High-Precision Magnetic Field Measurement and Mapping of the LEReC 180° Bending Magnet Using Very Low Field NMR Probe [140-400 Gauss]


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Outlines

- Introduction: Measurement specs
- Preps:
  - Hysteresis loop
  - Plan
  - Repeatability test at center points
  - Measurement along center-center lines
  - Single radius at various currents
- Measurement at 5 heights and 5 radii
  - Three currents
  - Compared with simulated results
- Summary
Electron Ion Collider

High Field IR Quadrupoles

Arc magnets
Multiple strategic R&D projects for eRHIC at BNL

The first ever electron cooling based on the RF acceleration of electron beams was experimentally demonstrated on April 5, 2019 at Low Energy RHIC Electron Cooler (LEReC) at BNL.

The Cornell-BNL Test accelerator has achieved Energy Recovery for the first time on June 24th, 2019.
Introduction

- The first critical step in obtaining successful 3D non-magnetized cooling of the Au ion bunches in the RHIC cooling section was matching the electron beam energy with a relative error less than $5 \times 10^{-4}$ to the ion beam energy.
- Since electron beam kinetic energy is just 1.6 MeV, measuring the absolute e-beam energy with required accuracy and eventually achieving the electron-ion energy matching was a nontrivial task.
- One of the key components is the 180 degree bend dipole which steers the electron beams from the “Yellow” to the “Blue” RHIC rings.
- Precise knowledge of the magnetic field is critical and $10^{-4}$ accuracy in the integral field is required.
Magnet overview, requirement, coordinate system

**Field Strength Range**  
180 – 325 gauss

**Measurement resolution**  
< 0.01 % (18.0 milligauss)

**Absolute Accuracy**  
50 milligauss

**Signal to noise ratio**  
< 20milligauss @ 180 gauss with a ~0.1 Hz measurement rate

**Remotely located electronics**  
100 m ± 20%

Coordinate system for magnetic measurement and scanning

- Modified design ----  
  1. Window inner width (on shield) now is wider (X = +/- 50 cm)  
  2. Shield is magnetically decoupled from magnet (keep the same gap 8 cm).

- 100 cm (unchanged)
Measurement Plan, Hall/NMR Probe w Fixture

- About 15 mm apart
- NMR height can be adjusted 10 mm/step
- Field at 5 heights to be measured, Z=0 mm, ±10 mm, ±20 mm

Along 5 radii
- Nominal R = 350 mm, R = 350 mm ±10mm,
  R = 350 ±20mm
NMR probe test, low field – homogeneous field

Measurements should be done at the field of **By=140 Gauss** to **300 Gauss** (2.6 MeV operation).
Challenges in the NMR locking and timing

- NMR Locking at low field is considerably challenging
  - Solutions, turn off the motor when starting to achieve NMR locking

- Motion drive:
  - X-axis direction is screw driven, and the Y-axis direction is belt drive though with linear encoder
  - Wait for ~10 seconds in total to achieve short-time equilibrium (ideally would maybe 20 seconds)
  - Even 10 seconds, overall each NMR runs takes 8-9 hours.
In-plane Z flatness <0.135 mm

Distance between NMR home and magnet center is
\[ \Delta X = -414.098 \text{ mm}, \quad \Delta Y = -444.192 \text{ mm} \]
Hysteresis loop optimization – python program

\[ i_n = I \left( 1 - (-1)^n \left[ e^{-cn} - k \right] \right), \quad n = 1, \ldots, M, \]

\[ t_n = \frac{|i_n - i_{n-1}|}{dI/dt}, \quad n = 1, \ldots, M, \]

With pre-cycle, repeatable
Repeatability test

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<th>Value</th>
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<td>20:25:29</td>
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Hybrid_4.2A

Exponential Ex0.075
Exponential demagnetization is better
All the data taken in the following way were

max ΔB of 27 milligauss.

max ΔB of 128 milligauss.
Precision Check at Magnet Center Point

NMR and Hall Repeatability Test at Magnet Center (0,0), at 301 Gauss with current 3.98A and over 12 hours

Hall precision, < 0.4 Gauss

NMR precision, 0.06 Gauss
Field on magnet center lines, (0,Y,0)

Hall can be corrected by NMR – design principle, Origin = center
Field on magnet center lines, \((X, 0, 0)\)

Modified design ----
(1) Window inner width (on shield) now is wider \((X = +/- 50 \text{ cm})\)
(2) Shield is magnetically decoupled from magnet (keep the same gap 8 cm).

Field along \(Y = 0 \text{ mm}\)

Field (Gauss)

X distance (mm)

Hall  NMR
Measurement plan

- Part A – multiple points of currents/fields, ZHeight = 0mm, Radius 350 mm, 274 points – Hall and NMR (uniform field)
  - 2.4 A
  - 2.7 A
  - 3.0 A
  - 3.4 A
  - 3.8 A
  - 4.2 A

White – data planned, Blue – data taken

Real-time Probe Location

Hall

NMR
Along beam trajectory – Z center

- Both NMR and Hall Center points along X axis are corrected for reference/validation/correction
- They are aligned based on 15 mm offset
Measured NMR (full field) + Hall (lower field)

Scanning the $Z = 0$ mm, $R = 350$ mm trajectory using different operational currents.
Field Mapping Plan and Procedure

Field of $I=2.6586\,A$:
- $Z=0\,\text{mm}$
- $Z=+10\,\text{mm}$
- $Z=+20\,\text{mm}$
- $Z=-10\,\text{mm}$
- $Z=-20\,\text{mm}$

Field of $I=3.1911\,A$:
- $Z=0\,\text{mm}$
- $Z=+10\,\text{mm}$
- $Z=+20\,\text{mm}$
- $Z=-10\,\text{mm}$
- $Z=-20\,\text{mm}$

Field of $I=3.9833\,A$:
- $Z=0\,\text{mm}$
- $Z=+20\,\text{mm}$
- $Z=-20\,\text{mm}$

All:
- $Z=0\,\text{mm}$
- $Z=+10\,\text{mm}$
- $Z=+20\,\text{mm}$
- $Z=-10\,\text{mm}$
- $Z=-20\,\text{mm}$
In-plane (same height) Results and Analysis

- A typical field scan with 5+1 different radii
  - Start with R 350 mm
  - R 330mm
  - R 340mm
  - R 350mm
  - R 360mm
  - R 370mm
CURRENT OF 2.6586A

- Results
- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)
Field of I=2.6586A and z=+20mm
In-plane horizontal comparison

Current 2.6586 A, z = +20.000 mm
Field

- Dropouts because of not-good NRM locking
- A method is being implemented to correct the data – on-going
Field of I=2.6586A and z=+10mm
In-plane horizontal comparison

Current 2.6586 A, z = +10.000 mm
Field

Current 2.6586 A, z = +10.000 mm
Normalized Field

Field [G]

Index

R = 350 mm (*)
R = 330 mm
R = 340 mm
R = 350 mm
R = 360 mm
R = 370 mm
Field of I=2.6586A and z=+00mm
In-plane horizontal comparison

Current 2.6586 A, z = +0.000 mm
Field

Current 2.6586 A, z = +0.000 mm
Normalized Field
Field of $I=2.6586\ A$ and $z=-10\ mm$

In-plane horizontal comparison

Current $2.6586\ A$, $z=-10.000\ mm$

Field

Current $2.6586\ A$, $z=-10.000\ mm$

Normalized Field

Field [G]

$R$ = 350 mm (*)
$R$ = 330 mm
$R$ = 340 mm
$R$ = 350 mm
$R$ = 360 mm
$R$ = 370 mm

Index
Field of I=2.6586A and z=-20mm
In-plane horizontal comparison

Current 2.6586 A, z = -20.000 mm
Field

Current 2.6586 A, z = -20.000 mm
Normalized Field
Data smoothing: correct drop-outs

\[ I, Z, R = [2.6586 \, A, 20 \, mm, 370 \, mm] \]

- Slight difference in quantity between simulated and measured data.
- Qualitative info helps data smoothing.
- Measured data → Beam operation
ANALYSIS AND DISCUSSIONS

I = 2.6586 A
Measured Results

Comparison plots of the measured magnetic fields for all radii, at a fixed $Z = 10$ mm elevation, with $I = 2.6586$ A. The radius of 350 mm was measured twice.

In plane full view

normalized

Zoom-in
Simulated data

Comparison plots of the simulated magnetic fields for all radii, at a fixed $Z = 10$ mm elevation, with $I = 2.6586$ A.

In plane full view

normalized

Zoom-in

Good agreement between measured and simulated
Same radius $R = 350$ mm, 
Same current $I = 2.6586$ A, 
Vertical comparison

Asymmetry observed in measured data

But field at magnet edge, low field strength, less contribution to the field integral.
Simulated data

Same radius $R = 350$ mm, 
Same current $I = 2.6586$ A, 
Vertical comparison

Asymmetry observed in measured data

But field at magnet edge, low field strength, less contribution to the field integral.
• More variations in measured vs simulated,
• But field at magnet edge, lower field strength, less contribution to the field integral.
• Symmetry has been improved with higher current
Field integral – measured data

Field integral calculated with corrected measured data for five radii, but same elevation of Z = 20 mm

Field integral information for the 180 deg dipole magnet for three different currents, at five radii, at different elevations.
Units: [Gmm]
Summary

- Have completed the mapping of 180 degree dipole for LEReC project.
  - Successfully applied high precision – low field NMR probe, combined with Hall probe.
  - Measured data provide very accurate picture, which is supported by its general agreement with computational predictions.

- Performed detailed analysis and comparison at various radius and height,
  - Slight asymmetry observed at magnet edges due to lower field strength, but small field strength \( \rightarrow \) less contribution to the field integral.

- Field and integral information shared with physicist, and findings from these measurements can be directly used to support beam operation.
Thank you for your attentions
Backup slides
CURRENT OF 3.1911A

- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)
Better symmetry
Field of I=3.1911A and z=+20mm
In-plane horizontal comparison
Field of I=3.1911A and z=+10mm In-plane horizontal comparison

Current 3.1911 A, z = +10.000 mm

Field

Normalized Field

Index

Field [G]

R = 350 mm (*)
R = 330 mm
R = 340 mm
R = 350 mm
R = 360 mm
R = 370 mm
Field of I=3.1911A and z=+00mm In-plane horizontal comparison

Current 3.1911 A, z = +0.000 mm
Field

Current 3.1911 A, z = +0.000 mm
Normalized Field

Field [G]

Index

$R = 350 \text{ mm (\*)}$
$R = 330 \text{ mm}$
$R = 340 \text{ mm}$
$R = 350 \text{ mm}$
$R = 360 \text{ mm}$
$R = 370 \text{ mm}$
Field of I=3.1911A and z=-10mm
In-plane horizontal comparison

Current 3.1911 A, z = -10.000 mm
Field

Current 3.1911 A, z = -10.000 mm
Normalized Field

Field [G]

Index

0 50 100 150 200 250

0 50 100 150 200 250

R = 350 mm (*)
R = 330 mm
R = 340 mm
R = 350 mm
R = 360 mm
R = 370 mm

Field [normalized to field for R = 350 mm]
Field of I=$3.1911\,\text{A}$ and $z=-20\,\text{mm}$

In-plane horizontal comparison

Data out of batch process
Likely to fix the data individually
CURRENT OF 3.9833A

- In-plane horizontal comparison – 5 heights of (5+1 radii)
- Vertical comparison – 5+1 radii of (5 heights)
Field of $I=3.9833\,A$ and $z=+20\,mm$
In-plane horizontal comparison

Current 3.9833 A, $z = +20.000$ mm
Field

Current 3.9833 A, $z = +20.000$ mm
Normalized Field
Field of \( I = 3.9833\, \text{A} \) and \( z = +00\, \text{mm} \)

In-plane horizontal comparison
Field of $I=3.9833\text{A}$ and $z=-20\text{mm}$

In-plane horizontal comparison
Field of I=3.9833A and R=330mm

Vertical comparison

Current 3.9833 A, R = 330 mm

Field

Field [G]

Index

Current 3.9833 A, R = 330 mm

Normalized Field

Field [normalized to field for R = 350 mm]

Index

z = -20 mm
z = +0 mm
z = +20 mm
Field of $I=3.9833\,\text{A}$ and $R=340\,\text{mm}$

Vertical comparison

Current $3.9833\,\text{A}$, $R = 340\,\text{mm}$
Field

Normalized Field

Field [G]

Index

Index

Current $3.9833\,\text{A}$, $R = 340\,\text{mm}$

Normalized to field for $R = 350\,\text{mm}$

Field (normalized to field for $R = 350\,\text{mm}$)

$z = -20\,\text{mm}$
$z = +0\,\text{mm}$
$z = +20\,\text{mm}$
Field of I=3.9833A and R=350mm_Init

Vertical comparison

Current 3.9833 A, R = 350 mm (initial)
Field

Current 3.9833 A, R = 350 mm (initial)
Normalized Field
Field of $I=3.9833\,\text{A}$ and $R=350\,\text{mm}$

Vertical comparison

Current 3.9833 A, $R = 350\,\text{mm}$

Field

Current 3.9833 A, $R = 350\,\text{mm}$

Normalized Field
Field of I=3.9833A and R=360mm

Vertical comparison
Field of I=3.9833A and R=370mm
Vertical comparison

Current 3.9833 A, R = 370 mm
Field

Current 3.9833 A, R = 370 mm
Normalized Field
A FEW MORE THINGS
Hysteresis Loop

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