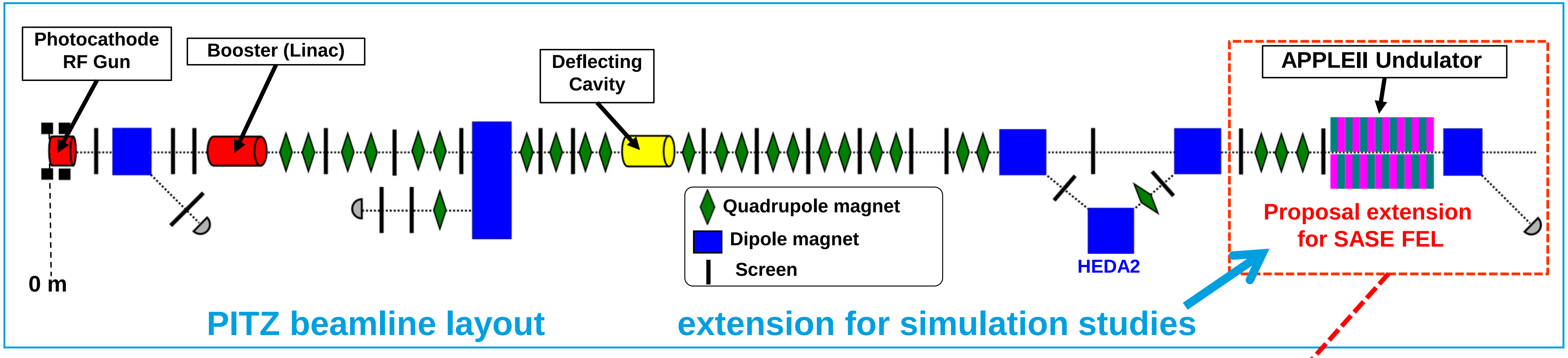

XFEL (experimental hall)


XFEL (photon beamline tunnel)

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

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

Case studies of generating THz radiation by PITZ electron beam



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

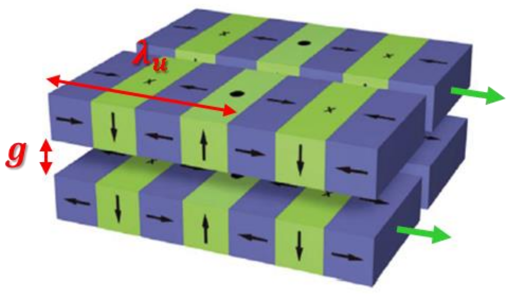
PITZ Highlights:
- Pulse train structure
- **High charge feasibility (4 nC)**
- **Advanced photocathode laser shaping**
- E-beam diagnostics
- Available tunnel annex
- …

Current PITZ "boundary conditions":
- 22-25 MeV/c max
- No bunch compressor
- No undulator (yet…)
- …

THz SASE FEL at PITZ

Undulator and beam parameter space

APPLE- II Undulator*



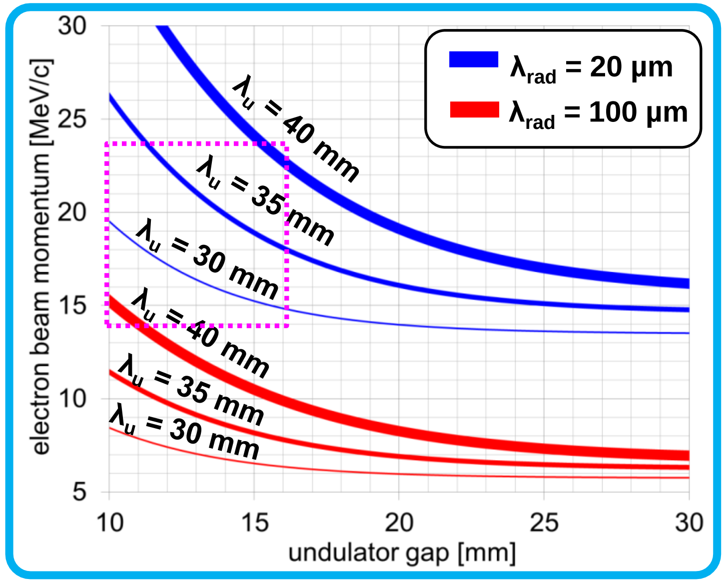
Radiation wavelength

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

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

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

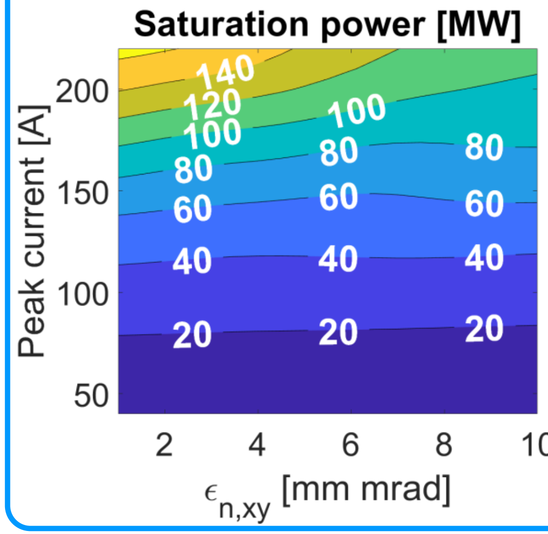
Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007

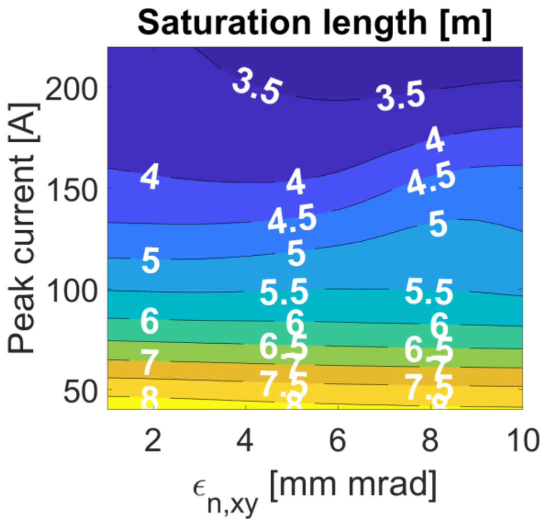


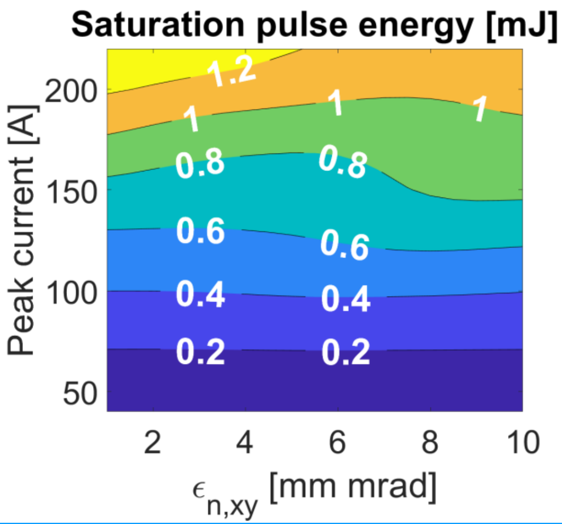
Conditions :
λ_{rad} of 20 – 100 μm
Max P_z ~ 22 MeV/c
gap $g \geq$ 10 mm

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

THz SASE FEL Parameter Space with GENESIS (λ = 100 μm)







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

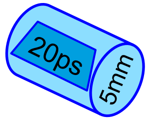
Preliminary conclusions:

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

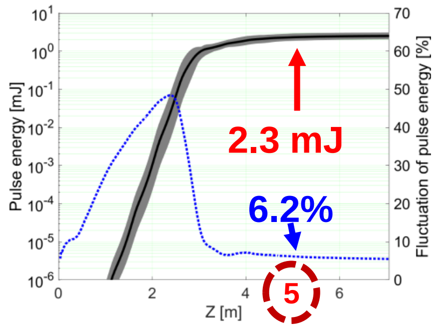
THz SASE FEL: Simulations for λ_{rad} = 100 µm (3 THz)

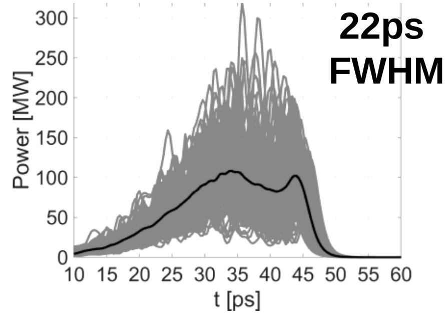
Setup: **4nC** → I_{peak}~200A, ~15MeV/c, λ_u=40 mm, K=1.8, L_u=5-7m	FEL pulse energy (average and rms fluct.)	FEL radiation pulse at z_U=5m: temporal profiles	FEL radiation pulse at z_U=5m: spectral profiles

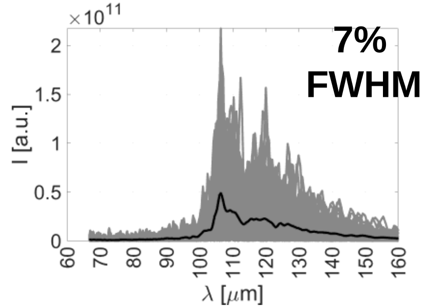
Start-to-end: ASTRA→GENESIS1.3



- Photocathode laser: ∅5mm, flattop 2/21.5\2ps
- Gun and booster phases and main solenoid optimized for high I_{peak} and small δE

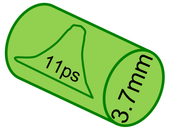


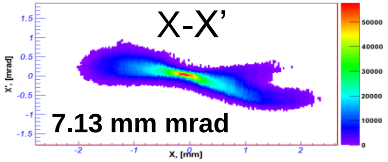


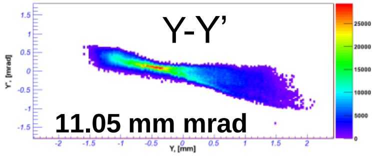


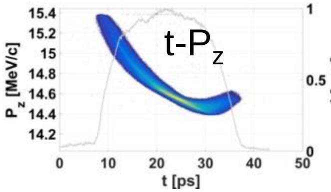
E-beam from experiment→ GENESIS1.3

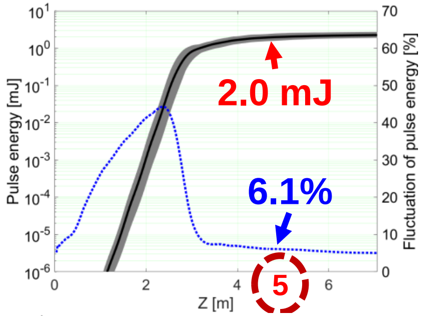
- Photocathode laser: ∅3.7mm, Gaussian 11ps FHWM
- Phase spaces → from measurements

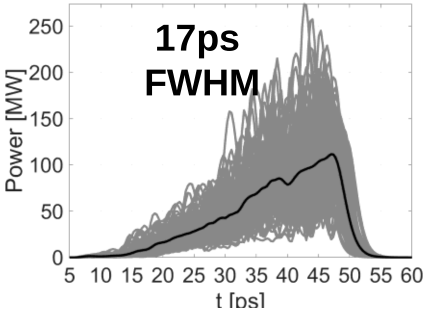


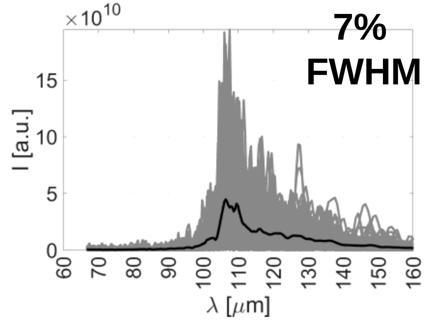


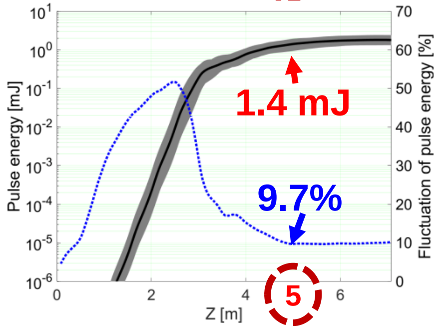


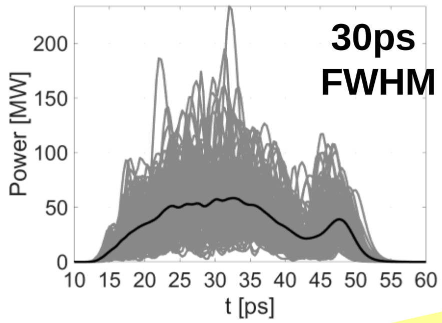


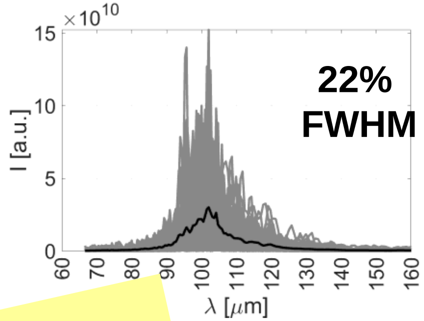










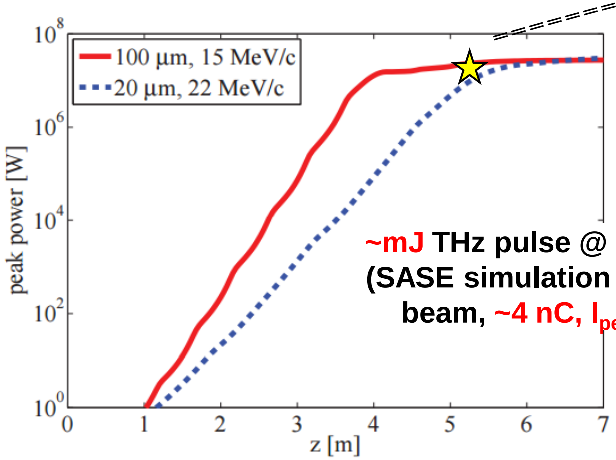


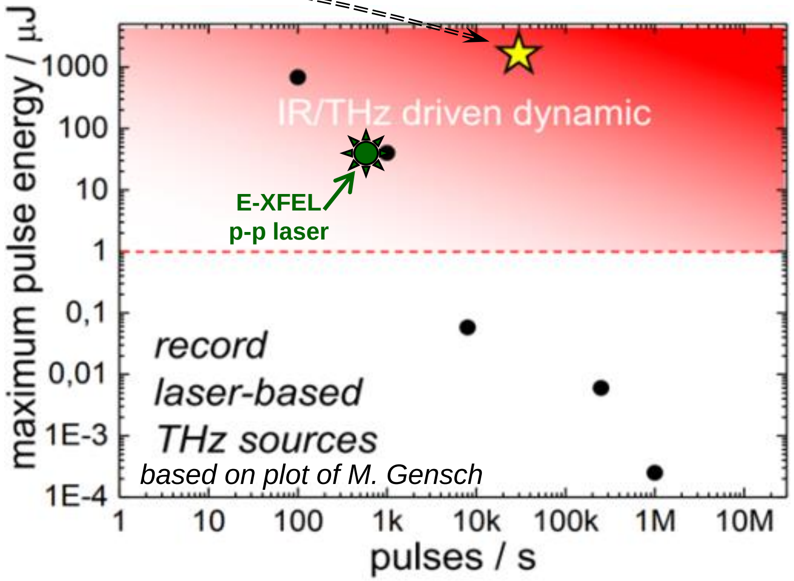
Simulations: P. Boonpornprasert

Studies on accelerator-based THz source at PITZ

High pulse energy, tunable, pulse structure

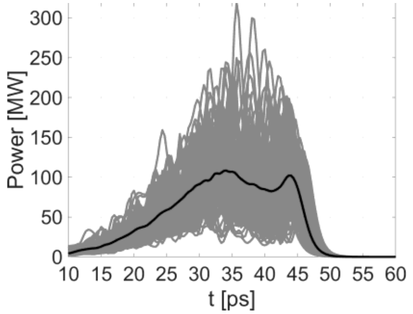
PITZ-like high repetition rate compact accelerator can produce ~mJ THz pulses (λ_{rad}=20-100μm) matching time structure of XFEL X-ray pulses.





Laser based THz pulse energy is limited at high repetition rate, while most IR/THz driven dynamics needs pulse energy above 1 μJ

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
Green, B. et al. High-Field High-Repetition-Rate Sources for the Coherent THz Control of Matter. Sci. Rep. 6, 22256; doi: 10.1038/srep22256 (2016).



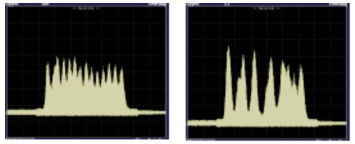
But still SASE (starting from the shot noise) ...

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

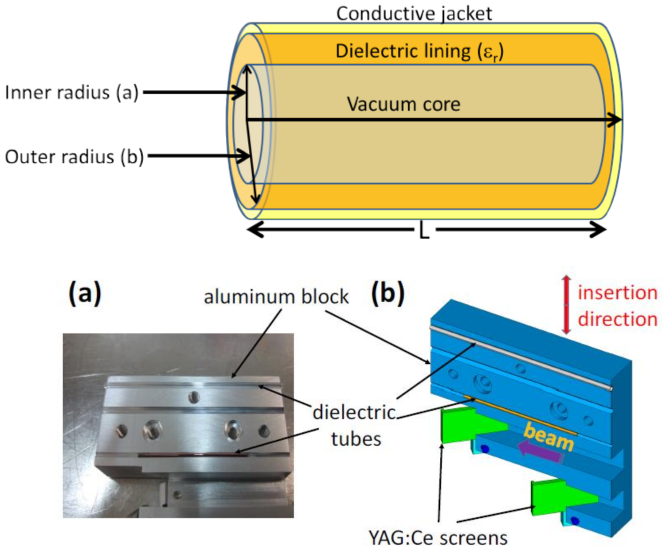
Options to improve THz radiation stability

Pre-bunching → "Seeding"

- **Photocathode laser pulse temporal modulation**



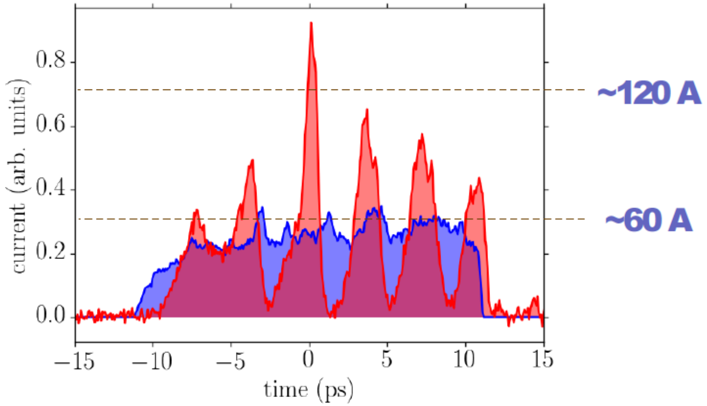
- Using IR laser, modulator and BC for E or δE modulations
- Using CDR from short seeding bunch
- **Using corrugated structures**
- **Using Dielectric Lined Waveguides - DLW (first experiments)**



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

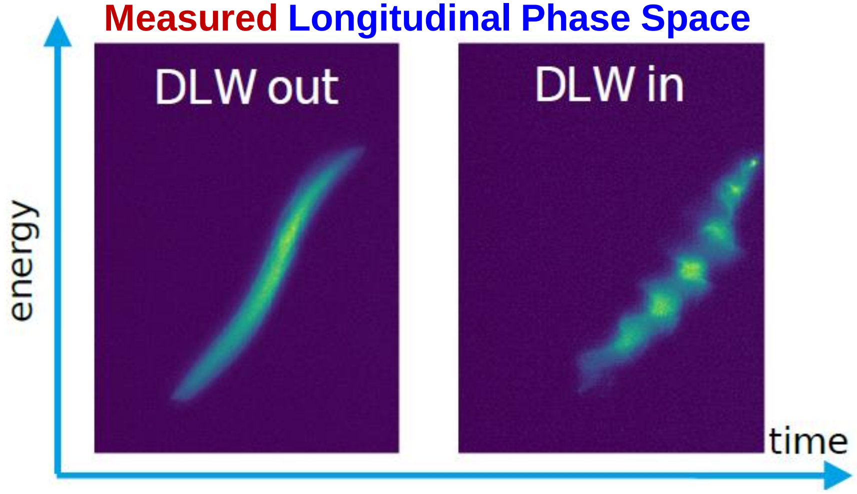
E-beam current profile

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



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

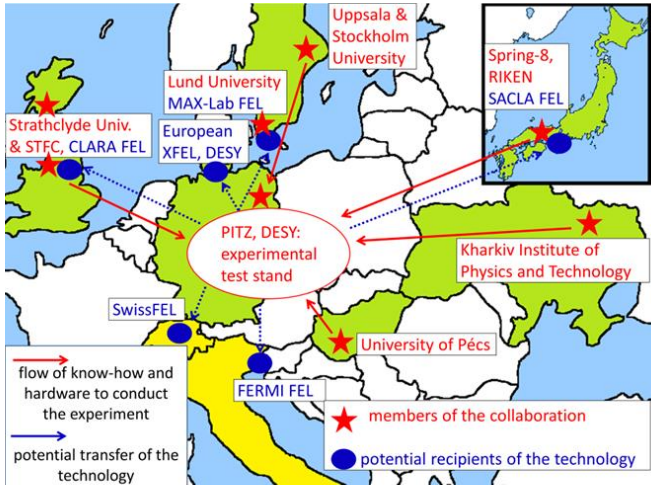
Measured Longitudinal Phase Space



Single Cycle THz Pulse Generation from Undulator

Re-submission to FETOPEN Horizon2020

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



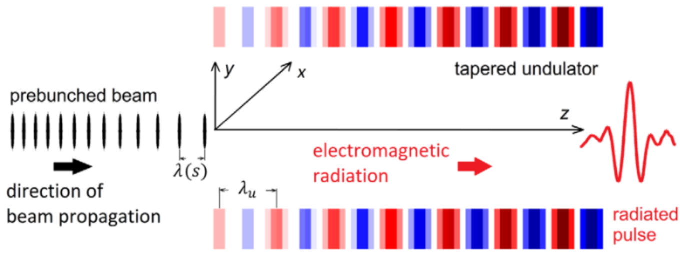
The **long-term vision** of this LUSIA project proposal is to develop a new FEL-like technology to generate *isolated **attosecond** single-cycle pulses of light in the X-ray region at a **microJoule** energy scale*.

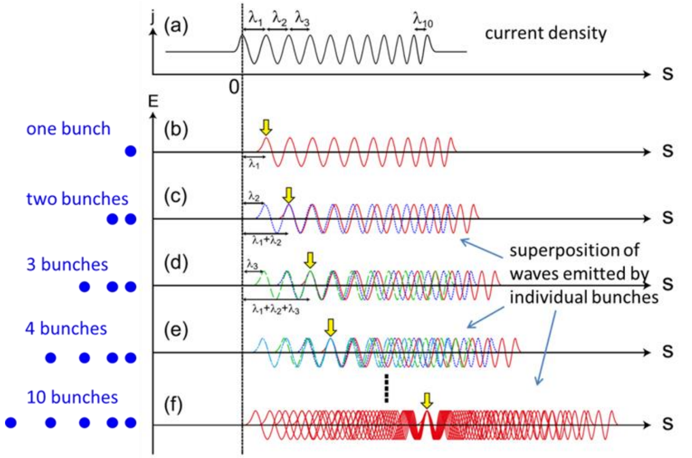
*A targeted **breakthrough** towards the vision is a proof-of-principle demonstration of single-cycle undulator radiation with a tailored electric waveform in the terahertz (**THz**) regime (fs pulses) at **PITZ**.*

1st experiment

2nd experiment

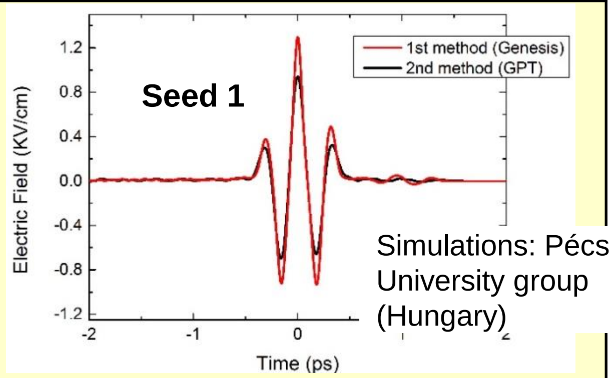
Manipulated undulator radiation: coherent emission from a chirped microbunched beam passing through strongly tapered undulator





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

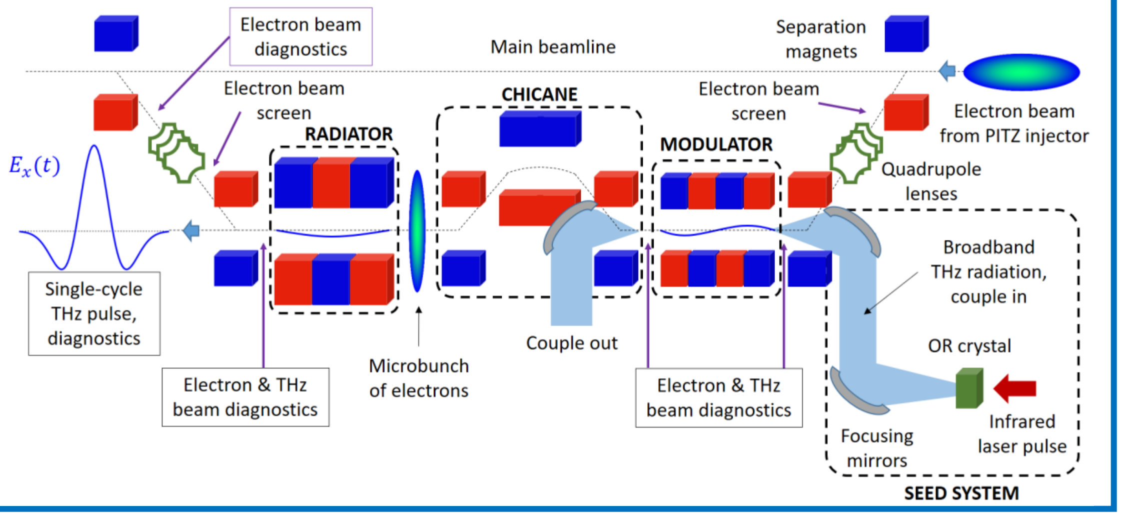
THz pulse calculated after the radiator undulator



Simulations: Pécs University group (Hungary)

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

Undulator radiation from microbunch seeded by short IR laser pulse



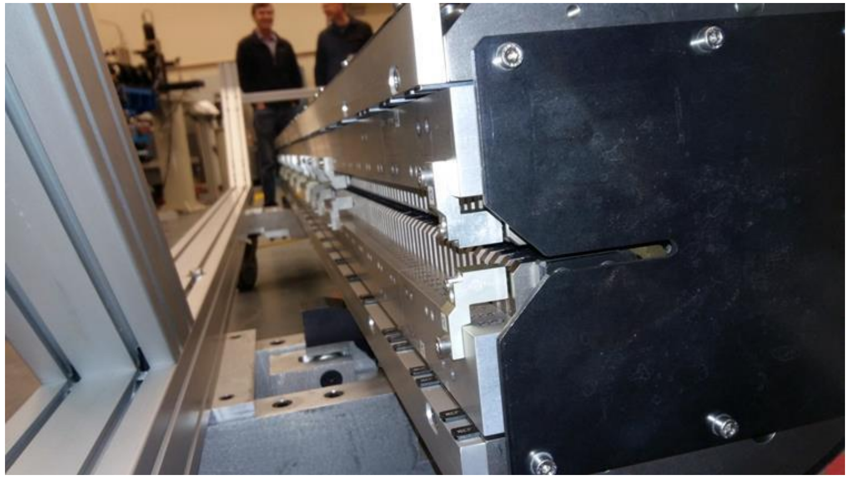
Proof-of-principle experiment on THz SASE FEL at PITZ

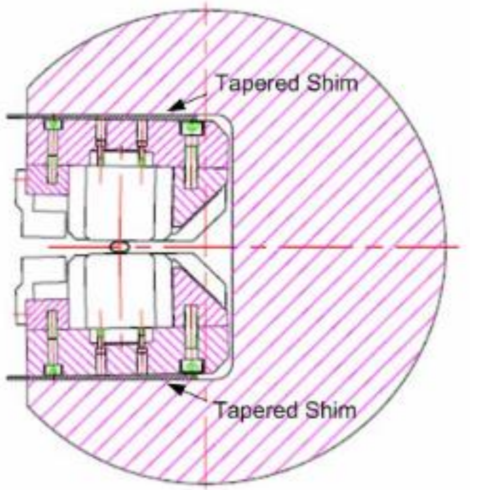
Using LCLS-I undulators (available on loan from SLAC) → under study and negotiations

Some Properties of the LCLS-I undulator

Properties	Details
Type	**planar hybrid** (NdFeB)
K-value	3.49 (3.585)
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.





λ_{rad}~100μm → <Pz>=**16.7MeV/c**

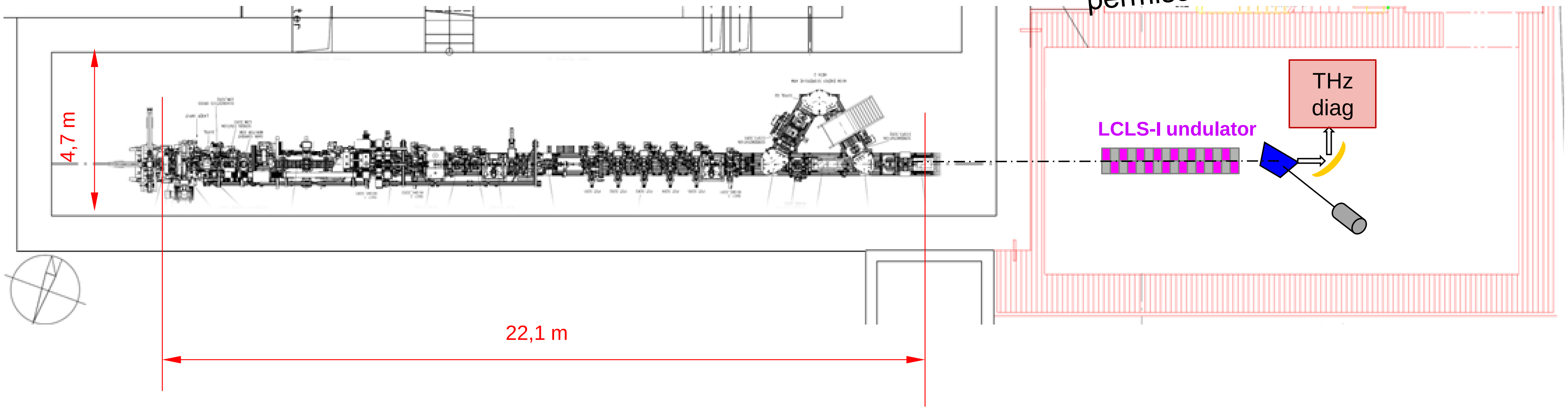
Preliminary conclusions on LCLS-I undulators at PITZ:

- Might be 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.

Start-to-end simulations for proof-of-principle experiment at PITZ

PITZ main tunnel and tunnel annex for the LCLS-I undulator installation

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



S2E simulations: from photocathode → undulator→ THz SASE FEL

Main challenges:

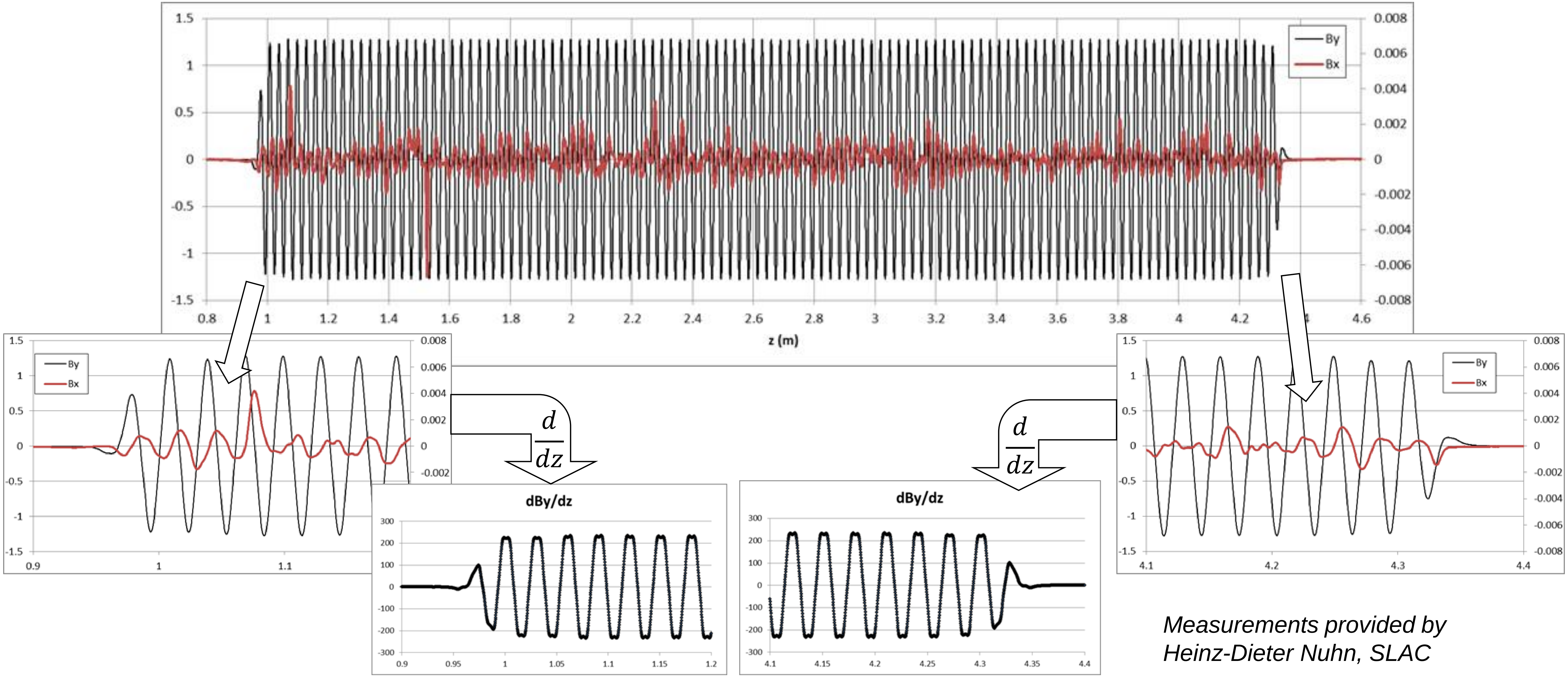
- 4 nC (200A) x 16.7 MeV/c → SC dominated beam
- ~30 m transport (incl. 1.5 m wall) → LCLS-I undulator in the tunnel annex
- 3D field of the undulator field
- Matching into the planar undulator (narrow vacuum chamber issue)

Tools:

- ASTRA
- SC-Optimizer
- GENESIS 1.3

LCLS-I Undulator field

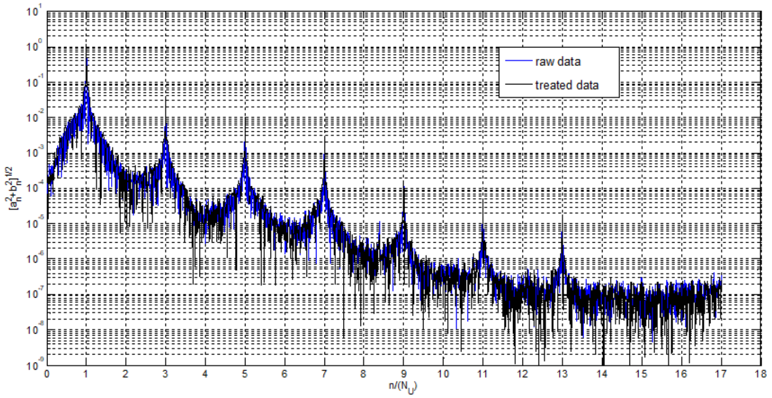
By(0,0,z) field profile measurements done on 02.10.2013 at SLAC for the undulator L143-112000-07 after the final tuning



Measurements provided by Heinz-Dieter Nuhn, SLAC

LCLS-I Undulator field

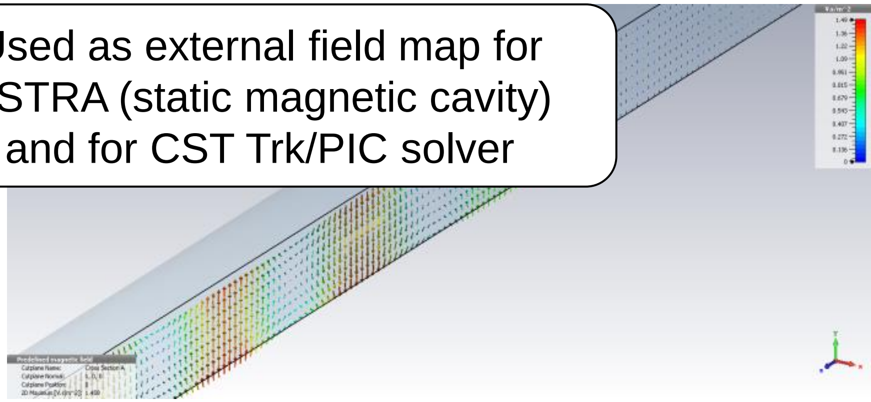
3D field map generation



Vertical and longitudinal components of undulator magnetic field:

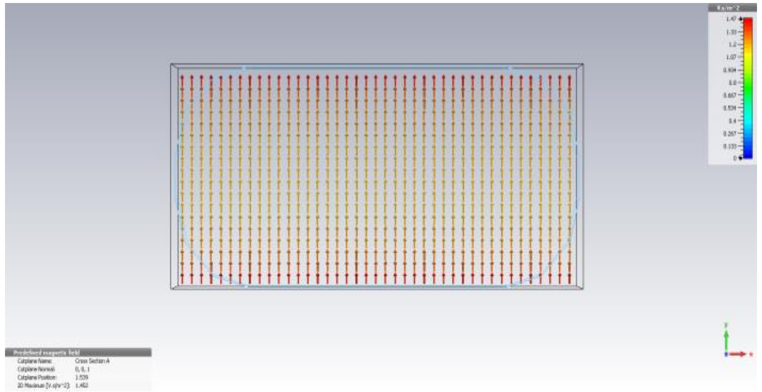
$$B_y(x,y,z) = \sum_{n=1}^{N_h \cdot N_U} \left[\left\{ \tilde{a}_n \cos(k_n z) + \tilde{b}_n \sin(k_n z) \right\} \cdot \cosh(k_n y) \right],$$
$$B_z(x,y,z) = \sum_{n=1}^{N_h \cdot N_U} \left[\left\{ -\tilde{a}_n \sin(k_n z) + \tilde{b}_n \cos(k_n z) \right\} \cdot \sinh(k_n y) \right],$$

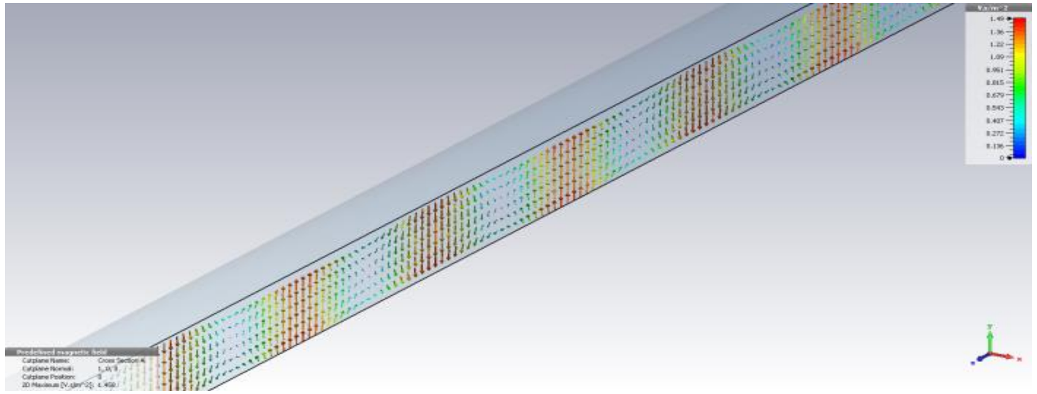
Used as external field map for ASTRA (static magnetic cavity) and for CST Trk/PIC solver



where $k_n = \frac{2\pi n}{N_U \lambda_U}$ is the wavenumber of the *n*-th Fourier harmonic.

$$\tilde{b}_n = \frac{2}{N_U \lambda_U} \int_{-\frac{N_U \lambda_U}{2}}^{\frac{N_U \lambda_U}{2}} B_{y,2}(x=0, y=0, z_1) \sin\left(\frac{2\pi n z_1}{N_U \lambda_U}\right) dz,$$

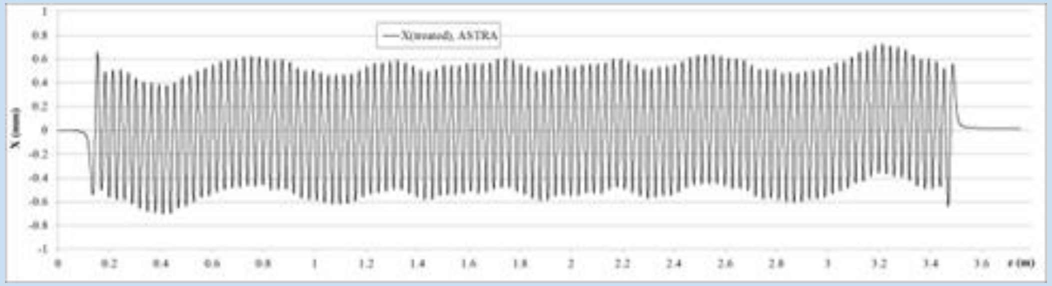
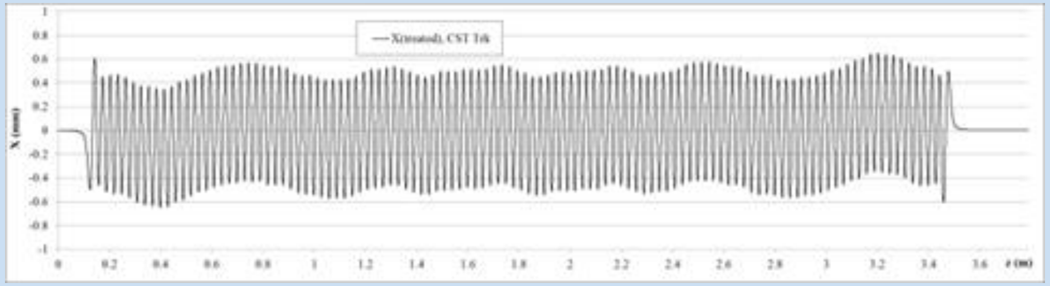
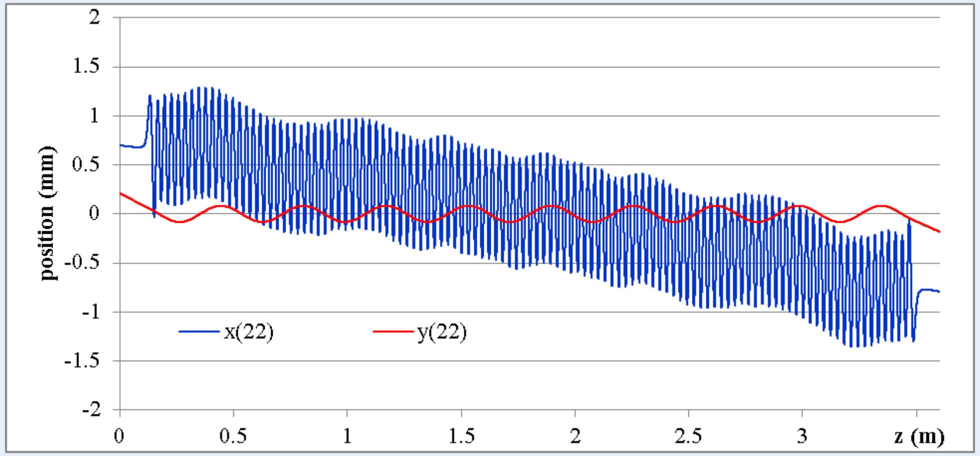
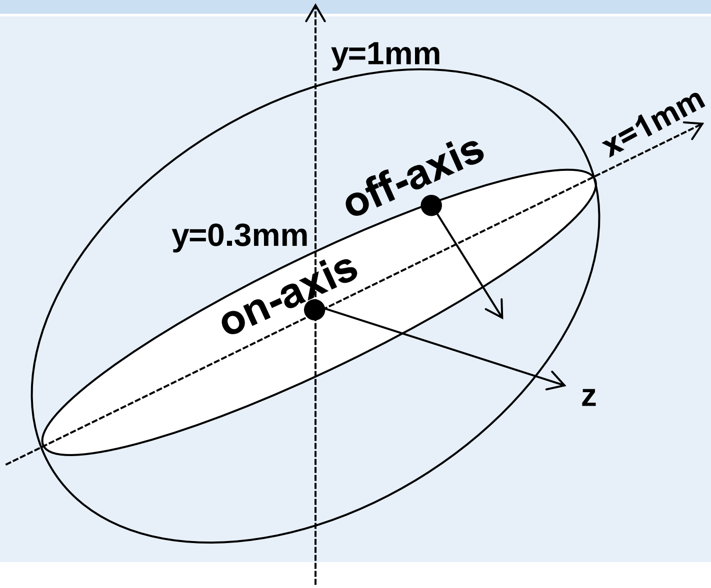




$N_h = 17;\ N_U = 120$

On-axis particle trajectory in the undulator

Reference particle: ASTRA and CST tracking

<table>
<tr><th>Reference particle</th><th>ASTRA with 3D field map</th><th>CST Particle Studio Trk</th></tr>
<tr><td>On-axis</td><td></td><td></td></tr>
<tr><td>Off-axis
<table><tr><td>X(0), mm</td><td>0.7</td></tr><tr><td>X'(0), mrad</td><td>-0.35</td></tr><tr><td>Y(0), mm</td><td>0.21</td></tr><tr><td>Y'(0), mrad</td><td>-1.19</td></tr></table></td><td>
</td><td>
</td></tr>
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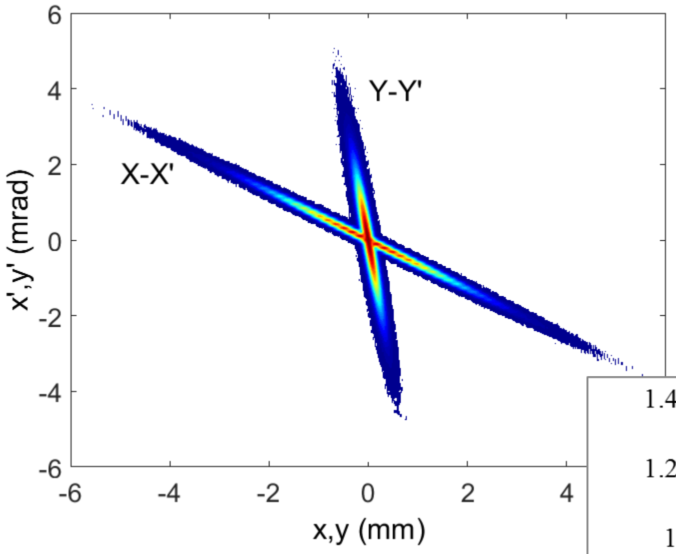
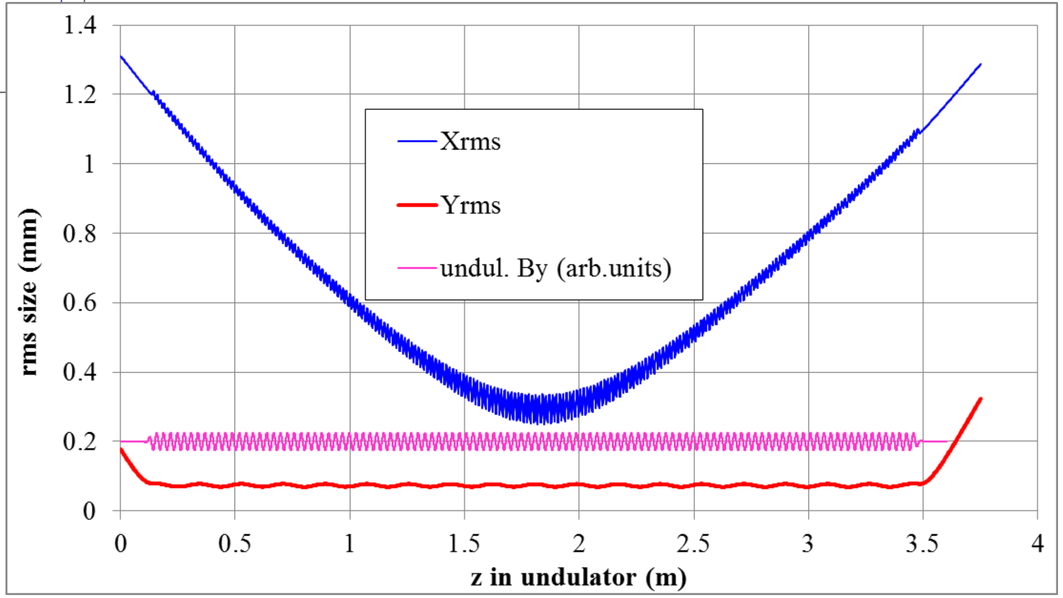
Beam matching into the undulator

ASTRA simulations with space charge and 3D undulator field map

- “Ideal” (Gaussian-FT) beam



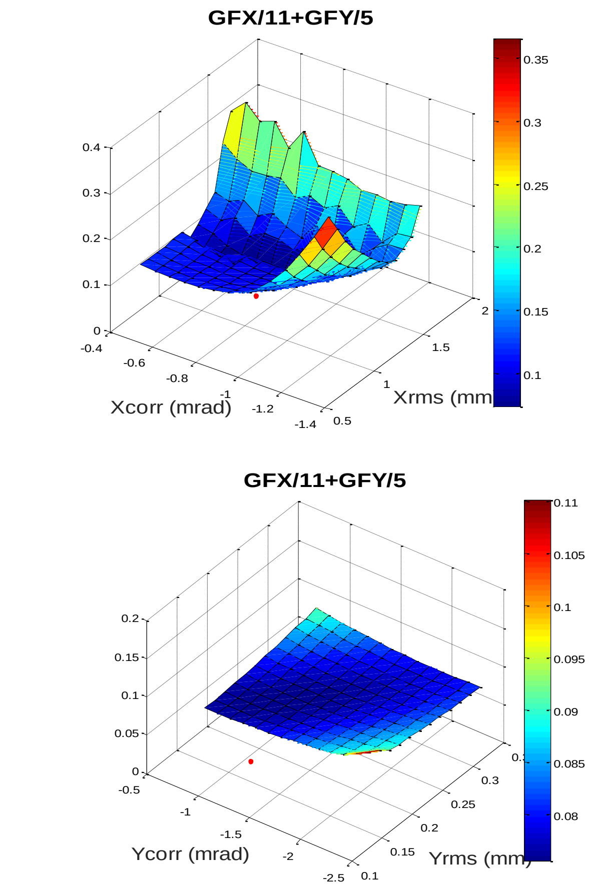
Asymmetric (X-Px-Y-Py) beam for proper matching into the unduator!



$$GF = w_x \cdot GFX + w_x \cdot GFY$$

$$GFX(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L}\int_0^L X_{\mathrm{rms}}\, dz$$

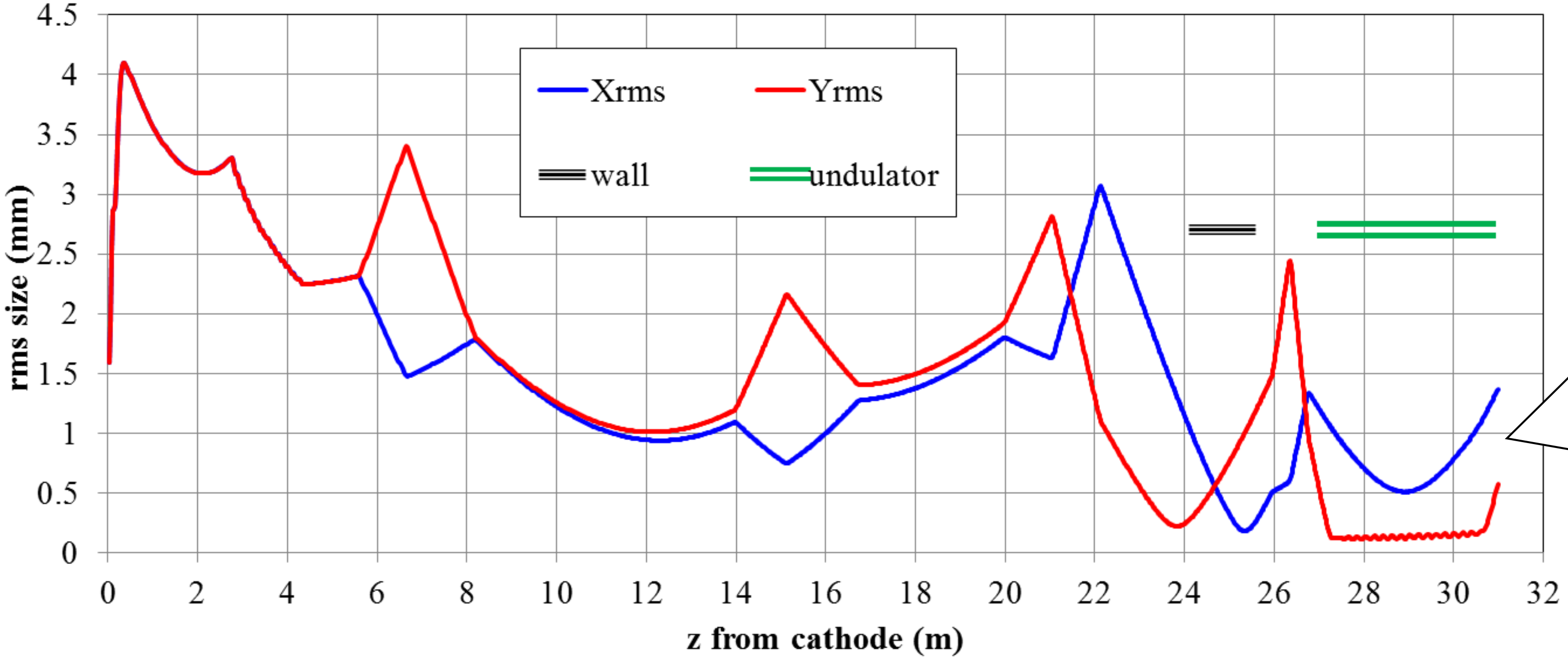
$$GFY(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L}\int_0^L std(Y_{\mathrm{rms}})dz$$

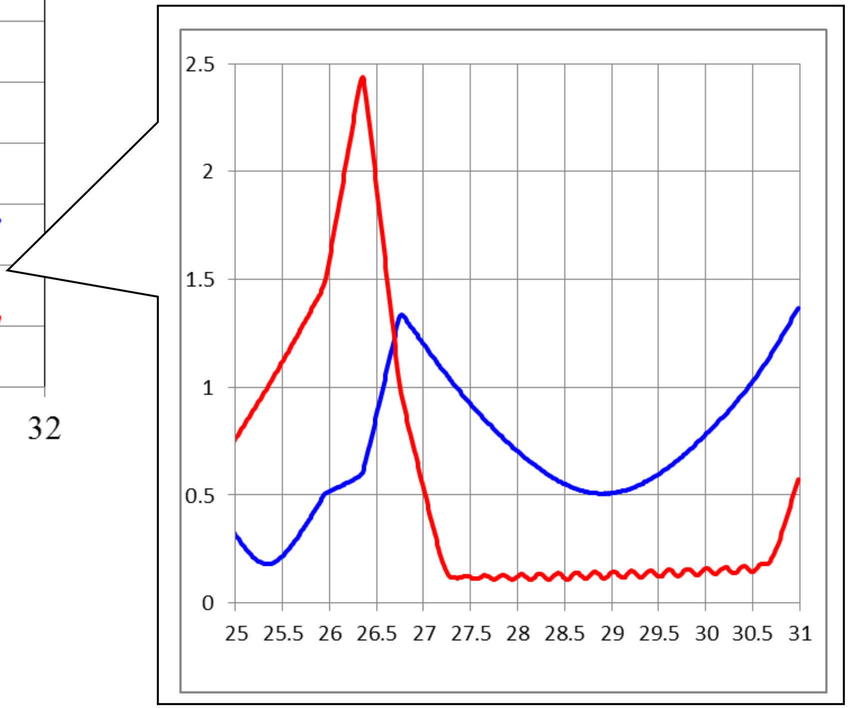


Electron beam transport for LCLS-I undulator option at PITZ

Matching into the undulator → beam size

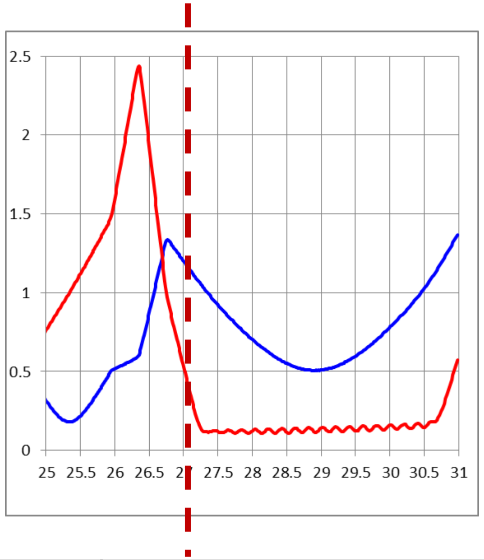
NB1: Space charge model is not fully correct for the undulator (dipole field)

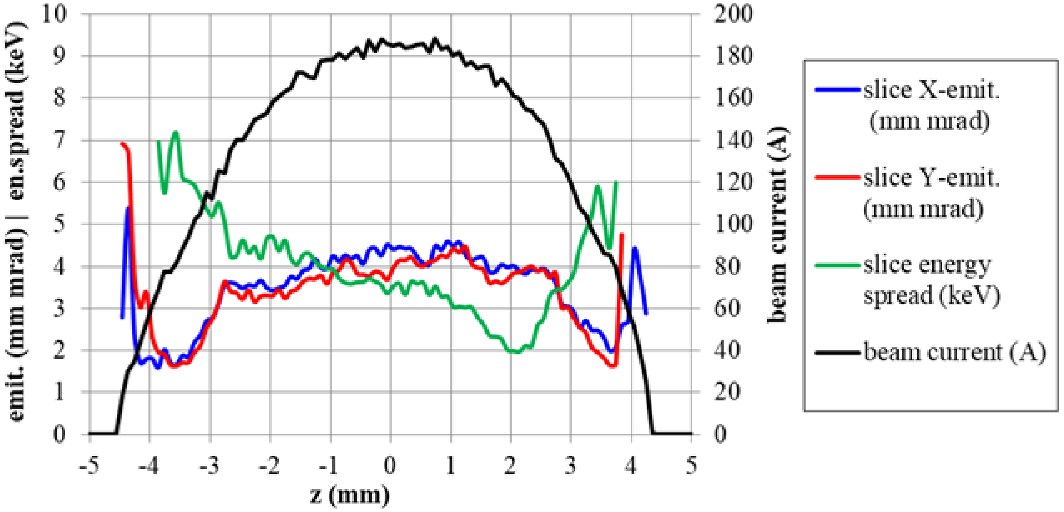


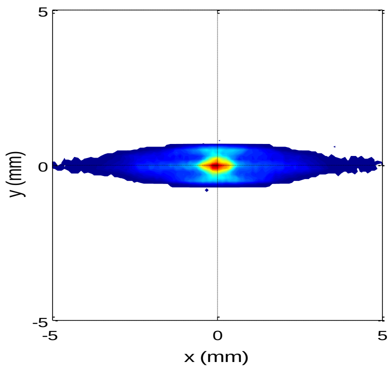
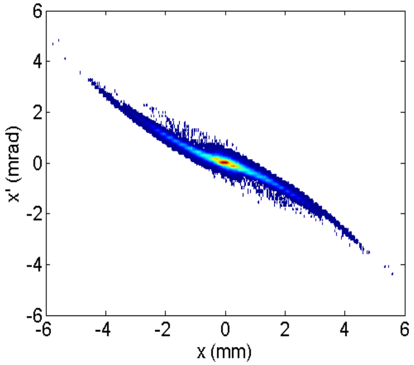
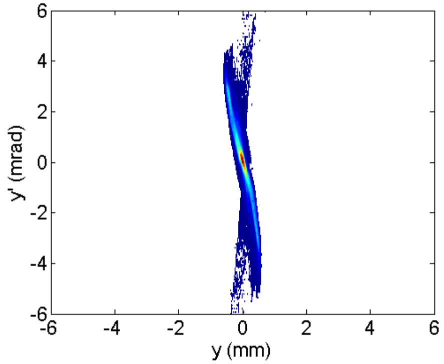
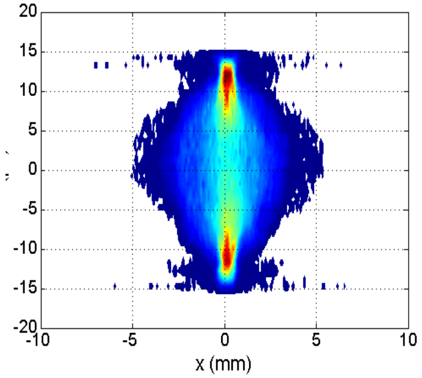
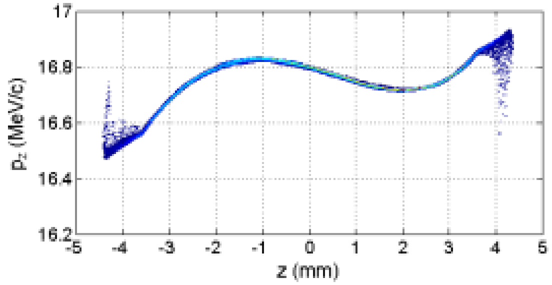


Beam at undulator entrance

ASTRA monitors at z=27.15m ➔ input for GENESIS 1.3 simulations

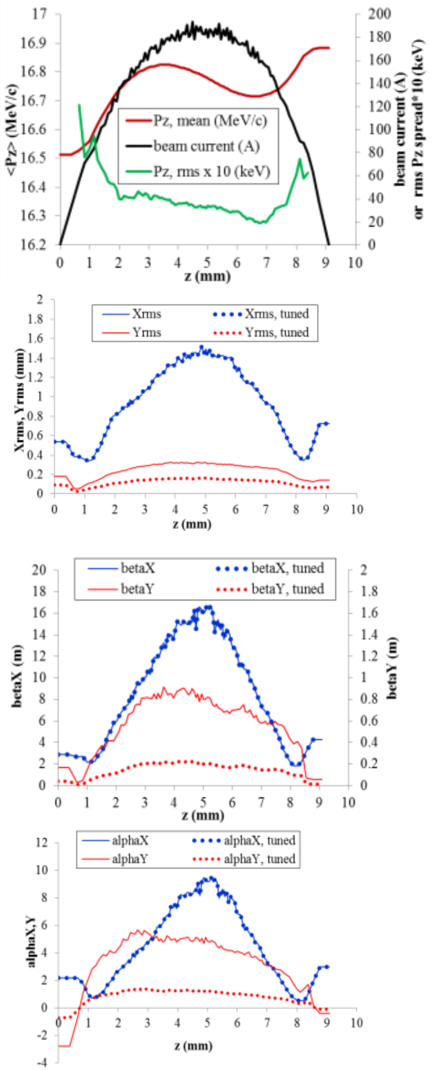


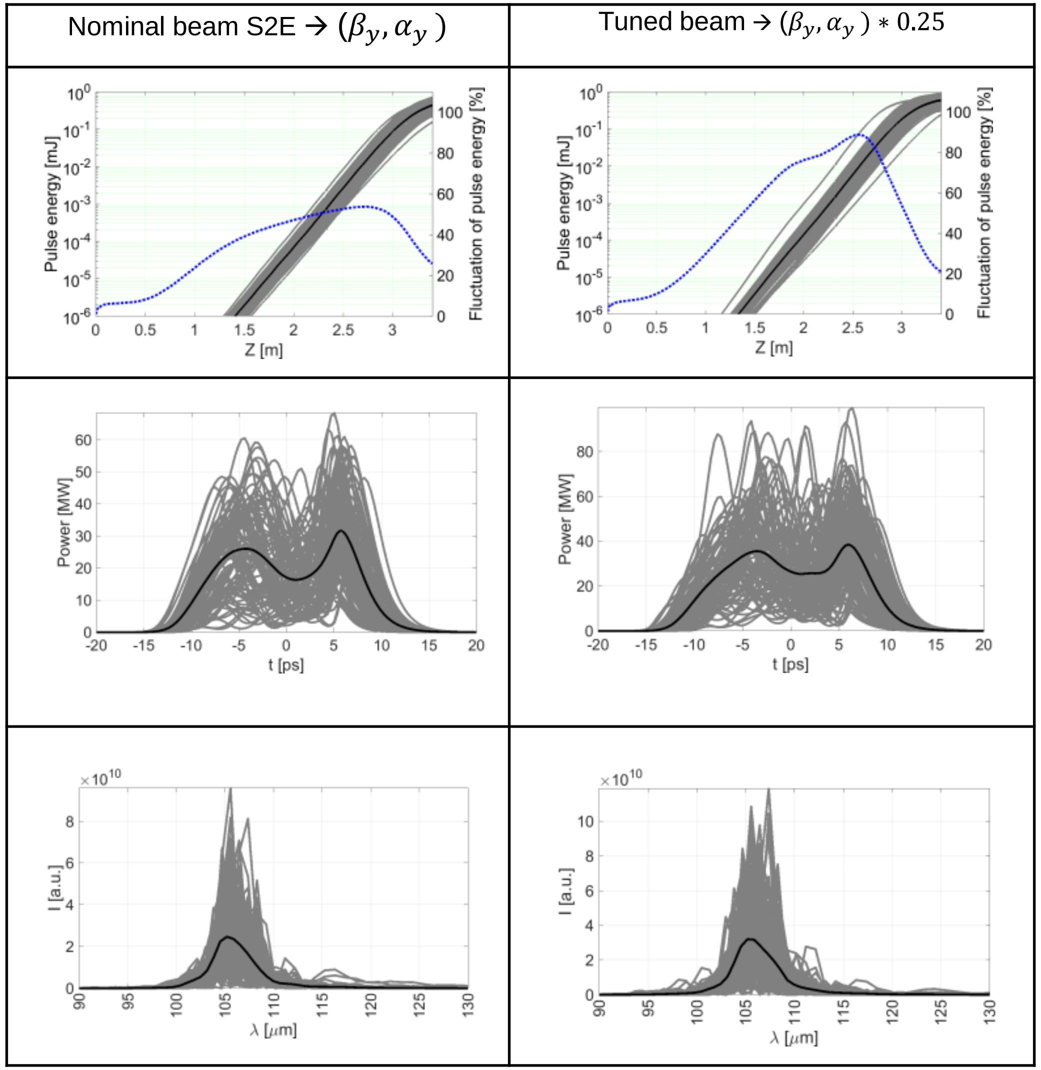


X-Y	X-X’	Y-Y’	X-T	Z-Pz
				

GENESIS 1.3 Simulations

ASTRA at 27.15m + tuning (scaling) → GENESIS1.3 Simulations



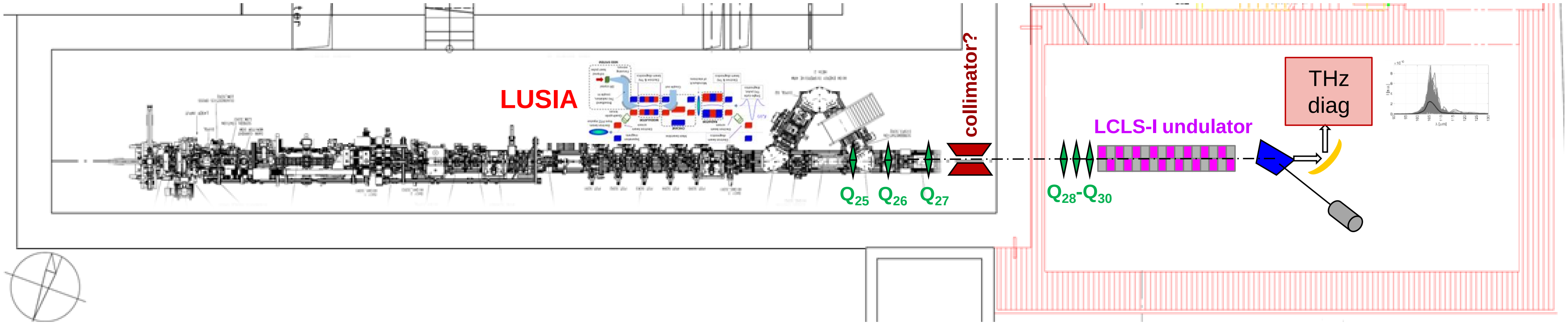


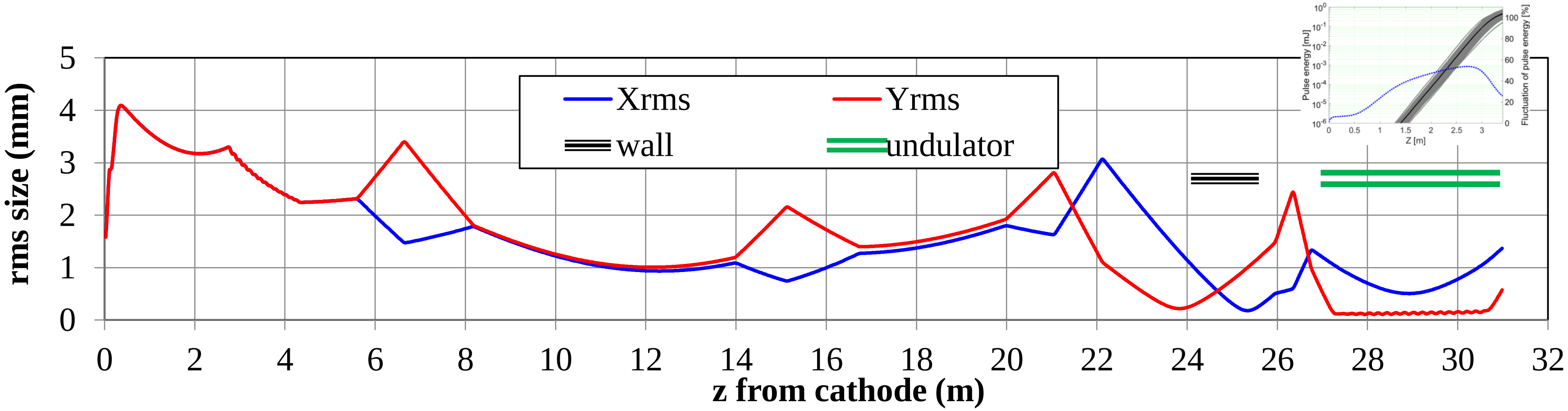
Parameter	Nominal beam (β_y, α_y)	Tuned beam $0.25(\beta_y, \alpha_y)$
Pulse energy (mJ)	0.44±0.11	0.60±0.13
Peak power (MW)	43.0±10.2	58.5±14.3
Pulse duration (ps)	5.6±0.7	5.7±0.7
Arrival rms time jitter (ps)	1.7	1.4
Centre wavelength (μm)	106.5	106.8
Spectrum FWHM width (μm)	4.5	4.8

GENESIS model:
- Only fundamental mode (λ_u=3cm) of one undulator
- No waveguide effect (vacuum chamber) included

Planned installation of LCLS-I undulators in PITZ tunnel annex

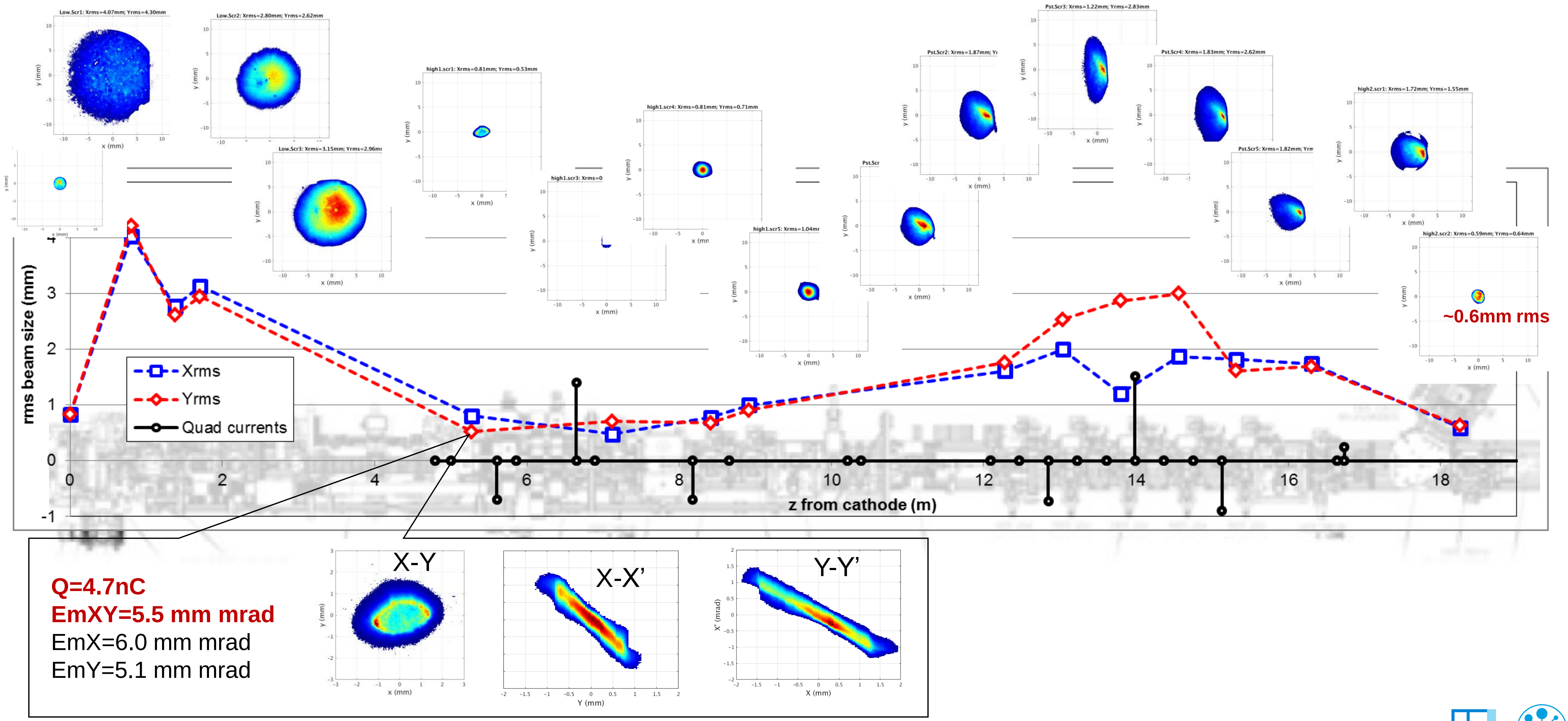
To use for proof-of-principle experiments at PITZ





Recent electron beam transport experimental studies at PITZ

4.7nC electron beam from Gaussian photocathode laser pulses (9.4ps FWHM) – November 2018



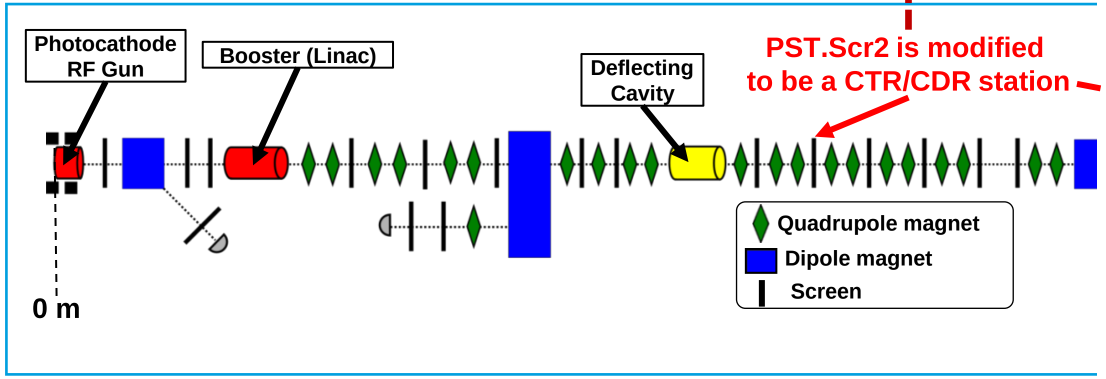
Q=4.7nC
EmXY=5.5 mm mrad
EmX=6.0 mm mrad
EmY=5.1 mm mrad

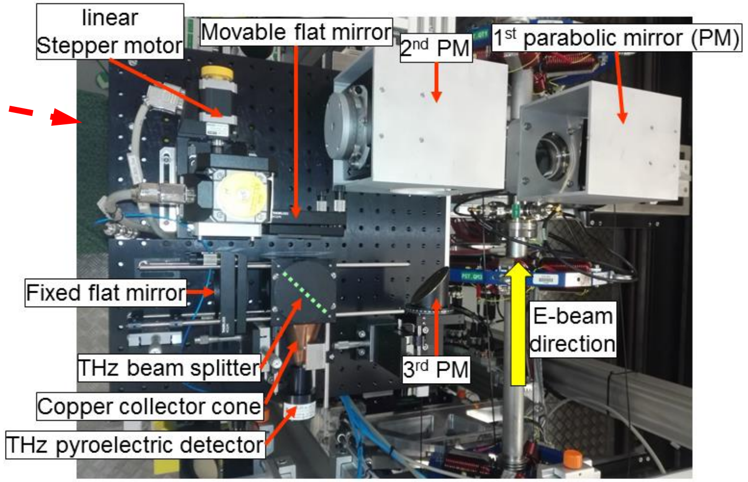
First THz Radiation Generated at PITZ

Using CTR/CDR for THz generation (also for seeding?)

PhD Thesis of P. Boonpornprasert "Investigations on the capabilities of THz production at the PITZ facility"

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



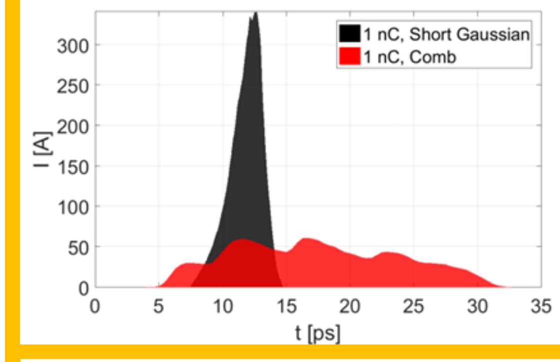


PITZ Highlights:
- Pulse train structure
- High charge feasibility (4 nC)
- **Advanced photocathode laser shaping**
- E-beam diagnostics
- Available tunnel annex
- …

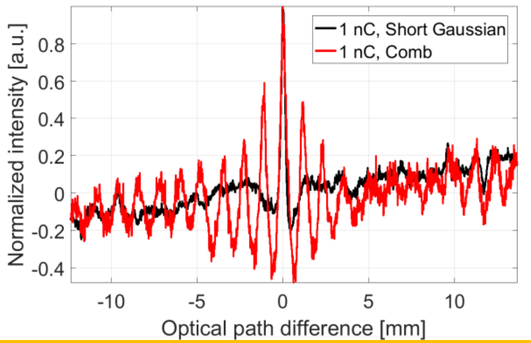
Current PITZ "boundary conditions":
- 22-25 MeV/c max
- No bunch compressor
- …

1^{st} experiments with CTR/CDR THz generation

Measured electron beam temporal profiles



THz Michelson interferometer measurements of CTR



Conclusions and outlook

PITZ developments of the THz facility for the E-XFEL

- PITZ is considered as a site for developments of the accelerator based tunable high power THz source for the pump-probe experiments at the European XFEL
- THz SASE FEL is considered as a primary option:
  - High bunch charge (4nC) with proper pulse shaping → mJ THz pulses
  - Pulse train structure similar to the nominal E-FXEL photo injector
- Current THz related activities at PITZ:
  - CTR/CDR station designed, installed, commissioned, first measurements
  - Detailed characterization of high charge beam generation, characterization and transport
  - Detailed studies of beam dynamics and THz SASE FEL simulations (start-to-end and from experimental e-beam)
- Next steps → considering LCLS-I undulator (on-loan from SLAC) for the **proof-of-principle** experiments:
  - Start-to-end simulations → hundreds of uJ in THz
  - PITZ electron beamline upgrade
  - Install LCLS-I undulator in the PITZ tunnel annex, commissioning
  - Study further options (e.g. seeding) for SASE stabilization
  - Optimizing a PITZ-like accelerator beamline in order to maximize the THz performance for various options while minimizing length/costs

Thanks for contributions and useful discussions:

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- P. Zalden

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- H.-D. Nuhn

and other colleagues

Thanks you for your attention!