TOP-UP SAFETY SIMULATIONS FOR THE DIAMOND-II STORAGE RING UPGRADE

A. Potter*, S. Birkett, J. Kallikadan, C. Lane, X. Liu, I. Martin, J. Toop-Rose,
Diamond Light Source, Oxfordshire, United Kingdom

Abstract

Top-up operation at the Diamond-II storage ring will involve injecting bunches of electrons into the ring whilst the photon beamlines are in use. It is important, for the safety of the users, that electrons from the newly injected bunches cannot travel down the photon beampipe to the front end. For a representative beamline, all possible trajectories through the ID straight were identified and tracked through the machine to determine if any combinations of magnet settings exist that would simultaneously allow for stored beam and for electrons to be extracted through the front end. The full range of strengths for all the magnets were considered to account for any magnet power supply failures or different operating modes. Here we present the method used to track the electrons, summarise the results for one beamline and describe the interlocks required to ensure safe operation.

INTRODUCTION

The kick-and-cancel injection scheme will be used during top-up operation at Diamond-II. During top-up, the newly injected bunch will travel around the storage ring off axis until radiation damping causes them to merge with the stored bunches [1]. There is also a risk that a pulsed magnet may fire at the wrong time, for example the beam dump or injection kickers, causing stored bunches to travel through the machine off axis. A bunch will be steered by multipole magnets when passing through them off axis. It is important that the bunches do not recieve a combination of steers from these magnets, that will result in them traveling through the front end beampipe where they could potentially result in an unacceptably high radiation dose

This study continued previous studies done at Diamond [2], and other facilities [3–6] to investigate whether such a combination of steers was possible for each of the front ends.

The method was then extended to investigate the effect that the strengths of certain magnets had, on the possibility of electrons reaching the front end. The results of the simulations were then used to find appropriate interlocks that restrict the range of magnet strengths such that the front ends are safe from electrons.

ACCEPTANCE OF THE FRONT ENDS

The front ends following standard straight sections were investigated first, the locations of the standard straights within the Diamond-II superperiod can be seen in Fig. 1. The acceptance of each front end was calculated as the total phase space area that can pass through the two limiting apertures within the front end. It was found that I15 has a large acceptance when compared to other standard straight front ends. Therefore, the initial studies of top-up safety were done by tracking all of the possible particle paths through the I15 standard straight and SM girder and comparing this with the acceptance of the front end.

Additionally, the I15 front end will contain a beam splitter meaning that there are three distinct paths that electrons could travel through the I15 front end. The straight ahead line (I15), a line angled inboard (I15.1), and a line angled outboard (I15.2).

SIMULATION PROCEDURE

The initial distribution of electrons was generated by calculating the maximum phase space area (in the horizontal plane) that can travel through the insertion device (ID) straight. This included the effects of any chicane magnets and trim coil correctors. The vertical phase space was initially set to zero. All electrons were given the same energy offset which was chosen manually at the start of each simulation.

The SM girder contains six quadrupoles, six sextupoles, one octupole, two anti-bends (offset quadrupoles), two permanent magnet dipoles and one combined function dipole-quadrupole (DQ). For all magnets except dipoles, it was assumed that they could be set to any value between the minimum and maximum strength. This was to account for magnet failures, tuning ranges, and future operation modes. It was assumed that the strength of the DQ could only vary between $\pm 10\,\%$ of its nominal strength without losing stored beam. The strengths of the permanent magnets were not varied throughout the study.

The field strength of each magnet, as a function of the electron coordinates, was calculated using a magnetic field map. This was because the possible paths to the front end involves passing through magnets far off-axis, where it is no longer appropriate to use an ideal field. The tracking through each magnetic element was done by splitting the element into slices, and then using a drift-kick-drift model. Some magnets also contain trim coils used for steering. Two additional field maps where defined for these magnets with the trim coils providing a positive and negative steer.

When the distribution was tracked through a magnet, it was tracked through the magnet multiple times at different strengths, equally spaced between the maximum and minimum possible strengths for that magnet. For the magnets containing trim coils, the distribution was tracked through the magnet three different times for every magnet strength

* andrew.potter@diamond.ac.uk

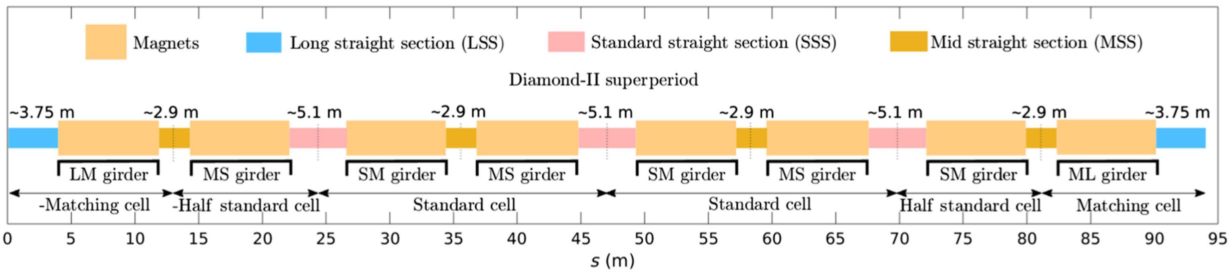

Figure 1: The structure of the cells within a single superperiod of the Diamond-II lattice showing the arrangement of straight sections and girders.

to account for no steer, and a steer in both the positive and negative direction.

After tracking through a magnet, there would be many different particle distributions (one for each of the magnet strength and trim settings). All the distributions were then combined into one overall distribution, and a 2D histogram of the combined distribution was constructed. The central bin coordinates of all of the bins with a non-zero count were then used to form a new particle distribution which was then tracked to the next magnet where the process was repeated again. This procedure prevented the number of particles growing by a factor of the number of different strengths and trim settings every time the distribution was tracked through a magnet.

As injection and all of the main bending occurs in the horizontal plane, only the horizontal phase space was considered. This was to save simulation time by reducing the size of the initial distribution. This is valid when there is no coupling between the tracking of the horizontal and vertical phase space. This is not the case in sextupole magnets where there can be a horizontal steer based on both horizontal and vertical coordinate. To model this, each particle was split into 9 different particles before being tracked through a sextupole, covering a range of vertical phase space coordinates. All vertical coordinates were lost when when distributions were combined after tracking through the sextupole.

After tracking through each element (and combining the distributions), the particles with a horizontal coordinate outside of the beampipe aperture were deleted before tracking through the next element. The apertures used were obtained from an engineering drawing of the SM girder. A tolerance of ± 1.15 mm was added to each aperture to account for the effects of beampipe misalignment.

The particles that survived the tracking were compared to the front end acceptance. It was found that, for the I15 straight, some of the particles were within the front end acceptance when the energy offset of the initial distribution was set to -5 %. The horizontal phase space coordinates of the surviving particles can be seen alongside the front end acceptances in Fig. 2.

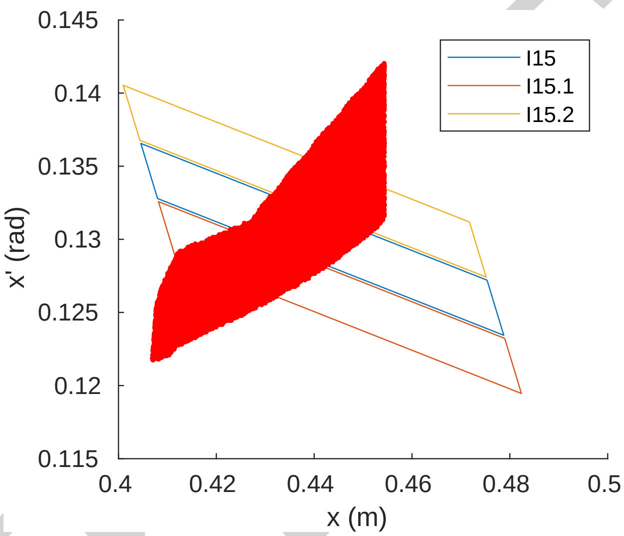

Figure 2: (red) The phase space area of all possible paths to the front end, for electrons with an energy offset of -5 %, after tracking through to the end of the girder. (blue, orange and yellow) acceptance region formed by the two smallest apertures in the front end for I15, I15.1 and I15.2 projected back to the start of the front end.

EFFECT OF MAGNET STRENGTHS ON POSSIBLE PATHS TO FRONT END

To prevent particles surviving through to the front end, it was decided that some magnets should have interlocks that restrict the maximum or minimum field strength of the magnet. Preliminary studies found that the size of the phase space region (shown in red in Fig. 2), was sensitive to the limits on the strengths of the antibends (A1N and A2N). It was also found that electrons with a negative energy offset were more likely to reach the front end.

The simulation was run again as explained in the simulation procedure, however the strengths of A1N and A2N were kept at a fixed value rather than varying over the whole range of strengths. The chosen energy offset of the particles was -5 % as it has been shown that interlocks of ± 1 % on the booster-to-storage ring transfer line dipoles can restrict the energy offset of injected particles to within ± 5 %. The simulation was run many times until the full 2D range of possible combinations of A1N and A2N strengths had been simulated. The number of possible trajectories to the front end was recorded each time. Figure 3 shows the effect that the combination of strengths of A1N and A2N has on whether particles are able to reach the front end or not. The yellow region of the plots show the combinations of A1N and A2N strengths that result in some particles within the acceptances for the three paths through the front end. The blue region of the plots show the combinations of A1N and A2N strengths that result in no particles within the acceptances. A green dot was plotted to show the values of the nominal setpoints for A1N and A2N.

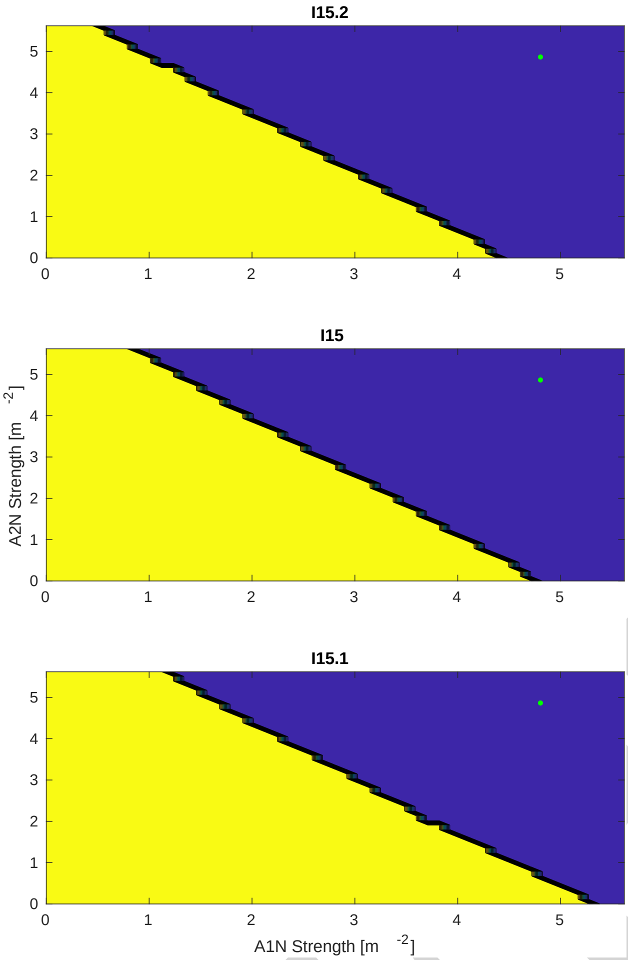

Figure 3: The results of tracking particles through the I15 front end with a different combinations of strengths in the antibend magnets. The yellow region shows the cases where the tracking resulted in particles within the front end acceptance. The green dot shows the nominal set points of the antibend magnets. The results are shown for the three paths through the I15 front end: (top) I15.2, (middle) I15, and (bottom) I15.1.

A single interlock would be successful if a vertical or horizontal line can be drawn on Fig. 3, to separate the green point from the yellow region. It can be seen in the results for I15.1 that this is not the case. The conclusion is that for the I15 front end, two interlocks would be required to guarantee protection. Interlocks restricting the minimum strength of both antibends to $k_1 > 3.1\ \mathrm{m}^{-2}$ would successfully protect the front end.

ALTERNATIVE PROTECTION METHODS

If the proposed interlocks are implemented into Diamond-II, they will need to be routinely checked to confirm they are operating as expected. A final decision on how the interlocks would be implemented has not been taken. However, experience with equivalent interlocks used on the existing storage ring indicate there is a risk that the hardware thresholds could drift over time, requiring significant manual intervention after each shutdown. A passive option that has been implemented at other facilities is the installation of clearing magnets. The clearing magnets are permanent magnets located along the front end so that if any charged particles travel into the front end, they will be steered into an aperture. The possibility of installing clearing magnets is currently being investigated. Issues such as the where is best to install them and the generation of electron showers still needs to be studied before any decision can be made on which option is better.

CONCLUSION

Simulations were set up that track a distribution of particles that filled the acceptance of the I15 beamline through the SM girder. The distribution was tracked through the full range of strengths for each magnet and the resulting distributions were combined before tracking to the next magnet. Particles were deleted from the simulation if they lay outside of the front end apertures after each element. The surviving particles after tracking to the end of the girder were compared against the acceptance of the I15 front end. Three different paths through the I15 front end were considered due to a beam splitter.

The simulation was used to investigate the effect that the strengths of the antibend magnets had on the possibility of particles reaching the front end. It was shown that, for the I15 front end, that two interlocks will be required to fully protect the front end.

As the acceptance for all other standard straight beamlines is smaller than the acceptance for I15, it may be possible to protect all the other beamlines with a single interlock. This is currently being investigated.

ACKNOWLEDGEMENTS

This study of top-up safety required collaboration between many of the groups at Diamond Light Source. Special thanks must be expressed to colleagues in front ends group for the work providing information about the limiting apertures in the front ends, the engineering group for supplying the aperture information in the SM girder and the magnets group for supplying the field maps for the magnets.

REFERENCES

[1] A. Lueangaramwong *et al.*, “Kick-and-cancel injection scheme for the Diamond-II storage ring”, *Physical Review Accelerators and Beams*, vol. 28, no. 6, p. 060701, 2025.

[2] I. P. S. Martin, C. P. Bailey, R. Bartolini, E. C. Longhi, and R. P. Walker, "Top-Up Safety Simulations for the Diamond Storage Ring", in *Proc. EPAC'08*, Genoa, Italy, paper WEPC044, pp. 2085–2087, Jul. 2008. https://jacow.org/e08/papers/WEPC044.pdf

[3] H.-J. Tsai, C. C. Chiang, P. J. Chou, and C.-C. Kuo, "Top-Up Safety Simulations for the TPS Storage Ring", in *Proc. IPAC'11*, San Sebastian, Spain, paper TUPS073, pp. 1707–1709, Sep. 2011. https://jacow.org/IPAC2011/papers/TUPS073.pdf

[4] M. Borland and L. Emery, "Tracking Studies of Top-Up Safety for the Advanced Photon Source", in *Proc. PAC'99*, New York, NY, USA, Mar. 1999, paper WEP26, pp. 2319–2321. https://jacow.org/p99/papers/WEP26.pdf

[5] G. Benedetti, "Top-up Safety Simulations for the ALBA Storage Ring", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPWA049, pp. 2229–2231, 2013. https://jacow.org/IPAC2013/papers/WEPWA049.pdf

[6] K. Manukyan, S. Dastan, and S. Krecic, "Top-up safety simulations for Elettra 2.0", in *Proc. IPAC'25*, Taipei, Taiwan, pp. 2886–2889, Nov. 2025. doi:10.18429/JACoW-IPAC2025-THPM096