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Lattice with Smaller Momentum Compaction Factor for PEP-II High Energy Ring [1]

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Abstract

At present, the PEP-II bunch length and vertical beta function β_y^* at the Interaction Point (IP) are about of the same size. To increase luminosity, it is planned to gradually reduce β_y^*. For the maximum effect, bunch length has to be also reduced along with β_y^* to minimize luminosity loss caused by the hourglass effect at IP. One of the methods to achieve a smaller bunch length is to reduce momentum compaction factor. This paper discusses a lattice option for the High Energy Ring, where the nominal 60° cells in four arcs are replaced by 90° cells to reduce momentum compaction factor by 30% and bunch length by 16%. The increased focusing in 90° cells results in 40% stronger arc quadrupoles and 150% stronger arc sextupoles due to reduced dispersion and larger chromaticity. Tracking simulations predict that dynamic aperture for this lattice will be ≥ 10 times the *rms* size of a fully coupled beam for a horizontal emittance of 30 nm and $\beta_y^* = 1$ cm. The lattice modification and results of simulations are presented.

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LATTICE WITH SMALLER MOMENTUM COMPACTION FACTOR FOR PEP-II HIGH ENERGY RING [†]

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Abstract

At present, the PEP-II bunch length and vertical beta function β_y^* at the Interaction Point (IP) are about of the same size. To increase luminosity, it is planned to gradually reduce β_y^*. For the maximum effect, bunch length has to be also reduced along with β_y^* to minimize luminosity loss caused by the hourglass effect at IP. One of the methods to achieve a smaller bunch length is to reduce momentum compaction factor. This paper discusses a lattice option for the High Energy Ring, where the nominal 60° cells in four arcs are replaced by 90° cells to reduce momentum compaction factor by 30% and bunch length by 16%. The increased focusing in 90° cells results in 40% stronger arc quadrupoles and 150% stronger arc sextupoles due to reduced dispersion and larger chromaticity. Tracking simulations predict that dynamic aperture for this lattice will be ≥ 10 times the *rms* size of a fully coupled beam for a horizontal emittance of 30 nm and $\beta_y^* = 1$ cm. The lattice modification and results of simulations are presented.

INTRODUCTION

One of the methods to increase luminosity at PEP-II [1] is to reduce a vertical beta function β_y^* at the Interaction Point (IP). The current plan is to reduce β_y^* from the present value of 12.5 mm to 9 mm this year, and to ~ 5 mm within the next few years.

Due to a finite bunch length σ_s, particle interactions occur over distance $-\sigma_s/2 < s < \sigma_s/2$ from IP. Because of angular divergence $\propto 1/\sqrt{\beta_y^*}$, beam size increases with distance s from IP according to: $\sigma_y(s) = \sigma_y^* \sqrt{1 + s^2/{\beta_y^*}^2}$. As a result, contribution to luminosity is gradually reduced with distance from the beam waist at IP. This so-called "hourglass" effect can be analytically estimated and translated into a luminosity reduction factor due to a finite bunch length [2]. For flat beams with equal beam size and emittance, this factor depends only on one parameter β_y^*/σ_s and is shown in Fig. 1.

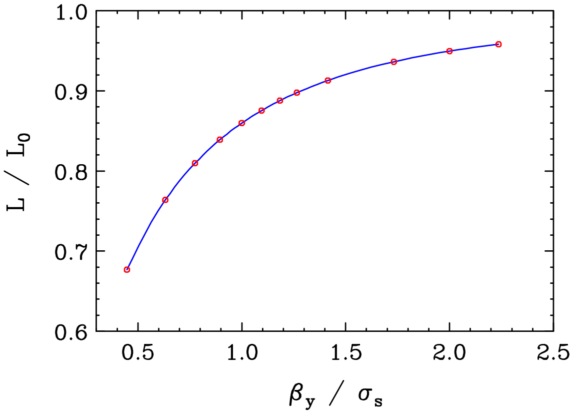

Figure 1: Luminosity reduction factor due to the hourglass effect for flat beams.

At present, the bunch length and β_y^* at PEP-II are about of the same size. According to Fig. 1, this corresponds to 14% of luminosity loss due to the hourglass effect. If β_y^* is reduced from the current 12.5 mm to 9 mm and then to 5 mm without changing σ_s, luminosity loss would increase to 21% and 35%, respectively. One can conclude, therefore, that for maximum PEP-II luminosity at lower β_y^*, bunch length has to be reduced as well.

Among other parameters, the equilibrium bunch length depends on the total accelerating rf-voltage V, momentum compaction factor α and bending radius ρ as

$$\sigma_s \propto \sqrt{\frac{\alpha}{V} \cdot \frac{\langle|1/\rho^3|\rangle}{\langle 1/\rho^2\rangle}}, \qquad (1)$$

where $\langle\rangle$ denote an average in the machine [3]. The PEP-II upgrade to increase rf-voltage for a smaller bunch length is being implemented. However, the bunch length is a relatively slow function of V, therefore many rf-cavities would be needed for a large reduction of β_y^*. To help reduce the bunch length, a reduction of momentum compaction factor may be considered.

The momentum compaction factor is defined by dispersion function η_x and bending radius ρ according to

$$\alpha = \langle \frac{\eta_x}{\rho} \rangle, \qquad (2)$$

where η_x depends on ρ and quadrupole focusing. A change of bending properties or magnet locations is not considered in this paper since it would require a modification of machine geometry. Therefore, for a fixed bending, a smaller momentum compaction factor could be achieved by reducing the average dispersion in bends by means of a stronger quadrupole focusing. Such optics modification is discussed below for the PEP-II High Energy Ring (HER) with $\beta_x^*/\beta_y^* = 50/1$ cm.

LATTICE MODIFICATION

Layout of the HER is shown in Fig. 2. The lattice consists of six arcs with periodic 60° cells and six straight sections with various matched optics for the Interaction Region (IR), injection, rf-cavities, and tune and coupling correction. The HER nominal dispersion function is shown in Fig. 3, where IP is in the middle at $s \approx 1100$ m. Modulation of η_x in the four arcs farthest from IR is introduced to

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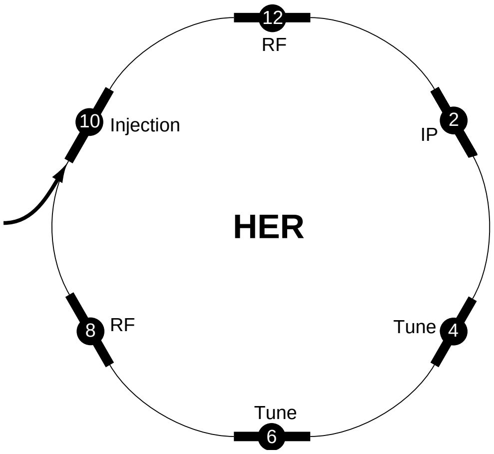

Figure 2: Top view of the High Energy Ring.

increase the HER horizontal emittance to 48 nm, while in the two arcs near IR it is caused by special β bumps for the IR sextupoles. Because in the four arcs this perturbation is a free betatron motion around the periodic η_x, it does not change the average dispersion $\langle\eta_x\rangle$ and bunch length, but increases $\langle\eta_x^2\rangle$ for a higher emittance. In the straight sections, dispersion is canceled by dispersion suppressors.

The most contribution to momentum compaction factor in HER comes from dispersion in the arcs. A simple way to reduce $\langle\eta_x\rangle$ is to increase phase advance in the periodic arc cells. The effect of phase advance per cell μ_c can be estimated using a thin lens approximation. This method gives the following well-known equations for the extreme ($\pm$) values of β and η_x, and the quadrupole integrated strength K_1L in the arc FODO cell:

$$\beta^{\pm} = L_c\,\frac{1\pm\sin(\mu_c/2)}{\sin\mu_c}, \tag{3}$$

$$\eta_x^{\pm} = \frac{L_c^2}{8\rho}\cdot\frac{2\pm\sin(\mu_c/2)}{\sin^2(\mu_c/2)}, \tag{4}$$

$$K_1L = \frac{4\sin(\mu_c/2)}{L_c}, \tag{5}$$

where L_c is a cell length. For an estimate of the average values of β and η_x in the arcs, one could use the following approximation:

$$\langle\beta\rangle \approx \frac{\beta^+ + \beta^-}{2} = \frac{L_c}{\sin\mu_c}, \tag{6}$$

$$\langle\eta_x\rangle \approx \frac{\eta_x^+ + \eta_x^-}{2} = \frac{L_c^2}{4\rho\sin^2(\mu_c/2)}. \tag{7}$$

Below, a modification of HER optics for a lower momentum compaction factor is considered, where phase advance in the four arcs farthest from IR is increased from 60° to 90° per cell. The other two arcs contain some of the IR sextupoles and skew quadrupoles to compensate the detector solenoid and non-linear chromaticity. In order to maintain the original IR optics and local correction, these two arcs were not changed.

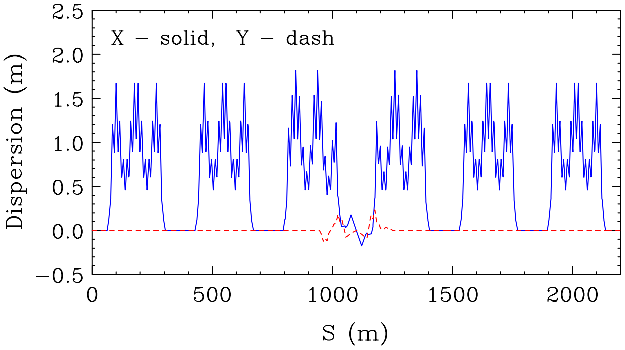

Figure 3: Dispersion in the nominal HER.

Since the maximum β functions are about the same in 60° and 90° cells, physical aperture acceptance will not be reduced by this modification. As in 60° optics, the 90° cells naturally provide $-I$ transformation between arc sextupoles to help compensate the third order sextupole aberrations. Also, the first order chromatic perturbation of β function is naturally suppressed in 90° lattice.

According to Eqn. 7, the average dispersion in 90° arc is reduced by a factor of 2 compared to 60° lattice. Consequently, the momentum compaction factor in four 90° and two 60° arcs is reduced by a factor of $\frac{2}{3}$ compared to the 60° value. From Eqn. 3–5, disadvantages of 90° cells are a factor of $\sqrt{2}$ stronger quadrupoles, a factor of $\sqrt{3}$ larger linear chromaticity per cell and a factor of $2\sqrt{2}$ stronger sextupoles ($K_2\propto K_1/\eta_x$).

To maintain the original non-dispersive optics in the injection, tuning and rf-cavity sections, quadrupole focusing in dispersion suppressors designed for 60° arcs was appropriately adjusted to match the straight sections to the new β functions and reduced dispersion in 90° arcs. One complication was related to the original design of arc sextupoles, where each of the four arcs has 12 SF and 12 SD sextupoles to correct linear chromaticity. Ideally, the same family sextupoles should have identical lattice functions to minimize residual sextupole aberrations. But in the HER, 2 SF and 2 SD sextupoles in each arc are extended into the dispersion suppressors which have different optics compared to the arcs. In the original 60° design, lattice functions at the above 4 sextupoles were made reasonably close to the periodic values in the arcs. It has been found particularly important to keep this property in the 90° modification as well. It was verified that a large change of β functions at these sextupoles could reduce dynamic aperture to unacceptable level. This is caused by an increase of the third order sextupole geometric aberrations if they are not sufficiently compensated due to breakdown of optical periodicity and $-I$ transformation at the 4 sextupoles.

The resultant dispersion in HER with four 90° arcs is shown in Fig. 4. In this option, a periodic dispersion without modulation is used in the 90° arcs, while dispersion in the two arcs near IR is not changed. Some of the HER global parameters for the original 60° and modified 90° lattice with $\beta_x^*/\beta_y^* = 50/1$ cm are shown in Table 1, where the

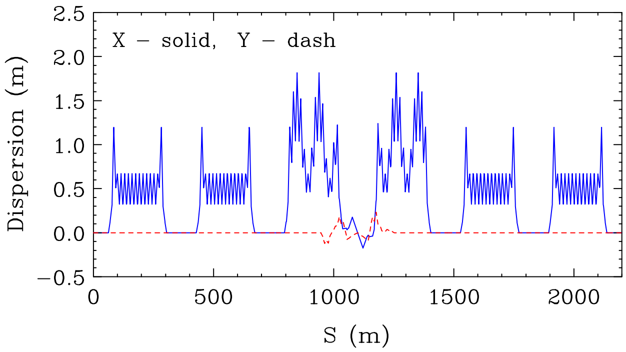

Figure 4: Dispersion in HER with reduced α.

Table 1: HER parameters for 60° and 90° lattice.

μ_c	α $[10^{-3}]$	ϵ_x [nm]	ν_x / ν_y	ν_s	ξ_x / ξ_y
60°	2.41	48	24.569 / 23.639	0.045	-44 / -71
90°	1.69	30	28.569 / 29.639	0.038	-56 / -81

total voltage of $V = 14$ MV was used.

Momentum compaction factor is reduced by 30% in the 90° modification, therefore the bunch length is expected to decrease by 16%. The reduced dispersion in 90° arcs results in a smaller horizontal emittance ϵ_x in this option. A modulation of η_x may be introduced to increase the emittance. For the same rf-voltage, synchrotron tune ν_s is also reduced by 16% since it scales as $\sqrt{\alpha V}$. If the voltage is increased for a smaller bunch length, ν_s could be restored.

Naturally, the stronger quadrupole focusing in 90° arcs increases the HER betatron tune ν_x/ν_y and linear chromaticity ξ_x/ξ_y. Quadrupole strength increases by 42% in the 90° arcs, and the SF, SD sextupoles become stronger by a factor of 2.3 and 2.5, respectively, compared to 60° design. The large increase in strength may require an upgrade for some of these magnets.

Optics and compensation schemes of the Interaction Region have not been changed in this modification. The IR sextupoles provide correction of the non-linear chromaticity generated in the final quadrupole doublets near IP. It has been important to verify that compensation of non-linear chromaticity has not been affected by arc modifications. Indeed, calculation of betatron tune and β^* in the 90° lattice versus relative momentum deviation $\frac{\Delta p}{p}$ showed a negligible change of non-linear chromaticity compared to the original optics. This confirms that the IR chromaticity correction is, indeed, local. Tune shift in the modified HER is shown in Fig. 5 for the range of $-10\sigma_p < \frac{\Delta p}{p} < 10\sigma_p$, where σ_p is the *rms* relative energy spread in the beam, and linear chromaticity is set to zero.

Finally, tracking simulations have been performed to verify dynamic aperture for the HER with 90° arcs and $\beta_y^* = 1$ cm. Simulations have been done using LEGO code [4] for 10 different combinations of random field and alignment errors, and $\pm 8\sigma_p$ synchrotron oscillations. Compensation of beam orbit, linear chromaticity, coupling and tune were simulated in LEGO prior to tracking. The resultant dynamic aperture at the injection point is shown in Fig. 6, where the 10 dash lines represent different error settings. The area inside a dash line corresponds to a particle stable motion. This dynamic aperture exceeds 10σ depicted by a solid line, where σ is the *rms* size of a fully coupled beam at injection with $\epsilon_x = 30$ nm and $\epsilon_y = \epsilon_x/2$. This dynamic aperture should be sufficient for beam operation. We conclude, therefore, that 90° optics in HER for a lower momentum compaction factor may be considered as an option for a shorter bunch length.

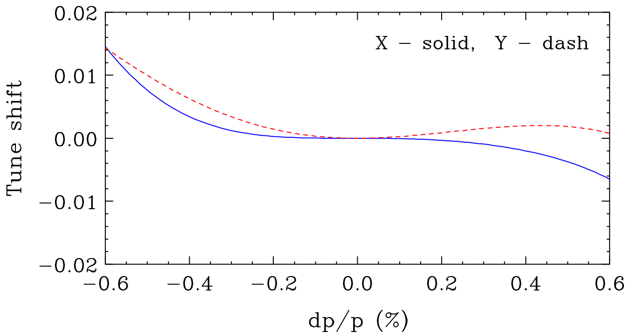

Figure 5: Tune shift vs. $\frac{\Delta p}{p}$ in HER with reduced α.

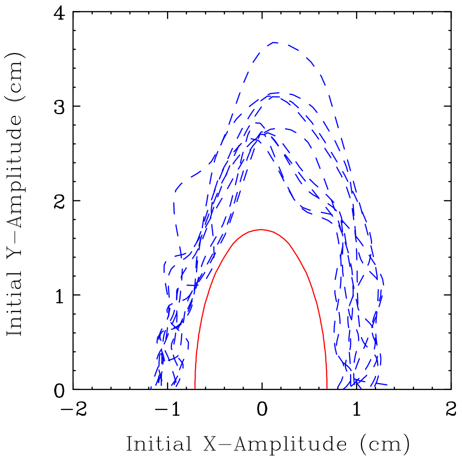

Figure 6: Dynamic aperture in HER with reduced α.

CONCLUSION

It has been shown that momentum compaction factor in HER can be reduced by 30% by increasing phase advance per cell from 60° to 90° in four arcs. The resultant dynamic aperture exceeds 10σ and is considered adequate. The expected reduction of bunch length in this option is 16%.

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