Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab

U.S. Particle Accelerator School
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Laboratory Session - Dipole Magnet

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

Depending on the schedule you have been assigned, you will either do the hands-on (1) or computer simulations (2) first.

1   Hands-on measurements

A power supply, two digital multimeters, cables and a Hall probe are supplied. You will need to connect these components together to be able to measure the total magnet coil current and voltage using the multimeters. 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). The magnet has two different types of return plates and pole pieces you will use to do the measurements. This experiment requires mechanical assembly and disassembly.

Please be **VERY** careful when doing the assembly/disassembly so that you do not damage the coils or connections. They can easily be damaged and develop shorts across coil turns. Be careful not to over tighten the screws so the threads do not get stripped. You can use MS Excel or your favorite similar application to plot and fit the data as well as calculate the field integrals.

1) Make a sketch of the mechanical dimensions of the magnet including all pole pieces and return plates for use in POISSON magnet field calculations in Section 2.

2) Sketch your electrical setup including magnet, coils, multimeters and power supply. Make sure you connect the coils *in series* with the power supply/multimeter circuit

3) Assemble the dipole magnet with ***thick*** return plates and ***wide*** pole pieces.
   a. Measure the magnetic field in the center of the magnet, $B_y(x = 0, y = 0, z = 0)$, and voltage across the coils as a function of current - up to 0.5 amperes or so below the maximum current the supply can provide. Make measurements while both increasing and decreasing the current. Derive the power required at each current.

b. Plot the magnetic field in the center of the magnet,
$B_y(x = 0, y = 0, z = 0)$ vs. current and fit a line to the data. Does the magnet exhibit any hysteresis in this configuration?
Derive the number of turns per coil from the slope of the fit.

c. Plot the power required vs. magnetic field. What would the power be at each magnetic field point if the coils had twice the number of turns and half the copper cross sectional area? Assume the magnet is not saturated.

d. Measure the magnetic field distribution transversely across the gap i.e. $B_y(x, y = 0, z = 0)$ at no more than the current measured in part 3a. What is the range, in mm, across the entire aperture where the field is good i.e. varies by no more than 3%?

e. Fit the transverse field data to sixth order in transverse position as measured from the center of the magnet. Which fit coefficients dominate? Why? *Note: you should take more data points where the field starts to change so you get a good fit. You may also want to only include field data that deviates by no more than 5 to 10 % from the central field.*

f. Measure the magnetic field distribution axially (perpendicular to the pole face) from far outside the magnet to the center of the magnet, $B_y(x = 0, y = 0, z)$ at no more than the highest current used in part 3a. From this data, find the field integral for the magnet and the effective length for the magnet. *Note: you should take more data points where the field changes rapidly to accurately map out the field.*
Calculate the total deflection angle for a 30 MeV electron beam passing through this magnet. Make a sketch of the beam trajectory through the magnet showing entrance/exit angles etc. for your calculation.

4. Assemble the magnet with *thin* return plates and *wide* pole pieces.

a. Measure the magnetic field in the center of the magnet,
$B_y(x = 0, y = 0, z = 0)$, and voltage across the coils as a function of current - up to 0.5 amperes or so below the maximum current the supply can provide as in 3a. Plot and fit the data as in 3b. Any hysteresis? Why is this data different than the data measured in part 3b? Using the number of turns/coil derived in part 3b, derive a value for the part of the Ampere's Law contour integral outside the

gap as a function of current. Explain why this part of the contour integral becomes larger with current.

b. Measure the magnetic field distribution transversely across the gap (ie. $B_y(x, y = 0, z = 0)$) at the highest current measured in part 3(a). What is the range in mm where the field is good (ie. varies by no more than 3%)? Is this range larger or smaller than that in part 3(d)? Why?

(c) Measure the magnetic field distribution axially from far outside the magnet to the center of the magnet (ie. $B_y(x = 0, y = 0, z)$) at the highest current used in part 3(a). From this data, find the field integral for the complete magnet and the effective length for the magnet. Are the field integral and effective length larger or smaller that those found in part 3(f)? Why?

4. Assemble the magnet with **thick** return plates and **narrow** pole pieces.

a. Measure the magnetic field in the center of the magnet, $B_y(x = 0, y = 0, z = 0)$, and voltage across the coils as a function of current - up to 0.5 amperes or so below the maximum current the supply can provide as in 3a. Plot and fit the data as in 3b. Does the magnet exhibit any hysteresis in this configuration? Do you get the same slope as in part 3b? If so, why? If not, why not?

b. Measure the magnetic field distribution transversely across the gap i.e. $B_y(x, y = 0, z = 0)$ at no more than the current measured in part 3a. What is the range, in mm, where the field is good i.e. varies by no more than 3%? Is this range larger or smaller than that found in part 3d? What determines the good field range?

c. Fit the transverse field data to sixth order in transverse position as measured from the center of the magnet. Which fit coefficients dominate? Why? *Note: you should take more data points where the field starts to change so you get a good fit. You may also want to only include field data that deviates by no more than 5 to 10 % from the central field.*
Compare the fit coefficients derived in this part with those derived in part 3e.

2   Magnetic Field Calculations for a Dipole 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.

If you have not yet done so, go to the dipole measurement location and measure relevant geometrical dimensions of the dipole.

1. Calculate the dipole magnetic field at a coil current equal to one used (or will use) in the hands-on Laboratory Assignment (Dipole magnet measurements...read this assignment if you have not already done so).
A suggested current is above 5 Amperes, but less than the maximum output of the power supply. Do this for thin/wide, thick/narrow, thick/wide return flux plates and pole width combinations respectively.

2. Print out the results from part 1 and compare the central field, (B_y at x = y = z = 0 cm) field distributions (B_y vs. x) with measurement data from Section 1 above.

3. Use a thick and then the thin return yoke with the wide poles. Run the program in both cases for increasing currents (0 < I < 10 A) and determine the excitation curve and saturation. For this, you increase the current for each run and note only the resulting field in the center of the magnet, B_y(x = 0, y = 0, z = 0). As you increase the current, note the fields in the iron at the locations where the field contours are the most dense. These are regions where saturation will occur first. Saturation means the field no longer increases linearly with current. If saturation becomes too large, the program may not converge anymore. Where in the magnet does the most severe saturation occur? Why? Do you have any suggestion to improve the magnet design if you had to build it again?

4. Plot both excitation curves, B_y(x = 0, z = 0) vs I_{coil} on the same graph along with the measurement data from Section 1.

5. Can you figure out a way to model the longitudinal field distribution (B_y vs. z)? Hint: look at the magnet at 90 deg with respect to the beam axis and put the return yoke at, say 10×gap apertures to the left from the magnet.

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 a 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, lets 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 runWSFPLOT 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.