Short-range wakefields in an L-shape corrugated structure and its application at x-ray free-electron lasers

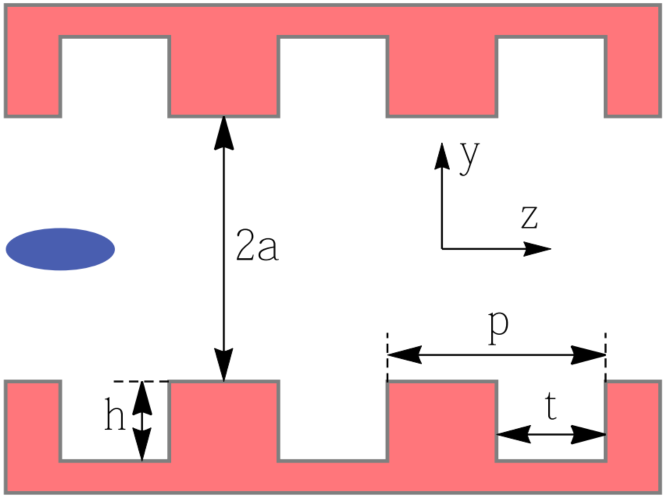
Weilun Qin
DESY, MXL

The 4th International workshop on
“Ultrafast Beams and Applications”

17-23 June 2024
Yerevan, Armenia

Corrugated structures in free-electron lasers

- Metallic surface with corrugations as **dedicated wakefield device**

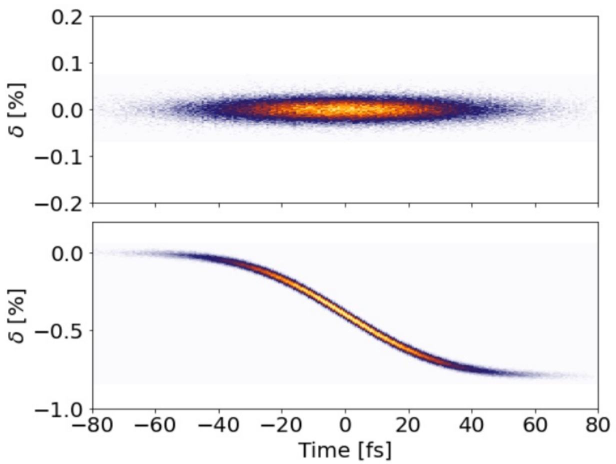


Parameter	Value	Units
Period, *p*	0.5	mm
Longitudinal gap, *t*	0.25	mm
Depth, *h*	0.5	mm
Nominal distance to plate, *d*	0.5	mm

Corrugated structures in free-electron lasers

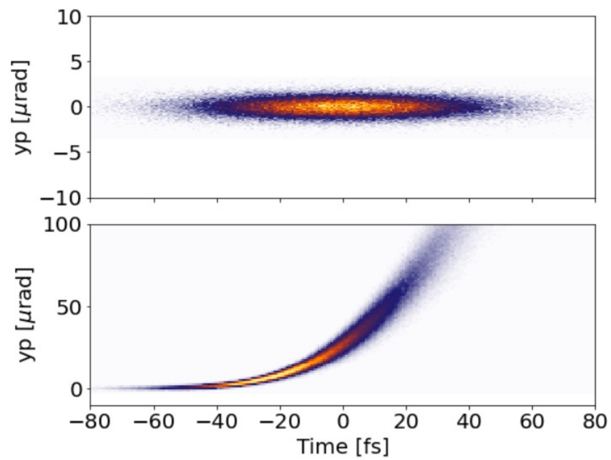
- Metallic surface with corrugations as **dedicated wakefield device**
  - Longitudinal wake → **beam chirp control: “dechirper”**
  - Transverse dipole wake → **beam tilt control: “streaker”**
  - Transverse quadrupole wake → **beam slice size control**

Longitudinal



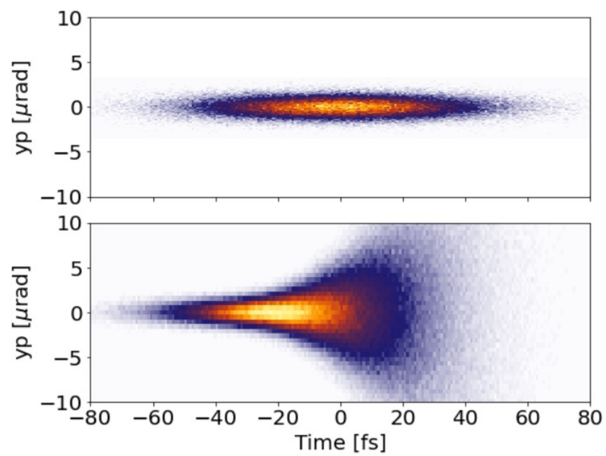
Phy. Rev. Lett. 112(3): 034801.
Phy. Rev. Lett. 113(25): 254802.

Dipole



Nat. Photonics 10(11): 745–750.
Phy. Rev. Lett. 120(26): 264801.

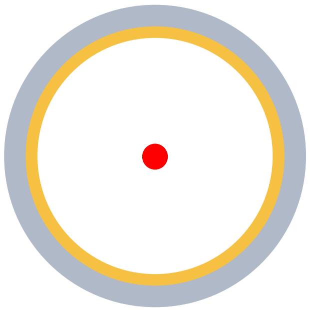
Quadrupole



Phy. Rev. Accel. and Beams 20(9): 090701.
Phy. Rev. Lett. 121(6): 064802.

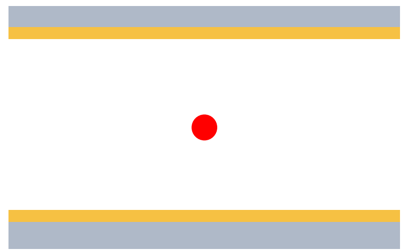
Corrugated structure with various transverse geometry

Round



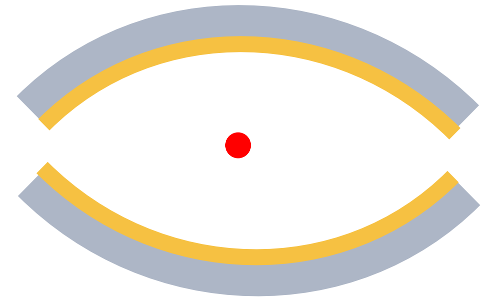
- Original propose
- Wakefield simple
- **Adjustability limited**
- Recently tested

Parallel-plate



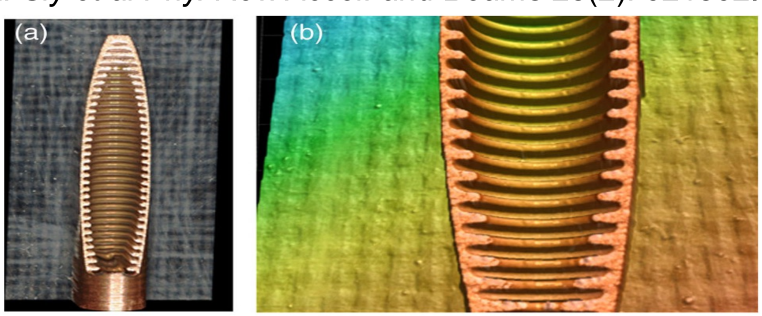
- Widely used
- **Quadrupole due to asymmetry**
- Adjustable
- Fabrication easy

Curved-plate

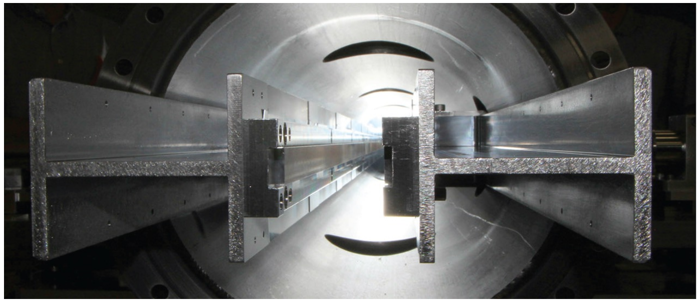


- More confined field
- Fabrication less easy

A. Siy et al Phy. Rev. Accel. and Beams 25(2): 021302.



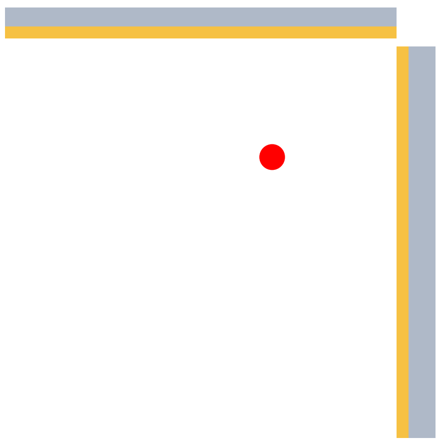
M. Guetg et al SLAC-PUB-16834



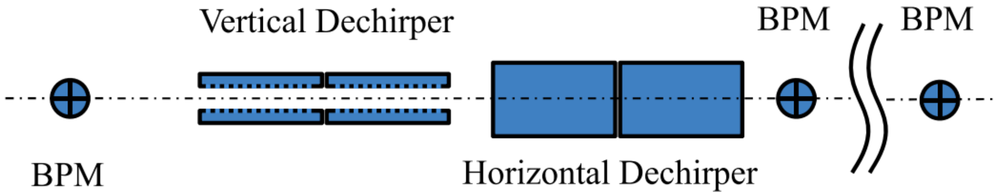
Idea of an L-shaped corrugated structure

- Quadrupole component are sometimes unwanted
  - Increase projected emittance
  - May not be able to match back inside an undulator
  - Smear the resolution for diagnostic

L-shape geometry



- Typical layout with parallel-plates



Zhen Zhang et al, *PRAB* 18, 010702

- An L-shape geometry
  - Cancel quad wake
  - Switch between L-mode and single-mode
  - Stronger kick
  - Open structure to allow parallel operation

Qin, Weilun et al, *FEL2022*, MOP038

Wakefield model for L-shaped structure is missing

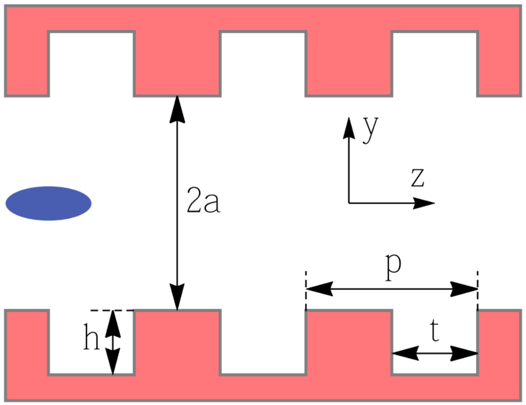
- Parallel plate model by Bane et al
- Generalized impedance expressed via surface impedance

$$Z_l(k,y) = \frac{2\zeta}{c}\int_{-\infty}^{\infty} dq q \operatorname{csch}^3(2qa) f(q,y), \qquad (10)$$

where the function $f = N/D$, with

$$\begin{aligned} N &= q(\cosh[2q(a-y)] - 2 + \cosh[2q(a+y)]) \\ &\quad - ik\zeta(\sinh[2q(a-y)] + \sinh[2q(a+y)]) \\ D &= [q \operatorname{sech}(qa) - ik\zeta \operatorname{csch}(qa)][q \operatorname{csch}(qa) - ik\zeta \operatorname{sech}(qa)]. \end{aligned} \qquad (11)$$

- Expand in 1/k and keep the first two terms → first order approximation
- Later extended to single-plate geometry



- Equivalent surface impedance

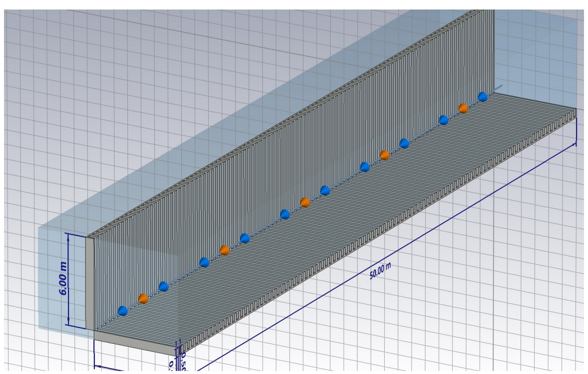
$$\zeta(k) = \frac{2}{a}\left(\frac{s_{0r}}{-ik}\right)^{1/2} = \frac{1}{\alpha p}\left(\frac{2t}{-i\pi k}\right)^{1/2}.$$

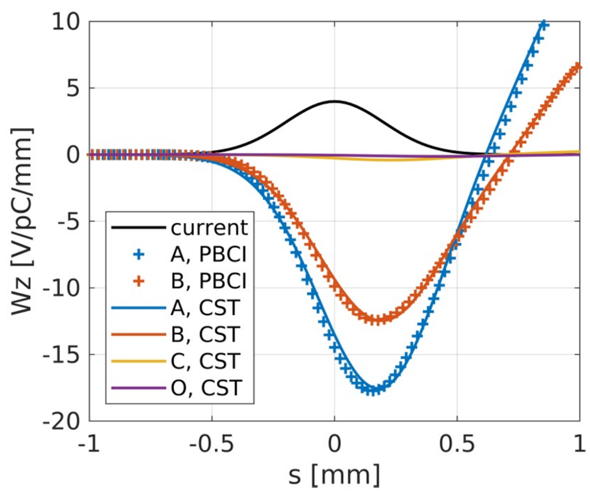
Bane, Karl, et al., http://arxiv.org/abs/1611.09460.
Bane, Karl, et al., *Physical Review Accelerators and Beams* 19, no. 8: 084401

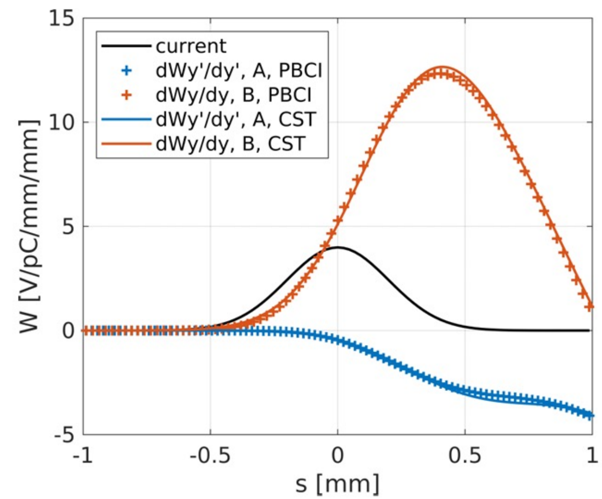
Wakefield model for L-shaped structure is missing

- Numerical methods (time-domain): requires significant large amount of computing resources
  - ECHO2D: can only model parallel plate with smooth side walls
  - CST/PBCI/ECHO3D: Meshing is huge for 10um bunch length

PBCI and CST calculation for 200um bunch







Qin, Weilun et al, *FEL2022*, MOP038

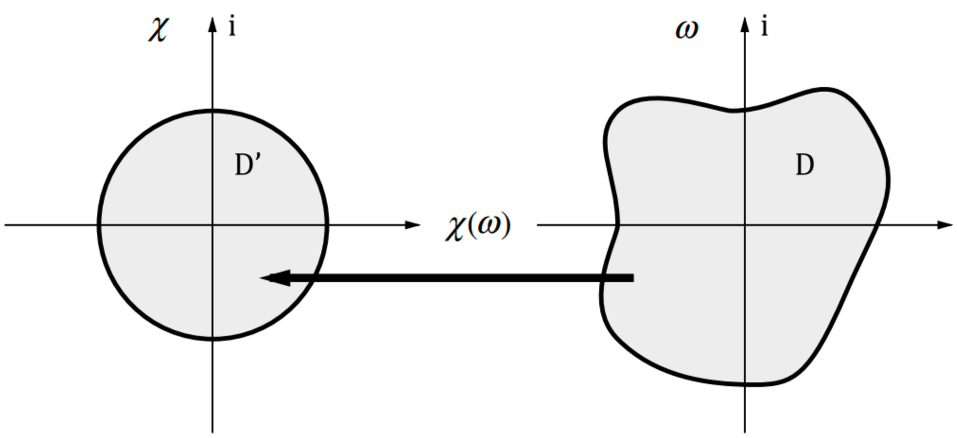
The conformal mapping method: exact at zeroth other

- Longitudinal and transverse component is related to the conformal mapping to a disk
- Exact solution at the origin of wakes → zeroth order
  - Longitudinal wake is a constant
  - Transverse wake has constant slope

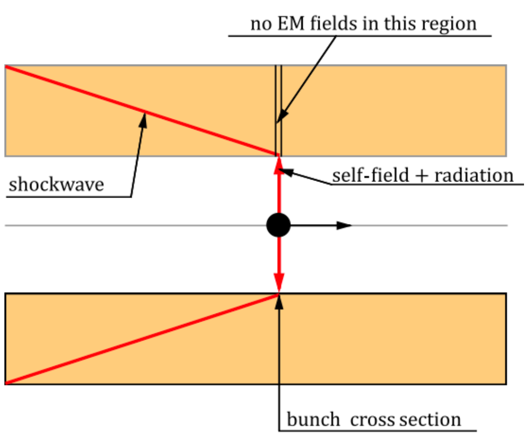
$$E_{\parallel}(z, z_0, 0^+) = -\frac{Z_0 c}{\pi}\frac{Q}{a^2}\Re[f'(z, z_0)^* f'(z_0, z_0)],$$

$$\frac{\partial}{\partial s}F_{\perp}(z, z_0, 0^+) = \frac{Z_0 c}{\pi}\frac{qQ}{a^2}f''(z, z_0)^* f'(z_0, z_0),$$

- Valid for any slow down layer



(a)

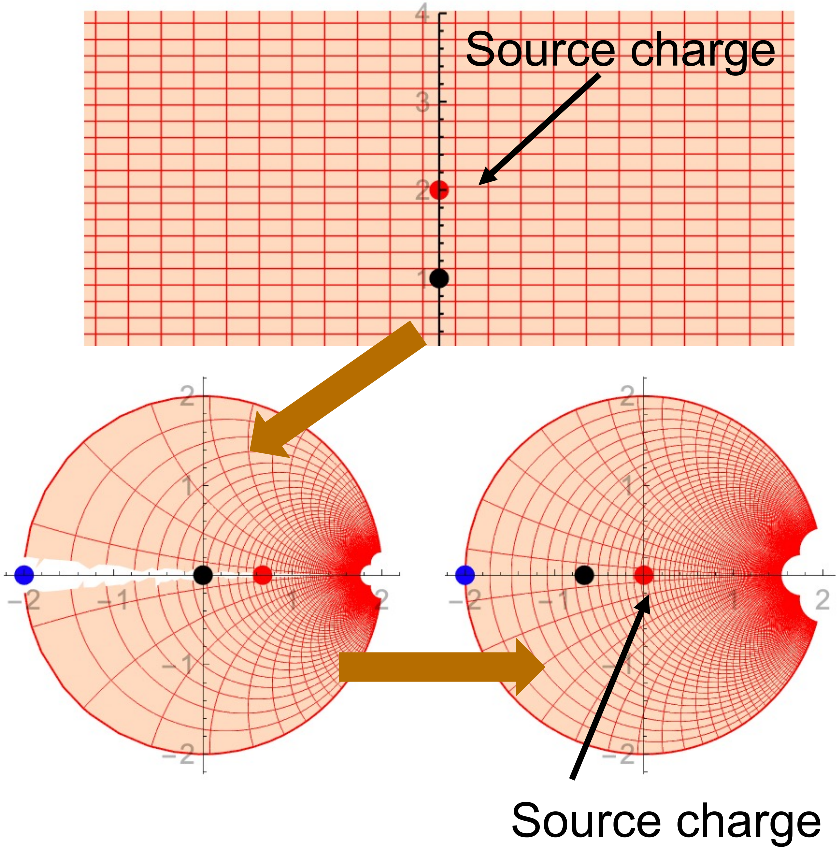


(b)

Baturin, S. S., and A. D. Kanareykin. *Physical Review Accelerators and Beams* 19, no. 5: 051001.

Single-plate geometry

- Upper half plane to disk



- Mapping:

$$f(z, z_0) = -a \frac{z_0^* - i}{z_0 + i} \frac{z - z_0}{z - z_0^*}.$$

- Longitudinal wake:

$$w_\parallel^S(\bar{y}, s) = A_\parallel^S(\bar{y})\theta(s), \qquad A_\parallel^S(\bar{y}) = \frac{Z_0 c}{4\pi} \frac{1}{\bar{y}^2}. \qquad (17)$$

- Transverse wake:

$$w_{xm}^S(\bar{y}, s) = 0, \qquad (20)$$

$$w_{ym}^S(\bar{y}, s) = A_m^S(\bar{y}) s\theta(s), \qquad A_m^S(\bar{y}) = -\frac{Z_0 c}{4\pi} \frac{1}{\bar{y}^3}, \qquad (21)$$

$$w_d^S(\bar{y}, s) = A_d^S(\bar{y}) s\theta(s), \qquad A_d^S(\bar{y}) = \frac{Z_0 c}{\pi} \frac{3}{8\bar{y}^4}, \qquad (22)$$

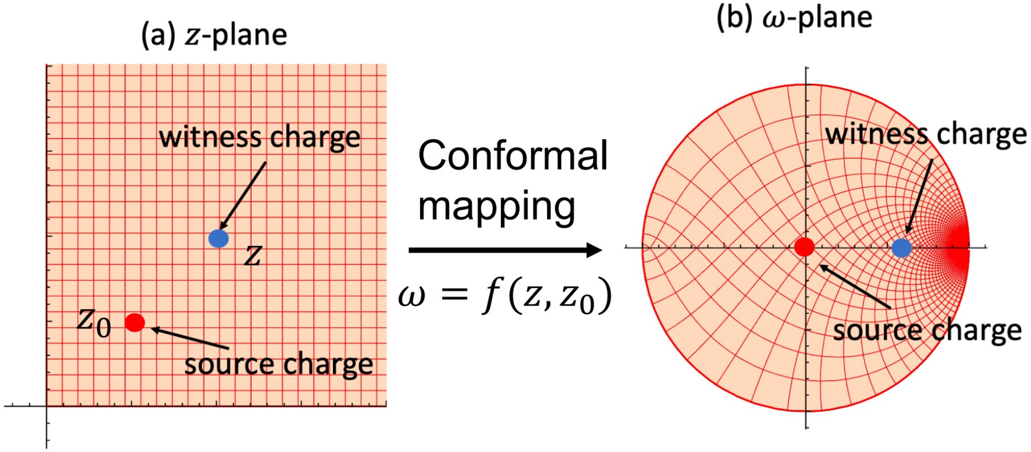
$$w_q^S(\bar{y}, s) = w_d^S(\bar{y}, s). \qquad (23)$$

L-shape geometry

- Mapping:

$$f(z, z_0) = -a \frac{z_0^{*2} - i}{z_0^2 + i} \frac{z^2 - z_0^2}{z^2 - z_0^{*2}}.$$

- First quadrant to disk



- Longitudinal wake:

$$w_{\parallel}^{L}(\bar{x}, \bar{y}, s) = (A_{\parallel}^{S}(\bar{x}) + A_{\parallel}^{S}(\bar{y}))\theta(s).$$

- Transverse wake:

$$w_{xm}^{L}(\bar{x}, \bar{y}, s) = A_{m}^{S}(\bar{x}) s\theta(s),$$

$$w_{ym}^{L}(\bar{x}, \bar{y}, s) = A_{m}^{S}(\bar{y}) s\theta(s),$$

$$w_{d}^{L}(\bar{x}, \bar{y}, s) = [A_{d}^{S}(\bar{x}) + A_{d}^{S}(\bar{y})] s\theta(s),$$

$$w_{q}^{L}(\bar{x}, \bar{y}, s) = [A_{d}^{S}(\bar{y}) - A_{d}^{S}(\bar{x})] s\theta(s).$$

- Important observation: at zeroth order, wakefield of the L-shape can be simply **added up by two single-plate structure** with 90 degree rotation

Revisit Bane’s first order approximations

- First order expression: zeroth order + decay term

$$w_{\parallel}^{P1}(\bar{y}, s) = A_{\parallel}^{P}(\bar{y}) e^{-\sqrt{\frac{s}{s_{\parallel}(\bar{y})}}} \theta(s),$$

$$w_{ym}^{P1}(\bar{y}, s) = 2A_{m}^{P}(\bar{y}) s_m(\bar{y}) \times \left[1 - \left(1 + \sqrt{\frac{s}{s_m(\bar{y})}}\right) e^{-\sqrt{\frac{s}{s_m(\bar{y})}}}\right] \theta(s),$$

- Parallel plate

$$s_{\parallel}(\bar{y}) = 4s_r \left(1 + \frac{1}{3}\cos^2\beta + \beta \tan\beta\right)^{-2}$$

$$s_m(\bar{y}) = 4s_r \left(\frac{3}{2} - \beta \cot 2\beta + 2\beta \csc 2\beta\right)^{-2}$$

$$s_q(\bar{y}) = 4s_r \left(\frac{56 - \cos 2\beta}{30} + \frac{0.3 + \beta \sin 2\beta}{2 - \cos 2\beta} + 2\beta \tan\beta\right)^{-2}$$

- Single plate

$$s_{\parallel}(\bar{y}) = \frac{2\bar{y}^2}{s_c}, \quad s_m(\bar{y}) = \frac{8\bar{y}^2}{9s_c}, \quad s_d(\bar{y}) = s_q(\bar{y}) = \frac{\bar{y}^2}{2s_c},$$

Wakefields of an L-shaped corrugated structure

- Empirical formulas
- Confirmed by numerical method based on integral equation

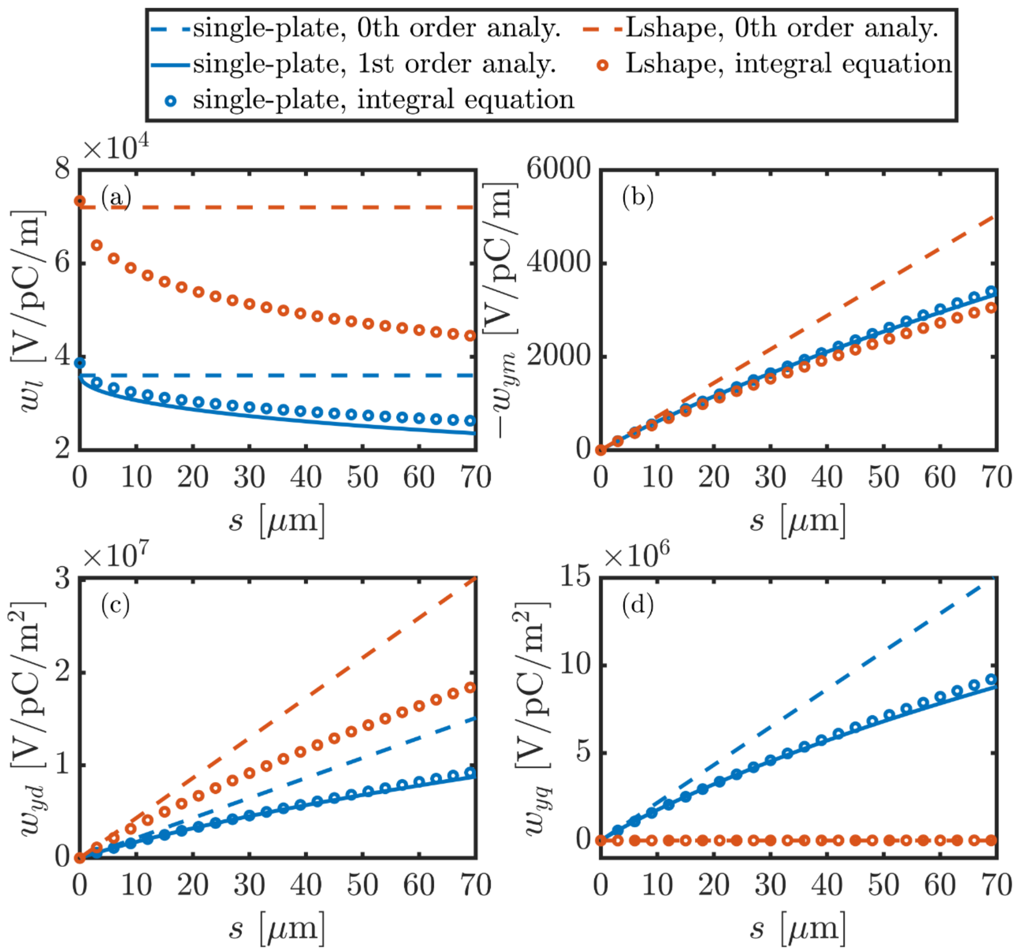
$$w_{\parallel}^{L1}(\bar{x}, \bar{y}, s) = w_{\parallel}^{S1}(\bar{x}, s) + w_{\parallel}^{S1}(\bar{y}, s),$$

$$w_{xm}^{L1}(\bar{x}, \bar{y}, s) = w_{ym}^{S1}(\bar{x}, s),$$

$$w_{ym}^{L1}(\bar{x}, \bar{y}, s) = w_{ym}^{S1}(\bar{y}, s),$$

$$w_{d}^{L1}(\bar{x}, \bar{y}, s) = w_{d}^{S1}(\bar{y}, s) + w_{d}^{S1}(\bar{x}, s),$$

$$w_{q}^{L1}(\bar{x}, \bar{y}, s) = w_{d}^{S1}(\bar{y}, s) - w_{d}^{S1}(\bar{x}, s),$$



Qin, Weilun, et al. *Physical Review Accel. and Beams* 26, no. 9: 064402.

Implementation in Ocelot for beam dynamics

Fast Particle Tracking With Wake Fields

M. Dohlus, K. Flöttmann, C. Henning

Jan 2012

Abstract

Tracking calculations of charged particles in electromagnetic fields require in principle the simultaneous solution of the equation of motion and of Maxwell's equations. In many tracking codes a simpler and more efficient approach is used: external fields like that of the accelerating structures are provided as field maps, generated in separate computations and for the calculation of self fields

Extension of Bane's model

$$h_{00} = \frac{1}{\bar{y}^2} e^{-\sqrt{s/s_{ly}}} + \frac{1}{\bar{x}^2} e^{-\sqrt{s/s_{lx}}}$$

$$h_{01} = -\frac{1}{\bar{x}^3} e^{-\sqrt{s/s_{mx}}}$$

$$h_{02} = -\frac{1}{\bar{y}^3} e^{-\sqrt{s/s_{my}}}$$

$$h_{03} = -\frac{1}{\bar{x}^3} e^{-\sqrt{s/s_{mx}}}$$

$$h_{04} = -\frac{1}{\bar{y}^3} e^{-\sqrt{s/s_{my}}}$$

$$h_{11} = -\frac{3}{4\bar{y}^4} e^{-\sqrt{s/s_{qy}}} + \frac{3}{4\bar{x}^4} e^{-\sqrt{s/s_{qx}}}$$

$$h_{13} = \frac{3}{4\bar{y}^4} e^{-\sqrt{s/s_{qy}}} + \frac{3}{4\bar{x}^4} e^{-\sqrt{s/s_{dx}}}$$

$$h_{24} = \frac{3}{4\bar{y}^4} e^{-\sqrt{s/s_{dy}}} + \frac{3}{4\bar{x}^4} e^{-\sqrt{s/s_{qx}}}$$

$$h_{33} = -\frac{3}{4\bar{y}^4} e^{-\sqrt{s/s_{qy}}} + \frac{3}{4\bar{x}^4} e^{-\sqrt{s/s_{qx}}}$$

$$h_{12} = h_{14} = h_{23} = h_{34} = 0$$

2nd order Taylor expansion of long. wake

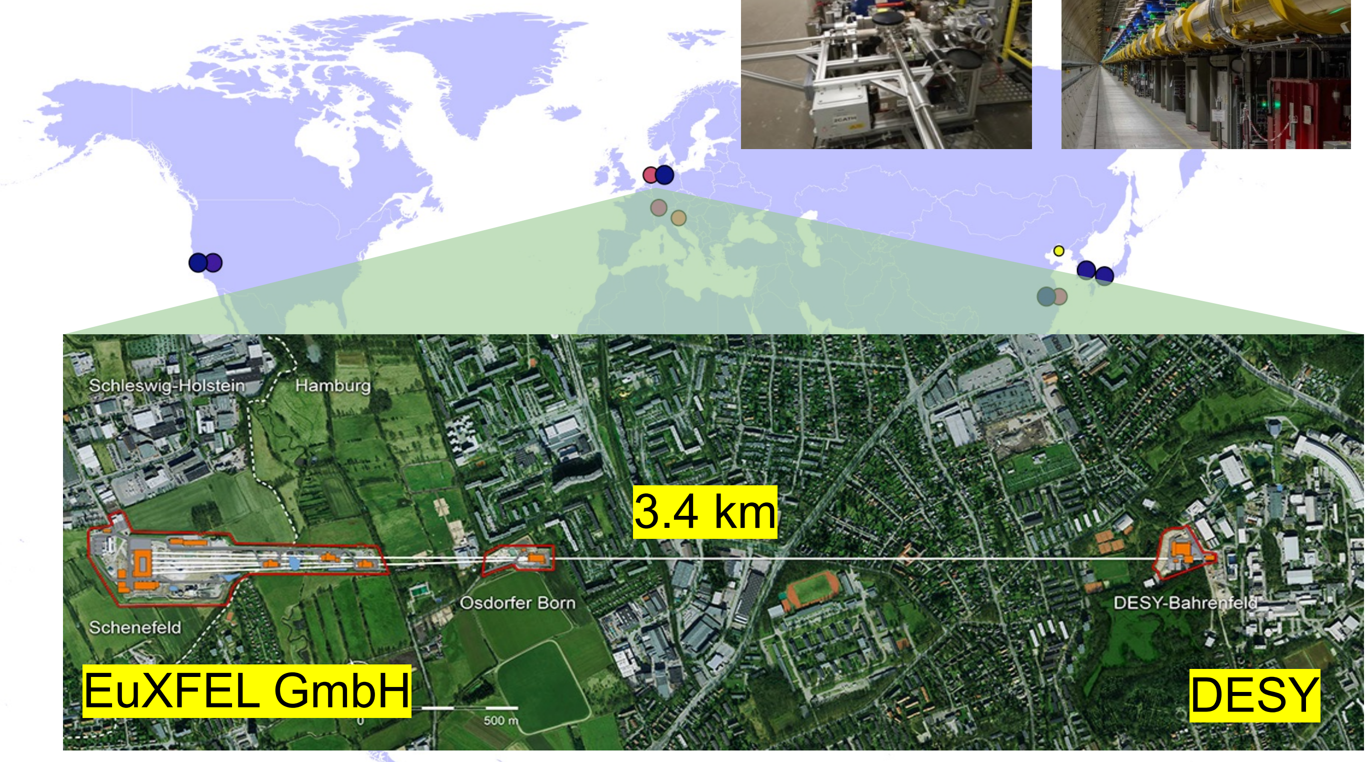
$$h_w(u_s, v_s, u_o, v_o, s) = \begin{bmatrix} 1 \\ u_s \\ v_s \\ u_o \\ v_o \end{bmatrix}^t \begin{bmatrix} h_{00}(s) & h_{01}(s) & h_{02}(s) & h_{03}(s) & h_{04}(s) \\ 0 & h_{11}(s) & h_{12}(s) & h_{13}(s) & h_{14}(s) \\ 0 & h_{12}(s) & h_{22}(s) & h_{23}(s) & h_{24}(s) \\ 0 & h_{13}(s) & h_{23}(s) & h_{33}(s) & h_{34}(s) \\ 0 & h_{14}(s) & h_{24}(s) & h_{34}(s) & -h_{33}(s) \end{bmatrix} \begin{bmatrix} 1 \\ u_s \\ v_s \\ u_o \\ v_o \end{bmatrix}.$$

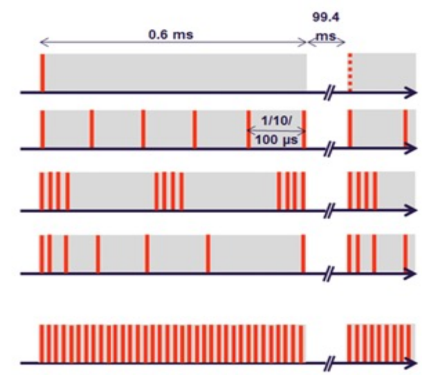
Transverse wake

$$h_u(u_s, v_s, u_o, v_o, s) = h_{03}^{(i)}(s) + 2h_{13}^{(i)}(s)u_s + 2h_{23}^{(i)}(s)v_s + 2h_{33}^{(i)}(s)u_o + 2h_{34}^{(i)}(s)v_o$$

$$h_v(u_s, v_s, u_o, v_o, s) = h_{04}^{(i)}(s) + 2h_{14}^{(i)}(s)u_s + 2h_{24}^{(i)}(s)v_s + 2h_{34}^{(i)}(s)u_o - 2h_{33}^{(i)}(s)v_o$$

The European XFEL

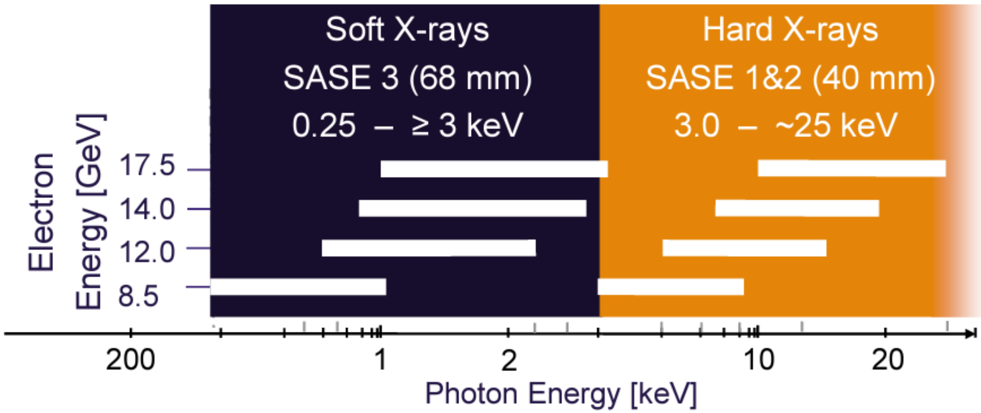




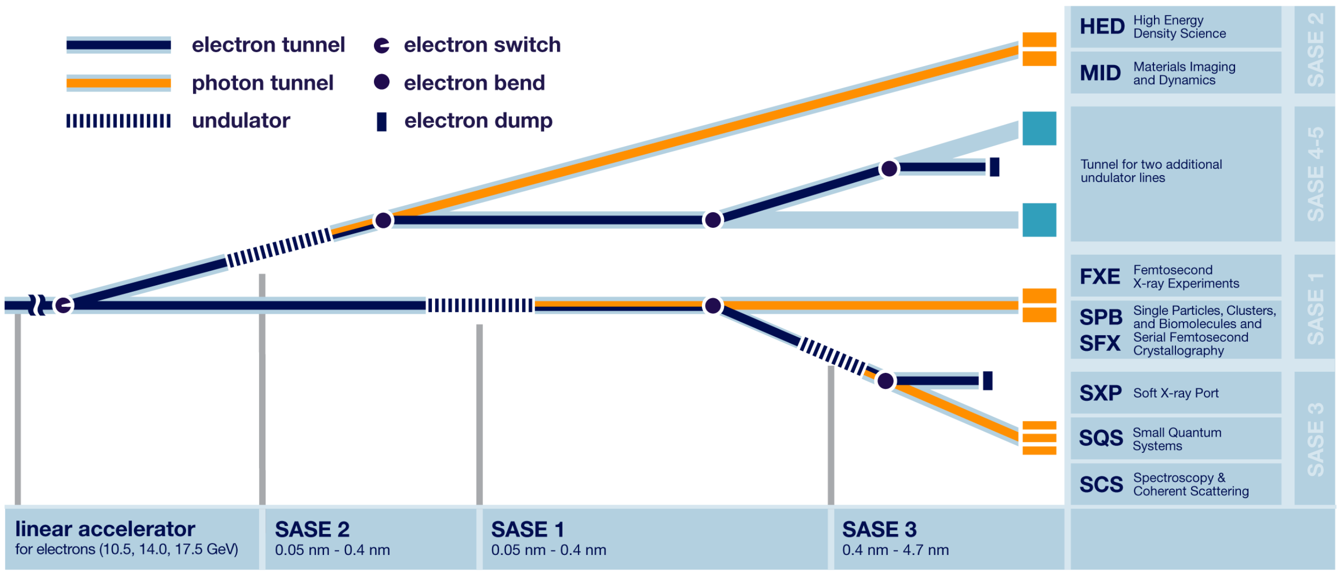
- 17.5 GeV with SC linac
- 27000 bunches per second in 10 Hz burst mode

The European XFEL

- 3 undulator lines
- 7 instruments in use
- Two empty tunnels can host more undulators

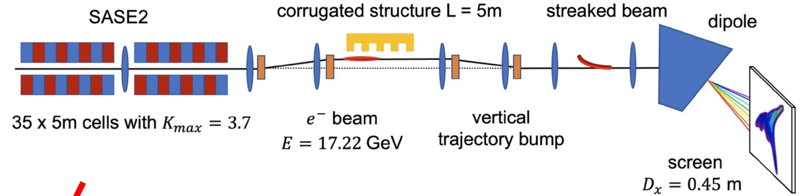


Parallel operation of SA1 and SA3

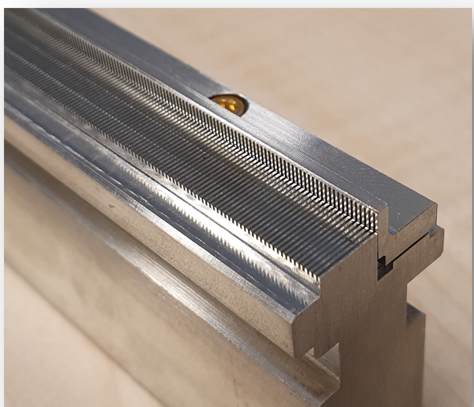


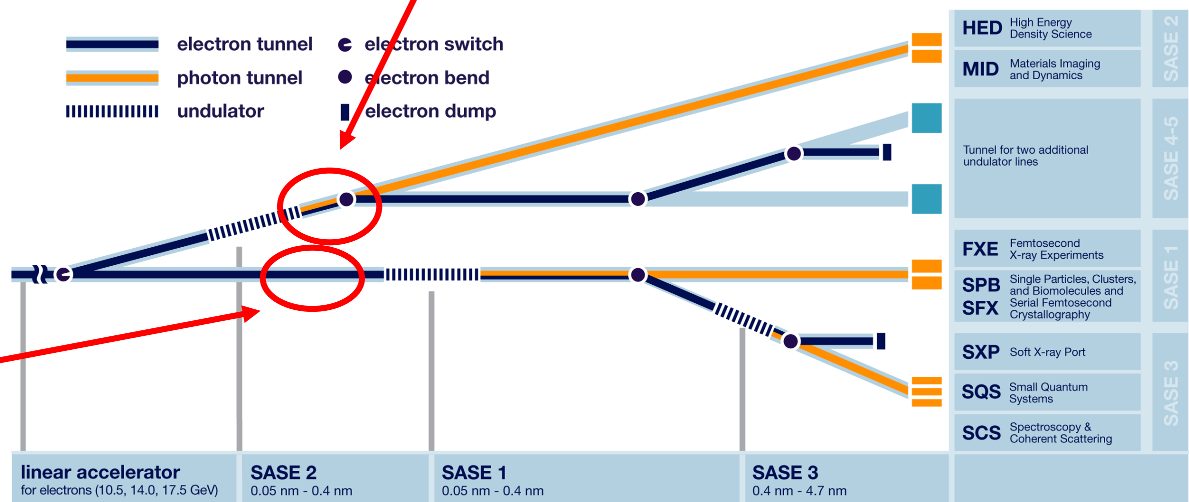
Corrugated structures at the European XFEL

- flat **single-plate** device for phase space diagnostic
- flat **L-shaped** device for fresh-slice lasing control
  - allow extra flexibility in streaking
  - allow parallel operation of soft and hard x-ray lines

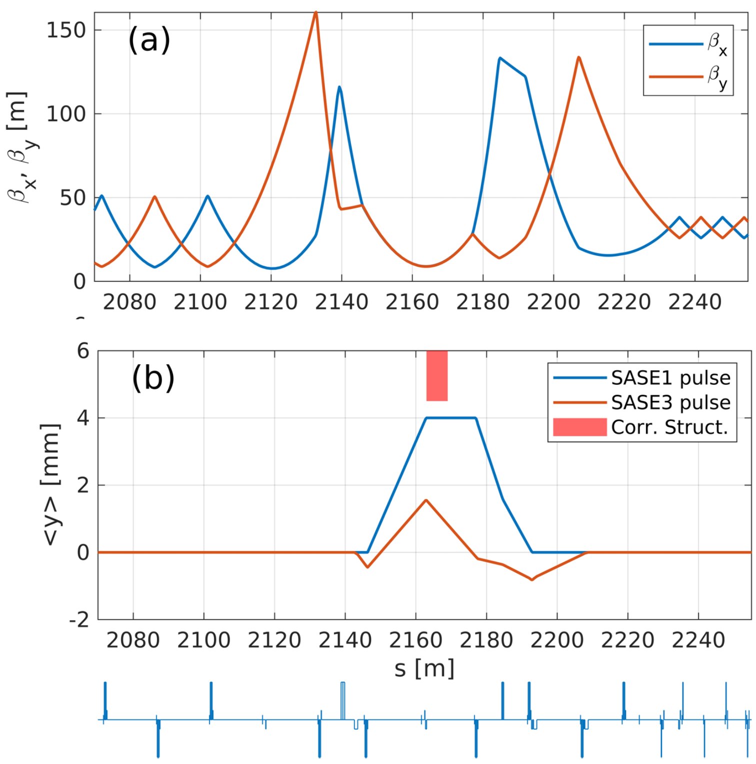


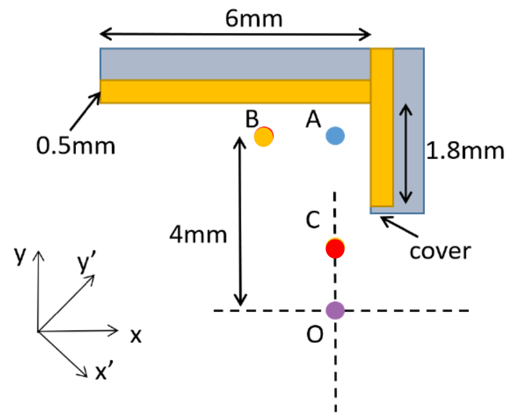
Tomin, Sergey, et al. *Scientific Reports* 13, no. 1 : 1605.





Low beta optics and orbit bumps

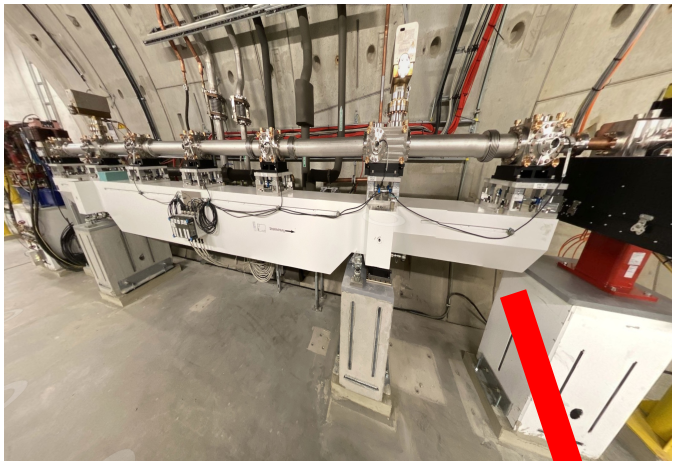




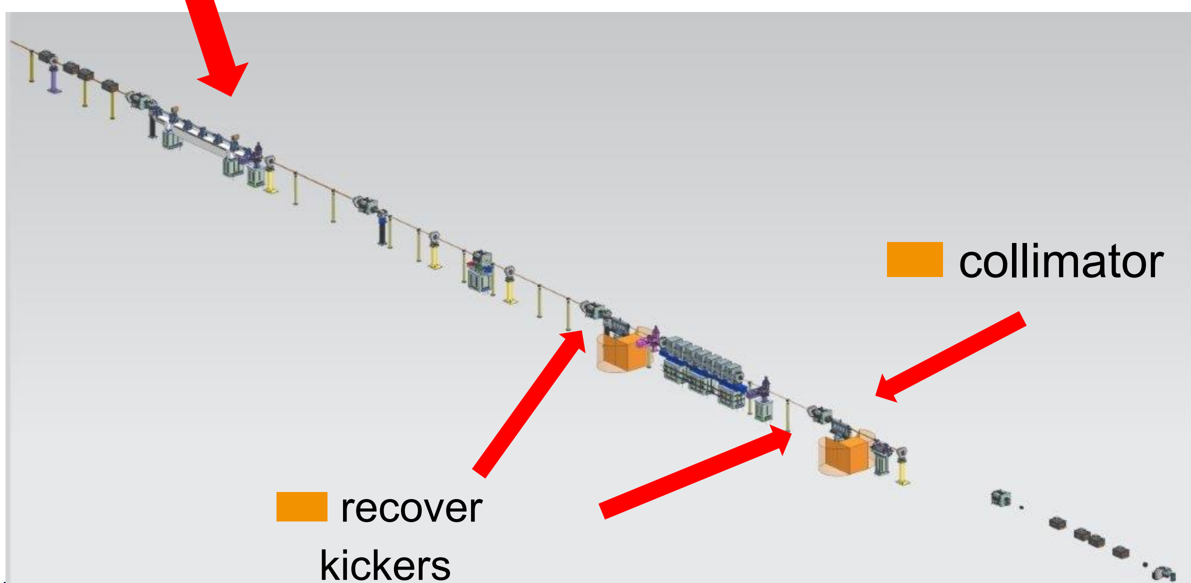
Cross-section view, e-beam goes into the screen

- ~11m low beta optics insertion around the corrugated structure
- Orbit bump in y (blue) and x (not shown), used HERA correctors
- A set of kickers to separate SA1 and SA3 bunches
- Matching quads and launch steers adjusted. Allow switch between special and standard optics

Integration of the system into beamline

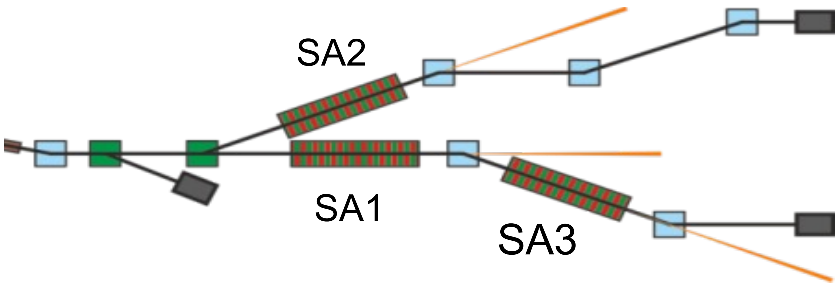


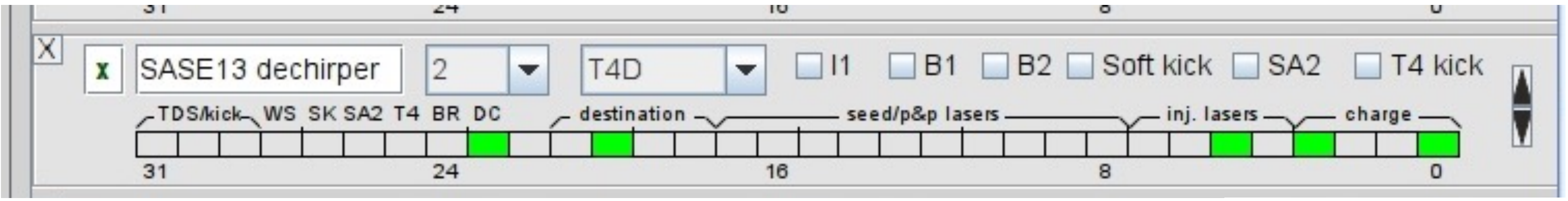
- Everything within the undulator tunnel, <100 m before undulator
- 6m structure, existing BPM, new quads
- 3 kicker for orbit separation
- collimator for beam loss control

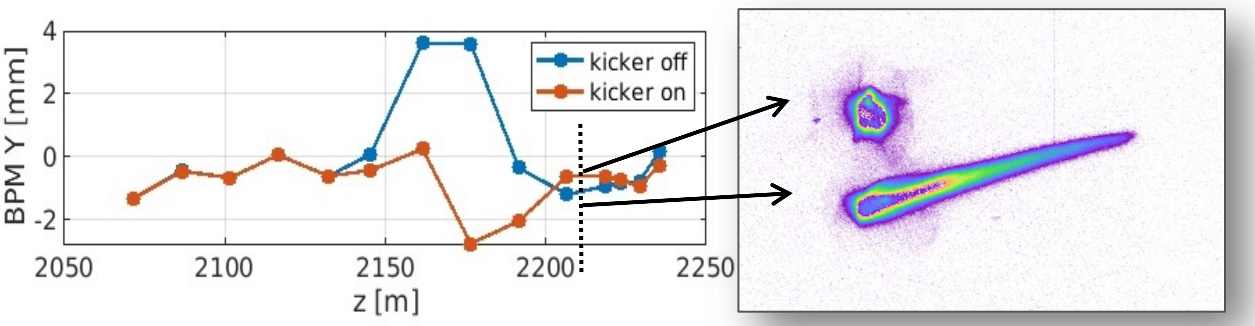


Commissioning of the device

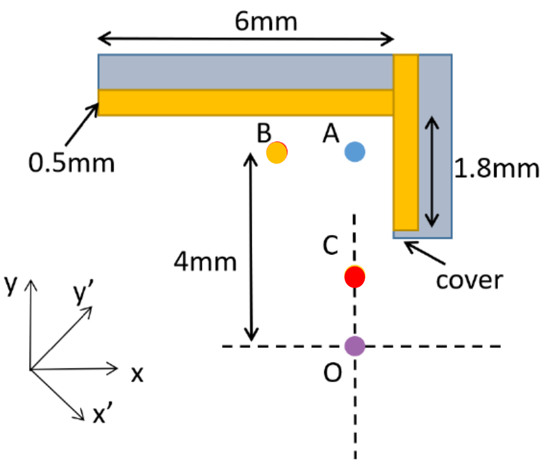
- Commissioned in the first half of 2023
- kicker triggered by timing pattern, switching SA1 and SA3 then can be easily realized







- 11 GeV, long bunch
- screen before SA1



- e-beam position control by bump + kicker system

Summary and outlook

- We have developed a corrugated structure system for applications at the European XFEL based on L-shape design.
- Short-range wakefield model was developed and implemented into simulation tool
- The system has been installed before SASE1/3 branch and has been commissioned. FEL pulse duration shortening down to a few spikes were demonstrated with high repetition rate.

- Further improvement of collimation for beam loss control
- Measurement of longitudinal phase space with a flat wakefield structure to be installed during 2025 shutdown
- Two color FEL after new chicane installed in SASE1 during 2025 shutdown

Acknowledgement

DESY

Marc Guetg
Winfried Decking
Philipp Dijkstal*
Nina Golubeva
Junjie Guo**
Shan Liu
Frank Obier
Torsten Wohlenberg
Igor Zagorodnov

TU Darmstadt

Erion Gjonaj

European XFEL

Gianluca Geloni
Svitozar Serkez

* Now at PSI, Switzerland
** Now at SHINE, China

Thanks for your attention!