SOLENOIDAL FOCUSSING INTERNAL TARGET RING

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Abstract

FFAGs have been considered for a high power proton source for a neutron target by means of an internal target. In an internal target type ring, protons are repeatedly passed through a thin foil, producing neutrons and other secondary particles. This technique has the potential to produce higher secondary particle fluxes with modest beam currents and energies. Scattering of the protons causes emittance growth in the beam, but this can be partially offset by energy lost through ionisation of the foil, which causes ionisation cooling. The resultant beams typically have large position and momentum spread, with transverse emittances of order mm. In this paper, the design of a solenoid-focussing ring is studied which may enable containment of large emittance beams.

INTERNAL TARGET SCHEMES

In conventional accelerator-driven proton targets, protons are accelerated to high energy and deposited onto a target. Secondary particles are produced for users and any remaining protons are captured on a beam dump. In so-called 'internal target schemes' [1–3], protons are accelerated to high energy and passed through a thin target that sits within a storage ring. Secondary particles are produced for users. The protons are recirculated through the ring, any lost energy being replaced by RF cavities, enabling many passes through the same target. The ionisation cooling effect limits the amount of emittance growth that occurs upon passing through the target. Emittance growth due to scattering in the target is offset by emittance reduction due to the ionisation of atomic electrons, resulting in a stable equilibrium emittance. The equilibrium emittance from ionisation cooling is given by [4]

$$\varepsilon_{eqm} \approx \frac{1}{2m_\mu}\frac{13.6^2}{X_0}\frac{\beta_\perp}{\beta\langle dE/dz\rangle} \tag{1}$$

The internal target scheme has several advantages over conventional target arrangements.

- Higher yield may be achieved from a relatively low current source due to repeated interactions with the target.
- The energy at which particle production occurs can be tuned, enabling tuning of the secondary particle yield.
- Space charge effects may be damped by ionisation cooling.

However several technical challenges must be overcome.

- The lattice must have a high acceptance in order to accommodate the large beam emittances.
- Heat deposition on the target material must be removed.
- Radiation near to the target may be operationally challenging.

Previous studies have used FFAG-type rings to accommodate the high emittances characteristic of internal target arrangements [2, 3]. FFAGs have excellent momentum acceptance and transverse acceptance, making them ideal candidates for such an arrangement. Solenoid rings have been studied extensively by the muon collider community for the purpose of ionisation cooling of muons, precisely because they have high acceptances [5]. In this paper we study the use of a solenoid ring for proton containment, in order to accommodate the high emittances characteristic of internal target arrangements.

Table 1: Lattice Parameters for Solenoid Ring

Number of Cells	12
Radius	3.0 m
Reference Energy	11.1 MeV
Energy Acceptance	6-15 MeV
Solenoid peak field	1.6 T
Dipole peak field	0.68 T
Magnet length	500 mm
Bore radius	400 mm
Foil thickness	10 microns
Foil material	Be
RF Voltage/turn	250 kV
RF phase	11°
RF frequency	2.452 MHz

RING MODEL

The ring parameters considered are shown in Table 1. The lattice is compact with relatively modest field requirements that may make normal conducting magnets a preferred option. The ring was simulated using MAUS [6], a Geant4-based simulation code [7] employed by the Muon Ionisation Cooling Experiment [8].

The magnetic field at a radius of 3.0 m is shown in Fig. 1. In this ring, combined-function solenoid and dipoles provide simultaneous focussing and bending. The solenoid component is simulated using a sum of the field contributed by infinitely thin cylindrical sheets. The dipole component is simulated using rectangular dipoles with fringe fields falling according to

$$B_y = \frac{B_0}{2}(tanh(\frac{z+z_0}{\lambda}) - tanh(\frac{z-z_0}{\lambda})), \tag{2}$$

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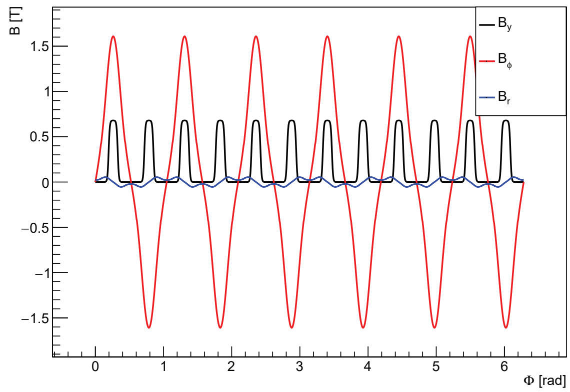

Figure 1: The magnetic field in the vertical, azimuthal and radial direction at a radius of 3.0 m is shown.

yielding a flat top of length $2z_0$ and an exponential fall-off with e-fold length λ. End poles were modelled to octupole order.

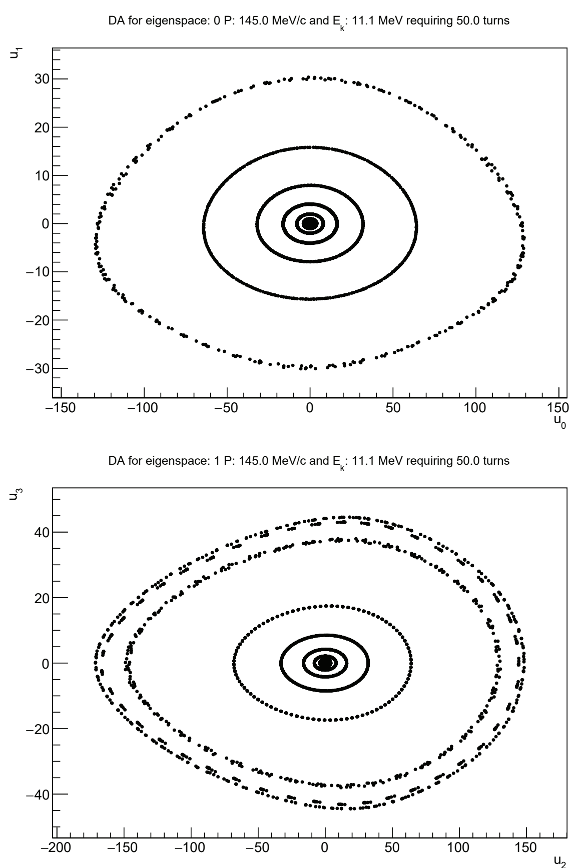

Figure 2: Evolution of particles in each dimensionless eigenspace through 50 turns (600 cells). The highest amplitude particles are on the dynamic aperture in (top) eigenspace 0 and (bottom) eigenspace 1.

The ring shows good transverse acceptance. Eigenspace analysis was performed by calculating the one-turn transfer matrix numerically and then applying the Parzen algorithm to find the decoupled eigenspaces [9]. The ring dynamic aperture in the two transverse eigenspaces is shown for the reference energy in Fig. 2, and as a function of energy in Fig. 3.

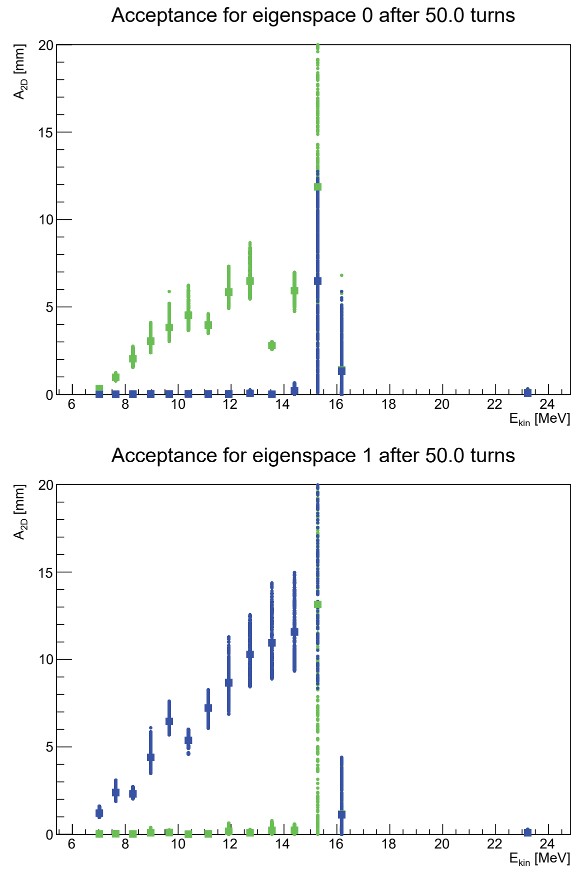

Figure 3: Amplitude of events at the dynamic aperture in the 0 (blue) and 1 (green) eigenspace as a function of energy. (Top) oscillations are excited in the 0 eigenspace and (bottom) oscillations are excited in the 1 eigenspace. Near to the 16 MeV stop-band, the eigenspaces are not well-decoupled.

The target was modelled as a 10 micron thick Beryllium foil. Simulation was performed in Geant4.9.6 using the `QGSP_BERT` model for hadronic interactions. The foil was assumed to cover the entire aperture.

The RF cavity was modelled as a 100 mm long pill-box type cavity operating in TM010 mode with harmonic number 1. The cavity was phased using MAUS's internal phasing routines [10].

PERFORMANCE

The performance was studied by injecting a pencil beam of 1000 protons onto the reference trajectory. The protons were tracked until they were lost from the ring. The transverse emittance and energy spread of the beam is shown in Figs. 4 and 5. The beam is observed to initially grow exponentially in transverse emittance. This is due to the scattering effect. An exponential fit was made to the emit-

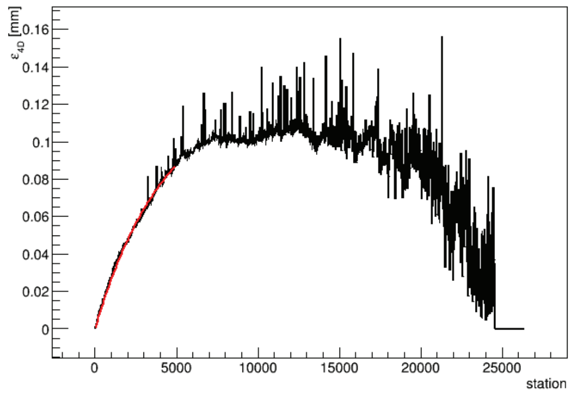

Figure 4: 4D transverse emittance as a function of number of cells traversed. The red line shows a fit of the form $A(1 - e^{-n/n_0})$.

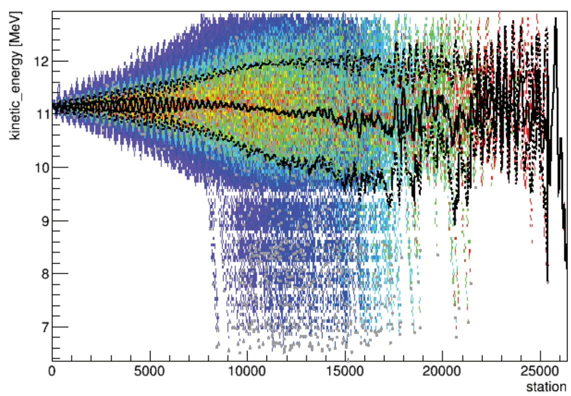

Figure 5: Energy spread as a function of number of cells traversed.

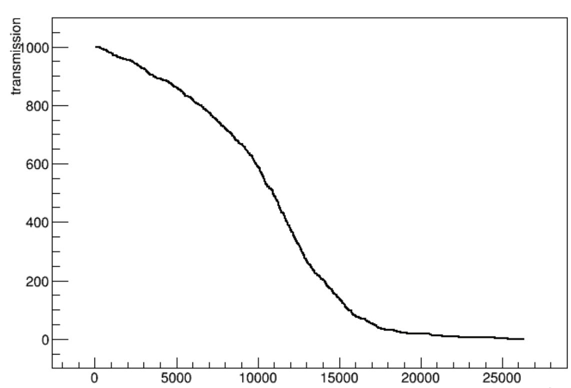

Figure 6: Transmission as a function of number of cells traversed.

tance growth, showing that the emittance is convergent on an equilibrium value of about 0.24 mm. This is consistent with the expected equilibrium emittance calculated using Eq. (1).

Transverse losses become significant before the beam reaches the equilbrium emittance value. Beam lifetimes of a few microseconds are expected.

Longitudinal emittance spread is also induced in the beam due to the effects of energy straggling in the foil. Particles are seen to fall out of the RF bucket and this leads to longitudinal losses later in the cycle.

The total energy deposited by the protons is enhanced by the internal target system. Protons lose on average 48 MeV energy in the foil during the lifetime of the beam.

CONCLUSIONS

The internal target scheme provides a factor of almost 5 more energy deposited on the target per proton, compared to conventional target schemes. A concomitant improvement in secondary particle yield is expected. Simulated beam lifetime is a few milliseconds, which is sufficiently long that the machine could be operated in a continuous ‘top-up’ mode given appropriate hardware. No injection scheme has been presented; charge-exchange injection would enable kicker-less injection.

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