Nonlinear Magnet for a Rapid-Cycling Synchrotron at Fermilab

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FAST/IOTA Collaboration Meeting
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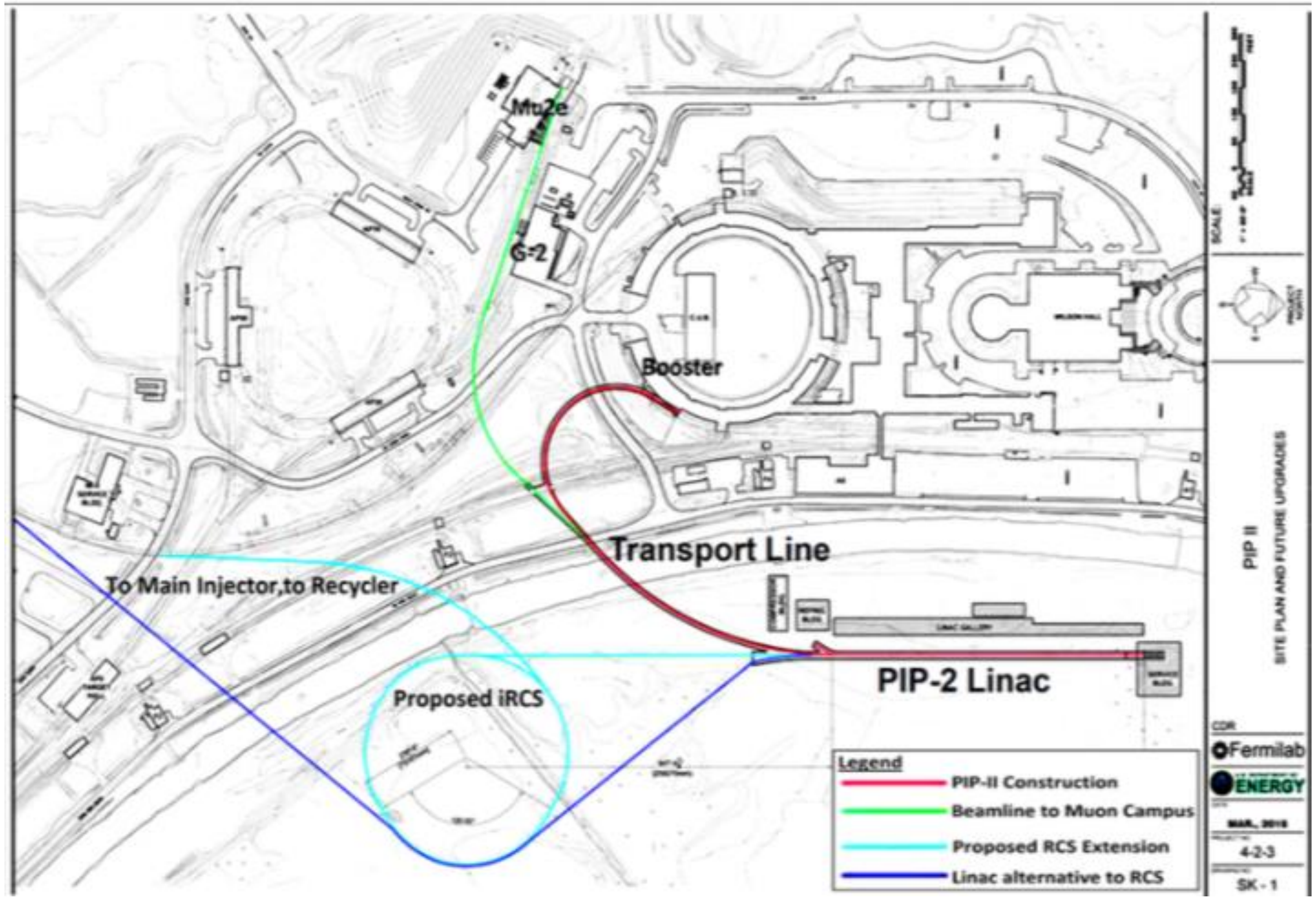
Outline

- Pole-face design and 3D model optimization
- Preliminary Tolerance Study
- Engineering Design
- Future Outlook



Design Progress

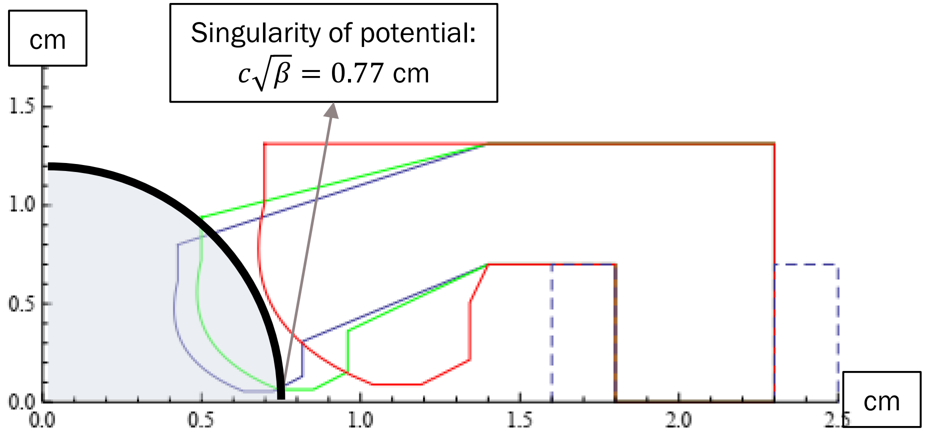
Technical Objective	Comments / Results
Analytic solution to allow proper harmonic content	Pole-face contour definition outside convergence circle allows exploration of designs with larger physical aperture, required for iRCS
Perform 3D simulations to obtain the required field	A full 8m-long NLI consisting 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

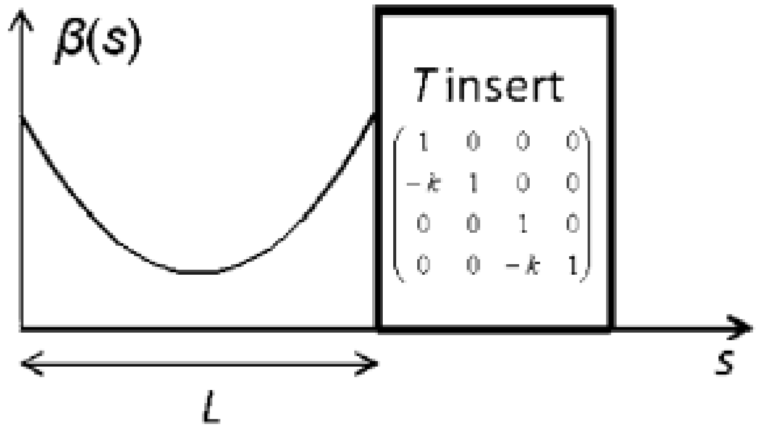
- IOTA was a testbed for NLI that will eventually be used in iRCS
- The more rigid beam of iRCS requires larger magnets, which is favorable for manufacturing

Parameter	IOTA	iRCS	Units
Particle	Electron	Proton	
Beam Energy	150	800	MeV
Momentum Rigidity, Bρ	0.5	4.9	T×m
Minimum Beta Function, β	0.73	5	m
Drift Length For NLI	2	8	m
Singularity = $c\sqrt{\beta}$	0.77	2.5	cm

IOTA Non-Linear Inserts (NLI)

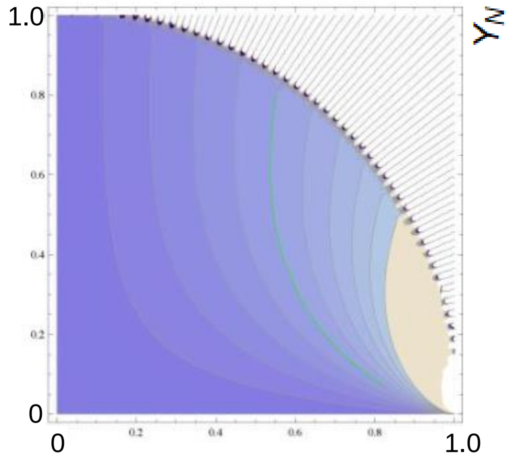
- The non-linear potential has a singularity on the x-axis, given by $c\sqrt{\beta} = 0.77$ cm, c is a scaling constant and β is the beta function of the beam at that location
  - For reference, quadrupoles have a singularity in their potential at infinity
  - Note that the pole-face must protrude well 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.

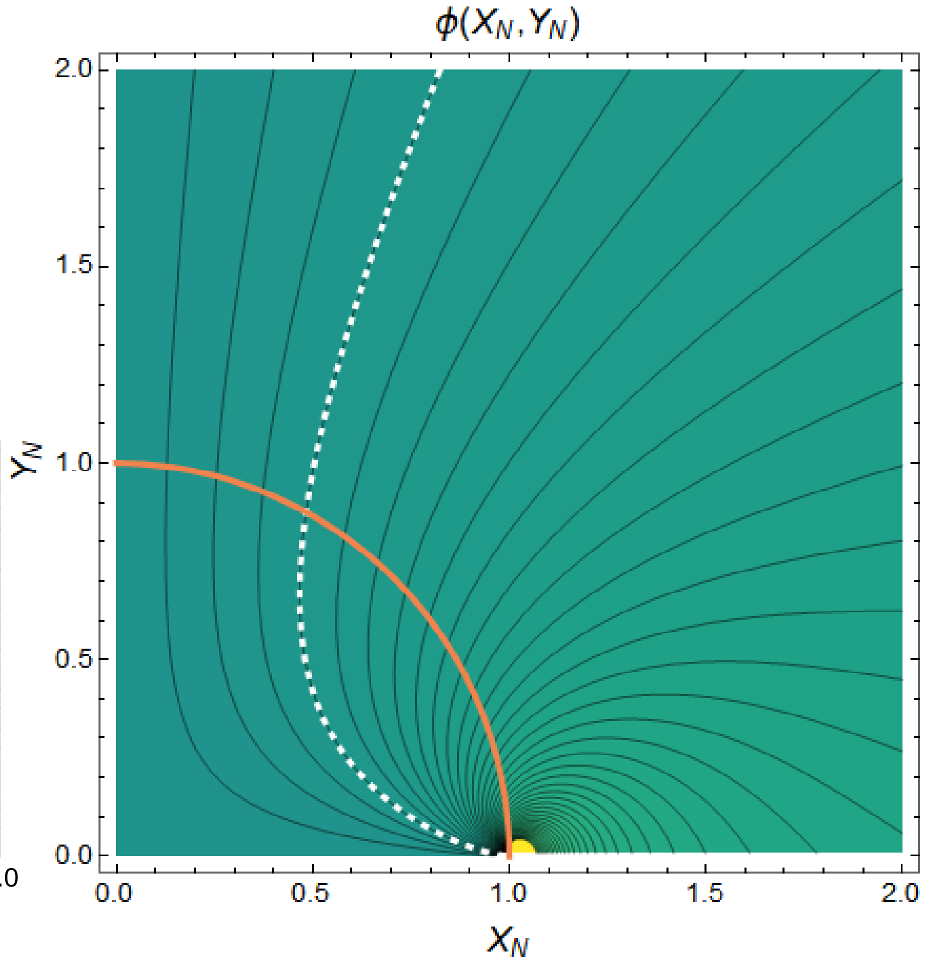




Pole-face Definition

- Defining the pole face is done by picking a equipotential line from the imaginary part of the auxiliary transverse magnetic potential
  - $F(z) = \frac{A+i\phi}{B\rho}$
- 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

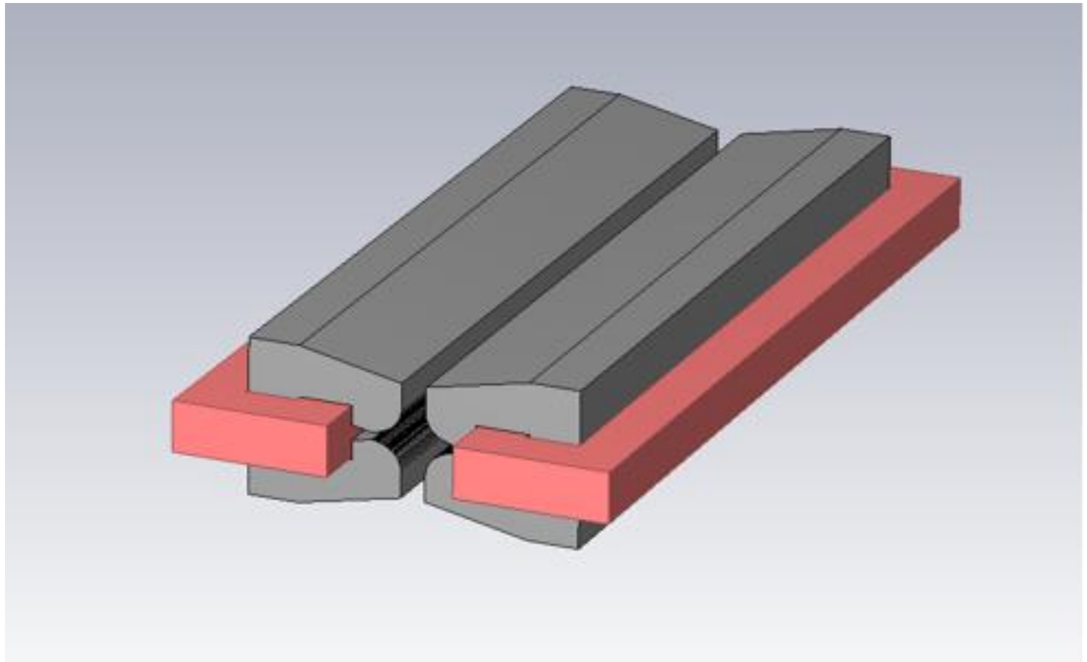


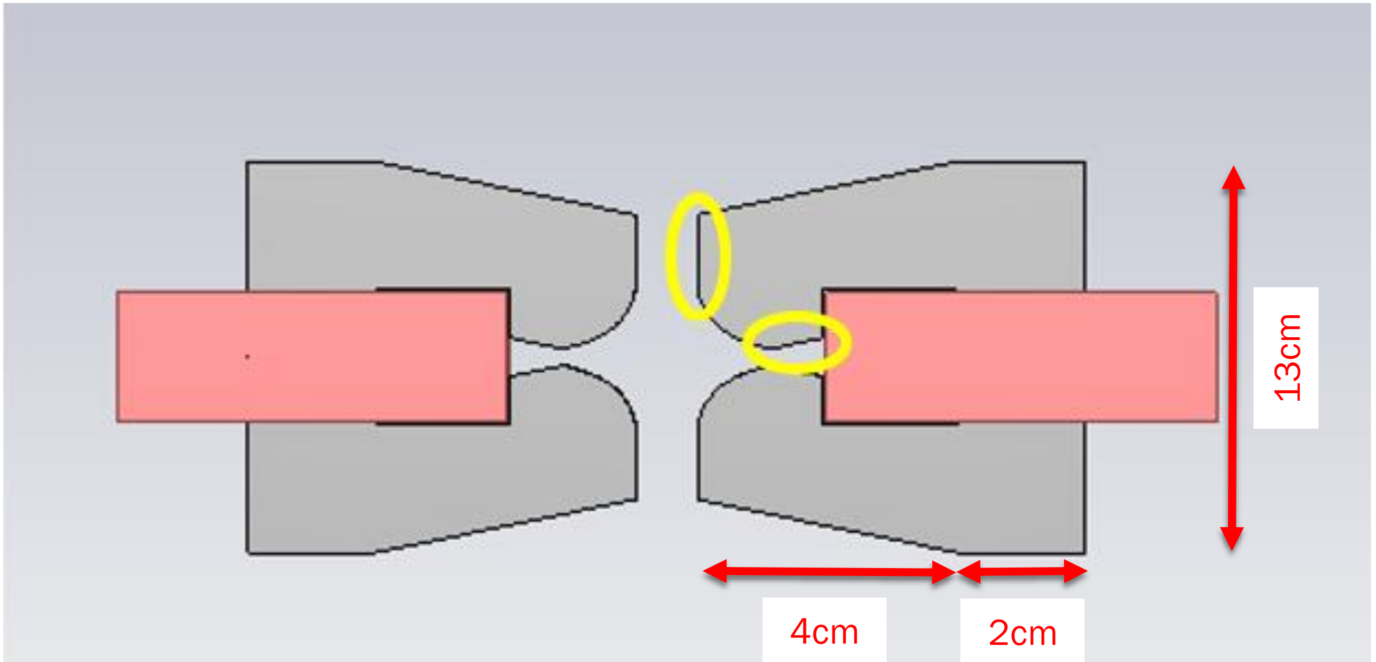


C. Mitchell, F. O'Shea, and R. Ryne, "Accurate Modeling of Fringe Field Effects on Nonlinear Integrable Optics in IOTA," *Proceedings of the 9th Int. Particle Accelerator Conf.*, vol. IPAC2018, p. Canada-, 2018, doi: 10.18429/jacow-ipac2018-thpak036.
C. E. Mitchell, "Complex Representation of Potentials and Fields for the Nonlinear Magnetic Insert of the Integrable Optics Test Accelerator," LBNL-1007217, 1468609, Mar. 2017. doi: 10.2172/1468609.

3D Modeling of NLI Magnet Segmets

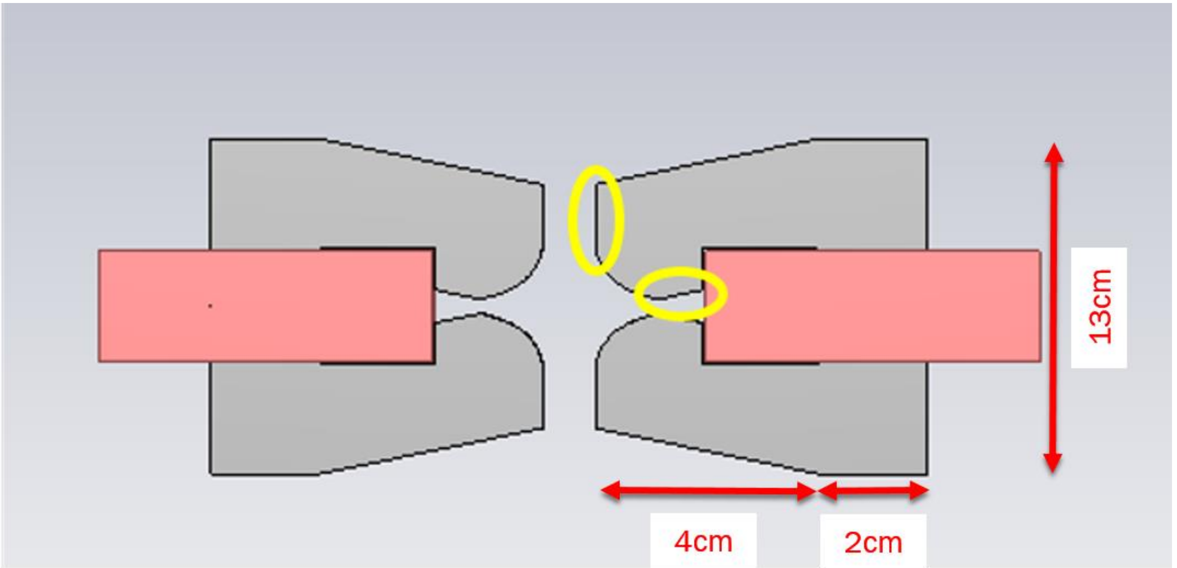
- Basic 3D model of the NLI magnet segment
- The truncation of the pole-face and its connection to the rest of the yoke has a strong impact on the transverse field
  - Future optimization will focus on this connection

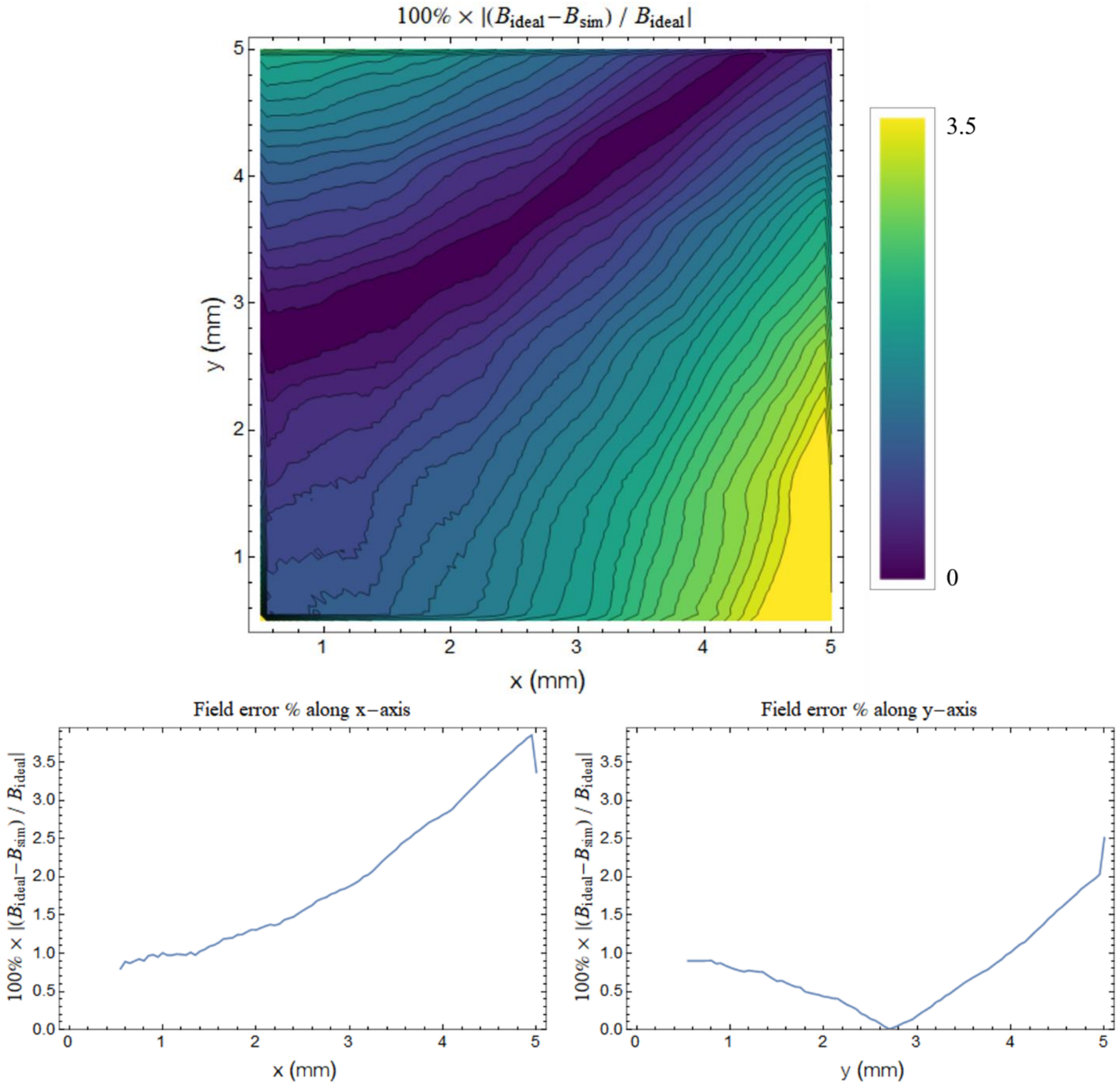




Field Error from Ideal

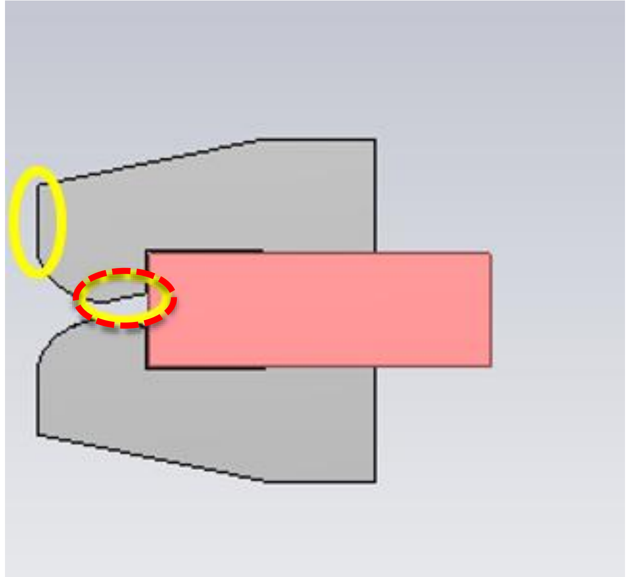
- Error from ideal transverse field increases toward the singularity
- Error is due to the finite terminations of the pole-face
- Further iterative optimization is required

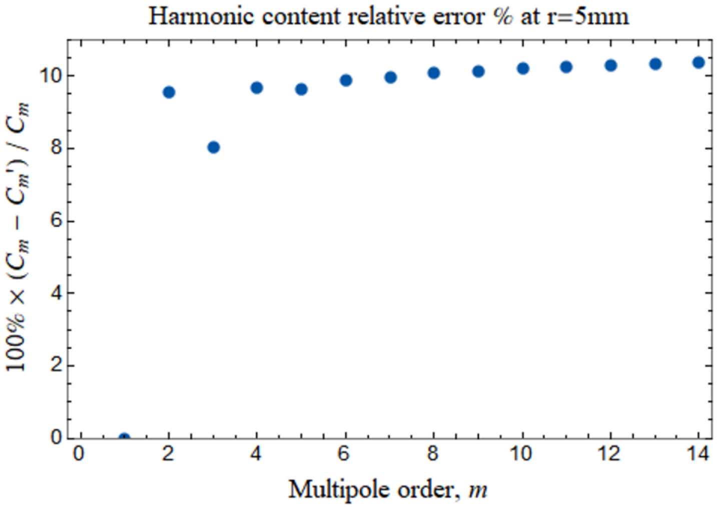


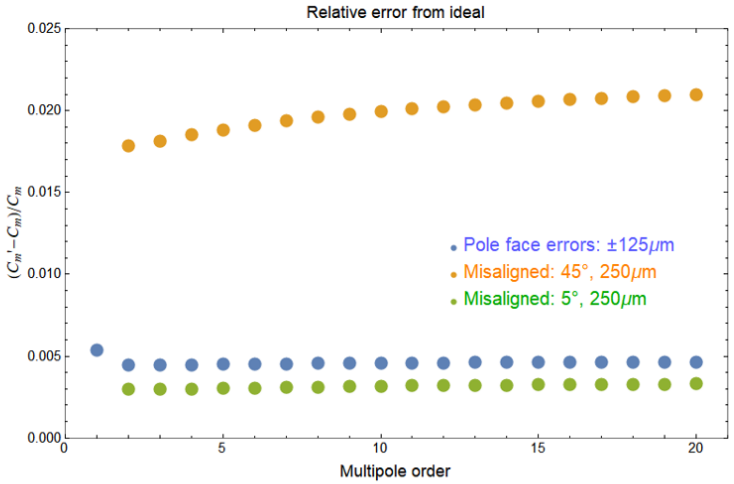


Harmonic Content

- 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





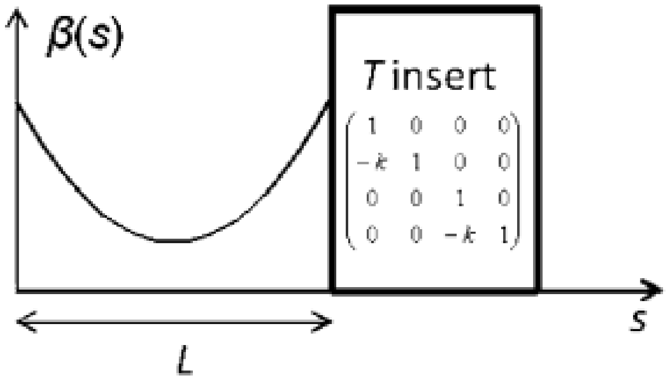


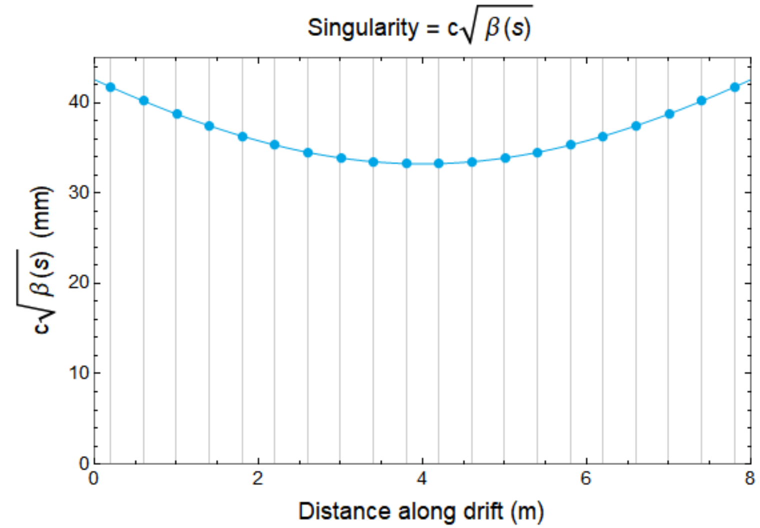
Tolerances

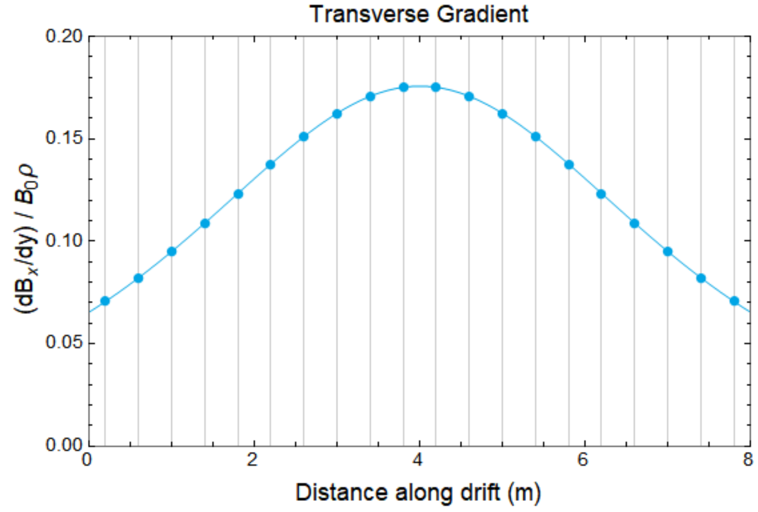
	IOTA	iRCS	unit
surface roughness of pole face cut	50	125	µm
horizontal offset between poles	50	250	µm
vertical offset betwen poles	25	125	µm
segment to segment alignment	50	200	µm

Longitudinal Variation of NLI

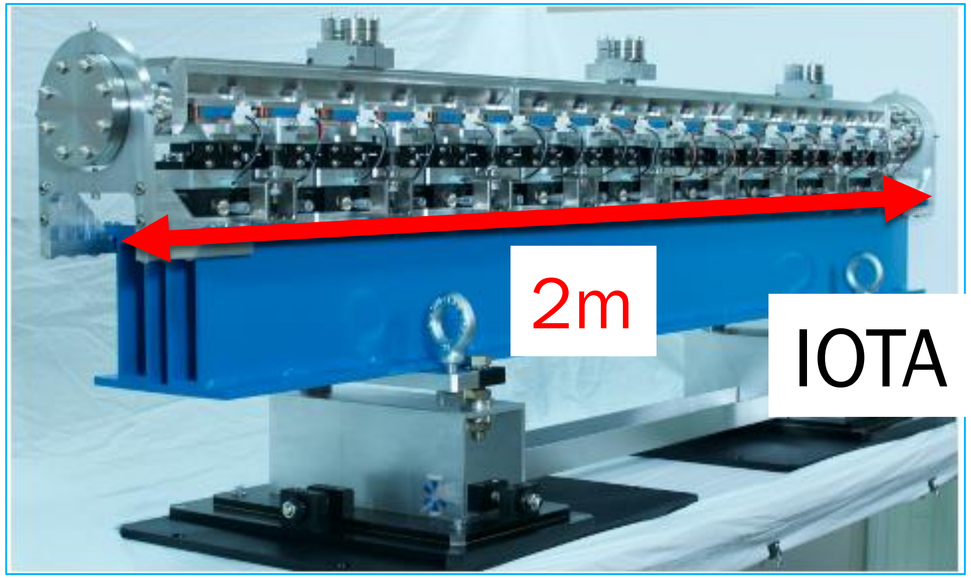
- The size and strength of the NLI will vary along the drift space
- In the plots, there are 20 segments of magnets
  - Good compromise between field quality and fabrication complexity
  - Transferred over from IOTA NLI design
- Each is 30 cm long with 10 cm gap between segments
- The singularity position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



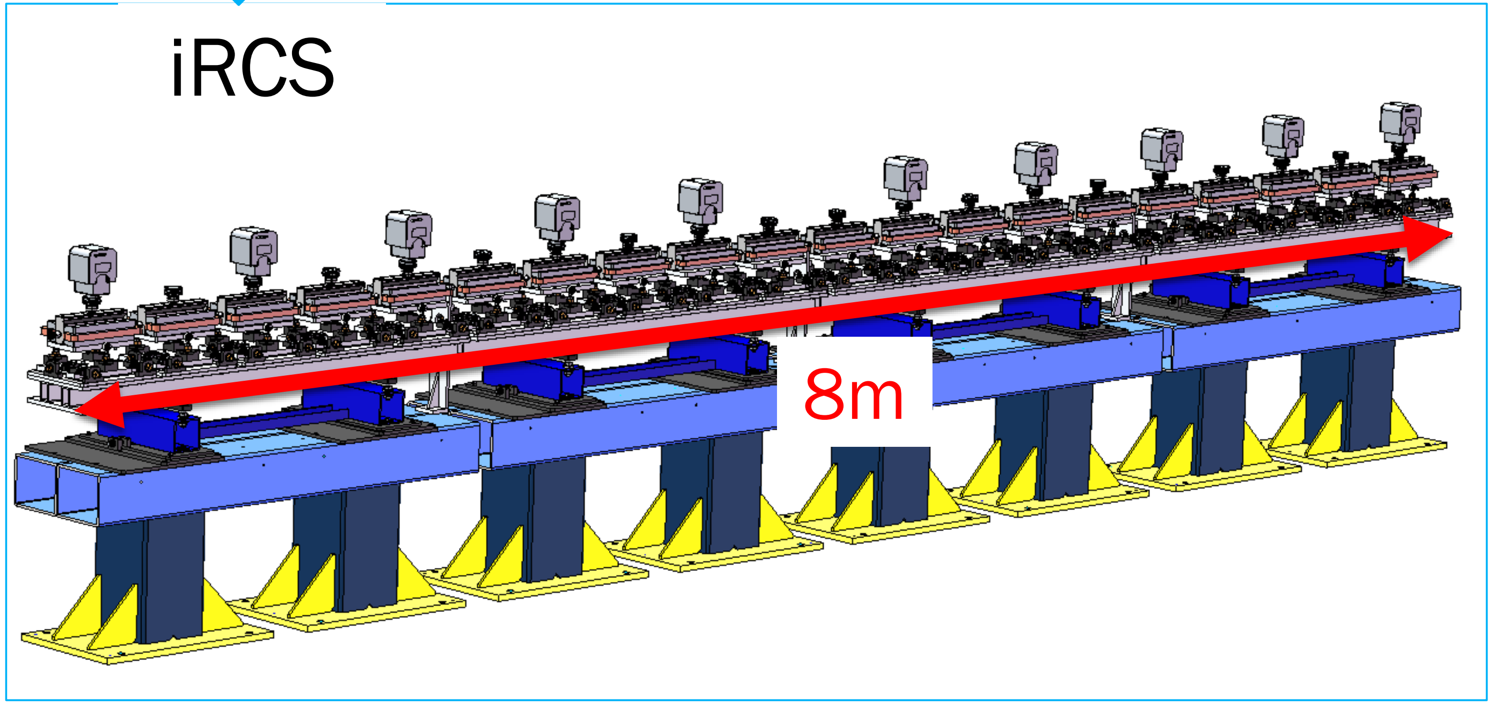




Scaling to iRCS NLI

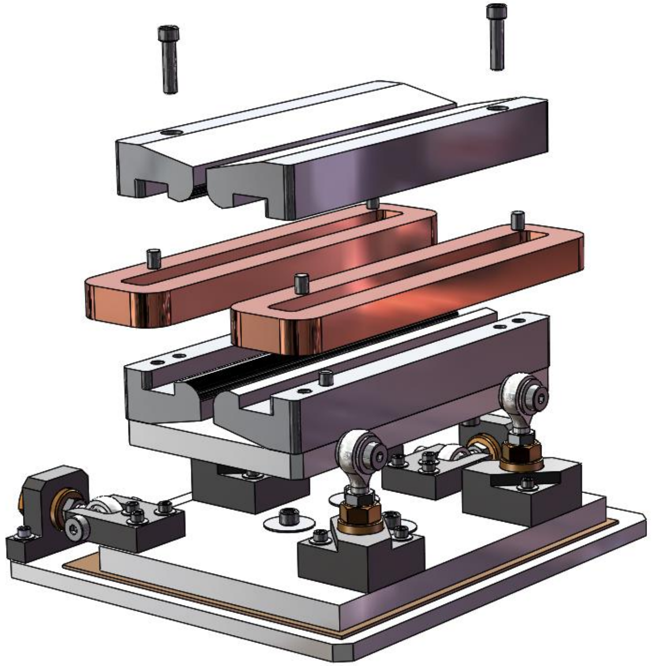


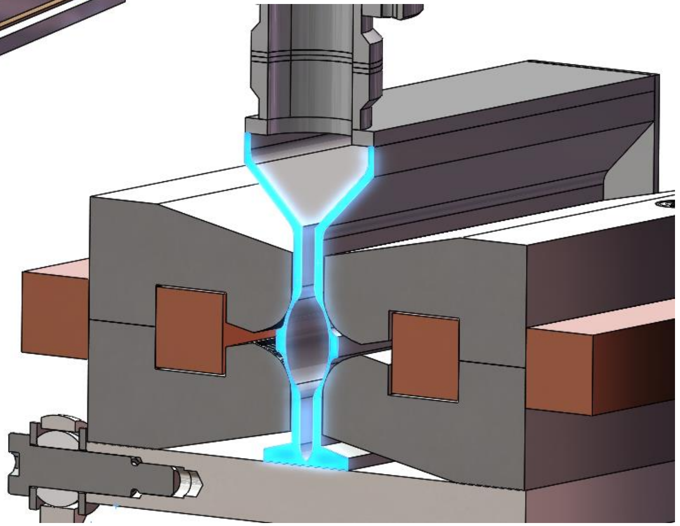
Advantage of more forgivable tolerance stack-up



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

radiabeam TECHNOLOGIES

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

Q4 2022

THANK YOU