Electron beam trajectory manipulation and correction in XFEL SASE1

Artsrun Sargsyan and Vahe Sahakyan

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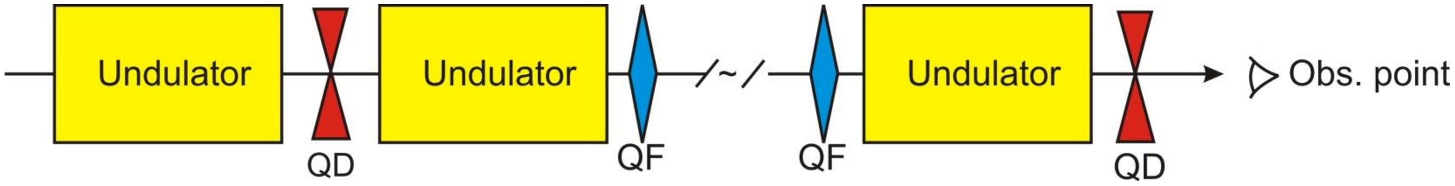
Introduction

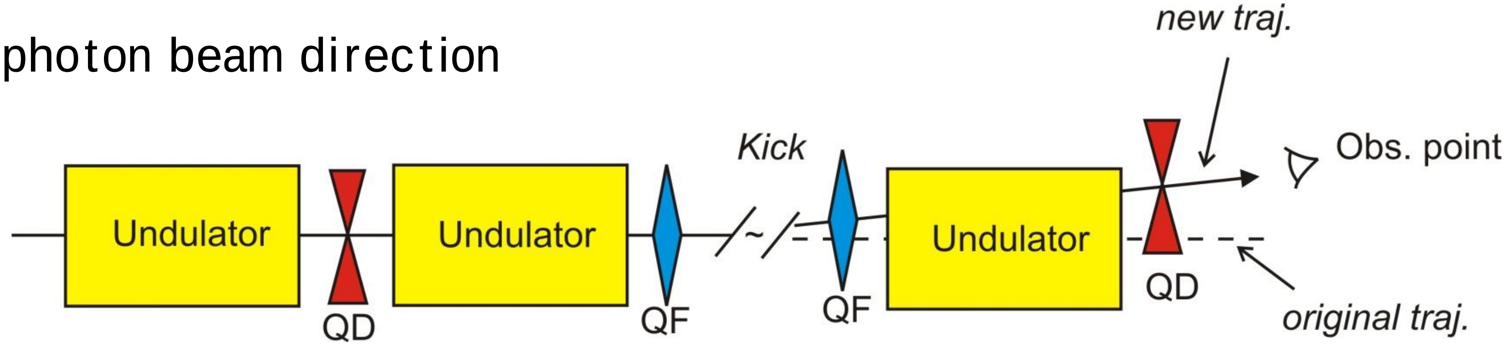
SASE1 undulator line

35 sections	
Undulator length –	5 m
FODO period length -	12.2 m

- Design case



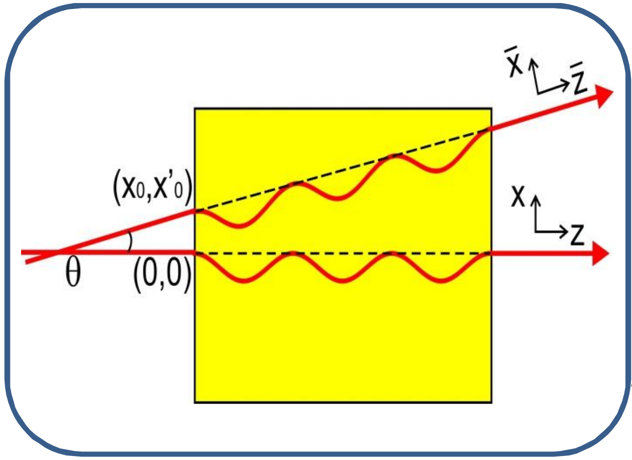
- New photon beam direction

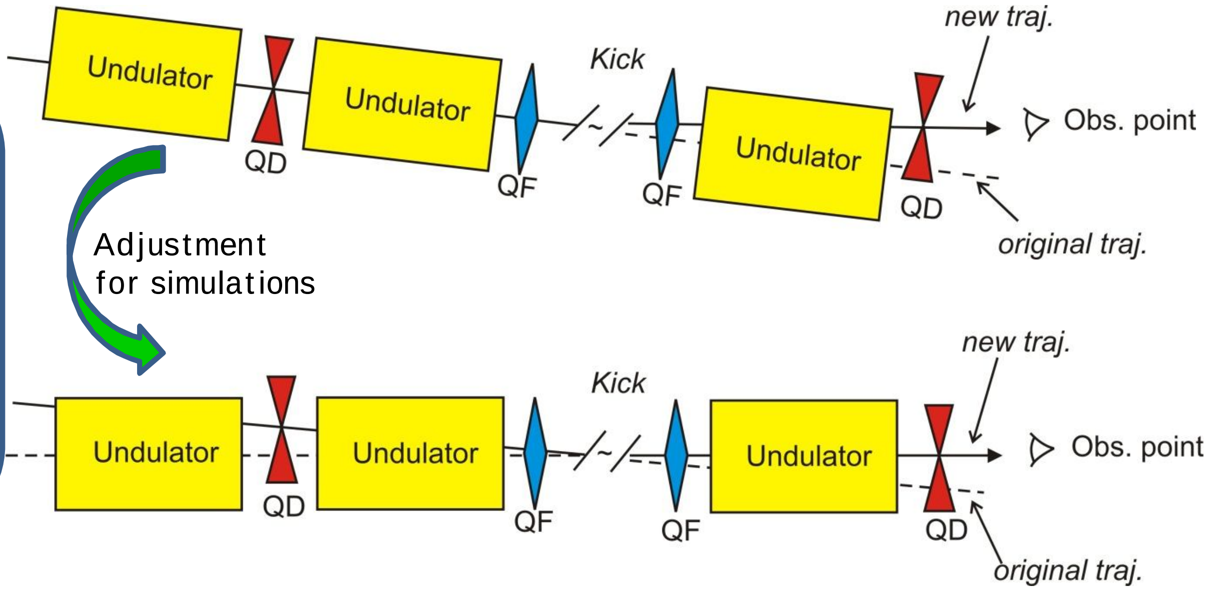


Consideration of different kick positions to have 1mm shift of photon beam after 100m from SASE1

Kick angle
$\theta \leq 10^{-5}\ rad$

Adjustment for Genesis simulations





traj. in (x,z) for $x_0 = x_0' = 0$

$$x(z) = \frac{K}{\gamma\beta k_u}\left(\cos k_u z - 1\right)$$

traj. in (x,z) for $x_0 \neq 0,\ x_0' \neq 0$

$$x(z) = \frac{K}{\gamma\beta k_u}\left(\cos k_u z - 1\right) + x_0' z + x_0$$

1-st order approx.

Rot. Trans. $(x,z) \Rightarrow (\bar{x},\bar{z})$

traj. in $(\bar{x},\bar{z})$

$$\bar{x}(\bar{z}) \approx \frac{K}{\gamma\beta k_u}\left(\cos k_u \bar{z} - 1\right)\left(1 + \frac{K}{\gamma\beta}\theta \sin k_u \bar{z}\right) \approx \frac{K}{\gamma\beta k_u}\left(\cos k_u \bar{z} - 1\right)$$

Time dependent simulation results

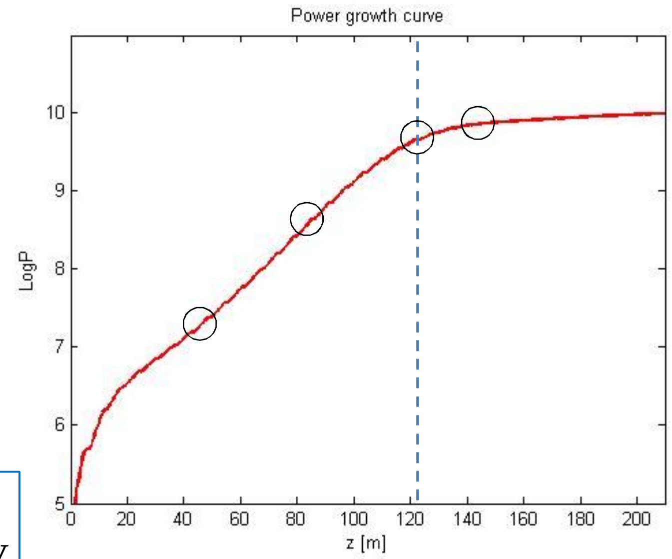
Beam parameters

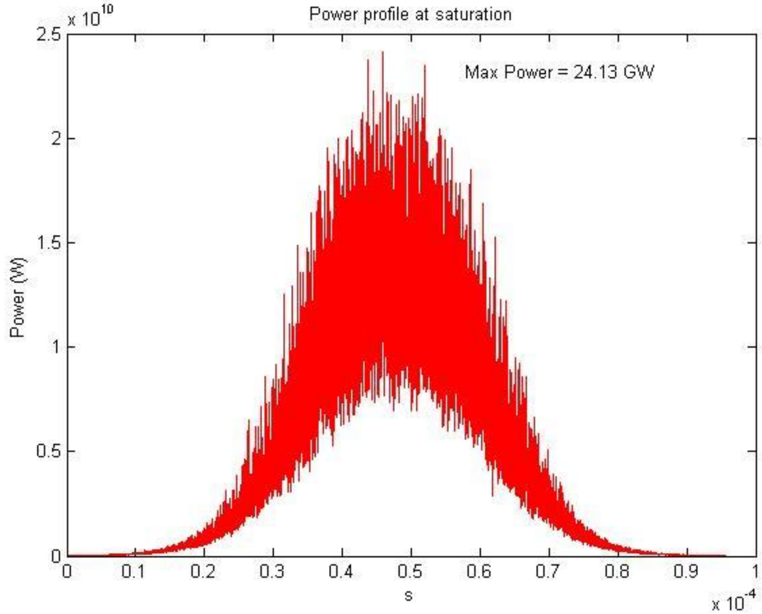
Beam energy	17.5 GeV
Bunch charge	1 nC
Peak current	5 kA
Bunch length (rms)	25 μm
Normalized emittance	1.4 mm mrad
Energy spread (rms)	1.5 MeV

Considered cases

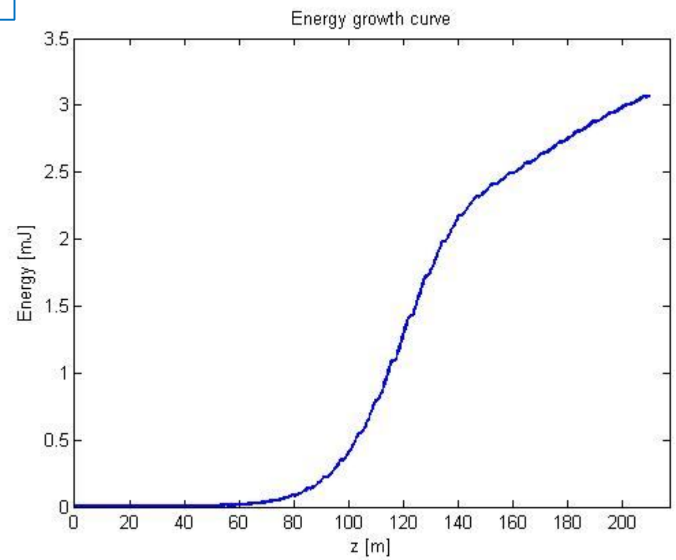
Kick at	Position
8-th quad	48.8 m
14-th quad	85.4 m
20-th quad	122 m
24-th quad	146.4 m

Simulation results for design case



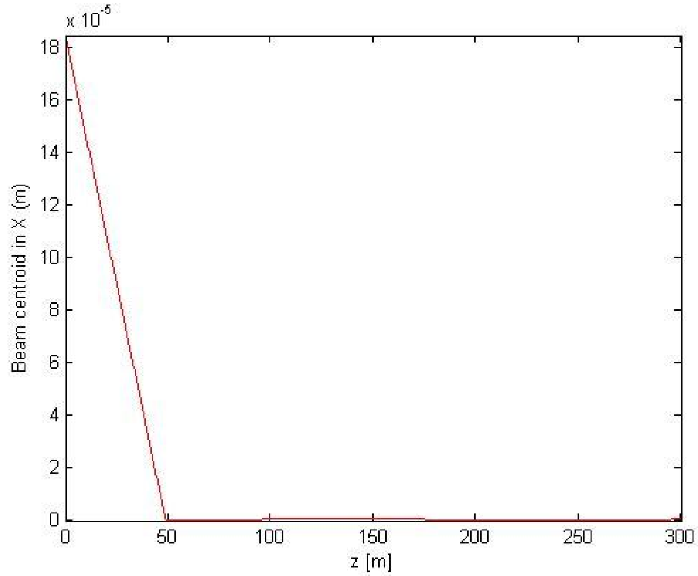


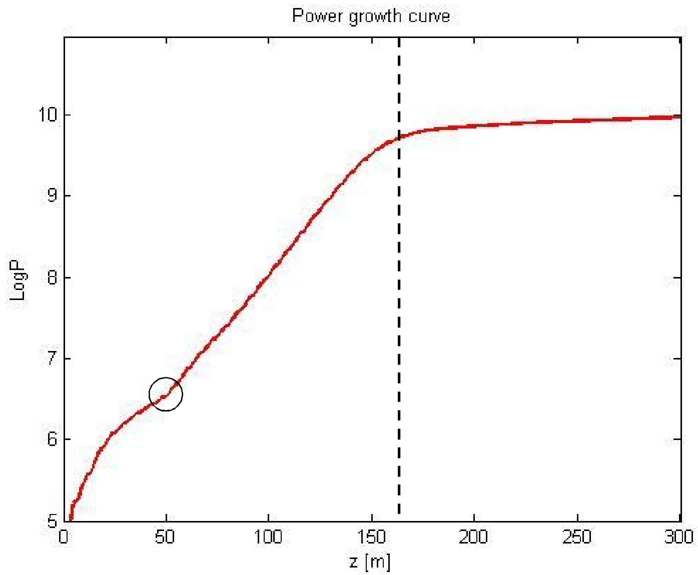
$$L_{sat} \approx 123m$$
$$P_{\max} \approx 24.13GW$$

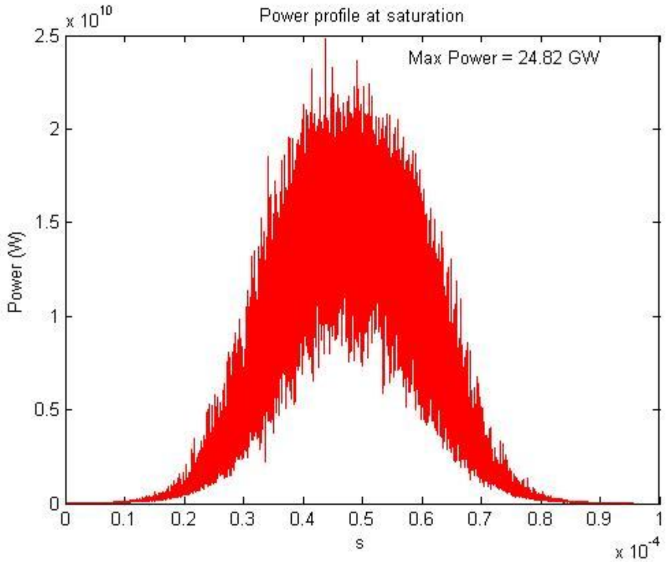


Time dependent simulation results

Kick at 8-th quad. to have 1mm offset after 100m from SASE1

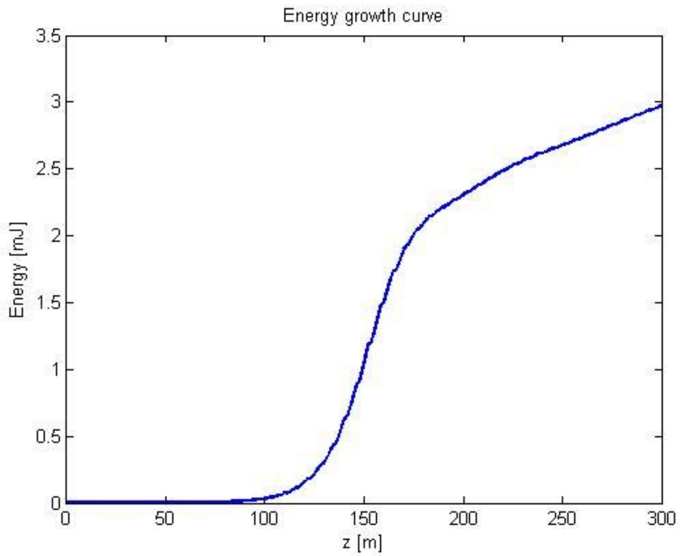






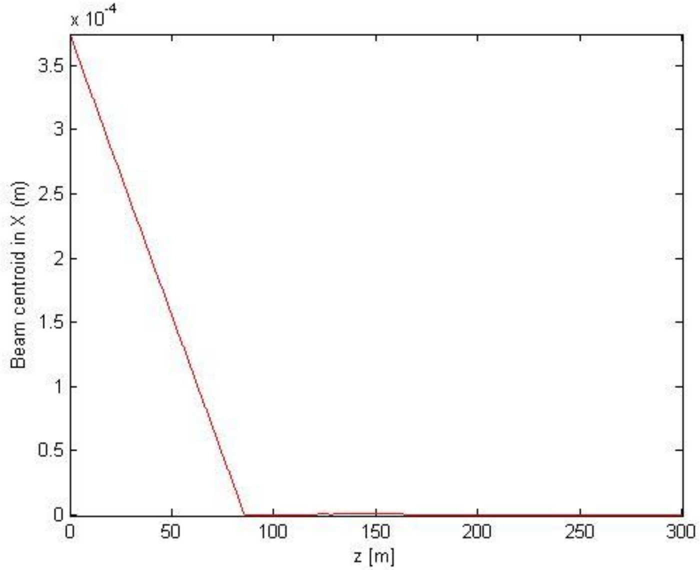
$$L_{sat} \approx 162\,m$$
$$P_{\max} \approx 24.82\,GW$$

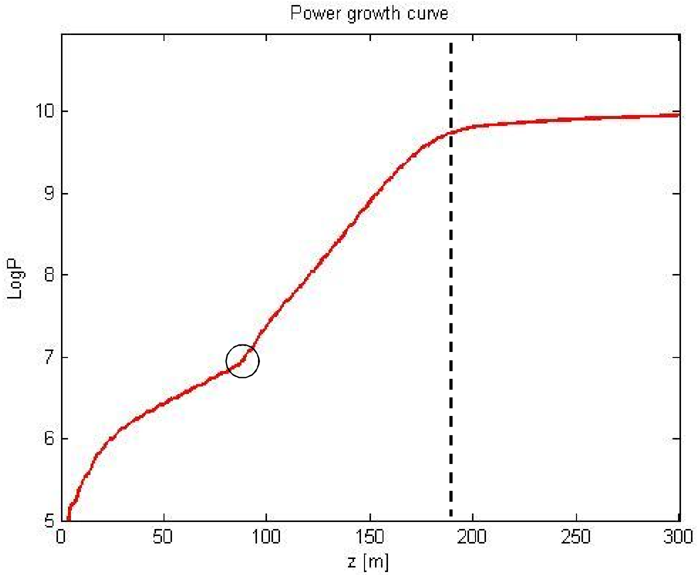
$$\frac{L_{sat} - L_{kick}}{L_{sat.des}} = 0.92$$

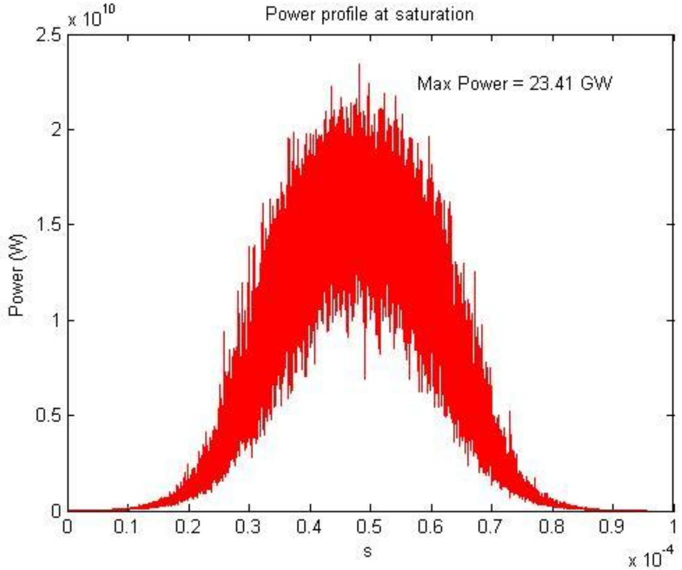


Time dependent simulation results

Kick at 14-th quad. to have 1mm offset after 100m from SASE1

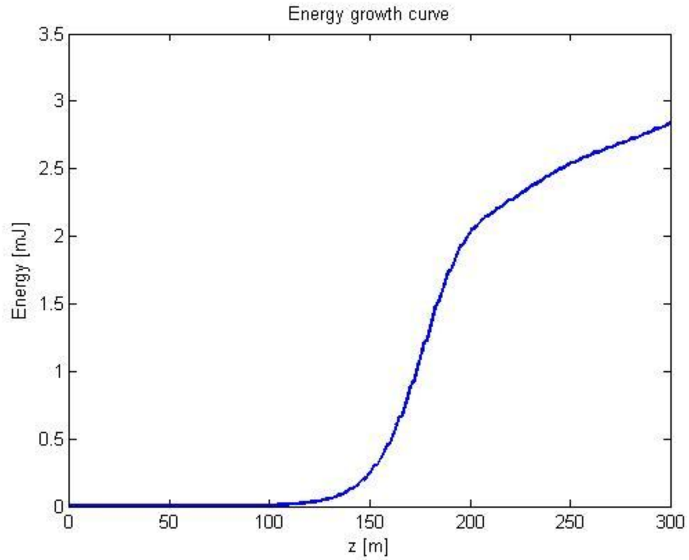






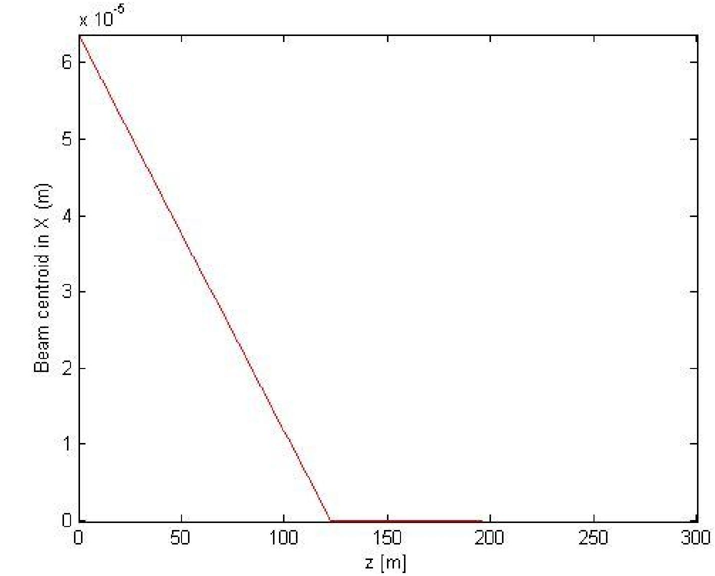
$$L_{sat} \approx 192\,m$$
$$P_{\max} \approx 23.41\,GW$$

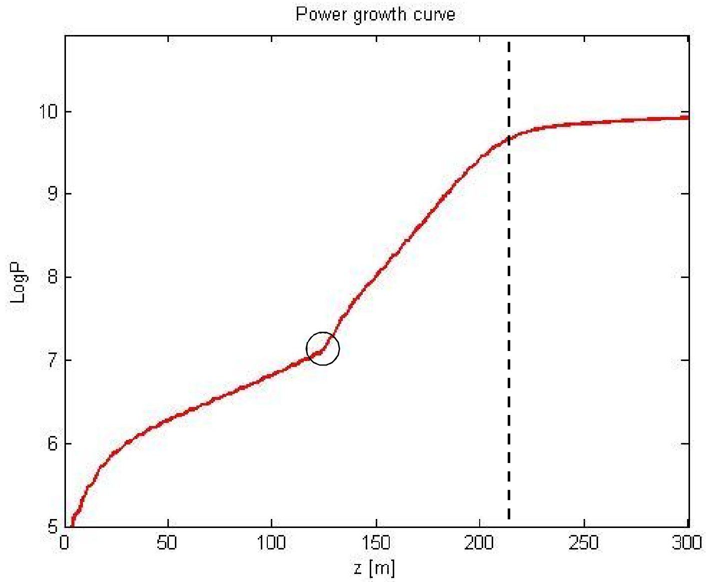
$$\frac{L_{sat} - L_{kick}}{L_{sat.des}} = 0.86$$

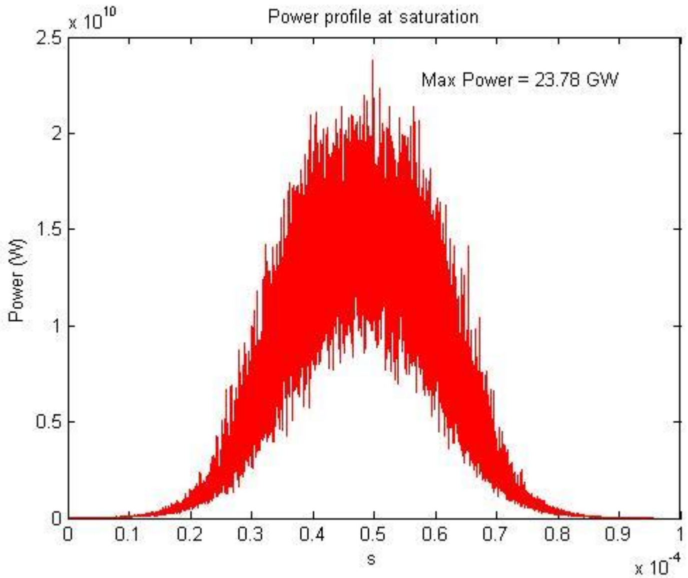


Time dependent simulation results

Kick at 20-th quad. (sat point for design) to have 1mm offset after 100m from SASE1

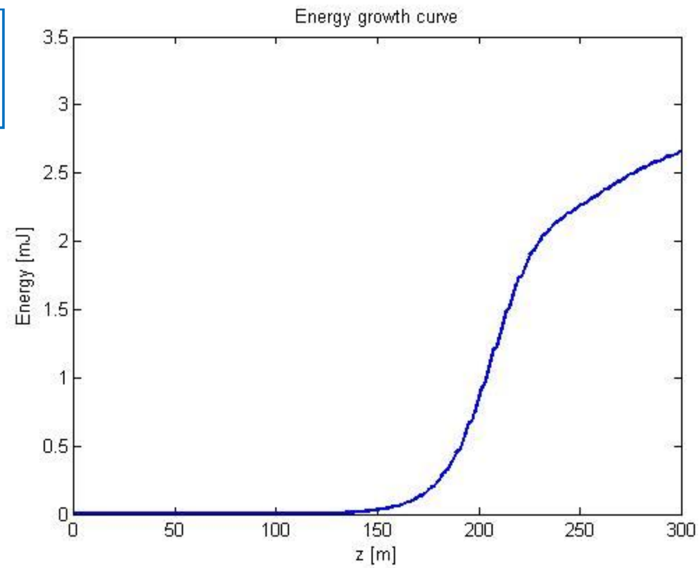






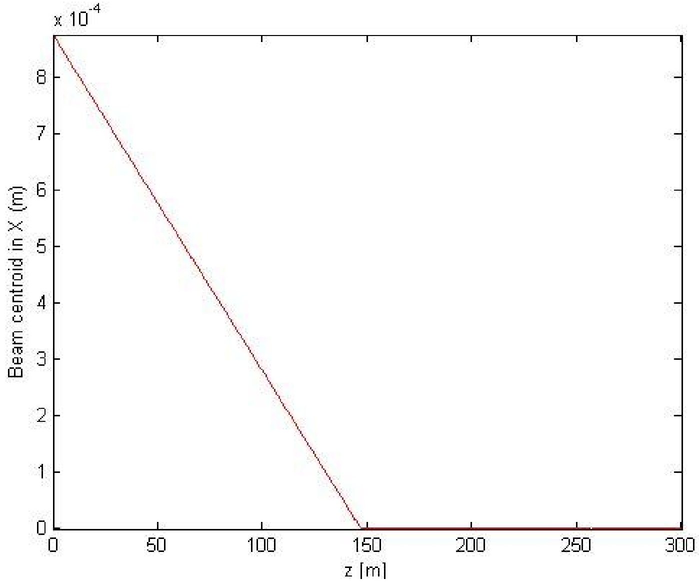
$$L_{sat} \approx 217\,m$$
$$P_{\max} \approx 23.78\,GW$$

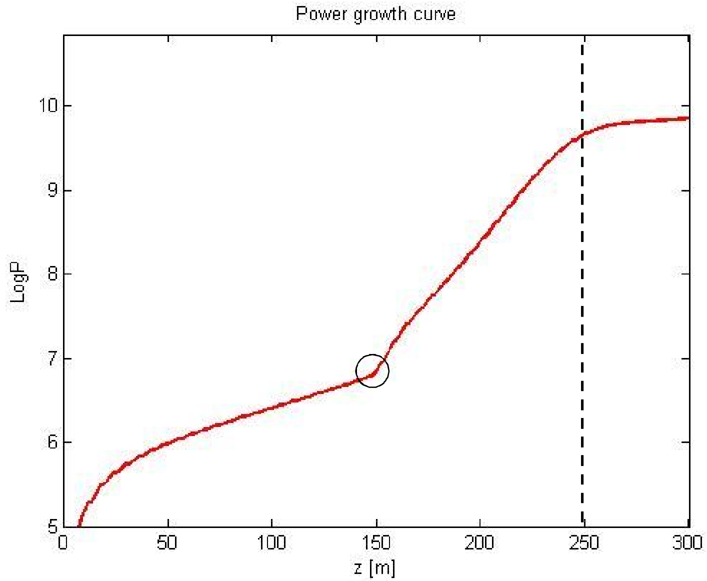
$$\frac{L_{sat} - L_{kick}}{L_{sat.des}} = 0.76$$

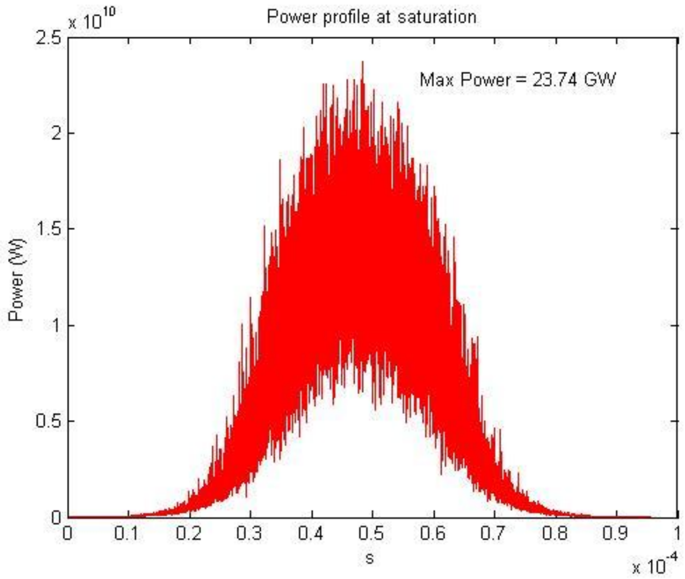


Time dependent simulation results

Kick at 24-th quad. to have 1mm offset after 100m from SASE1

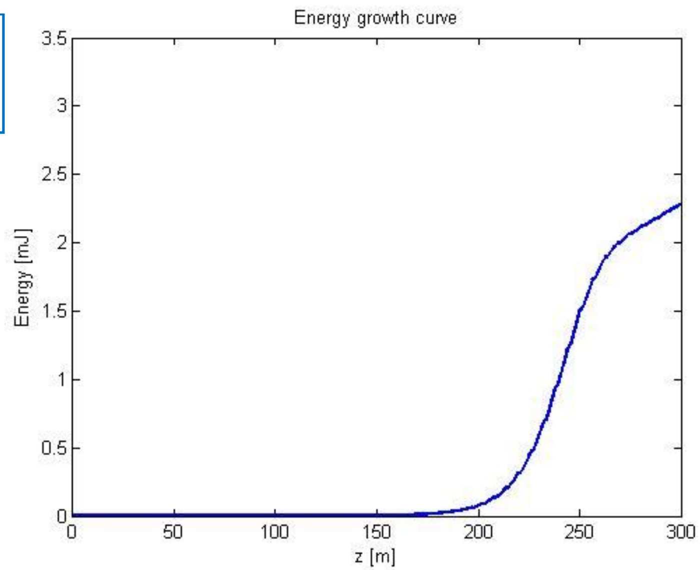






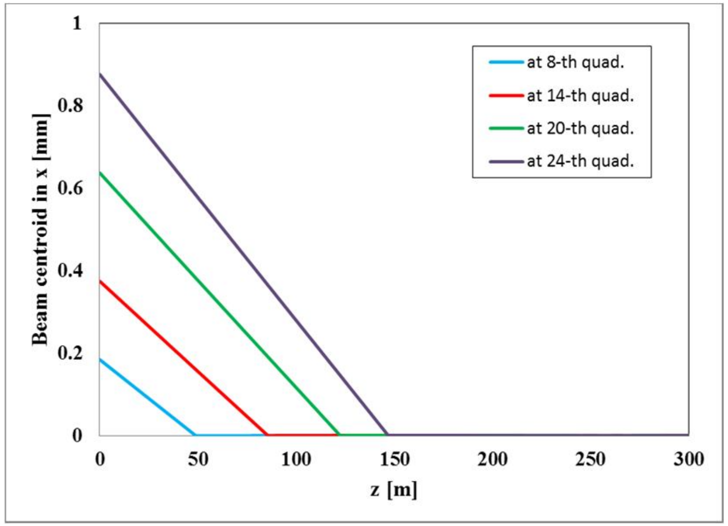
$$L_{sat} \approx 249\,m$$
$$P_{\max} \approx 23.74\,GW$$

$$\frac{L_{sat} - L_{kick}}{L_{sat.des}} = 0.83$$

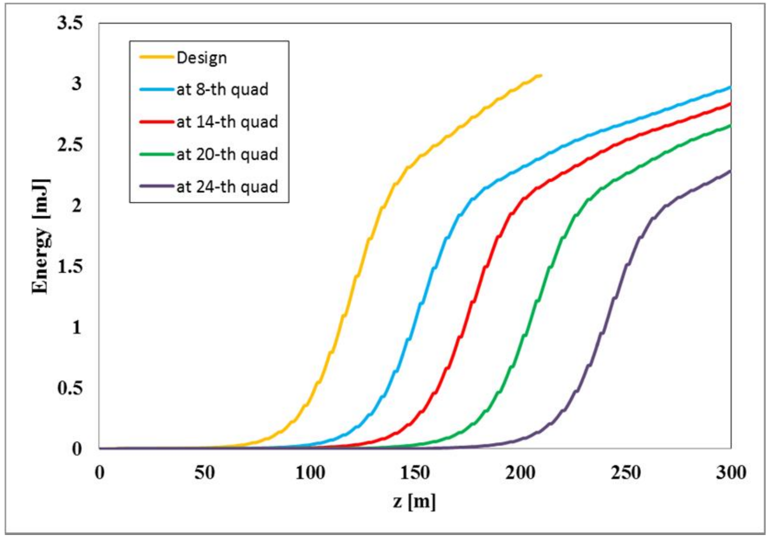


Time dependent simulation results

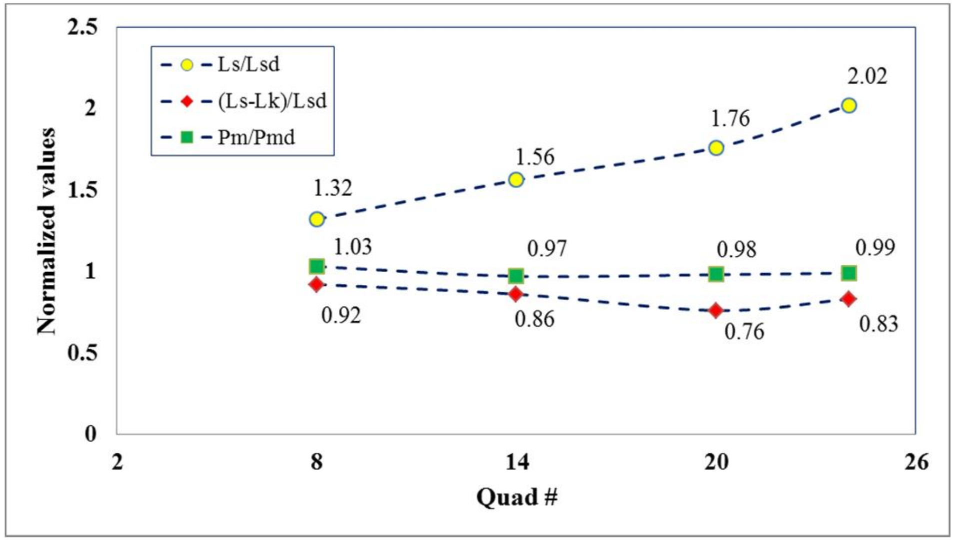
Considered trajectories



Energies for considered cases



Evaluation of saturation parameters



Conclusion

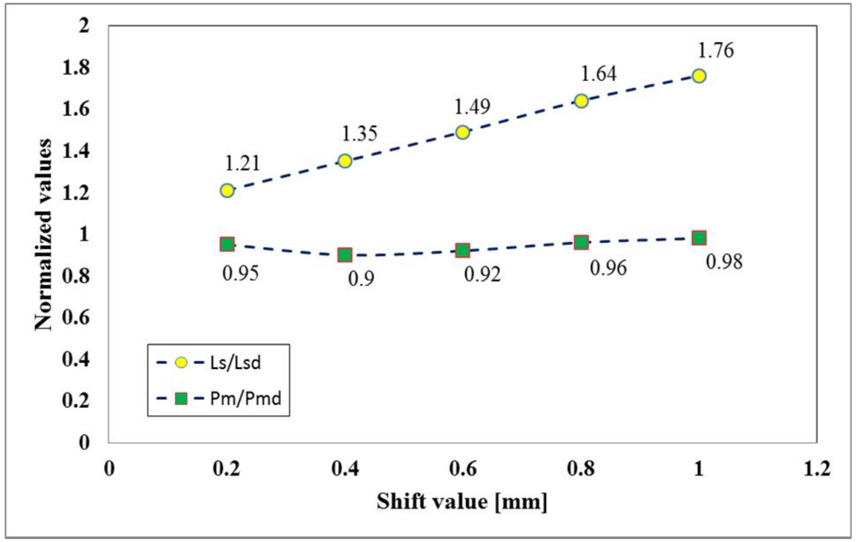
The shortest saturation distance after the kick is reached when the kick is performed at saturation point of the design case.

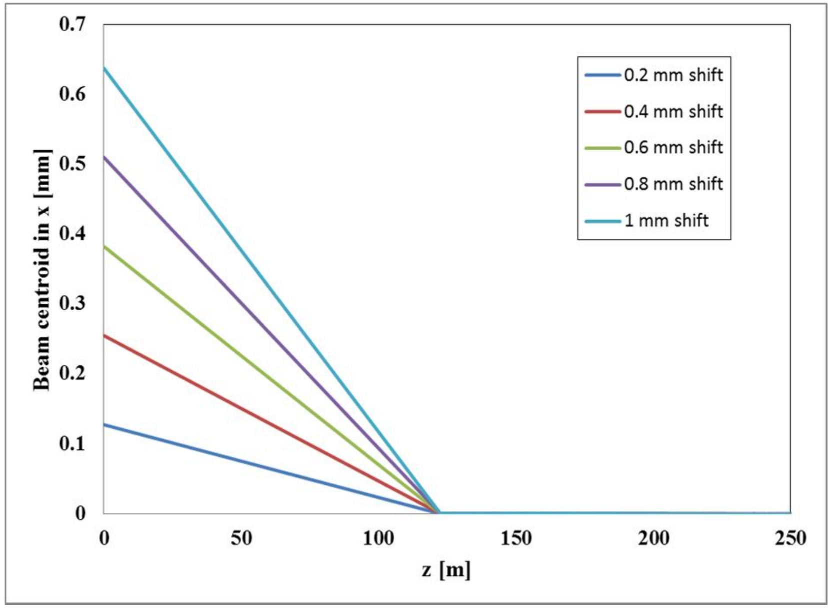
Time dependent simulation results

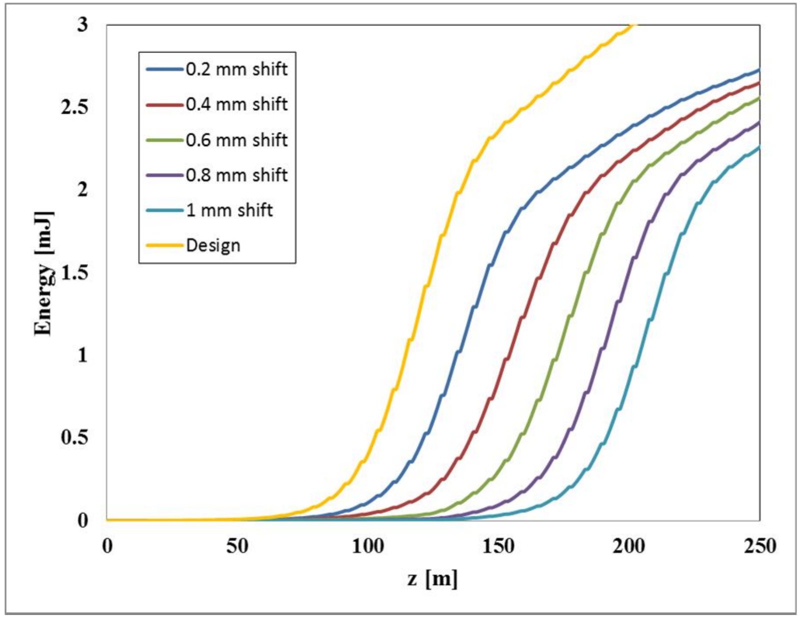
Kick at saturation point (at 20-th quad)

Considered cases

- 0.2 mm after 100 m
- 0.4 mm after 100 m
- 0.6 mm after 100 m
- 0.8 mm after 100 m
- 1.0 mm after 100 m

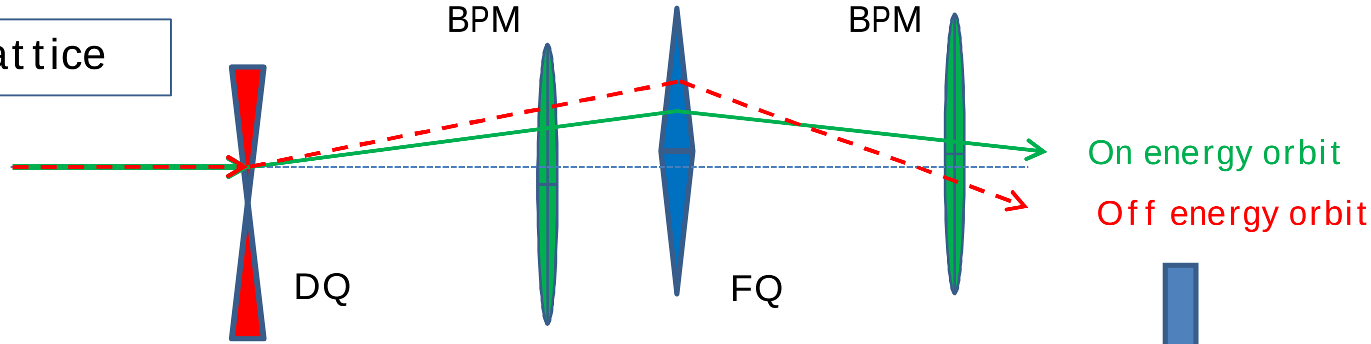






Introduction

Misaligned FODO lattice



Difference orbit correction with SVD without launch jitter and BPM resolution errors.

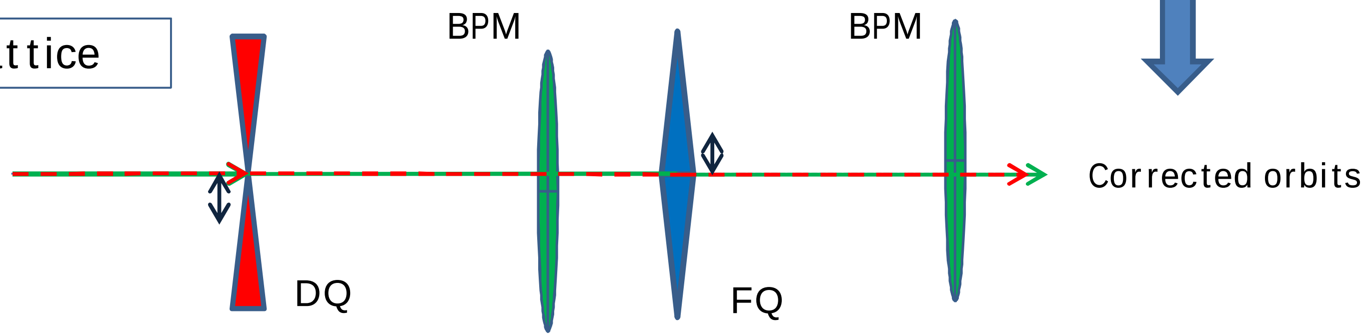
$$X_{E_1} = R_{ORM}^{E_1} \cdot \Delta Q + I \cdot \Delta B$$

$$X_{E_2} = R_{ORM}^{E_2} \cdot \Delta Q + I \cdot \Delta B$$

$$\Delta X = \left(R_{ORM}^{E_2} - R_{ORM}^{E_1}\right) \cdot \Delta Q$$

$$\Delta Q = \left(R_{ORM}^{E_2} - R_{ORM}^{E_1}\right)^{+} \cdot \Delta X$$

Corrected FODO lattice



Correction algorithm

Step 1 : Take BPM readings for many bunches considering 2 energies

$$X_{E_1} = R_{LRM}^{E_1} \cdot \left(X_{lrand}^{(1)} + X_{lsys}^{(1)} \right) + R_{ORM}^{E_1} \cdot \Delta Q + I \cdot \Delta B + \Sigma_{res}^{(1)}$$
$$X_{E_2} = R_{LRM}^{E_2} \cdot \left(X_{lrand}^{(2)} + X_{lsys}^{(2)} \right) + R_{ORM}^{E_2} \cdot \Delta Q + I \cdot \Delta B + \Sigma_{res}^{(2)}$$

Step 2 : Calculate the average of taken data for each energy

$$\left\langle X_{E_1} \right\rangle = R_{LRM}^{E_1} \cdot \left(\left\langle X_{lrand}^{(1)} \right\rangle + \left\langle X_{lsys}^{(1)} \right\rangle \right) + R_{ORM}^{E_1} \cdot \Delta Q + I \cdot \Delta B + \left\langle \Sigma_{res}^{(1)} \right\rangle$$
$$\left\langle X_{E_2} \right\rangle = R_{LRM}^{E_2} \cdot \left(\left\langle X_{lrand}^{(2)} \right\rangle + \left\langle X_{lsys}^{(2)} \right\rangle \right) + R_{ORM}^{E_2} \cdot \Delta Q + I \cdot \Delta B + \left\langle \Sigma_{res}^{(2)} \right\rangle$$

Step 3 : Calculate launch systematic average errors using 2 upstream BPMs readings and exclude from further calculations

Correction algorithm

Step 4 : Calculate the difference

$$\langle \Delta X \rangle_{calc} = \langle \Delta X \rangle_{real} + \Delta_{err}$$

where

$$\langle \Delta X \rangle_{real} = \left(R_{ORM}^{E_2} - R_{ORM}^{E_1}\right) \cdot \Delta Q$$

$$\Delta_{err} = R_{LRM}^{E_2} \cdot \langle X_{lrand}^{(2)} \rangle - R_{LRM}^{E_1} \cdot \langle X_{lrand}^{(1)} \rangle + \langle \Sigma_{res}^{(2)} \rangle - \langle \Sigma_{res}^{(1)} \rangle$$

Step 5 : Calculate quadrupole misalignments using SVD

$$\Delta Q_{calc} = \left(R_{ORM}^{E_2} - R_{ORM}^{E_1}\right)^{+} \cdot \langle \Delta X \rangle_{calc} = \Delta Q_{real} + \left(R_{ORM}^{E_2} - R_{ORM}^{E_1}\right)^{+} \cdot \Delta_{err}$$

To increase the precision ⇒ $\langle \Delta X \rangle_{real} >> \Delta_{err}$ ⇒

1. Big energy difference
2. Large number of taken data for averaging

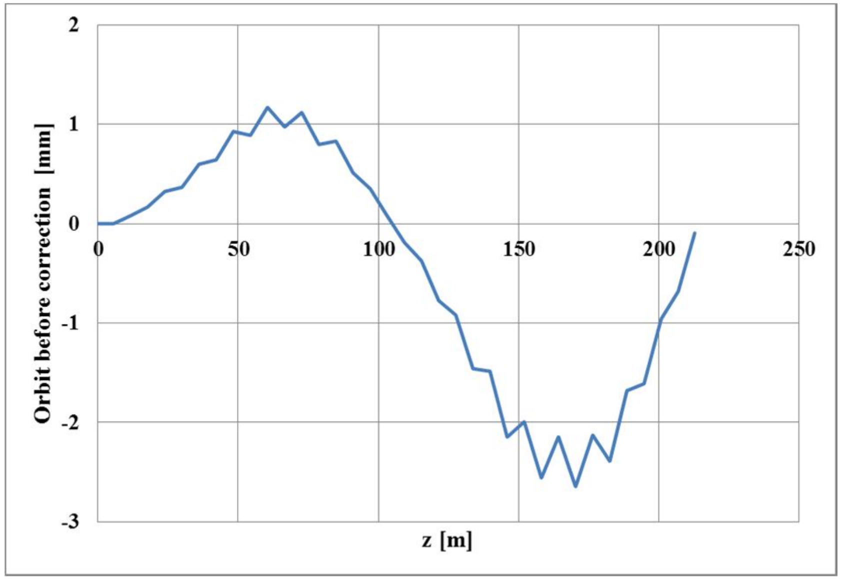
Step 6* : Calculate BPM misalignments by taking BPM readings after correction, excluding launch conditions impact and applying linear fit

Results for SASE1

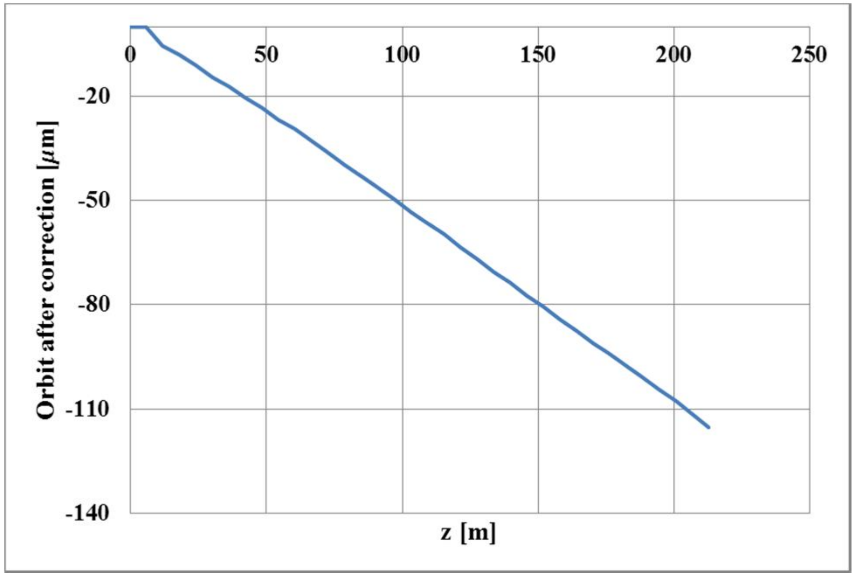
Considered parameters

Design energy	17.5 GeV
Quad. rms mis.	100 μm
BPM rms res. error	1 μm
rms initial offset	36 μm
rms initial slope	1 μrad

One seed of quad misalignments



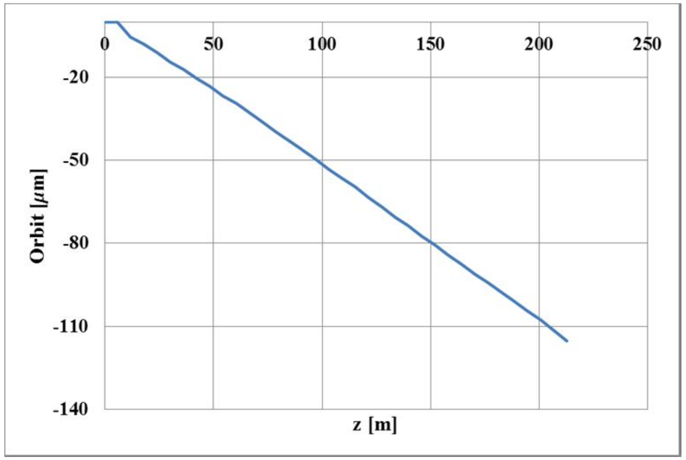
20% rel. energy difference and 3000 launch cond.

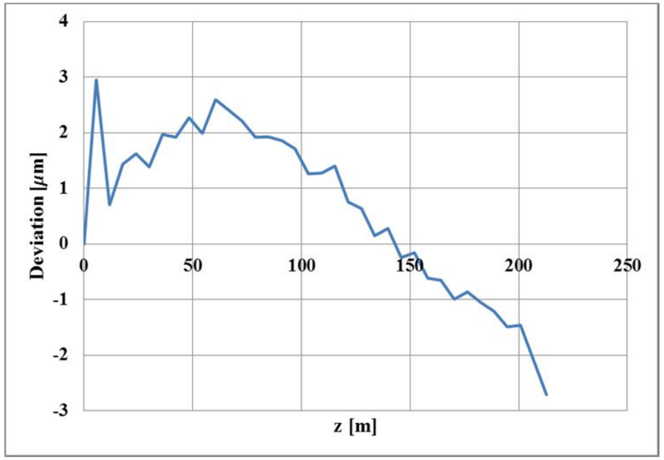


Orbit before and after correction

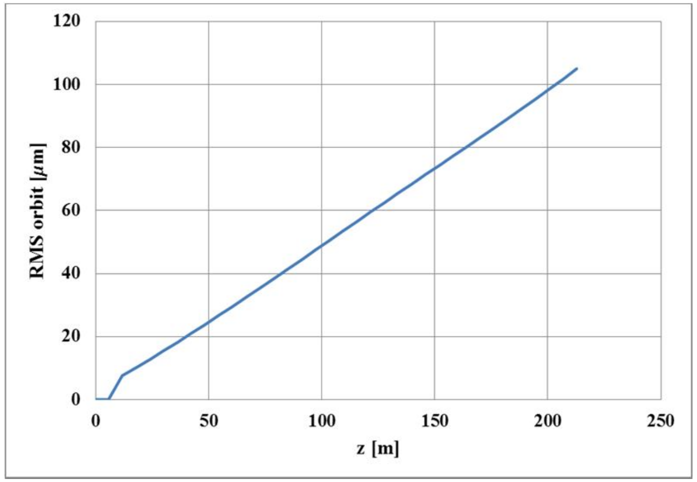
Results for SASE1

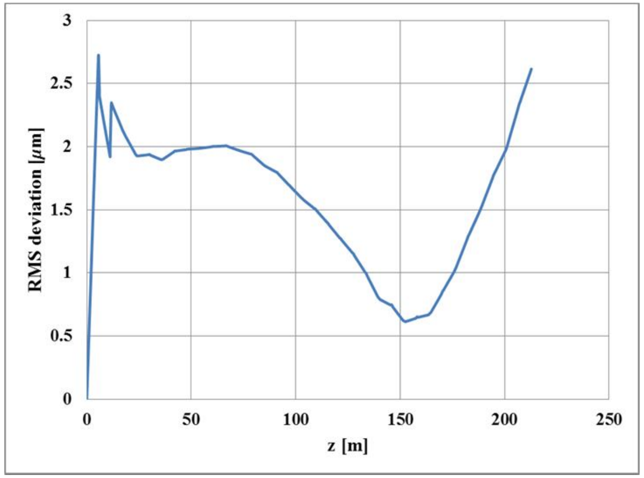
20% relative energy difference, 3000 launch conditions





Orbit and orbit dev. from straight line after corr. for one seed of quad. mis. and 3000 launch cond.

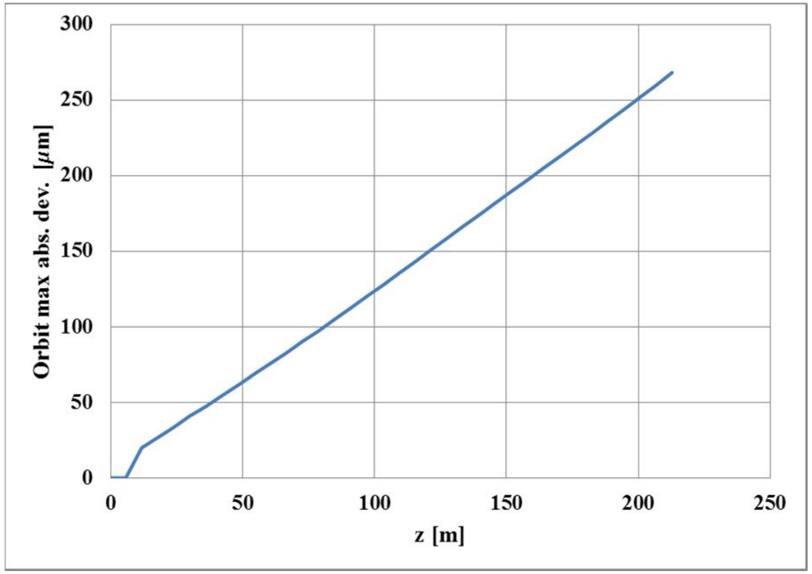


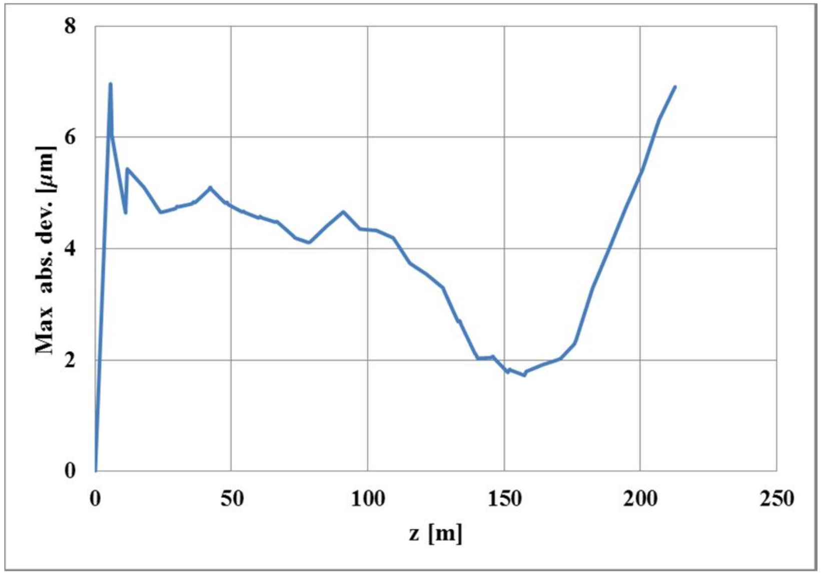


RMS orbit and rms dev. after corr. for 10 seeds of quad. mis. and 10 seeds of 3000 launch cond. per quad. seed

Results for SASE1

20% relative energy difference, 3000 launch conditions



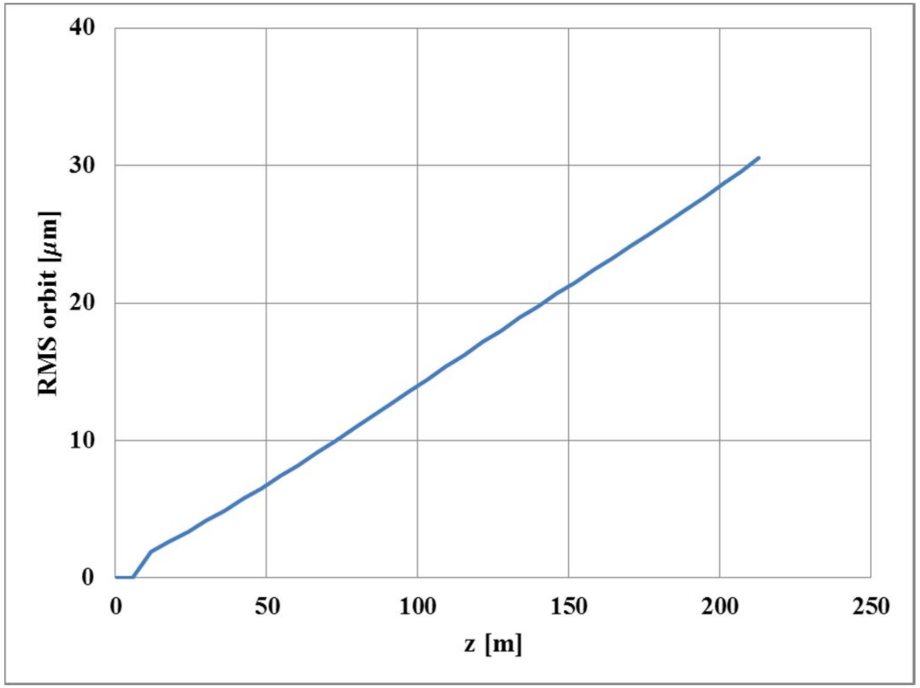


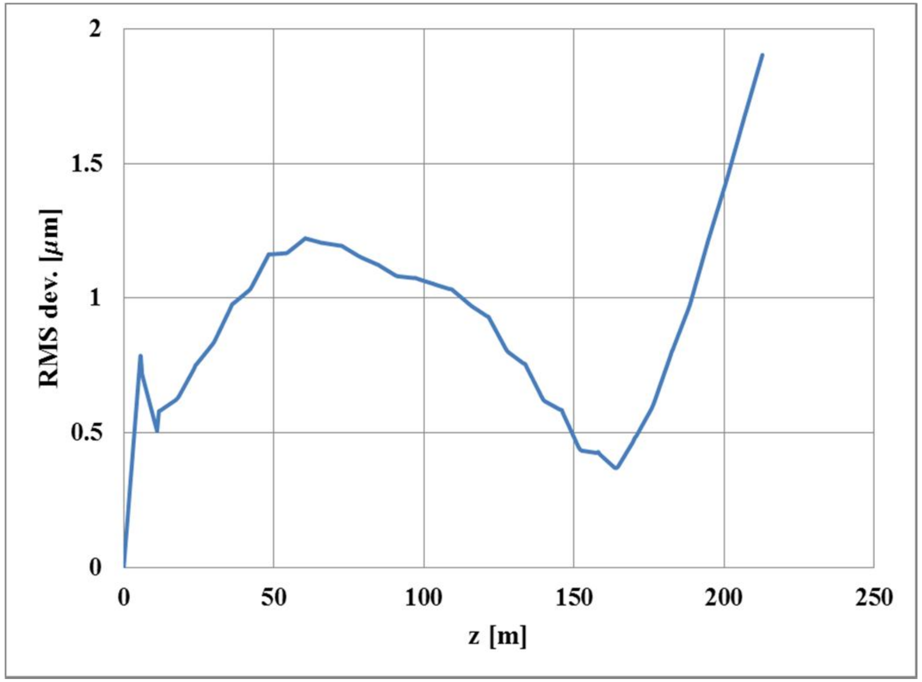
Orbit max abs. dev. and max abs. dev. from straight line after corr. for 10 seeds of quad. mis. and 10 seeds of 3000 launch cond. per quad. seed

- rms orbit $\leq$ 110 μm
- rms deviation $\leq$ 3 μm
- orbit max abs. deviation $\leq$ 270 μm
- max abs. deviation $\leq$ 7 μm

Results for SASE1

40% relative energy difference, 10000 launch conditions

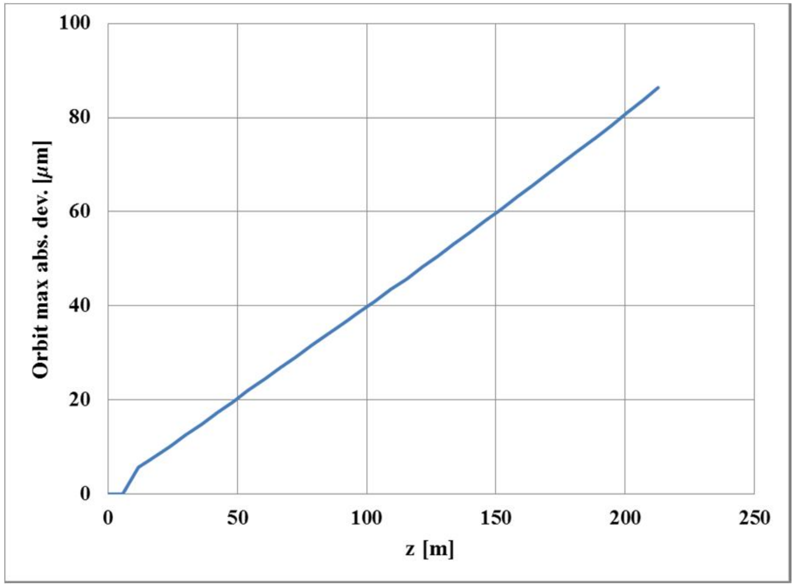


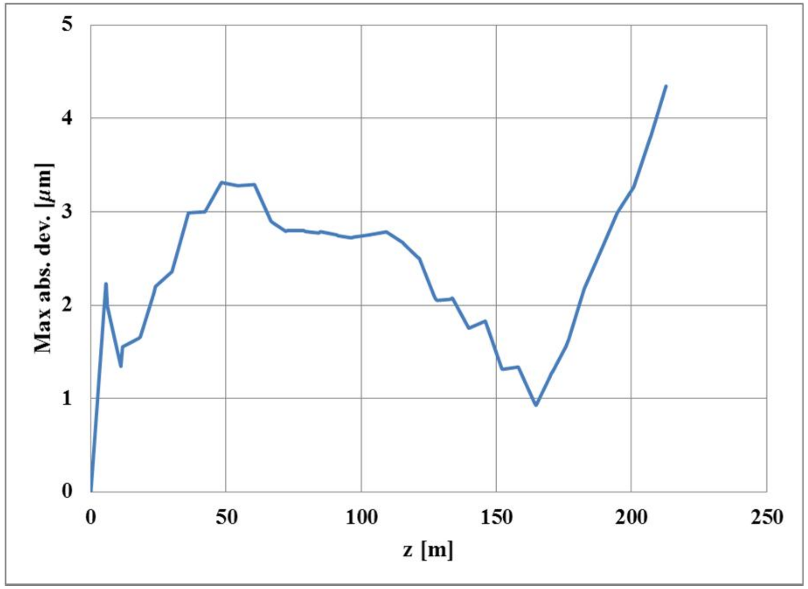


RMS orbit and rms dev. after corr. for 10 seeds of quad. mis. and 10 seeds of 10000 launch cond. per quad. seed

Results for SASE1

40% relative energy difference, 10000 launch conditions





Orbit max abs. dev. and max abs. dev. from straight line after corr. for 10 seeds of quad. mis. and 10 seeds of 10000 launch cond. per quad. seed

- rms orbit $\leq$ 35 μm
- rms deviation $\leq$ 2 μm
- orbit max abs. deviation $\leq$ 90 μm
- max abs. deviation $\leq$ 5 μm

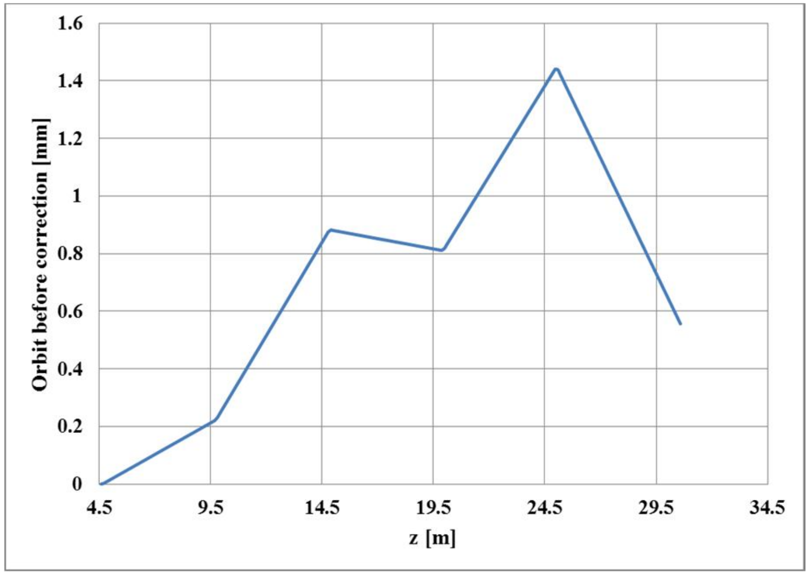
Results for FLASH undulator line

6 sections	
Undulator length –	4.5 m
FODO period length -	10 m

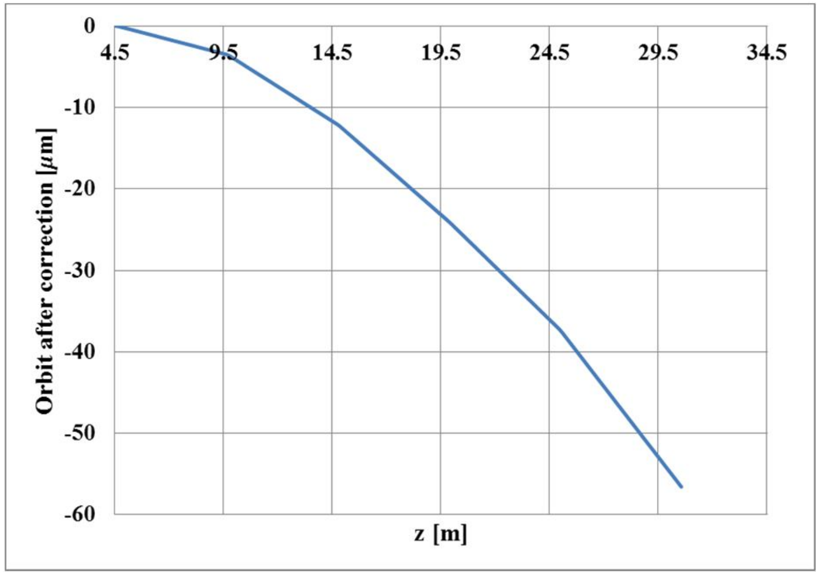
Considered parameters

Beam energy	1.2 GeV
Quad. rms mis.	300 μm
BPM rms res. error	20 μm
rms initial offset	100 μm
rms initial slope	10 μrad

One seed of quad misalignments



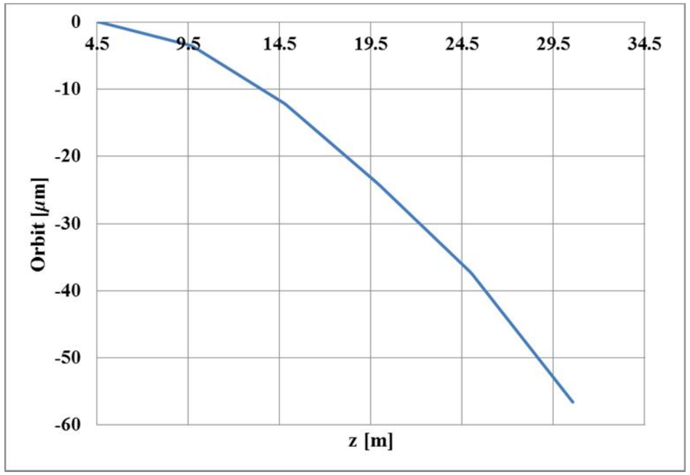
50% rel. energy difference, 10000 launch cond.

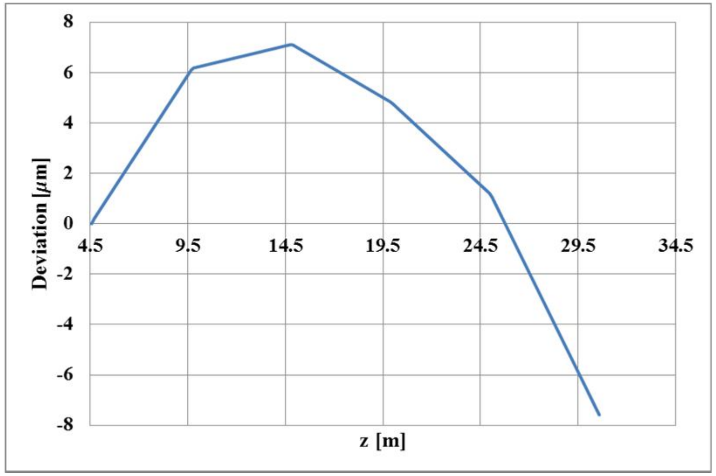


Orbit before and after correction

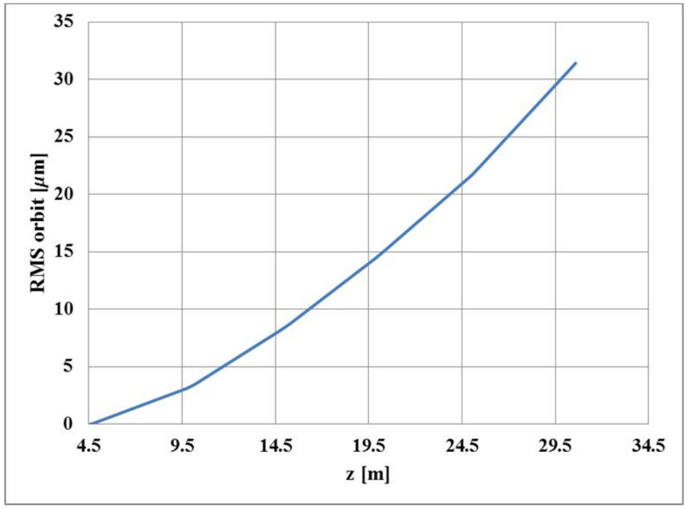
Results for FLASH undulator line

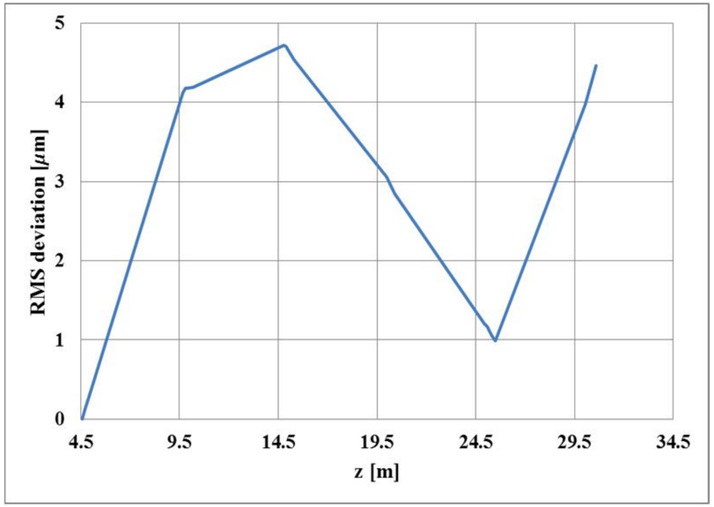
50% relative energy difference, 10000 launch conditions





Orbit and orbit dev. from straight line after corr. for one seed of quad. mis. and 3000 launch cond.

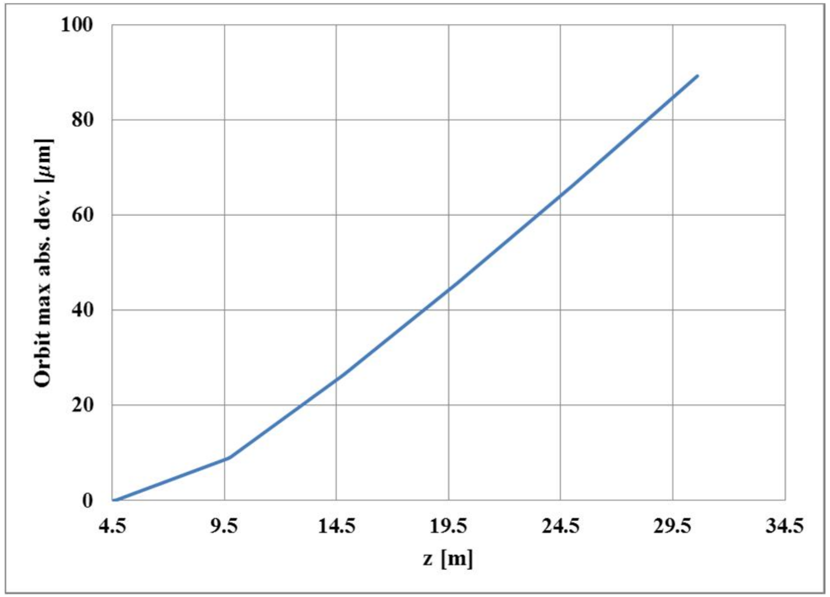


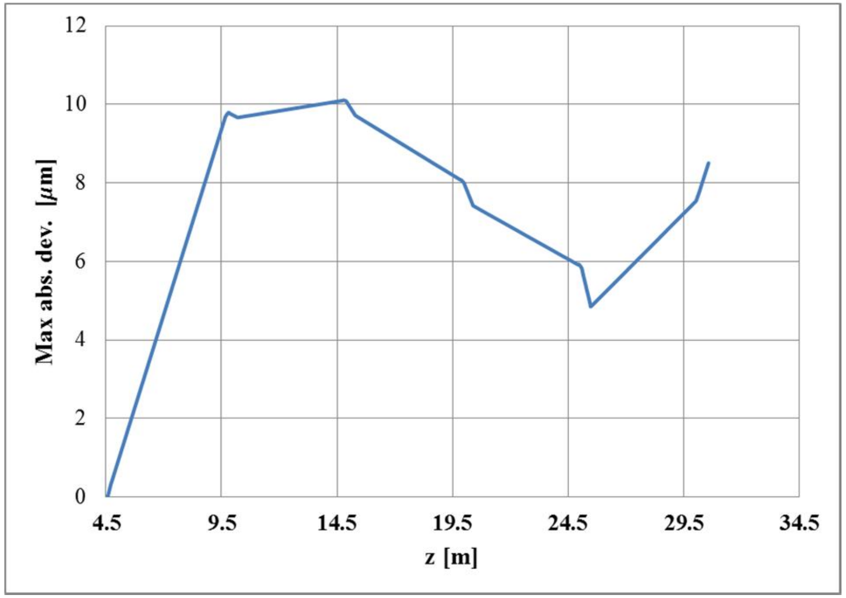


RMS orbit and rms dev. after corr. for 10 seeds of quad. mis. and 10 seeds of 10000 launch cond. per quad. seed

Results for FLASH undulator line

50% relative energy difference, 10000 launch conditions





Orbit max abs. dev. and max abs. dev. from straight line after corr. for 10 seeds of quad. mis. and 10 seeds of 10000 launch cond. per quad. seed

- rms orbit $\leq$ 33 μm
- rms deviation $\leq$ 5 μm
- orbit max abs. deviation $\leq$ 90 μm
- max abs. deviation $\leq$ 11 μm

Summary

- The impact of electron beam trajectory direction variation on radiation properties were studied for XFEL SASE1
  - ✓ Electron beam was kicked at different positions along SASE1 to have 1mm offset after 100m from SASE1 and the effect of already formed micro-bunched structure on radiation power and saturation length after electron beam trajectory change was analyzed.
  - ✓ Photon beam different offsets after 100m from SASE1 was considered when the electron beam was kicked at the saturation point.
  - ✓ Genesis time-dependent simulations of the radiation process were performed.

- New beam based alignment algorithm was proposed
  - ✓ applied for SASE1.
  - ✓ applied for FLASH undulator section.

THANK YOU FOR ATTENTION