Superconducting Magnets for Future Electron-Ion Collider

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Outline

- Introduction
- SC Magnets for Ion Rings
- SC Magnets for Interaction Regions
- Summary

Acknowledgement

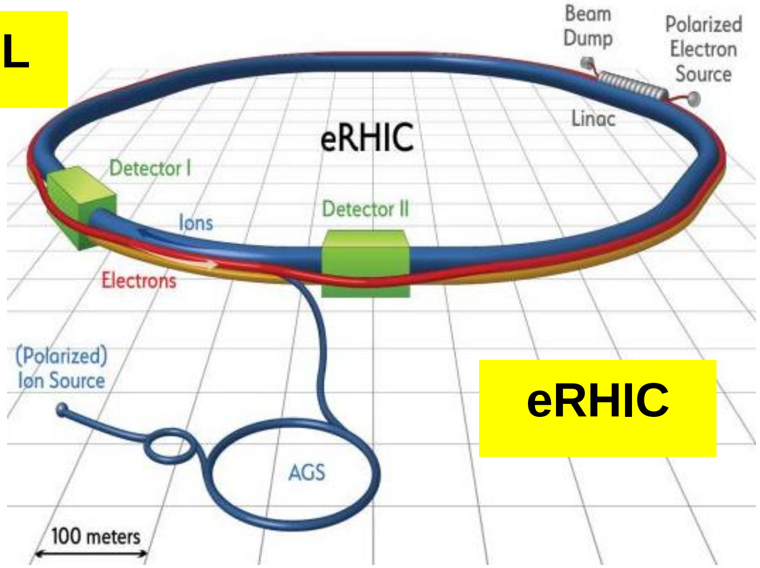
Tim Michalski (JLab), Peter McIntyre (Texas A&M Univ.), Brett Parker (BNL), Alexander Kovalenko (Dubna)

Introduction

- An electron-ion Collider (EIC) is likely the next major US facility to be built for nuclear science research – QCD frontier
  - Recommended by Nuclear Science Advisory Committee Long Range Plan 2015
  - National Academy of Science Review underway (last milestone for DOE approval)
  - Construction may start as early as 2022, likely cost at $1.5B
- Two DOE Labs (BNL & JLab) have proposed to host this collider
  - BNL eRHIC has proton/ion beams, need an electron beam (and an electron facility)
  - JLab JLEIC has an electron beam, need proton/ion beams (and an ion complex)
- Presently, two teams are focused on design optimization, value engineering and accelerator R&D
- EIC needs superconducting magnets
  - IR magnets: for both eRHIC and JLEIC
  - Ring magnets: for JLEIC ion booster and collider
  - Not pushing for new technology frontier, rather for better quality and cost efficient (value engineering)

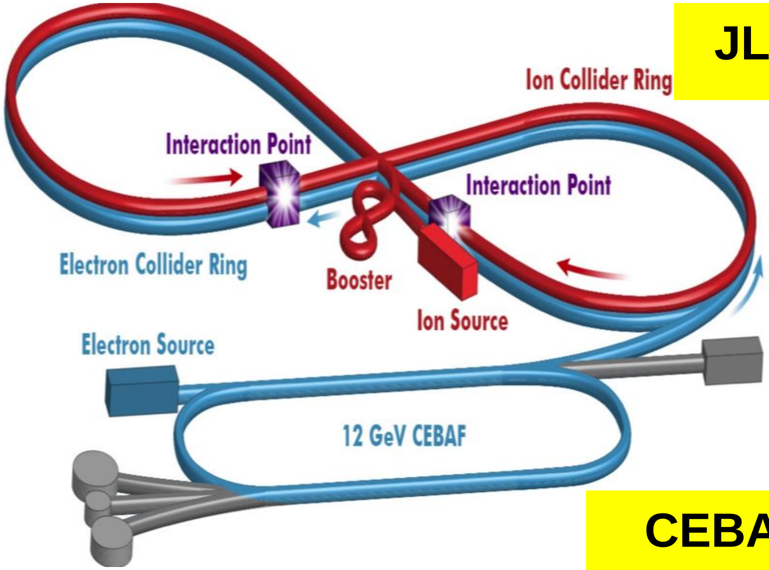
Two Labs Like to Host the US EIC

BNL



eRHIC

JLab



CEBAF

Has polarized proton & heavy ion beams
Needs a polarized electron beam

- **Based on RHIC and its injector complex**
  – polarized proton and 3He, up to 250 GeV/u
  – other all-stripped ions, up to gold 100 GeV/u
- **Add a polarized electron beam up to 18 GeV**
  – A storage ring (*ring-ring* design)
  – A full energy electron injector

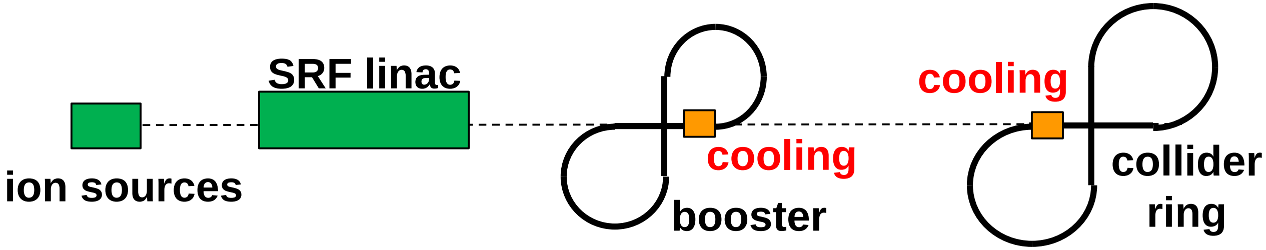
Has a polarized electron beam
Needs a proton/ion beam

- **Based on CEBAF** recirculated SRF linac
  – polarized electron beam up to 12 GeV,
- **Add ion injector and two storage rings** (*ring-ring* design)
  – Polarized proton, deuteron and ^{3}He
  – Up to 100 GeV/u

Superconducting Magnets for EIC

- **Hadron ring magnets** ***for JLEIC only***
  - Modest field for (present baseline) phase 1: 3 T Super-ferric, cost efficient
  - Medium field for upgrade or phase 1 (alternate): 6 to 12 T, high CM energy reach
  - Booster ring SC magnets need fast ramp (~0.3 T/s)
- **IR magnets** ***for both eRHIC and JLEIC***
  - High field: up to 9 T
  - Large aperture, high field quality
  - Radiation resistance
- **Solenoids** ***for cooling and spin rotators***
  - Modest field strength, up to 6 T

JLEIC Ion Booster and Collider Ring Magnets



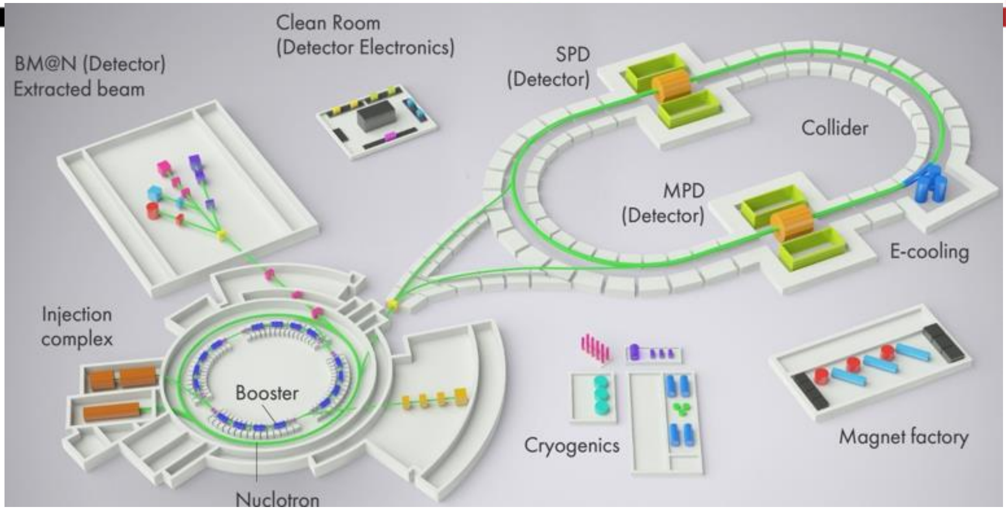
	Length (m)	Max. energy (GeV)	Max. dipole field (T)
SRF linac		0.2	
booster	~275	7.9 / 12	3
collider ring	~2250	100 / 200 / 266	3 / 6 / 8.3

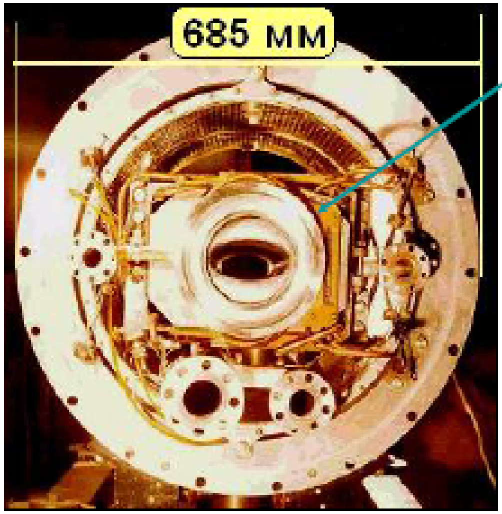
- A medium energy ion collider ring, not for energy frontier
- Cost efficiency is the primary goal (make the machine affordable)
- The booster and collider ring magnet field is 3 T
- The booster ring magnet needs fast ramp (~0.33 T/s ➔ 0 to 3 T in 10 s)
- The leading choice of technology is ***super-ferric magnet*** for baseline
  - – Cost efficient, similar to warm magnets
  - – Fast ramping, closed to warm magnets

NICA / Nuclotron Super-ferric Magnets

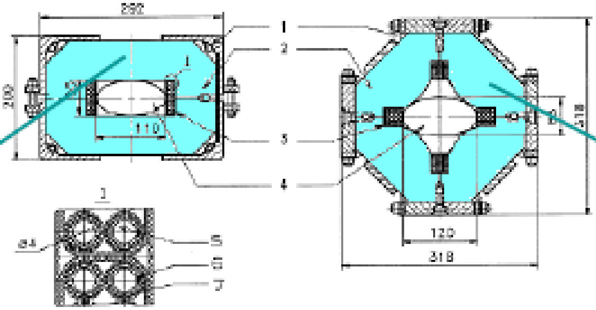
Kovalenko, Dubna

- A low energy ion-ion collider, circumference: 251.5 m
- 96 dipoles, 64 quads, beam pipe aperture 55 x 110 mm
- Accelerated and extracted particles from p to Xe

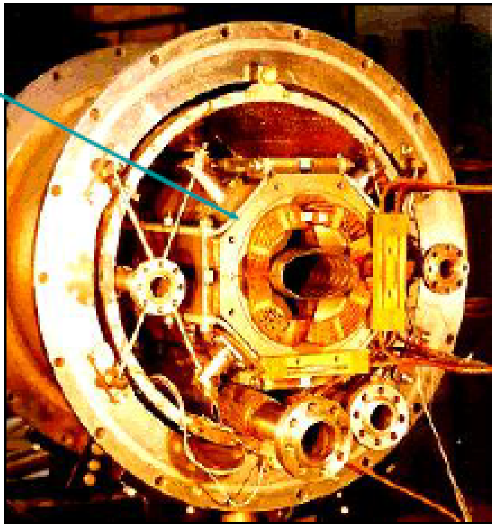




2 T, 4 T/s, 1 Hz dipole



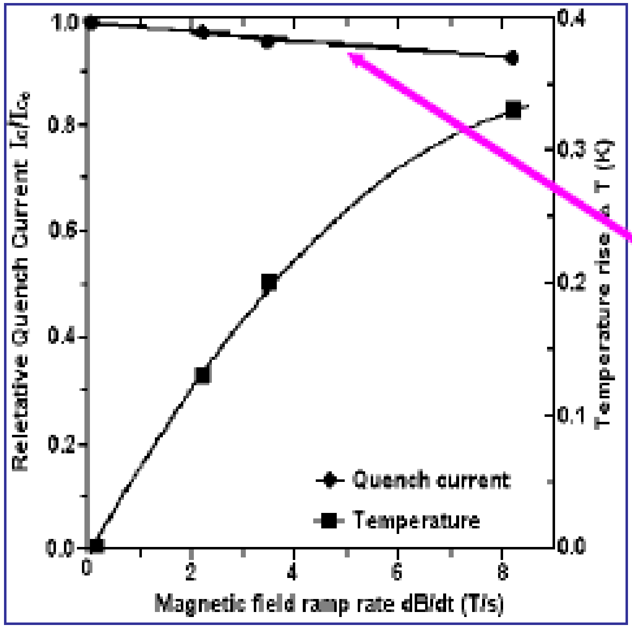
- Cold iron (T = 4.5 K)
- Hollow SC cable
- Two-phase helium



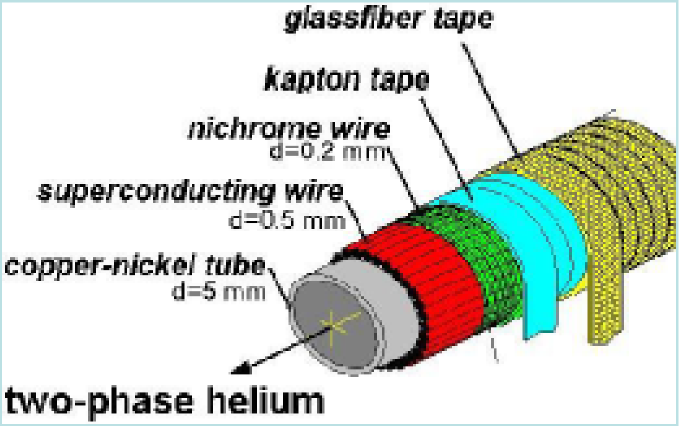
34 T/m, 68 T/m s, quad

Dubna Hollow SC Cable

Basic idea: SC-strands don't soldered to the tube but pressed with wire wound.

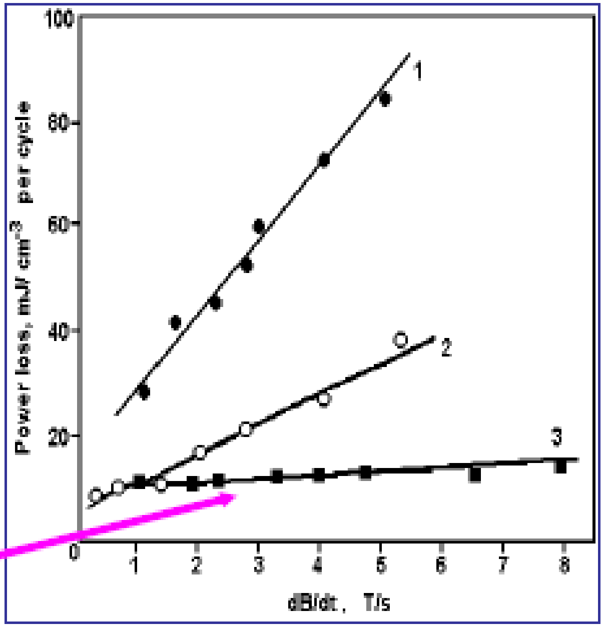


inventor A.Smirnov



Weak degradation of critical current at fast ramp (~ 5 % @ dB/dt = 4 T/s)

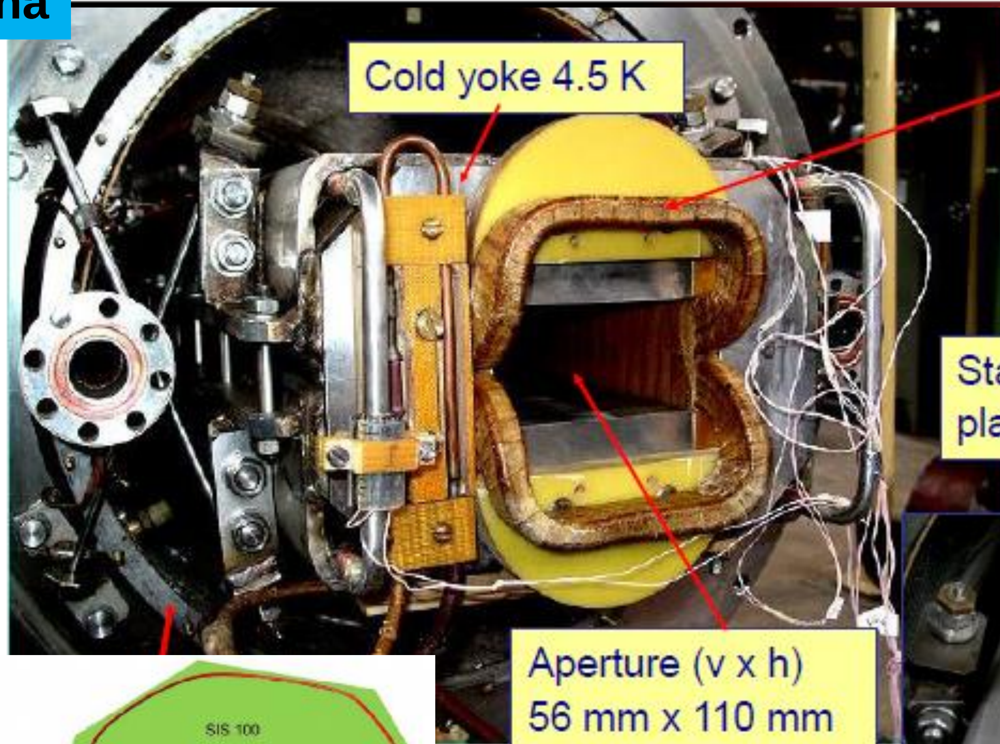
Weak dependence of the eddy current loss on the magnetic field ramp (3)

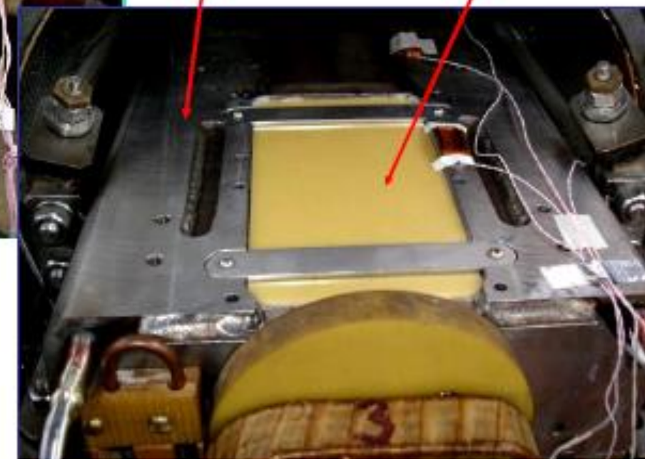


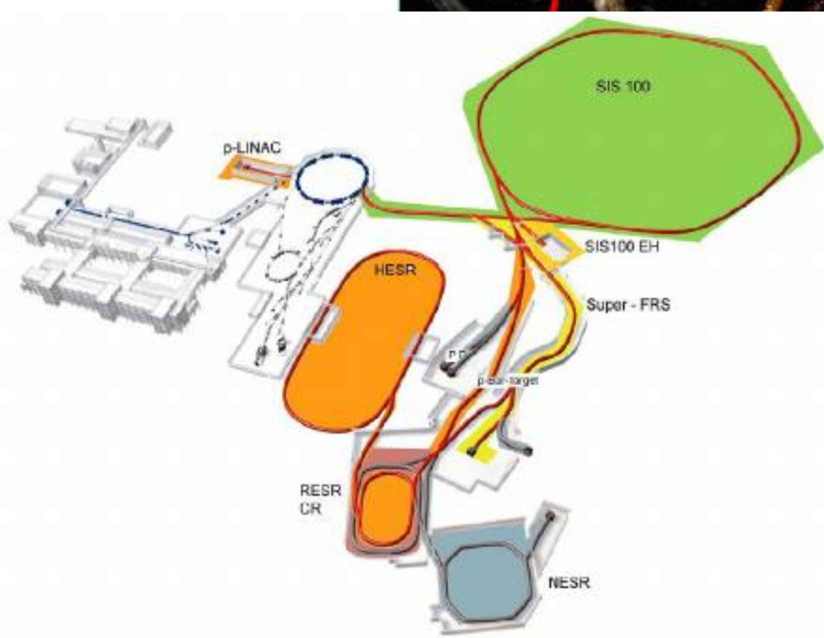
Kovalenko, Dubna

FAIR SIS100 Storage Ring Model Dipole

Kovalenko, Dubna







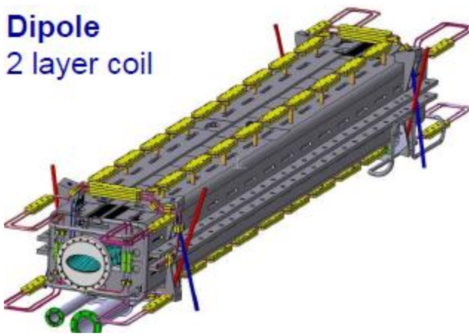
Jefferson Lab

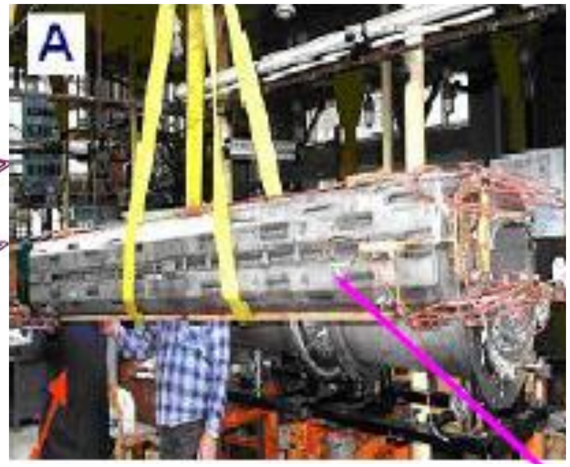
FAIR SIS100 Full Size Prototype

Kovalenko, Dubna

Manufactured and tested at JINR, Duban

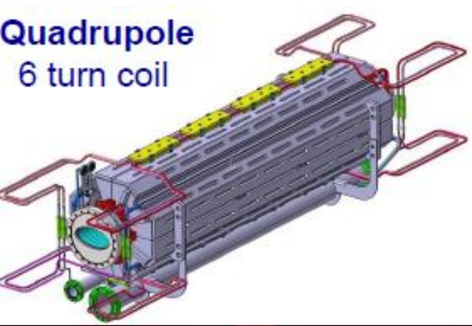
Dipole
2 layer coil

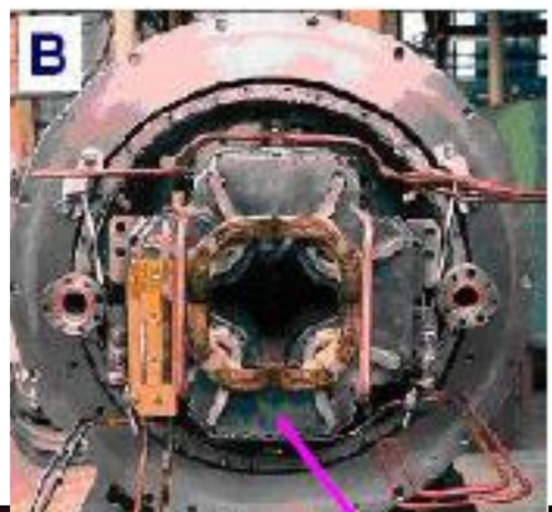




Straight dipole		
B x $L_{effective}$	T m	5.818
B	T	2.11
$L_{effective}$	m	2.756
L_{yoke}	m	2.696
Bending angle	deg	3
Radius of curvature	m	47.4
Aperture	mm	130 x 60

Quadrupole
6 turn coil





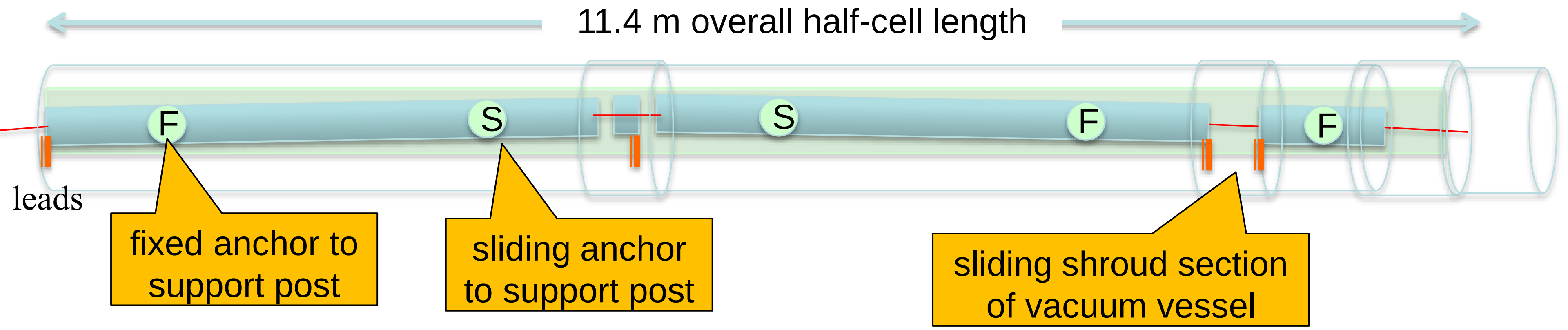
Quadrupole		
B' x $L_{effective}$	T	35
B'	T/m	32
$L_{effective}$	m	1.1
Estimated L_{yoke}	m	1
Aperture	mm	135 x 65

JLEIC Ion Ring Arc Cells and Magnets

P. McIntyre, Texas A&M

<u>Dipole aperture requirement:</u>

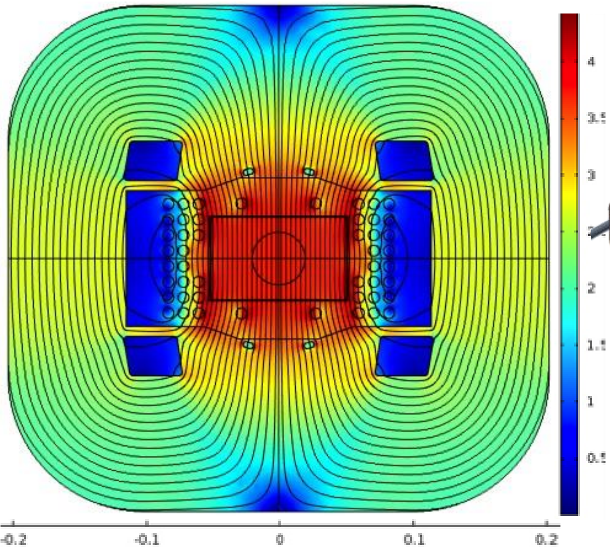
betatron amplitude (15 s) @ injection:	±3	cm
dispersion of ±0.5% momentum spread:	±1	cm
sagitta (with 4 m dipole length):	<u>±1.8</u>	<u>cm</u>
	±5	**cm**
Quad aperture radius requirement:	**4**	**cm**

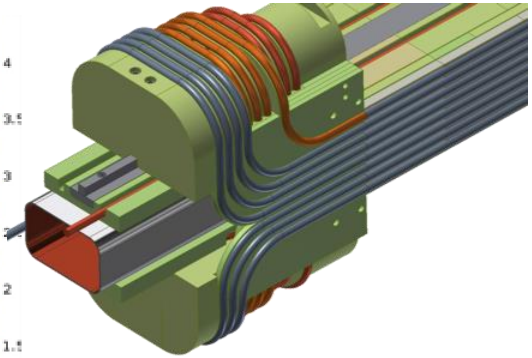


Each half-cell contains two 4 m dipoles, one 0.8 m quadrupole, 1 sextupole to correct body sextupole in dipoles (Neuffer):

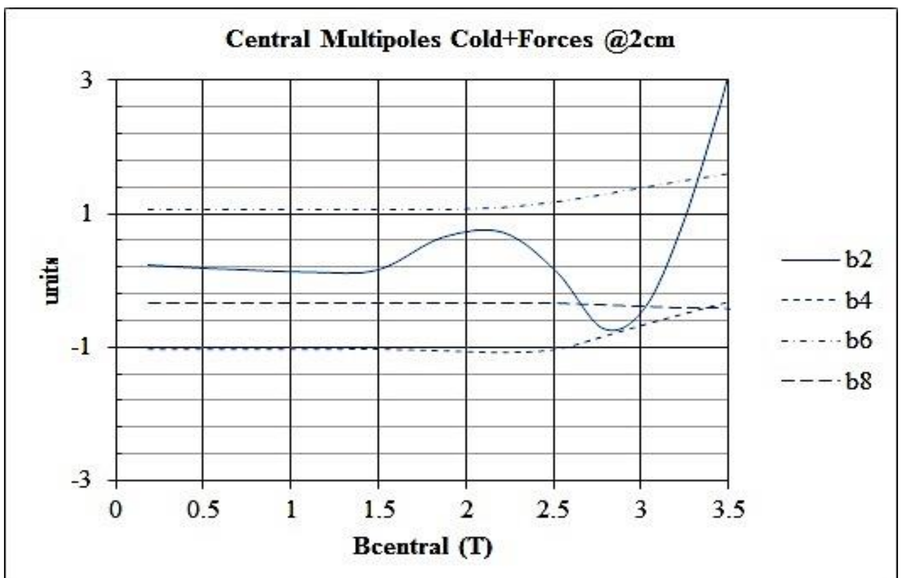
JLEIC Arc Dipole Design

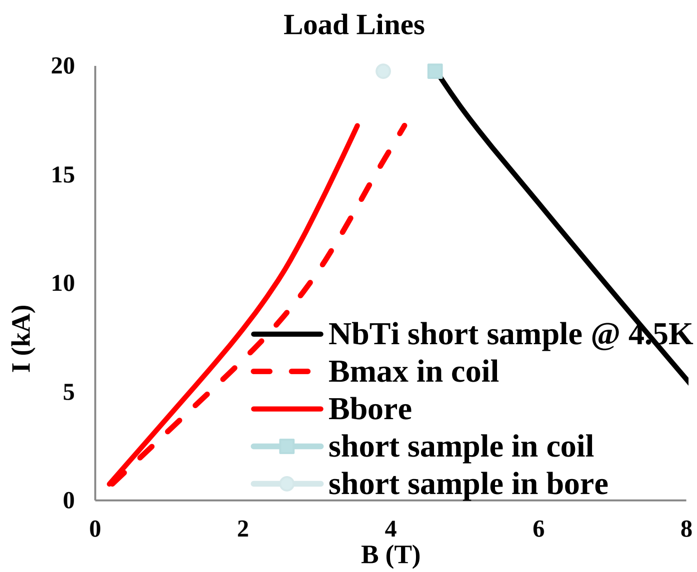
P. McIntyre,
Texas A&M





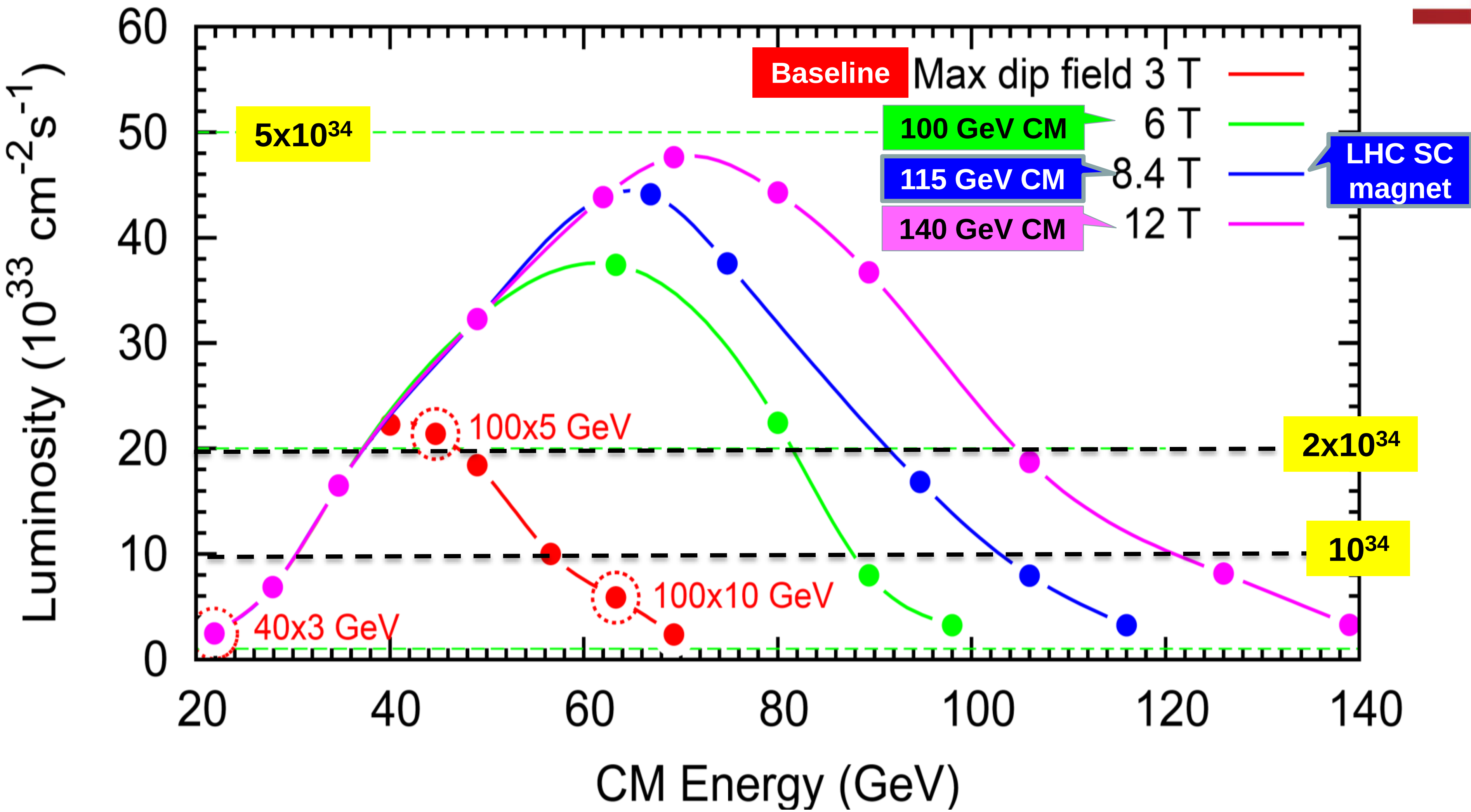
The biggest challenge is to create a 10 cm x 6 cm aperture with the *field quality* needed for high-luminosity collisions with long luminosity lifetime – dynamic aperture





Multipoles vs. field and load lines for MEIC dipole design.

JLEIC *e-p* Luminosity

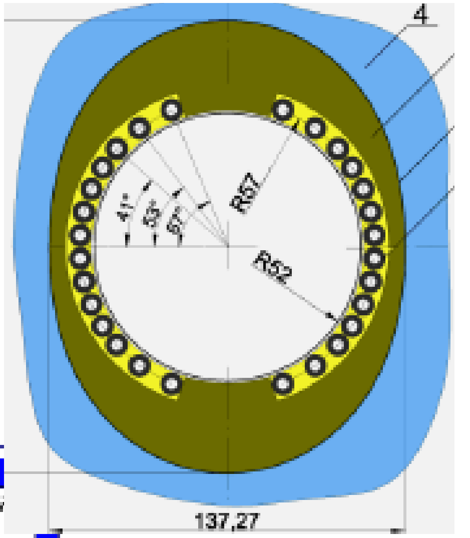


If it were feasible and affordable to make 6 T dipoles for the ion ring,
Maximum c.m. energy would increase by 40%; maximum luminosity would double.

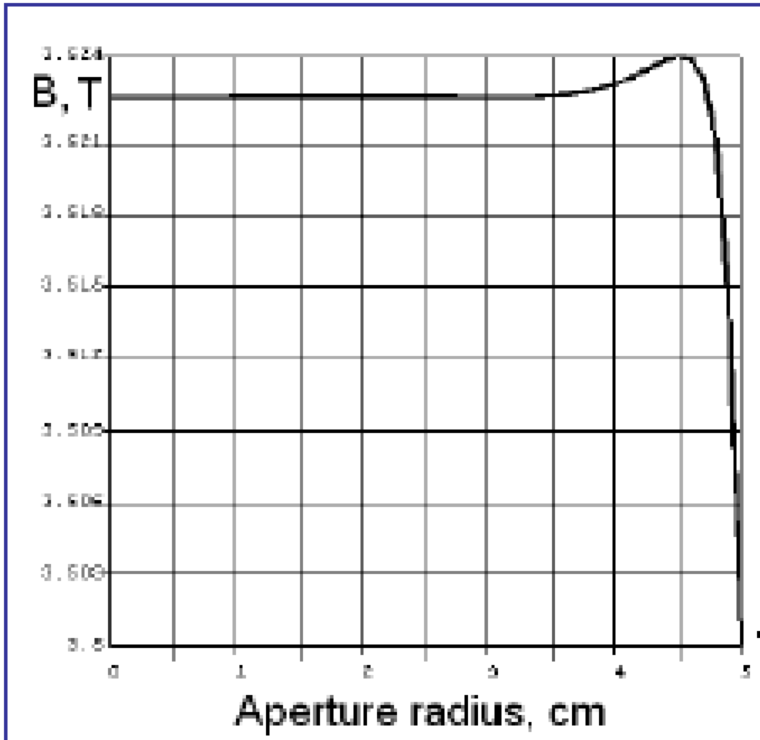
High Field (4 to 6 T) SC Magnets for JLEIC

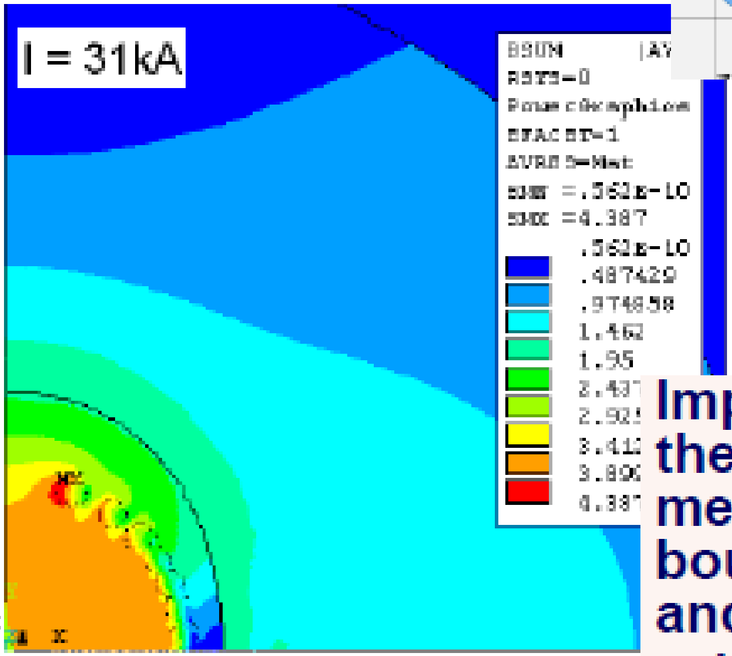
Kovalenko, Dubna

- Hollow SC cables can be applied to the design and construction of a (fast-ramping) 4 to 6 T dipoles
- Cosine θ style of magnet should be used
- For 6 to 6.5 T dipoles, use double-layer coil: a hollow cable for inner layer, and Rutherford one for outer layer



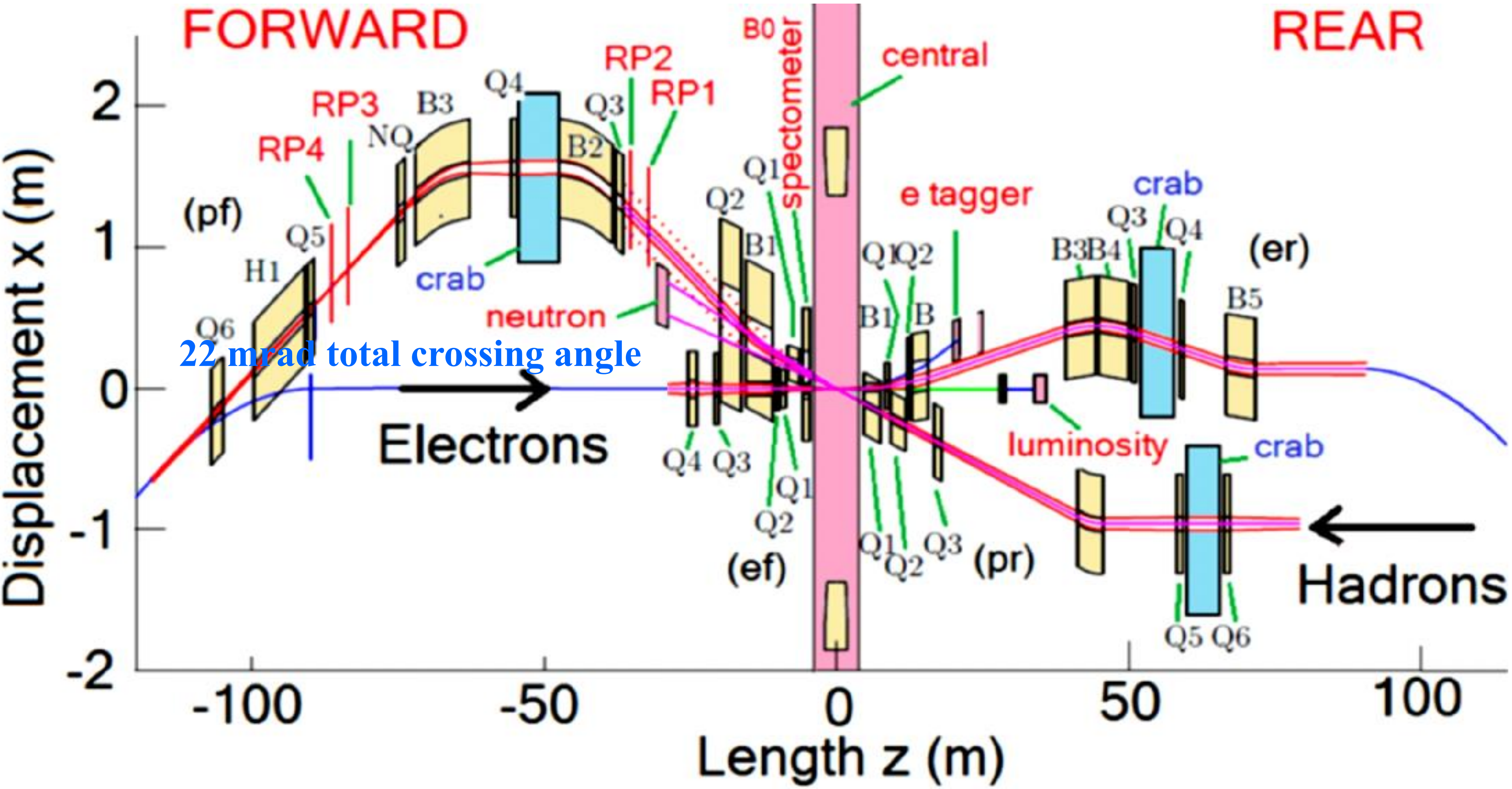
4 T Cosine θ-style dipole with 2-4 T/s ramping rate





Improvement of the field quality by means of the yoke boundary profile and the coil turns azimuth position

eRHIC Ring-Ring IR Layout



- ±4.5 m detector space with crab crossing.
- Magnets quite different forward/rear due to physics requirements.

EIC IR Magnet Challenges

B. Parker, BNL

- **Magnet Zoo**: Just within ±20m of the IP we need 12 different styles of superconducting magnets, most of which require closely spaced, double apertures or low-field shielded regions.
  - **We want to avoid having to create unique tooling for each style.**

- **Large Aperture/Strong Field**: A few of these magnets, i.e. on the forward hadron side, must have very large apertures with relatively strong quad gradients or strong dipole guide fields.
  - **Large coil fields/coil dimensions make external field shielding difficult.**
  - **We should consider a range of coil and yoke topologies/schemes.**
  - **We can benefit greatly by investing in shielding R&D (test facility).**

- **Monster Size:** Even when we can use a “traditional solution for magnetic shielding,” i.e. cutting holes in magnetic yokes to get reduced field regions, some of the resulting yokes are monster sized.
  - **With limited resources, we must then carefully consider what R&D prototypes are needed to validate performance goals (test facility).**

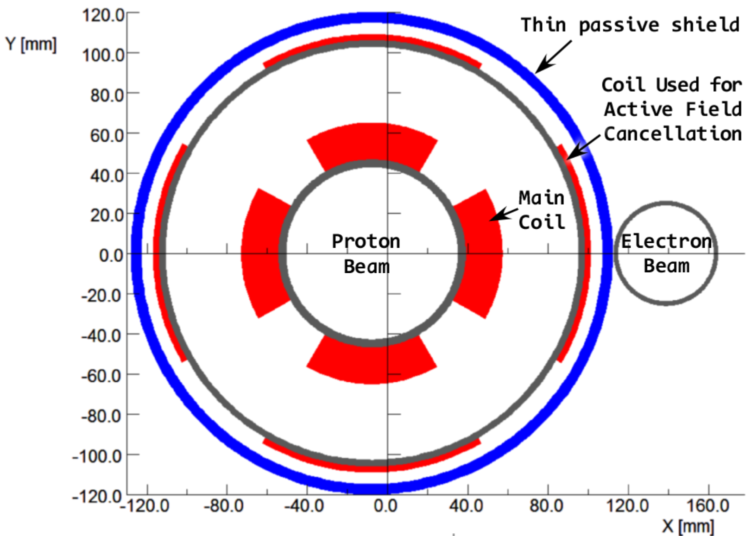
eRHIC Magnet R&D Accomplishments and Work Presently In Progress

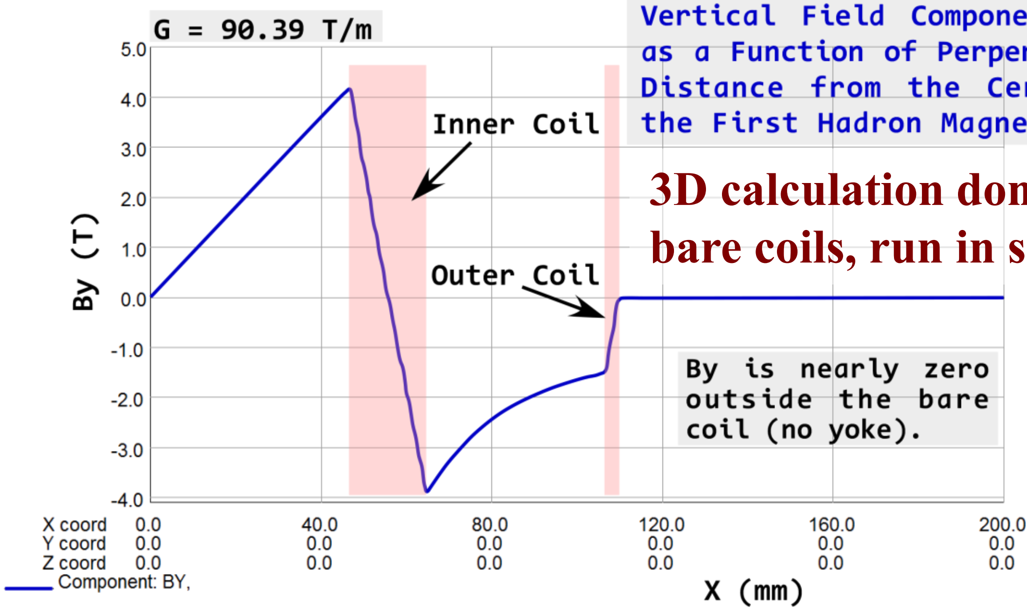
B. Parker, BNL

- Have successfully upgraded Direct Wind machine to handle 1.6 mm cable for more than twice capacity of the previous 1 mm cable (i.e. design with single strand wire and 1 mm or 1.6 mm cable).
  - **Now able to make large diameter coils with half as many cable layers.**
- The dipole Sweet Spot coil nearing its completion has coil sizes comparable to the Ring-Ring requirements and the prototype is designed to be operated at even higher field.
  - **So we gain direct experience with large coils and 1.6 mm dia. cable.**
  - **For the R&D prototype, inner/outer coils independently powered; we can run in both Sweet Spot and the active cancellation configurations.**
- We can provide a wide range of field strengths and varieties of field configurations over the "Sweet Spot test region."
  - **Opportunity to test passive magnetic/superconducting shield designs as well as Direct Wound, corrector-like active compensation schemes.**

Q1PF, First Forward Side Proton Quad

B. Parker, BNL

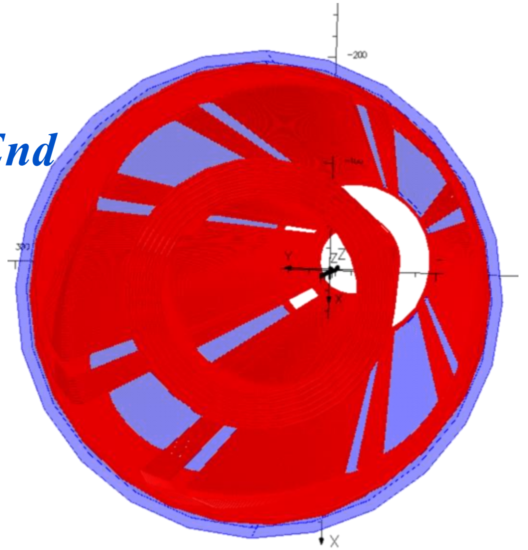




Vertical Field Component, By, as a Function of Perpendicular Distance from the Center of the First Hadron Magnet, Q1PF

3D calculation done for bare coils, run in series.

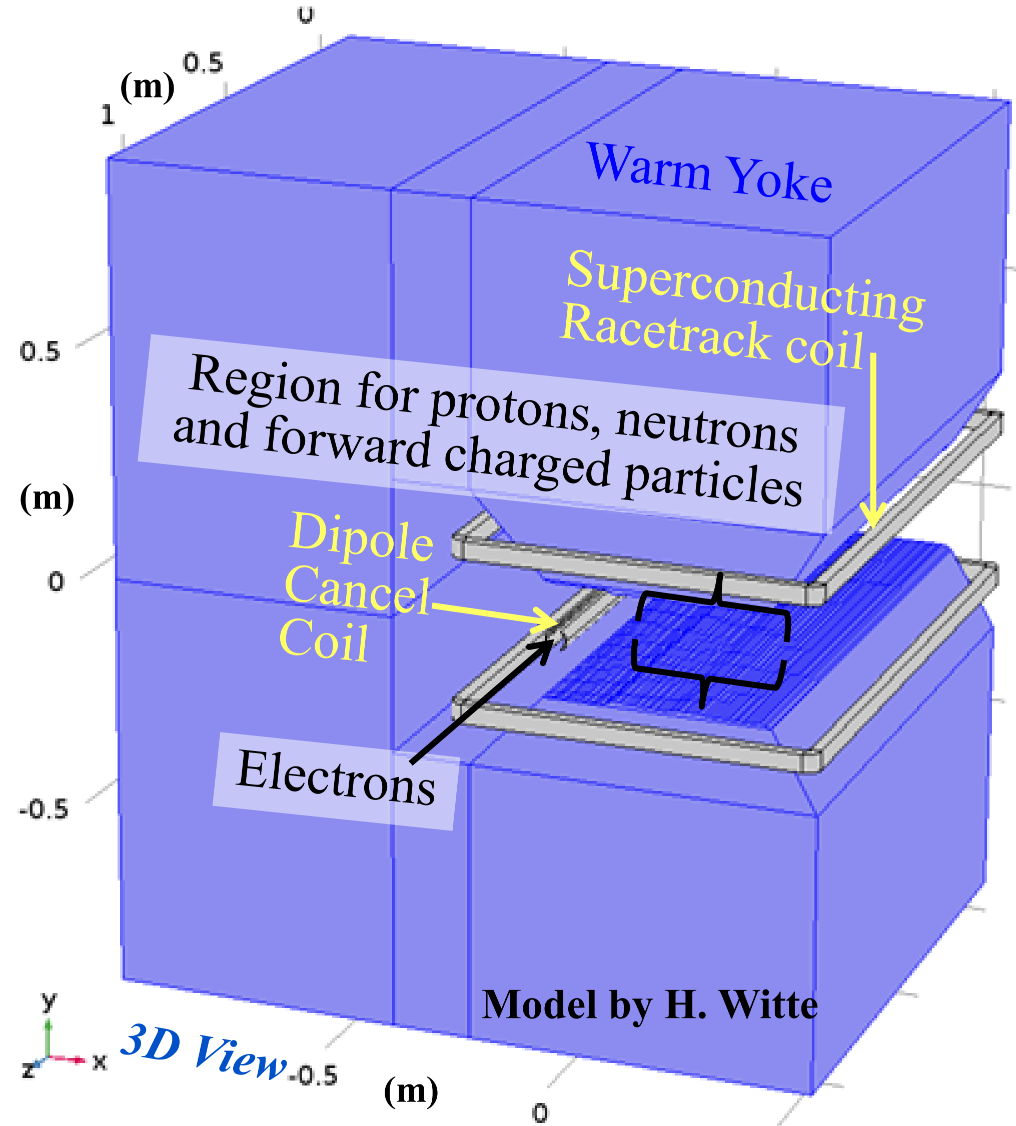
3D End View

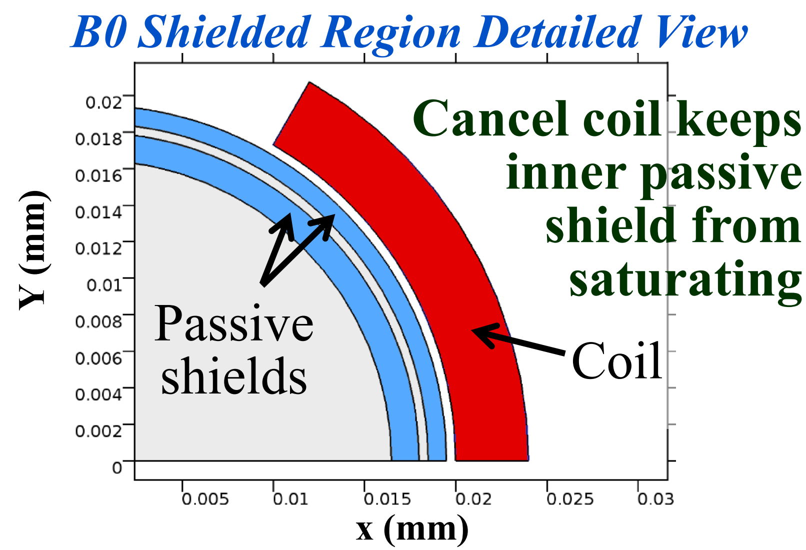


- Q1PF, active external field cancelation coil.
- 90 T/m gradient, clear bore is 86 mm ID.
- Peak field about 4.5 T with essentially zero external field outside body of the bare coil.
- Small cancellation undershoot/overshoot near the coil ends is handled via the use of a thin passive magnetic shield.

B0 Spectrometer Dipole Concept

B. Parker, BNL





- B0, a Superferric C-magnet.
- 1.7 T Field, 1.3 m long.
- Gives access for detectors.
- Use a Direct Wind dipole cancel coil to buck most of main field and then use passive shielding inside.

Summary

- EIC Will be the next big machine for US and for QCD research
- Jefferson Lab needs a new ion complex, which requires low to medium field SC magnets for ion rings, however, low cost is the key.
- SC magnets for interaction region for both eRHIC and JLEIC are challenging
- Some R&D for EIC rings and interaction region were initiated and in progress
- For more information of EIC accelerator design and R&D
  - JLEIC Accelerator Collaboration Meetings (5, 2015, 2016, 2017)
  - EIC Accelerator Collaboration Meeting 2017
  - All talks on the web