TESTING AND COMMISSIONING OF THE ALS ADJUSTABLE, HYSTERESIS-FREE CHICANE MAGNET

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Abstract

The magnetic performance and commissioning of a new Advanced Light Source (ALS) chicane magnet are presented. The new magnet is iron free using permanent magnet rotors and trim coils, resulting in hysteresis-free operation. The theory and method for magnetic adjustments are discussed. Results of adjustments are presented that produce a maximum dipole field and reduce unallowed harmonics to below the required level of $|b_n/b_1| < 3\times 10^{-3}$.

INTRODUCTION

Chicane magnets are used in Advanced Light Source (ALS) straights where two insertion devices are installed. The chicane provides an approximately 2.5 mrad angular separation between the two photon fans. A new iron free chicane magnet has been installed which employs a ring of counter-rotating permanent magnet pairs to create an adjustable dipole field for operation between 1.5 and 1.9 GeV. A previous iron core chicane magnet did not achieve the required precision for fast steering corrections due to magnetic hysteresis.

The theory and design of the new chicane have been previously reported [1, 2]. This paper presents the concepts and results of the procedure for magnet adjustments to maximize dipole and minimize unallowed multipoles.

Summary of Magnet Features

The chicane magnet design is iron free to eliminate magnetic hysteresis. Fig. 1 shows the magnet tuners and coil configuration. Coils are used for fast feed back steering correction. The primary field is provided by six NdFeB permanent magnet (PM) pairs. A cylindrical pair consists of two coaxial cylindrical magnets oriented parallel to the beam axis. The magnetic orientation is perpendicular to the axis. Two cylinders can be counter rotated to adjust the effective strength of the pair. Each magnet is enclosed in an aluminum case. The total magnetic length of a pair, L, is 7 cm (each magnet is 3.5 cm). The six magnet pairs are equally spaced in azimuth. A system of two chain drives with independent micro-stepping motors and encoders connects six rotor sets to control cylinder pair counter rotation.. Chain sprocket clamps are used at each rotor to allow for relative orientation adjustment. After final adjustments, the clamps are spot welded to the sprockets to hold them permanently. The drive system insures that changes in counter rotation is the same for each cylinder pair.

Requirements

Table 1 shows the integrated dipole fields corresponding to a 2.5 mrad bend for the storage ring operating energies of 1.5 and 1.9 GeV. The required multipole tolerance is $|b_n/b_1| < 3\times 10^{-3}$. The required fast feed back correction of magnitudes are $\pm 2\times 10^{-4}$ T-m for vertical steering and $\pm 7\times 10^{-5}$ T-m for horizontal steering.

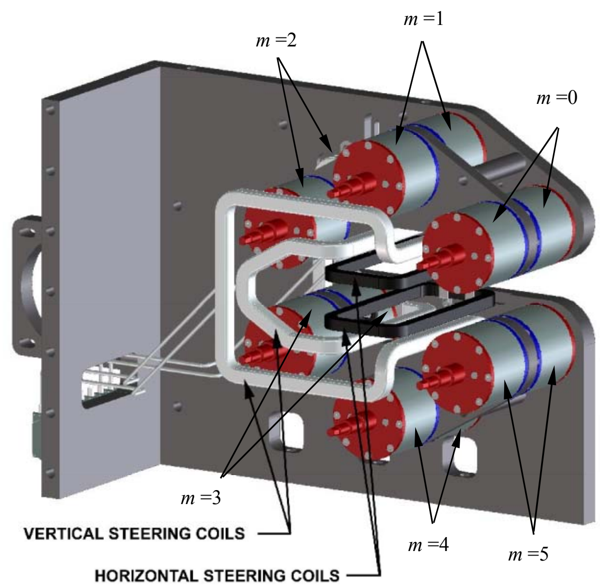

Figure 1: Chicane magnet tuners and steering coils

Table 1: Integrated dipole field corresponding to 2.5 mrad

Beam (GeV)	Integrated Dipole field (T-m)
1.5	1.251×10^{-2}
1.9	1.584×10^{-2}

Ideal Magnet Configuration

Table 2 shows the ideal dipole rotor configuration. Rotor azimuth relative to beam center is designated as β_m. Rotor angular magnetic orientation, or rotation, about the rotor center is designated as ϕ_m. The rotor number designation is shown in Fig. 1. Note that in this context a cylinder pair is designated as a rotor.

Table 2: Magnetic configuration

rotor, m	0	1	2	3	4	5
azimuth, β_m (deg.)	30	90	150	210	270	330
easy-axis orient., ϕ_m (deg.)	330	90	210	330	90	210

The ideal dipole configuration also generates allowed higher order multipoles. The multipole expansion of magnetic field integral $I^*(z)$ for the corrector ring of rotors with M cylinder pairs spaced uniformly in azimuth with pairs counter rotated $\pm\eta$ is

$$I^*(z) = \sum_{n=1}^{\infty} b_n z^{n-1};\ b_n = \frac{B_r L n r_c^2}{2R^{n+1}} \sum_{m=0}^{M-1} e^{-i(n+1)\beta_m + i\phi_m} \cos\eta_m \quad (1)$$

per Eq. 4, Ref. [1]. For the magnet considered here $M = 6$, $L = 7$ cm, rotor radius $r_c = 2.03$ cm, and $R = 7.5$ cm. Using these values in Eq. 1 with an assumed $B_r = 1.2$ T, the maximum dipole is $b_1 = i1.85\times10^{-2}$. The first two allowed multipoles are: $b_7/b_1 = i3.69\times10^{-5}$ and $b_{13}/b_1 = i3.85\times10^{-10}$ at reference radius $r_p = 1$ cm. The dipole strength can be reduced relative to the maximum by a factor of $\cos(\eta)$, where η is the counter rotation angle of all cylinder pairs.

SOURCES OF ERROR

The above discussion pertains to the ideal device where perfect six fold symmetry is maintained. Deviations from symmetry will result in a reduction in dipole strength as well as the introduction of new higher order multipoles. In particular, nonuniformity in the either the magnetic strength or length of rotors will result in errors. Backlash in the drive system will result in orientation and counter rotation errors.

Perturbations to the magnetic structure can be considered in the context of Eq. 2 below, per Eq. 19, Ref [1].

$$\delta P \frac{dI^*(z)}{dP} =$$
$$\sum_{n=1}^{\infty} \left\{ g_n \left(\frac{r_p}{R_m}\right)^{n-1} B_{r_m} L_m \left(\frac{r_{c_m}}{R_m}\right)^2 \right\} e^{i(\phi_m - (n+1)\beta_m)} \left(\frac{z}{r_p}\right)^{n-1} \quad (2)$$

The kernel, g_n, is specific to the particular error type. We will consider three error types, tabulated below with the specific kernel definitions.

- Strength errors: $g_n = (n/2)\left(\delta B_{r_m}/B_r\right)$,
- Orientation errors: $g_n = (n/2)\delta\varphi_m$,
- Counter rotation errors: $g_n = (n/2)\delta\cos\eta_m$.

For example, consider a 1% perturbation, due to either $\delta B_{r_m}/B_r$, $\delta\varphi_m$ or $\delta\cos\eta_m$, at rotor $m = 0$. This will result in an integrated dipole error of $\delta I^*/|I^*| = 0.002$, and a quadrupole error of $\delta I^*/|I^*| = 0.002 - 0.003i$

MEASUREMENT RESULTS

To maximize the dipole and minimize unallowed multipoles, each rotor is first carefully adjusted to the orientation ϕ_m given by Table 2, with counter rotation $\eta_m = 0^o$. Using a rotating field measurement coil, the multipoles are measured. Adjustments and measurements are iterated until the maximum dipole field is achieved. The measured maximum dipole field, 1.78×10^{-2} T-m is 3.4% less than the analytical expectation, as given above. This difference can arise from an inaccurate B_r assumption, the deviation from unity of dB/dH in the permanent magnet, or from measurement inaccuracy.

Over the range of interest of strength variation, corresponding to $25^o < \eta < 45^o$, it was found that the largest error term was the skew quad, which assumed its largest normalized value $B_2/C_1 = 3\times10^{-3}$ at $\eta = 40^o$ (See Table 3, left half). An advantageous feature of the PM ring is that unallowed harmonics may be nulled via slight adjustments of rotor orientations and counter rotations, so as to add vectorially to the existing magnetization vectors a new [e.g. skew quad] multipole contribution that is the negative of the existing error term.

This could effectively be a superposed Halbach six element PM quadrupole [3] per Eq.8, ref [1] with higher harmonics n=8, 14, etc. Though such a set of vectoral additions would themselves be symmetric, application to the exiting dipole configuration orientation would entail slight adjustments in both $\delta\phi_m$ and $\delta\eta_m$ unique to each individual rotor pair. Moreover, these are of the same order of magnitude as the orientation accuracy of the cylinders, which makes their adjustment a delicate task.

Table 3: Normalized multipoles before and after nulling the skew quadrupole at $\eta = 40^o$. Dipole strength $C_1/r_p = 1.31\times10^{-2}$ T-m before and 1.33×10^{-2} T-m after nulling.

	Before ($\times10^{-3}$)		After ($\times10^{-3}$)	
N	A_n/C_1	B_n/C_1	A_n/C_1	B_n/C_1
2	-1.57	-9.92	0.87	-1.37
3	-3.52	2.35	-1.86	0.51
4	0.72	1.98	-0.03	0.55
5	-0.81	0.67	-0.33	-0.13
6	0.48	0.08	0.21	-0.02
7	-0.05	0.33	0.06	0.12

Alternatively, the skew quad can be modulated as shown below, utilizing only equal counter rotations $\delta\eta_m$ of perturbed cylinder pairs 1&4 and/or pairs 0,2,3,&5 with existing orientations $\delta\phi_m$ unchanged.

Nulling the skew quad with magnetization perturbations ε_1 via identical counter rotations of cylinders in pair m=1 and in pair m=4 and/or pertubations ε_2 for identical counter rotations of pairs m=0, 2, 3 and 5 as shown in Fig. 2 generates a [skew] quadrupole (Eq. 1):

$$b_2 = \sum_{m=0,4} b_2\big|_m + \sum_{m=0,2,3,5} b_2\big|_m = 0.14\,\varepsilon_2 - 0.14\,\varepsilon_1 \quad (3)$$

Perturbation adjustments can be iterated to fully null the resultant skew quadrupole term at the energization excitation strength corresponding to the initial $\eta = 40^o$. Higher order harmonics introduced, n = 4,6,8 etc. are smaller in magnitude.

$$I^*(z) = \sum_{n=1}^{\infty} i \frac{nC_n}{r_p} \left(\frac{z}{r_p} \right)^{(n-1)}, \text{ where } C_n \equiv A_n + iB_n \qquad (4)$$

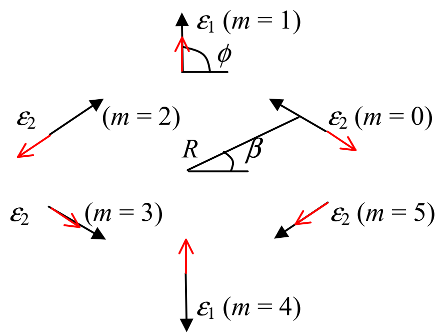

Figure 2: Skew quad nulling scheme, with field with design dipole orientation shown with red arrows and the nulling magnetization perturbations show in black.

Table 3 shows normalized multipoles before and after adjustment at r_p =1 cm, $\eta = 40^o$ where integrated field, $I^*(z)$ (Eq. 4). As can be seen, after the adjustment the normalized skew quadrupole $B_2/|C_1|$ meets the requirement as well as other higher multipoles. For n = 7, $b_7/b_1 = i5.901\times 10^{-5}$ - 1.230×10^{-4} which is higher than the expected design value $b_7/b_1 = i3.933\times 10^{-5}$ by Eq. 1. Part of the reason is because the measurement accuracy including electronic noise (~ 5×10^{-6} T-m) is the order of 1×10^{-5} T-m.

Table 4 shows normalized multipoles at $\eta = 25^o$, corresponding to a 2.5mrad kick at ~1.5GeV operation, before and after adjustment. All multipoles meet the requirement after adjustment.

Table 4: Normalized multipoles at η =25^o before and after the η =40^o skew quadrupole nulling. The dipole C_1/ r_p = 1.58×10^{-2} T-m before and 1.60×10^{-2} T-m after nulling.

	Before ($\times 10^{-3}$)		After ($\times 10^{-3}$)	
N	A_n/C_1	B_n/C_1	A_n/C_1	B_n/C_1
2	-1.48	-4.95	0.39	-1.52
3	-3.88	2.19	-2.24	0.85
4	0.88	1.85	0.05	0.69
5	-0.89	0.61	-0.22	-0.08
6	0.35	0.14	0.23	-0.07
7	0.04	0.41	0.03	0.01

More exactly, It is found that 2.5 mrad kick at 1.9 GeV can be obtained at 26.1^o of counter rotation, while 43.9^o produces the same kick at 1.5 GeV. Table 5 shows normalized multipoles at counter rotations $\eta = 0^o$, where the dipole field is maximized.

During the counter rotation from $\eta = 0^o$ to $\eta = 90^o$, the chain slack/backlash reduces the reproducibility of the magnetic field around $\eta = 90^o$.

There are some limitations for adjusting tuners. Sprockets are rotated by wrench. Since the wrench is not perfectly fit to the sprockets, it generates about 1^o error which is acceptable. Instead of using a chain driving system for counter rotation of magnets, motors can be directly attached to the tuners so that each tuner can be adjusted by the motor. This driving system may have electronic noise problem due to motors and motor drives. Motor drives for operating counter rotation of the tuners generate the noise to the measurement system. This noise can affect and interrupt the measurement. But in the current operation, since the motor drives are far from the magnets, there is no noise problem of motor drives.

Table 5: Normalized multipoles at $\eta = 0^o$. Dipole strength $C_1/ r_p = 1.78\times 10^{-2}$ T-m.

n	$A_n/C_1\times 10^{-3}$	$B_n/C_1\times 10^{-3}$
2	0.66	-3.64
3	-2.92	1.46
4	0.15	0.59
5	-0.36	-0.17
6	0.16	-0.09
7	0.13	0.10

CONCLUSION

After the magnetic adjustment of rotors, the new hysteresis-free chicane magnet can generate the required dipole field. Also, the multipoles of the magnet meet the requirement. The existing iron core chicane magnet is replaced with the new iron free chicane magnet.

ACKNOWLEDGEMENT

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