Non-Scaling FFAG Magnet Challenges

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The Cockcroft Institute,
and The University of Liverpool, Department of Physics.
BASROC:

- British Accelerator Science and Radiation Oncology Consortium;
- a group of academic, medical and industry specialists;
- the current aim - the construction of a hadron therapy facility;
- an FFAG is favoured;
- now focused on ‘non-scaling’ alternative (nsFFAG) - much reduced apertures;
- set up ‘CONFORM’ - the COnstruction of a Non-scaling FFAG for Oncology, Research and Medicine.
EMMA and PAMELA

UK funding has now been obtained to support:

• The construction of a small prototype nsFFAG – EMMA:
  • an ‘Electron Model for Many Applications’
  • accelerating between 10 and 20MeV;
  • being built at STFC’s Daresbury Laboratory, U.K;
  • will obtain e⁻ from the recently commissioned ALICE facility.

• The feasibility design of PAMELA:
  • a ‘Particle Accelerator for Medical Applications’;
  • a prototype nsFFAG for hadron therapy;
  • being designed at the John Adams Institute (JAI), Oxford.
  • first stage is the design of a 250 MeV proton accelerator;
  • including detailed lattice and tracking studies, magnet and rf design.
The EMMA concept
The EMMA Layout

An experimental facility;

Injection and extraction at any energy between 10 and 20 MeV.

~ 6 metres

see: WE4BI01; S.Smith: ‘EMMA, the World’s First Non-Scaling FFAG’.

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EMMA Magnet requirements

84 combined function magnets:
• 2 families – Fs and Ds
• with dipole and quadrupole component to be independently controllable.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>F magnet</th>
<th>D magnet</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend angle for 15 MeV orbit</td>
<td>- 0.499</td>
<td>0.199</td>
<td>radians</td>
</tr>
<tr>
<td>B length</td>
<td>55</td>
<td>65</td>
<td>mm</td>
</tr>
<tr>
<td>Max. dipole flux density</td>
<td>0.0302</td>
<td>0.102</td>
<td>T</td>
</tr>
<tr>
<td>Max. quadrupole gradient</td>
<td>9.3</td>
<td>5.8</td>
<td>T/m</td>
</tr>
</tbody>
</table>
Achieving independent harmonic control

Dipole and quadrupole components need to be independently controlled – How?

A dipole with inbuilt pole-face gradient and pole-face windings?
NO – quadrupole field is stronger than dipole!

Solution: conventional quadrupole located off-centre to provide dipole component:

• adjust quadrupole field by coil current;
• move quadrupoles radial to adjust dipole.
### Resulting quadrupole parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>F quad.</th>
<th>D quad</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inscribed radius</td>
<td>37.0</td>
<td>53.0</td>
<td></td>
</tr>
<tr>
<td>Yoke length</td>
<td>55.0</td>
<td>65.0</td>
<td></td>
</tr>
<tr>
<td>Offset of 15 MeV beam from magnet centre</td>
<td>7.51</td>
<td>34.05</td>
<td></td>
</tr>
<tr>
<td>Horizontal beam movement from 15 MeV orbit</td>
<td>-2.6 to +2.7</td>
<td>-5.3 to +14.5</td>
<td>mm</td>
</tr>
<tr>
<td>Good gradient with respect to magnetic centre</td>
<td>-32.0 to +15.8</td>
<td>-56.0 to -9.9</td>
<td>mm</td>
</tr>
</tbody>
</table>
Quadrupole configurations.

F quad – beam crosses magnetic centre – **full quad** required.

D quad – beam does **not** cross magnetic centre – use a half quad with magnetic mirror on centre line?

**NO** – magnetic mirror needs to extend outside magnet ends to give true 3D reflection – not possible due to straight length. Much gradient distortion results.

**Solution;** D magnet also needs to be a full quadrupole.
Fields in straights.

The straight between magnet doublets are very short – 110 mm (inscribed radii are 55 and 65mm!).

So – quad field penetrates into the straights:
  • distorts quadrupole field;
  • affects other components (particularly inject/extract magnets).

Solution: Insert ‘clamp (mirror) plates around each doublet.
The EMMA doublet (plus cavity)
Resulting EMMA layout.
Magnetic design

Very short magnets - ‘all ends and no middle’. Conventional quad. design (hyperbolas with tangential extensions) gave poor 3D gradients.

Solution:
- Replace hyperbolic pole face with series of straight lines.
- Adjust positions of vertices to optimise field distribution.
Additional optimisation was carried out on clamp-plate geometries; best solution was to mill clamp-plates with identical shapes to the poles.
Prototype magnets

Two prototypes were built (*) and measured:

![F magnet](image1) ![D magnet](image2)

Gradient quality \( \Delta \int g(x) / \int g(0) \):

• F magnet: +0.4%, -2.0% in ± 32mm – acceptable;
• D magnet: -1% at 35mm – needs to go to 56 mm – not acceptable.

Subsequently the poles of the D were shimmed and achieved similar quality to the F – acceptable.

(*) by Tesla Engineering, Storrington, UK

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Production magnets - Fs

34 F acceptable magnets have now been assembled, measured and delivered (*).

Gradient qualities $\Delta \int g(x)/\int g(0)$ for all 32:

(*) by Tesla Engineering, Storrington, UK
Production magnets - Ds

Measurement of the Ds presents problems:
With the rotating radius of 35 mm, repositioning of the coil to -20mm is necessary to cover the whole aperture of 56 mm. Data from 2 magnets; the twin scans are superimposed:
Girder Assembly Commences

Radial movement mechanism

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Magnet movement

THK slide with motor, limit switches and NUMERIK JENA 1 µm linear encoder.

<table>
<thead>
<tr>
<th></th>
<th>Range (mm)</th>
<th>Repeatability (µm)</th>
<th>Accuracy (µm)</th>
<th>Resolution (µm)</th>
<th>Backlash (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QF</td>
<td>±3 (6)</td>
<td>±3 (6)</td>
<td>±10 (20)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>QD</td>
<td>+15, -6 (21)</td>
<td>±3 (6)</td>
<td>±10 (20)</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
EMMA Injection and Extraction

Conventional beam manipulation (single septum and two kickers for each line) is envisaged.
But - space between quadrupole doublets is 110mm.
How is beam injected/extracted at the septum straight?
Conduct beam through a number of magnets pairs?
NO:
• beam would pass through fringe fields; EMMA is an experimental facility; fields will change so flight path geometry is not fixed;
• magnets are moved to adjust dipole component; beam-line hardware would therefore need to be flexible.
Injection and extraction

Solution:
Inject or extract in a single straight with injected or extracted beam missing adjacent magnets. This results in a large deflection angle $\sim 80^\circ$.

![Diagram of injection and extraction](image_url)
# Septum parameters

Magnet is based on:
- eddy-current passive septum;
- coil on the back-leg;
- short pulse excitation.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum deflection</td>
<td>77</td>
<td>degrees</td>
</tr>
<tr>
<td>Maximum flux density</td>
<td>0.91</td>
<td>T</td>
</tr>
<tr>
<td>Yoke length</td>
<td>82</td>
<td>mm</td>
</tr>
<tr>
<td>‘C core’ gap height</td>
<td>22.0</td>
<td>mm</td>
</tr>
<tr>
<td>Internal horizontal ‘stay-clear’</td>
<td>62.5</td>
<td>mm</td>
</tr>
<tr>
<td>Turns on excitation coil</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Current pulse half sine-wave duration</td>
<td>25</td>
<td>μs</td>
</tr>
<tr>
<td>Pulse peak current</td>
<td>9.1</td>
<td>kA</td>
</tr>
<tr>
<td>Pulse peak voltage</td>
<td>900</td>
<td>V</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>20</td>
<td>Hz</td>
</tr>
</tbody>
</table>
The septum magnet has been designed and is being built ‘in-house’.
- yoke assembled from 0.1mm silicon steel laminations;
- eddy-current shield is 3mm thick copper;
- mounted on a slide to provide radial movement and rotation about a vertical axis;
- copper braid conducts heat from eddy-shield to tank walls.
Extraction septum in its vacuum tank.
## Kicker magnet requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value 1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam deflection</td>
<td>105</td>
<td>mR</td>
</tr>
<tr>
<td>Maximum flux density in gap</td>
<td>54</td>
<td>mT</td>
</tr>
<tr>
<td>Horizontal good field region</td>
<td>± 23</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum vertical gap at beam</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>Length of ferrite yoke</td>
<td>100.0</td>
<td>mm</td>
</tr>
<tr>
<td>Horizontal deflection quality</td>
<td>± 1</td>
<td>%</td>
</tr>
<tr>
<td>Minimum flat top (+0, -1%)</td>
<td>≥ 5</td>
<td>ns</td>
</tr>
<tr>
<td>Field rise/fall time (100% to 1%)</td>
<td>&lt; 50</td>
<td>ns</td>
</tr>
<tr>
<td>Peak current (1 turn conductor)</td>
<td>1.1</td>
<td>kA</td>
</tr>
<tr>
<td>Peak voltage (with feed-through)</td>
<td>23</td>
<td>kV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>20</td>
<td>Hz</td>
</tr>
</tbody>
</table>
Kicker magnet engineering

The kickers have also been designed and a prototype constructed in house:

A single turn coil is mounted on the back-leg, with an eddy shield at the C core mouth.
Pulse Waveforms

A contract is placed with APP(*) to design and build the kicker supplies;
ideal waveform for injection:

Achieved to date (*):

The PAMELA Ring Magnets

The PAMELA project aiming to:
- accelerate p+ to 250 MeV;
- C+ to 68 MeV/A;
- up-grade potential to 400 MeV/A.

<table>
<thead>
<tr>
<th>Lattice</th>
<th>12 cells of triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet lengths</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Straights between magnets</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Straights between triplets</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Radial offset, Fs to Ds</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Bore aperture diameters</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Combined function</td>
<td>4 components, n=1 to n=4</td>
</tr>
<tr>
<td>Peak field</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>T</td>
</tr>
</tbody>
</table>

see: TH4GAC03; K.Peach et al; ‘PAMELA Overview: Design Goals and Principles’

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PAMELA Lattice Layout

Non-Scaling FFAG Magnet Challenges, Neil Marks.
Magnets are required:

• to generate 4 components, dipole to octupole;
• each component to be independently controllable;
• to be superconducting, to achieve the maximum field levels of > 4 T.

How?

**Solution:** a novel helical coil arrangement:

• each harmonic is generated by a pair of helical coils;
• counter wound, so that the axial component cancels;
• geometry generates required transverse component;
• end field have no harmonic distortion;
• multiple pairs give stronger amplitudes.

see: MO6PFP073 Witte et al; ‘PAMELA Magnets, Design and Performance’
Helical Coil Arrangements

dipole

quadrupole

combination

octupole

sextupole

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Generating Transverse Fields.

To generate the required transverse harmonics, the conductors are placed on specific curves given, in Cartesian coordinates, by:

\[
\begin{align*}
  x &= R \cos \theta \\
  y &= R \sin \theta \\
  z &= \frac{h \theta}{2\pi} + \frac{R}{\tan \alpha} \sin(n\theta)
\end{align*}
\]

where

- \( R \) is the helical coil radius;
- \( \theta \) is the azimuthal angle;
- \( h \) is the winding pitch;
- \( \alpha \) is the tilt angle of the solenoid;
- \( n \) is the order of the harmonic (dipole = 1, etc).
# PAMELA Magnet Parameters.

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>Quad</th>
<th>Sextupole</th>
<th>Octupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>560</td>
<td>565</td>
<td>555</td>
<td>564</td>
</tr>
<tr>
<td>No. of coil pairs</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Inner radius</td>
<td>140</td>
<td>162</td>
<td>177</td>
<td>185</td>
</tr>
<tr>
<td>Outer radius</td>
<td>160</td>
<td>173</td>
<td>183</td>
<td>187</td>
</tr>
<tr>
<td>Tilt</td>
<td>50</td>
<td>50</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Peak B at wire</td>
<td>5.1</td>
<td>5.4</td>
<td>5.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

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EMMA and PAMELA demonstrate certain features of nsFFAGs:

- they do provide the benefit of smaller magnets;
- but little lattice space and small narrow magnets present other problems;
- injection and extraction present big engineering challenges due to lack of space;
- for hadrons and high momentum gains, superconducting coils are probably necessary;
- independent amplitude control of harmonics is important;
- the PAMELA nested helical coils look a very attractive solution for s.c magnets;
- building EMMA with pure quadrupoles and using mechanical movement to adjust dipole component provides a sensible engineering solution.
Acknowledgements

Many have contributed to the EMMA & PAMELA, including:

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