QMM Project
(Quadrupole Magnetic Measurements)

A Proposal for field map measurement of the six HRS Quadrupoles in Hall A, CEBAF

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DAPNIA-SPHN, Centre d'Etudes Nucléaires, Saclay, France

Abstract

This document summarizes the proposed measurement of the magnetic field maps of the six HRS quadrupoles in Hall A at CEBAF. The LPC-Clermont-Fd and DPHN Saclay are responsible for this project, for which a Memorandum of Understanding will be established between CEBAF and IN2P3/DSM. The basis of the measurement using rotating coils and a preliminary design of the apparatus are presented.

1 Introduction

We refer to existing documents (CEBAF Design Report, 1990) for a review of the Hall A HRS spectrometers and their characteristics. Among the six quadrupoles, two are being built by Saclay (the Q1 pair) and the four others by Siemens (Q2 and Q3 pairs). They are superconducting magnets of \( \cos(2\theta) \) type, with a room temperature iron yoke. They have a large cylindrical bore and a relatively small length. This wide aperture is required by spectrometer acceptance and must be associated with a detailed knowledge of the field map, much better than that given by an integral measurement.

To measure field maps of cylindrical magnets one typically uses a set of radially spaced Hall probes which can both rotate around and move along the magnet axis. Hall probes are well suited for measuring uniform magnetic fields e.g. solenoids, but not so much for quadrupoles because of the uncertainties introduced by planar Hall effect and effective centering of the probe.
Furthermore, two different motions of the probe must be monitored with great accuracy, and this seems especially difficult in the case of CEBAF quadrupoles. Indeed, the latter have to be measured in situ, i.e. in their final configuration inside the spectrometer, with all expected problems of accessibility. Thus the mechanical tasks should be minimized, without losing accuracy. On the one hand this may imply that we shall need more software and computation work to extract the desired field map from the measurement. On the other hand, one should note that because the Quadrupoles are current-dominated, a theoretical field map can be computed from an ideal coil and yoke geometry. This will be a precious tool at all stages of the project, because we shall use it as a reference field map (see fig.9).

Based on the above arguments, we propose to measure the Qpoles field map by using the rotating coil technique which has been developed mainly for accelerator magnets. This technique has to be adapted to the particular case of spectrometer magnets of large aperture.

The measuring device will consist in a set of rotating coils, spread along the axis to cover the whole length of the quadrupole and its fringing field. Thus translation-type motion is no longer needed, and the probe will only rotate around the magnet axis.

The measured quantity is typically the EMF induced by the variation of the magnetic flux through the coils during their rotation. The basic idea is that, having at our disposal a computed field map already close to reality, only a small field contribution remains to be extracted from the data, thus releasing the relative precision to be achieved on this quantity. The consequence is that a small number of coils is convenient to measure the quadrupoles.

To go from the integrated measurement to the desired 3D field map, we shall use both experimental data and the computed field map in close combination.

Our aim in this paper is not to describe the analysis procedure, which needs to be further developed and optimized. It will be the subject of another paper. The present document only explains the measurement part of the project. Although some parameters of the probe have not yet been fixed, such as the actual number of coils and their actual position along the magnet axis, the Technical Groups at Saclay have already started R&D studies to keep on schedule, i.e. be ready for tests measurements on Q1 at Saclay in Fall 1994 and perform the final measurements at CEBAF in mid-95.

2 Notations

We use the cylindrical 2D notation for multipole expansion of the magnetic field components: $B_n$ is the normal $2n$-pole term and $A_n$ the corresponding skew harmonic at the useful bore radius. We chose the following coordinate system for each quadrupole:

- the origin $O$ is at the center of the magnet;
• Oz is the magnet axis, oriented parallel to the particles trajectory;

• Oy is either the vertical axis (for Q1, Q2) or contained in the vertical plane and pointing upwards (for Q3).

• \( \vec{O}_y = \vec{O}_z \times \vec{O}_x \) = horizontal axis.

3 The HRS magnetic elements

We recall here some basic features of the HRS as taken from CEBAF Conceptual Design Report, 1990. See also fig.1.

3.1 Overall features

• the HRS have a Q1/D/Q2/Q3 structure, Q2 and Q3 being identical

• Q1 is vertically focusing, Q2/Q3 is defocusing and the dipole is focusing

• (Q1/Q2) forms one mechanical unit capable of axial translation

• the HRS have a field dynamical range of 10:1 including both polarities.

• analysed momentum goes up to 4 GeV/c.

3.2 Dipole

• TRANSPORT's "bending magnet" with negative field gradient (curved and tilted pole faces)

• superconducting coil and room temperature H-frame yoke

• central bend angle : 45°

• maximum central field : 1.59 T

• central bend radius : 8.4 m

• central gap : 250 mm

• effective width : 1 m

• magnetic length : 6.6 m

• entrance/exit angle : −30°

• field index : −1.25

• iron weight : 430 tons.
### 3.3 Quadrupoles

Table 1 lists the main characteristics of the HRS quadrupoles. Updated values will be provided by Saclay for Q1 and by Siemens via CEBAF for Q2/Q3. See also figs 2 and 3.

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>Q2/Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic length</td>
<td>900.</td>
<td>1800.</td>
</tr>
<tr>
<td>nominal field gradient</td>
<td>8.33</td>
<td>3.5</td>
</tr>
<tr>
<td>useful bore diameter</td>
<td>300.</td>
<td>600.</td>
</tr>
<tr>
<td>field at useful bore diam.</td>
<td>1.25</td>
<td>1.05</td>
</tr>
<tr>
<td>gradient uniformity</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>correction coils</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>$B_n_{max}/B_2_{max}$ or $A_n_{max}/B_2_{max}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at useful bore radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mechanical length (from flange to flange)</td>
<td>1654. ± 5.</td>
<td>2952.</td>
</tr>
<tr>
<td>position of magnetic center (from flange to center)</td>
<td>720.</td>
<td>centered</td>
</tr>
<tr>
<td>inner diameter of entrance and exit flanges</td>
<td>≈ 300</td>
<td>651.</td>
</tr>
<tr>
<td>drill diameter of entrance and exit flanges</td>
<td>≈ 325</td>
<td>720.</td>
</tr>
<tr>
<td>outer diameter of entrance and exit flanges</td>
<td>≈ 356</td>
<td>750.</td>
</tr>
<tr>
<td>thickness of entrance and exit flanges</td>
<td>30.</td>
<td>24.</td>
</tr>
</tbody>
</table>

Table 1: Main characteristics of the HRS Qpoles. Specifications of the vacuum flanges are given in case they will be used to fix the probe.
4 QMM project : conceptual design

4.1 Overview of the instrumentation

The apparatus designed for the magnetic field measurements consists of several functional units:

- a transportable device (see fig.4) subdivided into:
  1. the rotating elements (from probe to motor)
  2. a probe container fixed to the magnet
- a coil multiplexer and a voltmeter-integrator (measuring the EMF)
- a computer system for monitoring and data acquisition.

4.2 Number of probes and overall dimensions

The measuring probe is basically a set of assembled coils which can rotate around the quadrupole axis. The probe has a diameter $\phi$ as large as possible (for best sensitivity) and its length $L$ is 150% of the magnet optical length to cover most of the entrance and exit fringing fields. Thus two different probes are needed:

- probe #1 for Q1 measurement: $\phi =300$ mm, $L =1600$ mm
- probe #2 for Q2 and Q3 measurement: $\phi =600$ mm, $L =3200$ mm.

Probe #2 will be approximately a copy of probe #1 at scale 2 (see table 1). Indeed if all measurements were to be performed with only one probe, the latter would have to be of small diameter because of Q1, and large length because of Q2/Q3. This would imply a loss of sensitivity for Q2/Q3 measurements as well as an unfavorable situation for rigidity in flexion and torsion, because of the small aspect ratio $L/\phi$.

Remark: the probe length of 1600 mm has been chosen to coincide with the length of the coil that is being built at Saclay for Q1 integral measurement. This allows to make partial cross-checks between the two types of measurements.

The two probes #1 and 2 are able to measure the central region of all three Qpoles, all fringing fields of Q1, Q2 and their interference, and Q3 exit fringing field. Q2 is far enough from the dipole so that one can neglect the Q2/dipole interference.

There is one interference region left to measure: the dipole/Q3 one. For that purpose we need a third probe able to go inside the dipole gap:

- probe #3 for D/Q3 interference: $\phi =250$ mm, $L =1500$ mm.

Remark: for this latter measurement, the reference map or “model” is given by linear interference, i.e. the sum of the dipole field measured with Q3 removed, plus Q3 reference field map.
4.3 The probe container and mechanical principles

Each rotating probe is enclosed into a fixed cylindrical container which holds the bearings on its sides, see fig.4. The container will be introduced manually inside the magnet aperture and can be hooked to the magnet via its entrance and exit vacuum flanges (the various pipes for vacuum connections will be taken off during the measurements, see fig.7). This container provides:

- mechanical coupling of the bearings to the quadrupole
- shielding of the probe (namely during its introduction into the magnet)
- electrical insulation, the thin aluminum walls of the container acting as a Faraday cup.

If we add the mechanical drive (for which two options are possible) the angular encoder and the cables, the full sequence of the rotating elements is the following (see fig.4):

- bearing of the probe, the furthest one to the motor
- probe (set of rotating coils)
- bearing of the probe, the closest one to the motor
- bellow #1
- transmission tubular shaft (containing the cables)
- cables output at the end of the shaft (? using the flexible spiral technique ?)
- bellow #2
- bearing of the encoder, the furthest one to the motor
- angular encoder mounted on a tubular shaft
- pulley (for the driving belt option)
- bearing of the encoder, the closest one to the motor
- bellow #3 (for the direct driving option)
- electrical motor.

The probe, its bearings, bellow #1 and the shaft will be placed inevitably in strong magnetic fields: thus they must be non-magnetic and insulating. The probe container will be non-magnetic and conducting. The other elements must be kept away from any strong magnetic field; for that reason and also for accessibility reasons, the transmission shaft must be long enough and of adjustable length: from 1 to 6 meters.
4.4 Geometrical accuracy

When the set of coils rotates during a measurement, the position of the coils relative to the probe axis must be known to an accuracy of 0.1 mm in all three directions, including the part of the coil sitting at large radius. The probe axis itself is visible only outside of the bearings. This specification puts strong constraints on:

- the bearings (axial and lateral play smaller than 0.1 mm)
- the rigidity of the probe in flexion due to its weight (sagging smaller than 0.1 mm, or measured and accounted for in the calculations) and due to vibrations.
- the rigidity in torsion (static or vibrational) of the probe, due to bearings friction torque, equilibration defaults and accelerations in the driving.
- the rigidity in torsion (static or vibrational) of the probe-to-encoder transmission i.e. bellow #1 - shaft - bellow # 2, due to the same above torques.
- the angular encoder: its stepping can be large (up to 1 degree) but its linearity and reproducibility must be better than:

\[(0.1\text{mm}/300\text{mm}) = 0.33\text{ milliradians} = 70\text{ arc seconds} = 1/19000 \text{ of a turn.}\]

This corresponds to the Q2/Q3 case which is the most restrictive one.

The probe container itself can have a sag larger than 0.1 mm at the bearings, provided that during the rotation the sag variation remains smaller than 0.1 mm. This may require not only a static equilibration of the probe but also a dynamical one.

4.5 Electrotechnics

Because of their small aspect ratio \(L/\phi\), the proposed probes have a better rigidity in torsion than usual rotating coils designed for accelerator magnet measurements. So we expect in our case to reach higher rotation speed (and tolerate higher torsion constraints).

A fast-measuring device is required both to reduce integrator instabilities and to keep the overall duration of the measurements reasonably short, i.e. a few months. Consequently data from the coil will be taken in flight while rotating. This procedure excludes the use of a step-by-step motor which creates unwanted accelerations during the motion. We plan to use a DC motor and perform the measurement on one turn (time: 10 s) preceded by acceleration ramping and followed by deceleration ramping. An angular encoder with a turn bit triggers the integrator periodically, each degree or so.
4.6 Rotating coils and magnetic principle

Each coil will be made of an insulated wire wound along the perimeter of a rectangular epoxy frame (see fig.5). The winding will be single-layered to maintain accurate positioning. The frame will have no groove in order to allow post-winding dimensional control; but this is still optional. The resulting thickness of the coil and frame can be as large as 10 to 20 mm to contain the required number of turns on one layer.

One edge of the coil will be positioned on the rotation axis in order to be sensitive to all field components including the quadrupolar one. The opposite edge will be positioned as close as possible to the useful bore radius of the quadrupole: \( R = 150 \) or 300 mm. The two other edges define the range in \( z \) covered by the coil.

The next coil starts in \( z \) exactly where the previous one terminates. This way the set of coils covers the full probe length without overlapping. The coils will be placed alternatively on one side of the axis and on the other, fulfilling theoretical static and possibly dynamical balance of the device.

The coils will be too large to be calibrated in a reference magnet, for which a gap of 300 mm would be needed. The determination of the coils area to a \( 10^{-3} \) relative precision will rely on an exhaustive control of their geometry (accurate machining, no overlapping, dimensional survey) and their positioning relative to the probe axis.

The coil thickness as well as possible chamfers on the corners (see fig. 5) will be taken into account in the data analysis and will not introduce any direct error. In the case of a quadrupolar field, the tolerance is released in positioning the coil edge that is near the rotation axis. So this edge will be used for placing the electrical connections and the turn-to-turn ramps.

The actual number of coils and their distribution along the rotation axis need to be optimized by computation. We anticipate that there must be more of them and that they must be of smaller size in \( z \) near the end of the magnet coils, where the field varies quickly (see fig.9). We take the following values as a starting point:

- about 10 to 20 coils per probe
- a coil length \( \Delta_z \) in the \( z \)-direction equal to 200 mm (probe # 1) and 400 mm (probe # 2) in the central field region
- the number of turns \( n \) necessary to obtain an EMF equal to \( V_{\text{max}} \) during the rotation is given by:

\[
    n = \frac{V_{\text{max}} T}{2\pi \Delta_z G R^2} \quad (\text{MKS})
\]

where:
- \( T \) is the time period,
- \( \Delta_z \) the coil size in \( z \),
- \( G \) the field gradient,
\( R \) the outer radius of the coil.

This expression is obtained when reducing the magnetic field to its quadrupolar component in 2D approximation. If we take \( V_{\text{max}} = \pm 5 \) Volts, \( T = 10 \) seconds, and the nominal values:

\[
G = 8.33 \, T/m, \quad R = 0.15 \, m, \quad \Delta_z = 0.2m \quad \text{for probe \# 1}
\]

\[
G = 3.50 \, T/m, \quad R = 0.30 \, m, \quad \Delta z = 0.4m \quad \text{for probe \# 2}
\]

we obtain 212 turns for probe \# 1 central coil and 63 turns for probe \# 2 central coil. The coils having a smaller size in \( z \) should either have an increased number of turns, or their data should be taken at higher rotation speed. To measure the fringing field in the far out region we shall use a coil with enough turns and set the voltmeter gain higher than 1.

The above design uses the nominal, i.e. maximum field gradient of the Qpoles. Measurements at lower inductions will also require higher gain setting and/or higher rotation speeds.

### 4.7 Mechanical structure of the probe

The array of rotating coils consists of a flat rectangular surface partly occupied by the coils (see fig.5). Its rotation axis must coincide with the symmetry axis of the rectangle parallel to \( z \). This array must be stiffened along three directions, to reduce both in-plane and out-of-plane flexion, and torsion. It must be connected to a rotation axis at each end.

We propose the following design (see figs 6 and 7):

- sandwiching the coils array between two plates by filling the empty space between the coils with wedges made of e.g. epoxy glass or honeycomb materials, and then glue thin epoxy glass foils on each side of the plate to ensure in-plane rigidity.

- provide the two other rigidities by adding pieces of material on each side of the sandwich plate. The optimal solution would be to cut a thin walled epoxy glass cylinder into two halves and glue them onto the sandwich plate in order to form an entire cylinder of radius as close as possible to the useful bore radius.

Other alternatives may use a crossed-bars structure or a combined crossed-bars plus cylinder structure.

- terminate the entire cylinder by two epoxy glass endplates which will hold the tubular axis.

The issues for reaching final accuracy are:

- **coils positioning and fixing inside the probe**
• initial and post-rigidification flatness of the sandwich plate

• axis positioning w.r.t. the magnetic z-axis

As the movable device must be both light and rigid, part or all of the epoxy material maybe replaced by carbon compounds or kevlar.

4.8 Container size and probe mechanical alignment

As explained above, each probe can rotate inside a cylindrical container. The three containers have the following indicative diameter and length:

\[(\phi < 300, \ L > 1600 \ mm) \text{ for container } \#1,\]
\[(\phi < 600, \ L > 3200 \ mm) \text{ for container } \#2,\]
\[(\phi < 250, \ L > 1500 \ mm) \text{ for container } \#3.\]

They are aluminum cylinders terminated by two endplates holding the bearings. Each container can be introduced inside the magnet with a loose gap which permits alignment of the probe w.r.t. the Qpole. The container is then fixed by its sides to the Qpole vacuum flanges. To allow for alignment, the mechanical connection must have five degrees of freedom:

• \(x\) and \(y\) positioning at the entrance flange

• \(x\) and \(y\) positioning at the exit flange

• \(z\) positioning by sliding-type supports.

4.9 Fixing of the motor/encoder/cable output package

Due to the expected difficulties of \textit{in situ} measurements, the motor drive, encoder and cable outputs must be delivered in a light and compact form, together with a light and adjustable holding structure (see the three-legged stand on fig.8).

The motor driving axis will first be aligned with the probe axis, in \(x\) and \(y\) directions and angles. It will then be connected to a tubular shaft to drive the probe.

As we shall have only one motor to drive three different probes, the shaft itself can be chosen either as a single piece of adjustable length, or as a set of shafts of various lengths. In the latter case the driving package also moves along the \(z\)-axis to adapt to the various shafts. In all cases the bellows must be of good enough quality to work in approximate alignment conditions and still ensure precise angular encoding.

5 QMM project: measurement runplan

The runplan is organized in four measuring sequences which are detailed below (see also figs 8-a, 8-b).
5.1 The Q1 measuring sequence

- probe # 1 is used
- range covered in $z$: if P1 designates a plane orthogonal to the Qpole axis and located between the exit of Q1 and the entrance of Q2 (see fig.8) the measurement extends from 1600 mm upstream of P1 to P1 itself.
- measurements are made for a series of Q1/Q2 current settings
- the probe is introduced from upstream
- alignment is made from upstream
- mechanical drive is set from upstream.

5.2 The Q2 measuring sequence

- probe # 2 is used
- range covered in $z$: from the P1 plane to 3200 mm downstream of P1.

The ending plane of the Q1 measuring sequence must coincide in $z$ with the starting plane of the Q2 measuring sequence to better than 0.1 mm.
- measurements are made for a series of Q1/Q2 current settings
- the probe is introduced from downstream with Q1/Q2 in their configuration closest to the target. The probe will have to be tilted during its installation and to be slided into the dipole frame structure (see fig.8)
- alignment is made from upstream through Q1
- mechanical drive is set from upstream through Q1.

5.3 The Q3 measuring sequence

- probe # 2 is used
- range covered in $z$: if P2 designates a plane orthogonal to the Qpole axis and located between the exit of the dipole and the entrance of Q3 (see fig.8) the measurement extends from P2 to 3200 mm downstream of P2.
- measurements are made for a series of dipole/Q3 current settings
- the probe is introduced from downstream through the floor of the detector's hut. Slide-bars are necessary to control the probe motion downwards at 45 degrees slope.
- alignment is made from downstream, through the hut's floor.
- mechanical drive is set from downstream through the hut's floor.
5.4 The dipole/Q3 measuring sequence

- probe # 3 is used
- range covered in \( z \): from 1200 mm upstream of the P2 plane (inside the dipole) to 300 mm downstream of P2 (in the Q3 entrance fringing field).

The starting plane of the Q3 measuring sequence must coincide in \( z \) with one of the boundary planes between rotating coils of the dipole/Q3 measuring sequence to better than 0.1 mm.

- measurements are made for a series of dipole/Q3 current settings
- the probe is introduced from downstream through the floor of the detector’s hut, using slide-bars.
- alignment is made from downstream, through the hut’s floor.
- mechanical drive is set from downstream through the hut’s floor.

Runplans are identical for the two HRS Leptos and Hadros. Obviously the probes and their containers must be as light as possible to be carried manually, although the heaviest probe (# 2) could also be crane-lifted with the help of straps.

6 Layout of a measuring sequence

The voltmeter-integrator will have two synchronized input channels. Channel # 1 is connected permanently to one of the central coils (or reference coil) for calibration purposes, and channel # 2 is connected to each other coil successively via a multiplexer (see Electronics section). A detailed measuring sequence is displayed in table 2.

Gain monitoring is a real concern because we shall operate in unfavorable conditions, namely large fluctuations in temperature and humidity.

7 Electronics

Our reference for voltmeter-integrator is the one manufactured by METROLAB: P.D.I. 5025 + P.D.I. 5150 model. It has two input channels, in-flight operating mode in the range \(-5V\) to \(+5V\) with default linearity, offset and noise level lower than 100 \( \mu V \). It can be synchronized with a relative encoder and can drive a DC motor. Given the price per channel the most cost-effective solution is to use a multiplexer and read the coils sequentially. That multiplexer should have high quality connections; it has to be purchased or designed and built at Saclay.
the above sequence is repeated in backward rotation

<table>
<thead>
<tr>
<th>CHANNEL # 1</th>
<th>CHANNEL # 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>motor stopped</td>
<td>offset meas. channel 1</td>
</tr>
<tr>
<td>forward rotation, one turn</td>
<td>reference coil</td>
</tr>
<tr>
<td></td>
<td>data taking</td>
</tr>
<tr>
<td></td>
<td>offset meas. channel 2</td>
</tr>
<tr>
<td></td>
<td>current coil</td>
</tr>
<tr>
<td></td>
<td>data taking</td>
</tr>
</tbody>
</table>

- test the quality of the measurements:
  - compare offsets data,
  - compare forward/backward data

Option: interchange the two channels and redo the above sequence

Option: determine the relative gain between the two channels

redo the above sequence for next coil

- test the stability of reference coil throughout the sequence
- calibrate the measurements
- average over forward and backward data
- compare with reference map, harmonic analysis
- compute and test probe misalignments
- store raw data

Table 2: Layout of one measuring sequence
8 Acquisition system and software

The Quadrupoles Magnetic Measurements are not coupled to any other CEBAF controlled system except for the Qpoles and dipole power supplies. These can be controlled manually, however they will have to be read out and their information transferred, e.g. via Ethernet interface. As no specific standard for acquisition or software is required we shall design our own system, with FORTRAN based software for on-line analysis and graphical display. Data transfer and storage for off-line analysis will be chosen in compatibility with CEBAF existing installations.

9 Timeline

Table 3 gives a draft agenda for the QMM project, which is expected to reach completion at the end of 1995. It should be noted that probe # 1 will be realized first, in view of test measurements on Q1 scheduled at Saclay in Fall 94.

<table>
<thead>
<tr>
<th>January 1st, 1994</th>
<th>start R &amp; D studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 12th, 1994</td>
<td>Project Review at Saclay</td>
</tr>
<tr>
<td>April, 1994</td>
<td>purchase and order material for probe # 1</td>
</tr>
<tr>
<td>July, 1994</td>
<td>assembling and testing probe # 1</td>
</tr>
<tr>
<td>November, 1994</td>
<td>- test measurements on the first Q1 magnet, at Saclay - purchase and order material for probes # 2 and 3</td>
</tr>
<tr>
<td>February, 1995</td>
<td>- test measurements on the second Q1 magnet at Saclay - testing probes # 2 and 3</td>
</tr>
<tr>
<td>May, 1995</td>
<td>shipping QMM setup to CEBAF</td>
</tr>
<tr>
<td>July – September, 1995</td>
<td>QMM Measurements at CEBAF</td>
</tr>
</tbody>
</table>

Table 3: Timeline for QMM Project

10 Responsibilities

H. Fonvieille : contactperson for the QMM project
P. Vernin : contactperson at Saclay (Physics Dept)
J. Le Bars : contactperson at Saclay (Technical Dept).
11 Figure captions

1. Figure 1: CEBAF High Resolution Spectrometers.
2. Figure 2: Q1 Quadrupole.
3. Figure 3: Q2 Quadrupole.
4. Figure 4: Layout of mechanical principles for QMM apparatus.
5. Figure 5: Schematic view of three rotating coils.
6. Figure 6: Schematic view of the sandwich plate assembly.
7. Figure 7: Transverse view of the probe.
8. Figure 8-a: HRS in its field map measurement configuration. Compared to fig. 1, note that the target, vacuum pipes, detector and (maybe) the detector hut are not yet installed.
9. Figure 8-b: The four QMM measuring sequences.
10. Figure 9: Q1 magnetic field components at radius $R = 150 \, \text{mm}$ versus $z$ for Q1.
4 GeV/c High Resolution Spectrometer

Figure 1.

Figure 2.

Figure 3.
QUADRUPOLE TERM
Azimuthal field component at fixed radius r=150mm

DODECAPOLE TERM
Azimuthal field component at fixed radius r=150mm

20 POLES TERM
Azimuthal field component at fixed radius r=150mm