The EMMA Non-Scaling FFAG Project:[1]
Implications for Intensity Frontier Accelerators

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Abstract. EMMA (Electron Model for Many Applications) is a proof-of-principle demonstration of a non-scaling, fixed-field, alternating gradient accelerator (nsFFAG). Although nsFFAGs are related to cyclotrons and scaling FFAGs, the normal requirement is broken that the orbit radius scales with beam energy at all azimuths, meaning that a large energy variation can be provided in a small magnet aperture at the expense of no longer having a constant betatron tune; this has the potential to reduce the cost, and increase the reliability and flexibility of future intensity-frontier accelerators. We present results of commissioning of this accelerator at Daresbury Laboratory and discuss its merits compared to alternative approaches to delivering high-intensity hadron beams, in particular for use as low-cost c. 1 GeV proton drivers for accelerator-driven subcritical reactors and for the DAEDALUS neutrino project.

Keywords: FFAG, cyclotron, neutrino beams, ADS
PACS: 29.20.dg,29.27.Bd,23.40.Bw,28.50.Ft,28.65.+a

CYCLOTRONS AND THEIR LIMITATIONS

Since its invention by Ernest Lawrence in 1931 [1], the cyclotron has undergone steady development in both extraction energy and beam power [2], culminating in the demonstration at the Paul Scherrer Institute's SINQ of over 1 MW continuous beam power in a 2.2 mA beam of 590 MeV protons. Whilst significant effort has been expended in achieving larger extracted beam energies and currents, to date SINQ remains the highest-power cyclotron in operation.

A number of alternative approaches have been proposed to allow cyclotrons to reach higher energies up to c. 1 GeV [3, 4], and to obtain powers up to 10 MW. Broadly speaking these can be divided according to the accelerated species: a summary is given in Table 1. Whilst the use H^+ allows a more convenient ion source, the extraction efficiency is limited by the turn separation that can be achieved at the extraction orbit, which leads to a large required acceleration per turn. This has been the approach adopted in SINQ [5], which achieves up to 2 MV per turn. Several higher-energy designs have been considered based on this approach, including the exotic superconducting TRITRON project [6].

If H^- ions are accelerated a stripping foil may be used to remove the single electron from the hydrogen ion, reversing the bend direction near the outer radius of the cyclotron, and allowing extraction at near 100% efficiency. This method has been successfully implemented on the TRIUMF cyclotron [3], and used at higher powers for efficient extraction from proton synchrotrons. However, the rather loosely-bound electron in the H^- ion may be removed during acceleration either by the Lorentz-transformed effect of the bending magnetic field (Lorentz stripping), or by the repeated passage through and collision with the residual gas within the vacuum vessel. Lorentz stripping is a threshold effect which limits the magnetic field at extraction (hence the very large circumference of the TRIUMF cyclotron to limit the extraction field to 0.4 T), whilst the gas stripping requires a trade-off between achievable residual gas pressure and a sufficiently-large acceleration per turn to limit the total accumulated path length during acceleration.

The use of H_2^+ ions may partly overcome the limitations in using H^- ions as the single electron in the H_2^+ ion is more tightly bound, allowing higher bending fields to be used. Stripping extraction results in two free protons each of half the original H_2^+ kinetic energy, which are then bent in the same direction but at half the extraction bending radius; an extraction channel is in principle possible which transports the extracted protons eventually through a gap between two sector magnets. Conceptual designs exist wherein superconducting dipole magnets provide for a compact extraction radius of 4.9 m, but gas stripping still requires a large acceleration per turn (using two types of radio frequency (RF)

[1] Work supported by Research Councils UK, Grant number EP/EO 32869/1
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TABLE 1. Comparison of high-power cyclotron options

Species	Advantages	Disadvantages
H^+	Simpler ion source	Poorer extraction efficiency
H^-	Stripping extraction	Lorentz & gas stripping
H_2^+	Stripping extraction	Lorentz & gas stripping; complex extraction path

structure) of 3.6 MeV/turn. Despite these issues, the H_2^+ approach is currently considered to be the most promising for the DAEδALUS neutrino project [7, 8, 9, 10].

ALTERNATIVES TO THE CYCLOTRON

The synchrotron has traditionally been seen as a way of overcoming the energy limitation of the cyclotron at the expense of a much lower pulse repetition rate (duty factor), and of course the synchrotron has thus dominated the design of high-energy physics facilities for many years, particularly in the guise of the storage ring which is not limited by the field variation rate required for acceleration. The rapid-cycling synchrotron is a recent development of dipole cycling rate to try to obtain comparable average currents to those of cyclotrons.

Fixed-field, alternating-gradient accelerators (FFAGs) were first considered in the 1950s as a method of achieving relativistic particle energies, and several electron models were constructed between 1956 and 1961 [11, 12]. Strong focusing is obtained from the gradients and edges of the discrete, fixed-field dipole magnets, selecting an appropriate total focusing strength to keep the betatron tunes in both planes away from resonant values during acceleration, and a so-called scaling optics adopted to keep the tunes roughly constant and therefore the orbit radius a monotonically-increasing function of energy; the variation of average dipole field with orbit radius should be $B \sim r^k$, where k is the average field index $k(r) = (r/B)dB/dr$. Development of proton FFAGs did not occur due to the difficulty of obtaining fast enough swept RF to keep up with the changing proton velocity.

Renewed interest in FFAGs has been prompted by the desire to rapidly accelerate unstable particles such as muons to enable muon colliders or neutrino factories based on muon storage rings [13, 14]. Several proton FFAGs have been constructed [15], but their scaling design requires large magnets with a complex variation of field with radius. These two issues limit the ratio of extracted to injected energies in scaling designs to three or less.

Mills and Johnstone suggested simply dispensing with scaling requirement, resulting in a non-scaling FFAG (nsFFAG) [13]. The field variation with radius may be reduced even to a simple linear form (i.e. quadrupole-like) whilst also reducing the range of radii for a given acceleration range; this allows the use of much smaller magnets and restricts the variation in orbit period so that fixed-frequency RF can be used. In simpler nsFFAG designs resonances must be crossed, but this can be done provided the acceleration rate is high enough. This was previously predicted in simulations [16, 17].

There are a number of potential applications of proton nsFFAGs in addition to their use to accelerate unstable particles. They have been proposed as a route to high-intensity (c. 10 MW) beam powers at intermediate energies (c. 1 GeV) for spallation neutron production, either for neutron science or to act as a driver for a accelerator-driven subcritical reactors (ADSRs) [18]. The fixed fields and rather smaller dipole magnets could give greater reliability at lower cost compared to cyclotrons, rapid-cycling synchrotrons, or linacs. Similarly, at low enough cost proton nsFFAGs could act as the pion production drivers in DAEδALUS [7], where up to ten accelerators are required each with 1 MW average beam power [8]. Finally, the flexible extraction energy offered by nsFFAGs, coupled to their high available repetition rate means that they are a promising route to high-energy and variable-energy energy proton/carbon accelerators for particle radiotherapy of tumours [19].

THE EMMA PROJECT

The EMMA project has sought to demonstrate fast resonance crossing, and therefore the feasibility of nsFFAGs, using a very compact 10.5-20.5 MeV/c electron model whose behaviour reflects the requirements of a muon accelerator. Constructed between 2008 and 2010 at Daresbury Laboratory, EMMA is a linear-magnet nsFFAG using 42 doublets of moveable quadrupoles to enable a variety of configurations to be studied; it uses the the ALICE accelerator as an injector. The design is described fully in an overview paper by Barlow et al. [20]; summary parameters are given in

TABLE 2. Principal EMMA parameters.

Momentum range	10.5 to 20.5 MeV/c
Circumference	16.57 m
No. of cavities, frequency, total voltage	19, 1.301 GHz,2.3 MV/turn
Nominal tune shift during acceleration	∼0.3/cell to ∼0.1/cell
Bunch repetition rate, bunch charge	1 to 20 Hz, 16-32 pC

Table 2 and a schematic layout shown in Figure 1. By varying the positions and strengths of the quadrupoles the time of flight profile and path across resonances during acceleration may be varied, as shown in the example configurations of Figure 2.

With sufficient voltage per turn a so-called serpentine channel appears between the conventional RF buckets, and particles injected into this channel may be accelerated beyond the separatrices bounding the buckets [21]. Due to the narrow variation of orbital radius with energy conventional spatially-based injection and extraction using static magnetic/electric fields may not be used, and instead pulsed magnets are required [20].

Acceleration Measurements

Orbital periods are measured by using a timing signal from one electron BPM located half-way around the ring from the EMMA injection point. Measurements of average position for all forty-two BPMs allow reconstruction of the variation of orbit radius with momentum, and the measurement of betatron tune as a function of momentum. These measurements were performed either by circulating beam at fixed momentum for many turns without acceleration, or by measuring BPM positions during a single acceleration cycle when RF was present. Injection at the intermediate fixed momenta was obtained not by changing the actual injected bunch mean momentum but by adjusting the lattice to mimic operation at this momentum. Good agreement between this latter 'equivalent momentum' approach and measurements taken during an actual acceleration pulse. Momenta during acceleration were derived by fitting the time-of-flight or betatron tunes to a machine model and found to agree well with each other.

A complete analysis is given elsewhere [22], but we illustrate in Figure 3 the reconstructed longitudinal phase space for acceleration using the orbit radius and tune data; this shows that acceleration has been achieved between 12.5 MeV/c and 19.2 MeV/c. The final beam momentum was confirmed by successful extraction of the accelerated bunch, whose momentum was determined to be 18.4+/-1.0 MeV/c using the first dipole in the extraction line as a spectrometer. The fact that integer resonances are crossed during this acceleration pulse indicates that the nsFFAG principle is valid, but more detailed measurements are required to understand the importance of magnetic errors on the closed-orbit and emittance growth.

FUTURE WORK

Whilst the EMMA results so far demonstrate that fast resonance crossing (i.e. in under ten turns) is possible, a number of developments are required before such a design may be applied to proton accelerators. Firstly, a better understanding is needed of the effect of the strength of magnetic errors, and measurements are in progress to measure the rate of emittance and closed-orbit growth as a function of rate of crossing of an integer resonance. It is already known of course that slower acceleration cycles (100 to 1000 turns) will place more stringent demands on the allowable magnetic errors in such designs, but slow acceleration is likely to be required in proton nsFFAGs due to limited acceleration voltage per cycle. Acceleration of multiple bunches in linear nsFFAGs may require induction-based acceleration to avoid the problem of synchronism that RF cavities suffer from [21], but induction cell voltages are naturally limited to much smaller values (c. 20 kV per cell) than are available from RF cavities (up to c. 1 MV per cell). Also, extraction efficiency issues are exacerbated even more in nsFFAGs than in cyclotrons due to the naturally narrower range of orbit radii.

An alternative to linear nsFFAGs are so-called 'semi-scaling' or other nonlinear FFAG designs, in which both tune flattening and time-of-flight flattening are in principle possible with appropriate optimisation of the magnetic field profiles [23]. Time-of-flight flattening to give an isochronous machine allows the use of fixed-frequency RF and thus convenient acceleration of multiple bunches, and this is a promising route to achieving high power proton acceleration.

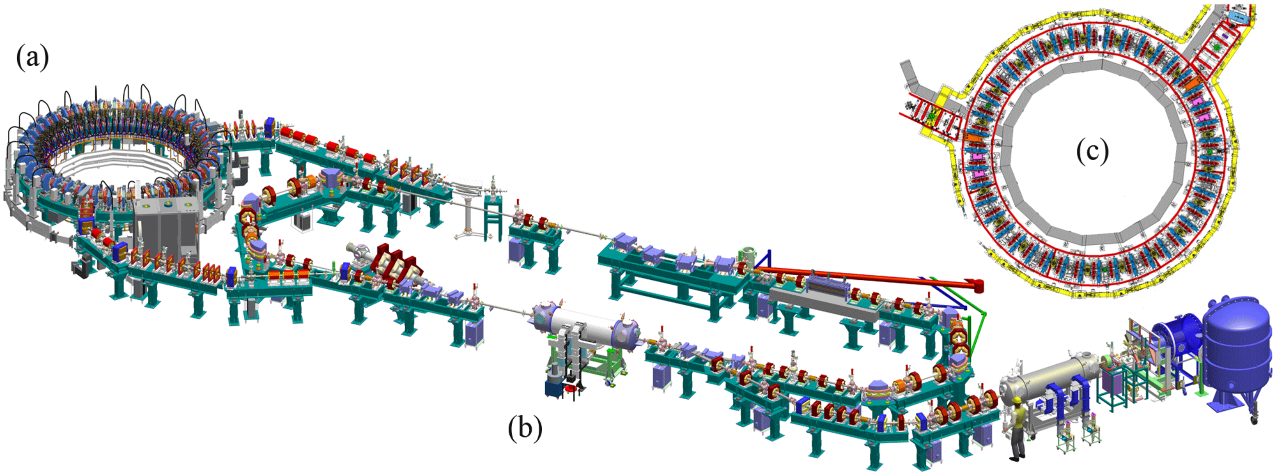

FIGURE 1. Layout of (a) EMMA and (b) ALICE injector, showing (c) EMMA in plan view.

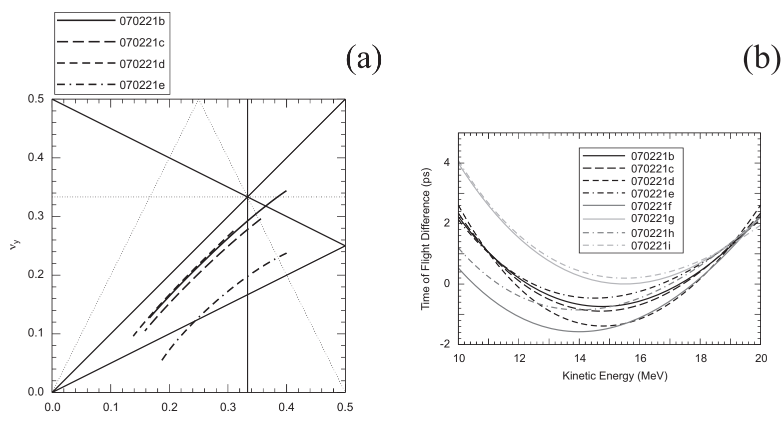

FIGURE 2. Example configurations of the EMMA lattice, showing in (a) how different resonance crossing may be accomplished, with (b) the corresponding time of flight profile.

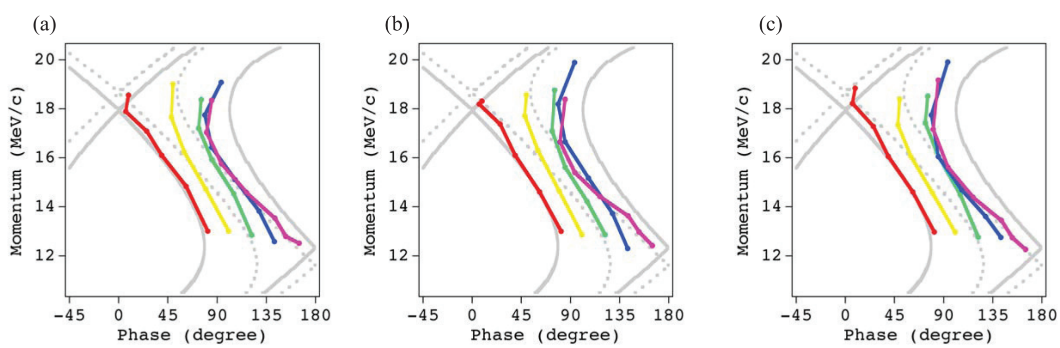

FIGURE 3. Reconstructed longitudinal phase trajectories for different injected bunch phases (indicated as different colours) using measurements of (a) horizontal average orbit radii with energy, (b) variation of horizontal tune with energy, and (c) variation of vertical tune with energy. The nominal separatrix boundaries between the fixed RF buckets and the intervening serpentine channel are also shown, and indicate that acceleration through the serpentine channel has been achieved.

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