ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL022

PRECISION MAGNET MEASUREMENTS FOR DEUTERON BEAM TRANSPORT *

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Abstract

A versatile 4 MeV and 7 MeV deuteron beam transport line is being developed at Lawrence Livermore National Laboratory in support of an accelerator-driven source for fast neutron imaging. The beamline design requires precise alignment and high quality quadrupole magnets to transport a low emittance beam to the target through diagnostics, a bending dipole, and a differential pumping line with minimum beam loss and emittance growth. Vector magnetic field measurements of these magnets have been completed using a mobile version of an existing magnet mapping capability. This magnet mapping system is being used to ensure the delivered magnets meet the field uniformity specification, and that the mountings are aligned and capable of reaching the specified alignment tolerances. Details of the magnet measurement and calibration process that enable accurate field measurements to represent the intrinsic magnet field quality and not the systematic error of the measurement setup are presented.

INTRODUCTION

A magnet test capability was developed at Lawrence Livermore National Laboratory (LLNL) in order to align the mechanical and magnetic centerline of a set of quadrupole magnets for a Laser-Compton source project, as reported in [1]. The test setup successfully aligned the magnets to within the 100 μm alignment tolerance, and has since been repurposed into a mobile capability to test larger magnets. The deuteron beamline of the Neutron Imaging project at LLNL will use water-cooled 100 mm bore Stangenes-built quadrupole magnets for beam transport [2, 3]. Quality assurance has been undertaken at LLNL to insure the magnets are greater than 99.5% homogeneous over 75 mm. The magnetic field measurements reported in this paper represent the final acceptance testing that the magnets meet specification.

The original test setup was mounted on a laser table and used a Lakeshore 3-axis probe to measure air-cooled quadrupole magnet triplets that could be lifted onto the table. The magnets for the new deuteron beamline are 900 lb water-cooled magnets that could not be supported on the computer floor of the original location. A portable stand allows for in situ measurements including the quadrupole magnets and the ~ 5000 lb bend dipole. A roll around computer rack was modified to house the control computer, monitor and keyboard as well as the lakeshore 3-channel Gaussmeter, and magnet power supply as shown in Figure 1. The 3-axis stage was modified to run on an adjustable vertical support so that the entire cart can be rolled into place and adjusted for height.

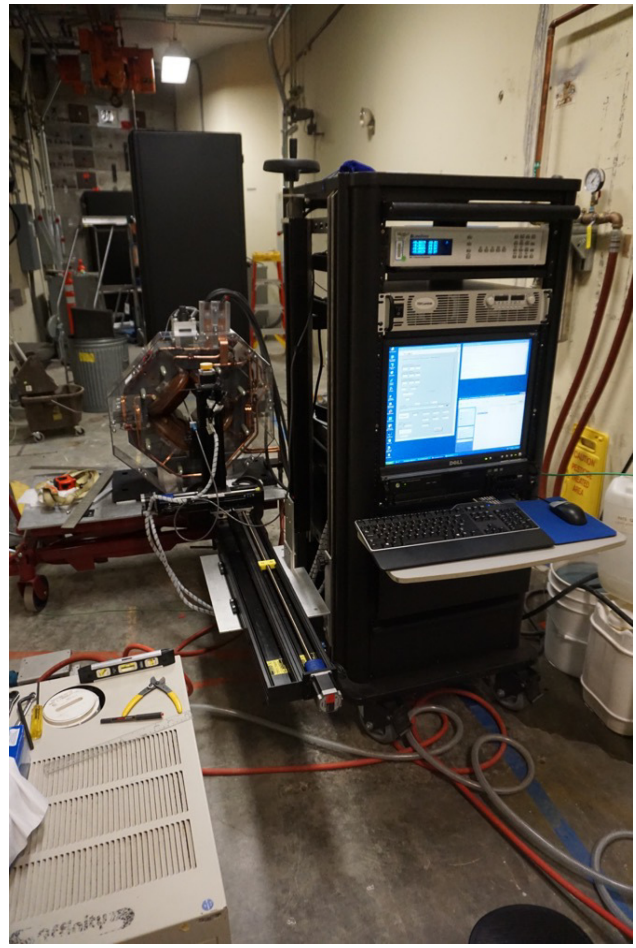

Figure 1: Magnet measurement arrangement: roll-around rack with computer, power supply, meter and probe translation stage.

MEASUREMENT PROCEDURE

To make measurements the stage is aligned with a square guide, clamped to the magnet support cart or pallet, and digitally leveled to ~0.1° to match the magnet under test. The 18 inch long probe is aligned to the magnet bore visually to within ~ 1 mm over the 300 mm typical range of the stage. The Lakeshore probe contains 3 orthogonal flux surfaces, and measures the x, y, and z components of the magnetic field (B_x, B_y, and B_z) at slightly different positions (which is corrected for in data analysis). The probe B_x and B_y surfaces

* This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344
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were found to be 0.3° off from perfect orthogonalality, which required independent B_x and B_y field measurements.

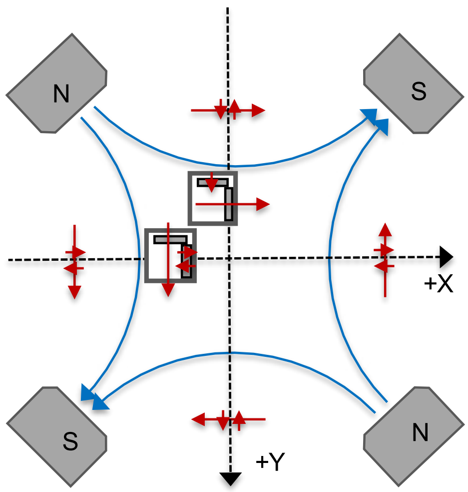

Figure 2: Schematic for probe zeroing procedure.

The following simplified procedure for zeroing the probe and making two independent 1D field measurements of $B_x(y)$ and $B_y(x)$ in order to verify field homogeneity was developed after many 2D and 3D field maps verified its sufficiency. A schematic for the coordinate system, field profile, and probe measurement surfaces is shown in Figure 2. The $B_y(x)$ measurement is described in detail and the same process is repeated for $B_x(y)$.

The coordinate axes are first zeroed to define the central region over which symmetric measurements are made. The $y = 0$ intercept is defined at a single point $x = -30\,mm$ such that the small B_x field measured by the finite extent probe averages to 0 G (probe in left position of Figure 2). This is repeated at $y = -30\,mm$to define the $x = 0$ intercept, and set a rough set of coordinate dimensions for the zeroing process. The probe is then moved to $x = +30\,mm$ and the small non-zero measurement of B_x is used to rotate the probe such that the field does average to zero over the probe surface. The field $B_x(y)$ is then measured over the full range in x from -30 mm to +30 mm until the $y = 0$ line is defined such that the field is zero to within 1 G (top of Figure 3). The B_x surface of the probe is now rotated and positioned precisely enough for accurate field measurements. The quadrupole field measurement of interest is actually $B_y(x)$, and so the probe is moved to $x = 0$ and a 1D scan is taken in y (probe in the top position of Figure 2, data in middle of Figure 3). A small field is measured slightly off position by the orthogonal probe, in this case $B_y(y)$ is not quite zero.

MEASUREMENT RESULTS

Results for a single quadrupole magnet are shown in Figure 3 for the measured zero field $B_x(x, y = 0)$, quadrupole field $B_x(x = 0, y)$, and residual field $B_y(x = 0, y)$. Zero field is measured to within 1 G over the full range in x of the probe to accurately orient the probe surface. The field of interest $B_x(x = 0, y)$ is measured and uniformity is confirmed to >99.5%. The residual field measured by the non-aligned surface $B_y(x = 0, y)$ serves as an indication of both the level of field error in the measurement and the rotation of the probe surfaces such that 0.3° of the non-zero B_x field is mixed into what should be a zero field B_y measurement.

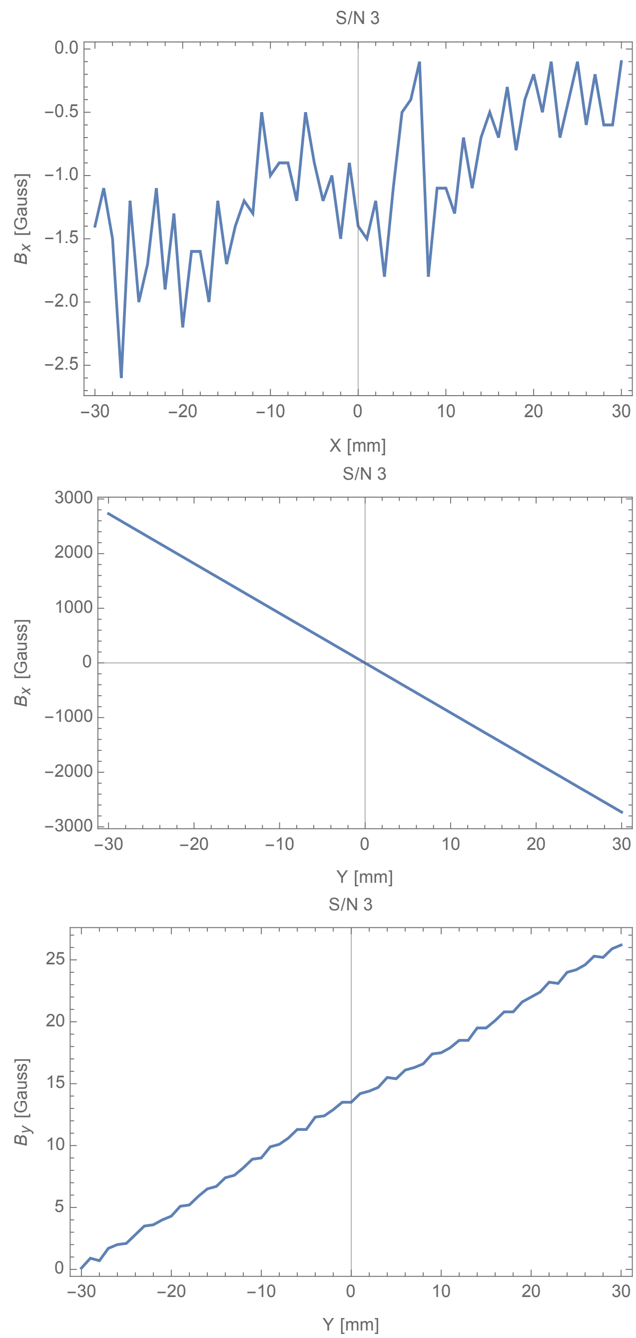

Figure 3: Quadrupole magnet field slice decomposition into multipole components: dipole term in red, quadrupole in blue, sextupole in green, octupole in purple.

This magnet, serial number 3, was measured to be 99.97% homogenous in both B_x and B_y.$B_y(x)$ and $B_x(y)$ scans were completed for each magnet along with residual field error for non-aligned probe surface. The homogeneity error is

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estimated at 0.03% and all quadrupole magnets met the 99.5% uniformity field specification. Effective length measurements and final alignment of the magnets with respect to the beamline are in process.

MULTIPOLE ANALYSIS

The multipole content of each quadrupole magnet gives a direct measurement on field errors, as well as alignment of the the physical or measuring axis to the magnetic axis. The vector magnetic field as a function of position, $B(z)$ at a given position, $z = x + \imath y$, can be written as [4]:

$$\begin{aligned} B(z) &= B_y(x, y) + \imath B_x(x, y) \\ &= \sum_{n=1}^{\infty} (B_n + \imath A_n)(z)^{n-1} \end{aligned} \tag{1}$$

For an ideal quadrupole magnet, an offset in measuring axis with respect to the magnetic axis manifests as a dipole term. For non-ideal quadrupole magnets, additional higher order terms are expected as well. The field data from magnet measurement using this technique provides a very large number of points for curve fitting, allowing slice-by-slice decomposition into dipole, quadrupole, sextupole, octupole, and higher order multipole components. The decomposition of field into components is shown in Figure 4 for each transverse scan as a function of longitudinal (z) distance. A clear hierarchy of terms is visible on the logarithmic scale.

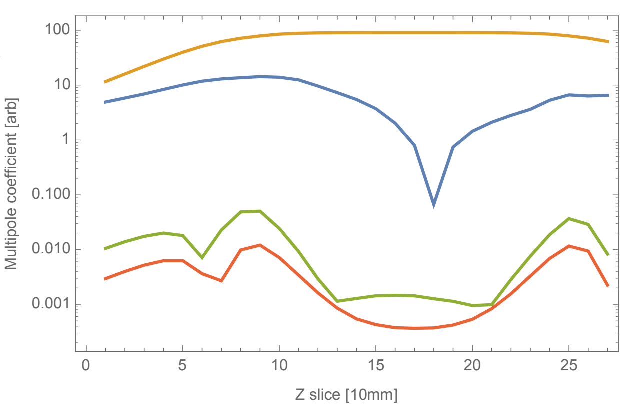

Figure 4: Quadrupole magnet field slice decomposition into multipole components: dipole term in blue, quadrupole in yellow, sextupole in green, octupole in red.

REFERENCES

[1] R.A. Marsh , S.G. Anderson, J.P. Armstrong, "Precision Magnet Measurements for X-band Accelerator Quadrupole Triplets", in *Proc. 3rd Int. Part. Accel. Conf. (IPAC 2012)*, New Orleans, LA, May 2012, paper THPD018, pp. 3536–3538.

[2] B. Rusnak *et al.*, "Advancement of an accelerator-driven high-brightness source for fast neutron imaging" in *Proc. 8th Int. Part. Accel. Conf. (IPAC 2018)*, Copenhagen, Denmark, May 2017, paper WEOBB3, pp. 2533?-2536.

[3] B. Rusnak *et al.*, "Development of a high-brightness source for fast neutron imaging" in *Proc. of 2016 N. Amer. Part. Accel. Conf. (NA-PAC 2016)*, Chicago, IL, October 2016, paper THB3IO01, pp. 1260–1264.

[4] "Handbook of Accelerator Physics and Engineering", edited by A.W. Chao and M. Tigner, World Scientific, Singapore, 2006.