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LOWERING THE VERTICAL EMITTANCE IN THE LER RING OF PEP-II*

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Abstract

The low energy ring (LER) in the PEP-II B-Factory has a design emittance of 0.5 nm-rad in the vertical, compared to nearly 0.1 nm-rad for the HER ring. This was thought to be caused mainly by the “vertical step” of 0.89 m in the interaction region straight, where the LER beam after horizontal separation gets bend vertical so it sits on top of the HER in the rest of the ring. Since the program MAD does not easily reveal the location of the major emittance contribution, a program was written to calculate the coupled “curly H” parameter of mode 2 (mainly vertical) along z. Weighting it with the magnet bending revealed that the weak long bends inside the “vertical step” did less than 20% of the emittance growth. More than 80% comes from the last quarter of each of the adjacent arcs with strong bends. This is caused by the coupling cancellation of the solenoid starting already there with the skew quadrupoles SK5 and 6. By introducing additional skew quadrupoles in the straight instead of SK5 and 6 the emittance could be reduced by a factor of ten in simulations, but with very strong skews. Reasonable strong magnets might generate a workable compromise, since a factor of two in emittance promises 50% more luminosity in beam-beam simulations.

INTRODUCTION

The LER beam in PEP-II required continuous tuning in the vertical plane and seemed to be always the “weaker” beam. Comparing the design emittances in y it seemed nearly obvious, since the LER emittance is about 4 times higher than the HER. Initial thoughts were to lower the bending strengths with longer weaker vertical bends, but it turned out that this was not the problem, which is discussed in the first section.

Figure 1: Prototype of permanent magnet skew quadrupole with 1.0 kG integrated strength.

After identifying that the main contribution to the vertical came from design coupling correction, it was relatively quick to modify the MAD design deck to reduce the vertical emittance by more than an order of magnitude (from 0.54 to 0.03 nm-rad). But the problem was how to install 4 to 6 new skew quadrupoles with stands, power supplies, and new vacuum chambers in a time frame of less than two years, before the shut down of PEP-II. The solution was to use permanent magnet skew quads (PSK) which fit directly around the octagonal beam chamber (Fig. 1). There are 1” to 2” gaps right after a flange just before the start of a cooling bar which accommodated in the end 12 such magnets (with aluminum frames).

EMITTANCE VS Z

Non-Coupled Case

In the non-coupled case the emittances in *x* and *y* can be calculated with the “curly H” function using the following formula:

$$\varepsilon_{x,y} = 3.84 \cdot 10^{-13} \gamma^2 \frac{\langle H_{x,y} / |\rho^3| \rangle}{J_{x,y} \langle 1/\rho^2 \rangle} ,$$

$$\text{where} \quad H = \beta\eta'^2 + 2\alpha\eta\eta' + \frac{1+\alpha^2}{\beta}\eta^2 .$$

α and β are the Courant-Snyder variables and η is the dispersion function, γ is the relativistic Lorentz factor. The bending radius ρ of the magnets come in twice, once for damping $\langle 1/\rho^2 \rangle$ averaged over the whole ring, and second for the excitation in the magnet $1/|\rho|^3$. This term is multiplied by the “curly H” at that magnet and averaged to get the final emittance number. Instead of averaging we can plot the individual terms along to pinpoint the largest emittance contributors. For the LER we get 0.1 nm-rad for the *y*-emittance, while the final MAD emittance (mode 2) is 0.54 nm-rad.

Coupled Case

The coupled case can be estimated by replacing the in plane variables e.g.: $\beta_y \eta_y'^2$ for the first term of H_y with the coupled part: $\beta_{2x} \eta_x'^2$ for H_{coup}. Since the dispersion function is about 10 times bigger in *x* than in *y*, we can estimate that a small 10% coupling from mode 2 into *x* (represented by the coupled beta function β_{2x}) will result in a 10 times bigger H_{coup} and therefore emittance.

The final “curly H” for mode 2 (H_2) is achieved by adding H_y and H_{coup} with a certain phase relationship. The formulas for H_2 (=A_2) were taken from V. Lebedev [1]:

$$\frac{d\varepsilon_2}{dt} = \left\langle A_2 \frac{d}{dt} \overline{\left(\frac{\Delta p}{p}\right)^2} \right\rangle_s \qquad A_{1,2} = \mathbf{D}^T \mathbf{B}_{1,2} \mathbf{D} ,$$

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$$\begin{bmatrix} D_x \\ D'_x \\ D_y \\ D'_y \end{bmatrix} \frac{\Delta p}{p} \equiv \mathbf{D}\frac{\Delta p}{p} \qquad \mathbf{B}_2 = \left(\mathbf{V}^{-1}\right)^T \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \mathbf{V}^{-1}$$

$$\mathbf{B}_2 = \begin{bmatrix} \frac{u^2 + \alpha_{2x}^{\ 2}}{\beta_{2x}} & \alpha_{2x} & B_{2_{13}} & B_{2_{14}} \\ \alpha_{2x} & \beta_{2x} & B_{2_{23}} & \sqrt{\beta_{2x}\beta_{2y}}\cos\nu_2 \\ B_{2_{13}} & B_{2_{23}} & \frac{(1-u)^2 + \alpha_{2y}^{\ 2}}{\beta_{2y}} & \alpha_{2y} \\ B_{2_{14}} & \sqrt{\beta_{2x}\beta_{2y}}\cos\nu_2 & \alpha_{2y} & \beta_{2y} \end{bmatrix}$$

$$B_{2_{13}} = \frac{\left(u(1-u) + \alpha_{2x}\alpha_{2y}\right)\cos\nu_2 + \left(\alpha_{2x}(1-u) - \alpha_{2y}u\right)\sin\nu_2}{\sqrt{\beta_{2x}\beta_{2y}}}$$

$$B_{2_{14}} = \sqrt{\frac{\beta_{2y}}{\beta_{2x}}}\left(\alpha_{2x}\cos\nu_2 - u\sin\nu_2\right)$$

$$B_{2_{23}} = \sqrt{\frac{\beta_{2x}}{\beta_{2y}}}\left(\alpha_{2y}\cos\nu_2 + (1-u)\sin\nu_2\right)$$

These formulas were implemented in a small program using the coupled beta functions, like β_{2x} from MAD. Plotting the emittance contribution for each bending magnet and then the integral along the circumference *z*, showed that the arcs adjacent to the interaction region (IR2) generate for most of the emittance (see Fig. 2).

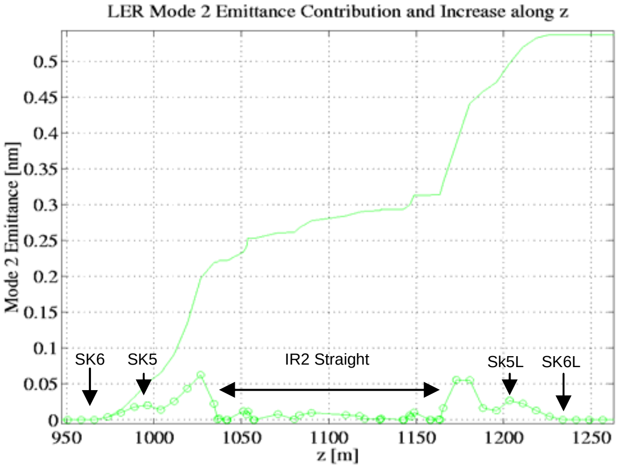

Figure 2: Mode 2 emittance growth along z.

Skew quadrupoles SK5 and SK6 on each side were originally used in a symmetric fashion to generate the necessary coupling to cancel the coupling from detector solenoid field, but keeping the vertical dispersion small. However, this creates a significant emittance growth due to coupling. To reduce this effect additional skew quadrupoles have to be added in the IR2 straight and the strength of SK5 and 6 reduced to zero.

LOW EMITTANCE LATTICE

To develop a low emittance lattice we started with the design lattice and added several skew quadrupoles at odd multiples of 90° in *y*-phase advance from the interaction point (IP), similar like the SK5/SK6 locations and lowered the strengths of SK5/6 on each side. This brought immediately the vertical emittance down by a factor of 2.5. At the same time one of us (Y. Cai) ran his beam-beam code with lower vertical emittances. The results are shown in Fig. 3 (green dots) predicting a luminosity increase from $12{\cdot}10^{33}$ to $20{\cdot}10^{33}$ /cm^2/s.

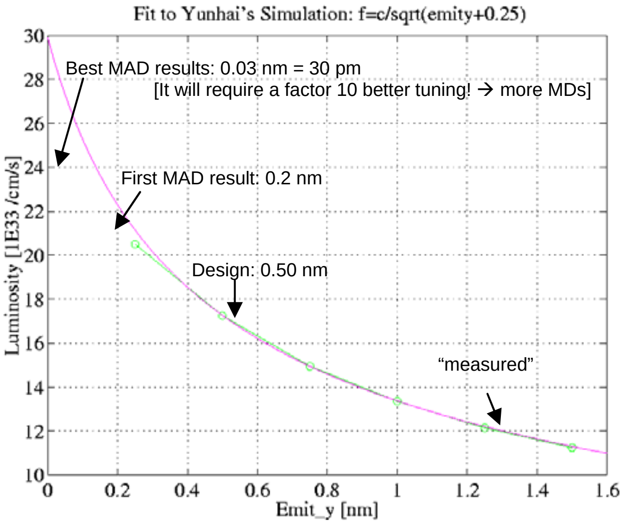

Figure 3: Luminosity vs vertical emittance.

Finally by setting SK5/6 to zero and using all possible locations for small permanent skew quads the emittance optimum went down to 0.034 nm-rad with 12 additional skew quadrupoles. The interaction region (IR) optics was kept matched to the adjacent arcs by adjusting the IR quadrupoles and correctors on each side of the IP. Figure 4 and 5 show that the coupling and dispersion correction happen much closer to the IP (at 1100 m). The dynamic aperture seemed even a little better than the original design. Recently we found that the chromatic beta function $W_x = \Delta\beta/\beta \ / \ \Delta E/E$ (and alpha terms) needed some additional adjustments [2].

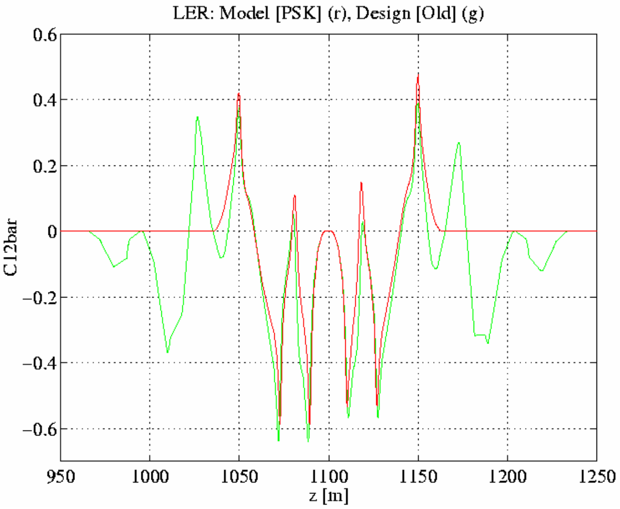

Figure 4: The coupling parameter C_{12}bar is corrected much closer to the IP in the new PSK model.

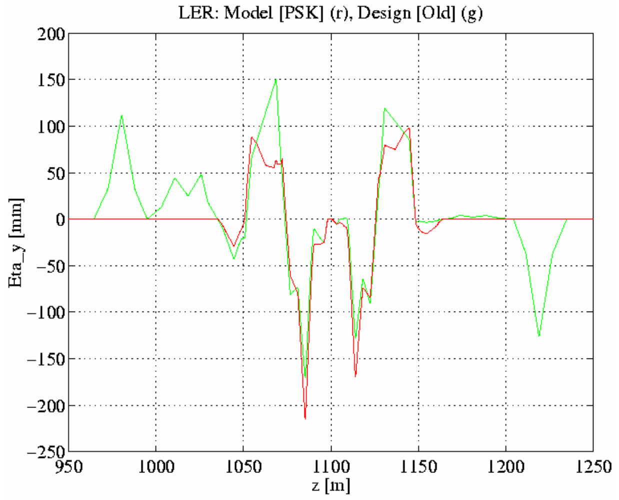

Figure 5: The vertical dispersion η_y is also corrected much closer to the IP in the new PSK model.

PERMANENT SKEW QUADRUPOLES

From the three ways to get a skew quadrupole term: electric, permanent magnet, or rotate normal quadrupole, we chose permanent magnets. The electric magnet would have required much more equipment and rotating existing quadrupoles was not feasible since they are mostly mounted together with a bending magnet on one support girder.

Default Magnet Values

To restrict number of different magnets to built and use commercially quickly available magnets [3], we planned for 1", 1.5" and 2" long magnets consisting of 4 or 7 layers of 1/8" thick magnets. 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.

Reducing 12-pole Component

Biot Savart calculations of the rectangular magnets 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 (see Fig. 1) the 12-pole is effectively eliminated (<1E-5), while the 20-pole becomes visible (6E-5 at 20 mm radius, see Fig. 6).

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.

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 it doesn't vary too much. E.g. for the 1"x1"x1/8" pieces measurements 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%.

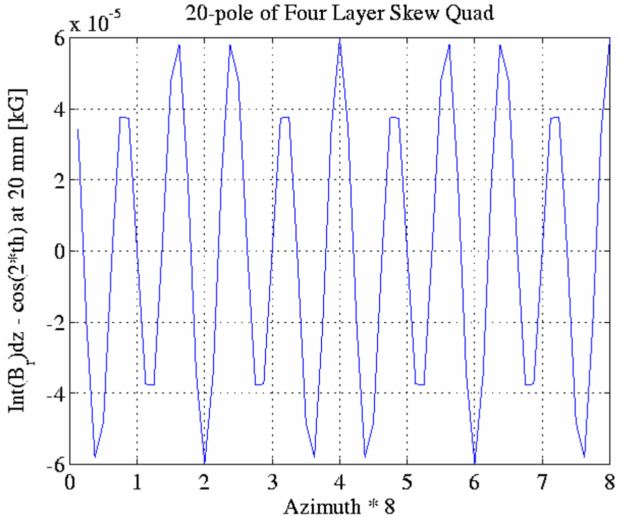

Figure 6: Theoretical higher order field of skew quad.

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

Finally all 12 assembled skew quadrupoles were measured with a rotating coil setup to high precision. The measured integrated strengths were within ±1.5% of the values used in simulations. The polarities were right with north on top of a skew quadrupole corresponding to a +value in MAD. The 12-pole term was 0.1% or lower.

A sextupole component of about 0.6±0.2% was measured at an angle of around +30 deg for north pole on top (or -30 deg for south pole). This seems to point to external iron excited by the quadrupoles during the measurement, the same effect might have caused also the measured rotation of -4±2 deg of the skew quadrupole field. These magnets were not shielded making their field susceptible to magnetic material nearby.

RESULTS

After the installation of the 12 PSK magnets and the associated adjustment of the original 12 skew and 16 normal quadrupoles, it took about a week till the LER beam became so strong that it could affect the HER lifetime. The expected drastic increase in luminosity or even specific luminosity has not been seen yet, although the LER runs typically with reduced currents, so that the HER lifetime is not too low and the specific luminosity is slightly higher.

REFERENCES

[1] Valeri Lebedev, et al., "Single and Multiple IBS in Hadron Colliders," HB-2004, October 18-22, 2004.
[2] J. Yocky, et al., "Optimization of Chromatic Optics Near the Half Integer in PEP-II," PAC'07, Albuquerque, June 2007.
[3] K&J Magnetics Inc. at kjmagnetics.com.