

MAGNETIC FIELD PROFILE OF A SHORT SOLENOID

INTRODUCTION:

Solenoid focusing is especially effective for low energy beams, and as such is not as well known as strong (magnetic quadrupole) focusing. Solenoid focusing finds applications in, for example, emittance compensation schemes in RF photocathodes, compact lattice designs for the front end of linacs (e.g. the superconducting solenoids for the planned project X at Fermilab), production of flat beams (in combination with skew quadrupoles), and in the UMER matching section.

Characterization of the magnetic field of solenoids is clearly paramount for lattice design calculations. In this experiment, we study in detail the axial profile of a short solenoid for calculations of effective length and focal length. Furthermore, we investigate magnetic hysteresis and solenoid degaussing.

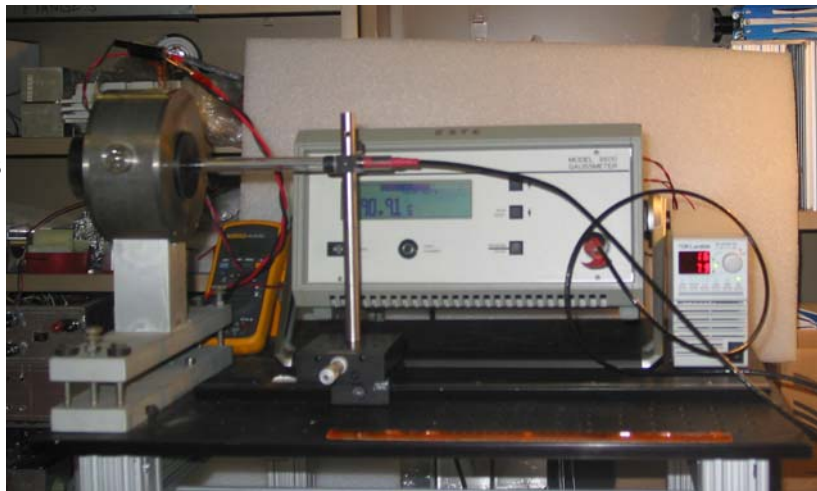
BACKGROUND:

Section 3.4.4 (p. 88-92) in M. Reiser's *Theory and Design of Charged Particle Beams*. Also, UMER Technical Notes UMER-010500-SB-*Matching Section Solenoid*, UMER-060306-SB-*New Hard-Edge Model for UMER Solenoid*, and note on Hall effect.

EQUIPMENT:

Short solenoid, 9500 Bell gaussmeter, axial Hall probe, DC power supply, Variac transformer, digital multimeter, Fluke AC meter, and optical stage. The solenoid is not identical to the one used in either UMER or the Hughes Gun setup, but it's close enough so your calculations will be relevant to experiments in UMER or the Hughes Gun setup.

Figure 1:
Setup for magnetic field profile measurements of short solenoid.



PROCEDURE:

1. Familiarize with equipment: gaussmeter, power supply, probe translation stage, etc.
2. Zero the probe using the built-in mu-metal chamber.
3. Align probe with solenoid mechanical axis. Try, for example, moving the probe horizontally and vertically so the tip is centered as it enters and exits the solenoid.
4. Adjust the gaussmeter to the most sensitive scale (30 gauss) and measure the longitudinal field at the solenoid middle plane, or near it, without applying any current to the solenoid. Repeat at points relatively far from the solenoid (say 15 cm).
5. Solenoid degaussing: The differences in your readings in the previous step may indicate that the solenoid is magnetized. Proceed as follows to degauss the solenoid: connect the Variac to the solenoid; slowly turn up the dial until you measure 8 A rms, approximately, with the AC Fluke meter or the built-in meter. Reduce the current to zero and repeat the measurements in step 4. Record your results and disconnect the Variac. You need to consider the earth's field to interpret the results.
6. Axial Field vs. DC Current: place the Hall probe near the middle plane of the solenoid and apply 0.5 A with the DC power supply. Move back and forth the Hall probe to find the location where you read the maximum field. Record the reading (in cm). Reduce the DC current to zero and record the axial field. Continue measuring the solenoid axial field at DC currents of 0.5, 1.0, 1.5,...8.0 A (do not exceed 8.0 A). Adjust the scale on the gaussmeter as needed. Repeat your measurement backwards, i.e. by reducing the current in steps of 0.5 A.
7. Axial Field Profile: check to see if the solenoid is magnetized and degauss it if needed. Place the Hall probe at the axial location where you found the maximum reading. Set the DC current to 8.0 A Measure the axial field every 0.5 cm starting at the middle plane, until you have moved the probe some 12.0 cm on either side.

ANALYSIS / QUESTIONS:

1. Tabulate your results and include measurement errors.
2. What is magnetic hysteresis? (Review your understanding of the B and H vectors used to describe magnetism). Explain the degaussing procedure in step 5. A diagram will help.
3. Plot the maximum solenoid axial field vs. solenoid current and do a least-squares linear fit. Comment on your results.
4. Plot the solenoid axial field per Amp vs. axial distance from the middle plane of the solenoid. Do a least-squares fit to the following function developed by Rami Kishek:

$$B_z(r=0, z) = B_0 \exp(-z^2/d^2) [\operatorname{sech}(z/b) + C_0 \sinh^2(z/b)],$$

where B_0 is the on-axis field on the middle plane of the solenoid, and d , b and C_0 are fit coefficients.

5. Find the effective length of the solenoid as defined in Prof. Reiser's book, p. 89 (2nd ed.). The effective length found this way is not quite right in our case, but still useful. We're not going to ask you to do the right calculation (a lot of work!), as described in UMER-060306-SB [it appears also in S. Bernal *et al*, PRST-AB, **9**, 064202 (2006)]. Instead, just comment on what is the basic idea behind the right calculation of effective length (hint: what do we mean by a "short" solenoid?).
6. Draw a schematic diagram showing the magnetic field lines of a solenoid lens and explain how solenoid focusing occurs.
7. Qualitatively, how would you expect the axial field profile of the solenoid to change without the low-carbon steel enclosure?
8. What is the focal length of the solenoid for a 10 keV electron beam if the solenoid is powered with 5.5 A?