Non-Scaling FFAG Magnet Challenges

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BASROC and CONFORM

BASROC:

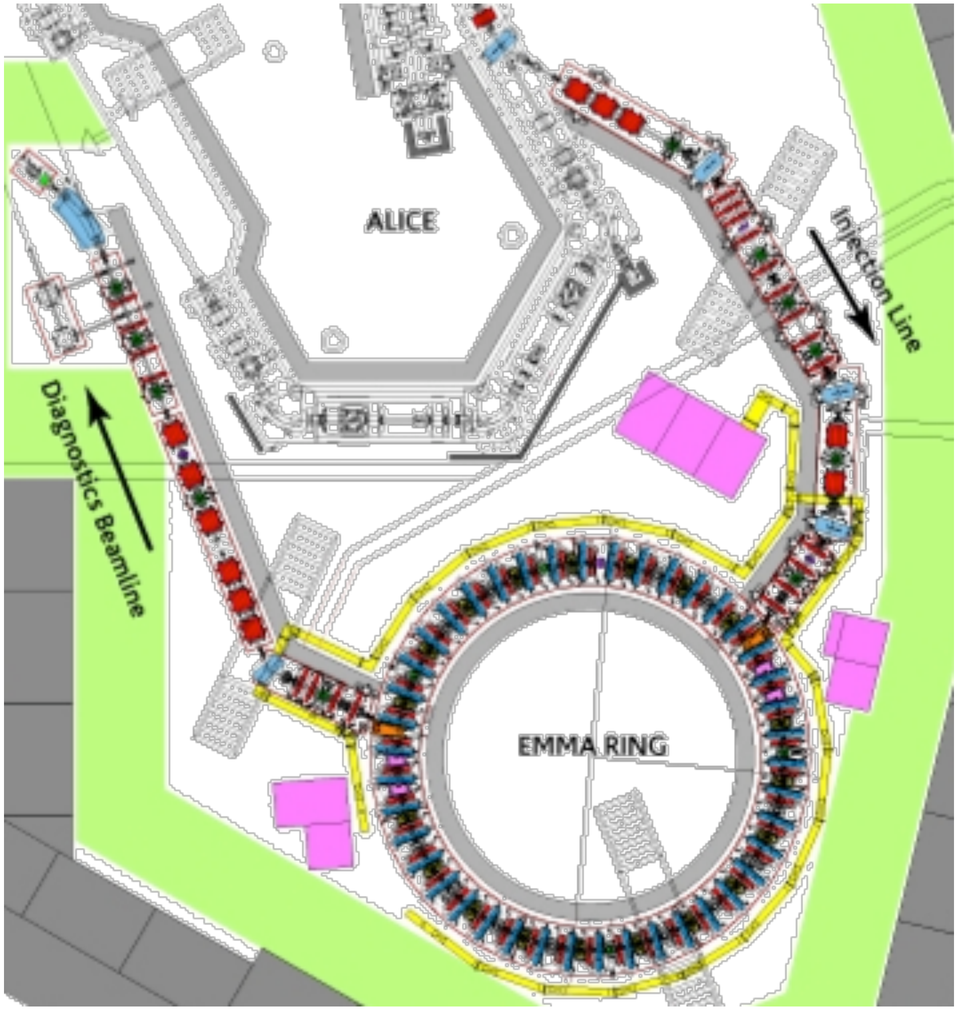
- British Accelerator Science and Radiation Oncology Consortium;
- a group of academic, medical and industry specialists;
- the current aim - the construction of a hadron therapy facility.;
- an FFAG is favoured;
- now focused on 'non-scaling' alternative (nsFFAG) - much reduced apertures;
- set up '**CONFORM**'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

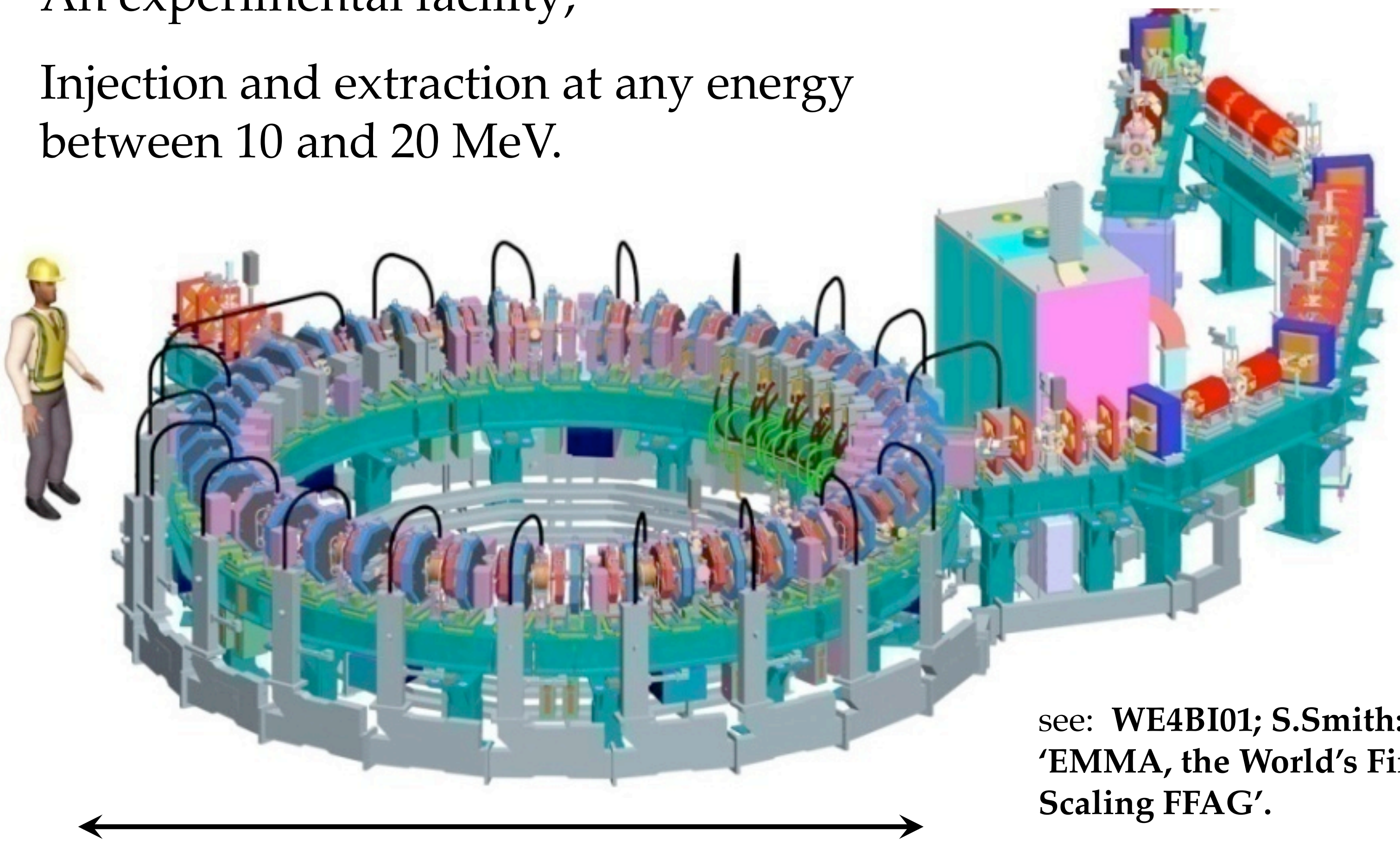
The EMMA concept



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'.**

EMMA Magnet requirements

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

Parameter	F magnet	D magnet	
Bend angle for 15 MeV orbit	- 0.499	0.199	radians
B length	55	65	mm
Max. dipole flux density	0.0302	0.102	T
Max. quadruole gradient	9.3	5.8	T/m

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: <u>conventional quadrupole located off-centre to provide dipole component:</u>

- adjust quadrupole field by coil current;
- move quadrupoles radial to adjust dipole.

Resulting quadrupole parameters

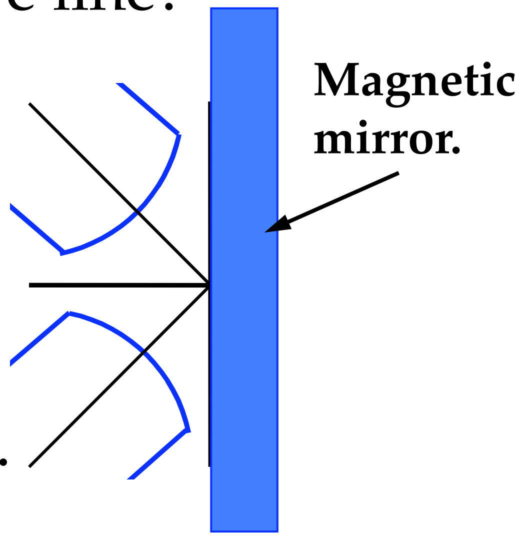
Parameter	F quad.	D quad	
Inscribed radius	37.0	53.0	mm
Yoke length	55.0	65.0	mm
Offset of 15 MeV beam from magnet centre	7.51	34.05	mm
Horizontal beam movement from 15 MeV orbit	-2.6 to +2.7	-5.3 to +14.5	mm
Good gradient with respect to magnetic centre	-32.0 to +15.8	-56.0 to -9.9	mm

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.

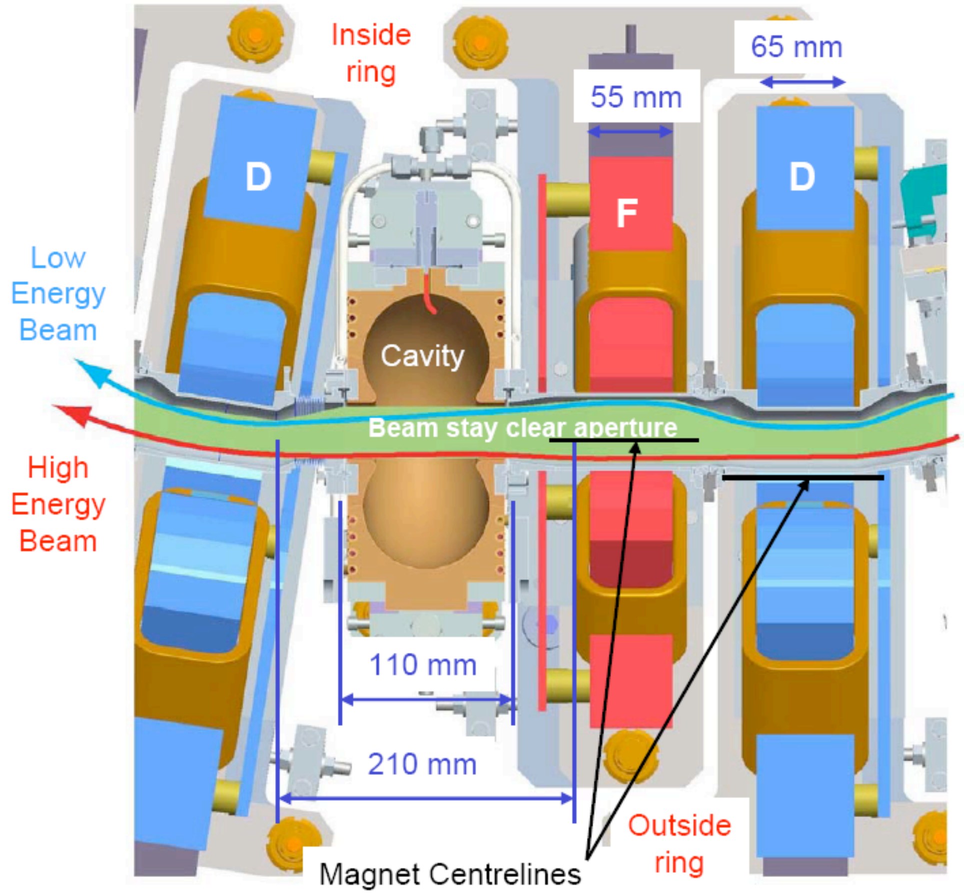
The straight between magnet doublets are very short – 110 mm (inscribed radii are 55 and 65mm!).

So – quad field penetrates into the straights:

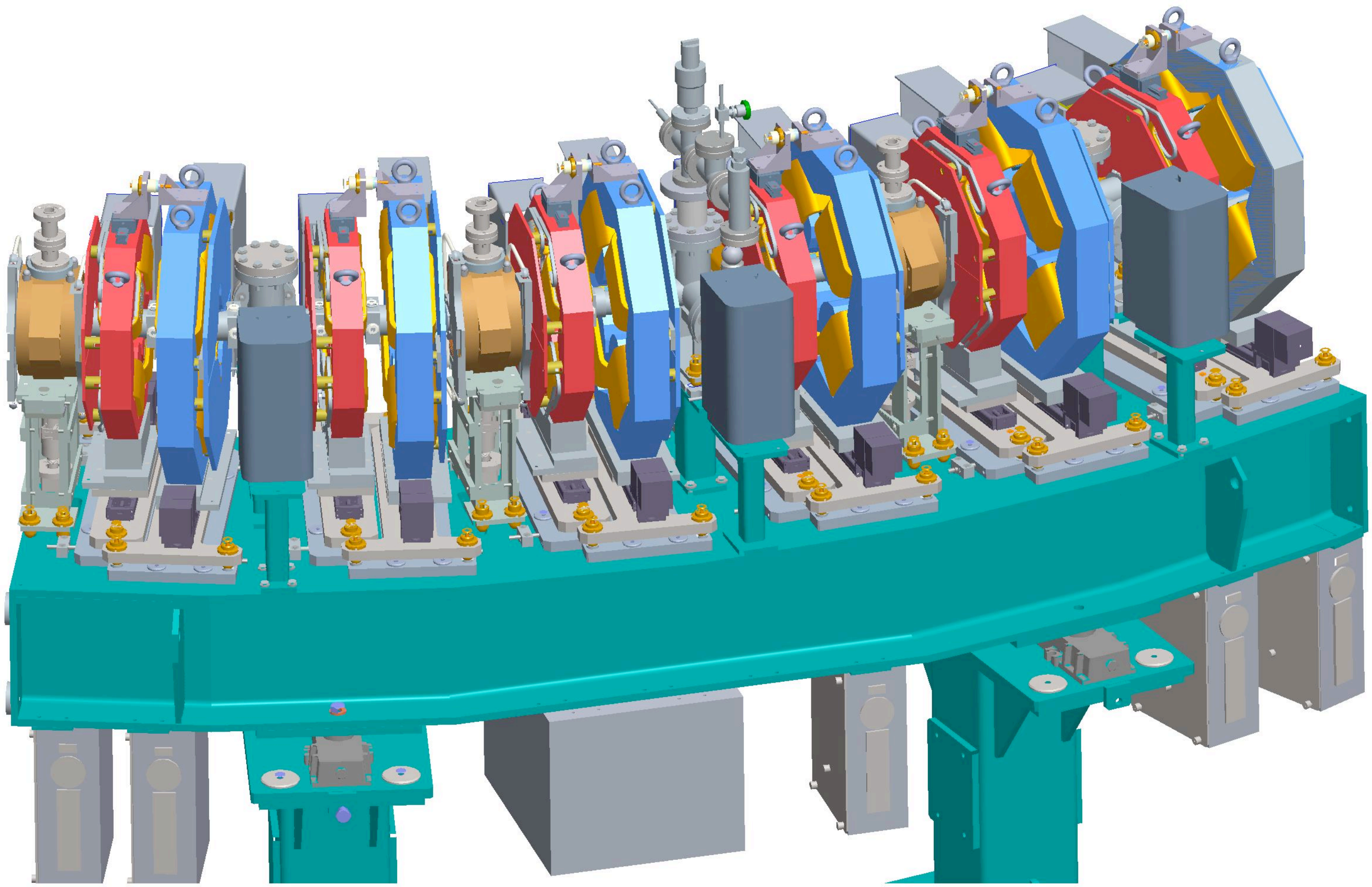
- distorts quadrupole field;
- affects other components (particularly inject/ extract magnets).

Solution: <u>Insert ‘clamp (mirror) plates around each doublet.</u>

The EMMA doublet (plus cavity)



Resulting EMMA layout.



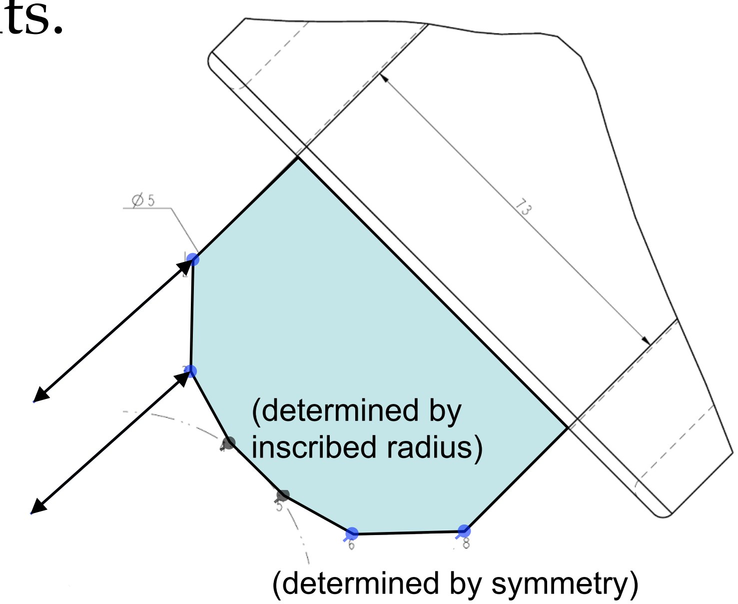
Magnetic design

Very short magnets - ‘all ends and no middle’.

Conventional quad. design (hyperbolas with tangential extensions) gave poor 3D gradients.

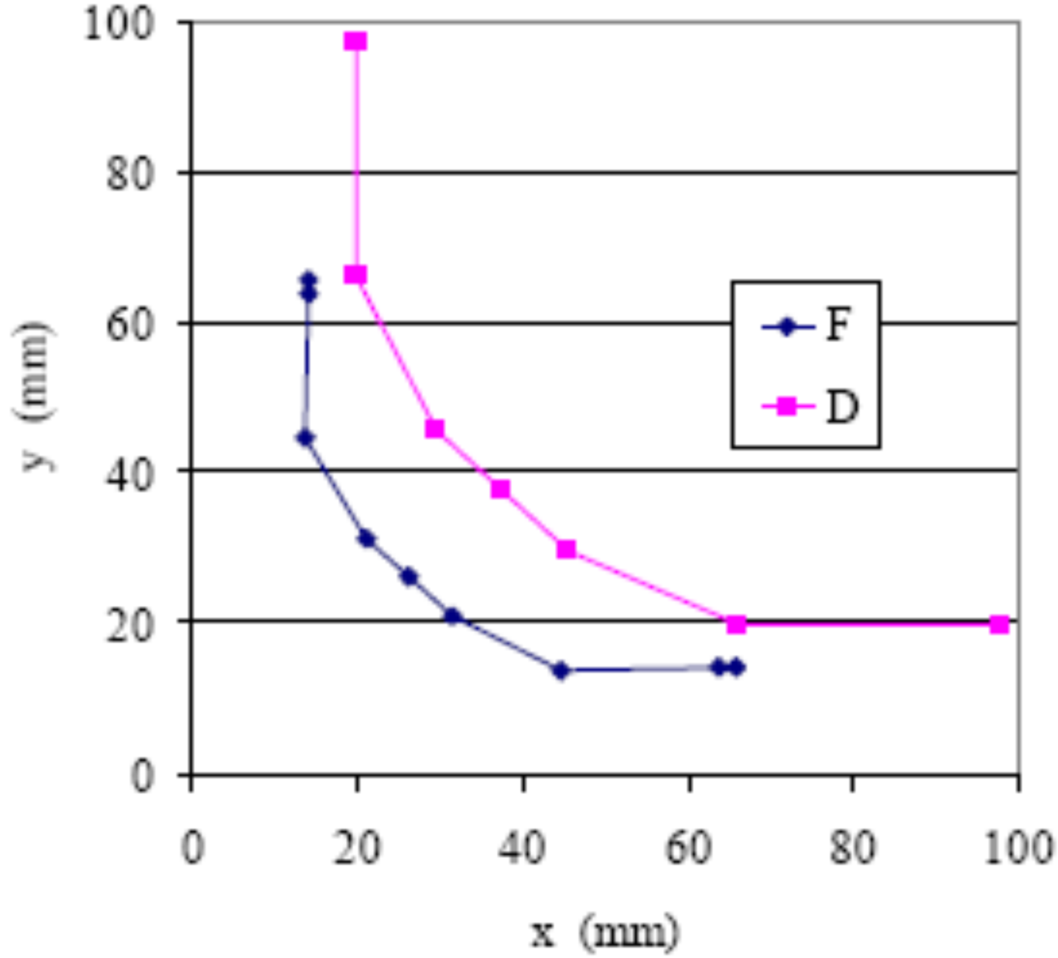
Solution:

- Replace hyperbolic pole face with series of straight lines.
- Adjust positions of vertices to optimise field distribution.



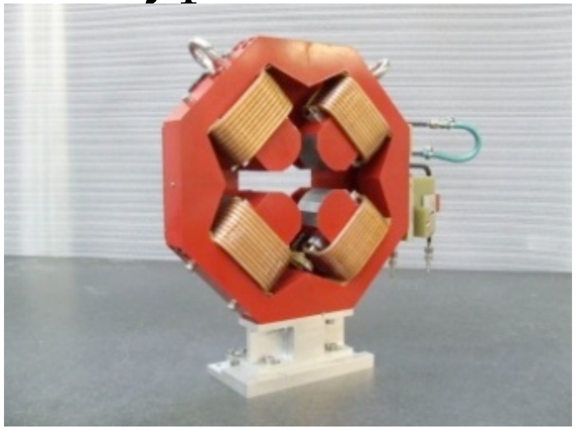
Pole profiles for the F and D magnets

Additional optimisation was carried out on clamp-plate geometries; best solution was to mill clamp-plates with identical shapes to the poles.

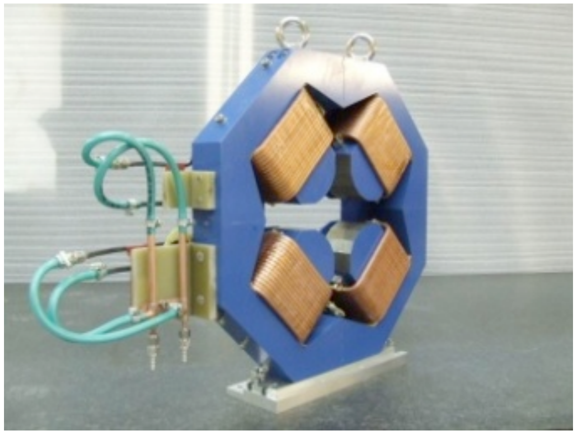


Prototype magnets

Two prototypes were built (*) and measured:



F magnet



D magnet

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.

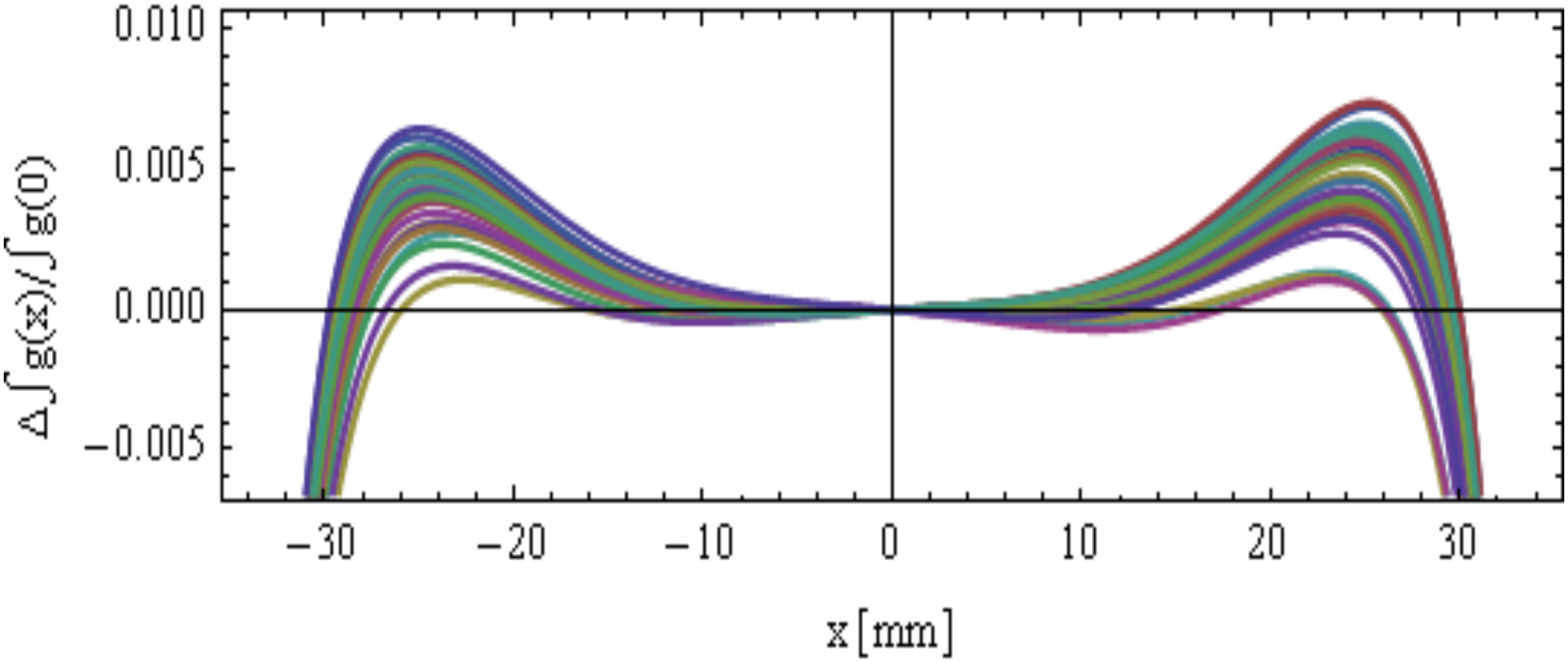
Subsequently the poles of the D were shimmed and achieved similar quality to the F – acceptable.

(*) by **Tesla Engineering,** Storrington, UK

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:

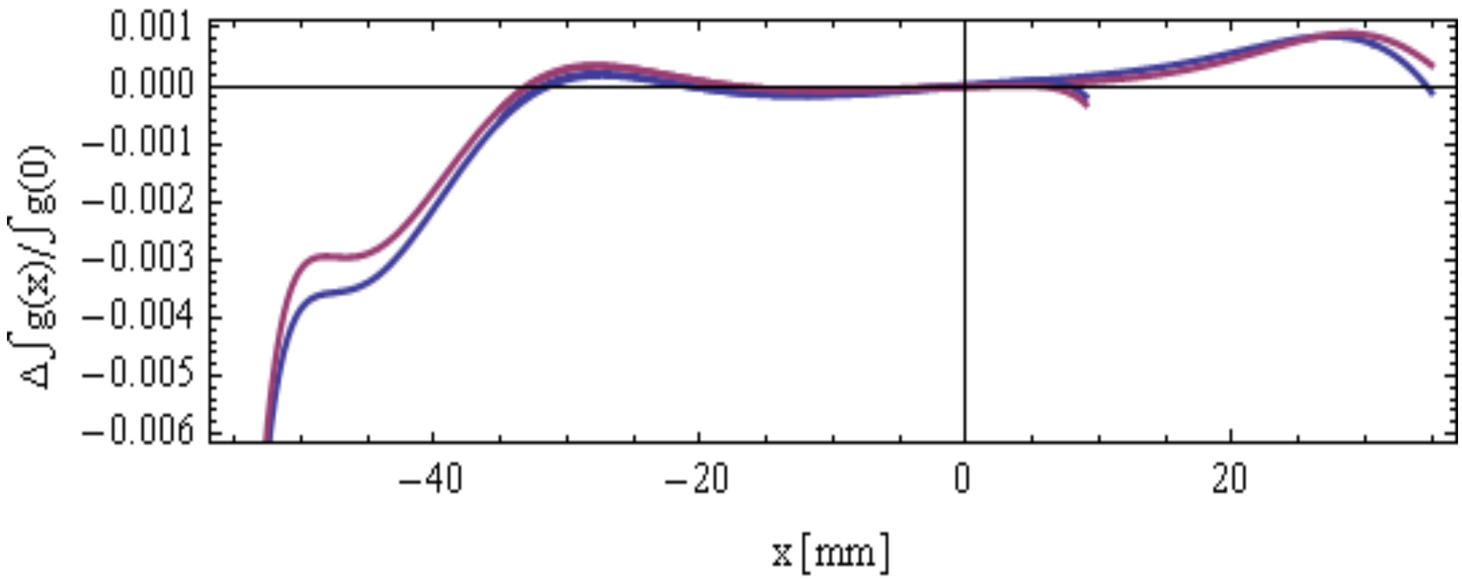


(*) by **Tesla Engineering,** Storrington, UK

Production magnets - Ds

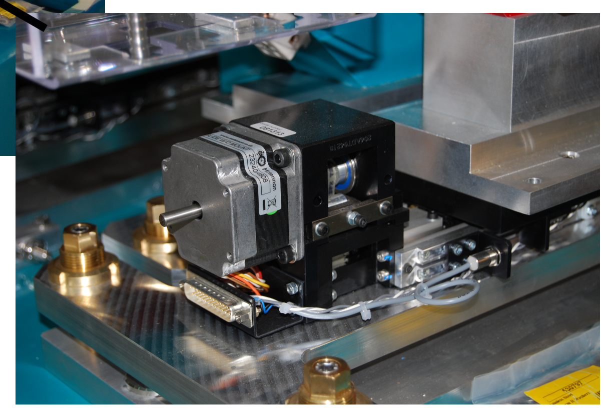
Measurement of the Ds presents problems:

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:



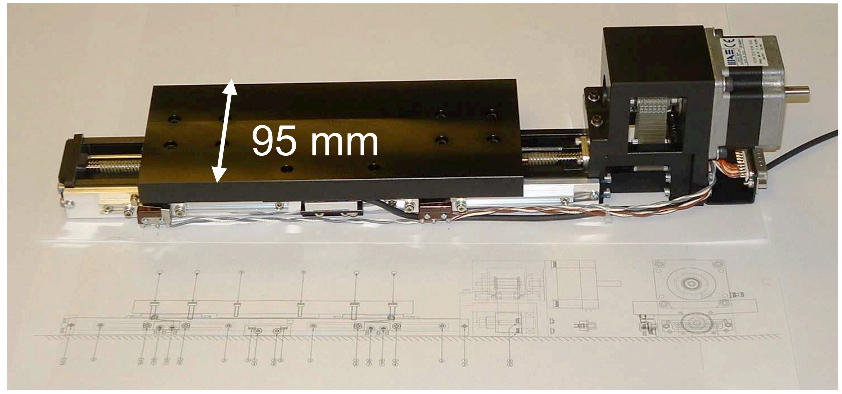
Girder Assembly Commences

Radial movement mechanism



Magnet movement

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



	Range (mm)	Repeatability (μm)	Accuracy (μm)	Resolution (μm)	Backlash (μm)
QF	± 3 (6)	± 3 (6)	± 10 (20)	1	3
QD	+15, -6 (21)	± 3 (6)	± 10 (20)	1	3

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:

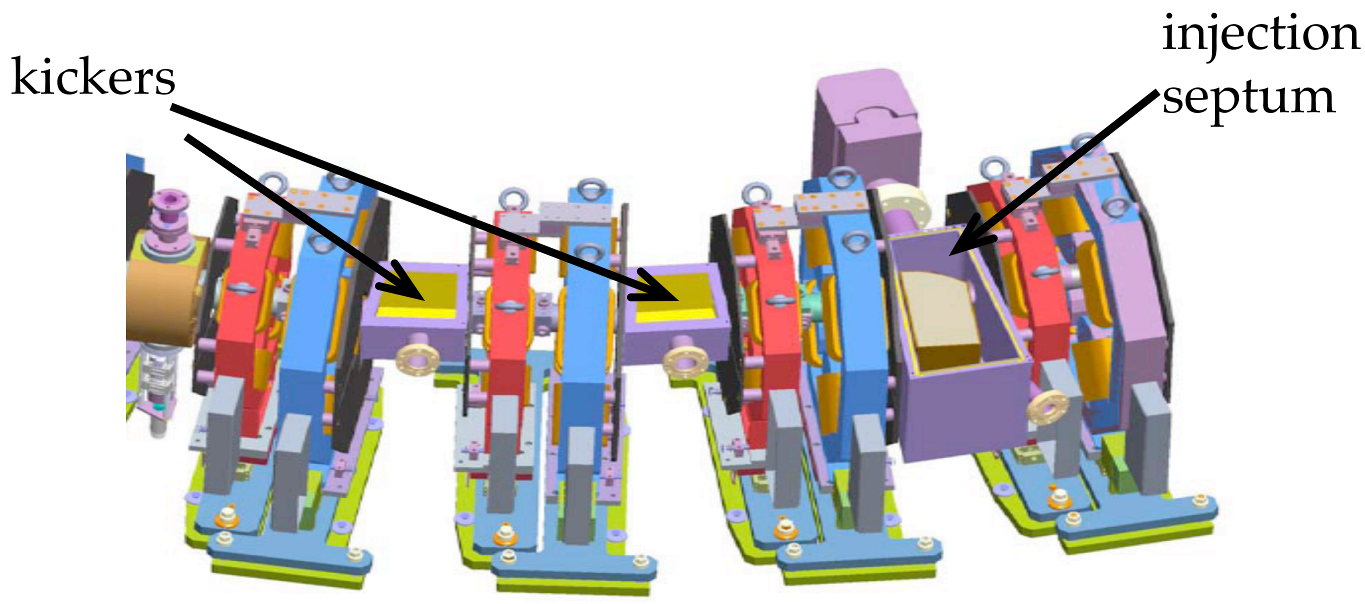
- beam would pass through fringe fields; EMMA is an experimental facility; fields will change so flight path geometry is not fixed;
- magnets are moved to adjust dipole component; beam-line hardware would therefore need to be flexible.

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 ~ 80°



Septum parameters

Magnet is based on:

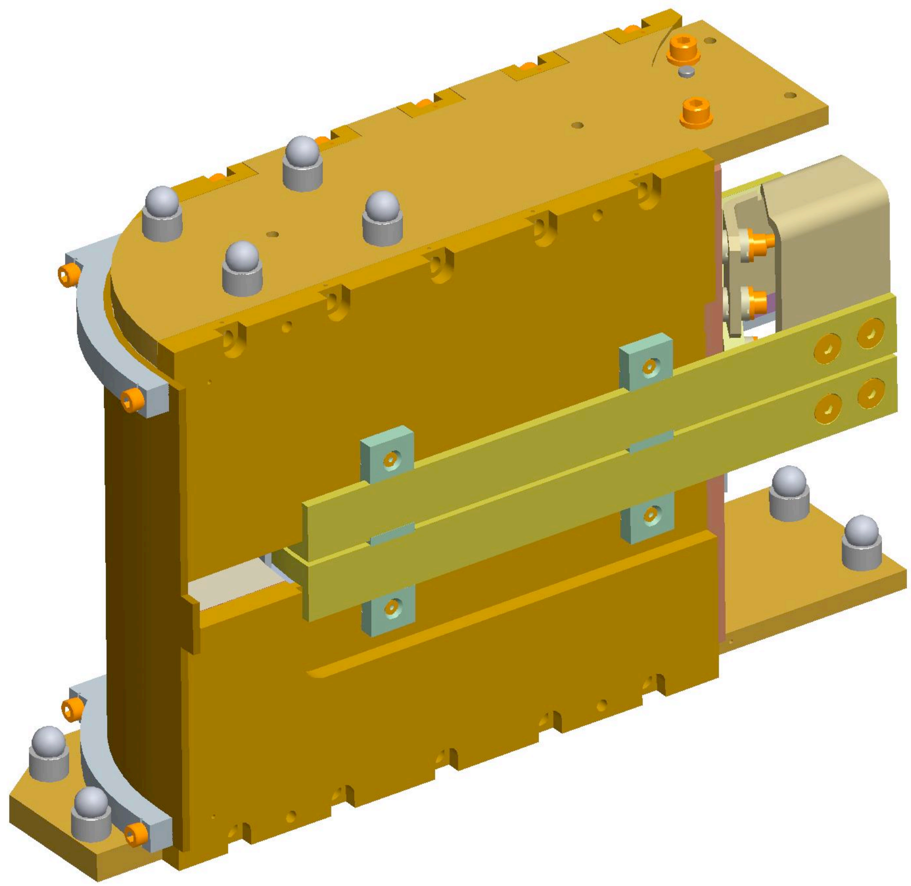
- eddy-current passive septum;
- coil on the back-leg;
- short pulse excitation.

Maximum deflection	77	degrees
Maximum flux density	0.91	T
Yoke length	82	mm
'C core' gap height	22.0	mm
Internal horizontal 'stay-clear'	62.5	mm
Turns on excitation coil	2	
Current pulse half sine-wave duration	25	μs
Pulse peak current	9.1	kA
Pulse peak voltage	900	V
Repetition rate	20	Hz

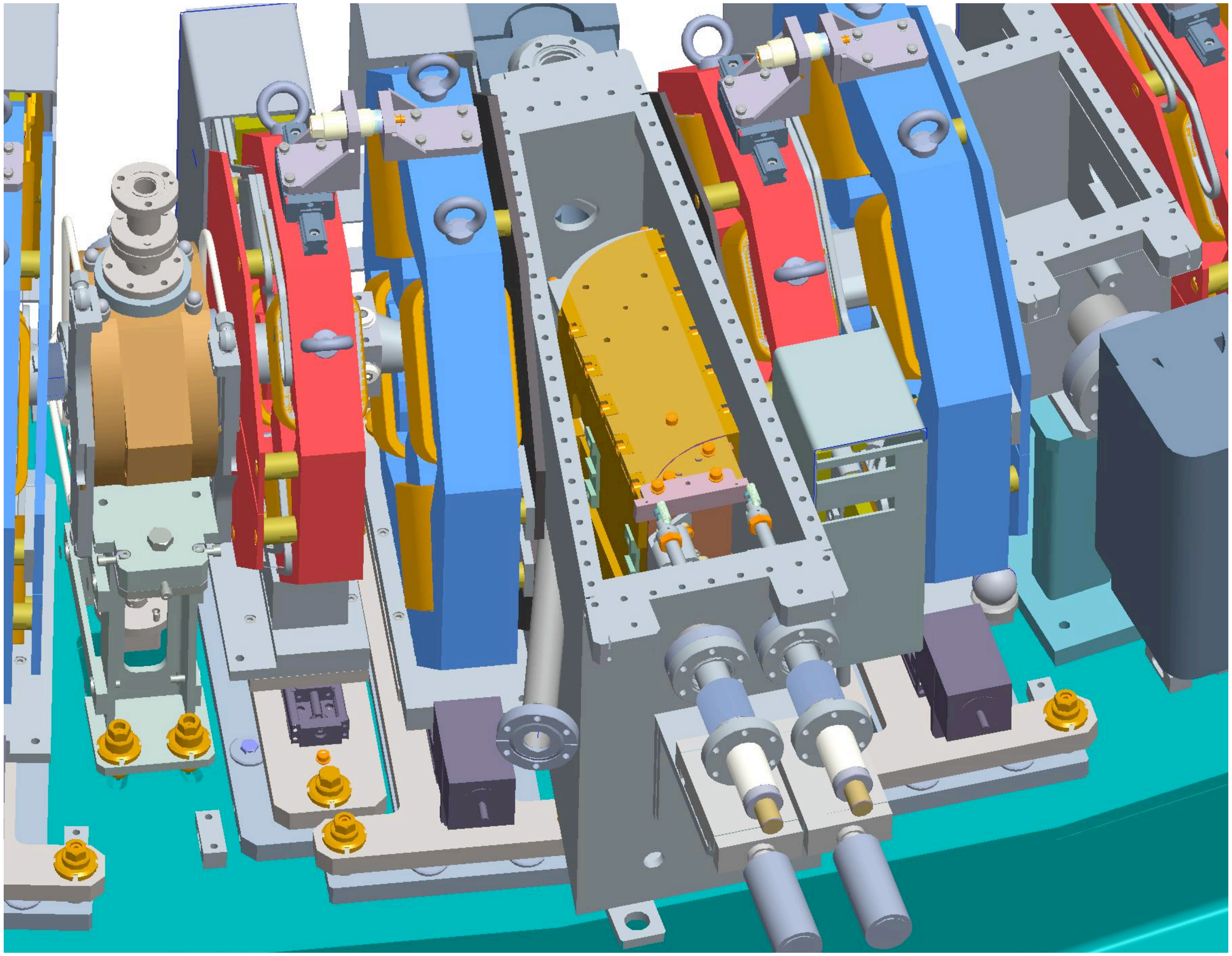
Septum engineering design

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.

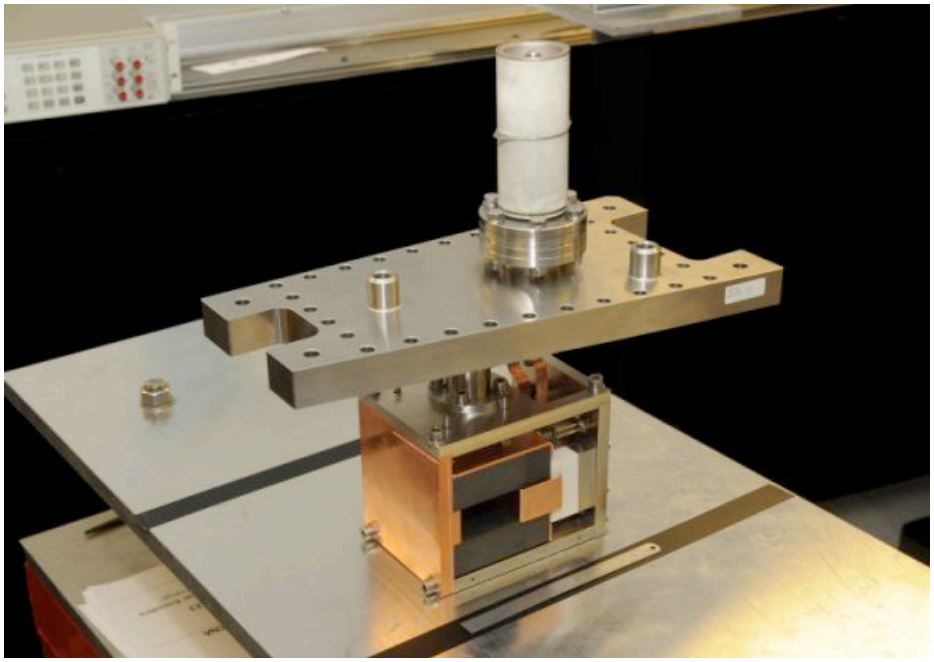


Kicker magnet requirements

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

Kicker magnet engineering

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

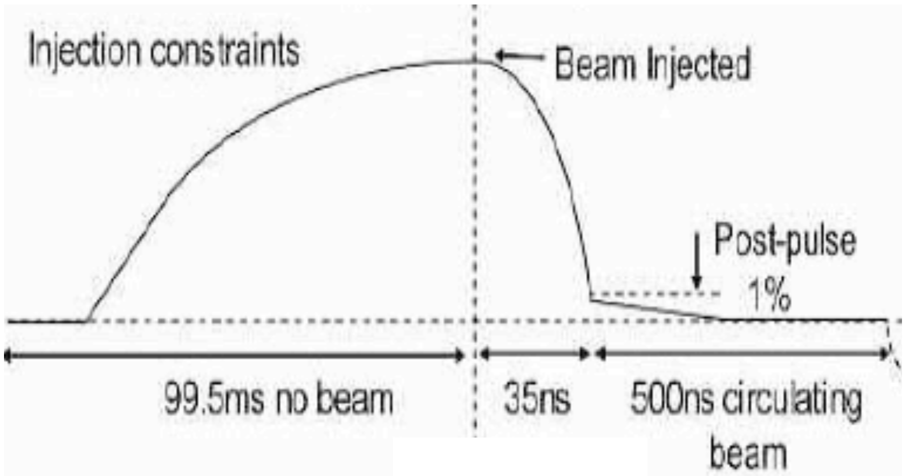


A single turn coil is mounted on the back-leg, with an eddy shield at the C core mouth.

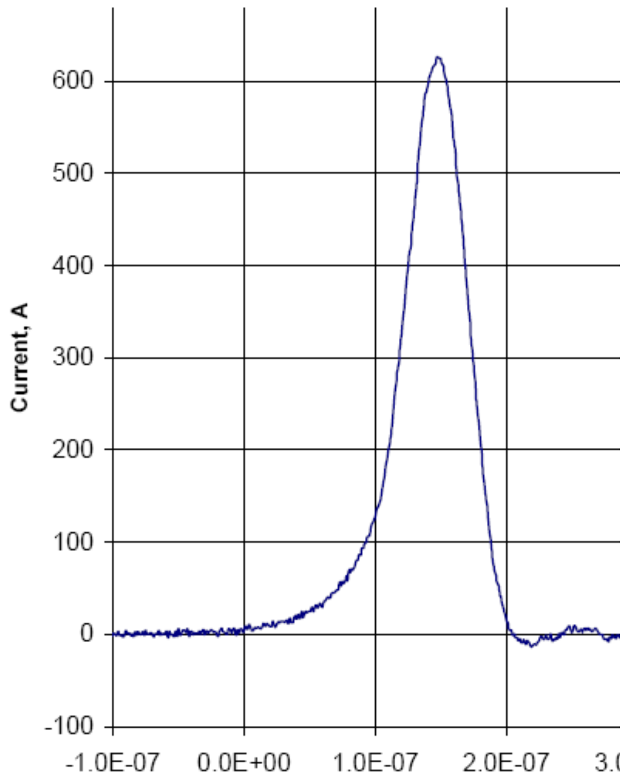
Pulse Waveforms

A contract is placed with APP(*) to design and build the kicker supplies;

ideal waveform for injection:



Achieved to date (*):



(*) **Applied Pulsed Power, Inc.**™ , Freeville, New York, 13068-0348.

The PAMELA Ring Magnets

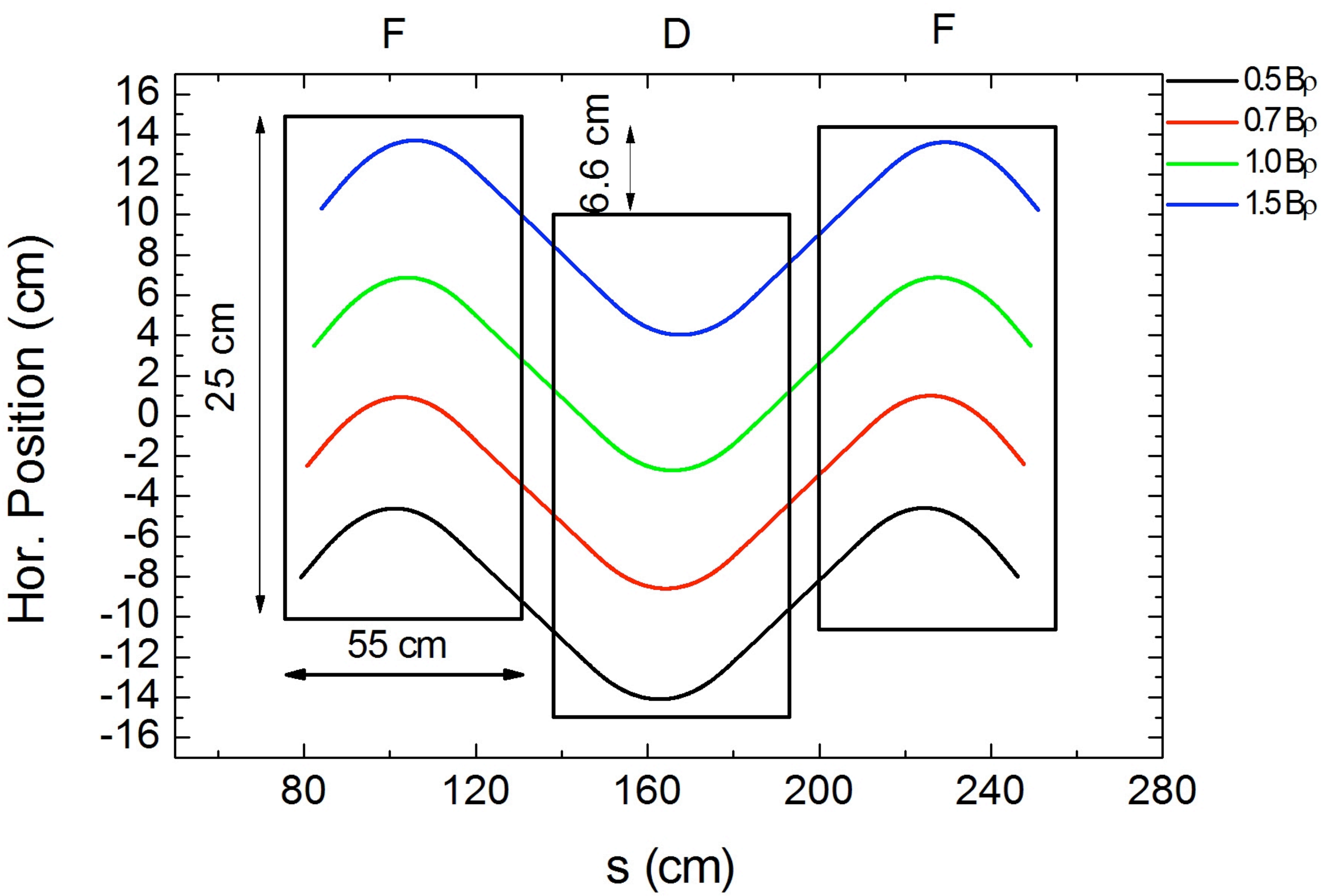
The PAMELA project aiming to:

- accelerate p+ to 250 MeV;
- C+ to 68MeV/A;
- up-grade potential to 400MeV/A.

see: **TH4GAC03; K.Peach et al; 'PAMELA Overview: Design Goals and Principles"**

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

PAMELA Lattice Layout



Magnet Engineering

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?

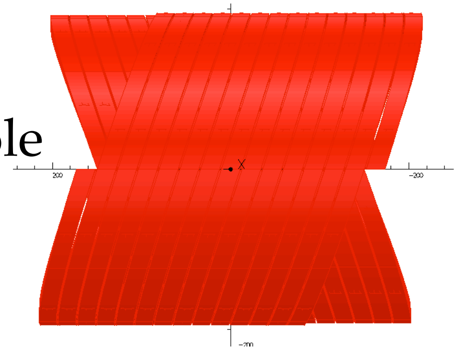
Solution: a novel helical coil arrangement:

- 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.

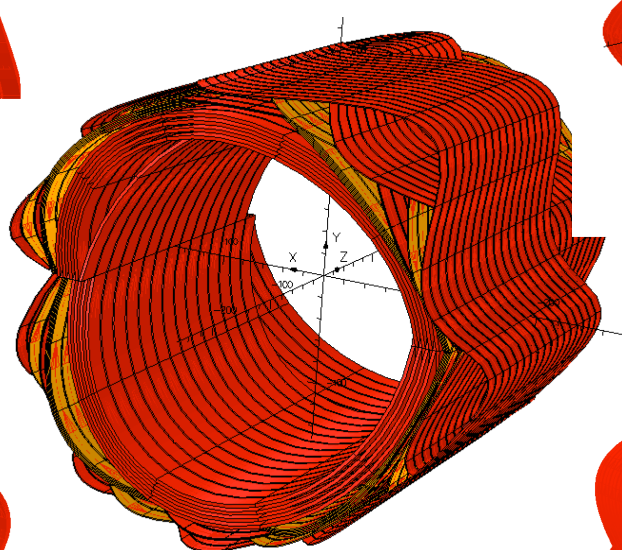
see: **MO6PFP073 Witte et al; 'PAMELA Magnets, Design and Performance"**

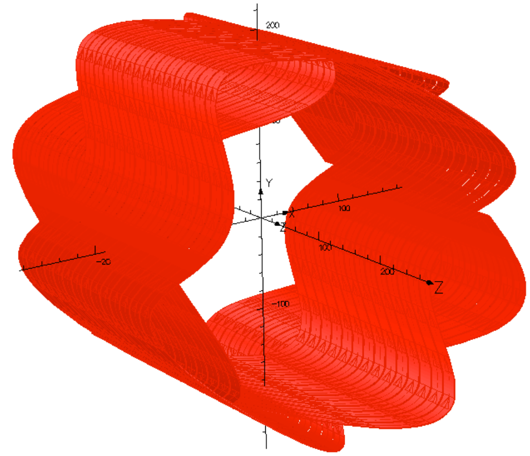
Helical Coil Arrangements

dipole



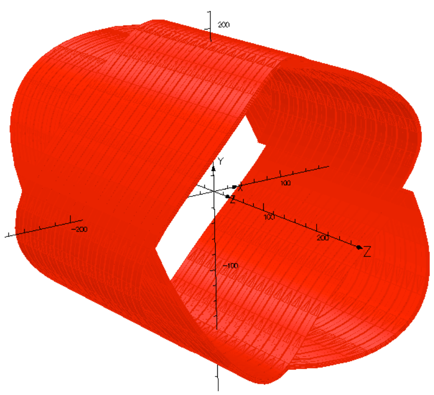
combination

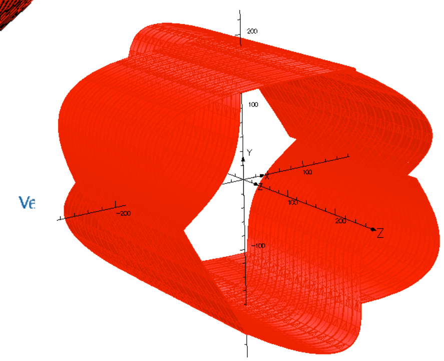




octupole

quadrupole





sextupole

Generating Transverse Fields.

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

$$x = R\cos\theta$$

$$y = R\sin\theta$$

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

where R is the helical coil radius;

θ is the azimuthal angle;

h is the winding pitch;

α is the tilt angle of the solenoid,

n is the order of the harmonic (dipole = 1, etc).

PAMELA Magnet Parameters.

	Dipole	Quad	Sextupole	Octupole	
Length	560	565	555	564	mm
No. of coil pairs	5	4	4	1	
Inner radius	140	162	177	185	mm
Outer radius	160	173	183	187	mm
Tilt	50	50	60	60	°
Peak B at wire	5.1	5.4	5.0	4.2	T

Conclusions

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:

- Ken Peach (J.A.I), Roger Barlow (CI), Bob Cywinski (U. of Leeds).

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