Optics issues at HERA

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HERA Parameter

HERA is a double ring collider:

- **two independent storage rings**
- **4 straight sections for experiments**
- **collision of protons & electrons at two interaction regions (North/South)**
- **internal gas target at IR East**
- **internal wire target at IR West**

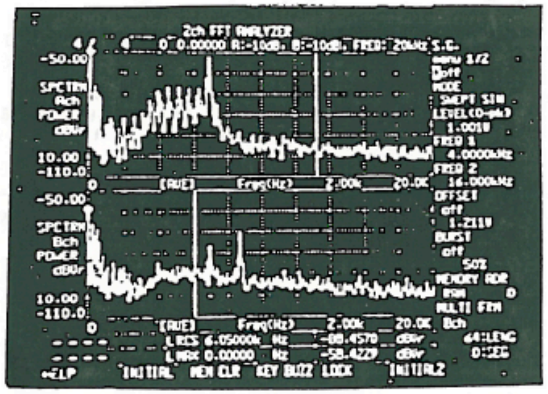
Circumference:	**6.3 km**	
Proton Beam:	**Injection Energy**	**40 GeV**
	Lumi-Energy	**920 GeV**
Electron Beam:	**Injection Energy**	**12 GeV**
	Lumi Energy	**27.5 GeV**
Dipole field p:	**5.1 Tesla**	
	at I=5500 A for 920 GeV	

HERA the main parameters

Parameter	Elektronen	Protonen
Energie E / GeV	27.5	920
Max. Strom I / mA (Designwerte für n_b=180)	58 / 41	140 / 102
Zahl der Bunche n_b	180 / 63 – 126 – 153	180 / 60 – 120 – 150
Zahl der kollidierenden Bunche n_c	174 / 57 – 114 – 147	
Horizontale Emittanz ε_x / π·nm·rad	20 / < 26	5.1 / 4.7
Vertikale Emittanz ε_y / π·nm·rad	3.4 / 3.0	5.1 / 4.7
Horizontale Beta-Funktion am IP β^*_x / m	0.63	2.45
Vertikale Beta-Funktion am IP β^*_y / m	0.26	0.18
Bunchlänge σ_p / m	0.0103	0.191 / 0.21
Hourglass-Faktor R	0.924 / 0.913	
Spezifische Luminosität L_s / 10^{30} cm^{-2}·s^{-1}·mA^{-2}	1.79 / 1.9 – 2.2	
Luminosität L / 10^{31} cm^{-2}·s^{-1}	7.44 / 2.5 – 5.1	

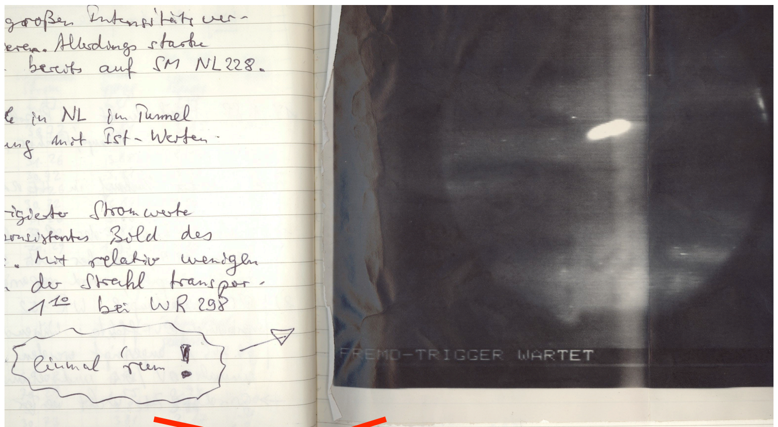
HERA History

1989 Commissioning of the electron storage ring
1991 Commissioning of the proton storage ring
Oct. 1991 First e/p collisions
July 2007: shut down



HERA-p tune spectrum

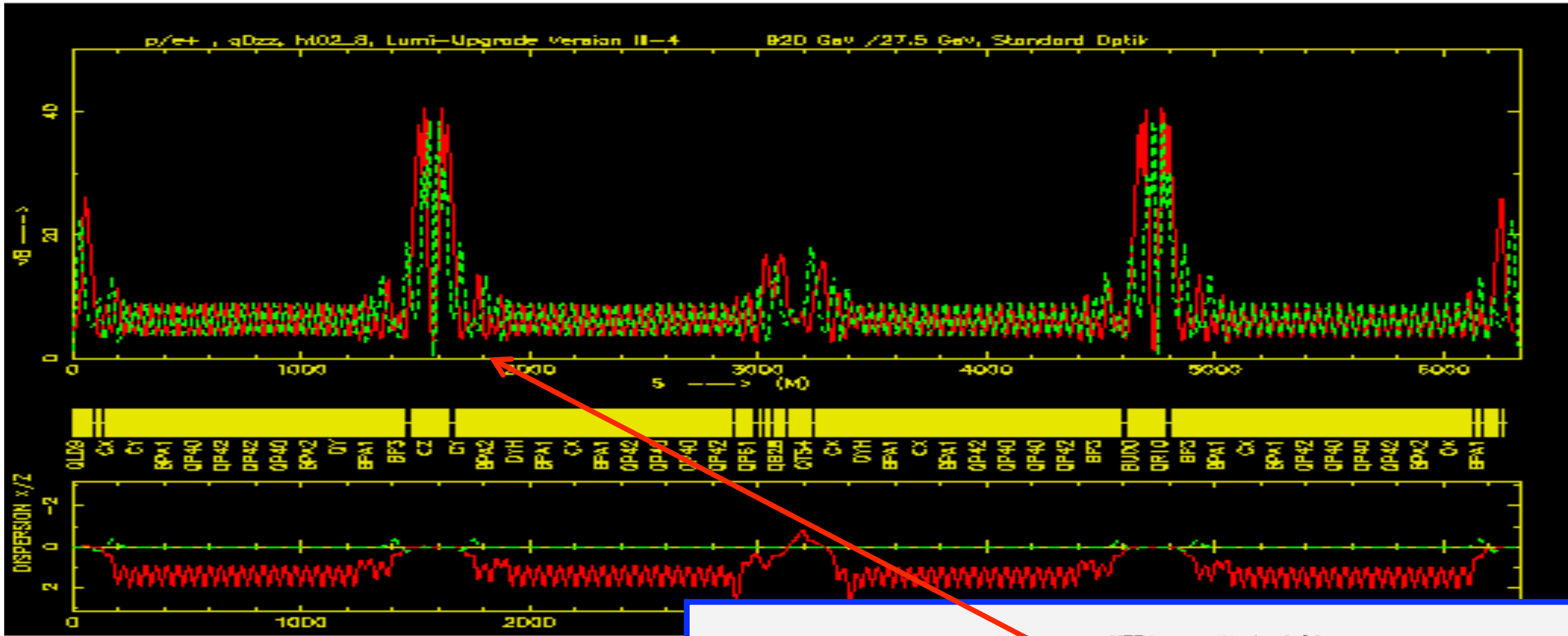
starting in 1989 with "very basic" tools



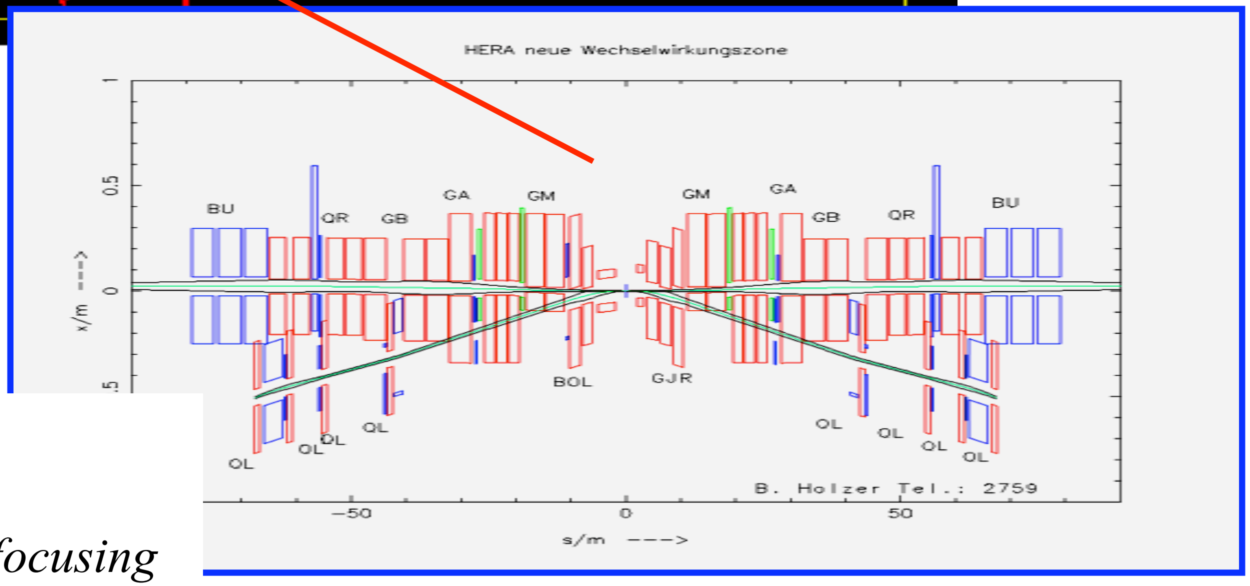
HERA-e ~~electronic~~ Logbook
very first BPM system

HERA Optics

... the special problem of interleaved beam lattices

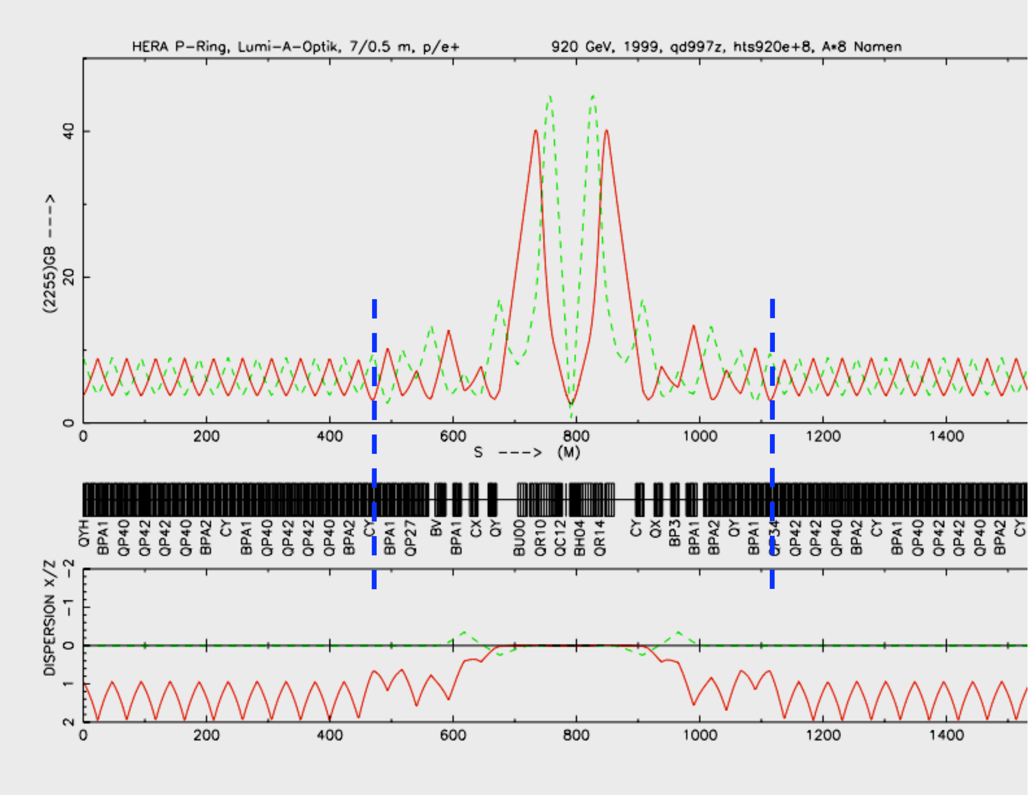


HERA-p optics: standard layout of FODO & mini β insertions



straight sections: interleaved scheme of electron optics (mini β), beam separation & proton doublet focusing

Optics Measurements:



Measurement of β

Different methods used:

Change gradients of quadrupoles

21 individual quadrupoles in the LSS, slow, but independent of bpm readings

Orbit response matrix measurement

faster than other method, depend on orbit stability & bpm quality

ORM specialities in HERA:

Amplitude of difference orbits: $\Delta x \approx$ *1mm in the arcs*

Unidirectional current change

For each corrector: 5 + 7 orbits (HERA-e), 3 + 5 orbits (HERA-p)

Time needed to measure matrix (both planes):

For HERA-e at 27.5GeV: ≈ *2 hours (556 correctors)*

For HERA-p at 920GeV: ≈ *4 hours (254 correctors)*

Stable conditions needed for several hours!

Orbit Update rate: HERA-e: 5 Hz, HERA-p:1 Hz

Limitation for the total time is the corrector magnet current change speed

Always problems with background and lifetime

Reference orbit is drifting (Hysteresis of corrector magnets)

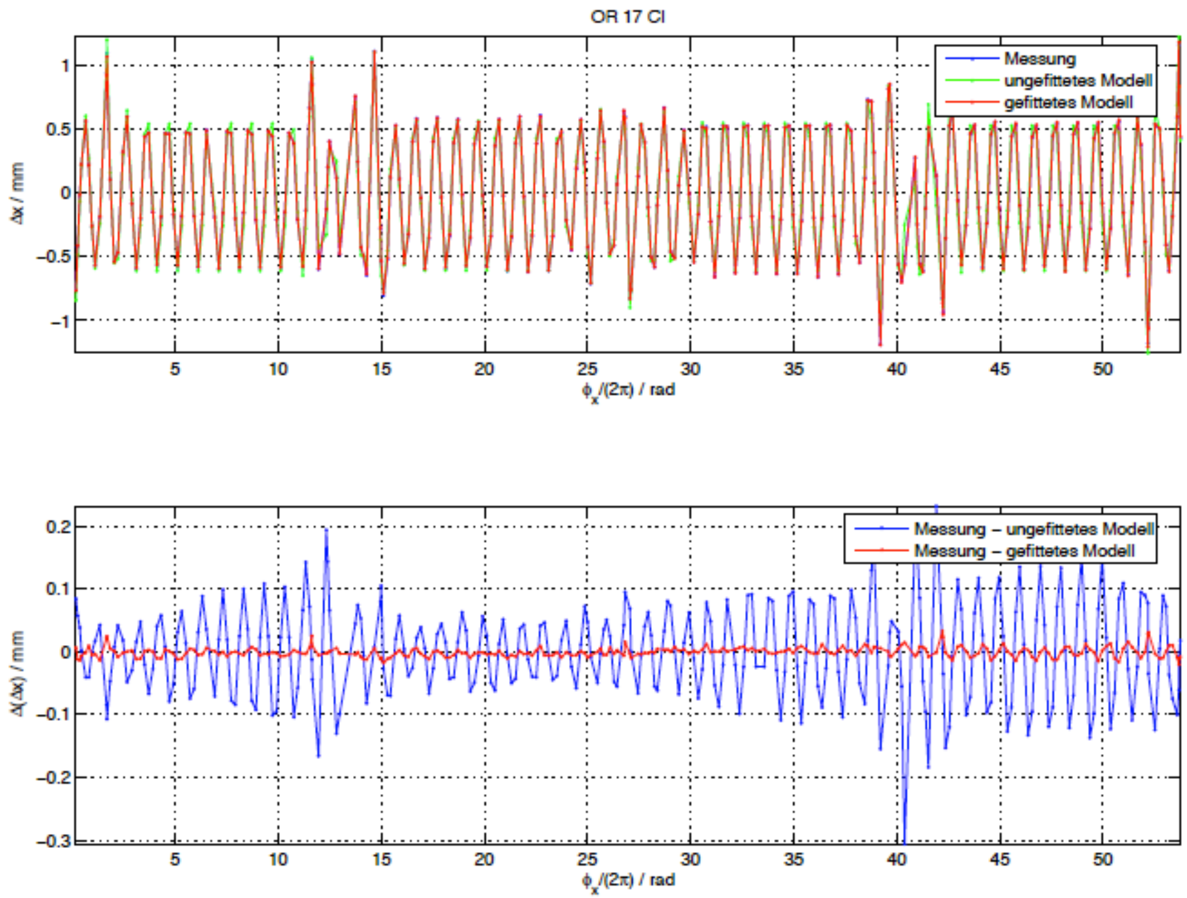
HERA-p: BPM electronic is aging; many BPMs not working; unfortunately many of them in the IR

ORM specialities in HERA:

Response-Matrix: Accuracy I

Top: Difference orbits (Measurement, unfitted and fitted model) for kick of corrector OR 17 CI

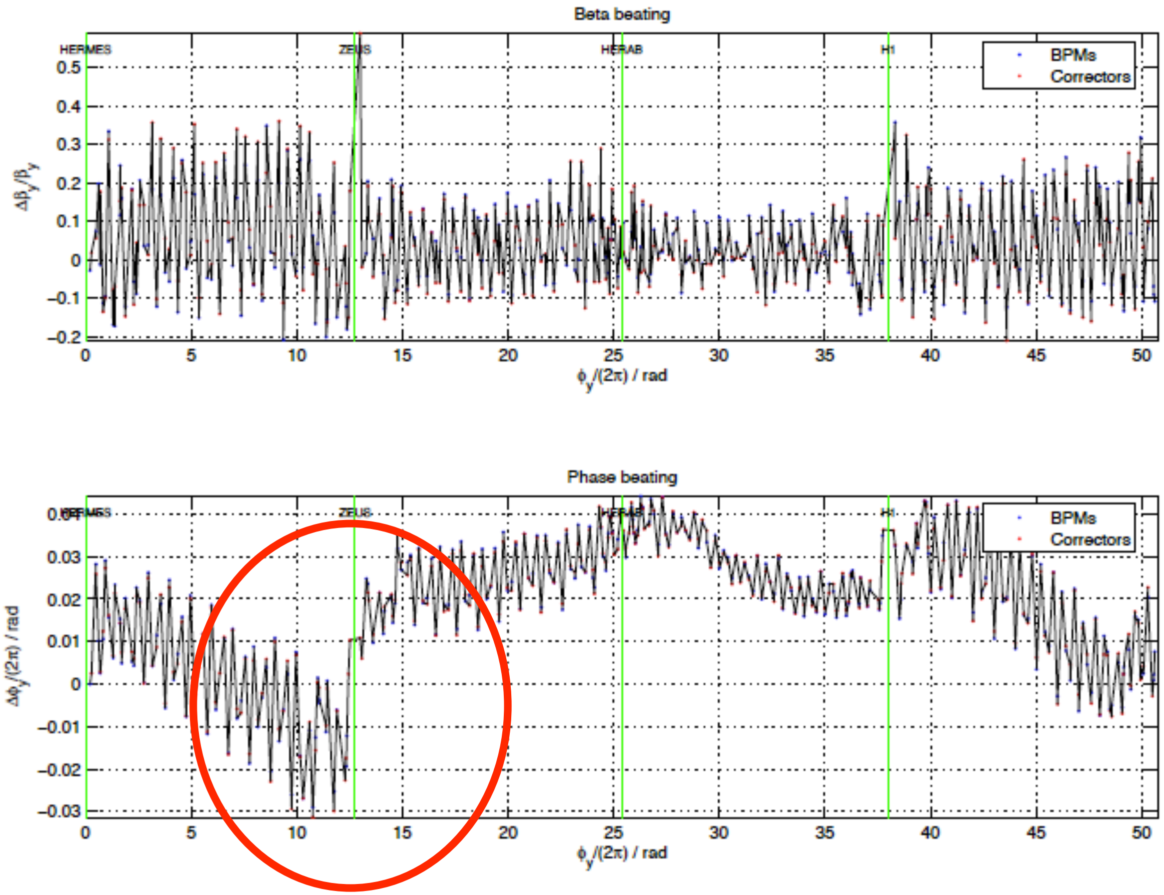
Bottom: Difference between measurement and model before and after fit



ORM specialities in HERA:

Example: Luminosity Optics HERA-e, y-plane

Before correction; ZEUS calorimeter closed

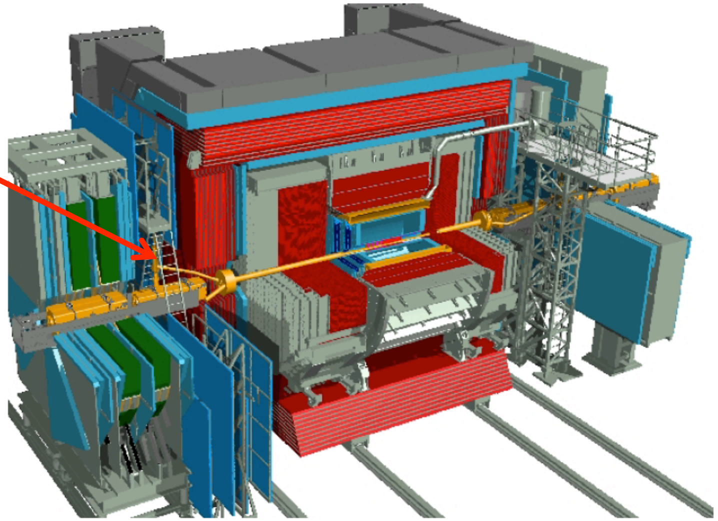


Optics Measurements:

specialities HERA-e

mini beta quads inserted in detector design

-> influence of calorimeter position on beam orbit & optics



$\Delta x \approx 5mm$

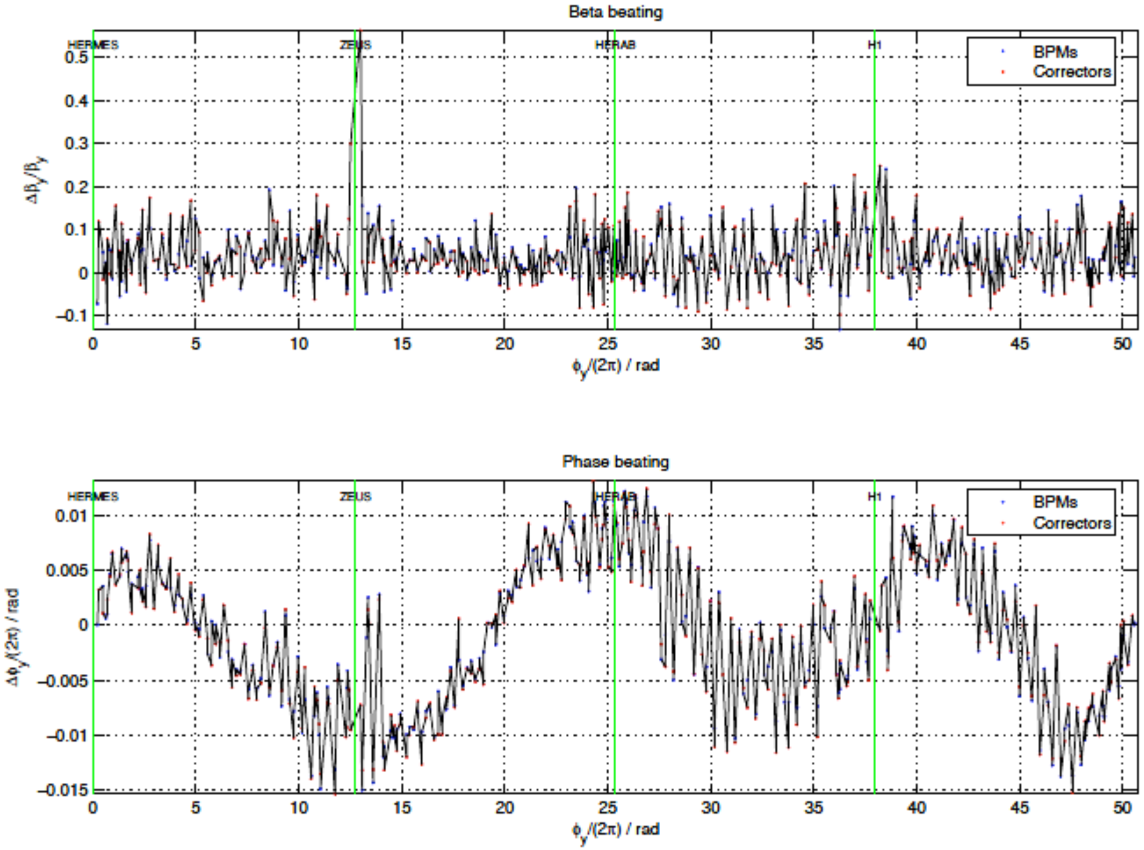
$\Delta\beta/\beta \approx 20\%$

to be corrected "on the flight"

ORM specialities in HERA:

Example: Luminosity Optics HERA-e, y-plane

After correction with 10 quadrupoles ($\Delta k/k$ up to 4 %)



Optics Measurements:

Dispersion Correction in HERA-e

$$\vec{u}_g = \vec{u}_m + S * \Delta\vec{u}' \qquad \vec{u}_g,\quad \vec{u}_m \qquad \textit{golden \& measured orbit}$$

$$\vec{D}_{u,g} = \vec{D}_{u,m} + R * \Delta\vec{u}' \qquad \vec{D}_{u,g},\quad \vec{D}_{u,m} \qquad \textit{golden \& measured Dispersion}$$

for an applied orbit kick Δu'

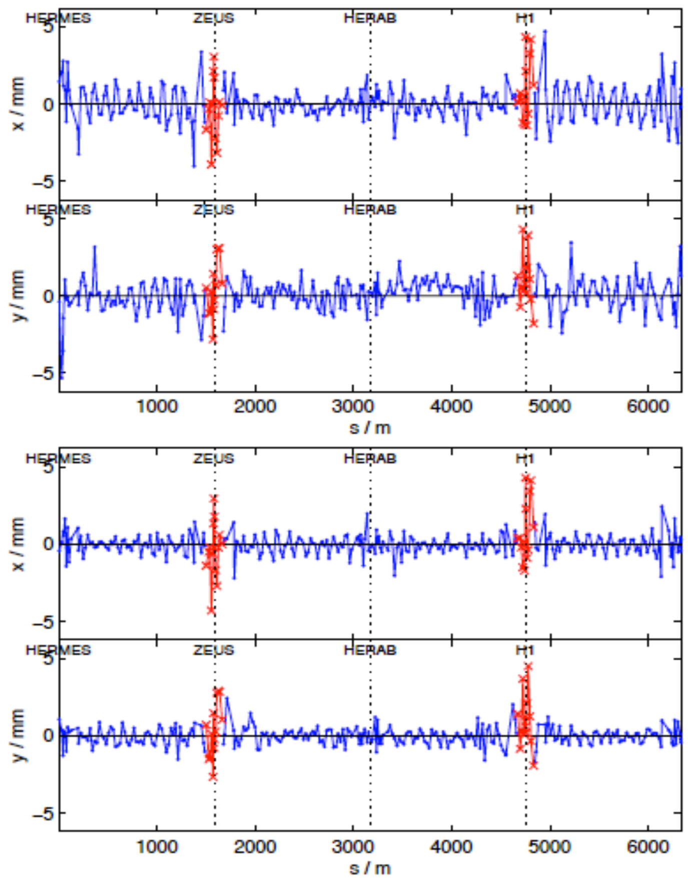


Figure 1: Orbit before (above) and after correction (below). Crosses show fixed BPM positions in the IRs.

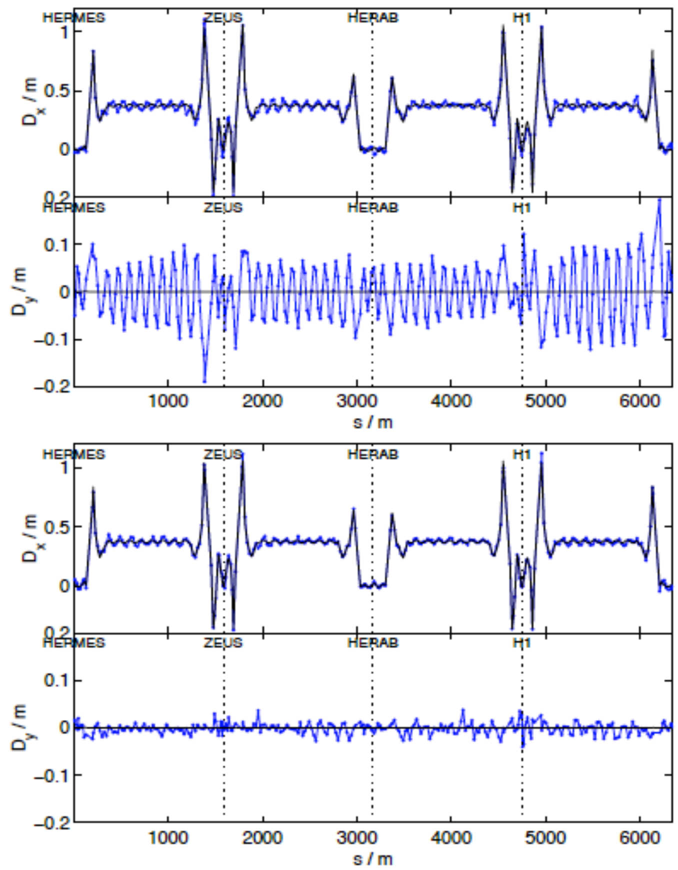
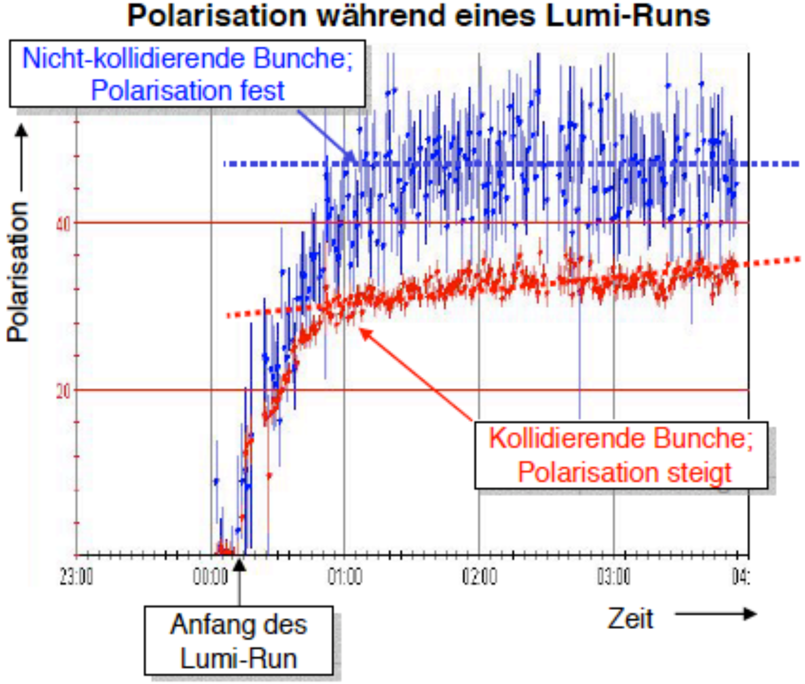


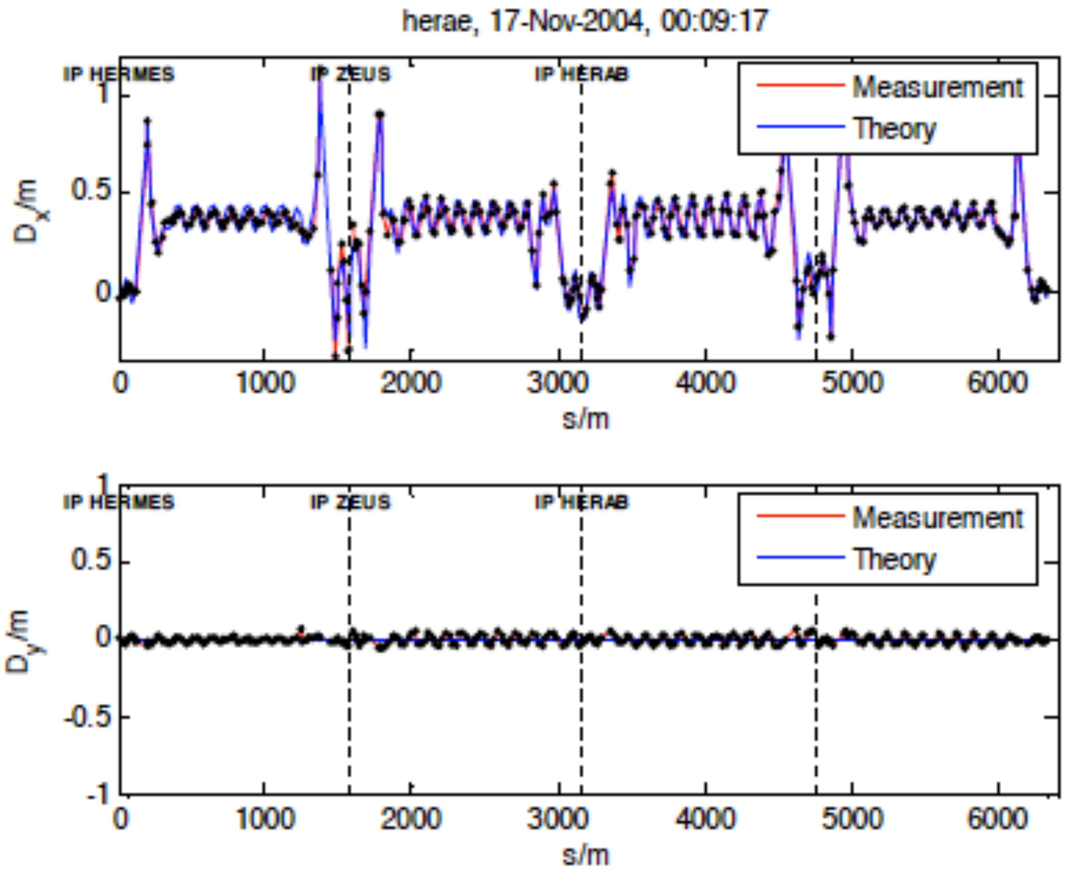
Figure 2: Dispersion before (above) and after correction (below).

court. W. Decking, J. Keil

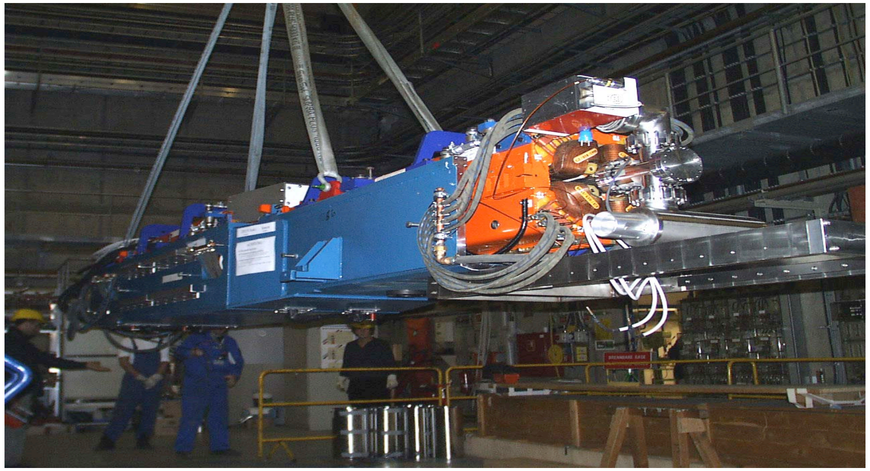
Dispersion Correction in HERA-e

essential for Beam Polarisation

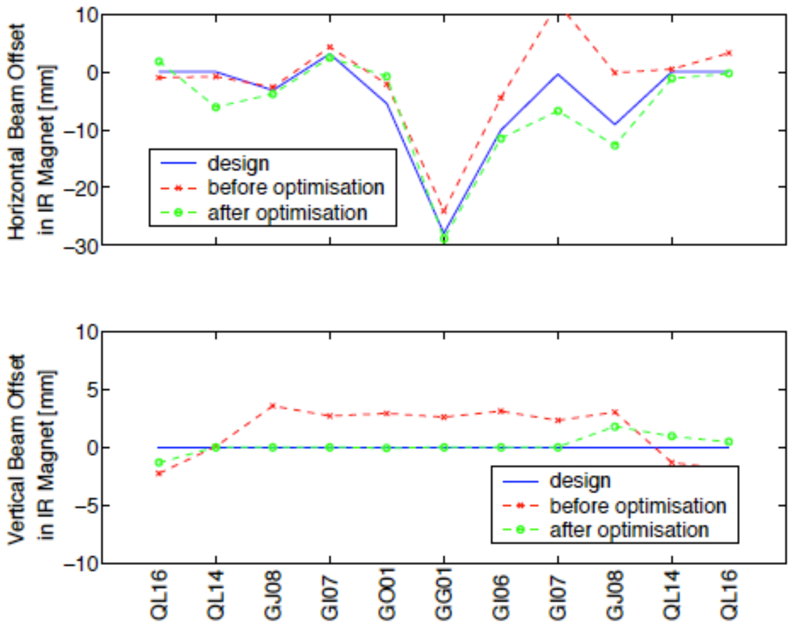




Beam Based Alignment

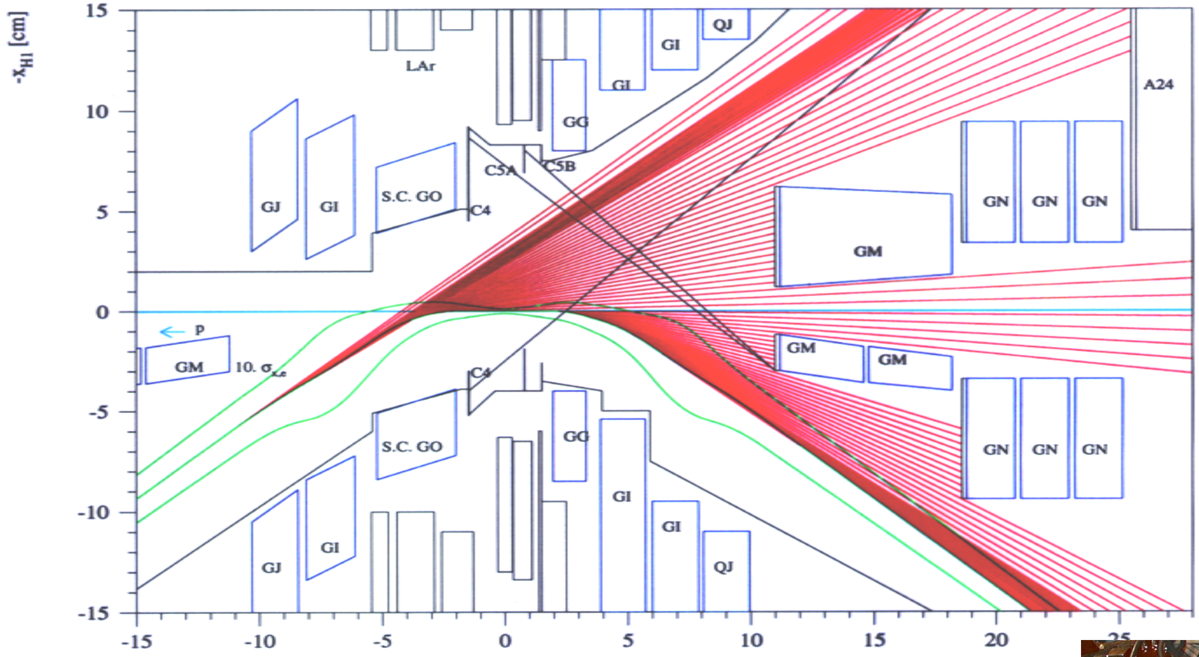


The relative offset of the beam in an IR quadrupole with respect to the magnet axis can be found by changing the quadrupole strength and measuring the thus generated difference in the orbit



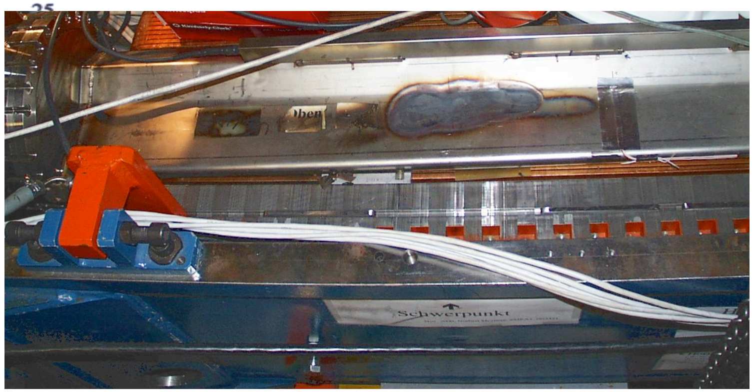
Beam Based Alignment

... the problem: control of synchrotron light



synchrotron light produced during beam separation:
P_{syn} = 30 kW per LSS

damaged vacuum chamber in mini beta quad



HERA Optics & Dynamic Aperture

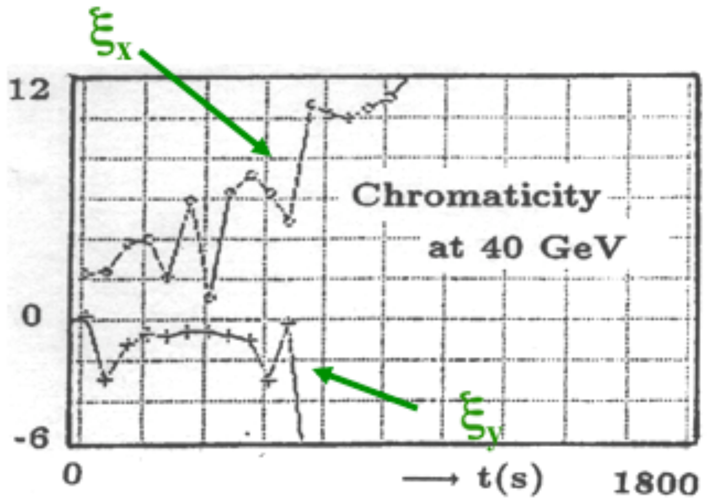
... the special problem of a sc. storage ring

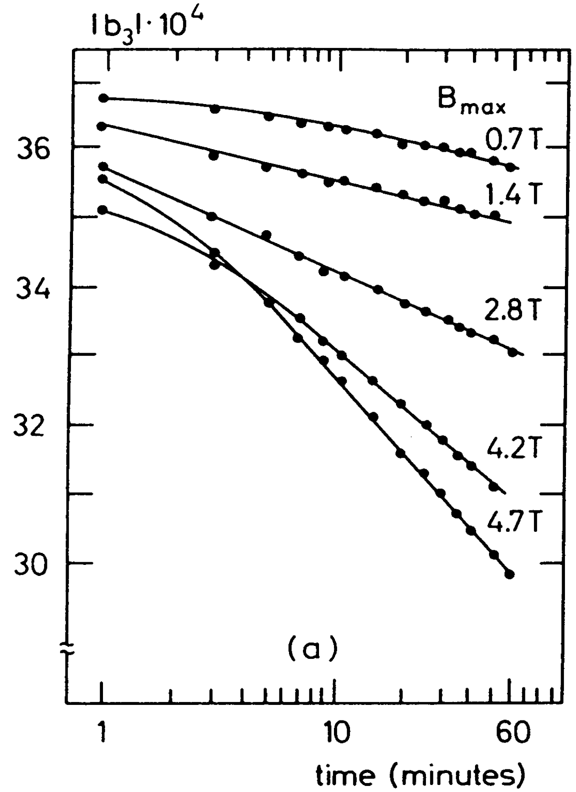
***Beam Optics at Injection:* a running target**

s.c. eddy currents / imbalance currents / persistent currents have a strong influence on the performance of the storage ring.

HERA proton ring at injection:

Chromaticity measurement at flat bottom „on beam“



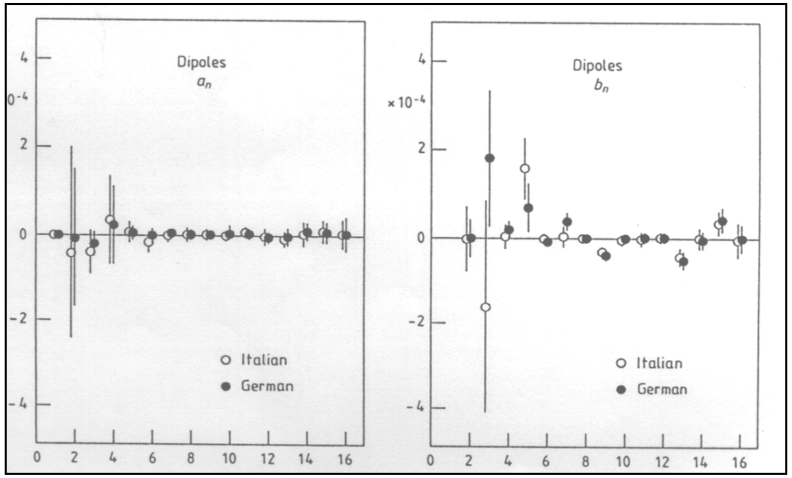


un-reproducibility after different pre-cycles

Dynamic Aperture

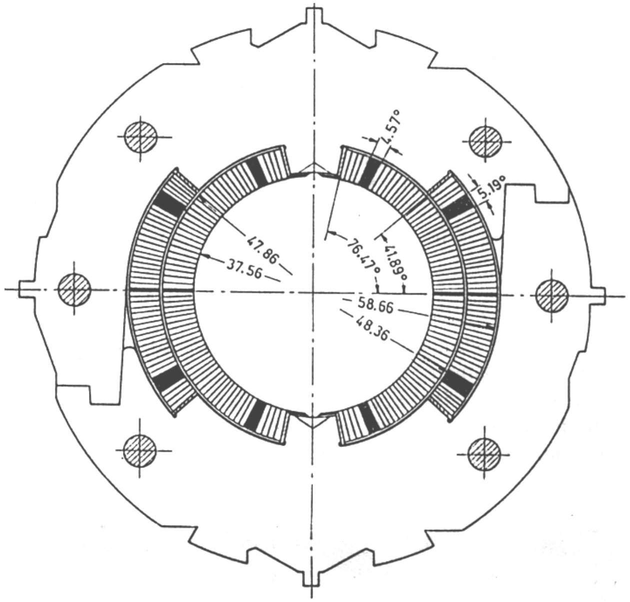
... the Mystery ?

Multipoles in HERA main magnets



HERA dipole magnets

measurements at 5000 A,
closed to the flat top operating point



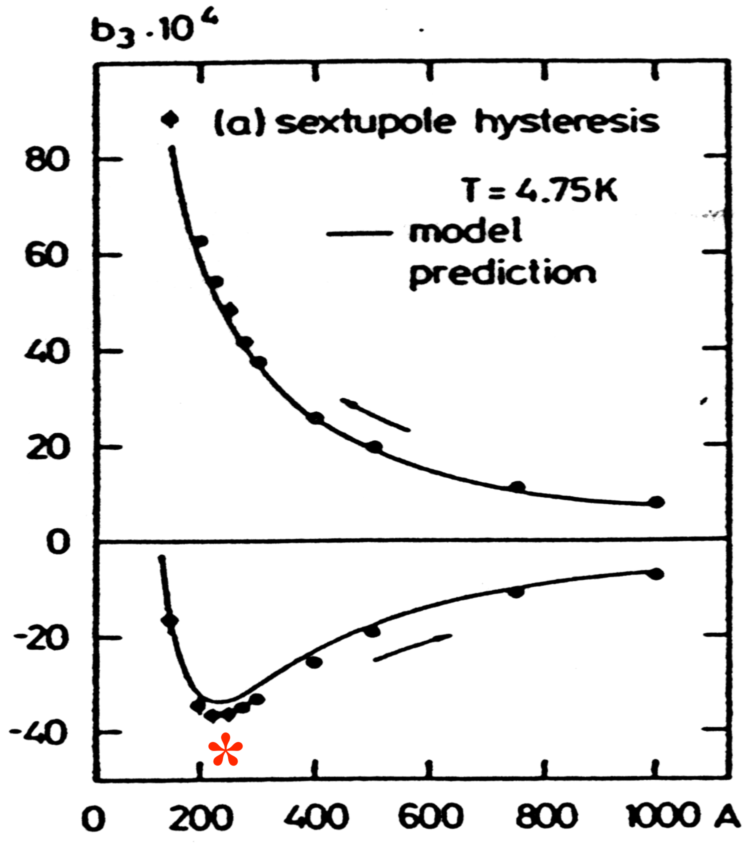
$$B_\varphi(r,\varphi) = B_{main} \cdot \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} \cdot (b_n \cos n\varphi + a_n \sin n\varphi)$$

r_0= 25 mm

Sextupole component at low field

Conditions at injection: I=244 A

b_3=32*10^{-4}



Effect on the beam:

chromaticity in a storage ring

$$\xi_{total} = \frac{1}{4\pi}\oint\{k(s) + m_{6pol}D(s) + m_{pc}D(s)\}\beta(s)\, ds$$

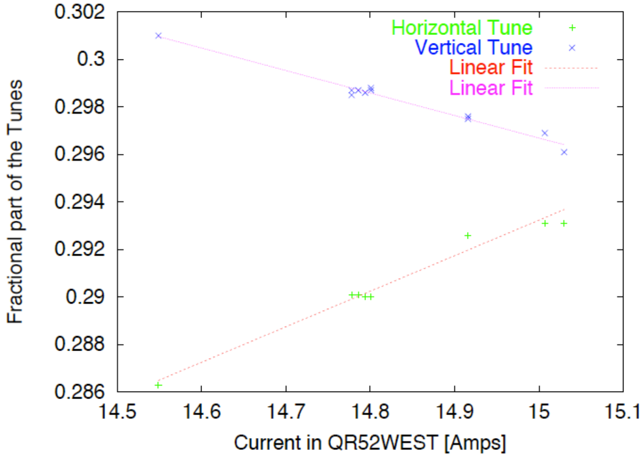
	natural	*b3 contribution*
ξ_x	*-44*	*-275*
ξ_y	*-47*	*245*

... is it stable ?

... is it reproducible?

Dynamic Aperture

... the Mystery ?



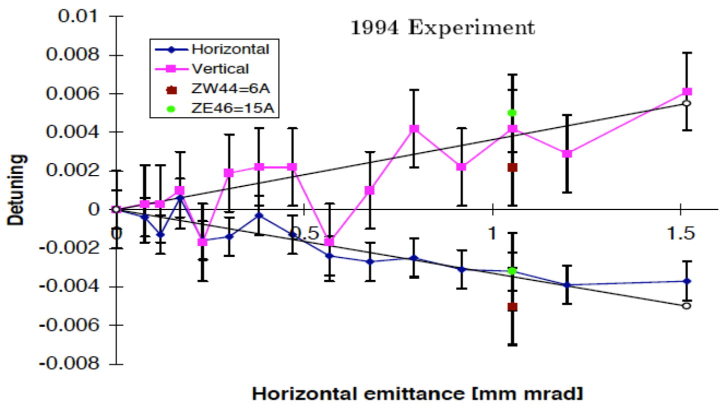
2000: new campaign to measure DA

careful optics measurement & correction

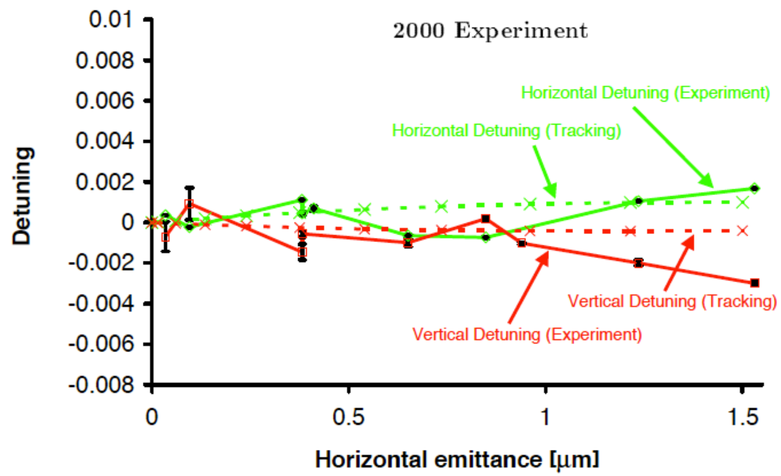
$$\left\langle \frac{\Delta\bar{\beta}}{\beta} \right\rangle_x = (4 \pm 7)\% \qquad \left\langle \frac{\Delta\bar{\beta}}{\beta} \right\rangle_y = (11 \pm 9)\%$$

detuning with amplitude:

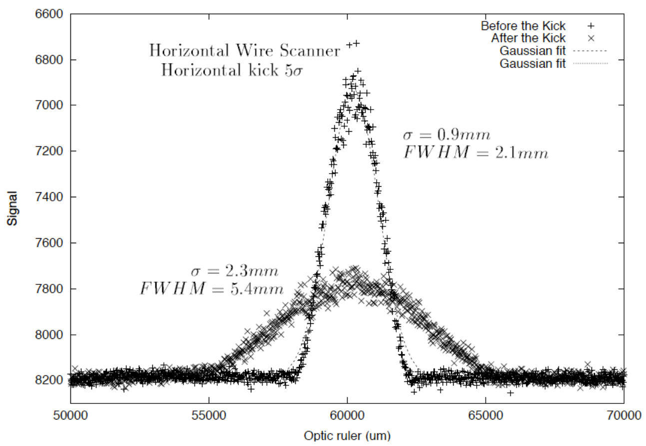
1994



2000

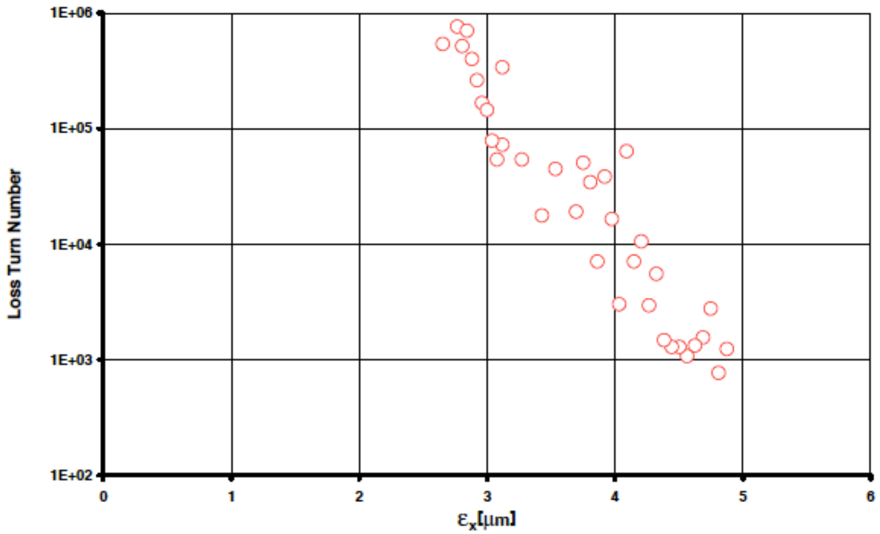


Dynamic Aperture
... the Mystery ?



2000: kicking the beam to 5σ & observing survival amplitude... geometriv aperture smaller than DA during the first measurement series in 1994

new sixtrack calculation ...
DA = 2.5 μm ➔ 4.5 σ



Dynamic Aperture

... the Mystery ?

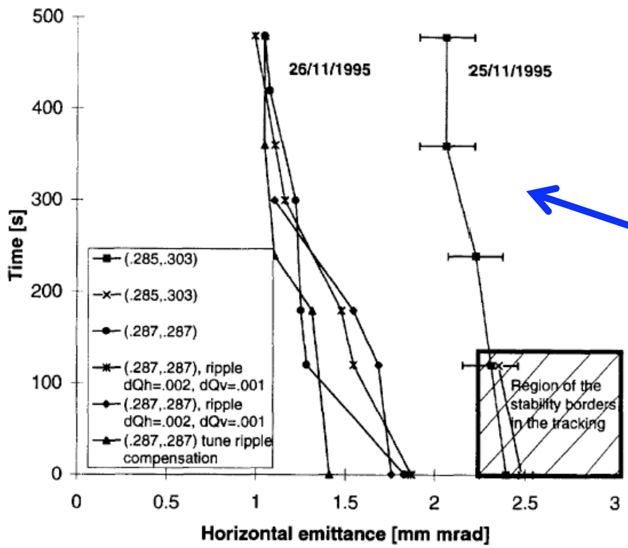


Figure 10: Horizontal Dynamic Aperture derived from Beam Profile Measurements

1994: kicking the beam, observing survival amplitude ... for different tunes

DA = 2.1 µm ➔ 4.1 σ

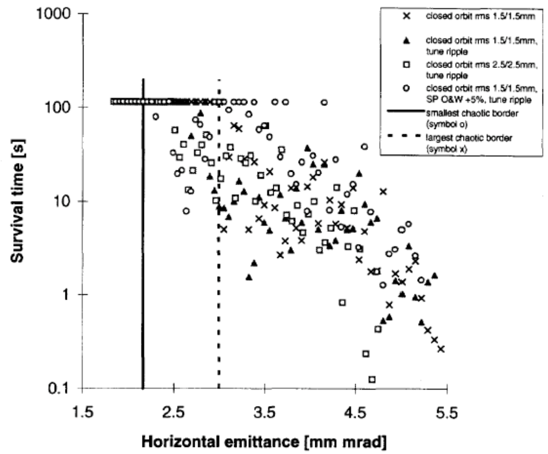


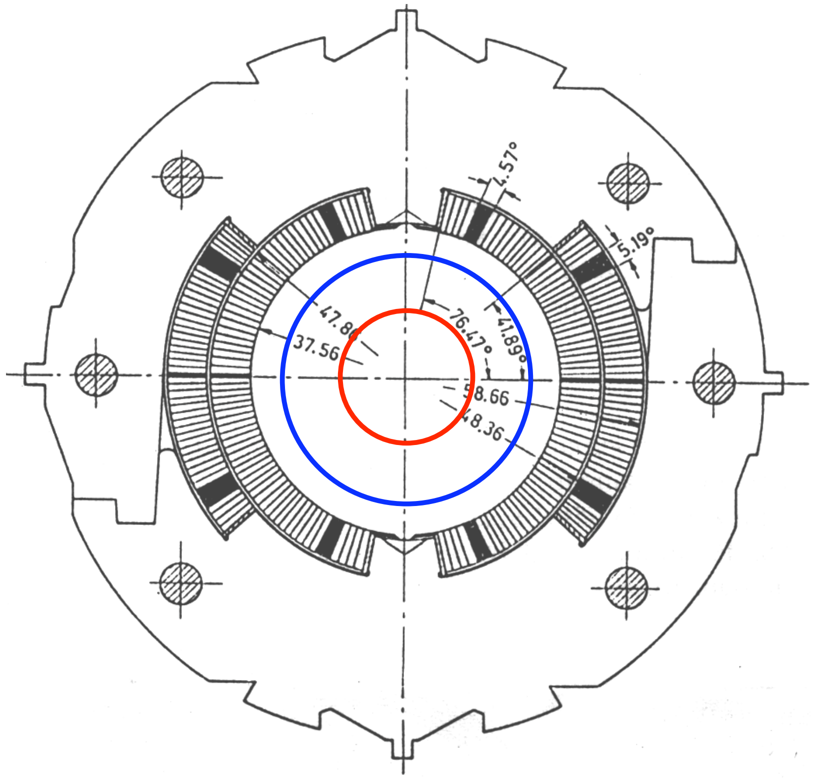
Figure 11: Survival plots for the cases #2, #10, #11 and #12 together with their smallest and largest chaotic border. SP stands for sextupoles correctors.

sixtrack calculation ...

DA = 2.5 µm ➔ 4.5 σ

Dynamic Aperture

... and beam size



Aperture of vacuum chamber:

$$r_0 = 27.5mm$$

Beam size at injection

$$\gamma = 42$$

$$\left.\begin{array}{l} \varepsilon_{n,2\sigma} = 20\,mrad\,mm \\ \varepsilon_0 = 1.2*10^{-7}, \quad \hat{\beta} = 120\,m \end{array}\right\} \quad \sigma = 3.8\,mm$$

ideal maximum aperture at injection:

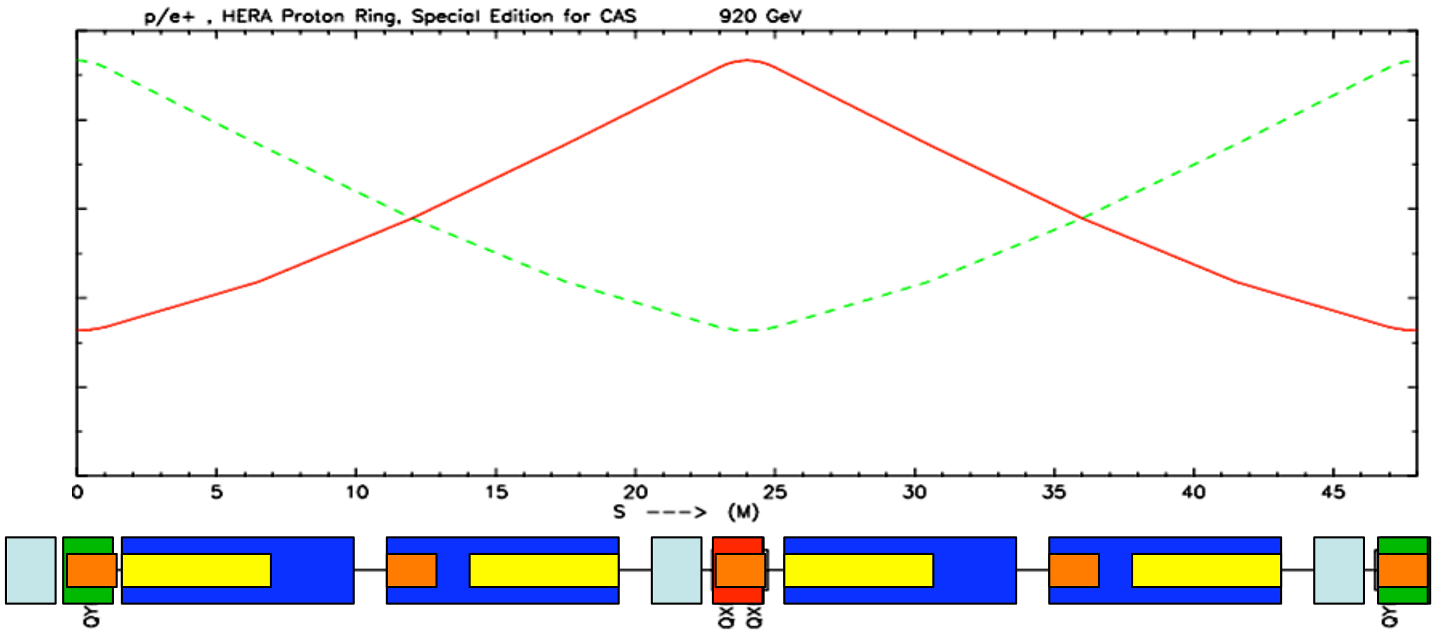
$$r_0 = 27.5\,mm \Leftrightarrow 6.5\sigma$$

measured dynamic aperture at injection:

$$r_0 \approx 17mm \Leftrightarrow 4.1\sigma$$

Dynamic Aperture

... and the multipole coils



HERA multipole compensation scheme

QD	**Dipole**	**Dipole**	**QF**	**Dipole**	**Dipole**	**QD**

qp / sextupole   qp/sextupole   qp/sextupole   qp/sextupole

cy b6   b5   cx b6   b5   cy b6

all correction coils (except the orbit correctors) were built as nested coils

-> special precycle to avoid influence on the optics / dynamic aperture.

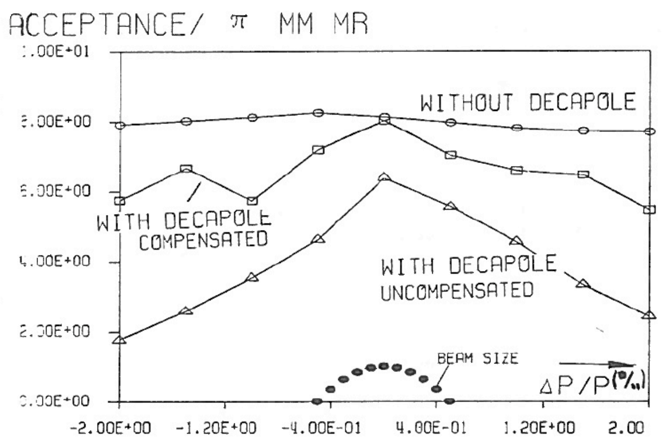
Dynamic Aperture

... and the multipole coils

the original calculations (1991 ?)

DA = 8 µm ➔ 8 σ

larger than geom. Aperture



*1.) **lifetime at injection: τ ≈ 5h***

*2.) after **re-arranging the sextupole corrector strengths** τ ≈ 10h*

*3.) after **tlc optimisation** by the one and only expert τ ≈ 20h*

4.) deca poles powered between I= ± ∞

5.) deca poles polarity switch between sectors (octants)

→goto point 1.)

Dynamic aperture was limited at injection,

beam parameter settings were extremely critical,

machine very non-linear

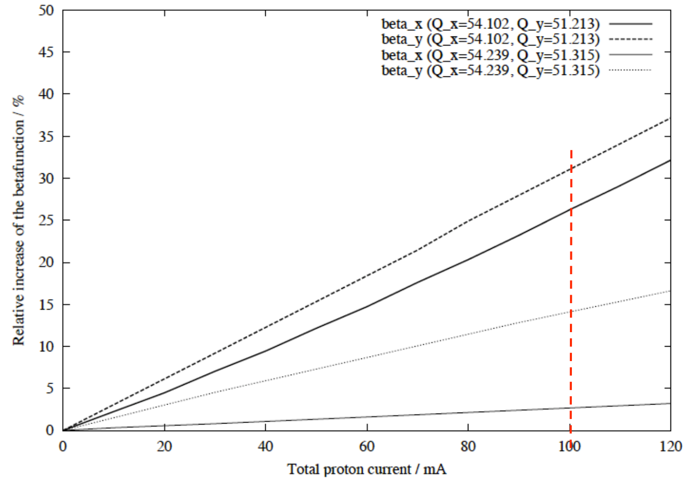
and still we did not see any influence from the higher order spool piece correctors

Effective beam cross section at the IP:

Luminosity – or van der Meer - scans

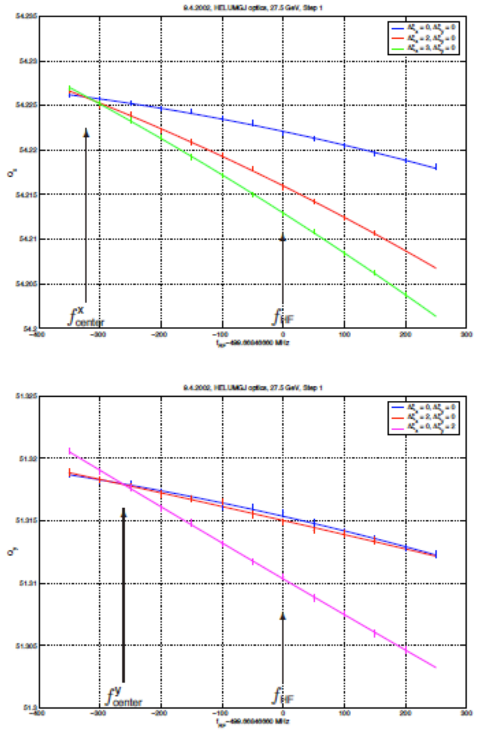
special care for ...

*** dynamic beta beat in HERA-e**



Δβ/β in e-ring as function of I_p

Lumioptik (HELUMGJ) 9.4.2002, Step 1, $\Delta f^{\mathrm{Soll}} = 350\,\mathrm{Hz}$

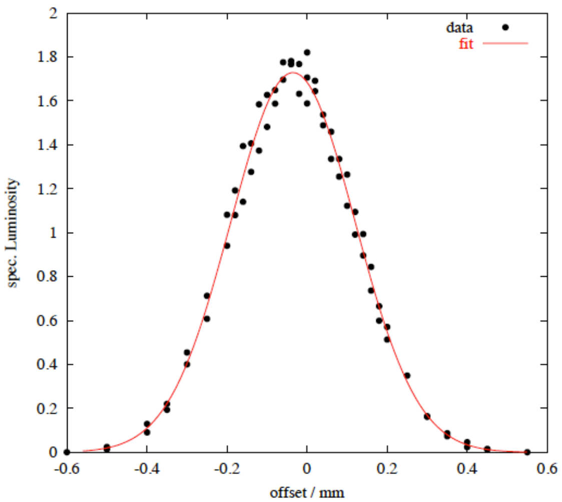


*** centre frequency of e-ring**

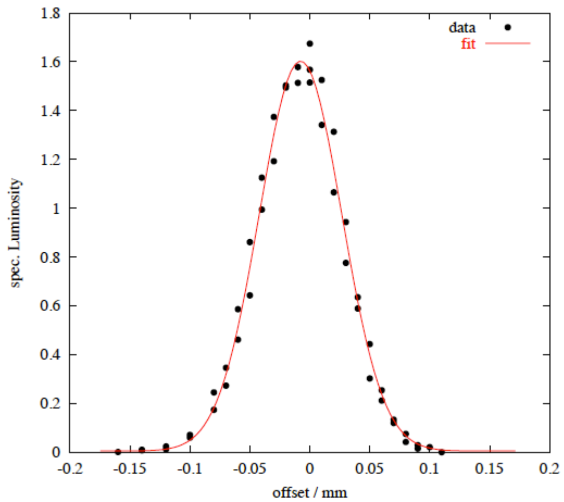
emittance reduction required Δf = +350 Hz

Effective beam cross section at the IP:

Luminosity – or van der Meer - scans



Horiz. plane, $\sigma_{eff,x} = 109.9\ \mu\text{m}$



Vert. plane, $\sigma_{eff,x} = 24.4\ \mu\text{m}$

theoretical values: $\sigma_{x,e} = \sigma_{x,p} = 112\,\mu m$

$$\sigma_{y,e} = \sigma_{y,p} = 30\,\mu m$$

$$\boldsymbol{L_{spec}} = \frac{f_0}{2\pi * \sqrt{(\sigma_{x,p}^2 + \sigma_{x,e}^2)} * \sqrt{(\sigma_{y,p}^2 + \sigma_{y,e}^2)}}$$

$$= 1.76 * 10^{30} cm^{-2} s^{-1} mA^{-2}$$