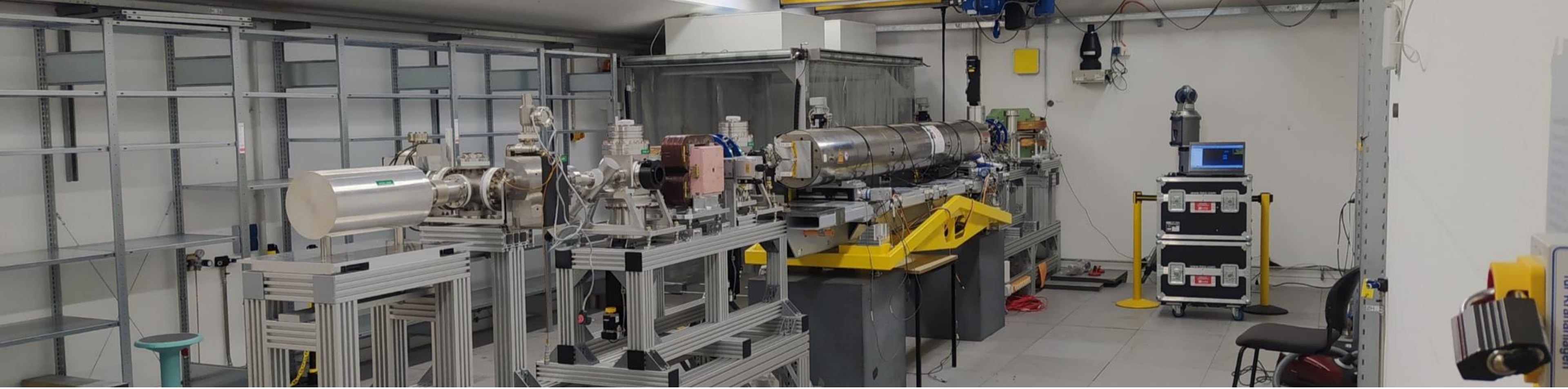


Commissioning status of the THz FEL at PITZ

Xiangkun Li on behalf of the THz team at PITZ, DESY Zeuthen
UBA Workshop, July 04-08 2022, Armenia

Outline

- Introduction
- Commissioning status & plan
- Summary

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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**

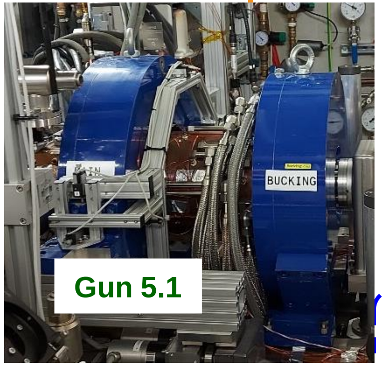
Research areas:

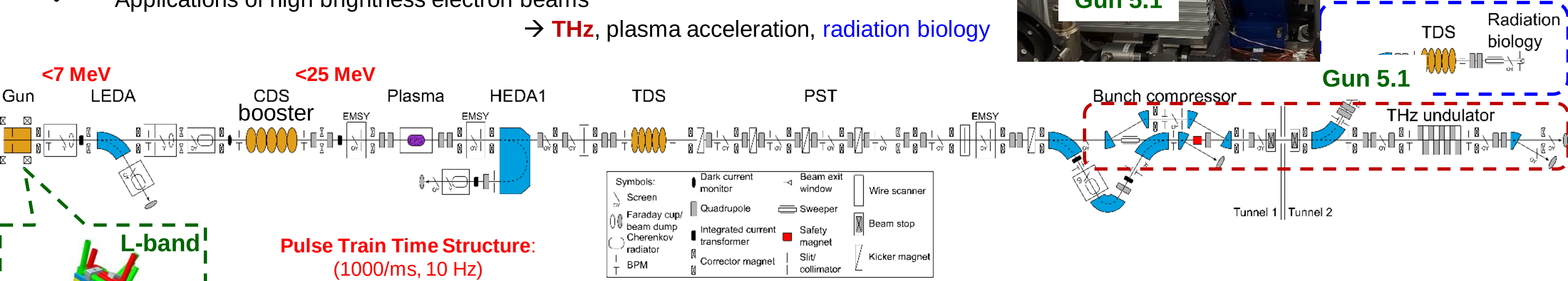
- Basic photo injector R&D
- Specific ARD work for FLASH & European XFEL

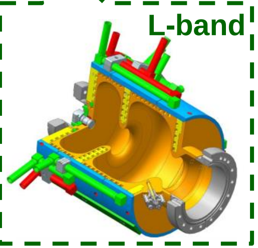
  → e.g., conditioning of **Gun 5.1**

- Applications of high brightness electron beams

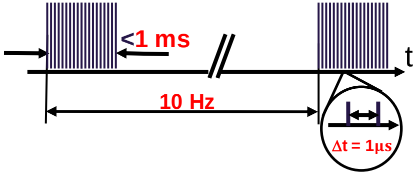
  → **THz**, plasma acceleration, radiation biology







Pulse Train Time Structure:
(1000/ms, 10 Hz)

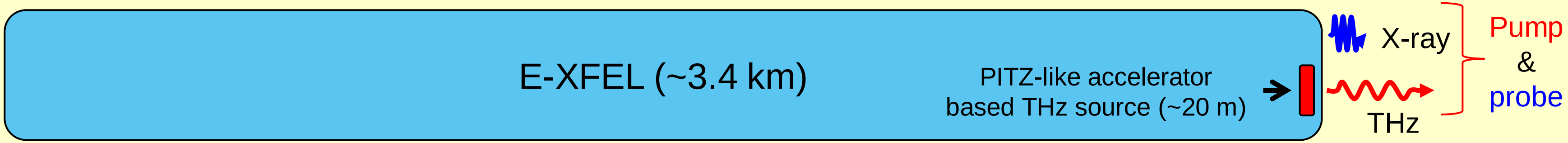


Key capabilities:

- 20 years experience in high brightness NC photo injectors with high average power
- Flexible photo cathode laser shaping (Gaussian, flattop) → up to 5 nC from CsTe
- Dedicated, well developed test facility with detailed beam diagnostics

Introduction

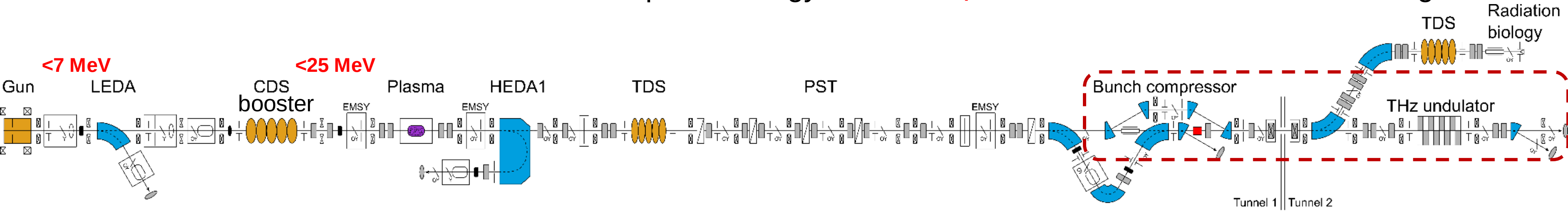
R&D of an accelerator-based THz source prototype for pump-probe experiments at the European XFEL are ongoing at PITZ.



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

- Proof-of-principle experiments at PITZ, supported by E-XFEL since 2019

→**3-5 THz** with **~mJ** pulse energy from **4 nC, 200 A** electron beam in SASE regime



- Conceptual design of an ideal accelerator-based THz source at the European XFEL

Commissioning status & plan

2022: Q1 | Q2 | Q3 | Q4 — **2023**: Q1 | Q2 | Q3 | Q4

Conceptual design of the accelerator based THz source at the European XFEL

First commissioning

Proof-of-principle experiments

First commissioning with electron beam

- New devices commissioning (screen stations, BPMs, magnets, etc.)
- Transport and matching of low charge electron beam (up to 100 pC) in the LCLS-I undulator
- Commissioning of the chicane bunch compressor
- THz radiation energy measurements

Proof-of-principle experiments

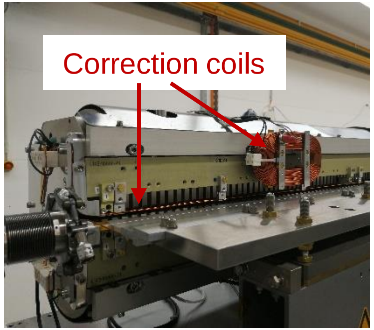
- THz diagnostics system upgrade for pulse energy, transverse profile and spectrum measurements
- Expectations for the experiments
  - **SASE FEL**: a few hundreds μJ @λ=60,100 μm
  - **Superradiant UR**: up to 100 nJ @λ = 100 μm
  - **Seeded FEL**: FEL stability improvements

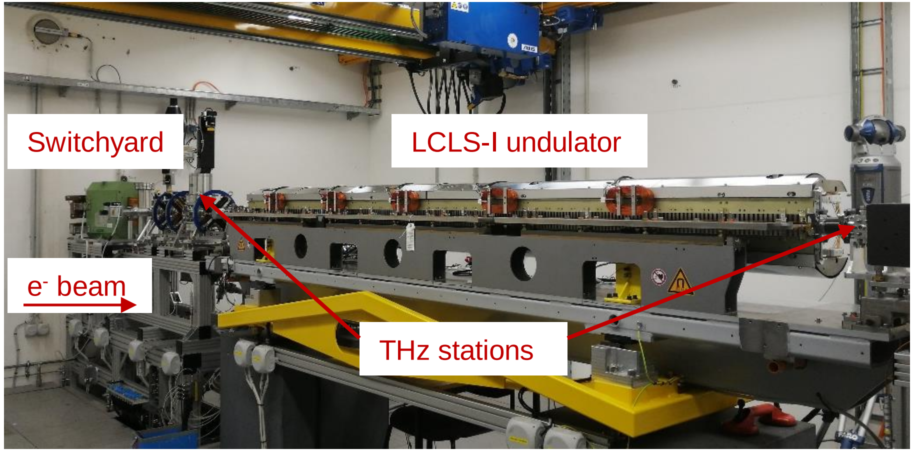
Conceptual design of ideal machine

- A preliminary beamline layout was defined.
- A preliminary S2E simulation was done.

Installation status as of June 2022

- Main new devices installed
  - LCLS-I undulator
  - Transport/matching quadrupoles
  - Chicane compressor
  - Steering magnets and BPMs
  - Screen/CTR/THz stations
  - Beam dumps
- Vacuum is closed; hardware is cabled and integrated into control system
- Hardware commissioning is ongoing
- First beam transport is coming soon

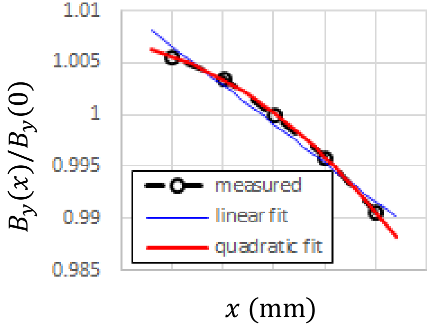




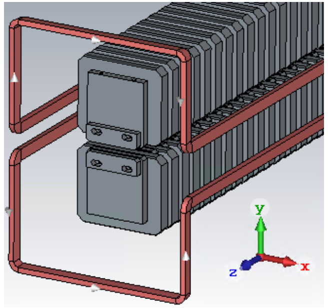
First beam transport in the undulator

Challenges

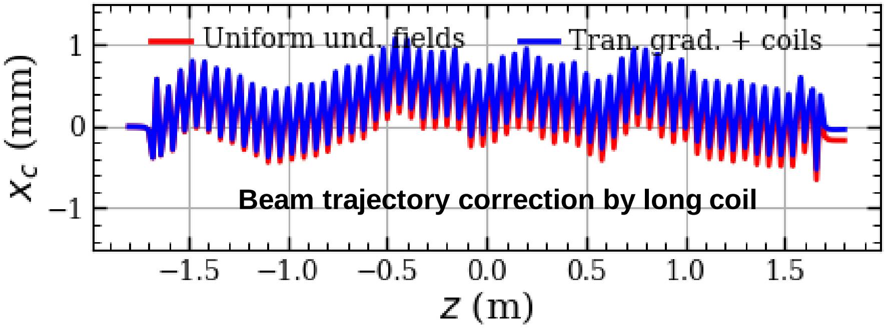
- Transverse gradient in undulator fields



Courtesy of
A. Lueangaramwong

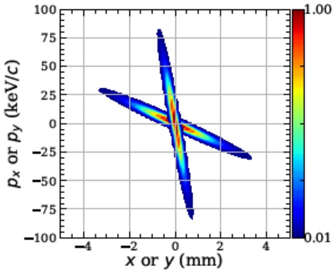


long coil compensation

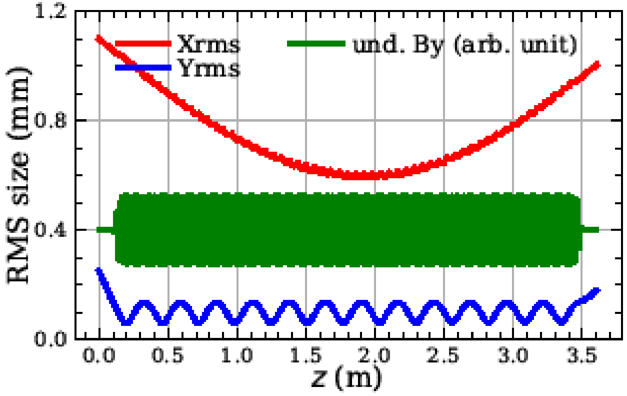


Beam trajectory correction by long coil

- Narrow vacuum chamber
  - **5mmx11mmx3.4 m**
- Strong focusing in vertical plane
- Strong space charge effects



Input beam



Beam envelope in undulator

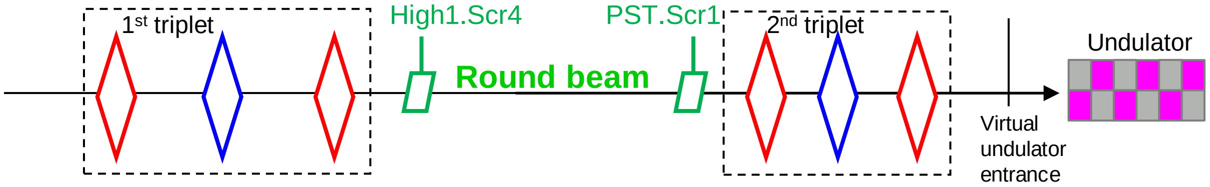
Simulation done by Astra, CST

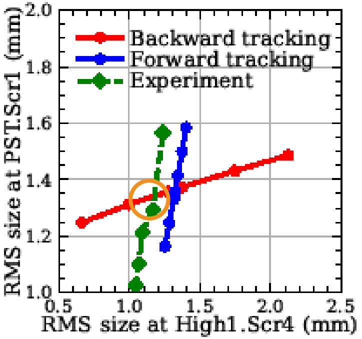
First beam transport in the undulator

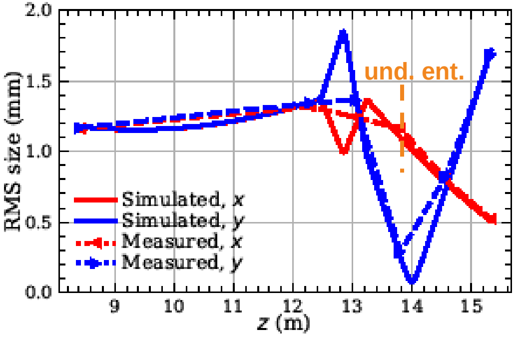
Challenges

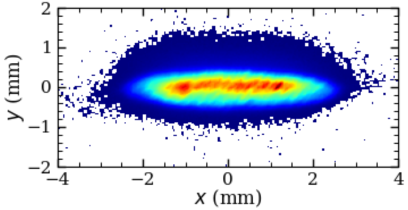
- Transverse phase space matching is difficult: space charge dominated beam; limited diagnostic devices in front of the LCLS-I undulator

→ Matching method has been demonstrated in the existing PITZ beamline successfully









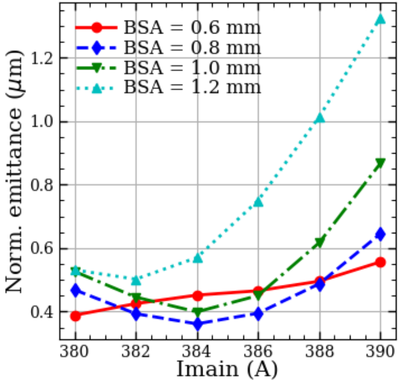
	Design	Exp.	Unit
σ_x	1.10	1.15	mm
$\langle xx' \rangle$	-0.50	N.A	µm
σ_y	0.25	0.27	mm
$\langle yy' \rangle$	-0.30	N.A	µm

Simulation done by Astra

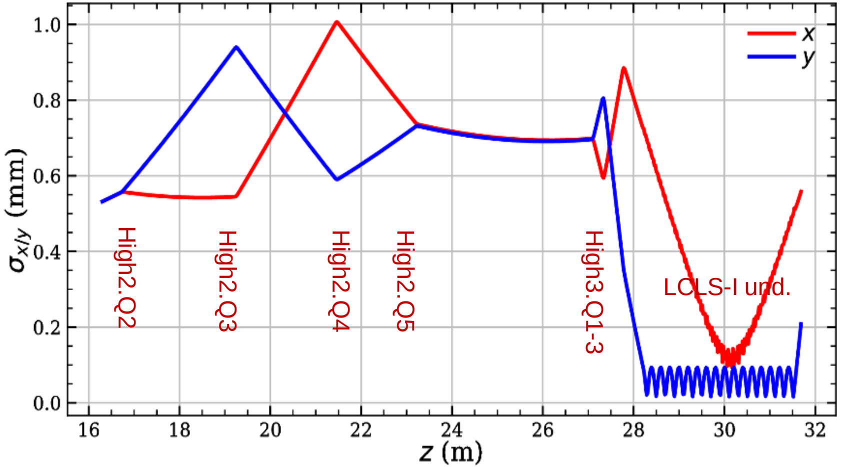
First beam transport in the undulator
Goals

- Optimization of the beam emittance
- Transport of the beam in diagnostics sections
- Beam matching in front of the undulator
- Beam trajectory correction and transport in the undulator

- Machine parameter
  - Laser: BSA 0.8 mm, Charge 100 pC
  - Gun: momentum 6.3 MeV/c at MMMG
  - Booster: momentum 17 MeV/c at MMMG+5



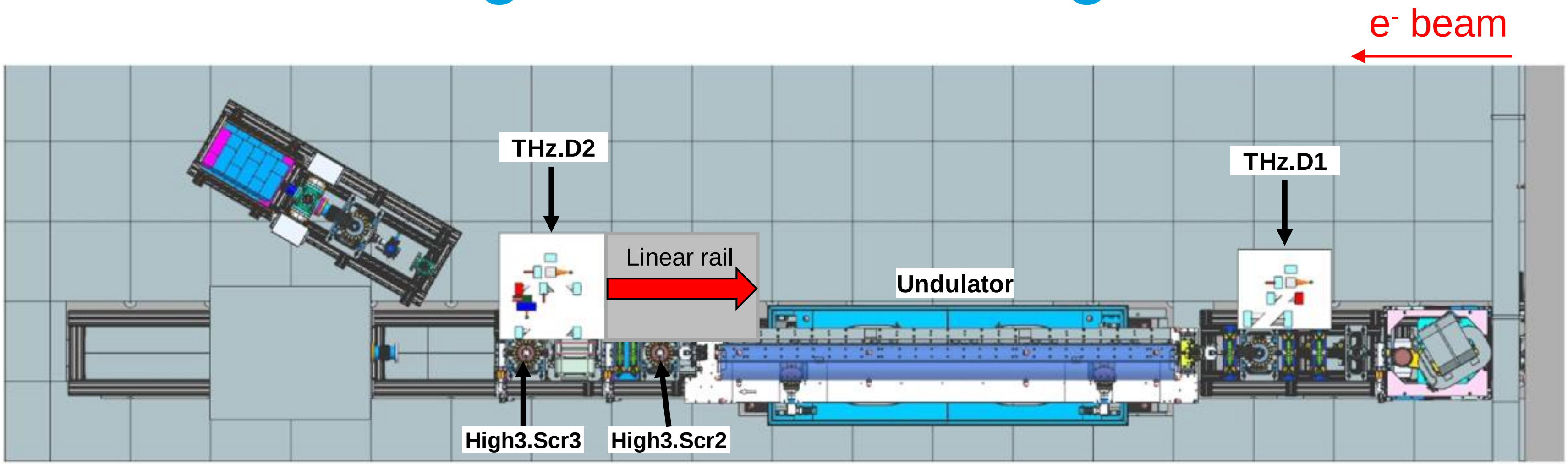
Emittance optimization at EMSY1



Simulation done by Astra **Beam matching and transport in the undulator**

Courtesy of P. Boonpornprasert

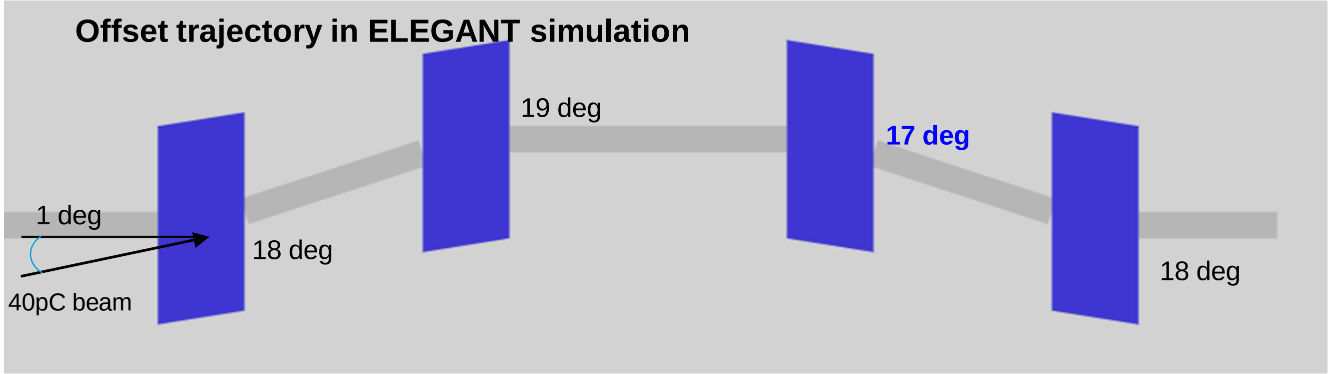
Commissioning of CTR/THz diagnostics



- THz.D1 for **CTR** diagnostics, and THz.D2 for **FEL**s diagnostics
- Each station can measured
  - **Average pulse energy** (pyroelectric detector) → **first** commissioning of THz.D1
  - **Frequency spectrum** (Michelson interferometer) and **transverse profile** (THz camera)
- Optical design and simulation is finished in June 2022, now mechanical design and construction

Chicane commissioning

- Goals: close dispersion and test beam matching
- Bunch compression vs booster phase will be measured with the downstream CTR station

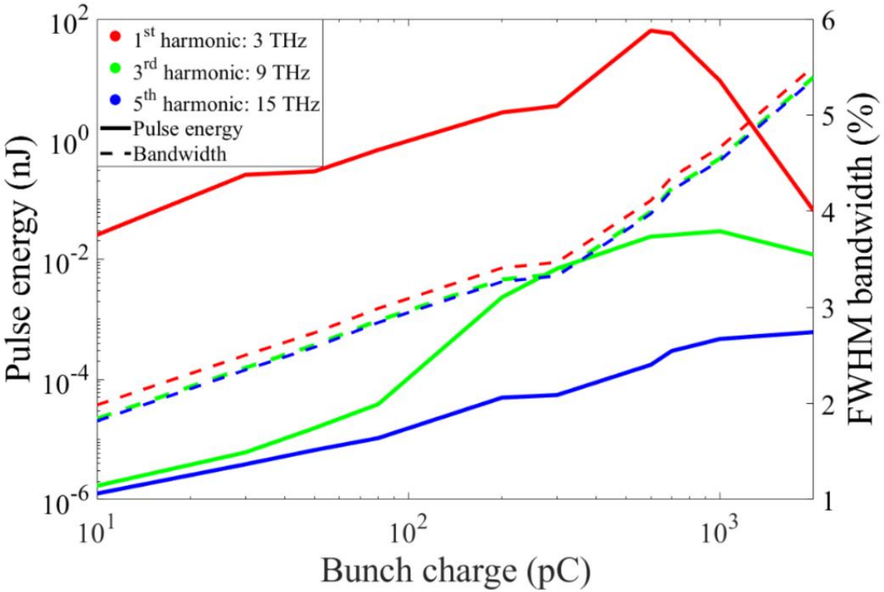


Unequal bending angles:
- $R_{56} = -0.19$ m
- $R_{16} = -1.26e-3$ m
- $R_{26} = -1.08e-2$ m
- $\langle x' \rangle \rightarrow \langle x'_0 \rangle + 0.3$ deg

- Will benefit supperradiance, SASE FEL and seeded FEL

Chicane for superradiance radiation

- Produce short beam at lower charges



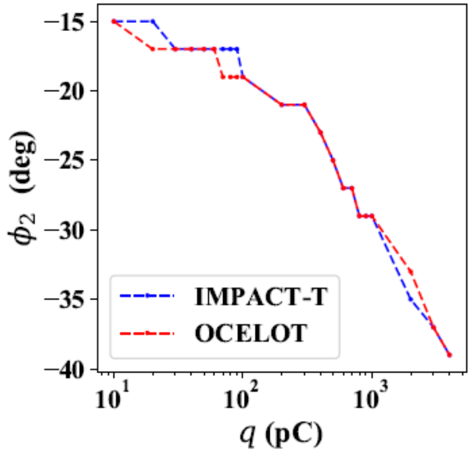
SUR radiation pulse energy of simulated electron beam with bunch charge of 10 – 2000 pC

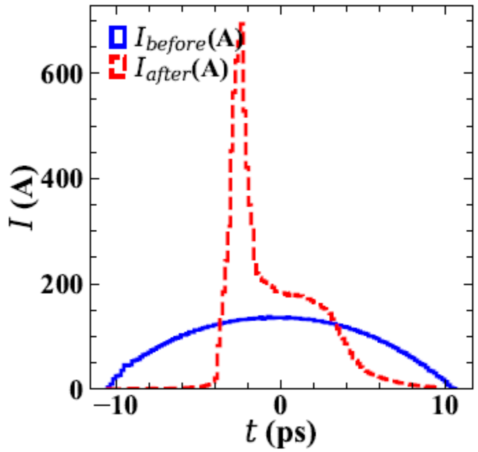
- 17-MeV beam from beam dynamics simulation (cathode → the chicane → undulator)
- Pulse energy of the first harmonic (3 THz) is in the order of sub-nJ to 100 nJ
- Maximum pulse energy reached at the bunch charge of around 600 – 700 pC

Courtesy of A. Lueangaramwong

Chicane for SASE FEL

- Optimize current profile/peak current at higher charges

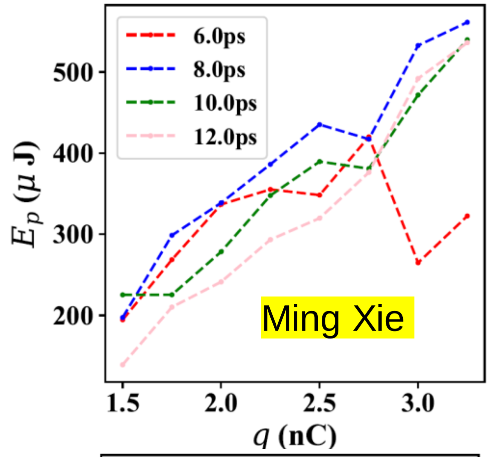


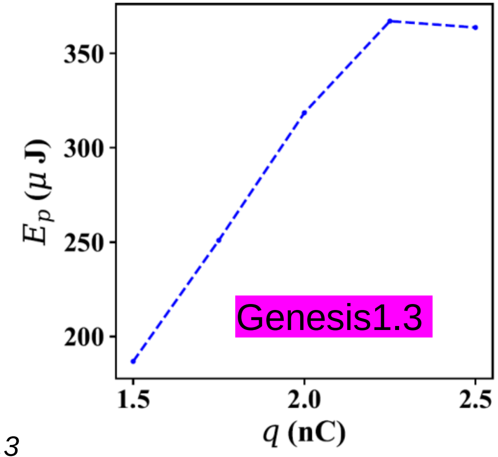


Benchmark booster phase
for full compression
for 6ps FWHM laser pulse

Undercompressed 2-nC
beam current profile @
booster phase of -39 deg,
8-ps laser pulse

THz FEL pulse energy

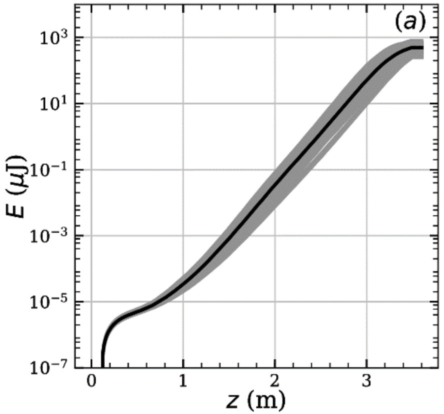




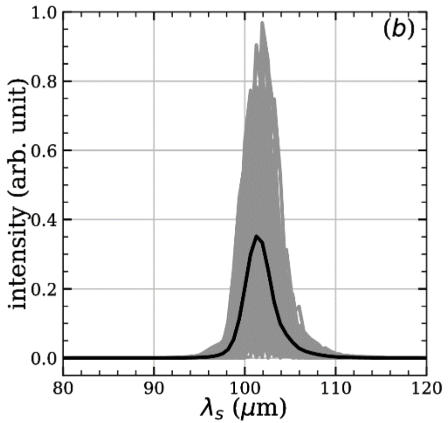
Simulation done by Astra, IMPACT-T, Ocelot and Genesis1.3

Lasing in SASE regime

- Start with 2-3 nC, 17 MeV/c (100 um), then go up to 4 nC
  - Similar procedure to that for 100 pC commissioning
- Then go to 2-4 nC, 22 MeV/c (60 µm)
- First without and then with bunch compressor



Gain curve



THz spectrum

Astra and Genesis1.3 simulation

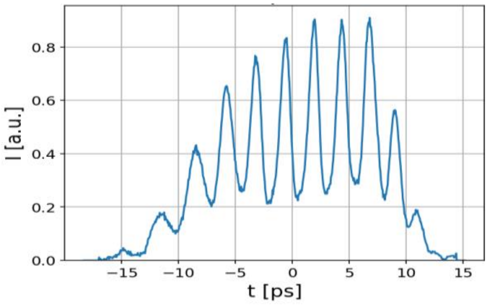
Simulated THz properties for 100 µm

Parameter	Gaussian	Flattop	Unit
Bunch charge	**2.5**	**4**	nC
Pulse energy	**323 ± 99**	**493±109**	µJ
Peak power	97±30	53 ±12	MW
Centre wavelength	**103 ±1.1**	**102 ±0.7**	µm
Spectrum width	3.6±1.0	2.0±0.4	µm
Arrival time jitter	**1.5**	**3.3**	ps

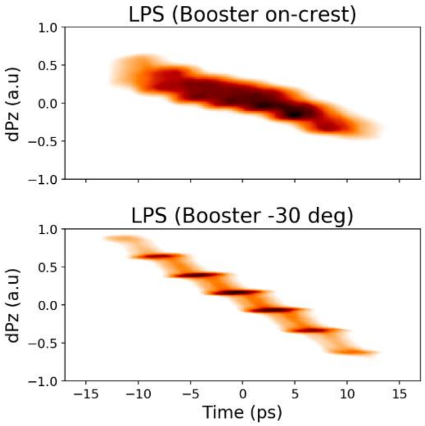
Main issue here: shot-to-shot fluctuation
Solution: seeded FEL

Seeded FEL with modulated beam

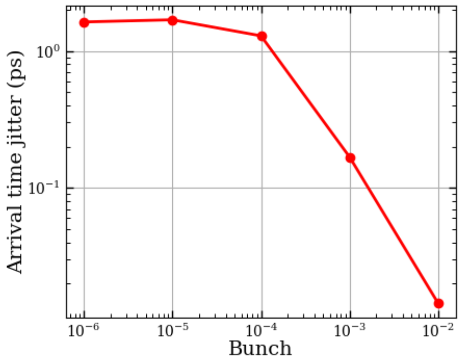
- Photocathode laser modulation
  - Frequency limit with current setup: MBI 0.4 THz, PHAROS 0.8 THz
  - Beam transport with space-charge
  - Non-linear plasma oscillations: high harmonics
- Dielectric lined waveguide modulation

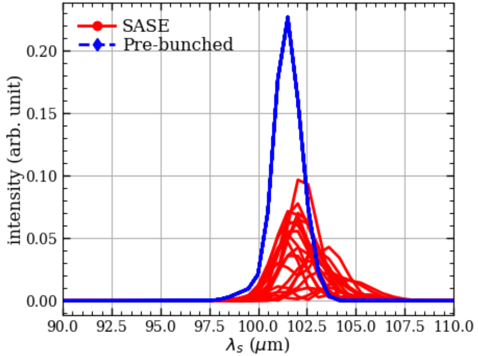


Measured laser temporal profile



Density & energy modulation
Bunch~$10^{-4}-10^{-3}$@3THz





- **Genesis1.3 simulation on seeded FEL@3THz**
- **Parameter study for maximizing bunching factor is foreseen**

Courtesy of G. Georgiev

Summary

- PITZ - a test facility for high brightness electron sources and their applications

  → Gun conditioning and photoinjector R&D, THz, radiation biology…

- The proof-of-principle experiments on THz SASE FEL is under commissioning at PITZ

  → Operation permit approved, hardware installed and integrated

  → First beam commissioning will come soon, aiming at the beam transport in the LCLS-I undulator

- Lasing in SASE regime will come next as THz diagnostics installation proceeds

  → THz energy, spectrum and profile to be characterized

  → Improve the shot-to-shot stability by seeding with higher harmonics from modulated beam

- Design of ideal machine with multiple options for THz generation is ongoing

Thank you for your attention!

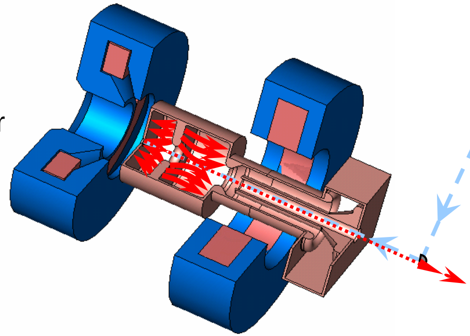
Backup

PITZ “engine”: RF-Gun and Photocathode Laser

Highlights of the facility

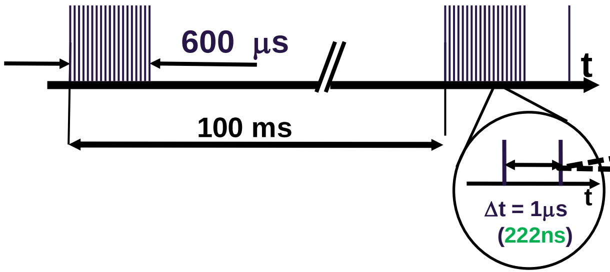
RF gun: in use at FLASH and European XFEL

- 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:

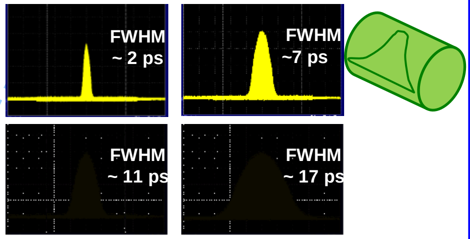
PITZ and E-XFEL trains with up to 600 (2700) laser pulses



Photocathode laser(s) (UV)

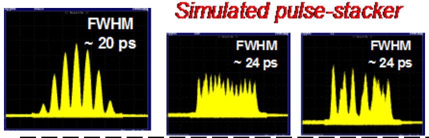
Default laser system (Max-Born-Institute, Berlin)

Gaussian:

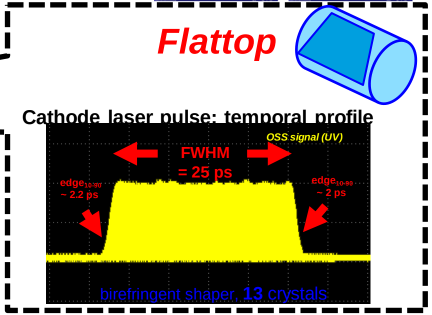


Multicrystal birefringent pulse shaper containing 13 crystals

Simulated pulse-stacker



Flattop



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

Different lasers

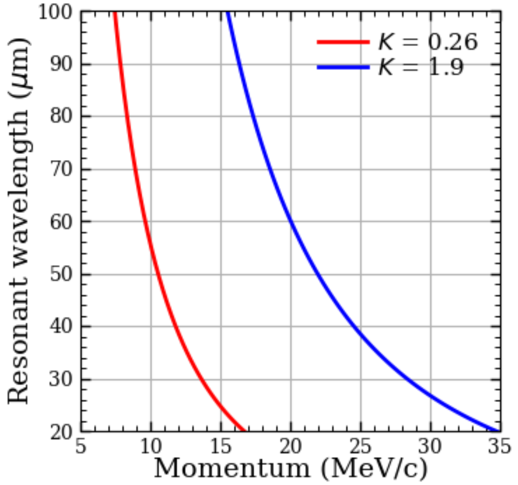
→various **THz options**

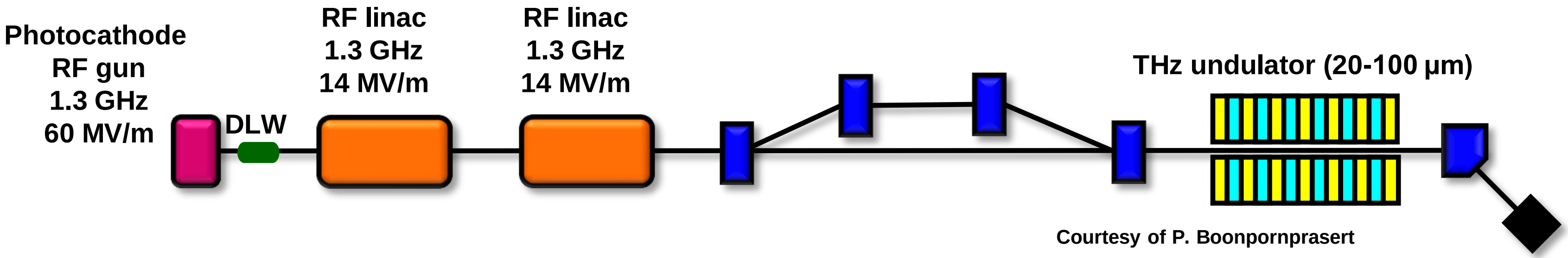
→possibility of **simultaneous** usage

Design of ideal machine

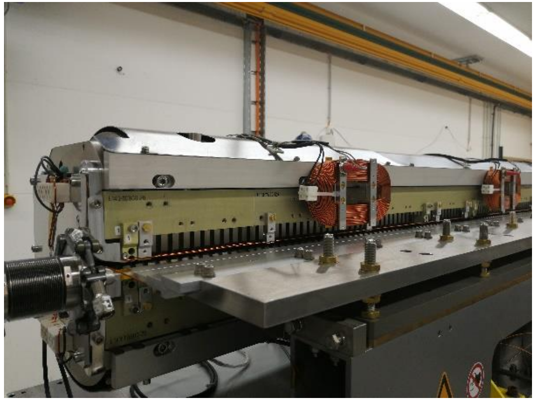
- Basic design parameters
  - Momentum: 7-35 MeV/c
  - Bunch charge: <5 nC
  - Apple II undulator: $\lambda_u = 40\ \mathrm{mm}, \mathrm{K} = 0.26 - 1.9$
  - Tunability: 20 – 100 μm (3-15 THz)
- Options for THz generation
  - SASE FEL, seeded FEL, superradiance

Resonance curve



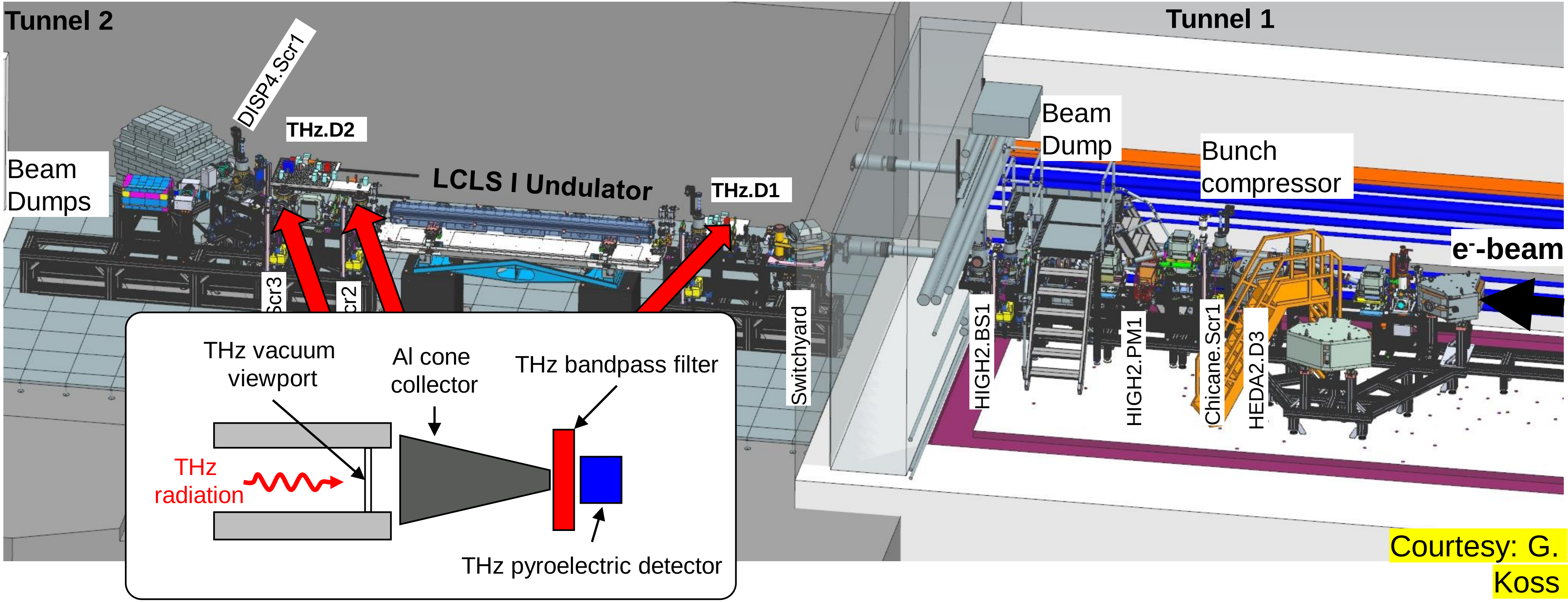


Courtesy of P. Boonpornprasert



THz radiation measurement for the first commissioning

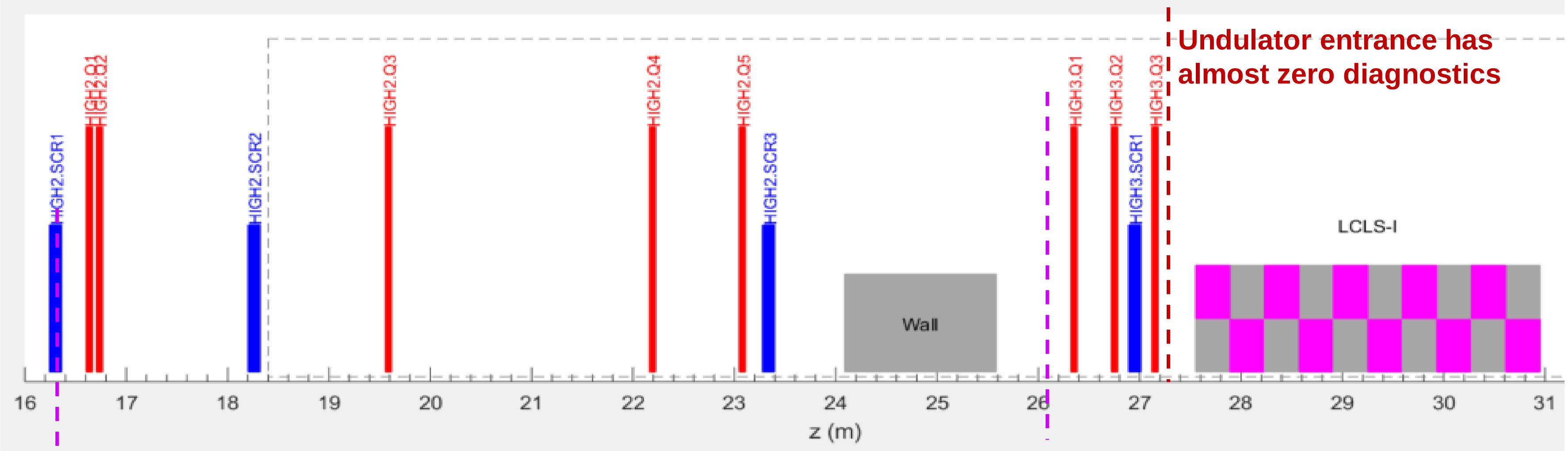
Simple setup just to measure THz pulse energy



Courtesy: G. Koss

Matching strategy

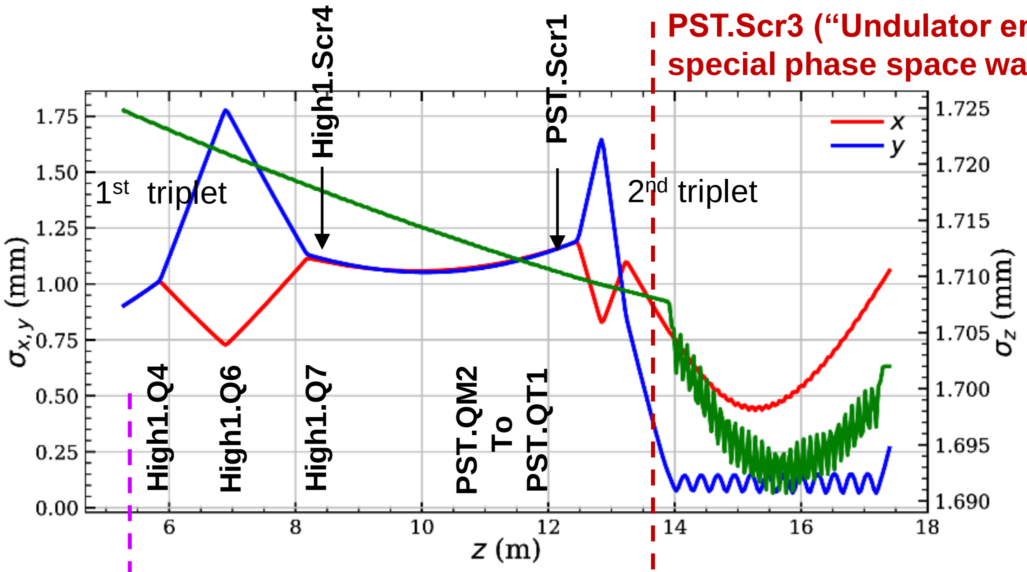
- Specific transverse phase spaces are expected before the undulator and parameter scan has shown that only four parameters need to be considered (Xcov, Xrms, Ycov and Yrms)
- If a round beam transport is made, the four parameters reduce to two (e.g., beam sizes at High2.Scr3 and High3.Scr1) and two free knobs are enough (one tuned in experiment and one tuned with simulations in advance)



Measure the beam envelope development after the quads at High2.Scr3 and High3.Scr1 ⇔ Backward simulation of beam envelope development (from High2.Scr3 to High3.Scr1) vs triplet strength

Matching study in PST section

PST.Scr3 (“Undulator entrance”): special phase space wanted

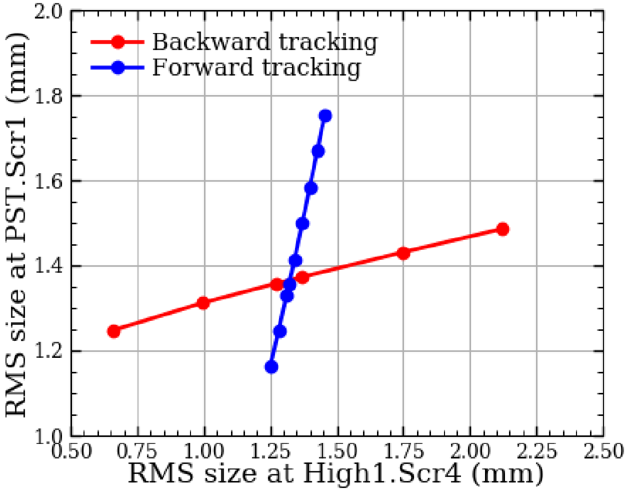


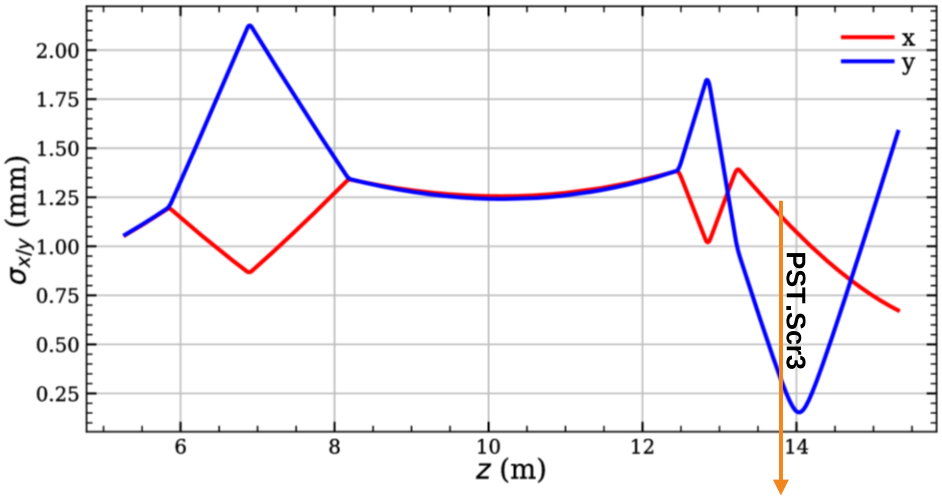
Tracking back to High1.Scr4 for the beam sizes at High1.Scr4 and PST.Scr1 vs 2nd triplet gradients

Transport the beam and get the beam sizes at High1.Scr4 and PST.Scr1 vs 1st triplet currents

Simulation on matching at PST.Scr3

- Software: SpaceChargeOptimizer.exe





Backward tracking:

PST.Scr3 to High1.Scr4, 2nd triplet strength tuned

Forward tracking:

EMSY1 to PST.Scr1, 1st triplet strength tuned

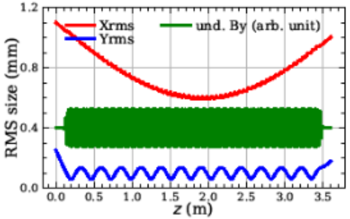
Expected:
Xrms = 1.10 mm
Yrms = 0.25 mm
Xcov = -0.50 um
Ycov = -0.30 um

Obtained:
Xrms = 1.14 mm
Yrms = 0.32 mm
Xcov = -0.47 um
Ycov = -0.33 um

Demonstration of matching procedure

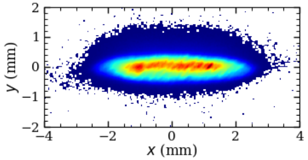
To be **matched**:

- **Trans. phase space** in front of undulation → σ_x, $\langle xx' \rangle$, σ_y, $\langle yy' \rangle$
- **Hor. phase space** in front of triplet in case of symmetric beam, or
- **Beam size** at two monitor screens (High2.Scr3 and High3.Scr1)

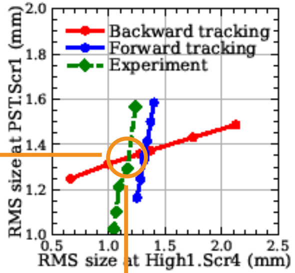


Beam transport in undulator

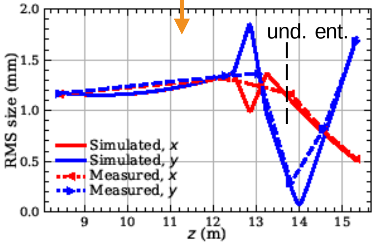
	Design	Exp.	Unit
σ_x	1.10	1.15	mm
$\langle xx' \rangle$	-0.50	N.A	µm
σ_y	0.25	0.27	mm
$\langle yy' \rangle$	-0.30	N.A	µm

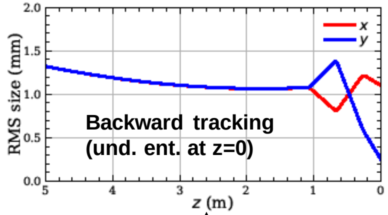


Beam @ virtual und. entrance

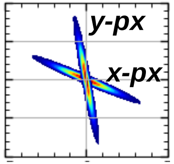


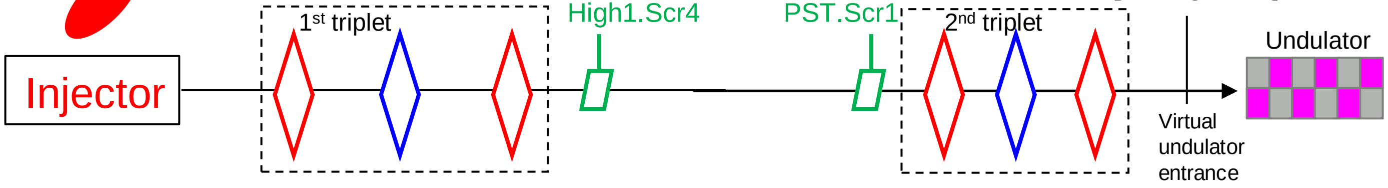
Beam transport



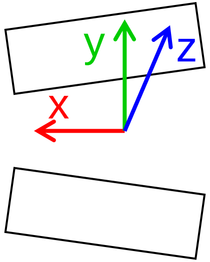


$p_x \rightarrow -p_x$
$p_y \rightarrow -p_y$

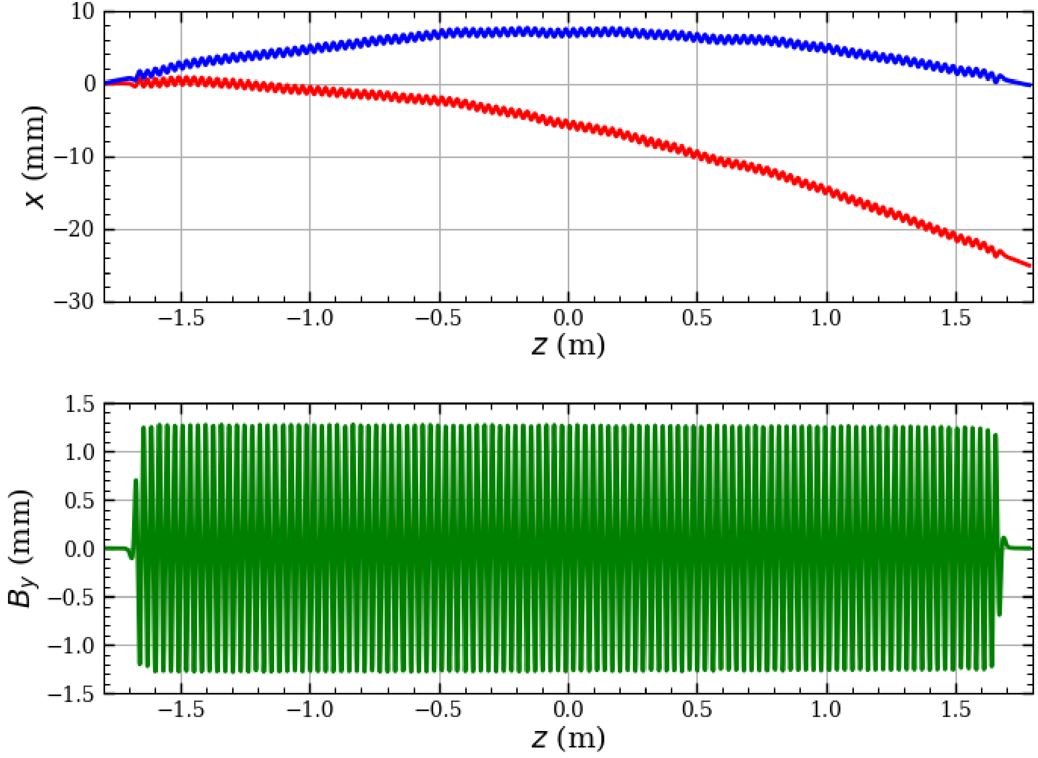




Off-axis trajectory due to the transverse field gradient

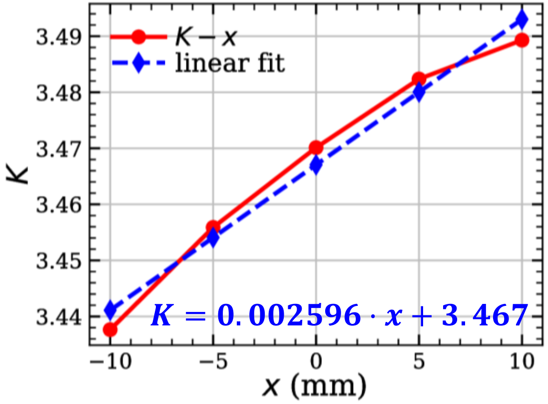


Definition of taper



With an external kick at the undulator entrance

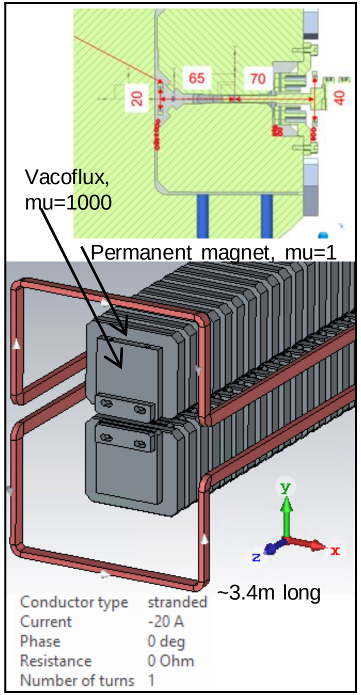
Injection w/o any correction



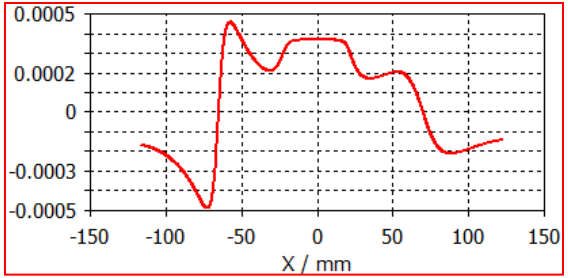
Air Coil Field Simulated by CST2020

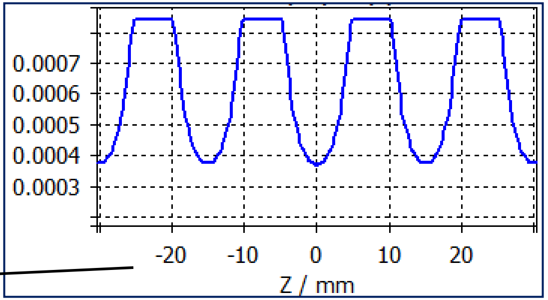
Use of Hexahedral mesh model and field results

- We simulated magnetic field of the air coil with a model including
  - Permanent magnet holders with relative permeability of 1000
- The air coil ends are lifted to lower edge field
- Permanent magnet holders are periodic and provide field enhancement periodically along z-axis

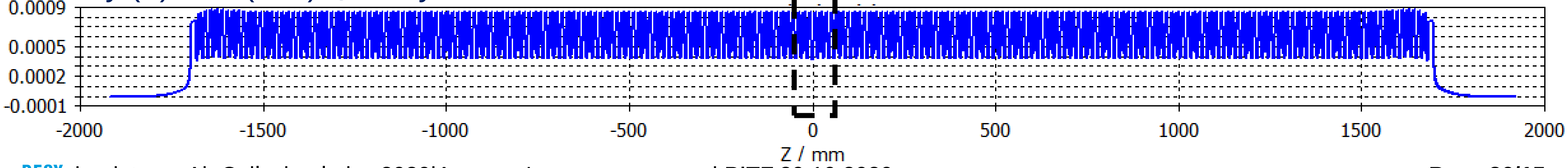


- By (T) vs x (mm) @y=0,z=0,I =20A



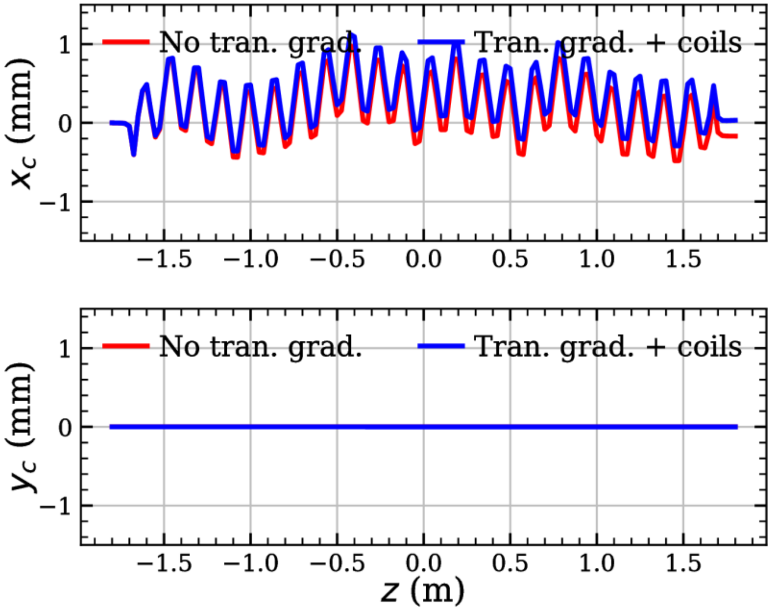


- By (T) vs z (mm) @x=0,y=0, I =20A

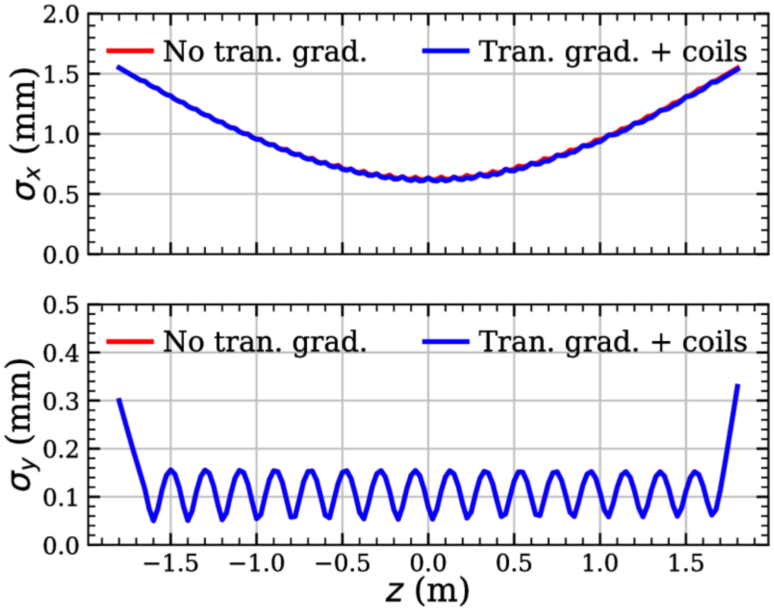


Particle tracking with correction coils by Astra

Maximum on-axis field of By is 322.9 uT (7.4 A turns)



Beam center along the undulator



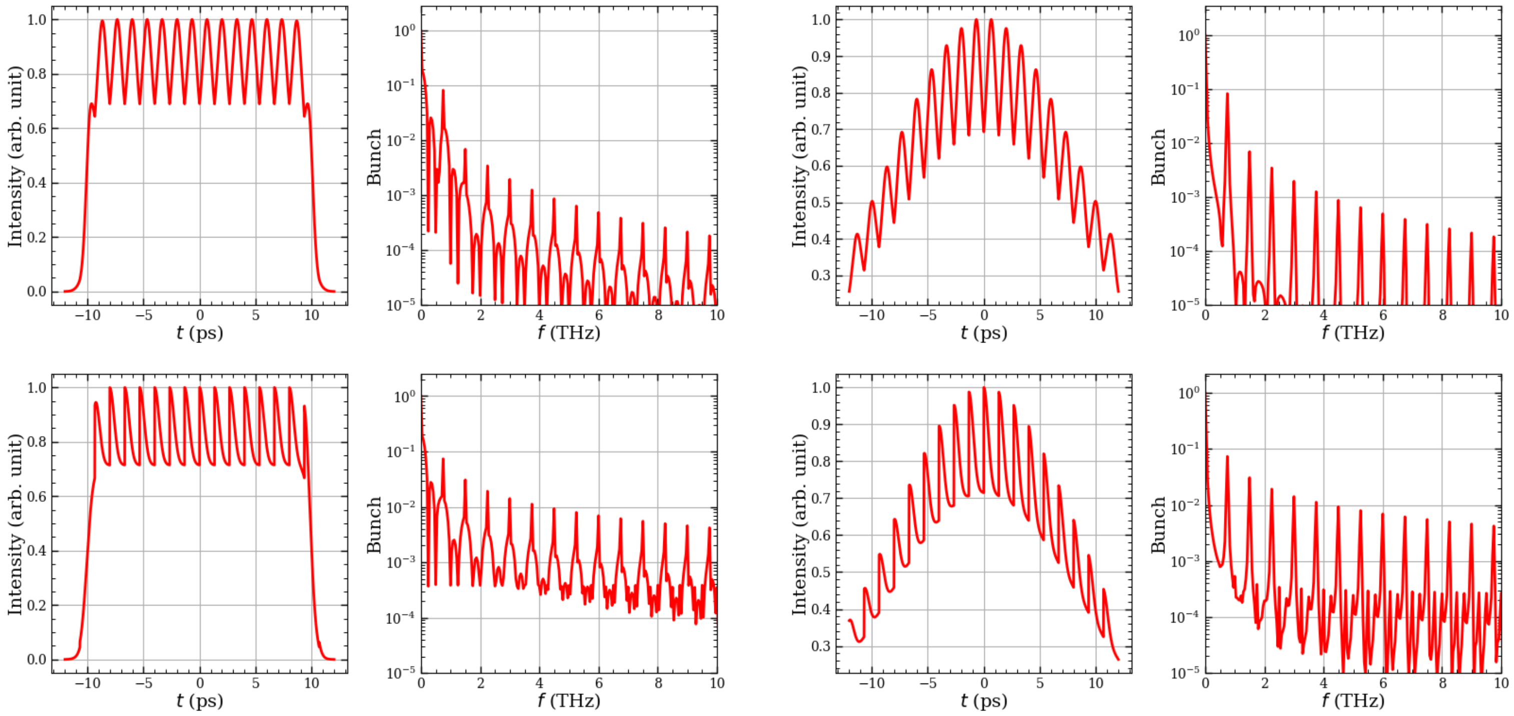
RMS beam size along the undulator

Bunching factor from modulated beam

- FWHM=20 ps, modulation freq = 0.75 THz, rate ~ 10%, (4th subharmonic w.r.t. 3 THz)

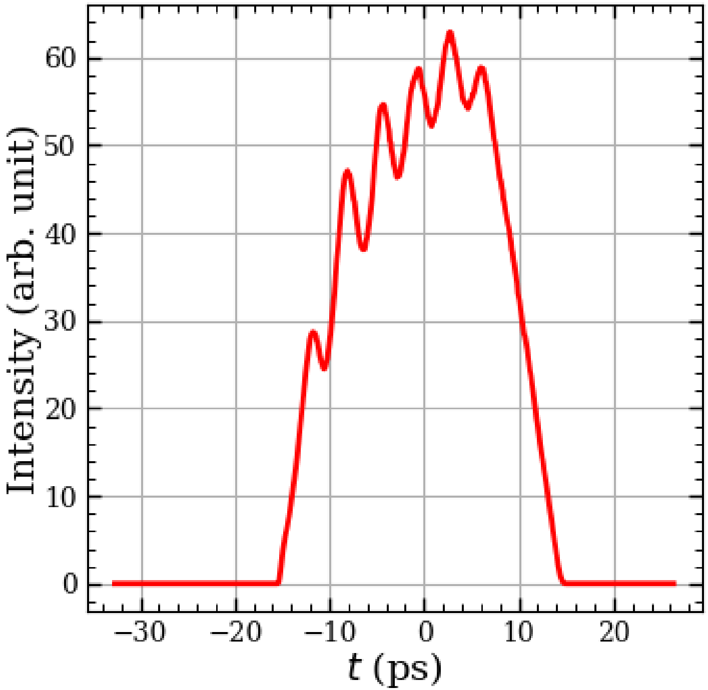
Symmetric modulation

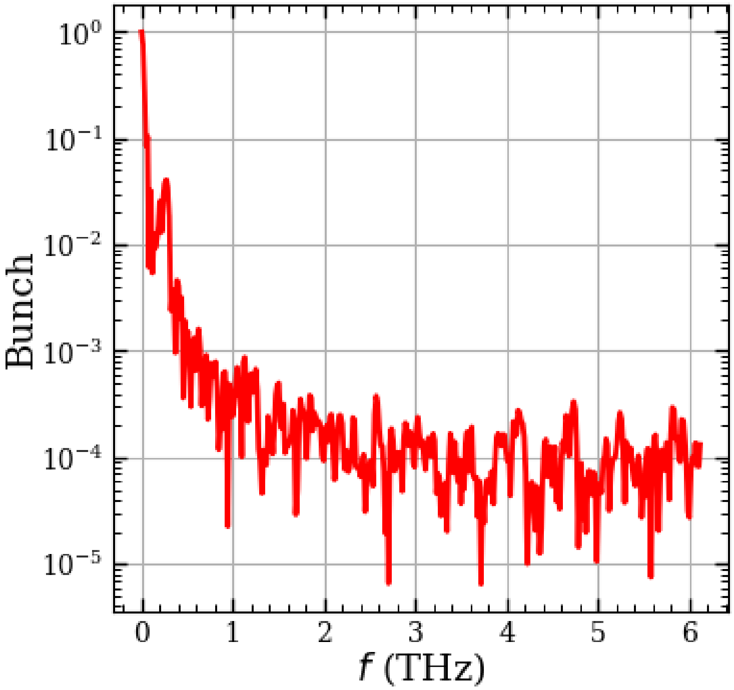
With sharper edge



Bunching factor from modulated laser

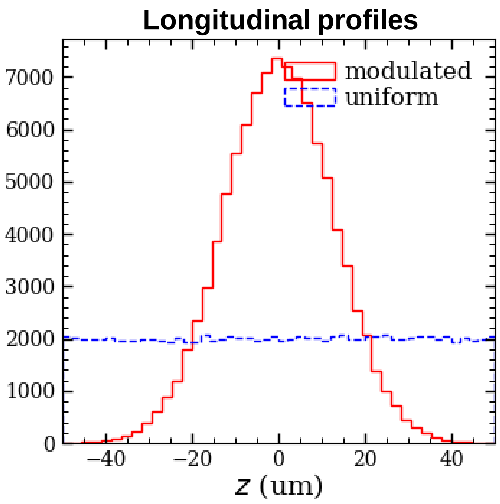
0.4 THz, 1 nC

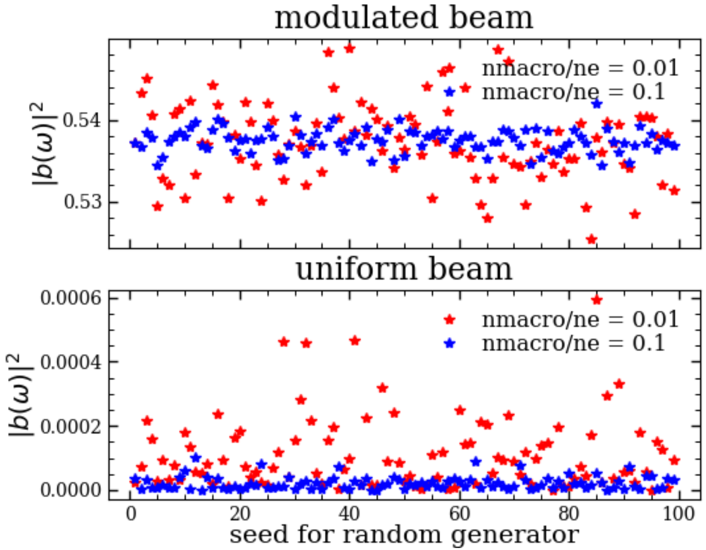




Bunching factor from modulated beam

- The bunching factor is defined as $b(\omega) = \langle \exp[-i\theta] \rangle$, where $\theta = (k_0 + k_u)z - \omega t$ is the ponderomotive phase





In the example, ne = 1e6 and $<|b(\omega)|^2>$=1e-6

- When we talk about initial shot noise, we actually care about the bunching factor from the initial beam
- For modulated beam, the bunching factor is dominated by the modulation, in the example, 5 orders higher than shot noise due to statistics
- For uniform beam, it is dominated by the initial number of particles (to generate the correct bunching factor, either use one macroparticle for one electron, or use techniques like mirror particles)