High Current Measurements of a QB and QC Quadrupole

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1. Introduction

Measurements were conducted the QB and QC family of quadrupole magnets using QB103 and QC069, to
determine their performance characteristics at excitations up to 12 GeV. The goal was to obtain general
saturation effects, harmonics and temperature data at these excitations. The measurements took place
between January and April 2005, with some follow on temperature measurements in July 2005 to quantify
the cool down time of the magnet coils.

The QB quadrupole is a six inch long, laminated quadrupole with a 2.125 inch diameter bore. The QC is
identical, but is twice as long (12 inches). Each magnet was characterized in a similar manner. The results
of the magnetic measurements are described below.

2. QB and QC Temperature Measurements

In individual tests, each magnet was ramped from five amps to twenty amps in one amp increments,
dwelling at each current for 15 minutes and then recording the coil temperature. Temperatures were
recorded using two different IR temperature probes, a Raytek Raynger MX (belonging to MMF) and a
Raytek PM Plus (belonging Hall C). On each of the two magnets there was a maximum of a two degree C
temperature difference between the two probes at temperatures around 64 C. Each magnet was connected
to LCW for all measurements.

Figure 1. shows the coil surface temperature on the flat side of the coil at the curve where the coil wraps
around the outside of the pole using the Raytek Raynger MX. The profiles are very similar through 17
amps, but QC069 suffered some type of offset at 18 amps and 19 amps. This offset could possibly be
related to a reduction in LCW flow or an offset in the LCW supply temperature, but these parameters were
not recorded during the measurements.

Table 1. Shows some basic parameters of the quadrupoles and temperature information from the July
follow on measurements. The goal of the follow on measurements was to determine a cool down time on
the coils and to determine LCW flow. The cool down time is an important factor in how much time should
be allotted at the start of an accelerator down, or a controlled access, before workers can handle these
magnets without needing personal protective equipment associated with a burn hazard.

<table>
<thead>
<tr>
<th>Current (amps)</th>
<th>Coil Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 1. QB and QC Coil Surface Temps
Table 1. Quadrupole Parameters

<table>
<thead>
<tr>
<th>Mag. ID</th>
<th>Length (in.)</th>
<th>LCW Flow (gpm)</th>
<th>Max Temp @ 20 amps (°C) (+/- 2 °C)</th>
<th>Time for coil to cool to 45 °C (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB</td>
<td>6</td>
<td>0.21</td>
<td>64</td>
<td>7</td>
</tr>
<tr>
<td>QC</td>
<td>12</td>
<td>0.53</td>
<td>63</td>
<td>12</td>
</tr>
</tbody>
</table>

3. Hall Probe Measurements

Along with the temperature readings described in the preceding section, Hall probe readings were also taken at each current. Two Hall chips were attached to a pole on each of the magnets, one chip taped upstream and one chip taped on the same pole downstream. The function of the Hall chips was to provide another way to monitor saturation effects as the magnet was ramped up to twenty amps. The Hall probes showed saturation effects on QC069 that were slightly over 2% at twenty amps while QB103 showed saturation effects slightly over 2.5% at twenty amps. The slope of the saturation curve was calculated between five and seven amps.

4. Magnetic Measurement Setup

For the strength and harmonic measurements, the magnets were cycled through two hysteresis loops at a ramp rate of ~6.5 amps/sec using the Danfysik 896 power supply. An EPICS-like hysteresis and current setting protocol was used for the measurement, setting the first current of 20 amps and continuing around the loop in one amp increments through -20 amps and back to +20 amps. The FW7344 was used as the DAQ to control the Danfysik 896 power supply. The current was read back by a +/-75 amp voltage output module in an Ultrastab 866 current transducer. Figure 2 shows the QB strength measurement setup on P1C.

Figure 2. QB103 with Probe P1C.
5. QC and QB Integrated Gradient

QC Gradient Integral on P1A and P2B
The integrated strength measurement for QC069 conducted with measurement probe P1C, shows an integrated gradient difference from linearity of about 970 G or ~2.1%, +/-0.2% at 20 amps. These results were confirmed by conducting the same measurement using measurement probe P2B which showed a saturation of ~2%, +/-0.05%.

QB Gradient Integral on P1A and P2B
The integrated strength measurement for QB103 conducted with measurement probe P1C, shows an integrated gradient difference from linearity of about 785 G or ~2.7%, +/-0.05% at 20 amps. These results were also confirmed by conducting the same measurement using measurement probe P2B which showed a saturation of ~2.5%, +/-0.1%. Table 2 summarizes the saturation effects across the different measurement devices.

<table>
<thead>
<tr>
<th>Magnet ID</th>
<th>P1A (%)</th>
<th>P2B (%)</th>
<th>Hall Probe (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB</td>
<td>2.7</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>QC</td>
<td>2.1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2. Saturation Effects at 20 Amps

Figure 3 shows the gradient integral of QC069 and QB103 at the probe radius of 1.159 cm on probe P1C. Figure 4 shows the difference from linearity in Gauss for QC069 and QB103. Figure 5 and Figure 6, zoom in on the upper and lower limit of the QC069 B’L vs I curve respectively.

Zooming in on the extremes of the QB, B’L vs I curve show similar results as that of QC069 shown in Figure 5 and Figure 6.
Figure 4. QC069 and QB103 Difference from Linearity

Figure 5. QC069 B’L vs I, Upper Curve
6. QC and QB Harmonics Measurements on Measurement Probe P2A

Harmonics measurements were conducted on subject magnets, QC069 and QB103, using the 2.461 cm radius Halbach probe. Harmonics relative to the quadrupole term, $n = 2$, for QC069 and QB103 are shown in Figure 7 and Figure 8 respectively.

Figure 7. QC069 Harmonics on P2A

Figure 6. QC069 B’L vs I, Lower Curve.
7. Conclusions

The hall probe and rotating coil measurements agreed that the saturation effects on the QB magnet were about 2.5% and saturation effects for the QC magnet were about 2% at 20 amps.

It takes the QC magnet approximately 12 minutes to cool from its maximum operating temperature of 64°C (147°F) to a working temperature of 45°C (113°F), about twice as long as the QB magnet. The steel temperature in did not exceed a 4°C temperature rise in either magnet at 20 amps.

The QB and QC magnet did not exhibit magnetic or thermal characteristics that would prohibit the use of these magnets, in their current state, from operating at excitations up to 20 amps. However, some precautionary measures that should be considered when running the magnet at such high excitations would include, outfitting higher magnets with thermal interlocks to protect the magnet in the event of LCW failure. Avoid plumbing multiple higher excitation quadrupoles in series, which would incrementally increase the LCW supply temperature for each successive magnet in the string.