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# Superconducting Helical Coils: The PAMELA Project Experience

Beam Dynamics meets Magnet Workshop

Darmstadt, Germany

2-4th December, 2013

Dr. Suzie Sheehy
ASTeC Intense Beams Group
STFC Rutherford Appleton Laboratory

# Outline

The PAMELA Design

Magnetic field requirements

Magnet options

Helical coil design

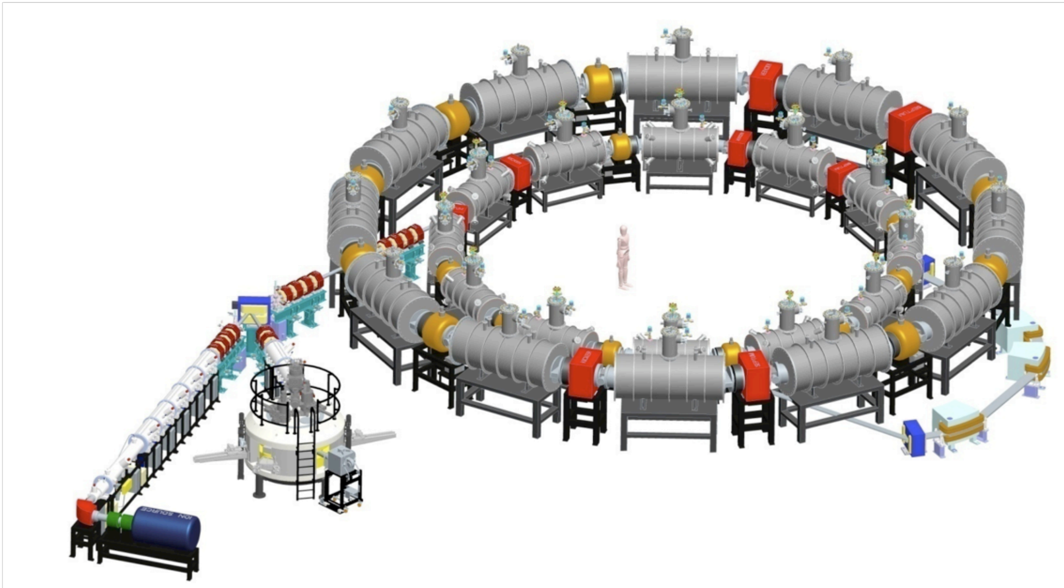
The beam dynamics/magnet design interaction

Beam dynamics effects

Lessons & Conclusions

# The PAMELA Project

## "Proton Accelerator for MEdicaL Applications"



Aim: "to design a prototype proton/ion non-scaling fixed field alternating gradient accelerator for medical applications"

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# A collaboration was assembled…

John Adams Institute for Accelerator Science
University of Oxford

John Cobb
Bleddyn Jones
Ken Peach
Suzie Sheehy
Holger Witte
Takeichiro Yokoi

Gray Institute
Mark Hill
Boris Vojnovic

- Lattice Design
- Injection
- Extraction
- Magnet Design
- Medical Requirements
- RF

Brunel University West London

Richard Fenning
Akram Khan

- Gantry
- Beam transport

Imperial College London

Morteza Aslaninajad
Matt Easton
Jaroslaw Pasternak
Juergen Pozimski

- Front end
- Injection line
- Ion sources

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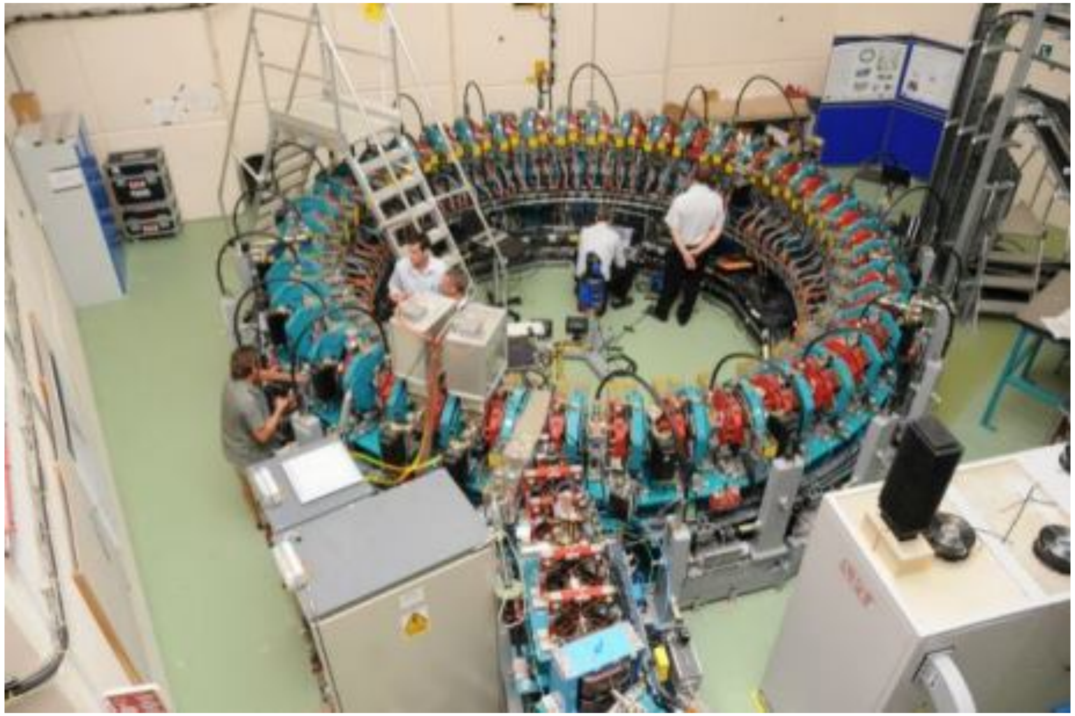
Elwyn Baynham
Neil Bliss
Rob Edgecock
Ian Gardner
David Kelliher
Neil Marks
Shinji Machida
Peter McIntosh
Chris Prior

- RF
- Lattice Design
- Magnets

PTCRi

Ken Peach
Bleddyn Jones
Dr Steve Harris
Dr Claire Timlin
P. Wilson
Dr Mark Hill
Boris Vojnovic
Jim Davies
John Hopewell
Gillies McKenna
Roger Berry
Dr Nadia Falzone
Charles Crichton
Daniel Abler
Tracy Underwood
Daniel Warren

# Many of the collaborators also worked on EMMA



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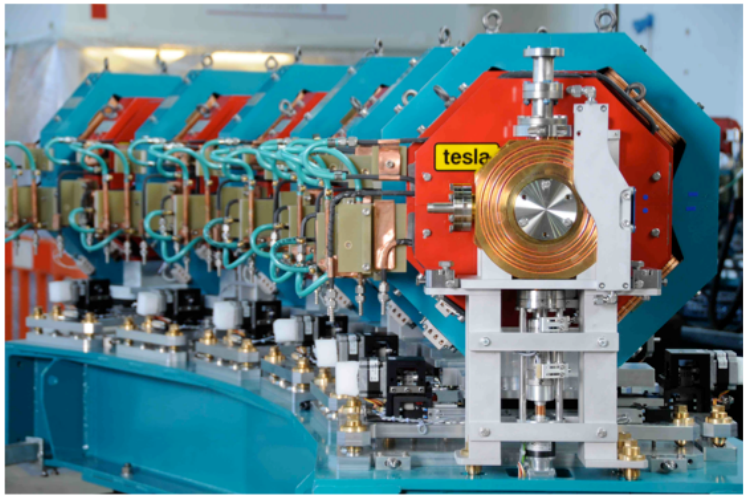
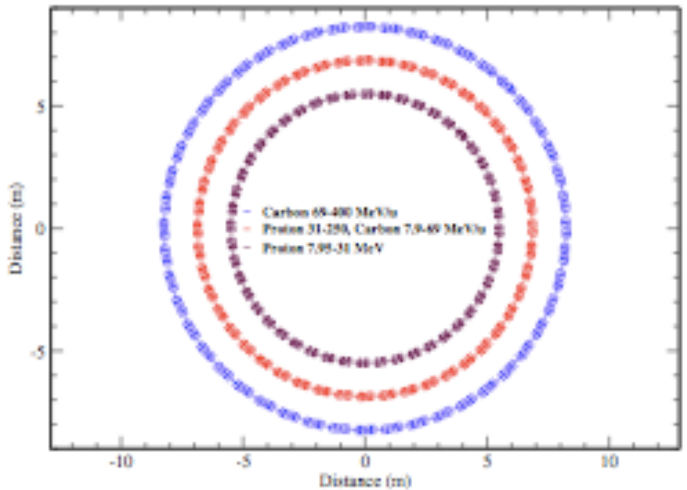
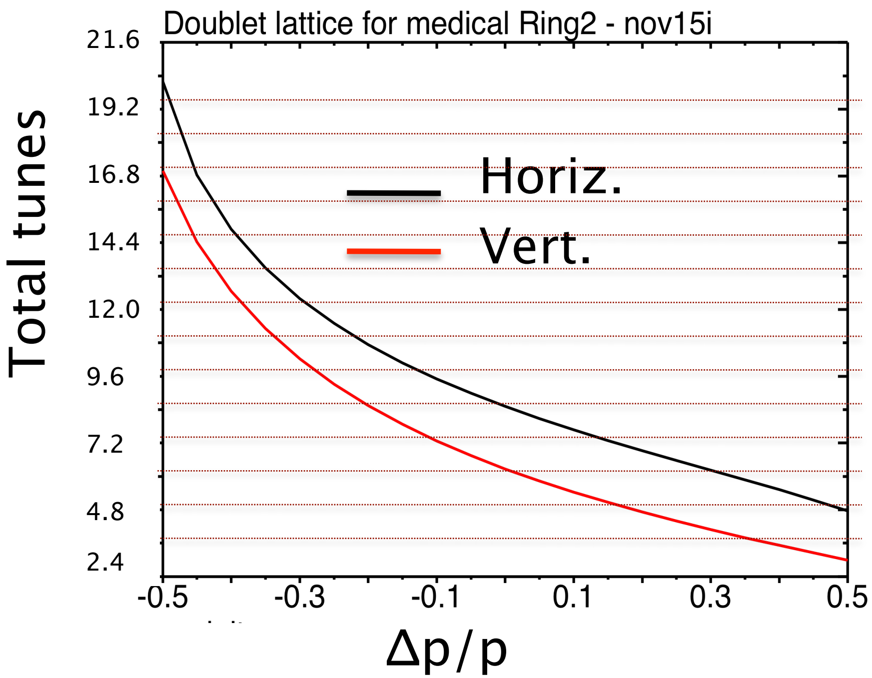
# The simplest approach was to use normal conducting, linear magnets

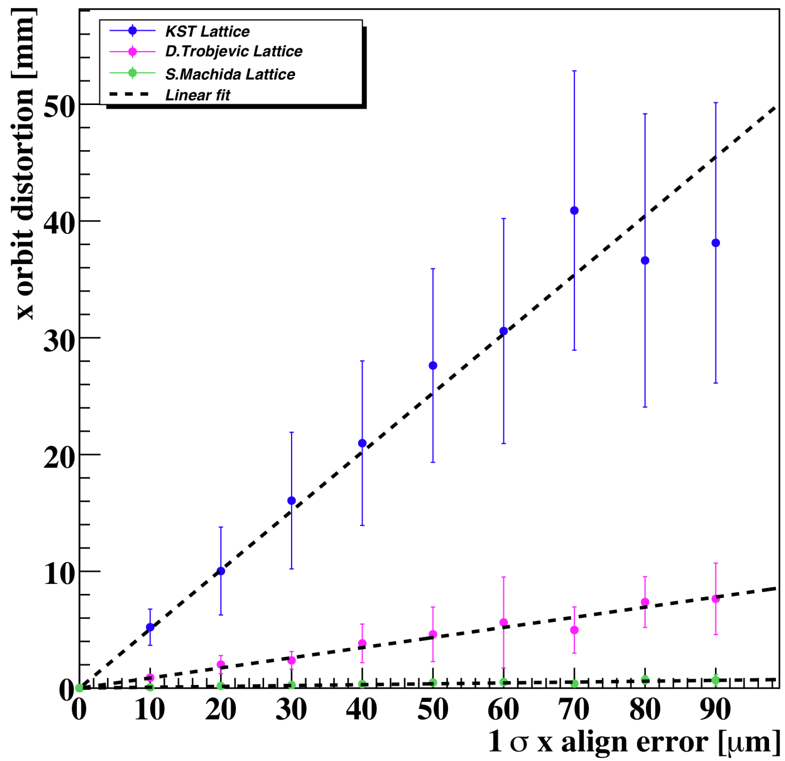



E. Keil, A. Sessler, D. Trbojevic, Phys. Rev. ST-AB, 10, 154701, 2007.

# But we found we wanted to avoid integer resonance crossing




Acceleration in 1000s instead of 10s of turns

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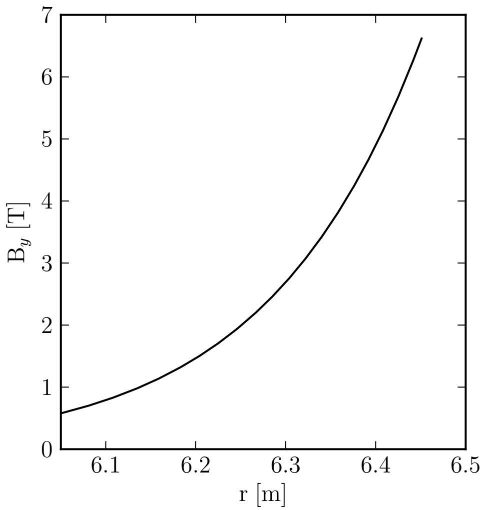
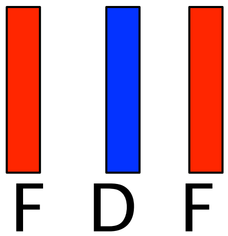
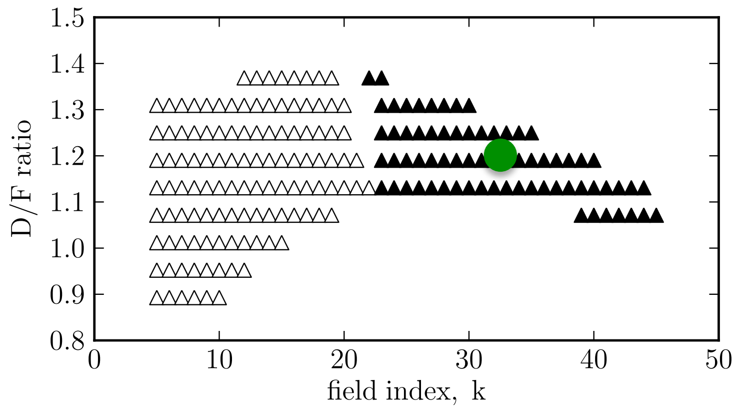
# We wanted something smaller, and simpler than a scaling FFAG

$$B_z = B_0\left(\frac{r}{r_0}\right)^k \Rightarrow \frac{B}{B_0} = 1 + k\frac{\Delta x}{r_0} + \frac{k(k-1)}{2!}\left(\frac{\Delta x}{r_0}\right)^2 + \ldots$$ (truncated)



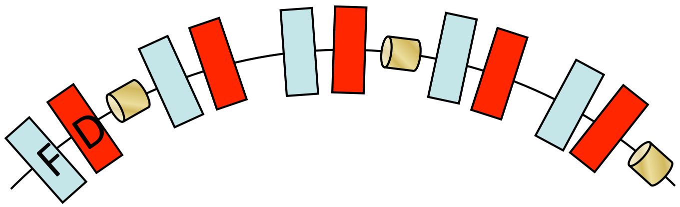



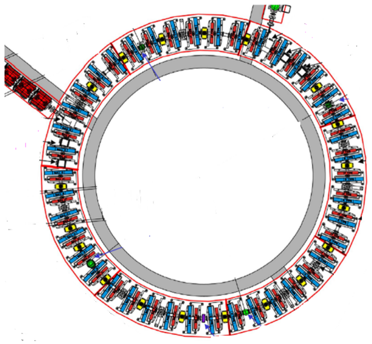

180° < Horizontal phase advance < 360°

Vertical phase advance <180°

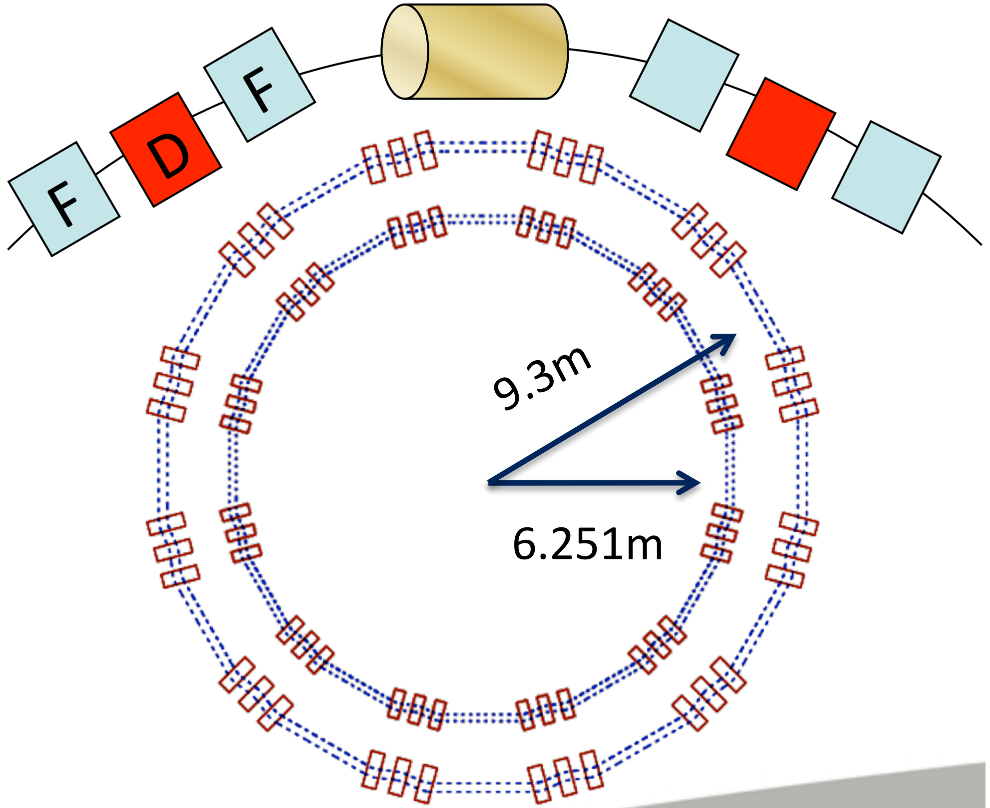
# We also needed space to inject & extract

## EMMA



## PAMELA

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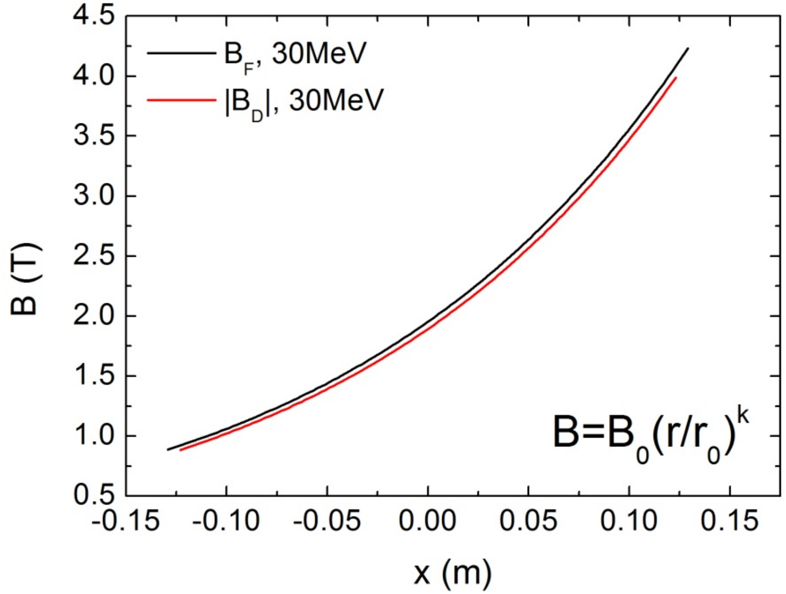
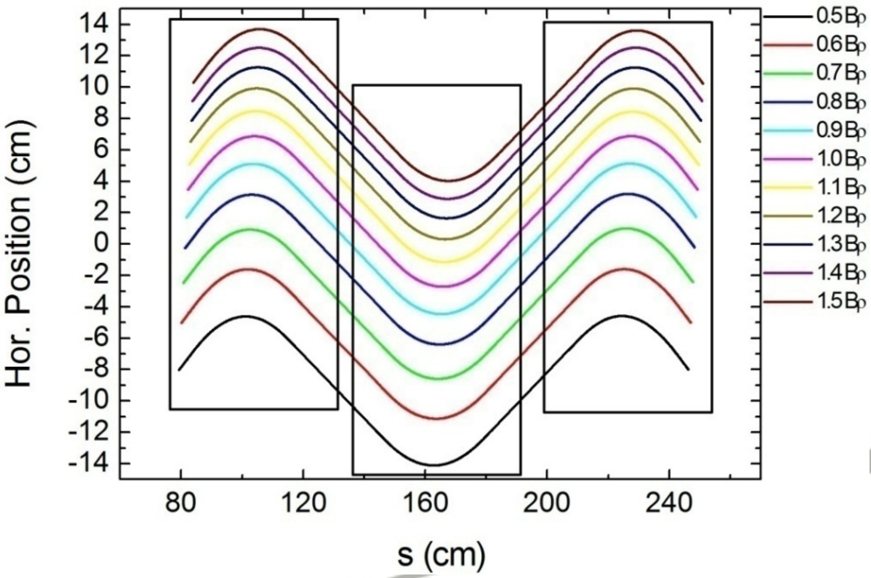
# The design required strong magnetic fields



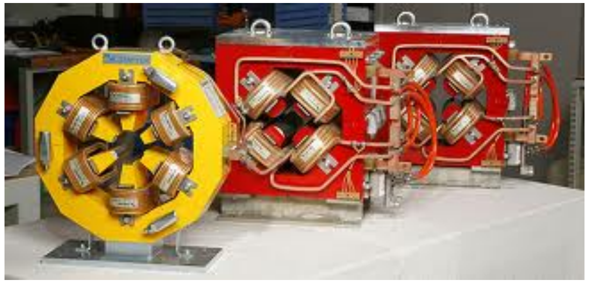




Maximum field (4.25T)

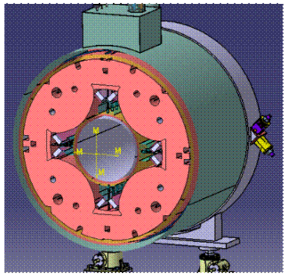
Length restriction (550 mm)

Required bore (>250 mm)

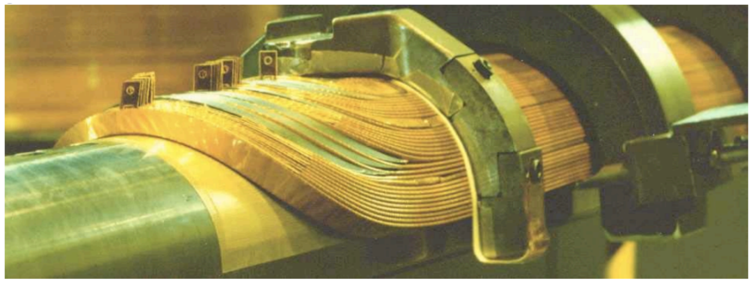
# Superconducting helical coils were 'the only option'



Danfysik.com



www.vecc.gov.in/

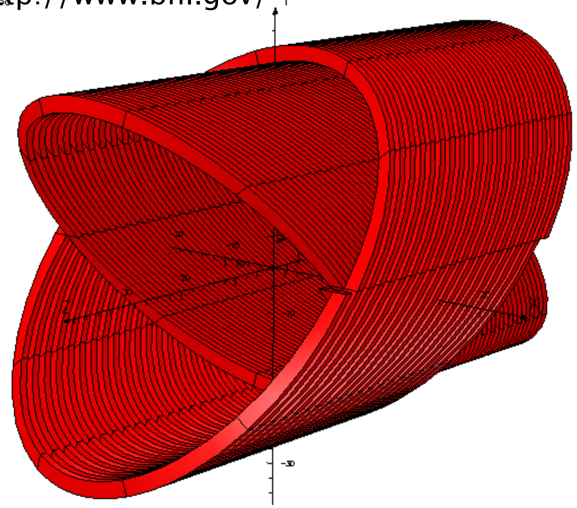


http://www.bnl.gov/

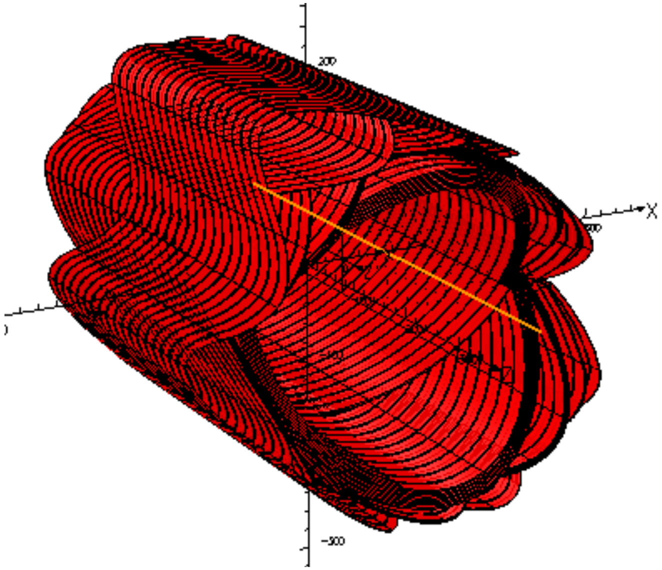
$$x(\theta) = R.\cos(\theta)$$

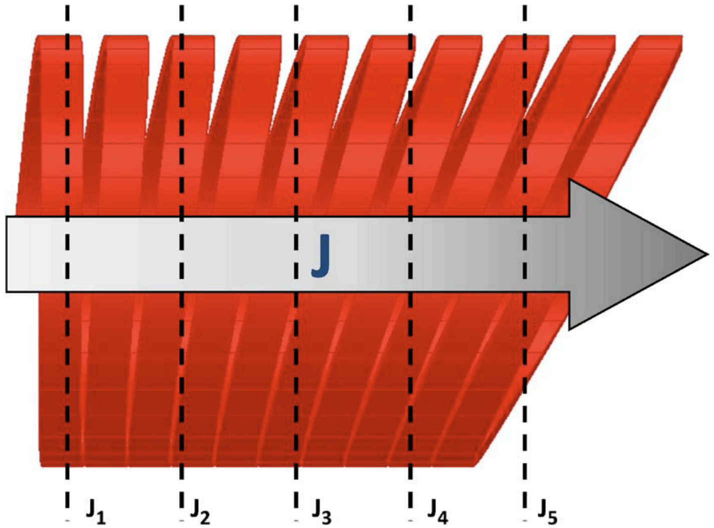
$$y(\theta) = R.\sin(\theta)$$

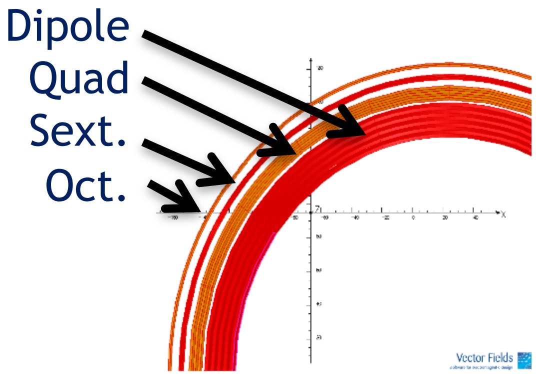
$$z(\theta) = \frac{h\theta}{2\pi} + \frac{R}{\tan\alpha}\sin(n\theta + \varphi_0)$$



# Helical coils are very flexible, high performance and give excellent field quality




$$z(\theta) = \frac{h\theta}{2\pi} + \frac{R}{\tan\alpha}\sum_{n} \varepsilon_n \sin(n\theta)$$

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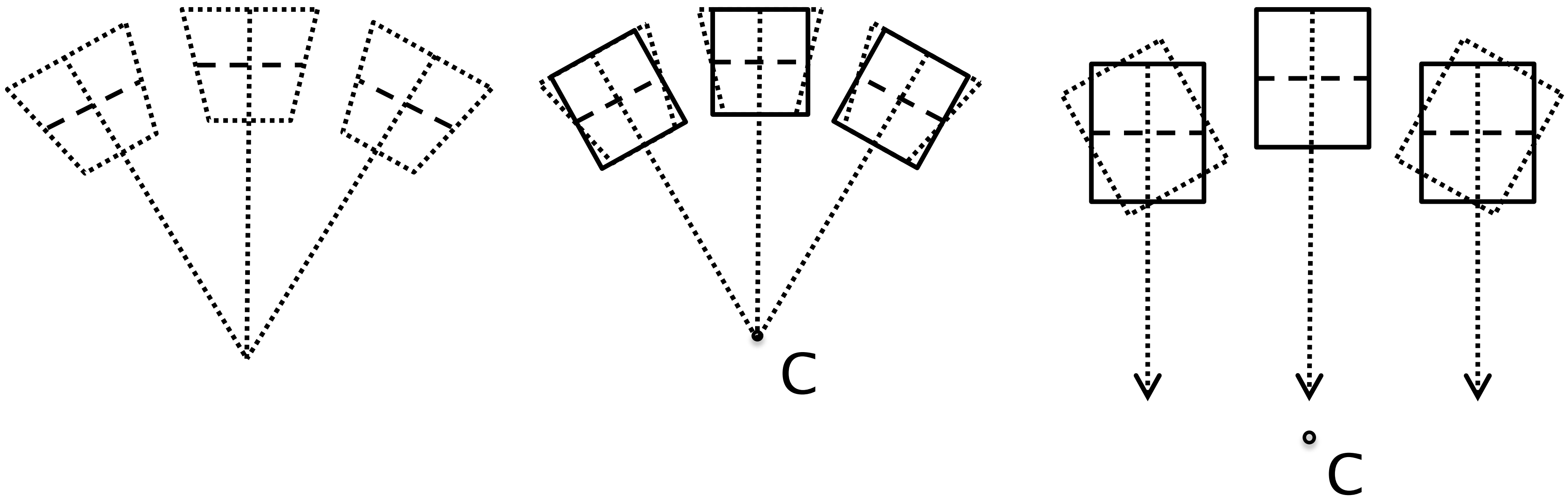
# The choice of magnet and layout made big changes in the dynamics



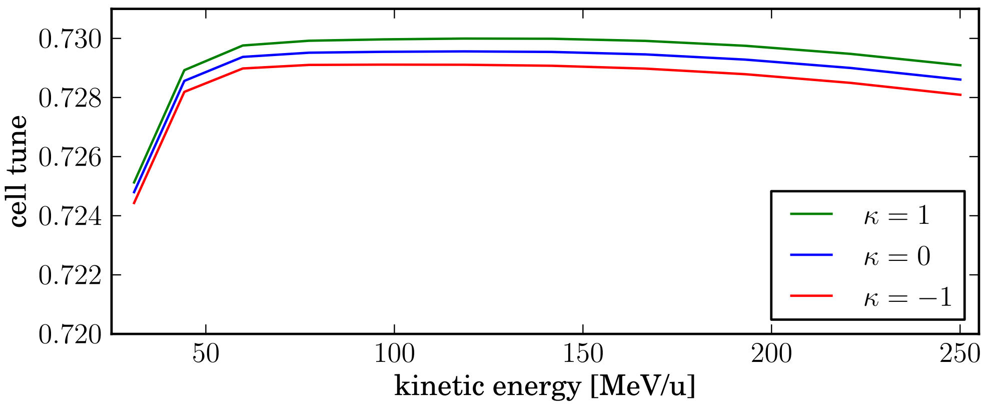

ΔQh=0.057
ΔQv=0.017

ΔQh=0.042
ΔQv=0.300

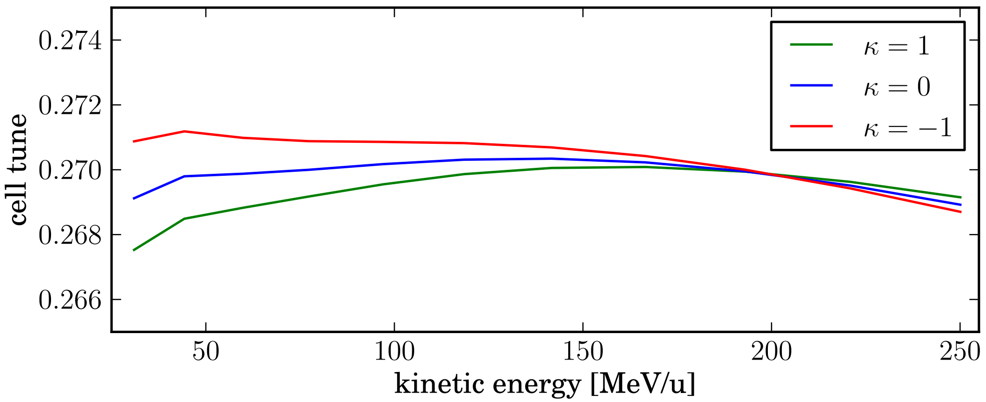
ΔQh=0.050
ΔQv= 0.250

Using up to decapole

# We already knew fringe fields would play an important role




horizontal




vertical

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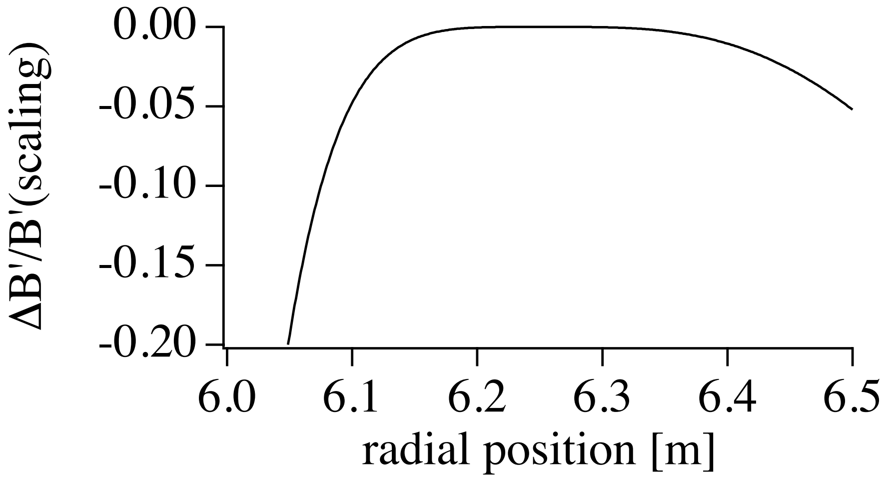
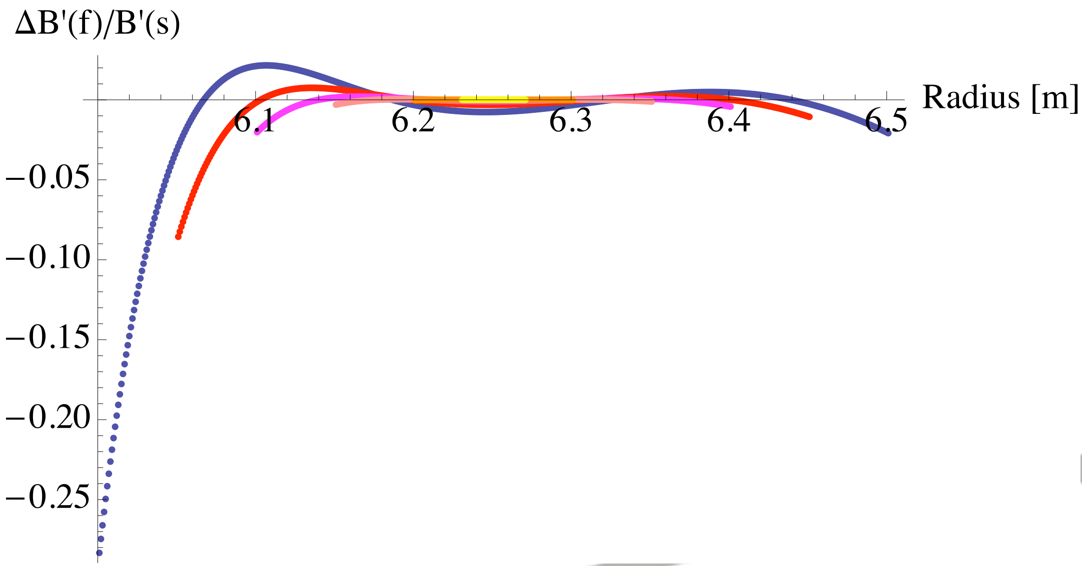
# How to determine multipole coefficients?



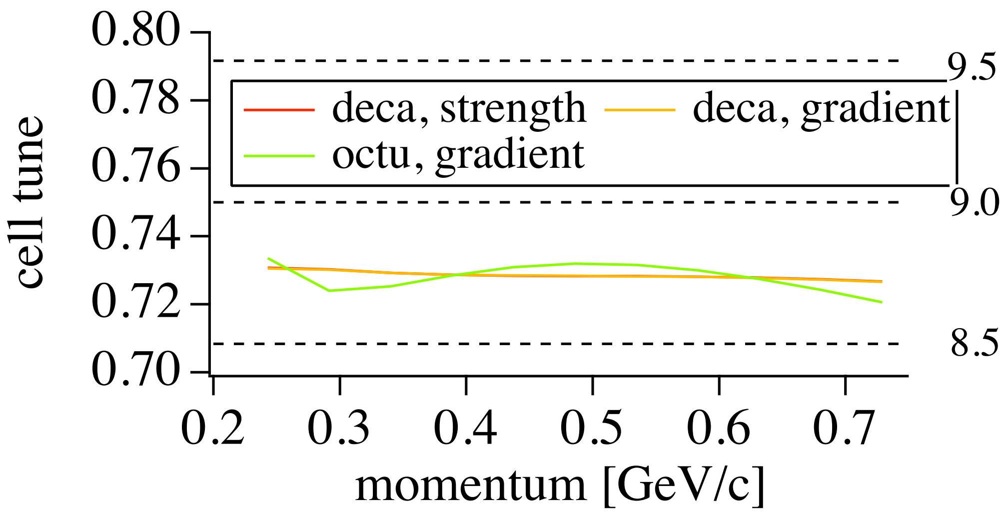




Taylor expansion around a point?

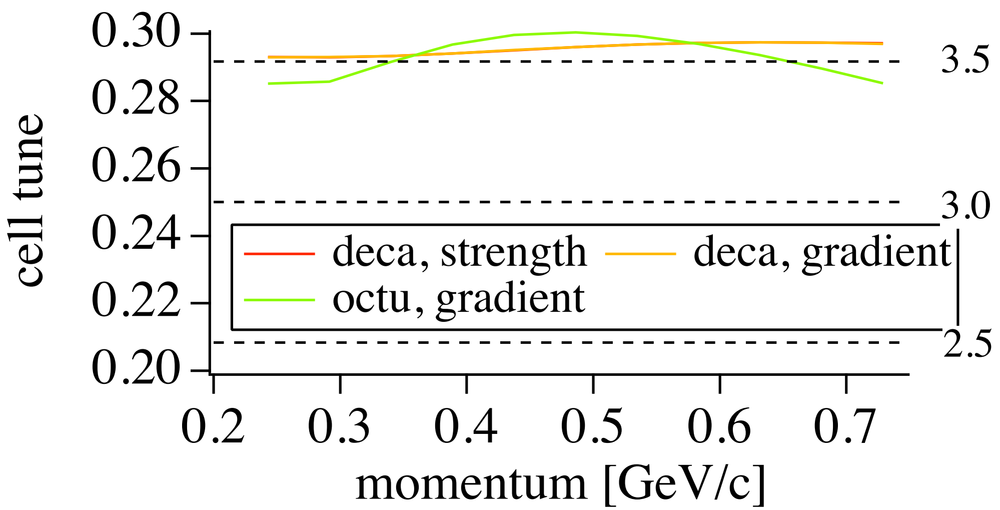
Or polynomial fit in a region?

Should you fit the field value or gradient?

Total tune variation:
(for decupole case)
ΔQh=0.049,
ΔQv=0.054




Total tune variation:
(for octupole case)
ΔQh=0.156,
ΔQv=0.182

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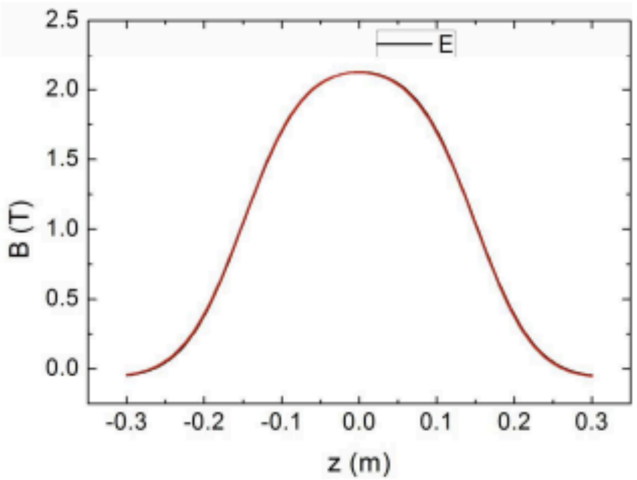
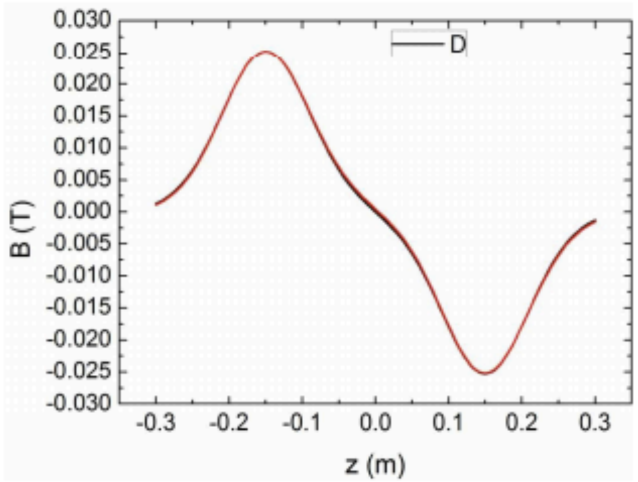
# We wanted to have more confirmation, so needed 3D field maps QUICKLY!

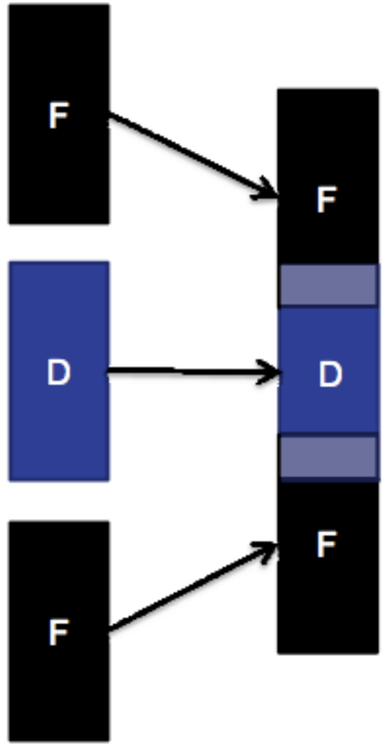
**By**




**Bx**

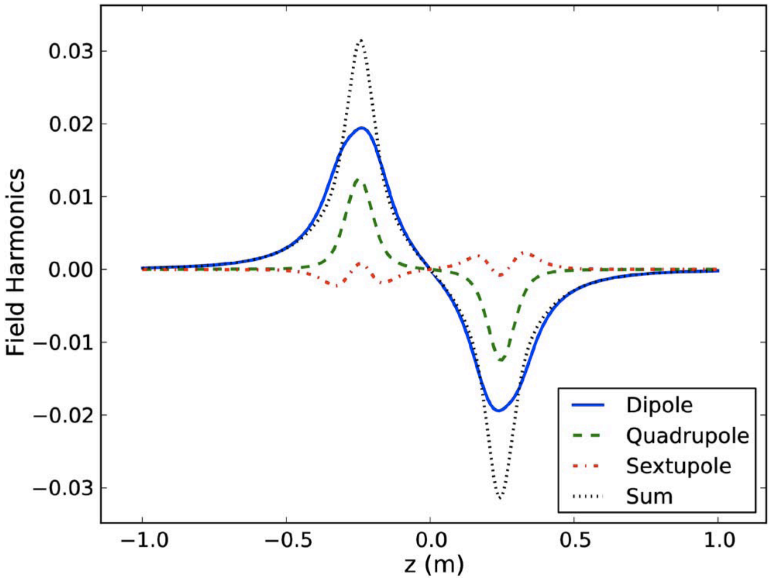


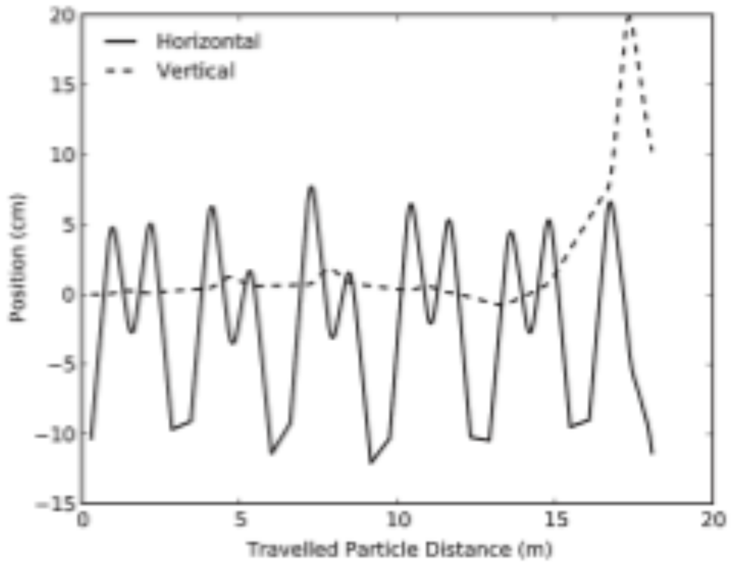

Centre of Coil – x=y=0




New field maps in minutes, not months!

# When we moved to using 3D field maps, we found a problem…

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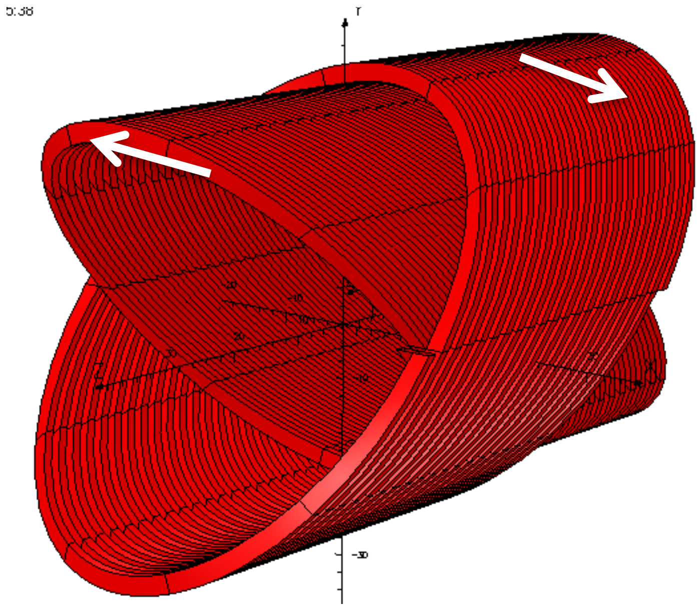
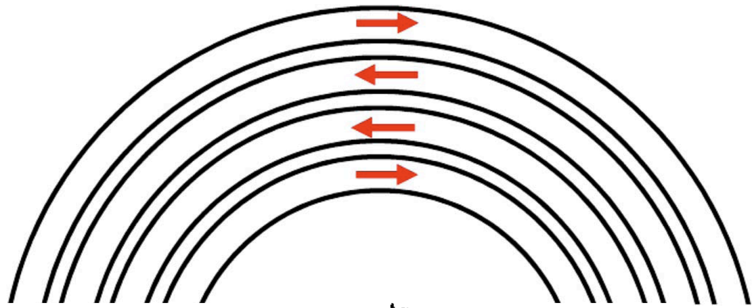
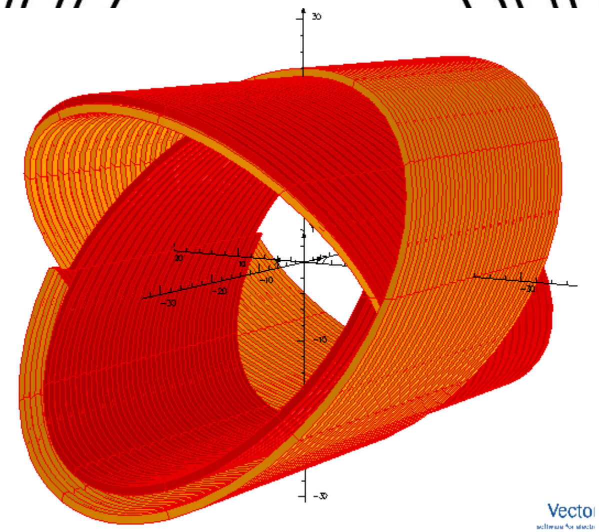
# New challenge brought forth new ideas (from the magnet designer, of course!)

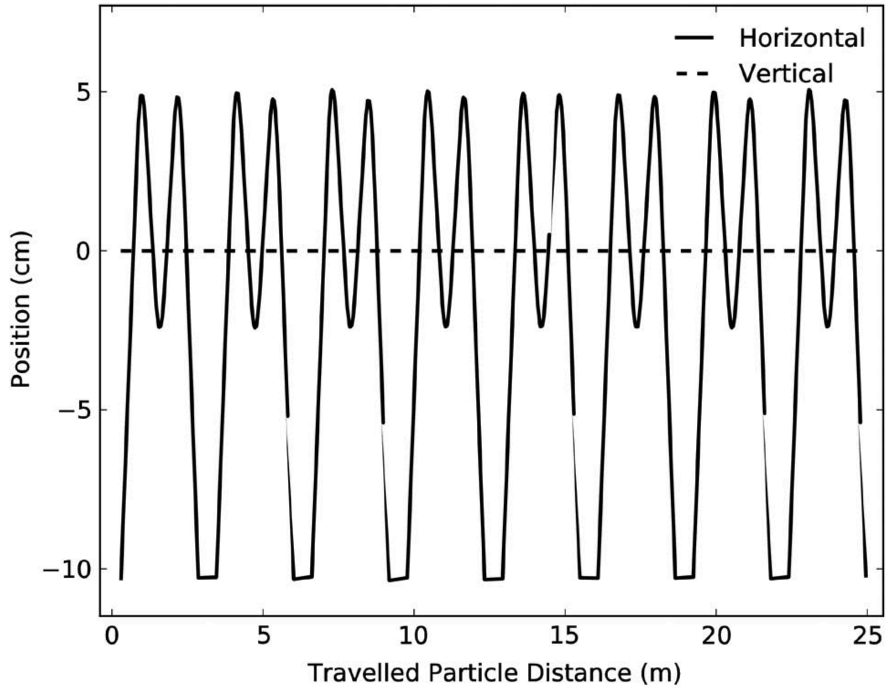






H. Witte, 2010
Patent GB 0920299.5
ISIS Innovation, Oxford University

# This solved the problem

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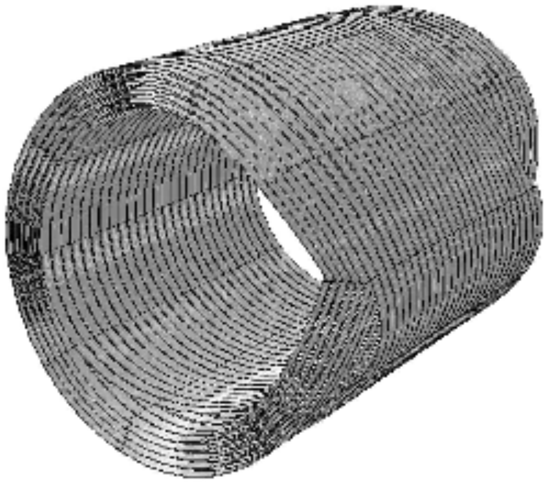
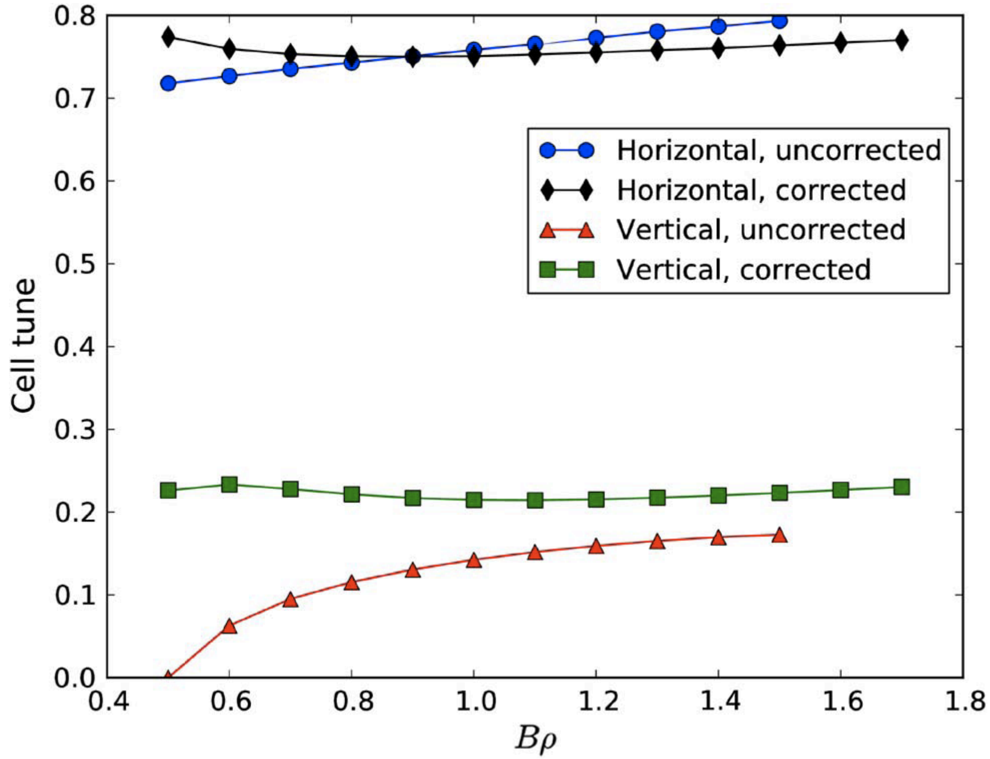
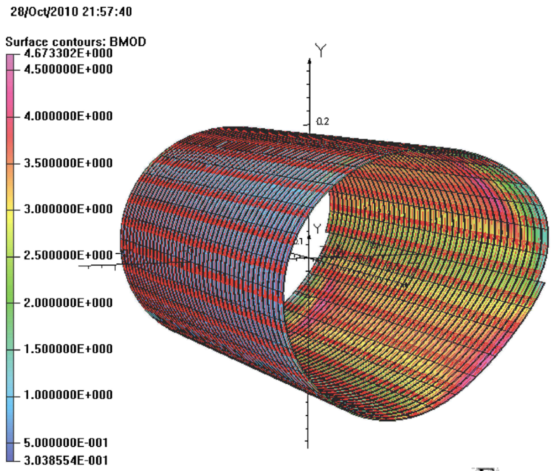
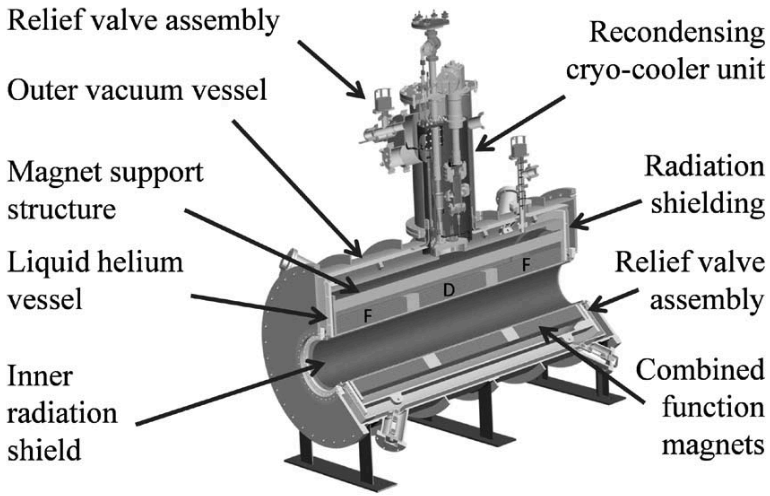
# The fringe-field effects of these magnets are not Enge-like. But we can correct for that.



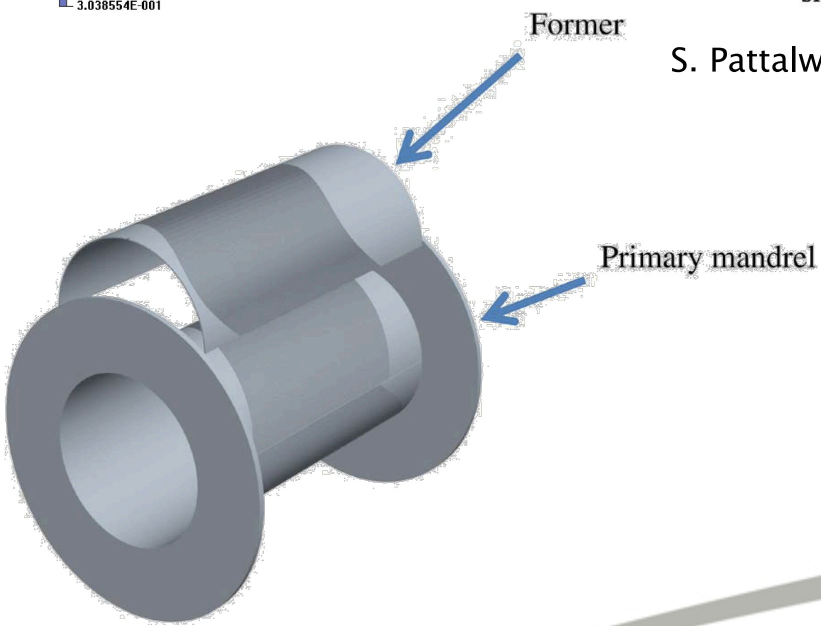


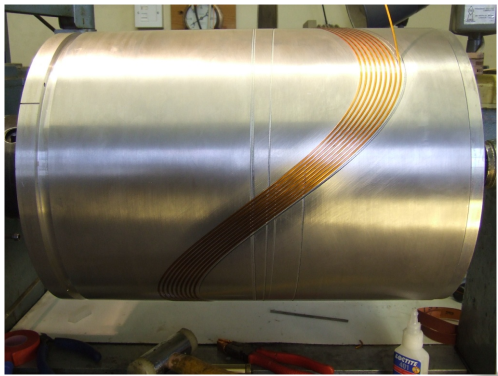
# Implementation looks achievable




S. Pattalwar, T. Jones, J. Strachan and N. Bliss



Thanks to Oxford Physics Mechanical Design Office & Magnet Group

# This was a real learning experience

Starting out, I thought of magnet design as a 3 step process:

1. Put my requirements in
2. Get a design + messy stuff out
3. Ignore messy stuff until the last possible moment

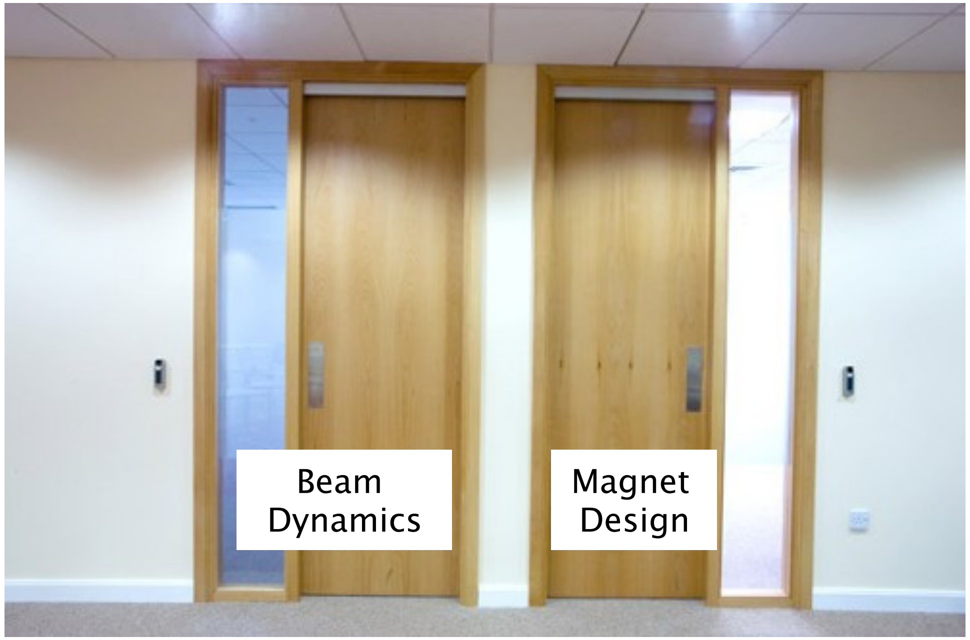
I imagined that if a 'magnet design' person worked hard enough, they would give me (within a small tolerance) the field I wanted.

**How wrong I was!**

This experience taught me to talk to a magnet designer at every point in the process of doing 'something new'.

# Communication is crucial

(We all know this already!)

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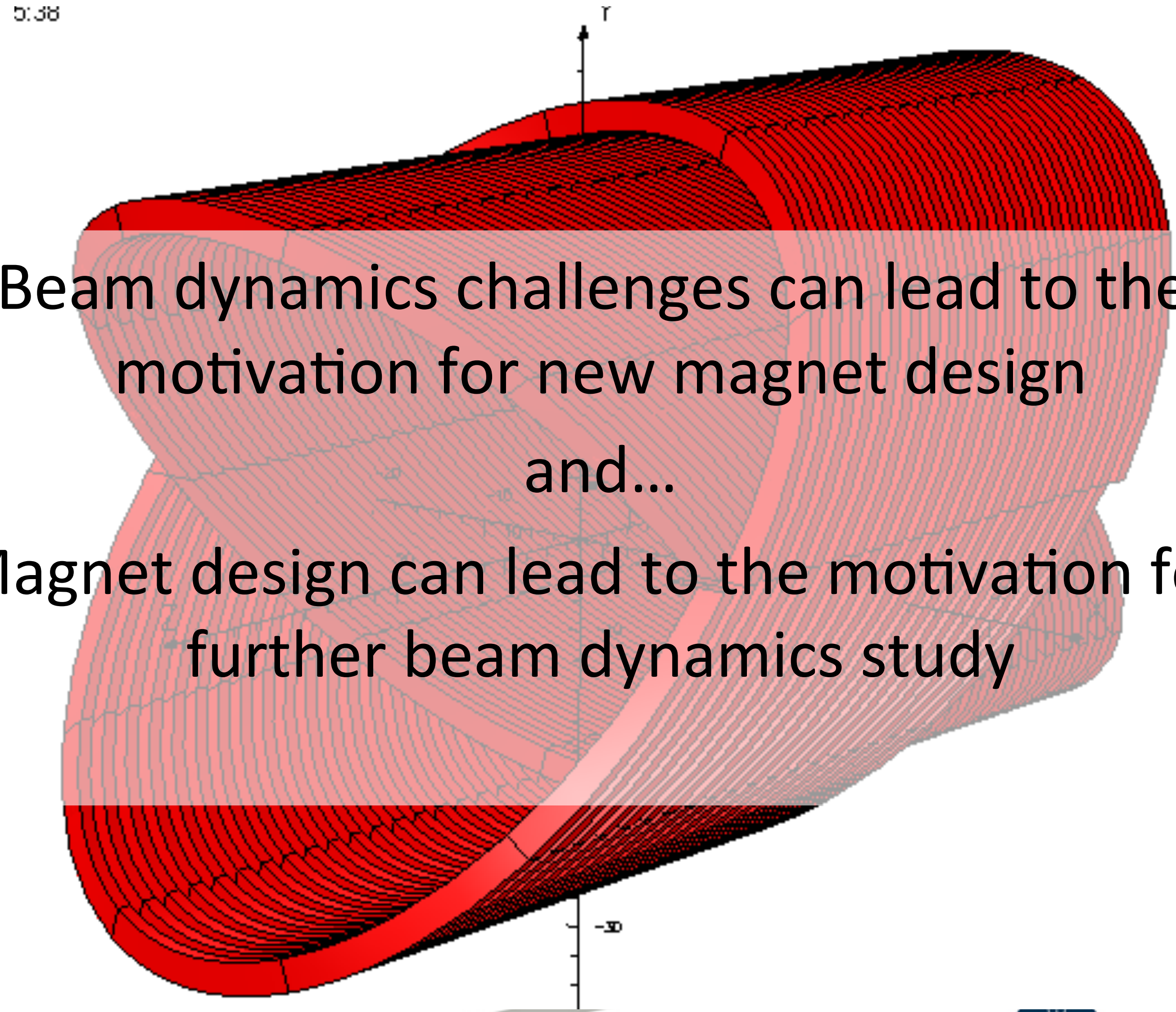

Beam dynamics challenges can lead to the motivation for new magnet design

and…

Magnet design can lead to the motivation for further beam dynamics study

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**PAMELA project overview:**

K. J. Peach et al., *Conceptual design of a nonscaling fixed field alternating gradient accelerator for protons and carbon ions for charged particle therapy*, Phys. Rev. ST Accel. Beams, 16, 030101, (2013).

**Helical coil magnet design:**

H. Witte, T. Yokoi, S. L. Sheehy, K. J. Peach, S. Pattalwar, T. Jones, J. Strachan, N. Bliss, *The Advantages and Challenges of Helical Coils for Small Accelerators – A Case Study*, IEEE Trans. Appl. Superconductivity, 22 (2), April 2012.

**Lattice Design:**

S. L. Sheehy, K. J. Peach, H. Witte, D. J. Kelliher, S. Machida, *Fixed field alternating gradient accelerator with small orbit shift and tune excursion*, Phys. Rev. ST Accel. Beams, 13, 040101, (2010).