Nonlinear Magnet for a Rapid-Cycling Synchrotron at Fermilab

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FAST/IOTA Collaboration Meeting
June 15 – 17, 2020
Outline

• Pole-face design and 3D model optimization
• Preliminary Tolerance Study
• Engineering Design
• Future Outlook
**Technical Objective** | **Comments / Results**
--- | ---
Analytic solution to allow proper harmonic content | Pole-face contour definition outside convergence circle allows exploration of designs with larger physical aperture, required for iRCS
Perform 3D simulations to obtain the required field | A full 8m-long NLI consisting of 20 segments has been designed, the required field profile is achieved
Simulate the effect of manufacturing errors to set fabrication tolerances | The transverse misalignments of the segments, pole profile deviation and gap between the poles should be less than ±125um in order to maintain <0.5% of harmonic content error
Develop engineering design for the prototype | Mechanical engineering model for the NLI based on 3D magnetic simulations has been developed along with cost-effective manufacturing plan to be followed in Phase II

- IOTA was a testbed for NLI that will eventually be used in iRCS
- The more rigid beam of iRCS requires larger magnets, which is favorable for manufacturing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IOTA</th>
<th>iRCS</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Electron</td>
<td>Proton</td>
<td></td>
</tr>
<tr>
<td>Beam Energy</td>
<td>150</td>
<td>800</td>
<td>MeV</td>
</tr>
<tr>
<td>Momentum Rigidity, Bp</td>
<td>0.5</td>
<td>4.9</td>
<td>T×m</td>
</tr>
<tr>
<td>Minimum Beta Function, β</td>
<td>0.73</td>
<td>5</td>
<td>m</td>
</tr>
<tr>
<td>Drift Length For NLI</td>
<td>2</td>
<td>8</td>
<td>m</td>
</tr>
<tr>
<td>Singularity = c√β</td>
<td>0.77</td>
<td>2.5</td>
<td>cm</td>
</tr>
</tbody>
</table>
IOTA Non-Linear Inserts (NLI)

• The non-linear potential has a singularity on the x-axis, given by $c \sqrt{\beta} = 0.77$ cm, $c$ is a scaling constant and $\beta$ is the beta function of the beam at that location.
  • For reference, quadrupoles have a singularity in their potential at infinity.
  • Note that the pole-face must protrude well into the aperture radius defined by the singularity (and reduce the real beam aperture), in order to produce the desired non-linear fields close to the beam axis.

• These NLI will be placed in a drift space where the beta function is $\beta(s) = \frac{L-sk(L-s)}{\sqrt{1-\left(1-\frac{Lk}{2}\right)^2}}$, for a drift length of $L$, and $k$ is the focusing strength of upstream optics (symmetric in x and y).
  • Therefore the size of the NLI must change along its length as depicted by the blue, green, and red outlines.
Pole-face Definition

- Defining the pole face is done by picking an equipotential line from the imaginary part of the auxiliary transverse magnetic potential
  - \( \mathbf{F}(z) = \frac{A + i \phi}{B \rho} \)
- The pole face contour is highlighted in the figure
- Only the positive x and y quadrant is shown due to symmetry
- The full analytic form of the potential has been derived by Mitchell, 2018
  - This allows for a faster computation of the pole face and extends the validity of the solution beyond a region close to the beam axis

3D Modeling of NLI Magnet Segments

- Basic 3D model of the NLI magnet segment
- The truncation of the pole-face and its connection to the rest of the yoke has a strong impact on the transverse field
  - Future optimization will focus on this connection
Field Error from Ideal

- Error from ideal transverse field increases toward the singularity
- Error is due to the finite terminations of the pole-face
- Further iterative optimization is required
Harmonic Content

- Multipole expansion of transverse potential: \( F(z) = \sum_m C_m z^m = \sum_m C_m e^{im\theta} r^m \)
- Harmonic content error at 5 mm is 10% for the 3D model presented above
  - Further iterative optimization is required
- Harmonic content is sensitive to pole-face misalignment in the vertical direction (pole-face gap is small in the vertical direction)
- Harmonic content is less sensitive to horizontal misalignment and pole face errors

<table>
<thead>
<tr>
<th>Tolerances</th>
<th>IOTA</th>
<th>IRCS</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface roughness of pole face cut</td>
<td>50</td>
<td>125</td>
<td>µm</td>
</tr>
<tr>
<td>horizontal offset between poles</td>
<td>50</td>
<td>250</td>
<td>µm</td>
</tr>
<tr>
<td>vertical offset between poles</td>
<td>25</td>
<td>125</td>
<td>µm</td>
</tr>
<tr>
<td>segment to segment alignment</td>
<td>50</td>
<td>200</td>
<td>µm</td>
</tr>
</tbody>
</table>
Longitudinal Variation of NLI

- The size and strength of the NLI will vary along the drift space
- In the plots, there are 20 segments of magnets
  - Good compromise between field quality and fabrication complexity
  - Transferred over from IOTA NLI design
- Each is 30 cm long with 10 cm gap between segments
- The singularity position scales the size of the magnet
- The vertical lines indicate the beginning edge of each magnet segment
- The beta function along the drift is: $\beta(s) = \frac{L - sk (L - s)}{\sqrt{1 - \left(1 - \frac{Lk}{2}\right)^2}}$
Scaling to iRCS NLI

Advantage of more forgivable tolerance stack-up

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Preliminary Engineering Considerations

- Iron yokes with copper wire coils
- Will examine high phosphor electronless nickel plating in order to reduce field deviations
  - Nickel may have adverse effect on magnetic field due to its magnetic susceptibility
- Each magnet segment will be mounted on a precision kinematic stand (designed at RadiaBeam)
  - Differential screws with <0.001” resolution
- Vacuum chamber:
  - Vacuum required: <10e-10 Torr
  - Antechamber on top of beam tube to increase conductance of vacuum chamber
  - Ion pumps are located on top of chamber, but want to move to side or bottom for decreased moment.
    - Prevent undesirable influence from stray fields or increased conductivity
# Phase II Plans

<table>
<thead>
<tr>
<th>Sub-task</th>
<th>Objective</th>
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<tbody>
<tr>
<td>1. Finalize iRCS engineering</td>
<td>Complete the full iRCS system engineering</td>
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<tr>
<td>2. Magnet Fabrication and validation</td>
<td>Machine the poles and yokes, facilitate machine shop work</td>
</tr>
<tr>
<td>3. Chamber Fabrication and validation</td>
<td>Machine vacuum chamber components and weld.</td>
</tr>
<tr>
<td>4. Support and kinematic fabrication</td>
<td>Machine all components of the support system</td>
</tr>
<tr>
<td>5. Magnetic validation system development and magnet segment measurements</td>
<td>Ensure full magnetic validation suite is functional and measure the field components and locate the magnetic field to tooling features</td>
</tr>
<tr>
<td>6. System assembly</td>
<td>Integrate the components into full system</td>
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THANK YOU