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BEAM DYNAMICS STUDIES FOR THE DIAMOND-II INJECTOR

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Abstract

The replacement, low-emittance booster for the Diamond-II project will have a racetrack structure consisting of 36 unit and 4 matching cells [1]. In this paper we report on how the design and performance characterisation of the booster has recently developed; this includes an increase in the injection energy from 100 to 150 MeV, a modified circumference to match to the storage ring RF frequency, and a new nominal tune point to improve the performance and to enable emittance exchange. The influence of the vacuum chamber impedance and intra-beam scattering on the electron bunch parameters during the ramp are presented, along with the necessary changes to the transfer line layouts.

INTRODUCTION

With the aim of providing transparent top-up injection, a single-bunch aperture sharing injection scheme [2] has been selected for the Diamond-II storage ring [3, 4]. Successful implementation of this method relies on upgrading the existing booster to provide the required electron bunch parameters, as described in [1]. The new booster has a racetrack structure to match the existing tunnel, with two arc sections consisting of alternating focussing and defocussing combined-function dipoles to provide almost a factor 8 reduction in the extracted beam emittance despite the higher extraction energy. The bunch length has also been reduced to allow a better match to the storage ring RF bucket. A key feature of the vacuum chamber design was to have low impedance, as this will enable high-charge bunches to be accelerated without degradation in extracted bunch properties.

In this paper we describe the recent changes to the Diamond-II injector design. The performance of the booster is analysed both in terms of its robustness to errors and the impact of collective effects during the energy ramp. Finally, changes to the linac-to-booster (LTB) and booster-to-storage ring (BTS) transfer lines are summarised.

BOOSTER-II LATTICE

The fundamental design of the booster remains unchanged since the status presented in [1]. However, a number of design choices elsewhere in the facility and an evolution of the engineering design have necessitated a number of modifications to the booster lattice.

The most significant change to the design is the decision to raise the linac energy from 100 MeV to 150 MeV. This is expected to have a number of benefits [1], particularly around improving capture and transfer efficiency through the booster ramp. The increase in linac energy will be achieved by replacing the two 5.2 m long structures with three 3.1 m structures and operating them with higher gradient. This allows 150 MeV to be reached without extending the linac footprint and minimises the changes needed in the LTB. Replacing the linac also allows the S-band operating frequency to be matched to the storage ring (6×499.511 MHz).

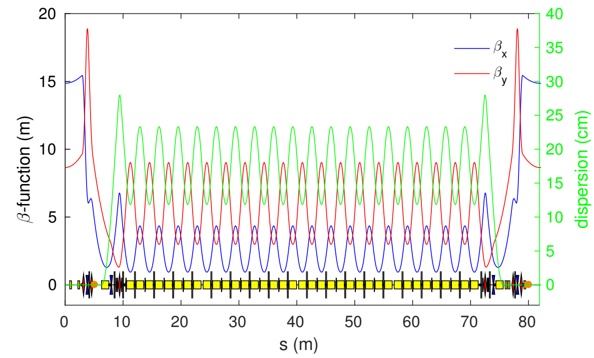

Figure 1: Twiss parameters and dispersion function for one super-period (half of the new booster).

Table 1: Booster Parameters and Beam at Extraction

Parameter	Present Booster	New Booster
Energy Range	0.1-3.0 GeV	0.15-3.5 GeV
# Cells	22	36 + 4
Circumference	158.4 m	163.847043 m
Harmonic Number	264	273
Betatron Tunes	[7.18, 4.27]	[12.41, 5.38]
Nat. Chromaticity	[-9.7, -6.3]	[-13.7, -12.3]
Mom. Comp. Factor	0.0252	0.0057
Natural Emittance	134.4 nm.rad	17.4 nm.rad
Energy Spread	0.073 %	0.087 %
Nat. Bunch Length	99.3 ps	38.9 ps
Loss per Turn	0.58 MeV	0.95 MeV

The next alteration to the design is a change in booster circumference, again to match the operating frequency to the storage ring RF. This necessitated lengthening the straight sections by 279 3.4 µm each and changing the harmonic number from 272 to 273.

The final change to the design is a shift in nominal tune from [12.20, 5.36] to [12.41, 5.38]. The primary reason for the change was to bring the working point closer to the coupling resonance to enable emittance exchange [5]. Subsequent studies of injection into the storage ring indicated emittance exchange would not be beneficial for the present optics; however, given the new tune point was also found to provide increased dynamic aperture it was retained for the combined-function magnet designs.

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The optics functions for one super-period of the new booster are shown in Fig. 1 and the main lattice parameters are summarised in Table 1.

PERFORMANCE STUDIES

Impact of Errors

The updated lattice design and new nominal tune point were studied following the same procedure and after applying the same errors as described in [1]. The resulting dynamic aperture over 50 seeds is shown in Fig. 2. The lattice shows a high degree of tolerance to errors and the dynamic aperture is expected to comfortably exceed the physical apertures.

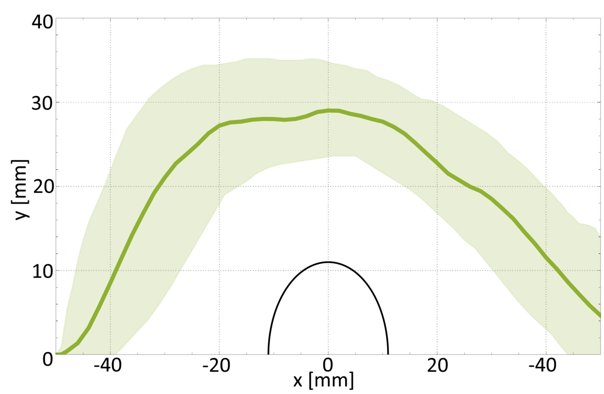

Figure 2: Dynamic aperture (DA) after orbit, tune and chromaticity correction. The solid green line shows the average DA over the 50 error seeds, whilst the shaded area illustrates the variance. The black line represents the vacuum chamber.

Linac-to-Booster Transfer Efficiency

Electron bunch phase shifts occur in the storage ring when operating with a harmonic cavity due to transient beam loading in the main cavities. To minimise this effect, the bunch-to-bunch charge variation should be kept below $\sigma_I = 5\%$ [3]. This implies an injected charge of ~100-150 pC per bunch. However, to provide confidence in the design and to allow for losses, the booster performance has been studied for a nominal bunch charge of 1 nC (0.5A) out of the gun. Higher charges (up to 16 nC / 8 A) have also been studied in case a future switch to swap-out injection is adopted.

Shown in Fig. 3 are the results of tracking the 1 nC electron bunch distributions from the exit of the linac, through the LTB and for the first 100 turns in the booster. Physical apertures were included, as were the standard errors, pulsed magnet jitter and 1% energy variation for 100 seeds. Capture efficiency into the booster was found to be close to 100%, with the majority of losses occurring at a high dispersion point in the LTB due to the long energy tails.

Single Bunch Collective Effects

The impact of the vacuum chamber impedance on the booster transfer efficiency was studied with particle tracking in ELEGANT [6]. The short-range resistive-wall and geometric contributions [1] were combined into a single

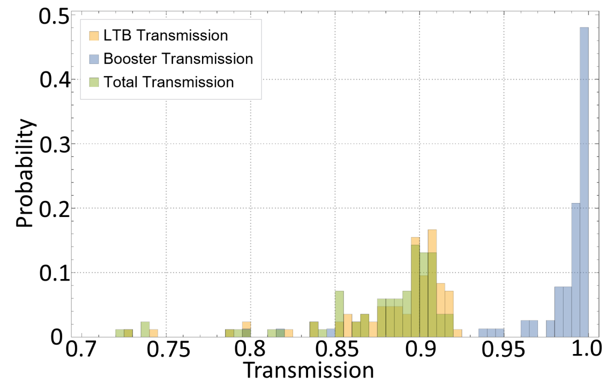

Figure 3: Injection efficiency into the booster for a 1 nC bunch with standard errors and physical apertures. Booster capture efficiency is calculated over the first 100 turns.

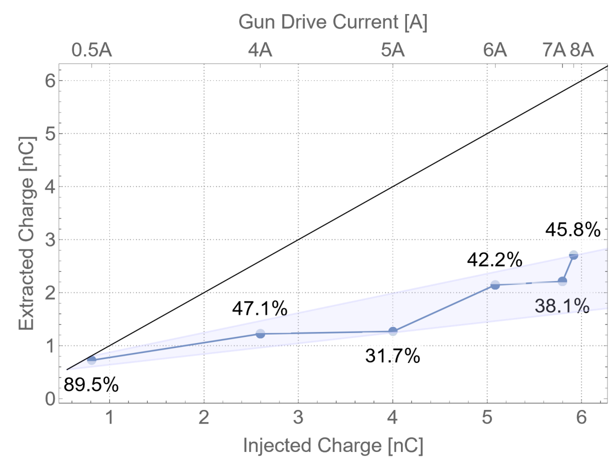

Figure 4: Extracted charge and transfer efficiency as a function charge at injection into the booster (central S-band bunch only). The black line indicates 100 % transfer efficiency.

impedance element, and 128,000 particles were tracked for the entire booster cycle using a one-turn-map, physical apertures and radiation effects [3]. The chromaticity was set to [+2, +2]. A strong blow-up in the horizontal emittance was observed, followed by significant particle losses for injected bunch charges above 2 nC, as shown in Fig. 4. Lowering the chromaticity to [0, 0] was found to be an effective way to prevent these losses (see Fig. 5). Based on this, a ramping of the chromaticity from [0, 0] at injection to [+2, +2] at extraction using the sextupole trim magnets has been adopted.

Shown in Fig. 6 are plots of the horizontal emittance and bunch length as a function of beam energy after implementing the proposed chromacitity ramp and using the same distributions from the gun as shown in Fig. 4. These results were produced using element-by-element tracking to allow the effects of intra-beam scattering (IBS) to be added, along with the lumped impedance element and physical apertures. As can be seen, at low bunch charges the bunch damps down to the natural ring parameters at extraction, with IBS causing a small growth at higher charges. Electron bunch parameters at extraction are summarised in Table 2.

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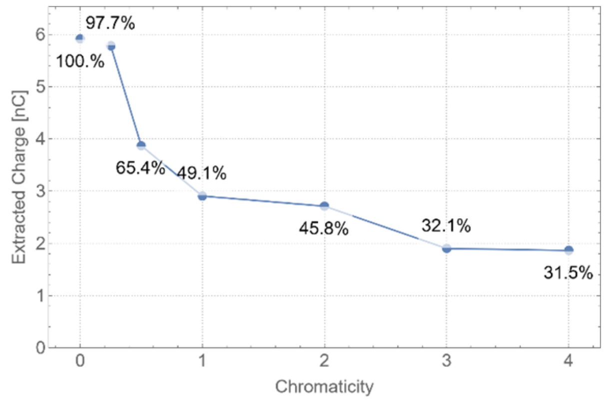

Figure 5: Extracted charge and transfer efficiency as a function of chromaticity. In all cases, the bunch distribution for an 8 A (16 pC) bunch out of the gun was used.

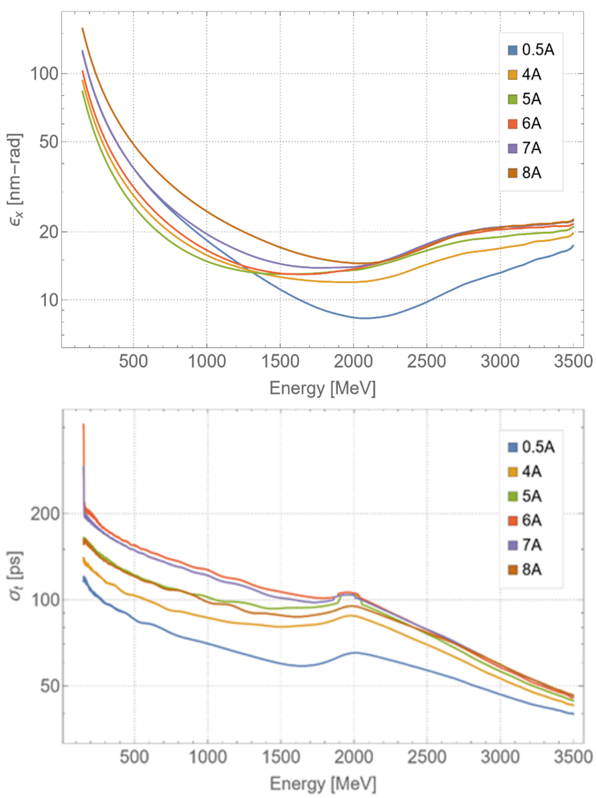

Figure 6: Horizontal emittance (top) and bunch length (bottom) as a function of energy including the chamber impedance, IBS and physical apertures. The chromaticity is ramped from [+0,+0] at injection to [+2,+2] at extraction. The initial distributions are the same as for Fig. 4.

Table 2: Booster Parameters at Extraction

Parameter	0 nC	1 nC	5 nC
$\epsilon_x (nm.rad)$	16.3	17.9	21.6
$\epsilon_y (nm.rad)$	1.76	1.92	2.47
$\sigma_E (\%)$	0.087	0.091	0.10
$\sigma_L (ps)$	38.9	39.8	45.1

TRANSFER LINES

With the aim of minimising tasks to complete during the dark period, changes to the LTB and BTS have been kept to a minimum. The main goal for the transfer lines is that they should be capable of transporting beam between accelerators with minimal losses and avoid causing significant degradation in bunch properties. They should be equipped with sufficient diagnostics to enable the beam parameters to be measured, and flexible enough for a range of optics parameters to be matched along their lengths.

Modifications to LTB

The changes to the LTB can be summarised as follows:

- a subset of girders in the booster vault will be relocated to match the new booster injection point;
- a new LTB dipole 3 and one new quadrupole will be added;
- new power supplies and cables will be required for LTB dipoles 1 and 2 to allow them to operate at 150 MeV (the magnets can be re-used);
- one new BPM and one new corrector magnet are required for trajectory control;
- new vessels, pumps, gauges and gate valves will be added as required.

Measurement and simulations of the existing quadrupoles have demonstrated these can be re-used for Diamond-II at the higher linac energy without modifications, as can the horizontal and vertical correctors. As such, the new magnets mentioned above can be replicas of the existing versions.

Modifications to BTS

The following changes are also required for the BTS:

- BTS dipole 1 is moved upstream to connect the new BTS path with shield wall penetration;
- BTS dipole 3 has been relocated to connect the transfer line with the new storage ring septum position;
- Five of the six girders supporting the BTS quadrupole doublets will be relocated;
- a new BTS dipole 0 has been added to account for an increase in the booster extraction angle;
- new vessels, pumps, gauges and gate valves will be added as required.

The existing BTS magnets are all suitable for re-use on Diamond-II at the higher beam energy without modifications.

CONCLUSIONS

Work on the physics design for the replacement booster has largely been completed, with effort now focussed on finalising the magnet and engineering designs. Particle tracking through the ramp including collective effects has demonstrated the design meets the standard operating requirements for the Diamond-II storage ring. The booster is also well-suited to meet the needs of fall-back injection options [3] or future optics changes in the storage ring.

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