INJECTION USING A NONLINEAR KICKER LOCATED IN THE EXISTING INJECTION STRAIGHT AT DIAMOND STORAGE RING

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Abstract

Injection studies using a non-linear kicker for the Diamond storage ring have been previously carried out [1]. These studies have been recently extended to investigate whether the non-linear kicker can be located in the injection straight downstream of the septum and outside the existing dipole kicker bump. If so, injection with a non-linear kicker becomes independent of the optics used, making it suitable for use in both standard and low alpha mode. With this configuration, the existing injection scheme could also be left in place, leaving open the possibility to study both schemes in situ before potentially removing the existing dipole kickers at a later date. In order to operate with the non-linear kicker, the injected beam needs to exit the transfer line at an angle of 3mrad; this has been successfully demonstrated during machine development time. The concept and feasibility studies of this scheme are presented in this paper.

INTRODUCTION

Various studies have been carried out of injection using pulsed non-linear kicker magnets both in existing and future rings [2-4]. These magnets are used to replace the traditional four-dipole kicker bumps, with the main benefit that the disturbance given to the stored beam during top-up injection cycles is significantly reduced. One difficulty with their operation is the need to maintain a strict phase advance from the injection point (IP) to the magnet, reducing the flexibility to operate with different optics.

Here we investigate whether a pulsed magnet (PM) can be located in the existing injection straight at Diamond. Space is available to locate at least a 0.4m long device after the existing kicker K4 (4m from the IP). Previous studies had investigated whether straight 2 could be used [1], but this turned out to incompatible with the upcoming double-double bend achromat (DDBA) upgrade [5]. Placing the PM in the injection straight could also potentially allow it to be utilized for an ID, as we are looking to create more spaces for new beamlines (e.g. the DDBA project and removal of a chromatic sextupole to create a space for a multipole wiggler [6]).

REVISITING INJECTION USING PM

The concept of injection using a PM is revisited in context of placing both the septum and PM in the same straight. The injection invariant *(b)* in normalized phase space is described by $X^2 + X'^2 = b^2$ where $X = x/\sqrt{\beta_x}$ and $X' = (\beta_x x' + \alpha_x x)/\sqrt{\beta_x}$. The PM acts to ensure that $X' = 0$ after the kick, as shown in Fig. 1. Using this notation, $X_{PM} = \left(x_{PM}/\sqrt{\beta_x}\right)$ is the residual amplitude of beam oscillations after the kick, and the reduced invariant is X_{PM}^2. From this, the injection angle required can be calculated easily since the beam travels in a straight line from the IP to the PM location (Fig. 2).

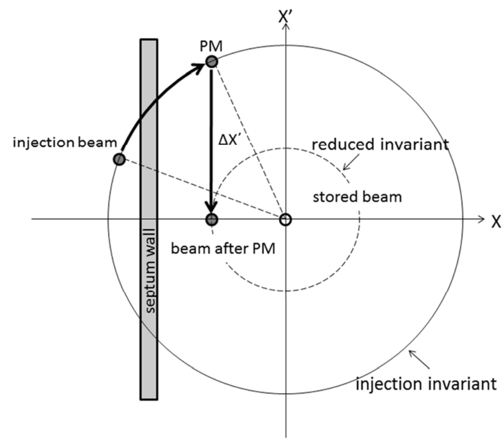

Figure 1: Schematic of injection using PM where PM is located in same straight as septum magnet.

The angle of injection is given by $x'_{IP} = (x_{PM} - x_{IP})/d$ (where d is the distance between IP and PM). The optimal kick angle for the PM is the one that minimises the invariant *b,* which after the PM is given by $X'_{PM} = (\beta_{xPM} x'_{PM} + \alpha_{xPM} x_{PM})/\sqrt{\beta_{xPM}} = 0$. Finally, the kick angle is given by $\theta_k = x'_{IP} - x'_{PM}$.

The schematic of the injection scheme is shown in Fig. 2. The inner plate of the septum is movable between 12-16mm from the central orbit (presently at 12mm), its thickness is ~3mm and the full injected beam size is 5mm. The Twiss parameters at the IP and PM locations are β_x=9.8m, α_x=-0.1 and β_x=12.4m, α_x=-0.1 respectively. The calculated kick and injection angle are 2.9mrad and 2.6mrad respectively. The injection angle is further optimized as discussed in the next section.

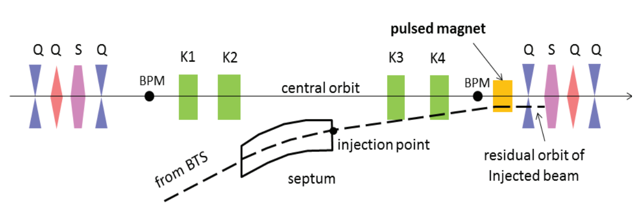

Figure 2: Schematic of the proposed injection scheme using PM which is to be located after kicker K4 of the four kicker bump injection.

SIMULATIONS

Optimisation with DDBA Optics

Due to the small apertures in the new DDBA section, the previous choice of positioning the PM at the end of the second straight shows the injection efficiency falling below 60%. Unavoidably, the injected beam amplitude needs to be reduced prior to the DDBA section, leaving the first straight (injection straight) as the only option.

Simulations were carried out taking into account the full detailed physical aperture to ensure a realistic situation. Optimisation of the injection efficiency and injection angle was conducted using Multi Objective Genetic Algorithm (MOGA) [7]. The optimisation is a direct tracking using the Elegant code. Injection amplitude, PM strength and injection angle are variables in the optimisation. The results are presented in Fig. 3.

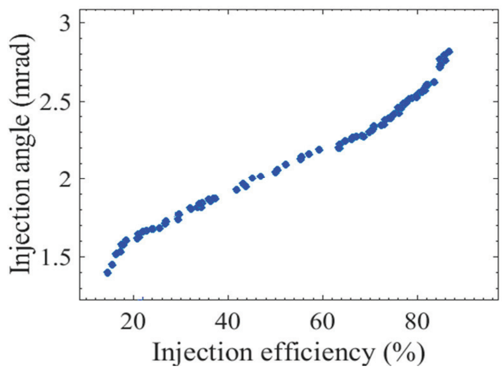

Figure 3: Optimal front from MOGA optimisation for injection angle and injection efficiency.

From the optimal front in Fig. 3, the MOGA solution with good injection efficiency (86%) and smaller injection angle (2.8 mrad from 3.0 mrad) can be selected. The injection efficiency would be improved with a shorter injected bunch length, which could be obtained with an upgrade of the RF voltage (one more RF cavity) in the booster. In this case an injection efficiency of about 95% can be obtained.

First turn multi-particle tracking shows that the injected beam passes through the narrow physical aperture in cell 2 (the DDBA cell) as shown in Fig. 4. The injected beam can be captured into the machine acceptance (red line) after the first turn kick as shown in Fig. 5. Although the peak field of the PM was calculated to deliver the best injection efficiency, it is clear that the effect of the PM kick, which varies with horizontal position, can perturb the injected beam shape.

Optimisation for Low Alpha + DDBA Optics

Preliminary calculations for the new injection scheme have also been made with the proposed low alpha optics solution for the DDBA lattice [8]. In this case, since there are no optical elements between the septum and pulsed nonlinear kicker, it is anticipated that the scheme should work equally well as for the standard optics. However, as noted previously, the transverse kick profile in both horizontal and vertical planes is not uniform across the injected beam cross-section, potentially altering the injection process.

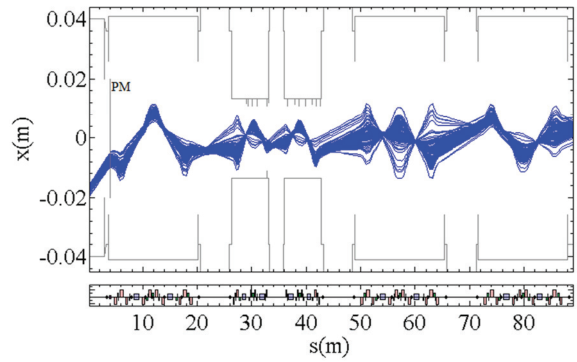

Figure 4: First turn trajectory of 100 injected particles (blue) with PM kick in the first super period with respect to the horizontal physical aperture (grey).

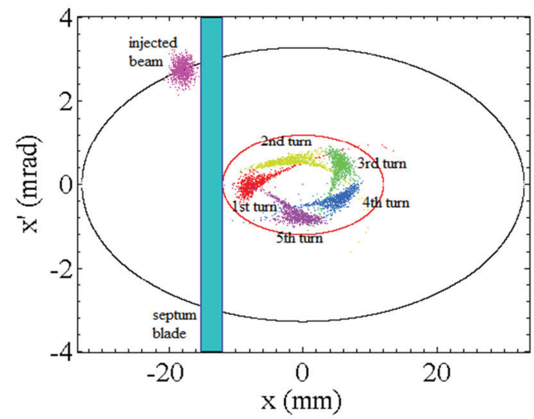

Figure 5: First five turns injected beam phase space. Injected beam inviant and machine acceptance is plotted in black and red line respectively.

The injection efficiency in low alpha at Diamond is primarily limited by the mismatch in natural bunch lengths between the booster and storage ring (29.8 mm and 0.7 mm respectively). This causes particles at the head and tail of the injected bunch to undergo large energy deviations due to synchrotron motion, leading to significant beam loss before the beam can be fully damped down. After the DDBA upgrade, the losses are anticipated to increase further due to a reduction in the on and off-momentum dynamic aperture.

The injection efficiency for the new scheme was compared to that found using the standard four dipole kicker bump by carrying out particle tracking using the Accelerator Toolbox [9] tracking code. In both cases, the separation between stored and injected beams was set to -6.8 mm, with the PM bend angle and incoming beam trajectory optimised to maximise injection efficiency in the new scheme. The injection efficiency as a function of these two parameters is shown in Fig. 6, and the first-turn trajectory is shown in Fig. 7.

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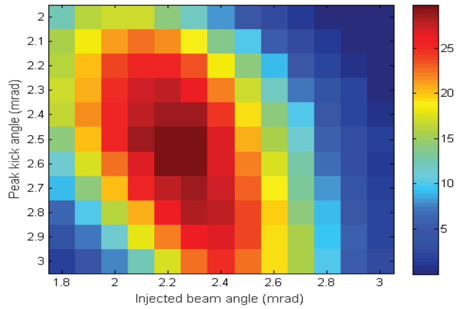

Figure 6: Injection efficiency as function of injected beam angle and kick angle of PM.

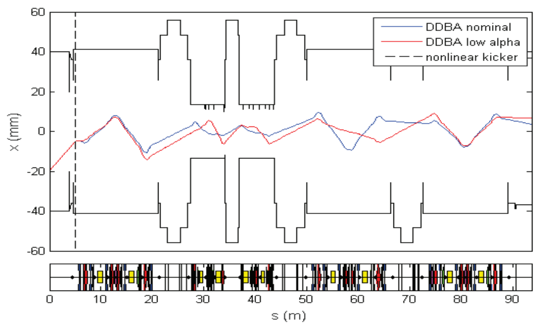

Figure 7: First turn trajectories for low alpha optic with DDBA lattice.

In the best case, the injection efficiency for the ideal lattice with the new injection scheme was calculated to be 29.8% for injection angle of 2.2mrad and PM kick angle of 2.6mrad, compared to 31.8 % for the existing four dipole kicker bump scheme.

MACHINE TESTS FOR 3 MRAD INJECTION

A series of tests have been conducted to assess the feasibility of injection with an angle of 3mrad. By making use of a YAG fluorescent screen camera positioned 254mm downstream of the exit edge of the septum it was possible to verify the change in the beam-spot position as a function of the septum current used to alter the exit angle of the beam. Since the septum length is L=1.694m, care must be taken when predicting the position of the beam spot, in other words a simple formula like $\Delta x= L \cdot \delta\theta$ is not a valid approximation, and indeed produces results quite far from the expected figures. A correct calculation is easily shown with the help of Fig. 8. The beam with nominal current (I_0) is shown as a black dash-dotted line. The radius of curvature for this beam is ρ_0, and $O_0(0,0)$ is the origin of the corresponding arc of a circle. In this reference frame $P(0,\rho_0)$ represents the entry point of the beam into the septum and with the initial current I_0 the exit point is A. If the septum current is reduced by a fraction δ ($I_0 \rightarrow I_0(1\text{-}\delta)$) the radius of curvature increases by the same amount ($r_0 \rightarrow r_0(1+\delta)$) and the exit point shifts to B.

The exit angle with respect to the downstream face of the septum also varies due to this current reduction. Putting together these two elements it is straightforward to infer the change in the beam-spot position at the YAG camera (green screen) for a given change in current δ.

The agreement is very good when a full non-linear calculation is taken into account. The short septum approximation is reported for comparison in square brackets, for the case δ=-2%, showing the large disagreement mentioned in the text, mainly due to the exit point B (Fig. 8).

Results are summarized on Table 1, showing a very good agreement between measurements and predictions from the exact calculations. It is also shown how a short septum approximation is completely inappropriate for a 1.694m long magnet. It is apparent how a reduction of about 2% in the septum current would generate an angle of about 3mrad, with a side shift of about 2.5mm towards the stored beam, at the septum exit edge. The septum h-apertures are ± 8mm enough for injection with more than 3mrad.

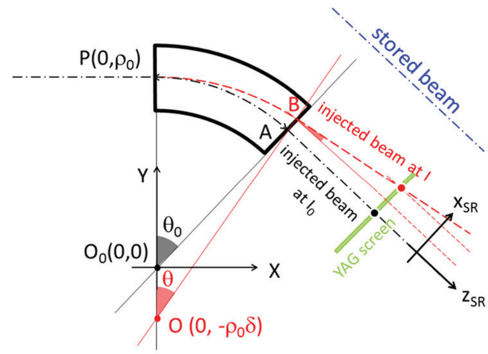

Figure 8: Schematic (not in scale) of the septum geometry used to illustrate the exact calculation of a trajectory change due to a variation in the septum strength.

Table 1: Summary of Predicted and Measured Displacements as Seen at YAG Fluorescent Screen Camera

	prediction [short septum formula]			data
dI/I_0 (%)	ΔX_{exit} (mm)	$\Delta\alpha_{exit}$ (mrad)	ΔX_{YAG} (mm)	ΔX_{YAG} (mm)
-1	1.3	1.5	1.63	1.73
-2	2.5 [5.1]	2.9 [3]	3.23 [5.86]	3.31
-4	4.9	5.7	6.34	6.53
-6	7.2	8.5	9.33	9.40

CONCLUSIONS

The proposed non-linear kicker injection scheme can work for the Diamond ring, even after installation of the DDBA cell. It is also feasible for the low alpha mode. In principle, it can also be used to vacate the central part of the injection straight to allow an insertion device to be installed. However, this would require the septum to be moved to the other end of straight and a major modification to the booster-to storage ring transfer line.

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