HIGH INTENSITY BEAM STUDIES USING THE KURRI FFAGS

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Abstract

Increasing the repetition rate of FFAG accelerators is one way of obtaining high average beam current. However, in order to achieve beam powers of up to 10 MW for applications like ADSR, the number of particles per bunch in an FFAG has to be approximately the same as in a high power synchrotron. Collective effects such as space charge then become crucial issues. To understand high current beam behaviour in FFAGs, an international collaboration has been established to carry out an experimental programme using the FFAGs at Kyoto University's Research Reactor Institute, KURRI. The goal is to demonstrate acceleration of high bunch charge and identify the fundamental limitations. In this paper, we will show simulation results toward the first beam experiment which is planned towards the end of 2013.

KURRI FFAGS

Kyoto University Research Reactor Institute currently has two scaling FFAGs of interest, which we refer to as the ADSR-FFAG and ERIT-FFAG. The former is a 150 MeV proton driver for a test reactor where basic ADSR concepts can be examined. The latter is a 11 MeV demonstrator of neutron production using an internal target which is also used for ionisation cooling. Both FFAGs have been successfully commissioned and have achieved their initial goals. The experiments discussed may be performed on either machine depending on their availability.

For illustration, this paper will mostly discuss ERIT-FFAG. This machine can be injected with up to 6×10^{11} particles per pulse, equivalent to a Laslett tune shift for a uniform beam of -0.25 assuming a bunching factor of 0.25 and 100% unnormalised emittance of 100π mm mrad. The accelerator parameters for ERIT-FFAG are listed in Table 1.

Table 1: General Parameters of the ERIT-FFAG

Parameter	Value
Mean radius	2.35 [m]
Sectors	8
Max. B field	0.9 [T]
Field index, k	1.92
FD radio	3
Horiz. tune, Vert. tune	1.74, 2.22
Horiz./Vert. acceptance	7000/2000 [π.mm.mrad]
Rev. frequency	3.01 [MHz]
RF voltage	200 [kV]
Harmonic number	6

PROPOSED EXPERIMENT

The purpose of the proposed experiment is to verify three specific aspects of high intensity beam behaviour in FFAG accelerators. Firstly, whether FFAGs face the same challenges in terms of space charge tune shift as synchrotrons. Secondly, whether we can keep a large ratio of beam size to aperture to accommodate more particles. Thirdly, whether beam intensity may affect ionisation cooling.

In scaling FFAGs, magnet nonlinearities are not perturbations but essential ingredients in helping to maintain zero chromaticity and a scaling orbit. Compared to synchrotron nonlinearities, those in scaling FFAGs are relatively strong. In addition, magnet misalignments excite harmonic components beyond the ideal lattice periodicity, and therefore lead to non-systematic resonances. Denser resonance lines in tune space may limit the maximum tune shift/spread more strongly than in a synchrotron.

In an FFAG the orbit moves radially outward throughout acceleration like in a cyclotron. The horizontal acceptance is much larger than the vertical. Enlarging the beam emittance in the horizontal plane at injection is one way to suppress space charge tune shift/spread. However, this is only possible if there is no coupling between the horizontal and vertical planes so that the vertical beam size does not get larger.

Finally, experiments on ERIT-FFAG have demonstrated the use of ionisation energy loss to suppress emittance growth from an internal Beryllium foil. The presence of collective effects in passage of charged particles through material, which may be an issue for ionisation cooling systems, could also be addressed experimentally at KURRI.

Diagnostics

Relevant experimental measurements will rely on two kinds of diagnostics available in the KURRI FFAGs: beam position monitors using probes or electro-static plates; and beam size measuring devices using collimators combined with beam current monitors.

The beam position at all locations in the FFAG can be obtained by installing available beam position monitors sequentially, assuming the orbit is not affected by the probes. This method would allow for comprehensive position mon-

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ISBN 978-3-95450-128-1

itoring despite there being fewer beam position monitors than straight sections.

Beam size is measured by controlling the aperture. A collimator is initially set near the edge of the beam and is moved radially inward. The beam size is determined at the onset of observed of beam loss. This cannot separate real beam size and effective beam size when coherent oscillations occur due to injection mismatch. However, we could in principle minimise the effective beam size at injection to reduce mismatch and observe any beam size growth at a later stage.

Emittance Growth due to Foil Scattering

The biggest potential barrier in the proposed experiment is the emittance growth due to foil scattering. In ERIT-FFAG, the beams go repeatedly through the stripping foil because there is no bump orbit for injection. In ADSR-FFAG, the acceleration makes the orbit move away from the foil, but the process is slow and foil scattering is not negligible. It may be difficult to distinguish between the emittance growth due to space charge effects and that due to foil scattering. Studying these effects is the main motivation behind detailed pre-experimental modelling studies.

MODELLING

To model the KURRI FFAGs accurately requires accurate particle tracking, incorporating both foil scattering and space charge. For initial modelling studies we use Simpsons [1] to estimate the ratio of emittance growth from space charge effects and foil scattering quickly. Subsequently, to reveal more quantitative and detailed behaviour, further modelling is being conducted using MAUS and OPAL.

Modelling Using Simpsons

In Simpsons, the FFAG lattice is described as a combination of hard edge magnets with an ideal field profile. Misalignment errors can also be included to see the effects of non-systematic resonances coupled with intrinsic lattice nonlinearities. The small amplitude tune can be easily adjusted by the quadrupole component of the main magnets.

Space charge effects are included using a PIC method in a cylindrical coordinate system. The code has been benchmarked against experimental observations in several synchrotrons, especially with recent results of J-PARC RCS [2]. The effects of foil scattering are not as sophisticated as those included in later studies, in this case adopting the Moliere model [3] to describe the momentum distribution function after scattering. The absolute spread of the momentum is then adjusted to give similar results to ICOOL [4]. There is no energy loss included.

Preliminary simulation results show that when the beam intensity is 6×10^{11}, emittance growth due to space charge could be observable when the lattice has random misalignment errors as shown in Fig. 1. However, this emittance growth may be comparable in magnitude to that due to foil scattering as shown below. Since foil scattering effects are independent of the beam intensity, contribution from the space charge effects may only be extracted with careful beam size measurement.

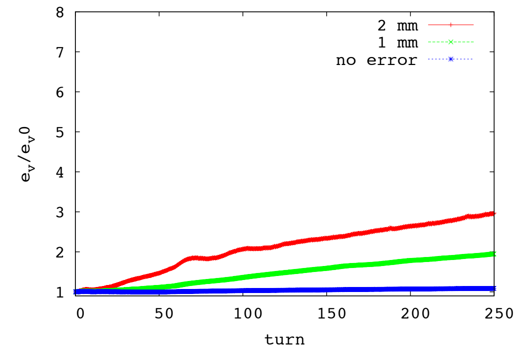

Figure 1: Simulation results of emittance growth as a function of turn using Simpsons. Only space charge effects are included. Legend indicates magnitude of misalignment error.

Modelling using MAUS and OPAL

Further code development and modelling effort has been made for the ERIT ring using both MAUS [5] and OPAL [6].

MAUS is a general particle physics analysis package with routines for modelling particle accelerators and reconstructing particle detectors, designed for the Muon Ionisation Cooling Experiment. Tracking and physics processes are provided by GEANT4 [7]. OPAL is an accelerator physics package designed for modelling cyclotrons, linacs and other accelerators.

A new routine was implemented in both MAUS and OPAL to read in 3D magnetic field maps in a sector geometry. Field values off grid points are found by linear interpolation in each dimension. Further discussion of extensions to OPAL can be found in [8].

The stability of tracking about the closed orbit has been studied. Both codes use 4th order Runge-Kutta as the default integrator for tracking, although other steppers are available. A step size of 10 mm in GEANT4 was found to yield a closed orbit distortion of 0.04 mm over 600 turns. A step size of 5 mm in OPAL was found to yield a closed orbit distortion of 0.01 mm over 300 turns. This is considered to be sufficient for tracking.

Physics Process Model in MAUS Modelling of physics processes is important in ERIT. The effects of Beryllium and Carbon foils has been studied on 11 MeV protons using the GEANT4 QGSP model.

The stopping power (energy lost per length per density) of each material is shown in Fig. 2. In this energy regime, mean energy loss can be estimated by the Bethe-Bloch formula with errors at the few % level [9]. GEANT4 QGSP model gives a mean stopping power in Carbon of 34.0 MeV cm^2/g compared to 37.6 MeV cm^2/g estimated by the

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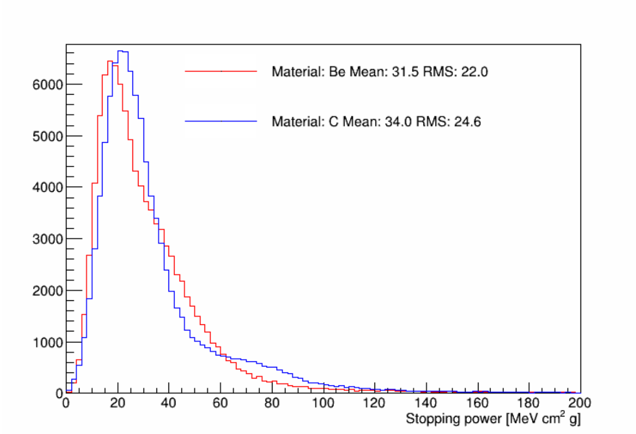

Figure 2: Stopping power of 11 MeV protons in Beryllium and Carbon.

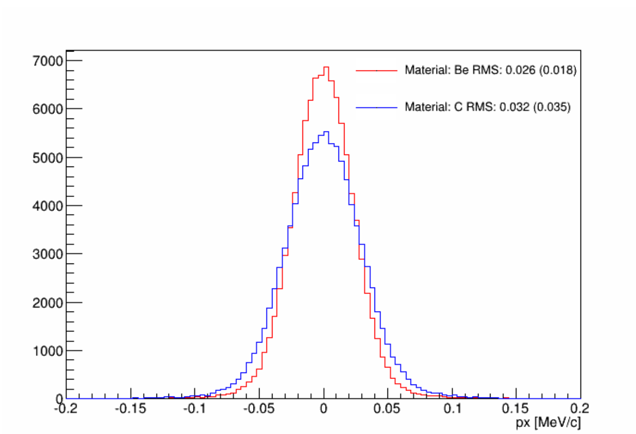

Figure 3: Scattering of 11 MeV protons in Beryllium and Carbon. The RMS scatter is listed in the legend together with expected RMS scatter in parentheses.

Bethe-Bloch formula, and 31.5 MeV cm^2/g compared to 34.9 MeV cm^2/g for Beryllium. It is also noted that the energy loss distribution in Carbon, expected to be a Landau distribution, has a pronounced bump in the tail. The origin is not clear.

In GEANT4.9.2 the QGSP model uses the Lewis model for multiple Coulomb scattering (MCS). The foils considered here are sufficiently thin that the MCS model may not be a good approximation for transverse scattering in the material. Nonetheless, we make a comparison between the GEANT4 model and the standard semi-analytical formula for MCS given by [9], as shown in Fig. 3. GEANT4 overestimates the scattering in Beryllium by some 20-30% and underestimates the scattering in Carbon by some 10% as compared to the standard formula.

Beam emittance growth due to Foil Scattering The effect of foil scattering in a Carbon foil has been modelled in MAUS and the results are shown in Fig.4. A beam was simulated with an initial geometric emittance of 8 microns

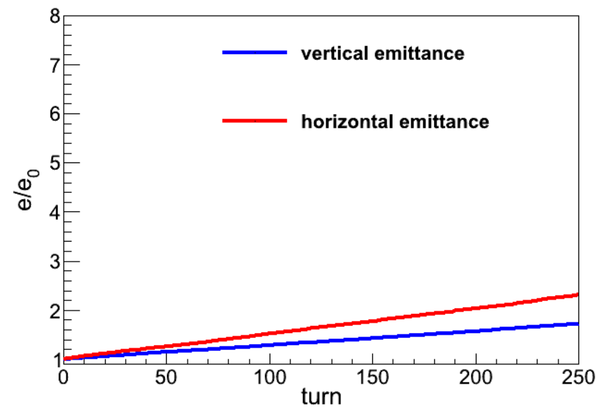

Figure 4: Geomtric emittance growth in x and y due to scattering as simulated in Geant4.

and allowed to coast through the ring for 250 turns. A mean energy loss of 0.18 MeV was observed and the beam moved transversely through 7 mm.

DISCUSSION

Initial simulations using Simpsons indicate that careful measurements will be required to distinguish between foil scattering emittance growth and that due to space charge. The extension of OPAL to incorporate 3D field maps along with the foil scattering modelling in MAUS will be utilised to make these more detailed simulations.

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ISBN 978-3-95450-128-1