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EVOLUTION OF EQUILIBRIUM PARAMETERS RAMP INCLUDING COLLECTIVE EFFECTS IN THE DIAMOND-II BOOSTER

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Abstract

Efficient top-up injection into the Diamond-II storage ring will require upgrading the booster lattice for a beam emittance of < 20 nm·rad and a bunch length of < 40 ps, including when operating with high single-bunch charge. The small vacuum chamber dimensions will drive the resistive wall instability and may adversely affect equilibrium parameters along the beam energy ramp. In addition, various diagnostic and vacuum chamber components will generate geometric impedances which may further disrupt the equilibrium parameters. Based on the detailed engineering designs, impedance models of the major components have been simulated using CST Studio and included in ELEGANT tracking simulations of the booster. In addition, the effects of synchrotron radiation emission and intra-beam scattering on the equilibrium parameters during the ramp are studied.

INTRODUCTION

Diamond Light Source is to be upgraded with an advanced low emittance storage ring, Diamond-II, using a multi-bend achromat lattice [1] to provide space for more beamlines and to increase the brightness and coherence of the photon beams. For efficient beam injection into the Diamond-II storage ring, the injector system also needs to be upgraded [1, 2]. This includes a new low emittance booster synchrotron with beam emittance < 20 nm·rad and bunch length < 40 ps at the 3.5 GeV extraction energy. The lower emittance is required to achieve off-axis beam accumulation into the reduced dynamic aperture of the new storage ring. A shorter bunch length will ensure a proper matching with the storage ring RF bucket so that energy errors during synchrotron oscillations for the injected beam remain small. The major Diamond-II booster parameters are given in Table 1, more lattice details can be found in Refs. [1-3].

The Diamond-II booster should be capable of accelerating high-charge single bunches or multi-bunch trains without degradation of the equilibrium parameters such as beam emittance, bunch length and energy spread. The beam energy needs to be raised from the injection energy of 100 MeV to 3.5 GeV at extraction. During the beam energy ramp process, the equilibrium parameters change due to synchrotron radiation (SR) emission. These parameters may deviate from the equilibrium values due to high intensity collective effects [4] such as coupling impedance (resistive wall and geometric impedance) and intra-beam scattering (IBS). Another important contribution comes from higher order modes (HOMs) in the RF cavities. If the beam impedance interaction become strong it may result in large disruption of the electron bunch and equilibrium parameters and could eventually lead to beam loss.

In this paper, we present simulation studies of the evolution of the equilibrium parameters during the beam energy ramp. These have been done considering a high-charge single bunch including impedances, SR and IBS effects with physical apertures applied.

Table 1: Main Parameters of the Diamond-II Booster

Parameters	At 100 MeV	At 3.5 GeV
Circumference	163.85 m	
Betatron tunes	12.41 / 5.38	
Chromaticity	+1 / +1	
Momentum comp. factor	5.65×10^{-3}	
Damping times	[156.3,173.1, 91.5] s	[3.67, 4.04, 2.13] ms
Energy loss/turn	0.63 eV	947.5 keV
Natural beam emittance	14.1 pm·rad	17.3 nm·rad
Natural energy spread	2.5×10^{-5}	8.6×10^{-4}
Bunch length	0.55 ps	38 ps
RF Voltage	200 kV	2 MV
Energy acceptance	2.8 %	0.93 %
RF frequency	499.51 MHz	

BOOSTER RAMP PROFILE

For the present studies, the energy and voltage ramp profiles of the Diamond booster are as follows. The beam energy is raised from 100 MeV to 3.5 GeV (compared to 3 GeV in the existing booster) with a biased sinusoidal waveform at 5 Hz repetition rate. At the injection energy the RF voltage is 200 kV. This provides sufficient energy acceptance (2.8 %) for the energy errors during initial synchrotron oscillations of the injected bunch. This voltage is kept constant up to 1.93 GeV and then increases with the fourth power of energy up to 2 MV at the extraction.

BOOSTER IMPEDANCE MODEL

The Diamond-II booster consists of a large number of components which contribute to the overall impedance. Initial engineering designs of the major components have been completed and an impedance database has been generated. A vacuum vessel of stainless steel has been selected with two different circular apertures with radii 18.3 mm (in the injection/extraction sections) and 11.5 mm (in the arc sections). In addition, there are four in vacuum ferrite kickers (one for the injection and three for beam extraction). Two ceramic breaks of 10 mm length and inner radius

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11.5 mm are included in each arc section to terminate the eddy currents generated due to the fast beam energy ramp rate. These are the major contributors to the overall resistive wall (RW) impedance in the booster. The impedances of these components are calculated using *ImpedanceWake2D* [5]. It was found that ferrite loaded injection/extraction kickers contribute significantly to the RW impedance. To reduce the impedance, it has been proposed to apply a 1 µm thick titanium nitrite coating to the ferrite. Significant sources of geometric impedance include BPMs, screens, tapers, etc. These are simulated using *CST Studio* [6].

The impedance database in terms of the total loss and kick factors calculated for all components in the booster are given in Table 2. A bunch length of 12 mm has been used for these calculations, corresponding to the bunch length at extraction. The main contributors to the overall impedance are vacuum chambers, injection/extraction kickers, cavity tapers, pumps and BPM blocks.

Table 2: Impedance database for all booster elements showing the kick (k_x, k_y) and loss ($k_{||}$) factors calculated for a 12 mm long Gaussian bunch. Total value of the kick and loss factor is the sum of all elements in the booster ring.

Component	No.	k_x (V/pC/mm)	k_y (V/pC/mm)	$k_{\|\|}$ (V/pC)
Screen	1	-7.59×10^{-3}	-5.24×10^{-3}	3.87×10^{-2}
Valve	4	-6.32×10^{-3}	-6.52×10^{-3}	3.44×10^{-3}
BPM 18.3mm	4	-4.40×10^{-4}	-3.60×10^{-4}	4.80×10^{-4}
BPM,11.5mm	44	-1.58×10^{-2}	-1.85×10^{-2}	4.40×10^{-4}
Pump	55	-8.69×10^{-2}	-8.53×10^{-2}	3.74×10^{-2}
Kicker	4	-7.50×10^{-2}	-1.92×10^{-1}	6.82×10^{-1}
Cavity taper	2	-1.91×10^{-2}	-1.91×10^{-1}	3.81×10^{-1}
RW (140 m)		-6.83×10^{-1}	-6.97×10^{-1}	1.329
Total		**-0.894**	**-1.024**	**2.476**

SIMULATION RESULTS

To calculate the equilibrium parameters during the ramp, we use the *ELEGANT* multiparticle tracking simulation code [7, 8]. In the simulations, both RW and geometric impedances, and HOMs in the main RF cavities are included. The total transverse impedance for all the components is calculated by summing the local beta function weighted impedances from the individual elements in the booster ring, whereas the total longitudinal impedance is calculated by a straight summation over all elements. In the simulations, the total transverse impedance is normalised with the beta function at the point at which it is inserted.

For these studies, an initial beam from the linac at 100 MeV is considered with two different electron gun currents 0.5 A and 1 A (corresponding to 1 nC and 2 nC charge). Considering the bunching and acceleration losses (10 %) in the linac and transmission losses (20 %) in the linac to booster transport line, a single bunch with charges of 0.72 nC and 1.44 nC has been taken for the *ELEGANT* booster tracking. The associated RMS beam emittance, bunch length and energy spread are 125 nm·rad in both the planes, 20 ps and 0.5 %, respectively.

We use 128,000 macroparticles in a bunch and tracking is performed for 182,970 turns (corresponding to the ratio of ramp time/revolution time). The 6D tracking uses a one-turn-map with lumped SR effects. A one-turn-map using the ILMATRIX is used to describe the full ring, as an element-by-element method has a very large execution time. However, the ILMATRIX does not support the IBS effect. A single point representing the apertures in both the horizontal and vertical planes is used by scaling the 11.5 mm arc apertures to the beta functions at injection point. A horizontal-vertical emittance coupling of 10% is assumed. In the simulation, we also assume an ideal lattice without any errors. During the beam tracking, a particle is supposed to be lost in the transverse plane if its oscillation amplitude becomes comparable to the physical aperture and is lost in the longitudinal plane when the energy error becomes comparable to the energy acceptance.

Simulation results for the variation of vertical beam emittance, bunch length and vertical centroid motion along the ramp for various chromaticities (ξ) are shown in Fig. 1. The vertical centroid motion is shown for two cases which show emittance growth (ξ = 1.5, 2) and for one case without emittance growth (ξ = 0).

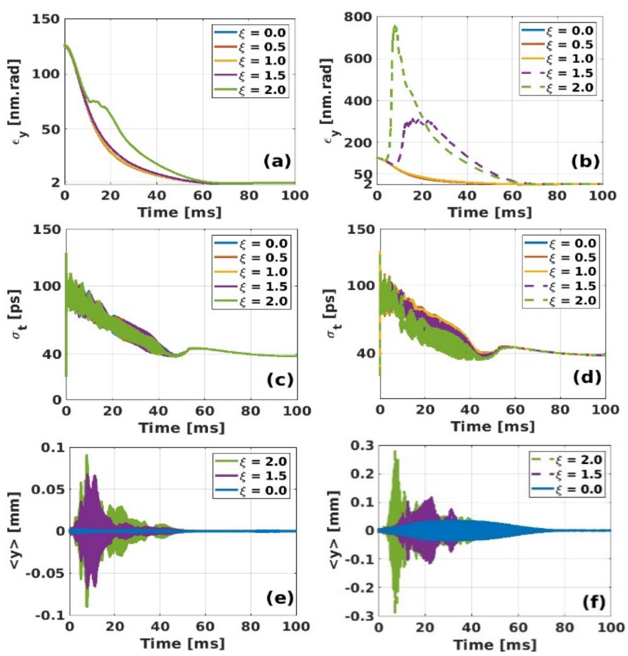

Figure 1: Variation of vertical emittance (a & b) and bunch length (c & d) vs. ramping time for a single bunch charge of 0.72 nC (left) and 1.44 nC (right) including RW impedance, geometric impedance, and RF cavity HOMs with scaled physical apertures at various chromaticities. Solid curves show the condition when there is no particle loss and dashed dotted curves with particle loss. The lower two figures show the bunch centroid motion (e & f) when there is emittance growth (ξ = 1.5, 2) and without growth (ξ = 0).

For a single bunch charge of 0.72 nC, there is no noticeable growth of the vertical emittance up to chromaticity 1. A large vertical emittance growth in the low energy regime can be observed for higher values of chromaticity. For the case of 1.44 nC charge, a significant vertical emittance growth and excitation of the vertical centroid motion are

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observed for higher values of chromaticity. This also results in beam loss of ~25 % for the case with $\xi = 2$ (dashed green curve). Similar results have been reported for the HEPS booster [9] at lower energy. A fast growth of centroid motion for high chromaticity at lower energies is due to the strong beam-impedance interaction. At lower energies, the growth time of the beam-impedance interaction is small compared to the SR damping time due to weak SR effect, which is of the order of 100 s (see Table 1). Further during the ramp, the SR damping become dominant, and the vertical emittance and centroid growth are suppressed. At the final energy, the beam emittance is damped down to the natural value of ~1.57 nm·rad (10% emittance coupling).

The horizontal emittance growth is rather small compared to the vertical emittance growth. The bunch length also grows due to the longitudinal impedance and gets damped to the natural value of ~38 ps at extraction. The outcome of the studies performed for the single bunch charges considered here is that the SR effect during the energy ramping helps to supress the growth of the equilibrium parameters. In the absence of the IBS effect, the equilibrium parameters converge to the zero current equilibrium values at the extraction energy.

We have also carried out an element-by-element tracking simulation including IBS effects and distributed physical apertures in addition to the impedances. The IBS effect results in additional growth of the equilibrium parameters with increased bunch charge. The equilibrium values at the extraction energy are summarized in Table 3.

In view of future possible options including swap-out injection in the Diamond-II storage ring, we have also carried out simulations with high bunch charges to assess bunch charge thresholds in the booster. As shown in Fig. 2(a), the threshold limit on the extracted bunch charge is ~2 nC.

As mentioned, the beam centroid and emittance growths occur at low energies during the energy ramp. As such, we have also performed simulations in which the injection energy is increased to 150 MeV. As expected, the instability takes relatively longer time to build up compared to the case of 100 MeV. As a result, the bunch charge threshold limit is increased to ~3 nC (Fig. 2(b)). The SR damping is still weak at lower energy to suppress the centroid growth effectively of the single bunch with high charges.

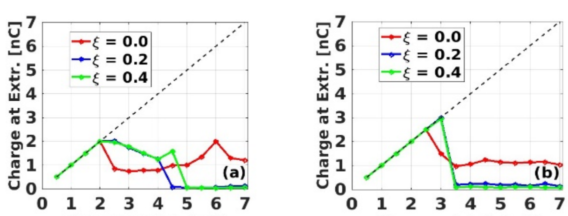

Figure 2: Extracted bunch charge thresholds with injected single bunch charges at (a)100 MeV and (b) 150 MeV.

CONCLUSIONS

Using an updated impedance model of the Diamond-II booster, ELEGANT tracking simulations have been carried out to study the variation of equilibrium parameters during

Table 3: Equilibrium parameters at extraction with collective effects including IBS effect at different single bunch charges.

Charge(nC)	ε_x(nm·rad)	ε_y(nm·rad)	σ_L(ps)	σ_ε(%)
0	17.3	1.57	38.0	0.086
0.72	19.1	1.58	42.3	0.095
1.44	21.3	1.60	44.9	0.100

the beam energy ramp. It was found that a single bunch charge of up to 0.72 nC is not of great concern for standard top-up operation; this is much higher than the required value of 0.1-0.2 nC for off-axis beam accumulation in the storage ring [1]. A significant vertical emittance growth and ~25 % beam loss was observed for a bunch charge of 1.44 nC at higher chromaticity at low energy. Without IBS effects, the equilibrium parameters were found to damp down to the zero current values at the extraction energy. The SR damping effect during energy ramping helps to supress the effect of instabilities on bunch properties. However, including the IBS effects, equilibrium parameters at extraction energy change by a small amount.

In view of the future possibility of swap-out injection in the Diamond-II storage ring, we have also carried out simulation for high-single bunch charge thresholds for the energy ramp from 100 MeV and 150 MeV. It was found that the extracted bunch charge of 3 nC can be achieved including impedance, RF cavity HOMs and physical apertures.

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