PROGRESS OF THE DIAMOND STORAGE RING AND INJECTOR DESIGN

Susan Smith, David Holder, James Jones, Jennifer Varley & Naomi Wyles, CCLRC, Daresbury Laboratory, Warrington, Cheshire, UK

Riccardo Bartolini, Ian Martin, Beni Singh, Diamond Light Source Ltd., Rutherford Appleton Laboratory, Oxfordshire, UK

Abstract

DIAMOND is a state of the art 3 GeV synchrotron light source that will be available to users in 2007[1]. Considerable further progress has been made on the accelerator physics design of the storage ring, booster and other associated injector systems. Detailed analysis of injection processes, lifetime, coupling, instabilities, feedback systems and dynamic aperture have been undertaken driven by the procurement activity and the desire to fully understand all aspects of the accelerator's performance.

INTRODUCTION

DIAMOND is a new 3rd generation light source currently under construction near Oxford in the UK. The 3 GeV 560m circumference machine has twenty one free straights for insertion devices as well as the option of up to 24 dipole sources. The design features a small 2.7nm-rad emittance and coupling of 1% or less. Strong focusing and the relatively low symmetry of the machine produce difficult non-linear behaviour that must be optimised to maintain a good dynamic aperture and lifetime. The injector system includes a full-energy booster synchrotron with minimised apertures to reduce the stored magnetic energy. This is required in order to use switch-mode power supplies allowing flexible top-up operation. The limited aperture, coupled with a large energy ratio, leads to tight tolerances on booster injection errors and a requirement for careful control of the orbit and non-linear behaviour during the ramp. The requirement to operate in top-up injection mode in the future also produces stringent implications for the storage ring injection system, which must be designed for as close to unity injection efficiency as possible. Another key aspect of the machine's performance from the users' perspective is the quality of closed-orbit correction and instability correction systems to deal with orbit perturbations over a wide range of timescales.

INJECTION STUDIES

Booster Injection

The booster injection process is a single turn on-axis system using a fast kicker and a single septum. The effects of higher order magnetic field errors in all main magnet families, taken from 3D modelling, are included in the analysis, as well as realistic assumptions on the tolerances of the pulsed injection magnets (which leads to an effective emittance increase). A realistic assumption on the beam loading from the linac is also included. The results show that the injection efficiency under semi-realistic conditions is an average efficiency of ~96%, sufficient for top-up injection.

The analysis also determined the likely loss points in the booster, and highlighted possible improvements to the design. It was seen that the highest losses occurred in the injection and extraction straights.

Storage Ring Injection

Injection into the DIAMOND storage ring has been simulated in more detail by tracking a realistic distribution of particles over the machine damping time. Non-linear effects have been included in the tracking and beam filamentation observed. A more precise calculation of beam stay-clear requirements for injection has been obtained, allowing beam stay-clear requirements around the storage ring to be finalised. The defining physical apertures have also been found, indicating the most likely locations for injection beam losses, although this is predicted to be negligible due to collimation in the booster-to-storage ring transfer line. Sufficient contingency has also been to allow for matched beta function errors at injection, and non-static errors in the injection pulsed magnets.

The injection straight layout and magnet specification have been revised in order to allow for the possible placement of collimators and additional diagnostics in the injection straight. The septum magnet has been specified at the reduced magnetic length of 1.67m, and increased maximum operational field of 0.9T. The septum pulse length is 160μs. The separation of the kicker magnets has been reduced from 1.98m to 1.75m, increasing their maximum operational field to 0.2T over the 5μs pulse. This has freed space to insert a vertical collimator between the 3rd and 4th kickers, a horizontal collimator after the 4th kicker, and an OTR screen after the septum. This layout is shown in Figure 1.

The horizontal position of the injection septum will be adjustable, and the useful range of adjustability of the septum has been investigated, as well as the impact on machine layout of introducing this adjustability.

The horizontal separation between storage ring axis and septum plate inner side will be adjustable between 12 and 20 mm, with the range of movement which will cover all scenarios of tune and dynamic aperture studied so far being 13 to 19 mm.

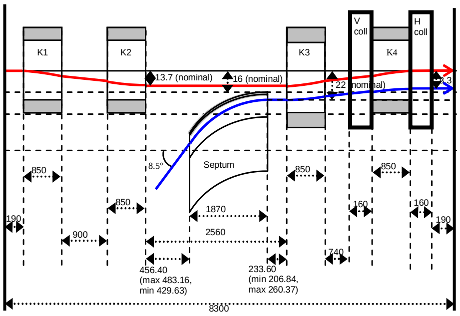

Figure 1: Layout of Storage Ring Injection Straight

Storage Ring Injection Pulsed Magnets

The tolerances of the storage ring injection septum and kicker magnets have been determined considering the storage ring operating in top-up injection mode, thus reliable pulsed magnets with tight tolerances are required to ensure a high injection efficiency and also a minimum disturbance to the stored beam. The non-closure of the kicker bump can induce a residual oscillation in the stored beam and may affect the data acquisition of the experiments on the beam lines.

The affects of these tolerances on the injected beam oscillations ($\Delta\varepsilon_x^i$) and upon the residual oscillations of the stored beam ($\Delta\varepsilon_x^s$) are calculated in terms of a dilution in the phase space invariance of the oscillations for the worst case. The limits are chosen as a compromise between the efficiency of top-up operation and the limits of economically achievable pulsed magnets tolerances. The final tolerances are listed in Table.1.

Table 1: Tolerances of Pulsed Magnets

Type of error	*Tolerances*	$\Delta\varepsilon_x^i$ *(nm.rad)*	$\Delta\varepsilon_x^s$ *(nm.rad)*
Septum magnet			
Peak to peak repeatability	± 400 ppm	30.0	…..
Flatness	± 50 ppm	0.6	…..
Leakage field	± 50 µTm	0.3	0.3
Kicker magnets			
Mag. field mismatch	0.2 %	17.0	56
Curr. pulse mismatch	0.1 %	8.5	28
Peak to peak repeatability	0.5 %	1.5	0.1

DYNAMIC STUDIES

Booster Synchrotron

A good dynamic stability of the booster synchrotron is needed to ensure high transfer efficiency throughout the injector complex, and so enable low loss top-up injection into the storage ring. The nominal dynamic aperture is sufficient to support a good lifetime; however, the change in tune point induced by long term variation in the main magnets is an issue. The magnet power supplies are to be specified at the limits of achievable reproducibility, but with a strong focusing lattice and no harmonic sextupoles, the effects on the dynamics of the machine could be an issue. The booster was modelled by varying the tune across several likely dangerous tune points within the tune space available to the quadrupole and dipole power supplies. Dynamic aperture studies showed clearly that, although the loss in aperture was relatively large in the horizontal plane, the impact on the machines overall performance was minimal, and at worst would only lead to a few percent loss in current.

Storage Ring

The non-linear dynamics of the storage ring have been investigated previously under a variety of conditions, including the influence of closed orbit errors and the inclusion of insertion devices. Modelling of the complicated sextupole design, which includes coils for the 168 ‘slow’ corrector magnets, highlighted an issue with the decapole component of these extra windings. The amplitude of this higher-order field is directly proportional to the required dipole corrector fields. To model the effects of the decapole on the machine dynamics therefore requires an analysis of the CO effects and their correction. Using an un-optimised correction scheme and all 168 dual-plane corrector windings, the dynamic aperture was not seriously reduced, though chaotic motion can be seen at the extreme of the phase space at nominal momentum. Using a fully optimised set of correctors, it is likely that the corrector requirements will be reduced and the effects of the decapolar component similarly reduced. Further work in this area will concentrate on refining the current harmonic sextupole tuning, as well as further investigations into the symmetry breaking effects of insertion devices. A ‘relaxed’ operating mode will also be investigated for use during initial commissioning.

TOUSCHEK LIFETIME AND LINEAR COUPLING STUDIES

The storage ring beam lifetime is limited by Touschek scattering especially in single bunch or few bunches modes (10 mA per bunch). The momentum acceptance of the ring was computed by numerical tracking using a realistic model of the storage ring including the limits set by the RF, engineering and dynamic apertures. A significant reduction of the Touschek lifetime is due to the effects of higher order momentum compaction. This reduces the lifetime from 26h to 17h[1], neglecting bunch lengthening effects.

The effect of a third harmonic cavity for bunch lengthening was investigated. Preliminary calculations on a passive S/C cavity of ELETTRA type [2] show that a two-cell system generates the 1.1 MV voltage required to lengthen the bunch by a factor of 3, thus increasing the lifetime by the same factor.

The linear coupling generated by random misalignment errors was estimated by means of a statistical analysis on a realistic lattice[1]. After CO correction, the average coupling is 2.1%. Skew quadrupole correctors embedded in the 168 sextupoles were used for correction. The correction method is based upon the analysis of the cross response matrix[3] and was set up to reduce linear coupling and the residual vertical dispersion. Using all 168 correctors the coupling was reduced to 0.15% on average. Due to the lowered Touschek lifetime, less aggressive schemes were considered. A system of 36 skew quadrupoles reduces the coupling to less than 0.8% whilst maintaining adequate lifetime.

CLOSED ORBIT FEEDBACK SYSTEMS

Booster

Closed orbit correction in the booster is provided by up to 22 horizontal and 22 vertical dipole corrector magnets positioned close to the F and D quadrupoles respectively, with up to 22 BPMs for position data. As in the storage ring, the correction scheme is global and uses the Singular Value Decomposition (SVD) technique. The magnets have the capability of being ramped, and can therefore provide accurate CO correction throughout the booster cycle. This has benefits for the required booster apertures.

Storage Ring

Closed orbit (CO) correction in the storage ring is to be performed using up to 168 of the dipole corrector magnets housed in the sextupoles and 96 dedicated fast correctors at the ends of the straight sections. Beam position information is provided by a state of the art BPM system, which is capable of delivering data with a resolution of 0.3µm [4]. The correction scheme is global, and uses the SVD technique to invert the machine response matrix.

The correctors in the sextupoles can deliver electron beam deflections of up to 0.8mrad full-swing at a frequency of 1Hz, and will be used predominately to tackle CO errors resulting from sources such as magnet imperfections and ground motion. Recent work has focussed on improving the correction scheme through the use of optimisation techniques such as genetic algorithms. Selection of the most efficient combination of corrector magnets, along with removal of inefficient Eigenvalues from the SVD significantly reduces the corrector strengths required, whilst also reducing the residual CO. Simulations using these techniques show RMS residual CO distortions of 50µm horizontally and 10µm vertically can be achieved in the straight sections, with maximum corrector strengths of 0.3mrad in both planes. The correctors in the sextupoles can also be used at higher frequencies to suppress higher frequency error sources, up to limits imposed by the power supplies and vacuum chambers of around 25Hz.

Dynamic CO errors are also tackled using the dedicated fast correctors in the straight sections. They are specified to give 0.3mrad full-swing deflections at 50Hz, and can be used as part of a global dynamic correction scheme operating at 100Hz. Simulations of the expected vibrations have shown the position and angle of the electron beam can be stabilized to less that 1/10 of the beam dimensions at the source points using either the fast correctors or the sextupole correctors, with the BPM resolution found to be the limiting factor.

The dedicated fast correctors can also be operated at higher frequencies as part of local correction or feed-forward systems, should the demands of a particular beam line require it.

COLLECTIVE EFFECTS

Current thresholds for microwave instability (MI) and transverse mode coupling instability (TMCI) were analysed to assess the impedance budget for DIAMOND operation in various modes. A 2D tracking code for the longitudinal dynamics in the presence of a broad band impedance (BBI) was used to determine the MI current threshold and the longitudinal BBI budget. For operation in multi–bunch mode, with a 500mA in a 2/3 filling, the impedance was set to Z/n 0.2Ω, corresponding to 6.3kΩ at the cut off frequency of the beam pipe. A significant bunch lengthening is expected due to potential well distortion with a beneficial effect on Touschek lifetime. This is shown in Figure 2.

The effect of a third harmonic cavity on the instability threshold was computed numerically, and is shown in Figure 2. Although the bunch lengthens by a factor of 3, the simulations showed the microwave instability threshold could be increased only by a factor of 2.

The analysis of the current threshold for the TMCI was performed with the MOSES code[5] using a BBI model for the transverse impedance. Setting the current threshold to a single bunch operation, 0.8 mA, an upper limit for the BB transverse impedance was found to be 3MΩ/m. The current threshold can be increased by setting large chromaticity values; however the impact of this procedure on the dynamic aperture, as well as a possible feedback system is under consideration.

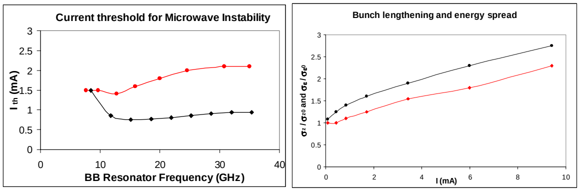

Figure 2: MI current threshold vs. resonator frequency with (red) and without (black) a 3HC (left) and the bunch lengthening (black) and energy widening (red) curves as a function of current (right) of a BBI modelled by an RLC resonator circuit

REFERENCES

[1] Richard Walker et al, these proceedings.

[2] R. Bartolini, N.G. Wyles, these proceedings.

[3] M. Svandrlik et al., "The SUPER–3HC Project: an Idle Superconducting Harmonic Cavity for Bunch Length Manipulation", Proceedings of the EPAC00, p.2052.

[4] J. Payet, BETA–LNS codes.

[5] G. Rehm, et al; "Beam diagnostics systems for the Diamond synchrotron light source", these proceedings.

[6] Y. Chin, "User's Guide for New MOSES. Version 2.0", CERN/LEP-TH/88-05