FFAG Lattice Design: 
Allowing Any Values on the Low-Energy Tunes 

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● Cost optimized FFAG designs

● Normally for my optimization, I fix the values of the tunes at the lowest energy
  ◆ Stay sufficiently away from half integer tune

● Higher tune improves time of flight variation

● Higher tune increases beta functions
  ◆ Larger aperture requirement
  ◆ More dynamics problems

● If tunes are the same, 0.35 is approximately optimum cost

● Remove constraint on tunes, see what cost optimization gives
Time of Flight vs. Energy

Time of Flight Deviation (ps) vs. Total Energy (GeV)
Required Voltage vs. Tune (FODO)

Minimum Required Voltage (GV) vs. Tune at Minimum Energy

- Minimum Required Voltage (GV) range: 0.24 to 0.32
- Tune at Minimum Energy range: 0.3 to 0.4
Beta Functions for Different Tunes (FODO)

- $\beta_x, \nu_{\text{min}} = 0.3$
- $\beta_y, \nu_{\text{min}} = 0.3$
- $\beta_x, \nu_{\text{min}} = 0.4$
- $\beta_y, \nu_{\text{min}} = 0.4$
## Results (10–20 GeV)

<table>
<thead>
<tr>
<th></th>
<th>Constrained</th>
<th>Unconstrained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells</td>
<td>105</td>
<td>95</td>
</tr>
<tr>
<td>Voltage (MV)</td>
<td>788</td>
<td>713</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>768</td>
<td>701</td>
</tr>
<tr>
<td>Cost (PB)</td>
<td>104</td>
<td>93</td>
</tr>
<tr>
<td>Magnet Length (m)</td>
<td>1.762</td>
<td>1.883</td>
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<tr>
<td>Magnet Radius (cm)</td>
<td>10.4</td>
<td>10.3</td>
</tr>
<tr>
<td>Pole Tip Field (T)</td>
<td>4.31</td>
<td>3.80</td>
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<tr>
<td></td>
<td>QD</td>
<td>QF</td>
</tr>
<tr>
<td>Magnet Length (m)</td>
<td>1.276</td>
<td>1.246</td>
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<tr>
<td>Magnet Radius (cm)</td>
<td>12.6</td>
<td>12.5</td>
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<tr>
<td>Pole Tip Field (T)</td>
<td>2.18</td>
<td>2.35</td>
</tr>
</tbody>
</table>
Conclusions

● Allowing tunes to go free improves cost

● Tunes split: horizontal is higher, vertical lower
  ♦ Higher horizontal improves path length
  ♦ Lower vertical avoids beta function spike
  ♦ Beam pipe size determined primarily by orbit swing, not beta functions
    ★ Orbit swing improved by higher horizontal tune
  ♦ Lower tune, less integrated magnet strength
    ★ Use the field strength wisely: to reduce path length
Orbits

Tunes Unconstrained
Tunes Constrained