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SUPERCONDUCTING PHASE SHIFTER DESIGN FOR THE AFTERBURNER AT THE EUROPEAN XFEL

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Abstract

At the European XFEL, a superconducting afterburner is under design for the SASE2 hard X-ray beamline. It will consist of 5 undulator modules. One module corresponds to two superconducting undulator (SCU) coils of 2 m length plus one phase shifter. Such an afterburner will enable photon energies above 30 keV. Superconducting (SC) phase shifters will be installed in each undulator module to keep the correct phase delay between the electron beam and photon beam. In this contribution, we present the required SC phase shifter parameters to enable operation in the electron beam energy range 11.5-17.5 GeV. We also analyze different magnetic designs satisfying the calculated specifications.

INTRODUCTION

The European XFEL is, so far, the only high repetition rate hard X-ray free-electron laser (XFEL) worldwide. It accelerates electrons up to an energy of 17.5 GeV exploiting a 1.7 km long linear accelerator (linac). The linac is built by superconducting (SC) cavities that enable burst mode operation with up to 27000 electron bunches per second distributed in 10 macrotrains with an intra-train repetition rate up to 4.5 MHz. The electron bunches are then distributed in three undulator beamlines that generate FEL radiation: SASE1, SASE2 and SASE3. Based on the scientific interest of increasing the energy of the delivered photons, this year will start the installation of an afterburner based on the APPLE-X undulators at the SASE3 [1]. Similarly, we are planning an afterburner based on the SC technology [2]. It will be installed after the 35 permanent magnet undulators (PMU) of SASE2, which will enable photon energies above 30 keV. The afterburner for SASE2 will have five cryomodules. Each of them includes two 2 m long SCU coils with a period of 18 mm and a maximum peak field of 1.82 T at 4.2 K. The length of the undulator intersection within the cryomodule should be minimized. Correction coils and a phase shifter to correct the phase mismatch are placed between the two 2 m long SCU coils.

In this contribution, we define the phase shifter specifications in terms of geometrical properties and phase integral to guarantee continuous tunability during wavelength changes. Based on these requirements, we describe three different designs for the phase shifter and we define the preferred configuration to minimize the physical and magnetic length.

PHASE SHIFTER SPECIFICATIONS

The afterburner under consideration generates photons with energy in the ranges 28 − 100 keV or 12.3 − 60 keV respectively at an electron beam energy of 17.5 GeV and of 11.5 GeV. Consequently, the phase shifter is designed to guarantee continuous tunability within these ranges. Figure 1 shows the phase integral calculated with Eq. (1) [3]

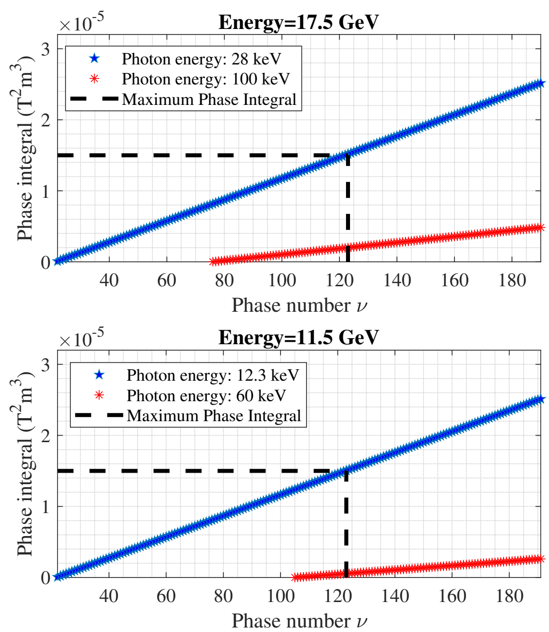

Figure 1: Phase integral as a function of the harmonic number ν for the photon energies 28-100 keV at 17.5 GeV and 12.3-60 keV at 11.5 GeV.

$$PI = \left(\frac{mc}{e}\right)^2 (\lambda_R \gamma^2 \nu - L), \tag{1}$$

where m is the electron mass, c is the speed of light, e is the electron charge, λ_R is the resonant wavelength, γ is the Lorentz factor of the electron, ν is the harmonic number and L is the length of the intersection between the two undulators in the cryomodule. For this study, we fix $L = 1.1$ m to have a higher limit on the phase integral. A phase integral of $1.5{\times}10^{-5}\,\mathrm{T^2\,m^3}$ is enough to guarantee continuous tunability for operation at both electron beam energies. The phase shifter has a fixed gap of 6 mm. To have a compact magnetic structure, the magnetic length of the phase shifter should be minimized. We define the magnetic length to include all magnetic fields except for $1.5{\times}10^{-4}$ T m of first field integral at each end of the phase shifter. $1.5{\times}10^{-4}$ T m is also the maximum allowed value for the first field integral [4]. Finally, the second field integral at the exit of the phase shifter should be:

$$I_2 \leq 1 \times 10^{-4}\,\mathrm{T\,m^2}. \tag{2}$$

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Table 1: Parameters of the Simulated Phase Shifter Designs - The First Column Shows the Scenario Number

	L [mm]	N_t	c_w[mm]	c_h[mm]	p_w[mm]	y_h[mm]	I_0[A]	I_{ext}[A]	L_{mag}[mm]	**PI** [$\mathbf{T^2\,m^3}$]
1	80	1733	7.1	13.9	12.2	–	20	6.5	168	1.52×10^{-5}
2	100	2173	10.2	12.1	7.6	–	20	7.7	158	1.54×10^{-5}
3	90	1185	10.2	6.6	5.6	15	20	7.7	80	1.62×10^{-5}
3a	79	1185	10.2	6.6	–	–	20	10	146	3.1×10^{-6}
3b	94	2780	14.0	11.3	–	–	20	10	202	1.50×10^{-5}

PHASE SHIFTER GEOMETRY

We have studied different phase shifter designs with Radia [5]. For the real phase shifter, we are going to use a round-shaped NbTi wire with an insulated diameter of $d = 0.254$ mm and bare diameter of $d_{bare} = 0.225$ mm. We define the racetrack width as: $c_w = N_c \cdot d$ where N_c is the number of turns in the odd layers, while for the even layers we have $N_c - 1$ turns. For the height of the racetrack, we consider the occupation factor of round wires. Therefore, it results:

$$c_h = d \cdot \left[\frac{\sqrt{3}}{2} \cdot (N_r - 1) + 1\right], \tag{3}$$

where N_r is the number of layers. The total number of turns in one racetrack is given by:

$$N_t = \sum_{odd}\left[N_c \cdot N_r - \frac{Nr-1}{2}\right] + \sum_{even}\left[N_c \cdot N_r - \frac{Nr}{2}\right], \tag{4}$$

where $\sum_{odd}$ is the sum in the odd layers and $\sum_{even}$ in the even layers. The general geometry of the designs that we have considered is presented in Fig. 2.

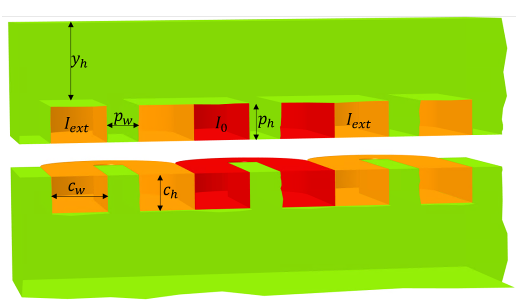

Figure 2: Geometry of the phase shifter.

In the simpler case (named *Scenario 1*), the phase shifter has three racetracks placed one next to each other, leaving a margin of 0.1 mm for insulation. Three iron (ARMCO) poles are placed in the central space of each racetrack. In *Scenario 2*, we study the effect of adding two poles upstream the first racetrack and downstream the last racetrack aiming at the reduction of the magnetic length. In *Scenario 3*, we add a yoke to cover the racetracks and the five poles to further minimize the magnetic length. In all the cases, the straight part of the racetrack has a length of 50 mm.

The current passing through the single wire I_0 is set to 20 A to limit the heat load from the current leads. For minimizing the second field integral, we have used a lower current I_{ext} for the two outer racetracks. For this reason, in the real phase shifter, we need to use two power supplies.

OPTIMIZATION PROCEDURE

For a given phase shifter design, the wished phase integral greater or equal $1.5 \times 10^{-5}\,\mathrm{T^2\,m^3}$ is achieved following the procedure described below:

1. The phase shifter length L and the margins for insulation are fixed before starting the optimization. The margin between the racetracks and the iron is 0.1 mm.

2. The phase integral as a function of N_c is studied for a fixed value of N_r. N_r is increased until the phase integral is between 20% and 40% more than the wished value. The additional percentage is needed to compensate for the reduction in current applied on the outer racetracks to fulfil the requirement on the second field integral $I_2 \le 1 \times 10^{-4}\,\mathrm{T\,m^2}$ Once this condition is achieved, we fix N_r and N_c.

3. With the chosen N_c and N_r, we change the current for the outer racetracks, up to the point where the first integral is close to zero.

After these three steps, we verify if the phase integral achieves $1.5{\times}10^{-5}\,\mathrm{T^2\,m^3}$. In case the condition is satisfied, we finalize the design, otherwise, we repeat the procedure from the second step.

SIMULATION RESULTS

In Table 1, we report the outcome of the optimization for the different designs (number of turns per layer, number of layers and current) and the resulting geometrical parameters (racetrack width c_w, racetrack and pole height, yoke height y_h). On the two last columns of the table, we report the resulting magnetic length and phase integral. The two last rows contain the results for scenarios *3a* and *3b*, where *Scenario 3a* has the same geometry as *Scenario 3* but without iron and *Scenario 3b* is the optimized version of *Scenario 3a*. Interestingly, we notice that by removing the iron from *Scenario 3*, the phase integral drops to $3.1{\times}10^{-6}\,\mathrm{T^2\,m^3}$ in *Scenario 3a*. In addition, we need to increase the number of turns by 1595 units to recover the wished phase integral. As a result, the iron helps to achieve the phase integral by keeping moderate the number of wire turns, which helps the winding process significantly with the very thin wire used for

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this application. Table 1 also shows that the lowest magnetic length is achieved in *Scenario 3*; therefore we choose this design for our phase shifter.

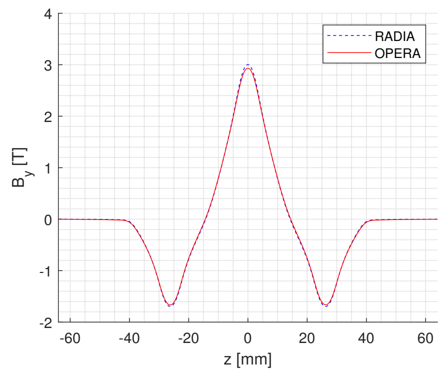

Figure 3: Projection of the magnetic field along the Y axis along the Z longitudinal direction simulated in Radia and Opera-3d.

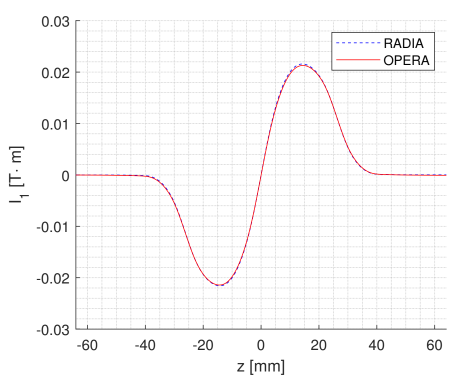

Figure 4: First field integral for *Scenario 3*.

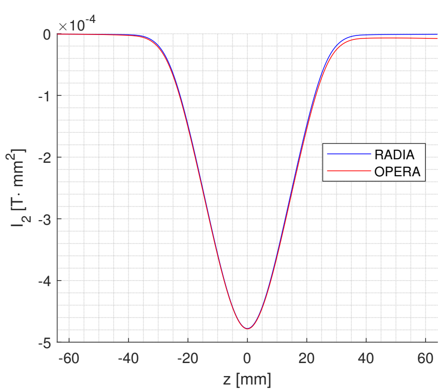

Figure 5: Second field integral for *Scenario 3*.

THE FINAL DESIGN

Figures 3 to 6 present the magnetic field along the longitudinal coordinate Z, the first and second field integral and the phase integral for the chosen phase shifter design *Scenario 3* respectively. The Radia simulation is in good agreement with the OPERA-3d [6] results. Figure 7 shows the phase shifter simulated in OPERA-3d where the magnetic field on the device is described in color map. The magnetic length of this scheme is 80 mm which will prevent any interaction with the magnetic field on the undulators upstream and downstream. The achieved phase integral is 1.62×10^{-5} T^2 m^3, which will guarantee continuous tunability for the photon energies generated by an electron beam of 17.5 GeV at the EuXFEL.

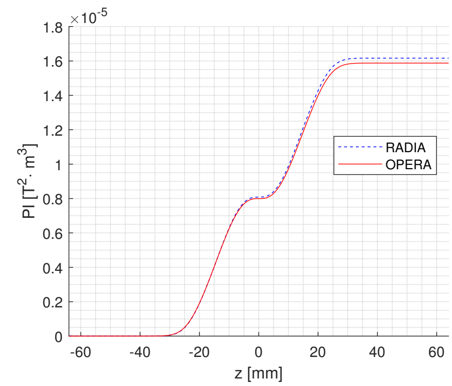

Figure 6: Phase integral for *Scenario 3*.

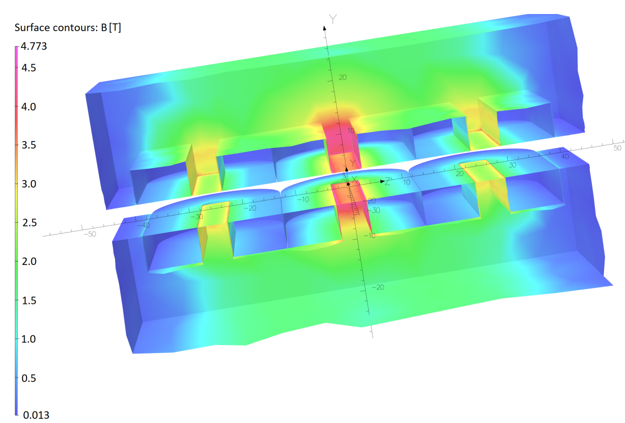

Figure 7: Magnetic field on the phase shifter from OPERA-3d simulation.

CONCLUSION

The phase shifter presented for the SCU afterburner under consideration at the EuXFEL satisfies continuous tunability for operation at electron beam energies between 11.5-17.5 GeV. Moreover, it is compact from the mechanical and magnetic point of view.

The intersection length inside the cryostat is planned to be about 0.4 m. As a consequence, the needed phase integral will decrease. The present design of the phase shifter allows to decrease the current below 20 A. The required value of the current will be defined once the intersection length will be finalized.

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