Electron Dynamics after the HERA Luminosity Upgrade

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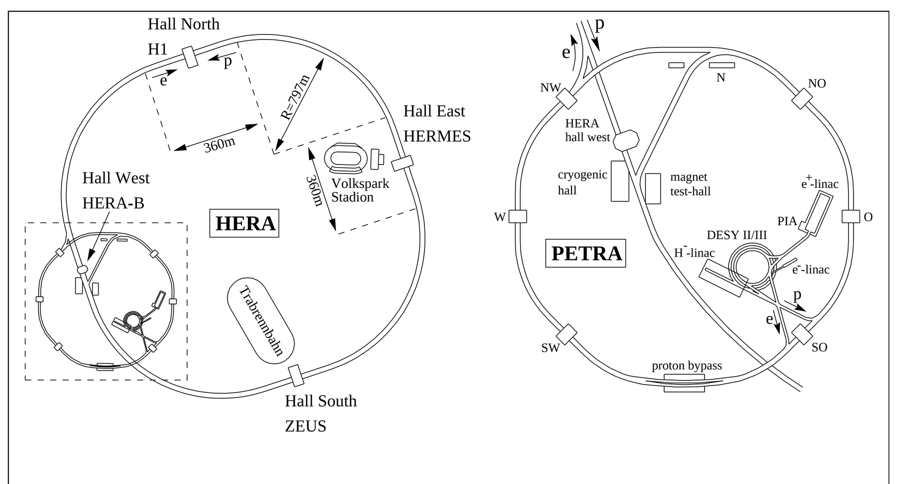
DESY is currently working on decreasing the size of the proton beam and of the electron beam in HERA at the collider experiments H1 and ZEUS by moving quadrupoles closer to the interaction points and by increasing their strength. To match the smaller proton beam size, the horizontal electron emittance has to be decreased by changing the damping partition numbers and/or by an increase in the phase advance per FODO cell. Together with reaching design currents, these measures should increase the luminosity of HERA from the current maximum value of $2 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $7.6 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. An increase from the current 60° to 72° phase advance per FODO cell in both planes which reduces the horizontal emittance from 41 to 30nm and a further reduction to 20nm by a shift of the RF frequency have been analyzed and found to have satisfactory properties in computer simulations including chromatic correction. Experimental tests of whether an increase of the RF frequency reduces the emittance as predicted and whether the current RF frequency is close enough to the center frequency to allow for the required increase have been carried out. Additionally tests of whether the increased focusing reduces the emittance as predicted and whether the dynamic aperture remains satisfactory in a 72° optics have been made. Finally, the reduction of the emittance has to lead to an increased specific luminosity and therefore experience with e/p collisions for a 72° electron optics are described.

HERA at DESY

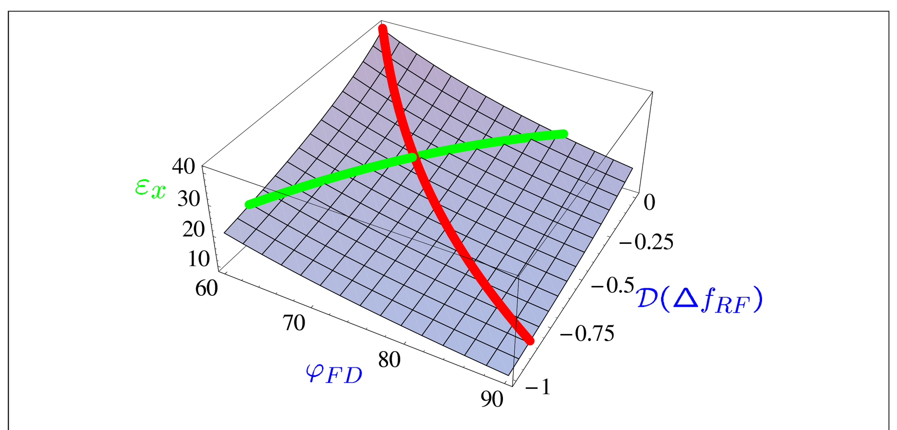


Sketch of HERA and of the preaccelerators at DESY. The two interaction regions (H1/ZEUS) will be completely rebuilt [1, 2, 3]. The preaccelerators will not be changed.

Luminosity Upgrade Parameters

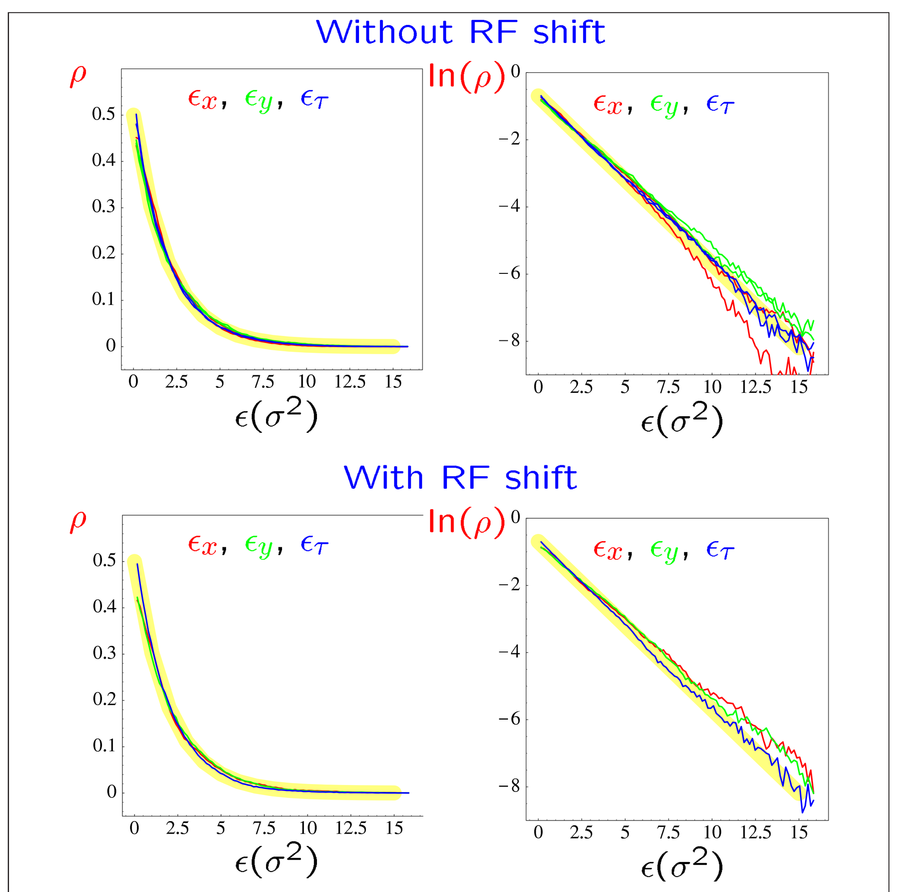
Parameters	currently		after the Upgrade	
	HERA-e	**HERA-p**	**HERA-e**	**HERA-p**
E(GeV)	27.5	920	27.5	920
I(mA)	50	100	58	140
$N_{ppb}(10^{10})$	3.5	7.3	4.0	10.3
n_{tot}/n_{col}	189/174	180/174	189/174	180/174
$\beta_x^\star/\beta_y^\star$(m)	0.90/0.60	7.0/0.5	0.63/0.26	2.45/0.18
ϵ_x(nm)	41	$\frac{5000}{\beta\gamma}$	20	$\frac{5000}{\beta\gamma}$
ϵ_y/ϵ_x	10%	1	17%	1
$\sigma_x/\sigma_y(\mu\mathrm{m})$	192/50	189/50	112/30	112/30
σ_z(mm)	11.2	191	10.3	191
$2\Delta\nu_x$	0.024	0.0026	0.068	0.0031
$2\Delta\nu_y$	0.061	0.0007	0.103	0.0009
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$16.9\cdot10^{30}$		$75.7\cdot10^{30}$	
$\mathcal{L}_s(\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{mA}^{-2})$	$0.66\cdot10^{30}$		$1.82\cdot10^{30}$	

Electron Emittance Reduction



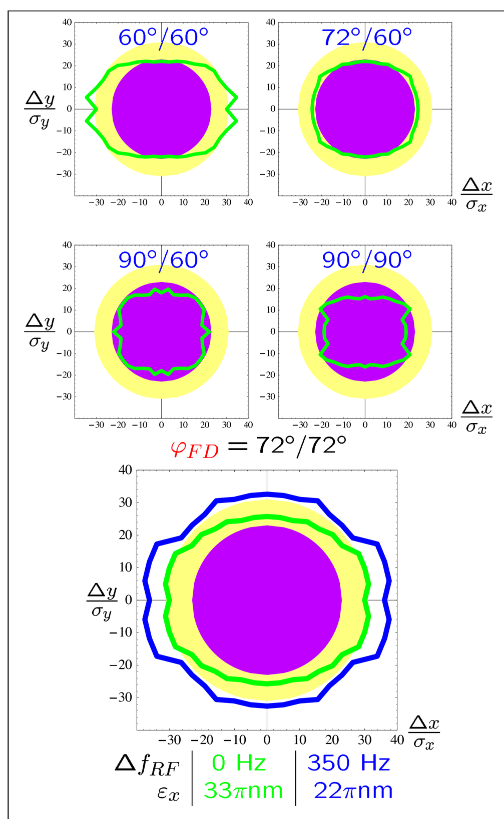
The emittance as a function of the damping integral $\mathcal{D}$ and of the phase advance per FODO cell. The green curve indicates which combinations lead to the 20πnm. The red curve shows for a given phase advance which RF frequency increase is possible without increasing particle loss from the RF bucket [8].

Electron Distribution

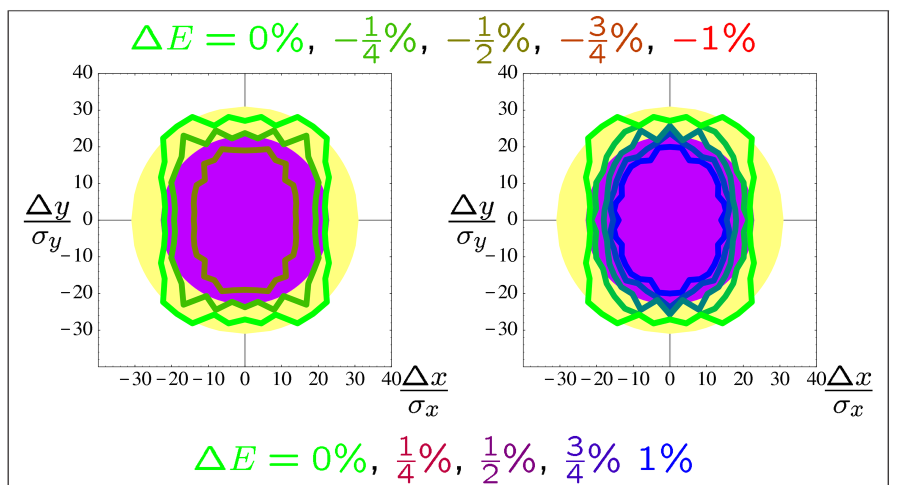


It was checked by long term tracking that the stronger nonlinearities in a 72° optics do not lead to a strong tail population: Result positive for moderate amplitudes.

Dynamic Aperture

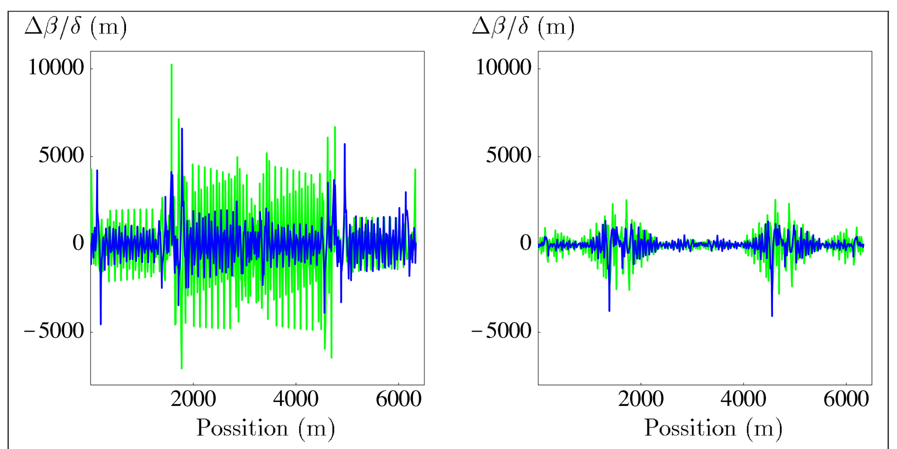


The dynamic aperture computed with MAD [4] for different horizontal/vertical phase advances ϕ_{FD} per FODO cell in the current HERA-e for particles without energy deviation. Plotted are (green) the boundaries of stable motion in x and y shown in units of beam sigmas. The largest dynamic aperture is achieved with 72° in both planes with 24 sextupoles per half arc for each plane. For the 72° optics, the horizontal emittance ε_x is 33πnm. After an RF frequency increase of 350Hz, ε_x is 22πnm 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 [9].



Dynamic aperture for the lumi upgrade optics with 72° phase advance in both planes and with only 20 sextupoles per half arc for each plane.

DA Chromatic Correction



The energy dependent fixed point $\vec{\eta}$ is given by $\vec{M}(\vec{\eta}, \delta) = \vec{\eta}$. With the nonlinear one turn map

$$\vec{M}(\vec{z}, \delta) = \underline{M}\vec{z} + \underline{M}^\delta \vec{z}\delta + \dots$$

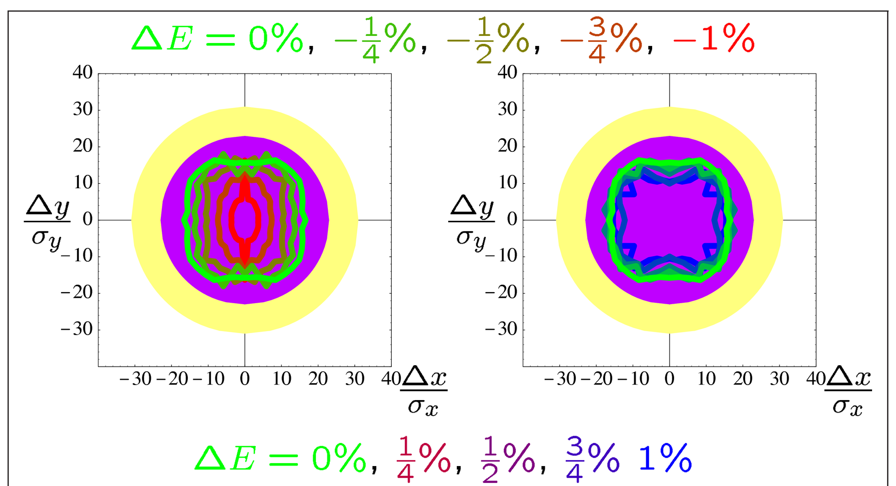
The map around this fixed point is

$$\vec{M}_\eta = \vec{M}(\vec{z} + \vec{\eta}, \delta) - \vec{\eta} = \underline{M}\vec{z} + \underline{M}_\eta^\delta \vec{z}\delta + \dots$$

The energy dependence of the beta function is contained in $\underline{M}_\eta^\delta$. With chromatic correction of β, α, and Φ one tries to eliminate $\underline{M}_\eta^\delta$ at the IPs and in the center of the arcs. It turns out that this condition is satisfied for a ring without dispersion at the IPs when

$$\underline{M}^\delta(IP \to cent.) = \underline{0}$$

for the transport maps from the IPs to the center of the arcs. Such a fit can easily be performed with differential algebra. Here COSY INFINITY [5] was used to find the best of 64 choices for sextupole families for each arc.



Dynamic aperture for the lumi upgrade optics with 72° phase advance in both planes. The 20 sextupoles per plane were used for chromatic correction. The wiring of 3 free power supplies to 5 families was optimized for each arc .

Tests with the Current HERA

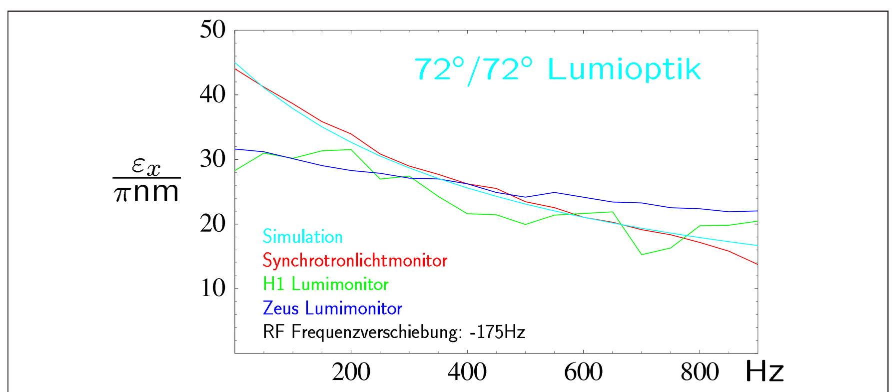
Measurement	$\Delta f_0 = f_0 - f_c$	random error
Beam loss at damping poles	-163 Hz	± 20 Hz
Extrapolation of damping times	-250 Hz	± 150 Hz
Horizontal center of sextupoles	+130 Hz	± 25 Hz
Vertical center of sextupoles	-70 Hz	± 50 Hz
Emittance change with frequency	-175 Hz	± 70 Hz
Luminosity for different f_{RF}	-175 Hz	± 75 Hz

Test of whether the current frequency allows for the required frequency shift: Result positive [6].

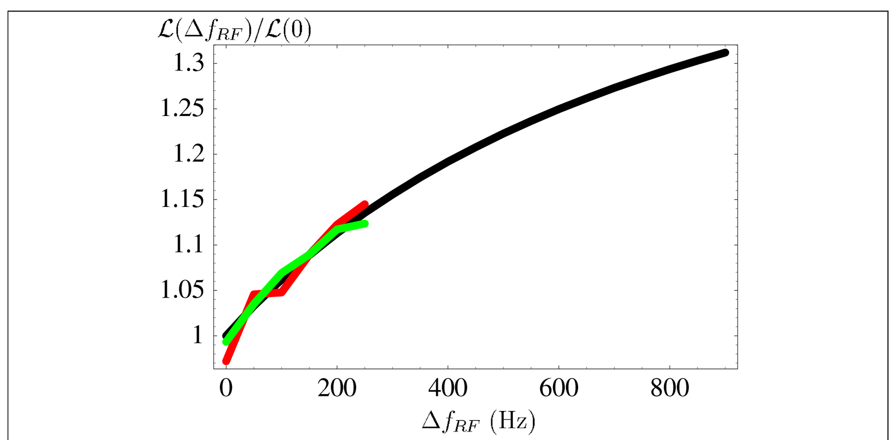
Optics	DA(mm mrad)	DA_{rel}	RF shift
60° injection	6.7	12.1σ	0Hz
60° injection	7.7	13.2σ	0Hz
60° luminosity	> 4.4	> 10.3σ	0Hz
72° luminosity	3.4	10.0σ	0Hz
72° luminosity	3.5	10.2σ	0Hz
72° luminosity	3.6	12.7σ	300Hz
72° luminosity	3.5	12.6σ	300Hz
72° luminosity	3.7	10.4σ	0Hz

Various tests of the dynamic aperture for the current optic (60°) and the upgrade focusing scheme (72°) by kicking to an amplitude where half of the beam is lost [7].

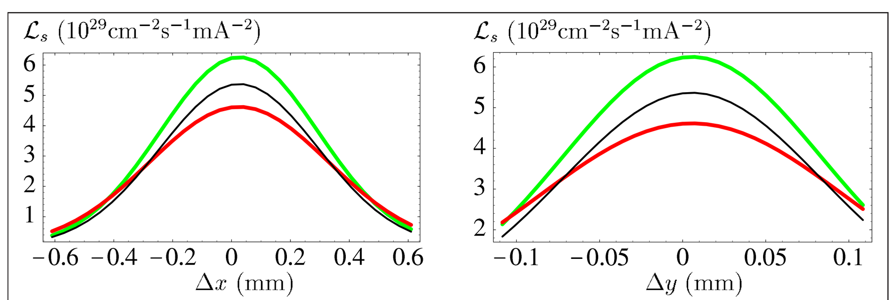
Measured Emittance Reduction



The emittance measured with the synchrotron light spot reflected the predicted reduction after the not well known systematic error of the monitor has been used as a fit parameter [6].



The relative increase of the luminosity at Zeus (red) and H1 (green) reflects the predicted emittance reduction, but the absolute luminosity was too small.



The luminosity scan indicates that the luminosity was too small due to a large vertical spot size ($\epsilon_y/\epsilon_x = 23\%$), which will have to be reduced in future measurements. It also indicates that the emittance reduction is satisfactory ($\epsilon_x = 25$nm measured at ZEUS and $\epsilon_x = 31$nm measured at H1 with $\Delta f_{RF} = 0$).

References

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[8] G. H. Hoffstaetter and F. Willeke, Electron Dynamics in the HERA Luminosity Upgrade Lattice of the Year 2000, *in Proceedings PAC99* (1999)

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