Design of the HERA-e lattice and chromaticity correction for the luminosity upgrade

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Abstract

The luminosity in HERA will be increased nearly five times by squeezing both the electrons and protons to smaller spot sizes at the interaction points (IPs). The electron spot sizes are reduced by a) additional focusing in the interaction regions (IRs) and b) increasing the horizontal phase advance per FODO cell in the arcs from 60 degrees to 90 degrees. The stronger focusing reduces the equilibrium horizontal emittance by nearly a factor of two and also increases the chromaticity. The linear and nonlinear chromaticities are corrected by a new arrangement of sextupoles. Non-interleaved sextupoles placed symmetrically about the IPs in the north and south insertions correct the nonlinear chromaticity generated in the IRs while the linear chromaticity of the ring is corrected by two families of sextupoles placed in the remaining FODO cells. Pairs of spin rotators have also been added in the north and south IRs to provide longitudinally polarized electrons for the H1 and ZEUS experiments. Additional constraints on the focusing strengths have been incorporated in the lattice to make it spin transparent and rotator strengths have been adjusted to ensure that the spin is longitudinal at the IPs even in the presence of the experimental solenoidal fields.

1   INTRODUCTION

HERA is now in the midst of planning a luminosity upgrade for the year 2000. The luminosity will be increased by squeezing both the protons and electrons to smaller spot sizes at the IPs. Stronger focusing in the interaction regions (IRs), earlier separation of the electron and proton beams and reduction of the electron emittance are the main features of the new design. The design of the IRs is described in a companion paper [1].

The equilibrium emittance of the electrons can be reduced in one of two ways: 1) changing the damping distribution with a shift in the RF frequency, or 2) by stronger focusing in the FODO cells in the arcs. The stronger focusing in the lattice increases the chromaticity and hence requires stronger sextupoles to correct the chromaticity. In turn the stronger non-linear forces reduce the dynamic aperture available to the beam. The issues that we will present here are: a) reduction of the emittance by changing the RF frequency or alternatively redesigning the focusing in the arcs, b) correction of the chromaticity by sextupoles.

1.1   Changing the Luminosity with a RF frequency shift

The transverse emittance can be reduced by increasing the horizontal damping partition number with an increase in the RF frequency. This action has several other consequences. The rms momentum spread σ_p increases but it turns out that the dynamic aperture is still acceptably large over a range of $\pm 9\sigma_p$. In order to have nearly the same quantum lifetime with the increased momentum spread, the RF voltage must also be increased. Since the normal conducting cavities are power limited, the beam current must be reduced if the voltage is increased. As a consequence of these constraints it was shown [2] that a) there is no gain in the luminosity by shifting the RF frequency if the RF acceptance (in units of the rms energy spread) is kept the same, b) if the relative RF acceptance is lowered by 15% then the luminosity can be increased only by 40%. Any further reduction in the RF acceptance shortens the quantum lifetime severely and is ruled out. From these calculations we concluded that shifting the RF frequency will not lead to the desired goal of increasing the luminosity by a factor of five. Instead the emittance must be reduced by stronger focusing in the arcs but a shift in RF frequency can be used in conjunction to increase the dynamic aperture.

If the RF frequency is kept constant but the horizontal phase advance in the FODO cells is increased to reduce the transverse emittance, then the slip factor decreases from its present value. This implies that the RF voltage can be decreased and the synchronous phase increased without any loss of RF acceptance. With a decrease in the RF voltage, the beam current can be increased, keeping the total RF power constant, and thereby increasing the luminosity further.

1.2   Electron Lattice

The electron lattice is composed of four quadrants: North, East, South and the West with the North and South quadrants being identical. Each quadrant can be further split into two mirror symmetric octants. Each octant consists of an arc with 18 FODO cells, a matching section 7 FODO cells long, a spin rotator section at present only in the East, an RF section, and then a straight section up to the interaction point. The optics and lattice changes with respect to the present machine are the following: 1) Increase of the focusing in the FODO cells. 2) Pairs of spin rotators in the North and South straight sections. 3) Redesign of the North and the South interaction regions with the two beams separated earlier (closer to the IP) and stronger focusing with quadrupoles moved closer to the IP.

Phase advances in the FODO cells   The electron equilibrium emittance is obtained as a balance between the damping of betatron oscillations due to the synchrotron radiation and excitation due to the fluctuating nature of pho-

ton emission. The emittance can also be reduced by increasing the focusing in the FODO cells. The equilibrium emittance decreases monotonically as the phase advance is increased reaching a minimum at a phase advance of $\mu^C = 135°$ before increasing again. However the chromaticity of a FODO cell increases with phase advance and the sextupole strengths required to correct the chromaticity increase even faster with the phase advance because the dispersion falls with increasing phase advance. For example the sextupole strengths required at a phase advance of 135° will be about nine times as strong as at 60°. Such large sextupole strengths will drastically reduce the dynamic aperture. A compromise choice for the horizontal phase advance which reduces the equilibrium emittance sufficiently is $\mu^C = 90°$. The equilibrium emittance of the real lattice at 27.5GeV is 22nm, about 50% higher than what a scaling relation for FODO cells would predict. In the north, south and east insertions following the spin rotators, there are sections with high dispersion in bending magnets which contribute significantly to the emittance. The vertical emittance is determined by the coupling ratio $\kappa = \epsilon_y/\epsilon_x$ and is not strongly dependent on the vertical phase advance. The optimal choice of the vertical phase advance is therefore one which minimizes the chromaticity of the whole lattice and hence reduces the required sextupole strengths.

1.3 Modular sections of the lattice

In addition to the arcs and the straight insertions, the lattice consists of sections where RF cavities are placed, spin rotators and matching sections which provide the transition from the spin rotators to the regular arcs. In the RF sections, the dispersion has to be minimized in order to avoid exciting synchro-betatron resonances, and the β functions have to be kept small so as not to increase the growth rates of the multi-bunch instabilities. Additional pairs of spin rotators will be placed in the north and south to provide longitudinal polarization for the experiments H1 and ZEUS respectively. The lattice has to be spin matched in order to minimize spin diffusion and this puts constraints on the phase advances through the north, south and east insertions. Within the matching sections the dispersion function reaches its peak values in the lattice so photon emission in these regions contributes more to the growth of the equilibrium emittance per unit length than in any other region. The matching quadrupoles must therefore be used to match into the arcs and also to minimize the peak dispersion in these regions.

2 CHROMATICITY CORRECTION

The vertical phase advance per FODO cell μ_y^C has to be chosen to minimize the vertical chromaticity of the ring. With the horizontal phase advance per cell of $\mu_x^C = 90°$, the absolute vertical chromaticity decreases as μ_y^C increases from 30°, has a minimum around 40°, is relatively flat until about 60°, and then increases monotonically thereafter. Of two possible choices $\mu_y^C = 45°$ and

$\mu_y^C = 60°$, the latter is possibly the better option because i)the smaller β_y^{max} implies that the beam will be less sensitive to field errors in the arcs and ii)in an interleaved sextupole distribution scheme only 3 sextupole families are required with $\mu_y^C = 60°$ while 4 families would be required with $\mu_y^C = 45°$. In the upgrade design we have opted for the phase advances $(\mu_x^C, \mu_y^C) = (90, 60)°$. Compared to the present HERA-e ring with 60° phase advance in both planes, the sextupole strengths will be nearly doubled in the upgrade because of the stronger focusing in the arcs and in the interaction regions.

2.1 Correcting the non-linear chromaticity

The tune shift ΔQ due to chromatic errors can be written as a power series in the relative momentum deviation $\delta = \delta p/p_0$ as $\delta Q = \xi_1 \delta + \xi_2 \delta^2 + \ldots$. The higher order chromaticities, unlike ξ_1, depend on the phase relationships between the chromatic sources. The second order chromaticity, for example, is given compactly by [3]

$$\xi_2 = -\frac{1}{8\pi} \int_0^C K(s) \Delta\beta_1(s) ds - \xi_1, \qquad (1)$$

where $\Delta\beta_1(s)$ is the first order chromatic beta wave. The interaction region quadrupoles with their large gradients and high beta functions are the primary sources of the chromatic beta wave propagating in the ring. This beta wave must be damped in order to reduce the second and higher order chromaticities.

The sextupoles introduced to correct the linear chromaticity must also reduce the nonlinear chromaticity and also not introduce large nonlinear effects in the transverse planes. Nonlinear geometric aberrations can be reduced by placing sextupoles in families with members of a family π apart in phase [4]. For on momentum particles, all nonlinear geometric aberrations cancel provided there is an even number of sextupoles per family. The cancellation for off-momentum particles is not as good because the phase advance between the sextupoles is different from π and the transverse displacement depends on the horizontal dispersion.

Interleaved Scheme In the initial stages of the design, an interleaved scheme was considered with two families in the horizontal plane and three families in the vertical plane. The nonlinear chromaticity correction was done using the module HARMON in MAD [5]. This program was used to correct second and third order chromaticities and also to reduce the geometric aberrations by lowering the tune shift with amplitude. The quality of the chromatic correction was adequate but it was worse in the horizontal plane. The reason being that with the (90, 60) combination, the members of a sextupole family next to the vertically focusing quadrupoles are $\pi/2$ apart in horizontal phase so their chromatic horizontal beta waves are exactly out of phase and hence they do not contribute to the correction of the nonlinear horizontal chromaticity. This is a disadvantage
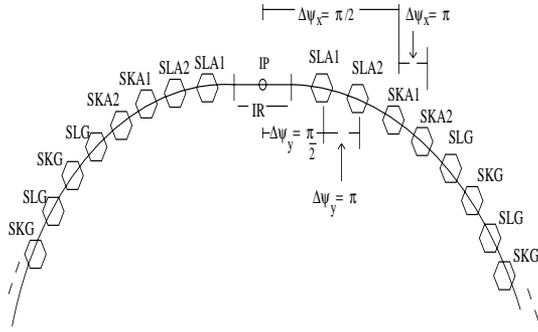
NONINTERLEAVED SEXTUPOLE DISTRIBUTION: VERSION 1

Figure 1: *Non-interleaved sextupoles SLA1, SLA2, SKA1, SKA2 are placed symmetrically about the IP in the arcs adjacent to the north and south insertions to correct for the nonlinear chromaticity of the IRs. $(\Delta\psi_x, \Delta\psi_y)$ are the phase advances in the horizontal and vertical planes respectively. SLA1 and SLA2 have sextupole strengths of the same sign as do SKA1 and SKA2. Between SLA1 and SLA2 and also between SKA1 and SKA2 there are cells where no sextupoles are powered. SLG and SKG are global sextupoles placed in every cell after the noninterleaved sextupoles. In a second version SLA2 is placed a vertical phase advance $\pi/2$ after SLA1 and SLA2 has the opposite sign to SLA1.*

of the interleaved scheme in the (90, 60) optics. The interleaved scheme must also be changed if the focusing in the FODO cells changes.

Non-Interleaved Scheme In general non-interleaved sextupole distributions require stronger sextupoles to correct the chromaticity when the sextupole distribution extends over the whole ring. A variation of this scheme has been considered for the upgrade design. The non-interleaved distribution is confined to the first few cells with dispersion adjacent to the IRs on both sides of the IP. This is done for both the north and south insertions. In the remaining cells of the arc, a single family of sextupoles in each plane correct for the linear chromaticities.

In the upgrade design, the second order chromaticity is larger in the vertical plane. Consequently the first pair of non-interleaved sextupoles closest to the IP must correct for the vertical nonlinear chromaticity and the next pair of non-interleaved sextupoles will correct for the horizontal nonlinear chromaticity.

Figure 1 shows the first of two versions of the sextupole distribution. In the first version, the first sextupole SLA1 is placed at a vertical phase advance of $\pi/2$ (mod 2π) with respect to the IP. SLA1 and SLA2 are placed a vertical phase π apart and have strengths of the same sign. SKA1 and SKA2 correct mainly the horizontal nonlinear chromaticity and are placed a horizontal phase advance π apart. In the second version, SLA2 is placed at a vertical phase advance $\pi/2$ after SLA1 and has a strength with the opposite sign to SLA1. In this configuration, the chromatic beta waves

of this pair are also in phase and cancel the second order chromaticity reasonably well but the cancellation of higher order effects may not be quite as effective as in the first version. The second version has the advantage that the sextupoles SLA1 and SLA2 affect the linear chromaticity very little. The layout of the SKA1 and SKA2 sextupoles is the same in both versions. The strengths of the non-interleaved sextupoles are small, even lower than the strengths of the sextupoles correcting the linear chromaticity. This scheme is also relatively insensitive to the focusing in the arcs.
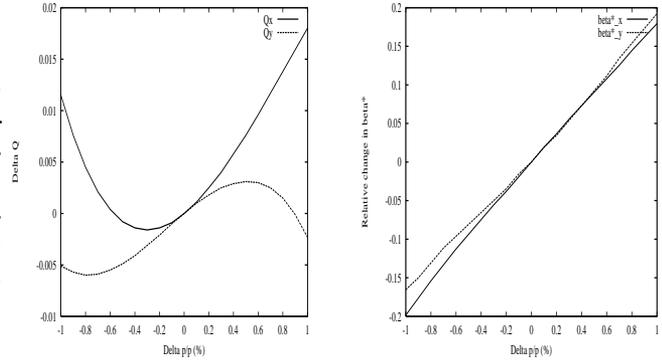
Figure 2: *Left frame: Tunes vs momentum deviation $\delta p/p_0$ in the non-interleaved scheme, version 1. Right frame: Relative change in β^* at the south IP vs $\delta p/p_0$ in the non-interleaved scheme, version 1*

Figure 2 shows the variation of the tunes and the relative change in β^* at relative momentum offsets up to $\pm 1\%$ with the first version of the nointerleaved sextupoles. The horizontal tunes change by less than ± 0.02 over this momentum window while the change in vertical tunes is less than ± 0.006. These changes are significantly smaller compared to the ones obtained with the interleaved scheme. It is desirable to keep the change in β^* small for two main reasons: i) to limit the loss in luminosity due to an increased spot size at the IP, and ii) to keep the beam-beam tune spread small. The β^* variation is under $\pm 20\%$ in both planes. This compares quite favourably with the β^* variation in the present (60,60) optics. The optics has also been designed to limit the chromatic variation of the maximum β in the ring.

3   REFERENCES

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