COLLIMATION SYSTEM DESIGN AND PERFORMANCE FOR THE SWISSFEL

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Abstract

Electron beam collimation in SwissFEL is required for protection of the undulators against radiation damage and demagnetization. The design for the SwissFEL collimation for the hard X-ray undulator (Aramis) includes transverse collimation in the final accelerating linac sections, plus an energy collimator in a post-linac chicane. The collimation system must ensure efficient protection of the undulator for various machine modes providing varied final beam energy to the undulator. The performance of the transverse and energy collimation design is studied in simulations including evaluation of the transverse collimation for various beam energies, and the effect of grazing particles on the energy collimator. Collimator wakefields are also considered.

INTRODUCTION

In accelerator-driven free electron lasers (FEL), electron beam halo can cause significant damage to undulators if not properly collimated. Calculations for the FLASH (Free electron Laser at Hamburg) facility[1] at DESY predicted that for ~ kW beam power halo losses on the undulator can cause significant demagnetisation very quickly. Measurements at FLASH in 2008 indicated an undulator demagnetisation of $\Delta k/k$=0.5% over 3 years of running [2].

The SwissFEL is a proposed X-ray FEL facility at PSI[3] featuring two undulators to cover the wavelength range 1-70 Angstroms. SwissFEL is a normal conducting accelerator with maximum energy 5.8 GeV and the maximum average beam power in each FEL line is around 100 W (single bunches of 200 pC delivered at 100 Hz to each undulator).

The SwissFEL beam power is an order of magnitude lower than FLASH, and around the same as the LCLS (Linac Coherent Light Source) facility at SLAC[4] which has an average beam power of 300W (13.6 GeV, 200 pC, 120 Hz). LCLS has a dedicated post bunch compression collimation section which has effectively reduced losses on the undulator to almost negligible levels[5]. Although the SwissFEL is a relatively low average beam power machine, significant undulator damage could still occur if the halo is not properly collimated.

Only collimation for the Aramis undulator is considered here, whose range of beam energies is 2.1 to 5.8 GeV, while the design for the soft X-ray beam line Athos has not been finalised yet. The SwissFEL beam collimation system for Aramis consists of transverse collimators in the final accelerating section, followed by an energy collimator in a chicane upstream of the undulator. In this paper the performance of the transverse and energy collimation sections are studied and wakefield effects are also considered.

COLLIMATION DESIGN

The design for the collimation system of the SwissFEL Aramis undulator is a series of transverse collimators located at the maximum beamsize in the FODO lattice of the final linac section, followed by an energy collimator in a post linac chicane. The optical functions in the collimation section are shown in Fig. 1.

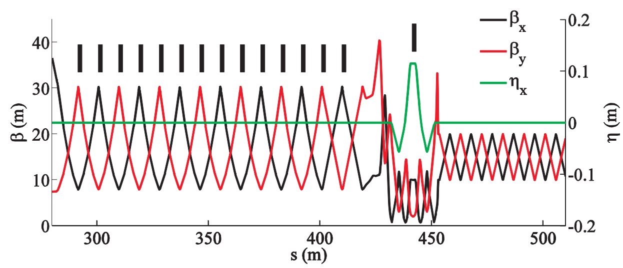

Figure 1: SwissFEL optical functions through final linac section, post linac chicane, and undulator. The collimator locations are indicated by the black rectangles; including transverse collimators from s ~ 300 to 410 m and the energy collimator at the mid-chicane point (s ~ 440 m) where the dispersion is ~ 12 cm.

The transverse collimation apertures must protect the undulator aperture from direct impact of high-amplitude halo particles. The apertures g_C are set, accounting for adiabatic damping of the emittance through the transverse collimation section, by the equation

$$g_C = F \times g_U \sqrt{\beta_C / \beta_U \cdot \gamma_U / \gamma_C} \quad (1)$$

where g_U is the undulator aperture, and γ_U (γ_C) is the beam energy at the undulator (collimator). F is a safety factor (F < 1) determined by simulation studies of collimation performance, as discussed later.

The Aramis undulator module minimum full gap will be 4 mm in the vertical plane. For the 5.8 GeV full energy operation of the undulator, the transverse collimation full gaps in the vertical plane range from approximately 7 mm to 5 mm, for the nominal optics design shown in Fig. 1. The horizontal gap is much larger in undulator modules (~ 3cm) and the intra-module vacuum chamber has a diameter of 8 mm in both planes. Therefore the admittance of the undulator beam line is solely defined by the vertical undulator gap. The Aramis undulator is approximately 60 m long.

The betatron phase advance between successive collimators in one plane is $2\pi/5$. The transverse

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collimators will be fixed gap and must provide adequate protection for different machine configurations with different final beam energies and different adiabatic damping of the beam dynamics throughout the collimation section. The collimators will be short (~ 2-3 cm of copper); it is assumed that any particles which penetrate the collimators will not be transported to the exit of the linac.

The adjustable-gap energy collimator, in addition to removing beam halo, has a machine protection role for sudden losses in beam energy; it must absorb full energy 5.8 GeV particles.

TRANSVERSE COLLIMATION PERFORMANCE

To simulate the performance of the transverse collimators a simple focussing defocusing lattice section of ~ 60 m length, with $\beta_{max,min}$ = 20, 10 m to represent the undulator beamline was matched to the exit of the chicane (the optics shown in Fig. 1).

The performance of the transverse collimation for the nominal 5.8 GeV final beam energy was then studied using ELEGANT[6]. The vertical plane was considered only, since the aperture of the undulator modules is effectively open in x. A ‘halo’ represented by a large area of vertical phase space, uniformly filled with 100 K particles, matching the beam energy, was tracked from the entrance of the transverse collimation section to the exit of the undulator.

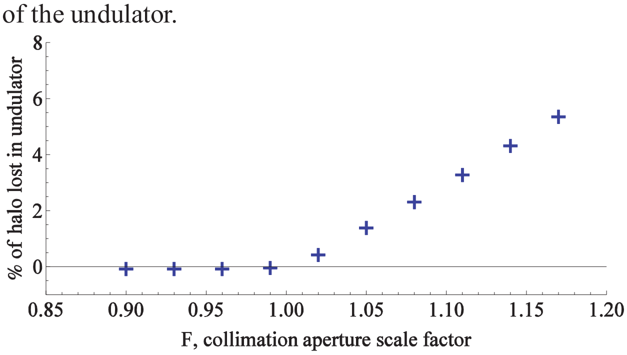

Figure 2: Simulated transverse collimation performance as a function of collimation aperture size factor F, defined in equation (1).

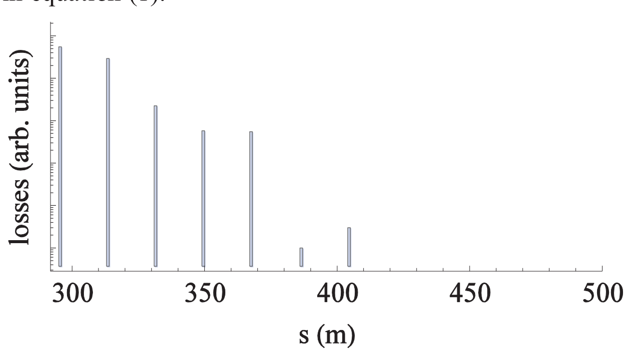

Figure 3: Simulated transverse collimation losses along beamline. The undulator entrance is at approximately s = 450 m (see Fig. 1). The vertical scale is logarithmic with arbitrary units.

The collimation apertures were set according to equation (1) varying the factor F to study the performance. The simulated particle losses on the undulator aperture (4 mm full gap) as a function of this factor are shown in Fig. 2. It can be seen that the losses reduce to zero at $F \leq 1$. The loss profile on the collimators for the maximum aperture size which achieves zero losses on the undulator is shown in Fig. 3.

The collimation performance was also simulated for varied acceleration in the final linac section. It is envisaged that different final beam energies to Aramis will be achieved by turning off cavities - rather than decelerating - in the final linac section. Setting and fixing the collimator apertures for full 5.8 GeV beam energy, the collimation performance for different configurations of the final linac was simulated. The results are shown in Fig. 4, indicating reduction of collimation gaps by 13% (F = 0.87) recovers good collimation performance over this range of final linac acceleration.

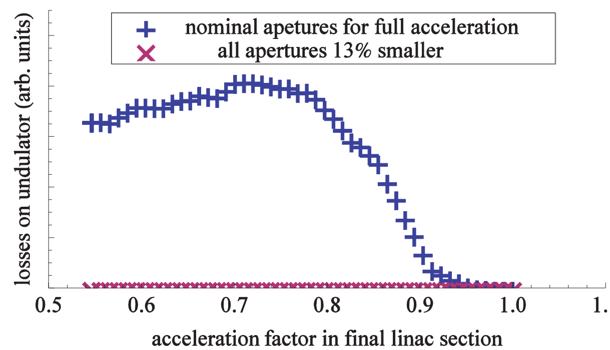

Figure 4: Transverse collimation performance for varied acceleration in the final linac section. On the horizontal axis 1.0 corresponds to maximum energy 5.8 GeV.

Collimation in the horizontal plane may also be desirable to protect the vacuum chamber (8 mm diameter) in the inter-module beam pipe sections. This would require x-collimator gaps in the final linac section twice the size of the y-collimator gaps, around 14 mm to 10 mm.

ENERGY COLLIMATION STUDIES

The energy collimator must completely absorb particles that hit the front face. This may not be possible in some scenarios where errant particles graze the surface of the collimator. The energy collimation chicane has a small bending angle of 1° (17 mrad) and the first undulator module is approximately 25 m from the final chicane dipole.

If copper is chosen as the collimator material (radiation length of 1.43 cm), a thickness of 20 cm should be sufficient to absorb 5.8 GeV electrons which directly impact the front face. FLUKA[7] simulations indicated that 95% of the incident total beam energy is absorbed for an incident beam energy of 5.8 GeV.

FLUKA was used to simulate grazing scenarios. Particles were simulated with 5.8 GeV energy and grazing angles on the collimator surface from 0.5 mrad to 1.3

mrad. The energy spectrum of the scattered particles at the exit of the collimator is shown in Fig. 5. The scattered particles were then tracked through the transport and undulator beamline using the DIMAD[8] tracking code. Losses along the beamline are shown in Fig. 6, indicating that there is a possibility of grazing particles on the energy collimator directly impacting the beamline within the undulator section, and additional shielding may be required.

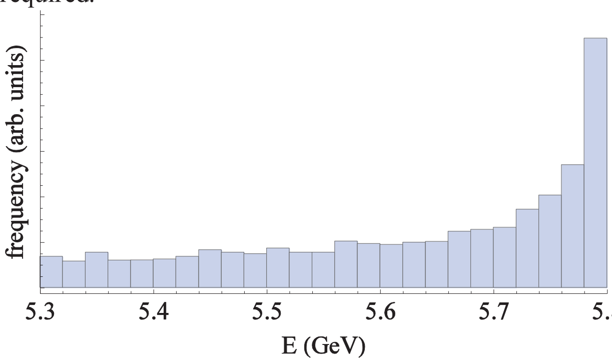

Figure 5: Simulated energy spectrum of scattered grazing particles from the energy collimator with initial energy 5.8 GeV and incident angles 0.5 mrad to 1.3 mrad.

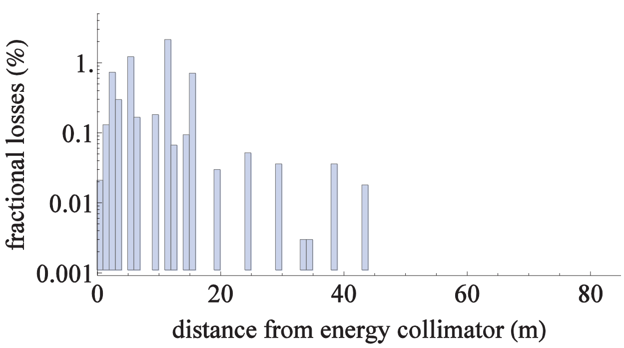

Figure 6: Simulated loss distribution of scattered grazing particles from energy collimator, as a fraction of the number of incident particles. The chicane exit is at s = 10 m, the undulator modules begin at s = 34 m.

An additional concern related to the energy collimator is that of sudden energy loss which lies within the acceptance of the energy collimator and causes a 'beta beat' in the beam size which may impact the undulator. This was checked by simulation, using ELEGANT in 'fiducialisation' mode; a sudden loss of ~ 2% energy (the maximum envisaged acceptance of the energy collimator) was simulated by setting zero acceleration in two cavities in the final linac section. The resulting change of beamsize downstream results in a beamsize only approximately 10% in the undulator.

WAKEFIELDS

The wakefields associated with the small collimator apertures are a concern for emittance dilution and beam centroid kicks. Tapering of collimators reduces the geometric wakefields. At the LCLS facility[4] at SLAC, a machine with similar parameters to SwissFEL, the final collimators were not tapered because the wakefield effects predicted were small due to the small ~ fs bunch length[9].

Measurements of collimator wakefields have been performed for ILC-like beam parameters at SLAC[10][11]. In these experiments the bunch length was much longer (~ ps) and so the applicability of the results to the SwissFEL scenario is not certain. The measurements indicate that adding short tapers to the collimators could reduce the geometric wakefield kick factors by a factor of approximately 4.

SUMMARY

The SwissFEL collimation system design has been studied with several simulation tools. The transverse collimation system performs well at the nominal full energy acceleration, while at other acceleration configurations a small reduction in the collimation apertures (~15%) is sufficient to recover collimation performance. The energy collimator at 20 cm Cu should effectively absorb all 5.8 GeV particles at direct impact, although if grazing particles are a concern additional undulator shielding may be required.

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