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AC FIELD MEASUREMENTS OF FERMILAB BOOSTER CORRECTORS USING A ROTATING COIL SYSTEM *

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Abstract

The first prototype of a new corrector package for the Fermilab Booster Synchrotron is presently in production. This water-cooled package includes normal and skew dipole, quadrupole and sextupole elements to control orbit, tune and chromaticity of the beam over the full range of Booster energies (0.4-8 GeV). These correctors operate at the 15 Hz excitation cycle of the main synchrotron magnets, but must also make more rapid excursions, in some cases even switching polarity in approximately 1 ms at transition crossing. To measure the dynamic field changes during operation, a new method based on a relatively slow rotating coil system is proposed. The method pieces together the measured voltages from successive current cycles to reconstruct the field harmonics. This paper describes the method and presents initial field quality measurements from a Tevatron corrector.

INTRODUCTION

The Fermilab Booster Synchrotron has been a key element of the accelerator complex since it initially began operating in early 1970. In recent years, with extension of the Fermilab physics program into new accelerator-based neutrino experiments [1], the demand for high intensity proton beams has rapidly increased. This has created new requirements for Booster operation (e.g. a reduction in beam losses) which cannot be satisfied by the capabilities of the existing corrector system to control beam orbit.

A new, stronger, water-cooled corrector package, including normal and skew dipoles, quadrupoles and sextupoles, was recently designed at Fermilab [2]. After a successful test of the first prototype, 60 corrector packages will be produced; 48 of them will be installed in the Booster Synchrotron during the shutdowns in the next two years. These correctors are designed to provide full control over the orbit, tune and chromaticity of the beam from the injection energy (400 MeV) up to the extraction energy of 8 GeV. In the standard operation, they have to track the 15 Hz cycle of the main Booster combined function magnets; moreover, the quadrupole and sextupole elements should swing through the full current range in ~1 ms during the transition crossing. Additional details on the design and operational specifications of the corrector package are reported elsewhere [2,3].

To check the field quality of the correctors during the production process, DC and AC magnetic measurements will be performed. For the DC measurements, the standard tangential rotating coil technique [4], with a measurement system described in [5] will be used. Two different methods were proposed for the fast changing AC field measurements. One of them, utilizing the same hardware as the DC measurements and based on the analysis of signals from a slow rotating tangential coil, is presented in the paper.

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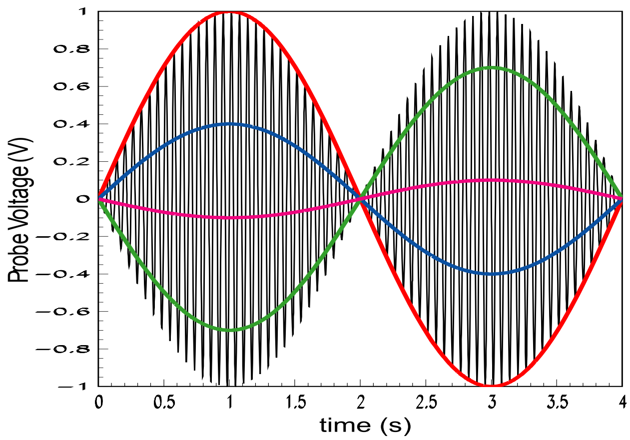

Figure 1: A simulated signal of slow rotating tangential probe (0.25 Hz) from a fast 16 Hz changing dipole field (black line). The color lines corresponds to the points with the same phases of the fast changing dipole field.

DESCRIPTION OF THE METHOD

The main challenge of the AC magnetic measurements is to obtain the field harmonics during the 15 Hz current cycles which emulate Booster operation. A standard way to perform this type of “fast” measurement is to use non-rotating probes that overcome the time resolution problem of the rotating ones. In this case, one needs a multiple probe system, similar to the described in ref. [6], to get the desired order of harmonic information.

A key feature of the proposed method is to use the existing fast Fermilab rotating coil measurement system [5]. The measurements will utilize a relatively large diameter probe having a tangential winding for determination of higher order harmonics as well as two dipole and two quadrupole windings sensitive to the lowest order field components. Fig. 1 shows the simulated signal (modulated sinus, black line) of the probe dipole winding when the dipole corrector is excited with 16 Hz AC. For this simulation, the rotational speed of the probe is assumed to be 0.25 Hz with 4096 points per rotation. For one full rotation of the probe, the current cycles 64 times per rotation and every cycle contains 64 points. The main idea of the method is: if the points with the same phases from the current cycles are selected (these points correspond to being acquired the same magnet current but have different voltages due to the probe rotation) one may reconstruct the field harmonics applying the standard rotating coil analysis as described in [4]. For example, four sets of same phase points are shown on Fig.1 connected with different color lines.

For this simulation, we assume 16 Hz current cycles. This requirement comes from the type of the triggering encoder (4096 points per rotation) currently used in the measurement system. For the Booster correctors measurements, we have to use a modified reconstruction algorithm extrapolating the voltages between the trigger points. An additional possible solution is to utilize an encoder with a number of pulses proportional to 15 Hz [7].

For field harmonic measurement of a sufficient accuracy, two major concerns need to be studied: rotational speed and power supply (PS) long and short range stabilities. Several tests were performed to estimate these factors.

Rotational Speed Stability

The probe was rotated by a stepper motor precisely controlled using feedback from an angular encoder attached to the motor drive shaft. The motor and the encoder were displaced as far as possible from the magnet to prevent disruption of motor rotation by the magnet fringe field. A 10:1 reduction ratio gearbox (25:1 is considered for the future measurements) is included in the probe drive assembly to smooth out the angular steps of the motor.

To check the rotational speed stability, two tests were performed. In the first one, we were looking at the time difference between the two consecutive triggers (Δt_{trig}). From Δt_{trig}, we subtracted the expected trigger time difference (1/4096 s) and filled a histogram. This distribution is shown in Fig.2 (left). The mean value from the Gaussian fit is 1.2 μs (essentially 0) while the sigma of the distribution, which is directly connected to the mechanical jitter, was found to be very small, on the order of 11.2 μs. A similar analysis was executed for a series of full probe rotations (Fig. 2, right). The Gaussian fit returned a mean value consistent with zero and a rotation to rotation sigma of 65 μs. Using these numbers, we generated 1000 pseudo rotations having random mechanical jitter and analyzed them as real ones. On average, we found that the probability of the low order field harmonics to fluctuate more than ±10% is below 11%.

Power Supply Stability

The utilized PS was designed specially for the Booster corrector package. Details on its operational specifications are reported elsewhere [4].

We performed several stability checks: short-term (~10 s) and long-term (~1 hour) DC and AC tests. During these tests, the PS was connected to a load with comparable resistance and impedance. The signal, from an accurate current transducer, was digitized by the 24 bit ADC.

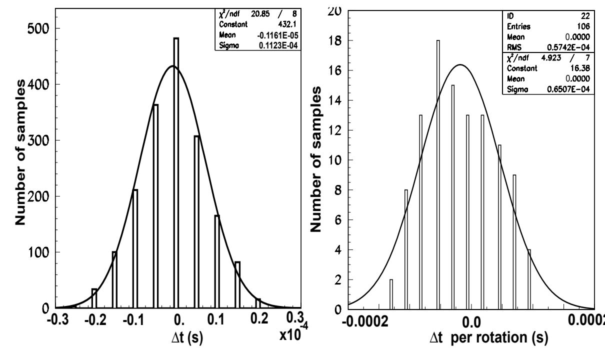

Figure 2: Distribution of the time difference between two consecutive triggers minus the nominal trigger value is shown in the left plot. A similar distribution for the full probe rotation is shown in the right plot.

The result from the long-term stability test is shown in Fig.3 (left). The positive (black points) and negative (red points) currents were measured for a duration of 10 s within an interval of 15 min. From the averaged values of every measurement, we subtracted the nominal currents of ±10 A. One can conclude that the current change is below 1 mA for a relatively long period of time.

In case of the AC stability measurement we performed the following procedure: a small trim dipole was powered from the corrector PS, which was driven with 16 Hz sinus by an HP function generator. At the beginning of the measurement, we took a 1 s test sample which was fitted with a 16 Hz sinus function. This first measurement was labelled "nominal" and all others were compared to it. We continued to take such samples of data during an 1 h interval.

From the measured currents, we subtracted the expected nominal values (Fig. 3 right plot). The mean of the distribution is below 1 mA, a value which was expected from the long term DC stability test. The Gaussian fit returned a sigma of 6.1 mA. Using this sigma and one nominal probe rotation, we generated 1000 pseudo rotations where the measured fluxes were scaled according to the current fluctuation for every trigger point

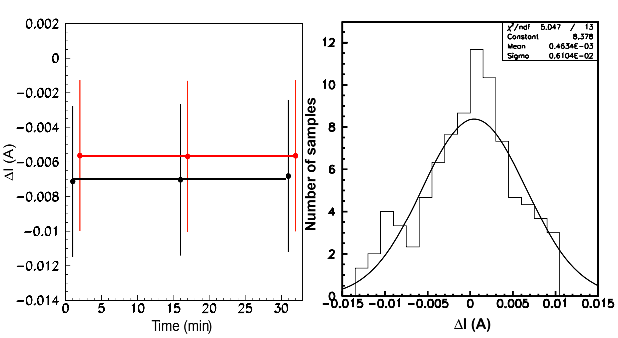

Figure 3: Average PS currents minus requested value versus time is shown on the left plot (long term DC stability). A distribution of the current difference between the measured AC (16 Hz sinus) minus the nominal values is shown in the right plot.

(we use a similar procedure for an estimation of the time effect from the probe jitter). As a result of this exercise, we found that the probability of field harmonics to change more than ±10% is below 8%.

FIRST RESULTS

We tested the method by measuring a small Tevatron horizontal trim dipole corrector (HDD004-1). The magnet was connected to the same type of PS, designed for the new corrector packages, and was powered with DC (+10 A) or 16 Hz AC, ~2 Vpp. The tangential probe was rotated with 0.25 Hz, thus 64 current cycles were registered per one rotation.

In Table 1, we show the comparison from three different measurements: the DC or AC corresponds to the type of recorded data and the abbreviation in the brackets represents the performed type of analysis: (RC) represents the standard rotating coil analysis while (ARC) stands for the proposed method. All the errors in the columns are renormalized to one rotation. For AC we report the value of the harmonics at the maximum positive current. The measurements show good consistency and the standard rotating coil analysis (DC) returned the smallest uncertainties, as expected.

To check time stability of the method we plot the sextupole measurements from analysis of five rotations (Fig. 4) distributed approximately equally over 20 min. An excellent agreement between rotations is observed.

CONCLUSION

We proposed a new method for AC field measurements for the corrector upgrade of Fermilab's Booster. The method is based on the existing, in house made [5], fast continuous rotating coil measurement system. It uses the ability to synchronize the AC current period with the rotation of the measurement probe and obtain the field harmonics connecting the points from different AC cycles.

We checked the rotational stability of the system, as well as the current stability of the corrector package power supplies, and found that these factors decrease our resolution on the level of 14% (0% correlated) to 19% (100% correlated), compared to the standard DC type measurements.

In addition, we measured a Tevatron trim corrector dipole, powered with 16 Hz AC, and found a good consistency with DC measurements and excellent time reproducibility. The proposed method can be used, with some limitation, to measure the harmonics in case of fast changing fields with accuracy sufficient for the warm corrector packages.

Table 1: Reconstructed field harmonics

Order	DC (RC)	DC (ARC)	AC (ARC)
b2	2.5±1.6	9.0±4.5.	12.2±6.3
b3	-64.6±3.8	-66±8.0	-51.0±10.0
b4	-1.4±0.9	-5.6±3.1	2.5±6.2
b5	-22.2±1.6	-23.0±3.5	-28.0±7.0
a2	-2.0±0.8	-3.3±3.0	10.7±7.3
a3	0.6±1.1	0.6±1.9	4.6±5.2
a4	-3.6±1.2	-4.9±2.0	2.54±4.7
a5	0.4±0.8	1.9±1.7	9.3±4.0

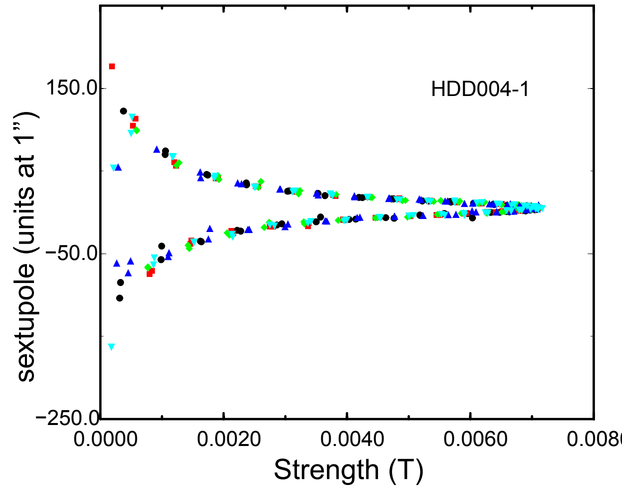

Figure 4: The measured sextupole vs the dipole strength, in case of 16 Hz AC, for different probe rotations, represented with the different color points. Every probe rotation produces 64 independent measurements for different magnet strength.

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