HERA Performance Upgrade: Achievements and Future Plans

M. Minty, DESY

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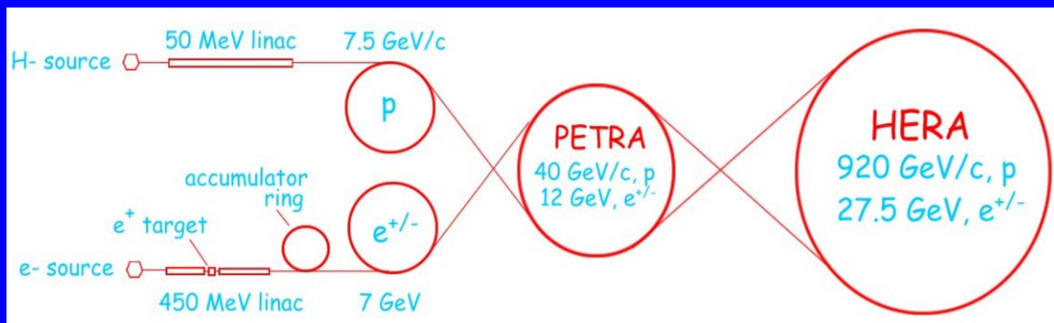
I Introduction – brief history of HERA I / II

HERA-I

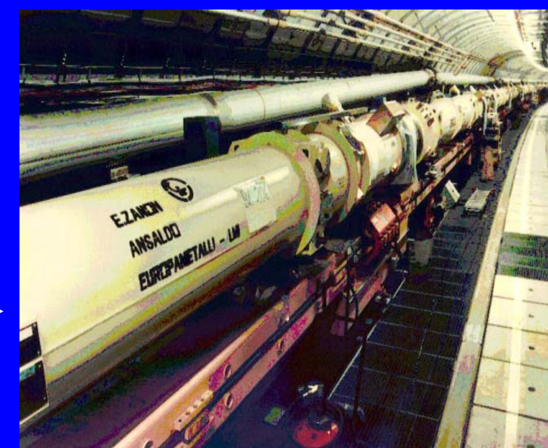
1981 HERA proposal

1984 beginning of construction

1988 commissioning of the proton injectors



1991 commissioning of the new 6.3 km, double-ring collider, HERA



1991 first proton-electron collisions

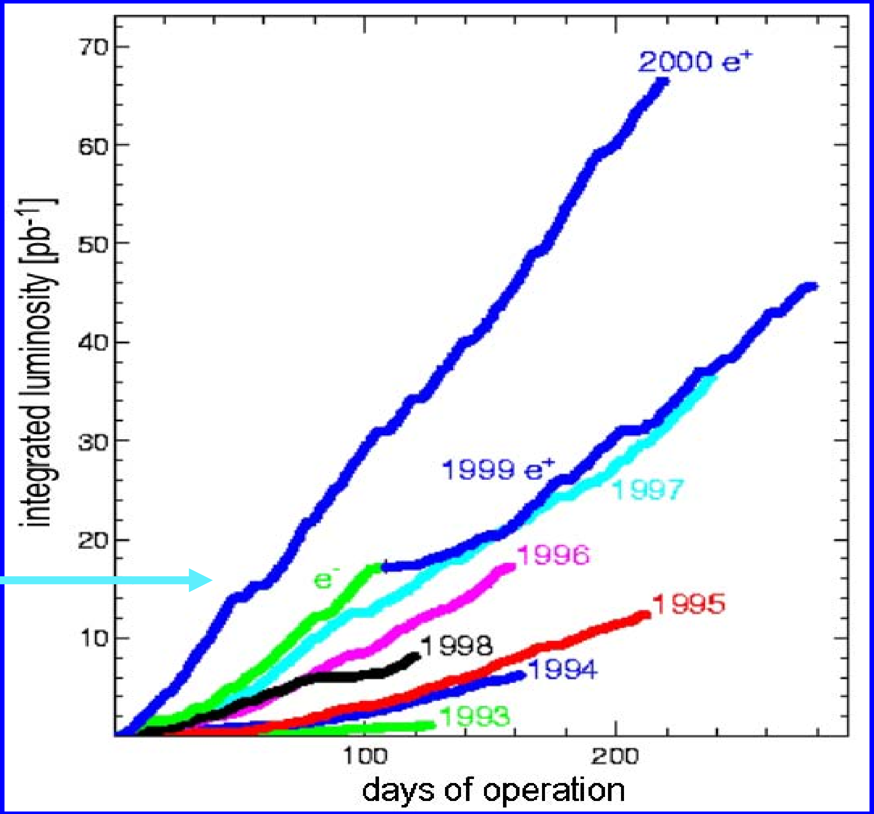
1992 first beams to 2 colliding beam experiments: H1 and ZEUS

1997 design peak luminosity (1.4×10^{31} cm^{-2}s^{-1}) achieved

1997/8 reliability upgrade (for higher integrated luminosity)

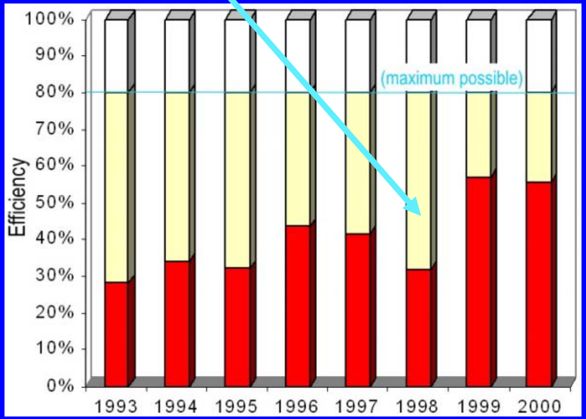
2000 end of HERA-I with 100 pb^{-1} y^{-1} delivered to experiments

Luminosity history at HERA-I:



design $<\hat{L}> = 1.4 \times 10^{31}\ cm^{-2}s^{-1}$
exceeded, 1997

reliability upgrade



luminosity operations with (year 2000)

$<\hat{L}_{sp}> = 0.6 \times 10^{30}\ cm^{-2}s^{-1}mA^{-2}$

$<\hat{L}> = 1.6 \times 10^{31}\ cm^{-2}s^{-1}$

$\int L dt = 100\ pb^{-1}$ per year

$<I_p> = 100$ mA

$<I_e> = 40$ mA

with N_b=174 colliding bunches

➡ to achieve $\int L dt = 1\ fb^{-1}$ an upgrade for higher luminosity was initiated

HERA-II

1998	upgrade proposal (L↑ and $P_{\|\|}$)
2001	installation
2001/02	commissioning (and protons to fixed target experiment, HERA-B)
2003	startup of luminosity operations
	first longitudinally polarized beams in collision
2004	luminosity operations with > 3.5×10^{31} cm^{-2}s^{-1} and >50% and continued steady increase in total beam currents
2007	planned end of HERA-II run

Design options for increased luminosity in the performance upgrade:

1) <u>higher proton beam brightness</u> $=10^{11}$ ppb / 4μm
concern: emittance growth in the preaccelerators

$$\mathrm{L} = \frac{\gamma_p}{2\pi e} \frac{\left(\frac{\mathrm{N}}{\epsilon}\right)_p \cdot \mathrm{I_e}}{\underbrace{\sqrt{\beta^*{}_{xp}\beta^*{}_{yp}}}}$$

2) <u>higher lepton beam current</u> – concern: total rf power (and potentially by beam-beam tune shifts imparted to the protons)

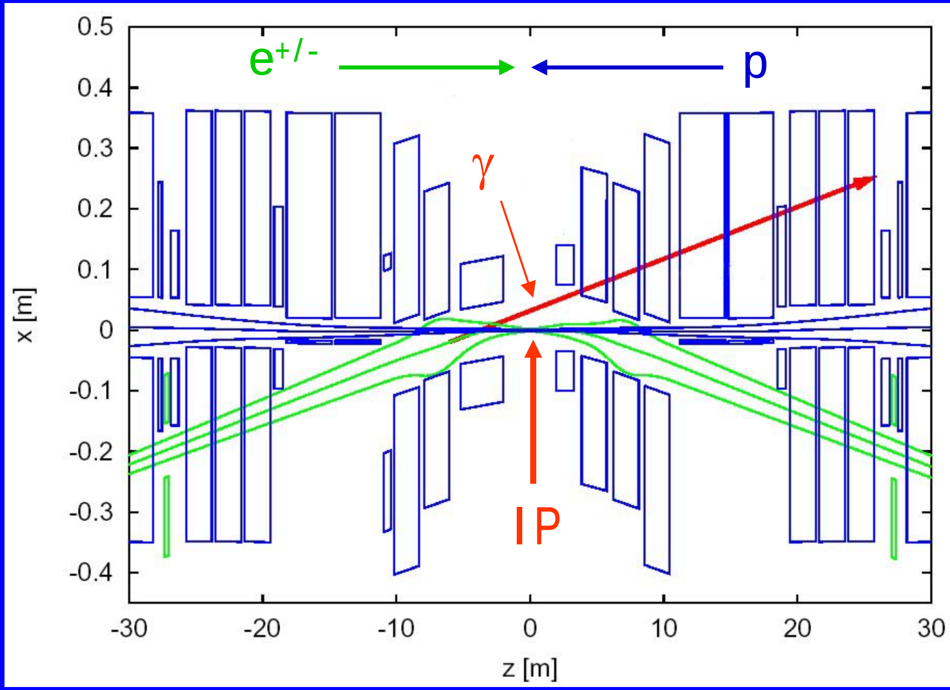
3) <u>smaller beam sizes</u> with stronger focusing (smaller β*) at the interaction points - concerns: increased synchrotron radiation in the interaction regions and large lepton beam-beam tune shifts

➡ the most conservative and cost-effective approach given by option #3

II The 3 major aspects of the HERA performance upgrade

a) higher luminosity – via stronger focusing of the proton & lepton beams

(extent of detector solenoid (H1))



modified IR's for smaller proton beam sizes:

β^*_{xp} = 7 m → β^*_{xp} = 2.45 m
β^*_{yp} = 50 cm → β^*_{yp} = 18 cm

key features:

- superconducting, combined-function quadrupoles including dipole fields to separate the beams (starting inside of the detector solenoid)
- septum quadrupoles with special mirror plates to further separate the beams
- unique vacuum chamber geometry for sufficient apertures and for synchrotron radiation, P_γ=28 kW
- unique vacuum chamber designs, in particular, in the quadruple triplet near IP
- additional masking and collimation

b) higher luminosity – matching the lepton beam sizes at the IP

- IP quadrupole design (stronger focusing)
- increased betatron phase advance (60 → 72° per FODO) } smaller momentum compaction, α, via decreased dispersion ➡ larger rf bucket
- frequency shift (J_x=1 → J_x=1.25) } larger energy spread, δ

} compensating

IP beam sizes:

$\sigma^*_{x,p} = \sigma^*_{x,e}$ = 190 μm → 112 μm
$\sigma^*_{y,p} = \sigma^*_{y,e}$ = 50 μm → 30 μm

total luminosity:

$L_{design} = 1.4\times10^{31}$ cm^{-2} s^{-1}

→ **L = 4.5×10^{31}** cm^{-2} s^{-1} with pre-upgrade beam currents

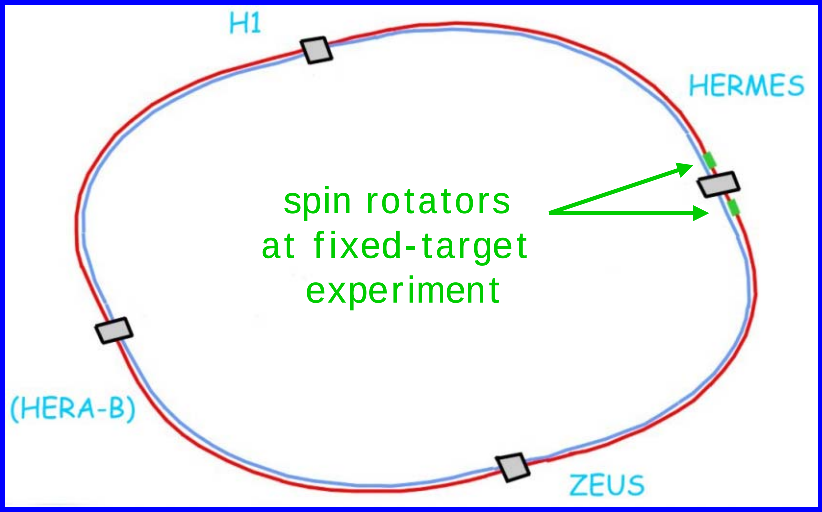
→ **L = 7.0×10^{31}** cm^{-2} s^{-1} with (1981) HERA design currents

specific luminosity:

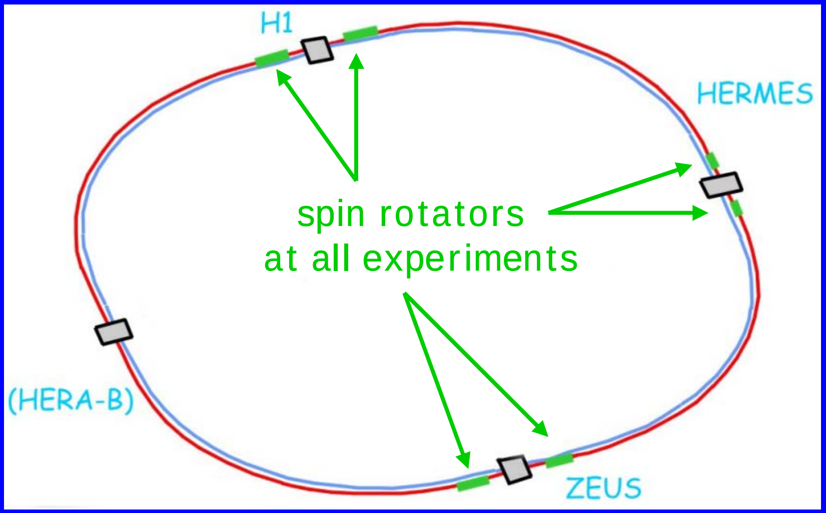
$L_{sp} = 0.6\times10^{30}$ cm^{-2} s^{-1} mA^{-2} → **L_{sp} = 1.8×10^{30}** cm^{-2} s^{-1} mA^{-2}

c) longitudinal polarization at the collision points

HERA-I



HERA-II

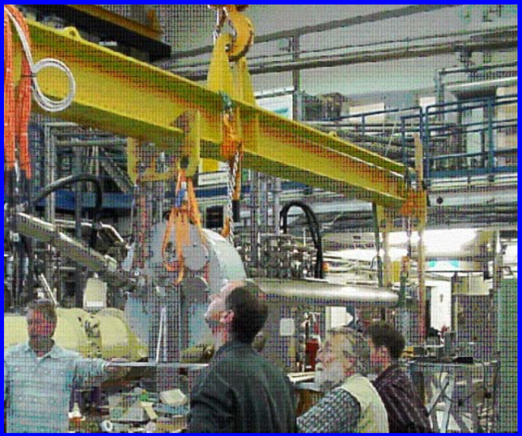


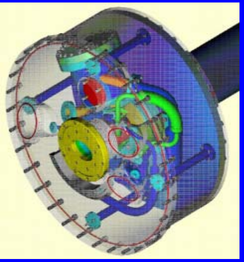
particular concerns for the colliding-beam experiments (H1 and ZEUS):

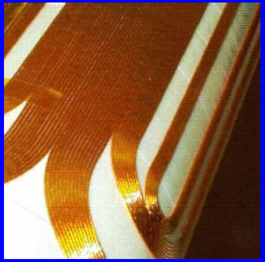
solenoidal fields not locally compensated (beam trajectories not perfectly parallel to solenoid axis)	complicated spin-matched optics	closed-orbit control and harmonic spin matching
increased lepton beam emittance coupling (for matched IP beam sizes)		
stronger effect of beam-beam interaction on polarization		no validation of theory by experiment

photographs of selected upgrade components:

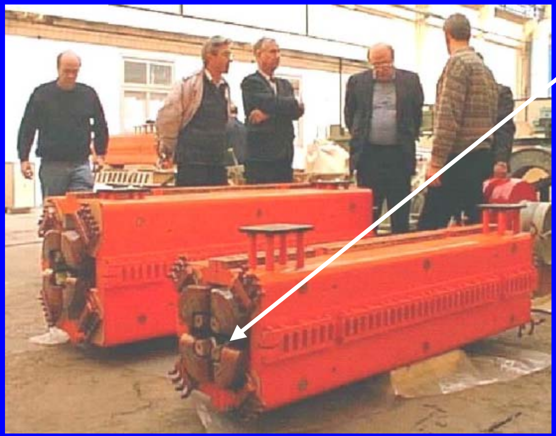
sc magnets
(2 m from IP)

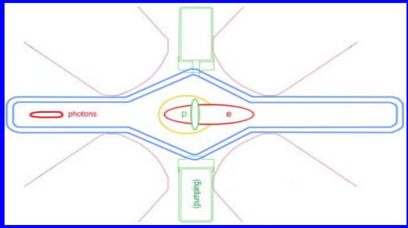






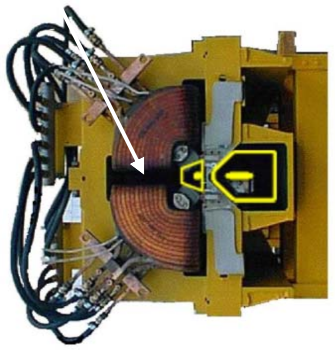
lepton focusing
(3-10 m)





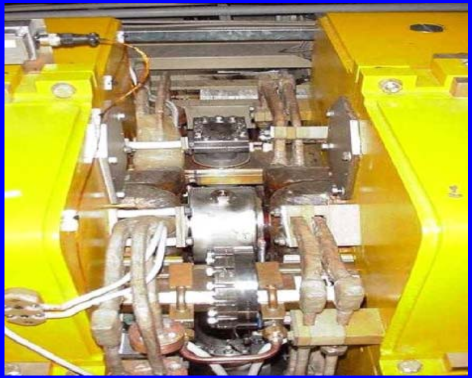
(gap for
emitted
γ-beam)

½-quad with 2 vacuum
chambers (11-18 m)

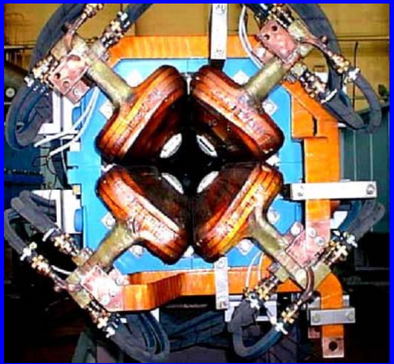


proton focusing
vertical (19-26 m)

vacuum chambers with 3
separate beam pipes (>22 m)



proton focusing
horizontal (~40 m)



III Upgrade Commissioning

2001/02

upgrade commissioning
+ protons to fixed target experiment, HERA-B
+ positrons to fixed target experiment, HERMES

- first evidence of unexpected backgrounds at both IPs
- implementation of several operational improvements

N_b = 174, nominal
I_p~35 mA
I_e~20 mA
(low single-bunch beam currents)

2003

- verification of luminosity upgrade parameters
- verification of polarization upgrade parameters (summer shutdown)

N_b = 120
I_p~70 mA
I_e~30 mA
(high sb beam currents)

startup of luminosity operations
experience gained with
- high current beam-beam interactions
- synchrobetatron resonances

N_b = 120 → nominal
I_p~35 → 100 mA
I_e~20 → 35 mA

2004

routine operation with steadily increasing total beam currents

N_b = 174 (nominal)
I_p → 100+ mA
I_e → 50 mA

A) detector leakage currents (backgrounds)

parameterization of the currents in the central tracking chambers, I_{ctc}:

detector pedestal (μA)

direct synchrotron radiation (μA/mA)

vacuum-related lepton beam-gas scattering (μA/mA^2)

proton beam-gas scattering (μA/mA)

$$I_{ctc} = c_0 + c_1 I_e + c_2 I_e^2 + c_3 I_p + c_4(I_e \times I_p)$$

$I_{e/p}$ = total lepton/proton current

mysterious term whereby
c_4 (with collisions) > c_4 (without collisions)

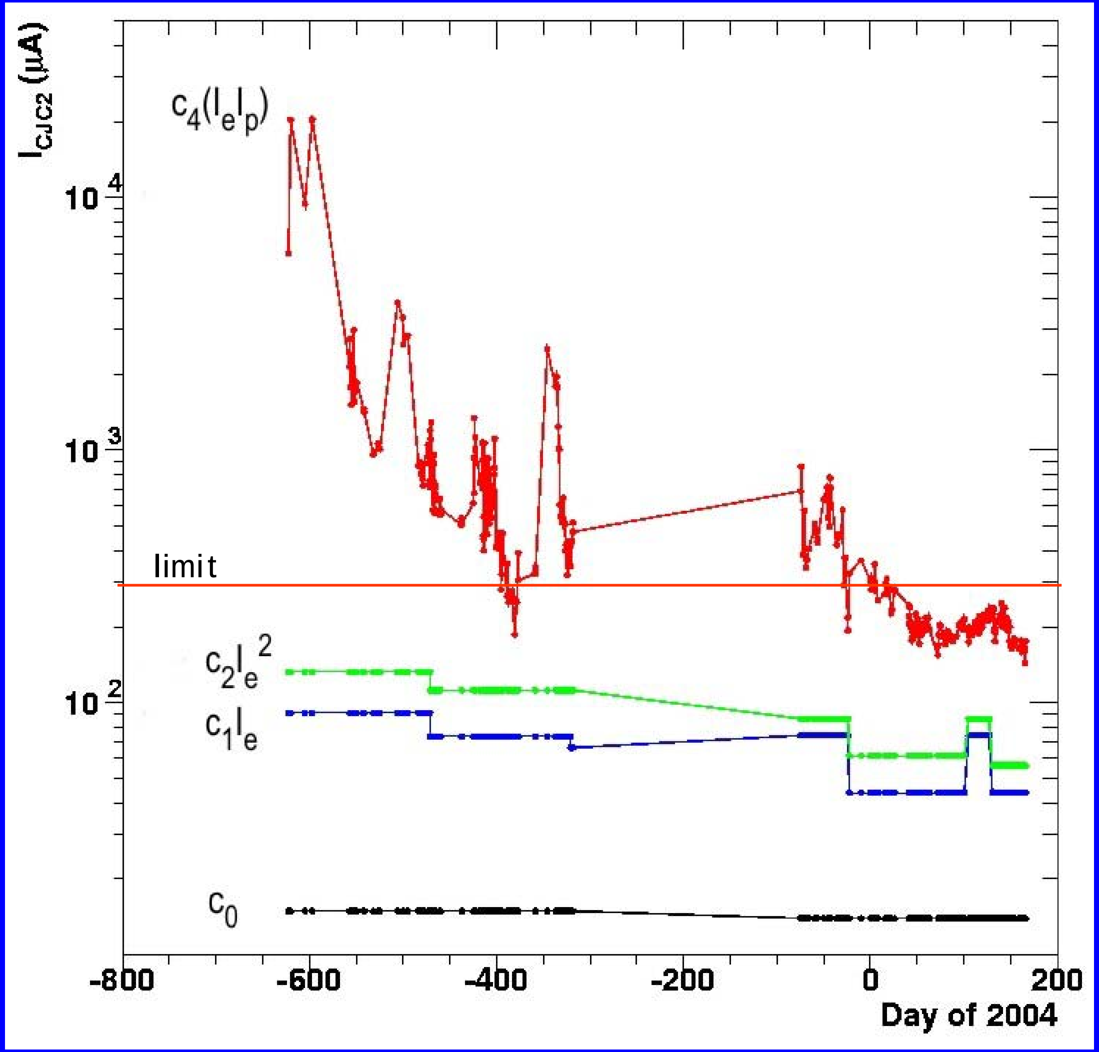
source: synchrotron radiation generated by leptons causing enhanced desorption of gas from vacuum chamber walls (some of which are superconducting and cooled to 40K) with which the protons interact via beam-gas scattering

time evolution of the background coefficients, c_i (at H1):

drift chamber currents extra-polated to

I_p=100 mA
I_e=50 mA

$$I_{ctc} = c_0 + c_1 I_e + c_2 I_e^2 + c_3 I_p + c_4 (I_e \times I_p)$$



(with exception of pedestal, c_0) all coefficients, in particular dominating $I_p \times I_e$ term, seen to decrease with time measures to control detector currents: (see also M. Seidel, MOPLT045)

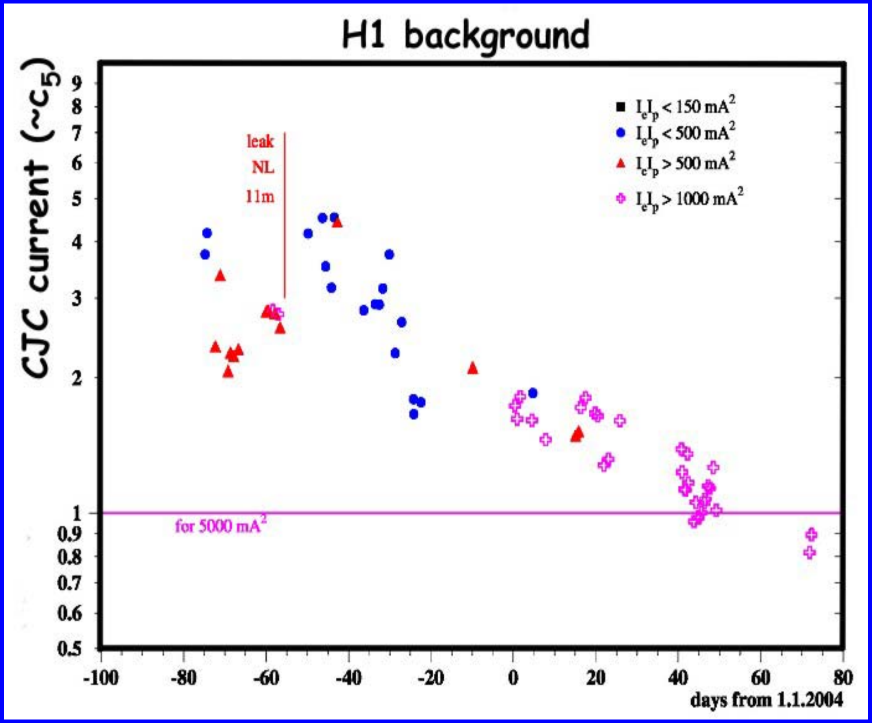
- additional collimators far upstream of IPs
- change in masking at ZEUS (critical)
- additional pump near IP at H1
- increased conductance of pumping ports

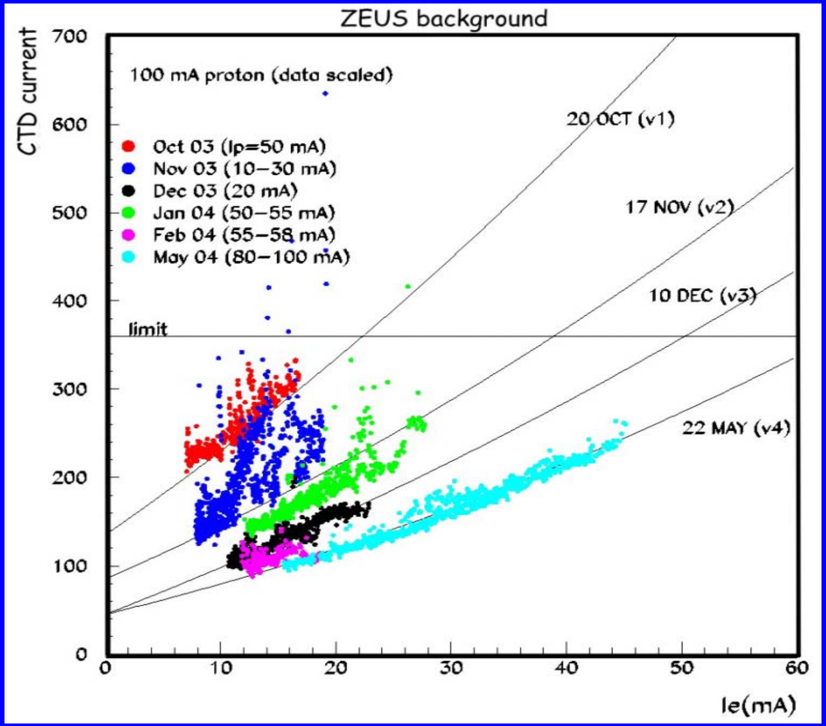
(in wind shadow of 2003 shutdown)

- warmup of sc magnets during scheduled maintenance
- steady operations with high beam currents

most effective

recent status at the colliding beam experiments:





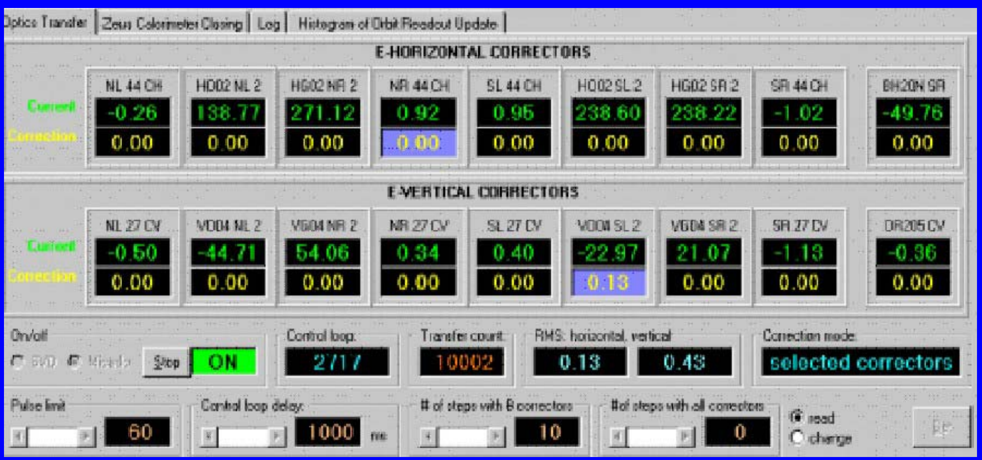
➡ HERA-II no longer current-limited due to backgrounds (2/2004)

B) operational improvements

beam-based alignment of combined-function magnets in IP
beam orbit feedback (with superimposed bumps) rms orbits ≤ 0.1 mm
automated beam optics corrections
faster sequencing (magnet cycling, ramping, and β-squeeze procedures)
fast background tuning toolbox
comprehensive data logging and post mortem buffering
electronic logbooks and extended communication systems

} to better control optics, avoid local heating due to synchrotron radiation, and to maximize the polarization

➔ despite increased complexity, HERA-II operates as well (or even better) than HERA-I



S. Herb et al, THPLT042

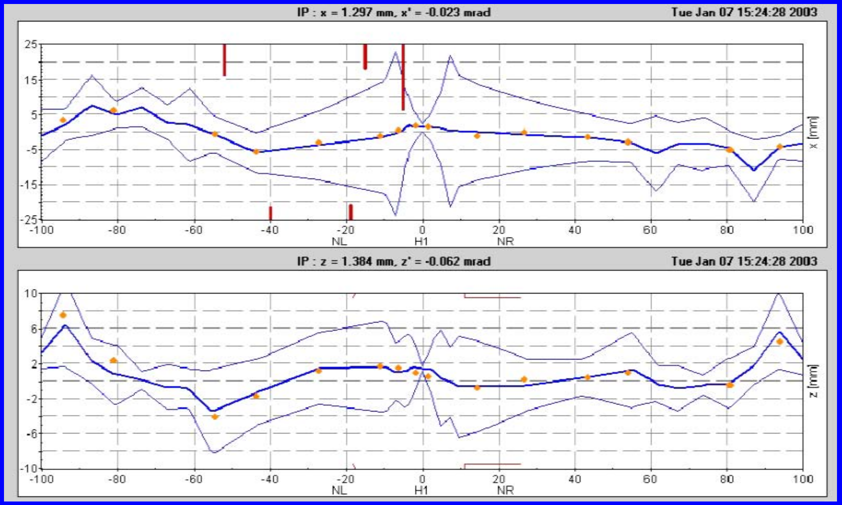
IP feedback

global feedback

wrt to a stored reference orbit

online absolute orbit measurement plotted wrt design orbit (off-center in some magnets) obtained from BBA results, applied magnet excitations, and BPM measurements:

F. Brinker TUPLT035



C) verification of the upgrade parameters (2/2003)

given the (at that time) limit on total beam currents, in dedicated experiments, the number of colliding bunches was reduced to maximize the luminosity

$$L = \frac{I_p I_e f_{rev}}{2\pi e^2 \Sigma_x \Sigma_y N_{col}}$$

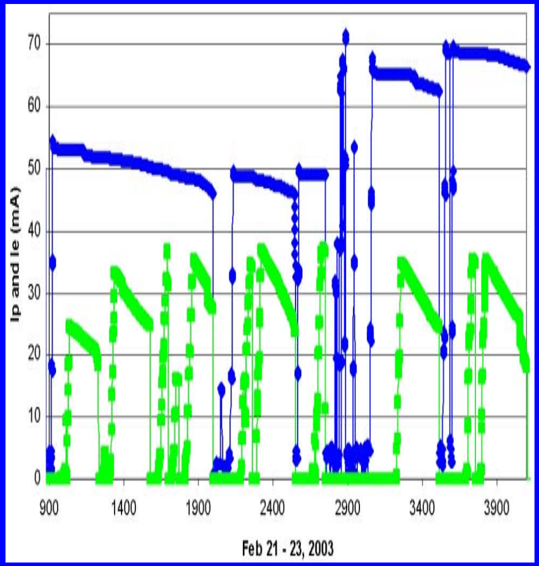
by maximizing the single-bunch (sb) beam intensities (thereby provoking maximal beam-beam tune shifts)

beam current distribution

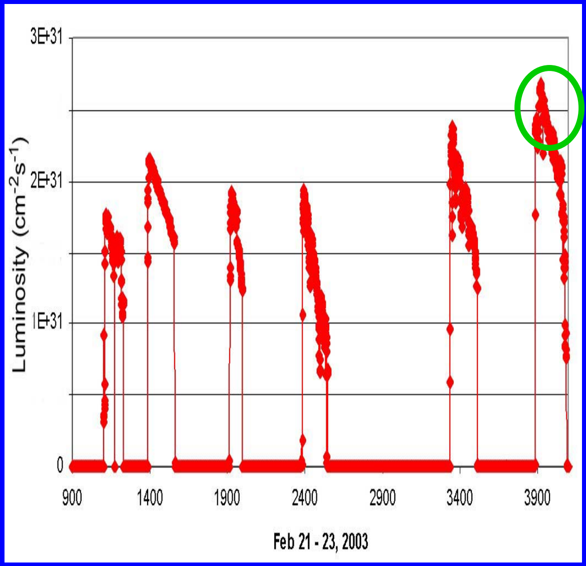
$I_{p,sb}$

$I_{e,sb}$

total beam currents vs time



measured luminosity vs time



(HERA-I design)

substantial (and maybe saturation limited) increase in measured total luminosity with

$L_{sp}=3L_{sp,0}$

(factor 3 increase with respect to HERA-I design)

D) beam dynamics: synchrobetatron resonances

choice of operating point in tune diagram:

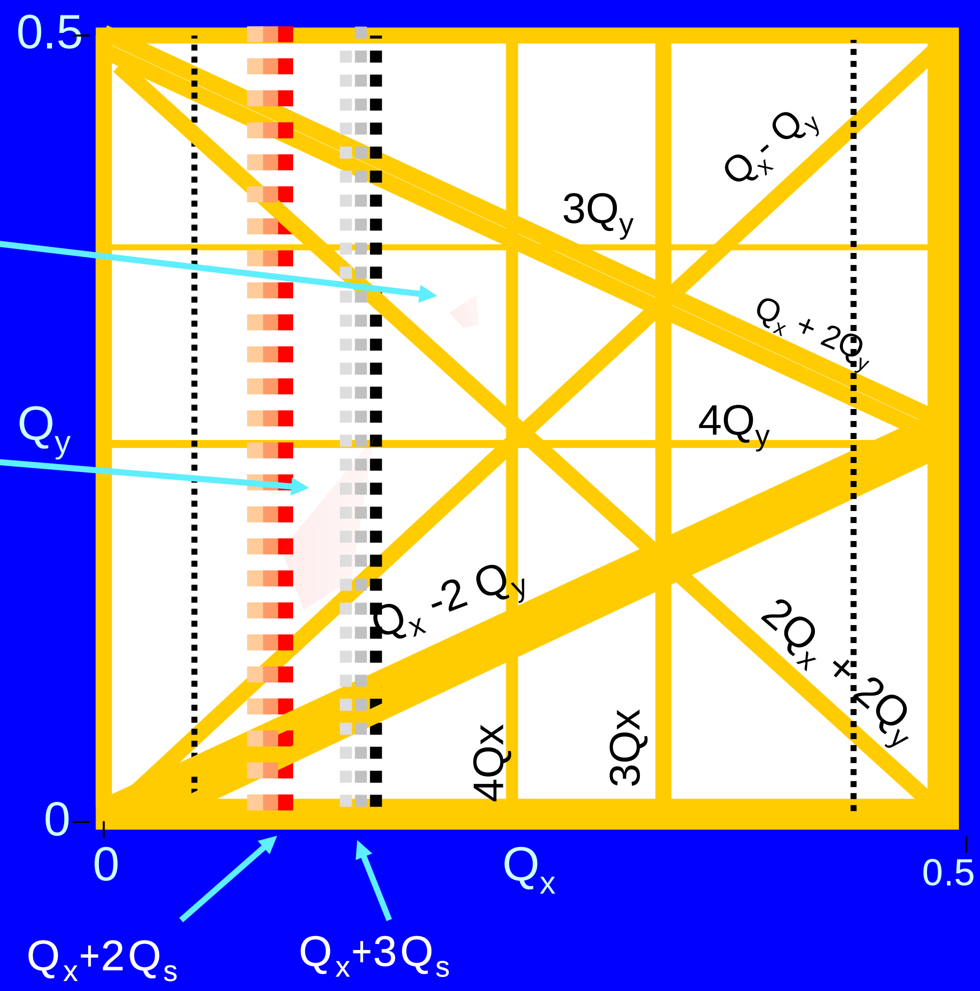
<u>injection</u>

sufficient dynamic aperture

<u>luminosity</u>

resonance-free region to accommodate beam-beam footprint ($\Delta Q_x \leq 0.04$, $\Delta Q_y \leq 0.1$ with 2 IPs)

small betatron tunes to maximize distance between intrinsic depolarizing resonances at $a\gamma = c_1 \pm c_2\, Q_\beta$



initial experience: poor beam lifetime due to strong synchrobetatron resonances

F. Willeke, MOPLT046, M. Vogt WEPLT045, J. Keil and W. Decking TUPL037

synchrobetatron resonances

F. Willeke, MOPLT046

non-compensated nonlinear chromaticity drives 1st satellite of the half integer resonance that interferes with 2nd satellite of the integer resonance

➔strong 3rd satellite in integer Q_x+3Q_s

➔ insufficient tune space

cured by optics with intrinsic compensation of non-linear chromaticity contributions from the two IPs

satellite Q_x+2Q_s excited by oscillatory closed orbit distortion

driving term ~ x L^2

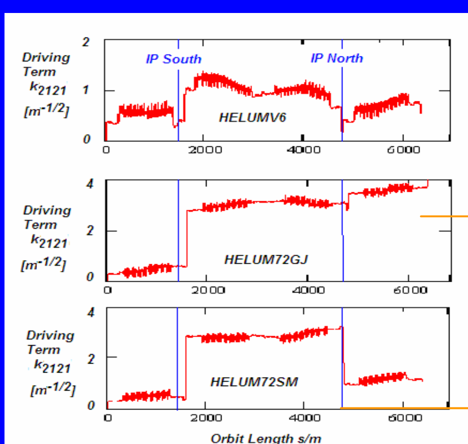
cure: orbit and dispersion control, orbit feedback

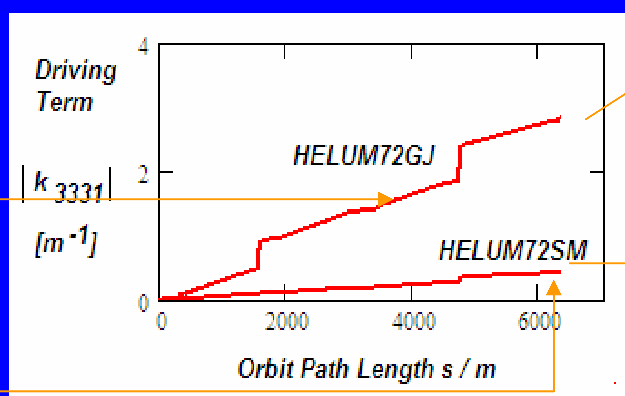
$2Q_x+Q_s$ driven by nonlinear chromaticity

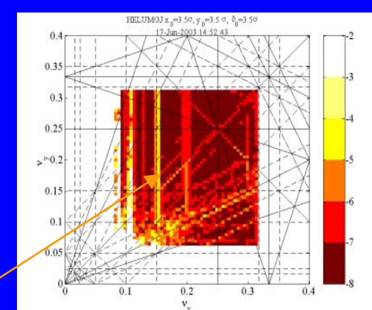
Q_x+3Q_s generated by interference of Q_x+2Q_s & $2Q_x+Q_s$

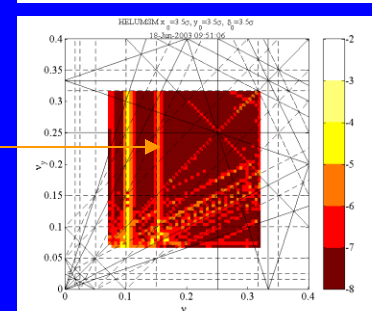
courtesy W. Decking

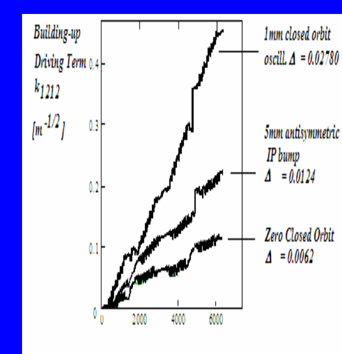
orbit effects on Q_x+2Q_s











E) beam dynamics: the beam-beam interaction

challenges with the upgrade optics:

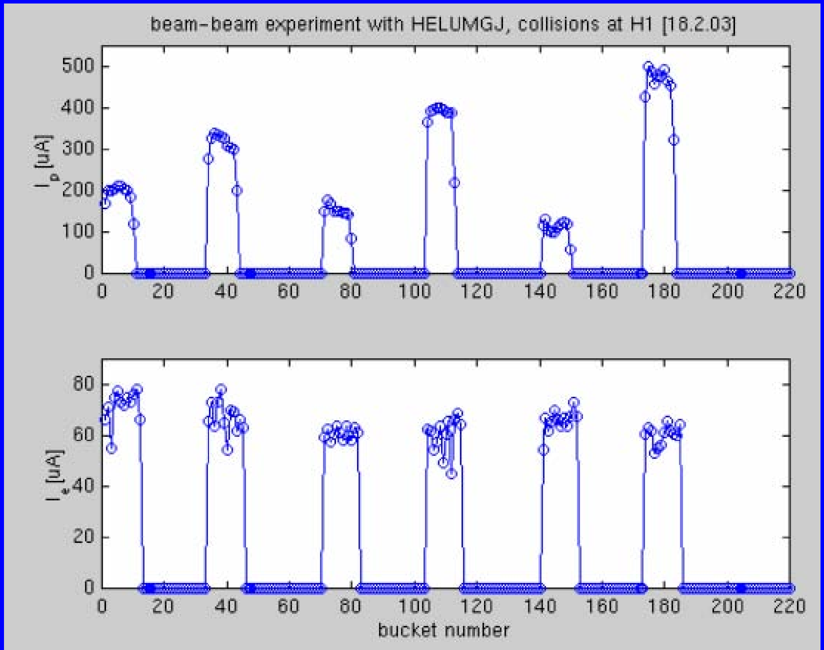
- linear beam-beam tune shifts of lepton beam at each IP: $\Delta\upsilon_x$=0.02, $\Delta\upsilon_y$=0.05
- dynamic beam-beam beta beat with lepton Q_x=54.12 (close to integer)
- tune spread of lepton beam: $2\Delta Q_x = 0.04$, $2\Delta Q_y = 0.10$

early experiences evidenced current-dependent specific luminosity:

current per bunch

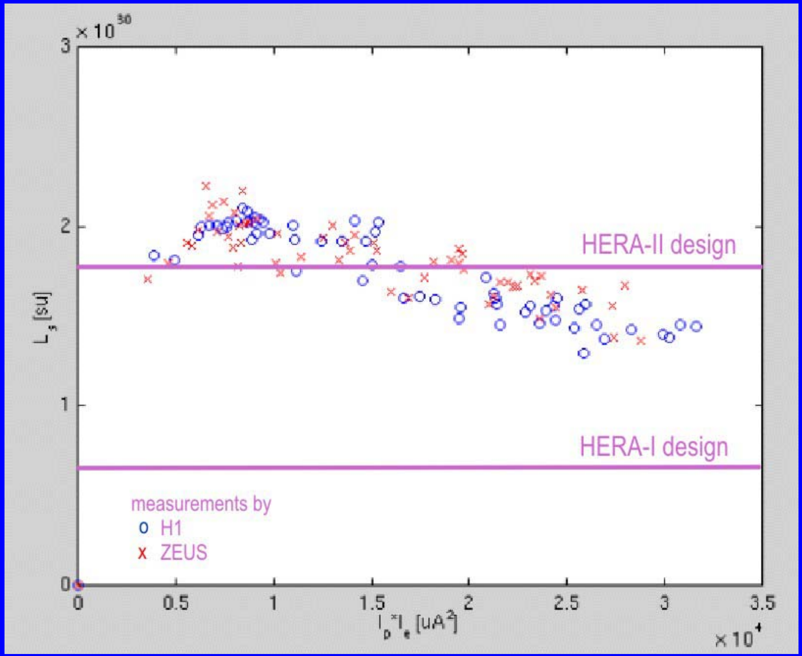
protons

leptons



position (1 turn full scale)

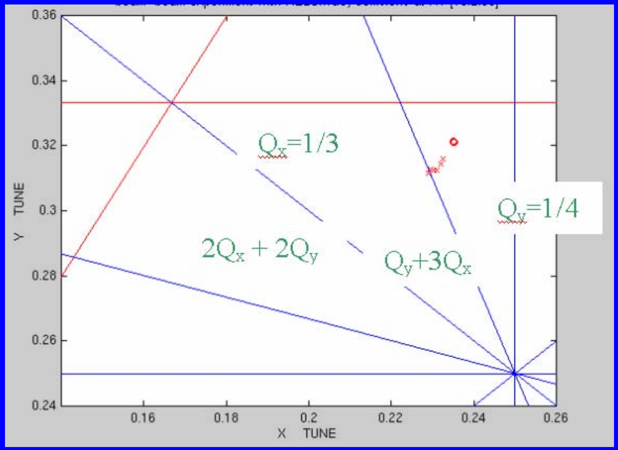
specific luminosity

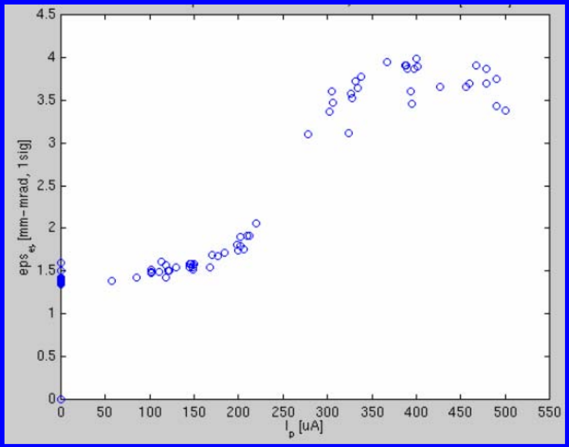


product of single-bunch beam currents, $I_e \times I_p$

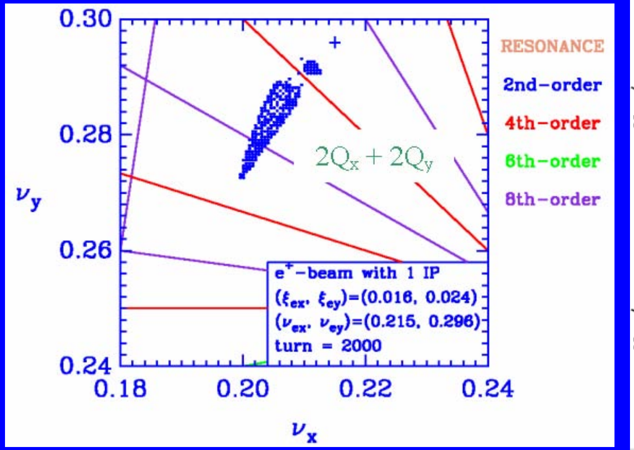
Experiments showed 5 possible causes, two of which related to the beam-beam interaction:

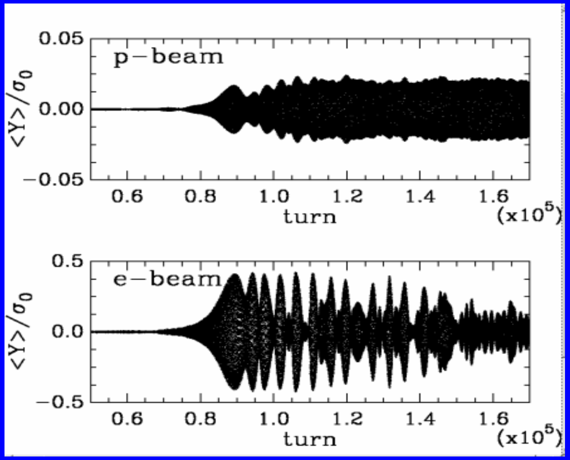
lepton beam emittance growth due to beam-beam resonances





proton beam emittance growth due to beam-beam resonances (predicted by J. Shi using strong-strong model of the beam-beam interaction and occassionally observed with improper adjustment of lepton tunes)



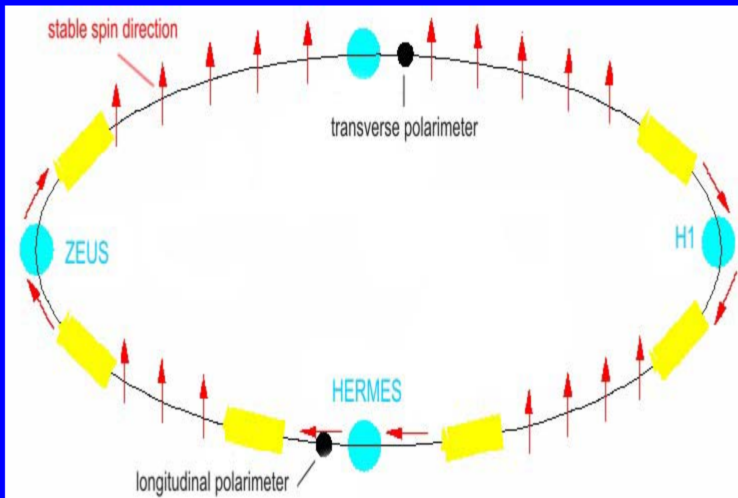


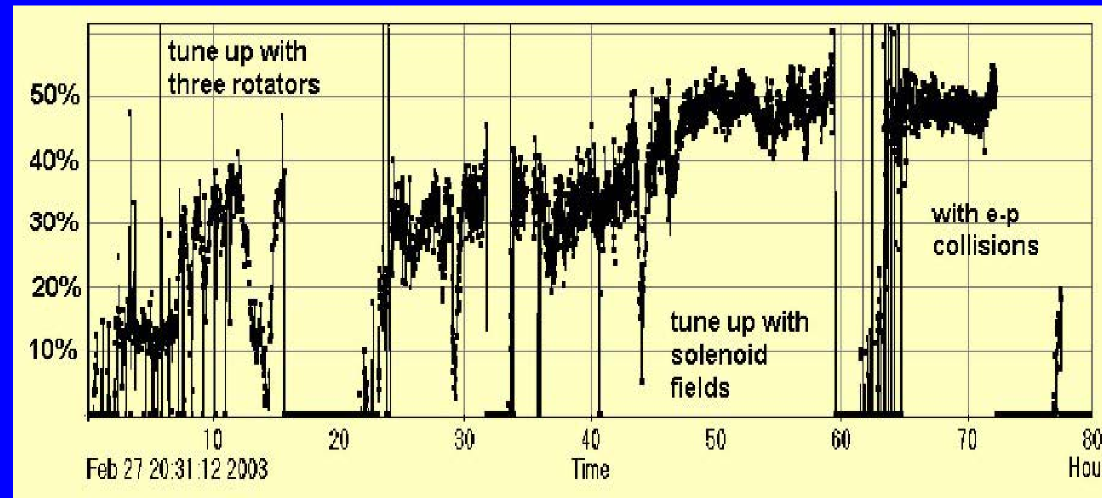
Presently, specific luminosity is maximized and maintained by

- choice of operating point in tune diagram (consistent with high polarization)
- careful control of the betatron tunes of both beams
- bringing the beams in collision at the two interaction points sequentially
- controlling strength of SBR resonances

F) lepton beam polarization

E. Gianfelice-Wendt and D. Barber MOPLT044





spin-matched optics
closed-orbit control
harmonic spin matching

polarization preservation including
nonlocal compensation of detector
solenoidal fields

so far, no direct evidence of depolarization
due to the beam-beam interaction (however
trade-offs between polarization and luminosity
are observed depending on Q_y)

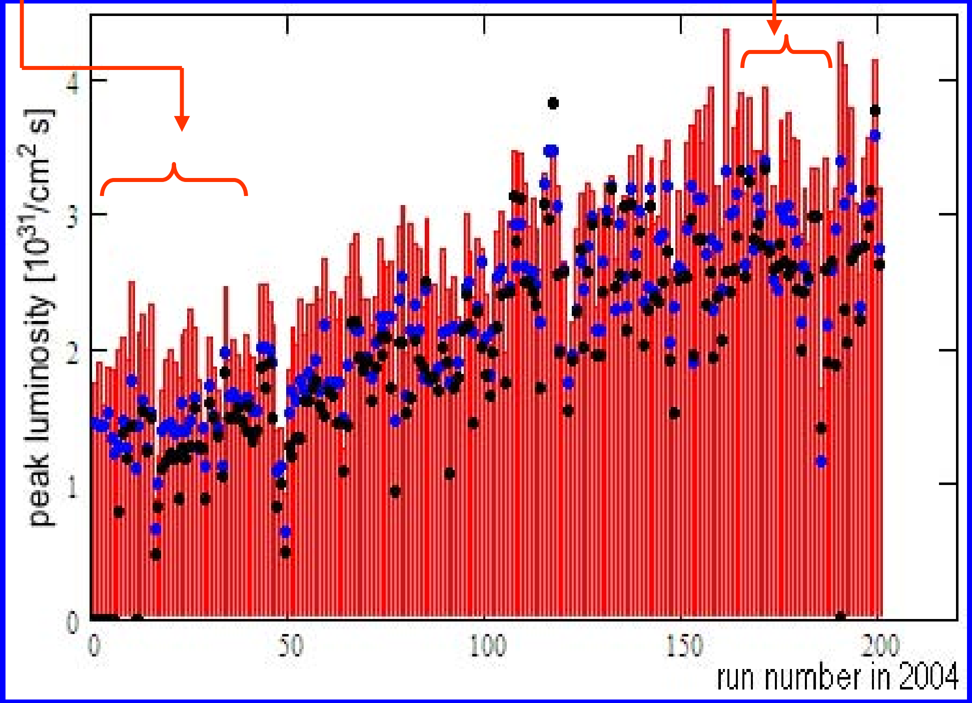
In general, performance upgrade of polarization extremely successful with still further room for improvement (e.g. BBA in arcs and fast polarimeter)

IV Present Performance and Future Plans

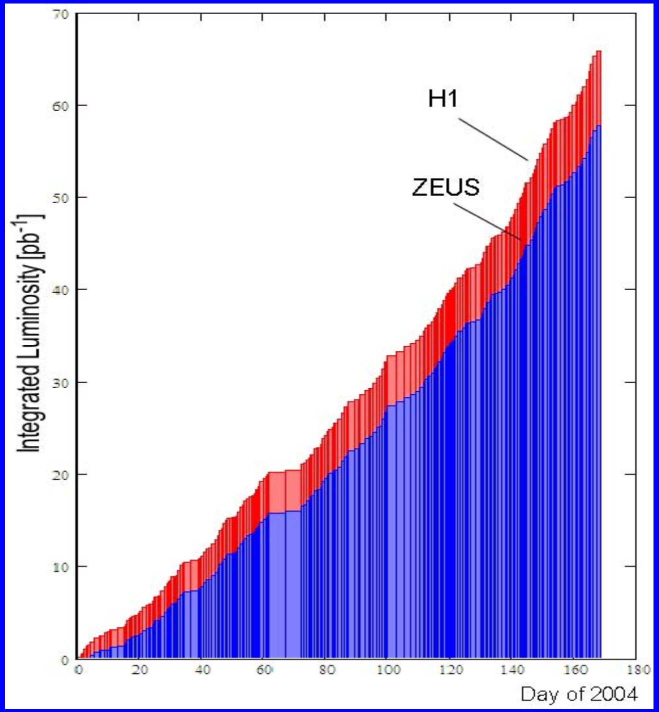
HERA is no longer limited by detector backgrounds
The total currents are being steadily increased
Luminosity is at present 2 times that of year 2000
two problems limited maximum luminosity operations in 2004:

- administrative (1/5th nominal) current limit ("uncontrolled" beam loss) for the protons
- generation of proton "coasting" (i.e. DC) beams (see also I. Agapov THPLT037)

peak luminosity vs time



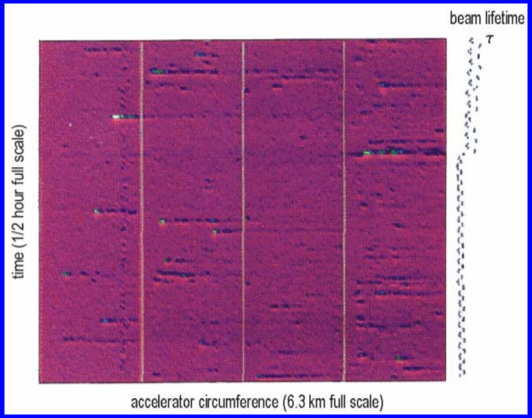
integrated luminosity vs time

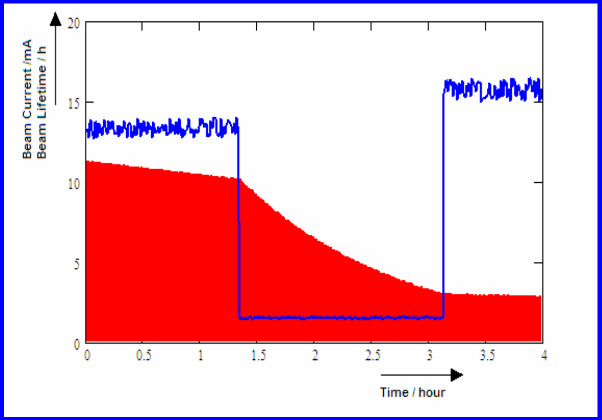


agreement between expectation (red histogram) and measurements (blue dots, H1; green dots, ZEUS) reasonable – remaining discrepancy under investigation

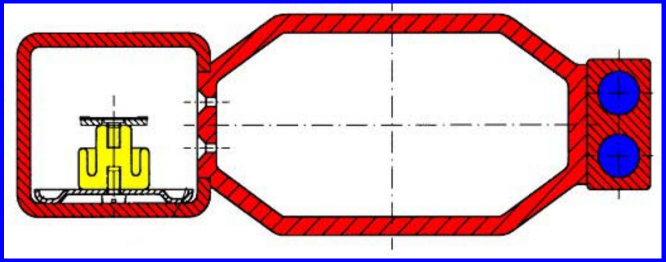
operation with electrons (beginning after 2004 summer shutdown)

Before 1998 hampered by dust particles trapped in potential well of beam





Improved by replacing all ion getter pumps with NEG pumps (1997/8)



Operational experience thereafter:

- ❖ successful high luminosity run with electrons in 1999
- ❖ however, electron beam lifetime reduced by 30-50% (compared to positrons)
- ❖ and total beam current limited to 70-80% of the positron intensities (could not be studied so far)

electron-proton collisions

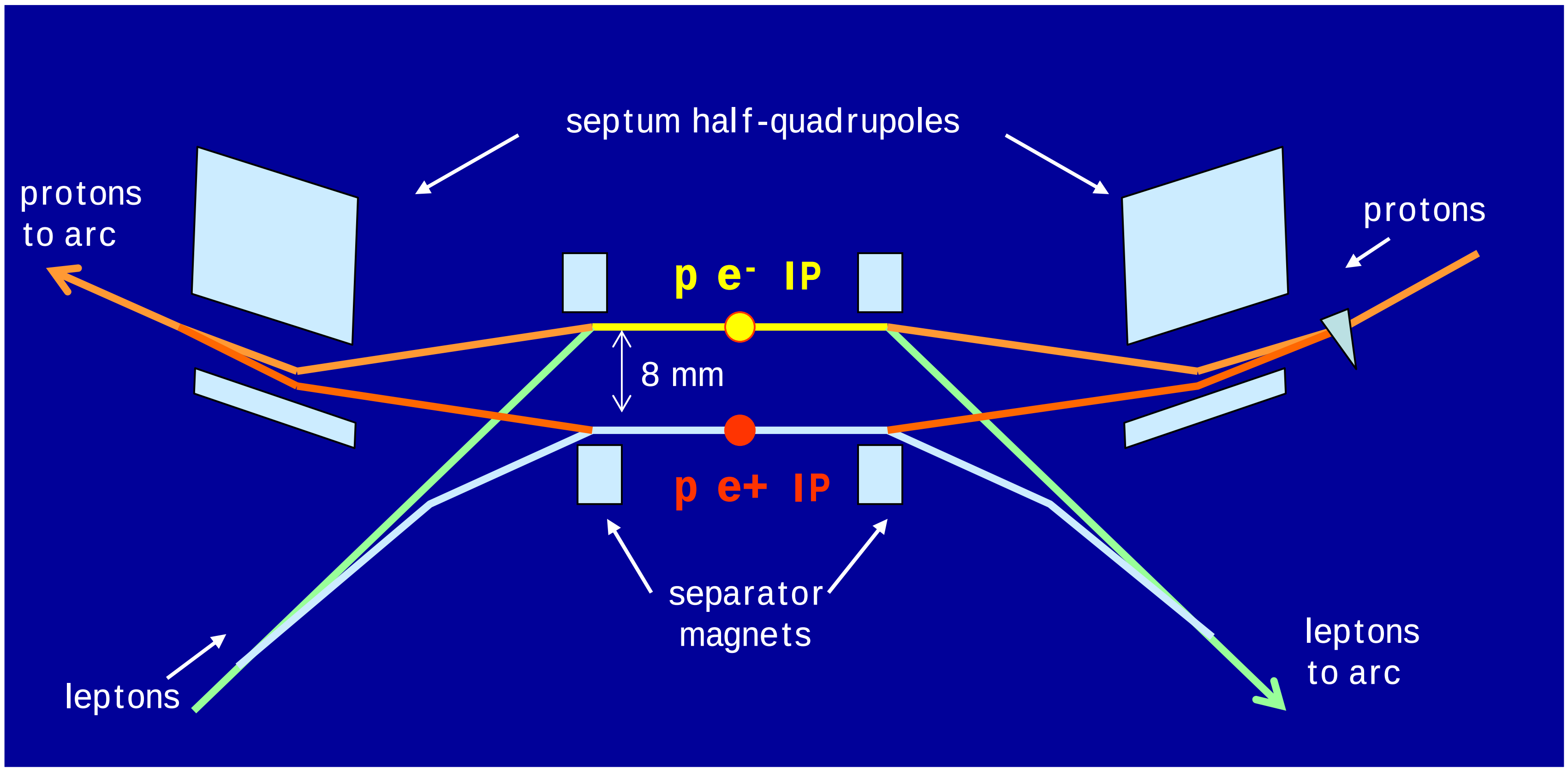
radial shift in IP by 8mm required

Orbits in IP will be different for

p - e^- collisions

p - e^+ collisions

(to save the space that would be necessary for additional magnets for compensation of the change in orbital deflection angle with switched polarity)



Present Performance and Future Plans, cont'd

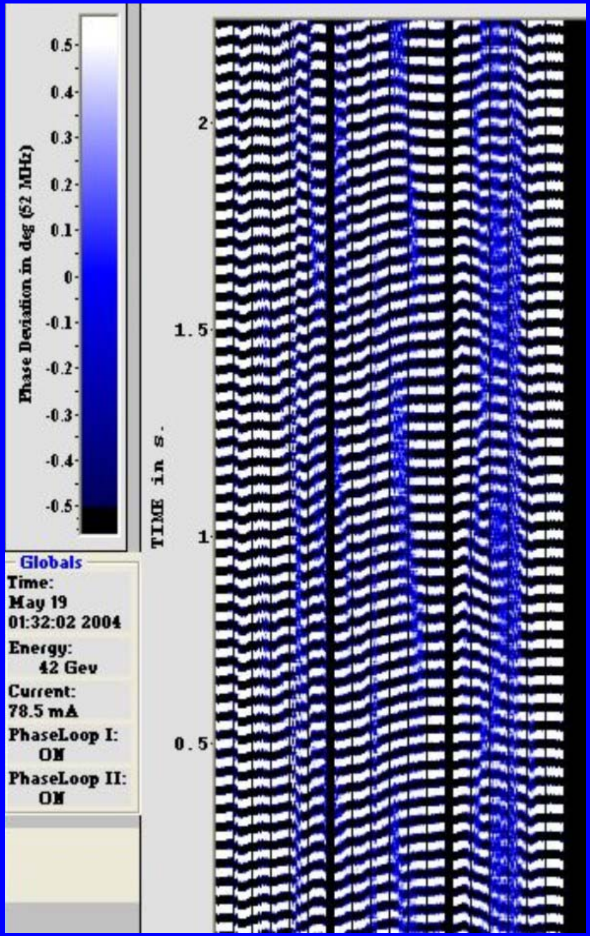
- Focus on improved accelerator availability:

  upgrade of low-level proton rf systems
  additional pumping near lepton rf cavities
  upgrade of cryogenic systems
  (compressors and controls)

- Focus on improved operational efficiency:

  improved beam position and profile instrumentation
  software modifications for collimation systems
  addition of longitudinal damping for protons

Better bunch length control during energy ramp could reduce hour-glass effect (presently a ~10% effect) and enable a further reduction of the beta functions at the interaction points



fast longitudinal diagnostics by E. Vogel

V Summary (1)

- having surpassed the design luminosity of HERA-I already in 1997, a performance upgrade was visualized (conception in 1998 and installation in 2001) consisting of:
    - higher luminosity in the 2 colliding-beam experiments via
        - stronger focusing of the proton beams
        - matching of the electron beam sizes at the IPs
    - longitudinal polarization in the colliding beam experiments

- recommissioning of the HERA performance upgrade was hampered by unexpectedly high detector backgrounds

- the "cures" for the backgrounds consisted of:
    - elimination of the "peek-hole" in one of the experiments (design issue)
    - improved vacuum in the IPs (now significantly better than pre-upgrade)
    - periodic "warm-up" procedure (every 1 to 3 months)
    - steady operations at high beam currents (vacuum conditioning)

- detector-based limitations on total beam currents are no longer an issue

V Summary (2)

- the design features (high specific luminosity and longitudinally polarized beams in collision) were verified in early 2003

- beam-based alignment in the IPs and orbit feedback proved critical for controlling the beam optics, for minimizing localized heating due to synchrotron radiation, and for maximizing the lepton beam polarization

- difficulties pertaining to beam-beam dynamics and synchrobetatron resonances are overcome using a lattice with precisely $\pi/2$ phase advance between IPs, careful setting of the betatron tunes of both beams, and by bringing the beams in collision sequentially at the two IPs

- luminosity > 3.5×10^{31} cm^{-2} s^{-1} achieved at both experiments with P>50% and means for further improvements available and/or planned

- improvement plans (reliability and operability) were described which aim towards highest possible integrated luminosity

- operations with proton-electron collisions to start in November

- HERA-II run planned to end around mid-2007

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