PERMANENT MAGNET SKEW QUADRUPOLES FOR THE LOW EMITTANCE LER LATTICE OF PEP-II*

F.-J. Decker, S. Anderson, D. Kharakh, M. Sullivan, SLAC, CA 94025, U.S.A.

Abstract

The vertical emittance of the low energy ring (LER) in the PEP-II B-Factory was reduced by using skew quadrupoles consisting of permanent magnet material. The advantages over electric quadrupoles or rotating existing normal quadrupoles are discussed. To assure a high field quality, a Biot-Savart calculation was used to cancel the natural 12-pole component by using different size poles over a few layers. A magnetic measurement confirmed the high quality of the magnets. After installation and adjusting the original electric 12 skew and 16 normal quadrupoles the emittance contribution from the region close to the interaction point, which was the biggest part in the original design, was considerably reduced.

INTRODUCTION

To strengthen the vertical behavior of the LER beam, a low emittance lattice was developed [1]. It lowered the original vertical design emittance from 0.54 nm-rad to 0.034 nm-rad. In order to achieve this, additional skew quadrupoles were required to bring the coupling correction out of the arcs and closer to the detector solenoid in the straight (Fig. 1). It is important, together with low vertical dispersion, that the low vertical emittance is not coupled into the horizontal, which is what we get if the coupling correction continues into the arcs. Further details of the lattice work is described in another paper [1]; here we concentrate on the development of the permanent skew (PSK) quadrupole solution.

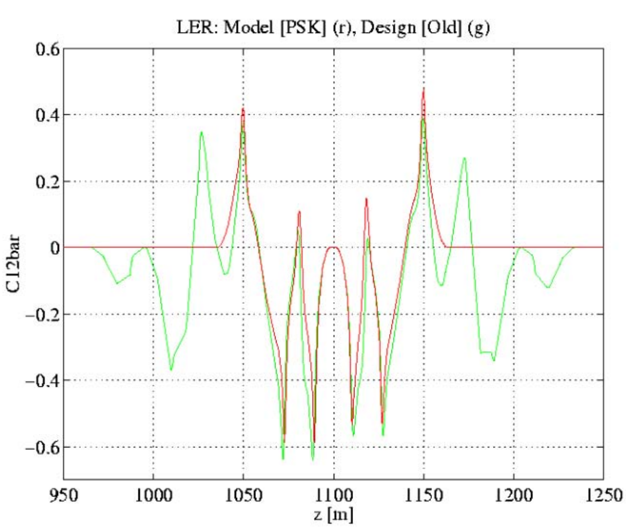

Figure 1: Coupling parameter C12bar for the original design (green) and the permanent skew lattice (red).

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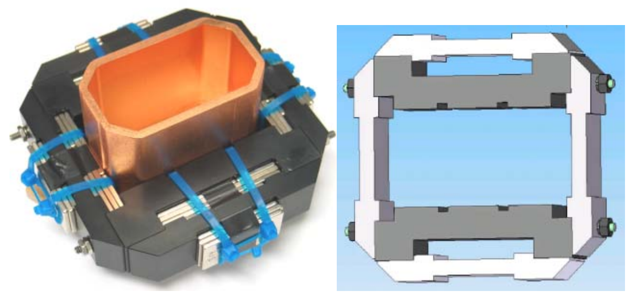

Figure 2: Layout of the frame (right) holding the permanent magnets close to the octagonal beam pipe (left).

Besides the permanent magnets there are two other possibilities, using electric magnets or rotating normal quadrupoles. Electric magnets would have required much more additional equipment like magnets stands, power supply, and new vacuum chamber sections. Rotating existing quadrupoles was also not feasible since they are mostly mounted together with a bending magnet on the same support girder.

PERMANENT MAGNET DESIGN

Mechanical Design

The design of the permanent magnet skew quadrupoles had many constraints and was very interrelated with the design of the lattice. For lattice purposes it was necessary to get only two additional skew quadrupoles on each side of the interaction point However, space for these stronger magnets was not available. There were only a few longitudinal spaces just under 1.5” to 2” available, mostly after a mask and a bellow, where the side cooling was interrupted for that distance (see Fig. 3). So the width of the frame was set to 1¼”, and it could hold four or seven layers of 1/8” magnets. This led to a total of 12 additional skew magnets. The upper three layers could slide slightly longitudinally against the lower four layers. This allowed the lower layers to fit under the mounting bolts of the nearby flange. Figure 2 shows the aluminum frame design and a 1.5 kG skew quadrupole magnet around a beam chamber.

Different Magnet Values

To restrict the number of different magnets to build and to use commercially available NdFeB magnet pieces [2], we planned for 1”, 1.5” and 2” long magnets consisting of 4 or 7 layers of 1/8” thick pieces. This gives an array of 1.0, 1.5, and 2.0 kG integrated strengths skew quadrupoles for 4 layers and 35% more for 7 layers. We mainly used seven layer skew quadrupoles with standard values of 1.35, 2.025, 2.70 kG, except for two on each side which were used for fine tuning (see Tab. 1).

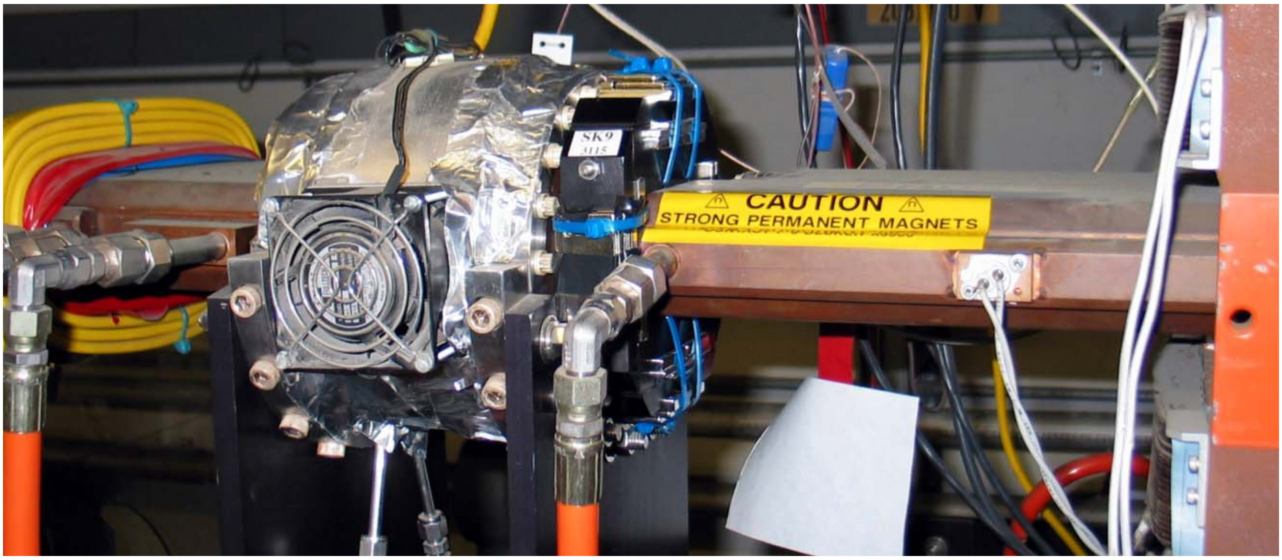

Figure 3: Permanent magnet skew quadrupole (SK9) installed on the beam line. The space for these magnets is very restricted, there is about a 1.5 to 2 inch gap in the cooling channel on the side just after a bellow (with fan here). Solenoid windings (yellow, left) to suppress electron cloud were sometimes in the way and had to be cut by a few windings. The iron of the quadrupoles or correctors (orange, right) should be far enough not to influence the field. The only magnetic metal near the skew quadrupole is the water pipe fitting at the orange hose (middle).

Skew Quadrupole	B*L [kG] simulated	Int. B*L [T] measured at 12mm	Sextupole [% deg]	Octupole [% deg]	10-pole [% deg]	12-pole [% deg]
SK7	-1.35	0.1370 S 89	0.361 -12	0.128 -5	0.035 -31	0.086 -21
SK8	-1.535	0.1505 S 86	0.700 -18	0.219 -7	0.031 15	0.040 19
SK9	-2.025	0.2009 S 84	0.887 -32	0.252 18	0.056 -5	0.069 21
SK10	-2.025	0.2006 S 89	0.701 -28	0.166 -15	0.028 -34	0.071 -27
SK12	-2.0935	0.2089 S 86	0.781 -17	0.154 -14	0.024 16	0.082 25
SK13	2.025	0.2053 N -3	0.573 24	0.269 -20	0.017 12	0.035 11
SK15	2.70	0.2688 N -3	0.331 23	0.258 28	0.097 16	0.074 -1
SK7L	1.3087	0.1312 N -6	0.435 26	0.218 -27	0.067 7	0.030 12
SK9L	2.025	0.2008 N -4	0.436 49	0.240 31	0.066 1	0.093 3
SK10L	2.025	0.2036 N -3	0.579 56	0.158 33	0.048 -1	0.104 -1
SK11L	1.8028	0.1847 N -8	0.456 37	0.206 -28	0.057 -31	0.069 1
SK15L	-2.70	0.2662 S 86	0.259 -12	0.204 -18	0.120 -20	0.023 23

Table 1: Measured field strength and higher order multipoles of the 12 installed permanent magnet skew quadrupoles.

Magnetic Measurement Summary

All 12 assembled skew quadrupoles were measured with a rotating coil setup to high precision. The integrated strengths of the skew quadrupole fields are within ±1.5% of that expected from simulation. The polarities are correct, north on top of the skew quad corresponds to a +value in MAD. The 12-pole (next "natural" harmonic of a quad) is 0.1% or lower. The sextupole component is about 0.6±0.2% at an angle of around +30 deg for the north pole (or -30 deg for the south pole) on top. This seems to point to external iron being excited by the quadrupoles during measurement. The same effect might cause that the skew quadrupole fields seem to be rotated by -4±2 deg. Thus, not shielding the magnets leads to the worry that the water hose fitting for the nearby cooling bar might create some multi-poles.

Reducing 12-pole Component

Before measuring the final magnets, Biot Savart calculations of the individual rectangular layers were performed to compensate the natural 12-pole component of this setup. Using two 3" wide pieces and two 2" wide for the four layers with a 2 mm spacer (tooth pick) on layer 3 the 12-pole is effectively eliminated (<1E-5 kG), while the 20-pole becomes visible (6E-5 kG at 20 mm radius, see Fig. 4). This compensation worked fine since the 12-pole component is not any worse than the other components when comparing in Tab. 1.

While this is a nice theoretical result the real magnets come with grade specifications (e.g. N42) with 5% strength intervals, so the magnet blocks should be between ±2.5%. Measurements showed a wider spread.

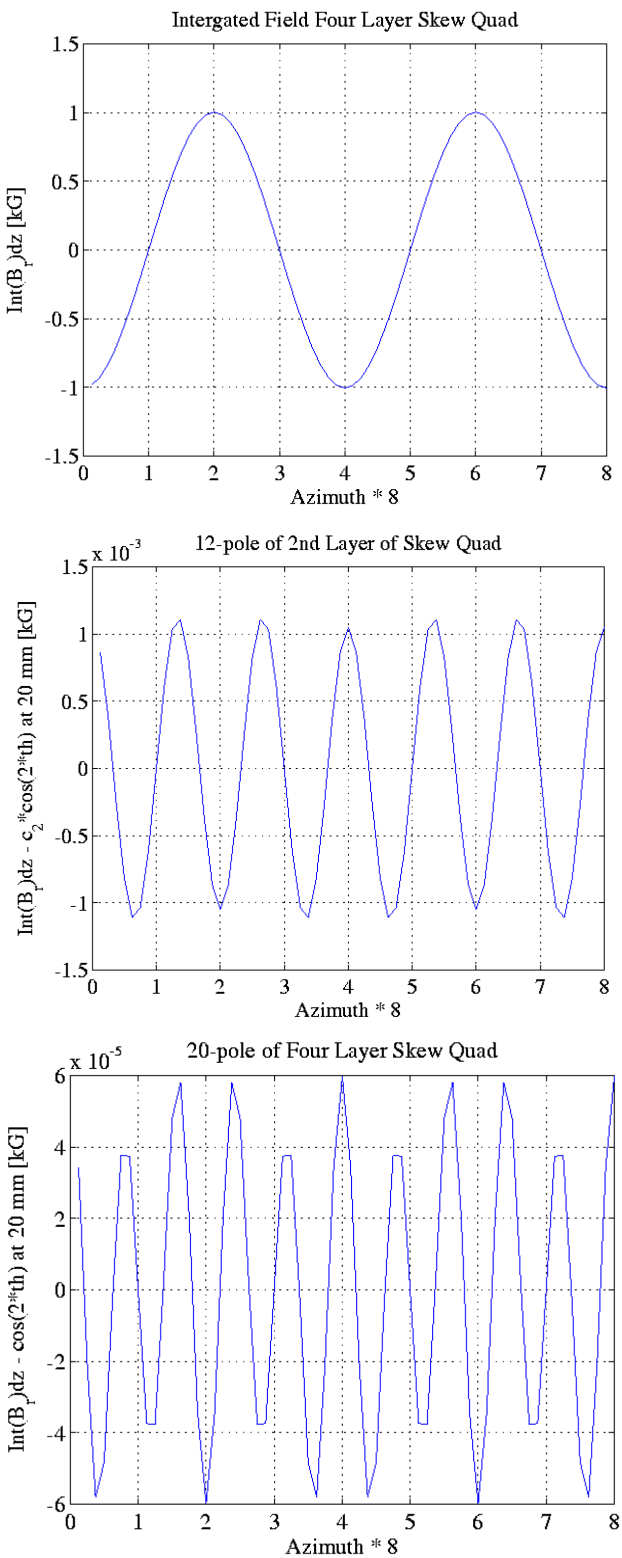

Figure 4: Theoretical integrated field of the skew quad indicates mainly a quadrupole (top), while subtracting a pure quadrupole results in some small, mainly 20-pole component (bottom). The 12-pole of a single layer (middle) is about 20 times bigger.

Hall Probe Measurements

A Hall probe was used to measure the individual blocks. Since the field in the middle of a surface is much smaller than at the edge or even in a corner, the Hall probe was setup at a distance (1¼") where the field is more uniform. Differences of the measurements for the 1"x1"x1/8" pieces showed 240 to 255 Gauss, or a batch of 220 to 230 G. Some pieces which were not used were as low as 210 G and as high as 280 G giving a range of 30%.

Some of the longer pieces (2"x1"x1/8") even had a gradient along their length and the thicker pieces (1/4") had opposite poles some times showing different values like 640/-660 G indicating that they were polarized in a diverging field. This made assembling the magnets with matching pieces more time consuming.

Figure 5 shows the Hall probe measurement of the first assembled skew quadrupole, indicating a good (< 1%) agreement with simulations. This plot created some discussion, since people expected a linear response for a quadrupole. But it can be understood when thinking about the integrated strength: Near the center (r < 10 mm) the field extends in z to about 50 mm similar to the distance of the magnet blocks from the center, while near the blocks (r > 40 mm), which are 1" or about only 25 mm wide the field is more concentrated. This would explain roughly a factor of 2 squared, which is close to what we see (factor 3.5).

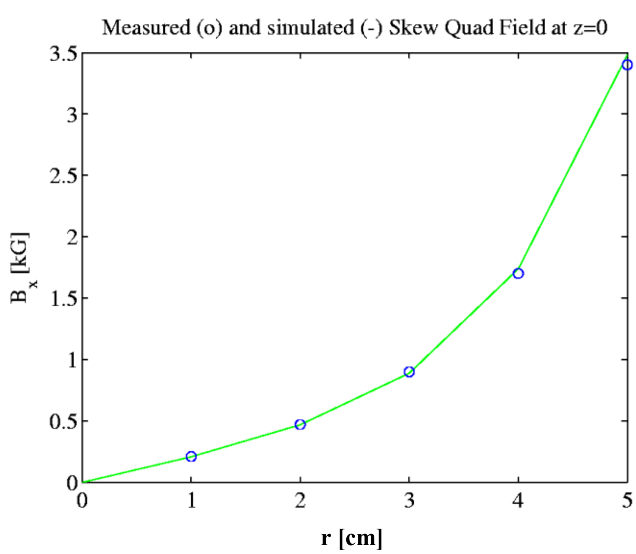

Figure 5: Point-like Hall probe measurement at center quadrupole (z=0) versus radius (going to one pole).

REFERENCES

[1] F.-J. Decker et al., "Lowering the Vertical Emittance in the LER Ring of PEP-II", PAC07, Albuquerque, June 2007.
[2] K&J Magnetics Inc. at kjmagnetics.com.