JOHN ADAMS INSTITUTE FOR ACCELERATOR SCIENCE
DEPARTMENT OF PHYSICS

UNIVERSITY OF OXFORD

PAMELA Overview

Suzie Sheehy

International Workshop on FFAG Accelerators (FFAG '10)
Kyoto University Research Reactor Institute, Osaka, Japan

J.A.I.

Oxford Physics

Outline

- Overview of PAMELA project
- Clinical requirements
- Injection and ion sources
- Lattice design & performance
- Magnet design
- RF design
- Beam transport & gantry
- Summary

Overview

PAMELA: Particle Accelerator for MEdicaL Applications

One of 3 work packages of the CONFORM collaboration

Aim: "*to design a prototype proton/carbon ion ns-FFAG accelerator for charged particle therapy*"

Other work packages:

- EMMA (Electron Model of Many Applications)
- Applications (ADSR, particle therapy, radioisotopes etc…)

Collaboration in UK

Oxford (JAI, Gray, PTCRi)

John Cobb , Bleddyn Jones, Ken Peach, Suzie Sheehy, Holger Witte, Takeichiro Yokoi, Mark Hill, Boris Vojnovic + others

Brunel University

Richard Fenning, Akram Khan

Imperial College London

Morteza Aslaninajad, Matt Easton, Jaroslaw Pasternak, Juergen Pozimski

STFC/ASTeC/RAL, STFC/DL

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

Lattice Design	■ (blue)	■ (green)
Injection	■ (blue)	
Extraction	■ (blue)	
Magnet Design	■ (blue)	■ (green)
Medical Requirements	■ (blue)	
RF	■ (blue)	■ (green)
Gantry	■ (red)	
Beam transport	■ (red)	■ (green)
Front end	■ (yellow)	
Injection line	■ (yellow)	
Ion sources	■ (yellow)	
Engineering solutions	■ (green)	

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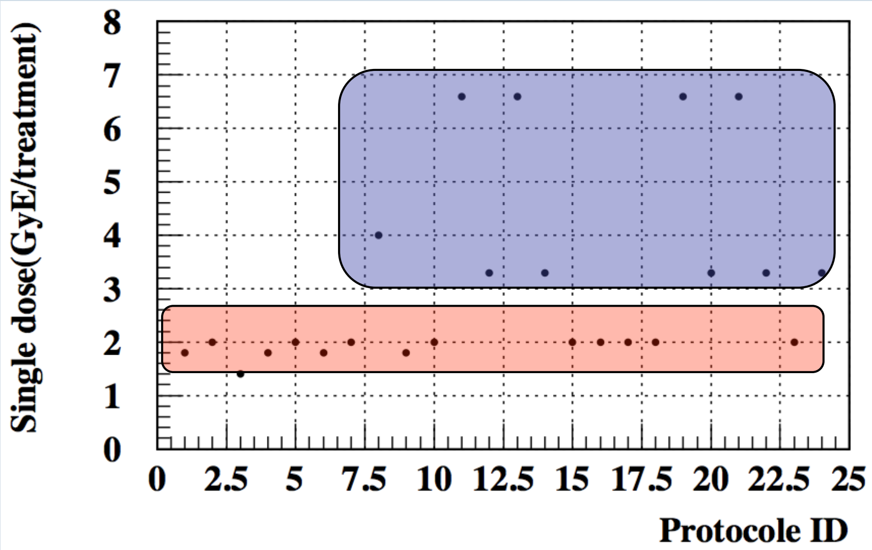
Doses for treatment

Low radiosensitive tissue
(lung, liver etc)

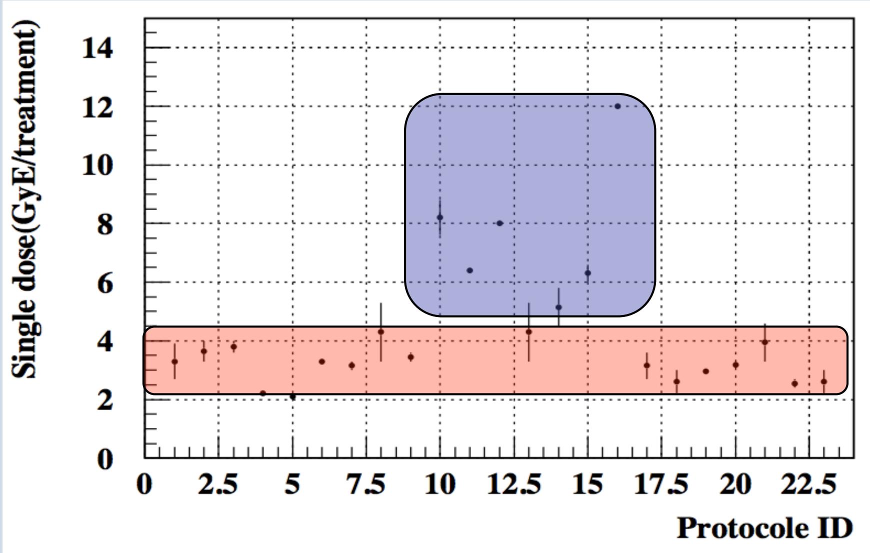
high radiosensitive tissue
(brain, perif. of digestive canal etc)

Proton



Courtesy of T.Okumura (Tsukuba univ.)

Carbon



Report by ANTM (Japan,2002)

Proton: 1~7GyE (Tsukuba Univ, Japan)

radio-sensitive tissues : **1 - 2 GyE**

non radio-sensitive tissues : **3 – 7 GyE**

Carbon: 2~12GyE (NIRS,Japan)

radio-sensitive tissues :**2 – 4 GyE**

non radio-sensitive tissues :**4 – 12 GyE**

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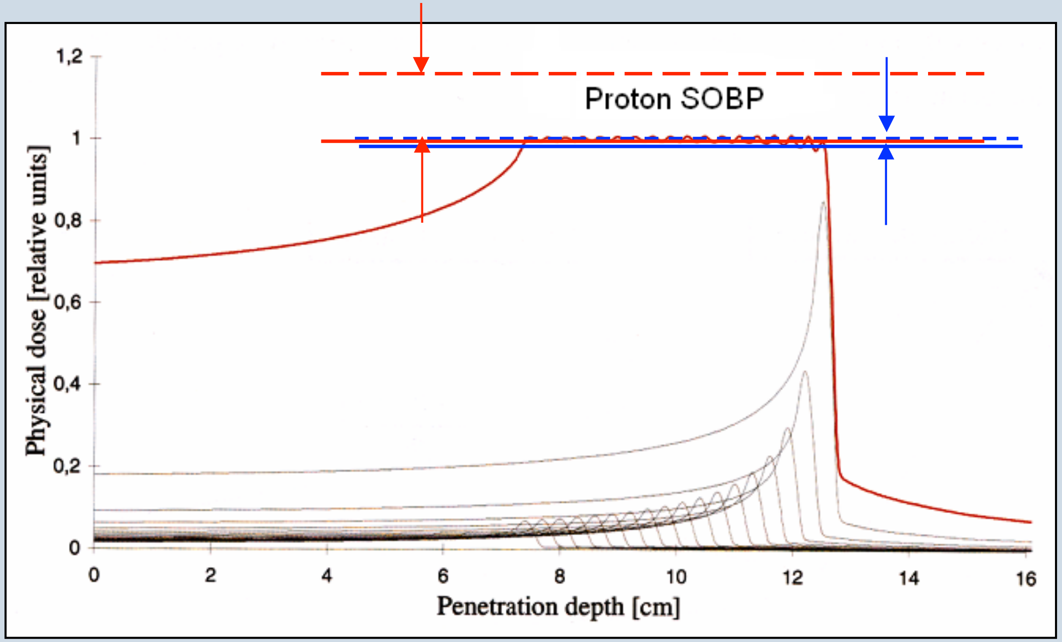
Clinical Requirements – dose control

In dose field formation: **uniformity** and **tolerance** are important



Uniformity => Stability
"deviation of local dose from average dose"

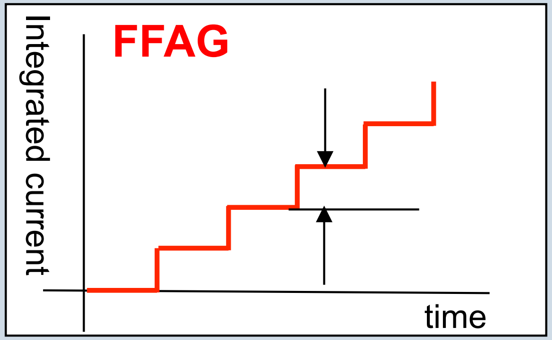
Tolerance => Tunability
"deviation of average dose from prescribed dose"

**** SOBP is not necessarily the ideal dose field in spot scanning**

Uniformity : <2%
Tolerance : <5% (existing facilities already achieved <2%)

Slide thanks to T. Yokoi, PAMELA Design Review 2010

Clinical Requirements



Step size controls dose (injection)

To achieve Intensity Modulated Particle Therapy:

- multi-beam painting with small bunch intensity
- simple system, but high repetition rate

Rescanning: ~ 5 may be needed to achieve good uniformity (multi-bunch)

Proton: 0.2nA/GyE ⇒ 0.05nA~0.4(1.4)nA (Carbon divide by 36) for 1L

Beam position reproducibility of 0.2 mm (achieved at PSI)

Scanning speed > 100 Voxel/sec

Beam size 4 mm – 10 mm FWHM (variable)

Facility lifetime > 20 years -> Flexibility is crucial!

Accelerator Challenges

Clinical requirements translate to:

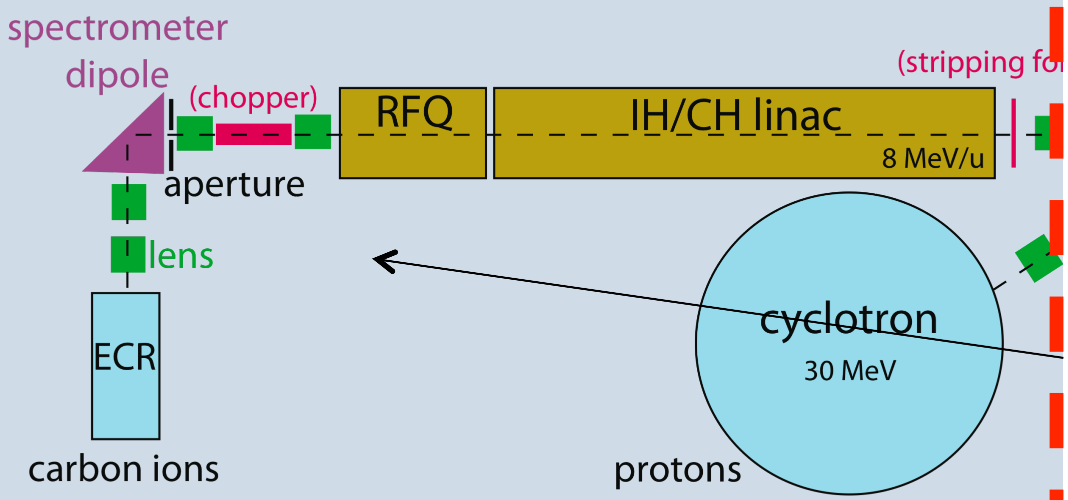
- Variable energy extraction
- 1 kHz repetition rate
- Small accelerator footprint

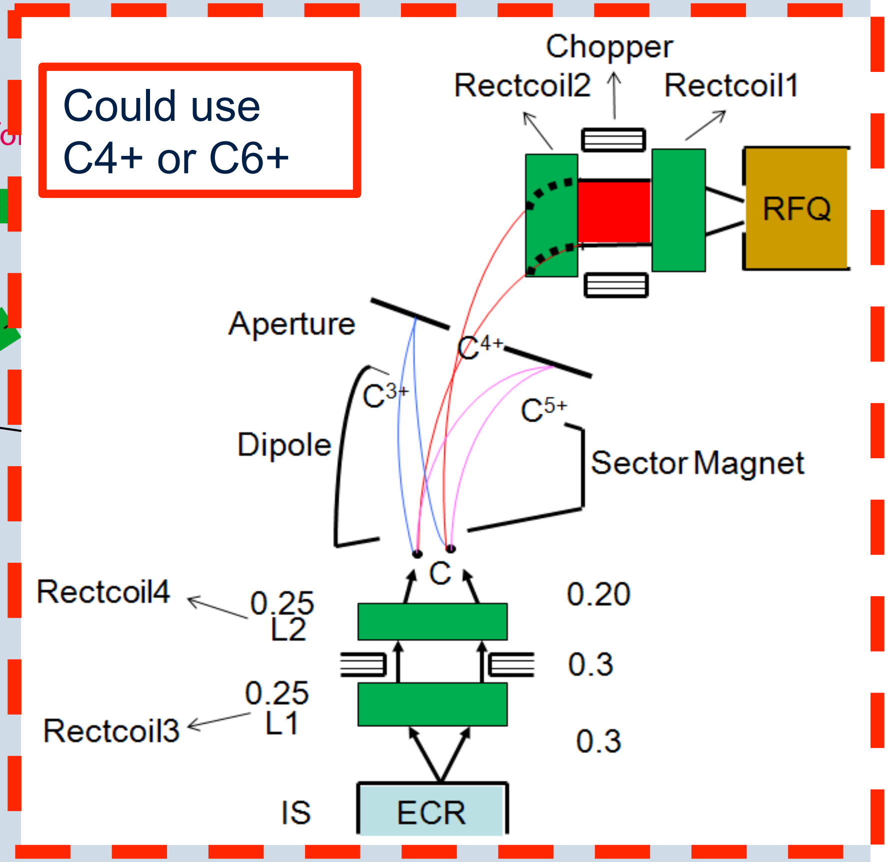
We also want:

- Small(ish) aperture (scaling FFAG > 1m!)
- Avoid crossing harmful resonances (linear ns-FFAG)

Slide thanks to M. Aslaninejad, PAMELA Design Review 2010

Injector and Ion Sources





ECR: ECRIS

Hypernanogun

We need 0.6 μA Carbon 6^{+}.

ECRIS can produce 1 μA Carbon 6^{+} => use this directly!

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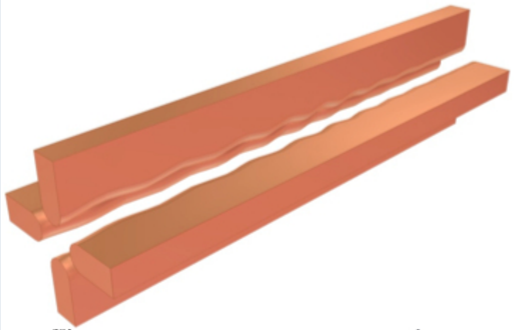
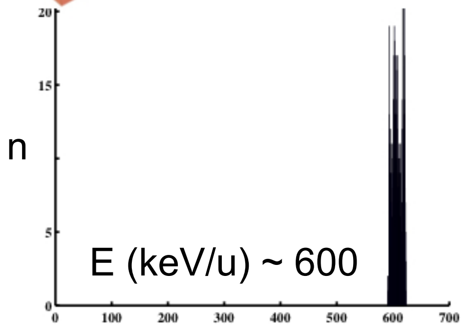
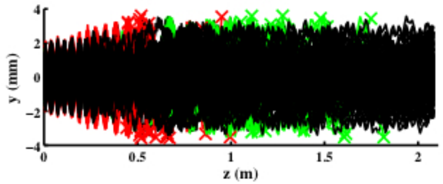
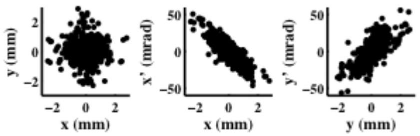
RFQ and IH/CH linac









RFQ
Transmission: 97%
Mean energy: ~600 keV/u
Frequency: 280 MHz
Length: 3.56m / 800 cells

Based on scaled version of FETS design

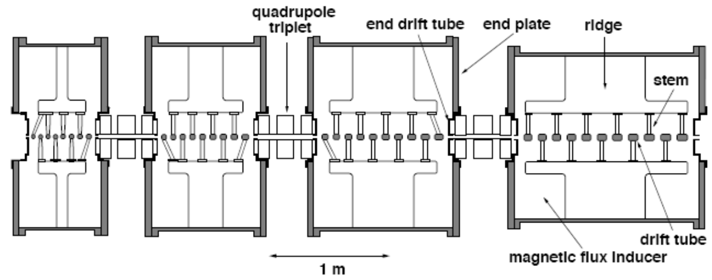
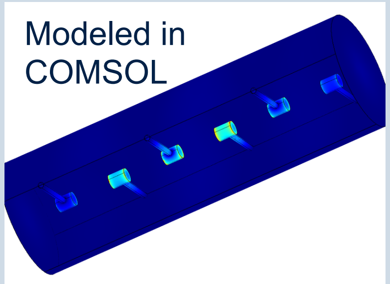
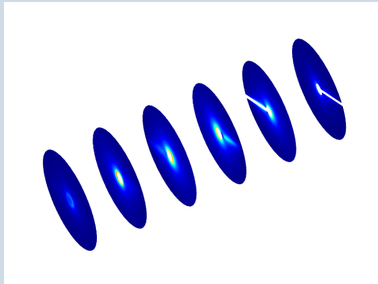


Figure 1: The structure of IH-linac





Drift tubes mounted on alternating sides.
- Pi mode -> enhanced transit-time factor
- Compact drift tube -> very small capacitance
- Higher Shunt Impedance

IH structure: shown, TE_110, Beta=0.1
CH structure: inter-digital fingers rotated by 90 deg., TE_210, Beta=0.1 to 0.5

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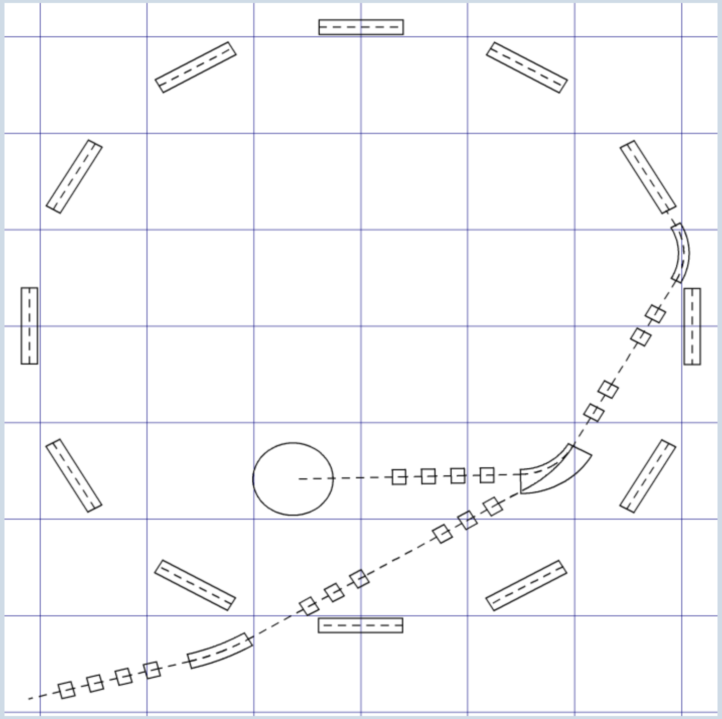
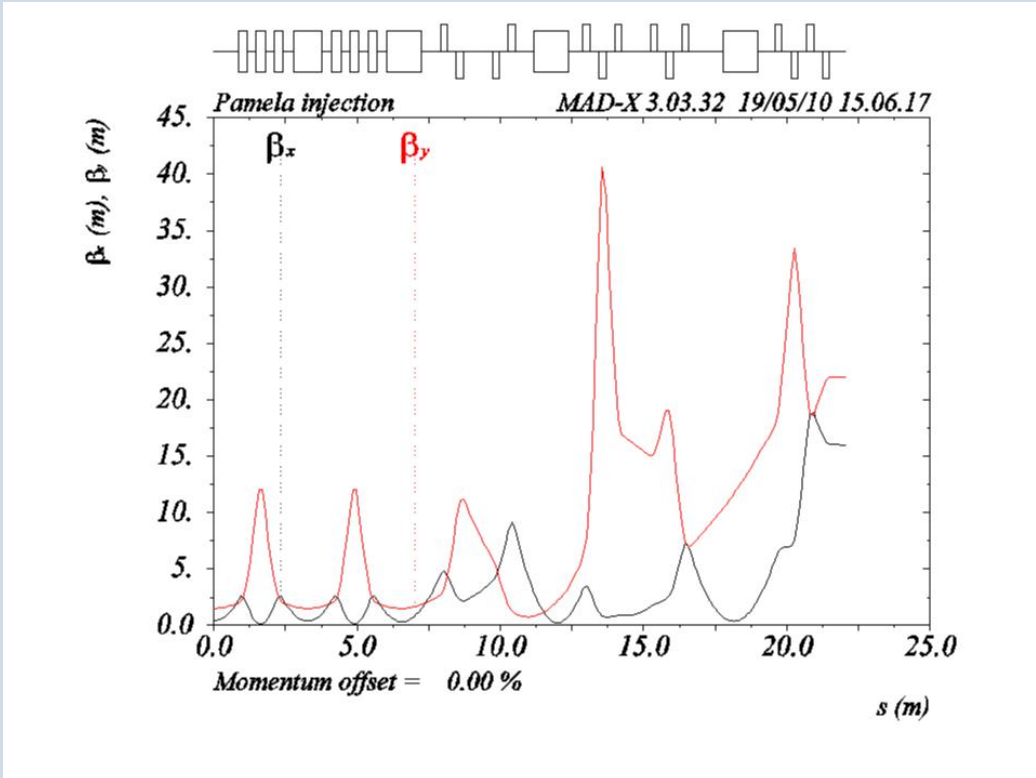
Injection into the ring



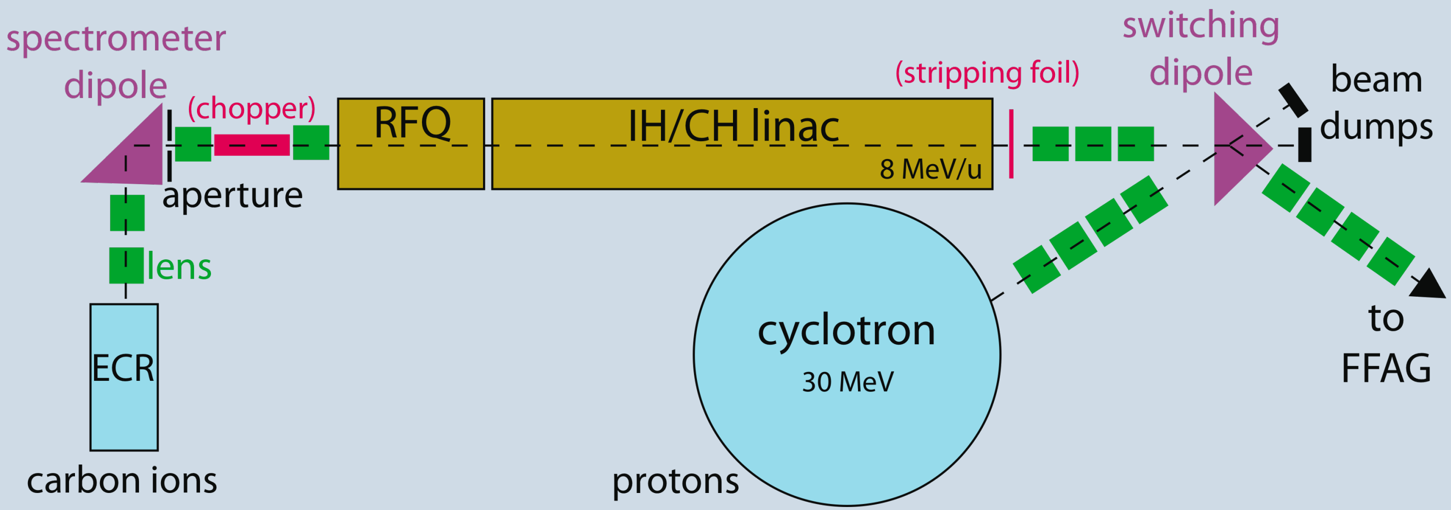
A possible layout of cyclotron inside the first ring



Beta functions of injection line

Slide thanks to M. Aslaninejad, PAMELA Design Review 2010

Injector and Ion Sources



- Pamela injection system is under development and substantial progress has been made
- The specification for PAMELA operation is compatible with C+6 intensities
- Detailed matching of beam from 30 MeV proton cyclotron has been studied.
- Space Charge is not an issue.
- Work on the RFQ is progressing well.
- Work on IH/CH structure, progressing.

Lattice Design

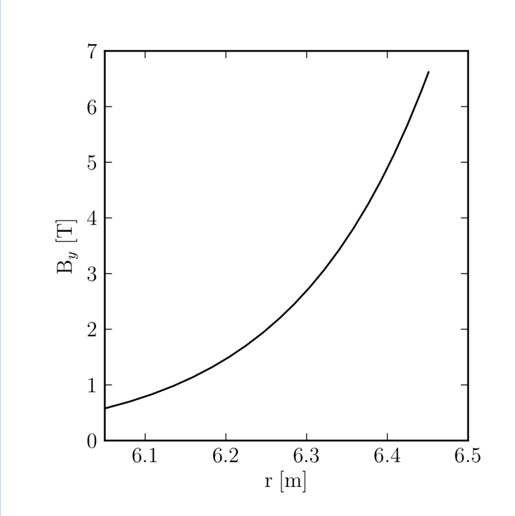
<u>Aim:</u> Minimise tune variation, retain small orbit excursion + hopefully increase long drift section.

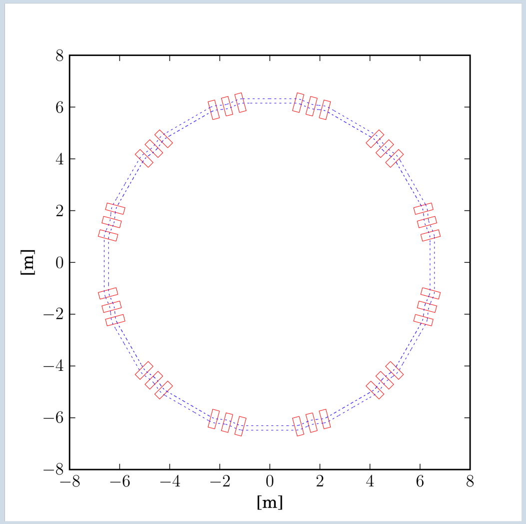
Start with scaling FFAG, FDF focusing

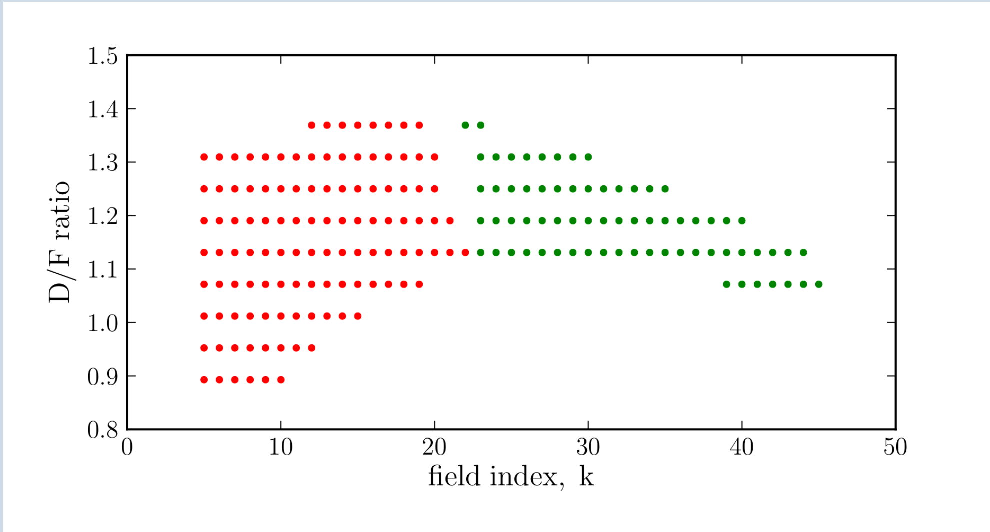
Break scaling law

1. Truncate expansion of scaling law
2. Make magnets rectangular
3. Align on straight line

Use 2nd stability region of Hill's equation







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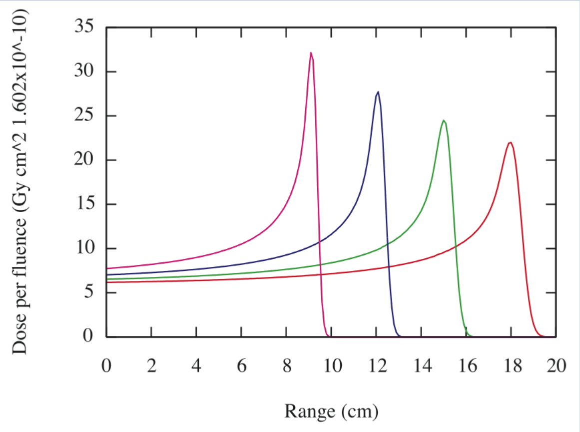
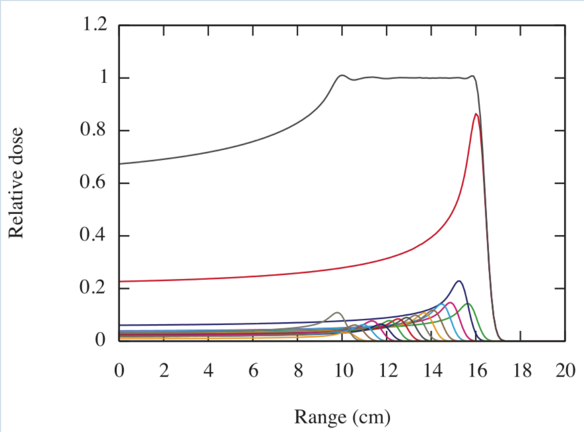
Lattice Design – Energies/rigidities

- 2 ring solution
- Could be concentric to reduce footprint

Particle	H+			C6+				
Ring	1 inj	1 ref	1 extr	1 inj	1 ref	1 extr 2 inj	2 ref	2 extr
Kin. En./u [MeV]	30.95	118.38	**250**	7.8394	30.977	68.357	208.749	**400**
Bρ [Tm]	0.811	1.621	**2.432**	0.811	1.621	2.432	4.401	**6.370**





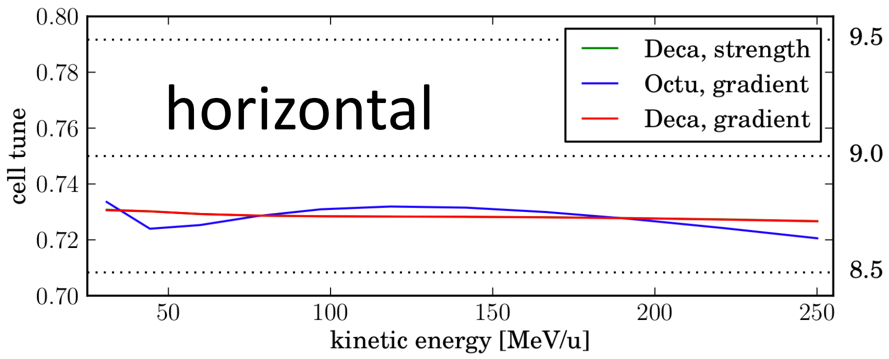
Lattice Design

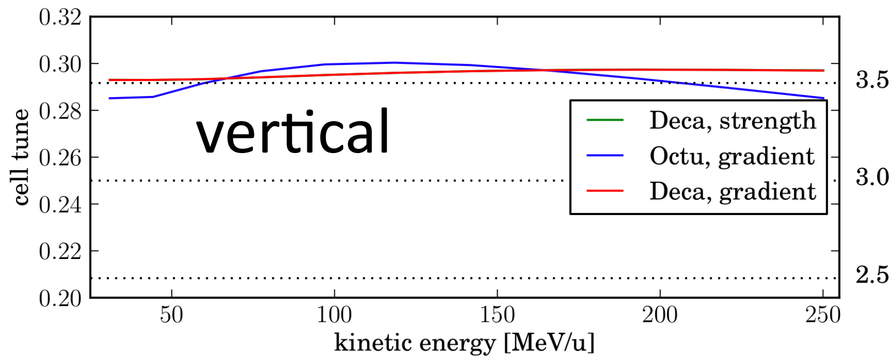
	Ring 1	Ring 2
Mean Radius [m]	6.251	9.3
Cells	12	12
Packing factor	0.48	0.65
Field index, k	36.721	42
Magnet length [m]	0.3144	0.6330
Orbit exc. [m]	0.1760	0.217 (400 MeV/u) 0.237 (430 MeV/u)
Bore size [m]	~0.24	~0.35

Lattice Performance

For both the proton and carbon rings:

- Not sensitive to alignment errors
- Total machine tunes within half an integer – no major resonance crossing
- Dynamic aperture > 50 π mm mrad (normalised)
- Meets all the requirements

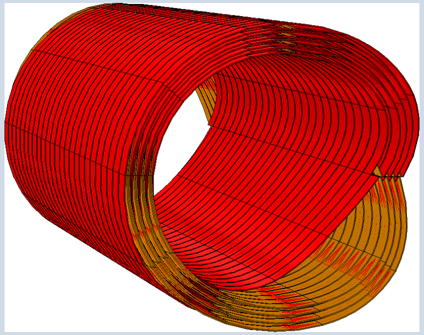




Slide thanks to H. Witte, PAMELA Design Review 2010

Magnet Design

- Magnet Technology Challenges
  - Length restriction
  - Maximum field (4.25T)
  - Combined function magnet (up to decapole)
  - Required bore (>250 mm)
  - Field quality: better than $1x10^{-3}$
- Approach: Double-helix coils

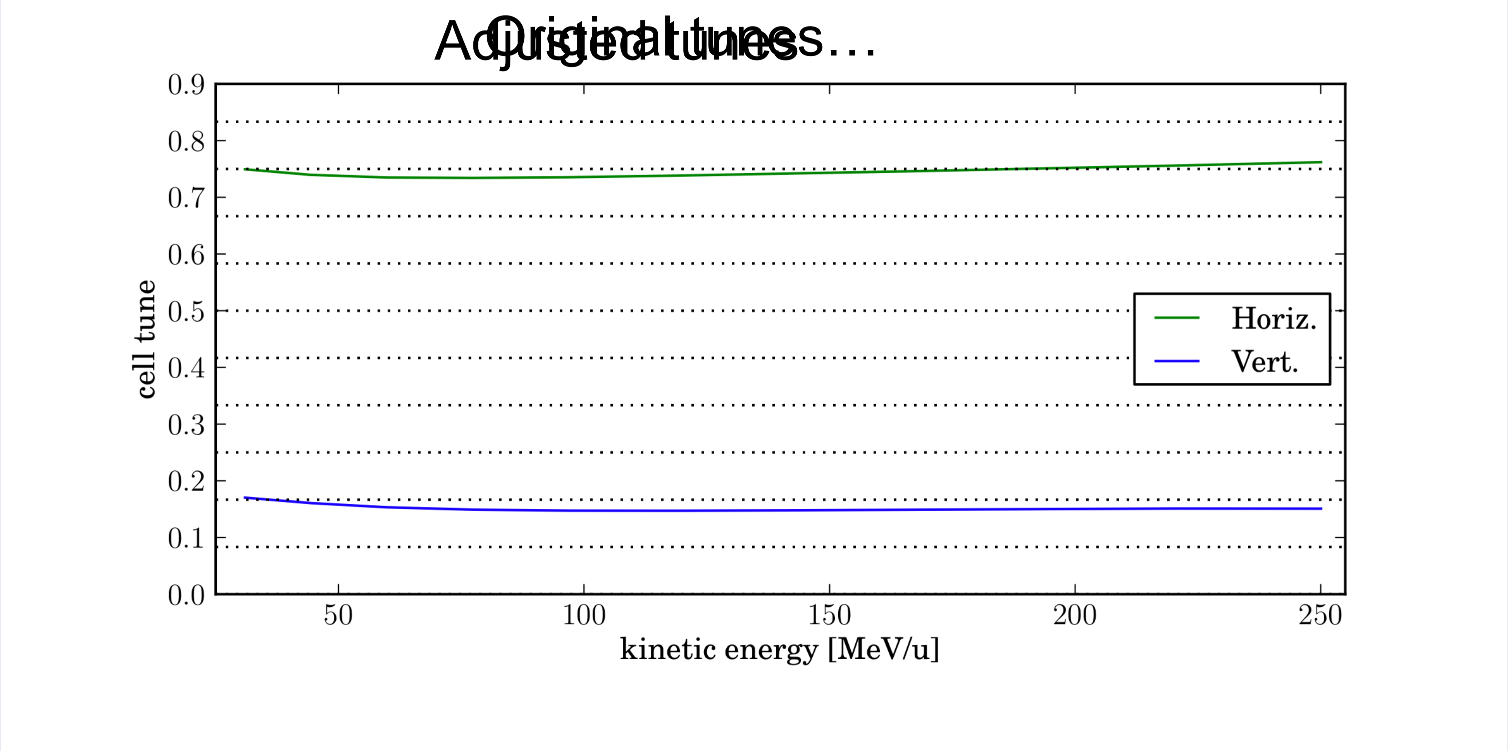


Combined function magnet
56.7% Dipole
30.6% Quadrupole
9.7% Sextupole
2.5% Octupole
0.5% Decapole

Slide thanks to H. Witte, PAMELA Design Review 2010

Magnet Design – 3D tracking

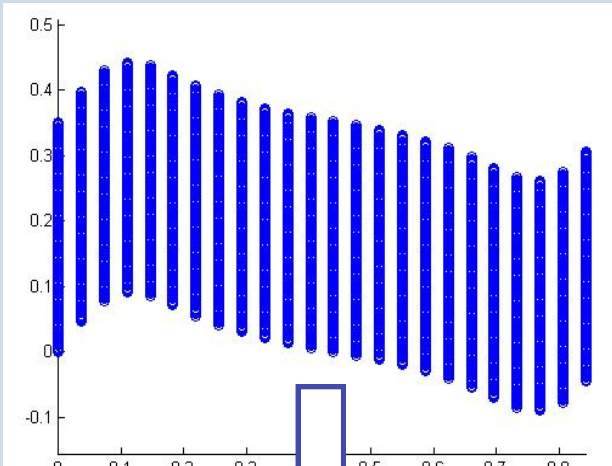
- Tracking: Unwanted field components
  - Patent Nov. 2009
- 3D field maps have been tracked in ZGOUBI.

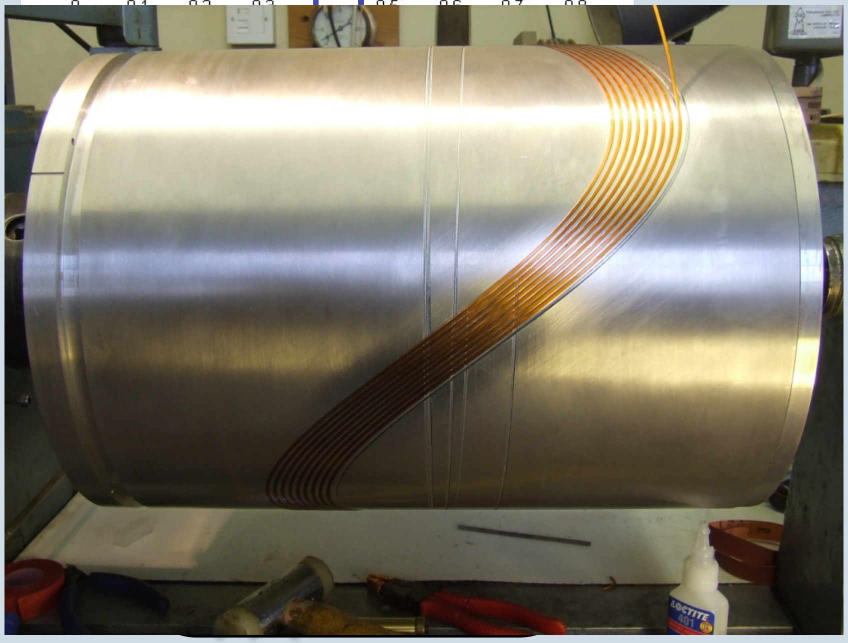


Slide thanks to H. Witte, PAMELA Design Review 2010

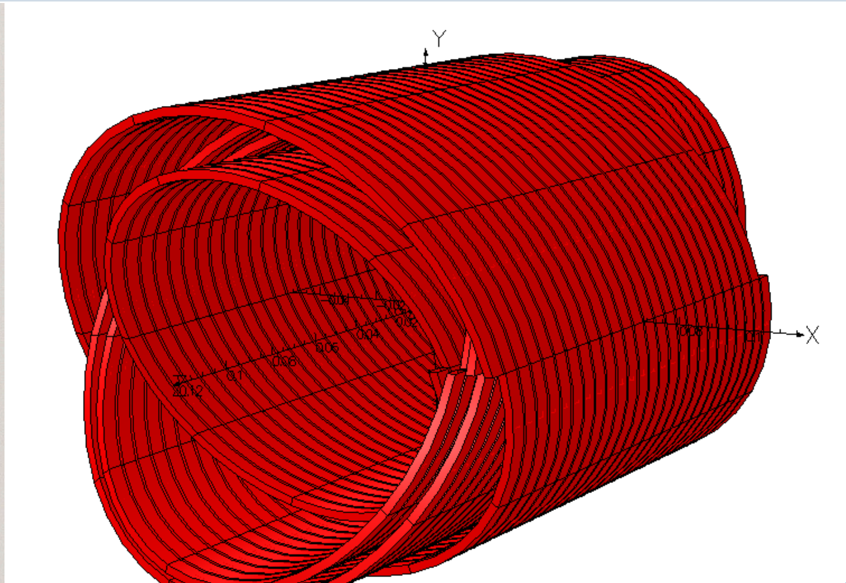
Magnet Design

- Aim: scalable manufacturing process
  - Grooves in flat sheet
  - Precision rolling
- Alignment system
  - Alignment pins
  - Key system
- Photo etching
- First quotations
- Neil Bliss, Shrikant Pattalwar, Thomas Jones, Jonathan Strachan, Holger Witte





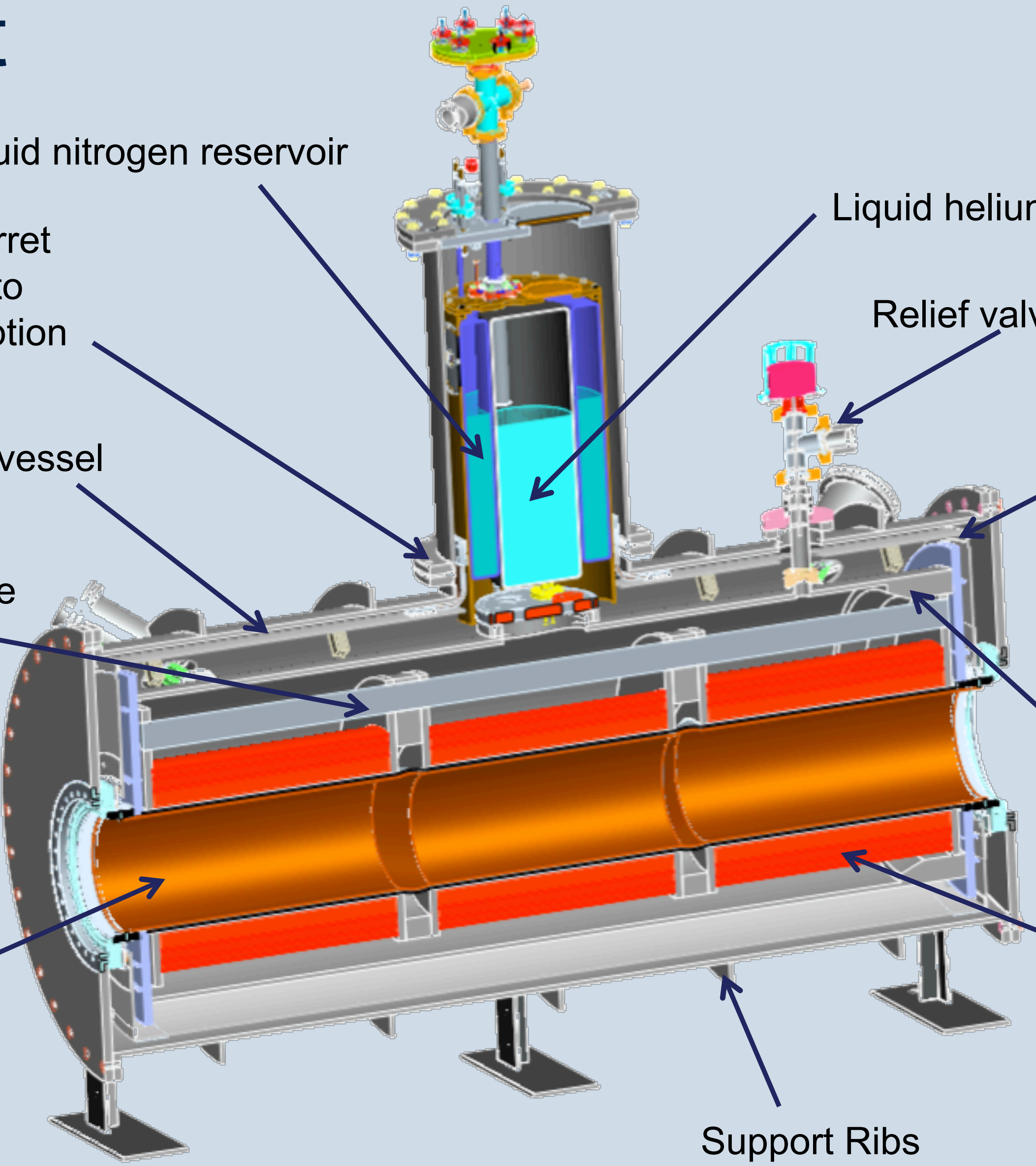
Proposal: Helical Test Coil



Rapid prototyping model – photo (27/10/10, 11:53pm)

Slide thanks to H. Witte, PAMELA Design Review 2010

Cryostat

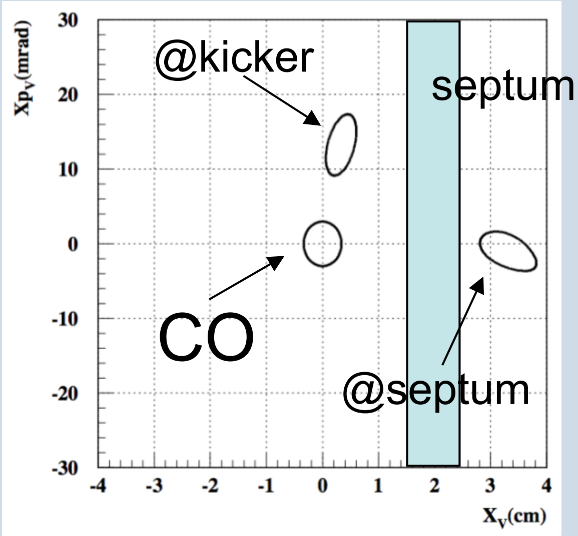


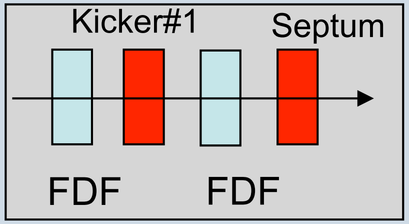
Slide thanks to H. Witte, PAMELA Design Review 2010

Injection/Extraction

•Extraction kicker proton ring = injection kicker carbon

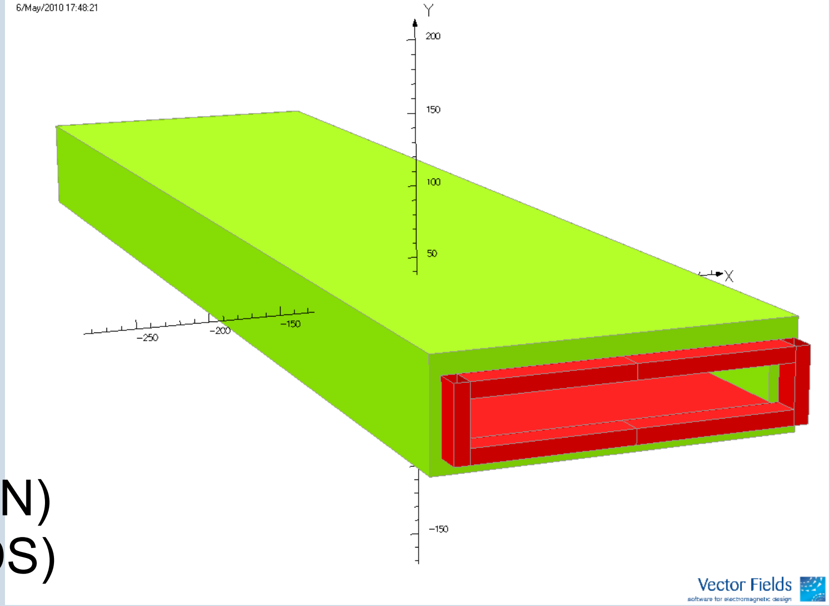
•Vertical injection & extraction





3D model kicker for proton lattice

- Arbitrary ferrite (B_{sat}=300 mT)
- Length: 1 m
- Current sheets: 1 mm thickness
- Current densities:
  - Carbon: 167 A/mm^2
  - Proton: 55.55 A/mm^2
- Magnetic Energy 16/150 J

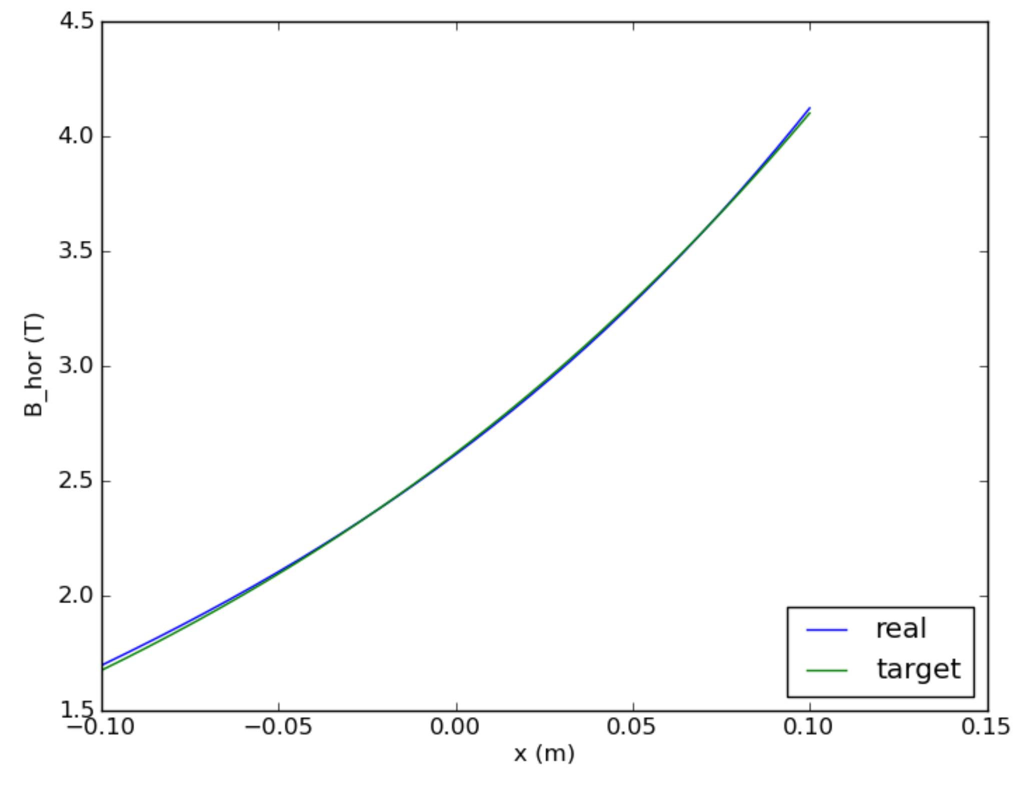


PFN

•Conceptual design (approved by CERN)
•Module concept (PAMELA, PRISM, IDS)

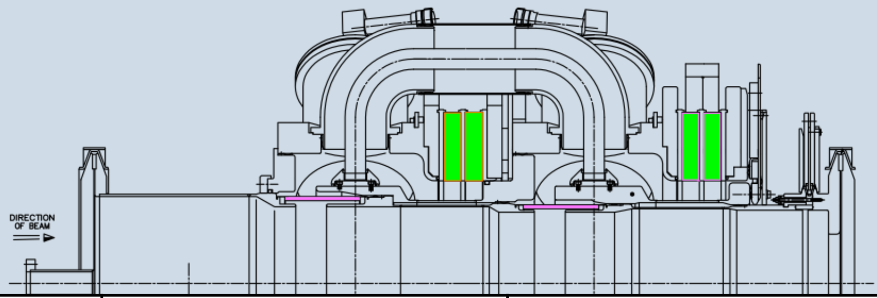
Proton lattice septum

- Challenges
  - Large aperture
    - Stray field
  - 4T peak field required
  - Variable energy extraction
    - Field needs to vary
- Superconducting FFAG septum
  - Nb_3Sn



Slide thanks to I. Gardner, PAMELA Design Review 2010

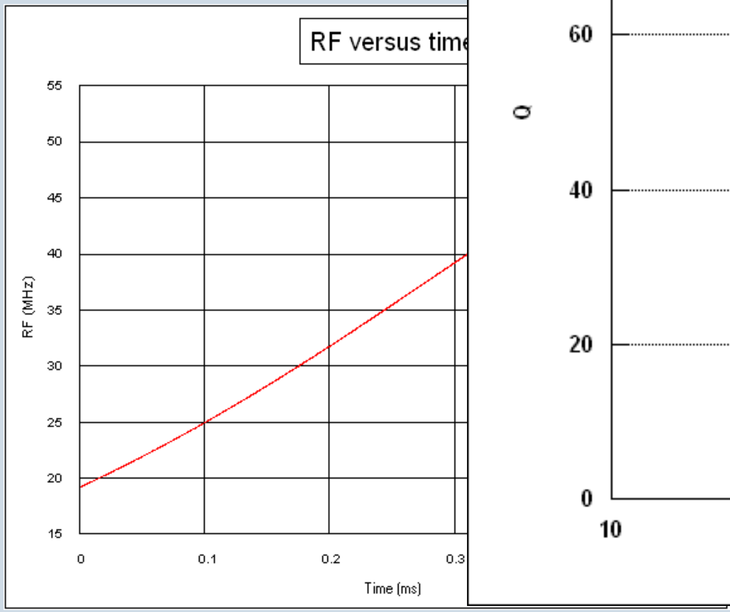
RF Design

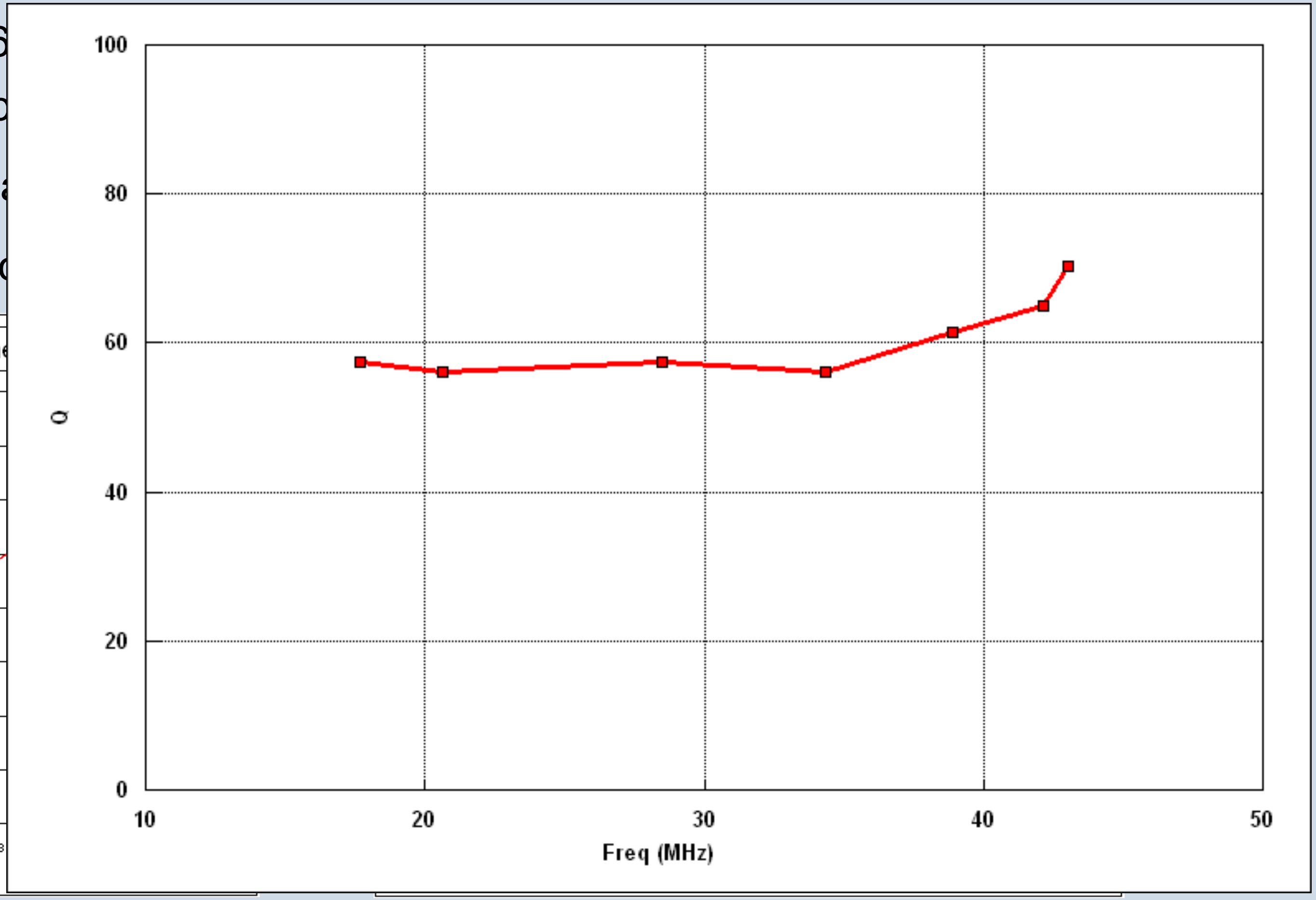


	RING 1 Protons	RING 1 C6+	RING 2 C6+
Harmonic	10	17	10
Low rf (MHz)	19.16	16.69	19.21
High rf (MHz)	45.64	45.80	39.10
Frequency swing	2.446	2.818	2.035
Voltage per gap	6-15 kV	6-15 kV	6-15 kV
No. of 2 gap cavs	8	8	8
Voltage per turn	96-240 kV	96-240 kV	96-240 kV
Accel. time	0.4 ms	0.44 ms	1.7 ms

RF Design

- ASSUMING Q ~ 6
- RF Power per gap
- RF Power per 2 ga
- Mean RF Power fo





Other ideas: Harmonic Number Jump systems (HNJ), Induction Cavities, Magnetic Alloy loaded cavities (MA), Drift tubes with ferrite resonators, Multiple fixed frequency cavities…

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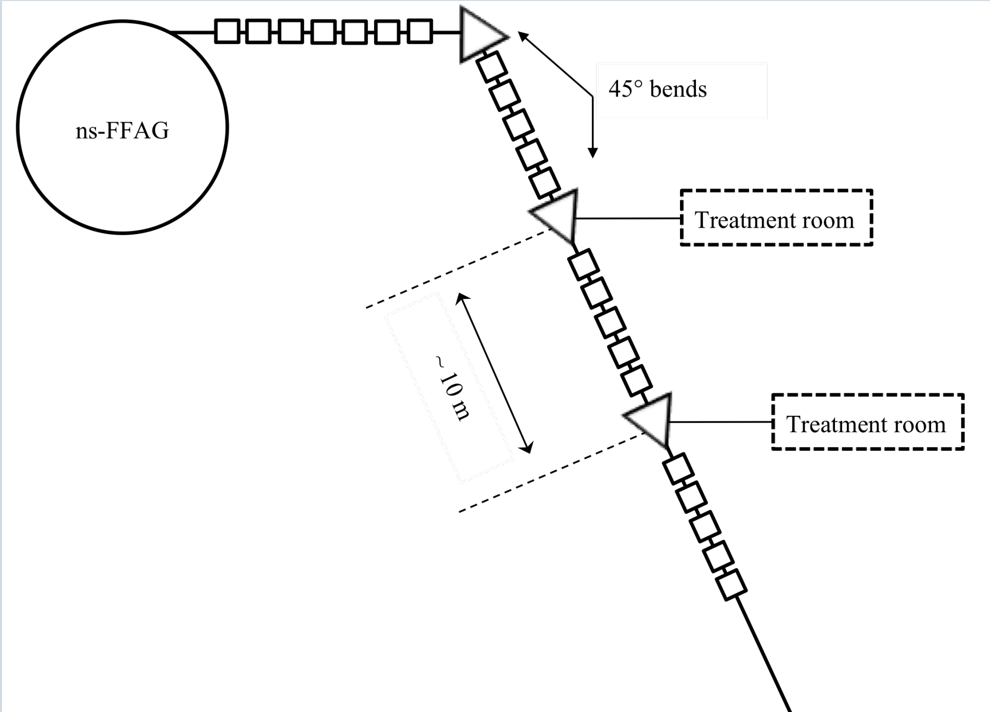
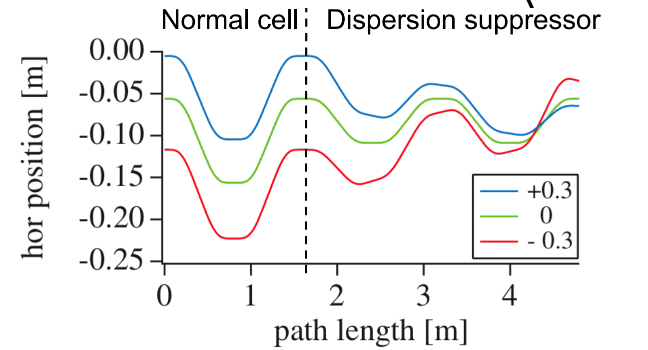
Beam Transport

- Many options available
  - Slowest part of system will be magnet changes for scanning & any physical movement – want to minimise
  - Hope to have full FFAG transport & gantry
- FDDF configuration
- Repeated cell structure is 1.6m in length

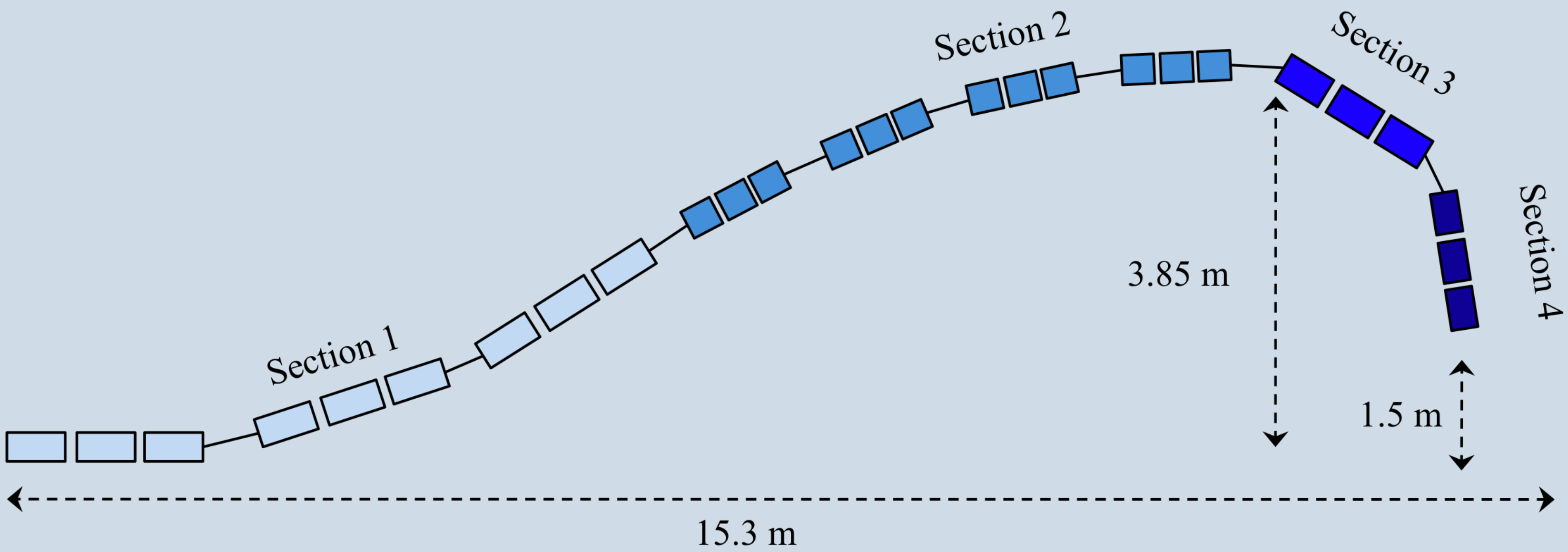
- Also: dispersion suppressor sections





See: S. Machida, R. Fenning, "Beam transport line with scaling fixed field alternating gradient type magnets", Phys. Rev. ST. Accel. Beams, **13**, 084001 (2010).

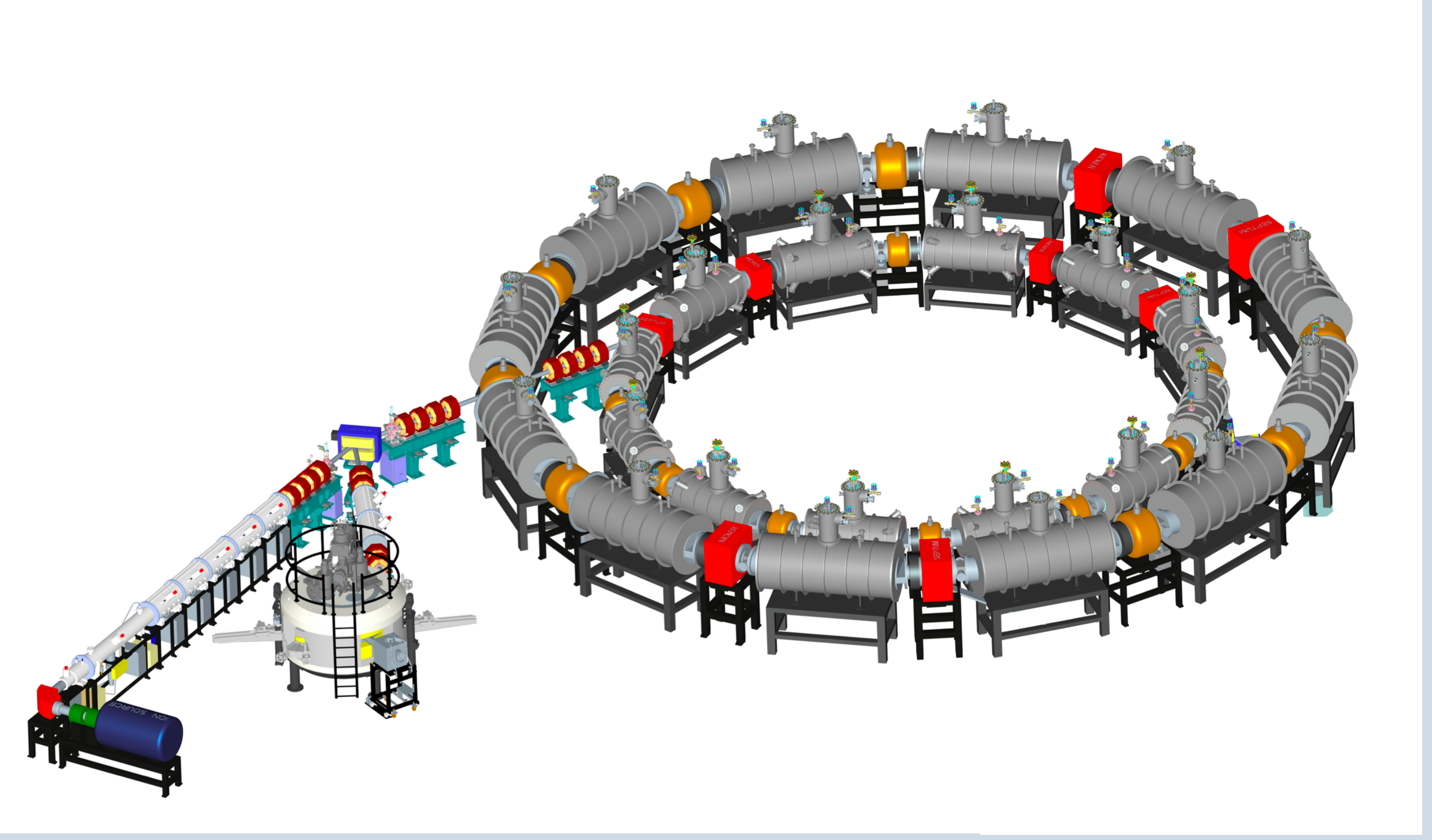
Treatment Gantry



- Ongoing work – initial design by R. Fenning for proton gantry
- Lots of ideas – discussions welcome! (T.Yokoi's talk)

Slide thanks to T. Jones, Daresbury Lab (STFC)

Layout ?



Where are we now?

- Final Design Review was October 4-7th 2010, Oxford
- Final design report being written (due January 2011)

- Need prototyping of:
  - Main ring magnets, kicker and septum magnets
  - RF
  - Ion source
  - Funds/collaborators sought!

- PTCRi – research: optimise treatment & minimise damage

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Oxford Physics

Thanks for your attention.

Oxford (JAI, Gray, PTCRi)

John Cobb , Bleddyn Jones, Ken Peach, Suzie Sheehy, Holger Witte, Takeichiro Yokoi, Mark Hill, Boris Vojnovic + others

Brunel University

Richard Fenning, Akram Khan

Imperial College London

Morteza Aslaninajad, Matt Easton, Jaroslaw Pasternak, Juergen Pozimski

STFC/ASTeC/RAL, STFC/DL

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

Please refer to the forthcoming PAMELA Design Report for detailed information.