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NORMA: Normal-conducting Racetrack Medical FFAG Accelerator

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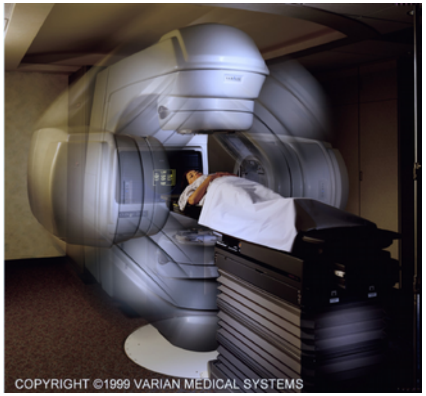
PASI 2015 FermiLab

The Cockcroft Institute of Accelerator Science and Technology

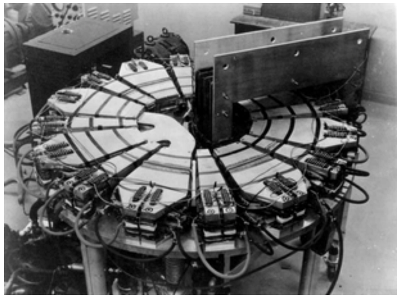
Science & Technology Facilities Council

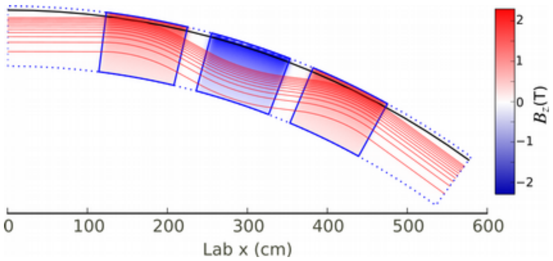
Introduction

- Proton therapy and tomography

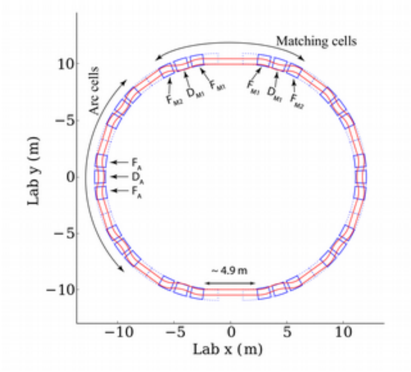


- Fixed-Field Alternating-Gradient Accelerators





- NORMA



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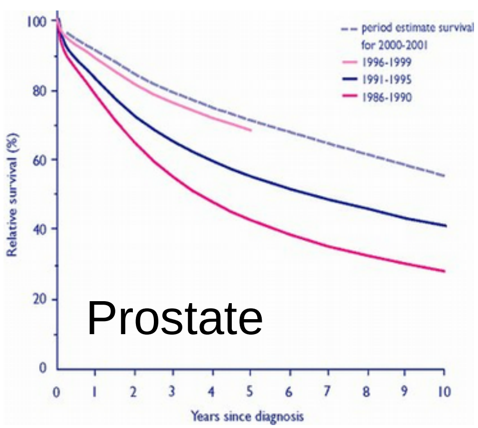
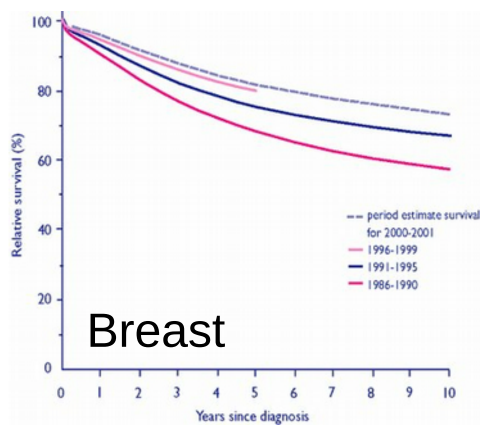
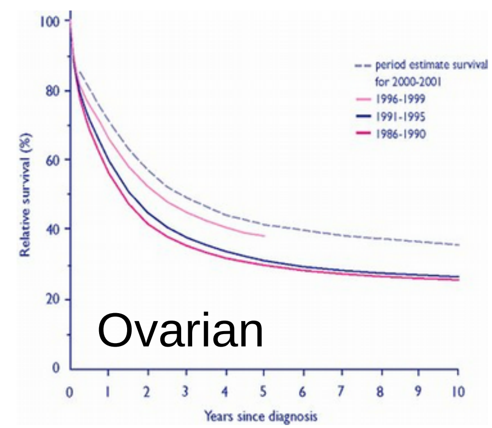
Cancer treatment

- 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

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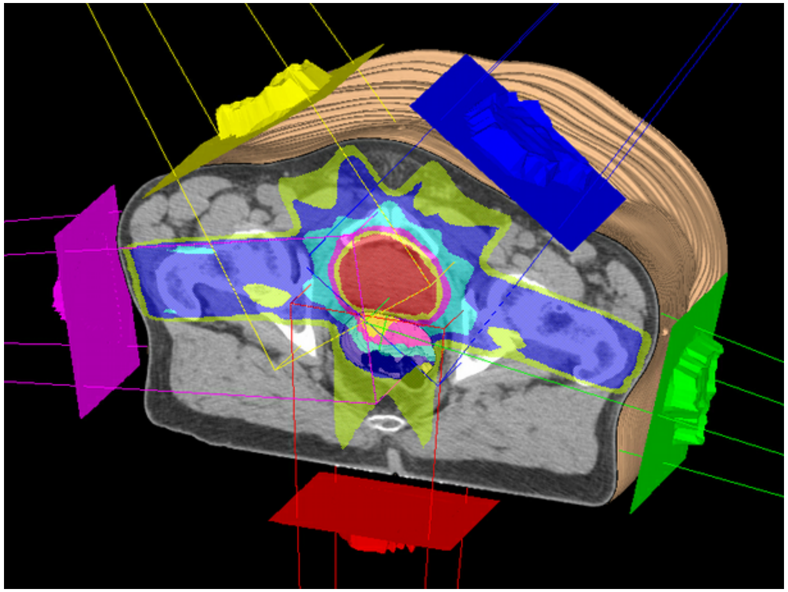
[1]Lancet 2012; 380: 2095–128
[2]Cancer Research UK

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



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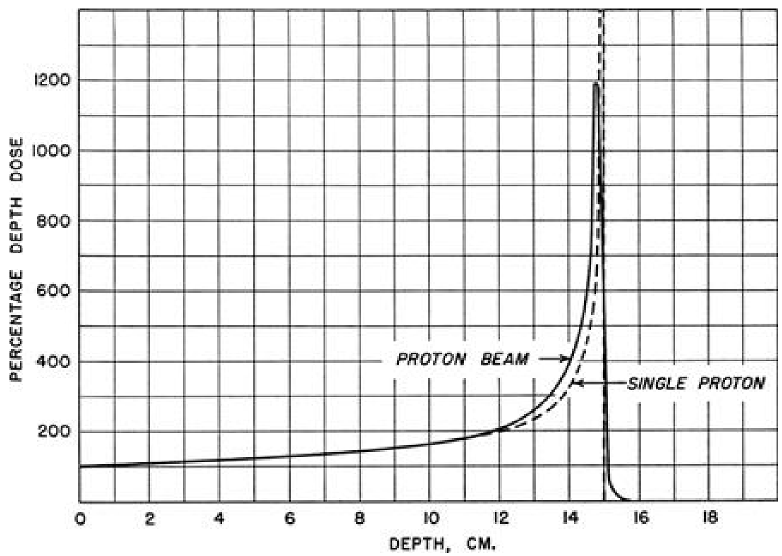
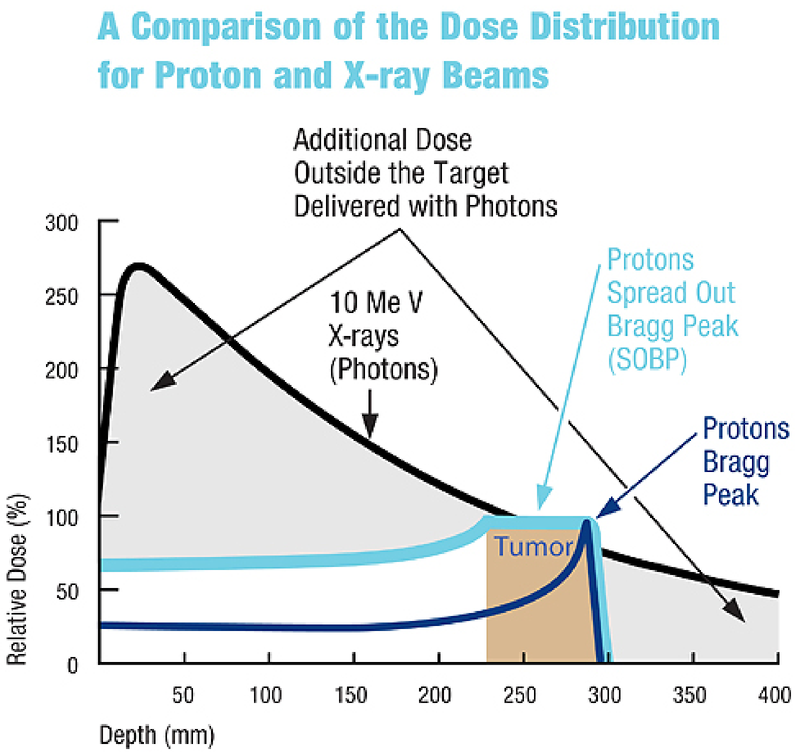
Proton Therapy

- 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)



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Proton therapy beam

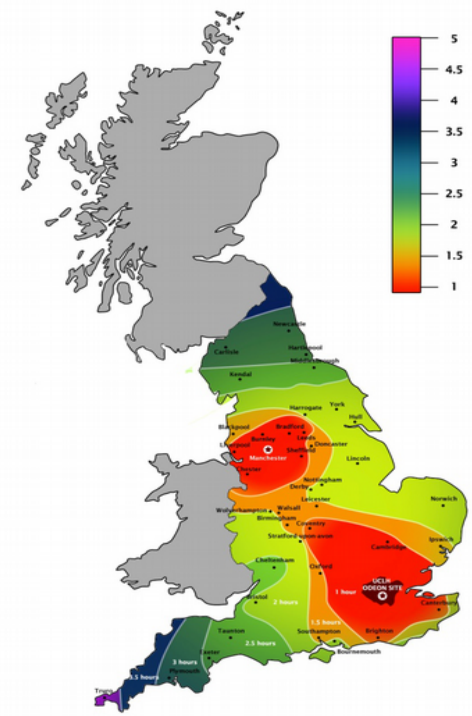
- To treat to 30 cm need beam energy up to ~250 MeV
- Need range of energies with small steps
- Need beam shaping or voxel scanning

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

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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

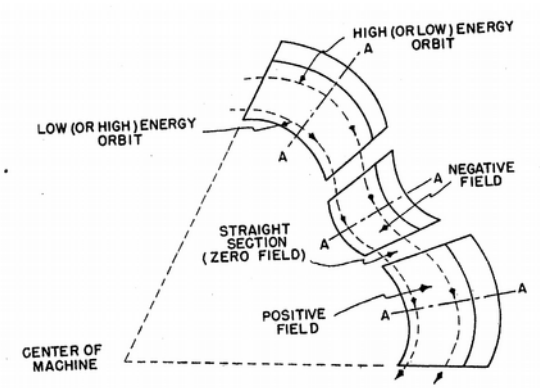
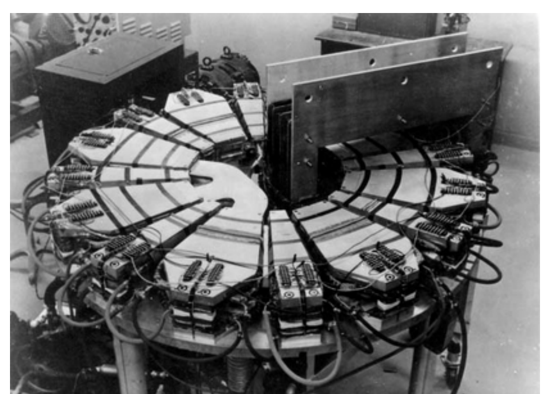
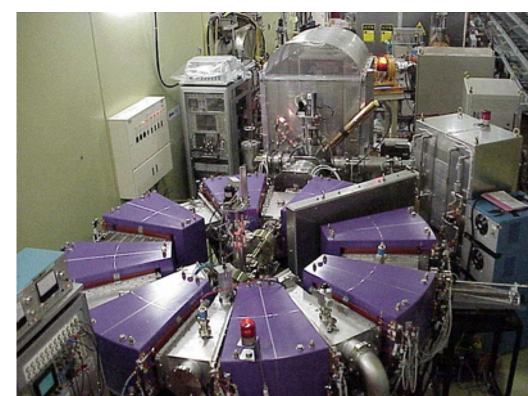


FIG. 2. Plan view of radial-sector magnets.


400 keV electron
MURA Radial sector (1956)


500 keV proton
KEK POP (2000)

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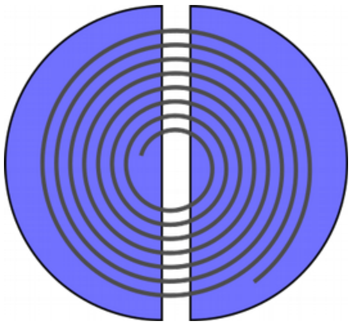
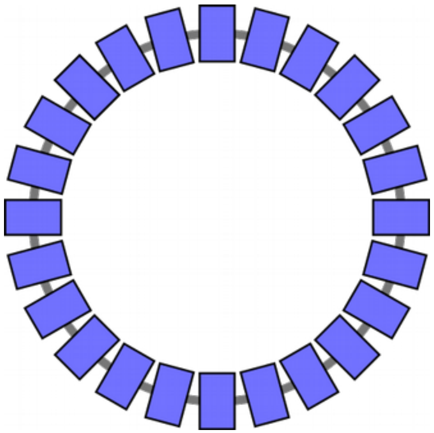
FFAG advantages



Compared to

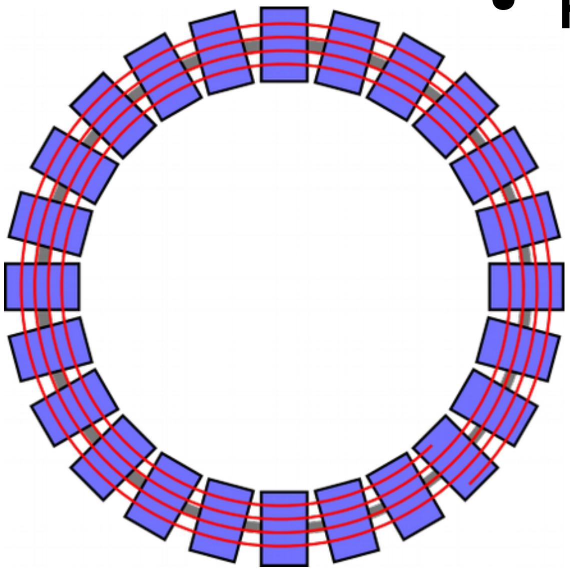


Cyclotrons

- Variable energy extraction
  - No degrader

Synchrotrons

- No magnet ramping
  - Simpler operation
- kHz repetition rate
  - Faster scanning



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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

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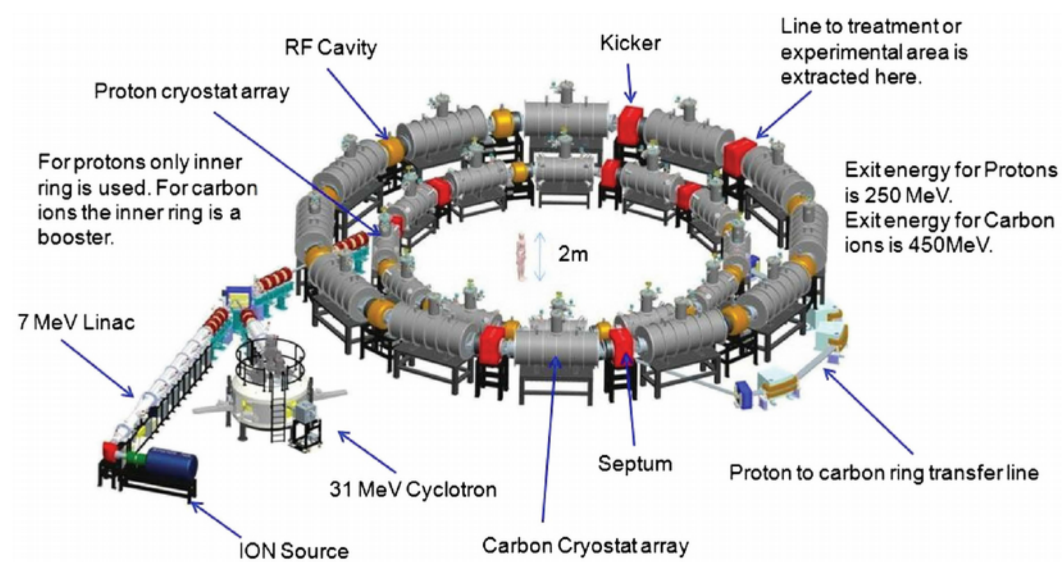
PAMELA

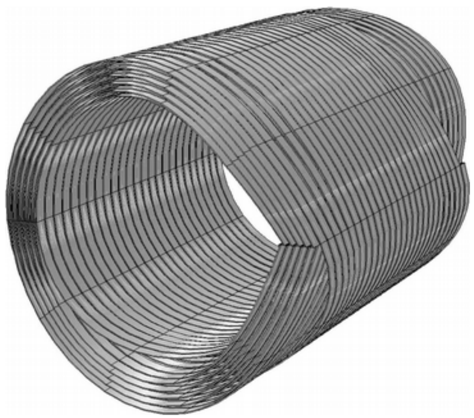
- PAMELA is a super-conducting non-scaling medical FFAG design
- 70-250 MeV protons (plus 440 MeV/u Carbon with second ring)
- Actually pseudo-scaling, field is approximately scaling using sum of multipoles
- Tune is very flat



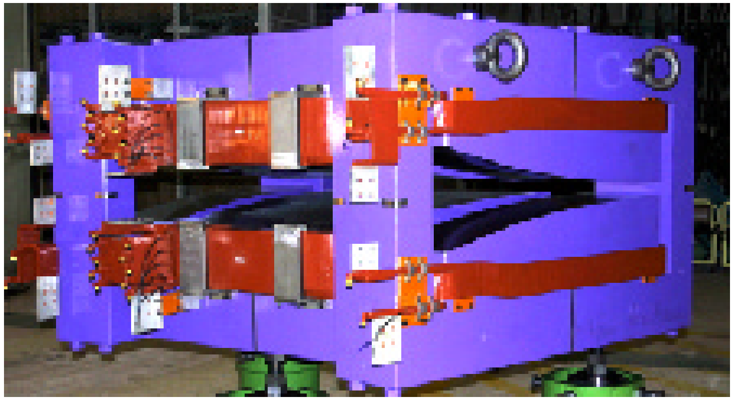
http://dx.doi.org/10.1103/PhysRevSTAB.16.030101

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

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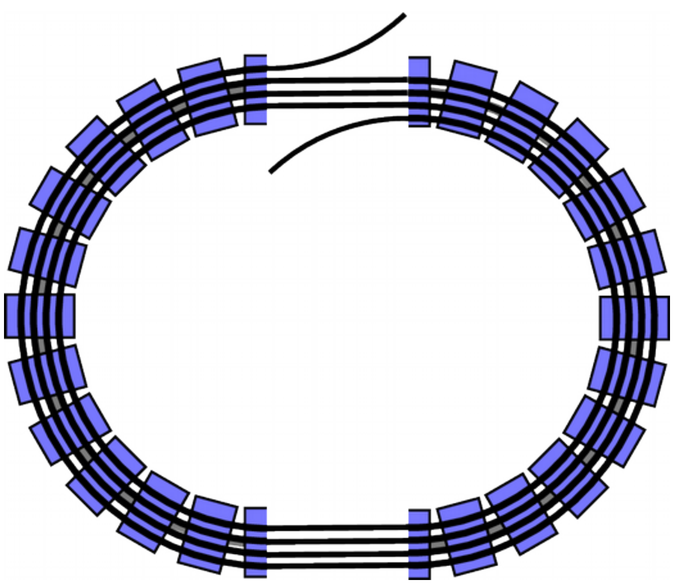
http://dx.doi.org/10.1109/TASC.2012.2186135
http://dx.doi.org/10.1109/PAC.2001.988075

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



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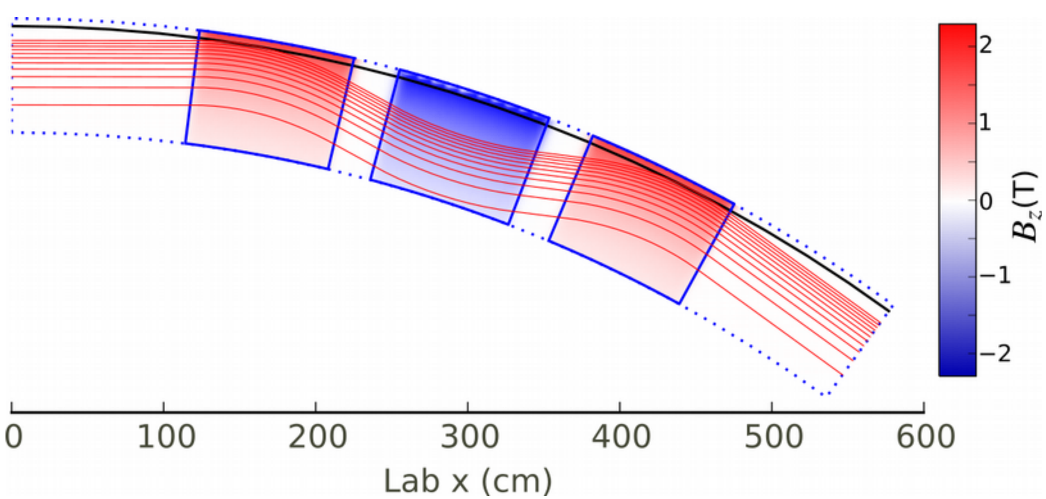
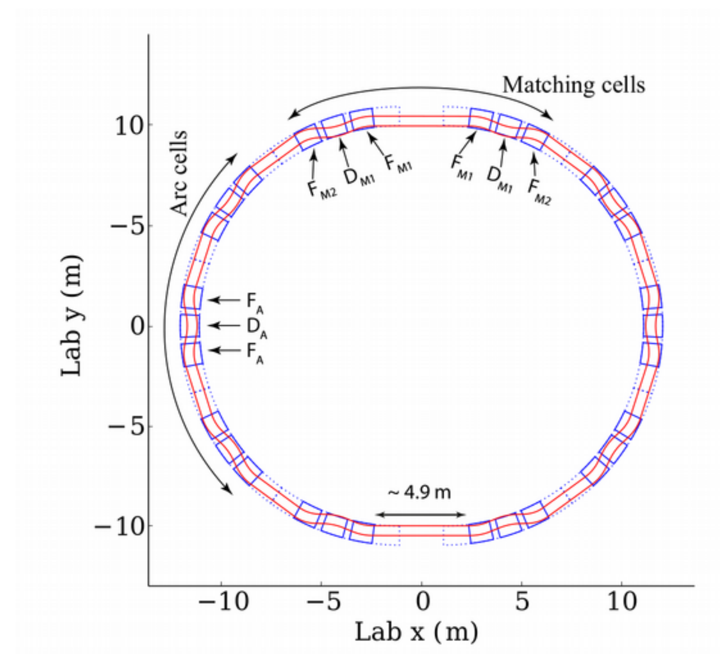
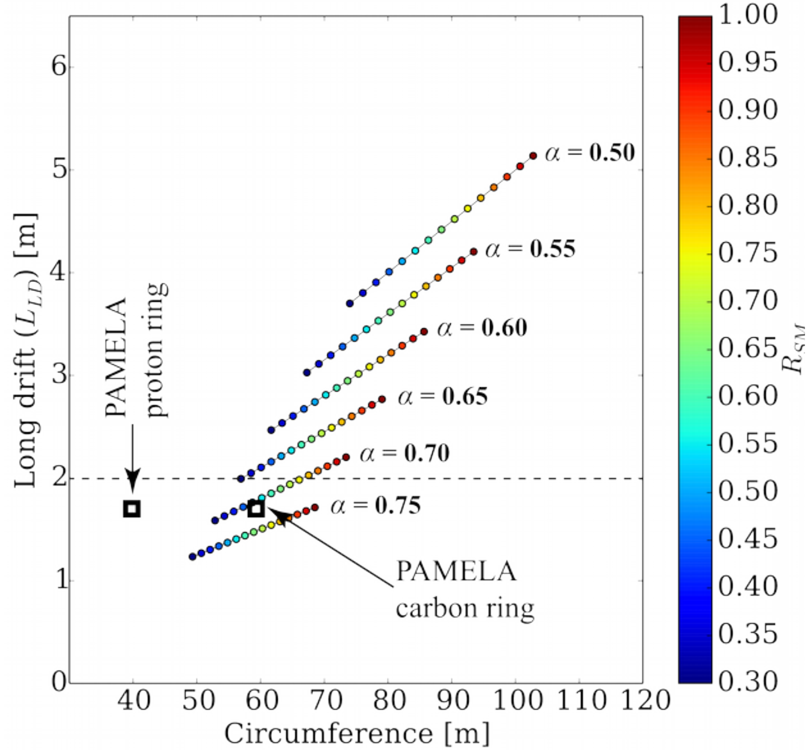
- Normal-conducting Racetrack Medical Accelerator
  - Scaling FFAG
  - 30 → 350 MeV protons
  - Straight section to give 'racetrack' shape

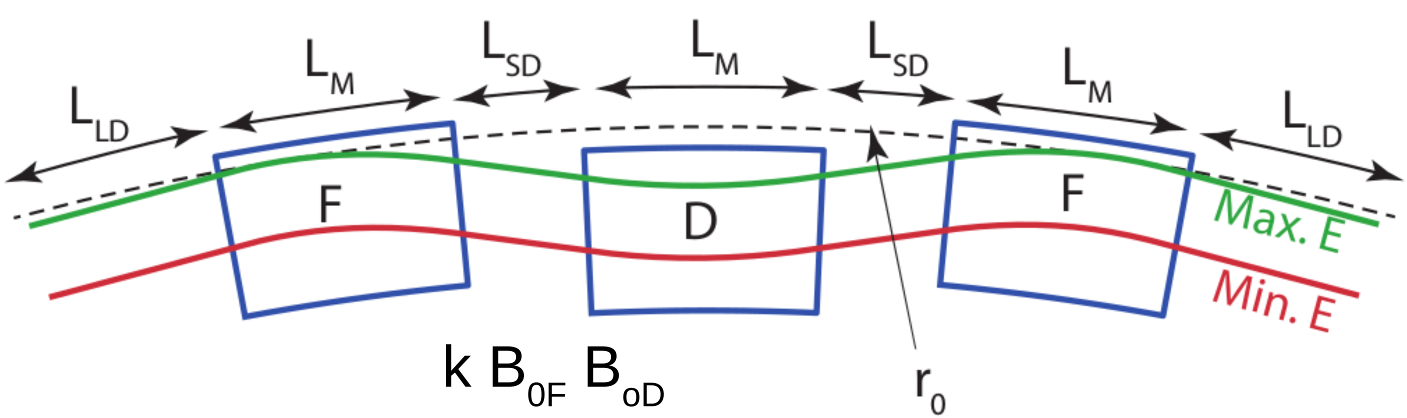




Design method

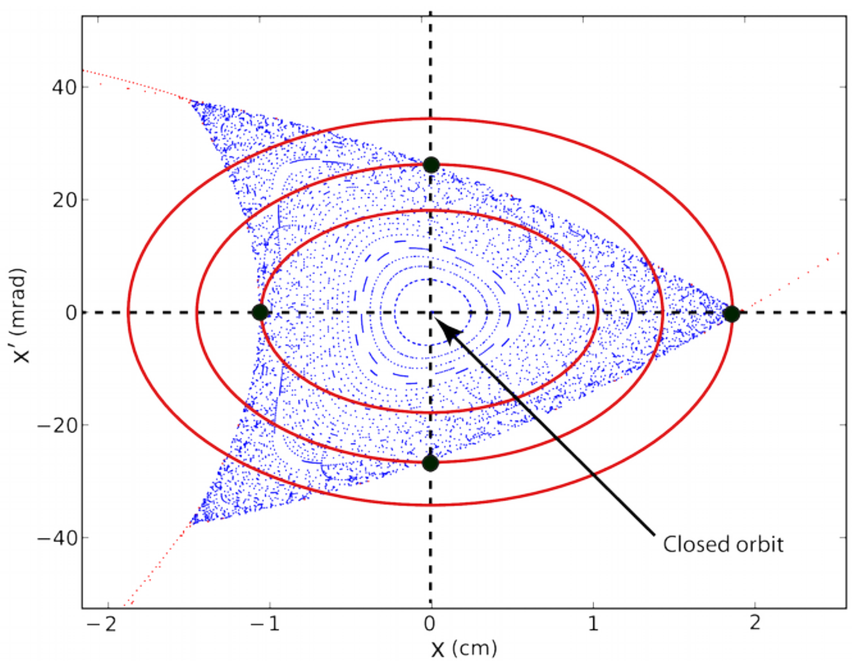
- Initial geometry
  - Triplet, equal length sector magnets
- Radius from basic principles (rigidity, magnet length)
- Optimisation on magnet and geometric parameters
- PyZgoubi framework for simulation and optimisation

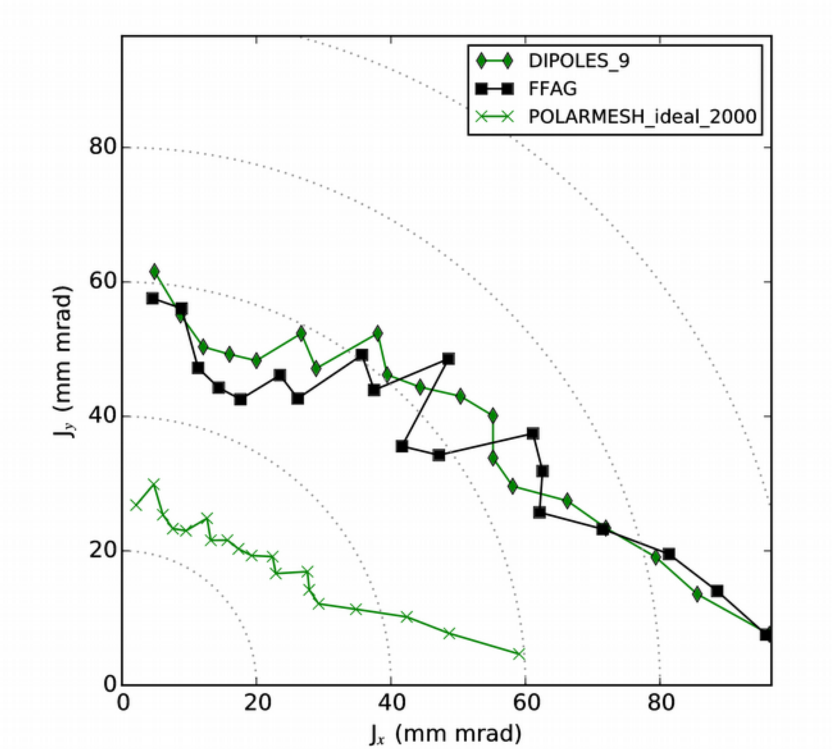




Dynamic Aperture

- 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 through out design, as it will probably drop as things are made more realistic
  - Realistic magnets
  - Misalignments





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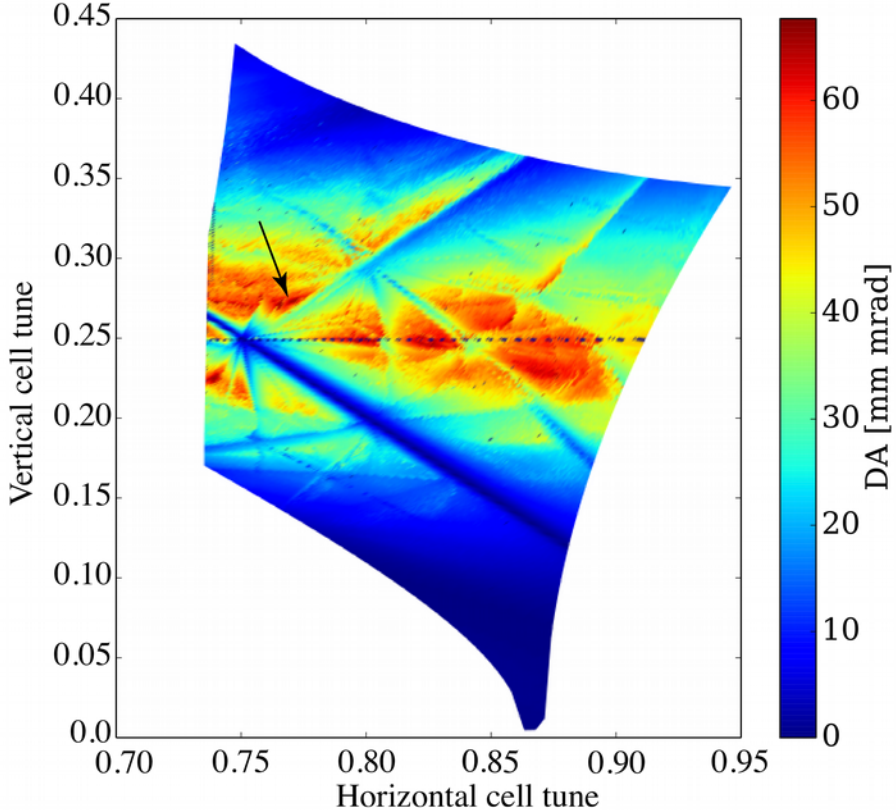
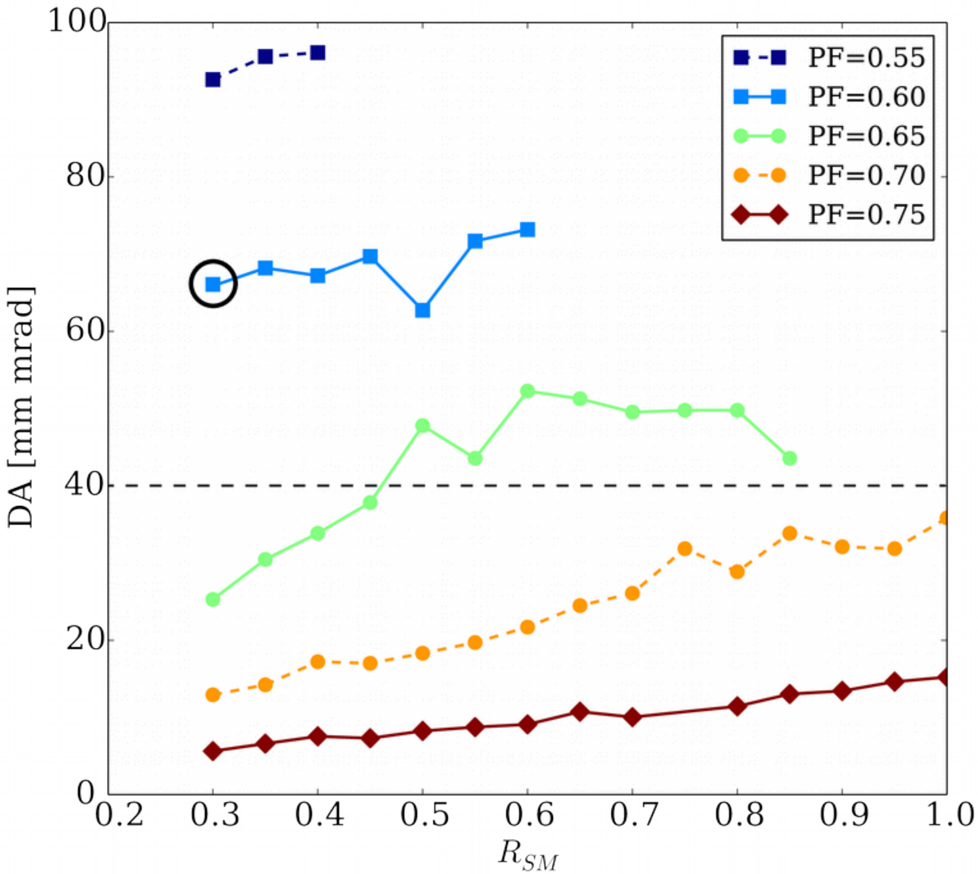
DA optimisation

- Cell geometry





- Fine tuning

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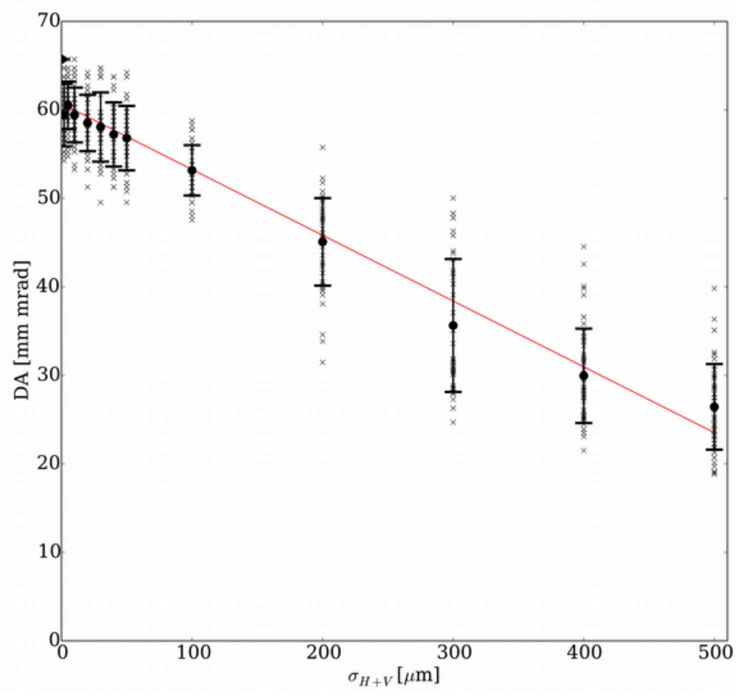
Misalignments and errors

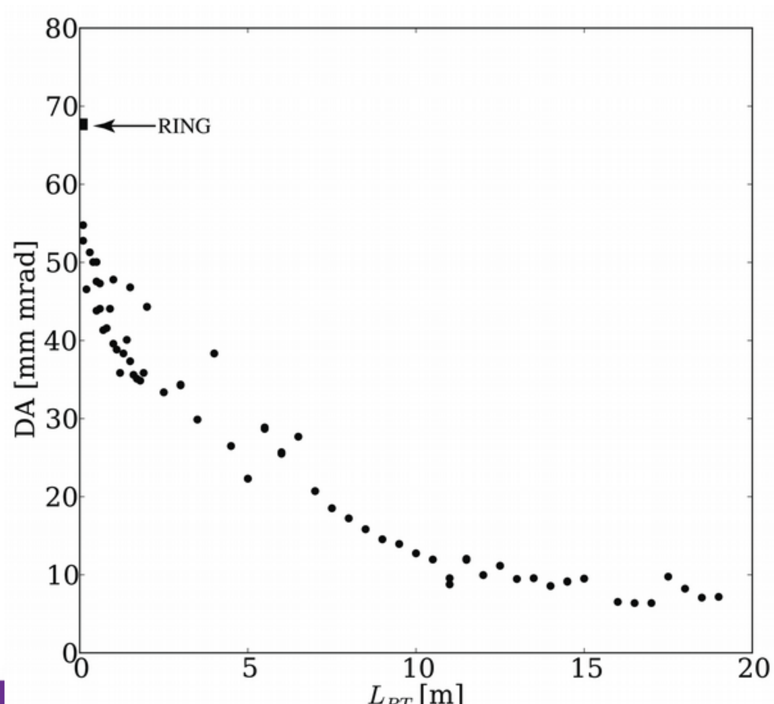
- In a real machine magnets will have misalignment errors
- Modelled horizontal and vertical misalignments
- Magnet error study in progress

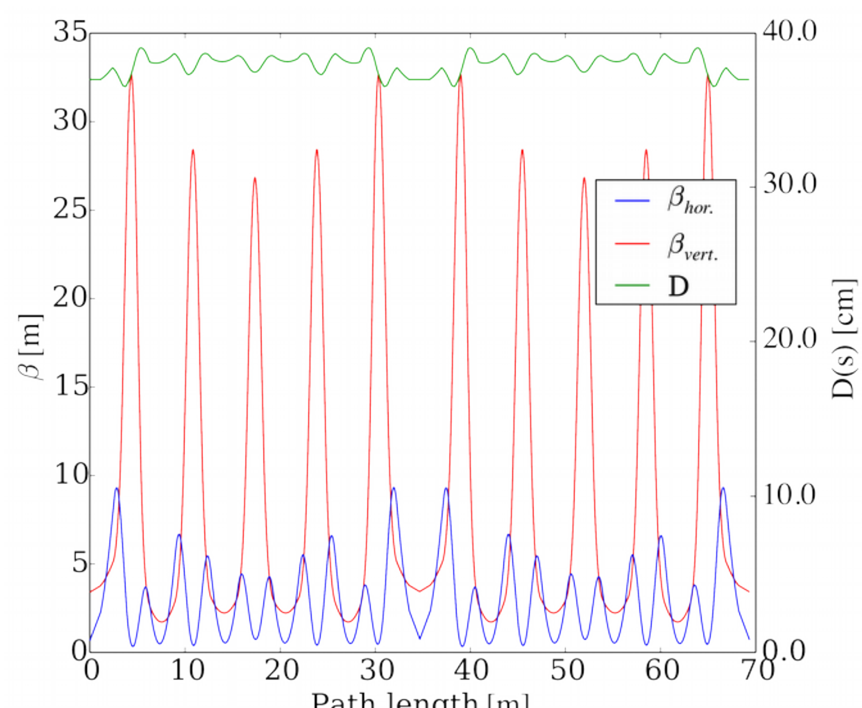


200 micron misalignments do not cause significant drops in DA

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





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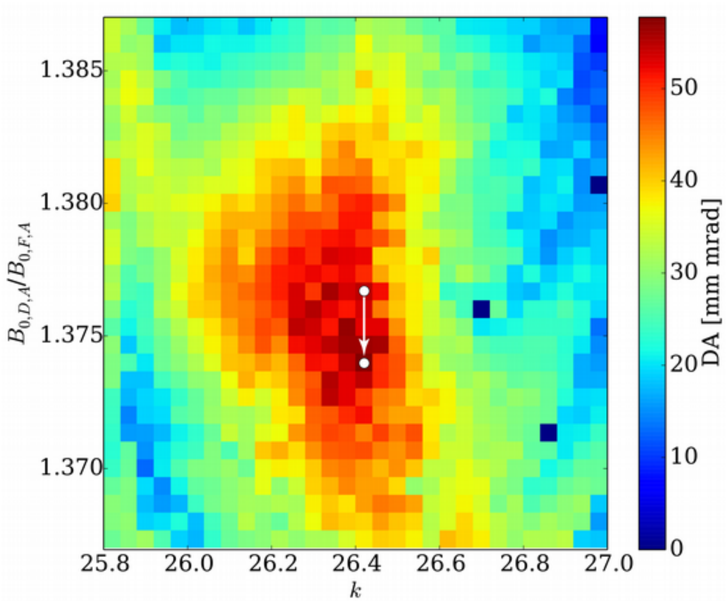
NORMA racetrack

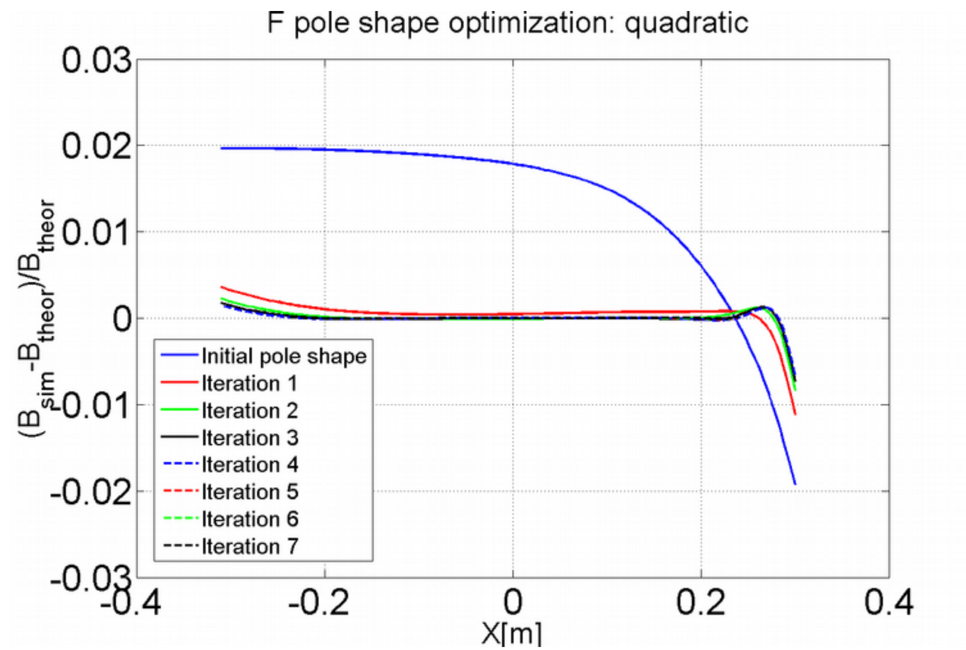
- Reasonable length injection and extraction straight
- Not too big reduction in DA
- 10 triplets with identical geometry and field index
  - 2+3 strength families

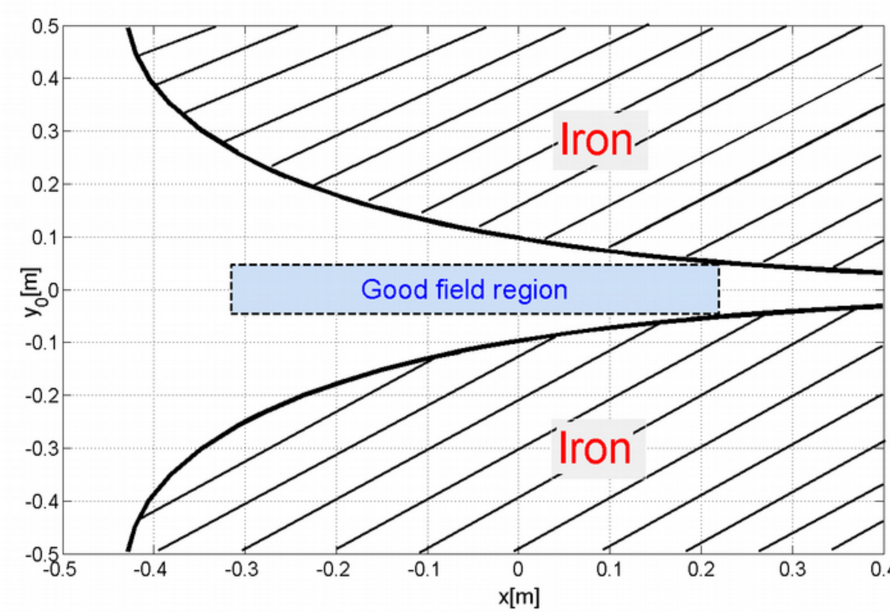


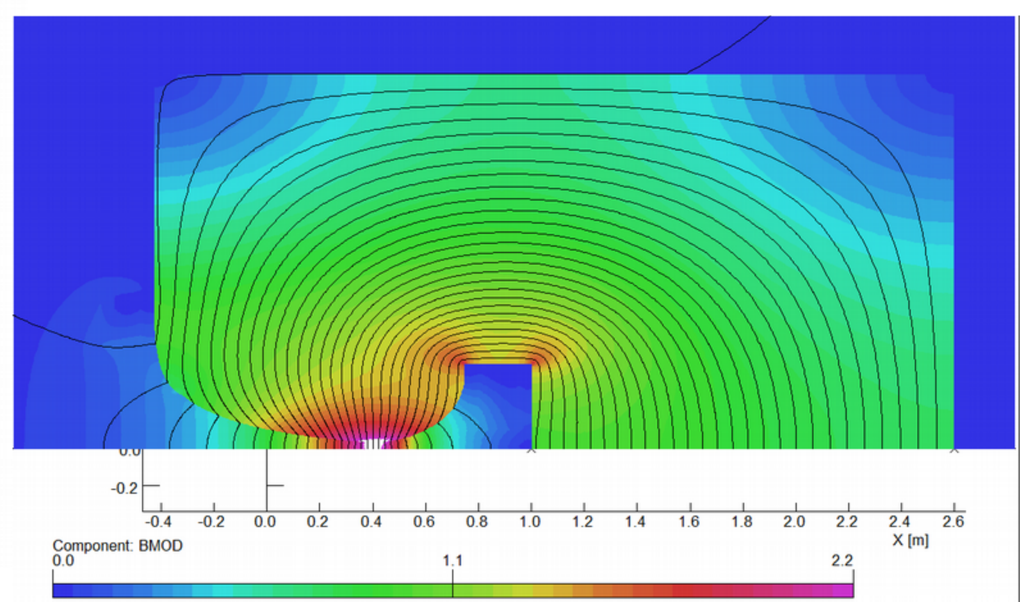
	Ring	Racetrack
Cell Radius (m)	9.6	10.55
Circumference (m)	60.4	70.7
Orbit excursion (cm)	43	49
Ring tune	7.72, 2.74	7.71, 2.68
Peak field (T)	1.57	1.74
DA (mm mrad)	68.0	57.7
Max drift (m)	2.4 (x10)	4.9 (x2)

Magnets

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







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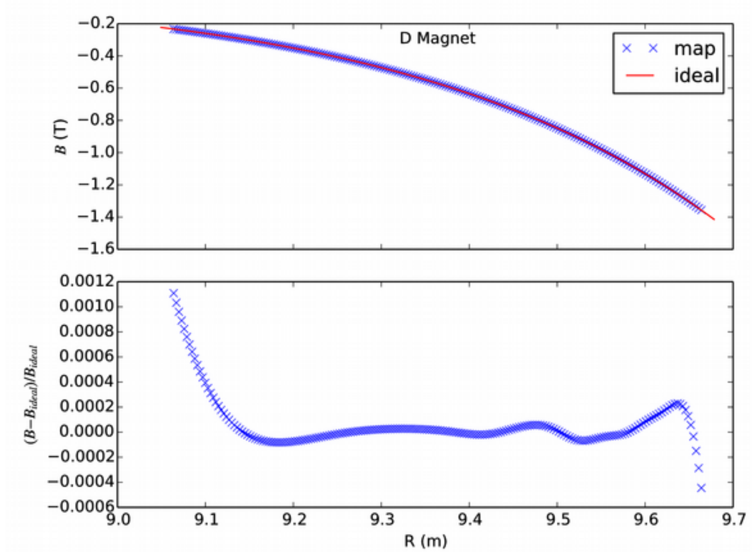
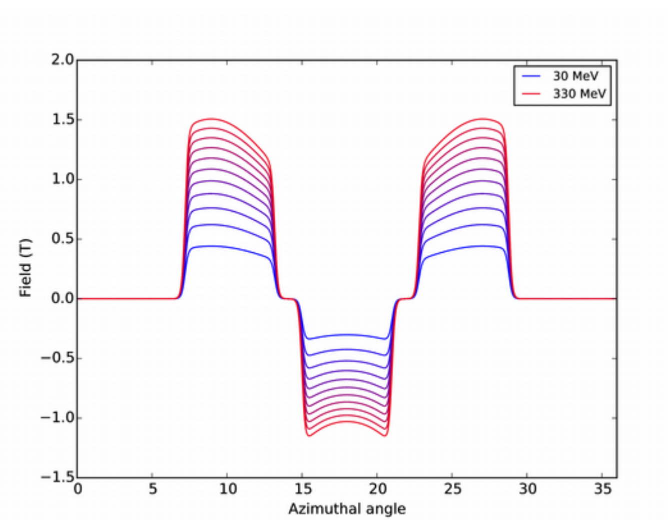
Tracking in magnets

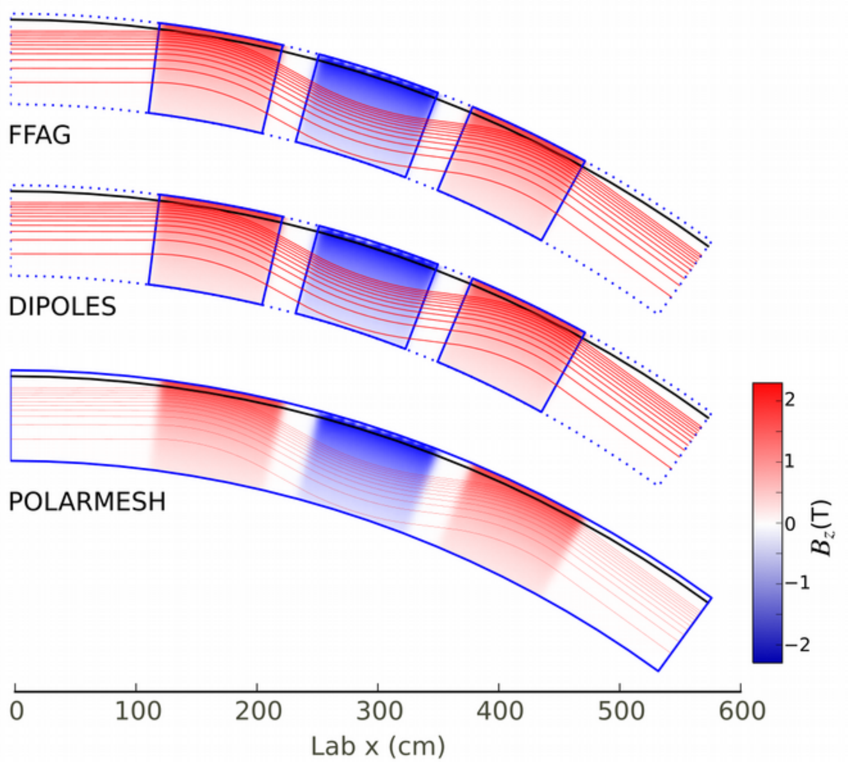
- From the 2D model we get the field profile along a radial line on midplane
- Combine with a fringe model (Enge) to get the full triplet midplane
- Do the same with an ideal profile for comparison

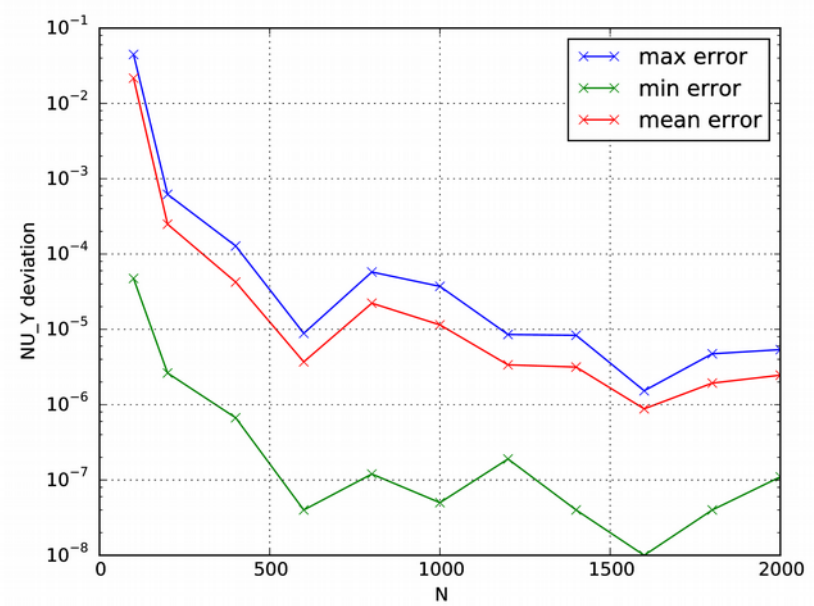




Current studies

- 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

The PyZgoubi framework and the simulation of dynamic aperture in fixed-field alternating-gradient accelerators, Nucl Instrum Meth A, (2015) 10.1016/j.nima.2014.11.067
Normal-conducting scaling fixed field alternating gradient accelerator for proton therapy, Phys. Rev. ST Accel. Beams, (2015) 10.1103/PhysRevSTAB.18.094701