# New Beam Optics for HERA-e: Theoretical Investigations and Experimental Tests

G. H. Hoffstätter

**Abstract**

In the HERA luminosity upgrade project, it is planed to achieve a luminosity of $7 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For this project, new interaction regions are installed and among other changes the horizontal electron emittance has to be reduced from currently $41\pi$nm to $22\pi$nm. It will be explained why the horizontal emittance can be reduced by stronger focusing in the arcs and by increasing the RF frequency. Furthermore it is shown how these two methods complement each other by partially compensating negative effects on energy spread and dynamic aperture. Therefore both methods should be applied simultaneously in HERA. Simulations show that going from 60° to 72° phase advance and simultaneously increasing the RF frequency by around 200Hz after the new interaction regions have been installed, leads to the design emittance as well as to acceptable dynamic aperture. It will be shown how some of the sextupoles in HERA were responsible for an initially reduced dynamic aperture and that eliminating these sextupoles leads to a satisfactory regions of particle stability. Several measurements have been performed on the current HERA electron ring to investigate the possibility of the planed emittance reduction. Some of these measurements involved the current optics but many were performed with a new 72° optics in order to investigate disadvantages which might be associated with such a phase advance in HERA. The theoretical investigations as well as these accelerator experiments have not shown problems with going to such a phase advance.

## 1 Introduction

In the HERA luminosity upgrade project, we plan to obtain a luminosity which is 4 times higher than the original design luminosity [1]. To achieve this luminosity of $7 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ we have to decrease the proton beam size by moving quadrupoles inside the detectors and by increasing their strength. Similar measures decrease the electron beam size at the interaction point. Moving proton quadrupoles closer to the interaction point requires an earlier separation of electron and proton beams. Therefore it is advantageous to have a smaller electron beam also at the point of separation. This is achieved by additionally reducing the horizontal electron emittance $\varepsilon_x$ as far as possible. It is planed to reduce HERA's $\varepsilon_x$ from currently $41\pi$nm to $22\pi$nm [2, 3, 4]. If obtaining this small emittance were simple, an important optimization tool would not be used efficiently [5].

This decrease of $\varepsilon_x$ can either be achieved by stronger focusing in the arcs, or by changing the damping partition numbers by means of an RF frequency increase.

Before investigating problems that can occur when using these techniques of emittance reduction, it will be explained how focusing and frequency shift change the emittance.

# 2 Reduction of the electron beam emittance

The horizontal emittance $\varepsilon_x$ in an electron ring is produced by stochastic quantum fluctuations of the energy. Whenever a synchrotron radiation photon with energy $\delta_E$ is emitted, the particle looses energy and starts to oscillate around the dispersive orbit $-\eta\delta_E$ rather than around the closed orbit. Frequent stochastic changes of the energy and thus of the orbit around which a particle oscillates causes the particle oscillation never to stop; it gets excited by the emission of ever new photon. An equilibrium emittance will be established when this excitation is counterbalanced by the damping of particle oscillations in electron rings. The amplitude of the oscillations is proportional to $-\eta\delta_E$, and reducing the dispersion $\eta$ in the arcs by stronger focusing in every FODO cell therefore reduces the horizontal emittance in HERA.

When a particle has a position and a slope just before it emits a photon with energy $\delta_E$ which happens to be close to position and slope of $-\eta\delta_E$ then its oscillation amplitude after emission will be very small, possibly smaller than before the emission. When the particle is far away from $-\eta\delta_E$ at the time of photon emission then the oscillation amplitude will be very large. Large oscillations will therefore be excited when synchrotron radiation is mostly emitted in parts of a magnet which is far away from $-\eta\delta_E$. In homogeneous dipoles, the same amount of synchrotron radiation is emitted everywhere. In a quadrupole, synchrotron radiation is emitted in equal strength inside and outside of the closed orbit since the field increases symmetrically to both sides. In combined function magnets on the contrary the fields to the inside and to the outside of the closed orbit are different. In a focusing combined function magnet the field has to be stronger outside the closed orbit and more synchrotron radiation is emitted in the outside part of the magnet. Since the dispersion $\eta$ is positive in the arc, $-\eta\delta_E$ is far away from the outside part of the magnet and larger oscillations are excited than in a defocusing combined function magnet.

The emittance can therefore be reduced by making all quadrupoles into combined function magnets which emit more radiation at the inside than at the outside of the closed orbit. This is easily done by shifting the closed orbit to the inside of the ring in each of these quadrupoles. Particles which travel even further inside and thus closer to $-\eta\delta_E$ see even stronger fields than particles on the closed orbit and they emit more synchrotron radiation. It should however be noted that particles with an energy below average will already travel closer to $-\eta\delta_E$ and will then loss even more energy by the stronger synchrotron radiation in this region. The energy spread will therefore be increased by the increased RF frequency.

In summary, the emittance is reduced by either reducing the dispersion by means of stronger focusing or by shifting the closed orbit to the inside of every arc quadrupole. This can be achieved by and increase of the RF frequency. Quantitatively the emittance reduction it is described by

$$\varepsilon_x = \frac{C_q\gamma^2}{1-\mathcal{D}} \frac{< |G|^3 \frac{1}{\beta}[\eta^2 + (\beta\eta' + \alpha\eta)^2] >}{< G^2 >} , \quad (1)$$

$$\mathcal{D} = \frac{< \eta G(G^2 + 2K) >}{< G^2 >} , \quad (2)$$

with the curvature $G$ of and the focusing strength $K$ on the closed orbit. The parentheses $< \ldots >$ indicate an average around the ring and $\eta$ is again the periodic dispersion. The optic functions $\alpha$ and $\beta$ are used and $C_q \approx 384$fm is a constant. On the design orbit of a separated function ring, which HERA is to a good approximation, $G \cdot K = 0$ around the ring.

The denominator describes the reduction of emittance with reduced dispersion. The discussed shift of the closed orbit to the inside of arc quadrupoles creates a negative curvature in focusing quadrupoles ($K > 0 \rightarrow G < 0$) and a positive curvature in defocusing quadrupoles ($K < 0 \rightarrow G > 0$). An increase in RF frequency thus produces a negative $\mathcal{D}$ which decreases the emittance by increasing the numerator. A changes in $\mathcal{D}$ of the order of one can easily be obtained which largely changes the horizontal emittance.

The horizontal emittance can therefore be reduced by combining more focusing with changing $\mathcal{D}$ by an RF frequency shift. Figure 1 shows the emittance as a function of $\mathcal{D}$ and as a function of the phase advance per FODO cell which is increased from currently 60° by stronger focusing . The green curve indicates which combinations lead to the $22\pi$nm design emittance of the luminosity upgrade.

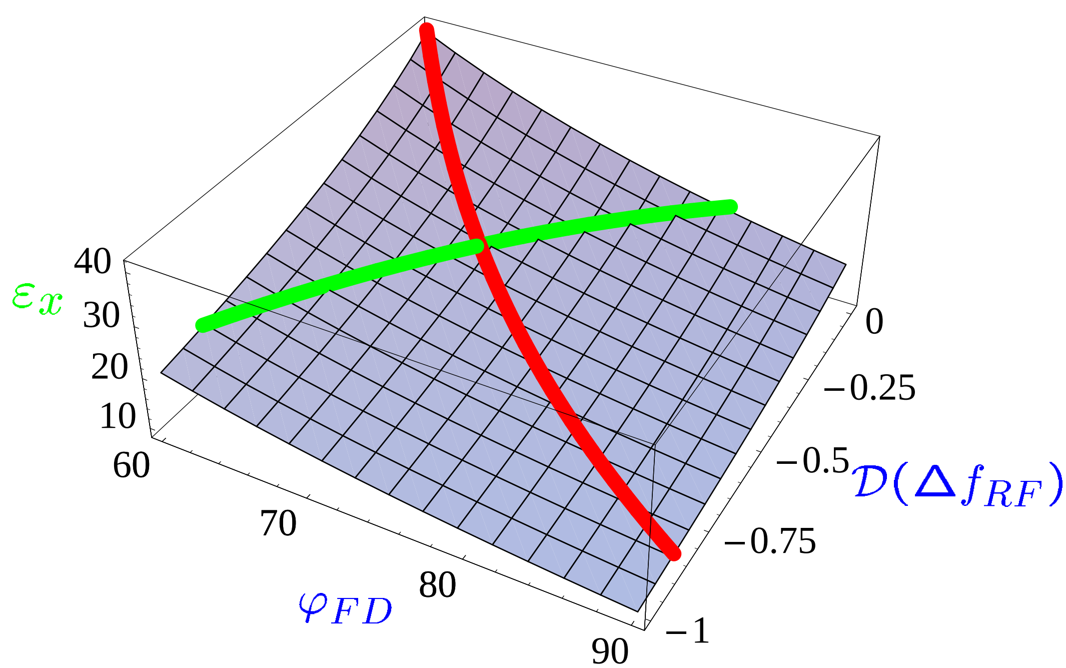


**Figure 1**: The emittance as a function of $\mathcal{D}$ and phase advance per FODO cell. The green curve indicates which combinations lead to the $22\pi$nm. The red curve shows for a given phase advance which RF frequency increase is possible without increasing particle loss from the RF bucket.

# 3 Problems with emittance reduction

## 3.1 Problems with increasing the RF frequency

The discussed increase of the energy spread $\sigma_\delta$ which goes along with the increase in RF frequency is quantitatively described by

$$\sigma_\delta^2 = \frac{C_q \gamma^2}{2+\mathcal{D}} \cdot \frac{<|G|^3>}{<G^2>} \ . \tag{3}$$

Negative values of $\mathcal{D}$ from an increased frequency increase the energy spread. One needs to increase the RF bucket accordingly to avoid increased particle loss out of the RF bucket. An electron in HERA which travels so extremely ahead of the bunch that it is nearly in the next RF bucket will gain some energy $\delta_E$ in the RF system and will then travel outside the closed orbit along $\eta\delta_E$. This trajectory is longer than the closed orbit and the particle will lag back and after some turns it will be in the center of the bunch and it will have picked up some energy during every turn. Since it requires the maximum number of turns to move from an extreme distance to the center, it will have the maximum possible energy deviation in the bunch which is the bucket height $\Delta E$. When the dispersion $\eta$ is decreased the particle lags back less during one turn and since it will take longer to come back to the center it can pick up more energy. The bucket height $\Delta E$ is therefore increased by a reduction of the dispersion $\eta$. Quantitative analysis shows that $\Delta E \propto 1/\sqrt{<G\eta>}$.

Increasing the horizontal focusing in every FODO cell above the current value of 60° will decrease the dispersion and not only decrease the emittance but also increase the RF bucket height. This in turn makes it possible to increase the beams energy spread by increasing the RF frequency. Along with every increase in focusing goes therefore a specific increase in RF frequency which uses up all the gained hight of the RF bucket to lead to the maximum possible reduction of $\varepsilon_x$. This optimum combination of more focusing and increased RF frequency is shown by the red curve in figure 1. The intersection of the green and the read curve shows where the optimum combination leads to the $22\pi$nm design emittance of the luminosity upgrade. The intersection point is very close to 72° phase advance per FODO cell, which allows for a regular structure since this is 360°/5.

## 3.2 Problems with more focusing

More quadrupole focusing per FODO cell increases the total tune and also the total natural chromaticity. The strength of the chromaticity correcting sextupoles therefore has to be increased also. The nonlinear fields of the sextupoles unfortunately reduce the dynamic aperture. Therefore the focusing should not be increased more than necessary.

To show how stronger focusing along with stronger sextupoles reduces the dynamic aperture in the current HERA electron ring, a HERA optics was produced for different phase advances per FODO cell and the stable region of horizontal and vertical motion was approximated by 1000 turn tracking in the program MAD. In figure 2 the stable region in horizontal and vertical amplitude space (the dynamic aperture) is expressed in units of beam sigmas. The partial compensation of dynamic aperture reduction by emittance reduction is therefore taken into account.

This analysis shows that with the current HERA interaction regions 72° phase advance would be a good choice for emittance reduction to $22\pi$nm. The dynamic aperture would even be higher than with the current 60° phase advance.

The increased dynamic aperture after shifting the frequency by 350Hz shows that the two methods of emittance reduction have competing effects on long term stability. The stronger focusing together with the required increase in sextupole strength usually leads to a greater reduction of the dynamic aperture than of the emittance. A change of the RF frequency on the other hand shifts the energy of the particles slightly and therefore introduces chromatic distortions, but this tends to produce a greater reduction of emittance than of dynamic aperture. The dynamic aperture relative to the emittance is therefore increased. Amending an RF frequency shift with a suitable increase in focusing keeps the particle loss rate from the RF bucket unchanged without a further change of RF parameters and at the same time it keeps the relative dynamic aperture acceptable.

In the current 60° optics there are 24 Sextupoles installed for the horizontal plane between each straight section and the center of each arc. This number was chosen since there is a beta beat phase advance of 360° between each third sextupole. The eight sextupoles which act coherently on the beta beat all have the same strength and HERA therefore has three independent sextupole families in the horizontal and three in the vertical plane. Similarly between every fifth sextupole in the 72° optics there is a beta beat phase advance of 720° and with 25 instead of 24 sextupoles one could build five independent sextupole families for each plane.

For the HERA electron ring after the luminosity upgrade, a lattice with 72° phase advance per FODO cell was produced which has 25 sextupoles per half arc for each plane, all being excited equally. The stable region of horizontal and vertical motion for this optics and its energy dependence is shown in figure 3. Dynamic aperture is high for on energy particles but it is strongly diminished for particles with energy deviation.

## 3.3 Reasons for dynamic aperture reduction

Since the dynamic aperture reduces in the 72° luminosity upgrade optics only when the energy is shifted, it was analyzed how the optics is changed by an energy shift. Figure 4 shows the horizontal chromatic beta beat $\Delta\beta$ for different energy deviations $\delta_E$ from -1% to 1% in the south right half arc. Figure 5 shows the horizontal dispersion beat $\Delta\eta$ also in the south right arc for the same energy deviations. Both beats are shown for the 72° luminosity upgrade optics (top) and for the current 60° optics (bottom). In the luminosity upgrade optics both beats are much higher than they are in the current optics.

The beta beat propagates around the ring similar to the propagation of a closed orbit distortion but with twice the betatron phase advance and with kicks which are not produced by corrector magnets but by quadrupoles and sextupoles. For particles with a relative energy deviation of $\delta_E$, a quadrupole with focal strength $K_Q$ produces a kick on the beta beat of $-\beta K_Q \delta_E$ and a sextupole with strength $K_S$ at a position with dispersion $\eta$ produces a kick on the beta beat of $\beta\eta K_S \delta_E$. These kicks are plotted in figure 6 for the 72° lumi upgrade optics.

By far the strongest kicks on the beta beat come from the low beta quadrupoles in the lumi upgrade interaction regions. The kicks of the sextupoles are rather weak

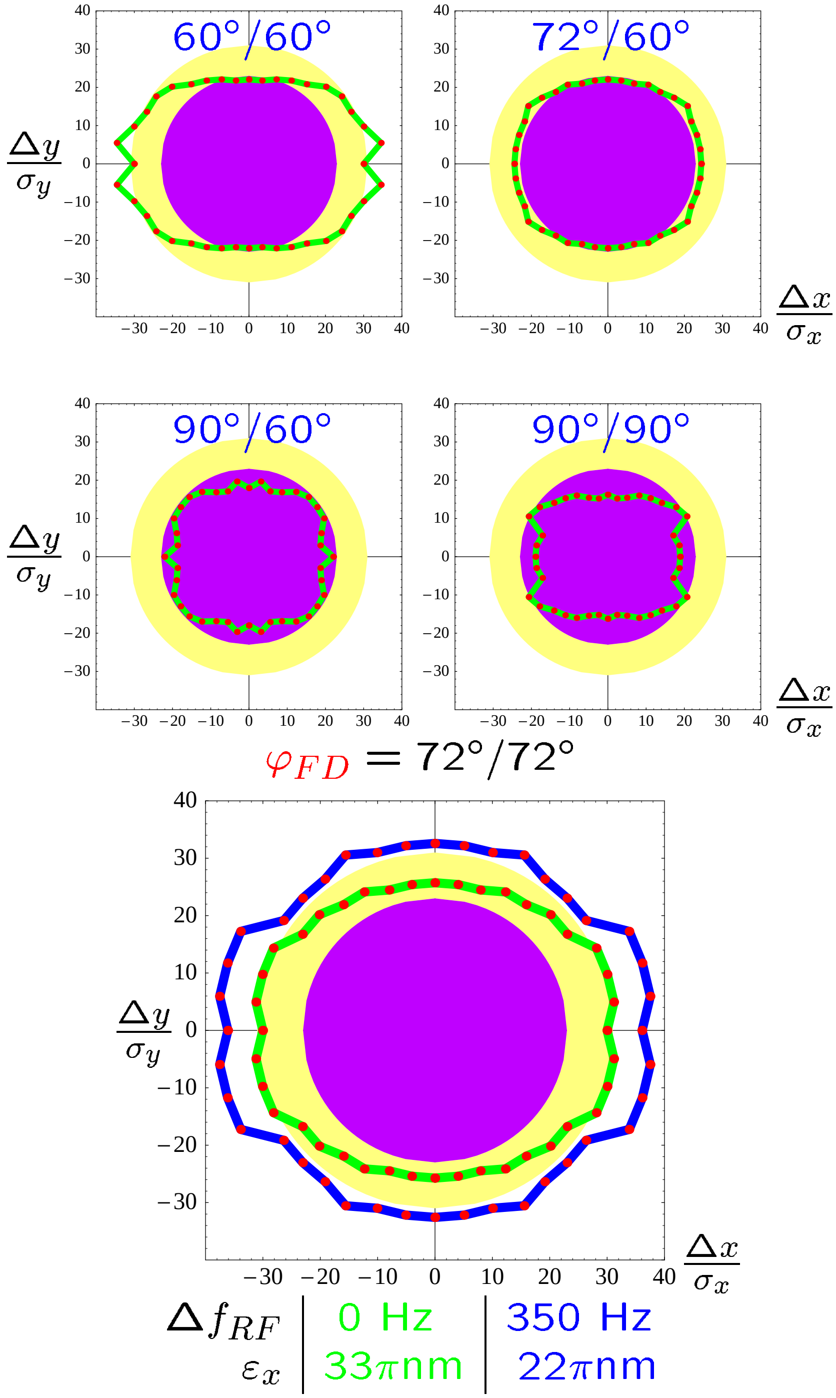


**Figure 2**: The dynamic aperture for different horizontal/vertical phase advances $\phi_{FD}$ per FODO cell for particles without energy deviation. Plotted are (green) the boundaries of stable motion in $x$ and $y$ shown in units of beam sigmas. The largest dynamic aperture is achieved with 72° in both planes. For the 72° optics, the horizontal emittance $\varepsilon_x$ is $33\pi$nm. After an RF frequency increase of 350Hz, $\varepsilon_x$ is $22\pi$nm and the corresponding boundary of stable motion is also show (blue). The yellow ring indicates a range in which all computed dynamic apertures of the HERA electron ring from 1997 to date were located. Boundaries of particle stability inside the purple area indicate an exceptionally small dynamic aperture.

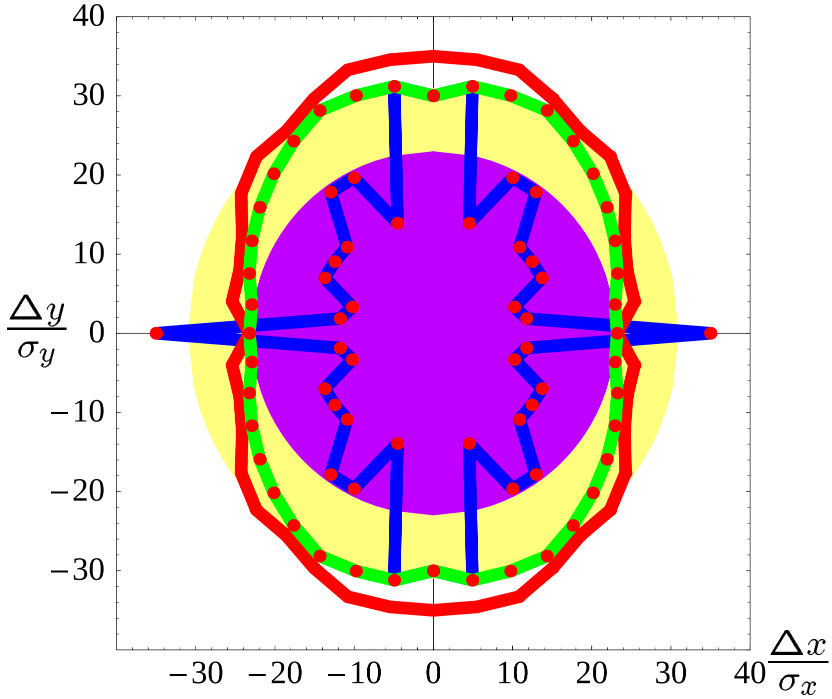


**Figure 3**: Dynamic aperture for the lumi upgrade optics with 72° phase advance in both planes. Plotted are the boundaries of stable motion in $x$ and $y$ shown in units of beam sigmas for particles with three different energy deviations: (red) -0.25%, (green) 0%, and (blue) 0.25%. The yellow and purple areas have the same meaning as in figure 2.

in comparison, even at the spikes close to the end the arc where the regularity of the FODO cells is disturbed in order to match arc into the straight sections. One can try to choose the strength of the five sextupole families in each plane to reduce the beta beat but this compensation would always be very nonlocal in the proposed optics due to the dominant kicks in the interaction regions far away from the sextupoles.

The dispersion beat also propagates around the ring similar to the propagation of a closed orbit distortion with the betatron phase advance and with kicks which are again produced by quadrupoles and sextupoles. For particles with a relative energy deviation of $\delta_E$, a quadrupole with focal strength $K_Q$ produces a kick on the dispersion beat of $-\sqrt{\beta}\eta K_Q\delta_E$, and a sextupole with strength $K_S$ at a position with dispersion $\eta$ produces a kick on the beta beat of $\sqrt{\beta}\eta^2 K_S\delta_E$. These kicks are plotted in figure 7 for the 72° lumi upgrade optics.

Here the strongest kicks on the dispersion beat come from the sextupoles and the new interaction regions contribute comparatively little. The sextupoles at the end of the arc, where the FODO cells are not regular, produce the largest part of the dispersion beat. These kicks on can be eliminated by using 20 sextupoles in each half arc rather than 25. Then again 5 sextupole families for the horizontal plane could be used. The reduced number of sextupoles leads to an increased strength of each sextupole for chromaticity correction. Figure 8 shows the dispersion beat in the south right half arc for energy deviations between -1% and 1%. Here all 20 sextupoles in each plane have equal strength. The dispersion beat is no longer stronger than in the current 60° lattice.

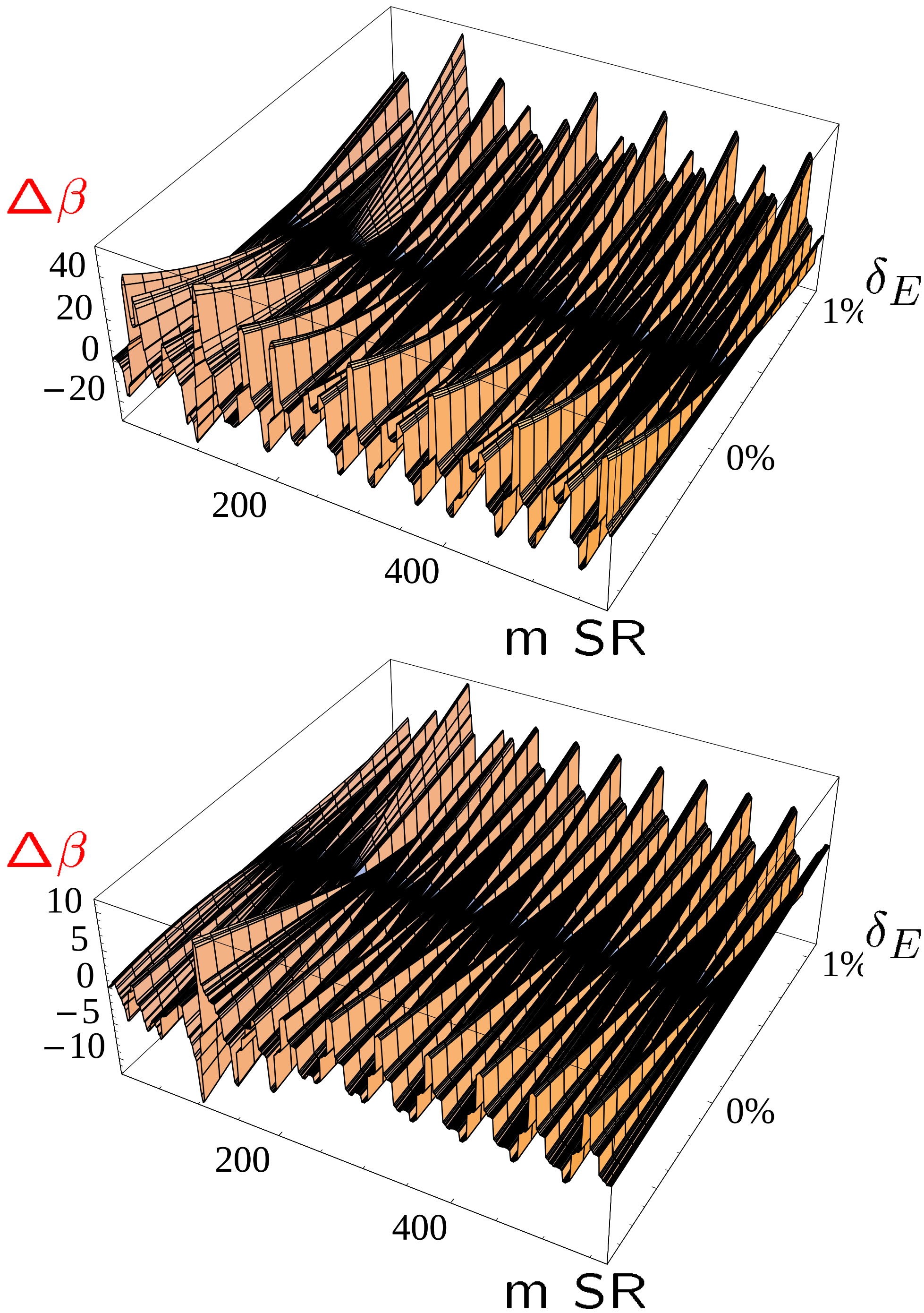


**Figure 4**: Horizontal beta beat in the south right (SR) for particles with different relative energy deviations $\delta_E$ between -1% and 1%. The top was computed for the 72° luminosity upgrade optics and the bottom for the current 60° optics.

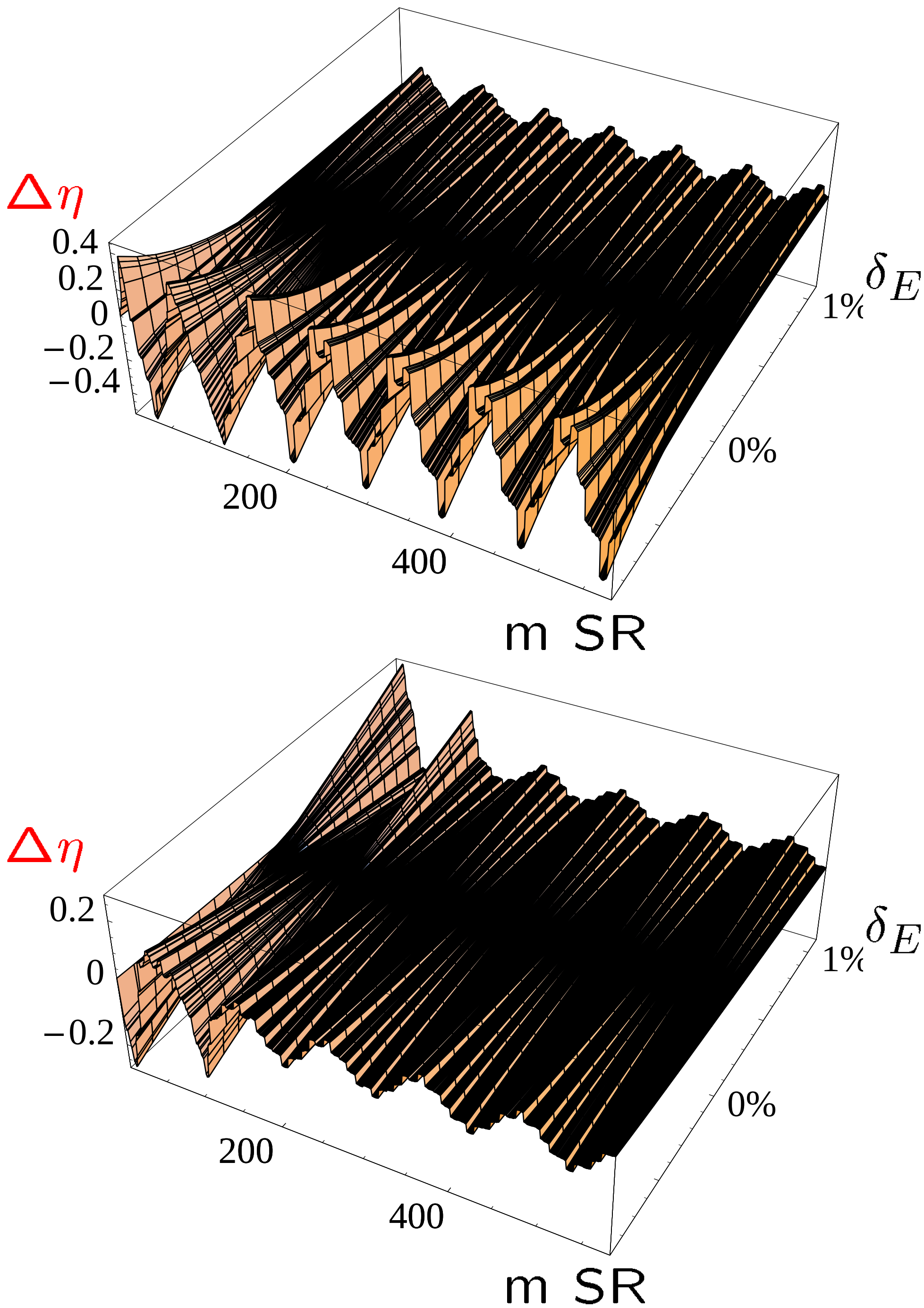


**Figure 5**: Dispersion beat in the south right (SR) for particles with different relative energy deviations $\delta_E$ between -1% and 1%. The top was computed for the 72° luminosity upgrade optics and the bottom for the current 60° optics.

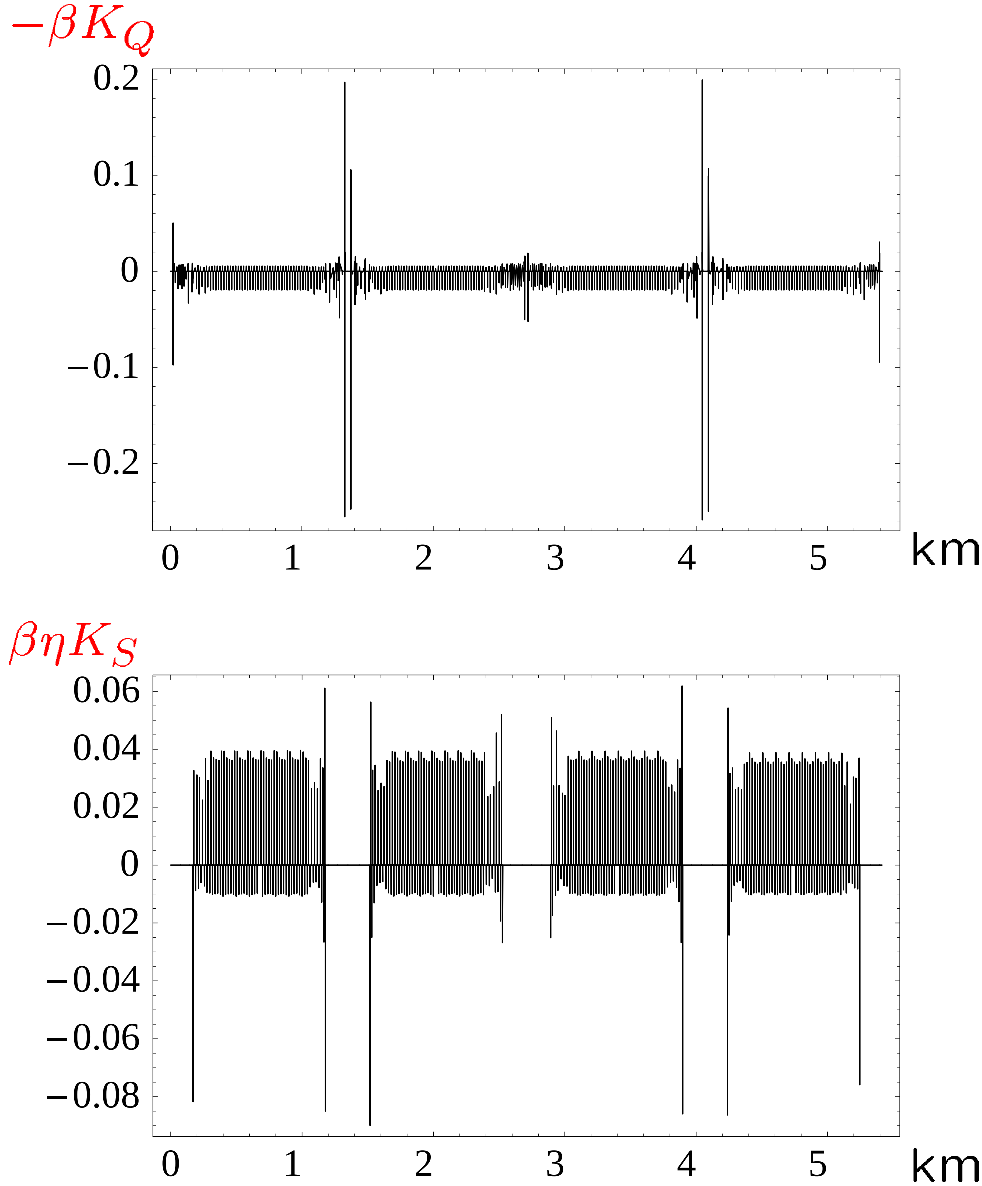


**Figure 6**: Kicks on the chromatic beta beat. Top: The kicks produced by quadrupoles. Bottom: the kicks produced by dispersion in sextupoles.

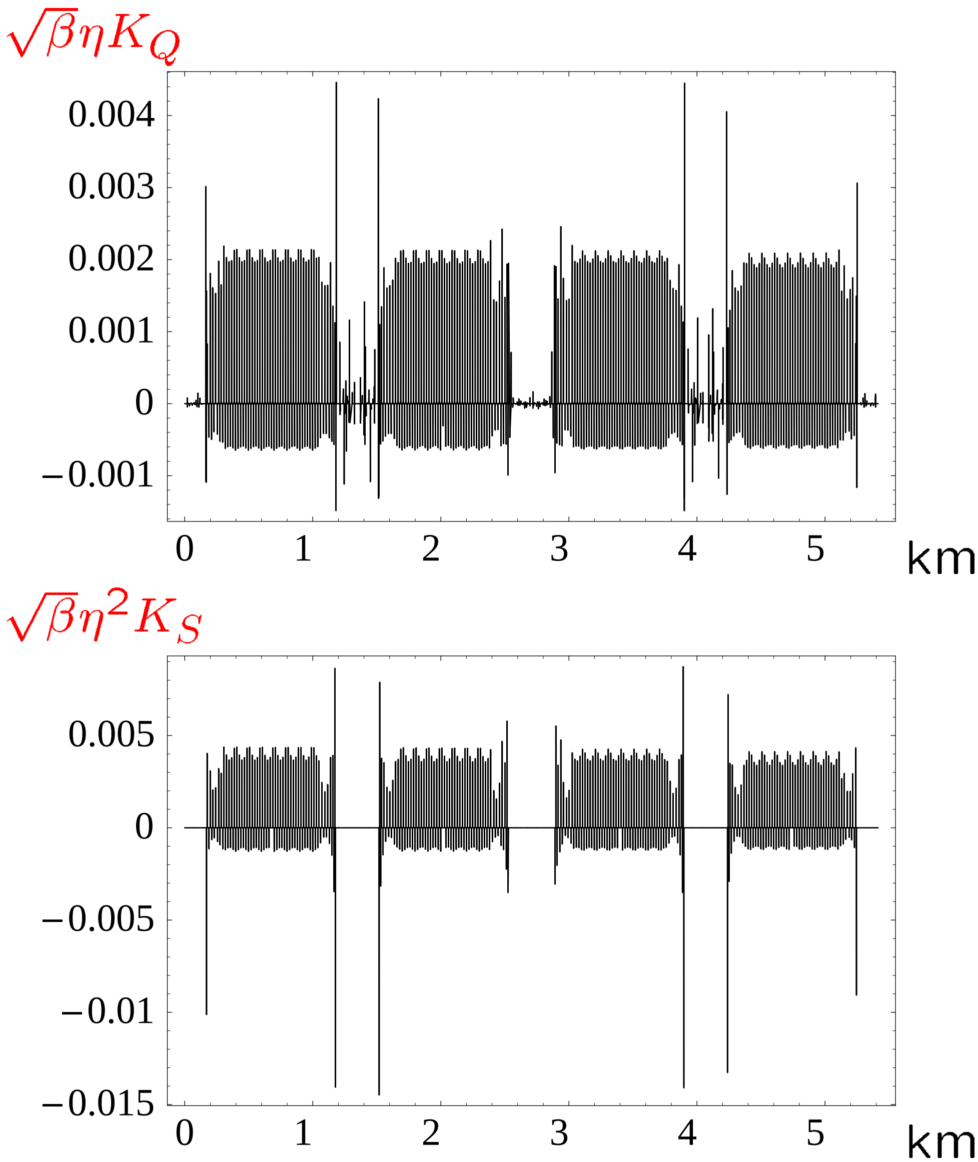


**Figure 7**: Kicks on the chromatic dispersion beat. Top: The kicks produced by dispersion in quadrupoles. Bottom: the kicks produced by dispersion in sextupoles.

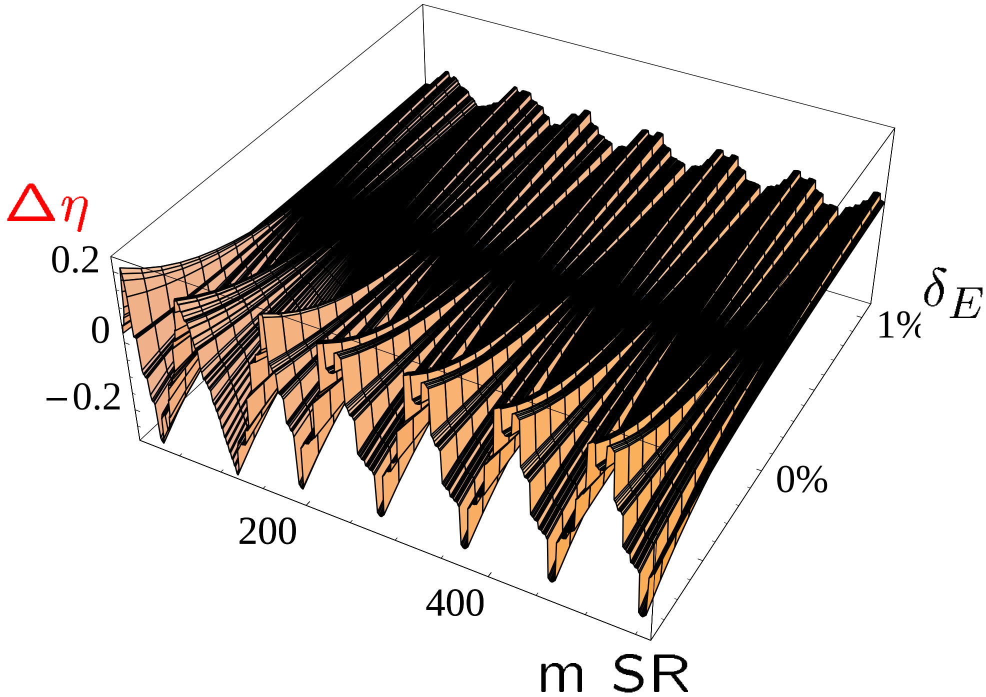


**Figure 8**: Dispersion beat in the south right (SR) for particles with different relative energy deviations $\delta_E$ between -1% and 1% for the 72° luminosity upgrade optics after all sextupoles in FODO cells outside the regular arcs were eliminated. In each plane 20 sextupoles per half arc are here used for chromaticity correction.

The stable region of horizontal and vertical motion shown in figure 9 was again approximated by 1000 turn tracking by the MAD program. Now the dynamic aperture is not only satisfactory high, it does additionally not strongly change with energy. Reducing the current number of 24 sextupoles per plane and per half arc to 20 is very helpful in case of the luminosity lattice. This would lead to 64 avoidable sextupoles. These sextupoles could be used to additionally optimize the dynamic aperture.

# 4 What can be tested in HERA today?

## 4.1 72° optics for HERA

In the HERA electron ring with its current interaction regions, several features required for the luminosity upgrade can already be tested. In order to find out whether 72° phase advance causes any unexpected problems in HERA, a two new optic were computed, one for injection and acceleration and one for luminosity. Storage of electrons into this new optics and acceleration of 27.5GeV was established without unexpected problems. The intermediate optics which are produced when linearly changing the quadrupole strength from injection optic to luminosity optic can have very distorted dispersion. After care has been taken that the injection optics scales well into the luminosity optics, it was also straight forward to store beam in the 72° luminosity optics. More details are mentioned in [6, sec.2.1]. Also establishing collisions and optimization of the luminosity was not

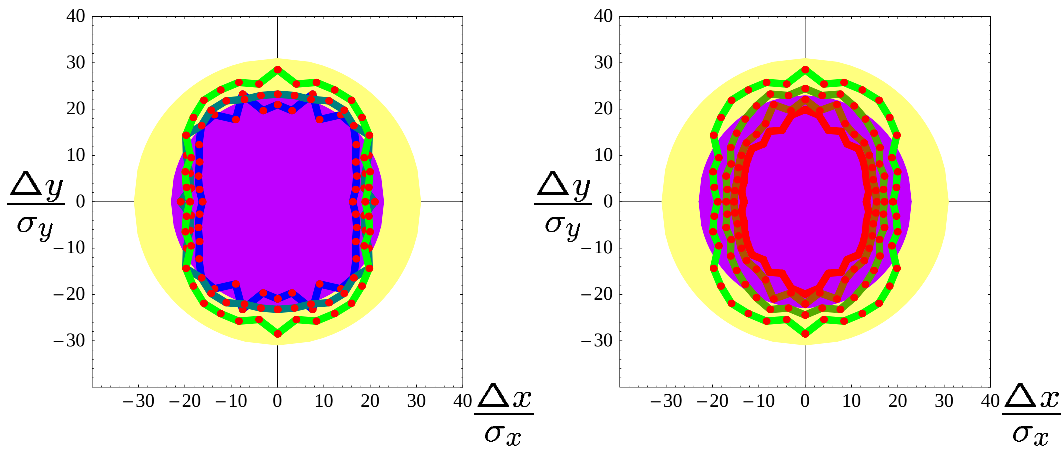


**Figure 9**: Dynamic aperture for the lumi upgrade optics with 72° phase advance in both planes with only 20 sextupoles per half arc for each plane. Plotted are the boundaries of stable motion in $x$ and $y$ shown in units of beam sigmas for particles with six different energy deviations: $\delta_E = -\frac{1}{2}\%$, $\delta_E = -\frac{1}{4}\%$, $\Delta E = 0\%$, $\delta_E = \frac{1}{4}\%$, $\delta_E = \frac{1}{2}\%$, $\delta_E = \frac{3}{4}\%$. The yellow and purple areas have the same meaning as in figure 2.

problematic, especially in the ZEUS interaction region where higher luminosity was obtained than at H1. Several studies were performed with this new optics and they are mentioned in the subsequent sections.

## 4.2 Current frequency shift

It is only possible to decrease the emittance by increasing the RF frequency if the current RF frequency $f_0$ during standard operation is not too far above its central value $f_c$ for which the closed orbit goes through the center of quadrupoles. Several experiments were performed to quantify a possible shift of the current RF frequency away from $f_c$.

The frequency $f_0$ of the RF system is measured very accurately. The central frequency $f_c$, however, is defined by the length of the specific closed orbit which goes through the center of quadrupoles. It is therefore not possible to quantify $f_c$ easily and accurately. Therefore four independent methods were applied to measure this frequency.

(1) The RF frequency was increased until the beam lifetime became very small due to $\mathcal{D}$ approaching -2 in equation (3). Then the frequency was decreased until the lifetime again dropped due to $\mathcal{D}$ approaching 1 in equation (1). The two limiting frequencies $f_+$ and $f_-$ where $\mathcal{D}$ becomes -2 and 1 respectively are referred to as the damping poles. Knowledge of the damping poles allows the computation of $f_c$ since the distance from the center frequency $f_c$ to $f_+$ is twice as large as the distance to $f_-$. The details of the measurement can be found in [6, sec.6.1].

(2) The central frequency $f_c$ makes the beam travel through the center of the quadrupoles, but assuming that the beam then also goes through the center of the sextupoles, we determined $f_c$ by finding the RF frequency for which

the horizontal tune does not depend on sextupole strength. Subsequently a different frequency was found for which the vertical tune does not depend on sextupole strength. This difference has not been conclusively explained but it could be caused by a systematic shift of all vertical sextupoles with respect to the horizontal sextupoles. The details of the measurement can be found in [6, sec.6.2].

(3) The damping rates depend on $\mathcal{D}$ and therefore change with RF frequencies. From measuring the dependence of damping rates on RF frequency, one can extrapolate to the frequencies where the damping rates are 0; these are the damping poles from which again $f_c$ can be determined. The details of the measurement can be found in [6, sec.6.3].

(4) The exact value of emittance reduction produced by an RF frequency shift depends on the distance between $f_0$ and $f_c$. This distance was therefore determined by measuring the functional dependence of emittance on an RF frequency shift. The details of the measurement can be found in [6, sec.6.4].

The measurements (1) and (4) were performed with the current 60° optics as well as with the new 72° optics. The results together with an estimate of the random errors of these methods are shown in the following table. They all indicate that the current frequency $f_0$ is not severely above $f_c$; more likely $f_0$ is even below $f_c$. The frequency can therefore safely be increased to reduce the horizontal emittance in the luminosity upgrade project.

| Measurement | $\Delta f_0 = f_0 - f_c$ | random error |
|---|---|---|
| Beam loss at damping poles | -163 Hz | ± 20 Hz |
| Extrapolation of damping times | -250 Hz | ± 150 Hz |
| Horizontal center of sextupoles | +130 Hz | ± 25 Hz |
| Vertical center of sextupoles | -70 Hz | ± 50 Hz |
| Emittance change with frequency | -175 Hz | ± 70 Hz |

## 4.3 The emittance in HERA

In order to know how far the emittance has to be decrease, the current emittance was measured by analyzing the synchrotron light spot for different RF frequencies. The spot size in the luminosity detectors measures the angle of bremsstahlung photons 108 meters behind the interaction regions and allows to determine the beam's divergence and thus its emittance. This emittance measurement was also performed for different RF frequencies. The results of these two emittance measurements do not agree, which can be seen in figure 10.

Especially surprising is the fact that the emittances obtained from the luminosity monitors do not reduce significantly with an increase in RF frequency and also not with the increase of phase advance from 60° to 72°. The details of the measurement can be found in [6, sec.6.4]. Because of this discrepancy a third measurement was performed. We established electron proton collisions and optimized the luminosity in the 72° optics. Then the luminosity was continuously optimized while the RF frequency was shifted simultaneously in the electron and in the proton ring. For the luminosity measurement, the detector uses the total number of measured

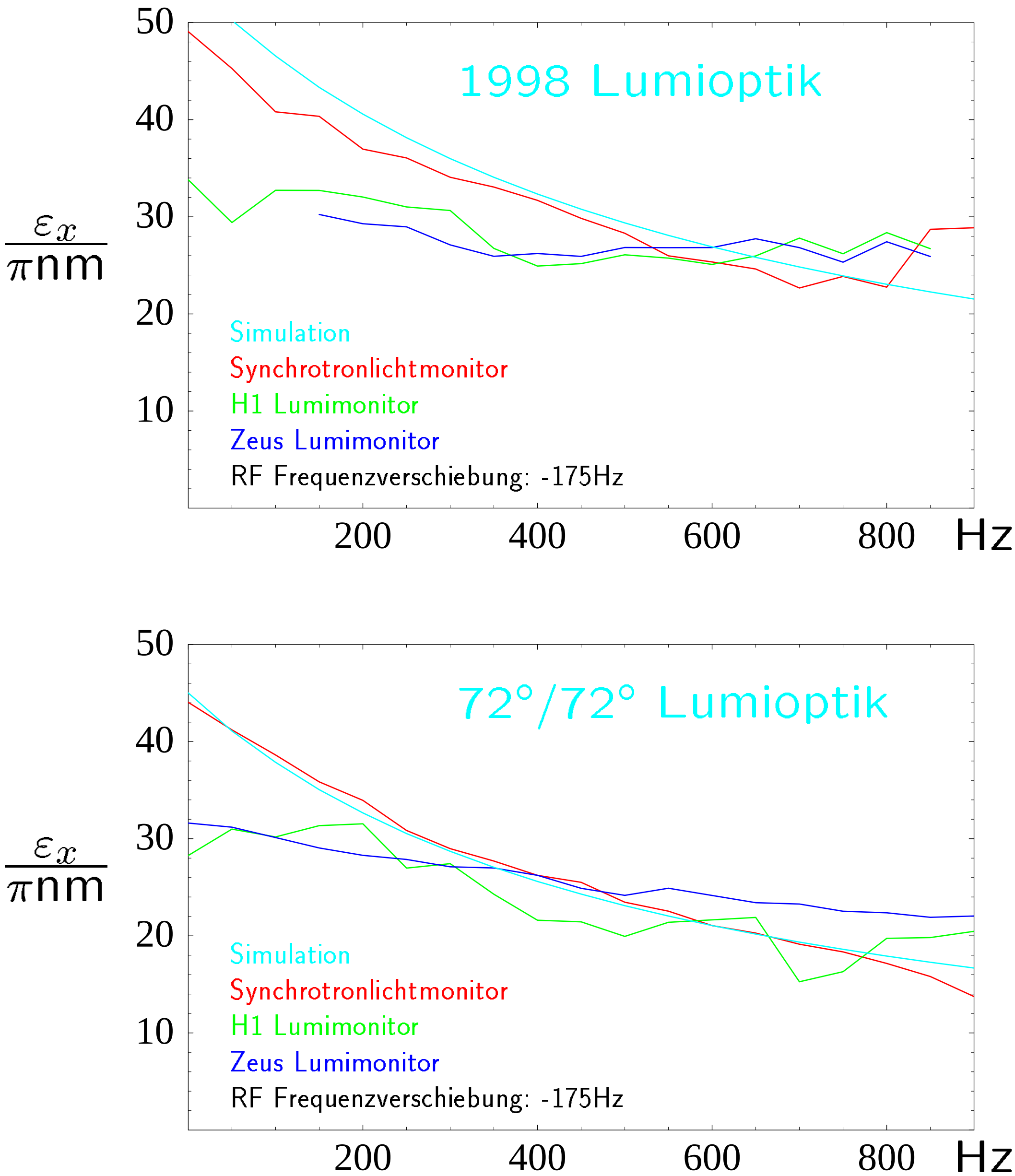


**Figure 10**: The simulated emittance reduction with an increased RF frequency is compared to the emittance measured by the synchrotron light monitor and to the emittance deduced from the H1 and Zeus luminosity monitors. For the simulations it was assumed that the current frequency $f_0$ is 175Hz below the center frequency $f_c$. Top: For the current 60° luminosity optics. Bottom: For the new 72°.

bremsstrahlung photons. Therefore the luminosity measurement can still be quite accurate even if the divergence of bremsstrahlung might not be very accurately measured. It was observed that the luminosity clearly increases significantly with RF frequency. The measurement was performed in the 72° optics and the specific luminosity at Zeus increased from 6.6 to $8.2 \cdot 10^{29} \frac{1}{cm^2 smA^2}$ while the frequency of both rings was increased by 250Hz. This clearly indicates that the measurements of the synchrotron light monitor, which agrees well with simulations, are trustworthy. Experiences with luminosity optimization in the 72° optics are presented in [7].

### 4.3.1 Emittance reduction with frequency shift

Since we plan to reduce the emittance by increasing the RF frequency for the luminosity upgrade, it is important to check whether the emittance is reduced by the expected amount in the current 60° and in the new 72° optics. As shown in figure 10 the decrease of the emittance as measured with the synchrotron light monitor agrees well with calculations if we assume that $f_0$ is currently 175Hz below $f_c$.

### 4.3.2 Emittance reduction with more focusing

Simultaneously with an RF frequency increase, the emittance has to be reduced by stronger focusing in the arcs for the luminosity upgrade; and therefore it is important to quantify whether the emittance is reduced by the expected amount when going from the current 60° optics to the new 72° optics. Figure 10 shows that simulations and the measured emittances agree within the accuracy of the measurement in case of both phase advances. The emittance reduction therefore is not in contradiction with theoretical expectations. The measurement accuracy for the 60° optics is rather low, which is mainly due to the fact that the current HERA optics has a 0.9m dispersion at the synchrotron light monitor. This makes it impossible to observe the horizontal emittance without disturbing effects from the energy spread. The dispersion at this monitor in the 72° optics is close to zero, which explains the better accuracy in the bottom of figure 10.

## 4.4 Dynamic aperture with different focusing

The calculation presented in figure 2 shows that the dynamic aperture in the 72° optics should not be reduced. In order to verify this finding, the dynamic aperture was measured for the 60° and for the 72° optics by kicking the stored beam until it looses half of its current. The dynamic aperture is approximated by the emittance corresponding to this kick amplitude. The detailed measurement procedure is described in [6, sec.2.2]. Here only the results from different measurements performed in 1998 are presented.

| Optics | Date | $V_2$ | $DA$ | $DA_{rel}$ |
|---|---|---|---|---|
| 72° luminosity | 20.Dec.1998 | 2.42 kV | 2.7πmm·mrad | 8.5σ |
| 72° ramp file | 20.Dec.1998 | 2.41 kV | 2.6πmm·mrad | 8.1σ |
| 60° luminosity | 14.Oct.1998 | 2.67 kV | 2.6πmm·mrad | 7.9σ |
| 60° luminosity | 14.Oct.1998 | 2.44 kV | 2.2πmm·mrad | 7.2σ |
| 60° luminosity | 17.Dec.1998 | 2.52 kV | 2.3πmm·mrad | 7.4σ |
| 60° luminosity | 17.Dec.1998 | 2.57 kV | 2.4πmm·mrad | 7.6σ |

The fact that the dynamic aperture did not decrease when installing the new optics confirms the applicability of a 72° optics in the luminosity upgrade. Since these studies, shortages to ground were found in three magnets. The repair of these shortages increased the injection efficiency strongly and more recent studies have shown that the dynamic aperture has also increased. An analysis of the difference in dynamic aperture after these repairs is presented in [7]. Even though the measurement from 1998 are disturbed by the magnet errors it is still worth while to see that the 72° optics does not react more sensitively to such errors than the 60° optic.

# 5 Conclusions

- Calculations indicate that it should be possible to reduce the emittance with little loss of dynamic aperture after the new interaction regions have been installed.
- With the current interaction regions, calculations indicate that it should be possible to reduce the emittance without loss of dynamic aperture, and in measurements no reduction of dynamic aperture was observed.
- The emittance can be reduced by increasing the RF frequency since the current frequency shift is small, likely even negative.
- No unexpected problems have been observed when beam was injected into the 72° optics for the current HERA ring. Also accelerating and establishing collisions worked without disruption.
- The Luminosity at ZEUS for the 72° optics was satisfactory and reflects the emittance reduction. At H1 the emittance could not be optimized as well as at ZEUS.
- The planed emittance of 22πnm for the luminosity upgrade project seems achievable with 72° phase advance per FODO cell in both planes and with an increase of the RF frequency by approximately 200Hz in HERA's 500MHz system which decreases the energy by 0.083%.

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