# LOW FIELD NMR PROBE COMMISSIONING FOR LEReC ENERGY SPECTROMETER

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T. Miller†, M. Blaskiewicz, A. Fedotov, D. M. Gassner, J. Kewisch, M. Minty, S. Seletskiy, H. Song, P. Thieberger, P. Wanderer, BNL, Upton, NY, USA
R. Boucher[1], C. Germain, JC. Germain, CAYLAR SAS, Villebon-sur-Yvette, FRANCE
[1]also at POLYTECH, Paris-Sud University, Orsay, FRANCE Country

Low Energy RHIC electron Cooling (LEReC) [1] is planned during a 7.7 – 20 GeV/n run with Au+79 starting in 2019 (200 GeV/n center-of-mass typical), to explore the existence and location of the QCD critical point. An electron accelerator for LEReC is being constructed to provide a beam to cool both the blue & yellow RHIC ion beams by co-propagating a 10 – 50 mA electron beam of 1.6 – 2.7 MeV. For effective cooling of the ion beam, the electron and ion beam energies must be matched with 10-4 accuracy. As the energy of the RHIC ion beam can be known to <1×10-4[2], the absolute energy of the electron beam must also be measured to 10-4 accuracy. A 180° bend transport magnet will be used as an energy spectrometer for the electron beam providing fields in the range of 180 – 325 gauss. A Nuclear Magnetic Resonance (NMR) gaussmeter has been customized to measure the field in the magnet (to as low as 143 gauss) with an accuracy of 50 milligauss and a noise floor of < 20 milligauss. The concept of the magnetic spectrometer and details and commissioning performance of the NMR instrument are presented in this paper.

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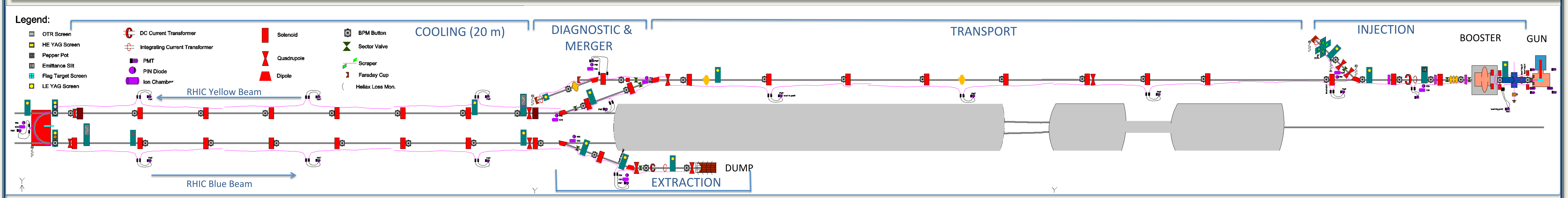
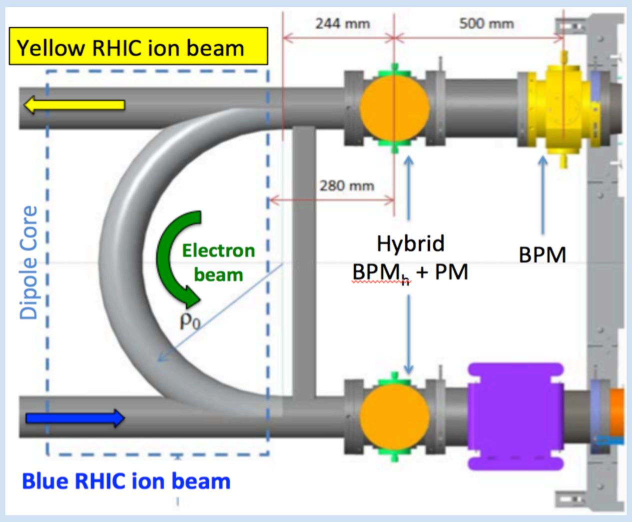



## MAGNETIC SPECTROMETER

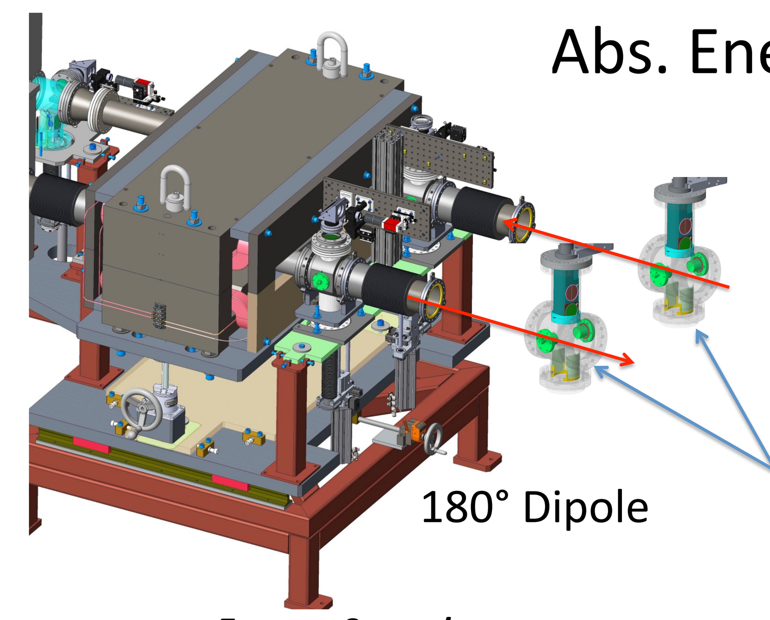
The spectrometer is composed of the 180° dipole magnet and three BPMs. It is designed for parallel beam entry and exit, and a bending radius ρ0 = 0.35 m.

The first BPM is for measuring entry angle. The other two BPMs are Hybrid horizontal BPM + PM. The radius of beam curvature is given by horizontal beam displacement between entry and exit BPMs. This displacement gives the absolute beam energy.

At the heart of the spectrometer is the measurement of the absolute magnetic field given by an NMR probe mounted in the gap of the magnet. Together with the integral of the field map through the beam trajectory, the NMR reading is combined with the beam displacement from the BPMs to give the absolute beam energy.




## Abs. Energy & Energy Spread




### *Absolute Energy Measurement*

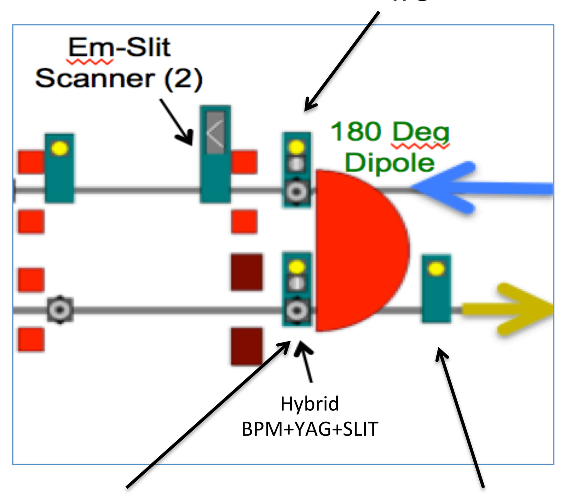
BPM accuracy requirement: 50 µm

Two BPMs will be used with the 180° dipole magnet in the cooling section as a spectrometer. For absolute calibration, a YAG screen profile monitor is inserted into the BPM chamber in the same X-Y plane as the BPM buttons.

### *Energy Spread*

An energy spread measurement is required with a resolution of better than 10% of the maximum Δp/p of 5×10-4.

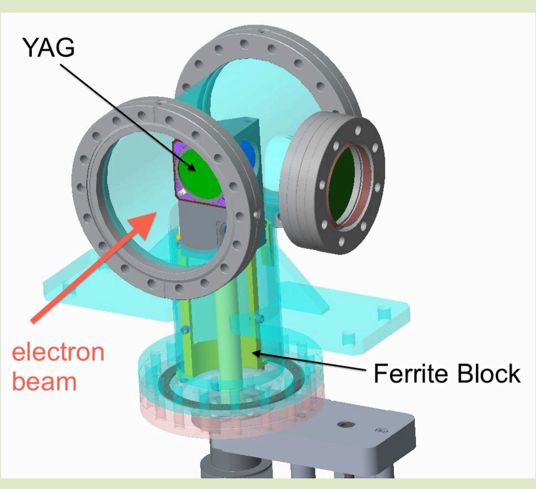
1) Insert slit in #1 ,turn off 180° Dipole, energize high field solenoid
2) Take Profile on #2
3) Energize 180° Dipole & take image on #3
4) Compare images from #2 - #3 in horizontal

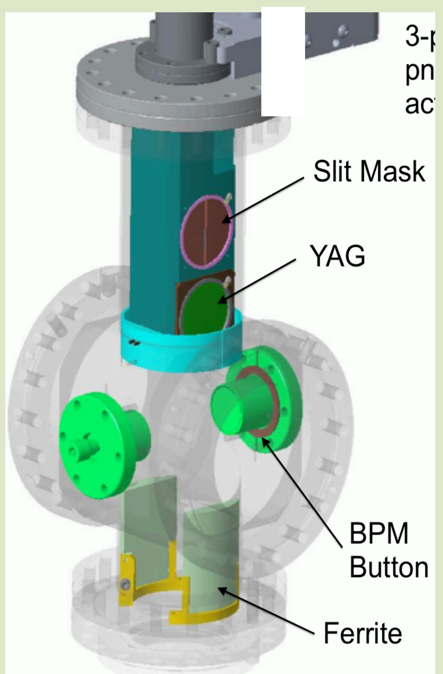



## Profile Monitor & Hybrid PM+BPM

**PM Key Parameters:**
- Cylindrical Vacuum Chamber
- 45 mm screen aperture
- YAG crystal 0.1 ✕ 50 mm
- 50 µm resolution
- Aluminum coating
- Normal to beam
- Copper mirror @ 45° behind YAG
- Low power (1 macrobunch / sec) ~1 – 6 nC

**Hybrid PM Functions:**
- Absolute Energy
- Beam Profile
- Energy Spread



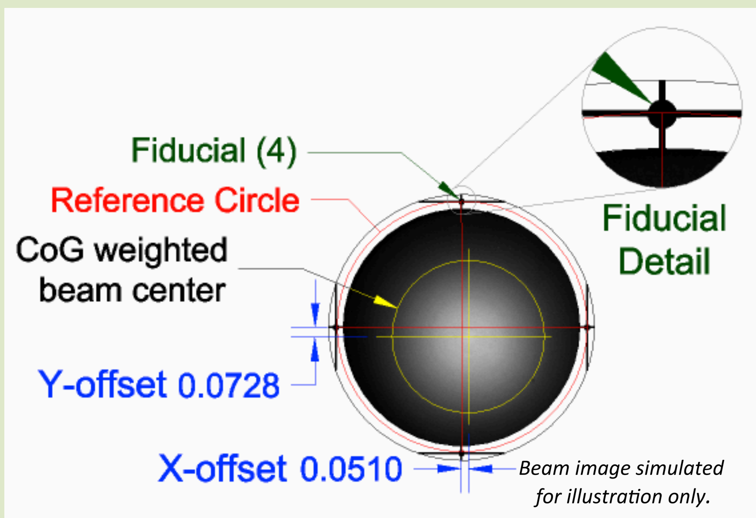




### *BPM Calibration Procedure*

Pre-surveyed YAG holder provides optical reference for comparison of beam spot center to BPM position data. Four optical features on the YAG holder are imaged along with a beam profile. Center of gravity (CoG) weighted beam center is compared in position to the center of the reference circle drawn through the optical features. The two resulting X and Y offset values are fed into the BPM data processing as offsets from actual center.

***Optical Fiducial Points***

Four optical features on the YAG holder are provided for BPM calibration




## Accuracy Study

To measure beam energy with an accuracy of 0.1%, a proper Taylor expansion of the exact expression for magnetic rigidity was performed, resulting in equation below :

$$x_{out} = -x_{in} - 2\rho_0 \frac{E_0 + mc^2}{E_0 + 2mc2}\delta$$

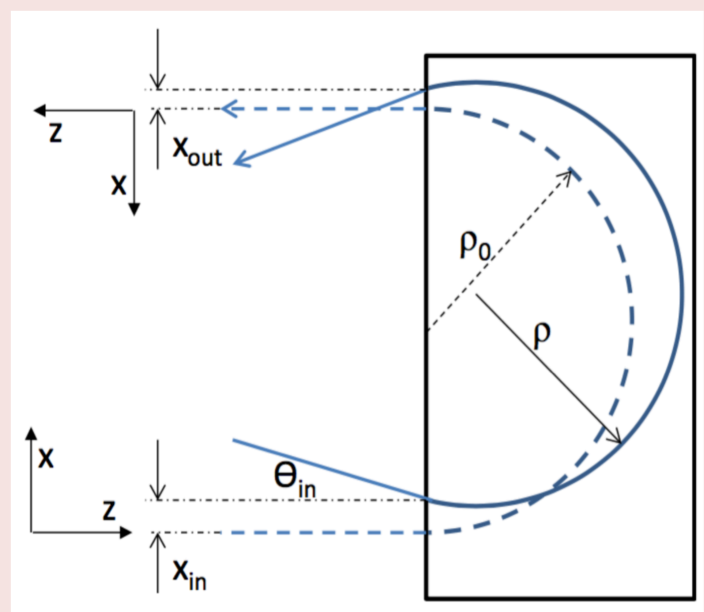
The horizontal beam displacement is given by $x_{out} - x_{in}$

Bending radius ρ0 = 0.35 m

For an accuracy of the magnetic field measurement/setting of 0.1% and an absolute error of the BPM reading of 0.1mm, at 1.6MeV the worst case accuracy of the energy measurement was found to be $\delta = 2x10^{-3}$.

For a case of relaxed BPM measurement/setting error of 0.5mm, $\delta = 5x10^{-3}$.

Simulating a 5%-off-energy beam trajectory and calculating the measured energy give a real beam energy accuracy of $2.6x10^{-3}$ and $6.7x10^{-3}$ in the worst case.



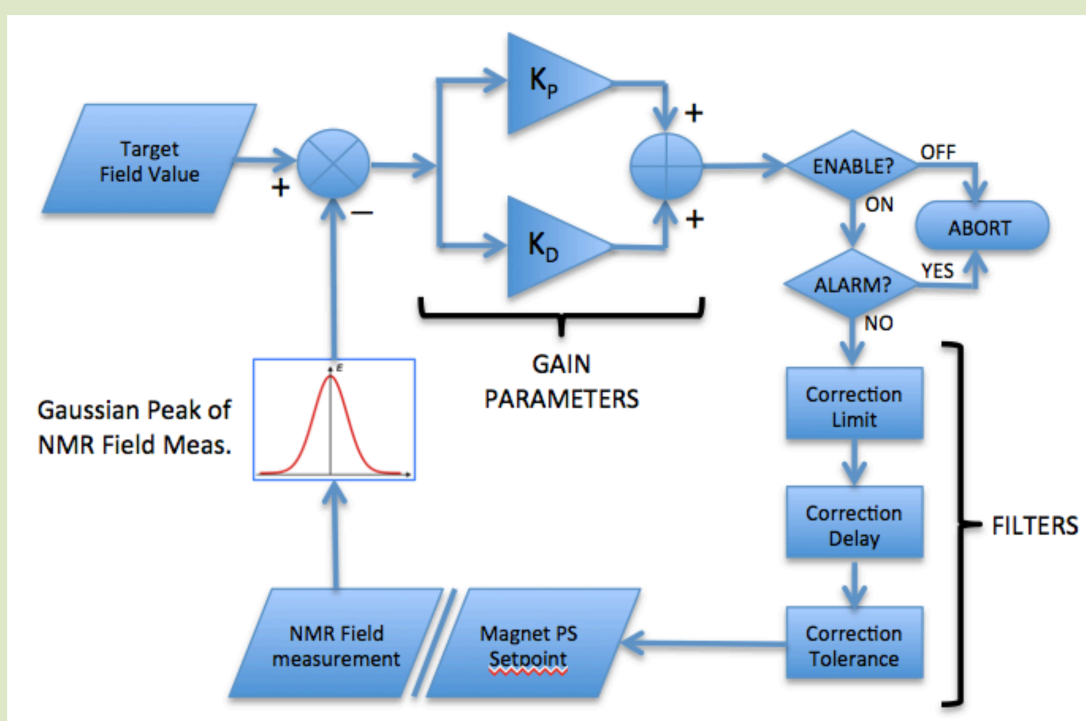

## Software Regulation Loop

The magnetic field is stabilized over long periods of time, a software based feedback loop, will correct the magnet current in small increments based on NMR field measurement. Gaussian statistics give exact field. The peak of the Gaussian, accumulated over an adjustable period of several minutes, is compared to a *target* value.

- PD gain values
- Field measurement by Gaussian statistics

**Corrections limits:**
- Amplitude
- rate
- Tolerance

**Loop Aborted if:**
- PS turned off
- Correction over limit
- Control conflict




## NMR Gaussmeter

To measure precisely the field of the magnet, a Nuclear Magnetic Resonance (NMR) gaussmeter has been customized and a special probe was design by CAYLAR to measure the field over a range of 146 – 561 Gauss with an accuracy of 5 milligauss. A noise floor of < 20 milligauss was achieved; which depends on the power supply and the homogeneity of the field.

A main design challenge was the extension of the sample from the electronics by 40 cm to remove the electronics from the higher radiation area in the beam horizontal plane and to develop a probe capable of measuring a field as low as 180 gauss. The electronics of the probe was also modified to improve the signal-to-noise ratio of the NMR signal allowing better detection and therefore a better stability of the measurement.

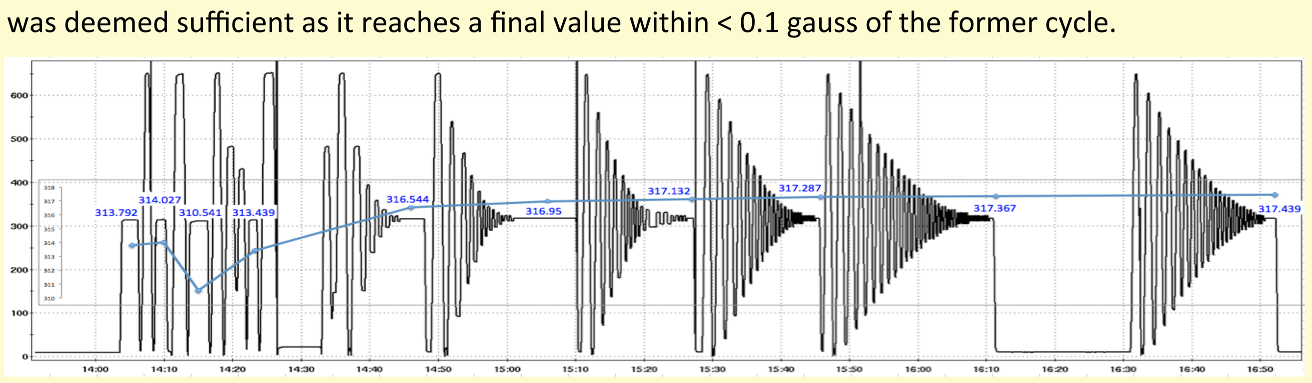
For remote control and monitoring, the gaussmeter includes Ethernet and RS232 connectivity.

The NMR20 gaussmeter allows several modes of operation:
- A **"manual" mode** for searching the NMR signal over the entire range of the probe using two potentiometers
- An **"auto" mode** which will scan the entire range of the probe and which will lock on the NMR signal and use it to stabilize the measurement at the resonant frequency
- A **"Digital" mode** which will function as the "auto" mode but only scanning around a reference field value given by the user
- A **"Hall Tracking" mode** that works like the "Digital" mode but using a Hall probe integrated in the NMR probe to define the field around which the Gaussmeter will sweep
- An **"Autograd" mode** which, like the "Auto" mode, searches over the entire range of the probe, but by adjusting the parameters of the gaussmeter according to the field

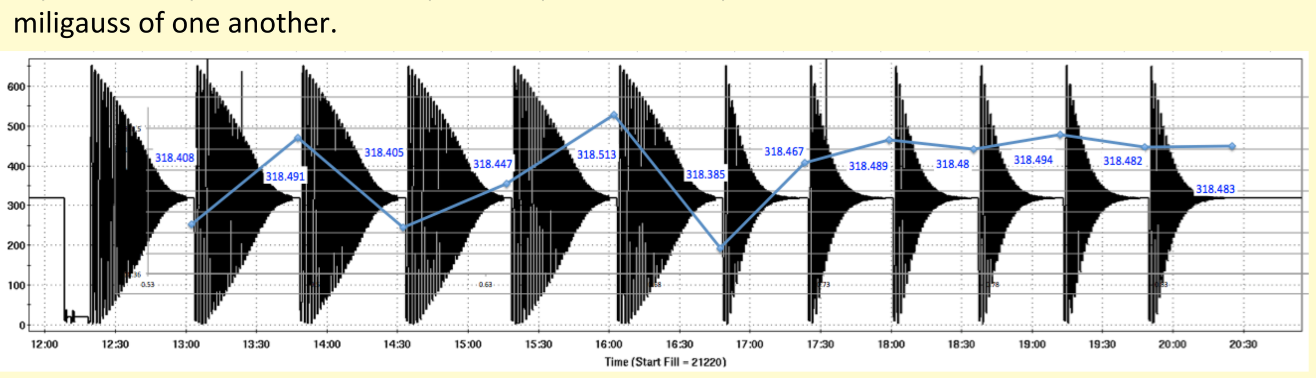
Once the probe is permanently mounted in the 180° dipole, the "Digital" mode will be used with the reference field set according to the expected energy.

## Hysteresis Cycle

At low fields there are non-uniform residual fields that alter the total integrated field of the magnet. A hysteresis cycle was developed to eliminate residual fields in the steel core. Without knowing what the absolute field value is, we started with a simple ramp to the operating point that leaves a residual filed and followed with multiple bipolar cycles around the operating point with an exponential taper to the envelope, as shown in the figure below. As the residual field is eliminated more and more, the final value approaches the ideal, as shown by the curve of final values. The last cycle with 48 points was deemed sufficient as it reaches a final value within < 0.1 gauss of the former cycle.



To test the reproducibility of the hysteresis cycle, two type of cycles were tested at an operating point of 4.2A for 317 Gauss with a 0.4 A/sec ramp rate and an amplitude of ±4.2A around the operating point. The two types of shape test were linear + exponential and exponential. Each was tested six times with a period of 45 min for the first one and 36 min for the second. The best reproducibility was obtained by the exponential shape with final values that were within ± 20 miligauss of one another.



The hysteresis cycle is run each time the magnet is set to a new operating point to ensure a repeatable absolute magnetic field.

## Dipole Magnet

| Parameter | Value | Units |
|---|---|---|
| Operating Field | 196 – 318 | Gauss |
| Nominal current | 2.7 – 4.2 | A |
| Maximum current | 7.3 | A |
| Coil resistance (65°C) | 5.5 | Ω |
| Coil Inductance | 3.6 | H |
| Number of turns | 298 | |
| Pole face | 50 x 110 | cm |
| Gap | 10 | cm |
| Core material | 1005 Low Carbon Steel | |

## Field Mapping

To predict the exact energy of the electron beam we need to now the integrated field value along the beam trajectory.

To do that, we used the NMR gaussmeter to map the field along 5 arcs across spanning an area ±20 mm on either side of the 130 cm beam trajectory through the magnet. These measurements were taken at each field operating point for five probe heights between +20mm and -20mm from the gap center.

The probe was mounted on a two-axis motion scanning system to move the probe through the beam trajectory and log the field data for both the Hall and NMR sensors within the probe. The servo-motors with linear optical position encoders were controlled by a LabView based program that collected the field data from the gaussmeter.