NORMA: Normal-conducting Racetrack Medical FFAG Accelerator

Sam Tygier*, Robert Appleby*, Hywel Owen*, Jimmy Garland*, Kiril Marinov†

*Manchester Cockcroft Accelerator Group, UK
†Cockcroft Institute, Daresbury, UK

PASI 2015 FermiLab
Introduction

• Proton therapy and tomography

• Fixed-Field Alternating-Gradient Accelerators

• NORMA
Cancer treatment

- 1 in 3 people will get cancer (UK)
- ~15% of all deaths (Global 2010)[1]
  - Increases as progress made on infectious disease and live expectancy rises
- Cancer survival rates have improved 25% → 50% in past 40 years (UK)[2]
  - Improvements in diagnosis and treatment

- 40% of treatment by Radiotherapy, mostly with x-rays

X-ray radiotherapy

- Aim to deliver radiation dose to tumour while minimising dose to healthy tissue
- With photons, must use multiple shaped beams that overlap at the tumour
Proton Therapy

- Protons deposit more energy as they slow down
- Dose rises to a sharp peak, Bragg peak
- Depth of peak depends on the beam energy
- Reduced unwanted dose in front and behind tumour

The original picture from R. R. Wilson's paper on proton therapy. (Radiology 47, 487–491, 1946)
Proton therapy beam

- To treat to 30 cm need beam energy up to ~250 MeV
- Need range of energies with small steps
- Need beam shaping or voxel scanning

Proton tomography

- Dose planning currently done with x-ray tomography
- Formula used to scale absorption to protons
- Proton tomography provides better data about where protons will deposit dose
- Requires ~350 MeV

See talk from Monday by George COUtrakON
Proton Therapy in the UK

• Existing site:
  – Clatterbridge Cancer Centre
  – 62 MeV Cyclotron – Uveal (ocular) melanomas

• New sites (2018)
  – Christie Hospital (Manchester)
  – UCL Hospital (London)
  – 230 MeV Cyclotron

See talk this morning by Karen KIRKBY
Fixed-Field Alternating-Gradient Accelerators

• In the 1950s the FFAG concept was developed
• Synchrotrons turned out to be much better for high energy physics, so interest dropped
• Since 1990s interest has increase for other applications
• Fixed magnets (in time) like a cyclotron
• Alternating gradient strong focusing (like a synchrotron)
• Field is stronger towards outside of machine

Fig. 2. Plan view of radial-sector magnets.

400 keV electron
MURA Radial sector (1956)

500 keV proton
KEK POP (2000)
FFAG advantages

Compared to

Cyclotrons
- Variable energy extraction
  - No degrader

Synchrotrons
- No magnet ramping
  - Simpler operation
- kHz repetition rate
  - Faster scanning
Scaling, Non-scaling

- Increase in energy → increase in radius → increase in field → increase in gradient → fixed in tune

- Scaling law for field
  \[ B_y = B_0 \left( \frac{r}{r_0} \right)^k \]

- No resonance crossing

- But means average gradient larger than peak gradient, so larger aperture required

- Can be relaxed to give non-scaling machines e.g. EMMA, which are suitable for fast acceleration

- For time scales of medical accelerator flat tunes are important
PAMELA

- PAMELA is a super-conducting non-scaling medical FFAG design
- 70-250 MeV protons (plus 440 MeV/u Carbon with second ring)
- Actually pseudo-scaling, field is approximately scaling using sum of multipoles
- Tune is very flat

http://dx.doi.org/10.1103/PhysRevSTAB.16.030101
Normal conducting

- Superconducting magnets have advantages in field strength giving smaller machines
- But they require a liquid helium cryogenic system, and may increase complexity and costs
- A normal conducting system, while larger, may be simpler
- Use pole face shaping to achieve desired field

Pamela F coil winding

KEK 150MeV FFAG triplet
Racetrack

• An accelerator needs sufficient gaps between magnets for injection, extraction, RF and other systems

• In a pure ring this space is in every cell
  – e.g. a 12 cell machine with 2m of space must have a circumference of 24m before it even has any magnets
NORMA

- Normal-conducting Racetrack Medical Accelerator
  - Scaling FFAG
  - $30 \rightarrow 350$ MeV protons
  - Straight section to give 'racetrack' shape
Design method

• Initial geometry
  – Triplet, equal length sector magnets

• Radius from basic principles (rigidity, magnet length)

• Optimisation on magnet and geometric parameters

• PyZgoubi framework for simulation and optimisation
Dynamic Aperture

- Measures how large the stable region of phase space is
  - Largest linearly matched ellipse that is stable
  - Define stable as a particle that survives 1000 turns
  - Multiple angles in phase space and real space
- Must pay attention throughout design, as it will probably drop as things are made more realistic
  - Realistic magnets
  - Misalignments
DA optimisation

• Cell geometry

• Fine tuning
Misalignments and errors

- In a real machine magnets will have misalignment errors
- Modelled horizontal and vertical misalignments
- Magnet error study in progress

200 micron misalignments do not cause significant drops in DA
NORMA racetrack

- From the optimised ring we add straights to produce a racetrack
- Re-optimise tunes
- Use matching section, vary strengths of triplets adjacent to straight
NORMA racetrack

- Reasonable length injection and extraction straight
- Not too big reduction in DA
- 10 triplets with identical geometry and field index
  - 2+3 strength families

<table>
<thead>
<tr>
<th></th>
<th>Ring</th>
<th>Racetrack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Radius (m)</td>
<td>9.6</td>
<td>10.55</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>60.4</td>
<td>70.7</td>
</tr>
<tr>
<td>Orbit excursion (cm)</td>
<td>43</td>
<td>49</td>
</tr>
<tr>
<td>Ring tune</td>
<td>7.72, 2.74</td>
<td>7.71, 2.68</td>
</tr>
<tr>
<td>Peak field (T)</td>
<td>1.57</td>
<td>1.74</td>
</tr>
<tr>
<td>DA (mm mrad)</td>
<td>68.0</td>
<td>57.7</td>
</tr>
<tr>
<td>Max drift (m)</td>
<td>2.4 (x10)</td>
<td>4.9 (x2)</td>
</tr>
</tbody>
</table>
Magnets

- Lattice design → Magnet design
- First a 2D design
- Opera – Finite Element
Tracking in magnets

- From the 2D model we get the field profile along a radial line on midplane
- Combine with a fringe model (Enge) to get the full triplet midplane
- Do the same with an ideal profile for comparison
Current studies

- Tracking simulations in the realistic fields
- 3D magnet simulations
- Magnet error studies
Conclusion

- Proton therapy is an important tool for cancer treatment
- FFAGs advantages over existing approaches
- NORMA
  - Optimised lattice
  - Misalignment studies
  - Realistic magnet models and errors in progress
- Collaboration welcome
