PAMELA OVERVIEW: Design Goals and Principles

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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

With X-rays
Clinical Requirements

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    - Particularly for childhood cancers

“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
## Main Clinical Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Extraction energy (proton) [Min, Max]</td>
<td>60, 240</td>
<td>MeV</td>
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<td>Extraction energy (carbon) [Min, Max]</td>
<td>110, 450</td>
<td>MeV/u</td>
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<td>Energy step (protons) [@Min, @Max]</td>
<td>5, 1</td>
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<td>Energy resolution $\Delta E/E$ [@Min, @Max]</td>
<td>3.5, 1.8</td>
<td>%</td>
</tr>
<tr>
<td>Voxel Size [Min, Max]</td>
<td>4x4x4</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>10x10x10</td>
<td></td>
</tr>
<tr>
<td>Smallest Field of view [Min, Max]</td>
<td>100x100</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>250x250</td>
<td></td>
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<td>0.5, 2</td>
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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


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

http://www.adams-institute.ac.uk  http://www.ptcri.ox.ac.uk
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Present Lattice – Proton Ring

- 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

See Sheehy et al, FR5PF001
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See Sheehy et al, FR5PFP001

<table>
<thead>
<tr>
<th>Packing Factor</th>
<th>No. cells</th>
<th>Radius</th>
<th>Orbit Excursion</th>
<th>Straight Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>12</td>
<td>6.251 m</td>
<td>0.172 m</td>
<td>1.702 m</td>
</tr>
</tbody>
</table>
Working Point and Tunes

- **Working point**
  - High $k$
    - minimize orbit excursion

- **Machine tune variation**
  (cell tune variation*12):
  - $v_x$ within 0.116
  - $v_y$ within 0.655
  - Well within an integer!

- **Beam blow up**
  - Linear lattice:
    - Amplification factor 360
  - Non-linear lattice:
    - Amplification factor 7.6
      \[ A = \frac{\text{orbit distortion [mm]}}{1\sigma \text{ alignment error [mm]}} \]

- **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 $\cos(\theta)$ magnets
  - S/C Double-helix coils

Choose: Double-helix coils

See Witte et al, MO6PFP073
Double-Helix Principle

Current density:

**Helix 1**
- \( J_x : \frac{J_x}{J_0} = -R \sin(\Theta) \)
- \( J_y : \frac{J_y}{J_0} = R \cos(\Theta) \)
- \( z : \frac{J_z}{J_0} = \frac{nR}{\tan \alpha} \cos(n\Theta) \)

**Helix 2**
- \( J_x : \frac{J_x}{J_0} = R \sin(\Theta) \)
- \( J_y : \frac{J_y}{J_0} = -R \cos(\Theta) \)
- \( z : \frac{J_z}{J_0} = -\frac{nR}{\tan(-\alpha)} \cos(n\Theta) \)

Double-Helix

\( J_x = 0 \)
\( J_y = 0 \)
\( J_z = \text{const} \cos(n\Theta) \)

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 $3 \times 10^{-4}$

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
- $E_1$ 8 keV/u
- $E_0$ 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
    - $<0.6 \text{kG} \sim 1 \text{m}$ (hor: $2.9 \text{kG}$)
  - Peak voltage:
    - $15 \text{kV}$ (hor: $223 \text{kV}$ for movable C-type)

- **R&D issues**
  - Large aspect ratio kicker (185x26 mm$^2$)
    - kicker inductance?
  - Kicker reliability
    - @1 kHz, 10h/day, 5d/week $\sim 10^8$ pulses/y
  - Scaling to carbon ring
    - high current PS
Beam Transport and Gantry

45° bends

FFAG-like achromatic beam transport & gantry

See Fenning et al TH6PFP022

Pamela

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

~10m

Treatment rooms

\[ \beta (m) \]

\[ \beta y, \beta z \]

\[ S (cm) \]

\[ Y (cm) \]

\[ S (cm) \]

0.25
0.5
0.75

Ken Peach (John Adams Institute & PTCRI, Oxford)  PAMELA OVERVIEW [TH46AC03]  PAC09, Vancouver  7 May 2009  19
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