MEASUREMENT OF SMALL RADIUS GRADIENT MAGNETS USING ION BEAMS

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Abstract

Several small and precise 90°, 20-inch-radius bending and focusing magnet systems will be needed for the transport line of the Fermilab Electron Cooling Project to transport 4.36 MeV electrons. Originally, it was anticipated that these magnets would have a gradient index of -1/2. To measure these magnets and complete achromatic bend modules, a well defined beam transport system was developed to determine the transfer matrix knowing the position and angle of several input and output beam rays passing through the magnet. The beam for this was a 12.5 keV proton beam that has the same magnetic rigidity as the electron beam in the final setup. The magnetic field is approximately 300 Gauss. For this purpose a high-brightness proton source was used and the beam collimated to give a low emittance (~10^{-8} m rad) pencil beam of ~1 mm diameter with a current of ~100 nA. Details of the system and results of measuring a magnet will be presented.

1 INTRODUCTION

The Fermilab Electron Cooling Project [1] requires several small-radius, large-angle and low-field bending magnets, some having an internal gradient, to transport an electron beam from an electrostatic accelerator (Pelletron) to an interaction region, for cooling an antiproton beam, and then returning the electrons to the accelerator for energy recovery. The antiprotons are at 8 GeV, so to match their velocity the electrons must have an energy of 4.357 MeV. Practical magnets, with a bend radius of 50 cm, to handle such an electron beam will have a field of ~300 Gauss. Because of the low emittance and precision necessary for the electron beam, it is important to measure and understand these magnets. Small-radius, large-angle bending magnets, especially those having an internal gradient, are difficult to measure using standard probe techniques. It was therefore decided to measure the magnets using an ion beam.

The basic principal for this measurement is to pass a thin beamlet, representing a ray of the total beam, through the magnet. Properties of the magnetic field can then be determined knowing the entrance and exit trajectory of several such beamlets. Several factors are significant to this measurement. First, assuming the ion beam is a proton (or H^-) beam, the beam energy must be 12.49 keV to have the same magnetic rigidity as the 4.357 MeV electron beam. At this energy the ion beam will pass through the magnet with the same trajectory as the electrons for the same field. Second, the angular precision of the electron paths passing through the cooling section must be ~2 x 10^{-5} radian. This places a desirable similar limit on the detection of the beamlets entering and leaving the magnet.

2 SYSTEM

Paramount to this measurement is the ability to define and detect a beamlet to the desired precision. It was chosen to collimate the beam through two 1 mm apertures separated by ~3 m (120 in), Fig. 1. This is already stringent but only allows defining the beamlet to ~6x10^{-4} rad unless the centroid can be well determined. These two collimators are mounted on X-Y positioners with 1 mil settability.

Typical reproducibility of these settings to the beamlet

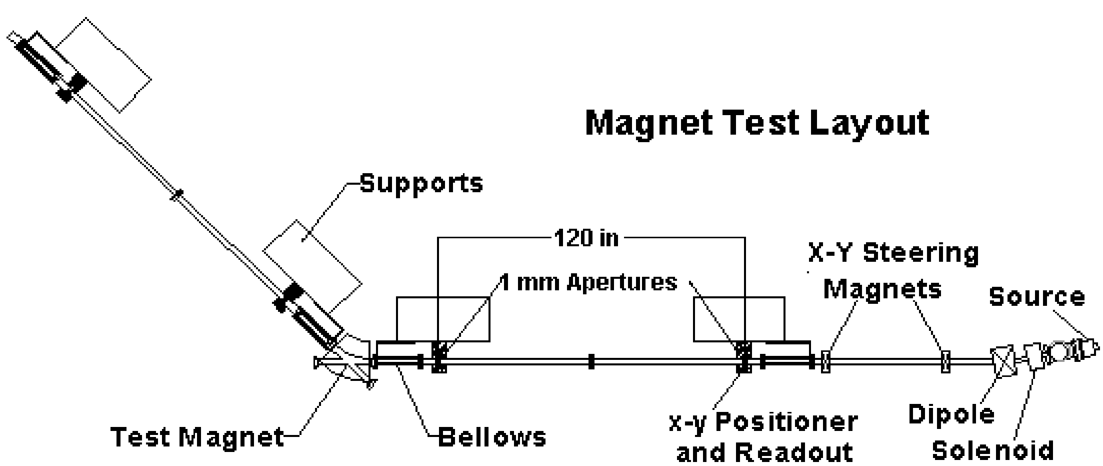

Figure 1. General view of the Magnet Test Layout.

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is ~10 mils improving the angular precision to ~2 x 10^{-4} rad. The other arm, detecting the exit beamlet, is identical to the entrance arm. This implies a beamlet 1 mm diameter and ~10 m long to pass through the entire measuring system. Geometrical requirements require the emittance to be below 10^{-7} m rad, while space-charge considerations show that the current density needs to be less than 10 μA/cm^2 or 10-100 nA.

2.1 Ion Beam

A Duoplasamatron ion source is used to produce the proton ion beam. The beam is extracted directly from the 30 mil anode aperture with a single conical extraction electrode. This produces a sufficiently bright beam that after focusing with a solenoid and collimation by the first aperture a beam of 10 to 100 nanoamperes current, 1 mm diameter and an emittance of ~10^{-8} m rad is obtained.

For a short time, a H^- ion source (semiplanotron [2]) was used to provide an H^- beam. A 10^o dipole magnet was used to separate ion species and provide a clean H^- beam. With H^- the test magnet polarity remains the same as for electrons. This would be useful in setting up a complete electron transport line.

2.2 Setup

In use, the two apertures on the entrance arm are adjusted in X and Y position for the desired position and angle of the beamlet entering the test magnet. A few microampere near-parallel beam, about 1 cm diameter, is imaged on the first aperture with maximum intensity, ~100 nA, passing through the aperture. Two X-Y steering magnets are used to adjust the position and angle so the formed beamlet centers on and passes through the second aperture. Each aperture plate includes position-sensing plates in front of the 1 mm aperture to assist in centering the beamlet (Fig. 2). In addition, a similar aperture is located midway between the end apertures. The three apertures are optically adjusted to be in a straight line. This gives some assurance that the beamlet goes in a straight path through the apertures and is well shielded and unaffected from stray magnetic fields so the position and angle leaving the arm is properly known.

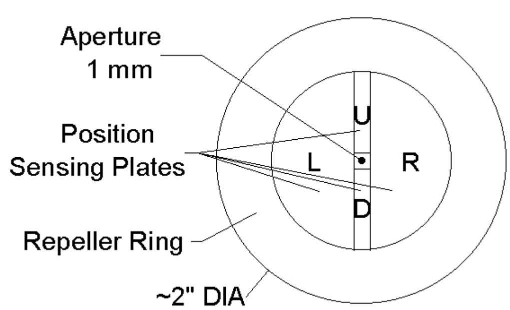


Figure 2. Aperture Detector.

The exit arm is then adjusted using the X–Y positioners to center the apertures on the beamlet and obtain maximum transmission through the last aperture. Typically a few to 10 nA passes through this aperture and is observed on a simple collector plate behind the last aperture with a high gain amplifier. The values of readouts (dial gauges) on the X-Y positioners give the position and angle of the beamlet leaving the magnet.

3 MEASUREMENT

A measurement of a magnet is carried out by moving the apertures of the entrance arm to provide beamlets entering the magnet at different positions and angles that simulate rays of a possible beam. For each beamlet the exit position and angle is determined by the exit arm. The data can then be assembled into a description of the integrated field through the magnet and the error from the central path. Only the integral field can be measured and different parts, such as, body field or end fields cannot be separately determined. The most successful interpretation has been to tabulate relative position errors into field errors at the magnet and to plot this error relative to the beamlet entering the magnet. This then gives a plot, which for a truly homogeneous or a perfect gradient magnet is a line with a slope of the first order focusing strength for the measured plane. Deviation from a line indicates higher order errors.

So far there has been no attempt to make enough measurements to allow an unconstrained fit of desired accuracy for a complete first order transfer matrix, much less for a second order matrix. Fits constrained by symplecticity reproduce the results even more poorly. Not only are numerous repeats required for statistical precision, but obtaining input rays that represent pure sine-like or cosine-like trajectories is tedious even for the first order matrix. Producing the pure principal trajectories for second order is not practical. Therefore, for the present and probably for the future as well, a few important numbers characterizing the field integral are calculated according to more graphic techniques.

3.1 Measurement of a Magnet

A typical magnet has a bend radius of 20 inches at a field of 328 Gauss and deflects the beam through 45^o. Both homogeneous and gradient magnets have been measured. Table 1 shows several beamlet input and output positions for a beamlet moved across the horizontal midplane. The output positions have been normalized to zero for the central ray. Table 2 gives the field errors at the magnet responsible for the measured position error. From here the input positions can be plotted against the field error, as in Graph 1, to give a graphical representation of the data. The points and solid lines are the measured fields. The dashed line is the normal focusing due to the sector shape of a homogeneous magnet. For this magnet the focusing is ~9% less than desired, probably due to end effects which can be significant in such a short magnet with a 2 inch gap. Graph 2 shows the difference between the desired and measured field errors. A sextupole is evident and corresponds to a second order coefficient of 1.3 G/in^2 or a beta ($\beta = R_o\, d^2B/2B_o\, dR^2$) of 1.6. Graph 3 shows similar data but taken moving the input beamlet vertically from the central orbit. In this case the sextupole is even more apparent since the dipole does not change. Again this is fitted with B = $1.3y^2$ or $\beta = 1.6$.

4 SUMMARY

A field measuring method based on passing an ion beam through the low field, small radius magnet has been demonstrated. The system here is useful for the purpose - to check a few magnets as they are prototyped and made.

There are some changes that could be taken to improve the results significantly: 1. A third center aperture was used to minimize the possibility of external fields affecting the measurement. Even with this aperture magnetic shielding had to be placed around the arms. Had the arms been made using high-μ magnetic shielding material the need for the center aperture would not be necessary. This would remove the need for aperture alignment, preserve a more symmetrical beamlet, and make adjustment of the output apertures easier. 2. The present system is manually operated. Having computer read readouts, computer settable positioners on the input arm, and possibly computer sensing and adjusting positioners on the output arm would be a significant advantage to taking better data. With these improvements, more data could be taken with better accuracy giving the possibility of better characterization of the magnet.

References

[1] S. Nagaitsev, et al. "FNAL R&D in Medium Energy Electron Cooling," Nuci. Instr. and Meth. A 441 (2000) 241-245.

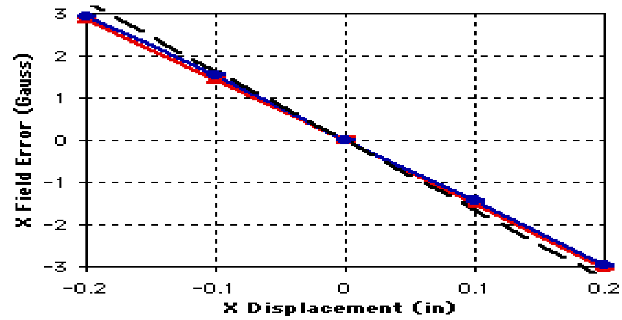
[2] Vadim Dudnikov, et al. "High Current Density Negative Ion Source for Beam Line Transport Studies," this conference.

Input Beam Position				Output Beam Position (inches)			
1X	1Y	2X	2Y	3X	3Y	4X	4Y
0.2	0.0	0.2	0.0	-0.053	0.000	-0.903	0.026
0.1	0.0	0.1	0.0	-0.025	0.003	-0.434	0.022
0.0	0.0	0.0	0.0	0.000	0.000	0.000	0.000
-0.1	0.0	-0.1	0.0	0.019	-0.002	0.477	0.000
-0.2	0.0	-0.2	0.0	0.038	-0.006	0.888	-0.014

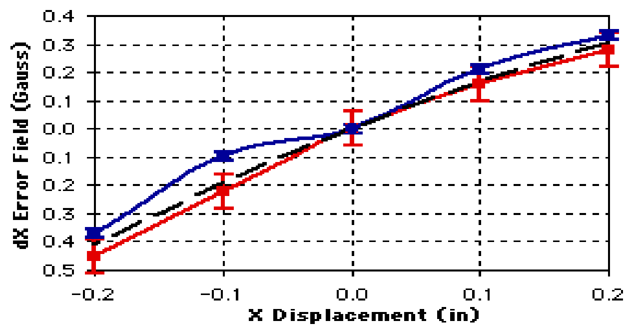
Table 1. Aperture positions for input and output beamlets.

Input Position	Output Bx3	Output Bx4	Design Field
0.2	-3.022	-2.970	-3.30
0.1	-1.491	-1.439	-1.65
0	0.000	0.000	0.00
-0.1	1.427	1.552	1.65
-0.2	2.850	2.928	3.30

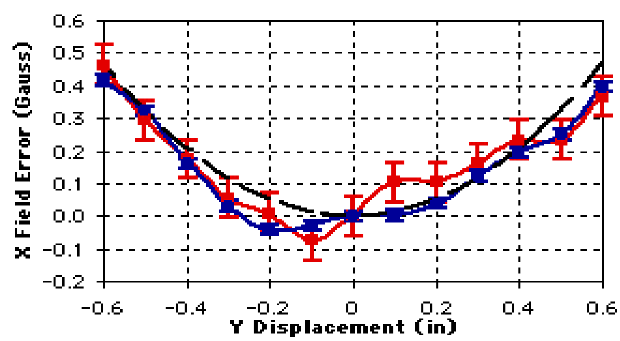
Table 2. Output beamlet positions converted to Field Errors (Gauss) through the magnet.



Graph 1. Field versus input ray position for a homogeneous sector dipole magnet. Dashed line is the expected value.



Graph 2. Difference between the desired and measured field showing a sextupole component and possible higher order errors.



Graph 3. Horizontal field component for vertical displacement of the input ray. A sextupole component (dashed line) is very evident.