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A New Type of Accelerator for Charged Particle Cancer Therapy

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Abstract. Non-scaling Fixed Field Alternating Gradient accelerators (ns-FFAGs) show great potential for the acceleration of protons and light ions for the treatment of certain cancers. They have unique features as they combine techniques from the existing types of accelerators, cyclotrons and synchrotrons, and hence look to have advantages over both for this application. However, these unique features meant that it was necessary to build one of these accelerators to show that it works and to undertake a detailed conceptual design of a medical machine. Both of these have now been done. This paper will describe the concepts of this type of accelerator, show results from the proof-of-principle machine (EMMA) and described the medical machine (PAMELA).

Keywords: FFAG, non-scaling, EMMA, PAMELA.
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INTRODUCTION

As is well known, protons are currently accelerated for cancer therapy using both cyclotrons and synchrotrons, while carbon ions are accelerated using just synchrotrons, though super-conducting cyclotrons are under development. Both types of accelerator work well for this application, though the fact that two are used is indicative that neither is ideal. Interest has arisen in Fixed Field Alternating Gradient accelerators because they combine important features from these machines: the fixed magnetic field during acceleration from cyclotrons and the alternating gradient or strong focusing of synchrotrons. The former allows more rapid cycling of the accelerator, limited next by the rate at which the RF system frequency can be varied to match the revolution frequency of the beam, and easier operation than a synchrotron, plus the possibility of using super-conducting magnets to make the machine more compact. The strong focusing results in a relatively compact magnetic ring, giving the possibility of extracting the beam at any energy and results in the accelerator being able to accelerate both protons and carbon ions to full therapy energy.

There are two basic types of FFAG [1]. Scaling FFAGs were invented in the 1950's [2,3,4] and a number of electron accelerators were constructed at the Midwestern Universities Research Association (MURA) [1]. They are so-called because they obey a "scaling" law, whereby the particle orbits scale with energy, resulting in constant betatron tunes during acceleration and thereby avoiding resonance crossings [5]. Non-scaling FFAGs (ns-FFAGs), on the other hand, were invented in the late 1990s [6]. The fact that these do not obey the scaling law removes a constraint on the design and allows more flexibility. This has been exploited in a number of lattice designs.

The first ns-FFAG invented employed a linear lattice for the acceleration of muons in a possible future facility called a Neutrino Factory [7]. The design has the properties of fast acceleration and large acceptance required for the muon acceleration [8]. It was also realized early on that this type of accelerator looked attractive for other applications, such as charged particle therapy, Accelerator Driven Systems [9] and the acceleration of high power proton beams for other uses. However, their unique features, resulting from their non-scaling nature, in particular the issue of resonance crossings, meant that a proof-of-principle machine had to be built to study these features and demonstrate that this type of accelerator works. This proof-of-principle machine is called EMMA. In addition, a conceptual design of a carbon and proton therapy complex has been made to show that this application is indeed possible for this type of accelerator and to determine what the benefits are over

existing technology. This machine is called PAMELA. Both are described in the following sections.

THE EMMA PROOF-OF-PRINCIPLE NS-FFAG

As a purely experimental machine, the design of EMMA [10] is governed by the need to measure how this type of accelerator works. It is a 10 to 20 MeV electron accelerator, but can accept a beam anywhere in that range. It has a linear, doublet lattice, largely for cost reasons, and has 42 cells, of 39 cm length, to ensure the beam crosses enough cells during an standard acceleration cycle, typing 11 turns. There are RF cavities in every other cell, except around injection and extraction to allow space for kicker magnets. The beam is provided by another accelerator called ALICE [11] and an injection line has been built between the two to transport the beam, match the optics and measure the beam parameters before EMMA. The beam trajectory around the accelerator is measured by 82 beam position monitors, two in each cell, except around injection and extraction. Diagnostic measurements that would damage the beam quality are made in a diagnostics beam line, into which the beam can be directed at any energy. EMMA construction started in April 2007 and was completed in January 2011. The complete machine is shown in Figure 1.

The full commissioning of EMMA took place between February and April 2011. The results from this have been published [12] and these demonstrate that the machine works as expected. Here we show only two example plots. Figure 2a shows the betatron tunes of EMMA during acceleration varying as expected, while Figure 2b shows the beam following the so-called "serpentine channel" [8] during acceleration. The full experimental programme is now underway.

THE PAMELA CHARGED PARTICLE THERAPY FFAG

This is the The aim of the PAMELA project has been to design an accelerator that will deliver carbon ions at any energy between 110 and 400 MeV/u and protons between 60 and 250 MeV, via a gantry with the ability to spot scan the beam, and a cycling rate up to 1 kHz. This has been achieved and the conceptual design is shown in Figure 3. This has separate injectors for protons and carbon ions, the former using a commercial cyclotron and the latter an RFQ plus short linear accelerator. These will deliver 31 MeV protons and 8 MeV/u C^{6+} ions to a common injection system. The inner, "proton" ring will accelerate protons to 250 MeV and carbon ions to 68 MeV/u, before both are extracted from this ring and injected into the outer, "carbon" ring. The protons can then be immediately extracted for therapy, but could also be accelerated to higher energies for proton tomography [13]. The carbon ring can accelerate carbon ions to 400 MeV/u before extraction. As well as fixed field accelerators, a fixed field transfer line and fixed field gantry have been designed. This allows the transport and delivery of the beam at any energy and hence treatment without changing any magnetic fields other than used for spot scanning. This makes it conceivable to use super-conducting magnets in the gantry, bringing the hope of a significant size reduction compared to the existing carbon gantry.

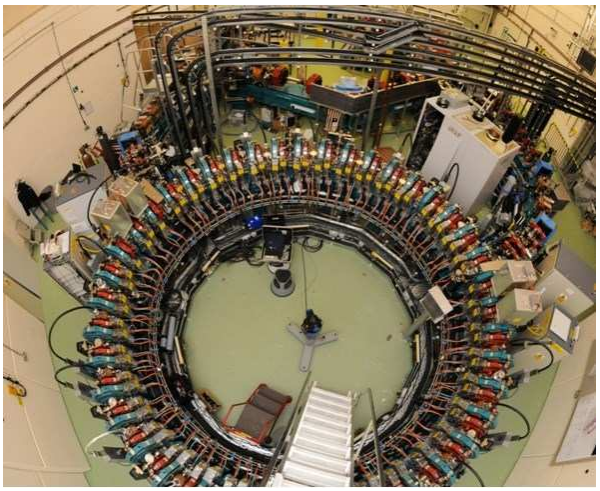

FIGURE 1. The EMMA accelerator photographed from the top. The EMMA ring is in the foreground and a section of ALICE in the background. The injection line is on the right and the diagnostics beam line on the left.

A full conceptual design of PAMELA has been undertaken and is soon to be published. Here, only a brief description of the main components of the machines is given. One of the future measurements planned for EMMA is to determine how slow the acceleration can be in a linear machine before resonance crossings significantly degrade beam quality. However, as the acceleration in PAMELA will be much slower than EMMA due to the non-relativistic nature of the ions, it has been assumed that a linear lattice cannot be used. Instead, magnets with multipoles up to octupole have been employed to reduce the betatron tune variations to a tolerable level. To increase the available field, these magnets will be super-conducting, making use of the fixed field nature of these machines [14]. To keep the beam orbit excursion small, 18 cm in the proton ring and 22 cm in the carbon, 12 cells are used in each, with a triplet lattice [15]. To achieve the required cycling rate, it is proposed to use ferrite loaded RF cavities, based on

the existing ISIS 2nd harmonic cavities [16]. A number of ferrites have been tested and 500 Hz looks achievable. Further work is underway to reach 1 kHz. It is planned to use 8 cavities per ring, with a target acceleration of 16 kV/cavity/turn.

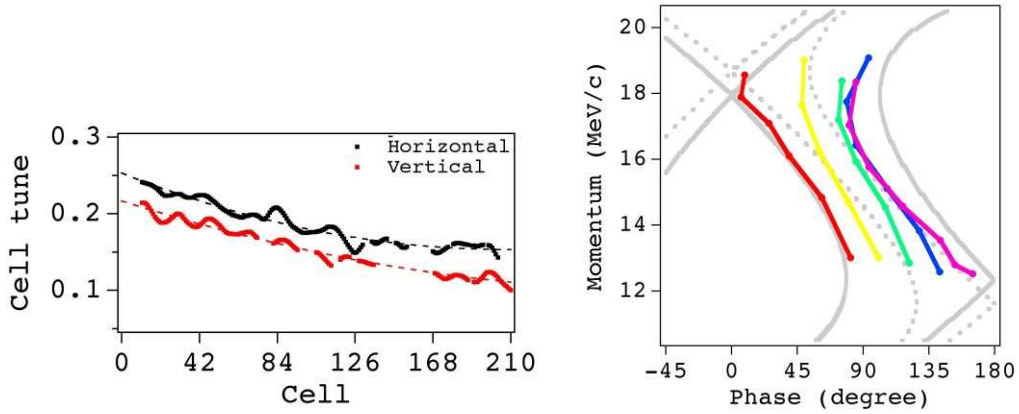

FIGURE 2. (a) Left: The horizontal and vertical betatron tunes in EMMA as a function of cell number during acceleration from around 12 MeV to 18 MeV. 42 cells corresponds to one turn in the machine. (b) Right: The phase of beam with respect to the phase of the RF system during acceleration, for 5 different starting phases. The grey lines indicate the so-called serpentine acceleration channel.

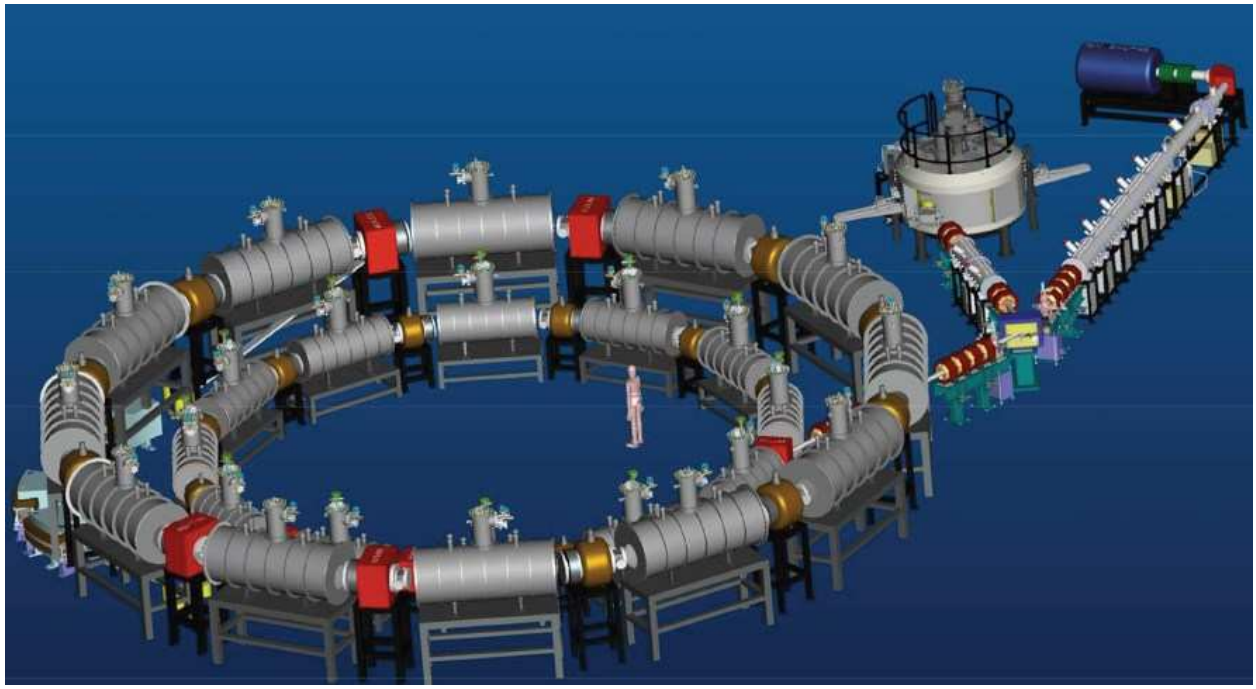

FIGURE 3. The layout of the PAMELA charged particle therapy facility.

The next step in the project is prototyping the main machine components, i.e. the ring magnets, RF cavities and injection/extraction kicker magnets and septum.

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