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PAMELA : overview and status

PAMELA OVERVIEW AND STATUS*

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Abstract

The status of PAMELA (Particle Accelerator for MEdical Applications) – an accelerator for proton and light ion therapy using a non-scaling FFAG (ns-FFAG) accelerator – is reviewed and discussed.

INTRODUCTION

Charged Particle Therapy (CPT) [1], which uses protons and light ions (for example, carbon) to treat some cancers, was discussed in [1]. There are than 20 hospital-based CPT centres in operation and several more are under construction. These use cyclotrons (mostly) and synchrotrons to deliver the charged particles (mostly protons but with some light ions) to the treatment room. While these technologies are successfully treating patients, there are limitations. Cyclotrons are reliable and can deliver the dose at essentially any required rate, but are usually fixed energy extraction and so use degraders to spread out the Bragg peak, leading to lower quality beams. Synchrotrons offer variable energy extraction but, because they are pulsed machines, have a low duty factor. Synchrotrons also have a larger footprint (although there is a recent development of a compact synchrotron). Several alternative approaches are being pursued aimed at ameliorating these limitations. One such uses a Fixed Field Alternating Gradient (FFAG) accelerator to combine the high current capability of the cyclotron (the fixed field) with the variable energy extraction (the reduced orbit excursion from injection to extraction which the alternating gradient allows). This paper describes an approach using a non-linear non-scaling FFAG to accelerate protons and light ions to 250 MeV and 400 MeV/nucleon respectively.

PAMELA

The non-scaling FFAG (ns-FFAG) was invented in 1999 [3]. The design compressed the orbit excursion and the magnet aperture, using a linear magnetic field, leading to expectations of smaller apertures, and significant cost reduction. EMMA (Electron Model with Many Applications) will demonstrate the technology, and is described elsewhere [4]. Briefly, EMMA is a 42-cell, densely-packed ring, with the linear magnetic fields provided by displaced quadrupoles, and achieving rapid acceleration by using 19 1.3GHz cavities, each with an accelerating voltage of 20-120kV, giving an energy gain per turn of between 0.38 MeV and 1.28 MeV.

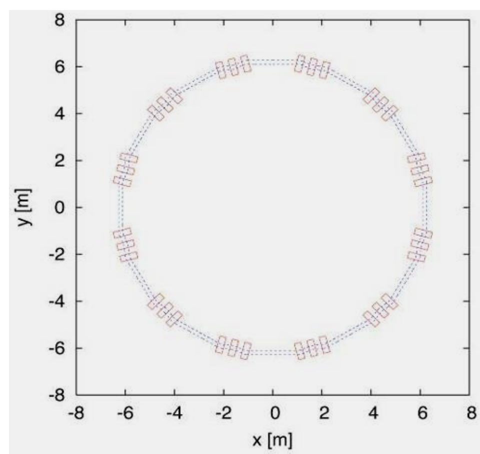

Figure 1: The PAMELA lattice for protons from 31 MeV to 250 MeV, with the orbit excursion from injection (inner) to extraction (outer) shown in blue.

As explained in [2], this lattice is not suitable for a non-relativistic ring. Instead, a less dense lattice with longer straight sections and small tune variation is used, departing from simple linear magnetic fields. The design principles of this lattice are discussed in [5], where the tune stabilisation procedure is described. The lattice selected for PAMELA is shown in Figure 1, with 12 triplet (FDF) cells, with a median radius of 6.25m and 1.95m long straight sections (about 1.7m of useful length, see Table 1). The basic design philosophy for the lattice is described in reference [5]. There are several steps in the development of the lattice.

a) Start with a scaling FDF triplet focusing FFAG
b) Break scaling by truncating the multipole expansion of the radial magnetic field profile, and then by

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making the magnets rectangular and aligning the FDF on a straight line.

c) Work in the second stability region of Hill's equation – vertical (horizontal) phase advance <180° (180° to 360°) – and adjust the lattice to restore approximate scaling (small tune variation).

Table 1: Lattice Parameters

Particle	H+			C6+				
Ring	1 inj	1 ref	1 ext	1 inj	1 ref	1 e/2 i	2 ref	2 ext
Kin En/u [MeV]	31	118.4	250	7.84	31	68.4	208.7	400
Bρ [Tm]	0.81	1.62	2.43	0.81	1.62	2.43	4.40	6.37
	Ring 1					Ring 2		
Radius [m], pf	6.251, 0.48					9.3, 0.65		
Cells, K-value	12, 38					12, 42		
LSS, SSS [m]	1.4506, 0.0628					1.1979, 0.1266		
L (magnet) [m]	0.5656					1.1395		
Orbit ex. [m]	0.1834					0.2459		
Bore size [m]	~0.24					~0.35		

The proton lattice design and performance are described elsewhere [7], and the carbon lattice is described in [8]. Both rings are optimised to ensure at least 1.2m long straight sections, realistic magnetic field strengths and minimised orbit excursion. A 12 cell lattice was chosen to make tune stabilisation (inversely proportional to the number of cells) easier, whilst providing sufficient straight sections for injection, extraction and RF acceleration. The normalised dynamic aperture of the proton (carbon) ring is greater than 30 (50 π-mm-mrad). A schematic layout of the injection and acceleration scheme for a combined proton and carbon ion facility is shown in Figure 2.

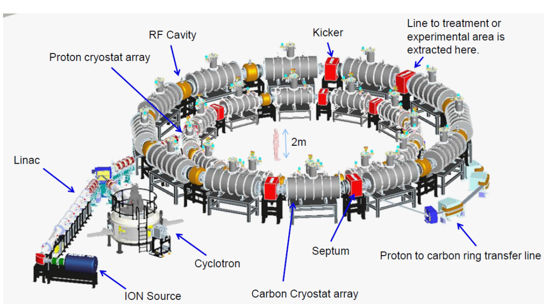

Figure 2: Layout of PAMELA for protons and C^{6+}.

The injection scheme needs the same magnetic rigidity for protons and C^{6+} at injection. An injection scheme is illustrated in Figure 2, and described in [8,9]. For protons, a commercial cyclotron with kinetic energy ~30 MeV, followed by a short Linac for bunching and injection is used. For carbon, an ECR ion source to produce an 8-10 keV/u C^{4+} beam, separated from other charge states by a spectrometer. An RFQ accelerates the C^{4+} to 400 keV/u and then accelerated to ~7.5 MeV/u in an IH/CH, (Interdigital H mode/ Crossbar H mode structure) Linac. The C^{4+} is stripped by a foil to C^{6+}.

The proton and carbon lattices avoid both integer and half-integer resonances. The tune variations from injection to extraction at the maximum energy are shown in Figure 3. The tune stabilisation is achieved by including multipole components up to the decapole, using a polynomial fit to the scaling law. The total tune variations for the proton (carbon) ring are 0.049 (0.129) horizontally and 0.054 (0.117) vertically.

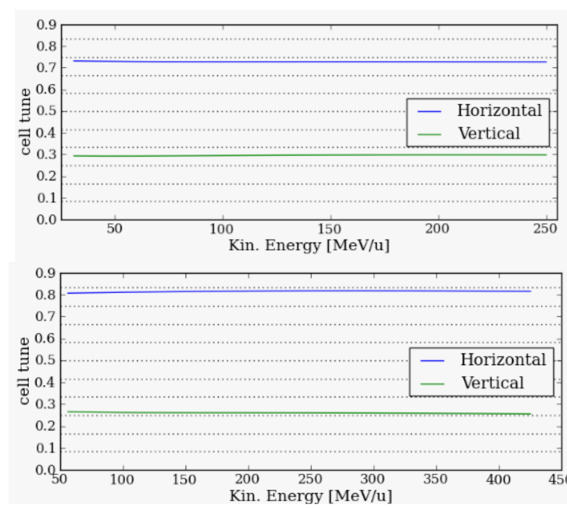

Figure 3: Cell tunes for the proton ring (upper) and carbon ring (lower), showing the avoidance of integer (dotted lines) and half-integer resonances.

PAMELA needs combined function main-ring magnets with multipole components to decapole and a field quality of about 10^{-3}. These represent a challenge due to the high magnetic field and large bore – 0.25m (protons) and 0.35m (carbon) – and the limited coil length – 600mm (protons) and 1200mm (carbon). The vertical magnetic field for the F magnets centre plane is shown in Figure 4, with a magnetic length of 0.3144m (0.633m) for protons (carbon). Helical coils [10] fulfil these requirements. A helical combined function magnet coil containing all required multipoles is proposed – see Figure 5 (left) – which benefits the cryogenic system, as only one current lead pair is needed, reducing the heat leak. A trial winding is illustrated in Figure 5 (right).

Additional helical trim coils may be added to tune each multipole. The design has a temperature margin lager than 2K assuming a NbTi superconductor with a Cu:Sc ratio of 1.35:1.

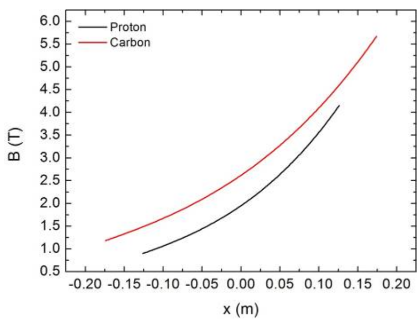

Figure 4: The required magnetic field as a function of radial displacement from the reference orbit.

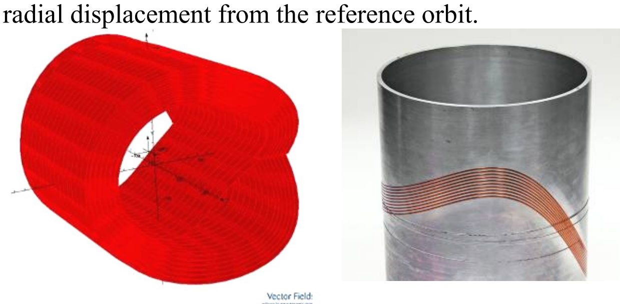

Figure 5: A multipole helical coil (left) and test winding (right)

The RF system was described in reference [11] and subsequent work has confirmed appropriate ferrites.

Variable energy extraction needs a large aperture kicker because of the relatively large orbit excursion. For hardware and dynamic reasons, PAMELA uses vertical extraction (see [12]), with a kicker bending power of 0.06 T-m. With this, the orbit separation is greater than 3 cm. The kicker voltage and current are about 40 kV and 10000 A-turn. The values are within the engineering limit of present technology, though the large required currents need careful engineering design. The kicker and power supply development is a major R&D item in the hardware development stage. A conceptual design is shown in Figure 6 (left), and the pulse shape shown in Figure 6 (right).

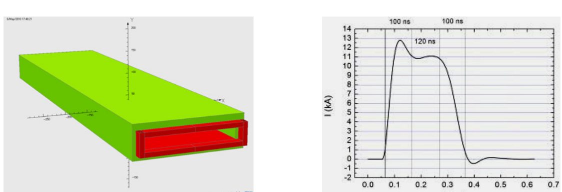

Figure 6: Preliminary kicker design (left) and pulse shape (right).

Finally, an FFAG-like beam transport and gantry is required to deliver the beam to the patient, permitting rapid energy variation for spot scanning. The PAMELA lattice structure may been transformed [13] to achieve and achromatic beam transport as shown in Figure 7 (left). The momentum dispersion could thus be suppressed at three points along the trajectory, as shown in Figure 7 (right) on this preliminary gantry design.

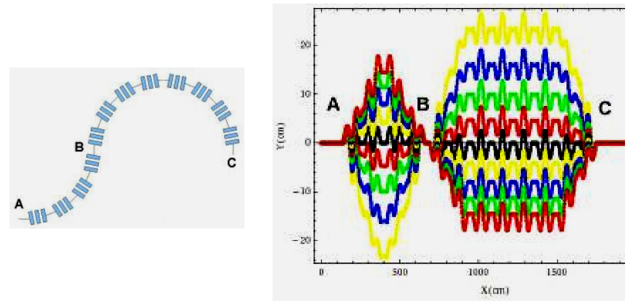

Figure 7: A transformed PAMELA lattice to create an achromatic beam transport (left) and the dispersion suppression at 3 points along the trajectory (right).

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