Start-to-end simulations of THz SASE FEL proof-of-principle experiment at PITZ

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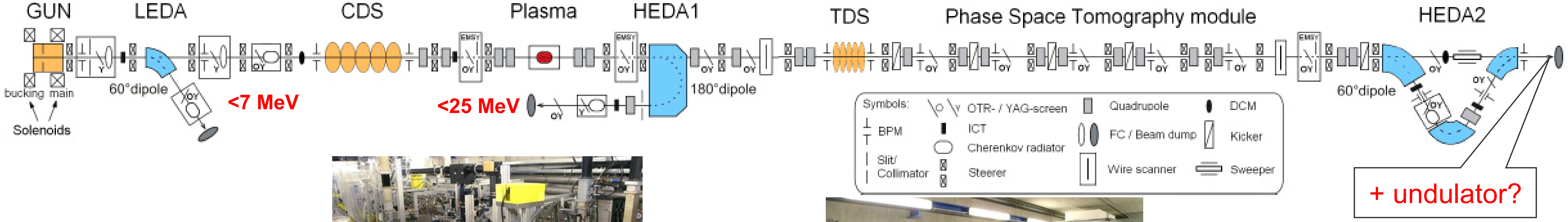
Photo Injector Test facility at DESY, Zeuthen site (PITZ)



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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

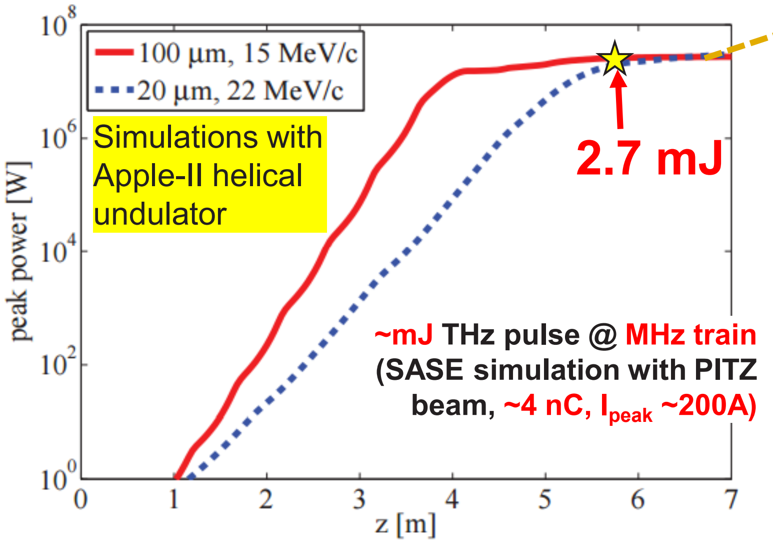
THz

Pump & probe

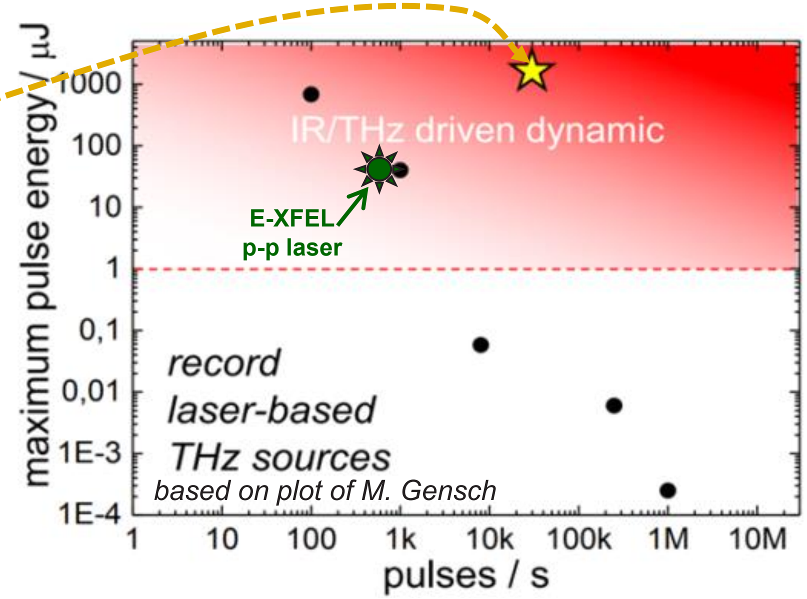
E.A. Schneydmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012

- 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



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



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!

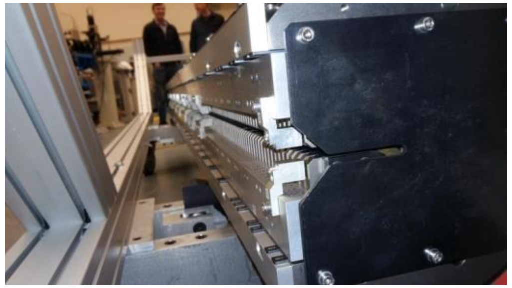
SASE FEL based on PITZ accelerator and LCLS-I undulators

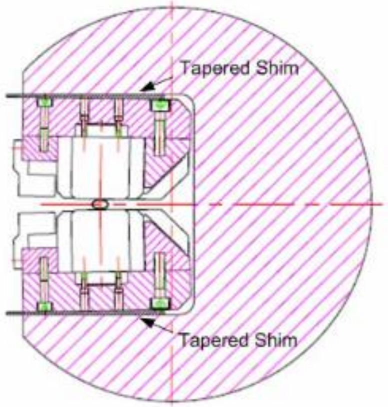
LCLS-I undulators (available on loan from SLAC) → under study and negotiations

Some Properties of the LCLS-I undulator

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

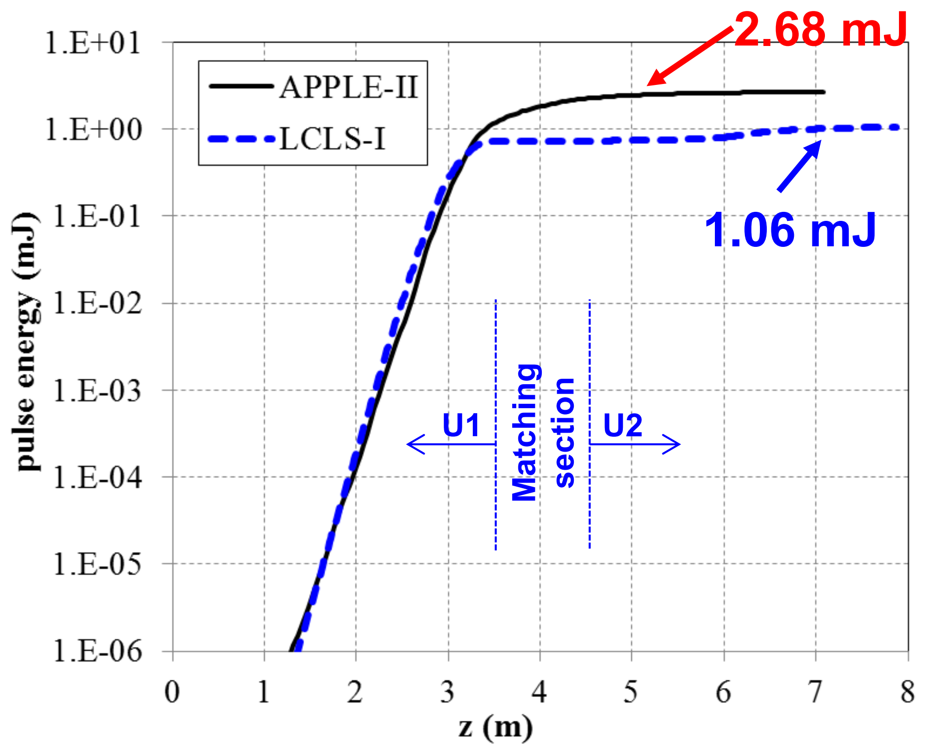
Reference: LCLS conceptual design report, SLAC-0593, 2002.





E-beam with PITZ parameters "ideally" matched into the undulator

Preliminary GENESIS Simulations (λ_{rad}=100μm)



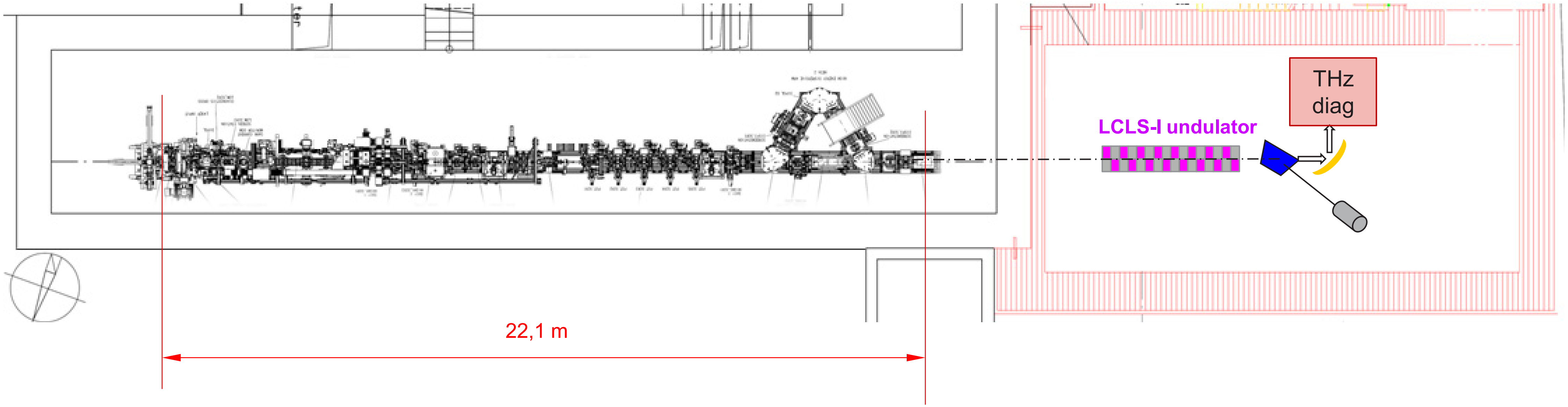
Preliminary conclusions on LCLS-I undulators at PITZ:

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

λ_{rad}~100μm → <Pz>=**16.7MeV/c**

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

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



S2E simulations: from photocathode → undulator→ THz SASE FEL

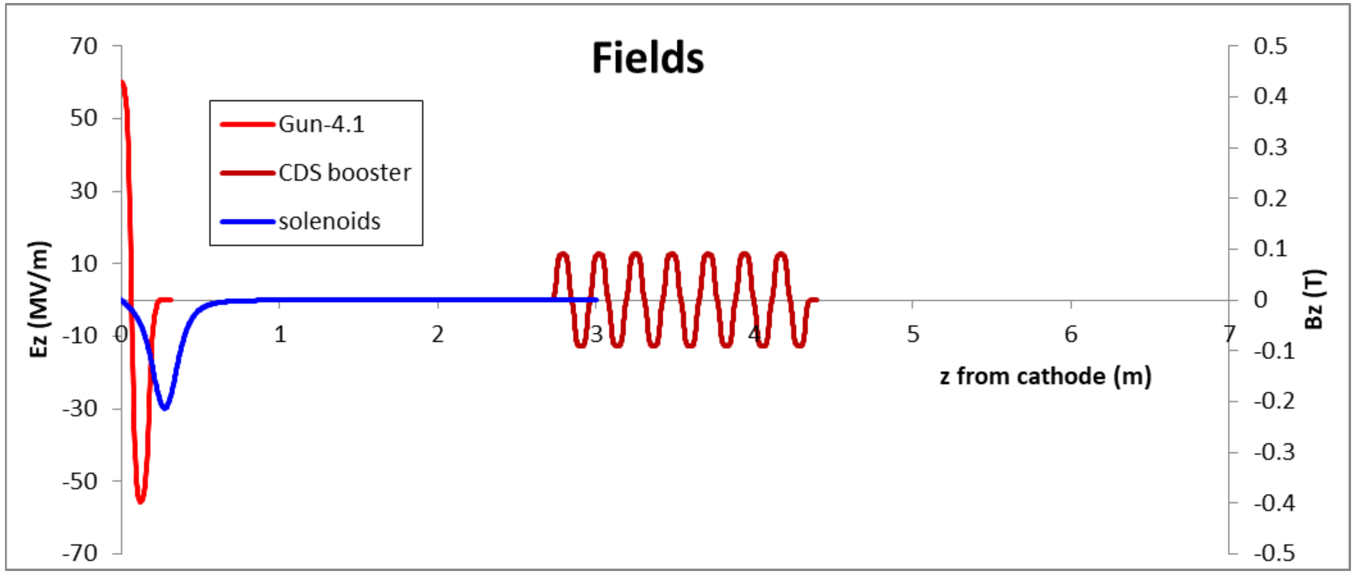
Main challenges:
- 4 nC (200A) x 16.7 MeV/c → SC dominated beam
- ~30 m transport (incl. 1.5 m wall) → LCLS-I undulator in the tunnel annex
- 3D field of the undulator field
- Matching into the undulator (narrow vacuum chamber issue)

Tools:
- ASTRA
- SC-Optimizer
- GENESIS 1.3

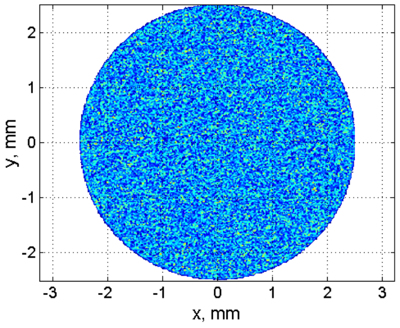
Beam Dynamics Simulation Setup

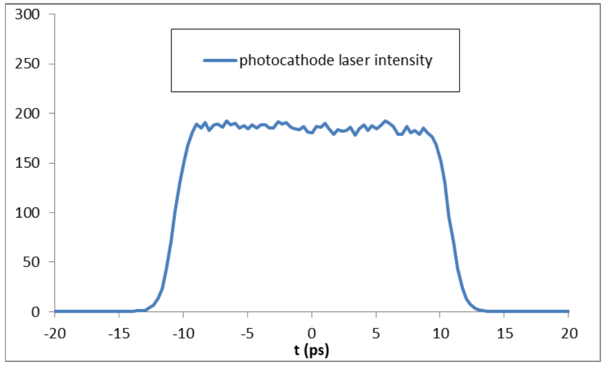
ASTRA

Gun +Solenoids + CDS-booster



Photocathode laser





Photocathode laser:

- FT 21.5ps FWHM
- ∅ ≤5mm
- 4nC

Gun:

- Ecath=60MV/m (fixed)
- MMMG

Booster:

- Emax<20MV/m
- Phase=phi2*

} → <Pz>=16.7MeV/c + min δE@undulator?

NB:

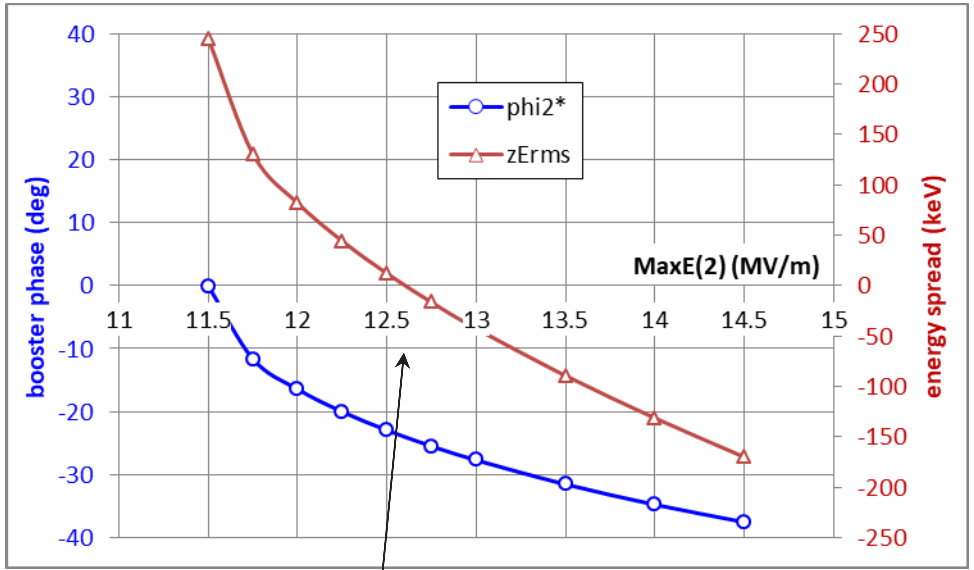
- Core + Halo model for real laser!
- Imperfections (photoemission + asymmetry)

Gun, solenoid, booster parameters

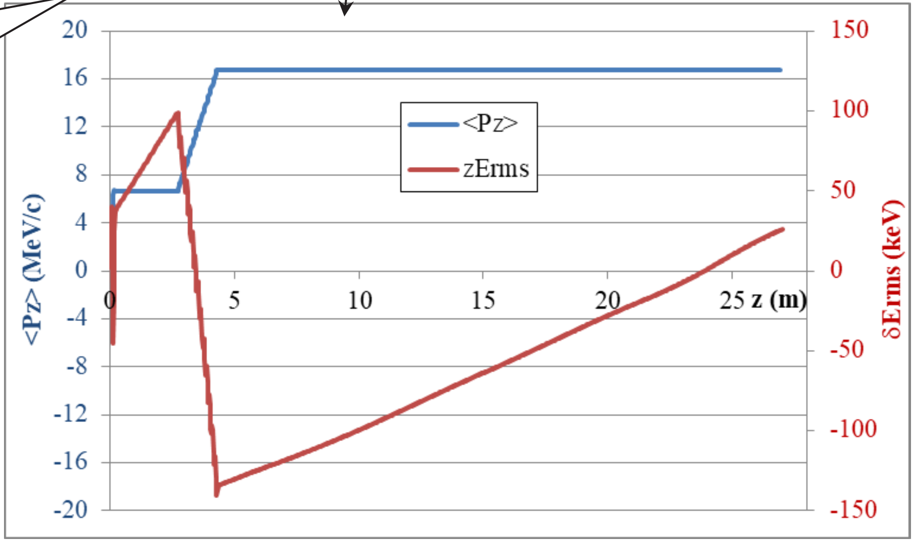
Extremely small emittance is not a goal

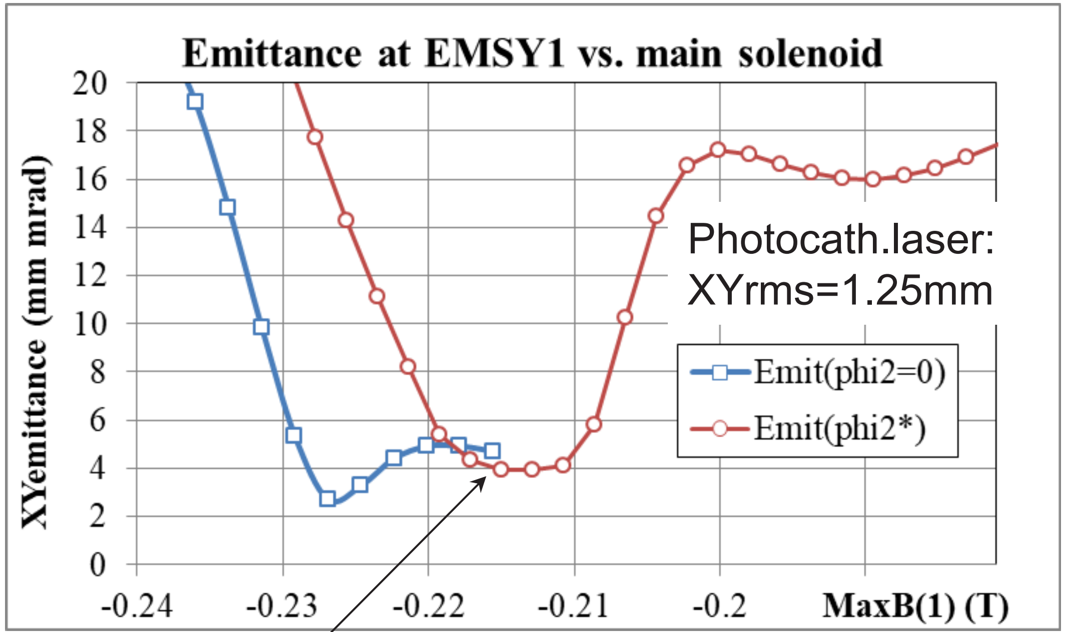
phi2* = booster phase for <Pz>=16.7MeV/c

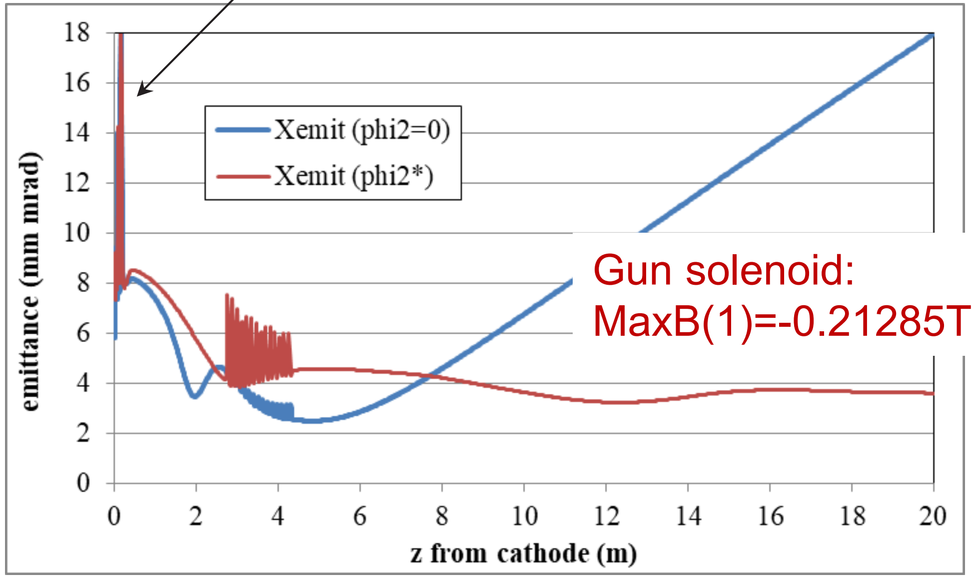
Minimizing correlated energy spread close to the undulator



Booster:
MaxE(2)= 12.6MV/m
Phi(2)= -24deg

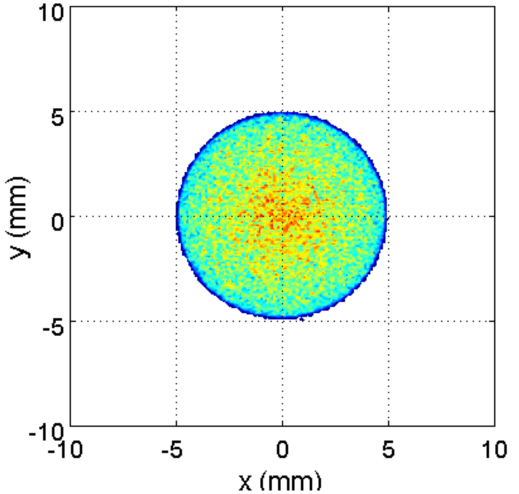


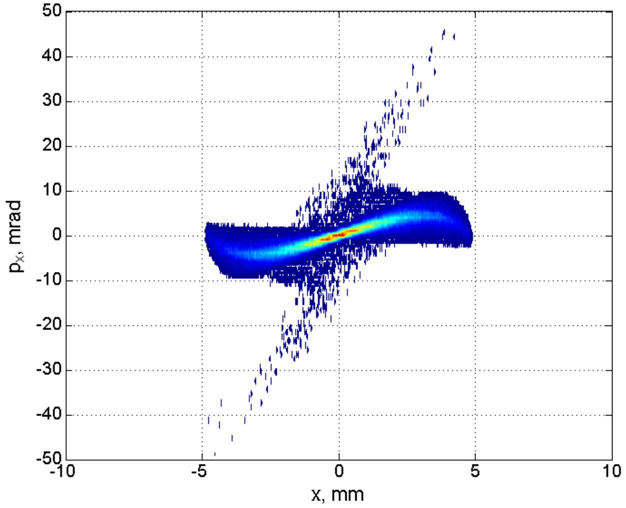


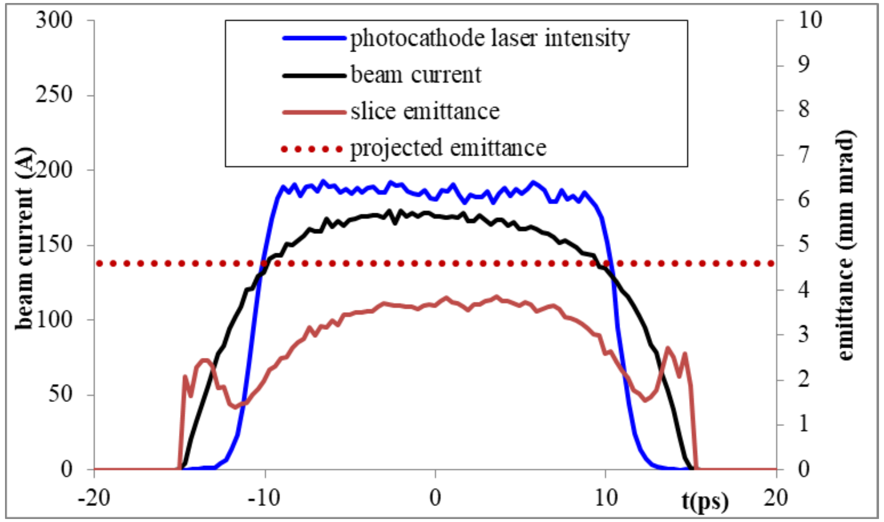


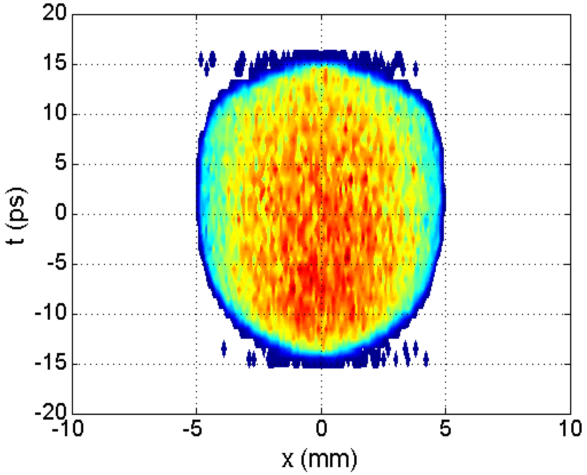
Beam at EMSY1 – “ready” for transport

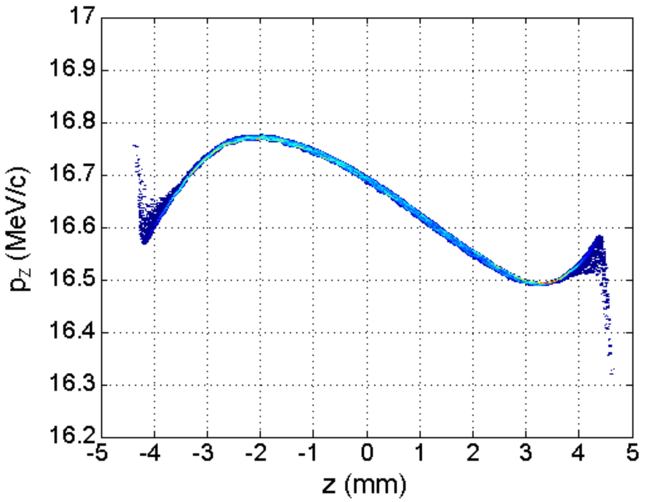
Z=5.277m from the cathode

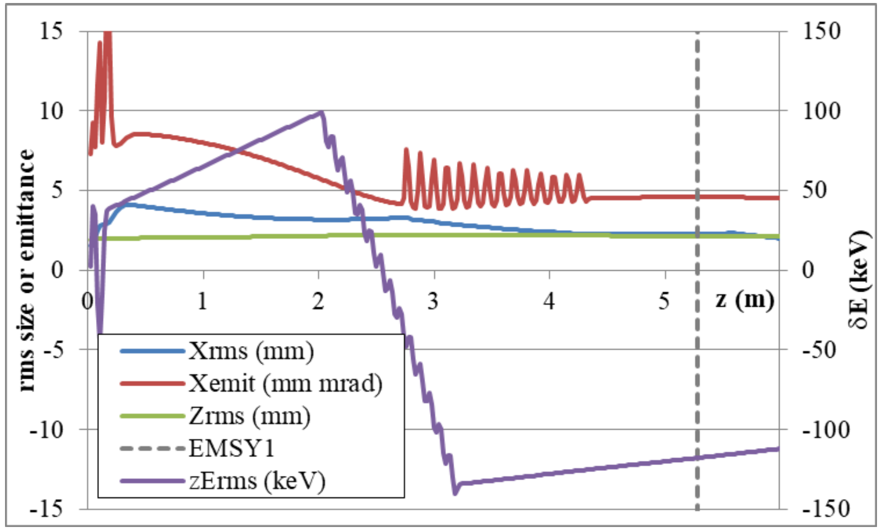






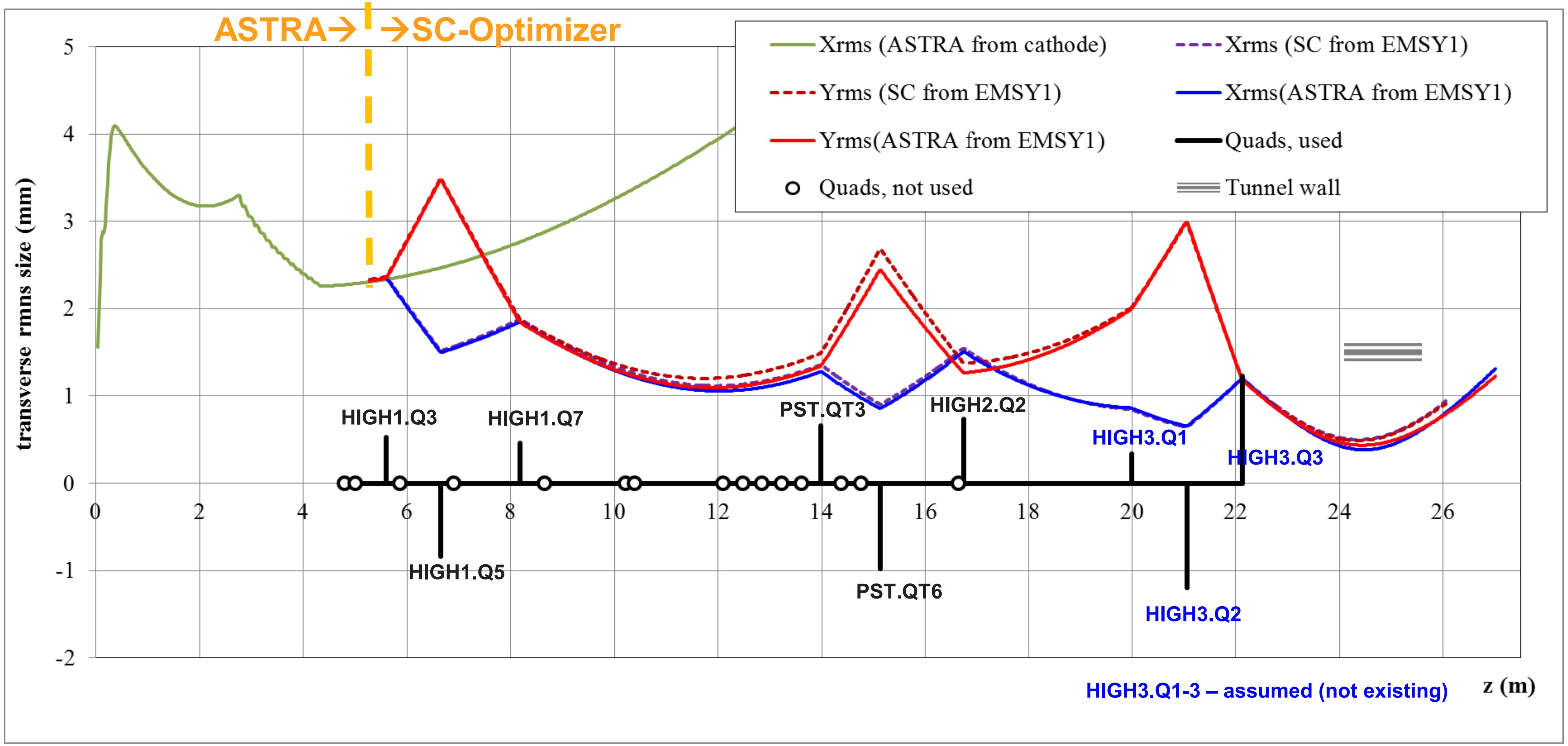






PITZ Beam from the cathode → tunnel wall

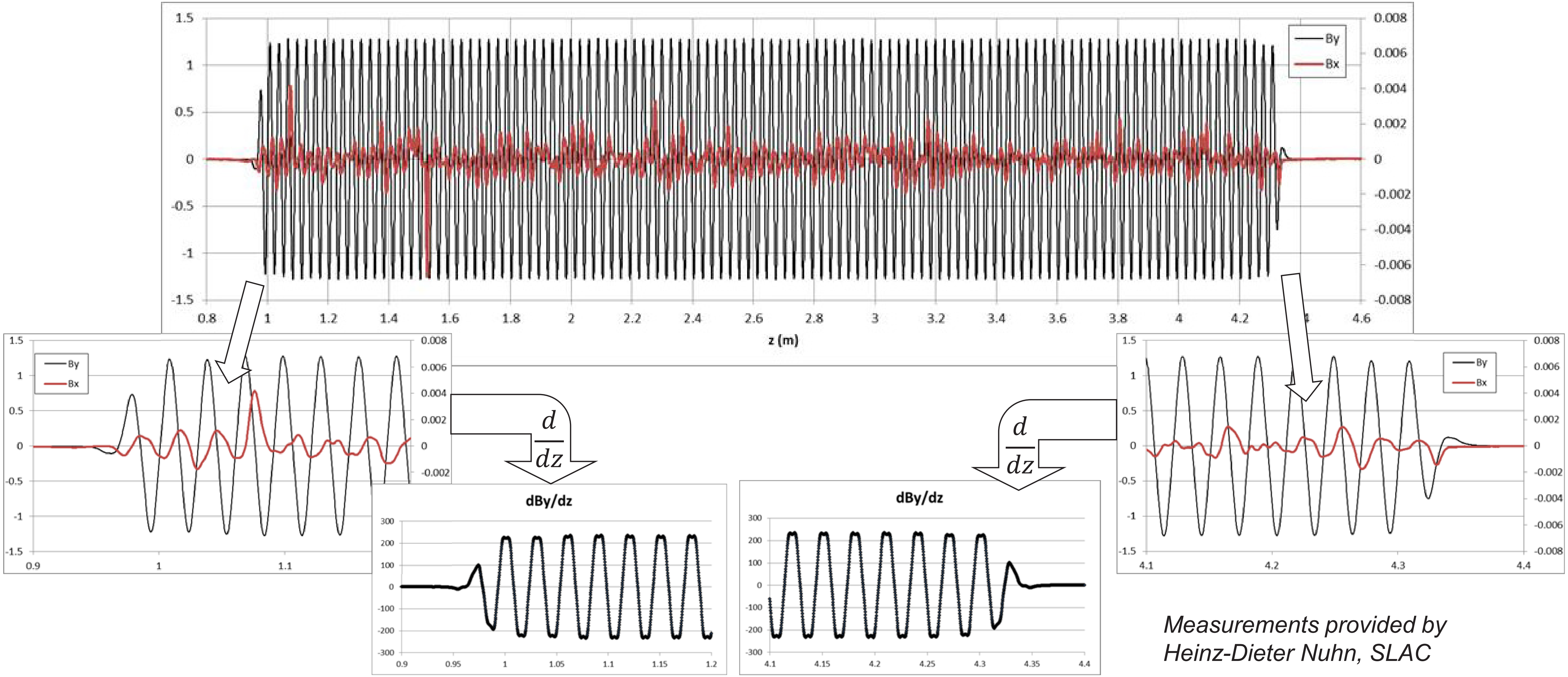
ASTRA input → SC-Optimizer → check with ASTRA



$$GF(Q_1, \ldots, Q_9) \propto \sqrt{\frac{1}{L} \int_{z_{wall}}^{z_{wall}+d} X_{\mathrm{rms}} \cdot Y_{\mathrm{rms}}\, dz}$$

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

Fourier Analysis

Performing Fourier transformation for $-\frac{L}{2} \le z \le \frac{L}{2}$, where $L = N_U\lambda_U$ is the undulator length:

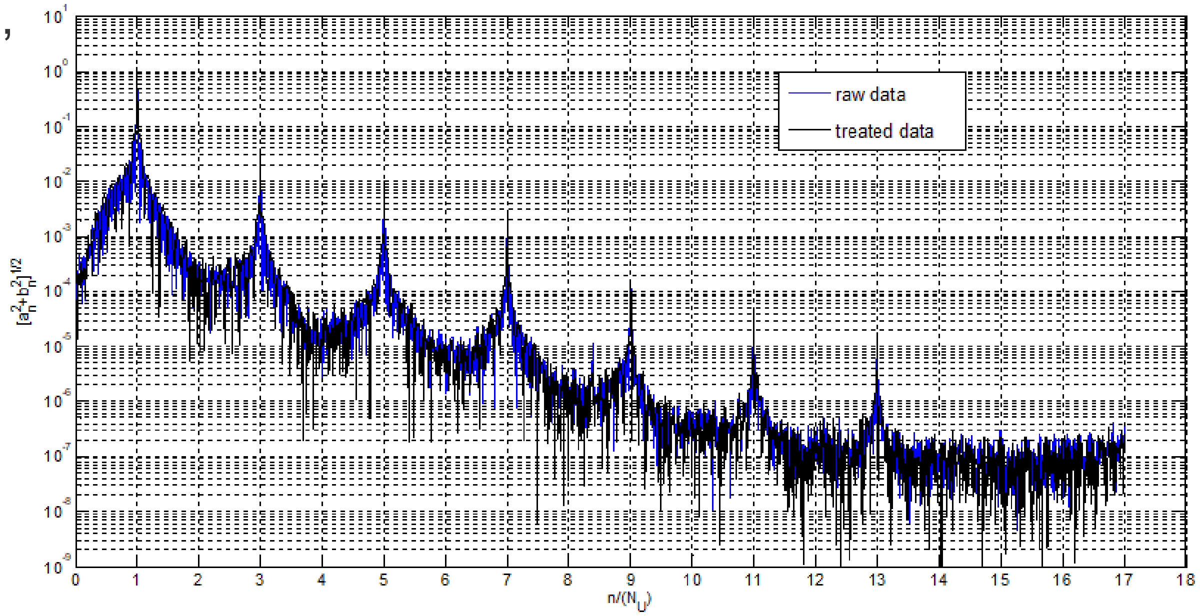
$$B_y(x=0, y=0, z) = \sum_{n=0}^{\infty}\left\{a_n \cos\left(\frac{2\pi nz}{N_U\lambda_U}\right) + b_n \sin\left(\frac{2\pi nz}{N_U\lambda_U}\right)\right\},$$

where

$$a_n = \frac{2}{L}\int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x=0, y=0, z)\cos\left(\frac{2\pi nz}{N_U\lambda_U}\right)dz,$$

$$a_0 = \frac{1}{L}\int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x=0, y=0, z)\,dz,$$

$$b_n = \frac{2}{L}\int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x=0, y=0, z)\sin\left(\frac{2\pi nz}{N_U\lambda_U}\right)dz.$$



Field integrals of the undulator:

$$I_{1y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} B_y(x=0, y=0, z)\,dz, \quad \Longrightarrow \quad I_{1y} = a_0 L, \quad \Longrightarrow \quad a_0 = 0$$

$$I_{2y} = \int_{-\frac{L}{2}}^{\frac{L}{2}} dz \int_{-\frac{L}{2}}^{z} B_y(x=0, y=0, z_1)dz_1. \quad \Longrightarrow \quad I_{2y} = \frac{L^2}{2}\left\{a_0 + \sum_{n=1}^{\infty}\frac{(-1)^n}{\pi n}b_n\right\} \quad \Longrightarrow \quad \sum_{n=1}^{\infty}\frac{(-1)^n}{\pi n}b_n = 0$$

LCLS-I Undulator field

3D field map generation

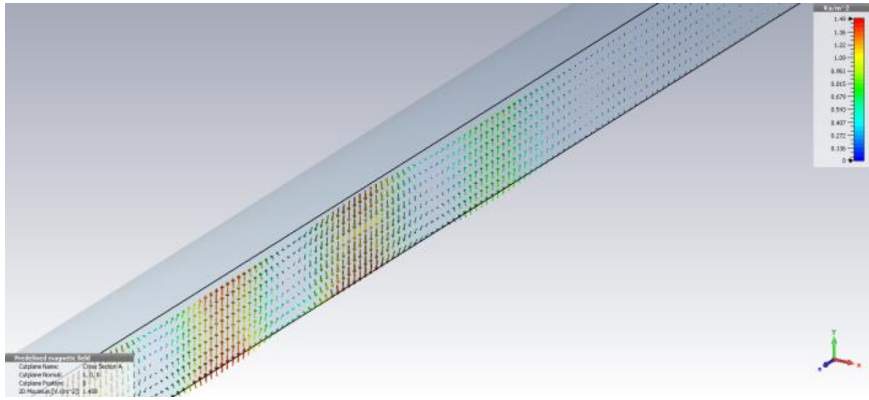
Vertical and longitudinal components of undulator magnetic field:

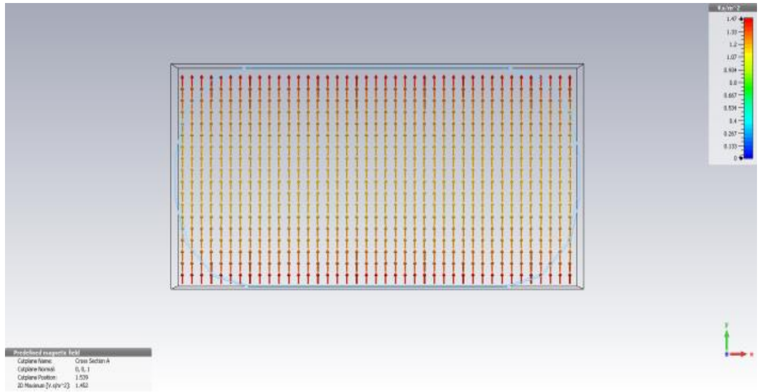
Used as external field map for ASTRA (static magnetic cavity) and for CST Trk/PIC solver

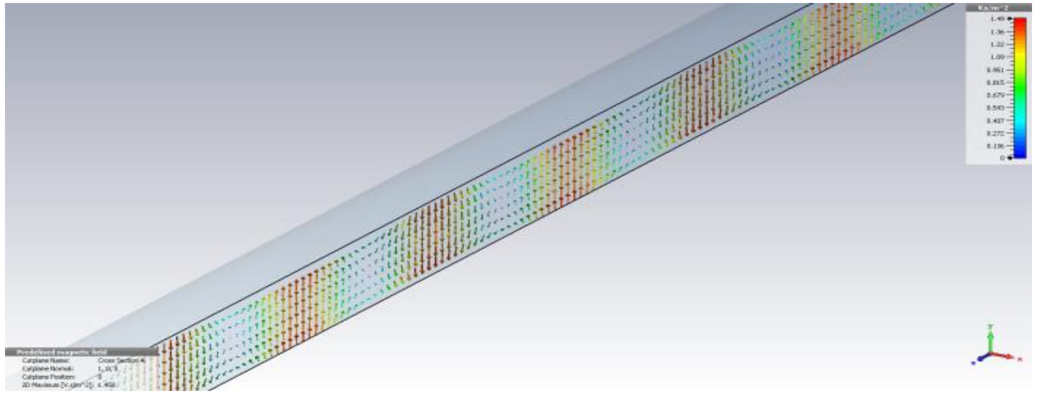
$$B_y(x,y,z) = \sum_{n=1}^{N_h \cdot N_U} \left[\left\{ \tilde{a}_n \cos(k_n z) + \tilde{b}_n \sin(k_n z) \right\} \cdot \cosh(k_n y) \right],$$
$$B_z(x,y,z) = \sum_{n=1}^{N_h \cdot N_U} \left[\left\{ -\tilde{a}_n \sin(k_n z) + \tilde{b}_n \cos(k_n z) \right\} \cdot \sinh(k_n y) \right],$$

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

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



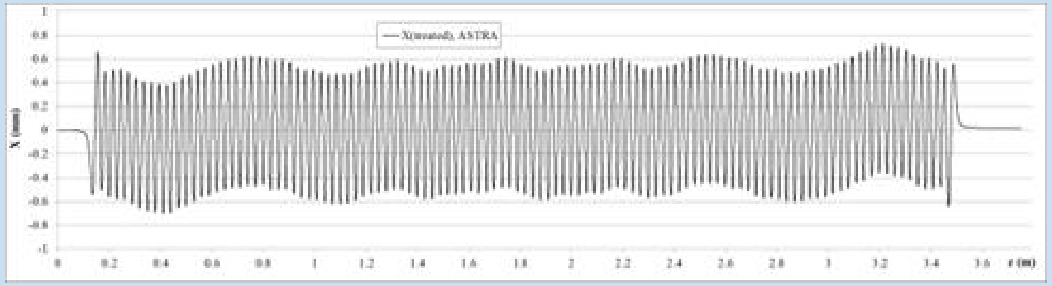
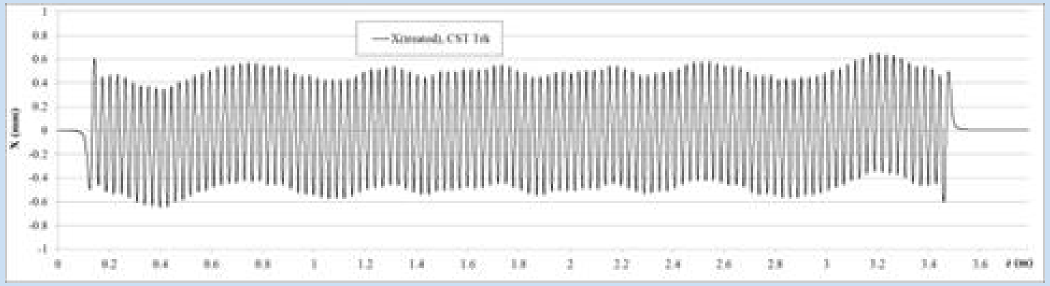
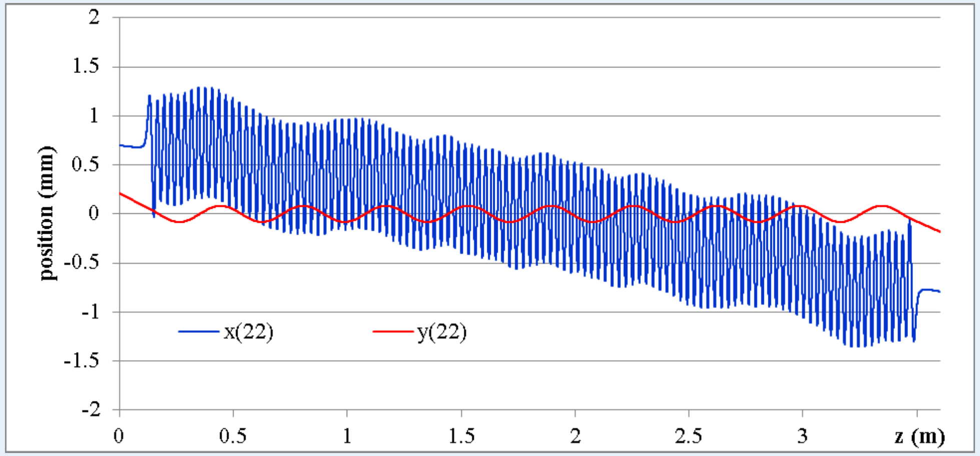
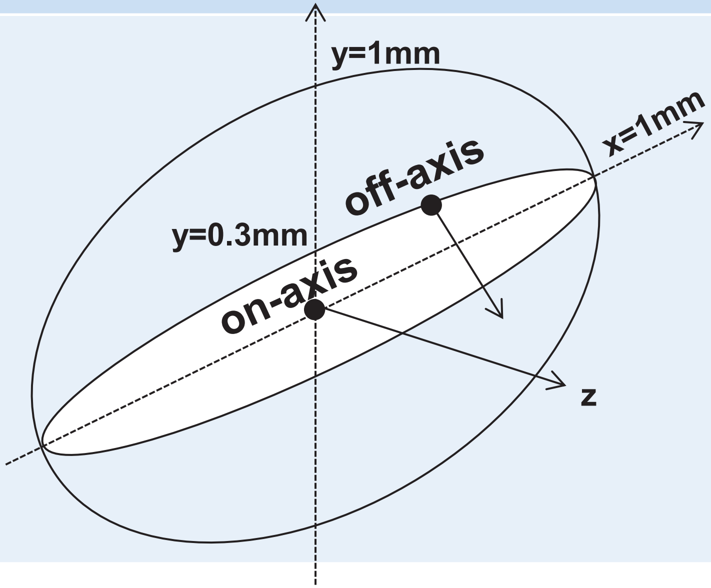




$$N_h = 17; \; N_U = 120$$

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>
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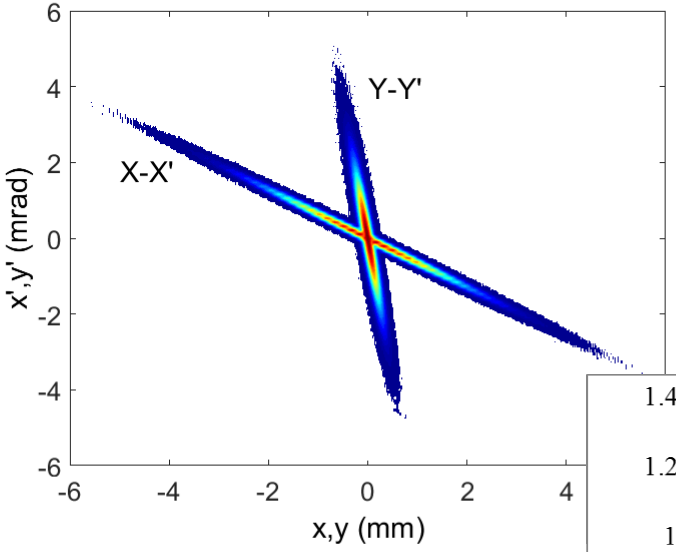
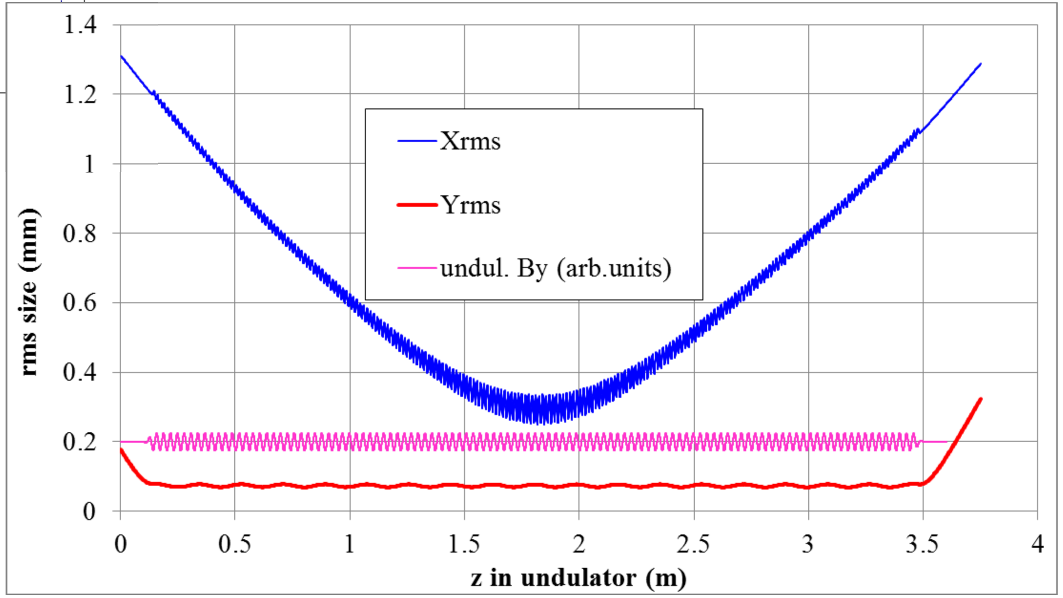
Beam matching into the undulator

ASTRA simulations with space charge and 3D undulator field map

- “Ideal” (Gaussian-FT) beam



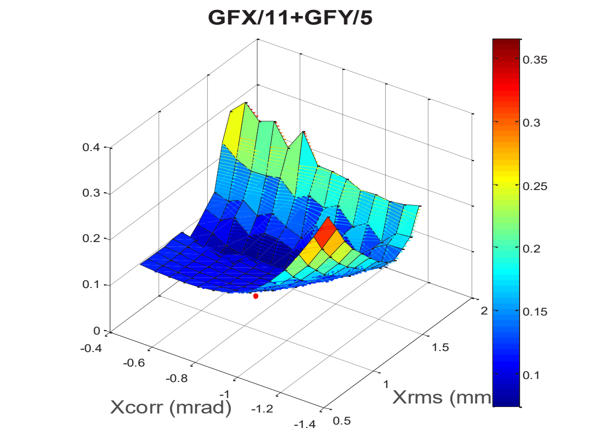
Asymmetric (X-Px-Y-Py) beam for proper matching into the unduator!

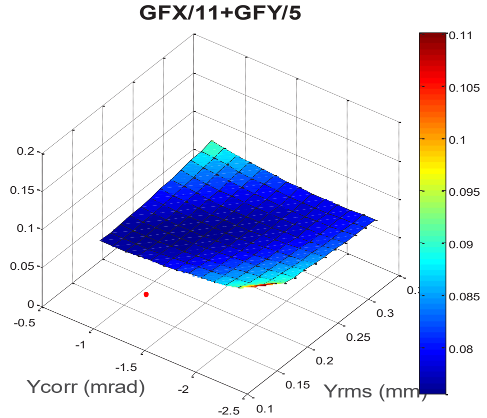


$$GF = w_x \cdot GFX + w_x \cdot GFY$$

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

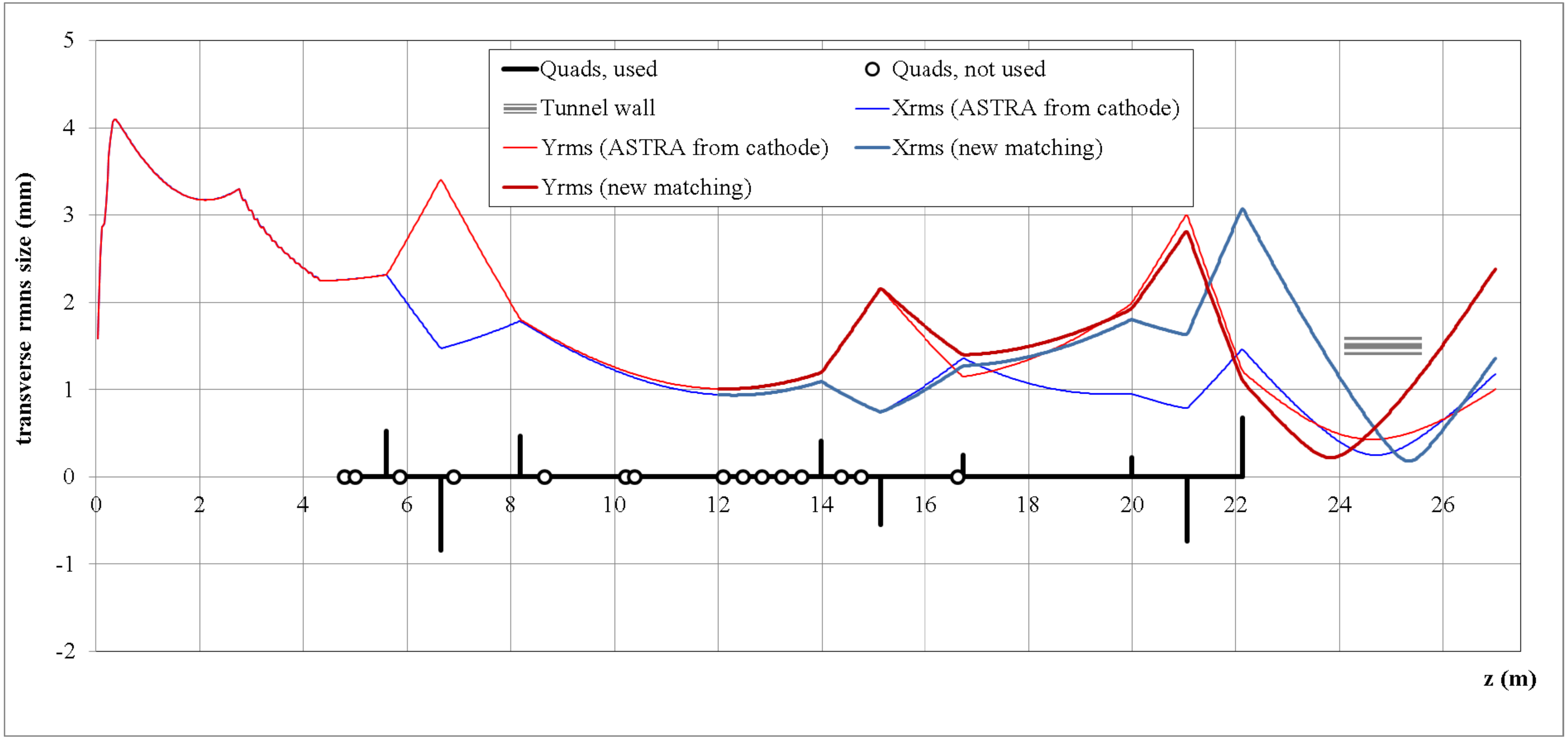
$$GFY(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L}\int_0^L std(Y_{\mathrm{rms}})dz$$





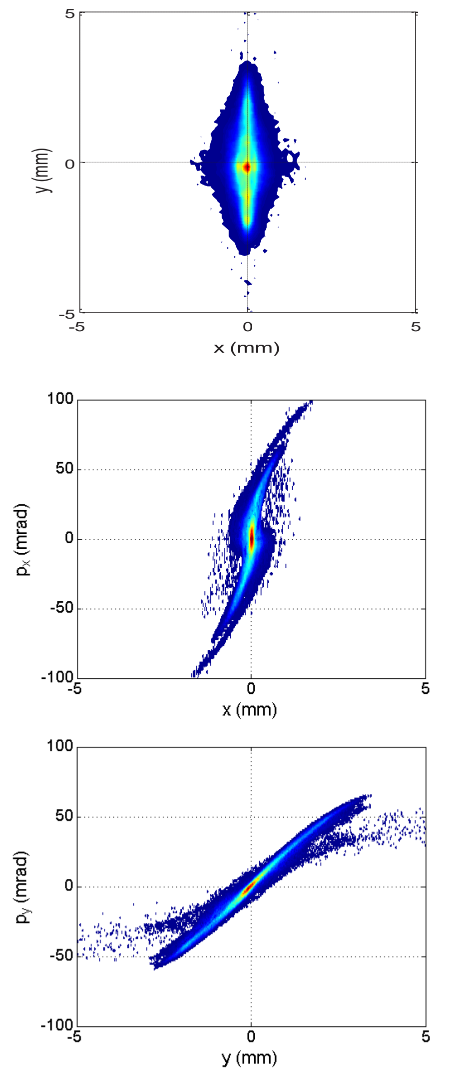
New transport / matching

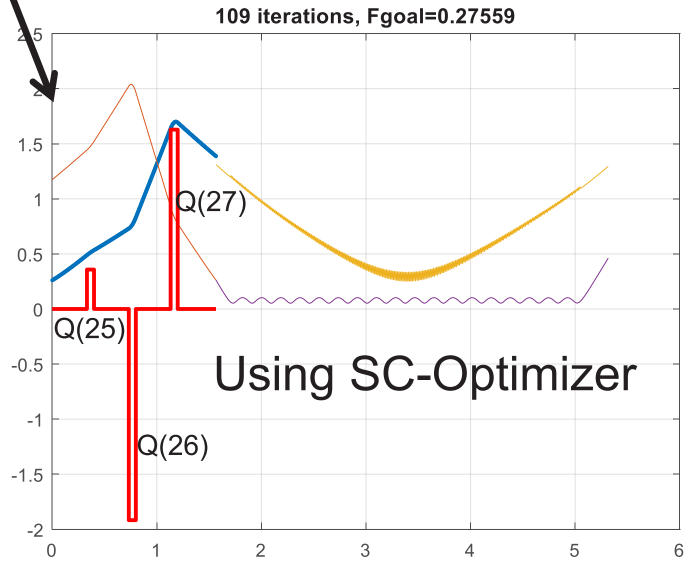
Further “through the wall” + prepare for asymmetric matching into the undulator



Fine matching into the undulator

Starting with “beam at wall of the new tunnel” z=25.587m





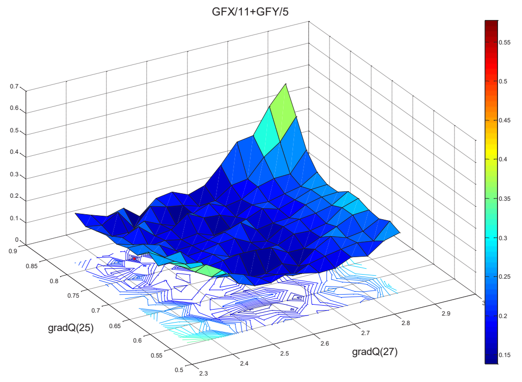
Quad	Z from wall	Z from cathode	Matching M1		Matching M2	
			T/m	A	T/m	A
Q(25)	0.3663	25.9533	1.107	~1.6	1.425	~2.1
Q(26)	0.7663	26.3533	-3.277	~-4.8	-3.277	~-4.8
Q(27)	1.1663	26.7533	2.564	~3.8	2.564	~3.8

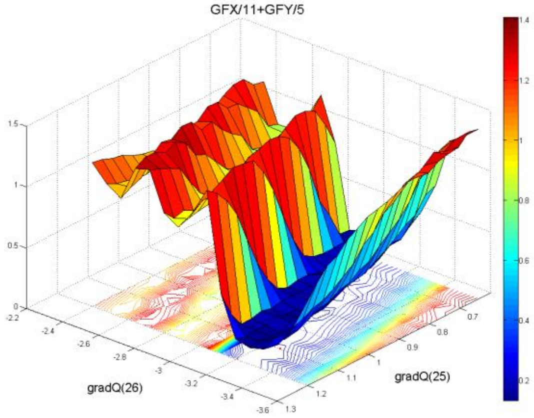
$$GFX(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L}\int_0^L X_{\mathrm{rms}}\, dz$$

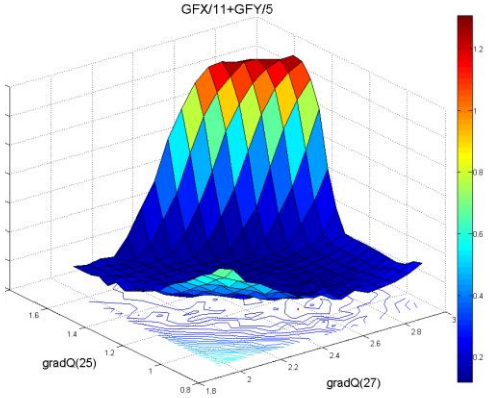
$$GFY(X_{rms,0}, Y_{rms,0}, X'_{rms,0}, Y'_{rms,0}) \propto \frac{1}{L}\int_0^L std(Y_{\mathrm{rms}}) dz$$

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

Using ASTRA



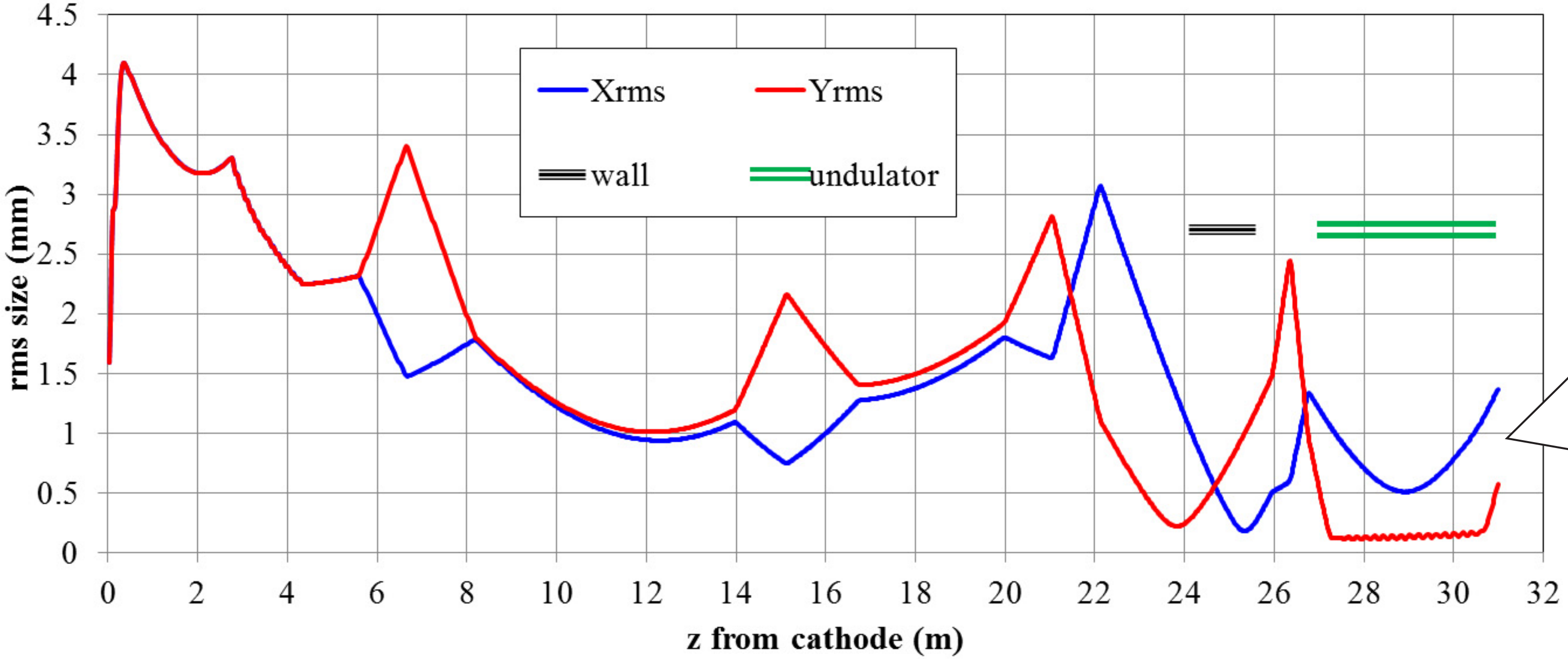


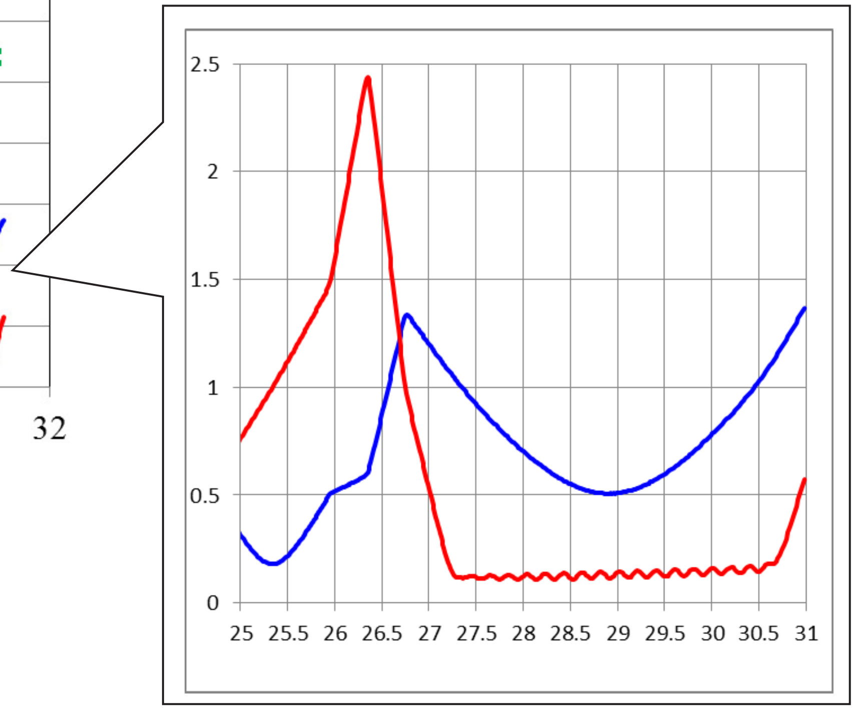


Electron beam transport for LCLS-I undulator option at PITZ

Matching into the undulator → beam size

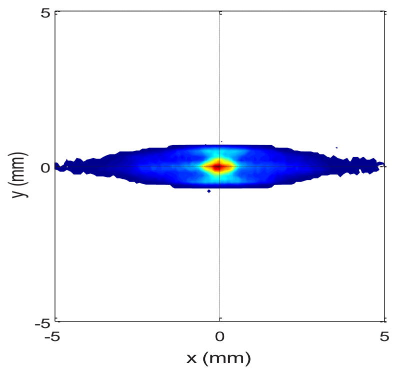
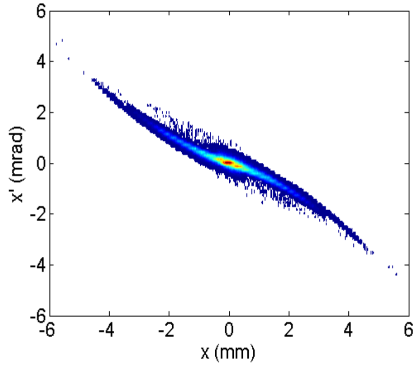
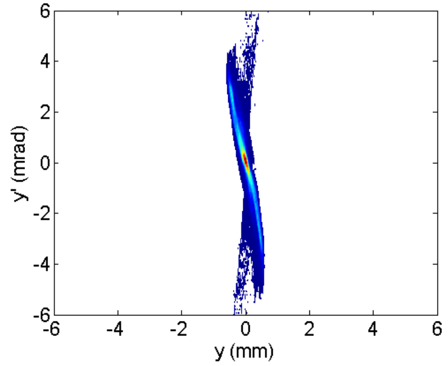
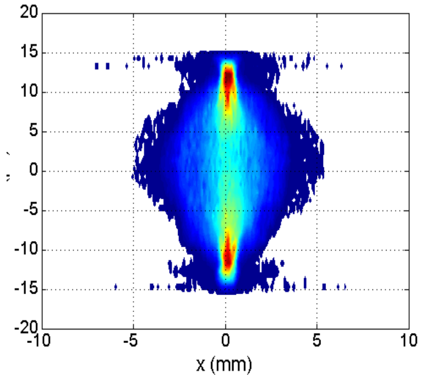
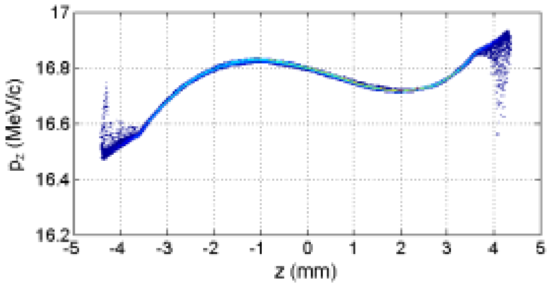
NB1: Space charge model is not fully correct for the undulator (dipole field)

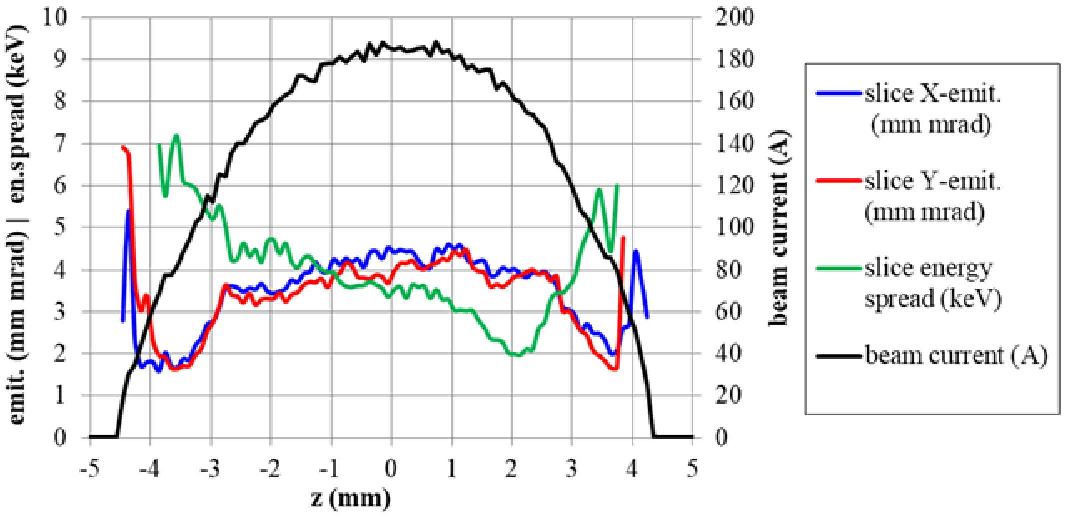




Beam at undulator entrance

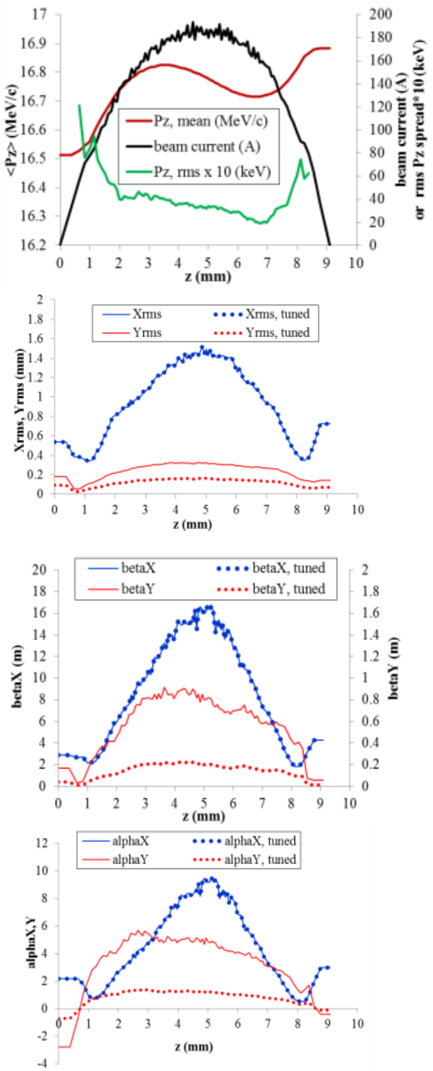
ASTRA monitors at z=27.15m ➔ input for GENESIS 1.3 simulations

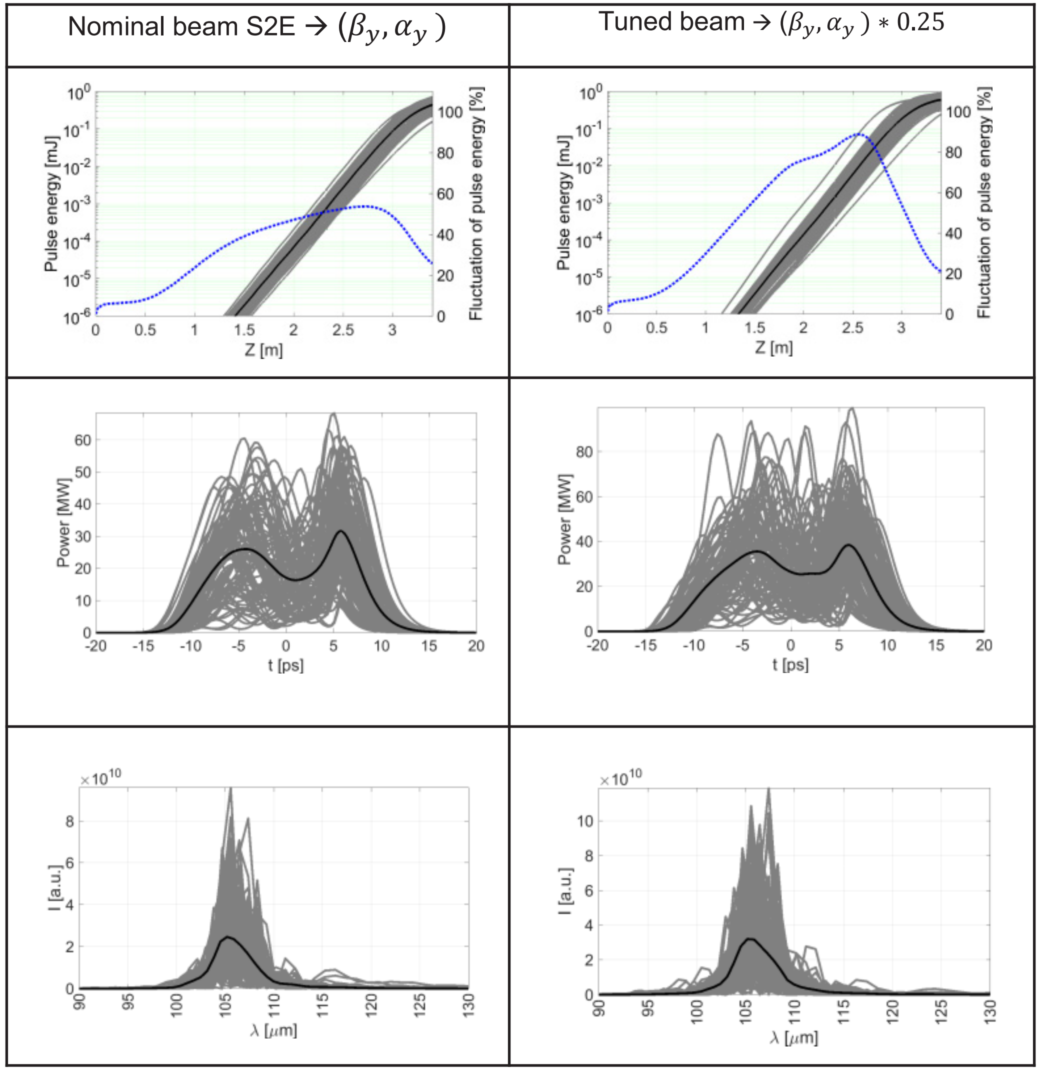
X-Y	X-X’	Y-Y’	X-T	Z-Pz
				



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

Conclusions and outlook

Star-to-End simulations for the proof-of-principle experiment for SASE THz FEL at PITZ using LCLS-I undulator

- PITZ Setup for THz SASE FEL:
  - Gun: 60MV/m, 0deg
  - Photocathode laser: ∅5mm, 21.5ps FWHM, 4nC
  - CDS booster setup: 12.6MV/m, -24deg → 16.7MeV/c + min dE@~undulator
  - Main solenoid: MaxB(1)=-0.21285T (~365A) → ε_{xy}(EMSY1)~4 mm mrad
  - Transport: 3 quad. triplets → transport through the tunnel wall (1.5m)
  - Transport: +1 quad triplet to match into undulator

→

- Refine (improve) preliminary optimum solution:
  - Realistic PC laser parameters ∅3-4mm, other temporal profiles, core+halo (using experimental data)
  - Other imperfections (photoemission, asymmetry)
  - Flat beam option?
- Transport with less quads?
- Collimator?
- Scale / re-optimize setup for λ_{rad}=50-60μm

- Undulator field:
  - Based on measured profile B_y(z,0,0)
  - Treated (improved) profile to minimize field integrals
  - 3D field map reconstructed → CST and ASTRA

→

- Undulator error, tolerances
- Implement horizontal gradient
- …

- Tracking beam through the undulator:
  - On-axis reference particle: CST Trk ←→ASTRA with 3D field map
  - Off-axis reference particle in ASTRA to find initial guess for matching
  - 4nC beam by ASTRA (with space charge*) → matching found

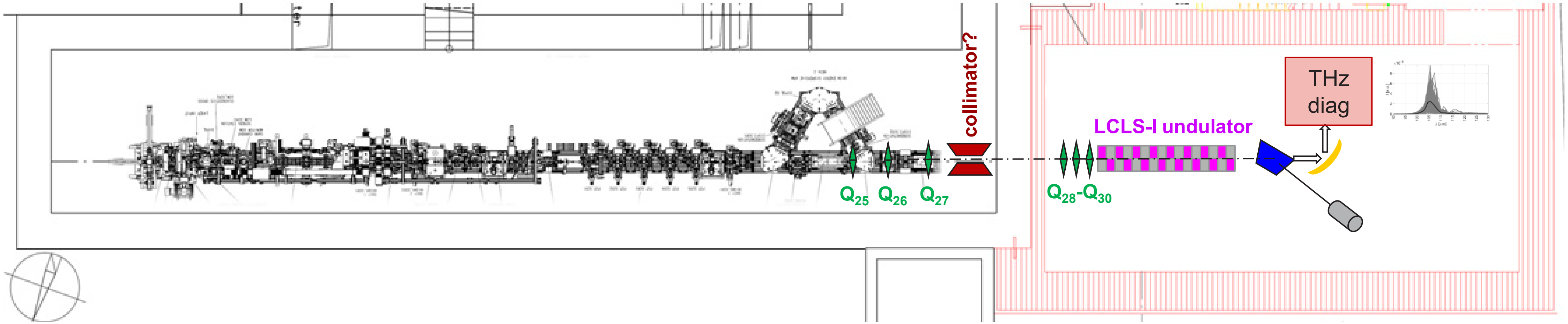
→

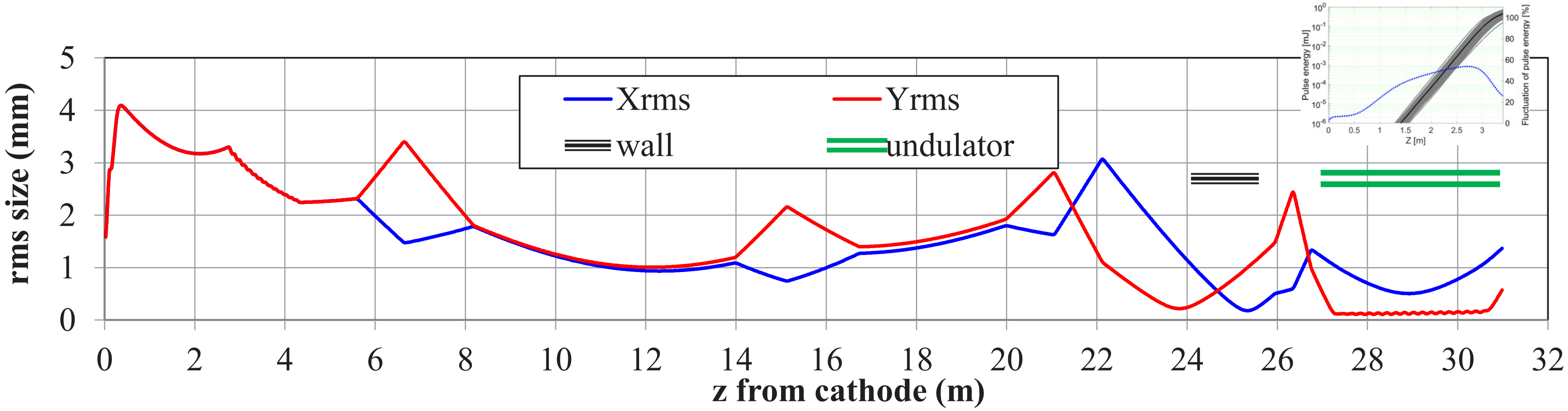
- "Full physics" FEL code?
- Waveguide effects
- Space charge effects
- Wakefields?
- Tolerances on the input beam (imperfections)
- …

- GENESIS simulations with s2e electron beam
  → **~440uJ** (up to **600uJ** by β_y-α_y-tuning) at λ_{rad}~100um

Planned installation of LCLS-I undulators in PITZ tunnel annex

To use for proof-of-principle experiments at PITZ





Backup slides

SASE FEL with LCLS-I Undulator at PITZ

Estimations of parameters (theory) for $\lambda_{rad}\approx 100\mu m$

e-beam

parameter	value
Energy, E_0	16.65 MeV
γ	32.6
σ_E	70 keV
$<\sigma_x>$	1..0.5..1 mm
$<\sigma_y>$	0.2 mm
charge	4 nC
I_{peak}	190 A
$\varepsilon_{n,x,y}$	4 mm mrad
β_x	8 m
β_y	0.3 m

FEL radiation

parameter	value
λ_{rad}	105μm
Q	0.43
A_{JJ}	0.74
θ_l	0.11
γ_l	12.0
Γ	5.4 m^{-1}
Γ^{-1}	0.19 m

$$Q = \frac{K^2}{4+2K^2}$$

$$A_{JJ} = J_o(Q) - J_1(Q)$$

$$\theta_l = K/\gamma$$

$$\frac{1}{\gamma_l^2} = \frac{1}{\gamma^2} + \frac{\theta_l^2}{2}$$

$$\Gamma = \sqrt{\frac{I_{peak}A_{JJ}^2\omega^2\theta_l^2}{2I_A c^2\gamma_l^2\gamma}}$$

Undulator

parameter	value
λ_u	30 mm
K	3.585
Vacuum chamber W / H / R_{eff}	11 / 5 / 4.2 mm

FEL dimensionless

parameter	value
B	0.052
Ω	5.7
ρ	0.013
$\hat{\Lambda}_p^2$	0.41
$\hat{\Lambda}_T^2$	0.11

$$B = \frac{2\Gamma\sigma_y^2\omega}{c}$$

$$\Omega = \Gamma R_{eff}^2\omega/c$$

$$\rho = \frac{\gamma_l^2\Gamma}{\omega/c}$$

$$\hat{\Lambda}_p^2 = \frac{4c^2}{[\theta_l\sigma_r\omega A_{JJ}]^2}$$

$$\hat{\Lambda}_T^2 = \frac{\sigma_E^2}{[E_o\rho]^2}$$

Reference: Saldin E.L., Schneidmiller E.A., Yurkov M.V. “The physics of free electron lasers” - Berlin et al.: Springer, 2000. pp. 41-48, 258, 280, 415-416