Acceleration System

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Acceleration System Goals

- Accelerate muons from cooling (momentum 200 MeV/c) to storage ring (total energy $\gtrsim 20$ GeV)
- Accelerate rapidly to minimize decay
- Minimize dynamic particle loss
- Minimize emittance growth (longitudinal and transverse)
- Keep costs down
Linac

Linac to 1.5 GeV

10–20 GeV FFAG

5–10 GeV FFAG

1.5–5 GeV Dogbone RLA
Linac

- Low energy requires short, inefficient cells for transverse acceptance
  - Shorter cells than Study II: larger transverse acceptance
  - Don’t use for most acceleration
- In RLA, each pass through linac must have nearly the same velocity; otherwise RF gets out of sync
  - Stay in first linac until reach sufficient energy
- Since lower energy, use solenoid focusing
- Have complete design
- Longitudinal acceptance is tight. To increase acceptance
  - Go to higher field, shorter solenoids at start, reducing cell length
  - Start further off-crest (but this increases linac length)
Linac Cryostats
## Linac Parameters

<table>
<thead>
<tr>
<th></th>
<th>3</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length (m)</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Cavities per period</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cells per cavity</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Periods</td>
<td>12</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Average gradient (MV/m)</td>
<td>3.8</td>
<td>4.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Max solenoid field (T)</td>
<td>1.5</td>
<td>1.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Matching

- Need to match from cooling to acceleration
- Beta functions somewhat different
  - Not as different as in Study II (cooling went up, linac went down)
  - Thus much simpler
- Need to accelerate a bit also
  - SC linac started at $p = 273$ MeV/$c$ due to acceptance concerns (cooling at 200 MeV/$c$)
- Use combination of cooling cavities and SC cavities
  - Gradually increase cell length in cooling cavities
  - Do matching over a large momentum range
- Result: pretty good transmission (3% loss)
Linac: Next Steps

- Do tracking with real magnet end fields, looking for emittance growth
- Do tracking in 6-D
- Integrate matching design with linac design
- Try to improve longitudinal acceptance
  - Shorter linac cells
  - Improved RF phase profile
Dogbone RLA

10–20 GeV FFAG

5–10 GeV FFAG

Linac to 1.5 GeV

1.5–5 GeV Dogbone RLA
● FFAGs inefficient at low energies; use RLA
● Use dogbone over racetrack due to
  ◆ Better energy separation at switchyard
  ◆ More cost effective (?)
● Triplet lattice, 2 cavities per cell (larger acceptance)

● Switch to FFAGs when they become more cost effective
● Most of the pieces are there, but still needs to be finished off
Dogbone RLA: Next Steps

- Finish off the existing design, and get component specifications
- Do 6-D tracking through the machine
- Optimize number of turns
FFAGs: Previous Work

- Had used an early version of an optimization procedure to determine FFAG designs
- Using triplet designs, had done
  - Injection/extraction scheme
  - Tracking study
- There is a wide collaboration interested in FFAGs
  - International (Canada, Europe, Japan)
  - Frequent workshops (twice per year)
  - Desire to build a model of the new type of FFAGs considered for muon acceleration (next talk)
Choose FFAG machine parameters by minimizing a cost function.

We have made improvements to the cost function in the last year:
- Changed magnet cost model so that zero-field magnets with nonzero size have nonzero cost.
- Assigned a cost to decays.
  - Minimum-cost rings had unacceptable decays.
  - Use detector cost as a baseline: for given performance, can make acceleration more efficient or make detector larger.

These changes cause fields to be higher than before.

Doublets are the most cost effective (as we’ve always found), compared with triplets, FODO.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient (MV/m)</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum total energy (GeV)</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Maximum total energy (GeV)</td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>No. of cells</td>
<td>50</td>
<td>65</td>
<td>82</td>
</tr>
<tr>
<td>D length (cm)</td>
<td>63</td>
<td>77</td>
<td>97</td>
</tr>
<tr>
<td>D radius (cm)</td>
<td>13.4</td>
<td>10.0</td>
<td>7.4</td>
</tr>
<tr>
<td>D pole tip field (T)</td>
<td>4.5</td>
<td>5.7</td>
<td>7.1</td>
</tr>
<tr>
<td>F length (cm)</td>
<td>96</td>
<td>113</td>
<td>141</td>
</tr>
<tr>
<td>F radius (cm)</td>
<td>21.2</td>
<td>16.3</td>
<td>13.1</td>
</tr>
<tr>
<td>F pole tip field (T)</td>
<td>2.7</td>
<td>3.5</td>
<td>4.3</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>42</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>RF voltage (MV)</td>
<td>534</td>
<td>620</td>
<td>704</td>
</tr>
<tr>
<td>Turns</td>
<td>4.7</td>
<td>8.2</td>
<td>15.0</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>204</td>
<td>286</td>
<td>400</td>
</tr>
<tr>
<td>Decay (%)</td>
<td>4.2</td>
<td>5.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Total cost (PB)</td>
<td>74.8</td>
<td>79.5</td>
<td>88.9</td>
</tr>
<tr>
<td>Cost per GeV (PB/GeV)</td>
<td>29.9</td>
<td>15.9</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Other Optimization Results

- **Costs vs. Gradient**
  - Relatively weak dependence on gradient in 10–17 MV/m range
  - Assumption is that only RF power costs increase with gradient
    - ★ If this is wrong (e.g., extra cryo costs, increased structure costs), cost benefit of 17 MV/m over 10 MV/m may be lost

- **Costs vs. Transverse Acceptance**
  - Cost depends strongly on acceptance
  - To do next: optimize cooling length and acceleration aperture together, considering decay cost
Longitudinal Parameter Choice

- Longitudinal motion in muon FFAGs described by two parameters
  \[ a = \frac{qV}{\omega \Delta T \Delta E} \quad b = \frac{T_0}{T} \]
- As \( a \) reduces, get more longitudinal distortion
- Choice of \( a \) drives the FFAG design
- We have developed a technique for computing distortion from ellipticity as a function of these parameters
  - Get optimum phase space ellipse orientation in the process
Longitudinal Motion in FFAG

\[ \frac{(E-E_{\text{min}})}{\Delta E} \]

RF Phase

-0.5\pi -0.25\pi 0\pi 0.25\pi 0.5\pi
Time-of-Flight in an FFAG

![Graph showing Time-of-Flight Deviation per Cell (ps) vs Total Energy (GeV)]

- Time-of-Flight Deviation per Cell (ps)
- Total Energy (GeV)

- \( \Delta T \)
- \( T_0 \)
Stages in FFAGs

- Different numbers of stages to get from 2.5 to 20 GeV
- 2 stages significantly more expensive than 3
- 3 stages wins slightly over 4
  - Machine cost slightly lower for 4, but decays make 4 stages worse
  - Extra cost of transfer line also adds to 4 stage cost
  - Prefer fewer stages to more
### Stages in FFAGs: Table

<table>
<thead>
<tr>
<th></th>
<th>4</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of stages</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Min. total energy (GeV)</strong></td>
<td>2.5 4.2 7.1 11.9</td>
<td>2.5 5.0 10.0</td>
<td>2.5 7.1 7.1</td>
</tr>
<tr>
<td><strong>Max. total energy (GeV)</strong></td>
<td>4.2 7.1 11.9 20.0</td>
<td>5.0 10.0 20.0</td>
<td>7.1 20.0 20.0</td>
</tr>
<tr>
<td><strong>Number of cells</strong></td>
<td>34 38 46 57</td>
<td>50 63 82</td>
<td>101 152</td>
</tr>
<tr>
<td><strong>Number of cavities</strong></td>
<td>26 30 35 38</td>
<td>42 48 56</td>
<td>88 97</td>
</tr>
<tr>
<td><strong>RF voltage (MV)</strong></td>
<td>331 382 434 477</td>
<td>534 606 704</td>
<td>1114 1230</td>
</tr>
<tr>
<td><strong>Turns</strong></td>
<td>5.2 7.6 11.4 17.7</td>
<td>4.7 8.5 15.0</td>
<td>4.2 11.3</td>
</tr>
<tr>
<td><strong>Circumference (m)</strong></td>
<td>144 174 228 306</td>
<td>204 279 400</td>
<td>389 653</td>
</tr>
<tr>
<td><strong>Decay (%)</strong></td>
<td>3.6 3.8 4.4 5.4</td>
<td>4.2 5.1 6.5</td>
<td>5.8 9.1</td>
</tr>
<tr>
<td><strong>Machine cost (PB)</strong></td>
<td>53.0 56.7 61.5 68.1</td>
<td>74.8 78.9 88.9</td>
<td>138.1 142.0</td>
</tr>
<tr>
<td><strong>... per GeV (PB/GeV)</strong></td>
<td>31.1 19.8 12.8 8.4</td>
<td>29.9 15.8 8.9</td>
<td>30.2 11.0</td>
</tr>
<tr>
<td><strong>Marginal decay cost (PB)</strong></td>
<td>18.0 18.9 21.9 27.1</td>
<td>21.1 25.6 32.3</td>
<td>28.9 45.5</td>
</tr>
<tr>
<td><strong>Total machine cost (PB)</strong></td>
<td>239.3</td>
<td>242.7</td>
<td>280.1</td>
</tr>
<tr>
<td><strong>Total decay cost (PB)</strong></td>
<td>85.9</td>
<td>78.9</td>
<td>74.5</td>
</tr>
</tbody>
</table>
● Preliminary design of FFAG magnet was done for costing purposes (Caspi/Hafalia)
● Did design with separate dipole/quadrupole layers
● J-PARC 50 GeV proton line, have built a SC single-layer combined-function magnet: uses less coil
Other Types of FFAGs

- FFAGs with warm magnets may be more cost-effective at low energy
- FFAGs with nonlinear magnets are also being looked at
  - Concern: poor dynamic aperture due to nonlinear magnets
  - Graeme Rees has proposed a lattice which is much more isochronous than our lattices

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O  bd(-)  o  BF(-,+o)  o  BD(+)  o  BF(-,+o)  o  bd(-)  O
```

- Lower RF requirement and/or shorter lattice
- Currently has dynamic aperture problems, but it doesn’t seem too far off (tracking by François Méot)
FFAGs: Next Steps

- Re-do optimization with consideration for longitudinal distortion calculation
  - For given $a$, choice of $b$ gives tradeoff between acceptance and decay
- Use optimization procedure to choose dividing point between stages
- Injection/extraction scheme with doublet lattice
- Do tracking studies with chosen lattices
- Get a more detailed magnet design
● Understand parametric dependence of designs of all stages (e.g., dependence on acceptance)
● Develop method for choosing when to switch stages
● Develop transfer line designs
● 6-D tracking through entire system