Status Report on Neutrino Factory Acceleration Schemes

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Acceleration Schemes

- Dogbone RLA to 5 GeV
- Linear non-scaling FFAGs, 5–10 GeV and 10–20 GeV
  - Not discussed here
- NuFactJ scheme
- Isochronous FFAGs
Dogbone RLA

- Full linear design exists
  - Needs to be converted into real terms, costed
  - Compare cost per GeV to FFAGs
- Misalignment and gradient error sensitivity studied
  - Orbit distortion manageable with 1 mm orbit errors
  - Quad fields tolerances 0.2%
- Next steps
  - Add sextupoles to get chromatics right
  - Look at beam with finite energy spread
NuFactJ Parameters

- Need a description of the field in the FFAG
- NuFactJ report: description based on arcs of sector magnets, run in SAD
- Need to convert to

\[ B(r, \theta) = B_0(\theta)(r/r_0)^k \]

\( B_0(\theta) \) piecewise constant
- Geometry determined, only specify fields
- For some lattices, no reasonable guess works
<table>
<thead>
<tr>
<th>Lattice number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>$p_{\text{min}}$ (GeV/c)</td>
<td>0.3</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>$p_{\text{max}}$ (GeV/c)</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Cells</td>
<td>32</td>
<td>16</td>
<td>64</td>
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<tr>
<td>Field index</td>
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<td>15</td>
<td>190</td>
<td>63</td>
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<tr>
<td>Average radius (m)</td>
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<td>30</td>
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<tr>
<td>$\beta_F$ (mrad)</td>
<td>26</td>
<td>52</td>
<td>12.7</td>
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<td>$\beta_D$ (mrad)</td>
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<td>$\theta_F$ (deg)</td>
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<td>Packing fraction</td>
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<td>$\mu_y$ (deg)</td>
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<td>$L_0$ (m)</td>
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<td>0.367</td>
<td>0.747</td>
<td>0.544</td>
<td>0.813</td>
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</table>
My Versions of NuFactJ Lattices

- Try to fit the tunes, assuming those were chosen carefully
- Can’t do this by just varying fields: degeneracy due to scaling
- Vary $\beta_F$, $B_D$, keeping $\beta_0$ fixed
My Versions of NuFactJ Lattices
Parameter Table

<table>
<thead>
<tr>
<th>Lattice number</th>
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<td>$p_{\text{min}}$ (GeV/c)</td>
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<td>Field index</td>
<td>50</td>
<td>15</td>
<td>190</td>
<td>63</td>
<td>220</td>
<td>280</td>
</tr>
<tr>
<td>$r_0$ (m)</td>
<td>21</td>
<td>10</td>
<td>80</td>
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<tr>
<td>$\beta_F$ (mrad)</td>
<td>27.24</td>
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<td>$2r_0\beta_F$ (m)</td>
<td>1.144</td>
<td>1.148</td>
<td>2.119</td>
<td>1.661</td>
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<td>$B_F$ (T)</td>
<td>1.958</td>
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<td>$\beta_D$ (mrad)</td>
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<td>$r_0\beta_D$ (m)</td>
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<td>0.306</td>
<td>0.700</td>
<td>0.490</td>
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<td>$B_D$ (T)</td>
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<td>4.334</td>
<td>3.250</td>
<td>5.056</td>
<td>5.672</td>
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</table>
My Versions of NuFactJ Lattices
Magnet Parameters and Cost

- Machine costs are huge (non-scaling FFAGs: \( \lesssim 100 \) PB each stage)
- Magnet apertures are large
- Fields are very high
- Note: no cavities in cost!

- RF systems used
  - 0.75 MV/m average over ring, air gap, 5–10 MHz
  - First ring may be variable frequency
    - New type of magnetic alloy core
  - All this needs more careful specification, R&D, costing
- RF cost will be a significant additional cost
<table>
<thead>
<tr>
<th>Lattice number</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>$L_F$ (m)</td>
<td>1.125</td>
<td>1.088</td>
<td>2.111</td>
<td>1.640</td>
<td>2.225</td>
<td>3.257</td>
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<td>$r_F$ (cm)</td>
<td>58.3</td>
<td>75.0</td>
<td>54.1</td>
<td>59.7</td>
<td>52.9</td>
<td>45.0</td>
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<td>$x_F$ (cm)</td>
<td>-35.5</td>
<td>-51.6</td>
<td>-32.9</td>
<td>-37.3</td>
<td>-34.0</td>
<td>-41.1</td>
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<tr>
<td>$L_D$ (m)</td>
<td>0.345</td>
<td>0.288</td>
<td>0.696</td>
<td>0.482</td>
<td>0.770</td>
<td>0.766</td>
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<tr>
<td>$r_D$ (cm)</td>
<td>52.2</td>
<td>67.2</td>
<td>48.1</td>
<td>52.1</td>
<td>47.4</td>
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<tr>
<td>$x_D$ (cm)</td>
<td>-40.6</td>
<td>-60.5</td>
<td>-40.4</td>
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<td>-48.5</td>
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<tr>
<td>Cost (PB)</td>
<td>281</td>
<td>355</td>
<td>396</td>
<td>527</td>
<td>1153</td>
<td>1410</td>
</tr>
</tbody>
</table>
My Impressions from Conversations

- These designs were just supposed to be “typical”
- Constrained to fit inside 50 GeV proton ring
- Nobody did anything beyond the SAD model
- RF systems are all R&D projects
FFAGs on Tokai Campus

FFAG-I
0.3-1 GeV/c

FFAG-2
1-3 GeV/c

FFAG-3
3-10 GeV/c

FFAG-4
10-20 GeV/c

MSR
20 GeV/c
Work was done on improving the high energy (10–20 GeV/c) FFAG lattice

- FODO lattice
- Two versions
  - Same number of cells, higher field index, smaller ring
  - Larger ring, more cells even higher field index

I ran the lattices based on a hard edge model

Cost reduced significantly from NuFactJ design
- Apertures and fields both much lower
- Still high
- Cost can be improved by increasing cells
  - Need to fold decays in as usual
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells</td>
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<td>Field index</td>
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<td>Reference radius (m)</td>
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<tr>
<td>Ends (m)</td>
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<td>0.20</td>
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<tr>
<td>D angle (deg)</td>
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<tr>
<td>D length (m)</td>
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<td>0.92</td>
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<td>D field (T)</td>
<td>5.795</td>
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<tr>
<td>F angle (deg)</td>
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<td>F length (m)</td>
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<td>F field (T)</td>
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<td>-4.857</td>
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<td>Drift length (m)</td>
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<tr>
<td>$L_F$ (m)</td>
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<td>$r_F$ (cm)</td>
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<td>$x_F$ (cm)</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>$B_F$ (T)</td>
<td>7.664</td>
<td>9.764</td>
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<td>$L_D$ (m)</td>
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<td>$r_D$ (cm)</td>
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<td>$B_D$ (T)</td>
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<tr>
<td>Cost (PB)</td>
<td>284</td>
<td>373</td>
</tr>
</tbody>
</table>
2002 LBNL Lattice Cost vs. Cells

![Graph showing the relationship between cost (in PB) and number of cells.]
New Lattices, not Analyzed as Yet

- There is a 10–20 GeV doublet scaling lattice (early 2003)
  - Expect cost improvement
  - Still waiting on specs for this
- Lowest energy lattice corrected to normal conducting
  - Need to work out costing for that
- New proposal by Mori: 10–20 GeV singlet spiral sector
  - Normal conducting, 100 m radius, 50 cm orbit excursion
  - Passive extraction: orbit jump
Next Steps

- Need to work out details of a working scheme for all stages
  - Analyze all the schemes I currently have
  - Lattices other than first and last probably need to be defined
    - Optimized to some extent for cost
  - Need to define RF systems

- Need some costing information
  - Normal-conducting scheme at low energy
  - All RF systems

- Start to do more complete simulations
Isochronous FFAG Scenario (Rees)

- Avoid time of flight problems: act like a linac, make machine isochronous
- Two stages: 3.2–8, 8–20 GeV
- Field description
  - Original description based on constructing multiple linear lattices, connecting appropriately
    ★ Resulting field is nonlinear
  - I fit fields using cubic spline
    ★ Good fit
    ★ No excess oscillations
    ★ Extrapolates well
  - Note highly nonlinear fields
5-Cell Lattice

O     bd(-)     o     F(±)     o     BD(+)     o     F(±)     o     bd(-)     O

2.4    0.45    0.5    0.62    0.5    1.26    0.5    0.62    0.5    0.45    2.4 m
Field Fits for Isochronous FFAG
Isochronous FFAG: Analysis

- Time of flight variation is exceptionally small
  - Factor of 10 below natural value
- In my computation, tunes go unstable at high energy
  - Possible cause: Rees uses second-order edge effect which I don’t
- Tracking results (Méot)
  - Beam loss at high energy end
  - Appears to come from hitting a resonance
    - Note it occurs just where I say the lattice goes unstable
  - Highly nonlinear fields at high energy could also be driving it into the resonance
Time of Flight in Isochronous FFAG

![Graph showing the relationship between Relative Time of Flight per Cell (ps) and Kinetic Energy (GeV).]
Tunes in Isochronous FFAG

![Graph showing the relationship between kinetic energy and cell tune for horizontal and vertical tunes.](image-url)
Isochronous FFAG Beam Loss

Transmission rate & E/20 Gev vs. cavity #

1st run, Transmission rate = 0.16%

2nd run, Transmission rate = 11%

3rd run, Transmission rate = 14%
Isochronous FFAG
Evolution in Tune Space
Isochronous FFAG
Observations, Recommendations

- Machine is very fussy:
  - Tiny changes in lattices (0.1% change in lengths) has substantial effect on time of flight
  - Small end effects give drastic change in tunes
- Probably related to very nonlinear fields, especially at high energy
  - Could possibly relax this: certainly room in time of flight
    - Amplitude dependence of time of flight will give big contribution to TOF anyhow
  - Could consider reducing energy range
- Notice “wiggles” in time of flight
  - More automated design method would take this out
  - May also improve performance
Isochronous FFAG Tasks

- Next, try to do some costing
  - Since lattice unstable at high energy, will have to make guesses for beam sizes there.
- Still want to add insertions
  - Short cells in arcs, longer cells in straights to fit RF
  - May reduce cost
  - Matching tricky
  - Get lattice without insertions working first