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OCELOT as a Framework for Beam Dynamics Simulations of X-Ray Sources

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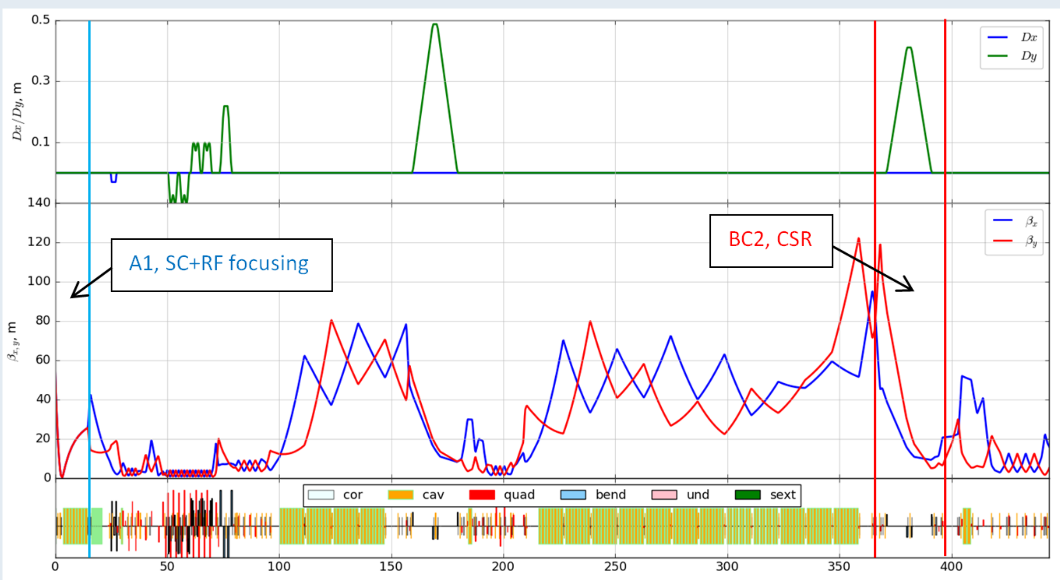
Introduction

OCELOT is a multiphysics simulation toolkit and an on-line control framework for FEL- and storage-ring-based light sources. The code is written in Python and includes native modules for beam dynamics and (spontaneous) synchrotron radiation calculations. Simulation of FEL physics is based on an external code Genesis 1.3 which is interfaced to OCELOT. Modules for online beam control and machine performance optimization are available.
In this work, we focus on the features of the code related to design and beam dynamic simulations of linear accelerators. Single-particle dynamics can be modelled in several ways (the transfer maps are configurable and can even be user-defined), for linacs the matrix formalism up to the second order is typically used (thick-lens non-symplectic integrators). The code includes special elements to describe asymmetric field effects in radiofrequency (RF) cavities. Collective effects include coherent synchrotron radiation (CSR), space charge (SC) and wakefields. Solvers for single-particle and collective effects are briefly described in what follows.
One of the most important and time-consuming stages of the beam dynamics code development is the cross-checking of simulation results with existing codes (e.g. ASTRA, CSRtrack). Here the cross-checking results for the European XFEL linac is presented.

Collective effects

- The tracking of particles uses matrix approach up to second order. The focusing effect of RF cavities is taken into account according to the Rosenzweig-Serafini model.
- In order to cross-check the code with codes ASTRA and CSRtrack we use the European XFEL lattice. Space charge and RF focusing effects are strongest for the low energy beam in the booster (the first TESLA cryomodule, A1 in Fig. 1). The CSR effects are strongest in the last bunch compressor BC2 and it was chosen to cross-check OCELOT with CSRtrack.

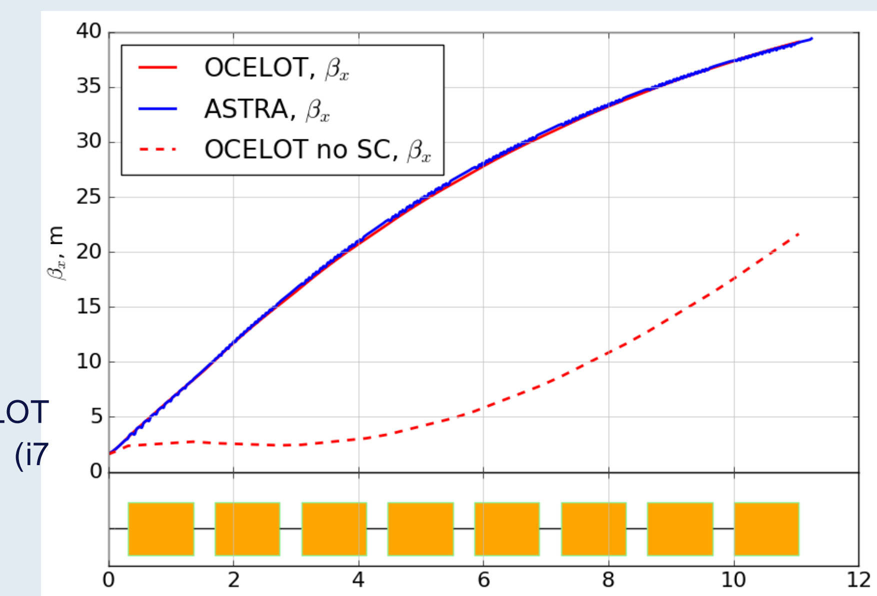


European XFEL lattice up to bunch compressor BC2

Space charge effect

- The space charge forces are calculated by solving the Poisson equation in the bunch frame. Then the Lorentz-transformed EM field is applied as a kick in the laboratory frame. For the solution of the Poisson equation we use an integral representation of the electrostatic potential by convolution of the free-space Green's function with the charge distribution. The convolution equation is solved with the help of FFT.
- The ideal linear map (with RF focusing) was used in OCELOT for particles tracking through the cavities while tracking through drift was performed up to second order. ASTRA uses the Runge-Kutta tracking with calculated 3D field profile..

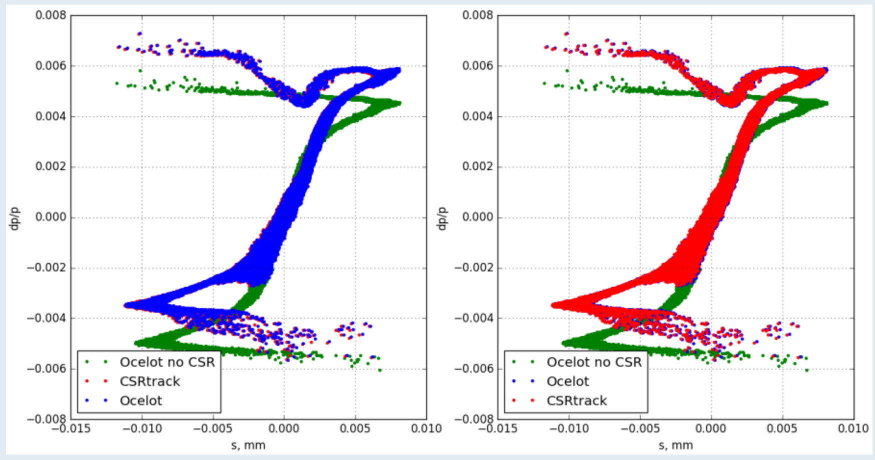
Beta-functions w/o SC
N particles: 20000,
Q = 250 pC,
Einit = 6.55 MeV.
N RF modules: 8
Vmodul = 19.54 MV
Phi = 18.73 grad
The calculation time in OCELOT for this setup: 3-10 mins (i7 CPU)



CSR effect

- The CSR module uses a fast 'projected' 1-D method from CSRtrack code. The particle tracking uses matrices up to the second order. CSR wake is calculated continuously through beam lines of arbitrary flat geometry. The transverse self-forces are neglected completely. The method calculates the longitudinal self-field of a one-dimensional beam that is obtained by a projection of the 'real' three-dimensional beam onto a reference trajectory. A smooth one-dimensional charge density is calculated by binning and filtering

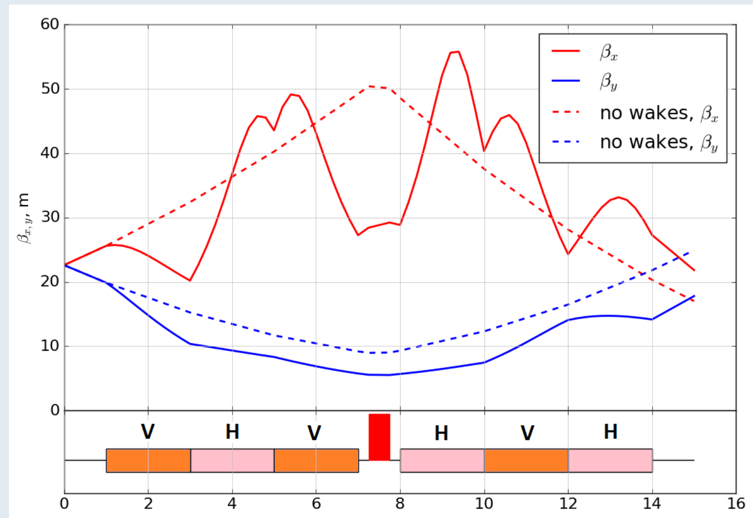
Longitudinal phase space after BC2.
N particles: 20000,
Q = 100 pC,
Eref = 2400 MeV
bend angle = 0.0336 rad.



Wakefields effect

- The longitudinal wake function is represented through the second order Taylor expansion. In general case we use 13 one-dimensional functions to represent the longitudinal component of the wake function for arbitrary offsets of the source and the witness particles near to the reference axis. The transverse components of the wake function are calculated with the help of Panofsky-Wenzel theorem. The wake field impact on the beam is included as a series of kicks
- The corrugated structure setup with parameters of corrugations suggested at SLAC. The setup contains 6 planar corrugated structures and one quadrupole

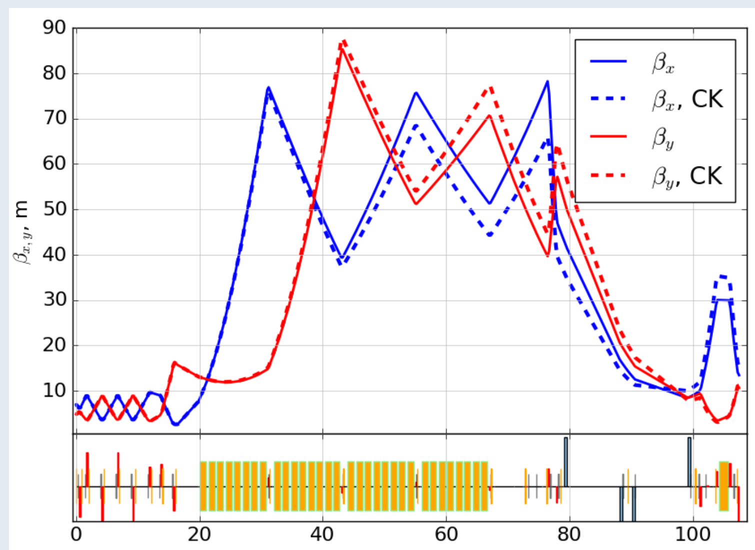
Beta-functions calculated from beam distribution with energy chirper.
N particles: 10000,
Q = 500 pC,
E = 14 GeV.



Coupler kick

- The input coupler and the higher order mode couplers of the RF cavities distort the axial symmetry of the electromagnetic (EM) field and affect the electron beam. For fast estimation of the coupler effect a discrete coupler model was implemented in OCELOT. The 1st order part of the model includes time and offset dependency; the offset dependency has a skew component.

The beta functions at L1 of the European XFEL w/o the coupler kick effect.
First-order effect (offset dependancy with a skew component).



Summary

- All major collective effects to be taken into account for simulations of XFEL driver linacs have been implemented and the calculation results cross-checked.
- This opens up several possibilities for future applications, e.g. optimization of accelerator performance and beam properties (e.g. using MOGA)
- Code optimization for multicore architectures is an important line of future work.