Magnetic Field Measurements for Fast-Changing Magnetic Fields

A. Marone

Superconducting Magnet Division
Brookhaven National Laboratory

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Abstract—Several recent applications for fast ramped magnets have been found that require rapid measurement of the field quality during the ramp. (In one instance, accelerator dipoles will be ramped at 1 T/sec, with measurements needed to the accuracy typically required for accelerators.) We have built and tested a new type of magnetic field measuring system to meet this need. The system consists of 16 stationary pickup windings mounted on a cylinder. The signals induced in the windings in a changing magnetic field are sampled and analyzed to obtain the field harmonics. To minimize costs, printed circuit boards were used for the pickup windings and a combination of amplifiers and ADC’s used for the voltage readout system. New software was developed for the analysis. Magnetic field measurements of a model dipole developed for the SIS200 accelerator at GSI are presented. The measurements are needed to insure that eddy currents induced by the fast ramps do not impact the field quality needed for successful accelerator operation.

Index Terms—Fast ramped magnets, Facility for Antiproton and Ion Research, magnetic field measurement, superconducting accelerator magnets.

I. INTRODUCTION

We have undertaken the development of a precise magnetic field measuring system for measuring magnets which will operate at high ramp rates (e.g., 1 T/s). High ramp rates are part of the design of the SIS100 and SIS300 rings to be built as part of the Facility for Antiproton and Ion Research (FAIR) [1], for J-PARC [2], and for a proposed upgrade of the AGS at BNL [3]. Another application is to magnets built to vary the field of NMR magnets so that the motion of awake animals can be tracked [4]. This paper reports the first set of measurements made with this system. The measurements were made on a model magnet built as part of the R&D for the SIS 200 ring at FAIR. The FAIR design now calls for a higher-energy ring, SIS300 [5].

II. MAGNET CONSTRUCTION

The model magnet (Fig. 1) was built using RHIC [6] and BNL/LHC [7] magnet tooling and components modified to accommodate the requirement for fast ramped magnets. Previous papers have reported details of the magnet construction and quench tests [8] and energy loss measurement [5]. The construction is briefly recounted below, with emphasis on changes made to the basic RHIC and BNL/LHC designs to permit fast ramping.

A. Superconductor

The strand used for the cable has diameter 0.641 mm and $J_c \sim 2900$ A/mm$^2$ (5 T, 4.2 K, measured via transport current). The strand is coated with Staybrite. Two 25 µm thick, 8 mm wide stainless steel cores were inserted in the cable as it was formed. The cable was insulated with two wraps of Kapton®, each 25 µm thick, with 50% overlap of each wrap and with polyimide adhesive. A laser was used to cut cooling holes in the insulation on the thin edge of the insulated cable.

B. Magnet

When feasible, this magnet used components made from insulators rather than metals. For example, the three wedges used in the coil were G11. Each half coil is 0.035” (0.89 mm) larger in the azimuthal dimension than RHIC coils, due to the stainless steel cores in the cable. To accommodate the coil...
oversize, the thickness of the G10 pole shim was reduced. 
The coils were collared with Kawasaki high-Mn stainless steel 
collars. The yoke laminations were 0.5 mm thick, low 
coercivity steel ($H_c = 31$ A/m) with 3.3% Si. Further details are 
given in [8].

III. CONSTRUCTION OF MEASUREMENT COIL.

We have developed a harmonic coil array for measuring 
fast-ramped magnets. Printed circuits are relatively inexpensive 
and reproducible, and are used for the windings. Sixteen 
printed circuits are mounted as tangential coils on a cylinder. 
We are sampling terms as high as the 16-pole, with the goal of 
obtaining reliable measurements at least as high as the 
decapole. The 16 probes were intercalibrated by rotating the 
coil in a reference dipole field [9]. However, the coil will be 
stationary when used for measuring fast-ramped fields.

The voltage can be sampled at rates as high as 10 kHz. The 
voltage sampling system also covers a wide range of signal 
amplitudes and allows for frequent calibration and DC offset 
checks.

In the stationary mode, the total flux seen by a given probe 
is determined by its angular position, as well as the multipole 
components of the field. The angular profile constructed with 
voltage signals from various probes is, in general, not a Fourier 
series.

For this magnet, we use a 10-layer printed circuit board with 
six turns per layer for a total of 60 turns. The lines on the 
circuit boards are 0.1 mm wide and have 0.1 mm gaps between 
them. The circuit boards are 0.3 mm long and the average width 
of the pattern is 8.2 mm. The boards are 1.6 mm thick and the 
effective radius of the cylinder on which the probe s are 
mounted is 26.8 mm. Fig. 2 shows the probe array assembled 
for this magnet. The fractional rms variation of the response 
of the boards mounted on the coil is $10^{-5}$.

IV. DATA ACQUISITION SYSTEM

We are using 16-bit commercial ADC’s and custom-built 
programmable gain amplifiers to obtain the factor of ~ 100 
needed for some of the measurements. For stability, the 
amplifiers have been mounted in a temperature-controlled box. 
The approximate offsets and amplifier gain corrections are 
obtained typically once a day by applying known signals to all 
the input channels for each of the 16 amplifier gain/ADC range 
combinations. For each ramp, the offsets are calculated during 
the time at constant current that immediately precedes the 
ramp.

V. DATA ANALYSIS

For the purpose of data analysis, a coordinate system 
internal to the coil is used. The X-axis is chosen along the 
centerline of one of the probes, as shown in Fig. 3. Since the 
relative angles of all the probes are determined by rotating the 
coil in a dipole field, the angular positions, $\theta_i$, of all the probes 
are known in this coordinate system. In practice, it is desirable 
to align this coordinate system as best as possible with the 
magnet’s principal axes. A perfect alignment, however, is not 
essential, and will not be assumed in the data analysis.

The flux linked at time $t$ through the $i$-th tangential coil of 
length $L_i$ and having $N_i$ turns is given by

$$\Phi_i(t) = \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left( \frac{R_i}{R_{ref}} \right)^n \sin \left( \frac{n \Delta_i}{2} \right) \times \left[ B_n(t) \sin(n \theta_i) + A_n(t) \cos(n \theta_i) \right]$$

where $B_n(t)$ and $A_n(t)$ are the normal and skew $2n$-pole terms 
respectively at a reference radius of $R_{ref}$ in a harmonic 
expansion of the 2-D field components. The induced voltage in 
the $i$-th probe in the stationary mode results from a time 
variation of the field components, and is given by

$$V_i(t) = \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left( \frac{R_i}{R_{ref}} \right)^n \sin \left( \frac{n \Delta_i}{2} \right) \times \left[ \dot{B}_n(t) \sin(n \theta_i) + A_n(t) \cos(n \theta_i) \right]$$

where the dot over $B_n$ and $A_n$ denotes time derivative. In a 
conventional rotating tangential coil, a complete angular 
profile is obtained by rotating the same coil. All the geometric 
parameters in this case are angle independent, and the 
expression for the flux, or the voltage, represents a Fourier 
series. In the case of an array of tangential coils in the 
stationary mode, the geometric parameters are not necessarily

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Fig. 2. The array of 16 printed circuits mounted on the cylindrical coil form 
used for fast-ramp measurements of the GSI magnet. The printed circuits are 
300 mm long.
the same for all the coils. Consequently, the various terms in
the summation in (1) or (2) are not the same as the Fourier
components of the voltage profile. Thus, a simple FFT analysis
of the voltage profile assembled from the signals of all the
probes does not directly give the harmonic terms.

In our analysis, we obtain the time derivatives of the 16
lowest-order harmonics (normal and skew, dipole through 16-
pole) by solving the 16 linear equations which link the
measured voltages and the harmonics (see Eq. 2).

The harmonic components at any time are obtained by
integrating the time derivatives:

\[
B_n(t) = B_n(0) + \int_0^t B_n'(t) \, dt; \quad A_n(t) = A_n(0) + \int_0^t A_n'(t) \, dt
\]

The initial values of the harmonics, \(B_n(0)\) and \(A_n(0)\), are
determined using the same coil in a rotating mode before the
magnet is ramped. After this measurement, the coil is aligned
with the frame used for the rotating mode data, as defined by
the index pulse of the angular encoder. The numerical
integration can be avoided if one uses digital integrators
instead of voltmeters to record the probe signals.

VI. MAGNETIC FIELD MEASUREMENT

For this first test, we report a measurement of the normal
sextupole generated by the ramping of the magnet. We began
by making DC measurements with an existing rotating coil
system and with the new system operating in the rotating mode.
The DC measurement of the geometric sextupole by the new
system, -37 units, is calculated by averaging the up and down
ramp measurements given in Table I. (A unit is defined as \(10^4\)
times the harmonic field divided by the fundamental field at a
reference radius of 25 mm.) It is in good agreement with the
measurement made by the existing system and with a
calculation for the magnet with its oversized coil [10]. The
existing ~1 m coil is much longer than the new coil and sees
some part of the magnet ends, so the two measurements are not
directly comparable. Good agreement between calculation and
measurement with the new system is found for the first four
allowed harmonics. After this measurement, the coil of the new
(i.e., fast ramp) system was rotated so that its reference frame
was aligned with the frame used for this coil in rotating mode.

With the fast ramp coil properly aligned, the magnet was
ramped from 50 A (0.03 T) to 6800 A (4T) at 4900 A/s (3 T/s)
and then back to 50A at the same rate. Two such ramp cycles
were carried out to set up the magnet history before taking data
in the third ramp. The offsets of the amplifier/ADC system
were measured at constant current (50A) immediately prior to
the ramp. The offsets were not measured at the end of the
ramping because of the finite decay time of the eddy currents.

Figs. 4 and 5 show the normal and skew dipole and
sextupole fields as a function of current, up and down ramp.
(At high current, the normal sextupole becomes more negative
due to the saturation of the yoke.) There is good point-to-point
reproducibility. The fields at the end of the down ramp are close to those at the start of the up ramp, indicating that the offset corrections are nearly correct.

Fig. 6 shows the normal and skew sextupole in units. The normal sextupole displays the usual hysteresis curve. The hysteresis in the skew sextupole may be due to inaccurate offset corrections.

To remove any systematic differences between the DC and AC measurements of the field, we compare the difference down ramp – up ramp (i.e., the width of the hysteresis loop) during the fast ramping to the down-up difference obtained from the DC measurement. The eddy current sextupole will appear at twice its magnitude in the fast-ramp difference but be absent from the DC difference. Fig. 7 shows the differences in the sextupole fields as a function of current for the DC and fast ramp measurements. It is useful to compare the DC and fast ramp differences in the region 1 kA – 2 kA, where the effects of magnetization are modest and the width of the hysteresis loop is much larger than the noise of ~ 1 x 10^{-4} T. The differences at 1 kA are listed in Table I, in units.

From Table I, we see that the width of the hysteresis loop of the normal sextupole is 13.1 units for the fast-ramp measurement and 5.7 units for the DC measurement. Half the difference, 3.7 units, could be attributed to the eddy current sextupole at 1 kA (0.63 T central field) during the up ramp. We estimate that the uncertainty in this measurement of the eddy current sextupole is ~ 2 units. Since the magnetic field produced by the eddy current is constant at constant ramp rate, whereas the central field is roughly linear with current, the eddy current harmonics (in units) will vary inversely with current. For example, at 500A, the eddy current normal sextupole is ~ 7.4 x 10^{-4}.

The eddy current decapole is estimated to be ~ 2 units, but is not well-determined at the present time.

VII. CONCLUSION

Initial harmonic measurements of an SIS200 model dipole ramped at the high rate of 3 T/s have been made. The normal sextupole due to the fast ramping is 3.7 units, with an uncertainty of ~ 2 x 10^{-4} units.

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