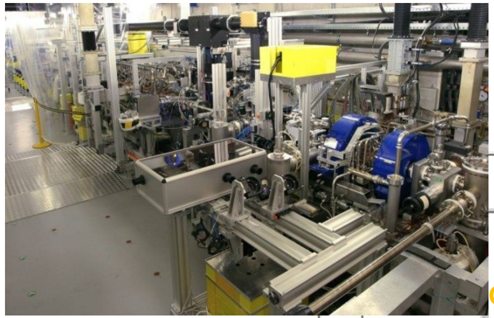
THz generation and Ultrafast Electron Diffraction at PITZ

M. Krasilnikov, DESY, Zeuthen, Germany

02.07.2019, Ultrafast Beams and Applications 2019, CANDLE, Armenia



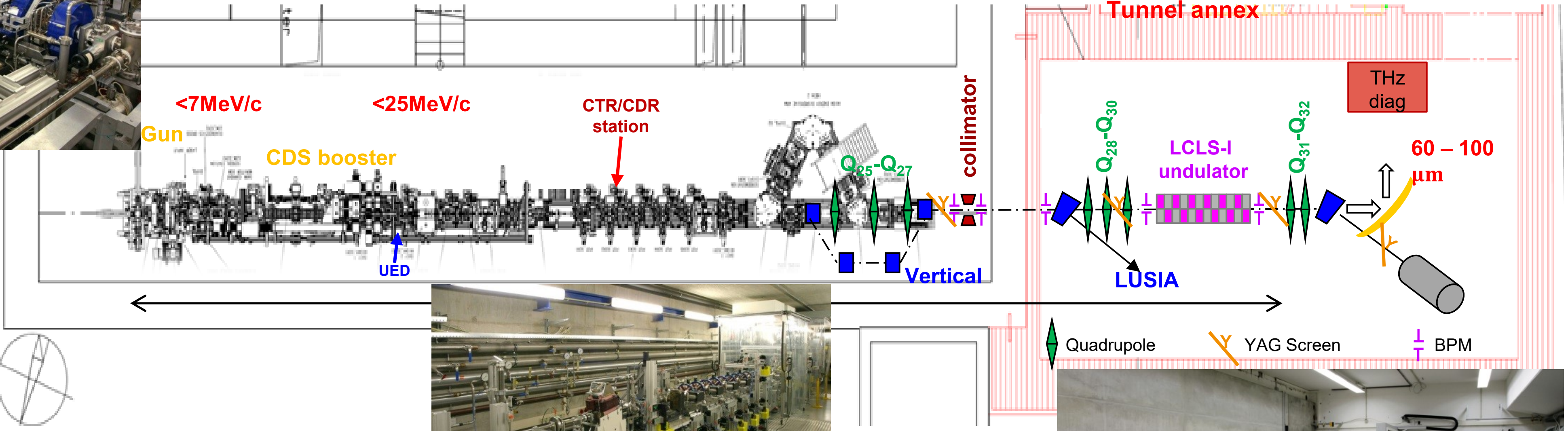
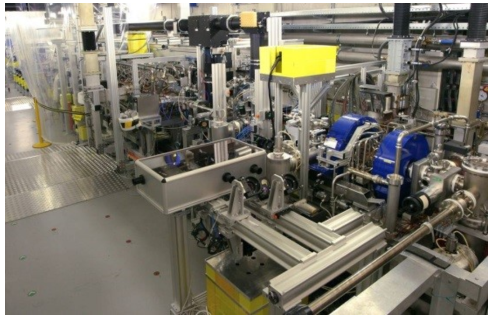


Photo Injector Test facility at DESY in Zeuthen (PITZ)

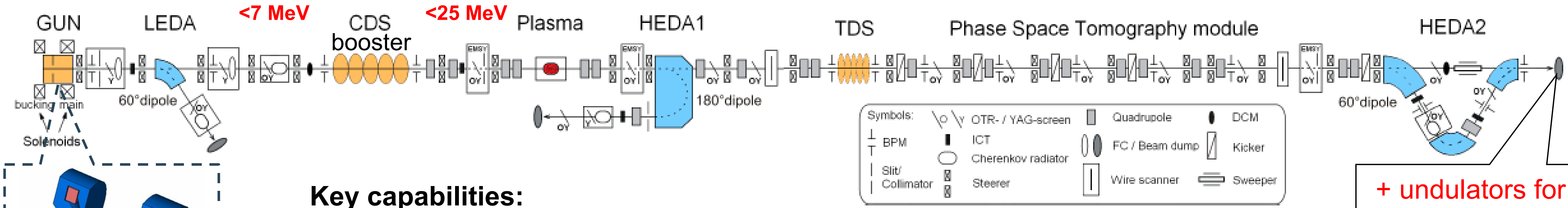
Main Goals:

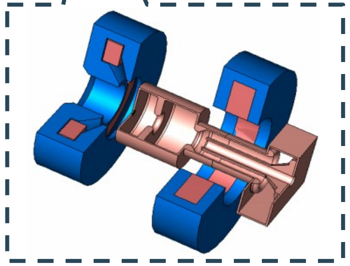
- provide optimized electron sources (minimum emittance) for FLASH and European XFEL
- do general accelerator R&D



Research areas:

- basic photo injector R&D
- specific R&D for FLASH & European XFEL (for current facilities and future upgrades
  → e.g. CW upgrade of European XFEL)
- application of high brightness electron beams + general accelerator R&D for novel acceleration techniques
  → applications like **THz**, plasma acceleration, **UED**, …





+ undulators for THz SASE FEL

Key capabilities:

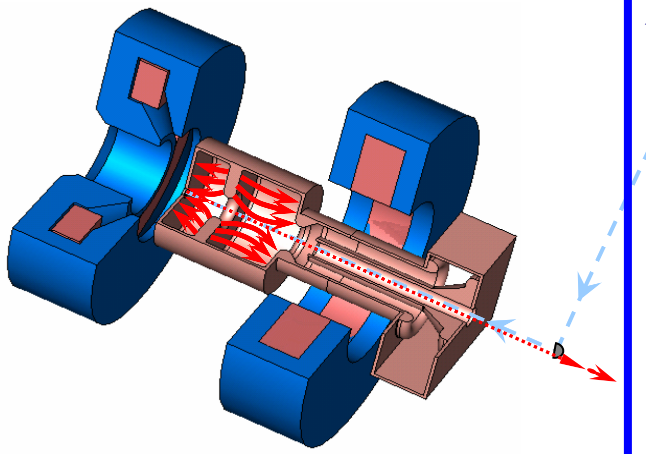
- Flexible photo cathode laser shaping
- Dedicated, well developed test facility with detailed diagnostics
- >15 years experience in high brightness NC photo injectors with high average power

PITZ “engine”: RF-Gun and Photocathode Laser

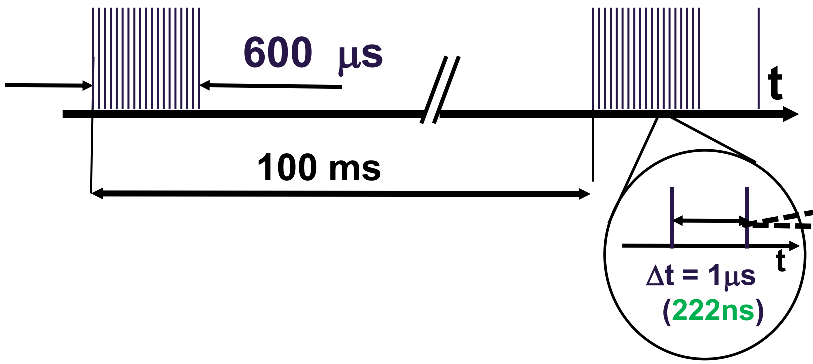
Highlights of the facility

RF gun: in use at FLASH and 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



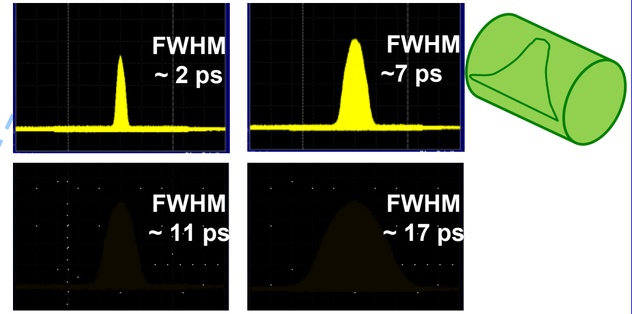
Pulse Train Time Structure:
PITZ and EXFEL trains with up to 600 (2700) laser pulses



Photocathode laser(s) (UV)

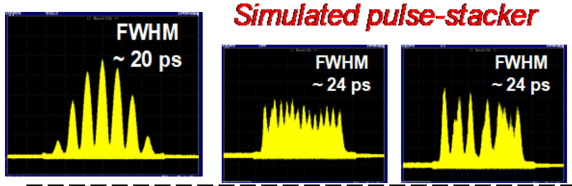
Default laser system (Max-Born-Institute, Berlin)

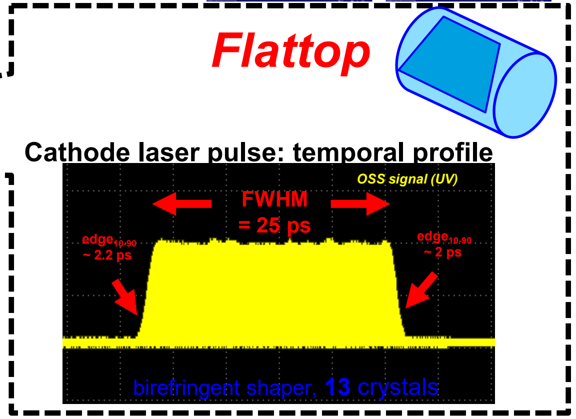
Gaussian:



Multicrystal birefringent pulse shaper containing 13 crystals

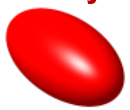
Simulated pulse-stacker





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

THz at PITZ

IR/THz SASE source for pump-probe experiments @E-XFEL

PITZ-like accelerator can enable high power, tunable, synchronized IR/THz radiation

European XFEL (~3.4 km)

PITZ-like accelerator based THz source (~20 m)

X-ray

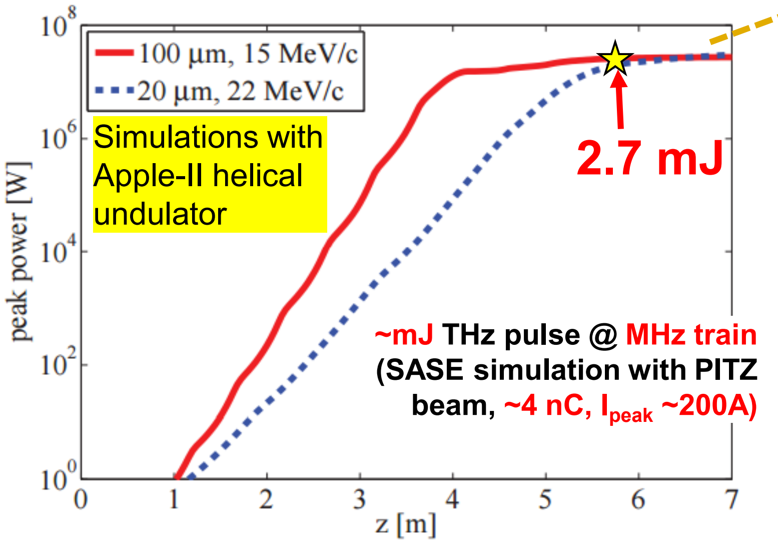
THz

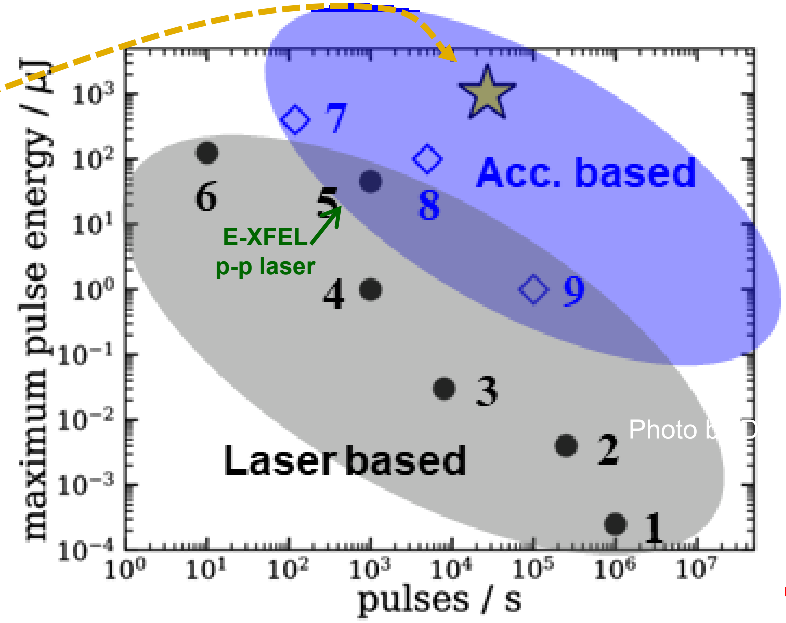
Pump & probe

E.A. Schneydmiller, 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

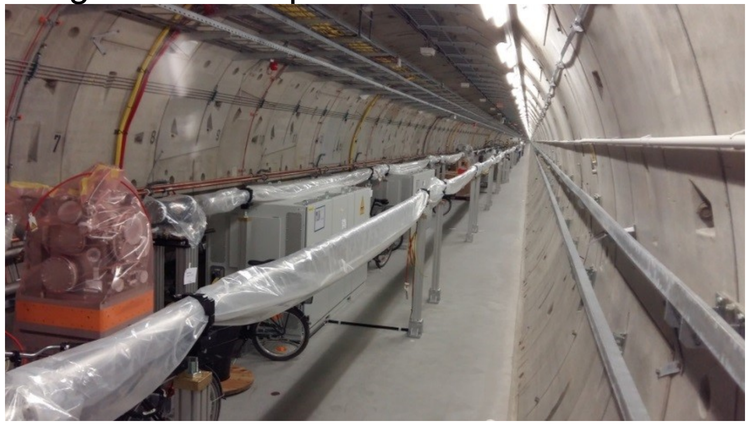
- Accelerator based IR/THz source meets requirements for pump-probe experiments (e.g. the same pulse train structure !)
- Construction of radiation shielded area for installing reduced copy of PITZ is possible close to user experiments at E-XFEL
- Prototype of accelerator already exists → PITZ facility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

Simulation of THz SASE FEL @PITZ





e.g. in E-XFEL photon beam line tunnel:

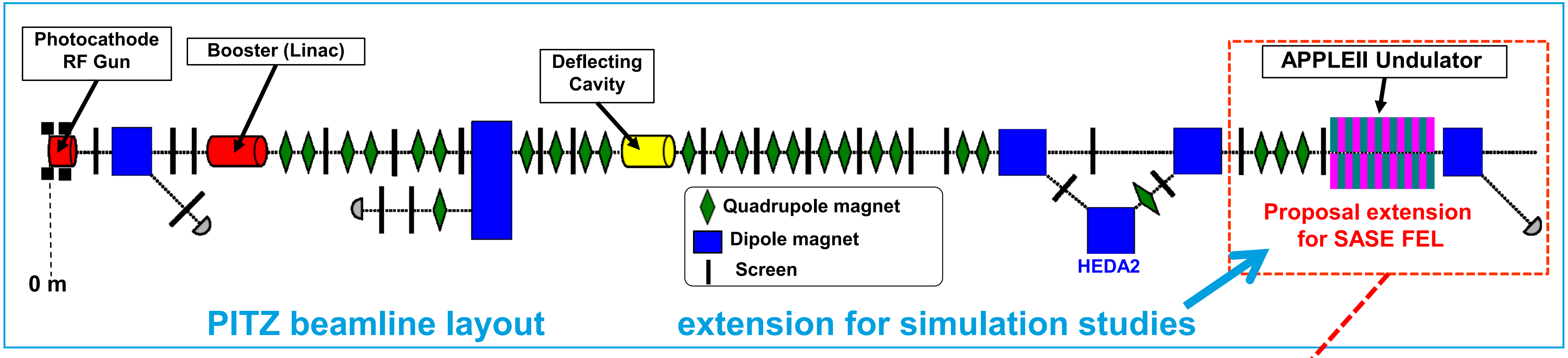


Required beam (~4nC, I_{peak}~200A) already demonstrated at PITZ

➔ **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 λ_{rad} ≤ 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
- …

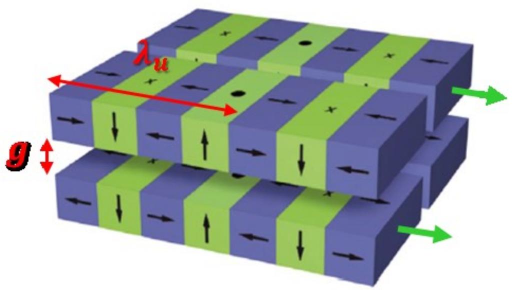
Current PITZ "boundary conditions":

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

THz SASE FEL at PITZ

Undulator and beam parameter space

APPLE- II Undulator*



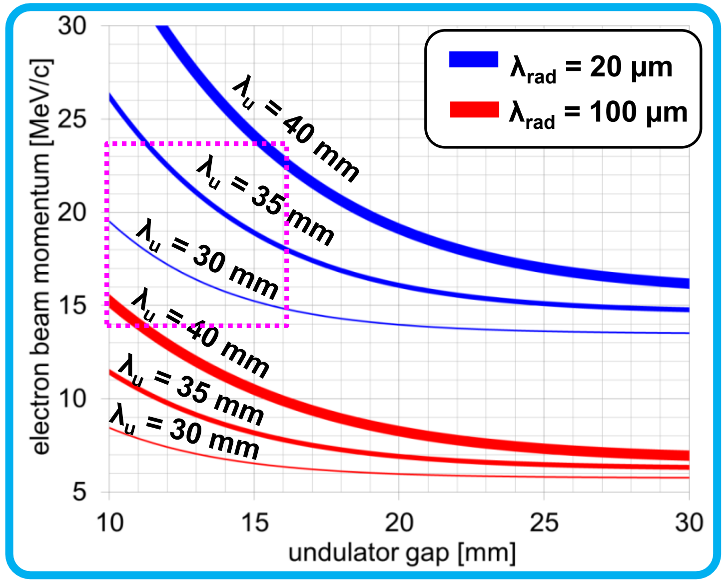
Radiation wavelength

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

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

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

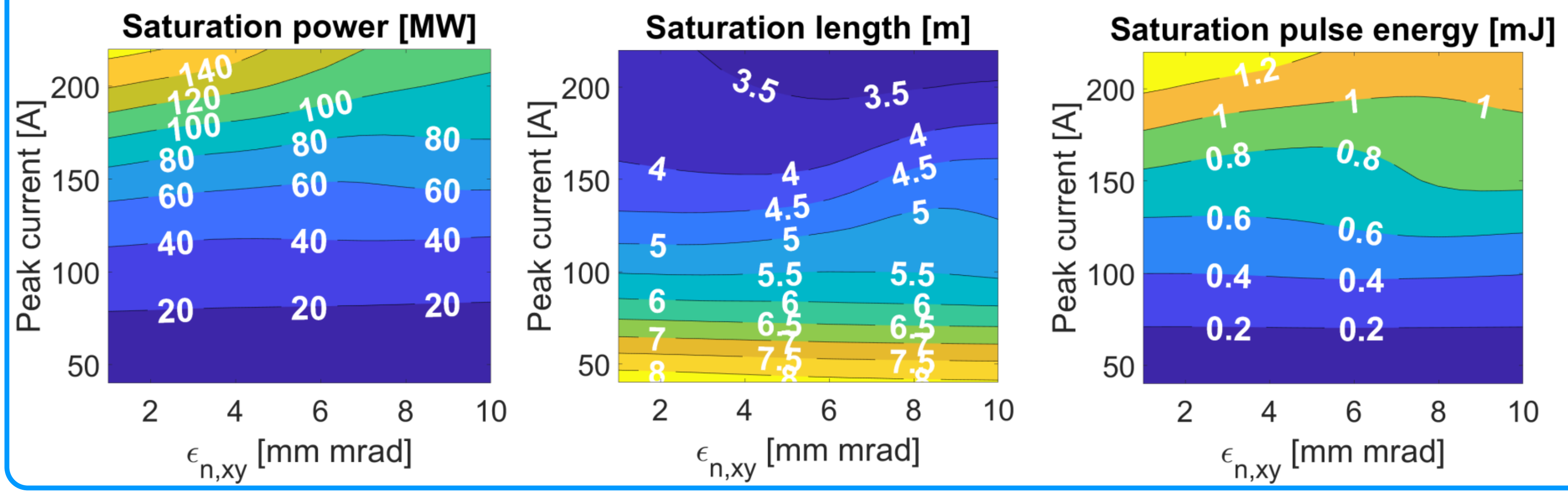
Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007



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

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)

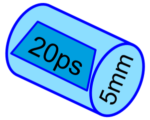
Setup: **4nC** → I_{peak}~200A, ~15MeV/c, λ_u=40 mm, K=1.8, L_u=5-7m

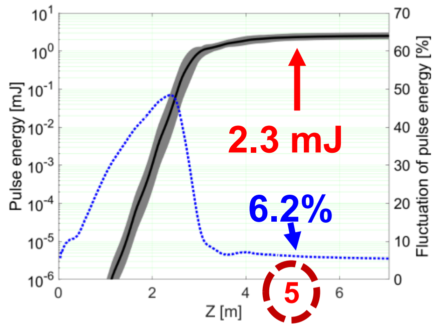
FEL pulse energy (average and rms fluct.)

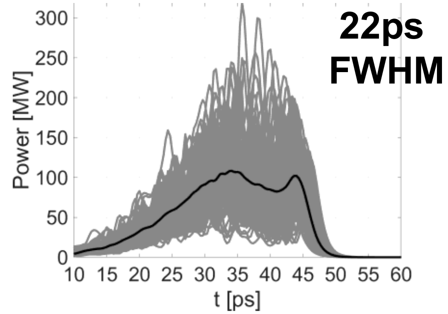
FEL radiation pulse at z_U=5m: temporal profiles, spectral profiles

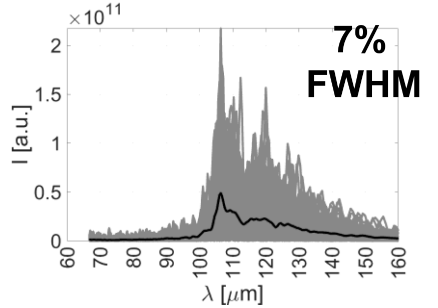
Start-to-end: ASTRA→GENESIS1.3

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



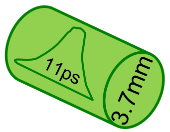


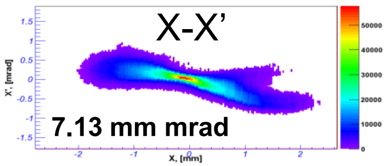


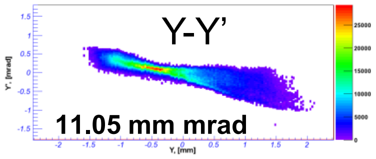


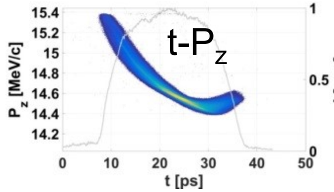
E-beam from **experiment**→ GENESIS1.3

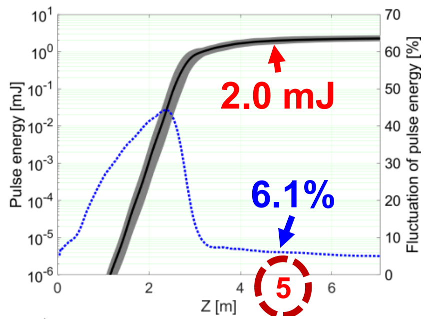
- Photocathode laser: ∅3.7mm, Gaussian 11ps FHWM
- Phase spaces → from measurements

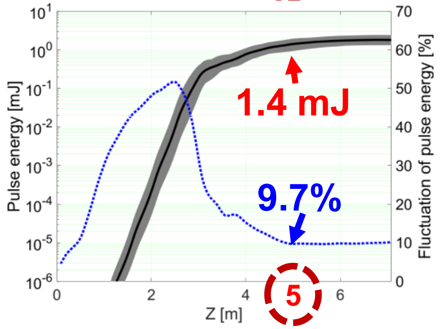


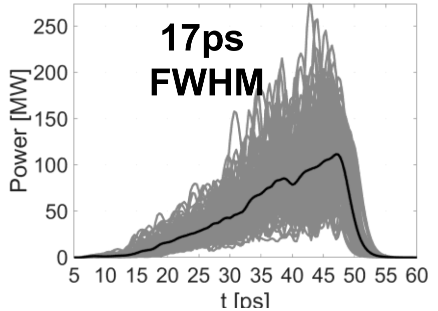


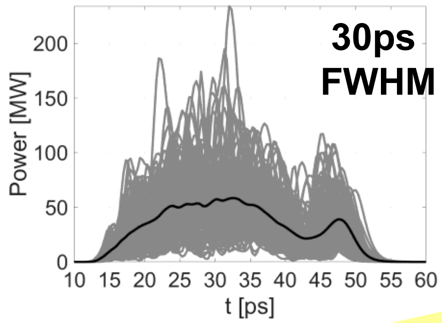


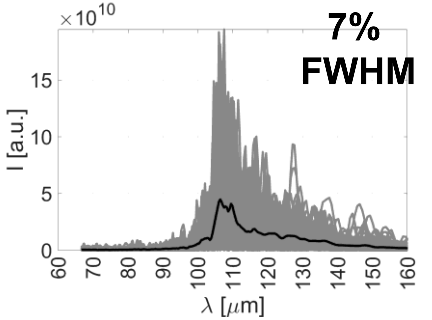


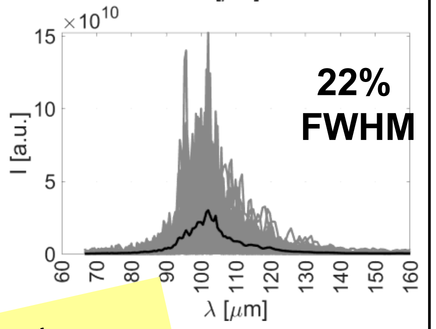








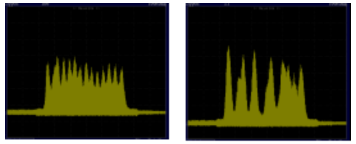




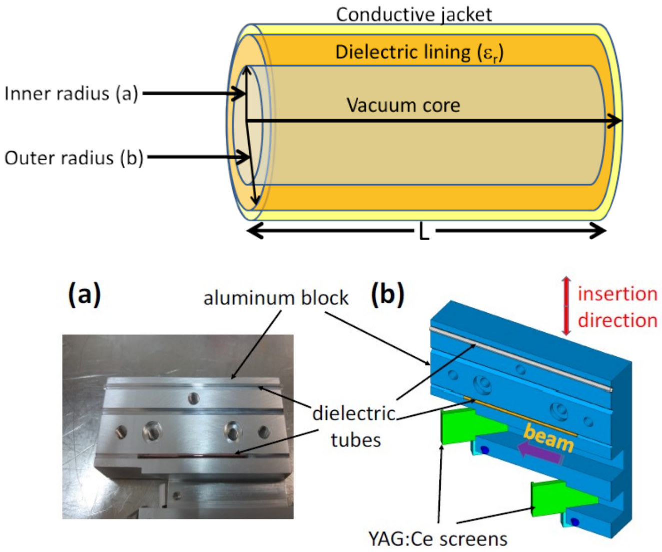
Simulations: P. Boonpornprasert

Options to improve THz radiation stability

Pre-bunching to improve CEP stability of SASE → "Seeding"



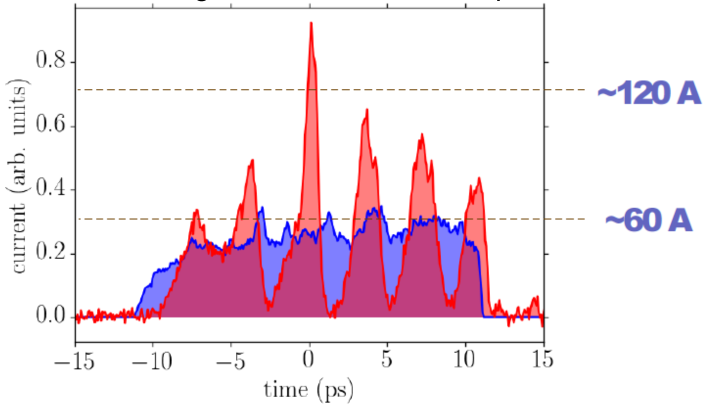
- **Photocathode laser pulse temporal modulation**
- Using IR laser, modulator and BC for E or δE modulations
- Using CDR from short seeding bunch
- **Using corrugated structures**
- **Using Dielectric Lined Waveguides - DLW (first experiments)**



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

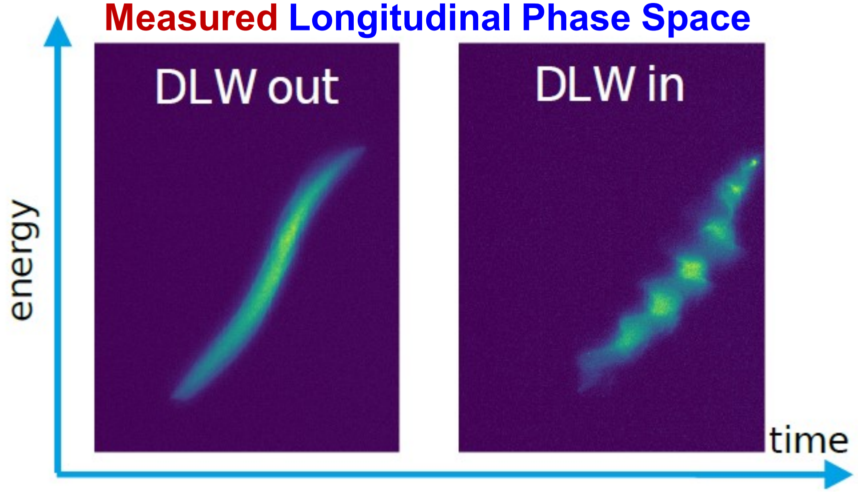
E-beam current profile

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., Passive Ballistic Microbunching of Nonultrarelativistic Electron Bunches Using Electromagnetic Wakefields in Dielectric-Lined Waveguides, Phys. Rev. Lett.,122 044801 (2019)

Measured Longitudinal Phase Space



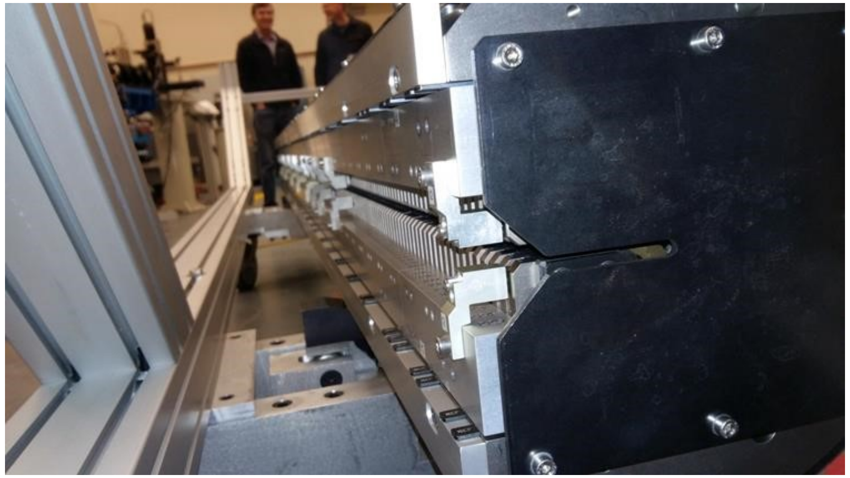
Proof-of-principle experiment on THz SASE FEL at PITZ

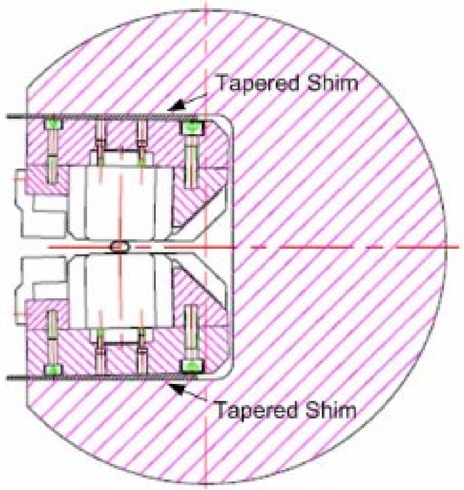
Using LCLS-I undulators (available on loan from SLAC) → under implementation

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

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





λ_{rad}~100μm → <Pz>=**17.05MeV/c**

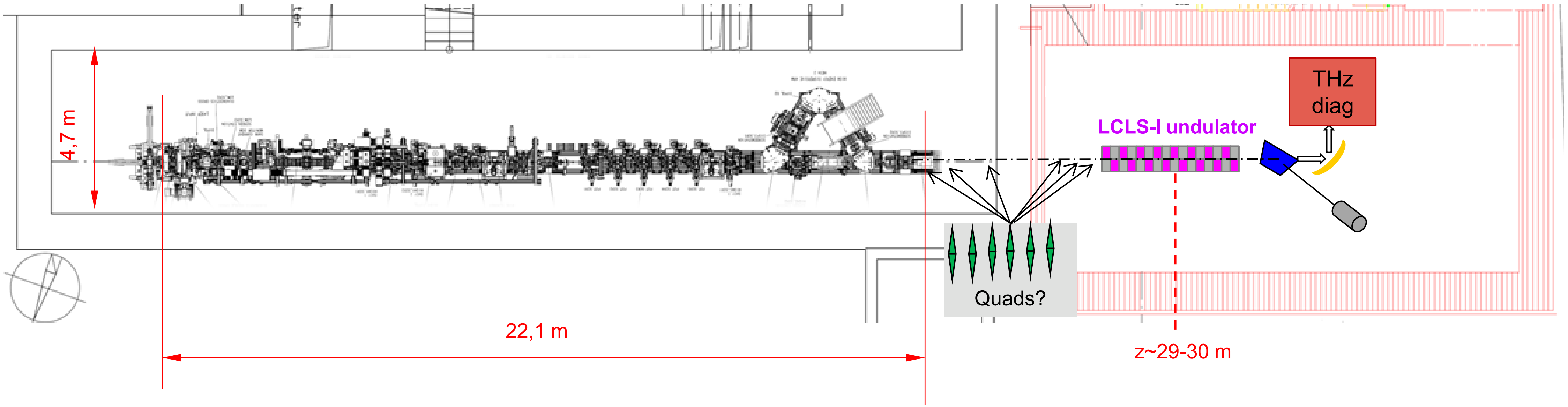
Preliminary conclusions on LCLS-I undulators at PITZ:

- 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

- Radiation shielding is improved (based on FLUKA simulations of Zohrab Amirkhanyan, CANDLE)
- Preparation for operation permission for annex is ongoing



S2E simulations: from photocathode → undulator→ THz SASE FEL

<u>Main challenges:</u>

- 4 nC (~200A) x 17.05MeV/c → SC dominated beam
- ~30 m transport (incl. 1.5 m wall) → LCLS-I undulator in the tunnel annex
- 3D field of the undulator
- Matching into the planar undulator (narrow vacuum chamber issue)

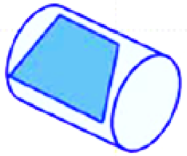
<u>Tools:</u>

- ASTRA
- SC-Optimizer
- GENESIS 1.3

Start-to-end simulation with flattop photocathode laser

Optimization of the photo-injector (~5m) + Design of transport line (~27m)

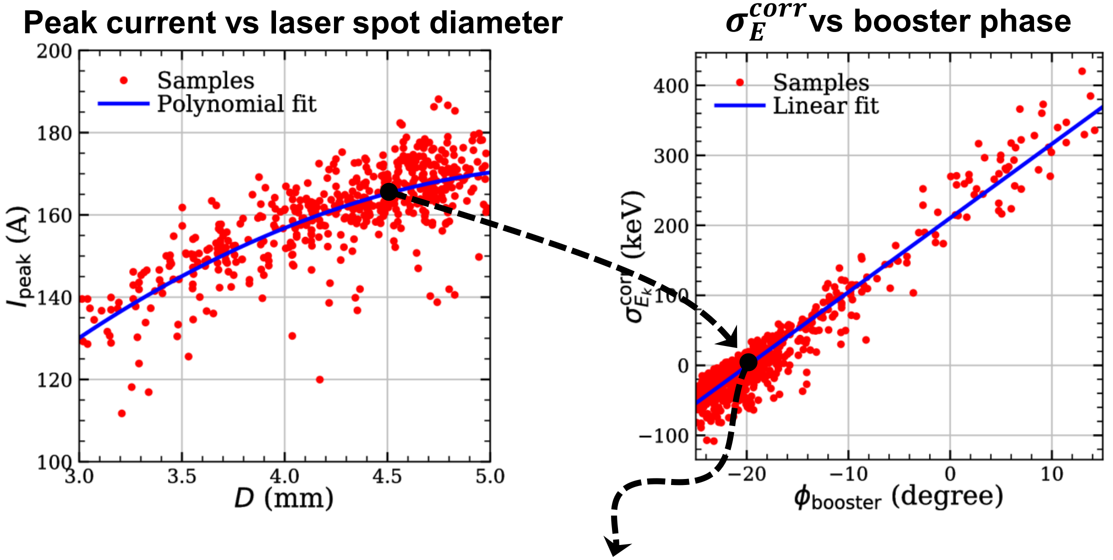
- For the photo-injector optimization
- Laser
  - Flattop longitudinally: 21.5 ps
  - Uniform and tunable transversely: < 5 mm



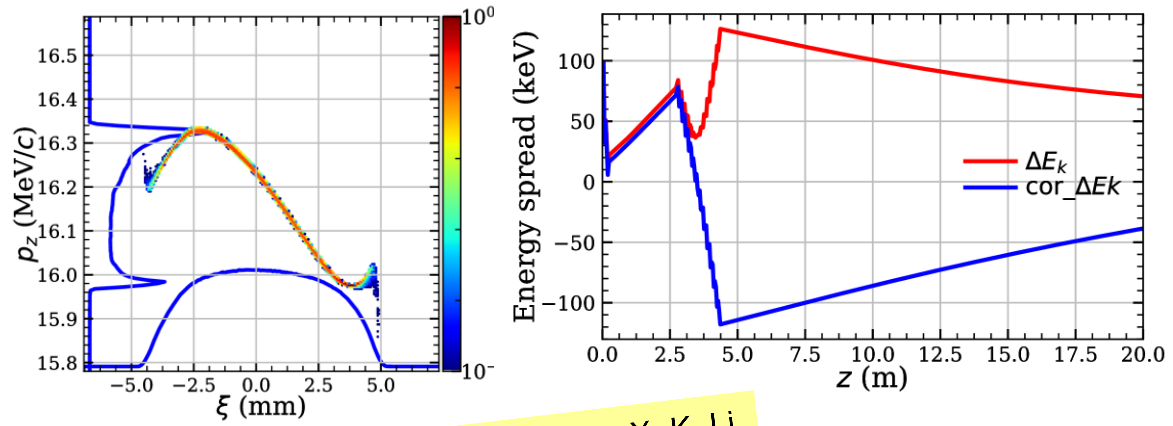
- Gun: highest gradient achievable: Ecath=60 MV/m
- Other tunable parameters: Gun phase, Booster phase, Solenoid current

$$\rho = \left[\frac{1}{16}\frac{I_{\text{peak}}}{I_A}\frac{K_0^2[JJ]^2}{\gamma^3\sigma_x^2 k_u^2}\right]^{1/3} \qquad \frac{\varepsilon_{\text{n}}}{\beta\gamma} \le \frac{\lambda_s}{4\pi} \rightarrow \varepsilon_{\text{n}} \le 200\mu\text{m}$$

- Goal function: $F = f(\langle\varepsilon_n\rangle, \sigma_E^{\text{corr}})$
  - Beam momentum 17.05 MeV/c <= booster gradient
  - Minimizing emittance oscillation after the booster
  - Minimizing correlated energy spread $\text{cor\_}E_k = \langle zE_k\rangle/\sigma_z$ at the undulator
- Results: many solutions with different laser spot sizes



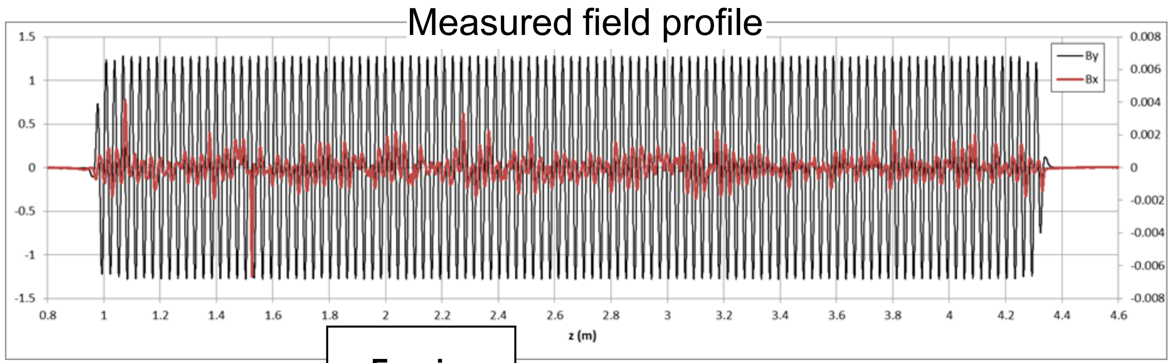
Booster phase = MMMG – 20



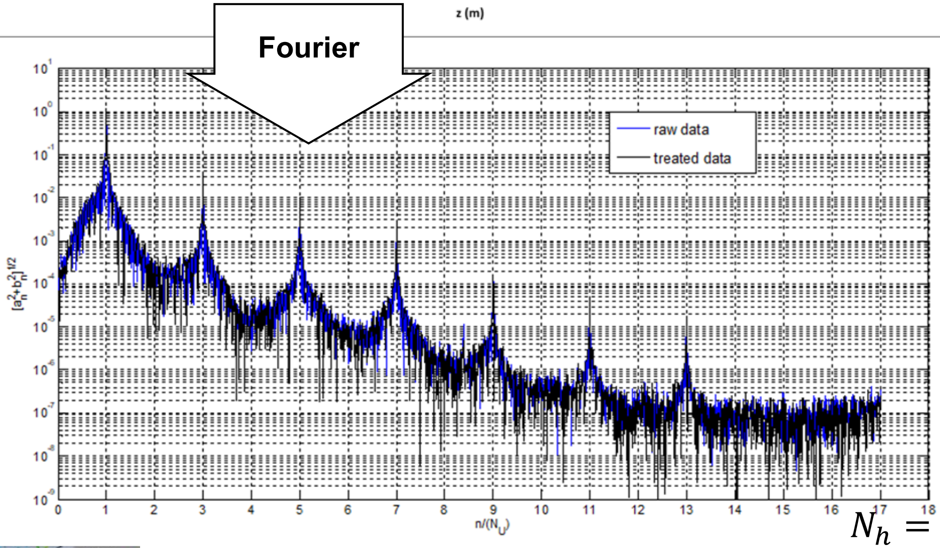
Simulations: X.-K. Li

LCLS-I undulator field modeling

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



$$B_y(x=0,y=0,z)=\sum_{n=0}^{\infty}\left\{a_n\cos\left(\frac{2\pi nz}{N_U\lambda_U}\right)+b_n\sin\left(\frac{2\pi nz}{N_U\lambda_U}\right)\right\}$$

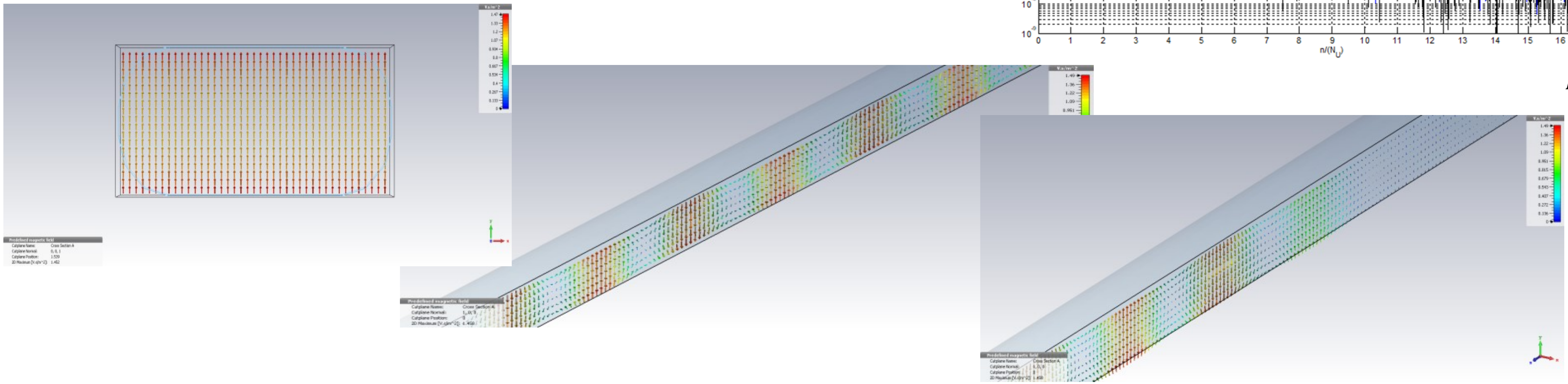


$N_h = 17$
$N_U = 120$

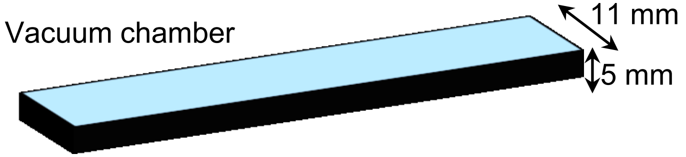
3D field map generation (to be used as external field map for ASTRA (static magnetic cavity), CST(Trk/PIC) and LW code):

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

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



Start-to-end simulation with flattop laser

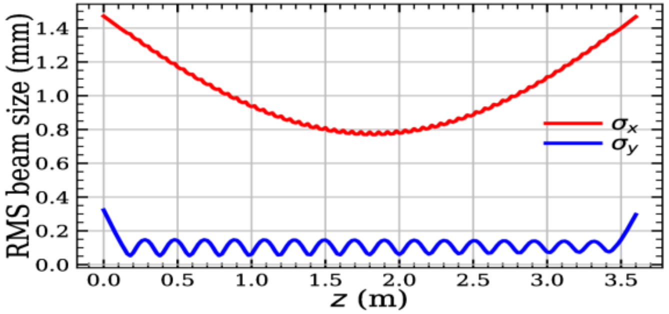


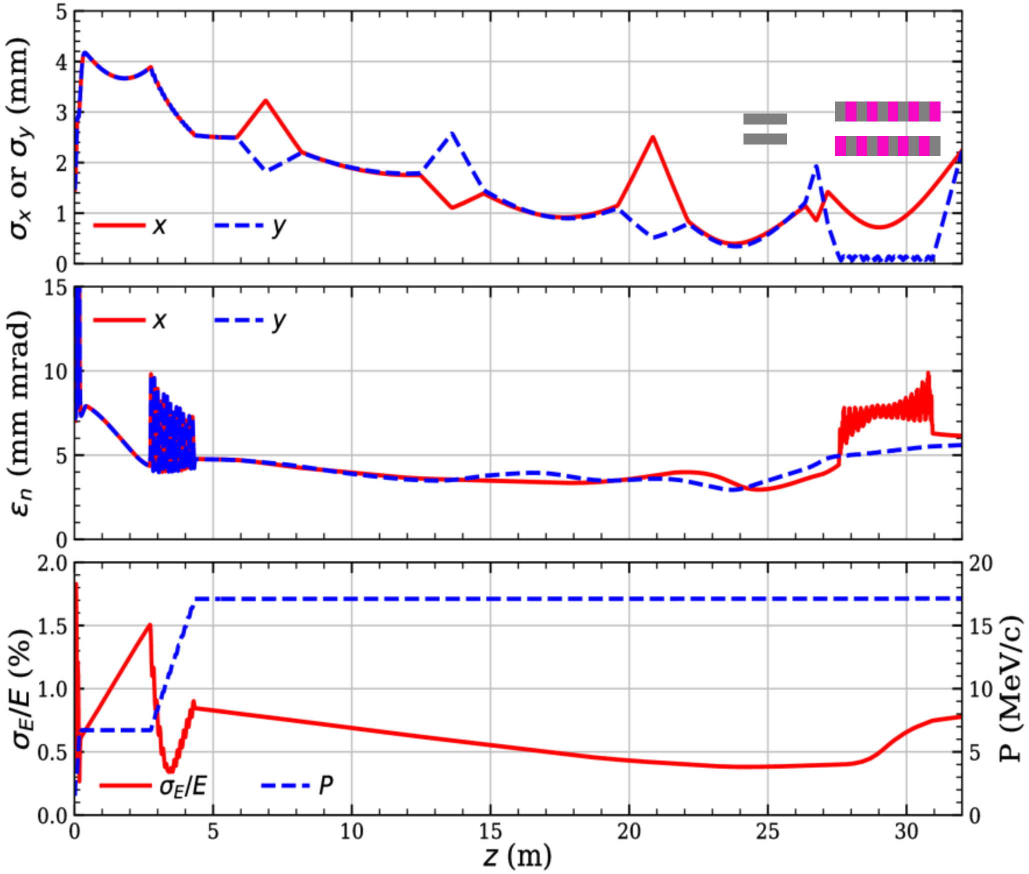
Transport and matching of the beam to the undulator

- Astra + SCO simulation
  - Two quadrupole triplets to focus the beam when passing through diagnostics sections
  - Another two triplets to match the beam into the vacuum chamber of the undulator module

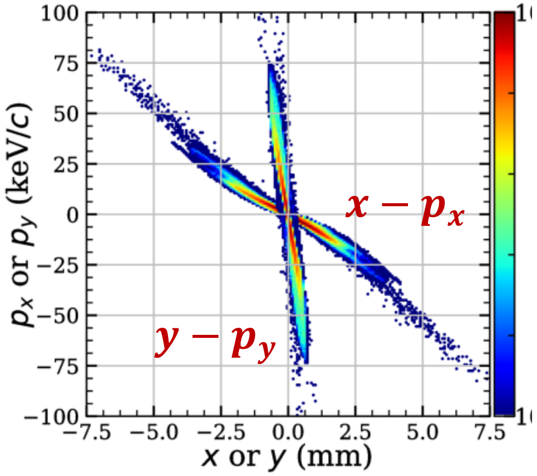
Matching condition:

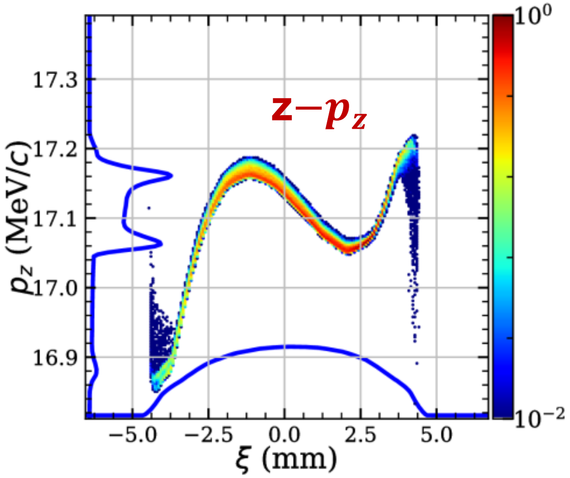
σ_x, σ_y, $\langle xx' \rangle$, $\langle yy' \rangle$ defined





Trans. & long. phase spaces at undulator entrance



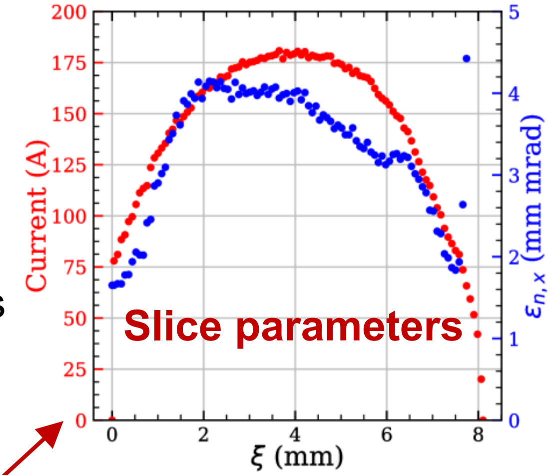


Simulations: X.-K. Li

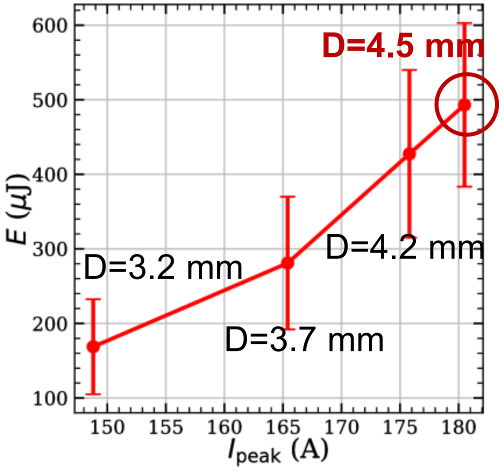
Start-to-end simulation with flattop photocathode laser

THz radiation generation

- Genesis 1.3 simulation
  - Beam from Astra simulation used as input
  - No transverse space charge effects
  - No waveguide effects

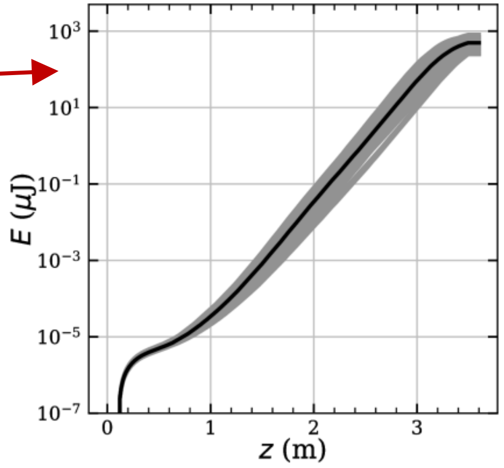


Parameter	Value	Unit
Pulse energy	**493.1±108.8**	μJ
Peak power	52.7±11.8	MW
Centre wavelength	**101.8±0.7**	μm
Spectrum width	2.0±0.4	μm
Arrival time jitter	1.45	ps

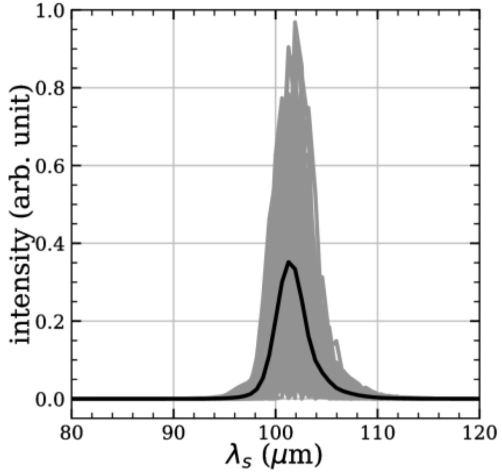


Pulse energy vs peak current

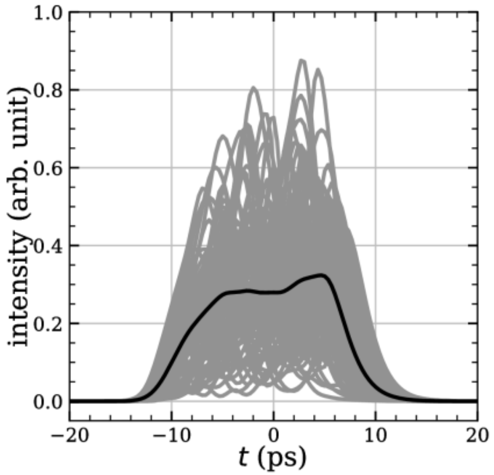
D-photocathode laser spot diameter



Pulse energy along und.



Spectrum at und. exit

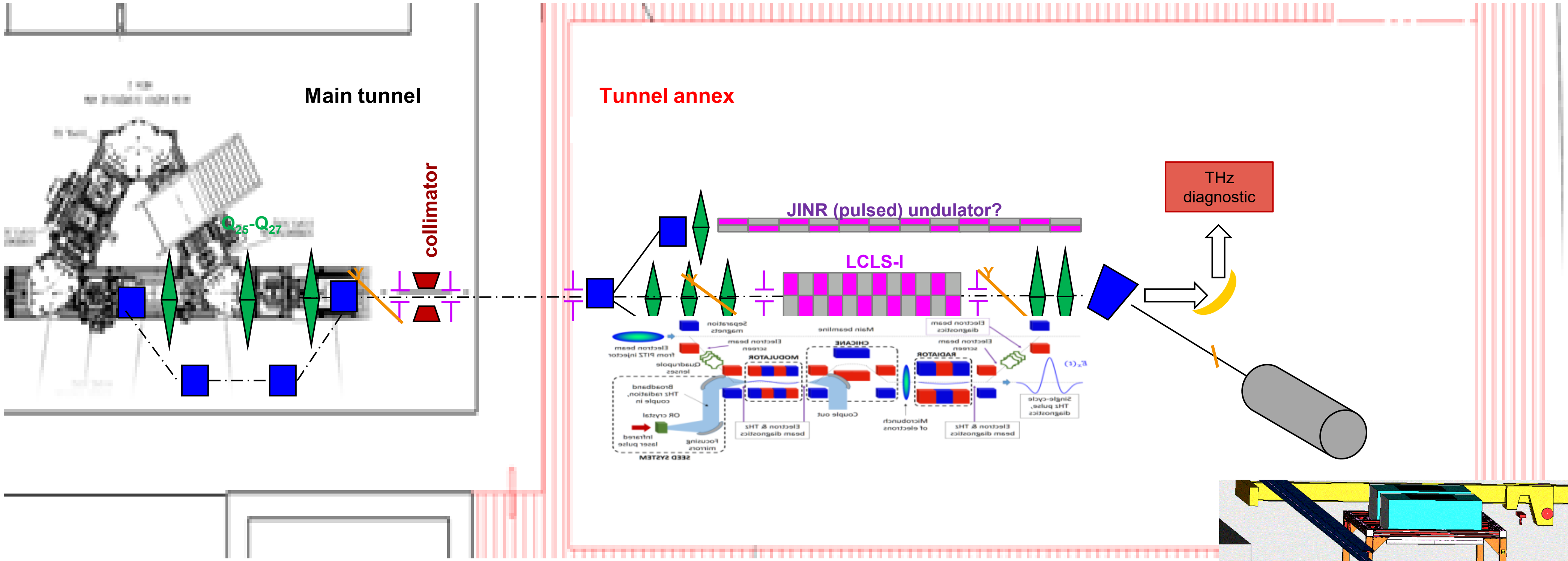


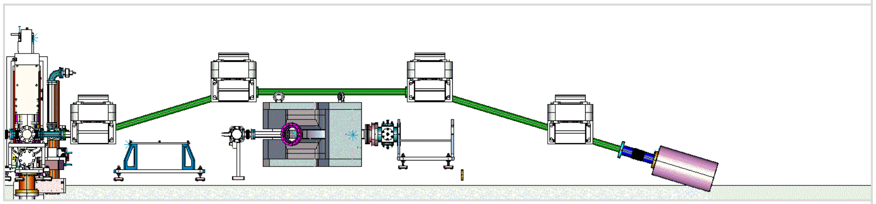
Temporal profile at exit

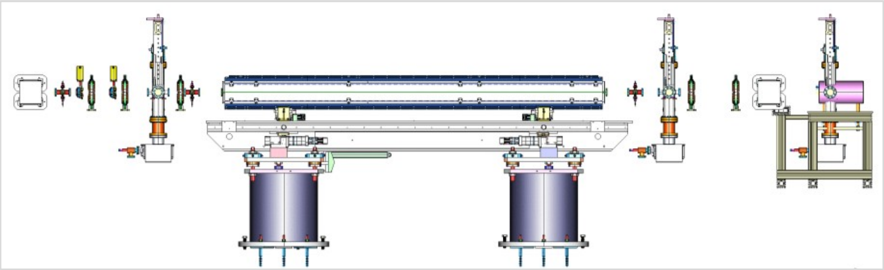
Simulations: X.-K. Li

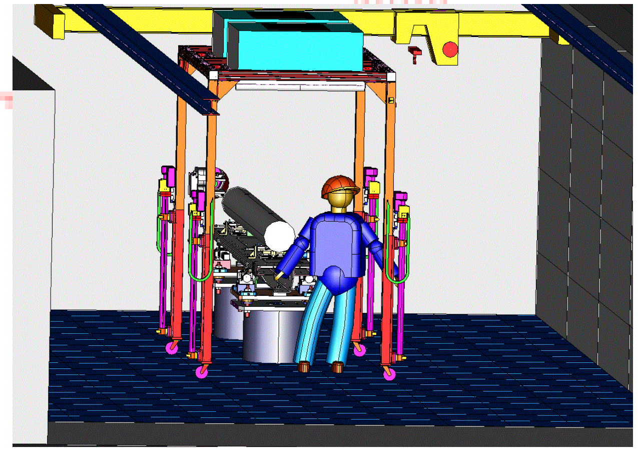
Plans in the PITZ tunnel annex: PITZ4 – Phase 1 (PITHz)

Beam line upgrade towards proof-of-principle experiments on THz generation







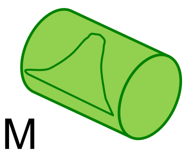


Experimental studies with Gaussian photocathode laser pulses

High charge beam generation

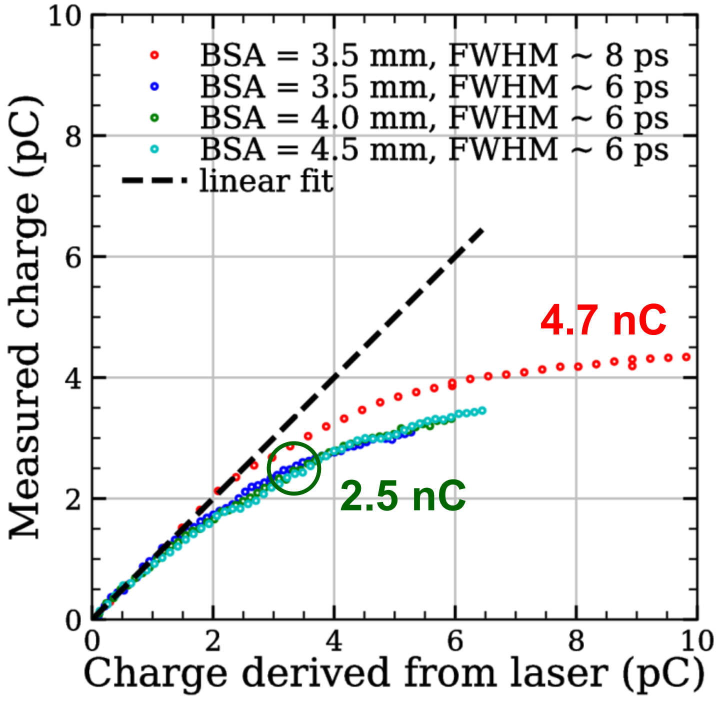
- Laser distributions used for simulations
  - Flattop longitudinally: 21.5 ps
  - Uniform and tunable transversely: < 5 mm

- Actual laser distributions
  - Gaussian longitudinally: 6-7 ps FWHM
  - Gaussian truncated transversely: ~3 mm FWHM



- From the short (~6ps FWHM) Gaussian laser, it is possible to extract 4 nC bunch charge, but at the cost of strong saturation, which is difficult to model with Astra
- To suppress strong saturation, large BSA (**4 mm**) was used for bunch charge of **2.5 nC** while maintaining high peak current

Emission curves for various BSA (laser spot) diameters

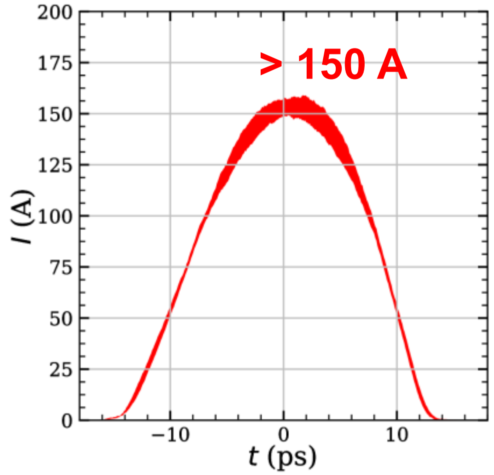


Experimental studies with Gaussian photocathode laser pulses

High charge beam characterization

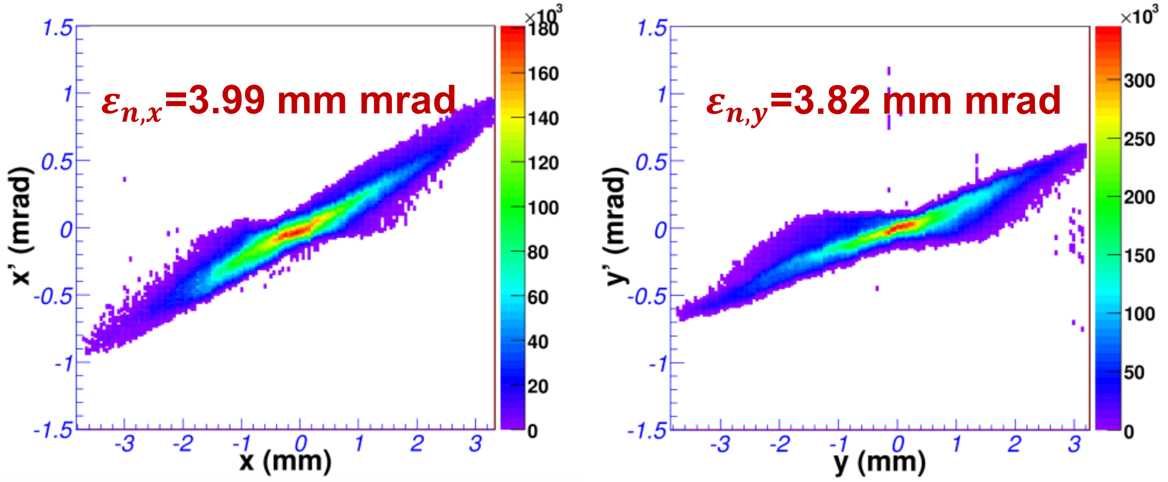
- At reduced bunch charge of **2.5 nC**, the beam has been characterized after acceleration & transportation
  - Laser: Gaussian longitudinally with FWHM of 6-7 ps and Gaussian truncated transversely with FWHM of ~3 mm
  - Gun: maximum accelerating gradient and MMMG phase => 6.6 MeV/c
  - Booster: MMMG -20 degree, gradient tuned => 17.05 MeV/c

Temporal bunch profile by TDS



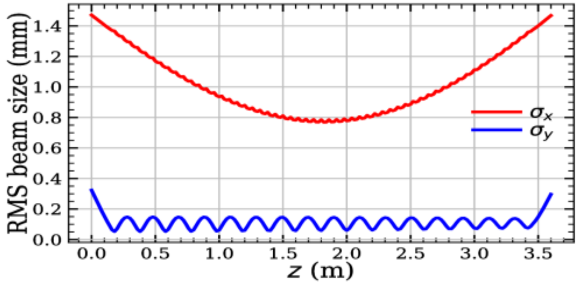
Parameter	Meas.	Simul.	Unit
Laser FWHM	6.2	6	ps
Laser BSA	4	4	mm
Bunch charge	2.53±0.05	2.5	nC
Momentum	17.0	17	MeV/c
Peak current	153±0.5	156	A
xy emittance	3.90	4.14	mm mrad

Transverse phase spaces measured with slit-scan



Experimental studies with Gaussian laser pulses

Transport and matching of the beam

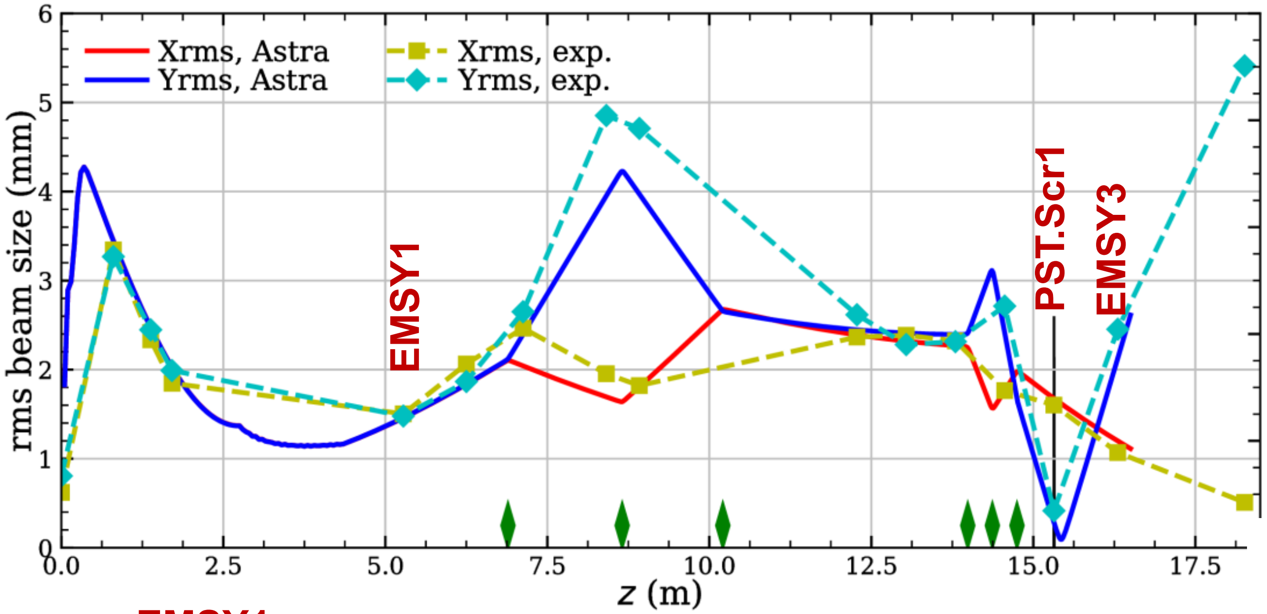


Matching condition:
σ_x, σ_y, $\langle xx' \rangle$, $\langle yy' \rangle$ defined

- Matching with two quadrupole triplets in the existing beamline (2.5 nC)

Procedure:
1, Phase space matching at EMSY1
2, Tuning the first triplet
3, Tuning the second triplet

All based on simulation results

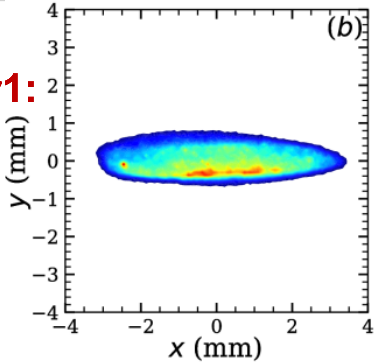


EMSY3:
Xemit = 9.61 mm mrad
Yemit = 13.02 mm mrad

Results:
1. The beam was matched at PST.Scr1
2. Currents of triplets were different from simulated ones.

EMSY1:
Xemit = 6.06 mm mrad
Yemit = 5.79 mm mrad

Beam size @ PST.Scr1:
Xrms = 1.54 mm
Yrms = 0.32 mm

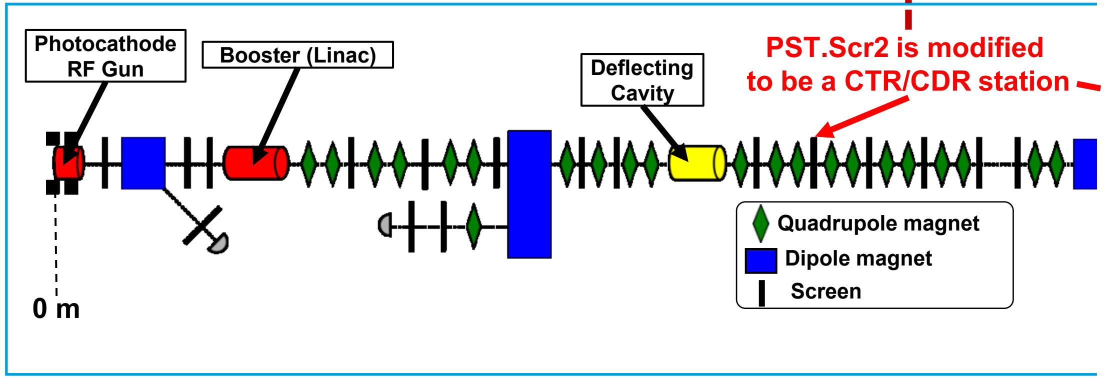


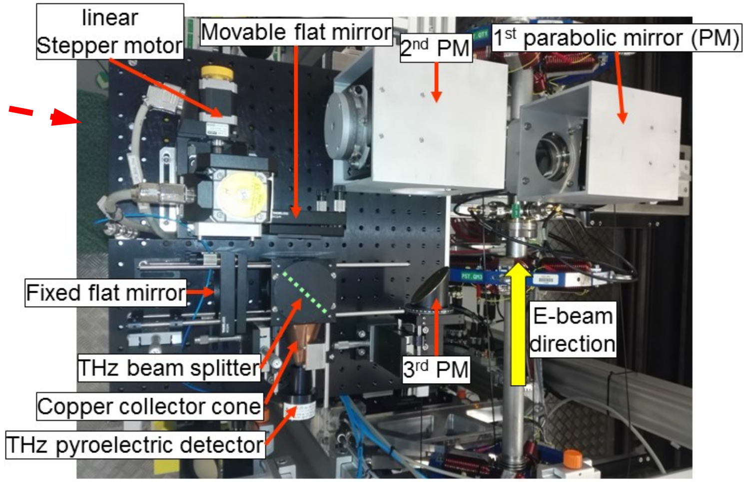
	H1.Q6	H1.Q8	H1.Q9	PST.QT3	PST.QT4	PST.QT5	
Astra	-0.446	0.899	-0.369	-1.324	3.453	-1.428	A
Exp.	-0.60	0.88	-0.14	-1.75	3.75	-1.43	A

First THz Radiation Generated at PITZ

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

▶ **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
- …

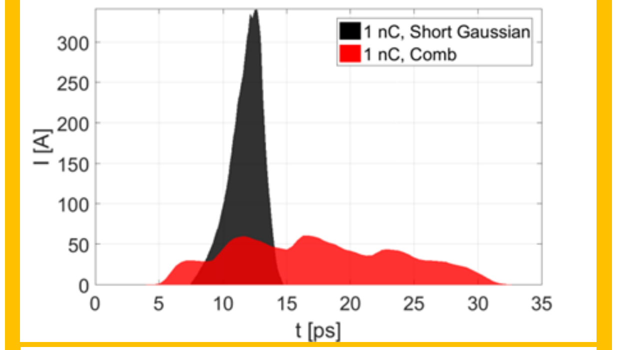
PhD Thesis of P. Boonpornprasert "Investigations on the capabilities of THz production at the PITZ facility"

Current PITZ "boundary conditions":

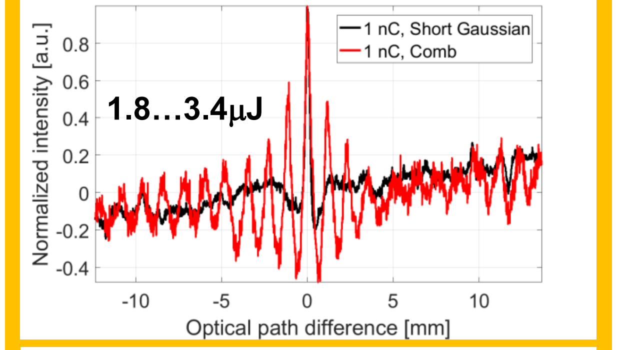
- 22-25 MeV/c max
- No bunch compressor
- …

1st experiments with CTR/CDR THz generation

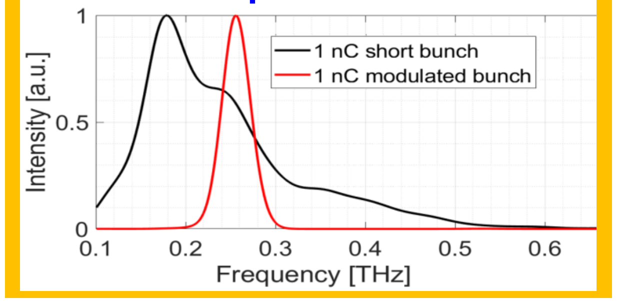
Measured electron beam temporal profiles



THz Michelson interferometer measurements of CTR



Spectrum



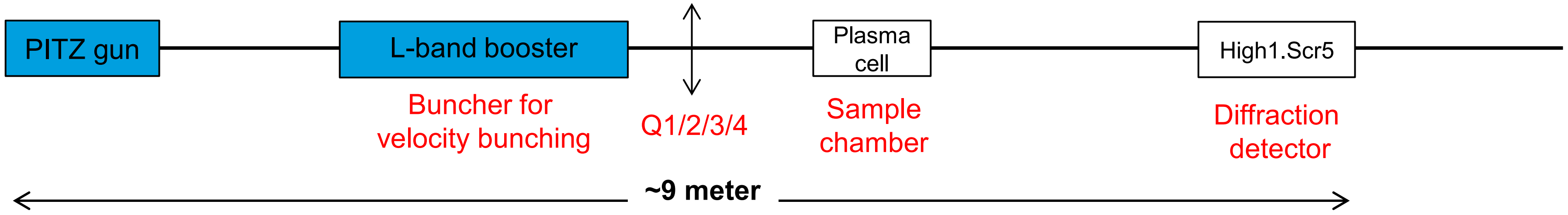
Ultrafast Electron Diffraction at PITZ?

Beam simulation of UED test at PITZ

Optimized for solid state samples

- Simulations of two operation modes
  - Cathode laser 2 ps Gaussian, cathode with 0.5 mm.mrad/mm thermal emittance
  - No beam aperture is used

Beam at sample	'Single shot' (irreversible UED)	'High coherence' (micro-nano UED)	Unit
Energy (tunable)	~4		MeV
Wavelength (tunable)	~0.3		pm
Bunch length (FWHM)	<50		fs
Pulse rate (tunable)	$10 \sim 10^4$		pulse/s
Electron per pulse	~100 (10^6 e^-)	~0.1 (10^3 e^-)	fC/pulse
Normalized emittance	20	0.2	nm.rad
Beam rms size at sample	100	1	um
Transverse coherence length	2		nm
Source size at cathode	200	2	µm

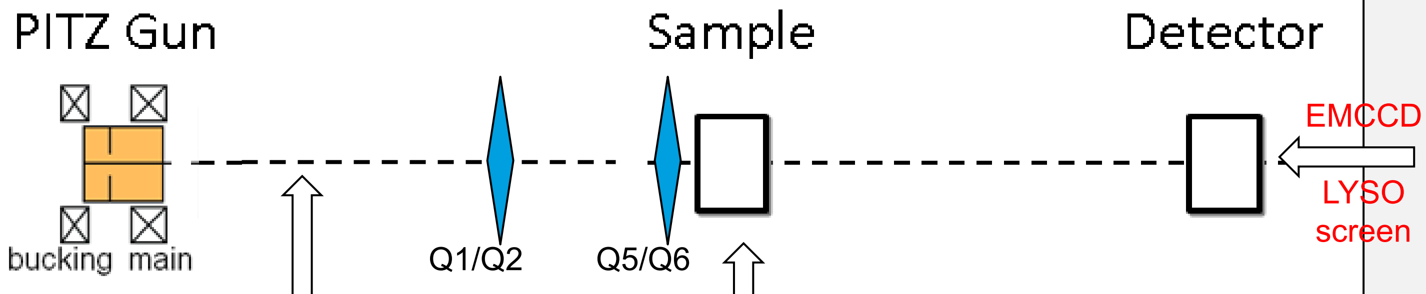


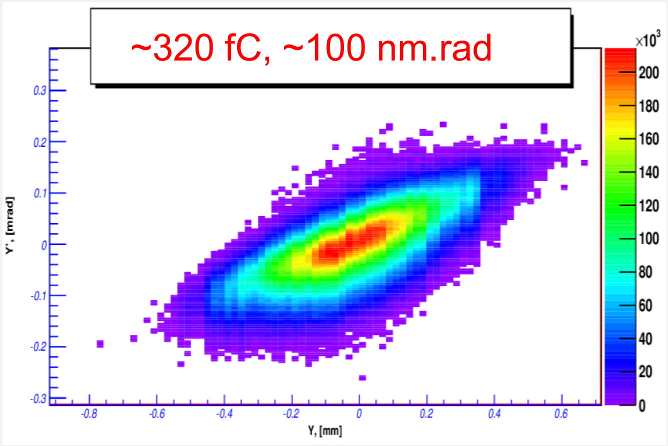
Courtesy H. Qian

Preparation of first static MeV electron diffraction test at PITZ

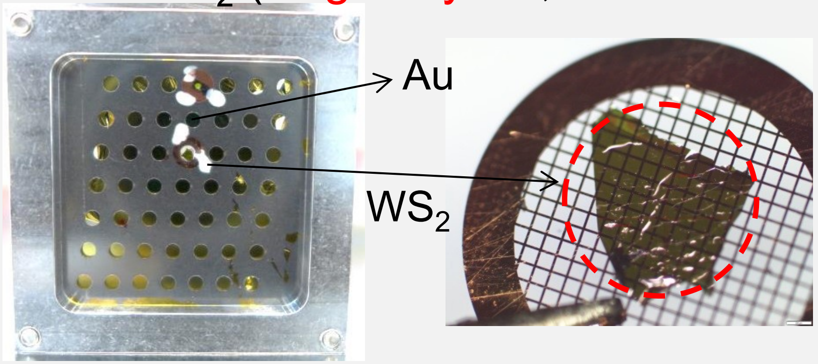
Collaboration between PITZ, Max-Born-Institute (MBI) and Fritz-Haber-Institute (FHI)

- DESY/PITZ: Installation, beam experiment, …
- MBI: Sample substrate, Au sample, EMCCD + Lens, beam experiment, …
- FHI: WS_2 sample, diffraction pattern analysis, …





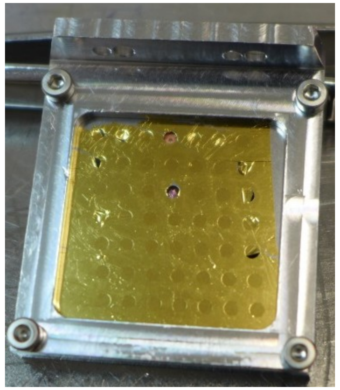
Au (polycrystal, 100 nm thick)
WS_2 (single crystal, 50-60 nm thick)



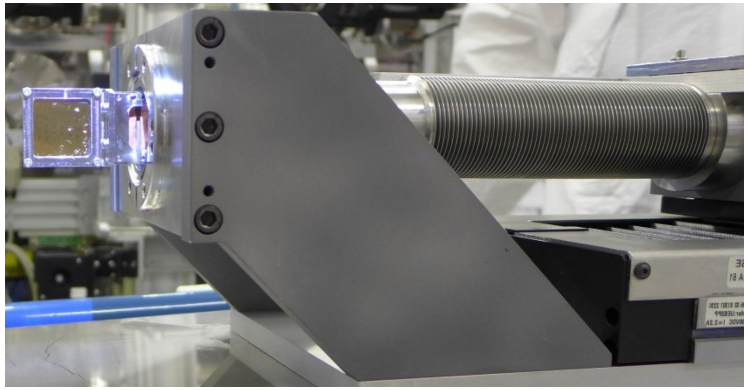
Courtesy H. Qian

Preparation of first static MeV electron diffraction test at PITZ

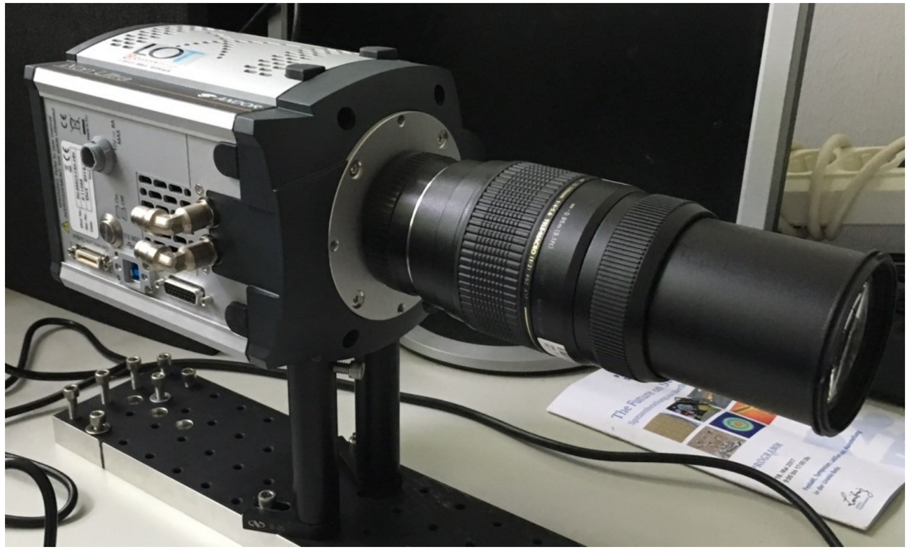
Sample substrate
(MBI)



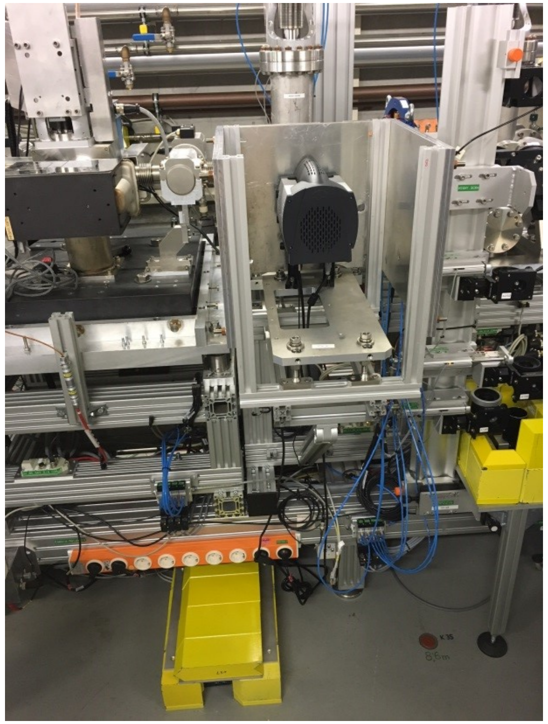
+Au(MBI) +WS2(FHI)
+Sample holder(PITZ)



+Actuator
(PITZ)



EMCCD camera
(MBI)

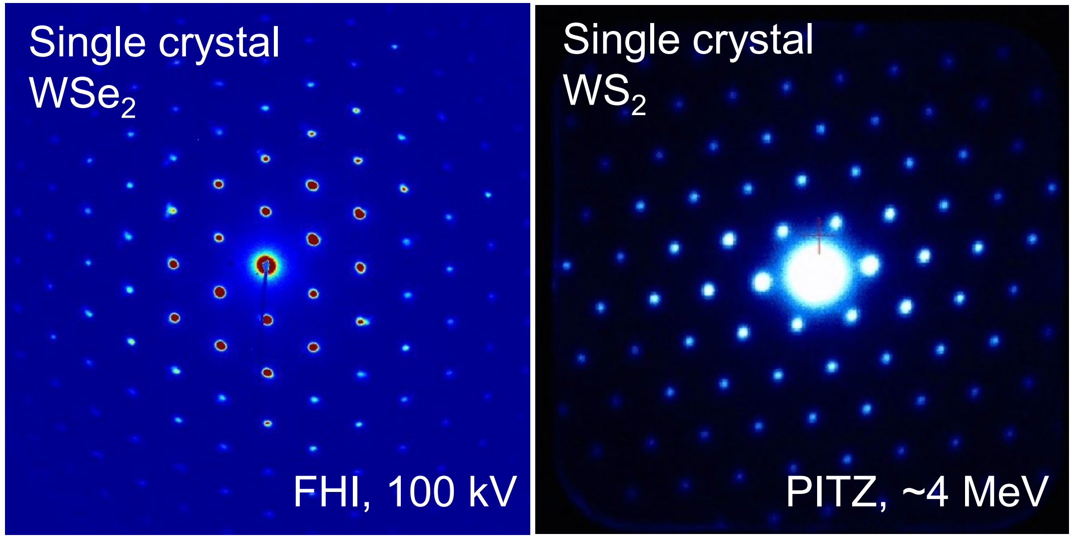


EMCCD camera
Installed at PITZ beamline

Courtesy H. Qian

PITZ 1st test vs FHI table-top electron diffractometer

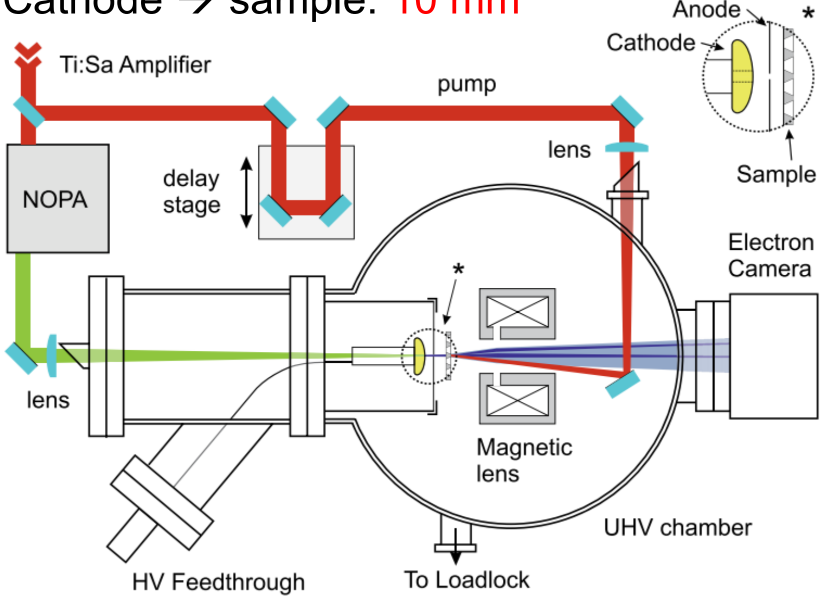
- Comparison of diffraction patterns



- Comparison of beam parameters

	FHI typical	PITZ 1st test	
beam energy	<0.1	~4	MeV
wavelength	3.7	0.27	pm
coherence length	2.8	1.9	nm
beam size at sample	~0.1	~1	mm
beam pulse duration	60~100	~2000	fs
bunch charge	1~5e3	~2e6	e/bunch
beam repetition rate	<4	<6	10^3 pulse/sec
time resolution	200-300	~400 (estim.)	fs

FHI table top electron diffraction instrument
Cathode → sample: 10 mm



Compared to FHI instrument
- Emittance → a factor of 15 (by beam aperture)
- Pulse length → a factor of 20 (short laser or bunch compression)
- Time resolution → to be demonstrated
- Higher voltage, higher bunch charge

Courtesy H. Qian

Conclusions

THz generation and UED at PITZ

- PITZ: developments on sources of high brightness electron beams and their applications

- PITZ = prototype of accelerator based IR/THz source for pump-probe experiments at the European XFEL

- High-gain THz SASE FEL at a PITZ-like accelerator
  → mJ THz pulses expected

- Proof-of-principle experiment on THz SASE FEL at PITZ:
  →LCLS-I undulator in the PITZ tunnel annex
  →S2E simulations for 4nC (~200A) → ~0.5mJ @ 100um
  →Experimental studies with Gaussian photocathode laser pulses
  → First THz Radiation Generated at PITZ

- Ultrafast Electron Diffraction (UED) at PITZ
  → first static MeV electron diffraction tests

Thank you!