POST-LINAC COLLIMATION SYSTEM FOR THE EUROPEAN XFEL

V. Balandin*, R. Brinkmann, W. Decking, N. Golubeva
DESY, Hamburg, Germany

Abstract

In this article we give an overview of the the post-linac collimation system for the European X-Ray Free-Electron Laser (XFEL) Facility [1] with main emphasis on lattice and optics design.

INTRODUCTION

The post-linac collimation system should simultaneously fulfill several different functions. In first place, during routine operations, it should remove with high efficiency off-momentum and large amplitude halo particles, which could be lost inside undulator modules and become the source of radiation-induced demagnetization of undulator permanent magnets.

The system also must protect the undulator modules and other downstream equipment against miss-steered and off-energy beams in the case of machine failure without being destroyed in the process. Because the collimation system is designed as passive, the collimators must be able to withstand a direct impact of such number of bunches which can be delivered to their locations until a failure will be detected and the beam production in the RF gun is switched off.

From the beam dynamics point of view, the collimation section, as a part of the beam transport line from linac to undulator, must meet a very tight set of performance specifications. It should be able to accept bunches with different energies (up to $\pm 1.5\%$ from nominal energy) and transport them without any noticeable deterioration not only of transverse, but also longitudinal beam parameters, i.e. it must be sufficiently achromatic and sufficiently isochronous. This will not only reduce jitter of transverse beam parameters and time of flight jitter due to an energy jitter, but also will allow to fine-tune the FEL wavelength by changing the electron beam energy without adjusting magnet strengths (an energy change of $\pm 1\%$ corresponds to $\pm 2\%$ change in the FEL wavelength) and, even more, will make possible to scan the FEL wavelength within a bunch train by appropriate programming of the low level RF system.

Some of above requirements are not in good agreement with one another and, as often, the basic problem is to find a balance among all competing factors so as to have at the end a system which still satisfactory fulfills design goals. For example, relatively large betatron functions, which are needed at the collimator locations to guarantee their survival during occasional beam impacts, lead, as a rule, to unacceptable chromatic aberrations and, therefore, chromaticity correcting sextupoles are essential in preventing the dependence of linear optical parameters on the energy deviation. Chromatic-aberration correction with sextupoles, in the next turn, requires a beamline with dispersion, which makes separate regulation of transverse and energy collimation depths difficult and thus reduces flexibility of a system.

In this article we give an overview of the optics solution which fulfills all listed above requirements, and more details can be found in [2].

LAYOUT AND FUNCTIONALITY

The part of the beam transport from linac to undulator, which we call the **post-linac collimation section** and which is shown in Fig. 1, consists of two arcs separated by a straight section (phase shifter) and includes matching modules at both ends to adapt the optic to the desired upstream and downstream beam behavior. The collimation section bends the beam in the vertical plane and its length measured in the projection on the linac axis is about $215.3\,m$. The outgoing beam axis points slightly downward with an angle of about $0.021°$ and the vertical offset of the center of the last quadrupole of the second arc from the linac axis is $2.4\,m$. The arcs are almost identical except that in the second arc the polarity of dipole and sextupole magnets is reversed and dipole bending angles are slightly smaller in absolute values in order to produce the net downward beam deflection. Each arc consists of four $90°$ cells, constitutes a second-order achromat and is first-order isochronous.

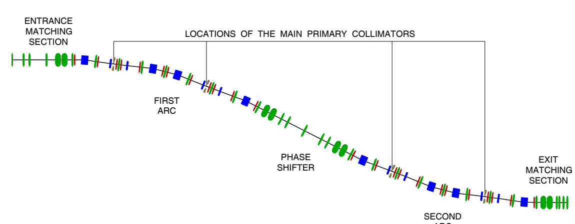

Figure 1: Overall layout of the XFEL post-linac collimation section. Blue, green and red colors mark dipole, quadrupole and sextupole magnets, respectively.

Three different types of collimators are foreseen in the XFEL post-linac collimation system: Main primary collimators, supplementing primary collimators and secondary collimators (absorbers). The principal purpose of the main primary collimators is to intercept trajectories of all incoming particles which would otherwise appear outside of the downstream dynamic aperture. The main collimators will also shade a part of the beam pipe in the collimation section (but not all) from uncontrolled beam impacts. Supplementing primary collimators assist to accomplish this work or,

* vladimir.balandin@desy.de

at least, reduce the probability of such events. Simultaneously, the supplementing collimators will not affect the transverse and energy collimation depths set by the main collimators. To improve the overall cleaning efficiency at the exit and better localize losses inside of the collimation section several absorbers placed in the shadow of the primary collimators will be used.

The first arc will collimate transverse positions of incoming particles and the second, after a shift of vertical and horizontal betatron phases by odd multiples of $90°$, their transverse momenta. The energy and vertical plane collimation will be done simultaneously, and therefore the ratio of dispersion to vertical betatron function at collimator locations has to be properly adjusted in order to achieve the required transverse and energy collimation depths. Because, according to the optics design, dispersion can not be varied during machine operations, the rough preliminary adjustment was made already during design stage by appropriate selection of the arc parameters, and the operational flexibility will be provided by usage of collimators with exchangeable apertures and by tuning betatron functions at the collimator locations.

OPTICS AND BEAM DYNAMICS

Large beam spot size requested at the collimator locations and, in the same time, the possibility to transport bunches with different energies (up to $\pm 1.5\%$ from nominal energy) while preserving with good accuracy energy independent input and output matching conditions, make the control of chromatic effects one of the main issues in the design of the optics in the collimation section. Without correction the chromatic aberrations are unacceptable and, therefore, introduction of chromaticity correcting sextupoles becomes essential in improving overall system performance. There are different approaches to the problem of compensation of chromatic effects, and the solution, which we found to be most adequate to the design requirements, is as follows: We compensate the arc chromatic effects by tuning arcs to become second-order achromats. Reduction of chromatic aberrations in the system straight sections is done for the particular betatron functions transported through these parts and without involving sextupole fields, simply by an accurate drift-quadrupole optics design (a straight drift-quadrupole system can not be made an achromat, but it can be made a second-order apochromat with respect to certain incoming beam ellipses, i.e. it can transport these beam ellipses without introducing first-order chromatic distortions).

Adjustment of Linear Isochronicity

In the first design, which is described in the TDR [1], the linear momentum compaction of the whole collimation system (r_{56} matrix coefficient) was approximately equal to $-0.8\,mm$, which at that time was considered as acceptable value. In later studies of the microbunching instability

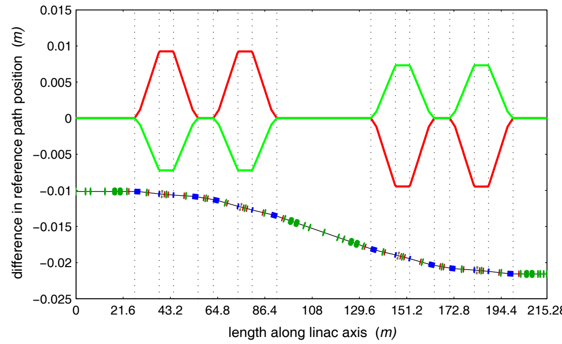

Figure 2: Changes in the vertical position of isochronous beam line with $r_{56} = 0$, which are required to bring linear momentum compaction of the collimation section to $r_{56} = -1\,mm$ (red curve) and to $r_{56} = +1\,mm$ (green curve).

it was found that even such a small value can not be neglected in the calculation of the gain of this instability and that, in order to reduce this gain, it is desirable to have r_{56} of the collimation section equal to zero or, even better, to bring it to a positive value of about $0.2\,mm$ [3]. Because some other reasons for the choice of the linear momentum compaction could appear and the exact value of r_{56} is not clear yet, we made system modifications in such a way, that though r_{56} could not be varied dynamically during machine operations, the linear momentum compaction can be adjusted within about $\pm 1\,mm$ limits by system realignment while keeping space positions not only of the system end point and the system straight sections but also of the arc centers unchanged, as can be seen in Fig. 2. The design which we describe in this paper (**baseline design**) is the first-order isochronous beam line with $r_{56} = 0$.

Linear Lattice Functions

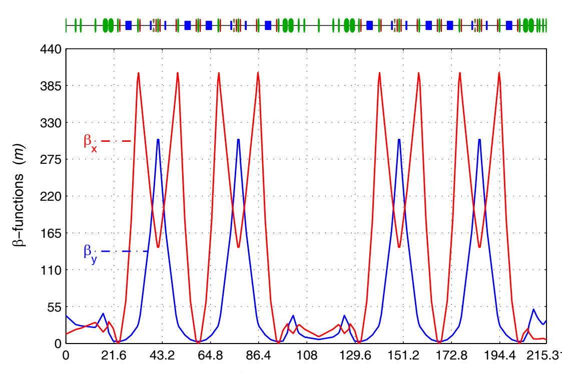

Figure 3: Betatron functions along the XFEL post-linac collimation section. Standard collimation optics.

According to the system design the arcs are tuned to become second-order achromats and this, together with the fixed system geometry and the requirement of the first-order isochronicity, completely determines the setting of

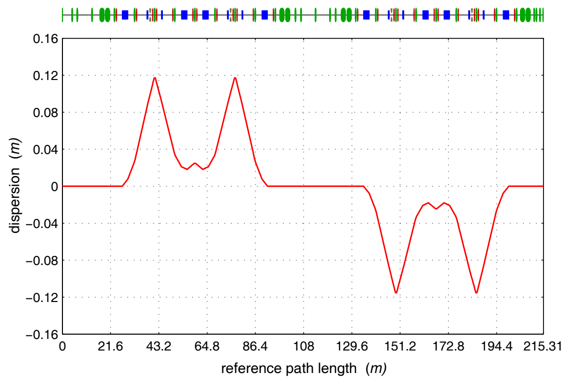

Figure 4: Dispersion function along the XFEL post-linac collimation section.

the arc magnets and also the behavior of linear dispersion function. Thus the modifications of the betatron functions along the collimation section can be provided only by retuning of quadrupoles in the matching sections and in the phase shifter. This is not a limitation in our case, because the design of these sections is done in such a way that with appropriate adjustment of their quadrupoles we are not only able to provide betatron functions of about $200\,m$ at the points where the collimators are located (**standard collimation optics**), but also able to translate smoothly the standard collimation optics into an optics with regular FODO-like transport through the entire collimation section.

This flexibility is an important property of the designed system and will be extensively used during machine commissioning and/or during measurements of beam parameters. For example, commissioning starts with optics set to provide regular FODO-like transport and with sextupoles switched off and then, with experience gained, this optics can be translated step by step into the standard collimation optics.

Betatron functions corresponding to the standard collimation optics can be seen in Fig. 3. Fig. 4 shows the linear dispersion, which is independent on setting of quadrupoles in the matching sections and in the phase shifter.

SUMMARY

The optics solution for the XFEL post-linac collimation section described in this paper meets all design specifications. It is capable of providing simultaneously a large beam spot size at the collimator locations (Fig. 5) and, in the same time, to transport bunches with different energies (up to $\pm 1.5\%$ from nominal energy) while preserving with good accuracy energy independent input and output matching conditions (Fig. 6). These criteria are met by designing a magnetic system whose second-order chromatic and geometric aberrations are controlled by the symmetry of the first-order optics and sextupole fields.

The system uses four main primary collimators and the studies presented in [2] show that these collimators are able to confine all particles which passed the collimation section freely (without touching collimator apertures) into a volume in the phase space, that can be safely transported through all downstream beamlines (including undulator modules) to the beam dumps.

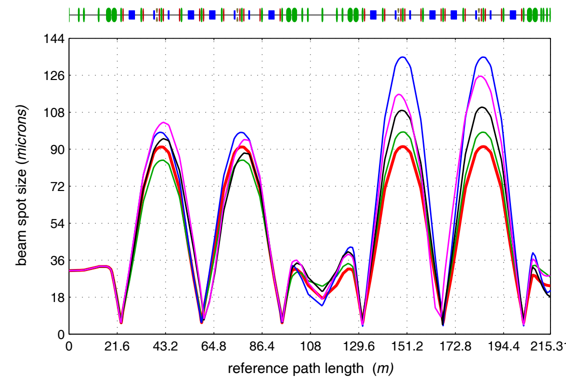

Figure 5: Evolution of beam spot size ($\sqrt{\sigma_x \sigma_y}$) along the collimation section. Beam energy 17.5 GeV. Normalized emittances 1.4 $mm \cdot mrad$. Red curve shows the design spot size (linear theory). All other curves are results extracted from the tracking simulations. A matched Gaussian beam at the entrance with -3% (blue) and $+3\%$ (green) energy offsets, with $40\sigma_y$ transverse offset (black), and with both -3% energy and $40\sigma_y$ offsets (magenta). Sextupoles are switched on.

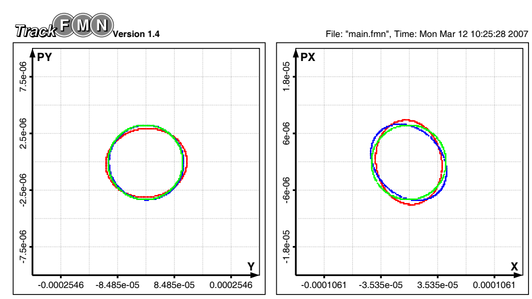

Figure 6: Phase space portraits of monochromatic $3\sigma_{x,y}$ ellipses (matched at the entrance) after tracking through the entire collimation section. The relative energy deviations are equal to -1.5%, 0% and $+1.5\%$ (red, green and blue ellipses, respectively). Sextupoles are switched on.

REFERENCES

[1] M. Altarelli, R. Brinkmann et al. (Eds), “XFEL: The European X-Ray Free-Electron Laser. Technical Design Report”, DESY 2006-097, DESY, Hamburg, 2006.

[2] V. Balandin, R. Brinkmann, W. Decking, N. Golubeva, “Optics Solution for the XFEL Post-Linac Collimation Section”, TESLA-FEL 2007-05, DESY, Hamburg, May 2007.

[3] M. Dohlus, FEL Beam Dynamics Group Meeting, DESY, `http://www.desy.de/xfel-beam/meetings_2006.html`