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STUDIES OF PARTICLE LOSSES FROM THE BEAM IN THE EU-XFEL FOLLOWING SCATTERING BY A SLOTTED FOIL

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Abstract

One technique for producing short radiation pulses in an FEL involves the use of a slotted foil in a bunch compressor. However, the scattering of particles from the foil can lead to increased particle losses and the generation of secondary particles. This is a particular concern for high rep-rate FELs, such as the European XFEL, where there are plans to implement the slotted-foil technique for short pulse generation. The study reported here aims to characterise the impact of a slotted foil in the European XFEL on the radiation dose in the front section of one of the undulators. Simulations were performed using BDSIM: this code tracks primary particles along the beamline, models the interaction between particles and accelerator components and tracks secondary particles produced by these interactions. The results indicate the amount of energy deposited in the front section of one of the FEL undulators, and provide a basis for optimisation of the collimation system to keep the energy deposition and radiation doses within acceptable limits.

INTRODUCTION

Studies are in progress for production of ultra-short radiation pulses in the European XFEL (EuXFEL) [1] by use of a slotted foil in a bunch compressor. The combined effect of the correlation between the energy and longitudinal position of particles within a bunch in the bunch compressor together with the effect of vertical dispersion leads to a correlation between the longitudinal and vertical coordinates of particles (a "beam tilt") at the location of the foil. As the bunch passes through the foil, particles will be scattered leading to an increase in emittance, except for those passing through a narrow slit in the foil. The result is that except over a short section of the bunch, the slice emittance will be too large for lasing to take place in the undulators: only the short section of particles that are not scattered in the foil will then lase, producing a correspondingly short pulse of radiation [2, 3].

One potential issue with this technique is that scattered particles can be lost from the beam, leading to an increased radiation dose rate along the machine downstream from the foil. This is of particular concern for the undulators, where radiation can damage the magnetic material. Some protection for the undulators is provided by a collimation section after the linac; however, an increase in the number of particles outside the collimator aperture could lead to damaging heat loads on the collimators themselves [4].

To quantify the impact of the slotted foil on radiation and heat loads in the machine, detailed particle tracking studies are being carried out, to determine (in advance of experimental tests) whether any additional machine protection measures are required and if so, how they may best be implemented. In this paper, we report the latest results from particle tracking simulations, which suggest that additional shielding may be required to provide full protection for the undulators.

SIMULATIONS

Simulations are carried out using BDSIM [5], which allows tracking of primary particles (i.e. particles in the beam from the electron source), and models the scattering of particles in components including the slotted foil planned for generation of short-pulse radiation, the collimators, and the vacuum chamber and surrounding components. BDSIM also allows tracking of secondary particles generated by interaction of a particle with an accelerator component.

In each tracking run, a single bunch is represented by 2×10^5 macroparticles. The initial beam distribution at the bunch compressor is taken from (separate) start-to-end simulations. The section of machine modelled in BDSIM starts just before bunch compressor 1 (BC1), where the foil is inserted, and finishes just after the second undulator module in the first SASE section (SASE1). The model includes acceleration in the linac from 700 MeV to 14 GeV.

The fact that BDSIM tracks primary and secondary particles and models their interaction with accelerator components makes it is possible to construct a "map" showing the heat and radiation loads from lost particles along the length of the machine. An example is given in Fig. 1, which shows the energy deposition along the accelerator from the first bunch compressor (where the foil is inserted) up to the second main undulator module in SASE1. The first set of "spikes" in Fig. 1 shows the energy deposited in the foil itself, and the energy deposited shortly after the foil by primary particles scattered by the foil and by secondary particles produced by the interactions of primary particles with the foil. The large amount of energy deposited after $s = 1\,500$ m indicates the energy deposition in the collimators.

To estimate the potential for damage in the undulators, we calculate the peak radiation dose (as a function of position) in these components. In the model, each undulator is divided into a three-dimensional grid of volume elements. BDSIM calculates the energy deposited in each volume element; dividing this by the mass of that element provides the radiation dose in grays (Gy). Figure 2 shows an example of the dose distribution (from a single bunch) in the diagnostic undulator (which has been installed specifically for machine studies in the beamline upstream of the main FEL undulators, imme-

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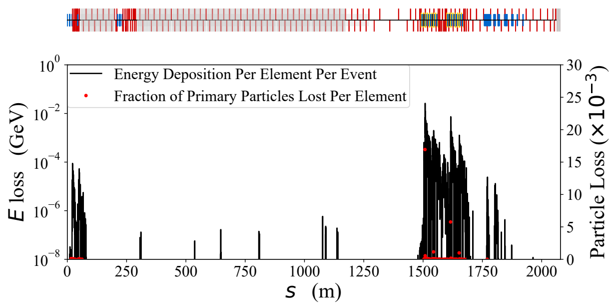

Figure 1: Energy deposition from primary and secondary particles along the EuXFEL starting from the first bunch compressor (where the slotted foil is inserted) to the first main undulator modules. Red dots show the fraction of primary particles lost at different points.

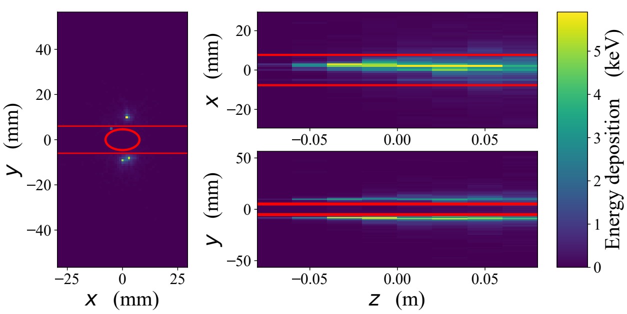

Figure 2: 2D projections of the dose deposited in small volume elements in the diagnostic undulator, calculated from tracking a single bunch of macroparticles. In this example, a relatively large amount of energy is deposited compared to the majority of cases.

diately after the end of the beamline shown in Fig. 1). The images in Fig. 2 show two-dimensional projections of the three-dimensional dose distribution onto different planes.

The nature of the scattering processes means that with 2×10^5 macroparticles, different random seeds lead to large variations in the simulated radiation dose at any given location. As an illustration, Fig. 3 shows the number of seeds leading to different peak dose rates in the diagnostic undulator. For the results in this case, 100 different random seeds were used, with the same initial distribution of primary particles.

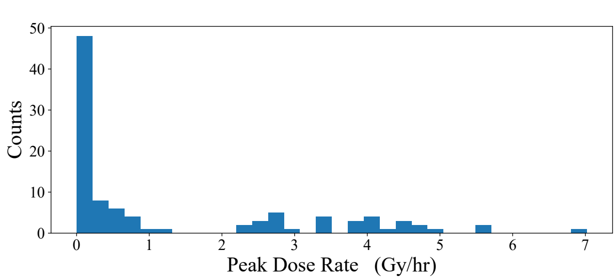

Figure 3: Histogram of the peak dose rates in the diagnostic undulator found from 100 random seeds for the tracking simulations when a 4 mm collimator aperture is used.

Given the variation in simulated dose rate, tracking simulations to characterise the effects (for example) of varying the collimator apertures need to be repeated many times, to provide a reasonable indication of the dose rate to be expected in operation of the machine. The computational cost of running a simulation including the production and tracking of secondary particles is high, and simulations are therefore performed on a parallel-computing cluster [6]. Even so, the number of initial (primary) macro particles is limited to $\sim 2 \times 10^5$. The number of different random seeds that can be used is also limited, so the final values obtained will have significant uncertainties.

Machine imperfections, including alignment errors on the foil, collimators, and other components have not been included in the simulations so far, but will be a subject for future studies.

RESULTS

The dose rate at a particular location in the machine is found from the simulations by multiplying the dose from a single bunch (a bunch has 200 pC of charge, the results are scaled to the actual number of particles in a bunch, compared to the number of macroparticles in the simulation) by the average bunch rate (27 kHz). Repeating the tracking simulation over many seeds gives a distribution of peak dose rates: the expected dose rate is given by the mean of this distribution. Since the distribution is far from a normal distribution, we use the range between given percentiles (rather than the standard deviation) to indicate the width of the distribution, and hence the uncertainty in the result.

The dose rate in the undulators varies with the aperture settings in the collimation section. Several different apertures are available; a particular aperture can be selected by inserting an appropriate collimator unit into the beam. The peak dose rate in the diagnostic undulator as a function of collimator aperture is shown in Fig. 4.

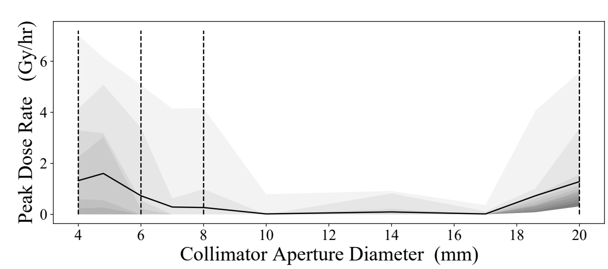

Figure 4: Peak dose rate in the diagnostic undulator as a function of collimator aperture. The solid line shows the mean of the distribution, and the shaded regions show different percentile ranges (in steps of 10% from 90% for the lightest shading). The dashed lines indicate the apertures that are available in EuXFEL.

A limit of 55 Gy is assumed for the maximum dose that can be accumulated in the SASE1 undulators before resulting in radiation damage [7]. With an aperture of 4 mm for each collimator, the peak dose rate in the diagnostic undula-

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tor has a mean value 1.3 Gy/hr. This would lead to a dose of 55 Gy in a little over 41 hours of machine running: the fact that the damage threshold would be reached in quite a short period of time means that the dose rate in this case is unacceptably high. The peak dose rates in the first and second modules of the main undulator are 110 mGy/hr and 15 mGy/hr respectively: these dose rates are lower than in the diagnostic undulator, but there is still potential for radiation damage in the first module after a few months or years of machine operation.

The simulation results suggest that as the collimator aperture is reduced, the undulator dose rates initially decline as expected; but further reduction below an aperture of about 10 mm leads to an *increase* in the dose rates. To understand this behaviour, further tracking studies were performed, focusing on individual particle trajectories. In particular, primary particles leading to energy deposition in the undulators were identified, and their individual trajectories recorded from a point just upstream of the foil to the undulators.

As an example, the trajectory of one primary particle leading to energy deposition in the undulators is shown in Fig. 5 (top and middle plots for horizontal and vertical trajectory components, respectively). We see that the betatron amplitude of the particle *increases* after the collimation section, although the beta functions are much larger in the collimation section than in the adjacent sections. Further inspection shows that this particle just reaches the edge of a collimator aperture, and is scattered rather than being absorbed. This appears to be a common situation: primary particles that are scattered from the edge of a collimator aperture travel along the remaining length of the machine with large betatron amplitude, and often impact the vacuum chamber just upstream of the undulators, where there is a reduction in chamber aperture. The resulting shower of secondary particles then leads to energy deposition in the undulators. The bottom plot in Fig. 5 shows the energy deposition from the particle as a function of distance along the machine: we observe some initial energy deposition in a collimator (at approximately 200 m), and a larger amount of energy deposited at the entrance to the undulators (at approximately 580 m).

Based on the investigation of trajectories of individual particles, the variation in peak dose rate as a function of collimator aperture observed in Fig. 4 can be explained in terms of the beam density. At large collimator aperture, particles scattered by the foil remain uncollimated, and are eventually lost in the undulators, generating some radiation dose. When the collimator apertures are reduced, the particles scattered by the foil are collimated, and the radiation dose in the undulators is reduced. However, if the collimator apertures are reduced too far, the edges of the apertures start to intercept regions of increasing particle density within the beam: significant numbers of particles are then scattered from the collimators, and this leads to an increase in the dose rate in the undulators.

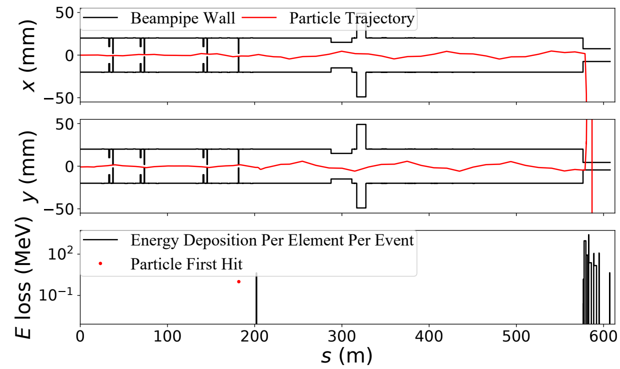

Figure 5: Top and middle plots: horizontal and vertical components (respectively) of the trajectory of a single particle leading to dose in the undulators, from the start of the collimation section to the end of the second module in the main undulator. Bottom plot: energy deposition from the particle with the trajectory shown. The first energy deposition event (at around 200 m) occurs in the collimation section.

CONCLUSIONS

The results from the tracking studies indicate that use of a slotted foil for generation of short radiation pulses in EuXFEL could lead to unacceptable radiation dose rates in the undulators. Optimizing the collimator apertures may reduce the dose rate to acceptable levels. However, if the apertures are too small, a large dose rate can result from particles scattered from the edges of the collimators. This means there may be some risk in finding a suitable aperture that fully protects the undulators. However, since the radiation dose in the undulators comes from particles hitting the vacuum chamber at a point just upstream of the undulators, where the chamber aperture is reduced, a possible solution is to install shielding between this point and the undulators. Further studies are planned to evaluate whether additional shielding will provide sufficient protection.

So far, studies have focused on radiation dose rates in the diagnostic undulator, as this device will be subject to the highest radiation loads. Further studies should be performed to characterise the radiation loads on the main undulator modules downstream of the diagnostic undulator. A further potential problem arises from the increased power load on the collimators due to the particles scattered by the foil. Future studies will evaluate the heat loads in detail, to determine whether this may be an issue in practice.

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