SPACE CHARGE LIMITS ON THE ISIS SYNCHROTRON INCLUDING THE EFFECTS OF IMAGES

B. G. Pine, C. M. Warsop, ISIS, Rutherford Appleton Laboratory, STFC, UK

Abstract

The ISIS synchrotron provides a pulsed, 50 Hz, 800 MeV proton beam for spallation neutron production. Each pulse from the synchrotron contains $\sim 2.8 \times 10^{13}$ protons per pulse (ppp), and at this beam intensity space charge and image forces have a strong effect on transverse beam dynamics. In order to increase intensity in the present machine, and to prepare for possible upgrades running at a higher intensity, studies are underway aimed at understanding the most critical features of such forces and their impact on beam loss. These studies are focused on working point optimisation, including resonances due to space charge and images.

A 2D simulation code, Set, has been developed to improve understanding of transverse dynamics at ISIS, using a particle-in-cell algorithm to include space charge and image forces self-consistently. The ISIS synchrotron has profiled vacuum vessels and RF shields which conform to the shape of the beam envelope, and have a distinctive influence on the beam dynamics. Set is specifically designed to include these image forces. A systematic simulation study of possible working points is presented, along with an assessment of the effect on apertures.

INTRODUCTION

ISIS Accelerators

The ISIS linac provides H^- ions at 70 MeV for charge-exchange injection into the synchrotron, which then accelerates the protons to 800 MeV. Acceleration is synchronised on the rising edge of the sinusoidal 50 Hz main magnet field. Beam is accelerated using 6 ferrite loaded RF cavities operating at a harmonic number of 2: as a result two bunches are formed in the synchrotron. Bunch shaping is provided with 4 more RF cavities operating at a harmonic number of 4, which have lowered the peak line density and allowed routine operation with beam losses lower than 5%. There are 10 super periods in the synchrotron, which has a circumference of 163 m, with specialised sections for injection, extraction and collimation. Each super period contains 2 trim quadrupoles which allow sensitive manipulation of the working point. The full transverse acceptances are (H, V) = (520 , 430 π mm mrad), but the beam is collimated at $\sim 300\ \pi$ mm mrad in each plane. ISIS operates at the highest safe intensity, limited by the control of beam loss.

ISIS Upgrade

A design study is in progress looking at replacing the 70 MeV ISIS linac with a new injector accelerating H^- ions to 180 MeV [1]. This would reduce space charge forces in the synchrotron and enable a higher intensity to be accumulated. In addition, as the new linac will include a beam chopper, beam would be injected directly into the RF buckets in the synchrotron, reducing loss during the bunching process and further increasing the intensity available for acceleration. As a result of these considerations, space charge would be reduced by a factor of 2.6, which suggests that the intensity of 3×10^{13} ppp possible with the current linac could be increased to 7.8×10^{13} ppp [2]. For the present machine, space charge peaks during the non-adiabatic trapping process (~ 1 ms into acceleration), while in the upgrade design it would do so at the end of injection. At present, and for future ISIS upgrades, space charge and images play a crucial role in loss mechanisms, therefore it is important to understand their influence on beam dynamics. Previous work on transverse dynamics on ISIS has examined the effect of half integer resonance [2, 3], images and closed orbits [4, 5]. Key studies for understanding the current machine [6, 7] and injection upgrade [8, 9] are presented elsewhere.

Motivation for a New Working Point Simulation

ISIS suffers from a resistive-wall head-tail instability when the vertical tune is just below 4 and this could impose intensity limitations when space charge prevents lowering the tune. It will be important to mitigate this instability at higher levels of beam intensity and two options are being considered. One is to remain at the current working point of the machine $(Q_h, Q_v) = (4.31, 3.83)$ but to use an active damping system to control the instability. The other option is to move the vertical working point to a position where the instability is not a concern. Transverse simulations exploring the consequences of moving the working point are the subject of this paper.

Due to the high space charge levels at which the ISIS synchrotron operates, the peak incoherent tune shift in both planes is of the order 0.5. To prevent loss, the coherent quadrupole moments must be kept above the corresponding half integer driving terms. The nearest available vertical working points are below 3.5, or above 4.3, see Figure 1.

One major complication is the structure of the ISIS vacuum vessel, which conforms to the shape of the design beam envelope as determined by the design tunes (4.31, 3.83) and optics. Any changes to the working point alter the shape of the beam inside the beam-pipe and run the risk of reducing useful aperture, or increasing image forces. Figure 2 shows the variation of horizontal and vertical apertures over one super period, compared with the design beam envelopes for a 300 π mm mrad test beam.

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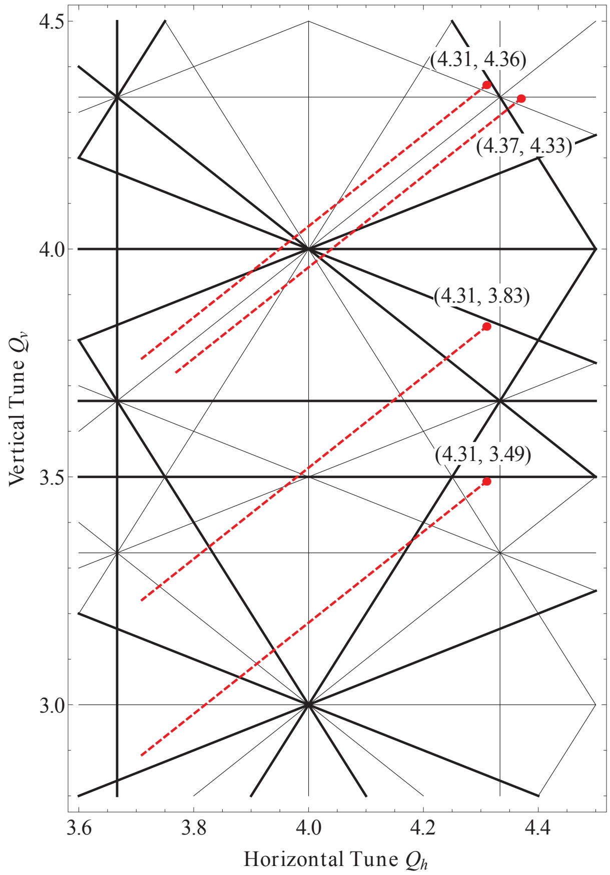

Figure 1: Tune plane with working points under consideration, resonance lines up to third order and a dashed red line highlighting the maximum incoherent tune shift.

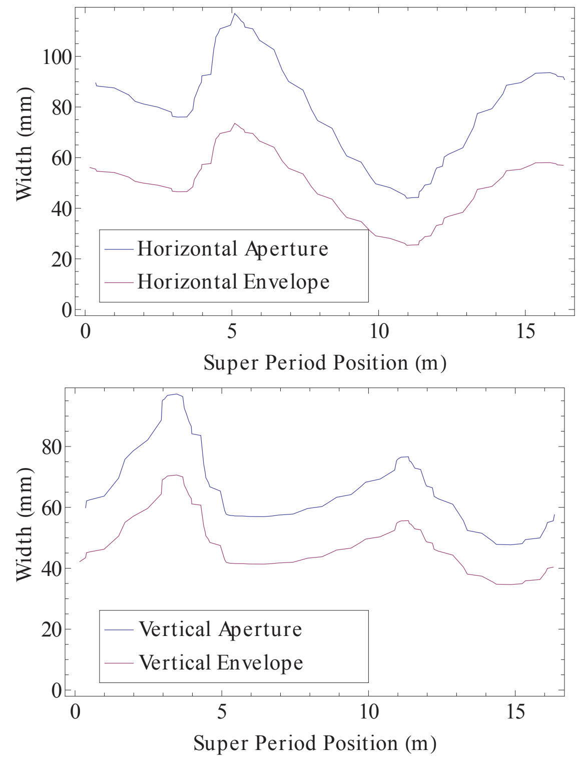

Figure 2: Aperture versus envelope for ISIS nominal working point, for a 300 π mm mrad 100% emittance beam.

WORKING POINT STUDIES

Three alternatives to the nominal working point were investigated during the course of this study. One option moved Q_v below the half integer and two options moved it above 4.3. The tune was modified by varying the strength of the trim quadrupoles in each straight section. The tune plane including these points and their peak incoherent tune shift (calculated for a water-bag beam using the Laslett formula [10]) at 7.8×10^{13} ppp is shown in Figure 1. For each of these cases the impact on available aperture was calculated and a series of simulations performed with intensities ranging from $0 - 2 \times 10^{14}$ ppp (equivalent to 7.8×10^{13} ppp when bunched). During these simulations relevant behaviour occuring at different intensities was investigated to ascertain the impact on beam loss.

All simulations were performed using the in-house transverse code Set. Matrices were used to produce a detailed AG lattice model and an FFT based particle-in-cell algorithm was used to solve for the space charge and image forces of the beam. Simulations used 50000 macro-particles and ran for 100 turns for each intensity level. A 300 π mm mrad 100% emittance water-bag distribution was RMS matched to the lattice at the start of each simulation. The simulations assumed a constant energy of 180 MeV and coasting beam conditions, while $\frac{\Delta p}{p}$ was not included. Collimation was not included, with beam considered lost at the aperture of the beam-pipe. For comparison, collimation on ISIS is normally at 75-80% of the aperture in both planes. During the simulations records were kept of beam moments up to fourth order, RMS emittance, beam loss, space charge, single-particle tunes and bunch distibutions.

Working Point 1: $(Q_h, Q_v) = (4.31, 3.49)$

Adjustments to the trim quadrupoles were made to move the vertical tune to 3.49 while leaving the horizontal tune unchanged. The effect on the beam envelope can be seen in Figure 3. The available aperture is reduced in the second half of the super period which may cause issues with beam loss, or demand challenging control of the beam orbit. The reduced aperture is of significant concern, potentially increasing image forces and losses. However the effects may be manageable with a suitable optimisation of other lattice elements.

The simulation study indicates that there is a structure resonance at $3Q_v = 10$ (ISIS has 10 super periods) which the vertical third moment of the beam passed through during the intensity scan. This resonance is driven by image forces from the centred beam in the rectangular vacuum vessel, possibly caused by terms examined in [11].

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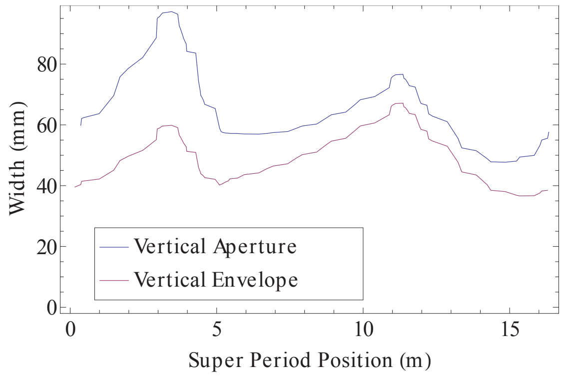

Figure 3: Vertical envelopes when $(Q_h, Q_v) = (4.31, 3.49)$.

More work is required to establish the risk such an image driven resonance would pose for ISIS operating at a lower working point, or indeed a similar effect driven by sextupole or other systematic errors. The sextupole frequency (third moment), emittance and beam loss during this scan are shown in Figure 4, displaying the emittance changes and beam loss as the vertical sextupole frequency passes through 10. Figure 5 shows the vertical third moment at an intensity of 0.64×10^{14} ppp (coasting beam), where the resonant behaviour is clear.

A separate simulation was run where the beam intensity was increased each turn during the simulations (crudely representing injection) and in this case the third moment passed through the structure resonance without any loss. This result suggests that as far as driving terms due to images are concerned the working point might be a feasible solution. A detailed analysis of such driving terms is in progress. An experimental programme is underway to examine the possibility of running trials with the ISIS tune at this working point.

Working Point 2: $(Q_h, Q_v) = (4.31, 4.36)$

When the vertical tune is moved above 4.3, in this case to 4.36, the situation is quite different. As can be seen from Figure 6, the envelope of the test beam is now tightly constrained by the aperture. Even at zero space charge some of the beam is clipped by the aperture. However, it is still of interest from a beam dynamics point of view and there is a possibility that more sophisticated studies of the lattice may mitigate the extent to which the beam optics are distorted.

Figure 7 shows the dipole, quadrupole and sextupole (1st, 2nd and 3rd moment) frequencies for the discrete intensity scans from $0 - 2 \times 10^{14}$ ppp. As the intensity increases image forces depress the vertical moments faster than the horizontal (as the vertical aperture is narrower) and as a result the coherent modes cross the coupling resonance. During coupling there is a characteristic emittance exchange shown in Figure 8 for an intensity of 1×10^{14} ppp.

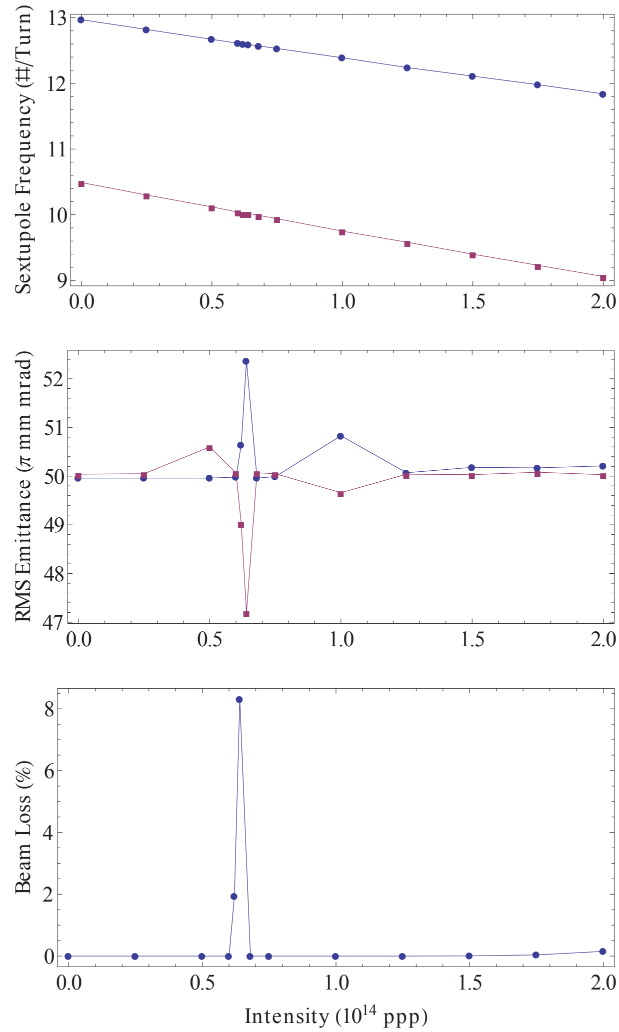

Figure 4: Sextupole frequencies, RMS emittances (horizontal blue, vertical red) and beam loss when $(Q_h, Q_v) = (4.31, 3.49)$.

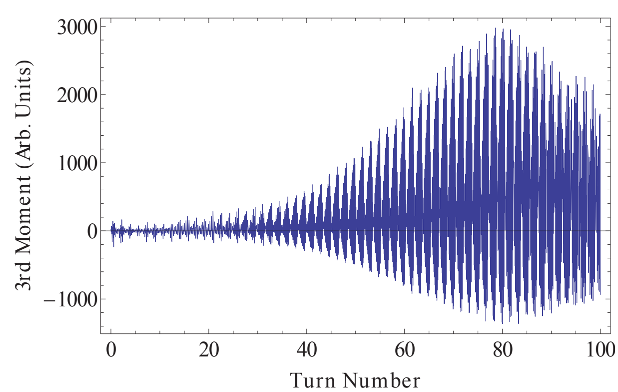

Figure 5: Vertical sextupole moment during resonance when $(Q_h, Q_v) = (4.31, 3.49)$.

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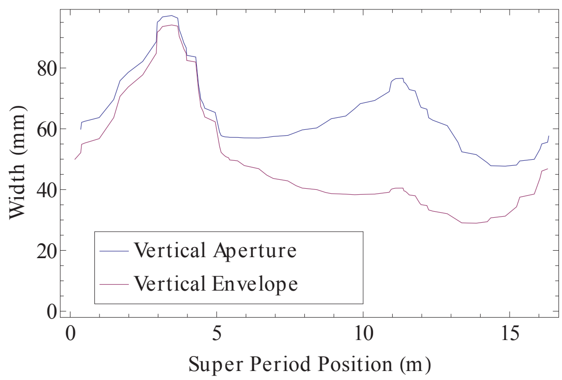

Figure 6: Vertical envelopes when $(Q_h, Q_v) = (4.31, 4.36)$.

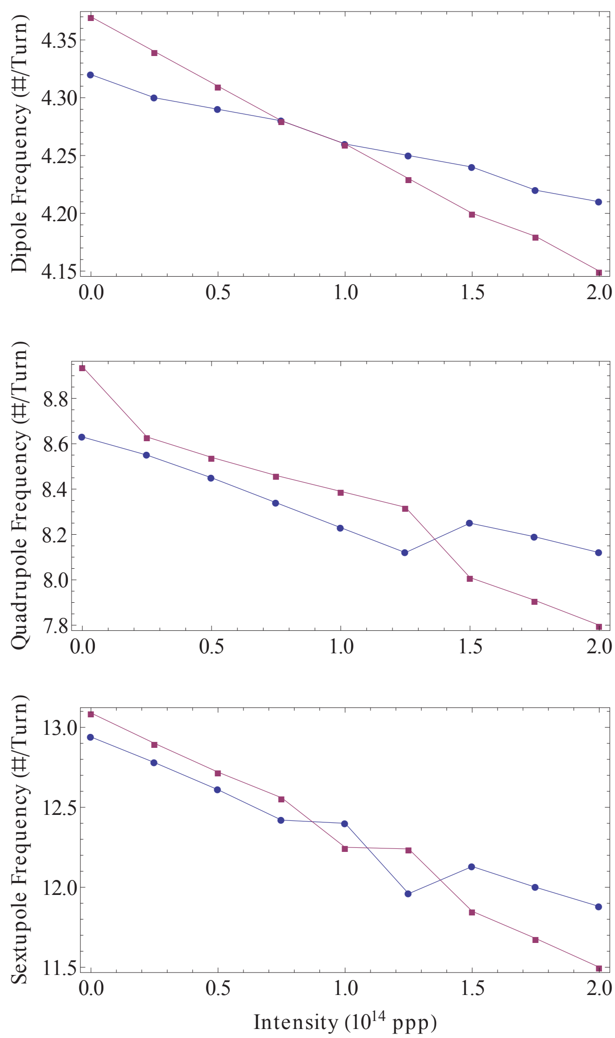

Figure 7: Dipole, quadrupole and sextupole frequencies (horizontal blue, vertical red) when $(Q_h, Q_v) = (4.31, 4.36)$.

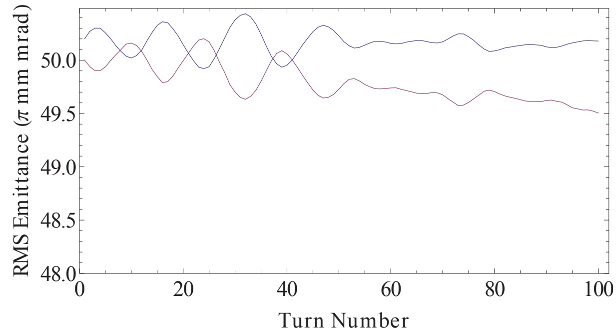

Figure 8: RMS emittance (horizontal blue, vertical red) at an intensity of 1×10^{14} ppp when $(Q_h, Q_v) = (4.31, 4.36)$.

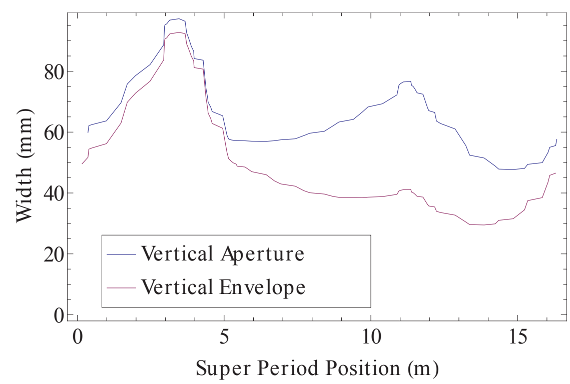

Figure 9: Vertical envelopes when $(Q_h, Q_v) = (4.37, 4.33)$.

Working Point 3: $(Q_h, Q_v) = (4.37, 4.33)$

An additional effort was made to see if the coupling behaviour exhibited at working point 2 could be avoided. Therefore another series of simulations was run moving the horizontal tune in addition to the vertical. The new point was $(Q_h, Q_v) = (4.37, 4.33)$ and the resulting vertical envelope can be seen in Figure 9. The beam envelopes were very similar to the previous case with $Q_v = 4.36$ and some beam was lost even at zero space charge levels. However the coupling behaviour was eliminated, Figure 10, suggesting that if a practical solution to the beam optics issues were to be found, this might be a valid solution.

SUMMARY

If the injection energy into the ISIS synchrotron is raised from 70 MeV to 180 MeV there will be an impact on transverse dynamics. An investigation has been performed looking at moving the working point, including the effects on available aperture due to changes to the beta functions and possible high intensity effects. Due to constraints from the large coherent tune shifts the available points are below 3.5, or above 4.3. Moving the working point down vertically appears to be the best of the available options, though there is still a loss of aperture in the vertical plane. Worryingly

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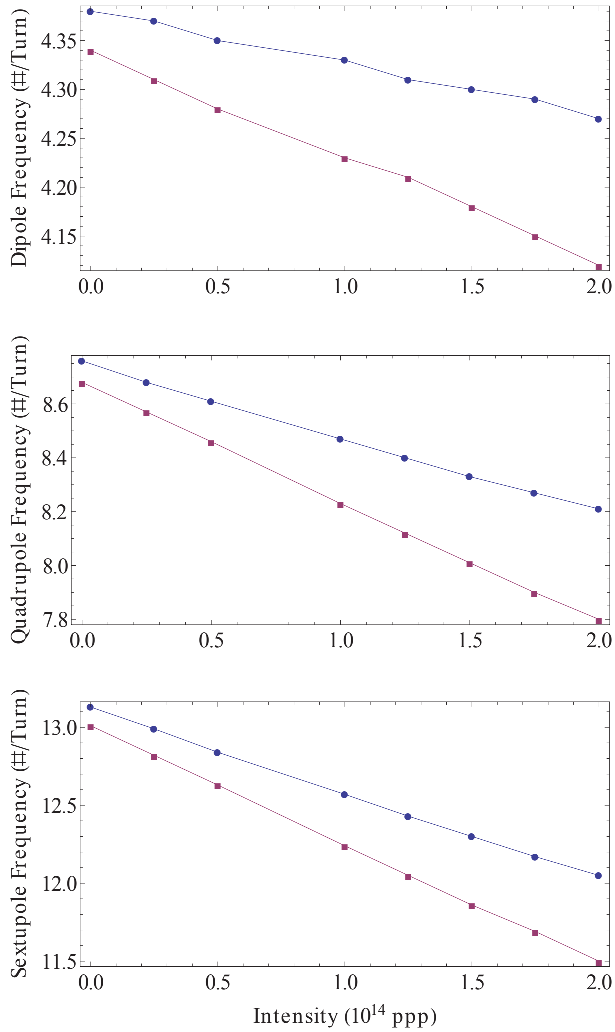

Figure 10: Dipole, quadrupole and sextupole frequencies (horizontal blue, vertical red) when $(Q_h, Q_v) = (4.37, 4.33)$.

this working point also brings the vertical tune dangerously near to the $3Q_v = 10$ structure resonance which could potentially be driven by magnet imperfections or image terms. Early simulation work suggests that it may be possible to pass through this resonance if it is driven solely by images.

Moving the working point up vertically appears to be difficult as these early studies suggest that much of the aperture is lost due to the change in beam envelopes. If Q_h is left where it is then there is also a considerable amount of coupling between the transverse planes which might make this position even less favourable. Fortunately, if adjustments are made to both the horizontal and vertical tunes, the coupling can be avoided. More work is required to establish whether suitable optics for this working point can be found.

FUTURE WORK

Experimental work at low intensity has already begun, aimed at mapping the impact of magnet errors on beam survival. Early indications are that linear errors dominate beam loss, with a small contribution from third order effects. This work is ongoing. In order to ascertain whether moving Q_v below the half integer is viable it is planned to perform some experiments on the ISIS synchrotron to investigate the presence of image effects or systematic resonances. A fast ramping of the tunes through such a resonance may be possible.

There is a comprehensive programme of simulation work planned, extending the work discussed here through representative half integer error terms. The effect of closed orbits on image induced beam loss has been discussed in [4] and [11]. These studies will be expanded and an analytical approach including the effects of higher order image terms undertaken.

If a new working point is recommended there will be additional work in other areas of the design study, particularly for injection dynamics and collimation.

Finally, work is well underway to merge the transverse code Set with another in-house, longitudinal code [12] with added injection. The combined code will allow the study of image effects with longitudinal motion and injection painting included.

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