TOP-UP SAFETY SIMULATIONS FOR THE DIAMOND STORAGE RING

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Abstract

To ensure that it is not possible for a train of injected electron bunches to pass down an open beam-line during top-up operation at the Diamond Light Source, an extensive program of tracking studies has been performed. Various error scenarios have been investigated, with realistic magnetic field, trajectory, aperture and energy errors all taken into account. We describe the tracking methods used, scenarios considered and the interlocks required in order to maintain safety during top-up operation.

INTRODUCTION

Preparations are being made to implement top-up operation in Diamond [1]. Before it can be brought into operation it must be established that it is safe to inject electrons into the storage ring with beam-line shutters open. The main concern is that, rather than be captured in the storage ring, an injected beam of electrons could pass down an open beam-line and be lost inside the optics hutch, potentially leading to an unacceptably high radiation dose close to the hutch walls.

In order to demonstrate that an accident of this type cannot occur, other facilities have performed extensive tracking studies to determine electron beam motion under a wide range of error scenarios [2-4]. The work described in this report applies the methodology described in [4] to the case of the Diamond storage ring, with the primary aim of determining whether it is possible for electrons to pass into the optics hutch. Should such a hypothetical situation be identified, the secondary aim of the studies is to identify effective interlocks which would prevent the situation from arising in reality.

METHOD OUTLINE

The method used for the simulations is a mixture of forwards and backwards tracking. To simplify the task, only a small section of the storage ring between the ID straight section and respective beam-line front end (BLFE) is selected for study. The first step is to establish which electron trajectories can pass through the straight section based on the local aperture restrictions, and then to specify a boundary in horizontal phase space enclosing all these trajectories. A similar acceptance region can be defined from the apertures in the BLFE. From these boundaries, two distributions of particles are generated for tracking, the first set to be tracked forwards from the ID straight to the entrance of the first bending magnet, the second set backwards from the BLFE to the entrance of the same bending magnet. If the resulting phase-space distributions overlap, this indicates that a possible accident scenario exists.

The apertures for individual ID straight sections and BLFEs vary significantly. Beamline I20.2 has an acceptance lying closest to the stored beam centre line (SBCL) and has been used for the in-depth investigations. If top-up can be demonstrated to be safe for this beam-line, all other beam-lines will also be safe. Shown in figure 1 is a schematic for how the front-end acceptance is defined, and figure 2 shows the acceptances of all current and planned BLFEs. Positions and angles are marked with respect to the SBCL.

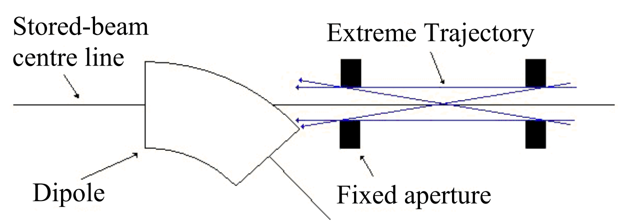

Figure 1: Extreme trajectories for electrons back-tracked through a front end (blue) are limited by two apertures within the BLFE.

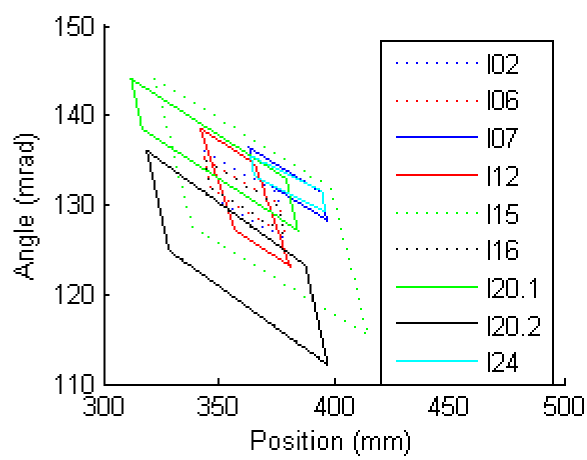

Figure 2: Boundaries in phase space enclosing all possible trajectories for each of the Diamond BLFEs.

TRACKING CODE DESCRIPTION

The particle tracking was carried out in 2D using the Accelerator Toolbox [5] tracking code. Since the spatial accuracy of calculated electron trajectories is of prime importance here, new pass-methods were developed to include magnet field maps valid to large horizontal amplitudes. Each of these new pass-methods have been thoroughly tested to ensure that at small amplitudes the tracked particle closely follows that predicted by the original pass-method, but at large amplitudes the expected field roll off is faithfully reproduced.

Magnet Modelling

Bending magnets are modelled as hard-edged magnets and include the field roll-off at large transverse displacements predicted from finite element analysis (FEA) calculations. The magnets are split into 100 segments with a total length equal to the mean measured magnetic length. An aperture-check is included at the end of each segment. A conservative lower limit of 90% of nominal was placed on the bending magnet field strength in the safety simulations, as 94.5% was found to be the lower limit below which no closed orbit exists, even accounting for the action of the fast-orbit feedback.

Quadrupoles are modelled as thick elements, again using field maps found from FEA calculations (see fig. 3). The magnets were split into 25 segments with aperture checks included at each point. Changes in quadrupole gradient could occur due to e.g. feed-forward settings, power supply failure or simple operator error. As such, the gradients were varied from 0-110%, with the additional 10% required to account for field distortion close to the magnet pole tips when vertically off-axis. Using the full range of possible strength allows the simulations to retain lattice-independence (no specific set-point assumed).

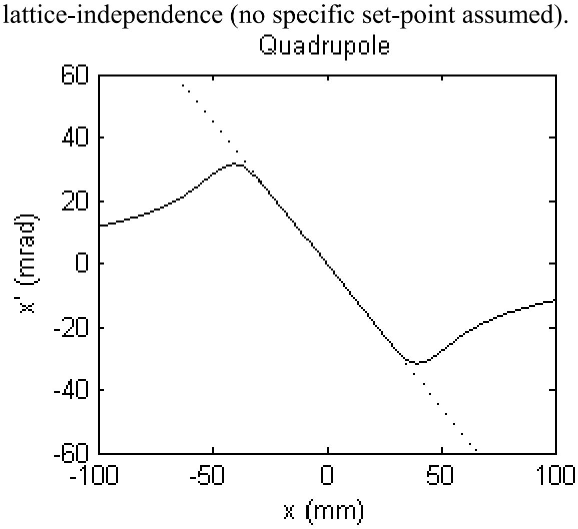

Figure 3: Tracking through a quadrupole using the new pass method. The ideal path is shown for comparison.

Sextupole magnets are modelled as thin elements, again based on field maps calculated from the FEA model. The sextupole power supplies are a mixture of unipolar and bipolar, the strength of which were varied across the full range in the simulations. Moving vertically off-axis in a sextupole adds an additional horizontal deflection, the upper limit of which is given by the maximum sextupole strength and the vertical aperture limitations:

$$B_{y,sext} = \frac{1}{2}\frac{d^2B}{dx^2}(x^2 - y^2)$$

$$\theta_{x,additional} = -S_{\max} y_{\max}{}^2 L$$

where S_{max} is the maximum sextupole strength and L is the length of the magnet. This effect was included in the simulations by extending the range of the horizontal corrector magnets housed in the sextupoles.

The effect of moving vertically off-axis in a skew quadrupole can be accounted for in a similar way, as the maximum horizontal deflection is again independent of horizontal position (dipole-like) and only depends on the vertical apertures and maximum skew gradient:

$$B_{y,skew} = \frac{dB}{dy} y$$

$$\theta_{x,additional} = K_{\max} y_{\max} L$$

where K_{max} is the maximum skew quadrupole strength.

The corrector magnets themselves are modelled as thin elements located at the centre of the sextupole magnets, each of which are capable of deflecting the beam by up to ±1mrad in addition to the contributions from vertical motion in sextupoles and skew quadrupoles.

Remaining Sources of Error

In addition to magnet strength variations and electron trajectory errors, there exist many other potential sources of error which have been accounted for in the simulations:

- Electron energy errors of ±15% , which could occur due to booster magnet errors, extraction timing errors or a scaling down of all magnet strengths in the storage ring, have been included.
- Sources of error in the ID straights including chicane magnet and trim coil setting error and ID pole damage have been accounted for by increasing the effective apertures in the ID straight.
- Errors in the aperture dimensions could be present from initial alignment, settlement and manufacturing tolerances. All apertures have therefore been increased by ±2.5mm, and have been implemented in the code in such a way that any particles tracked outside the apertures are replaced by new particles lying on the boundary. This ensures that a continuous phase-space boundary is always being tracked.
- Finally, the effects of partial shorts in dipoles, quadrupoles and sextupoles have also been calculated and taken into account. Given the lower probability of these errors, they have only been considered in combination with magnet setting errors for on-energy particles.

RESULTS

The results of tracking for the nominal lattice with no errors are shown in fig. 4. As can be seen, there is a wide separation between the forwards and backwards tracked boundaries, indicating an accident cannot occur for this situation.

Two regions of the parameter space have been identified which could potentially lead to a top-up accident, both of which require multiple errors to occur. The first situation is for close to on-energy particles, and requires all of the magnets between the ID straight and first bending magnet to be at either zero or maximum strength (see fig. 5). The dipole must be below 90% of nominal, a situation which will not simultaneously allow stored beam. An interlock inhibiting injection in the absence of stored beam will prevent this accident scenario from occurring.

The second scenario also requires the magnets before the bending magnet to be either off or close to maximum, but this time the bending magnet is not required to be low. However, the energy of the injected beam must be greater than 10% above the stored beam energy. An interlock preventing an energy mismatch of this magnitude will provide sufficient protection against an accident of this type occurring. This can be implemented by monitoring the strength of BTS and storage ring bending magnets to be with 1% of nominal, as this has been demonstrated to limit the energy mismatch to be below ±5%.

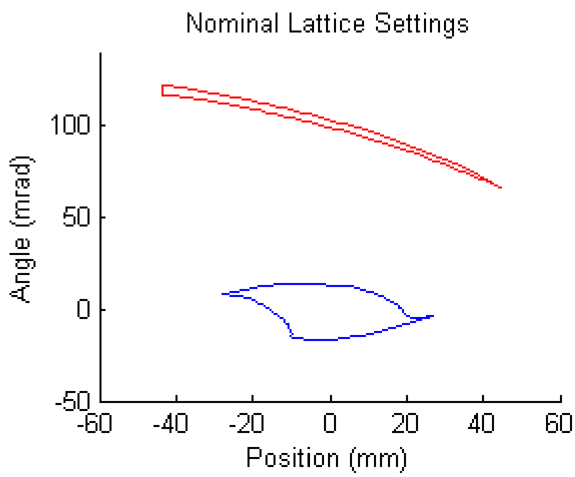

Figure 4: Comparison between forwards (blue) and backwards (red) tracked phase-space boundaries for the nominal lattice with no errors present.

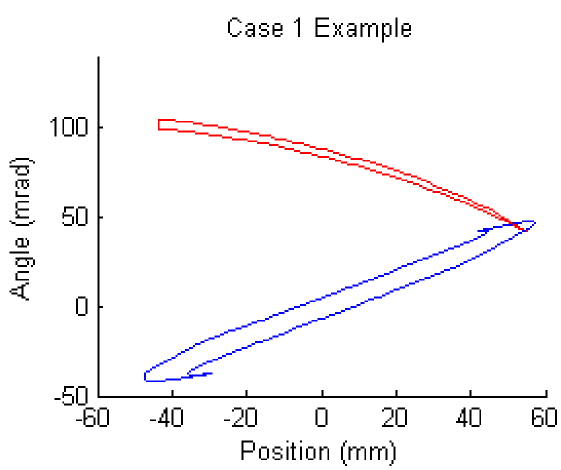

Figure 5: As fig. 4 for the first accident scenario identified.

Interlock Limitations

Whilst the stored beam and energy interlocks have been found to be effective at preventing electrons from travelling through an open BLFE and entering an optics hutch, they do not exclude the possibility that electrons could be lost at some mid-point along the front end but still within the storage ring tunnel.

The closest electrons can get to the optics hutch occurs when the electrons have a trajectory lying close to the beam-line centre line. This worst-case trajectory has been identified to occur for an error scenario similar to the first accident scenario described above, with the exception that the bending magnet field strength has been fixed to nominal by the interlocks. The distribution of forwards tracked particles at the entrance of the BLFE with respect to SBCL is shown in fig. 6. The consequences for this situation depend on the particular apertures for the BLFE. For the majority of beamlines particles following the worst-case trajectory would be lost at the first fixed aperture, but for some particles could pass beyond the first aperture and be lost within the front end before the second limiting aperture.

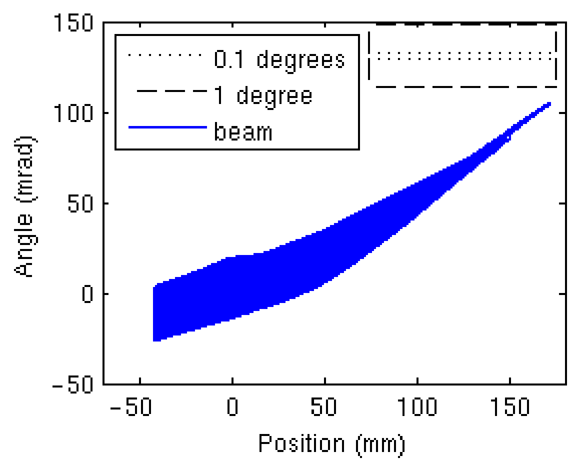

Figure 6: Forwards tracked particles at the entrance of the BLFE for all combinations of errors not excluded by the two interlocks. Dashed lines at ±0.1 and ±1 degree are marked to show typical BLFE acceptance regions.

CONCLUSIONS

Extensive tracking studies have been performed in order to identify any situations which could lead to electrons being transmitted down an open beam-line. The AT tracking code has been adapted for the particular purposes of tracking particles at large amplitudes, and wide-ranging, comprehensive error scenarios have been investigated in the simulations. Two hypothetical accident situations were found, and the two interlocks required to prevent this situations from arising have now been implemented in the machine.

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