U.S. Particle Accelerator School 2008, U. of Maryland, College Park

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ROTATING COIL MAGNETOMETER

INTRODUCTION:

Detailed characterization of magnets is a key component for the design and development of any accelerator. A widely used instrument for magnet measurement is the rotating coil. It consists of a rectangular coil that spins with one side aligned along the axis of the magnet. The voltage induced in the coil is Fourier-analized to obtain the multipole content of the magnet. In this experiment, we will use a simplified version of the apparatus described in the PRST-AB paper mentioned below. Our coil is much shorter than the one used for the measurements in the paper. Besides, the setup for the short coil does not have a synchronous signal. With these limitations, the magnetic field of the UMER magnets will be scanned only around the magnet's center, and no phase information from the output signal of the coil will be obtained. However, it will be possible to observe the main features of a full-fledged rotating coil and learn about the UMER magnets.

The *B*-field inside a magnet with circular cross section of radius r_0 can be written as

$$B_r(r,\theta) = \sum_{n=1} \left(\frac{r}{r_0}\right)^{n-1} \left[b_n Sin(n\theta) + a_n Cos(n\theta)\right], \qquad r < r_0 \quad (1a)$$

$$B_\theta(r,\theta) = \sum_{n=1} \left(\frac{r}{r_0}\right)^{n-1} \left[b_n Cos(n\theta) - a_n Sin(n\theta)\right], \qquad r < r_0 \quad (1b)$$

Where B_r, B_θ are the radial and azimuthal components of the field (see Figure 1 below), and b_n, a_n are the <u>*normal and skew components*</u> of the field. The expansion above characterizes a 2-dimensional field, valid only at or near the middle plane of the magnet, perpendicular to the magnet axis (Fig. 1). However, the same expansion is applicable if B_r, B_θ are understood as <u>axially (i.e. along "*z*") integrated quantities</u>.

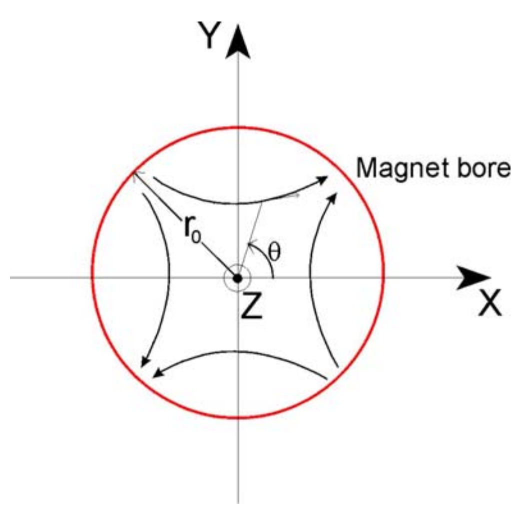


Figure 1: cylindrical coordinate system for magnet B-field description.

From symmetry considerations, it can be shown that a quadrupole magnet can only have the $2n$-poles given by $n = 4k+2$ (k=0, 1, 2, …), i.e., n=2 (quadrupole), n=6 (duodecapole), etc. By contrast, a dipole magnet can have $2n$-poles given by $n = 2k+1$ (k=0, 1, 2, …), i.e., n=1 (dipole), n=3 (sextupole), etc.

BACKGROUND:

W. W. Zhang, S. Bernal, H. li, *et al*, "Design and field measurements of printed-circuit quadrupoles and dipoles", Phys. Rev. ST Accel. Beams, **3,** 122401 (2000), Rawson-Lush Instruments, Bulletin 780: Rotating Coil Gaussmeters (not dated, attached to this document).

EQUIPMENT:

Rawson-Lush rotating coil gaussmeter model 780, quadrupole and dipole printed-circuit magnets, DC power supply, and oscilloscope.

Figure 2: Rawson-Lush rotating coil and setup with UMER quadrupole magnet.

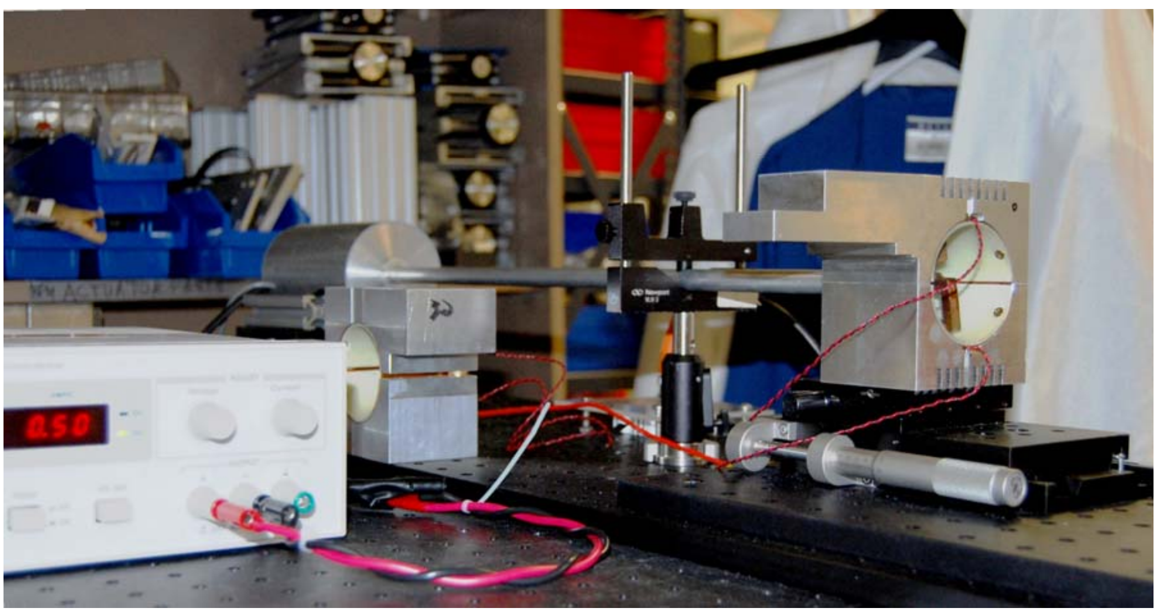
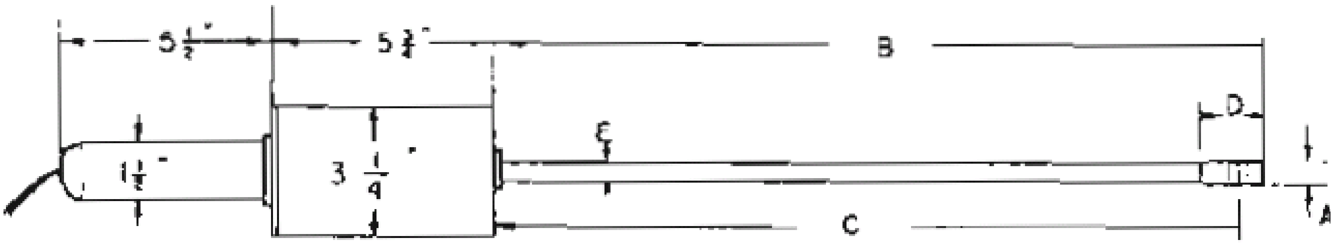


Figure 3: Rawson-Lush Model 780 rotating coil magnetometer (see also attached document).



Tip Diameter. **A**: 6.35 mm
Probe Length **B**: 50.0 cm
Length to coil center **C**: 48.9 cm
Tube Diameter **E**: 6.35 mm
Number of Turns:

PROCEDURE:

1. Familiarize with equipment: rotating coil, power supply, magnet translation stage, etc. Be especially careful with the coil at the tip of the magnetometer: *make sure the coil is free to turn before turning the motor on*. Read the Rawson-Lush bulletin and learn as much as possible about the model 780 rotating coil gaussmeter.
2. Align and level the coil axis so it is centered as best as possible inside the quadrupole (or dipole) magnet. Also make sure that *vibrations of the long rod are reduced as much as possible* by properly adjusting the rod support. Get assistance as needed.
3. Apply 1.0 A to the magnet and connect the BNC cable from the rotating coil to the scope.
4. *Scope settings (Tektronix…)*
   Coupling: 50Ω. Trigger: edge. Horizontal scale: 50 ms/div, sampling rate: 2kS/s, bandwidth: smallest. Horizontal acquisition: average, 8-16 frames.
   FFT (Math setup): Magnitude, linear. Window: rectangular. Gate position: -150 ms, Gate duration: 500 ms. Center frequency: 80 Hz, frequency span: 160 Hz. Obtaining a steady rotating coil signal is not easy because no external trigger is available, i.e. the signal is triggered to itself. However, the main FFT peaks and relevant harmonics should be easy to discern.
5. Carefully observe and record the frequency corresponding to the first peak of the frequency spectrum. It should be slightly less than 30 Hz. Turn down the quadrupole current to zero. Do you still see the first peak?
6. Record the frequency of the large peak. Turn up the magnet current to 2.5A. Many additional peaks may appear that reflect the residual vibration of the coil instead of additional magnet multipole content. However, a larger than usual peak may appear at some frequency that is a small

multiple of the main peak frequency. Record the frequency of such component *if* observed.

7. For currents of 0.5, 1.0, .., 2.5 A applied to the quadrupole measure the amplitude of the rotating coil output
8. Repeat your measurement of the main frequency component with the dipole magnet. Also repeat step 7 with the dipole magnet (time permitting).

ANALYSIS / QUESTIONS (don't have to answer *both* 2 and 3, choose one)**:**

1. Tabulate your results and include measurement errors.
2. Show that the multipole expansion in Eqs. 1a-b is equivalent to

$$B(x,y) = B_y + iB_x = \sum_{n=1} \left(b_n + ia_n\right)\left(\frac{x+iy}{r_0}\right)^{n-1},$$

$$r = \sqrt{x^2+y^2} < r_0,$$

   where complex notation is used.
3. (a) Use symmetry arguments to show that the allowed multipoles in a dipole magnet are of the form *n=2k+1, k=0,1,...*(b) Show that the spectrum is *n=4k+2, k=0,1,…*for a quadrupole magnet. (Hints: an 180^0 rotation of a dipole is equivalent to inverting its polarity; a 90^0 rotation of a quadrupole is equivalent to inverting its polarity. Complex notation will help.)
4. In the experiment, did you observe a frequency component corresponding to a sextupole of the dipole magnet? Any higher multipoles, including "forbidden" ones? Comment also on the spectrum observed for the quadrupole.
5. Plot the voltage peak amplitude for both dipole and quadrupole magnets as a function of applied current. Discuss your results.
6. (Bonus) From the coil dimensions, number of turns, rotation frequency, magnet aperture radius, and applied current, derive a formula for the expected voltage peak amplitude resulting from the rotating coil inside a UMER quadrupole. (Essentially, derive Eq. 7 in the PRST-AB paper mentioned in the references. Since the coil in the paper is long, you have to introduce some correcting factor in our case).

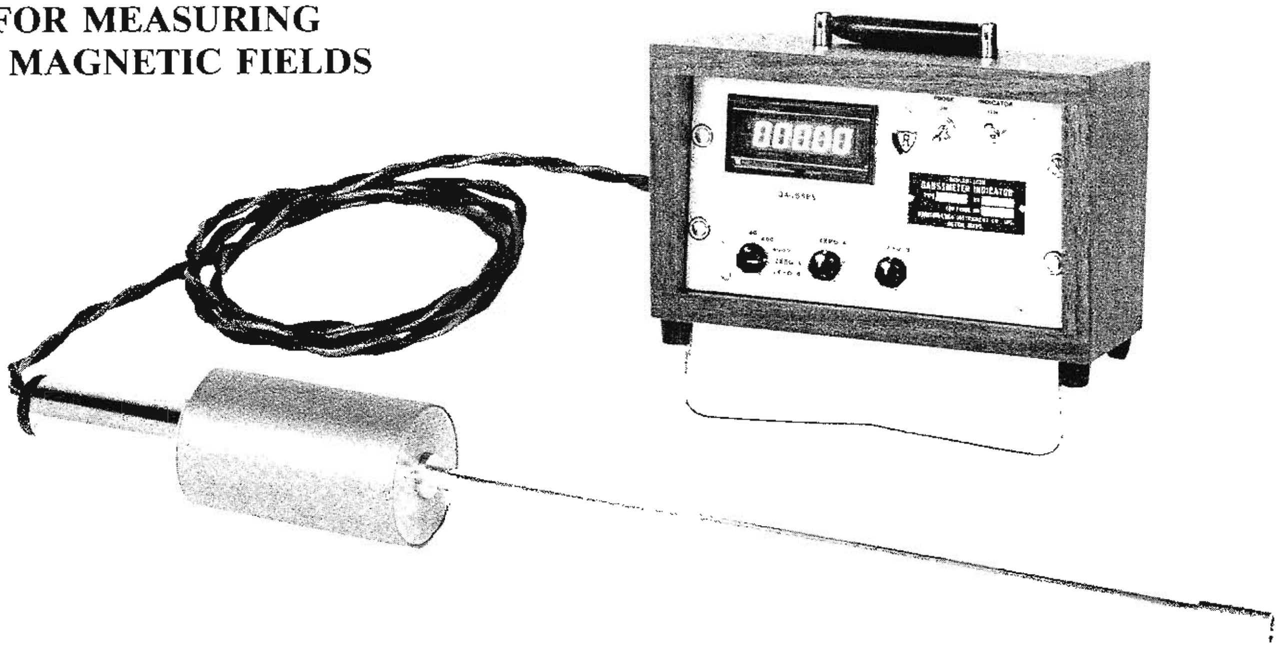
RAWSON-LUSH INSTRUMENTS

FIRST IN THE FIELD

BULLETIN 780

ROTATING-COIL GAUSSMETERS

FOR MEASURING DC MAGNETIC FIELDS



GENERAL DESCRIPTION

The voltage induced in a rotating coil is accurately proportional to the magnetic field in which it is located. This fundamental principle of classical physics is the basis of the Rawson-Lush ROTATING COIL GAUSSMETERS. Since their introduction in 1950, we have sold thousands of them to fill the needs of those working with large and small electromagnets, permanent magnets, and with the earth's magnetic field. They are simple and easy to use, and make possible accurate measurements of field strength in complicated magnetic fields. Continuous readings are obtained, so that changes in the field strength are shown almost instantly. Many improvements have been made during the years in sensitivity, accuracy, and convenience. The original Type 720 series have been replaced by the Type 780 series DIGITAL GAUSSMETERS, using operational amplifiers for amplification and rectification of the coil voltages, and a small Digital Voltmeter as the output indicator. The output display is in large, bright numbers that can be seen from a distance and with excellent resolution. In addition, the 780 series have both analog and BCD outputs.

LINEARITY OF RESPONSE

The proportionality of the coil voltage to the field strength is essentially perfect, whether the field is a milligauss or two hundred kilogausses. This linearity of response is an outstanding advantage of these rotating-coil gaussmeters. They can be used over a very wide range of field strengths without loss of accuracy. Another advantage is that good measurements can be made even if the field is not uniform. The average coil voltage will always be proportional to the field at the center of the coil.

ACCURACY

The rated accuracy of readings on the 780 series gaussmeters is .05% of full scale on each range.

PROBE DESCRIPTION

The above photograph shows a typical instrument, the Type 782. The rotating coil is located inside the tip of the long probe tube, as far away from the motor as possible. The coil is wound with many turns of fine wire and with dimensions chosen to give the maximum field pickup in a small volume of space. It is encapsulated in epoxy and rotates inside a metal casing to protect it. A long, thin and somewhat flexible shaft supports the coil and runs in a series of bearings spaced inside the probe tube. The lead wires from the coil are coaxial with the shaft to minimize extraneous pickup. The coil voltage is taken from a pair of silver slip rings inside the motor housing.

MOTOR

The drive motor is a high quality instrument type with ball bearings. Our original 720 line of gaussmeters used a synchronous motor, but this is no longer needed for the present 780 line. By driving the coil with a non-synchronous motor at a rotation frequency slightly below 30 Hertz, the circuit is made less sensitive to AC fields and hum pickup, which are synchronous with the power line. The non-synchronous motor also has much more torque and a smoother rotation than a corresponding synchronous motor. The motor housing now has a cover of steel tubing to give the motor some protection against strong magnetic fields.

AMPLIFIER AND RECTIFIER

Since the coil output is proportional to the rotation frequency, a special amplifier with 1/f frequency response is used to make the output independent of the rotation frequency. Unlike our previous 720 series gaussmeters, the Type 780 series have a SELF-SWITCHING RECTIFIER. You do not have to turn the probe around on its axis to adjust the phase angle for maximum reading. Just insert the tip of the probe into the field with the axis at right angles to it, and the gaussmeter will read the value of the field, whatever the angle is. Fields of either polarity produce a positive output. No field component ALONG the axis can be measured. (Axial field models are described in another bulletin.)

INDICATOR

The indicator unit contains the amplifier, rectifier, and digital voltmeter circuits and can be located at a distance from the probe if desired. The DIGITAL VOLTMETER in the indicator unit is the Newport Type 2004, with a maximum reading of 39,999 digits. The stability of readings is excellent, so that practically the full resolution of the voltmeter is available for the field measurement. The DC analog output voltage to the DGVM is brought out to terminals on the rear of the indicator unit, for driving recorders or automatic field controls. The voltmeter also has BCD digital outputs which can be used for connection to computers and printers.

The indicator unit is housed in a walnut grained Formica cabinet with a tilting stand for convenience. The unit can be removed from the cabinet and installed in a standard half-width relay rack mounting if desired.

NEGLIGIBLE TEMPERATURE EFFECT

Magnetic field readings are very little affected by the temperature of the rotating coil. The coil area changes a very small amount with temperature, but this is approximately balanced by the change in the coil resistance. For best operating life of the bearings, we suggest keeping the temperature of the probe tip between 0 degrees and 60 degrees C. For extremely hot environments, we can provide water-cooled sleeves to protect the coil, and vacuum-insulated sleeves for use in liquid helium. For accurate readings, the indicator unit should be used at ambient temperatures between 15 degrees and 35 degrees C.

FIELD CONTROLS

These instruments can be used as excellent field controls for electromagnets with only simple added circuitry. Please contact us if you want further information on this.

MAINTENANCE

After each thousand hours of use, the slip ring brushes should be checked for wear. The brushes can easily be replaced if needed. No other regular maintenance is required.

PROBE SIZES AND RANGES

Larger coils give more voltage output, and therefore can be used to measure weaker fields. The present list of standard types is as follows:

Type	Tip Diameter	Full Scale Ranges
783	1/8" (3.18mm)	39,999G - 100kG**
780	1/4" (6.36mm)	3,999.9G - 39,999G -100kG**
784	1/2" (12.7 mm)	399.99G - 3,999.9G -39,999G
782	3/4" (19.1 mm)	39.999G - 399.99G - 3,999.9G
786	1-1/4" (31.75mm)	3.9999G - 39.999G - 399.99G

**these 100kG ranges are not recommended for continuous use above 60kG because of eddy current heating of the shaft. Special models are available for VERY HIGH FIELDS, see below.

PROBE DIMENSIONS

Type	Tip Diam.A	Coil Diam.	Probe Length B	Length to Coil Center C	Chamber length D	Tube Diam.E
783	1/8"	.05"	17 5/16"	17"	2 1/2"	1/4"
780	1/4"	1/8"	19 11/16"	19 1/4"	-	1/4"
784	1/2"	1/3"	19 1/2"	18 15/16"	-	1/2"
782	3/4"	1/2"	19 3/4"	19 1/16"	1 9/16"	1/2"
786	1 1/4"	1"	20 3/4"	19 3/4"	2 9/16"	1/2"

SPECIAL MODELS AVAILABLE

Longer or shorter probe lengths can be supplied. Standard lengths are as shown in the table above. A 50 inch length should be ordered for Type 780 if it is to be used with the Type 732B Cryogenic sleeve. To make the probe more compact, the 5-1/2 inch long "handle" at the rear of the motor housing can be omitted if desired, with the wires coming out the rear or the side. We have built special probes with VERY TINY rotating coils for high spatial resolution in distorted fields. With some simple switching and adjustments, you can use MANY PROBES with a single indicator. We can build a small transformer into the indicator to allow for operation on 220 volt power lines. Gaussmeters for VERY HIGH FIELDS (up to 200kG or higher) are now made possible by using special motors with very slow rotational speeds (1Hz to 5Hz). Our standard probes are resistant to moderate amounts of NUCLEAR RADIATION. Special probes can be built to withstand greater amounts.

If you have any special requirements in magnetic field measurement, do not hesitate to contact us.

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Fine instruments since 1918
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