Status of PAMELA
an overview of particle therapy facility
using NS-FFAG

PAMELA collaboration

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TRIUMF(CA)
Contents

• Overview of CONFORM & PAMELA

• PAMELA design
  • Medical requirement
  • Lattice
  • Magnet
  • RF
  • Injection & Extraction
  • Transport & Gantry
Introduction ...

- **FFAG** (Fixed Field Alternating Gradient) Accelerator has an ability of rapid particle acceleration with large beam acceptance. ⇒ wide varieties of applications

**Particle physics**
- EMMA
- ν-factory, muon source, proton driver

**Medical**
- PAMELA
- Particle therapy, BNCT, X-ray source

**Energy**
- (PAMELA)
- ADSR, Nucl. Transmutation

**CONFORM** (Construction of a Non-scaling FFAG for Oncology, Research and Medicine) aims to develop the Non-scaling FFAG as a versatile accelerator. (Project HP: www.conform.ac.uk)

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CONFORM: Project Overview

• 3.5 years project (Apr. 2007~) with total funds £6.9m from STFC (UK government). Now finishing
• 3 parts to the project are funded
  1. **EMMA** : Construction of electron NS-FFAG as a scale down model of muon accelerator for neutrino factory
  2. **PAMELA** : Design of proton and HI accelerator for particle therapy using NS-FFAG
  3. (other Applications) : ex ADSR (THoreA)
• International Collaboration
  (UK, EU, US, Canada etc)
PAMELA: overview

- **PAMELA (Particle Accelerator for MEdical Application)** aims to design a particle therapy facility using NS-FFAG

- It aims to provide spot scanning with proton and carbon beam.

- 2 cascaded rings (For proton, 1st ring is used. For carbon, 1st ring is used as a booster)

- Flexible change of beam energy and particle is required

- Extracted beam: pulsed beam \( \Rightarrow \) high repetition rate is required for active beam scanning

<table>
<thead>
<tr>
<th>Particle</th>
<th>p, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext Energy:p (MeV)</td>
<td>70~250 (variable)</td>
</tr>
<tr>
<td>Ext Energy:C(MeV/u)</td>
<td>110~450 (variable)</td>
</tr>
<tr>
<td>Repetition rate(KHz)</td>
<td>0.5~1</td>
</tr>
<tr>
<td>Voxel size (mm)</td>
<td>4×4~10×10</td>
</tr>
<tr>
<td>Active beam scanning</td>
<td>Spot scanning</td>
</tr>
<tr>
<td>Switching time:p↔c(s)</td>
<td>&lt;1</td>
</tr>
<tr>
<td># of ring</td>
<td>2 (*2nd ring : for C)</td>
</tr>
</tbody>
</table>

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Intensity modulation in pulsed accelerator

For active beam scanning, beam intensity needs to be modulated. Pulse accelerator requires different approach for intensity control.

Synchrotron & cyclotron

Integrated current vs. time

Gate width controls dose

“Analog IM”

With pulsed beam, to realize intensity modulation ….

(1) Dynamic modulation of injector beam intensity

complicated system, but low repetition rate

(2) multi-beam painting with small bunch intensity

simple system, but high repetition rate

“Digital IM”

With pulsed beam, to realize intensity modulation ….

PAMELA employs “multi-beam painting”, and spot scanning is the only choice for active beam scanning (no raster scanning for PAMELA).
A numerical study of SOBP formation with analytical Bragg peak model tells bunch intensity modulation of 1/100 is required to achieve the dose uniformity of 2%.

*minimum pulse intensity:* \(10^6\) proton/1Gy

⇐ Now, refined study with treatment planning system is under going.

If 1kHz operation is achieved, more than 100 voxel/sec can be scanned even for the widest SOBP case.

⇒ 1 kHz repetition is a present goal (For proton machine: 100kV/turn)

High repetition rate (>1kHz) and optimization of bunch intensity granularity are crucially important for efficient treatment with pulsed accelerator
Dynamic range of intensity modulation

In real treatment, single prescribed dose varies more than factor of 7.

Even with “multi-bunch painting scheme”, intensity modulation of more than factor of 30 would be required for efficient spot scanning with pulsed beam** ⇒ Intensity control at injector is a requirement

**multi-field irradiation is assumed (numerical study using treatment planning system is under going )
Efficiency of multi-bunch painting

In ideal situation, multi-bunch painting is about factor of 10 less efficient compared to dynamic intensity modulation.

However, in real beam scanning, beam position has an inevitable systematic deviation from ideal position ⇒ systematic dose field non-uniformity is incurred

\[ \Delta D/D: 1 \times 10^{-4} \]

\[ \Delta D/D: 4 \times 10^{-2} \]

Ideal case: \( \Delta x: 0 \text{mm}(\sigma) \)

\( \Delta x: 0.3 \text{mm}(\sigma) \)

Grid size: 5mm, Beam size: 5mm \((\sigma)\)

Beam positioning error vs maximum dose field error
(Grid size: 5mm, Beam size: 5mm\((\sigma)\) 10cm \times 10cm field, 100 random samples)

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Efficiency of multi-bunch painting

- Rescanning can improve the uniformity caused by the beam position error, but only proportional to $\sqrt{N_{rescan}}$.

- To achieve the overall uniformity for most case, required number of rescanning increases drastically as the beam positioning error gets worse.

- Even the best case ($\Delta x:0.2mm(\sigma)$), rescanning more than 5 times would be needed.

- Multi-beam painting is in itself rescanning, if beam spot moves bunch by bunch.

- In the case of rescanning, efficiency of multi-bunch painting and that of dynamic intensity modulation are almost similar (For multi-bunch painting, combination with active chopping will provide further improvement of efficiency.

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What is Scaling FFAG?

Acceleration rate of ordinary synchrotron is limited by the ramping speed of magnet (magnet PS: \( V = L \cdot dI/dt \), eddy loss: \( \text{rot} \ E + dB/dt = 0 \))

Scaling FFAG realizes stable betatron tune by non-linear field \( B/B_0 = (r/r_0)^k f(\theta) \)

- It requires large excursion combined function magnet \( p/p_0 = (r/r_0)^{k+1} \)
- It can accelerate large emittance beam with high repetition rate (ex KEK PoP FFAG: 1ms acceleration, 5000\( \pi \) mm·mrad)

KEK 150MeV FFAG 100Hz extraction
PAMELA : Lattice
=simplification based on scaling FFAG(triplet FDF)

Step 1. Truncated multipole field

\[ B = B_0 \left( \frac{r}{r_0} \right)^k = B_0 \left( 1 + \frac{k}{r_0} x + \frac{k(k-1)}{2!r_0^2} x^2 + \ldots \right) \]

Tune drift width depends on included orders of multipole field (in PAMELA, up to decapole)

Step 2. Sector magnet ⇒ rectangular magnet

Step 3. Magnet is linearly aligned (* scaling FFAG is co-centric)
Cell layout

Circumference = 39,281 m
12 cells

Diagnostic device
Cavity
Pumping Port
Bellows
BPM
Superconducting Magnet

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### PAMELA Rings…

**Injector**
- **(p)**: Cyclotron
- **(c)**: RFQ + LINAC

**Proton ring**

**Carbon ring**

- Stable betatron tune $\Delta \nu < 1$
- Long straight section (~1.3m)
- Small beam excursion (<20cm)
- Strong field (max 3.5T) $\Rightarrow$ SC magnet
- High repetition rate (~1kHz) is a big challenge

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<table>
<thead>
<tr>
<th></th>
<th>Ring #1 (p, c)</th>
<th>Ring #2 (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>30~250MeV</td>
<td>68~400MeV/u</td>
</tr>
<tr>
<td></td>
<td>8~68MeV/u</td>
<td></td>
</tr>
<tr>
<td><strong># of Cell</strong></td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>12.5m</td>
<td>18.4m</td>
</tr>
<tr>
<td><strong>K-value</strong></td>
<td>38</td>
<td>41</td>
</tr>
<tr>
<td><strong>Orbit excursion</strong></td>
<td>18cm</td>
<td>21cm</td>
</tr>
<tr>
<td><strong>Rev. freq</strong></td>
<td>1.94~4.62MHz(p)</td>
<td>1.92~3.91MHz(c)</td>
</tr>
<tr>
<td></td>
<td>0.98~2.69MHz(c)</td>
<td></td>
</tr>
<tr>
<td><strong>Magnet</strong></td>
<td>Triplet(FDF), SC</td>
<td>Triplet(FDF), SC</td>
</tr>
<tr>
<td></td>
<td>length</td>
<td>57cm</td>
</tr>
<tr>
<td></td>
<td>aperture</td>
<td>25cm</td>
</tr>
<tr>
<td><strong>Long Drift</strong></td>
<td>1.3m</td>
<td>1.2m</td>
</tr>
<tr>
<td><strong>Packing factor</strong></td>
<td>0.48</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Inj./Ext</strong></td>
<td>1turn inj/ext</td>
<td>1turn inj/ext</td>
</tr>
<tr>
<td></td>
<td>2 LD (each)</td>
<td>2 LD (each)</td>
</tr>
<tr>
<td><strong>RF</strong></td>
<td>Max 8 LD</td>
<td>Max 8 LD</td>
</tr>
</tbody>
</table>

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Proton ring performance: tune & acceptance

Tune drift per turn of present lattice: $\Delta \nu_h < 0.1$, $\Delta \nu_v < 0.1$

$\Rightarrow$ No worry about beam distortion due to resonance

* Tracking is carried out using ZGOUBI
  (developed by F. Meot)
Carbon ring performance: tune & acceptance

Carbon ring has relatively larger packing factor and longer magnet length \( \Rightarrow \) higher order field distortion caused by rectangular linear magnet configuration could give larger influence compared to proton ring.

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PAMELA: Magnet

Challenges: Large aperture, short length, strong field

- Applicable to superconducting magnet
- Each multipole can be varied independently
  ⇒ Operational flexibility
- Present lattice parameters are within engineering limit

Superposition of helical field can form multipole field

Dipole Quadrupole Octupole Sextupole

~23cm 55cm

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PAMELA : Magnet (Development)

New coil winding scheme, “Quadruple-helix winding” is proposed to cancel unwanted multipole field components ⇒ (PCT Patent applied)

Double-helix

Quadruple-helix

Engineering development and design are proceeding

Proof of principle NC coils are under development

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Injector needs to realize
(1) flexible beam change between proton and carbon
(2) flexible and precise bunch intensity control
(intensity modulation with more than factor of 30)

Dual Injector is employed
Proton  : Cyclotron (commercial)
Carbon  : RFQ (newly developed)
Injector: RFQ and transport

Tracking simulation results indicate transmission efficiency is more than 99%
Intensity modulation at injection

Intensity modulation larger than factor of 30 needs to be achieved at injection for efficient treatment

Active chopper can realize precise and flexible real time intensity control with limited range

(Commercial delay generator can adjust delay timing with a precision <1ns.)

Dynamic range of modulation with chopper

: ~5 (proton), ~50 (HI)

** depend on the bunch separation of injector beam

For proton, additional intensity modulation of factor of ~6 is feasible in the cyclotron.

⇒ Both proton and HI, required dynamic range of intensity modulation can be realized (optimization of bunch intensity can improve treatment efficiency furthermore with beam chopper)
RF system

Requirement: 1kHz repetition $\Rightarrow$ 100kV/turn
Available space: 8 drift space $\times$ 1.2m ($L_{\text{drift}} \sim 1.7m$)

Target energy gain: 15kV/turn/cavity

Challenge: high duty cycle, high rate FM, high field gradient

Power dissipation is the most serious problem in high repetition operation

$$P = \frac{V^2}{4\pi fQL}$$

Higher Q, higher f are favorable

One solution: Ferrite loaded cavity
* tuning with bias current is required

✓ Relatively high Q (~20)
✓ $h=10$
  $\Rightarrow$ power consumption is~100kW/cavity

**The target repetition rate, ~1kHz, is quite similar to that of ADSR accelerator $\Rightarrow$ possible collaboration for rf development with ADSR**

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**RF : development status**

- Q-value measurement with ferrite sample indicates $Q \sim 60$
  - promising for the realization of cavity (net power dissipation for proton $\sim 300$ kW).
- Now, dynamic property during frequency modulation is under investigation.
- R&D proposal is under preparation

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**Measured Q-value of Feroxcube 4E2**

**Expected rf power vs. frequency in PAMELA proton ring**

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Beam extraction

Challenges: Energy variable extraction in fixed field accelerator

In FFAG, beam orbit excursion makes it difficult to extract beam of different energy due to the beam dynamics of nonlinear field and kicker specification. For example, in PAMELA proton ring: ~11cm (70MeV-250MeV)

⇒ Vertical extraction was adopted in PAMELA

Advantages:
(1) Weaker field, (max 0.6kgauss x 1m)
(2) Good matching with FFAG transport,
(3) Extraction kicker can be used as injection kicker

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>70-230MeV</td>
<td>110-450MeV/u</td>
</tr>
<tr>
<td>Kicker length</td>
<td>1m</td>
<td>1m</td>
</tr>
<tr>
<td>Aperture</td>
<td>160 x 30 mm</td>
<td>160 x 30 mm</td>
</tr>
<tr>
<td>Max field</td>
<td>0.6kgauss</td>
<td>1.8</td>
</tr>
<tr>
<td>Rise time</td>
<td>100ns</td>
<td>100ns</td>
</tr>
<tr>
<td>Max current</td>
<td>10kA</td>
<td>30kHz</td>
</tr>
</tbody>
</table>

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**Extraction kicker : R&D**

**Challenges: wide gap (large current), high duty cycle**

- Large pulse current handling is a key issue
  - Proton: ~10kA, Carbon: ~30kA

<table>
<thead>
<tr>
<th>Material</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>~10kA</td>
</tr>
<tr>
<td>Carbon</td>
<td>~30kA</td>
</tr>
</tbody>
</table>

- Proton: Compensation network (easy, fast)
- Carbon: Traveling wave (complicated, but high current)

Circuit study is under going

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Test circuit of kicker circuit

- PFN
- Compensation Network
- 50 Ohm Coax 25 in parallel

Pulse from the test circuit

- 200ns

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Beam transport : ring ⇔ transport

Vertical beam extraction in PAMELA
⇒ Horizontal orbit excursion is conserved during beam extraction.

Two options can be taken for the downstream beam transport

(1) FFAG transport ( + FFAG gantry)
   Pro. : Fixed field, fixed setting
   Con. : Matching, need development

(2) Conventional beam delivery system
   Pro. : Existing system can be used
   Con. : Varied field, finite transient time

With present scheme, both FFAG transport and conventional beam delivery system can be used ⇒ it provides flexibilities in facility design
FFAG Beam transport

Challenge: beam transport with large momentum acceptance

One solution: (scaling) FFAG transport

As the magnet for the transport, helical coil magnet can be used (provide flexible variation of multipole field)
FFAG Beam transport (cnt’d)

- With the latest design, ~3.6m of straight section is available in each transport cell
  ⇒ good for beam line switching
- Horizontal acceptance is sufficiently large (>100πmm mrad)
- Still, matching scheme is under investigation

Orbit

Field

Optics & field of FFAG transport unit cell

Horizontal phase space distortion in various amplitude beam
FFAG Gantry

Beam delivery system with Full FFAG optics is an optimal option for PAMELA due to the fixed field nature. (FFAG transport + FFAG gantry)

Thus, FFAG gantry is an important development item.

At the moment, two approaches .....  
(1) non-scaling FFAG gantry (see D. Trbojevis’s talk at this workshop)

(2) a truncated field approach similar to PAMELA field (application of FFAG transport)
FFAG Gantry

- By adjusting k-value, phase advance of a lattice can be adjusted to \( \pi \). Then, the closed orbit of various momentum of FFAG transport can be converged to one point \( \Leftrightarrow \) non-linear field of FFAG needs multi-pole field trimming due to nonlinear detuning (Helix magnet provides flexible multipole trimming)

- Present proton gantry lattice can transport entire treatment energy with almost perfect dispersion suppression (final beam divergence: <1mm, <1mrad)
Summary

- PAMELA aims to design particle therapy facility to deliver both proton and carbon using NS-FFAG.
- 1kH is the target repetition rate. The repetition rate is a crucial parameter for a pulse accelerator for particle therapy.
- Overall facility study is done (design report is to be published soon).
  ⇒ Hardware R&D proposals are now being prepared.
Special thanks to PAMELA collaboration for their efforts, and

Thank you for your attention