MODELLING OF THE EMMA ns-FFAG RING USING GPT

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Abstract

EMMA (Electron Machine with Many Applications) is a prototype non-scaling Fixed-Field Alternating Gradient (ns-FFAG) accelerator whose construction at Daresbury Laboratory, UK, was completed in the autumn of 2010. The energy recovery linac ALICE [1] will serve as an injector for EMMA, within an energy range of 10 to 20 MeV. The injection line consists of a symmetric 30° dogleg to extract the beam from ALICE, a matching section and a tomography section for transverse emittance measurements. This is followed by a transport section to the injection point of the EMMA ring. The ring is composed of 42 cells, each containing one focusing and one defocusing quadrupole. Commissioning of the EMMA ring started in late 2010.

A number of different injection energy and bunch charge configurations are planned; for some the effects of spacecharge may be significant. It is therefore necessary to model the electron beam transport in the injection line and ring using a code capable of both calculating the effect of and compensating for space-charge. Therefore the General Particle Tracer (GPT) code [2] has been used. A range of injection beam parameters have been modelled for comparison with experimental results.

INTRODUCTION

Commissioning of the EMMA ring (the world's first ns-FFAG) commenced in Autumn of 2010. The energy recovery linac ALICE acts as the injector for EMMA, providing single bunches of electrons at an energy between 10 to 20 MeV with a maximum bunch charge of 32 pC. A schematic of the EMMA ring is shown in Fig. 1, highlighting some of the important diagnostic components of the beamline.

The beam injected from ALICE into EMMA is at quite a low energy there may be significant space-charge emittance growth, depending on the input conditions. Therefore rigorous analysis of the effects of space-charge is necessary. Consequently the particle tracking software used must incorporate the ability to model the effects of space-charge; thus GPT was chosen. This paper is an account of the GPT modelling of the EMMA ring using and including the effect of space-charge, for a range of injection parameters.

THE EMMA RING

Modelling in MAD and GPT

MAD [3] (Methodical Accelerator Design) is an analyti-

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Figure 1: The EMMA ring, with a circumference of 16.57 m

cal program designed to model accelerators using a transfer matrix method and, as such, ignores space-charge. The initial modelling of the EMMA ring was conducted using MAD, with an example of the output produced in Fig. 3. This shows the beta functions obtained in both transverse planes in the first magnetic cell downstream of the EMMA injection septum. A schematic of such a magnetic cell can be seen in Fig. 2.



Figure 2: A schematic of a few magnetic cells, which comprise the EMMA ring.

One revolution of the ring was then modelled in GPT for Beam Dynamics and EM Fields Dynamics 05: Code Development and Simulation Techniques comparison with MAD, transporting a beam of 10 MeV (as well as a nominal bunch charge of 0 pC) with the same initial transverse beam parameters as was used for the MAD modelling. In addition the bunch was initiated with a uniform energy and finite length for ease of computation. The 42 magnetic cells of the ring were modelled in GPT using the repeated input of a single field-map of one magnetic cell. This magnetic field was then held constant, allowing for optimisation of the initial beam parameters to achieve a closed orbit solution. The beam is expected to complete several revolutions of the machine. The constraints, therefore, are required to be extremely specific across one full turn in order to minimise an increase in beam-size across many turns.

Fig. 3 shows $\beta_{x,y}$ for the first magnetic cell of EMMA, as produced by MAD and GPT (without space-charge). The difference in the x-axis is accounted for by variations in the composition of the magnetic cells: the quadrupole pair appears after the initial drift length in the MAD model, but before in the GPT model. There are also subtle differences in the initial parameters of the beam. These are justified by the difference between the hard edged magnetic model employed by MAD and the magnetic field-map method of GPT.

Space-charge in GPT

The optimisation of beam parameters initially performed in GPT was for a bunch charge of 0 pC with the full 3D space-charge function enabled. Within a drift-length, space-charge is locally equivalent to a quadrupole field, defocusing in both the x- and y-planes. Thus space-charge directly affects the beam-size such that the transverse beam emittance evolves according to

$$\epsilon_x = \epsilon_{x_0} \sqrt{1 + \beta_{x_0}^2 \left[\left\langle \frac{1}{F_x^2} \right\rangle - \left\langle \frac{1}{F_x} \right\rangle^2 \right]}, \qquad (1)$$

(for a Gaussian beam only) where ϵ_{x_0} and β_{x_0} are the initial emittance and beta function respectively, and F_x is the focal length of the bunch (with a similar expression for the vertical plane) [4]. As the EMMA ring consists of drift lengths and quadrupole doublets this approximation may not hold for the entire ring; another reason why spacecharge calculations are crucial to an accurate model. Due to our interest in this beam blow-up we also consider the transverse beam-size as opposed to $\beta_{x,y}$.

The results of Fig. 2 were then recalculated for two different bunch charges within the range that may be injected into EMMA from ALICE: 16 and 30 pC. The effect of the inclusion of bunch charge can be seen in Fig. 4, where the transverse planes have been separated for clarity. The initial beam parameters of the model without space-charge have not been re-optimised for each bunch charge.

The results displayed in Fig. 4 are again for the first magnetic cell of the ring but after one complete revolution of the machine. It can be seen that increasing the bunch charge



EMMA - baseline lattice

Figure 3: Beta functions, $\beta_{x,y}$, for the first magnetic cell of the EMMA ring, as modelled by a) MAD and b) GPT.

corresponds to an increase in beam-size in both transverse planes. The effects, however, are more prominent in the xplane. As the beam is expected to complete many turns of the machine the effects of space-charge will have to be compensated for to avoid beam blow-up. The desired beam-sizes may be achieved expediently during data taking through modest quadrupole strength adjustments.

Fig. 5 expands upon the σ_y plot of the first cell from Fig. 4. This demonstrates the effect of space-charge on beamsize across the first 21 cells of the the ring. One solution to this would be to rematch the line for each different injected bunch charge, such as in [5]. However, as the YAG screens (designed to analyse transverse emittance) are positioned between quadrupole doublets, where the beam-size values are equivalent, it may be possible to vary other beam parameters rather than rematching the quadrupoles for each different bunch charge.

In this analysis the beam is given a Gaussian one sigma bunch length of ~ 4 ps, however a longer bunch length would reduce space-charge effects as the total charge of the bunch would be extended over a larger physical volume. Similarly the beam substantiated in the GPT model

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Figure 4: Beam-size in the a) x- and b) y- plane for the first cell of a second turn of the EMMA ring, detailing a range of bunch charges with a spread of 0 to 32 pC.

has an energy of 10 MeV - in the middle of the injection energy range - where the effects of space-charge will be more profound than at higher energies.

FUTURE WORK

The next step is to repeat the analysis while varying other beam parameters such as bunch length, emittance, and energy, to highlight the necessity of rematching the quadrupole values for differing bunch charges. If the impact of space-charge on beam-size is as acute as demonstrated in this paper then a model will have to be created for multiple turns. In some cases the number of revolutions traversed by the beam may be upwards of 100 turns.

Installation of the EMMA ring and injection/extraction line is now complete. Initial data has already been taken with preliminary results shown in [6]. In parallel to further collection and analysis of the data from the EMMA injection line and ring, measurements in the EMMA extraction line will begin in April 2011. Further work also includes time of flight and tune analysis. Data from the entire machine will then be compared to further GPT simulations.



Figure 5: Beam-size in the *y*-plane, demonstrating the effect of a range of bunch charges on half of a full revolution of the EMMA ring.

CONCLUSIONS

The modelling of the EMMA ring in both MAD and GPT has been compared, with the effect of space-charge on beam-size at 10 MeV demonstrated. Further work, such as rematching the initial parameters in GPT to attempt to eliminate the effect of space-charge, has to be verified.

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