Test S2E simulation for the Ideal THz source (100 µm SASE FEL; Beam 4nC, ~15 MeV/c)

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PITZ Physics Seminar
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

Test S2E Simulation

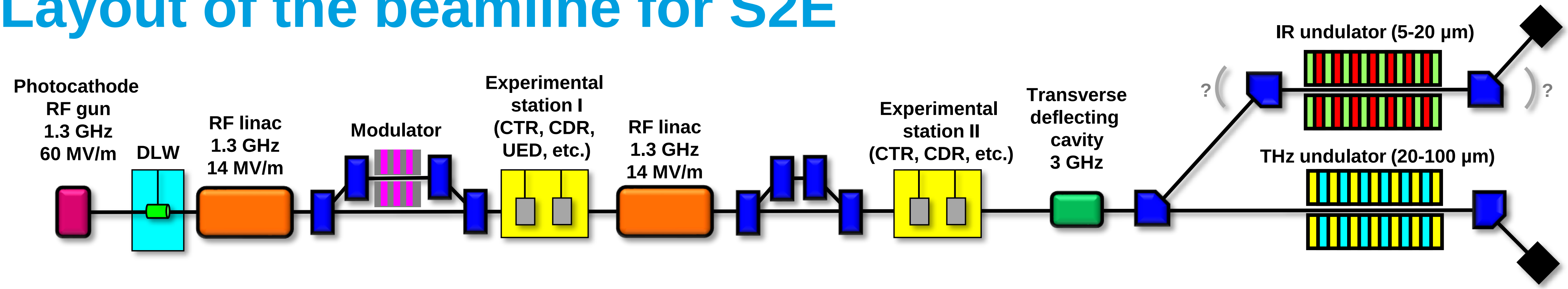
- Layout of the beamline for S2E
- Simulation Setup
- S2E Results
  - Beam Parameter Evolutions
  - Beam at the undulator entrance
  - FEL Results
- Summary and Outlook

Comparison ASTRA and Ocelot

- Limitations of Ocelot
- Simulation Setup
- Results Comparison of Tracking from 10 m to 26 m
  - Beam Parameter Evolutions
  - Beam at the undulator entrance
- Summary and Outlook

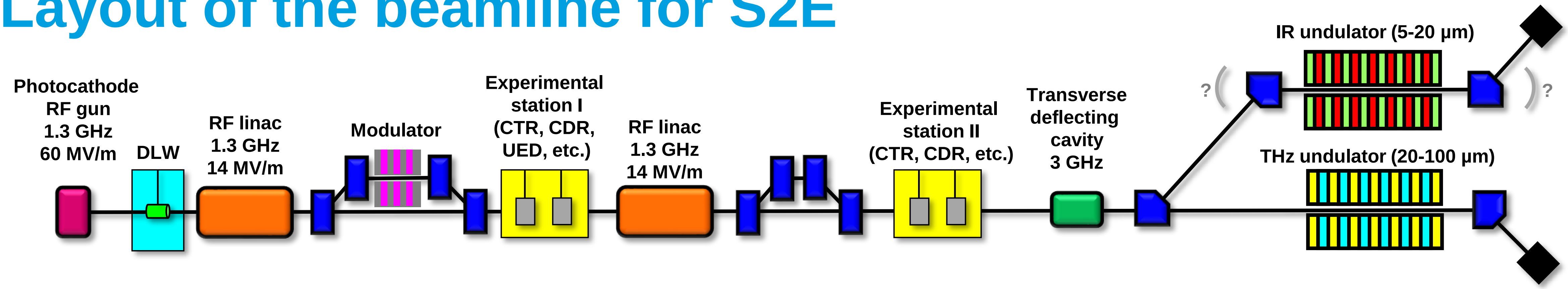
Test S2E Simulation

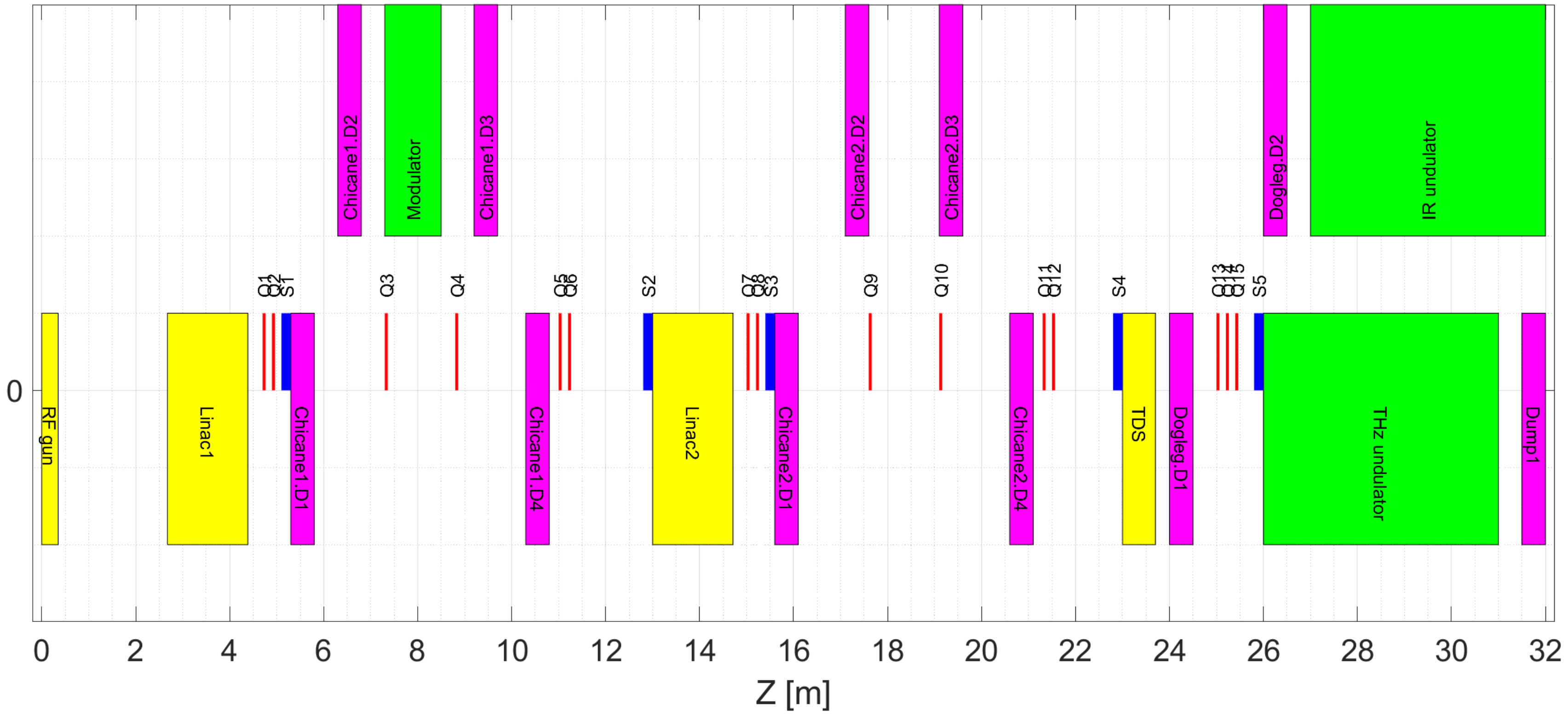
Layout of the beamline for S2E



Section	Length	Purpose	Detail
RF gun	0.204 m	Generate and accelerate e-beam	DESY NC L-band RF gun, 1.3 GHz, E_{max} ~ 60 MV/m
DLW	a few cm	Induce beam modulation for FEL seeding	To be newly designed
1^{st} and 2^{nd} Linacs	1.710 m	Accelerate e-beam	PITZ-type CDS cavity, 1.3 GHz, E_{max} ~ 14 MV/m
1^{st} chicane	5.500 m	Compress e-beam	Copy of BC0@EXFEL, to be newly designed
Modulator	?	Induce beam modulation for FEL seeding	To be newly designed
2^{nd} chicane	5.500 m	Compress e-beam	Copy of BC0@EXFEL, to be newly designed
TDS	0.687 m	LPS diagnostics	PITZ TDS, 3 GHz
Dogleg	0.500 m	Bending e-beam to another beamline	To be newly designed
THz undulator	5.000 m	Generate FEL 20-100 µm (3-15 THz)	λ_p = 40 mm, APPLE-II type undulator
IR undulator	?	Generate FEL 5-20 µm (15-60 THz)	To be newly designed

Layout of the beamline for S2E





Simulation Setup

Highlights of input parameters

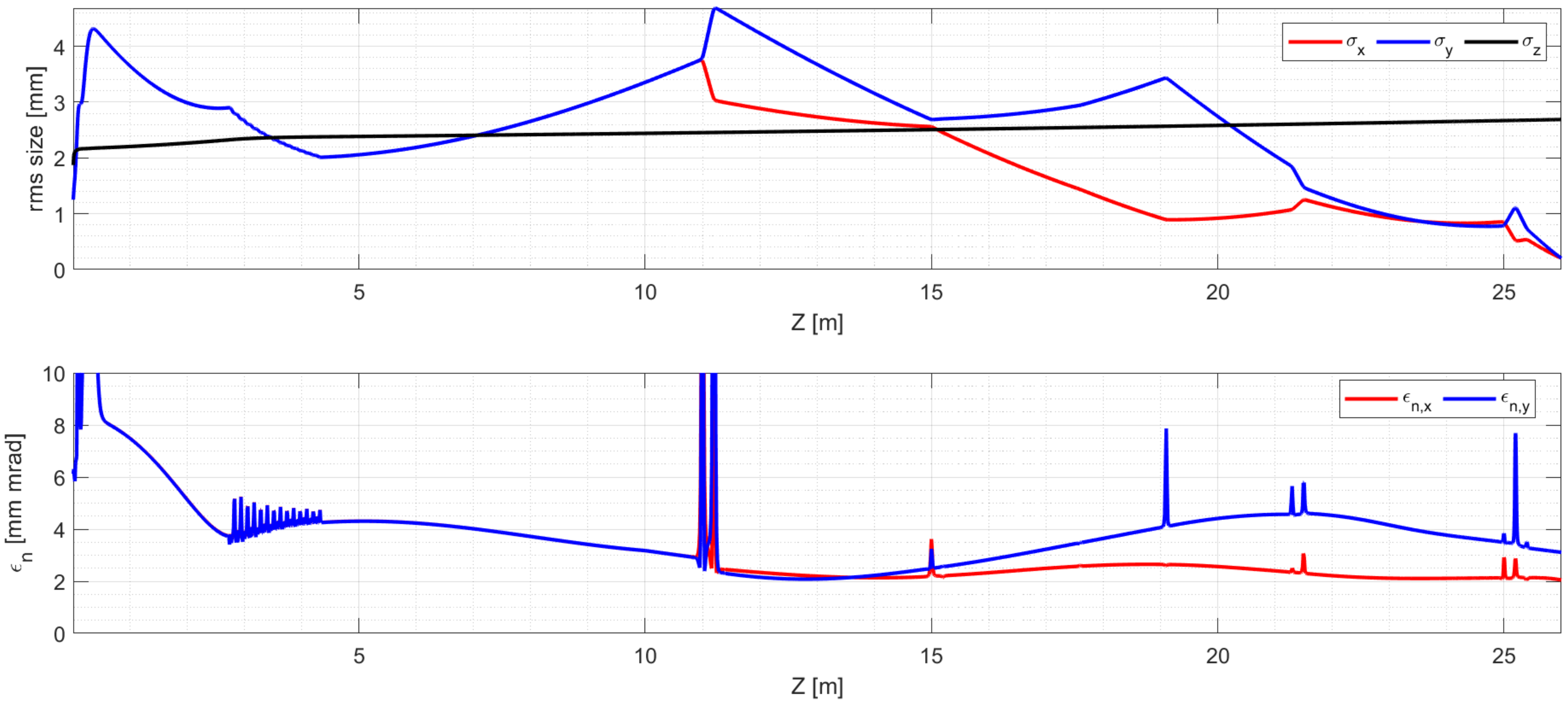
ASTRA

- Distribution = '../InitialBeam/200k_ft215.ini’
- Xrms=1.0000 — BSA 4 mm
- Yrms=1.0000
- Qbunch=4.0000 — 4 nC
- LSPCH=TRUE
  - 2D from gun:
    Nrad=40, Nlong_in=80, N_min=200.0000
  - 3D:
    Nxf=16, Nx0=1, Nyf=16, Ny0=1, Nzf=64, Nz0=1
- File_Efield(1) = '../AstraPortal/gun46cavity.txt’
  MaxE(1)=60.5000
- File_Efield(2)= '../AstraPortal/CDS14_15mm.txt'
  MaxE(2)=9.8000
- File_Efield(3)= '../AstraPortal/CDS14_15mm.txt'
  MaxE(3)=0.0000 — Didn’t use the 2nd linac

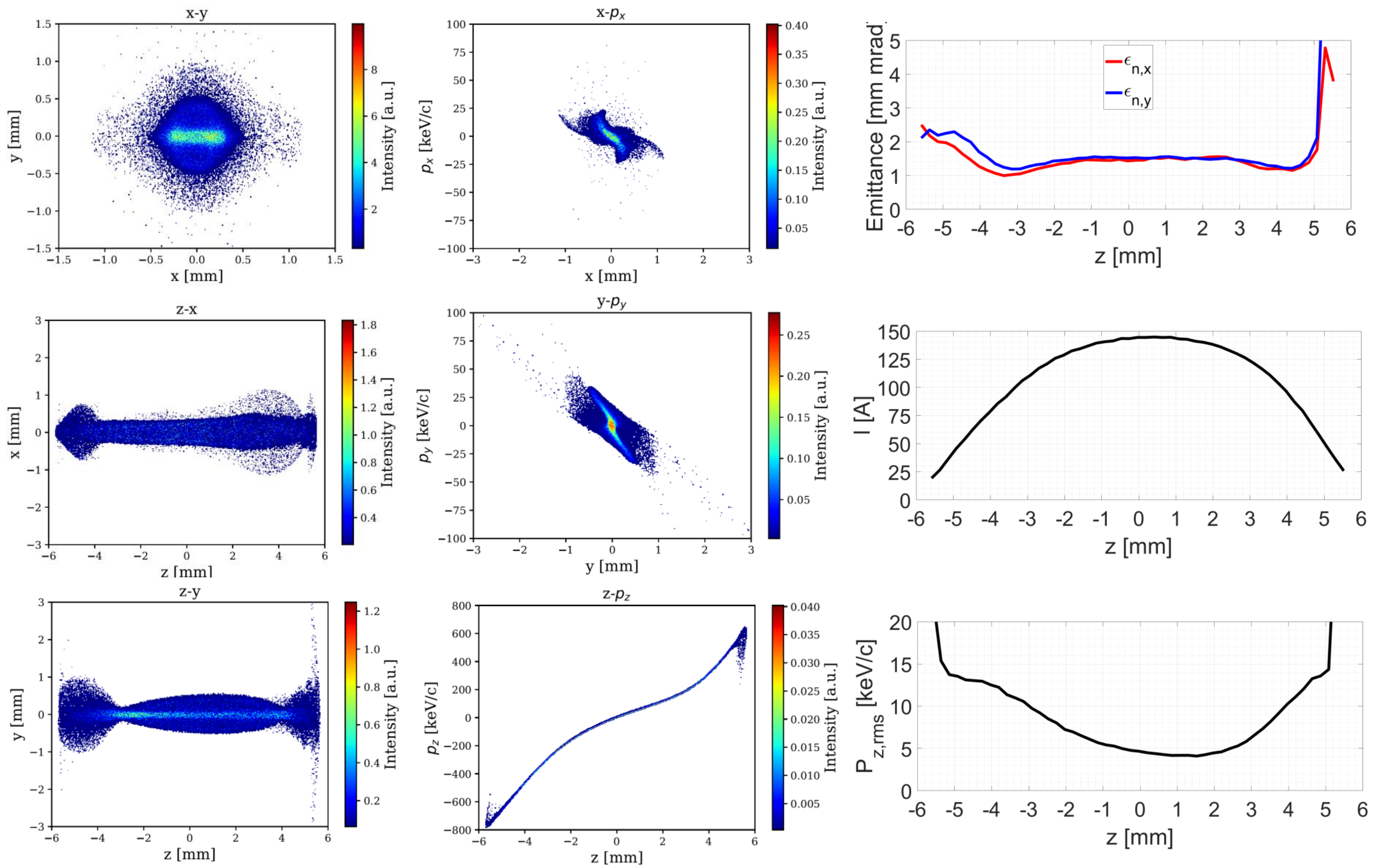
Genesis 1.3 version 2

- AW0 = 1.8464
- IWITYP = 1 XKX = 5.0000E-01 XKY = 5.0000E-01 — Helical undulator
- XLAMD = 0.0400 NWIG = 125 NSEC = 1 — λ_U = 40 mm
- NPART = 8192
- PRAD0 = 0.0000E+00 — SASE FEL
- XLAMDS = 1.0000000E-04 — λrad = 100 µm
- ITDP = 1 — Time-dependent simulation
- ZSEP = 1.00
- NSLICE = 300 NTAIL = -5
- SHOTNOISE = 1.00
- DELZ = 0.5000

S2E Results: Beam Parameter Evolutions

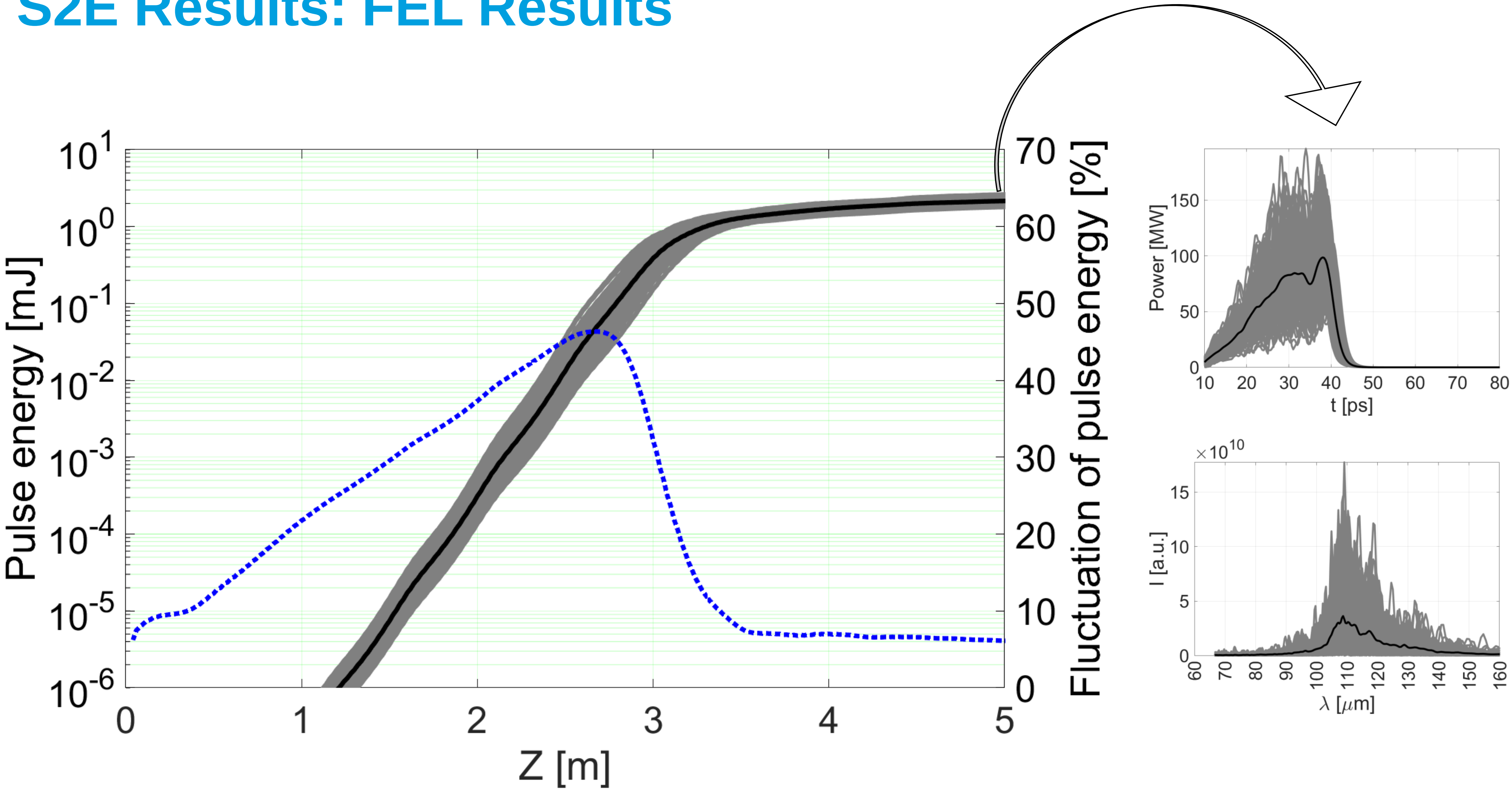


S2E Results: Beam at the Undulator Entrance



Parameters	ASTRA
σ_x [mm]	0.205
σ_y [mm]	0.204
σ_z [mm]	2.688
σ_{Pz} [keV/c]	257.940
P_z [MeV/c]	15.166
Lorentz factor	29.696
ε_x [mm mrad]	2.052
ε_y [mm mrad]	3.113
β_x [m]	0.610
β_y [m]	0.396
α_x	1.235
α_y	1.374
γ_x	4.144
γ_y	7.288

S2E Results: FEL Results



Summary & Outlook

- The first S2E simulation of a SASE FEL for the ideal THz source was done.
  - Beam 4nC, ~15 MeV/c ➔ ~mJ pulse energy for 100 µm SASE FEL
- Repeat the test S2E simulation with Ocelot
  - We have to simulate bunch compressors and doglegs which ASTRA couldn't handle them well.
  - Instead of using many tools for an S2E work such as ASTRA, Elegant, CSRTrack and ImpactT, We should use Ocelot if it works well with dipole transports and S2E simulations.
  - Igor Zogorodnov already repeated S2E simulations for EXFEL with Ocelot (https://www.desy.de/fel-beam/s2e/xfel.html). Since we will transfer our simulations to them, we should use the same tool.
- Design consideration of the Chicanes
- Test S2E simulations with ultra-short bunch schemes (CTR & superradiant)
- Test S2E simulations with the IR Undulator
- …

Comparison Results between ASTRA and Ocelot

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Comparison ASTRA and Ocelot

- Limitations of Ocelot
- Simulation Setup
- Results Comparison
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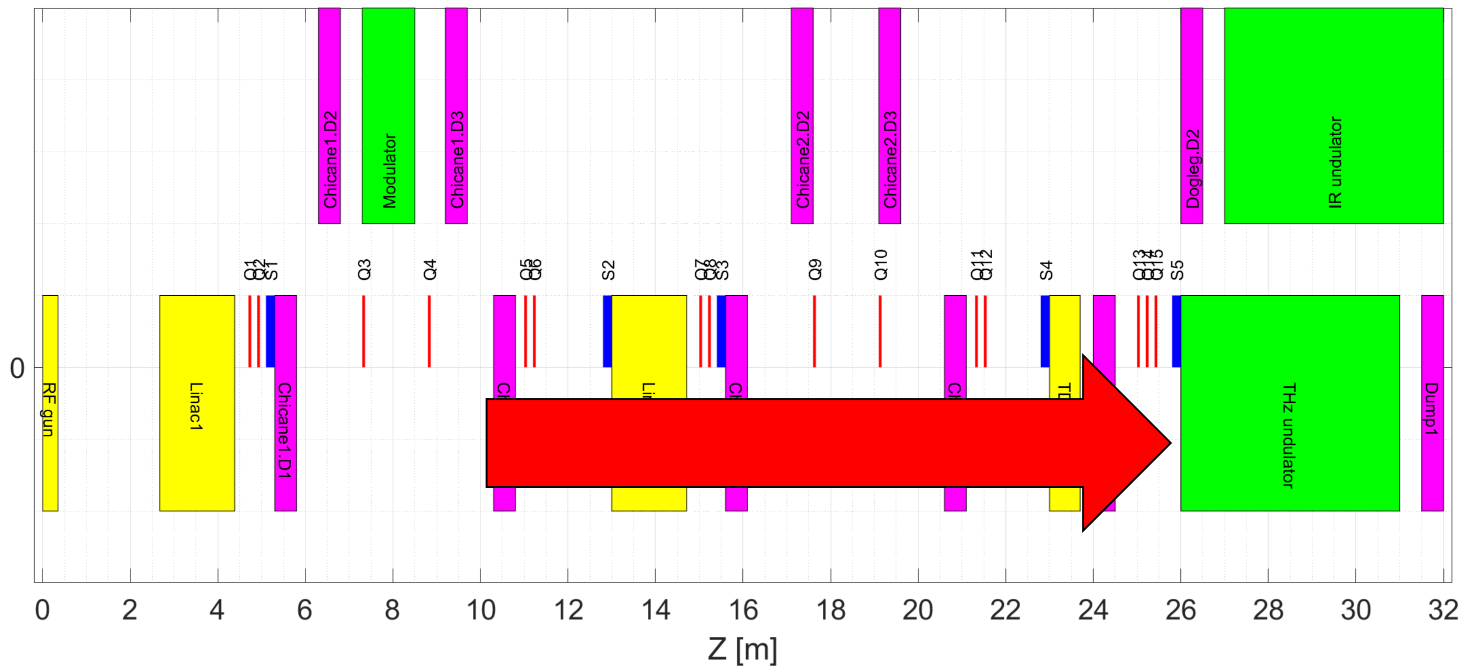
Limitations of Ocelot

- No cathode emission module? ➔ couldn't start from the gun
- Couldn't import external fields
- No good user's manual ➔ Not sure how to use the module for time-dependent FEL simulations
- Therefore, the simulation with Ocelot was done only for tracking the beam from 10 to 26 m (through drifts and quads, no dipoles and 2nd linac)



Simulation Setup

Examples of input parameters

$$k_{\mathrm{Ocelot}}[\mathrm{m}^{-2}] = 0.2998\,\frac{g_{\mathrm{ASTRA}}\left[\frac{\mathrm{T}}{\mathrm{m}}\right]}{1.59\beta E[\mathrm{GeV}]}$$

Scaling factor got from manual simulation scan (ASTRA ⇔ SCO)

ASTRA

- LSPCH3D=TRUE
- Nxf=16, Nx0=1, Nyf=16, Ny0=1, Nzf=64, Nz0=1
- ZSTART = 10, ZSTOP = 26
- Q_type(5)='../AstraPortal/Q3.data'
  Q_grad(5)=1.31861
  Q_noscale(5)=FALSE
  Q_pos(5)=11.0000
- Q_type(6)='../AstraPortal/Q3.data'
  Q_grad(6)=-1.35188
  Q_noscale(6)=FALSE
  Q_pos(6)=11.2000
- Q_type(7)='../AstraPortal/Q3.data'
  Q_grad(7)=0.23268
  Q_noscale(7)=FALSE
  Q_pos(7)=15.0000
  .
  .
  .

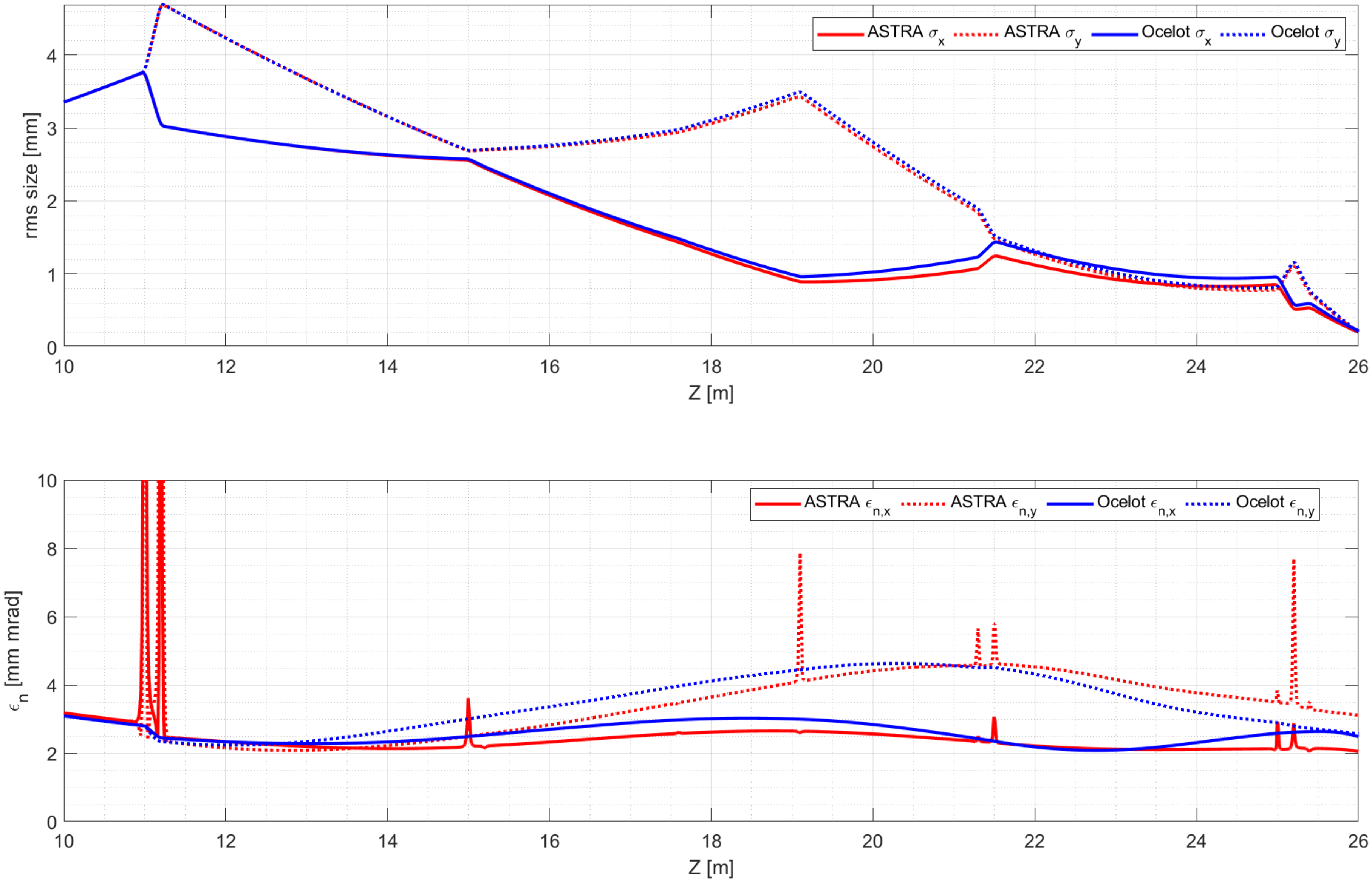
Real quad field profile

Ocelot

- sc1 = SpaceCharge()
- sc1.nmesh_xyz = [15, 15, 63]
- D4 = Drift(l=0.966)
- Q5 = Quadrupole(l=0.068, k1=KQArray[5], eid='Q5')
- D5 = Drift(l=0.132)
- Q6 = Quadrupole(l=0.068, k1=KQArray[6], eid='Q6')
- D6 = Drift(l=3.733)
- Q7 = Quadrupole(l=0.068, k1=KQArray[7], eid='Q7')
- D7 = Drift(l=0.132)
  .
  .
  .
- Lattice = (start_sim, D4, Q5, D5, Q6, D6, Q7, D7, Q8, D8, Q9, D9, Q10, D10, Q11, D11, Q12, D12, Q13, D13, Q14, D14, Q15, D15, start_und, und, end)

Use HZB method to calculate the effective length

Results Comparison: Beam Parameter Evolutions (10-26m)

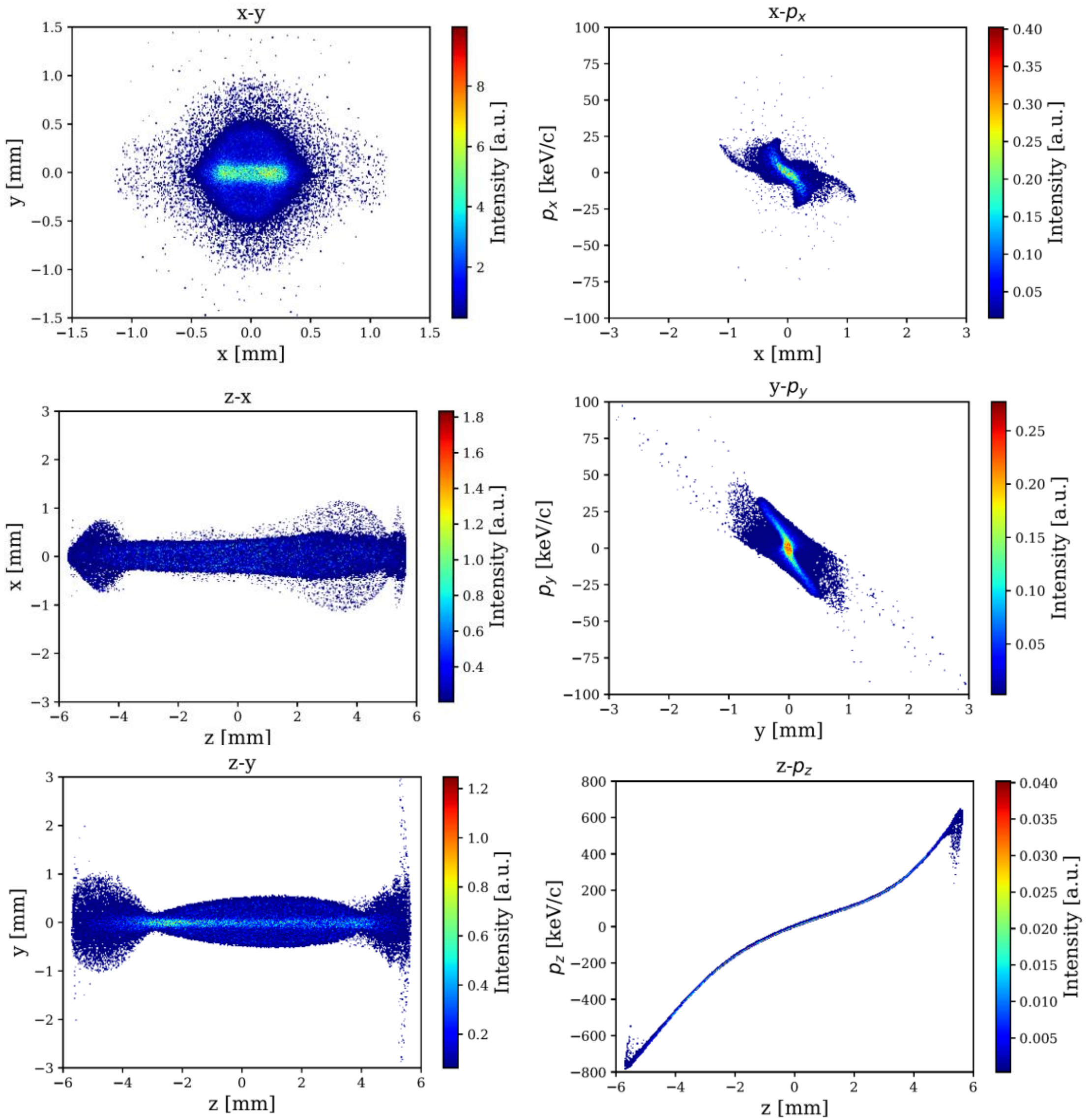


Results Comparison: Beam at the Undulator Entrance

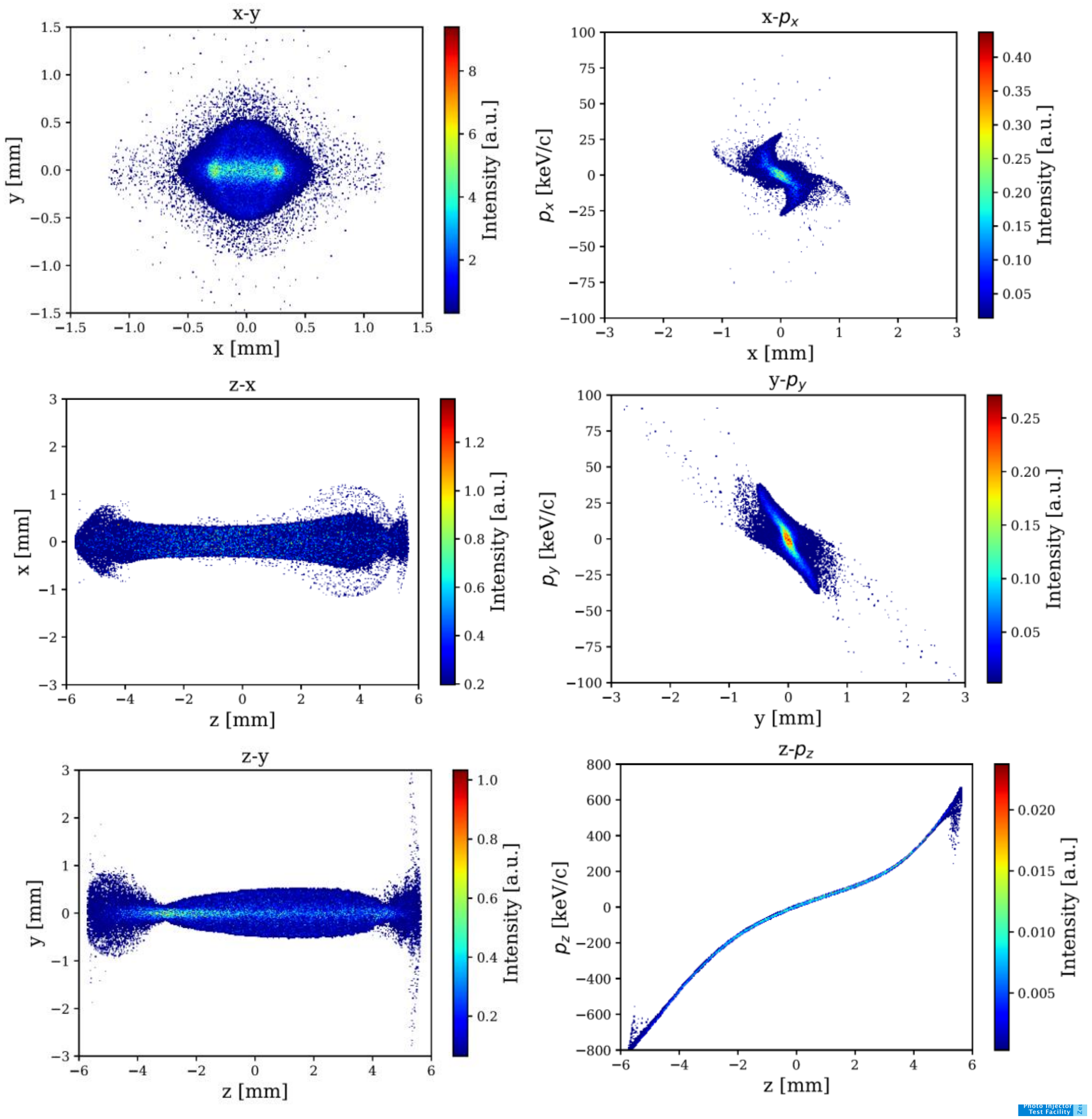
Parameters	ASTRA	Ocelot	Δ [%]
σ_x [mm]	0.205	0.221	7.80
σ_y [mm]	0.204	0.205	0.49
σ_z [mm]	2.688	2.688	0.00
σ_{Pz} [keV/c]	257.940	259.635	0.66
P_z [MeV/c]	15.166	15.174	0.05
Lorentz factor	29.696	29.711	0.05
ε_x [mm mrad]	2.052	2.544	23.98
ε_y [mm mrad]	3.113	2.627	-15.61
β_x [m]	0.610	0.568	-6.89
β_y [m]	0.396	0.473	19.44
α_x	1.235	1.151	-6.80
α_y	1.374	1.802	31.15
γ_x	4.144	4.092	-1.25
γ_y	7.288	8.985	23.28

Results Comparison: Beam at the Undulator Entrance

ASTRA

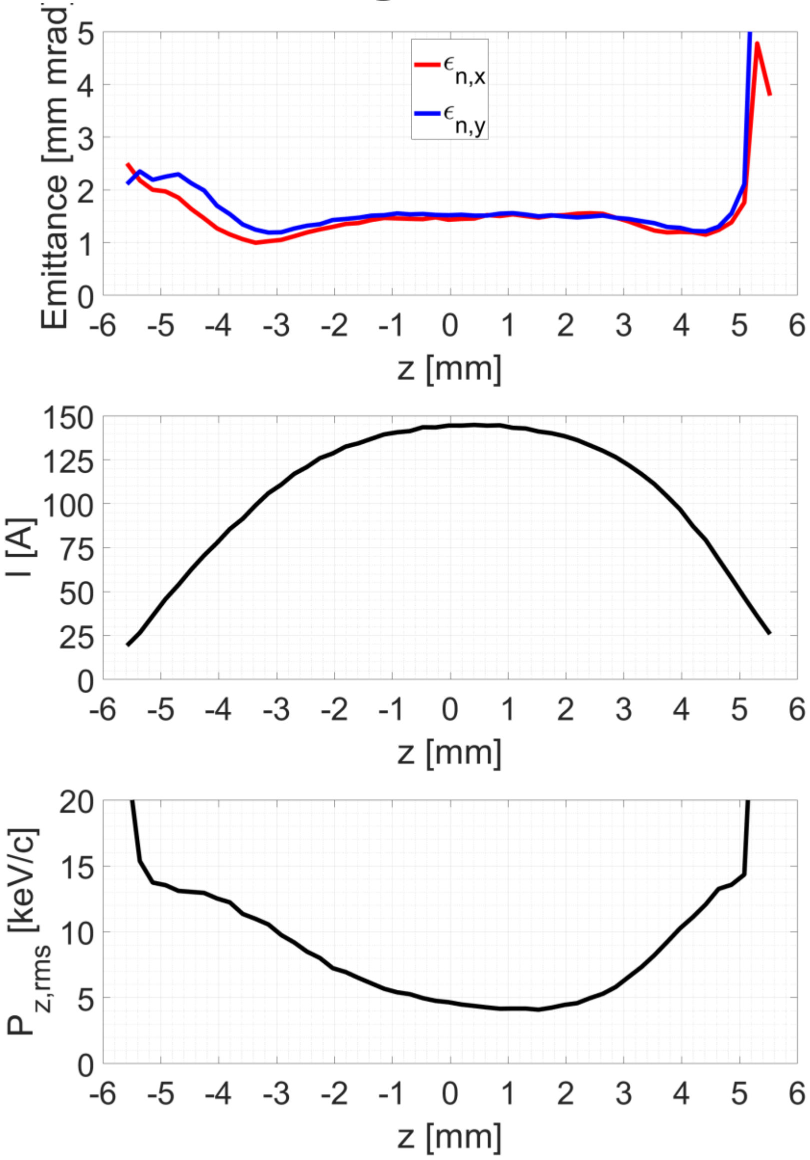


Ocelot

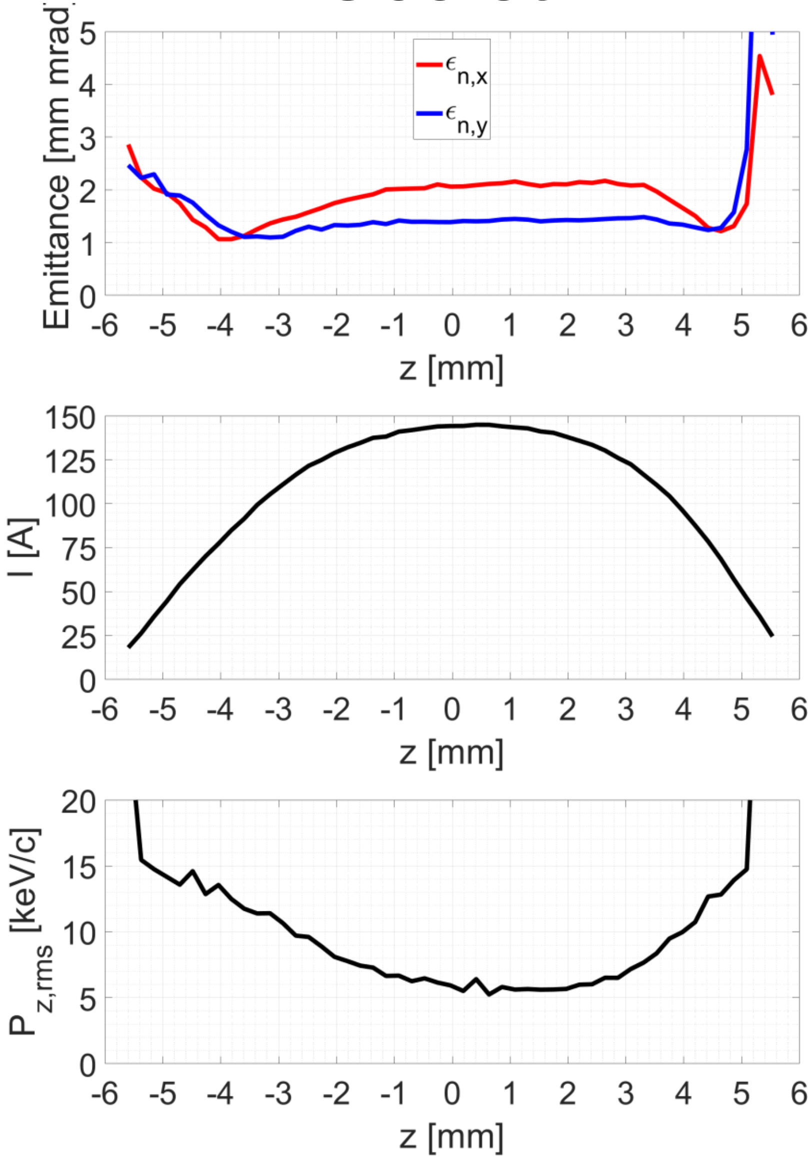


Results Comparison: Beam at the Undulator Entrance

ASTRA



Ocelot



Summary

Comparison Results between ASTRA and Ocelot

- The results of ASTRA and Ocelot are comparable.
- Note that, for space-charge calculations, Ocelot uses matrices up to 2nd order while ASTRA uses Runge-Kutta integration method.
- Comments on Ocelot

  Pro

  - Much faster tracking with space-charge (For example, 16 m tracking with quads, ASTRA → 2.5 hours, Ocelot → 5 minutes) and get comparable results
  - On Python environment

  Con

  - No good user's manual
    - Not sure how to use the module for time-dependent FEL simulations (and many more)
    - Many results are treated internally, have to look into the source files to understand the results
  - No cathode emission module, Can't import external fields

Ocelot can't completely replace ASTRA

Outlook

- Repeat the test S2E simulation with Ocelot
  - We have to simulate bunch compressors and doglegs which ASTRA couldn't handle them well.
  - Instead of using many code for an S2E work such as ASTRA, Elegant, CSRTrack and ImpactT, We should use Ocelot if it works well with dipole transports and S2E simulations.
  - Igor Zogorodnov already repeated S2E simulations for XFEL with Ocelot (https://www.desy.de/fel-beam/s2e/xfel.html). Since we will transfer our simulations to them, we should use the same tool.
- Design consideration of the Chicanes (idea → +/- R56)
- Test S2E simulations with ultra-short bunch schemes (CTR & superradiant)
- Test S2E simulations with the IR Undulator
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Capabilities of the ideal THz source

P.Zalden et. al, "TECHNICAL NOTE Terahertz Science at European XFEL" XFEL.EU TN-2018-001-01.0, 2018

- **Bandwidth:** Tunable bandwidth ΔE/E between 1 (single-cycle, shortest pulse possible) and 0.05 (multi-cycle, to coherently drive matter).
- **Frequency:** Tunable centre frequency in the range 0.1 to 30 THz (3 mm to 10 μm wavelength). Within this range, 3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies.
- **Pulse fluence/field strength:** More than 2 MV/cm, which corresponds to > 10 GW/cm2. Pulses of 1 ps duration would then generate fluences of > 10 mJ/cm2. Assuming a focus size with diameter of the wavelength, this requires pulse energies of 3 mJ at 0.1 THz and 30 μJ at 1 THz. At 10 THz, 0.3 μJ would be sufficient in principle, but the ideal focussing can most likely not be achieved and therefore a minimum of 10 μJ should ideally be achievable at all frequencies.
- **Carrier envelope phase (CEP):** Should be either stable (i.e. each pulse has the same temporal electric field E(t)) or, alternatively, it must be measured for each pulse. The CEP-stable option simplifies data processing significantly.
- **Repetition rate:** To make best use of the potential of the European XFEL, the source should operate at least at 0.1 MHz but ideally could follow the 4.5 MHz bursts.
- **Synchronization:** Temporal jitter must be better than 0.1/frequency to resolve the electric field cycles, e.g. < 20 fs at 5 THz. This could be either the intrinsic jitter or the resolution of a timing measurement.
- ***Optional:*** **Polarization control:** Could be achieved with optics after THz generation and does not need to be considered here.