PAMELA OVERVIEW: Design Goals and Principles

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&

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Outline

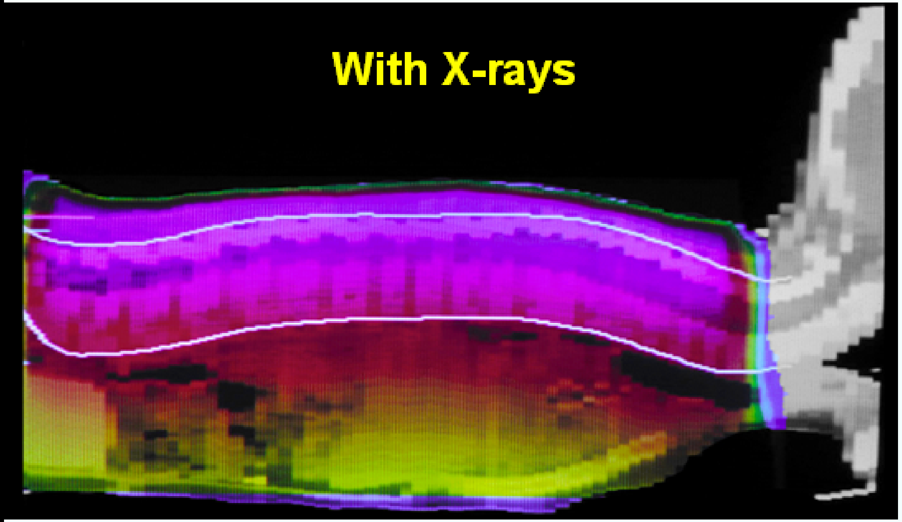
PAMELA

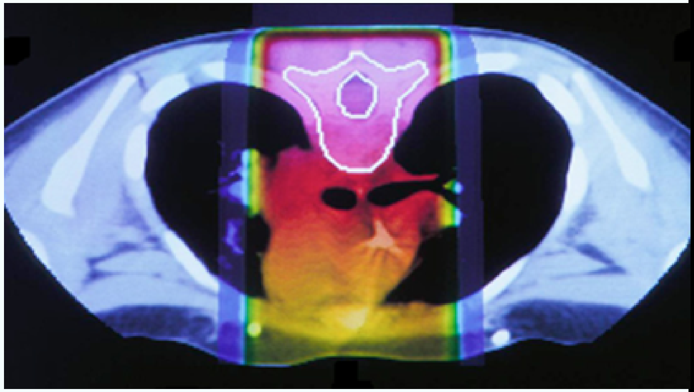
Particle Accelerator for MEdicaL Applications

- Clinical Requirements
- Accelerator Technologies
- PAMELA – status
- Summary

Clinical Requirements

- **Charged Particle Therapy (CPT)**
  - Protons and light ions
  - Used to treat localised cancers
    - Less morbidity for healthy tissue
    - Less damage to vital organs
    - Particularly for childhood cancers





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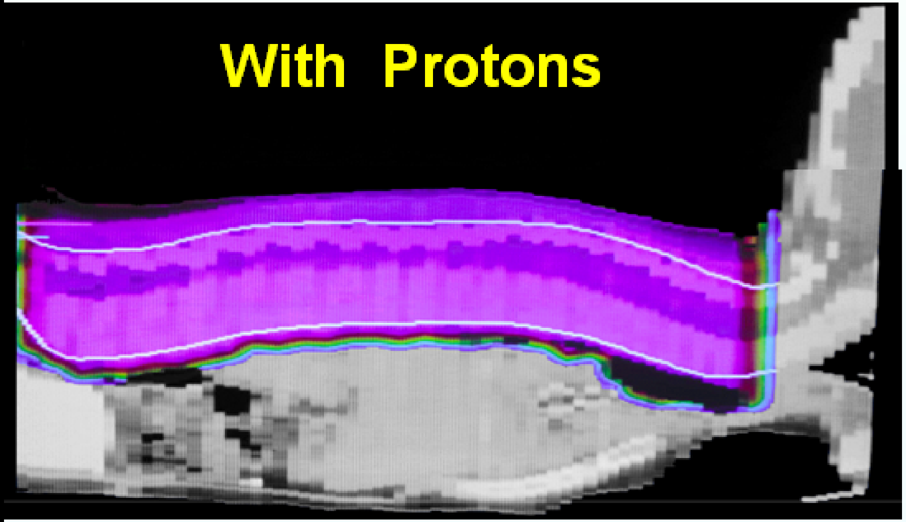

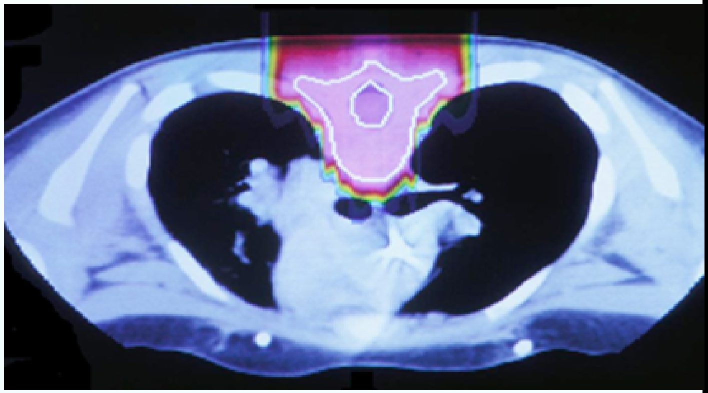

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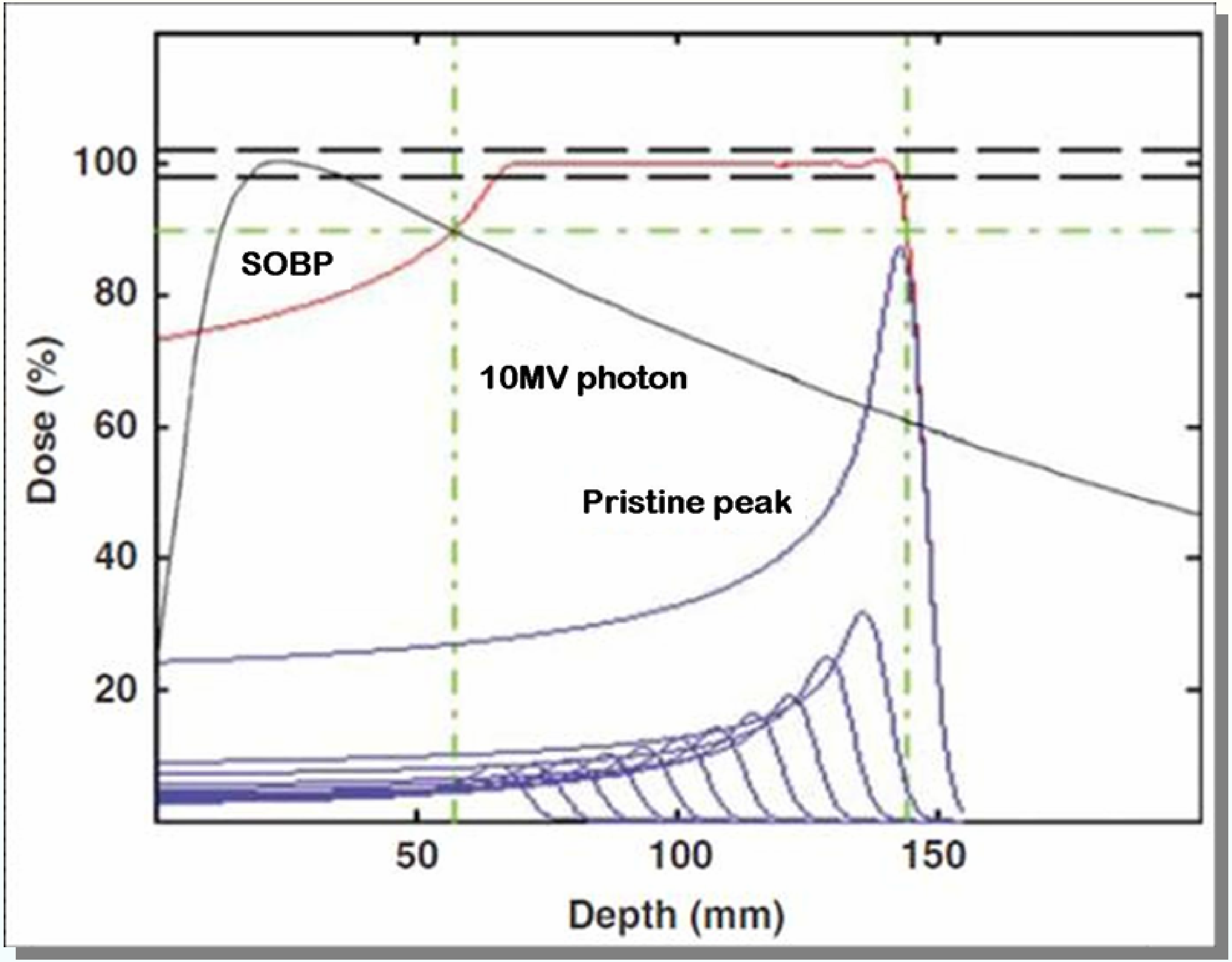
"When proton therapy facilities become available it will become malpractice not to use them for children [with cancer]."

Herman Suit, M.D., D.Phil., Chair, Radiation Medicine, Massachusetts General Hospital

CPT – why?



SOBP
10MV photon
Pristine peak
Dose (%)
Depth (mm)
100
80
60
40
20
50
100
150

Main Clinical Requirements

Parameter	Value	Units
Extraction energy (proton) [Min, Max]	60, 240	MeV
Extraction energy (carbon) [Min, Max]	110, 450	MeV/u
Energy step (protons) [@Min, @Max]	5, 1	MeV
Energy step (carbon) [@Min, @Max]	15, 6	MeV/u
Energy resolution $\Delta E/E$ [@Min, @Max]	3.5, 1.8	%
Voxel Size [Min, Max]	$4\times4\times4$ $10\times10\times10$	mm
Smallest Field of view [Min, Max]	100×100 250×250	mm
Clinical Dose rate (protons) [Min, Max]	2, >10	Gy/min
Clinical Dose rate (carbon) [Min, Max]	2, >10	Gy/min
Cycle rate [Min, Max]	0.5, 2	kHz
Bunch charge (protons) [Min, Max]	1.6 - 16	pC
Bunch charge (carbon) [Min, Max]	300 - 3000	fC
Bunch charge stability and bunch charge measurement accuracy	<10	%

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TREATMENT PLAN SHOULD BE DETERMINED BY CLINICAL NEED NOT LIMITED BY ACCELERATOR TECHNOLOGY

Accelerator Technology?

- **Cyclotrons**
  - Fixed energy extraction, difficult for Carbon at full energy (equivalent to 1.2 GeV/c protons)
- **Synchrotrons**
  - Flexible, but too slow?
- **FFAG**
  - Flexible, rapid cycling (fixed field), variable energy … but … new technology
    - Scaling (Mori) & non-Scaling (Johnstone, PAMELA)
- **(Compact) Linear Accelerators**
  - e.g. Dielectric Wall Accelerators
- **…**
- **Laser-Plasma Ion accelerators**
  - Far in the future …

Challenges

- **The non-scaling Fixed-Field Alternating Gradient Accelerator is a new type of accelerator**
  - Lattice?
  - Magnets, injection/extraction
  - Challenging RF
  - Resonance crossing?
  - Stability
- **EMMA is a relativistic ns-FFAG**
- **PAMELA is a non-relativistic ns-FFAG**

See Marks: TU1RAI02
Witte et al, MO6PFP073

See Smith: WE4PBI01

Solutions

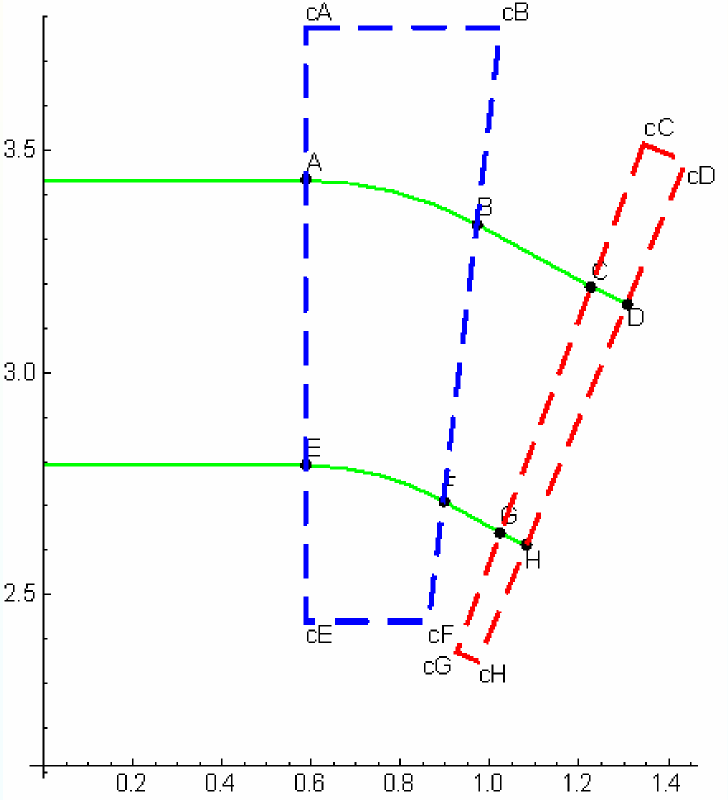
1. **(Johnstone & Koscielniak)**
   - **Use wedge-shaped magnets**
     - Stabilize betatron tune
     - Longer straight sections

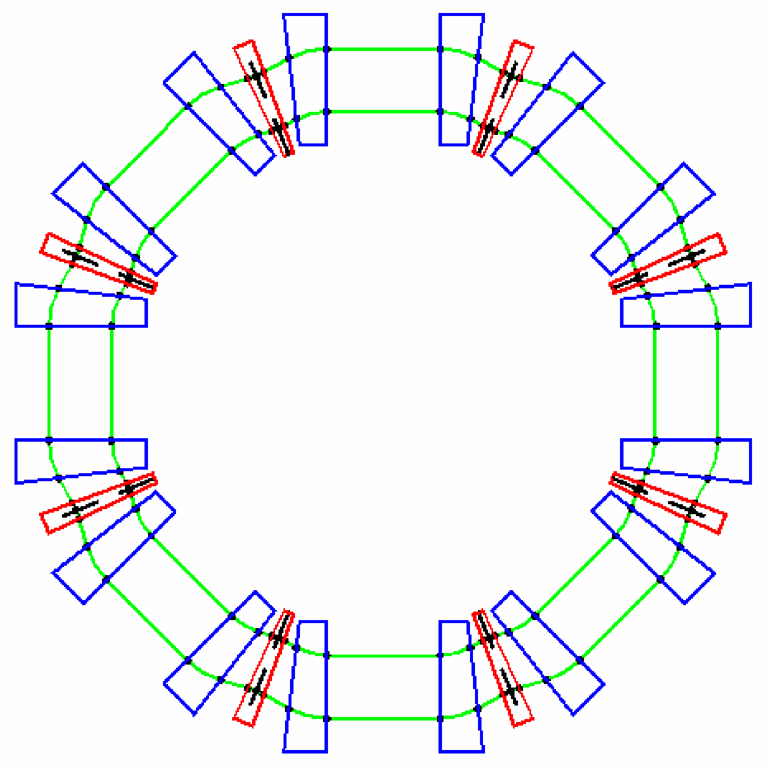
See Johnstone and Koscielniak,
"Tune-Stabilized Linear-Field FFAG for Carbon Therapy", EPAC Edinburgh (2006), 2290.
Johnstone: TU6PFP080
"Non-Scaling FFAG Accelerator Variants for HEP and Medical Applications"

2. **(Machida)**
   - **Introduce higher multipoles**
     - Stabilize betatron tune
     - Longer straight sections

S. Machida, "FFAGs for proton acceleration", FFAG'08 workshop, Manchester, 2008

A Johnstone/Koscielniak lattice





PAMELA

STATUS

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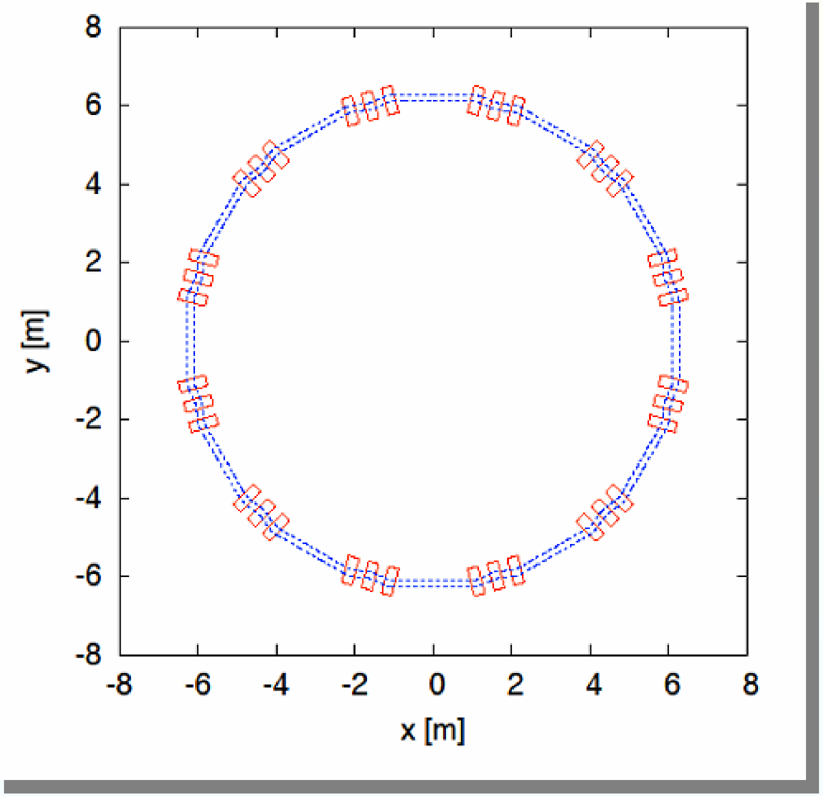
Present Lattice – Proton Ring



Packing Factor	No. cells	Radius	Orbit Excursion	Straight Section
0.48	12	6.251 m	0.172 m	1.702 m

See Sheehy et al, FR5PFP001

- Proton ring (30 to 250 MeV)
  - Carbon requires second ring
  - Work in progress
- non-scaling, non-linear lattice
  - Tune-stabilisation
- Principle idea:
  - Start with scaling FFAG
  - Relax scaling law
    - Rectangular CF magnets
    - Aligned on straight line
    - Multipoles up to octupole
  - Results in FFAG with...
    - Small orbit excursion (<172 mm)
    - Compact magnets
    - No/little tune shift
- 12 cells, FDF-triplet
  - Straights: 1.7 m
  - Sufficient space
    - Injection/extraction
    - RF

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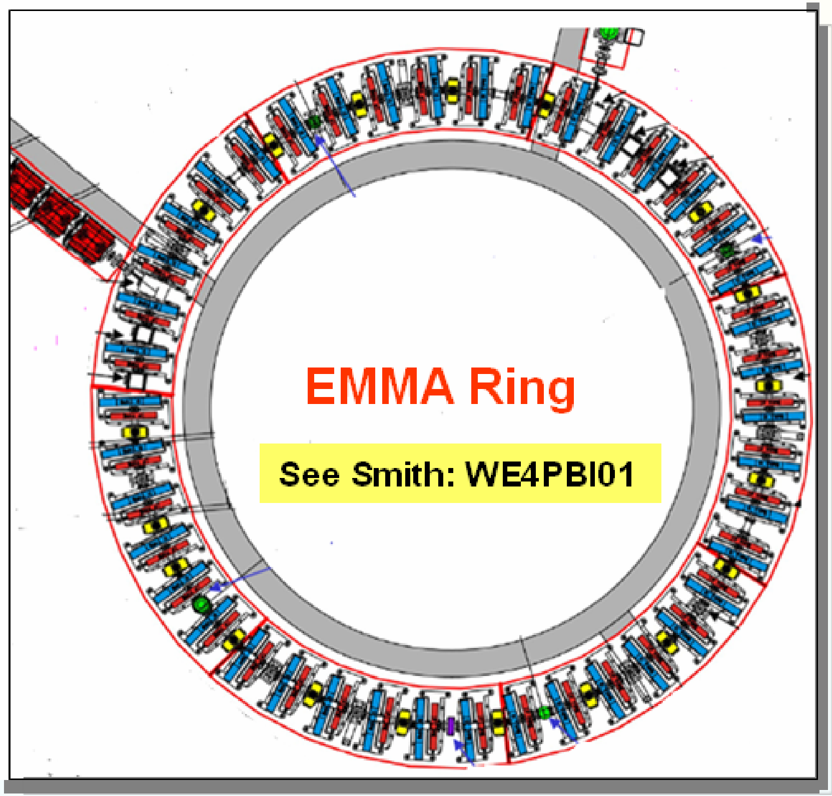

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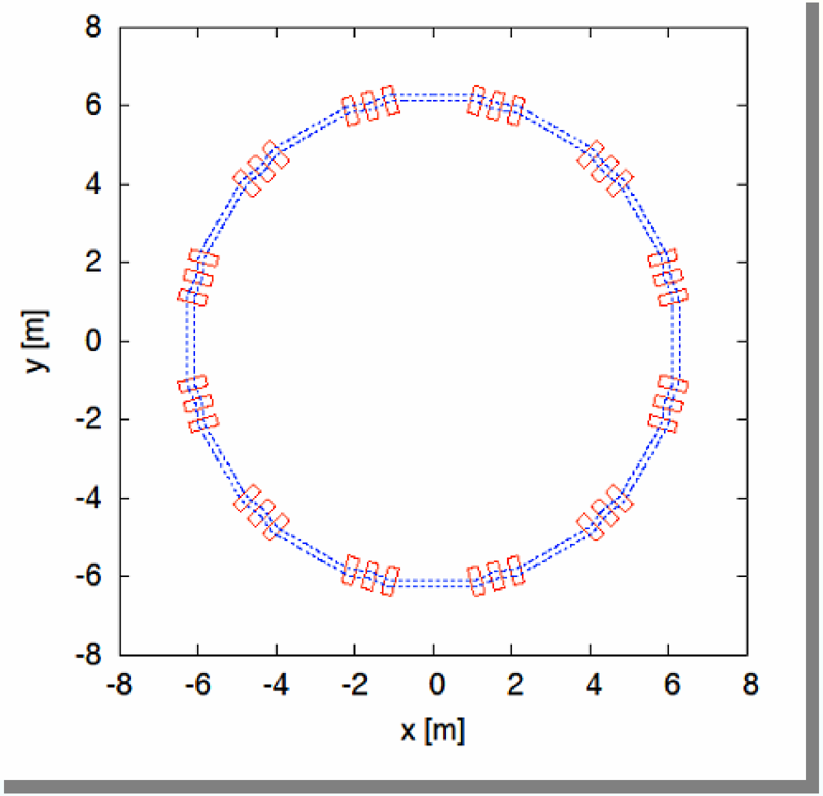

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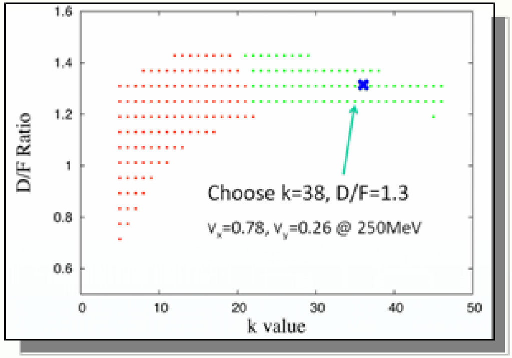
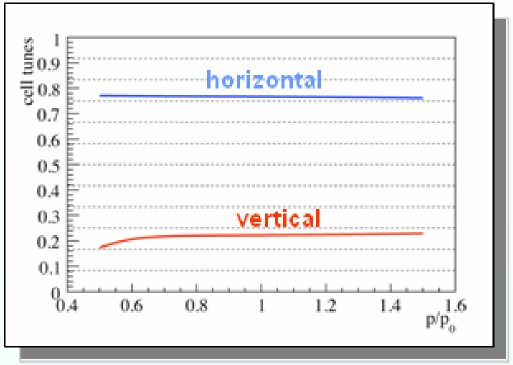
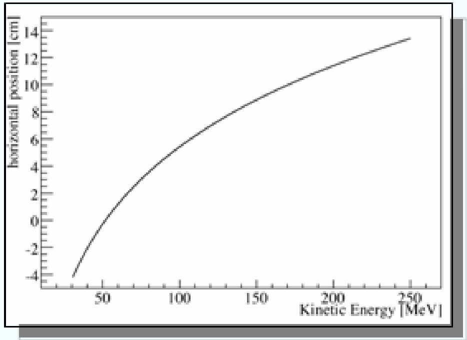
Working Point and Tunes





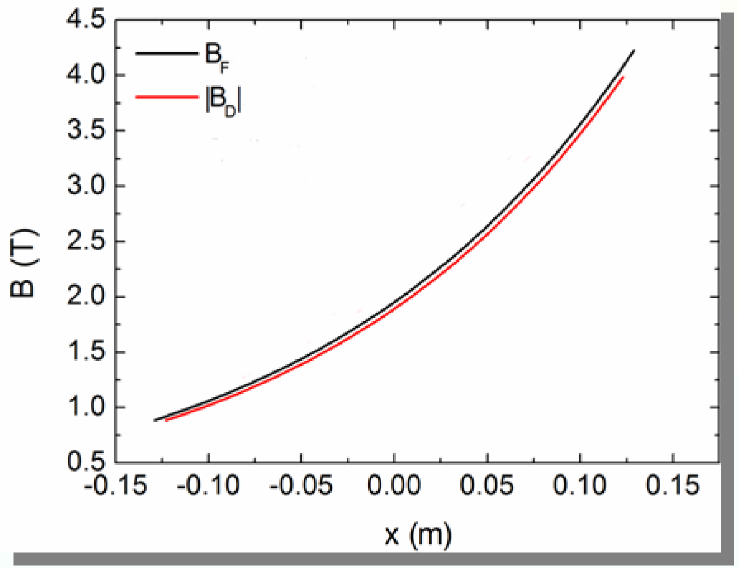


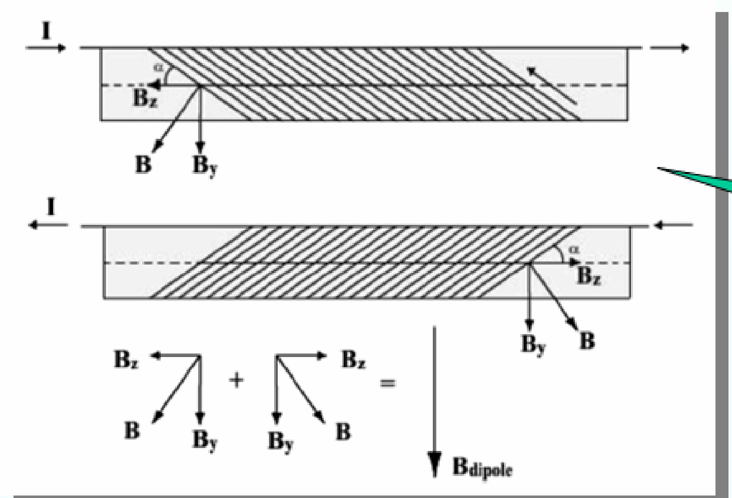
- **Working point**
  - **High k**
    - minimize orbit excursion
- **Machine tune variation** (cell tune variation*12):
  - ν_x within 0.116
  - ν_y within 0.655
  - **Well within an integer!**
- **Beam blow up**
  - **Linear lattice:**
    - Amplification factor 360
  - **Non-linear lattice:**
    - Amplification factor 7.6

      (A = orbit distortion [mm] / 1σ alignment error [mm])
- **Achievable tolerances**

See Sheehy et al, FR5PFP001

Magnet Requirements





- Non-scaling, non-linear FFAG
  - Multipoles up to octupole
- Challenges
  - Maximum field (4.25T)
  - Length restriction (314 mm)
  - Required bore (>250 mm)
- Magnet options
  - n/c Iron cored magnets
  - Superferric coils
  - S/C cos(θ) magnets
  - S/C Double-helix coils

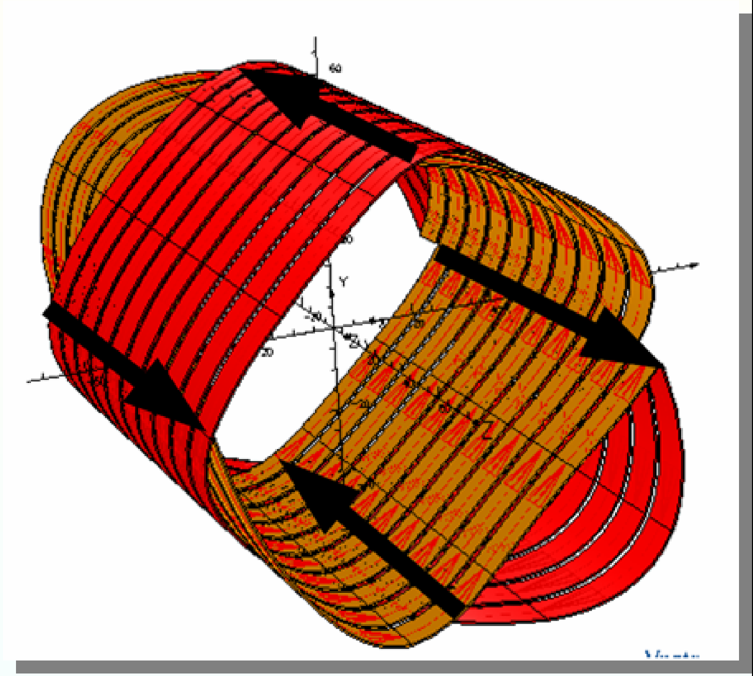
Choose: Double-helix coils

See Witte et al, MO6PFP073

Double-Helix Principle

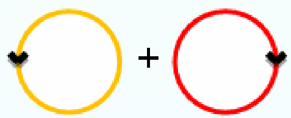
Current density:

Helix 1	Helix 2
$x: \quad \frac{Jx}{J_0} = -R\sin(\Theta)$	$\frac{Jx}{J_0} = R\sin(\Theta)$
$y: \quad \frac{Jy}{J_0} = R\cos(\Theta)$	$\frac{Jy}{J_0} = -R\cos(\Theta)$
$z: \quad \frac{Jz}{J_0} = \frac{nR}{\tan\alpha}\cos(n\Theta)$	$\frac{Jz}{J_0} = -\frac{nR}{\tan(-\alpha)}\cos(n\Theta)$



Double-Helix

$$Jx = 0$$
$$Jy = 0$$
$$Jz = const\cos(n\Theta)$$



Double-helix coil:

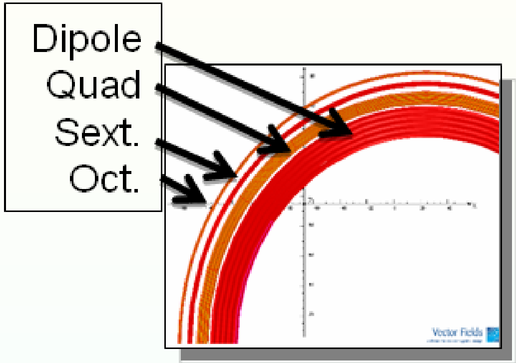
Smart way of creating a cosine-theta magnet

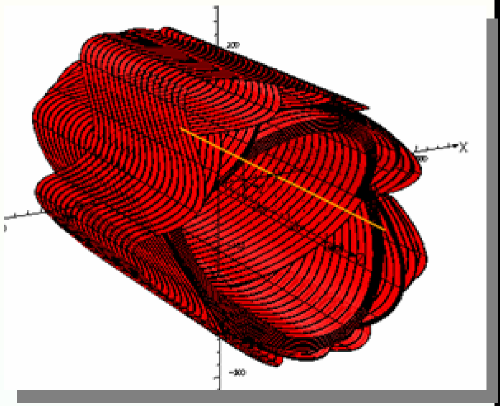
Main advantage for PAMELA: **No coil end problem**

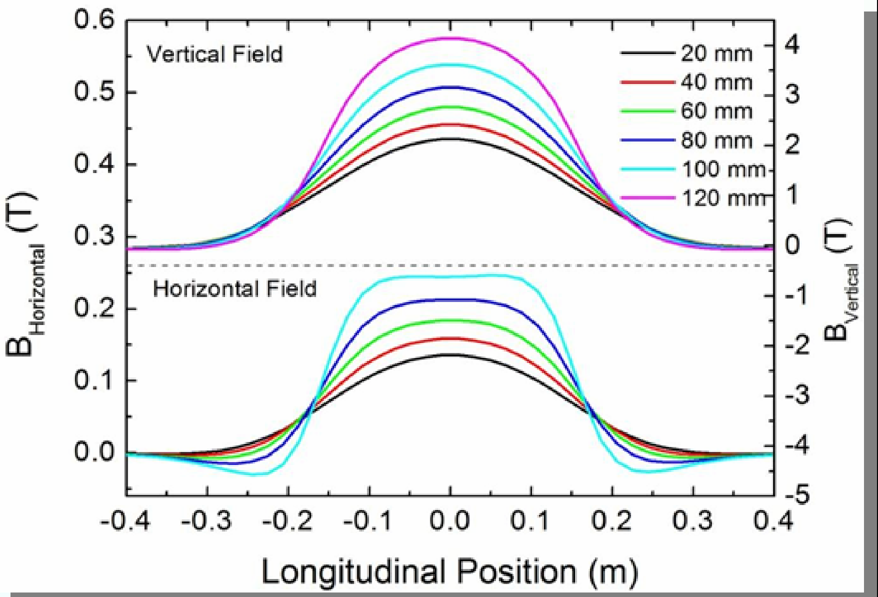
See Witte et al, MO6PFP073

Example: PAMELA F Magnet

- **Combined function magnet**
  - One double-helix coil/multipole
- **Solutions for all multipoles (F and D)**
  - Length: ~560 mm
  - Bore: 280 mm
  - NbTi at 4.2K
    Cu:Sc ratio 1.3:1 and 2:1
  - Temperature margins: >1.5K
  - Mechanical stresses OK
- **Field quality:**
  - better than $3x10^{-4}$



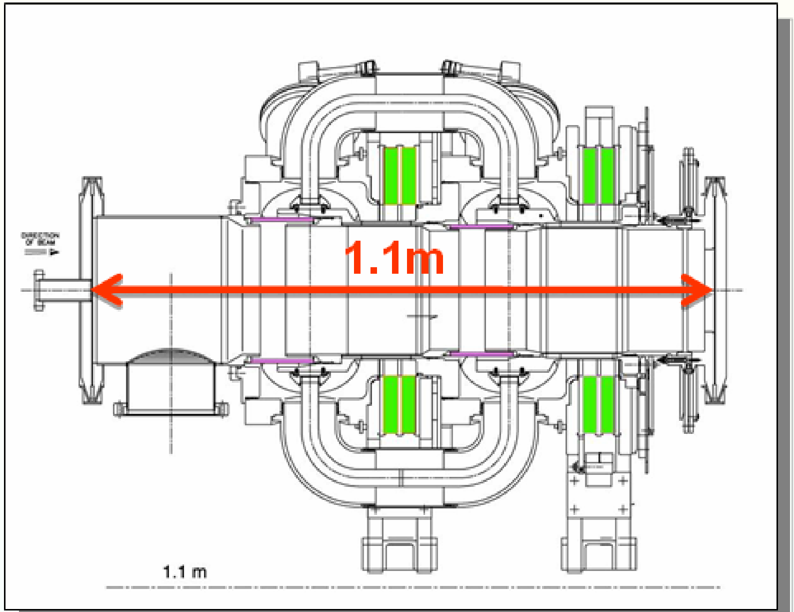


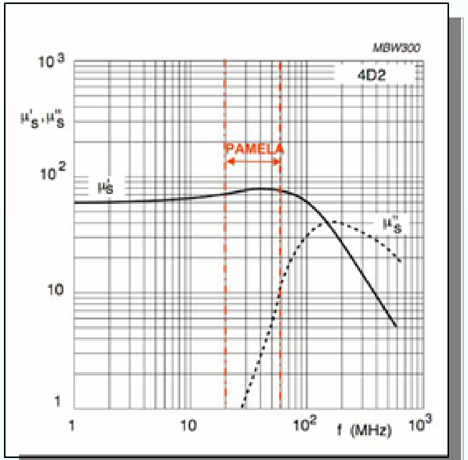


See Witte et al, MO6PFP073

RF System

- **1kHz repetition rate ~ 100kV/turn**
- **Drift space ~1.7m**
- **Target energy gain:**
  - **~16kV/turn/cavity**
- **Challenges:**
  - **duty cycle, Modulation, gradient**
- **Ferrite loaded cavity**
  - **baseline: ISIS 2nd harm. cavity**
    - **Relatively high Q (~100)**
    - **sufficient accelerating field**
    - **h=10 ?**
    - **heat load @ 1kHz ~100kW/cavity**
- **Development started**
  - **Ferrite property measurement**
    - **Q-value, FM rate dependence**



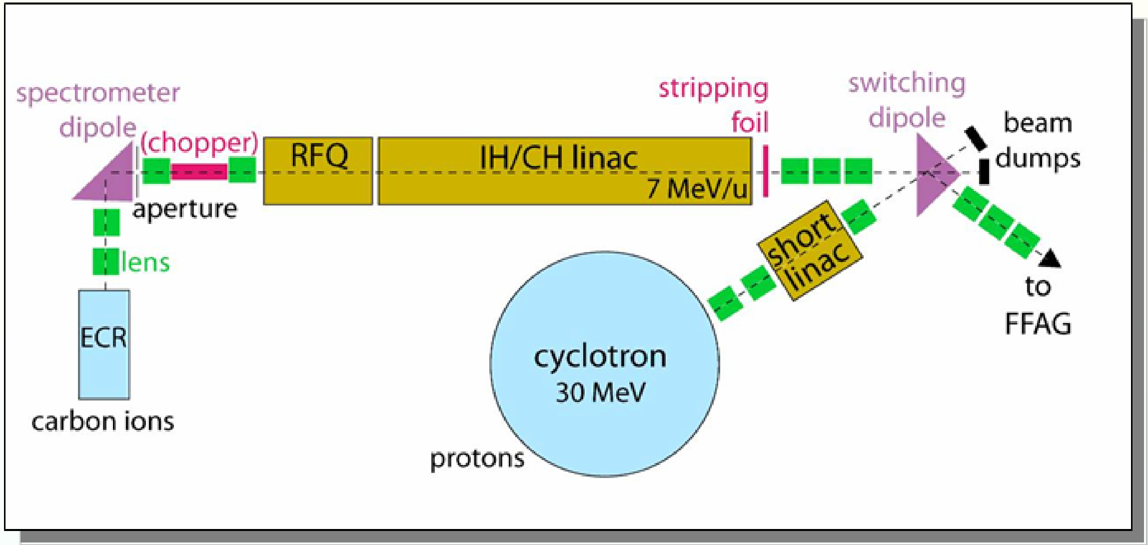


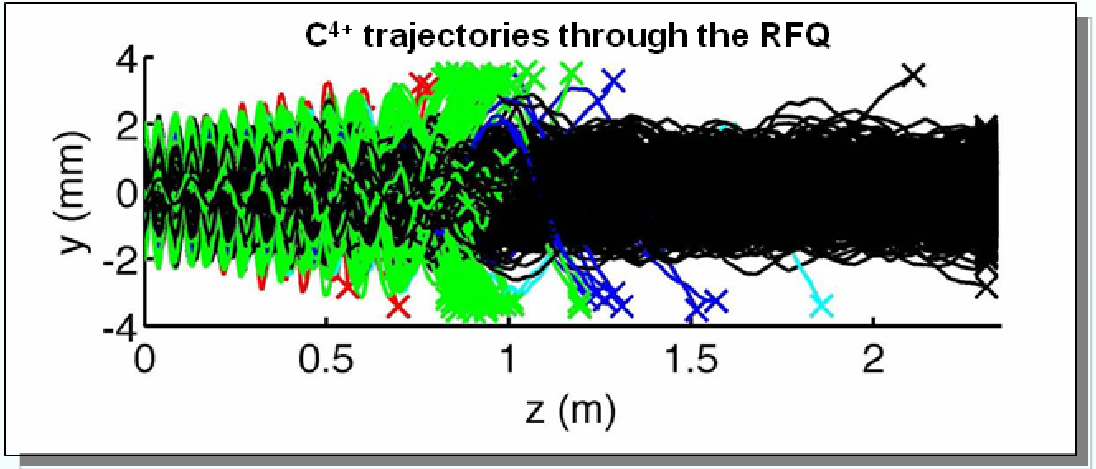
See Yokoi et al, WE5PFP011

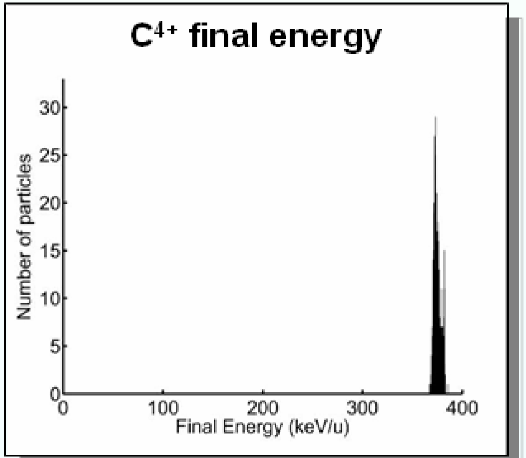
Ion sources

Carbon RFQ Parameters

E-field frequency 200MHz
E_I 8 keV/u
E_f 382 keV/u
Transmission 75%
RFQ length 2.4m
Electrode potential 80 kV



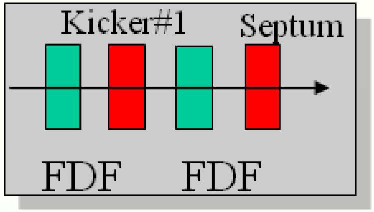




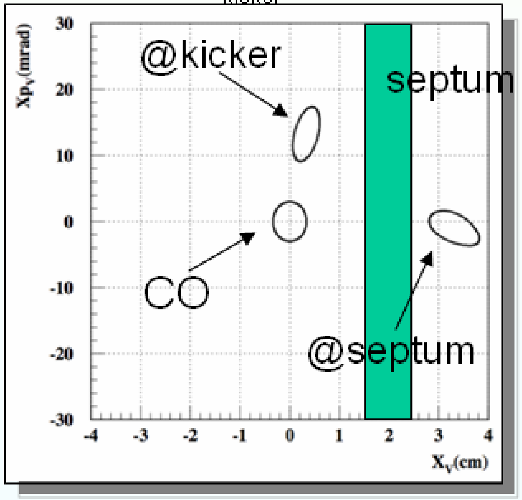
See Easton et al MO6RFP029, FR5REP066

PAMELA: Beam extraction

- Kicker system
  - Work in progress
- Difficulty: horizontally distributed beam
  - Studying vertical extraction
- Advantages over horizontal extraction
  - weaker field
    - <0.6kG ~1m (hor: 2.9 kG)
  - Peak voltage:
    - 15kV (hor: 223 kV for movable C-type)
- R&D issues
  - Large aspect ratio kicker (185x26 mm^2)
    - kicker inductance?
  - Kicker reliability
    - @1 kHz, 10h/day, 5d/week ~10B pulses/y
  - Scaling to carbon ring
    - high current PS



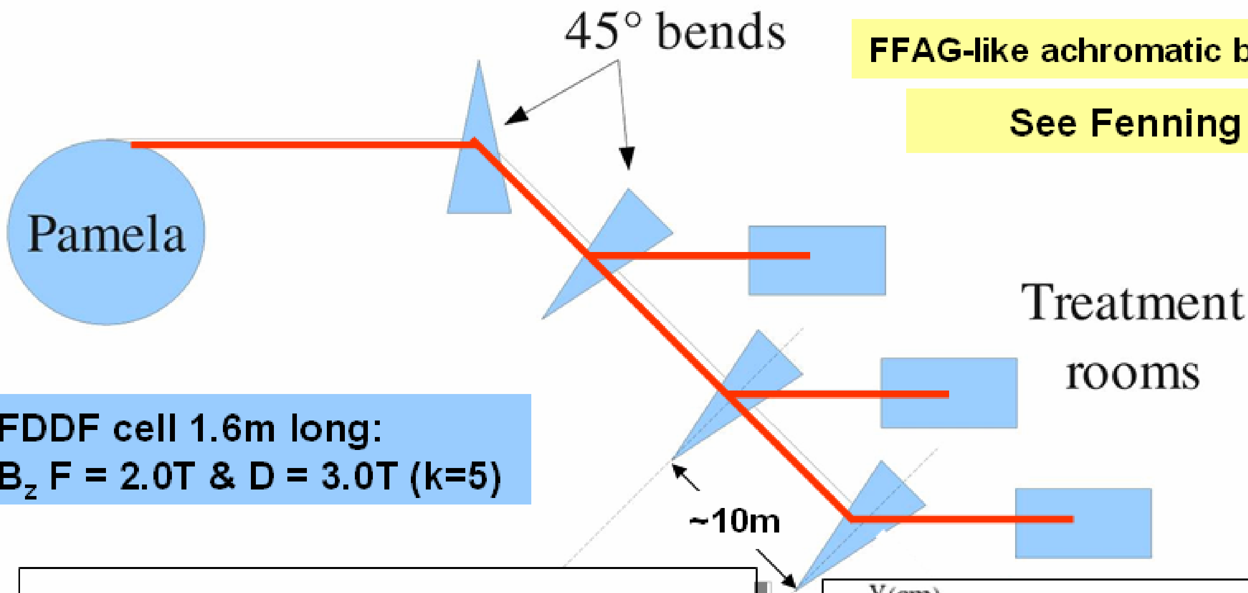
230MeV (B_{kicker}:0.6kgauss)



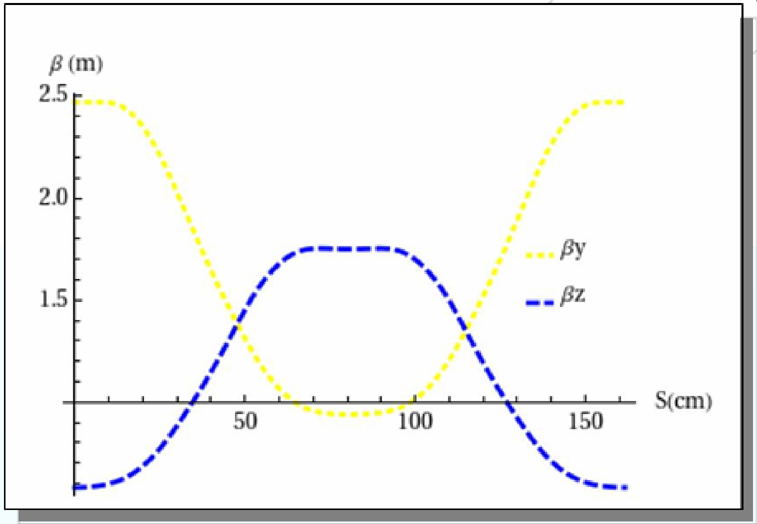
Beam Transport and Gantry

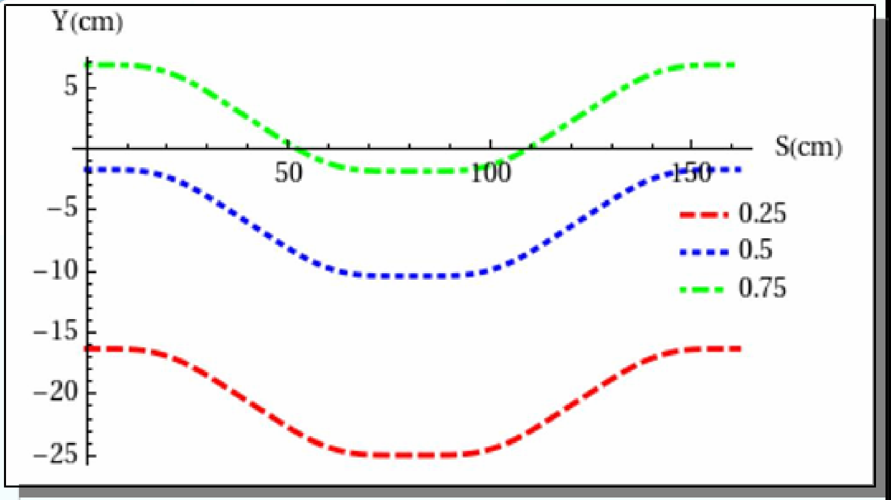
FFAG-like achromatic beam transport & gantry

See Fenning et al TH6PFP022



FDDF cell 1.6m long:
B_z F = 2.0T & D = 3.0T (k=5)





Next steps

1. Complete the proton ring design
2. Develop the carbon ring
3. Develop beam transport & gantry
4. Seek component prototype funding
   - Main ring magnets
   - RF
   - Kickers
   - Carbon RFQ
5. Seek machine funding
   - Demonstrator for CPT

Summary

- **The conceptual design of a Charged Particle Therapy (protons and light ions) accelerator using a non-linear non-scaling FFAG is well advanced**
  - A realistic lattice design exists (proton)
    - Feasible magnets & RF
  - Ion source, injection, extraction and beam transport
    - Under investigation
  - Gantry & carbon ring
    - Still to be done