LATTICE STUDIES FOR THE XFEL-INJECTOR

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Abstract

The XFEL injector building has a length of 74.3 meters and is divided by 2.5m long concrete shielding wall. The section upstream the shielding wall will have a length of 42.3m and give place for the gun, accelerating module, a possible 3rd harmonic section, laser heater and the beam diagnostics section. At its end the possibility for the beam dump is foreseen so that the tuning of the beam in the injector becomes possible without any impact on the subsequent parts of the XFEL. Each of these components sets certain requirements on beam optics which may compete with each other.

Since there are two injectors foreseen for the XFEL the injector will be vertically displaced by 2.75 m from the linac. The displacement of the beam line takes place downstream the shielding over the distance of 20m by means of the so called dogleg – a combination of two four cells arcs (8 cell system). It is important there to optimize cells in such an order that the chromatic effects don't impact the beam quality noticeably. In this paper we describe the solution for the beam optics at the XFEL injector.

INTRODUCTION

The XFEL injector plays a crucial role for the beam quality along the subsequent transport of the beam through the XFEL. Therefore it is important to have the possibility for both the understanding of the beam parameters at the injector as well as for the flexible change of the beam parameters there. For the tuning and analysis of the beam parameters the section upstream the shielding wall is foreseen. At the end of this section a possibility for a separate beam dump will be given so that the tuning of the beam may proceed without any impact on the actions at the other sections of the XFEL. The section is about 42.3m long and has to give place for numerous components. They are the gun and gun diagnostics, accelerating module, 3rd harmonic RF section, laser heater, transverse deflecting structure (TDS) and the diagnostics section with four OTR monitors. Besides, a spare place of about 2.4m at the end of the section is needed in order to provide the change of the absorber body. Each of these components sets certain requirements on the beam optics, which may compete with each other. Since a very short length of the beam line of less than 40 meters for this purpose available the design of the beam optics at the injector becomes a challenging problem for the investigations.

Downstream the shielding wall the beam will be vertically displaced by 2.75m over the beam line length of 20m. Since the vertical displacement takes place one has to be cautious with the choice of the magnet arrangement there so that the optics doesn't affect the chromatic features of the beam noticeably.

We describe the possible optics solution for the XFEL injector in which these considerations and requirements of each component on the optics have been taken into account.

REQUIREMENTS ON OPTICS AT THE LASER HEATER

The purpose of the laser heater is to enhance the uncorrelated energy spread of the electron beam which would lead to the increase of the Landau damping and thus reduce the sensibility of the beam to the sources of the instabilities during the bunch acceleration and transport through the linac [1].

However not only the net value of the uncorrelated energy spread plays an important role for the effectiveness of the Landau damping but also the form of the energy distribution in the bunch. It has been found [1] that the laser beam size has to be equal or slightly larger than the transverse size of the electron beam to provide an effective Landau damping. This condition would require a reasonable matching of both laser and electron beams and thus sets constraints on the optics at the laser heater.

The possibility to suppress the microbunching instability by means of the laser heater has been discussed in [1]. The design of the laser heater for the XFEL injector has been described in [2]. It was found that the optics at the laser heater has to been chosen in such a way that the electron beam size doesn't change a lot during the transport through the undulator. Since the length of the undulator is L=0.5m the change of the beta-function along the undulator can be than roughly estimated according to the formula:

$$\Delta\beta[m] \approx -2\alpha L = -\alpha$$

The transverse beam size goes as $\sqrt{\beta}$ so that the reduction of the beta function by factor of 2 (i.e. α=0.5β) causes the change of the transverse beam size by approximately 30%. This boundary, though floating, has been proven to be a reasonable limitation on the α-function at the laser heater.

The smallest acceptable value for the beta function at the undulator is set by the condition of the stable laser beam spot size. The Rayleigh length shouldn't be shorter than the undulator length. Furthermore both beams should have the same transverse size. If one assumes the smallest possible transverse size of the laser and therefore also of the electron beam one gets for the design emittance of 1.0mm mrad that the beta function shouldn't be smaller than 7m along the undulator.

The upper limit for the beta function is given by the highest possible laser beam power. However it is expected that the laser will be powerful enough to provide matching for any reasonable electron beam size.

REQUIREMENTS ON OPTICS AT THE DIAGNOSTICS SECTION

The diagnostics section consists of the transverse deflecting structure and the OTR monitors section. According to the formula [3]:

$$\beta_y \geq \left(\frac{\lambda}{\pi\sigma_z} \cdot \frac{1}{eV_o \sin\phi_y} \right)^2 pc \cdot mc^2 \varepsilon_N \tag{1}$$

the beta function has to be not smaller than 1.0m at the TDS. Further requirement concerns the phase advance between the TDS and the OTR screens which could be described by

$$\prod_{i=1}^{4} \sin(\phi_y(TDS, OTR_i)) = \max \tag{2}$$

Besides the allowed transverse size of the electron beam as it passes through the OTR screen is determined by the resolution of the OTR monitors on one hand and the size of the streaked beam on the other hand. A reasonable assumption for the resolution of the OTR monitor is given by 12µm [4] whereas the streaked beam should not be larger than 25mm. These conditions set borders for the beta function at the OTR stations as

$$0.9m \leq \beta_{x,y} \leq 5.9m \tag{3}$$

OPTICS SOLUTIONS FOR THE DIAGNOSTICS SECTION

Three different options for the implementation of the optics in the diagnostics section have been considered. The simplest one is the so called “waist” solution in which the OTRs are placed in a common drift section. Hereby the beta function is adjusted in such a way that it assumes a parabola form with the vertex in the middle of the diagnostics section. The OTR monitors are arranged then symmetrically around the vertex in such an order that the phase advance between the neighbour OTRs reaches 45°. This option, though the simplest one, has been found not to be flexible enough to provide a good matching for all expected initial values of the beta function at the entrance. Besides, it was not possible to get a suitable phase advance between the TDS and OTR screens so that the condition (2) could be satisfied.

Another option, a 45° FODO lattice, uses FODO cells to control the phase advance between the OTR screens. One OTR screen per FODO cell is used in so that total 3.5 cells are necessary to house all OTRs. Contrary to the waist solution an additional matching section between the undulator and OTR section is needed, which allows to choose a suitable place for the TDS so that condition (2) could be fulfilled easily.

In the third option, a 76° FODO lattice, there are two OTR screens per cell, so that 1.5 FODO cells are required. Therefore the whole solution becomes more compact and suitable for injector.

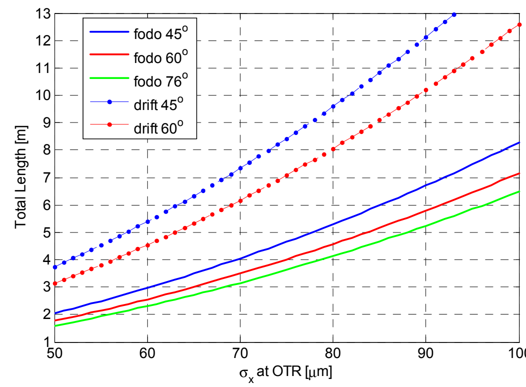

Figure 1: length needed by the diagnostics section for different solutions. Though FODO solutions require less space an additional matching section (not taken into account here) in front of the diagnostics would be needed. Nevertheless the FODO 76° solution even together with the matching section requires less space than other solutions and offers enough flexibility for the beam optics.

OPTICS AT THE DOGLEG

General Requirements and Preliminaries

The magnet lattice of a dogleg has to fulfill a number of requirements, both in terms of beam dynamics as well as geometry considerations:

- Provide a vertical displacement of the beam for a distance 2.75m at the length 20m as measured along linac axis.
- It should be able to accept (matched) bunches with different energies (up to 10% from nominal energy) and transport them without deterioration of transverse beam parameters.
- First order momentum compaction (r56 matrix coefficient) should be zero.

Dogleg as Combination of Two, Four Cell Arcs (8 Cell System)

Solution considered in this section is constructed using the idea presented in [5]. The dogleg is formed by two arcs, where the second arc is made from the first arc by taking magnets of the first arc in reverse order and switching polarities of all odd multipoles (dipoles and sextupoles). Besides that each arc is mirror symmetric with respect to its center. The symmetries involved in design of such a system guarantee that if one makes the arc to be a second order achromat, the nonlinear dispersions will be automatically zero at least up to fifth order.

The only difference with systems considered in [5] is that for constructing second order achromatic arc we use not four identical cells, but the symmetry FRFR as in [6]

Note that again as in [5], it is sufficient to correct only horizontal (deflecting plane) motion and the good beam transfer properties for the vertical dynamics can be provided simply by small betatron functions and properties of the linear achromat. So both sextupoles are working only for horizontal motion. Additional optimizations made to obtain so good beam transfer properties include finding right balance between positive and negative dipole angles (it is important not only for r56 control, but also for effective sextupole usage), positioning of dipoles and central quadrupole (which is not in the cell center), positioning and strength reduction of sextupoles.

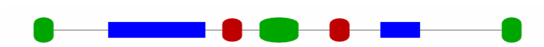

Figure 2: Forward cell of the dogleg. The cell length is about 2.53m as measured along curved beam path. Blue, green and red colours mark dipole, quadrupole and sextupole magnets, respectively.

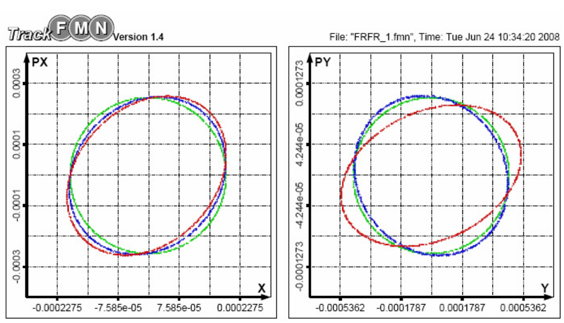

Figure 3: Phase space portraits of monochromatic $3\sigma_{x,y}$ ellipses (matched at the entrance) after tracking through the dogleg. The relative energy deviations are equal to -15%, 0% and +15% (red, green and blue ellipses respectively).

PRELIMINARY OPTICS SOLUTION

Figure 6 shows preliminary optics solution for the XFEL injector. It begins at the entrance of the 3,9GHz RF section with design values for the initial optics functions (β_x=β_y=45.0m and α_x=α_y=0). After it follow the laser heater, TDS, diagnostics section with a FODO 76° solution, shielding and dogleg. The optics is well-defined after the matching section between the laser heater and TDS. Simulations have also shown that the matching is possible for any values of the initial beta-functions from the expected range (20-100m).

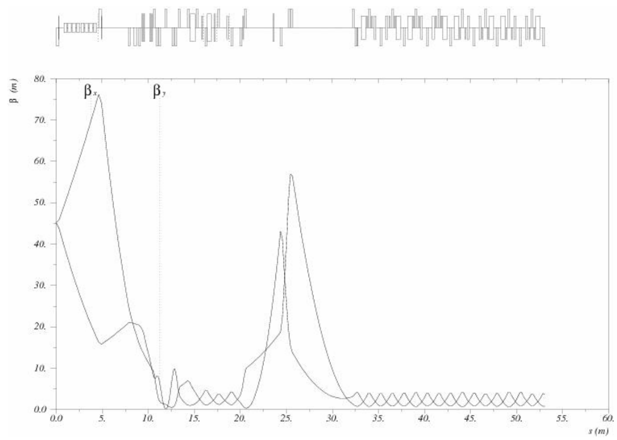

Figure 4: Preliminary optics solution for the XFEL injector.

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