



Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab

U.S. Particle Accelerator School
15 - 26 January 2018

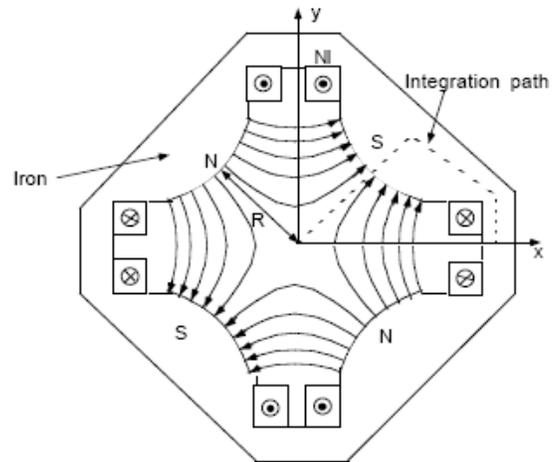
Syphers, Harms
Old Dominion University

Laboratory Session - Quadrupole Magnet

This session is divided into two parts: a hands-on measurement section where you will perform magnetic field measurements on a quadrupole magnet, and an *OPTIONAL* computer simulation one where you will use a software package to compare the field calculations with actual measurements.

1 Hands-on measurements

In this assignment you will measure the magnetic field in a quadrupole magnet. A power supply, multimeter, cables, Hall probe, and x-z-mover are supplied. You will connect these components together to allow you to measure the magnet current and voltage. Make sure you put the power supply in **current** control mode so the current does not change as the coils heat up (voltage knob turned up to maximum, then control current using the current knob). Use a maximum current of 8.5 Amps.



Pure quadrupole, NI turns/pole

1. There are four coils, which must be connected in a certain way to make a quadrupole field. Produce a diagram of the electrical wiring with power supply and multimeter to measure the current and coils. The mechanical dimensions of this magnet are supplied in a separate handout. You will need them for use in the *optional* POISSON magnet field calculations in Section 2. Pay particular attention to the polarity of each pole piece in your sketch.
2. With the quadrupole coils wired in series, measure the magnetic field at $x = 1.0$ cm, $B(x = 1.0$ cm, $y = 0$, $z = 0)$, as a function of current up to 8.5 amps. Using the slope of a linear fit to this data, derive the number of turns/coil.
3. Measure the magnetic field, $B(x, y = 0, z = 0)$, as a function of transverse position x at the maximum current used in (2).
 - a. Fit the transverse field data to the highest order that Excel (or your analysis application) will support in transverse position as

measured from the center of the magnet. Note: you should take more data points where the field gradient ($g = a_1$) starts to change so you get a good fit. Which fit coefficients dominate and why? To get a good fit you may want to only include field data where the gradient deviates by no more than 5 to 10% from the central gradient at $x = 0$ cm.

- b. Determine the 'good field' region from your fit in 3a where the gradient does not vary by more than $\pm 0.5\%$.
4. Measure the magnetic field, $B(x = 1.0 \text{ cm}, y = 0, z)$, as a function of axial position z for the maximum current used in part 2.
 - a. Determine the effective length of the quadrupole from the data. The effective length is calculated by an integral along the path taken by the beam's center of mass as it passes through the field and then normalized using the peak field value: $L = \frac{1}{B_{MAX}} \int_{-\infty}^{\infty} B dz$.
 - b. Compare the effective length calculated in part 4(a) with the sum of the physical length of the quadrupole and the radius from the center of the quadrupole to the pole tip. How close are these two measurements, 1%, 5%, etc?
 5. Do you have a horizontally focusing quadrupole for an electron beam? If not, how do you make it horizontally focusing?
 6. Calculate the focal length of this quadrupole for an excitation current of 5 A and an electron beam with energy of 30 MeV (for reference see *Syphers & Edwards* chapter 3).

2 **OPTIONAL** Magnetic Field Calculations for a Quadrupole Magnet Using *POISSON*

A PC computer program (*POISSON*) is available to simulate magnetic fields. The program is largely self-guiding, but we've included some tips at the end of the document in the section "Using *POISSON*."

Start with an input file for a magnet of the same type and modify profiles/coils as desired. A sample file already exists: open the " " folder on the desktop. The geometry of the quadrupole is given in a handout. You can verify the geometry by direct measurement, too.

1. Calculate the quadrupole magnetic field at a current equal to the one you used (or will use) in the hands-on section. (Quadrupole magnet measurements...read this assignment if you have not already done so). If you have not done the measurement yet, use a power supply current of 5A and 100 turns/coil. Print out the results and compare the vertical field $B_y(x)$ on the midplane with measurements. If you did quadrupole measurements already, compare the measured field gradient with the simulated one. Do you have any suggestion to explain the difference?

2. Run the program for different currents and determine the excitation curve and saturation, if any. For this, you increase the current for each run and note down only the resulting field ($B_y(x = 1.0 \text{ cm}, y = 0, z = 0)$) at $x = 1 \text{ cm}$. As you increase the current, note the magnetic fields at which the field lines are most dense. At what point does the gradient fail to follow the current linearly? Where in the magnet does the most severe saturation occur? Do you have any suggestion to improve the quadrupole magnet design if you had to build one?

3. Plot the excitation curve $B_y(x = 1, y = 0)$ vs. I_{coil} and compare with measurements in Section 1.

4. What are the higher harmonics up to 5th order from the POISSON output? How do these compare with coefficients to the fit to the transverse field data in part 3a in Section 1?

3 Using POISSON for Magnet Simulation

Thanks to Michael Borland of Argonne National Laboratory who provided these guidelines for a previous USPAS.

The PC computer program (POISSON) is available to simulate magnetic fields. The program is largely self-guiding, but we've included some tips in this section. POISSON is actually part of a suite of programs that includes programs for magnetic, electrostatic, and RF field calculations. The suite is maintained by the Los Alamos Accelerator Code Group and available (for Windows-based PCs only) from their web site.

The programs that you'll use in this part are

- AUTOMESH: the purpose of automesh is to take input giving the profiles of the iron, air, and coil regions of the problem, and generate a mesh that matches the problem. AUTOMESH uses an adaptive triangular mesh that is well-suited to magnets with curved boundaries.

- POISSON: this program performs the actual magnetic field computations, using data generated by AUTOMESH.
- WSFPLOT: this program plots problem geometry from AUTOMESH, along with field lines and arrows from POISSON.
- SF7: this program extracts data from the field map generated by POISSON and saves it in a form that can be easily plotted with TBLPLOT.
- TBLPLOT: this program makes line plots of data extracted from the POISSON output by SFO. It also allows saving the data in ASCII form, which can be imported into an EXCEL worksheet.

Here are step-by-step instructions for using these programs:

1. Find an input file for a magnet of the same type (e.g., dipole or quadrupole) that you want to simulate. You will find a selection of input files in subdirectories of c:\LANL\Examples\Magnetostatic. Do not modify the files here! Rather, copy them to your own area before you begin work. The files you start with are “Automesh Input” files, with file extension .AM. To be concrete, let's assume this file is called INPUT.AM.

Note: We have made some additional examples of our own, namely, HFull.am and EHQuadrupole.am. You may wish to start with these examples as they are simpler and closer to the problems you are doing. These are in the c:\LANL\Examples\USPAS 2012 directory.

2. Before setting up your own problem, you should run the input file without modification to get some experience. To start, simply double-click on the file to run AUTOMESH. A window will pop up that will show the status of AUTOMESH as it runs.

3. Once AUTOMESH completes (the window disappears), you'll find a new file called INPUT.T35. Double-click on this file to run WSFPLOT and show the magnet profile. You'll also see the mesh. When you are finished looking at this, close the window.

4. Right-click on INPUT.T35 and select “Run Poisson.” Again, a window will pop up showing the progress of the program. Watch the convergence numbers. They'll (generally) decrease monotonically until they are below 10^{-6} , at which point POISSON terminates.

5. Once POISSON completes, double-click on INPUT.T35 (which now contains the POISSON solution). WSFPLOT will again pop up a plot of the magnet profile, along with field contours and the mesh. You can turn on and off the various elements of the plot using the “View” menu. Moving the mouse around on the plot allows you to determine the field at any point in the magnet.

6. To see a text printout of the POISSON results, look for the file OUTPOI.TXT. To read it, right-click and select Edit. In the “old days,” this was all you’d get from POISSON. These days, you don’t need it for much except harmonic analysis. The harmonic analysis tables appear at the very end of the file.

7. To plot field data vs x or y, you need to extract data from the INPUT.T35 file another form. Start by right-clicking on INPUT.T35 and selecting “Interpolate.” A dialog box will pop up. Note the four entry boxes in the center. You can use these to enter the x and y coordinates of the start and end of a line along which you want the fields. Warning: the default values give a line extending from the lower-left and to the upper-right corner of the problem, which is not really very useful. Usually, you can get what you want by just setting both y coordinates to zero.

8. After completing this dialog, another file with a name like INPUT01.TBL will appear. Double-click on this file to run TBLPLOT, which will plot the selected data. You can use the “Select X and Y” submenu under the “Data” menu to change which data is plotted. You can also use the “Save Data” submenu of the “File” menu to write the data to an ASCII file; the name of this file is chosen automatically, and is typically something like INPUT0100.TXT.

Now that you are familiar with POISSON, you should copy INPUT.AM and modify it to reflect your problem. To do this, copy the file and right-click on the copy. Choose “Edit” to edit the file, then go through the steps above. Note that units for x and y are centimeters, while units for current are ampere-turns.

Some common problems using POISSON:

1. AUTOMESH doesn’t complete successfully. Usually this means that you have an error in your input. Occasionally, it means that your problem is too complex and AUTOMESH is having trouble. Check for things like:

- (a) Two points in a row with the same coordinates.
- (b) Mesh spacing (DX and DY) too large.
- (c) Region boundary not closed. The first and last points of a region should be identical.
- (d) Line regions (XREG1, YREG1, etc) that are close to but not exactly corresponding to a problem feature. Line regions (which determine where AUTOMESH changes the mesh spacing) should either coincide exactly with problem features (e.g., a line or corner) or else be in a location with no problem features.

2. POISSON runs for a long time and doesn’t converge. The magnet is probably very saturated. You may have entered an unreasonably high current.

3. The field doesn't agree with what's expected. Did you enter the source current instead of the total current in ampere-turns?

4. There is documentation available on the computer. To find it, go to LANL/Docs and double-click on SFCODES.DOC.

4 Acknowledgements

These lab sessions are built upon those of previous USPAS Fundamentals classes. The efforts of our predecessors: Helmut Wiedemann, Louis Emery, Nick Sereno, Weiming Guo, Hairong Shang, J. Sebek, R. Soliday, and Michael Borland are greatly appreciated.