Beam-based alignment for the XFEL SASE1

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FEL Beam Dynamics Meeting
2013.03.12

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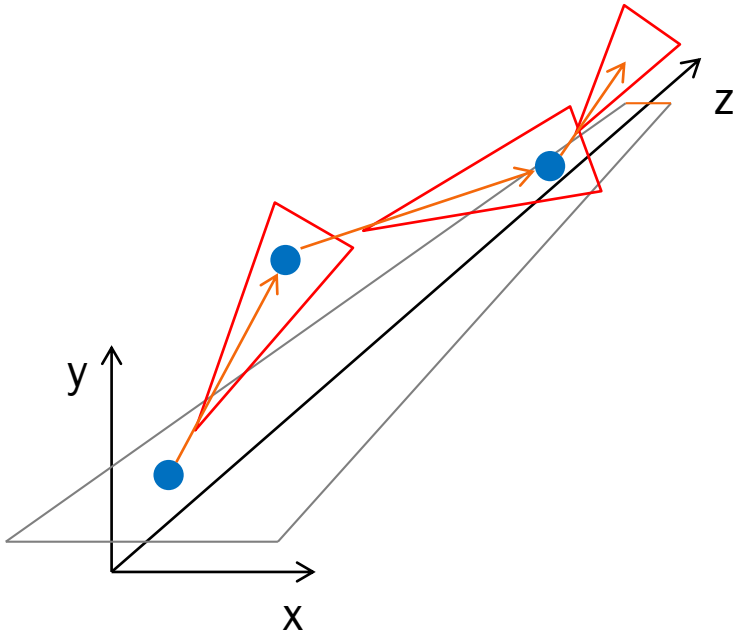
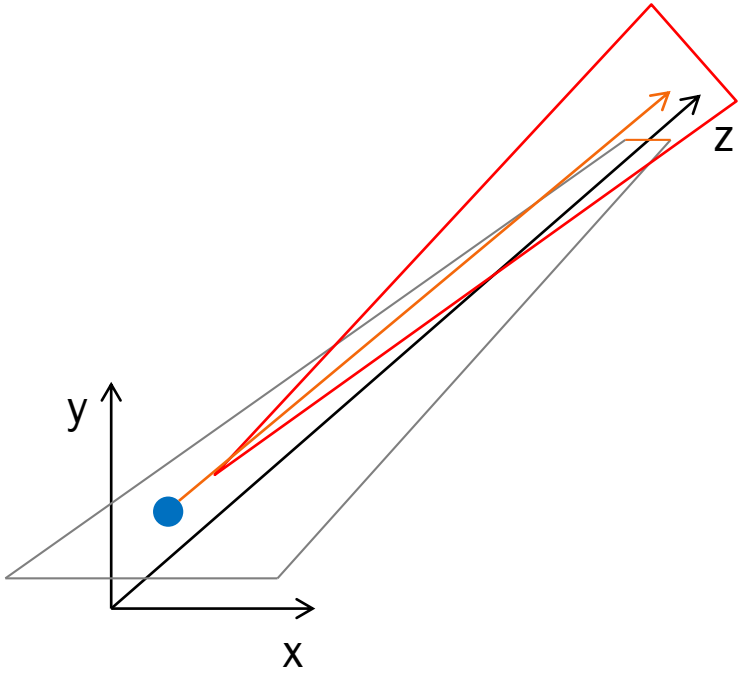
Motivation (I)

- The electron trajectory through undulators less than a few μm is required over a gain length for strong overlap between particle orbit and radiation cone in the XFEL undulators.
- Conventional alignment technique is not enough → beam-based alignment (BBA) with different beam energies is used.



Bad orbit



Good orbit

Motivation (II)

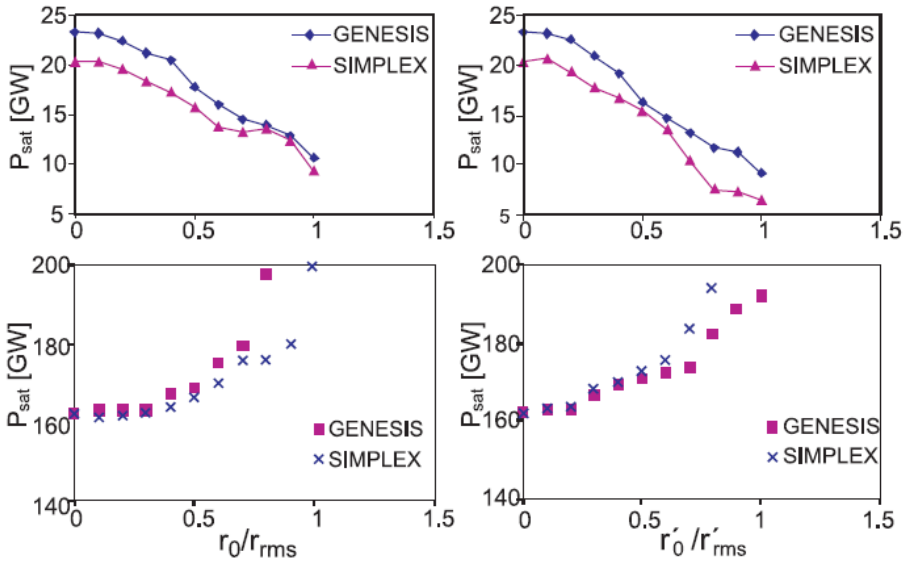


Figure 3: Saturation power (top) and saturation length (bottom) versus beam initial space (left) and angular (right) offsets.

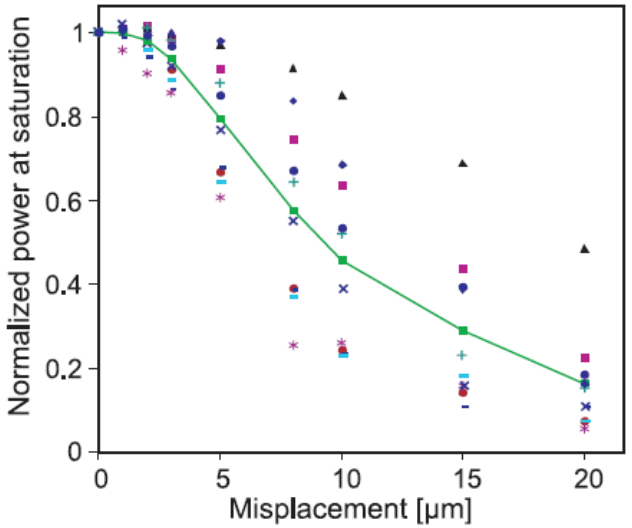


Figure 4: The saturation power versus quadrupole rms misalignments for 10 random seeds.

V. Khachatryan, Proceedings of EPAC08, Genoa, Italy

- Steady-state simulation of the radiation process at the XFEL SASE1 was presented by V. Khachatryan in 2008. The impacts of the initial offset and quadrupole misalignment were investigated.
- Time-dependent simulations of the radiation process are needed for more precise results in XFEL SASE1.

BBA implementation
- LCLS method - (H. Loos/SLAC)

1. Make response matrices for 4 different beam energies (4.0, 10.0, 14.5, 17.5 GeV)
2. Save BPM readings for each energy
3. Calculate quadrupole & BPM offsets with SVD ⟶ set to new positions for quadrupoles and correct the offsets for BPMs
4. Linear fit from corrected offsets ⟶ correct launch position & angle
5. Steer BPM readings to remove remaining small oscillations using a minimum number of quad-movers
6. Repeat above steps until saturation

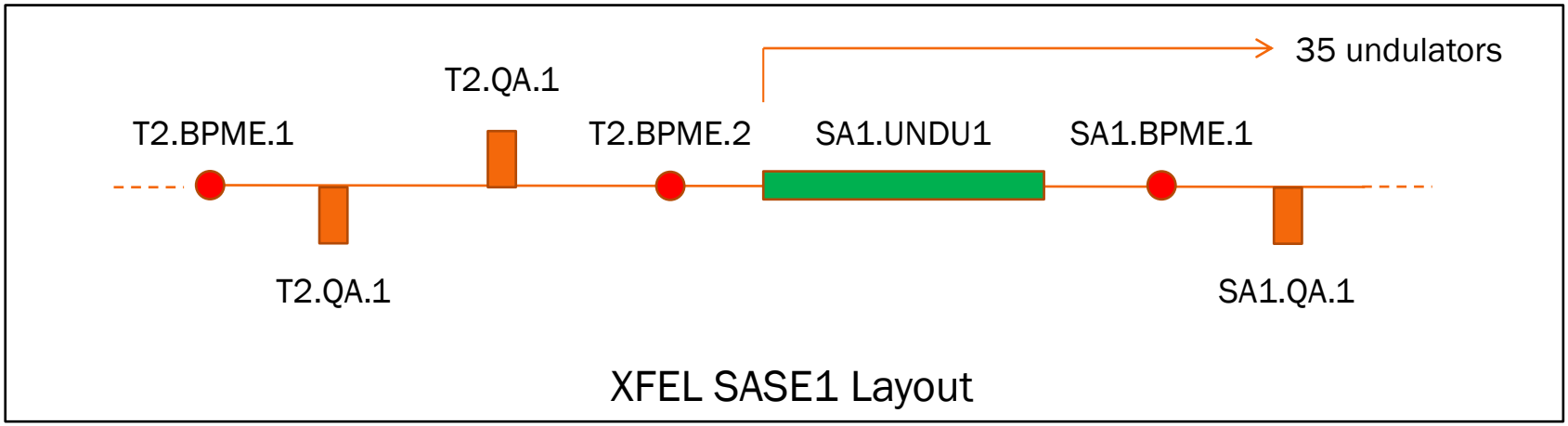
Beam positions at BPMs with launch condition & errors

$$\begin{bmatrix} x_1 \\ . \\ . \\ . \\ x_n \end{bmatrix} = \begin{bmatrix} & & \\ & LRM_{E1} & \\ & & \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix} + \begin{bmatrix} & & \\ & ORM_{E1} & \\ & & \end{bmatrix} \begin{bmatrix} \Delta Q_1 \\ . \\ . \\ \Delta Q_m \end{bmatrix} + \begin{bmatrix} & & \\ & I & \\ & & \end{bmatrix} \begin{bmatrix} \Delta B_1 \\ . \\ . \\ . \\ \Delta B_n \end{bmatrix} + \begin{bmatrix} \xi_1 \\ . \\ . \\ . \\ \xi_n \end{bmatrix}$$

Parameter		Parameter	
x_i	Transverse position at BPM i	(x_0, x'_0)	Transverse launch condition
LRM	Launch response matrix	ORM	Orbit response matrix
n	# of BPMs	m	# of quadrupoles
ΔQ	Quadrupole offset	ΔB	BPM offset
ξ	BPM resolution error		

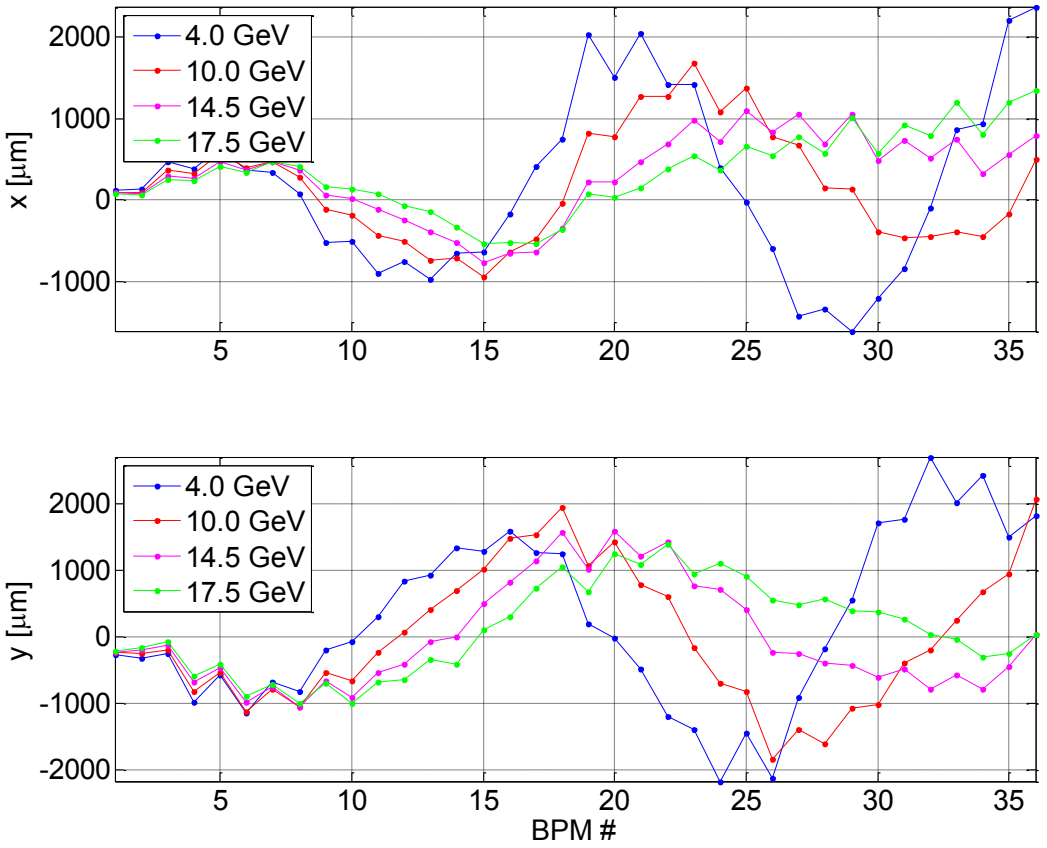
Beam-based alignment simulation

- Simulation code : Elegant
- Errors
  - BPM rms resolution : 1 μm (±1σ)
  - BPM rms offset : 100 μm (±3σ)
  - QUAD rms offset : 100 μm (±3σ)
- Fixed quadrupole field
- Simulations for 100 random seeds



XFEL SASE1 Layout

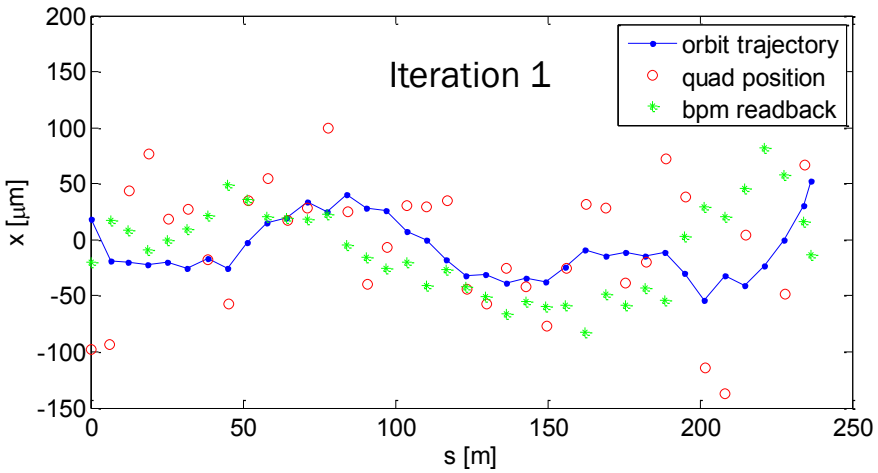
Orbit size with BPM & quadrupole errors



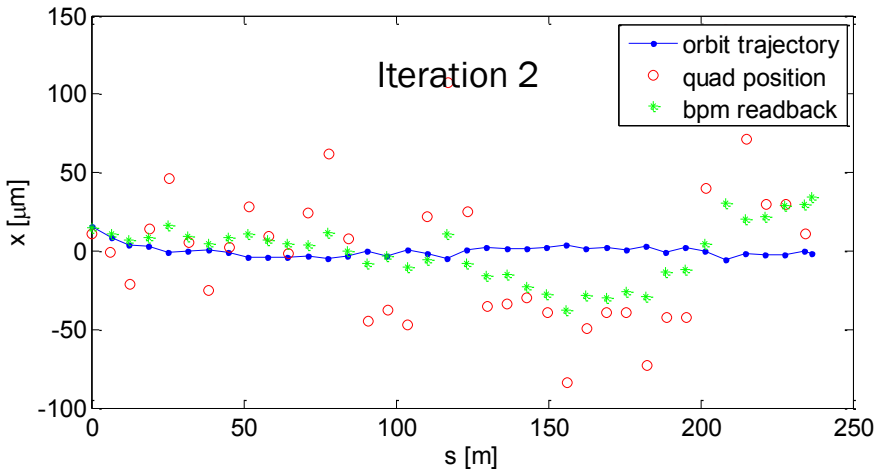
1 random seed

Orbit trajectory, quadrupole position, and BPM reading during 3 iterations at 17.5 GeV

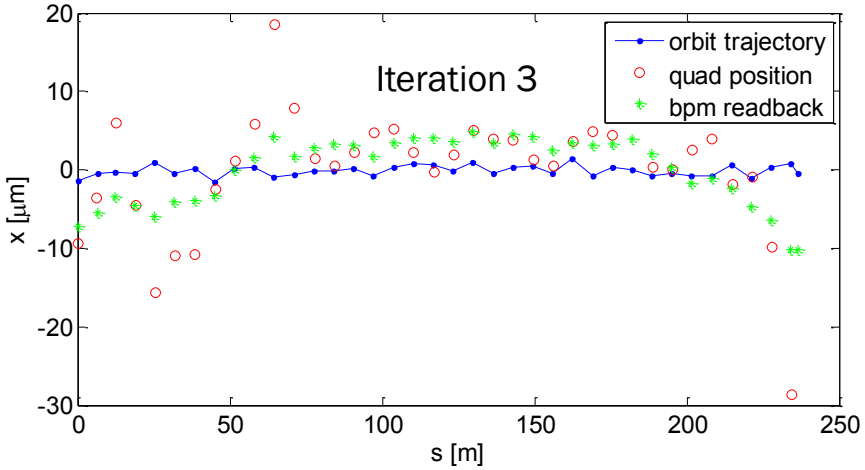
$< x >_{rms}$=27m,$< x_{BPM} >_{rms}$=40μm,$< x_{QUAD} >_{rms}$= 63μm



$< x >_{rms}$=4.7μm,$< x_{BPM} >_{rms}$=19 μm,$< x_{QUAD} >_{rms}$= 47μm

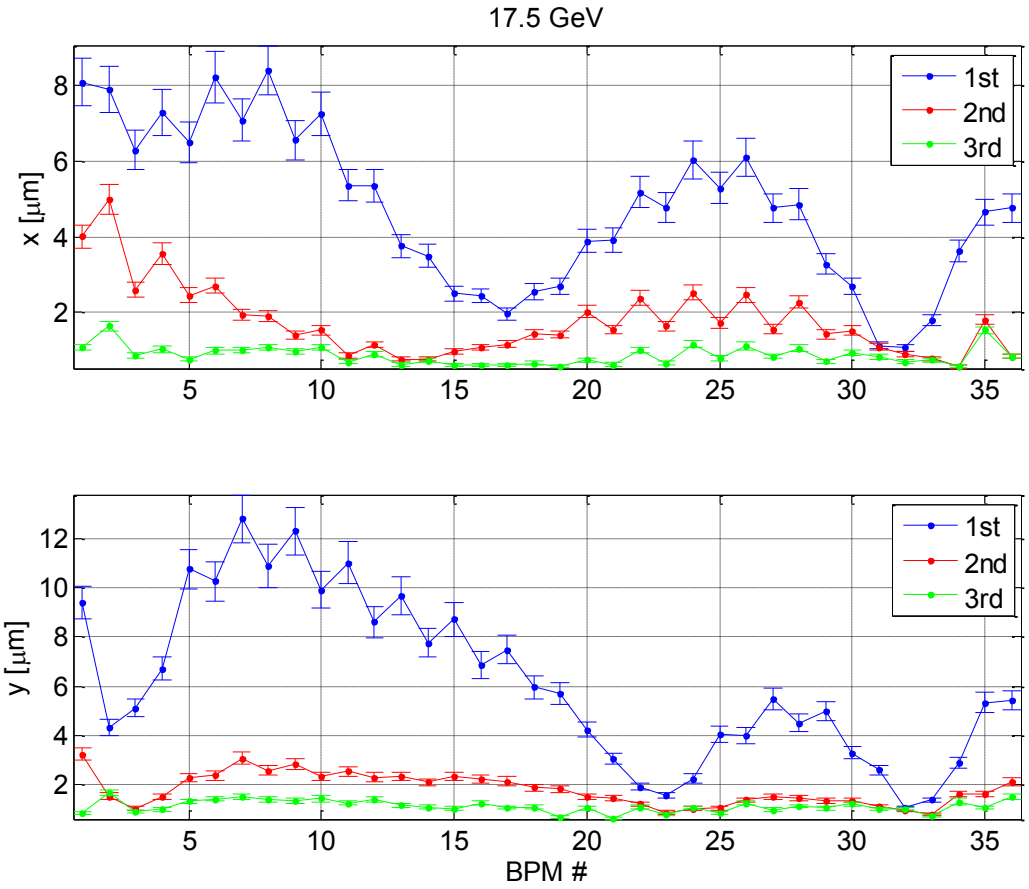


$< x >_{rms}$=0.7μm,$< x_{BPM} >_{rms}$=4.3μm,$< x_{QUAD} >_{rms}$= 7.8μm



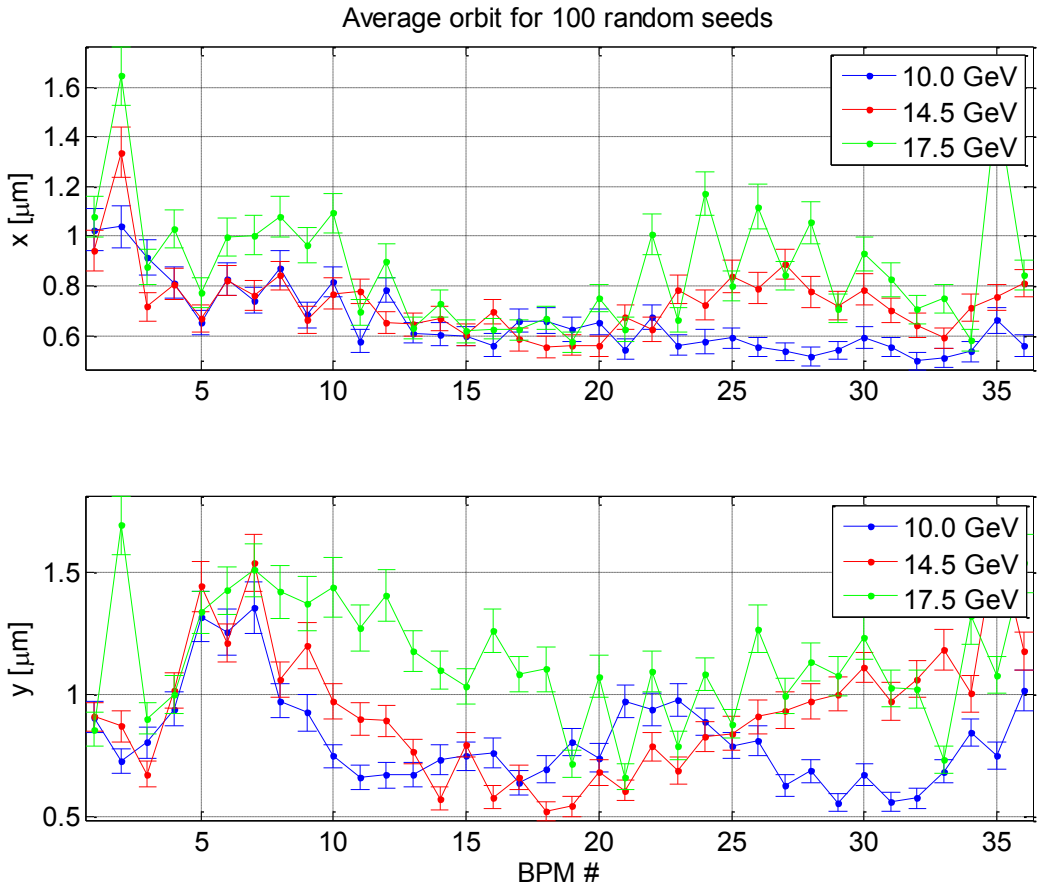
Orbit trajectory (blue line), quadrupole position (red circle), and BPM readback (green star) for 1 random seed during 3 iterations at 17.5 GeV (linear component removed for clarity).

Average orbit size during 3 iterations at 17.5 GeV



100 random seeds, absolute value

Average orbit size after 3 iterations at three beam energies



100 random seeds, absolute value

Rms orbit size is about 1-2 μm after 2 or 3 iterations.

Start-to-end simulation for radiation process at SASE1

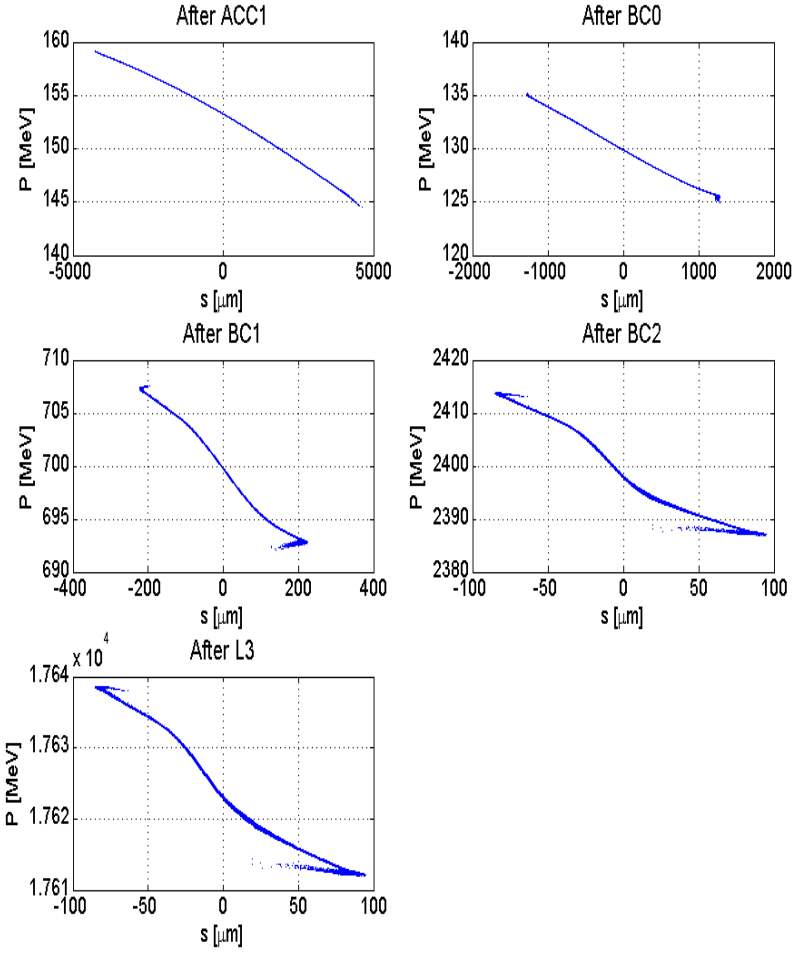
- Simulations
  - Bunch charge : 1 *nC*
  - Macro-particles : 200,000
  - Programs :

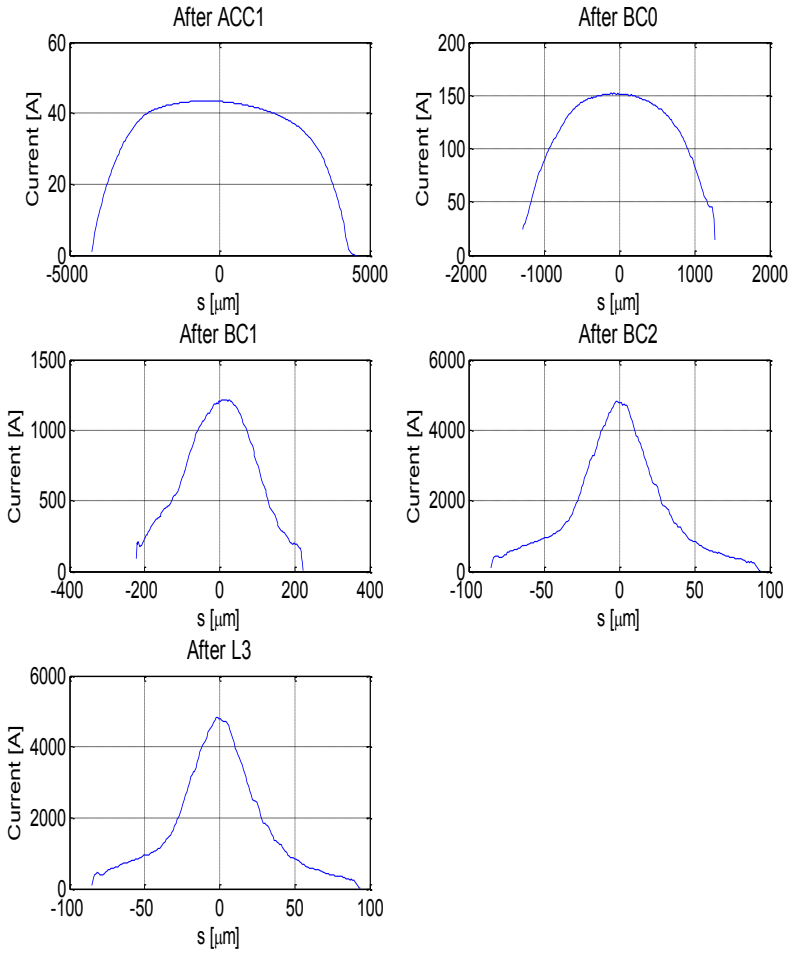
Program	XFEL lattice	
Astra	Gun – ACC1	
Elegant	After ACC1 – before SASE1	(CSR, LSC, no wake)
Genesis	SASE1	

  - RF settings :

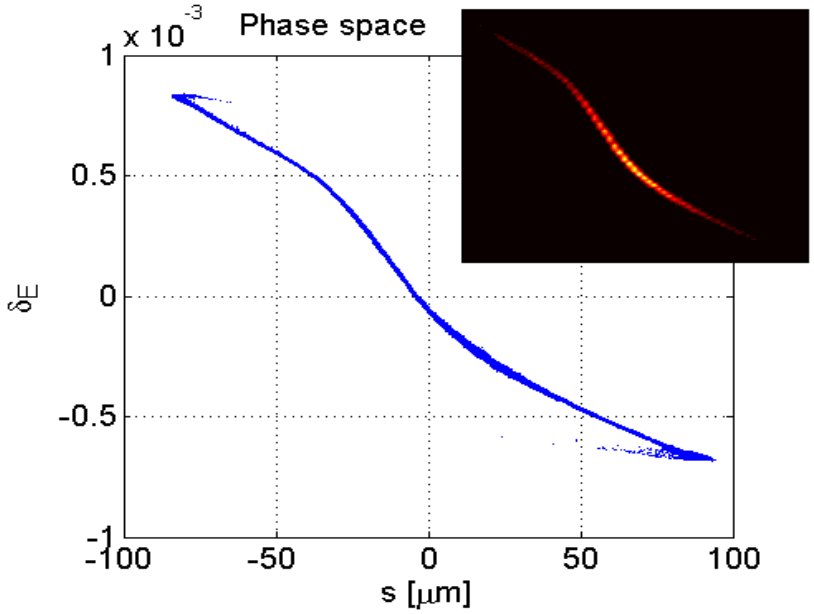
V_{11}[MeV]	ϕ_{11}[deg]	V_{13}[MeV]	ϕ_{13}[deg]	V_2[MeV]	ϕ_2[deg]	V_3[MeV]	ϕ_3[deg]
145.0	90 – 5.4	24.1	90 + 166.0	574.6	90 – 7.9	2000.5	90 – 31.8

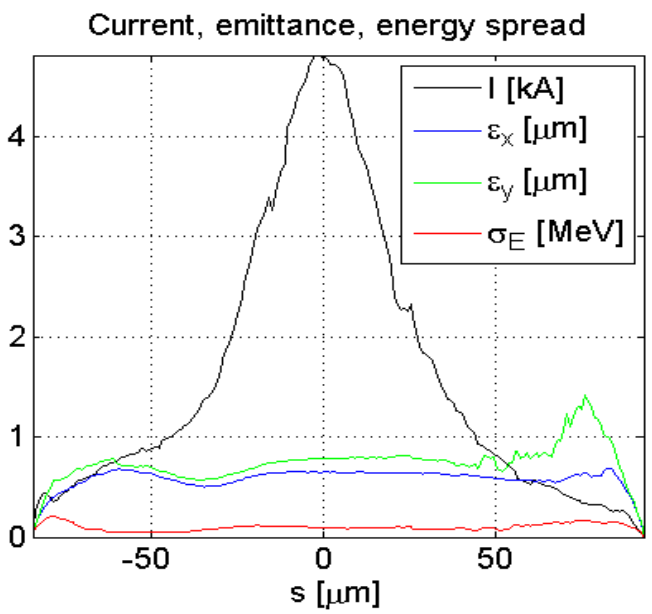
Longitudinal phase space & beam current along BCs & linacs





Beam profile after main linac





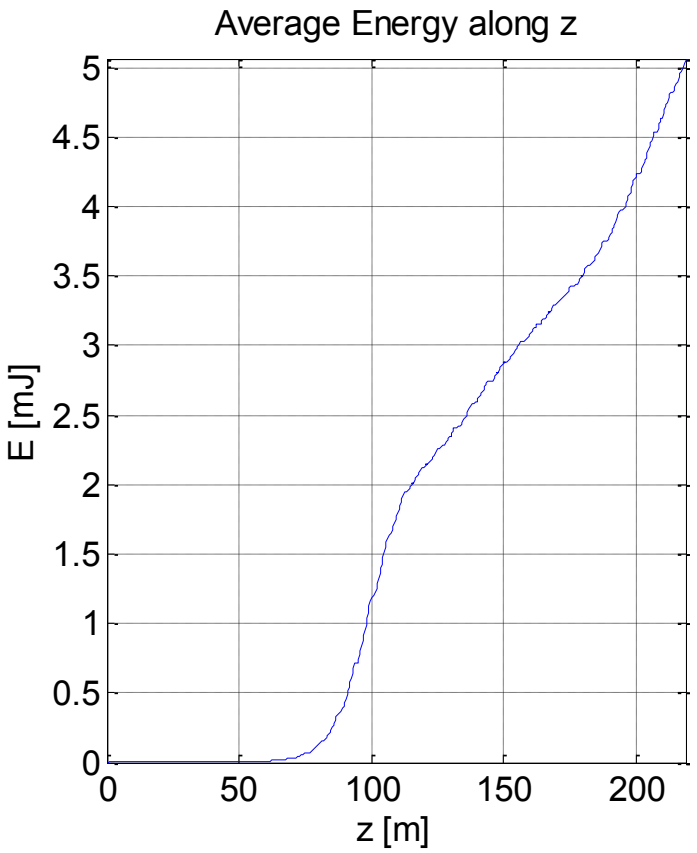
Remove about 3% bad particles in the analysis

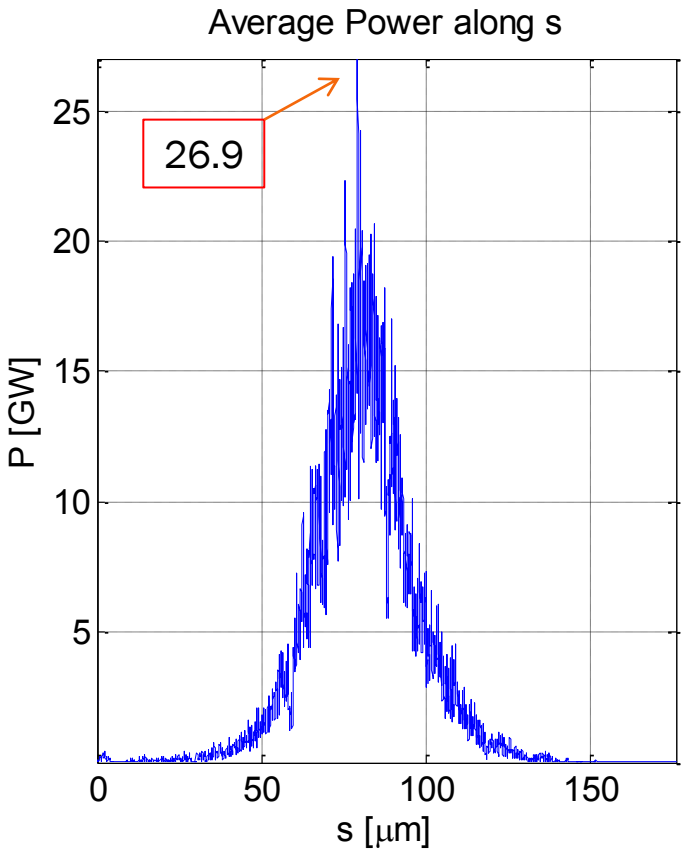
$\varepsilon_{proj,x}$ = 0.8 μm

$\varepsilon_{proj,y}$ = 2.9 μm

FWHM = 163.5 fs

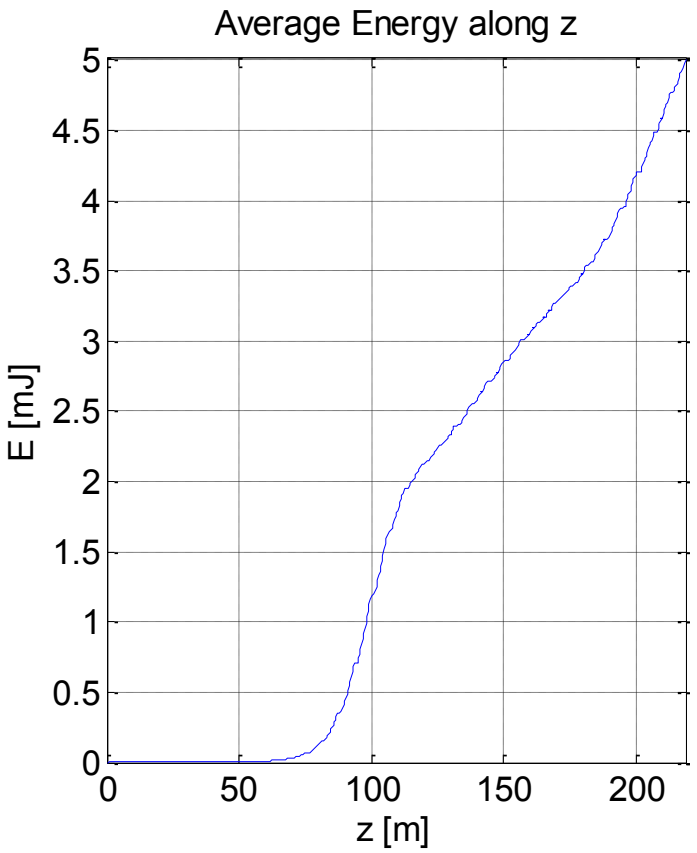
Average radiation energy & power

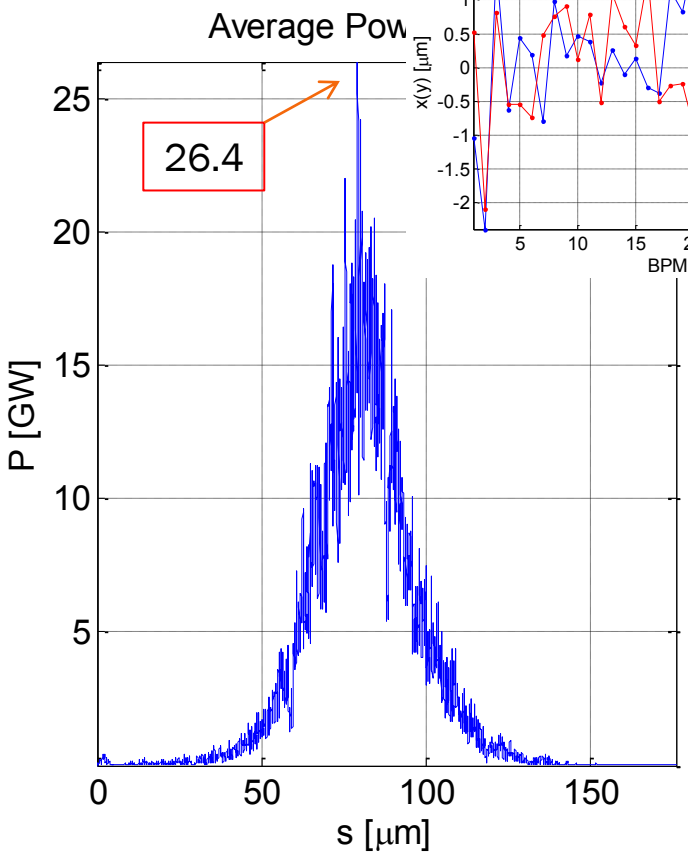


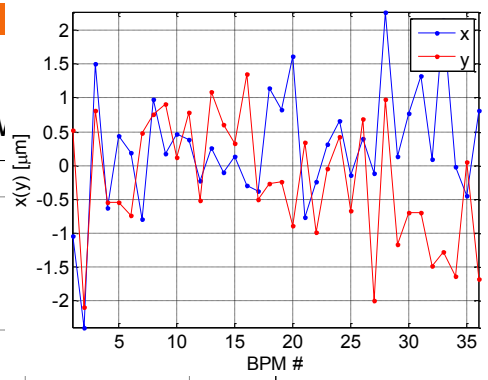


10 random seeds for shot noise

Average radiation energy & power with orbit after BBA

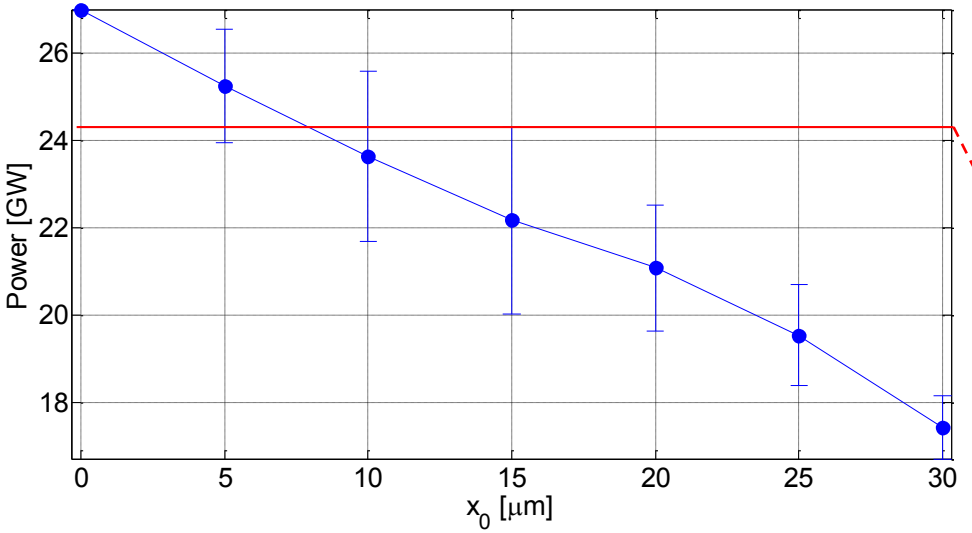






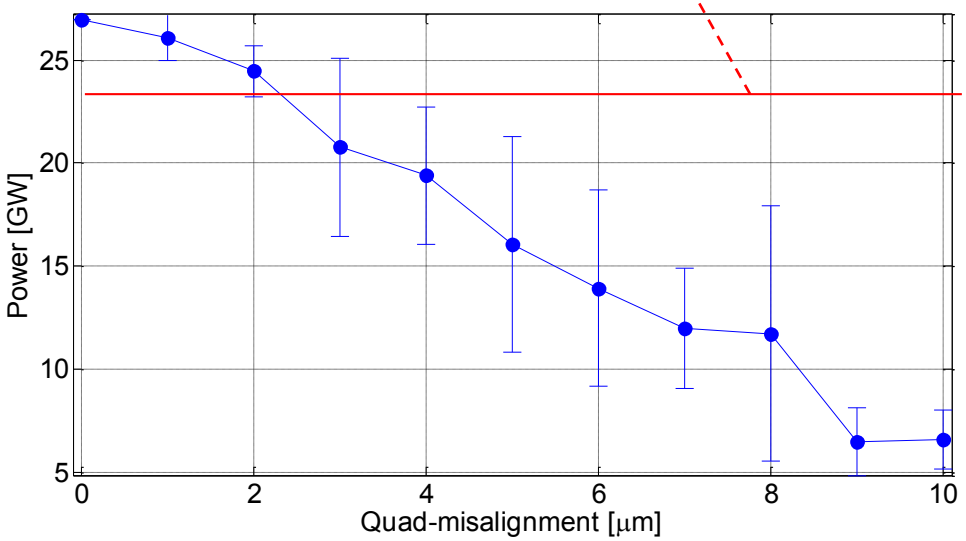
10 random seeds for shot noise

Average radiation power with initial x-offset & quad-misalignment



Average radiation power vs. initial horizontal offset (5 random seeds for shot noise)

10 % decrease of average radiation power



Average radiation power vs. rms misalignments of quadrupoles (5 random seeds for misalignments & 1 random seed for shot noise)

Summary

- Achieved
  - Beam based-alignment technique of LCLS was applied to the XFEL SASE1.
  - Rms orbit size decreased to about 1-2 μm after 2 ~ 3 iterations for 100 μm (±3) BPM- and quadrupole-offset errors.
  - Time-dependent simulation of the radiation process was performed in SASE1. Average radiation power was strongly dependent on initial x-offset and quadrupole misalignment.
- To do
  - To include other errors (quadrupole gradient error, mover calibration error etc.)
  - To study the radiation process at low charges
  - To apply this method into FLASH undulators. Last month BBA experiment was performed in FLASH with M. Vogt. However the lattice which was used in calculation was wrong in some parts. Therefore new experiment will be done in Aug. or later 2013 with the revised data.

Thank you for your attention