SPACE CHARGE STUDIES OF A 1 GeV ISOCHRONOUS NON-SCALING FFAG PROTON DRIVER*

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Abstract

The production of very high power proton drivers in the 10 MW range is a considerable challenge to the accelerator community. Non-scaling FFAGs have gained interest in this field, as they may be able to provide smaller, cheaper accelerators than existing options. The recent development of an isochronous non-scaling FFAG is a promising advance, but must be shown to have stable beam dynamics in the presence of space charge. Simulations of this design are presented and the implications for future space charge studies discussed.

INTRODUCTION

Non-scaling FFAGs are a promising candidate for a compact, reliable high-power source of protons for various applications. One proposed application is for their use as a proton driver for ADSR, which would require a 10 MW beam, most likely a beam of 10 mA at 1 GeV [1].

To date, there has been little work on the effects of space charge in FFAGs, and that which has been done has assumed pulsed operation, which results in a peak current of 30 A in order to achieve an average current of 10 mA [2]. Such a large peak current would result in an unacceptable space-charge tune shift. In fact, in the 30-cell design studied in Ref. [2], at an injection energy of 35 MeV with an emittance of 100 π mm mrad the maximum acceptable tune shift of around 0.25 occurs at a peak current of 2 A, a factor of 15 below the requirement.

The development of a truly isochronous non-scaling FFAG would make CW operation conceivable, employing both fixed radio-frequency acceleration and a fixed magnetic field. This could allow very intense beams to be accelerated in the FFAG with a current requirement two to three orders of magnitude lower than in the pulsed case, the limit being imposed by longitudinal acceptance, rather than repetition rate.

The lattice design considered here consists of four triplet cells with long drift sections of approximately 2 m. The design incorporates wedge-shaped magnets with a radial magnetic field dependence in order to produce stable tunes and isochronous behaviour to within $\pm 3\%$. Originally proposed by C. Johnstone [3, 4], the transverse dynamics have been recently verified using an accurate tracking code [5].

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SIMULATIONS

Few simulation codes are able to incorporate the non-linear magnetic field of this type of FFAG with detailed space-charge calculations. The OPAL 'Object-Oriented Parallel Accelerator Library' Framework developed at PSI for cyclotrons [6] incorporates both of these abilities, and is flexible in lattice definition by reading in magnetic field maps in polar co-ordinates. This code has the added feature of being able to deal with the interaction between subsequent orbits in a compact CW accelerator [7], which may be necessary in this FFAG design.

The original magnetic field map produced from the machine design in [3, 4] was read in using OPAL. First, the basic dynamics were confirmed without space-charge, including a study of the longitudinal dynamics. An example of multi-particle tracking of a 10 mA beam with and without space charge is then presented.

Single Particle Tracking

Transverse dynamics In order to establish closed orbits in the lattice using OPAL, a python-based closed orbit finder was created which minimises the phase space area traced out by particles tracked over a number of turns. The variation in radial closed orbit position throughout acceleration in energy steps of 50 MeV is shown in Fig. 1.

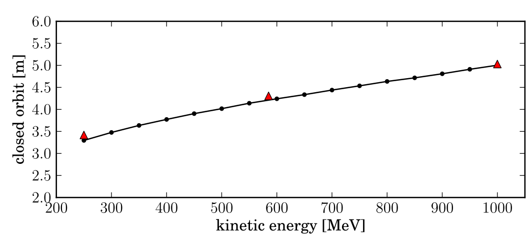

Figure 1: Variation of the closed orbit with energy established using OPAL (black), compared to the original COSY Infinity results (red markers).

After establishing closed orbits, a suitable RF frequency for longitudinal dynamics studies is found by calculating the variation in time-of-flight per turn throughout acceleration using particle tracking. This also confirms the quasi-isochronous behaviour of the lattice design. The time-of-flight per turn at 50 MeV intervals throughout acceleration is shown in Fig. 2. The cause of the slight variation from the expected parabolic shape at 550 MeV and 800 MeV is not known exactly, but is thought to arise from the interpolation between radial points in the field map, as the radial granularity in the finest map available was 50 mm. (Note that the map extends radially from 2500 to 6300 mm). The general shape of the curve matches that produced in both COSY Infinity and ZGOUBI [3, 5].

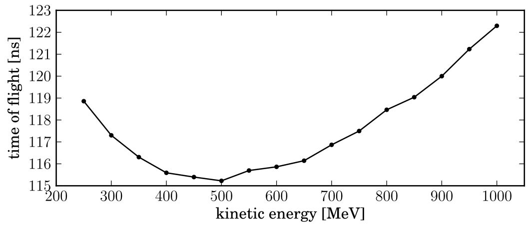

Figure 2: Variation of the time-of-flight per turn with energy established using OPAL.

Longitudinal dynamics One important unknown in this design has been whether the lattice is sufficiently isochronous to be able to accelerate with fixed-frequency RF. Studies were undertaken in OPAL using a single RF cavity halfway around the ring, with a constant radial voltage profile over the full radial extent of the particle orbits.

The initial assumption in this design was that it would be possible to do "phase-slip" acceleration similar to that in a cyclotron, where the particle is placed slightly off-crest and the phase-slip due to the time-of-flight variation is small enough to ensure that the particle stays at an accelerating phase for sufficient time to cover the energy range. However, tracking results have revealed that the turn-by-turn phase slip was too large for this mode of operation, so that the particle simply oscillates from accelerating to decelerating phases and therefore oscillates up and down over a small energy range.

Another mode of acceleration is possible in a non-scaling FFAG where the variation in the time-of-flight is parabolic with energy; the non-linear acceleration mechanism in the the so-called "serpentine channel" [8], recently demonstrated in the EMMA experiment [9]. For a perfectly parabolic time-of-flight curve, the optimal frequency for operation in the serpentine channel over the required energy range is given by Equation 1, where T_{min} is the minimum time-of-flight and δT is the difference between the maximum and minimum time-of-flight. This sets a frequency of $f_{RF} = 8.547$ MHz for the first harmonic to be used for simulations.

$$f_{RF} = \frac{1}{T_{min} + \delta T/4} \qquad (1)$$

$$\delta E = \frac{\omega\, \delta T\, \Delta E}{16} \qquad (2)$$

The required energy gain per turn to open up the serpentine channel (δE) can then be estimated by Equation 2, in which the total energy gain required is ΔE and $\omega = 2\pi f_{RF}$. In this case, we expect δE to correspond to a voltage of 18 MV/turn.

In tracking simulations the voltage is actually lower (about 12 MV/turn) for a serpentine channel to appear which allows acceleration up to around 900 MeV. This is because the time-of-flight curve is not perfectly parabolic and the value of δT is lower in the smaller acceleration range. Tracking results showing the phase space traced out by single particles starting with a range of initial phases are shown in Fig. 3.

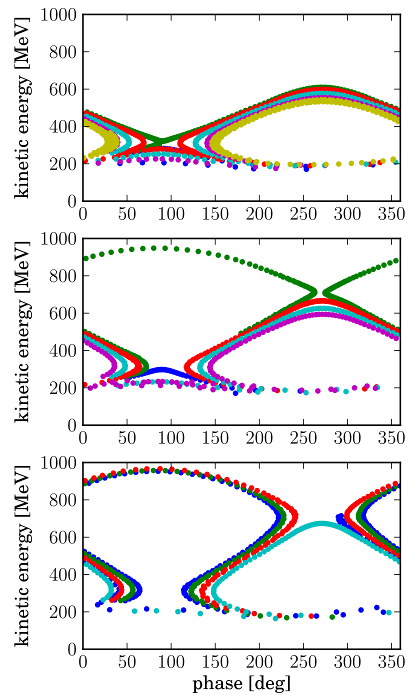

Figure 3: Longitudinal phase space (upper) with 10 MV/turn, an insufficient accelerating voltage to open a serpentine channel, (middle) with 12 MV/turn, a sufficient voltage for a serpentine channel less than 1° wide and (lower) with 15 MV/turn, for a serpentine channel with a 20° width.

The required accelerating voltage for serpentine acceleration is too high to be considered feasible in this application. Given the availability of four 2 m drift sections, a maximum of two would be available for acceleration, as the other two would have to incorporate injection, extraction, vacuum ports and diagnostics. This would limit the achievable accelerating voltage to a maximum of between 2 and 4 MV/turn if large aperture normal-conducting cavities are employed.

Multi-particle Tracking

The direct space charge tune shift assuming a uniform, unbunched round beam in a synchrotron can be calculated by the simple expression in Equation 3. For a 10 mA beam at injection with a normalised emittance of 10 π mm mrad, the expected tune shift is -0.0023, rising to -0.023 for a transverse emittance of 1 π mm mrad. This is only a small tune shift, but this basic estimate does not include image effects which are expected to play in important role since the injection energy in an FFAG corresponds to a position near the inner radius of the beam pipe.

$$\Delta Q_{x,y} = \frac{-r_0 N}{2\pi\epsilon_{x,y}\beta^2\gamma^3} \quad (3)$$

To simulate this space charge tune shift requires a number of post-processing tools that are not currently available in OPAL. These tools are being developed at present to aid future work on the effect of space charge in non-scaling FFAGs.

As an example of the effect of space charge during particle tracking in OPAL, a 10 mA round beam with transverse normalised emittance of 10π mm mrad containing 10,000 macroparticles which uniformly fill a 4D hyper-ellipsoid in phase space (a 'waterbag' distribution) is tracked at injection over ten turns without acceleration. The bunch has a longitudinal emittance of 1π mm mrad. The horizontal phase space evolution per turn is shown with and without space charge in Fig. 4. The space charge effects are severe due to the very short bunch length used.

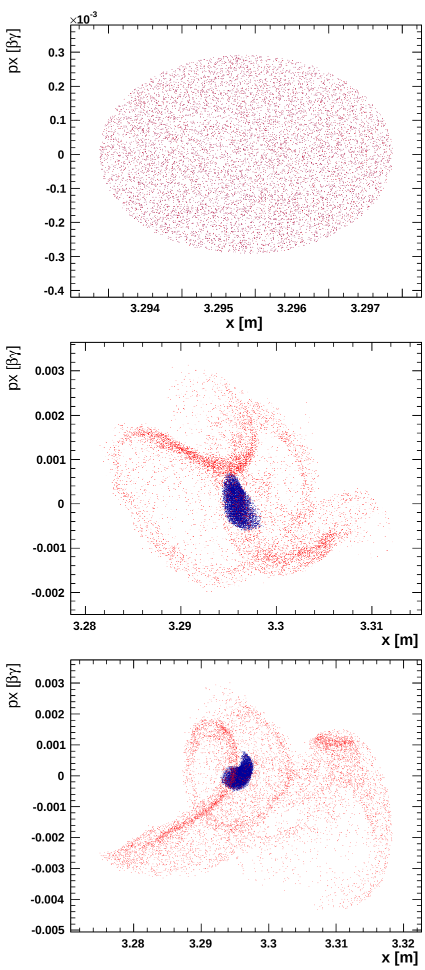

Figure 4: Example of tracking in OPAL with and without space charge for a 10 mA beam with 10π mm mrad normalised transverse emittance.

DISCUSSION

Longitudinal studies of this ns-FFAG lattice design have established that isochronicity needs to be improved in order to accelerate using fixed radio-frequency cavities. If phase-slip acceleration is employed the isochronicity will need to be improved dramatically, and if serpentine acceleration is employed an improvement of at least a factor of three is required. Presently, the required acceleration voltage is at least 12 MV per turn, which is not feasible in such a compact machine. A machine optimisation may be able to achieve the required isochronicity, but this could come at the expense of the current control over the betatron tunes, and may result in the of one or two major resonances. Such a compromise would have to be explored with detailed simulations including space charge to assess it's practicality. Detailed space charge simulations including those over a full acceleration cycle are an item of future work once the lattice design has been optimised and statistical tools developed for OPAL.

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