

**6D ACCELERATION STUDIES IN PROTON FIXED FIELD  
ALTERNATING GRADIENT ACCELERATOR LATTICES**

S. Tygier, R.J. Barlow, H. Owen.  
Cockcroft Institute and University of Manchester, UK

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## Abstract

It has been proposed to use a proton Fixed Field Alternating Gradient (FFAG) accelerator to drive an Accelerator Driven Subcritical Reactor (ADSR) as they have the potential to provide high current beams at the energies needed - 500 MeV to 1 GeV. This paper describes the results of 6D simulations of acceleration in possible lattice designs to explore longitudinal acceptance. This is needed to evaluate accelerator duty cycle and options for acceleration such as harmonic number jumping.

## INTRODUCTION

### ADSR

Accelerator Driven Subcritical Reactors (ADSRs) are a novel design of nuclear fission reactor. A traditional reactor for power generation operates with the effective neutron multiplication factor,  $k$ , very close to unity: each fission releases neutrons that causes on average one further fission. In a subcritical reactor,  $k$  is less than one and the reaction is not self sustaining. The principle of an ADSR is to drive the reaction by external means.

Carlo Rubbia proposed a design which he called the Energy Amplifier[1]. The design consists of a high-intensity proton beam incident on a spallation source, producing a flux of neutrons. These neutrons cause fission in the fuel and secondary neutrons cause further fissions, sustaining heat output. The heat produced can be used to generate electricity as in a conventional fission reactor, some of which (perhaps 10 percent) is used to power the accelerator that produces the initial beam.

The subcritical nature of ADSRs is an inherent safety feature. The reaction cannot run away, and will not continue without the drive beam. It is possible to fuel ADSRs with thorium, which is four times as abundant in the Earth's crust than uranium.

The optimal proton beam energy for spallation process in an ADSR is between 500 MeV and 1 GeV. For an industrial power station with 600 MW electrical output, it is expected that a 10 MW beam would be needed. This could be for example 20 mA at 500 MeV, or 10 mA at 1 GeV.

### FFAG

Fixed Field Alternating Gradient accelerators may be able to provide the high current beam that ADSRs require. FFAGs similarities to both cyclotrons and synchrotrons. It

has a fixed magnetic field (with respect to time) like a cyclotron, but has alternating-gradient strong focusing like a synchrotron. During acceleration an injected particle's orbit moves progressively outwards to regions of higher field. Scaling FFAGs have a radial field variation that preserves tune with energy, to avoid resonance crossing. Non-scaling FFAGs (NS-FFAG) allow the tune to vary, and can have smaller orbit shift with energy.

The first non-scaling FFAG, EMMA [2], is currently being built at the Daresbury Laboratory in the UK. It will accelerate electrons from 10 to 20 MeV, and be used to confirm that fast resonance crossing works as simulations predict.

## A PROTON LATTICE

We consider a lattice for a possible NS-FFAG proton driver, in which a 70 MeV cyclotron is used as the injector, and the beam is accelerated in the FFAG to 500 MeV. Proton velocity in the FFAG therefore changes from a relativistic  $\beta$  of 0.37 to 0.76. As the change of path length with frequency is very small, the revolution frequency will change by about a factor of 2. Bunches must therefore be accelerated by sweeping the RF frequency, and it is assumed in this paper an RF cavity can sweep quickly enough over the required range.

Sweeping the RF prevents the accelerator being used in continuous (CW) mode like a cyclotron, as the machine state varies with time. This will limit the duty factor, and hence the average current of the machine. To understand this limit one needs to know the acceptance of the RF buckets, and how many buckets can be filled per cycle.

## LATTICE

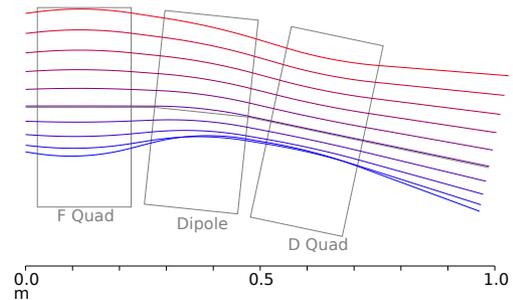


Figure 1: FFAG cell.

We consider a simple FFAG ring with 30 FODO cells each of length 1 m. Each cell (shown in Fig. 1) consists of

\* roger.barlow@manchester.ac.uk

a dipole, focusing quadrupole and defocusing quadrupole. All magnets are 0.2 m long with rectangular ends. The (constant) quadrupole gradients are 24.6 T/m so as to be stable for the lowest energy, and the dipole strength is 2.58 T so that the beam stays close to the magnet centres. Table 1 shows the machine parameters. Particle simulation was carried out using the Zgoubi [3] tracking code and python scripting.

Table 1: Machine Parameters

	Injection	Extraction
Energy (MeV)	70	500
$\beta$	0.37	0.76
Path length (m)	29.93	31.33
Frequency (MHz)	3.7	7.3
Harmonic number		1
Turns		1000
Sweep time (ms)		0.17
Mean gain per turn (kV)		430

## MODELLING

### Single Bunch Acceptance

Protons were launched into the ring every at 1 degree of RF phase over the first lap, at 70 MeV along the closed orbit for that energy. They were tracked for 1000 turns using an RF sweep from 3.7 to 7.3 MHz.

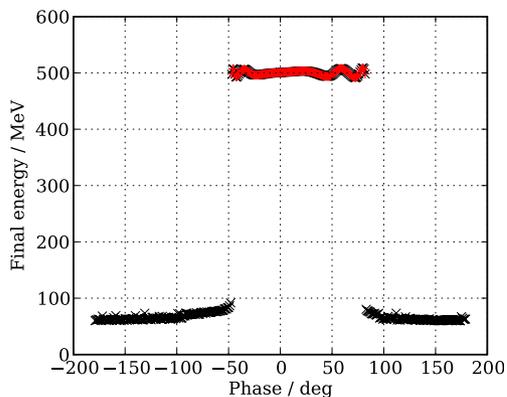


Figure 2: Energy after 1000 turns for range of launch phases.

Figure 2 shows the final energy of particles after 1000 turns for a variety of phases around the reference particle. Particles still in the same RF bucket as the reference are shown in red. The longitudinal acceptance is 130 degrees wide.

Figure 3 shows the particles in longitudinal phase space. Particles within the 130 degrees around the reference particle, from -47 to +82, are trapped, and oscillate in phase and energy similar to the motion in a synchrotron. Particles outside the longitudinal acceptance are progressively retarded in phase and energy.

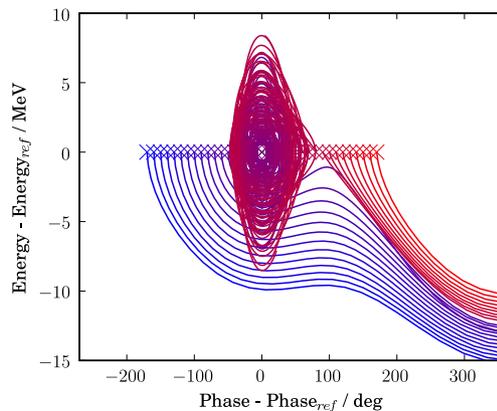


Figure 3: Longitudinal phase space over 1000 turns. Blue particles start earlier than the reference phase, whilst red particles start later. Starting positions are marked with an X.

### Second Turn Acceptance

To compare, we show a similar bunch launched with an initial energy still at 70 MeV, but now on the second turn. Note that by the second turn this bunch is not matched to the RF frequency, which has begun sweeping for the first bunch.

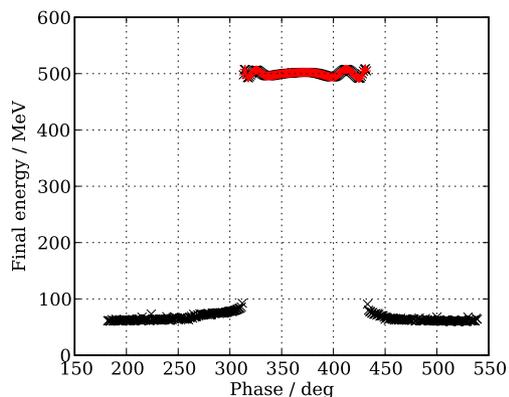


Figure 4: Energy after 1000 turns for range of launch phases on the second turn.

Figure 4 shows the final energy of particles after the remaining 999 turns. Particles still in the same bucket as the second turn reference particle are shown in red. The region of acceptance is 120 degrees wide (see Fig. 5).

### N Bunches

To investigate how the acceptance falls on successive turns, bunches were launched on each turn. Figure 6 shows the acceptance for successive injections, and which falls to zero after 7 turns. This means particles could be injected for 7 turns from the start of the RF sweep.

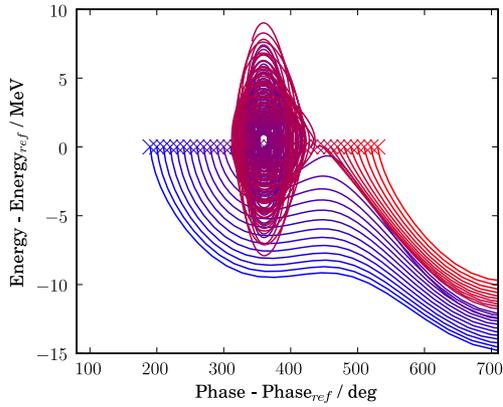


Figure 5: Longitudinal phase space over 1000 turns, for particles launched on the second lap.

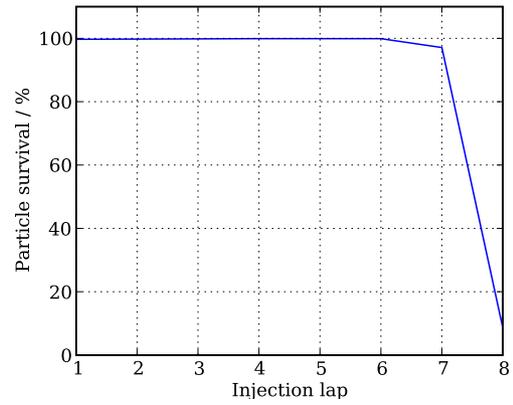


Figure 7: Survival of realistic bunches injected on successive turns.

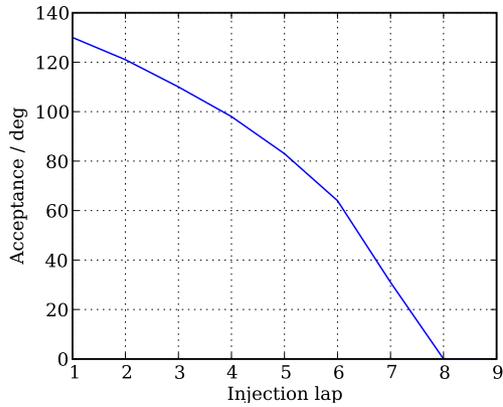


Figure 6: Longitudinal acceptance for injecting on successive turns.

## REFERENCES

- [1] C. Rubbia, *Conceptual design of a fast neutron operated high power energy amplifier*, CERN technical report, CERN-AT-95-44 ET, 1995.
- [2] R. Edgecock, et. al., *EMMA - the World's First Non-scaling FFAG*, EPAC 08 Proceedings, Genoa, Italy, THPP004, 2008.
- [3] F. Méot, *Zgoubi*, <http://sourceforge.net/projects/zgoubi>.
- [4] *List of Cyclotrons*, Proceedings of the 18<sup>th</sup> international conference on Cyclotrons, 2007.

## A Realistic Cyclotron Beam

To see the acceptance of this accelerator for realistic beams, we injected gaussian-distributed bunches with vertical and horizontal  $\sigma$  of  $\sqrt{\pi}$  mm and  $\sqrt{\pi}$  mrad, and  $\sqrt{0.01}$  % dE/E and  $\sqrt{10}$  degrees RF phase. These values are similar to those of the output beam of the PSI Injector 2 Cyclotron [4]. Figure 7 shows the survival of the realistic bunch injected on successive laps. For bunches injected on laps 1 to 6 the survival is above 99 %, on lap 7 it is 97.1 %.

## CONCLUSION

The FFAG lattice shown in this paper has a wide longitudinal acceptance, without any specific optimisation of the RF sweep or lattice. Simulations with a realistic injector output show that this should be possible, and that it is possible to continue injecting after the first turn even though the frequency sweep has begun. This would increase the duty factor by nearly an order of magnitude, in this case from 1/1000 to 7/1000.