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PROPOSED NONLINEAR INJECTION KICKER FOR THE AUSTRALIAN SYNCHROTRON

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Abstract

Future beamline development at the Australian Synchrotron requires free floor space within the straights for a short undulator and relocation of diagnostics. Our current injection method uses a four-dipole kicker configuration that perturbs the stored beam during injection while also taking up approximately 4 meters of valuable space.

To free this valuable space and provide transparent injections to the beamlines, a single pulsed nonlinear magnetic field kicker (NLK) will be deployed. The desirable property of a NLK is that it has a flat and zero field at the stored beam but maximum field where the injected beam is located off-axis. NLKs deflect only the injected beam, leaving the stored beam undisturbed. NLKs have been extensively prototyped by many facilities around the world already and can produce injection efficiencies of 99% [1, 2].

This paper presents the preliminary magnet design for installation of a NLK at the Australian Synchrotron. We discuss the beam dynamics and thermal transfer constraints on kicker placement, field-flatness and the magnet and ceramic chamber design for adaptation to our 3 GeV beam. Installation plans and other constraints for future deployment are also outlined.

INTRODUCTION

The Australian Synchrotron (AS) is 3 GeV, 3rd generation facility located in Melbourne, Australia. Recently, the second phase of beamline development at the AS through the BRIGHT program was announced; culminating in the production of 8 new beamlines. The current injection system in the storage ring of the AS uses a traditional 4 dipole kicker magnet configuration. In this method, 4 dipole kicker magnets are used to bump the stored beam close to the septum during top-up injection. However, this injection method introduces unavoidable beam oscillations that result in a momentary drop in photon flux at the beamlines in addition to taking up space in straight sections 2 and 14. Additionally, optimisation of the injection system does not eradicate the oscillation entirely (see e.g. [1, 3]).

The unavoidable oscillations in the beam arise from two contributions. The first is the non-perfect/non-synchronous kicker magnets – where to obtain a perfect kick and zero oscillations, the kicker magnet response and components need to be perfectly identical. A uniform kicker response is impossible due to unavoidable differences in the magnet, chamber or kick amplitudes. The second is that the 4 kick bump stretches across two arc sectors that contain sextupoles and the second order fields would require the relative strengths of the four kickers to change along the ramp. This is currently not possible with our half-sin pulsers. Mitigation methods such as linearising the nonlinear fields by scaling the sextupoles to the kick amplitude at the sextupole as been tried but the resultant decrease in beam lifetime meant this could not be implemented.

The result is a noticeable change in the beam size due to the oscillations induced by the injection kicker. To continue providing cutting-edge research infrastructure and considering the expansion of beamlines through the BRIGHT program, a new compact and efficient injection system should be used. A more compact and transparent injection system would free the space within the ring for future insertion devices without affecting the stability of the beam.

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PROPOSED SOLUTION

To free up space and provide the user community with more stable source, we propose installation of a single nonlinear kicker (NLK). NLKs have been extensively prototyped by many facilities around the world already (e.g. DLS [1], LNLS [2], ALS [4], BESSY II [5]). A non-linear kicker deflects only the injected beam leaving the stored beam undisturbed. As shown in Figure 1, the NLK is designed so it has a nonlinear magnetic field that is flat and zero at the stored beam (umperturbed) but maximum where the injected beam is located off-axis (to kick the injected beam into the acceptance of the stored beam). The kicker design that has been adopted is similar to LNLS design with the conductors in air surrounding a narrow gap ceramic vacuum chamber.

PRELIMINARY MAGNET DESIGN

Electromagnetic Simulations

NLK electromagnetic calculations were completed using the Finite Element Magnetics Method (FEMM) [6]. The initial starting geometry selected for investigation was a 4 copper conductor symmetrical configuration with a magnetic depth of 280 mm. While this configuration would be simpler to implement, our investigations showed that the y-component field had an unacceptable field gradient that would perturb the stored beam. As such, we turned to a higher order NLK configuration that consists of 8 conductors mounted on a Titanium coated ceramic chamber.

The coil design will consist of 8 copper wire conductors that are precision mounted on the ceramic chamber. The wires will be arranged in symmetry with 2 wires per quadrant with each wire generating the opposing current.

Design Constraints

We require the final geometry to meet the following criteria:

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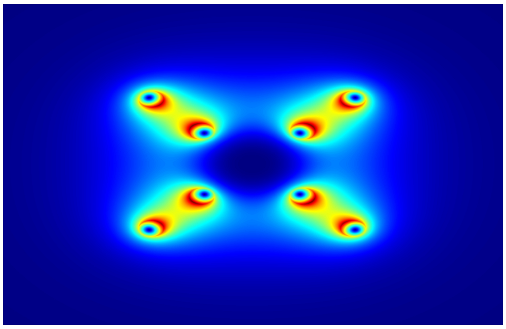

Figure 1: Nonlinear injection kicker field map for the 8 conductor configuration.

Table 1: Parameters of the NLK Design

Deflection θ_{Kick}	1 mrad
Inductance	< 1 μH
B_y maximum	x = 18 mm
Nominal field	B_x < 0.01 mT
Nominal integrated field	$\frac{dB_x}{dy}$ < 0.01 T.m

Parameters for the NLK design are shown in Table 1. For a 1 mrad kick and a magnetic length of 330 mm, the peak field required is:

$$B = \frac{10\theta}{L} = \frac{10}{330} = 30.3 \text{ mT} \tag{1}$$

where B is the magnetic field, θ is the kick angle and L is the magnetic length.

Working Design

The 2D electromagnetic simulations were conducted using FEMM. The 8 conductor design consists of a 74 mm× 20 mm (H ×V) Ceramic Chamber with an internal aperture of 64 mm× 10 mm (H ×V) and a internal coating of Titanium (Ti) or Titanium Nitride (TiN). The 8 copper conductors are arranged in a 4 fold-symmetry configuration with 2 wires per quadrant where each wire generates the opposing current. For this design, the inductance was 1.0 μH using 1000 A conductors connected in series.

Two pure copper bars with dimensions 8 mm×2 mm (H × V) will be placed at $y = \pm 16$ mm (vertical). The copper bar does not impact the magnetic field of the copper conductors, but increases the magnetic reluctance and decreases the flux of the beam. This produces a flat field gradient at the stored beam; ensuring that the stored beam remains unperturbed. The magnetic design shown in Figure 1 assumes that the ceramic chamber is transparent to the field. However, the conductive coating and ceramic chamber dimensions does impact the obtainable field and power deposited across the chamber.

THE CERAMIC CHAMBER

Conductive Coating

The ceramic vacuum chamber must have a thin Ti or TiN conductive coating (typically 0.5 μm – 10 μm thick) as external fast pulsed magnetic fields cannot penetrate metallic vacuum chambers [7]. The conductive coating provides a path for the image currents, minimising the beam impedance and decreasing the charge accumulation across the ceramic chamber. Both thinfilm Ti and TiN are candidate materials for the coating as both are conductive and TiN may be a better option compared to Ti [8].

The optimal coating will fulfil several criteria. The coating must:

- Have equal or less electrical resistance compared to the bare chamber
- Low heating effects from image currents
- Be thin enough such that the magnetic field can penetrate with little distortion of the field

The interplay of these factors will impact the magnetic response. For example, a thin material will provide a small field distortion but will deposit more power from the image currents impinge on the thin coating. To decide on the optimal coating, the field distortion, thermal analysis, and effect on injection variables must be considered. The field distortion calculations have been conducted and are presented below.

Field Distortion

The field in the ceramic chamber is dependent on the separation, coating thickness and conductivity. The surface resistivity ($R_s = \frac{1}{\sigma d}$ where d is the thickness of the film coating and σ is the conductivity) determines the uniformity of the thin film. We take the conductivity of a thin film of Ti as $\sigma_{Ti} = 2\times10^6$ S/m and for a thin film of TiN, we take $\sigma_{TiN} = 6\times10^6$ S/m.

The field distortion of Ti coatings at various thicknesses are shown in Figure 2. The field is distorted in amplitude and phase; at 1 μm thickness, the film induces a delay in the peak pulse of 45 ns. Assuming we have a 100 ns bunch train and taking into account our storage ring (SR) revolution of 720.47 ns, the kicker maximum rise time will be 620.47 ns (SR revolution minus the bunch train). With a flat top of 100 ns, the kicker will then have a maximum fall time of 620 ns. Hence, the kicker design can have a maximum total pulse duration of 1.34 μs (2×maximum fall time + induced delay).

Power Deposition

The conductive coating will experience beam induced power deposition due to eddy currents. The amount of power deposited depends on the thickness of a ceramic chamber coating. The power density equation for a circular cylindrical chamber was taken from [9].

The power density calculations for 400 mA stored beam with various coating thicknesses and bunch lengths are shown in Table 2. The lower limit bunch length is 360 and the upper extreme limit is 240 bunches which experiences

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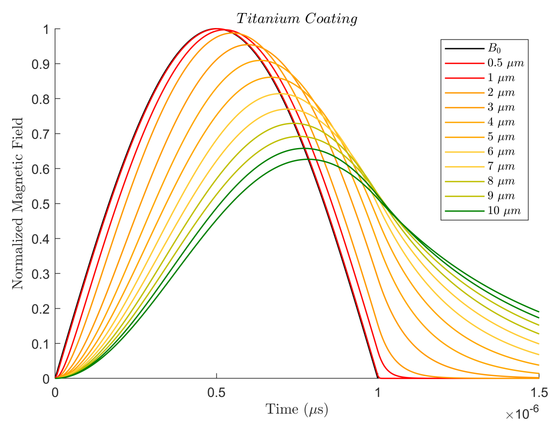

Figure 2: Field Distortion with Titanium Conductive Coating Thickness.

a maximum 400 mA beam. Note that normal operation is 200 mA; 400 mA represents the upper extrema of operation (potential future upgrade). For a 1 μm coating, the power deposited is 625.8 W/m^2 for 360 bunches for Titanium coating and 512.6 W/m^2. For a coating of 3 μm, this reduces to 312.9 W/m^2 for Titanium coating and 256.3 W/m^2 for Titanium Nitride.

THERMAL ANALYSIS

It has been shown by several researchers that the thickness of the conductive coating will undergo heat transfer from the stored beam. Thermal calculations of the heat load and temperature rise across the ceramic surface were completed using:

$$\Delta T = p\frac{l_c}{K} \tag{2}$$

where ΔT is the temperature rise (°C), l_c is the thickness of the ceramic and K is the heat conductivity.

The convection heat transfer coefficient of air is 5 W/m^2 and the heat conductivity at 25°C is 34.1 W/m K for alumina. The thermal conductivity for TiN was taken as 28.8 W/m K and 11.4 W/m K for Ti at room temperature. The temperature distribution simulations for our kicker design with coating thicknesses of 1-10 μm were completed using the Partial Differential Equation Toolbox in Matlab.

In the extreme case, when 400 mA of beam current fills 300 buckets, the temperature (max) 66.9°C and 59.3°C for 3 μm Ti and 3 μm TiN coating thicknesses, respectively. Temperatures higher than 80°C will require active cooling. Forced convection cooling of the kicker during injection can be implemented to mitigate this heat load.

Table 2: Power Deposition (W/m^2) for Titanium and Titanium Nitride Conductive Coatings for 400 mA and 300 bunches

Thickness (μm)	**Power Ti** (W/m^2)	**Power TiN** (W/m^2)
1	625.8	512.6
2	312.9	256.3
3	208.6	170.9
10	62.58	51.26

PLACEMENT IN STORAGE RING

The placement and final location of the NLK depends on the current availability of space in the storage ring and future accelerator development under the Bright beamline program.

Sector 5 is therefore the most likely location for the NLK. The usable space is 330 mm when we take into account absorber and flange adaptors on either side of the NLK. Tracking of the injected particles from the septum end and through 8 subsequent turns when the NLK is housed in Sector 5 are shown in Figure 3. The initial particle distribution maximum aperture of the septum with an angular distribution of ± 1 mrad tracked to the proposed location of the NLK (red). The subsequent turns are shown in blue (1st turn), cyan (2nd turn), magenta (3rd turn) and green (8th and last turn) indicating the surviving particles.

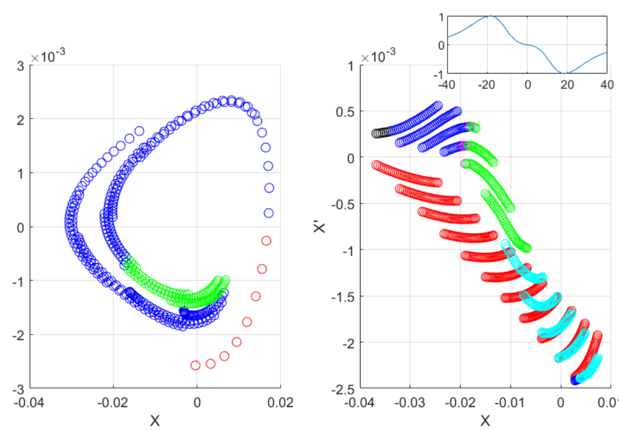

Figure 3: Sector 5 particle distribution for a 1 mrad kick.

CONCLUSION

This report outlines the preliminary nonlinear kicker design for installation at the Australian Synchrotron. The single nonlinear kicker will be an 8 copper conductor configuration designed to kick the injected beam 1 mrad without perturbing the stored beam. The conductors will be housed in a matrix around a 74×20 mm ceramic chamber (aperture 64 × 10 mm) with a conductive Ti/TiN coating optimised to 3 μm thickness. The kicker will be located upstream in Sector 5. We presented estimates on the thermal effect of the stored beam. We noted that for a 2 μm Ti coating, the stored beam at its maximum will heat the chamber to 87.7°C.

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