MEASUREMENT OF HERA'S CENTRAL RF FREQUENCY

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Abstract

For the HERA luminosity upgrade the horizontal emittance of the electron beam was reduced from 41 nm to 22 nm firstly by an increased quadrupole focusing in the arcs' FODO structures and secondly by a change of the damping partition numbers by means of an rf frequency shift. The stronger focusing alone, which increases the phase advance per FODO cell from 60 to 72 degrees, would only reduce the emittance to 35 nm. It was therefore critical for the luminosity upgrade to make sure that there is sufficient room in the damping window for increasing the frequency of HERA's 500 MHz system by the required 300 Hz. For this purpose HERA's rf frequency had to be compared to the central frequency of the ring, for which the design orbit goes through the center of the quadrupoles. Since the accuracy of most methods of finding the central frequency is quite limited, we have used 7 different methods. Their results and their accuracies are compared in this paper.

1 INTRODUCTION

The most common method of measuring the center frequency f_c where the closed orbit on average goes through the center of the quadrupoles actually finds the center of the sextupoles in a storage ring by finding the frequency shift for which the tunes do not change when the strengths of the sextupoles are varied. In HERA we have observed that the horizontal tune and the vertical tune become independent of the strength of the sextupoles at significantly different frequencies. We therefore needed to investigate other approaches of measuring f_c [1]. The result of the 7 methods is shown in table 1 and the different measurements are described below. The measurement showed that the 500 MHz system of HERA has operated about 160 Hz below f_c so that there was sufficient space for increasing the rf frequency for phase 2 operation. And in fact, during the ongoing commissioning of phase 2, no problem has been observed with the increased frequency.

2 BEAM LOSS AT DAMPING POLES

The transverse and longitudinal emittances ε_x and ε_s of an electron storage ring are inversely proportional to the damping partition numbers $J_x = 1 - \mathcal{D}$ and $J_s = 2 + \mathcal{D}$ [2],

$$\varepsilon_x \propto \frac{1}{1-\mathcal{D}}\ ,\ \ \varepsilon_s \propto \frac{1}{2+\mathcal{D}}\ , \tag{1}$$

where $\mathcal{D}$ changes linearly with $\Delta f = f_0 - f_c$ with good accuracy. Therefore the damping pole frequencies f_+ and f_- where one of the emittances tends to infinity can be used to determine f_c by

$$f_c = \frac{1}{3}(2f_- + f_+)\ . \tag{2}$$

Simulation with the MAD program yielded a separation of the damping poles for the phase 2 optics of 2290 Hz. It is not possible to change the frequency by more than the distance to the damping pole without loosing the beam. But the beam can also be lost before one of the damping poles is reached due to the energy change induced by the frequency shift or due to the changing closed orbit. We therefore measured the lifetime as a function of rf frequency for different optics and energies as shown in figure 1. The most extreme frequencies are $f_+ = f_0 + 1830$ Hz and $f_- = f_0 - 670$ Hz leading to a central frequency f_c which is 163 Hz above the current operation frequency f_0.

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Method	Δf(Hz)	Error
Beam loss at damping poles	-163	$\pm$20 Hz
Center of sextupoles, horizontal	$+140$	$\pm$25 Hz
Center of sextupoles, vertical	-70	$\pm$50 Hz
Increase of luminosity	-175	$\pm$50 Hz
Emittance from scraping	-154	$\pm$60 Hz
Emittance from synchr. light	-175	$\pm$70 Hz
Change in damping times	-250	$\pm$150 Hz

Table 1: Measured frequency shift $\Delta f = f_c0 - f_c$ obtained by different methods

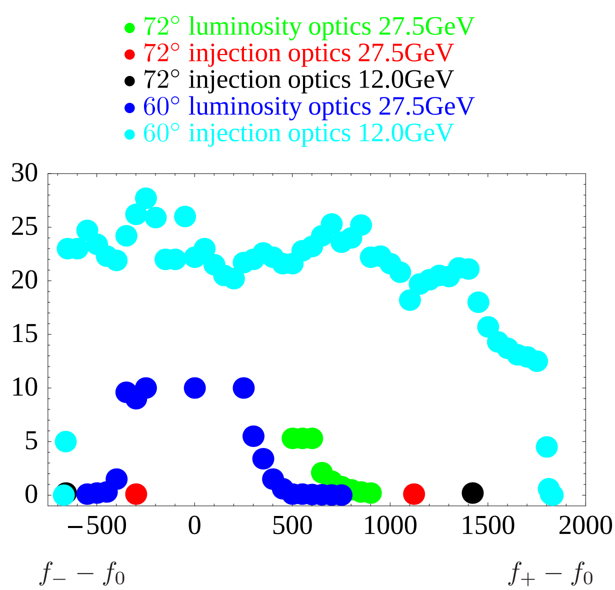

Figure 1: Lifetime (in hours) as a function of rf frequency shift Δf for four different machine settings.

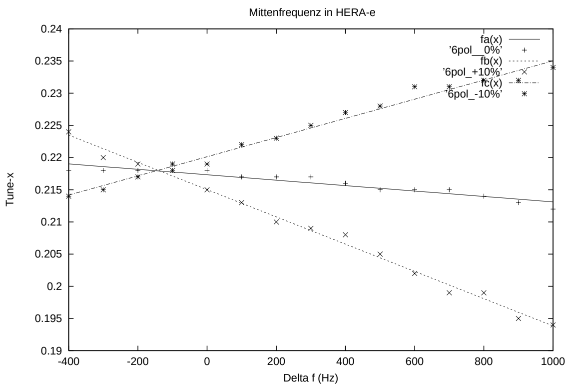

Figure 2: Measurement of the horizontal tune shift as a function of the changing rf frequency. The crossing point of the fitted lines reflects the center frequency of the machine.

3 HORIZONTAL SEXTUPOLE CENTER

A straight forward method to determine the center frequency f_c is to measure the average offset of the beam in the sextupole magnets: The horizontal tune of a stored electron beam was determined as a function of a frequency shift in the 500 MHz rf-system. The measurement was repeated after changing the strength of all sextupole magnets in the ring by a small amount. The resulting horizontal tune values as a function of the frequency now have a different slope. When the beam goes through the center of the sextupoles different strengths of these magnets will have no effect on the tune. This determines f_c since usually the center of the sextupoles agrees with that of the quadrupole lenses. In figure 2 the horizontal tune is plotted as a function of the frequency shift. The three curves correspond to the standard sextupole settings and to $\pm 10\%$ variation of the sextupole fields. The straight lines are a least-square-fit through the data. They cross at a frequency of about $f_c = f_0 - 140$ Hz, which means that the true center frequency found by the measurement is about 140 Hz lower than the frequency f_0 used at that time.

4 VERTICAL SEXTUPOLE CENTER

This measurement can be performed for the horizontal and for the vertical tune leading to two independent measurements of f_c. In HERA the vertical tune becomes independent of sextupole settings at $f_{centre} = f_0 + 70$ Hz. While this method of determining f_c is routinely applied in other accelerators, we did not want to rely on it as the evaluations in the two planes differ significantly from each other and from other measurement results in HERA, as shown in table 1.

5 LUMINOSITY CHANGE WITH f_0

A similar study of the electron beam emittance can be performed measuring the luminosity of the colliding beams. It is related to the bunch dimensions at the interaction point by

$$\mathcal{L} \propto \frac{1}{\sqrt{(\sigma_{xp})^2 + (\sigma_{xe})^2}\sqrt{(\sigma_{yp})^2 + (\sigma_{ye})^2}} \, . \qquad (3)$$

During a collision run the rf frequency was shifted. The resulting increase of the luminosity from the ZEUS and H1 detectors is plotted in figure 3. If a frequency offset of 175 Hz is assumed, the computed curve shifts to the left so that a good agreement between the measured luminosity curves is achieved.

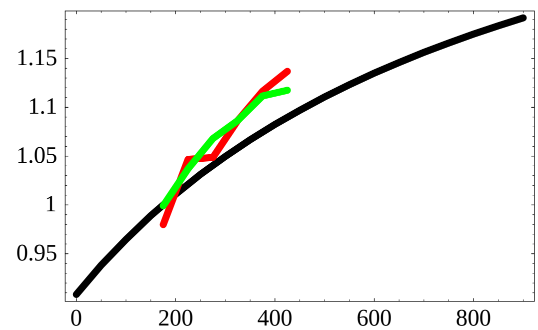

Figure 3: Relative increase of luminosity with increasing rf frequency for ZEUS (red), H1 (green), and simulated (black). If the simulation would assume f_0 to be 175 Hz below f_c, the curve would shift to the left leading to good agreement with the measurement.

6 SCRAPER MEASUREMENTS

Since the emittance of the beam depends on the distance of the rf from f_c, tail scraper experiments which determine the emittance can be related to f_c. Assuming a Gaussian particle distribution in the core of the beam [3], the beam lifetime and the scraper position, can be used to calculate the standard deviation of the transverse beam distribution. The beam lifetime τ_{qz} as a function of the transverse aperture z, and the standard deviation of the transverse beam distribution σ_z is given by [4]:

$$\tau_{qz} = \frac{\tau_z}{2} \frac{e^{\frac{z^2}{2\sigma_z^2}}}{\frac{z^2}{2\sigma_z^2}} \, , \qquad (4)$$

if there is no dispersion at the location of the scraper. The index z refers either to the horizontal or vertical plane and τ_z is the transverse damping time. Using this formula, beam emittance can be deduced from the lifetime at a given scraper location. One measurement is shown in figure 4.

For the regular and upgrade lattice in the arcs (60 and 72 degrees phase advance respectively) theses measurements are summarized the table 2 and compared to the theoretical expectations assuming a centered frequency and a shift of $\Delta f = 154$ Hz respectively.

The theoretical values are in good agreement with the data if a frequency shift of 154 Hz is taken into account.

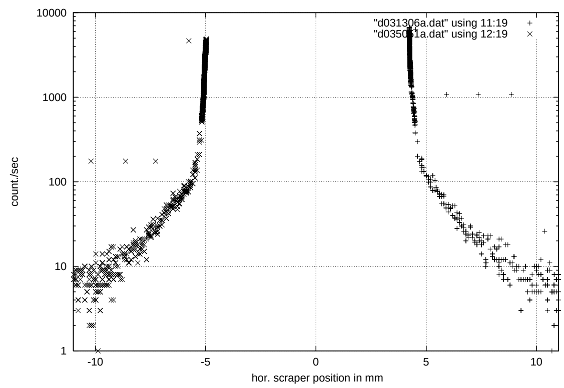

Figure 4: Beam loss rates versus scraper position

focusing scheme	60°	72°
theoretical: $\Delta f = 0$ Hz	0.843mm	0.731mm
theoretical: $\Delta f = 154$ Hz	0.953mm	0.810mm
measured	0.950mm	0.800mm

Table 2: The theoretical and the measured standard deviation σ_x of the horizontal beam distribution

7 EMITTANCE CHANGE WITH f_0

The horizontal emittance has been measured using the synchrotron light monitor of HERA. In figure 5 the horizontal size $\sigma_h \propto \sqrt{(\varepsilon_x)}$ of the electron beam deduced from the measured light spot is shown as a function of the frequency shift. In addition the theoretical value from a MAD simulation is plotted. In order to match the two curves, an offset of the operation frequency of 175 Hz with respect to the center frequency of the storage ring had to be assumed.

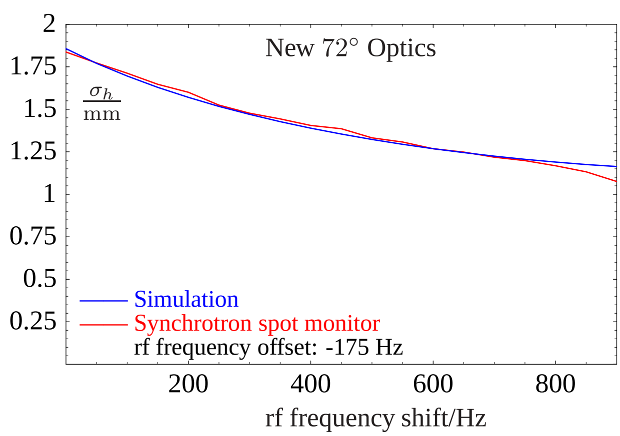

Figure 5: Horizontal beam size σ_h at the synchrotron light monitor as a function of a shift in rf frequency: Computed with MAD [5] and measured with the synchrotron light monitor.

8 HORIZONTAL DAMPING TIME

The change of the damping partition number as a function of a frequency shift has a direct influence on the damping rates of the beam since $\tau_x^{-1} \propto 1 - \mathcal{D}$ and $\tau_s^{-1} \propto 2 + \mathcal{D}$. The decay of coherent beam excitations therefore can be used to determine the position of the damping poles and the center frequency of the machine.

In HERA horizontal beam oscillations were excited for different shifts of the rf frequency and the decay rates of the oscillations were measured as shown in figure 6. A contribution from Landau damping has been subtracted from the data.

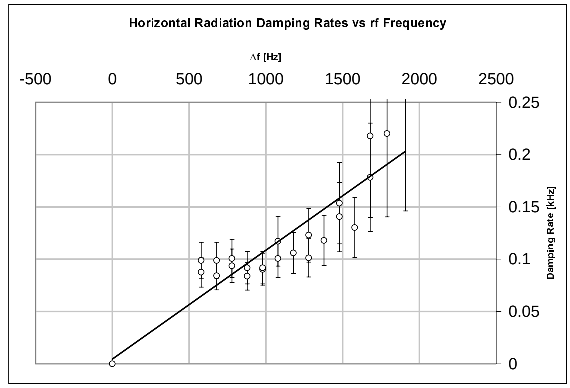

Figure 6: Radiation damping rates as a function of the rf frequency shift.

The horizontal damping pole is reached if the measured damping rate approaches zero. If the longitudinal damping pole would be found by investigating longitudinal damping rates, f_c could be determined by equation (2). Due to the lack of a longitudinal kicker, this was not done in HERA. We therefore used a MAD simulation to find that f_c is 763 Hz above the damping pole and it was then concluded that the actual frequency of the storage ring is about 250 Hz below f_c. The measured damping time of 15 ms at that frequency is in good agreement with the theoretical expectation of $\tau = 14.3$ ms.

9 REFERENCES

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