HIGH CURRENT PROTON FFAG ACCELERATORS

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Abstract

Accelerator Driven Subcritical Reactors (ADSR) require a high current of energetic protons. We compute the limits imposed by space charge, and explore what can be achieved using a proposed Fixed Field Alternating Gradient (FFAG) lattices. Limitations due to beam losses and reliability are also discussed.

INTRODUCTION

FFAG accelerators have been proposed for use as the proton drivers for ADSRs. The proton beam is used to produce neutrons, by spallation, which cause fission in the reactor core. In order to achieve a 600 MW electrical output, it is estimated that a 10 MW proton beam will be needed. A suggested beam is 10 mA at 1 GeV [1]. At this high current, effects such as space charge will need to be taken into account.

SPACE CHARGE

In a bunch of same-charge particles, each will feel a repulsive Coulomb force from the others. The more intense the bunch, the stronger the force. This will tend to cause the bunch to expand, giving an accelerator lattice larger beta functions. This is known as space charge.

Space charge is suppressed at high energies due to relativity. Therefore it will be most problematic during the start of the acceleration cycle.

Linear transverse space charge

A full n-body simulation is very time consuming, so it is useful to start with approximate models. By assuming that the bunch has a circular cross-section and a uniform density, the force on each particle can be computed from the bunch width and the particles distance from the centre [2]. The electric field in x is,

$$E_x = \frac{Nqx}{2\pi\epsilon_0 a^2} \quad \mathrm{NC}^{-1} \tag{1}$$

where N is the number of particles, q the charge per particle, and a the bunch width. For an elliptical bunch with the major and minor axes a and b, this becomes,

$$E_x = \frac{Nqx}{2\pi\epsilon_0 a(a+b)} \quad \mathrm{NC}^{-1} \tag{2}$$

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From this the equation of motion is found to be,

$$x'' + k(s)x = \frac{q}{m_0\gamma^3\beta^2c^2}E_x \tag{3}$$

where $k(s)$ is the quadrupole along the lattice, m_0 is the mass and γ and β are the relativistic factors.

SIMULATION METHOD

Simulations were carried out using Zgoubi [3]. Zgoubi is commonly used for FFAG studies as it can model non-standard magnets and track particles far from the magnet centres or reference orbits. The PyZgoubi interface allows additional algorithms to be added. Each magnet was split into slices, the particles where tracked through the slice, and then the space charge kick was applied using equation 3, before tracking through the next slice.

Benchmarking

Zgoubi was benchmarked against an existing space charge code KVBL [4] using a synchrotron lattice from JAERI. Figures 1 and 2 show the agreement between the simulations.

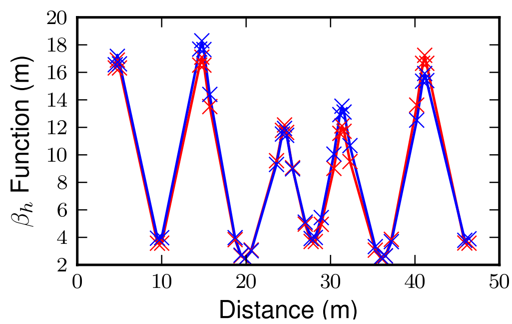

Figure 1: Beta functions. Red shows space charge off, blue on. Lines are KVBL and Xs are Zgoubi

SIMPLE FFAG LATTICE

The accelerator for an ADSR operates in a relativistic regime where the speed changes considerably. If the orbit shift is kept small, the revolution frequency will change. The length of the acceleration cycle, and therefore the repetition rate, will be limited by the time taken to sweep the RF cavity.

This pulsed operation means that the peak current will be higher than the average current. A single FFAG achieving 10 mA average current with 1000 lap acceleration cycle, and 120° (one third) fill, would have a peak of 30 A.

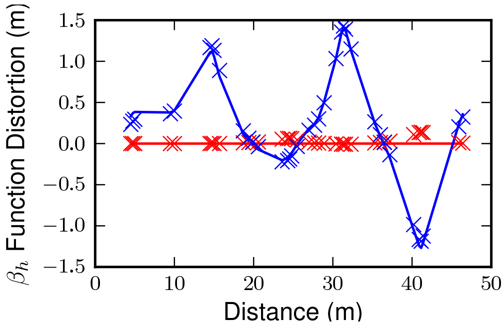

Figure 2: Beta function distortion. Red shows space charge off, blue on. Lines are KVBL and Xs are Zgoubi

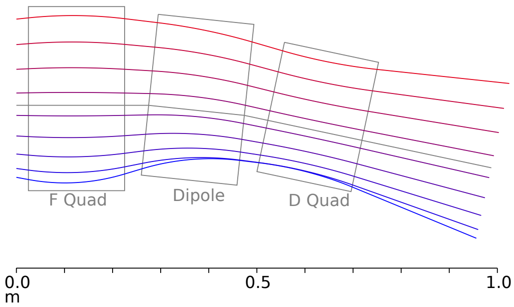

Figure 3: Closed obits through lattice cell

Figure 3 shows a non-scaling FFAG (nsFFAG) cell composed of focusing and defocusing quadrupoles and a dipole. The full ring is composed of 30 of these cells. This cell is designed to hold beams from 35 to 400 MeV, but space charge simulations were only run at the injection energy, where the effect is largest.

The space charge force depends on the beam size, and so on the emittance of the bunch. Figures 4 and 5 show how the beta function increases for currents 0 (black) through 0.5, 1, 2, 5, 10 to 30 A (blue).

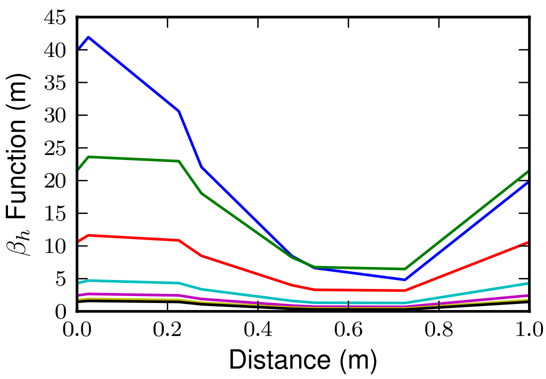

Figure 4: Beta functions at 1 mm mrad

It is clear that the distortion is much larger for the low emittance beam. It can also be seen that the 30 A line at 1 mm mrad is not closed: that is, a matched beam could not be achieved.

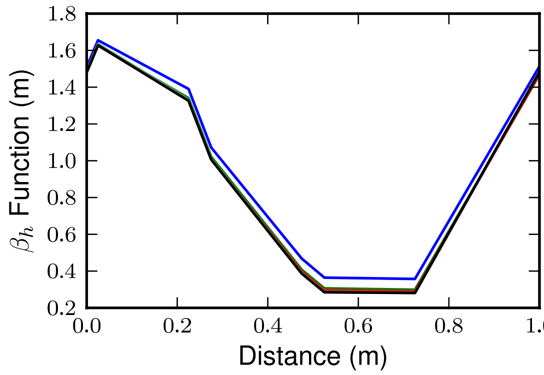

Figure 5: Beta functions at 100 mm mrad

Table 1: Horizontal Cell tunes

Current (A)	Emittance (mm mmrad) 1	5	10	50	100
0.0	0.321	0.321	0.321	0.321	0.322
0.5	0.207	0.300	0.310	0.319	0.321
1.0	0.138	0.276	0.300	0.317	0.320
2.0	0.076	0.233	0.279	0.313	0.318
5.0	0.031	0.138	0.219	0.301	0.313
10.0	0.015	0.076	0.139	0.281	0.303
30.0	0.610*	0.614*	0.527*	0.208	0.264

Table 2: Vertical Cell tunes

Current (A)	Emittance (mm mmrad) 1	5	10	50	100
0.0	0.475	0.475	0.476	0.476	0.476
0.5	0.342	0.449	0.462	0.473	0.475
1.0	0.265	0.424	0.450	0.471	0.473
2.0	0.181	0.386	0.428	0.466	0.471
5.0	0.098	0.266	0.383	0.452	0.464
10.0	0.075	0.185	0.267	0.431	0.454
30.0	0.331*	0.290*	0.217	0.383	0.420

It is not just the beta function that is affected. The tune is also depressed, due to defocusing force. Tables 1 and 2 show how the cell tunes change for various emittance and current values. Note that for some of the high current values the tune has wrapped, and is not a stable value. These bad values are marked with '*'.

In a synchrotron the space charge lattice tune shift must be kept below 0.25 to avoid crossing resonances. This limit is approximately 0.008 per cell for a 30 cell design. As can be seen, this limit is passed by 2 A for the 100 mm mrad case, and earlier for smaller emittances.

For a system with rapid acceleration it may be possible to cross resonances fast enough that they do not cause beam blow up. This is an aim of nsFFAG acceleration.

The physical beam width,

$$\sigma = \sqrt{\beta\epsilon} \quad (4)$$

is a function of both beta function and emittance, ϵ. Table 3 shows the maximum beam widths. For the low emittance beams an increase in current cause an increase in beam size. For large emittances the beam size is less effected by current.

Table 3: Horizontal beam width (mm)

Current (A)	Emittance (mm mmrad)				
	1	5	10	50	100
0.0	1.266	2.836	4.013	8.864	12.760
0.5	1.376	2.826	4.016	9.001	12.773
1.0	1.632	2.853	3.998	8.971	12.770
2.0	2.170	2.946	4.022	8.971	12.787
5.0	3.410	3.646	4.239	8.954	12.758
10.0	4.860	4.851	5.155	8.996	12.751
30.0	6.475	7.112	7.928	9.664	12.865

RELIABILITY

To avoid thermal stress on the spallation target, the proton beam must be continuous. Gaps in the beam of the order of a second are likely to be problematic if they occur more than a few times per year (there are a range of values quoted in the literature). This requires very much higher reliability than is normally achieved with accelerators.

Even so, complex pieces of technology are manufactured to run reliably and there is no reason why an accelerator should not be as reliable as a radio set.

To achieve a high system availability the mean time between failure (MTBF) must be kept high, and mean time to repair (MTTR) low.

To improve MTBF: components can be underrated from their design specification; a strict maintenance routine can be used, ensuring that components are removed before they fail.

To reduce MTTR: one can have spares of critical parts on site, and the machine designed so that components can be quickly swapped.

One can also use redundancy, so that a component failure does not result in a system failure. However, a thorough understanding of the accelerator system is needed in order to ensure that these measures, which increase cost, are taken only where they are useful.

Having several complete accelerators would give redundancy and also reduce the current requirements for each of them.

BEAM LOSS

Loss of protons from the beam in to the accelerator components will cause radioactivation. This would prevent humans entering the accelerator area even when the beam was off, hindering maintenance. In order to reduce activation beam loss must be minimised.

The ISIS proton synchrotron runs with an average beam loss rate of $\approx$6 W/m [5], from a 0.2 MW beam. However beam loss of $\approx$1 W/m is also commonly quoted as a safe limit. As beam loss tends to be concentrated in specific areas, for example injection regions, so detailed loss simulations may be more useful than averages.

For a 10 MW beam the loss fraction will need to be very low in order to stay within safe limits.

Activation from injection losses may be reduced by having a lower injection energy. However raising the injection energy would reduce space charge effects.

CONCLUSION

There are still challenges to be overcome in order to design an FFAG to accelerate a 10 mA beam. Parameters must be found to minimise space charge effects, and non-linear effects must be simulated. A good understanding of component reliability and beam loss is also needed.

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