Fundamentals of Accelerator Physics and Technology
With Simulations and Measurements Lab

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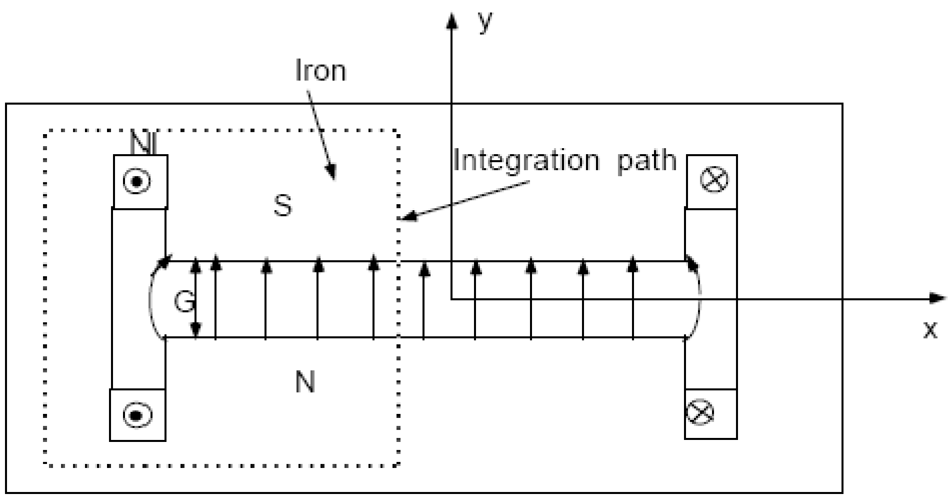
Laboratory Session - Dipole Magnet

This session is divided into two parts: (1) a hands-on measurement section where you will perform magnetic field measurements on a small dipole magnet and (2) 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 (1) hands-on or (2) computer simulations first.

CAUTION! This lab requires mechanical assembly/disassembly, please be careful so you do not damage the coils or connections leading to possibly dangerous shorts across the coil turns. Be careful not to over tighten the screws so the threads do not get stripped.



Pure dipole: NI turns/pole

1. Hands-on measurements

1.1. Assemble the dipole magnet with the **thick** return plates and **wide** pole pieces

1.2. Connect the power supply, two digital multi-meter, and magnet together to be able to measure the total magnet coil current and voltage. Make sure the power supply is in **current** control mode so the current does not change as the coils heat up (voltage knob turned up to maximum, then use current knob to adjust current). Make sure to connect coils ***in series*** with the power supply/multi-meter. Please have an instructor check your connections before powering up the magnet.

1.3. 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.

1.4. Sketch your electrical setup including magnet, coils, multi-meters and power supply.

1.4.1. 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 below the maximum current the supply can provide. Make the measurement with both increasing and decreasing current. Derive the power required at each current setting.

1.4.1.1. Plot the magnetic field in the center of the magnet 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.

1.4.1.2. 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.

1.4.2. Measure the magnetic field transversely across the gap, i.e., $B_y(x, y=0, z=0)$ at the highest current setting used in section 1.4.1. *Note: you might want to take more data points where the field starts to change.*

1.4.2.1. Plot the magnetic field vs position. What is the range, in mm, across the entire aperture where the field does not vary more than 3%?

1.4.2.2. Fit the transverse field data to the sixth order in transverse position as measure from the center of the magnet. Which fit coefficients dominate? Why? *Note: you may want to include field data that deviates by no more than 5-10% from the central field.*

1.4.3. Measure the magnetic field axially from far outside the magnet to the center of the magnet, i.e., $B_y(x=0, y=0, z)$ at the highest current setting used in section 1.4.1. *Note: you should take more data points where the field changes rapidly to accurately map out the field.*

1.4.3.1. Plot the magnetic field vs position. Determine the field integral for the magnet and the effective length for the magnet. 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: $L = \frac{1}{B_{MAX}} \int_{-\infty}^{\infty} B dz$

1.4.3.2. 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.

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

1.5.1. 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 below the maximum current the supply can provide. Make the measurement with both increasing and decreasing current.

1.5.1.1. Plot the magnetic field in the center of the magnet vs current and fit a line to the data. Does the magnet exhibit any hysteresis in this configuration? Why is this data different than the data measured with in part 1.4.1.1? Using the number of turns/coil determined above, derive a value for the part of Ampere's Law contour integral outside the gap as a function of current. Why does this part of the contour integral become larger with current?

1.5.2. Measure the magnetic field transversely across the gap, i.e., $B_y(x, y=0, z=0)$ at the highest current setting used in section 1.4.1. *Note: you might want to take more data points where the field starts to change.*

1.5.2.1. Plot the magnetic field vs position. What is the range, in mm, across the entire aperture where the field does not vary more than 3%? Is this range larger or smaller than previous measurement, 1.4.2.1? Why?

1.5.3. Measure the magnetic field axially from far outside the magnet to the center of the magnet, i.e., $B_y(x=0, y=0, z)$ at the highest current setting used in section 1.4.1. *Note: you should take more data points where the field changes rapidly to accurately map out the field.*

1.5.3.1. Plot the magnetic field vs position. Determine the field integral for the magnet and the effective length for the magnet. Are the field integral and effective length larger or smaller than those found in part 1.4.3.1.

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

1.6.1. 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 below the maximum current the supply can provide. Make the measurement with both increasing and decreasing current.

1.6.1.1. Plot the magnetic field in the center of the magnet vs current and fit a line to the data. Does the magnet exhibit any hysteresis in this configuration? Do you get the same slope as section 1.4.1.1? Why or why not?

1.6.2. Measure the magnetic field transversely across the gap, i.e., B_y(x, y=0, z=0) at the highest current setting used in section 1.4.1. *Note: you might want to take more data points where the field starts to change.*

1.6.2.1. Plot the magnetic field vs position. What is the range, in mm, across the entire aperture where the field does not vary more than 3%? Is this range larger or smaller than previous measurement, 1.4.2.1? What determines the good field range?

1.6.2.2. Fit the transverse field data to the sixth order in transverse position as measure from the center of the magnet. Which fit coefficients dominate? Why? Compare to coefficients from section 1.4.2.2. *Note: you may want to include field data that deviates by no more than 5-10% from the central field.*

2. Magnetic Field Calculations for a Dipole Magnet Using POISSON

POISSON is a computer program used to simulate magnetic fields. Please reference "Using POISSON" at the end of this document for help.

2.1. Start with an input file for a magnet of the same type and modify the geometry as desired.

2.1.1. If you have not completed the hands-on portion of this lab, go to see the lab group with that assignment and measure the relevant dimensions, including pole pieces and return plates.

2.1.2. Calculate the dipole magnetic field at a coil current of 0.5 Amperes less than the maximum supply output. Do this for the thin/wide, thick/narrow, and thick/wide return flux plates and pole width combinations, respectively.

2.1.2.1. Print out the results and compare with the central field and transverse field B_y(x, y=0, z=0) distributions from measurement data.

2.1.3. For the thick/wide and thin/wide return/pole pieces, measure the central field as a function of increasing current ($0<I<10$ Amperes). Plot the field vs current. Determine the saturation-where the field no longer increases linearly with current. As you increase the current, note the field in the iron where the field contours are most dense. These are the regions where saturation will occur first. If the saturation becomes too large the program might not converge anymore. Where in the magnet does the most severe saturation occur? Why? Do you have any suggestions to improve the magnet design?

2.1.4. Can you figure out a way to model the longitudinal field distribution, B_y(x=0, y=0, z) ? Hint: look at the magnet at 90 degrees with respect to the beam axis and put the return yoke at about 10x 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.