EXPERIMENTAL CHARACTERIZATION OF PERMANENT MAGNET HARMONIC CORRECTOR RINGS*

A. Madur, S. Marks, S. Prestemon, R. Schlueter, LBNL, Berkeley, CA 94720, USA

Abstract

A total of three permanent magnet chicane magnets have been installed at the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory. The magnet design incorporates an annular array of counter-rotating permanent magnet pairs (PMs) with supplemental fast trim coils (EMs). The purpose is to provide a fixed angular separation between two successive elliptically polarizing undulator (EPU) photon fans (with the PMs) and to correct steering perturbation resulting from EPU polarization state and gap changes (with the hysteresis-free EMs). This paper presents a method for fine tuning relative orientation settings of the rotors in the presence of initial uncertainty of the exact PM rotor geometrical and magnetization parameters by performing magnetic measurements with rotating coils. The measurement method will be developed and illustrated with experimental data from the measurement of a 16 cylinder permanent magnet harmonic corrector ring.

INTRODUCTION

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory uses the concept of Permanent Magnet Harmonic Corrector Ring (PMHCR) [1] within chicane magnets used to bend the electron beam to operate two insertion devices on a single straight section [2]. The PMHCR plus the EM trim coils provide adequate magnetic field harmonic correction in less than a second as needed by the insertion device operation mode, and avoid hysteresis phenomena inherent in conventional iron-core electromagnets.

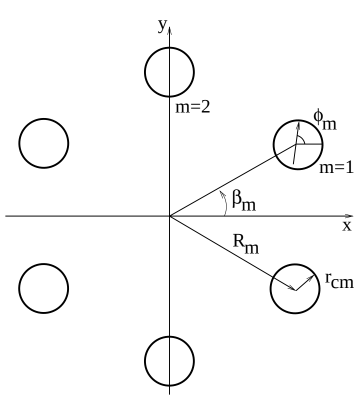

Figure 1: Permanent Magnet Harmonics Corrector Ring

A PMHCR is made of M permanent magnet cylinders as showed by figure 1:

- spaced uniformly in the azimuthal direction at nominal angles $\beta_m = m\frac{2\pi}{M} + \beta_0$,
- with nominal magnetization direction ϕ_m,
- with nominal strength B_{rm},
- with nominal radius r_{cm}
- located at nominal radius R_m,
- and of nominal length L_m

where m refers to the cylinder index ($m = 1..M$), β_0 is the offset angle that rotates all the cylinders to give the right orientation to the PMHCR harmonic correction.

The complex conjugate integrated magnetic field ($I^*(\zeta)$) provided by a PMHCR is known [1] as:

$$I^*(\zeta) = \int_{-\infty}^{\infty} B^*(\zeta)\, dZ \tag{1}$$

$$\begin{aligned} &= \sum_{n=1}^{\infty} \sum_{m=0}^{M-1} \left[\frac{L_m}{2} \frac{r_{cm}^2}{R_m^2} \left(\frac{r_p}{R_m}\right)^{n-1} \right. \\ &\left. \times\ n\, B_{rm}\, e^{i(\phi_m-(n+1)\beta_m)} \left(\frac{\zeta}{r_p}\right)^{n-1} \right] \\ &= \sum_{n=1}^{\infty} C_n \left(\frac{\zeta}{r_p}\right)^{n-1} \end{aligned} \tag{2}$$

where $\zeta = x + iy$ and where $B^*(\zeta) = B_x - iB_y$ is the conjugate of the 2-D complex magnetic field density. In Eq. 1, Z is the longitudinal cartesian coordinate.

As demonstrated by the Eq. 2, $I^*(\zeta)$ can be expanded as a power series of ζ/r_p where r_p is the reference radius, n the harmonic order ($n = 1$: dipole, $n = 2$: quadrupole...) and C_n the complex harmonic coefficients.

The quality of the correction provided by the PMHCR depends on how accurately their magnetic characteristics are known. We presents here how these characteristics could be determined by means of rotating coil magnetic measurements while the PMHCR is already assembled.

CHARACTERIZATION METHOD

This section is focused on the determination of the parameters of one cylinder with index m. One PMHCR cylinder with index m is completely determined by 6 parameters (see Eq. 2): L_m, r_{cm}, R_m, B_{rm}, ϕ_m and β_m.

* This work was supported by the Director, Office of Science, U. S. Department of Energy under Contract No. DE-AC02-05CH11231.

General Method

The only degree of freedom used in our characterization method is ϕ_m which is used to isolate the effect of the cylinder m from the others in Eq. 2.

Two measurements are taken for 2 different values of ϕ_m (ϕ_m^0 and ϕ_m^1) and lead to two sets of complex harmonic coefficients (respectively C_n^0 and C_n^1) . ϕ_m^0 and ϕ_m^1 are not known but we accurately measure their difference $\delta\phi_m$:

$$\delta\phi_m = \phi_m^1 - \phi_m^0 \tag{3}$$

Then, by calculating the difference between the 2 sets of harmonic (ΔC_n) we obtain a formula in which remains only the influence of the cylinder m.

$$\begin{aligned}\Delta C_n &= C_n^0 \; - \; C_n^1 \\ &= L_m \, \frac{r_{cm}^2}{R_m^2} \left(\frac{r_p}{R_m}\right)^{n-1} n \, B_{rm} \, sin\left(\frac{\delta\phi_m}{2}\right) \\ &\times \; e^{i(\phi_m - (n+1)\beta_m + \frac{\delta\phi_m}{2} - \frac{\pi}{2})}\end{aligned} \tag{4}$$

Eq. 4 is the core relation of the proposed method, all the formulae needed to determine the parameters are deduced from it.

Parameters Determination

The harmonic difference modulus is a function of 4 of the wanted parameters and its argument is a function of the remaining parameters:

$$|\Delta C_n| = f(L_m, r_{cm}, R_m, B_{rm}) \tag{5}$$

$$Arg[\Delta C_n] = g(\phi_m, \beta_m) \tag{6}$$

From Eq. 5 and Eq. 6, 4 parameters can be determined with 2 values of n: the 2 angles, and only 2 cylinder paremeters. This requires some assumptions about the 2 others that we will develop later.

Formulae for angles From Eq. 4, we can deduce the two following relations:

$$\beta_m = Arg\left[\frac{\Delta C_n}{\Delta C_{n+1}}\right] \tag{7}$$

$$\phi_m = Arg\left[\Delta C_n\right] + \; (n+1)\beta_m - \frac{\delta\phi_m}{2} + \frac{\pi}{2} \tag{8}$$

Formulae for 2 cylinder parameters From Eq. 4, the only parameter of the modulus that depends on powers of n is R_m which can be isolated and calculated with:

$$R_m = \frac{n+1}{n} r_p \left|\frac{\Delta C_n}{\Delta C_{n+1}}\right| \tag{9}$$

Then from the three remaining parameters to determine, we can assume that both the cylinders length (L_m) and radius (r_{cm}) can be mechanically measured with an accuracy close to the micron range. This accuracy enables us to consider these two mechanically measured parameters as data in the next formula allowing us to more precisely determine B_{rm}.

$$B_{rm} = \frac{1}{n \, L_m \, sin\left(\frac{\delta\phi_m}{2}\right)} \frac{R_m^2}{r_{cm}^2} \left(\frac{R_m}{r_p}\right)^{n-1} |\Delta C_n| \tag{10}$$

SENSITIVITY TO ERRORS

We develop here some calculations to determine the sensitivity of the parameters we propose to use to characterize to measurement errors. As the previous relations are deduced from the ΔC_n, we propose to investigate the influence of the harmonic differences modulus ($|\Delta C_n| = d_n$) and argument ($Arg[\Delta C_n] = \theta_n$) errors on the parameters. The errors are defined respectively as ϵ_{d_n} and ϵ_{θ_n}, respectively for the modulus and the argument (see Eq. 11).

$$\Delta C_n^{real} = (d_n + \epsilon_{d_n}) \, e^{i \, \theta_n + \epsilon_{\theta_n}} \tag{11}$$

If ϵ_{β_m} is the error on β_m defined by Eq. 7 then we get:

$$\epsilon_{\beta_m} = \beta_m^{Real} - \beta_m = 2 \, \epsilon_{\theta_n} \tag{12}$$

Then, we can deduce the error (ϵ_{ϕ_m}) performed on the cylinder orientation angle (ϕ_m):

$$\epsilon_{\phi_m} = \phi_m^{Real} - \phi_m = (2n+3)\epsilon_{\theta_n} + \frac{\epsilon_{\delta_{\phi_m}}}{2} \tag{13}$$

$\epsilon_{\delta_{\phi_m}}$ represents the error performed on the measurement of the cylinder magnetization orientation ϕ_m.

The same calculation can be led for ϵ_{R_m}:

$$\begin{aligned}\epsilon_{R_m} &= R_m^{Real} - R_m \\ &= r_p \left(\frac{n+1}{n} - \frac{R_m}{r_p}\right) \frac{\epsilon_{dn}}{d_{n+1} + \epsilon_{d_n}}\end{aligned} \tag{14}$$

Two remarks can be formulated concerning the minimization of ϵ_{R_m} (See Eq. 14).

- The harmonic order (n) can be chosen to reduce the difference in the parenthesis which depends on the ratio between R_m and r_p,
- getting d_{n+1} as big as possible will minimize the effect of the error on the harmonic difference modulus (ϵ_{d_n}).

We can also evaluate the error through dimensionless variables which could be more convenient for the next calculations. We then define k_{d_n}:

$$k_{d_n} = \frac{\epsilon_{d_n}}{d_n} \tag{15}$$

$$d_n^{Real} = d_n + \epsilon_{d_n} = d_n(1 + k_{d_n}) \tag{16}$$

In the most unfavorable case we take $k_{d_n} = Max[k_{d_n}, k_{d_{n+1}}]$:

$$k_{R_m} = \frac{\epsilon_{R_m}}{R_m} \tag{17}$$

$$= \frac{1}{R_m} \left(\frac{n+1}{n} r_p \frac{d_n(1+k_{d_n})}{d_{n+1}(1-k_{d_n})} - R_m\right) \approx 2k_{d_n} \tag{18}$$

We can finally deduce $k_{B_{rm}}$ with the assumptions that possible errors on the mechanical measurements of L_m and r_{cm} are too small to disturb the determination of B_{rm}.

$$k_{B_{rm}} = \frac{\epsilon_{B_{rm}}}{B_{rm}} \approx (1+4k_{d_n})(1+2k_{d_n})^{n-1} - 1 \quad (19)$$

EXPERIMENTAL DATA

We have begun testing the method presented with a 16 cylinder PMHCR whose nominal parameters have been designed as:

- $R_m = 68\,mm$, $r_{cm} = 9.5\,mm$, $L_m = 6.25\,mm$,
- $\beta_m = m\frac{\pi}{8} - \frac{\pi}{16}$, $B_{rm} = 1.04\,T \pm 2\%$

To tune the ϕ_m angles without the method we are proposing, we have to rely on the magnetization orientation marked on the cylinder ($\pm 1°$ accuracy). Moreover as these cylinders are tuned manually with a $360°$ graduated disk, it adds an additional error of $\pm 0.5°$. If it is performed without the magnetic measurement method, the ϕ_m are then tuned with only a $\pm 1.5°$ accuracy ($\pm 26\,10^{-3}\,rad$).

According to Eq. 4, the maximum dipole and quadrupole component variation we could expect to measure ($\delta\phi_m = \pi$) at a $25\,mm$ reference radius (r_p) are:

- Dipole: $dc_1 = |\Delta C_1| = 1.27\,10^{-4}\,T.m$,
- Quadrupole: $dc_2 = |\Delta C_2| = 0.94\,10^{-4}\,T.m$

Expected Measurement Sensitivity

This PMHCR has been measured with a 400 hundred-turn rotating coil which largest radius is 25 mm. The reproducibility of the measurement bench could be evaluated to $\pm 4\,10^{-7}\,T.m$ for the harmonic modulus ($|C_n|$) and $2.10^{-3} rad$ for their arguments. From these reproducibility measurements we can deduce how the harmonic differences are affected and we get: $3.10^{-6}\,T.m$ for ϵ_{d_n} and $2\,10^{-2}\,rad$ for ϵ_{θ_n}.

The ϕ_m angles are measured with a 4000 points per turn encoder which leaves us with an uncertainty on $\delta\phi_m$ of $1.6\,10^{-3}\,rad$. We can then deduce how accurately the parameters can be determined with the Eq. 12, 13, 14 and 19. By working with the dipole and the quadrupole components, we obtain:

- $\epsilon_{\beta_m} = 4.10^{-3} rad$, $\epsilon_{\phi_m} = 11.6\,10^{-3}\,rad$,
- $\epsilon_{R_m} \approx 0.5\,mm$, $\epsilon_{B_{rm}} = B_{rm} * k_{B_{rm}} = 0.13\,T$

These errors are not small enough to obtain a sharp parameter characterization but it should allow us to check the order of magnitude of the measured parameters.

Parameters Measurements

We measured the parameters for 2 diametrically opposed cylinders (m=2 and m=10) and we worked on the dipole and quadrupole differences.

Table 1: Parameter comparison: design vs measurements

		$\beta_m\ (rad)$	$R_m\ (mm)$	$B_{rm}\ (T)$
m=2	Design	0.59	68	1.04
	Measured	0.568	69.7	1.01
m=10	Design	-2.55	68	1.04
	Measured	-2.61	70.8	1.12

Concerning ϕ_m, we took 2 successive measurements with 2 different δ_{ϕ_m} to validate Eq. 8 and obtained: $\phi_{10}^{Meas1} = 0.87\,rad$ and $\phi_{10}^{Meas2} = 4.26\,rad$. The difference between these measurements ($3.39\,rad$) has to be compared with the real rotation applied to the cylinder ($3.28\,rad$).

The results from table 1 and the previous experiment shows that the measured values are of the right order of magnitude. However these parameter measurements are not accurate enough (especially for R_m) to provide a better harmonic content than the one obtained with the imperfections [1].

CONCLUSION

We proposed here a method that would lower the PMHCR correction error levels since this method is meant to determine the uncertainties about the parameters of assembled PMHCR. The measurements showed earlier could be more accurate if obtained from an adapted rotating coil. Indeed, the rotating coil we used had a 25 mm measurement radius compared to the 55 mm bore radius of the PMHCR we studied. However, even with a small radius rotating coil, it was possible to lower by a factor of 2 the accuracy on the magnetization orientation(ϕ_m) and have a reasonable accuracy on the other parameters determination (β_m, R_m and B_{rm}) to verify their related formulae.

The next step of this work is to characterize completely the PMHCR with a rotating coil sensor dedicated to it. Once these parameters will be known, the final step would be to generate a proper correction scheme and apply it to determine the magnetic field the PMHCR should provide. Then a magnetic measurement will check how pure the correction provided by the corrected PMHCR is.

REFERENCES

[1] R.D. Schlueter, D. Humphries and J. Tanabe, Permanent Magnet Harmonic Corrector Ring, Nuclear Instruments and Methods in Physiscs Research A, VOL. 395, pp 153-158, 1997.

[2] S. Marks, R. Schlueter, D. Anderson, W. Gath, J.Y. Jung, D. Robin, C. Steier and T. Stevens, New Chicane Magnet Design for Insertion Device Straights at the Advanced Light Source, IEEE Transactions on Applied Superconductivity, VOL. 12, NO. 1, 2002.