Field Quality Measurements at High Ramp Rates in a Prototype Dipole for the FAIR Project

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***Abstract*— Brookhaven National Laboratory (BNL) has built a prototype superconducting dipole for the Facility for Antiproton and Ion Research (FAIR) at GSI that can be ramped at a high rate (1-4 T/s). To characterize the field quality at such high ramp rates, a measurement system consisting of 16 printed circuit windings was developed. In this system, the signals induced in all the windings as the magnet is ramped are analyzed to obtain the field harmonics. Initial measurements with this system suffered from somewhat poor resolution of the ADCs used for data acquisition. Also, only a few low order harmonics could be obtained with the 16 signals. These drawbacks have been addressed by replacing the ADCs with HP3458A voltmeters and by combining data taken with two different orientations of the probe. This has allowed us to measure very precisely (~10 ppm of the dipole field) all the harmonics up to the 26-pole at ramp rates up to 4.3 T/s. The data analysis and results with this improved system are presented.**

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

I. INTRODUCTION

FIELD quality in accelerator magnets is generally expressed in terms of the harmonic coefficients in a Fourier series. These coefficients (harmonics) can be accurately measured under DC conditions using rotating coils [1-3]. While this is very often sufficient, there are many instances where magnets in an accelerator are required to operate at very high ramp rates. For example, 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) [4]. Very high ramp rates are also encountered in rapid cycling synchrotrons where fields varying at several tens of Hz may be used. The field harmonics can not be measured in these situations with the usual rotating coils which typically have a period of several seconds. Since the field quality may be affected by eddy currents, it is desirable to carry out field quality measurements under the dynamic conditions.

As part of the magnet development program [5] for the FAIR project, a system using 16 printed circuit coils was developed at BNL to measure field harmonics at very high ramp rates [6]. Only a few low order terms could be measured with it due to use of data at only 16 angular positions.

In this paper, we describe some improvements made to the data acquisition and analysis scheme which allows higher order terms of interest to be measured using the same 16-coil probe. Results obtained at ramp rates of up to 4.3 T/s in an 80 mm aperture, 1 meter long dipole prototype magnet built at BNL for the FAIR project are also presented. The construction features special to this magnet can be found in [5].

II. EXPERIMENTAL DETAILS

A. Measurement System

The measurement probe consists of a set of 16 printed circuit tangential coils mounted on a cylindrical coil form. The windings are 300 mm long with 60 turns each, and are located at a nominal radius of 26.8 mm, with a nominal opening angle of 17.5 degrees. The probe is held stationary while the magnet is ramped. The voltage signals from all the windings are recorded and analyzed to extract the field harmonics. Earlier measurements used amplifiers with 16-bit ADCs to record the data. In this work, the signals were directly fed to a set of 16 high resolution HP3458A digital voltmeters to get better resolution. Another HP3458A meter was used to record the current profile. For the present work, the data sampling rates varied from 45 Hz to 175 Hz, providing a data point at roughly every 40-60 A during the ramp.

The probe can also be used in a rotating mode to measure DC fields. This feature was used for baseline measurements under DC operation, to measure the initial values of harmonics at a constant current just before the start of a ramp (needed for data analysis) and also to precisely calibrate the geometric parameters of each coil using DC reference magnets. A precise calibration is of utmost importance to ensure measurement accuracy since calibration errors would effectively distort the measured angular distribution, leading to spurious harmonics.

B. Ramp Details

The magnet was first cycled three times between 0.1 kA and 7 kA (4 T) at the intended ramp rate to set the history. All field measurements were started at a current of 0.1 kA. The DC

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field at 0.1 kA was first measured with the probe operated in a rotating mode. The probe was then held stationary while the magnet was repeatedly ramped up and down between 0.1 kA and 7 kA. A ramp up consisted of an initial dwell at 0.1 kA of 0.6 s, a quadratic acceleration phase, a linear (i.e., constant ramp rate) segment, and finally a quadratic deceleration phase leading to 7 kA flat top. The parameters of the acceleration and deceleration phases were adjusted such that each phase lasted for about 10% of the total ramp time. After a 0.1 s dwell at 7 kA, a similar profile was used for ramping down to 0.1 kA, which completed one ramp cycle. Four such ramp cycles were repeated one after the other providing four sets of up and down ramp harmonics, thus allowing a cycle-to-cycle comparison to be made. Finally, the entire sequence of four up and down ramp cycles was measured multiple times.

C. Overcoming limitations of earlier measurements

The limitation of poor resolution of ADCs in earlier work was overcome in this work by using HP3458A voltmeters. Apart from their limited resolution, the measurements also suffered due to the availability of data at only 16 angular positions. This allowed measurement of only a few harmonic terms, which could also be subject to errors due to aliasing. Furthermore, one needs to measure fairly high order terms in order to properly center the data in a dipole magnet. One solution to this problem could be to increase the number of coils in the probe. However, this may not be practical due to physical size limitations. Moreover, increasing the number of channels would also be very expensive with HP3458A meters.

In this work, we have effectively doubled the available angular positions by performing the measurements in two parts. At first, measurements were made with one orientation of the probe, giving data at 16 angular positions. The probe was then rotated around its axis by 11.25 degrees (half of the nominal angular separation between the probes) and the measurements were repeated. The precise angle of rotation was measured using an angular encoder. Combining all the data from the two angular positions of the probe, we obtained data at a total of 32 angular positions, thus extending the number of harmonics measured, as well as improving the reliability of the lower order terms by reducing aliasing. The disadvantage of this approach is that the measurement time is increased, and it is necessary to ensure somewhat reproducible current ramps. On the other hand, this approach can be extended to use any combination of number of coils and number of angular positions. Thus, one could obtain good measurements even with fewer coils by measuring more angular positions.

III. Data Analysis

The measurement coordinate system (X-Y) is defined by an index pulse from an angular encoder in the rotating mode and coincides with the coordinate system $(\mathrm{X}_p\text{-}\mathrm{Y}_p)$ internal to the probe when the probe is positioned at the index pulse. The angular positions of all the coils are known in the internal coordinate system from calibrations. When the probe is held stationary and oriented at an angle φ_p with respect to the

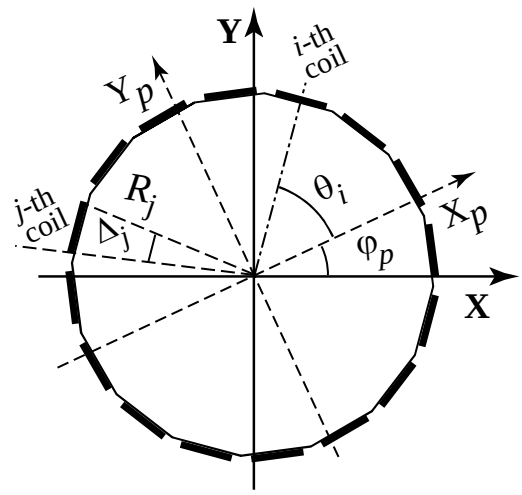

Fig. 1 Measurement and probe coordinate systems for a probe rotation given by angle φ_p.

index pulse position, as shown in Fig. 1, the voltage induced in the *i*-th coil due to a time variation of the flux, Φ_i, linked to the coil at time t is given by

$$V_i(t) = \frac{d\Phi_i}{dt} = \sum_{n=1}^{\infty} \frac{2N_i L_i R_{ref}}{n} \left(\frac{R_i}{R_{ref}}\right)^n \sin\left(\frac{n\Delta_i}{2}\right) \times \left[B_n'(t)\sin(n\theta_i + n\varphi_p) + A_n'(t)\cos(n\theta_i + n\varphi_p)\right] \quad (1)$$

where L_i is the length, N_i is the number of turns, R_i is the radius, Δ_i is the opening angle, and θ_i is the angular position of the *i*-th coil. $B_n(t)$ and $A_n(t)$ are the normal and skew 2*n*-pole field harmonic components respectively at a reference radius of R_{ref}. The prime over $B_n(t)$ and $A_n(t)$ denotes time derivative. The flux through any coil at any instant can be obtained by integrating the voltage signal and adding a constant corresponding to the flux at the start of the ramp. This constant is derived from harmonics measured using the rotating mode just before starting the ramp. There is often a small offset in the voltage signals resulting in a drift when integrated. The offset correction is derived for each signal by studying the cycle-to-cycle drift in the computed flux at a given current. This procedure is very similar to the one described in detail in an earlier paper [6]. The harmonics $B_n(t)$ and $A_n(t)$ are derived from a least squares fit to all data using terms up to n = 13 (26-pole). Including more terms did not affect the lower order terms much, but the results for harmonics higher than 26-pole were not very reliable. The series in Eq. (1) was therefore terminated at n = 13.

A. Combining data from different probe orientations

In order to combine data from measurements with different probe orientations, φ_p, it is essential that all flux values be computed at exactly the same current in the ramp cycle and at the same ramp rate. This poses a problem since different ramps may not match exactly in practice, and the triggers to record data may not be at exactly the same currents. This problem was solved by interpolating all data at uniform

current steps of 50 A (comparable to typical steps in the real data). This ensured that data for all coils from all orientations of the probe correspond to the same current in the ramp cycle. Although it is still desirable to keep the ramp profiles as closely matched as possible, the interpolation considerably relaxes the requirements. It was also found that a better cycle to cycle consistency could be obtained by including all the data from multiple runs taken at a given probe orientation in a single fit. In this work, three measurements of four cycles each were made for each of the two probe orientations. Thus, three data points at each of the 32 angular positions (for a total of 96 data points) were used to obtain the field harmonics at any given current in any given cycle.

B. Centering corrections

The availability of higher order terms allows us to compute the relative offset between the magnetic axis and the probe axis. We used a first order feed down from the 22-pole terms to the 20-pole terms to compute this offset, although all orders of feed down were included in computing the centered harmonics. Since the feed down from such high order terms may have significant higher order contribution depending on the offset, we computed the residual error in centering from the first pass centered data, and then reapplied this residual correction. This residual correction was generally small, well below 0.1 mm. All data were centered using average offsets computed in the current range of 1 kA to 6 kA.

IV. Results and Discussion

Examples of cycle-to-cycle consistency in the harmonics are shown in Fig. 2 for the case of the normal sextupole term (allowed by dipole symmetry) and in Fig. 3 for the skew quadrupole term (unallowed by dipole symmetry) at a ramp rate of 3.1 T/s measured in four successive ramp cycles. The values are in "units" of 10^{-4} of the dipole field at a reference radius of 25 mm. The difference between successive cycles is hardly seen in these plots. Even for higher order terms, e.g. the 18-pole term shown in Fig. 4, the reproducibility is better than ±0.1 unit in the entire current range. Similar results are obtained for the 22-pole and 26-pole terms. The results from all the four cycles were averaged to obtain the up and down ramp excitation curves for each harmonic. Finally, the hysteresis in any harmonic at any given current is calculated as the difference between the down and the up ramp values. Since the eddy currents are expected to change sign in the down ramp, one may assume that their contribution to the field harmonics is about half of this hysteresis.

The absolute values of hysteresis in Tesla are shown in Fig. 5 for the sextupole term as a function of current at various ramp rates from DC to 4.3 T/s. The DC values were obtained from measurements using the probe in the rotating mode. The

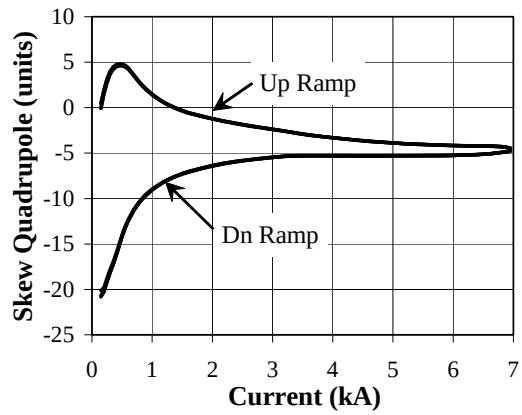

Fig. 3 Skew quadrupole term measured in the up and down ramps at 3.1 T/s in four successive cycles. The values are in "units" of 10^{-4} of the dipole field at a reference radius of 25 mm.

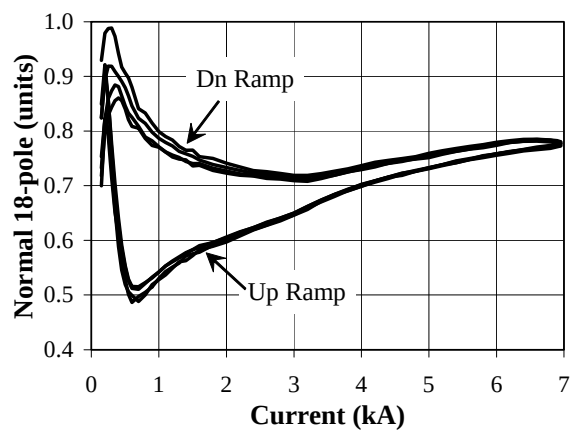

Fig. 4 Normal 18-pole term measured in the up and down ramps at 3.1 T/s in four successive cycles. The values are in "units" of 10^{-4} of the dipole field at a reference radius of 25 mm.

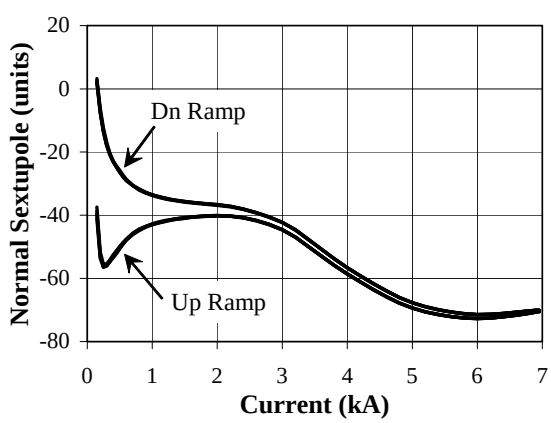

Fig. 2 Normal sextupole term measured in the up and down ramps at 3.1 T/s in four successive cycles. The values are in "units" of 10^{-4} of the dipole field at a reference radius of 25 mm.

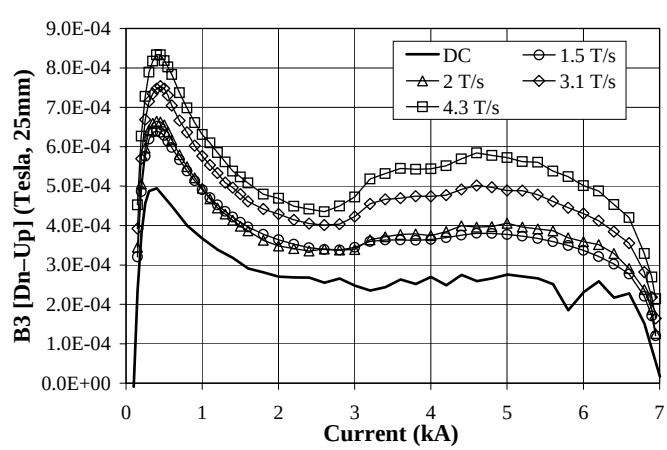

Fig. 5 Hysteresis in the normal sextupole term as a function of magnet current for different ramp rates.

large geometric value is a result of using a magnet coil which was not optimized for the special cable used. As can be seen from Fig. 5, the hysteresis increases with ramp rate, but the shape of the current dependence is very similar for both DC and ramped data. The shapes of these curves can be qualitatively understood [7] in terms of contributions due to persistent currents [8], inter-filament coupling currents [9] and inter-strand coupling currents [10].

A striking result obtained in this work is the rather large hysteresis seen in the unallowed skew quadrupole term under ramped conditions (see Fig. 6). The hysteresis at a fixed current of 1 kA is shown in Fig. 7 as a function of ramp rate. A linear dependence on the ramp rate can be clearly seen. A similar linear behavior is seen for nearly all harmonics. Table I summarizes the parameters of linear fits to all harmonics at a fixed current of 1 kA. The numbers in bold correspond to the terms allowed by the dipole symmetry. It can be seen that in addition to the quadrupole, several other skew terms have a pronounced ramp rate dependence, indicating significant up-down asymmetry in the eddy current distribution. The exact cause for this asymmetry is not known. The intercepts represent hysteresis under DC operation, and are as expected.

For an azimuthally uniform distribution of contact resistances in the coil, the relative strengths of eddy current induced decapole and sextupole can be estimated using an analytic formula [11]. The measured ramp rate induced decapole and sextupole (see Table I) are inconsistent with this simple model. A similar conclusion was drawn from a numerical simulation of ramp rate effects in this magnet [7]. It is necessary to invoke rather large up-down differences in order to explain the skew terms based on the inter-strand resistance alone, and eddy currents in the yoke or other surrounding objects may also have a role to play.

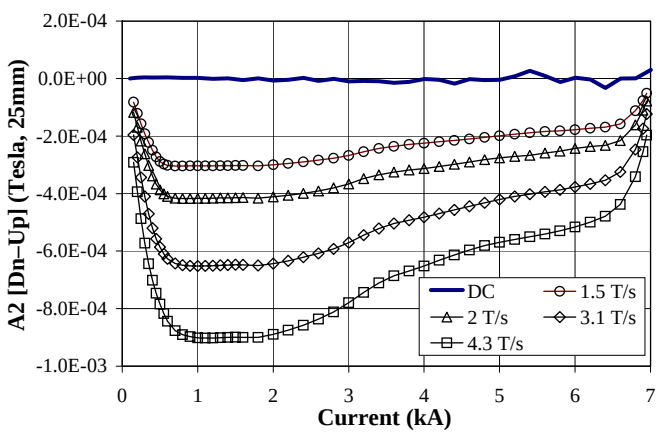

Fig. 6 Hysteresis in the unallowed skew quadrupole term as a function of magnet current for different ramp rates.

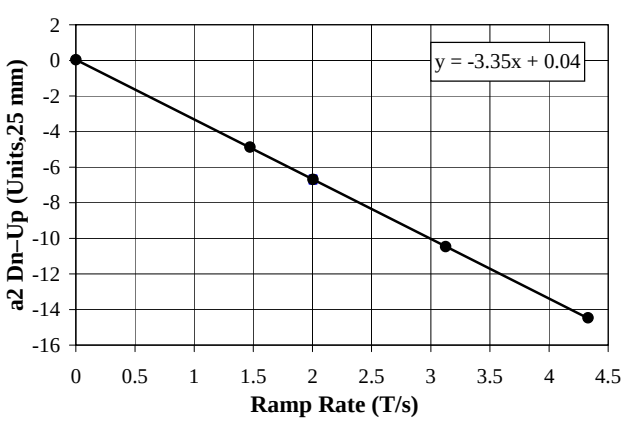

Fig. 7 Hysteresis in the unallowed skew quadrupole term at a fixed current of 1 kA as a function of ramp rate. The values are in "units" of 10^{-4} of the dipole field at a reference radius of 25 mm. The solid line is a linear fit to the data.

RAMP RATE DEPENDENCE OF HARMONICS AT 1 KA

n	Slope (units/Ts^{-1})		Intercept (units)	
	Normal	**Skew**	**Normal**	**Skew**
2	0.01	-3.35	0.14	0.04
3	**0.96**	0.51	**6.15**	0.14
4	-0.19	-2.07	-0.01	0.11
5	**1.60**	-0.01	**0.71**	0.02
6	-0.07	-0.31	0.03	0.09
7	**0.42**	-0.02	**0.42**	-0.04
8	-0.04	0.00	0.00	-0.02
9	**0.07**	0.00	**0.01**	-0.03
10	-0.02	0.00	-0.02	0.02
11	**0.07**	-0.02	**0.07**	0.04
12	-0.02	0.00	0.05	0.00
13	**-0.03**	0.00	**0.06**	-0.08

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