Experience with HERA

(an Asymmetric High–$\mathcal{L}$ $e^{\pm}/p$–Collider with Polarized $e^{\pm}$)

17.07.2006

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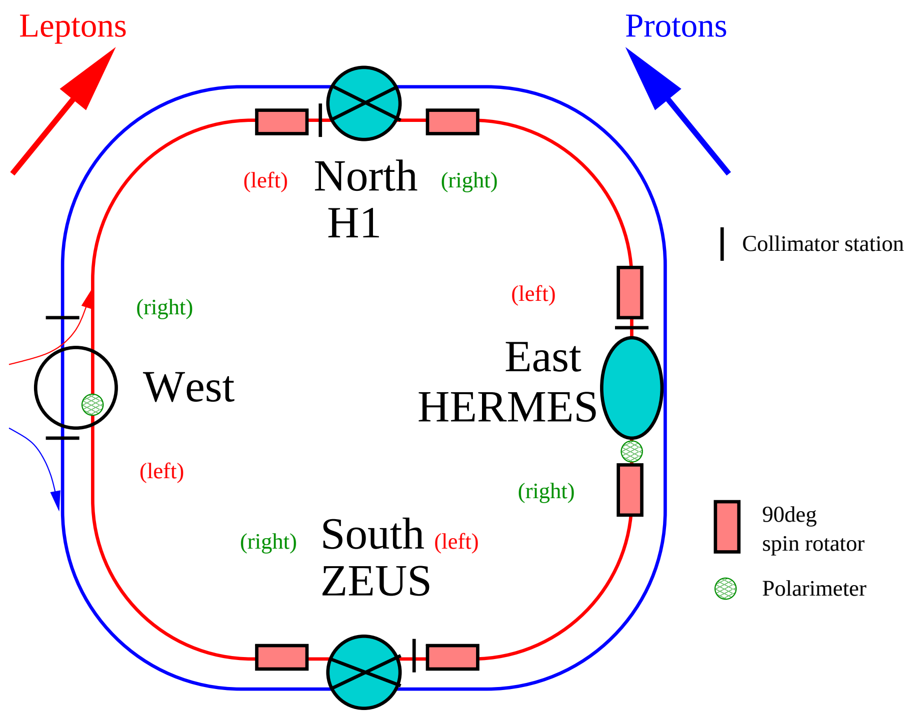
- **Overview**
- $e^{\pm}/p$–Collisions : "Two Worlds Collide"
- The HERA–II IRs
- $\left\{\right.$ **Luminosity** / **Lepton–Polarization** / **Experimental Backgrounds**

*: some slides stolen from F.Willeke

Overview (1)

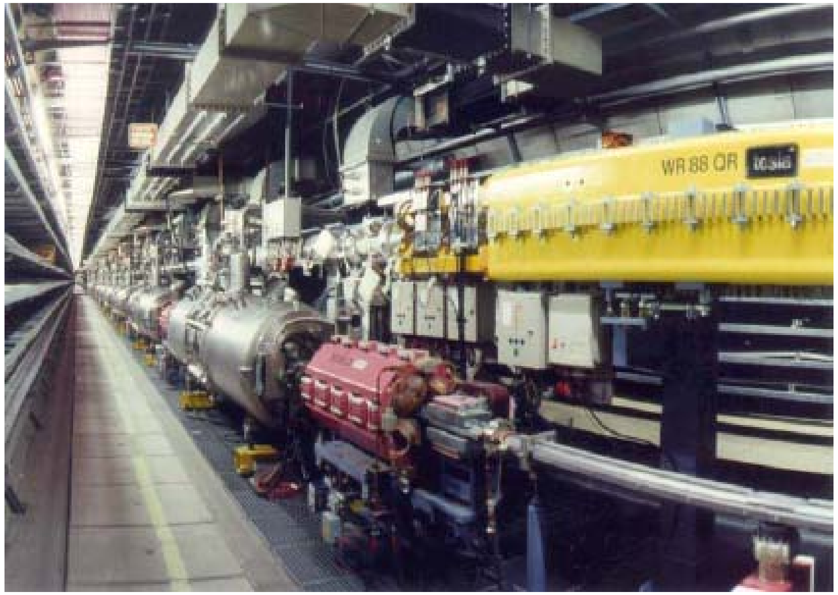
- superconducting 6.3km 920GeV p–ring (HERA–p) on top off :
- normal conducting 6.3km 27.6GeV $e^{\pm}$–ring (HERA–e)
- 4 halls: West,North,East,South
- 2 collider experiments: H1 & ZEUS
- 1 internal target experiment: HERMES (27.6GeV $e^{\pm}$ on gas jet: H, D, Kr,...)

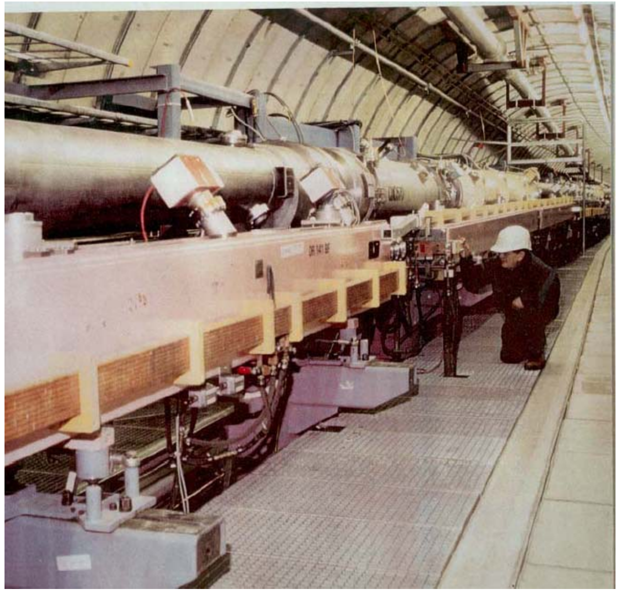


- longitudinal polarization at all 3 experiments
- 2 polarimeters (long.=East & transv.=West)
- (until 2003: 4-th experiment in West–hall : scattering of p–halo at metal wire)

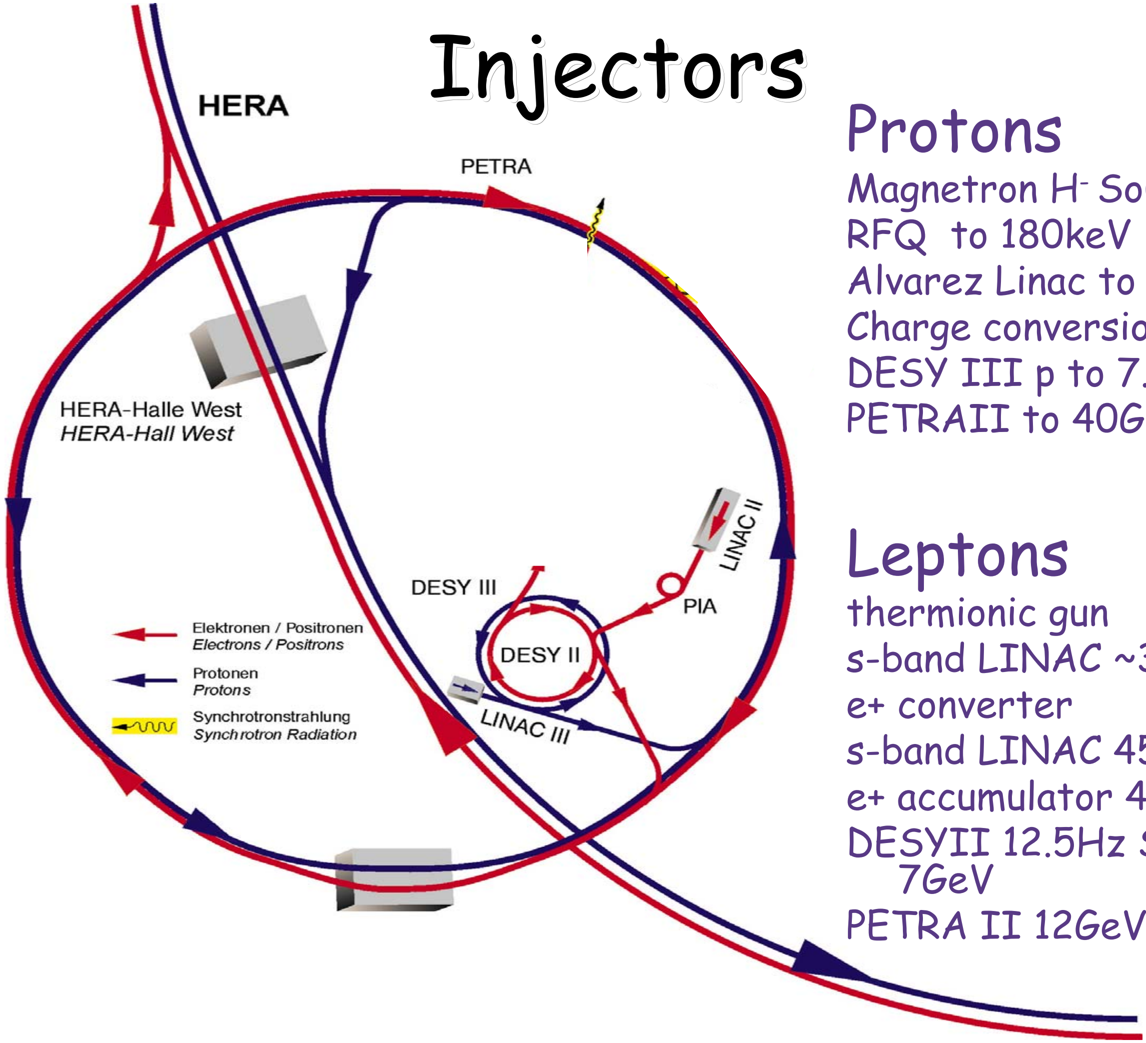

HERA
PETRA
N
S
W


E.ZANON
ANSALDO
EUROPAMETALLI - LMI


WR 88 QR



Injectors



Protons

Magnetron H^- Source
RFQ to 180keV
Alvarez Linac to 50MeV
Charge conversion injection
DESY III p to 7.5GeV/c
PETRAII to 40GeV/c

Leptons

thermionic gun
s-band LINAC ~300MeV
e+ converter
s-band LINAC 450MeV
e+ accumulator 450MeV
DESYII 12.5Hz Synchrotron 7GeV
PETRA II 12GeV

Overview (2)

- beams matched ⇒

$$\boxed{\mathcal{L} = \frac{1}{4\pi e^2 f_0} \frac{I_e \langle I_p^{\text{bunch}} \rangle}{\sigma_x \sigma_y} h(\sigma_l^p)}$$

- HERA–e: total I_e limited by RF–power. Up to 40mA @ 27.6 GeV → 8× (left & right of each straight) 1.2MV RF–transmitters.
- HERA–p: maximum I_p^{bunch} limited to ≈ 700μA ⇐ **injector chain** → up to 110 mA in 180 bunches
- p–rms-bunchlength ≈1.0–1.8ns ↙
  ⇒$h(\sigma_l^p)$ ≈ 0.92—0.95

HERA–II IP–parameters:

	x	y
β^e /m	0.63	0.26
β^p /m	2.45	0.18
$\varepsilon^e_{1\sigma}$ /nm	22	3–4
$\varepsilon^p_{1\sigma}\beta\gamma$ /μm	4–5	4–5
σ_{matched} /μm	≈ 120	≈ 30
incoherent beam–beam tune shifts:		
ξ_e per IP at 670μA	0.037	0.056
ξ_p per IP at 250μA	$1.2 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$

HERA-II Luminosities :

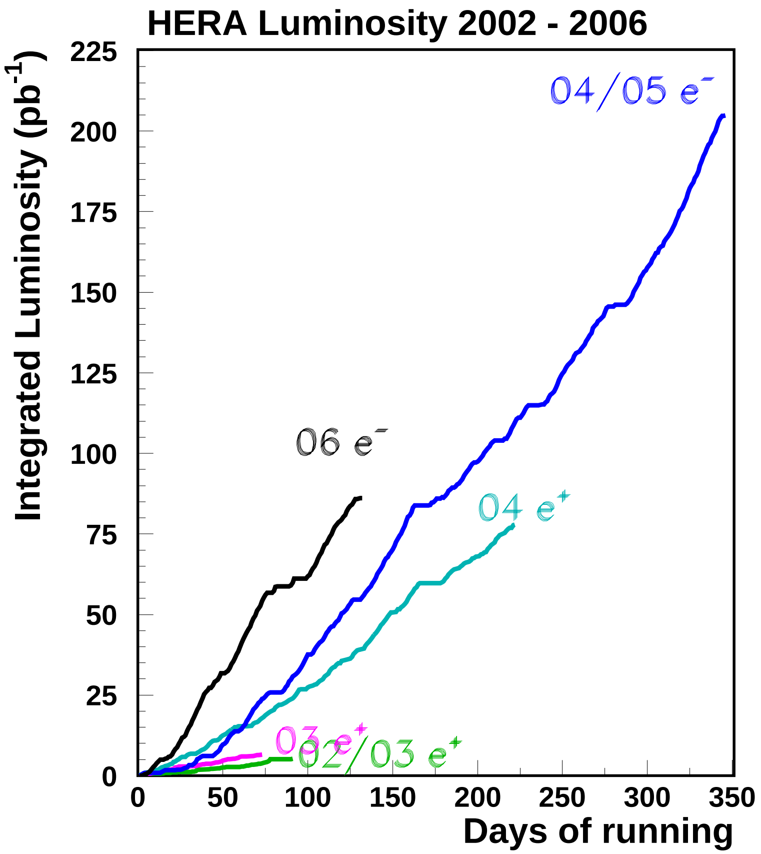
$\mathcal{L}^{\text{peak}}$	max $\int \mathcal{L}\, dt$ (run)	max $\int \mathcal{L}\, dt$ (24h)	$\mathcal{L}_s^{\text{peak}}$
4.9	0.9	1.5	2.1[†] , 1.8[*]
10^{31} Hz cm^{-2}	pb^{-1}	pb^{-1}	10^{30} Hz cm^{-2} mA^{-2}

†: e^- tunes above integer, (e^+ below ??)

*: e^+ tunes above integer, (e^- below !!)

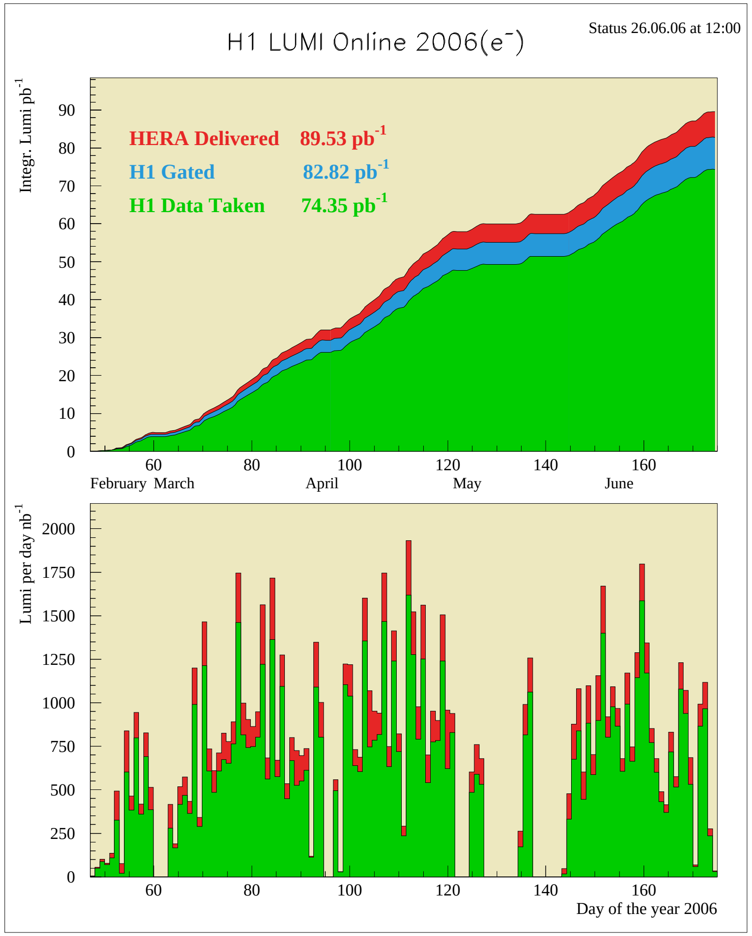
Luminosity Production

ZEUS: HERA–II



by curtesy of U.Schneekloth (ZEUS)

H1: 2006 (e^-)



by curtesy of D.Pitzl (H1)

$e^{\pm}/p$–Collisions : Two Worlds Collide

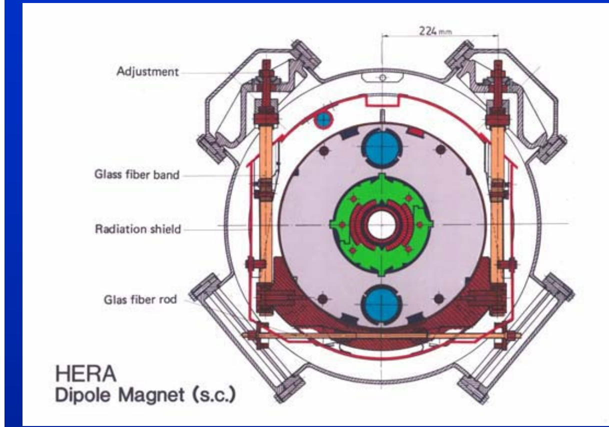
HERA–p: 40GeV → 920GeV

- 5.2T superconducting main dipoles →sensitive ! ← "QuenchProtection"
- hadrons → no SynRad–damping → **"Protons never forget"**
- $E_{\rm lumi}/E_{\rm inj} = 23$ **!!!** low energy regime difficult ← eddy–current induced multipoles
- sensitivity to noise → magnet–PS & RF–transmitters
- vacuum at IP ← hadronic showers in experiments
- action diffusion
- WS-BB : the strong beam is weaker than one thinks!

HERA–e: 12GeV → 27.6GeV

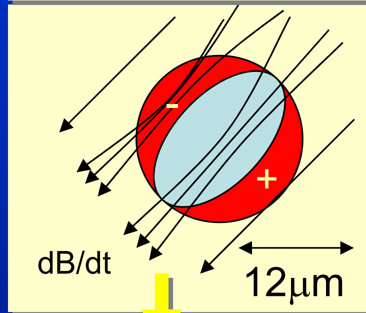
- leptons → **high SynRad power**
  → 117 MV sum voltage needed at 27.6GeV
  → cooling and/or shielding of vacuum chambers, bellows,...
  → desorption → vacuum
  → SynRad (direct/backscattered) at experiments
- lifetime (Q-lifetime, vacuum, DynAp, e^-: dust)
- polarization **and** luminosity → choice of working point
- WS-BB : the weak beam is stronger than one thinks!

The technically most challenging component of HERA: the 400 superconducting 5.6T dipoles (@1TeV)

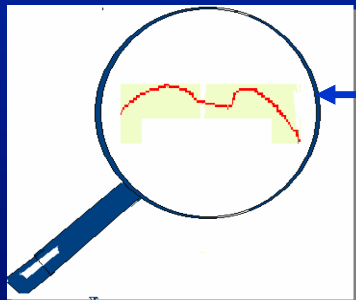


Rutherford type S.C. Cable 6kA, NbTi, Cu/NbTi=1.8

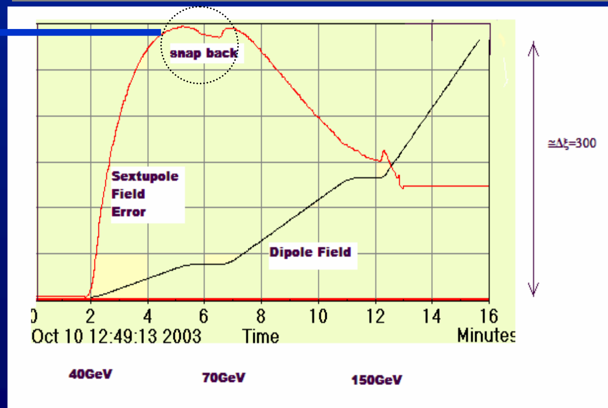
Induced persistent eddy currents



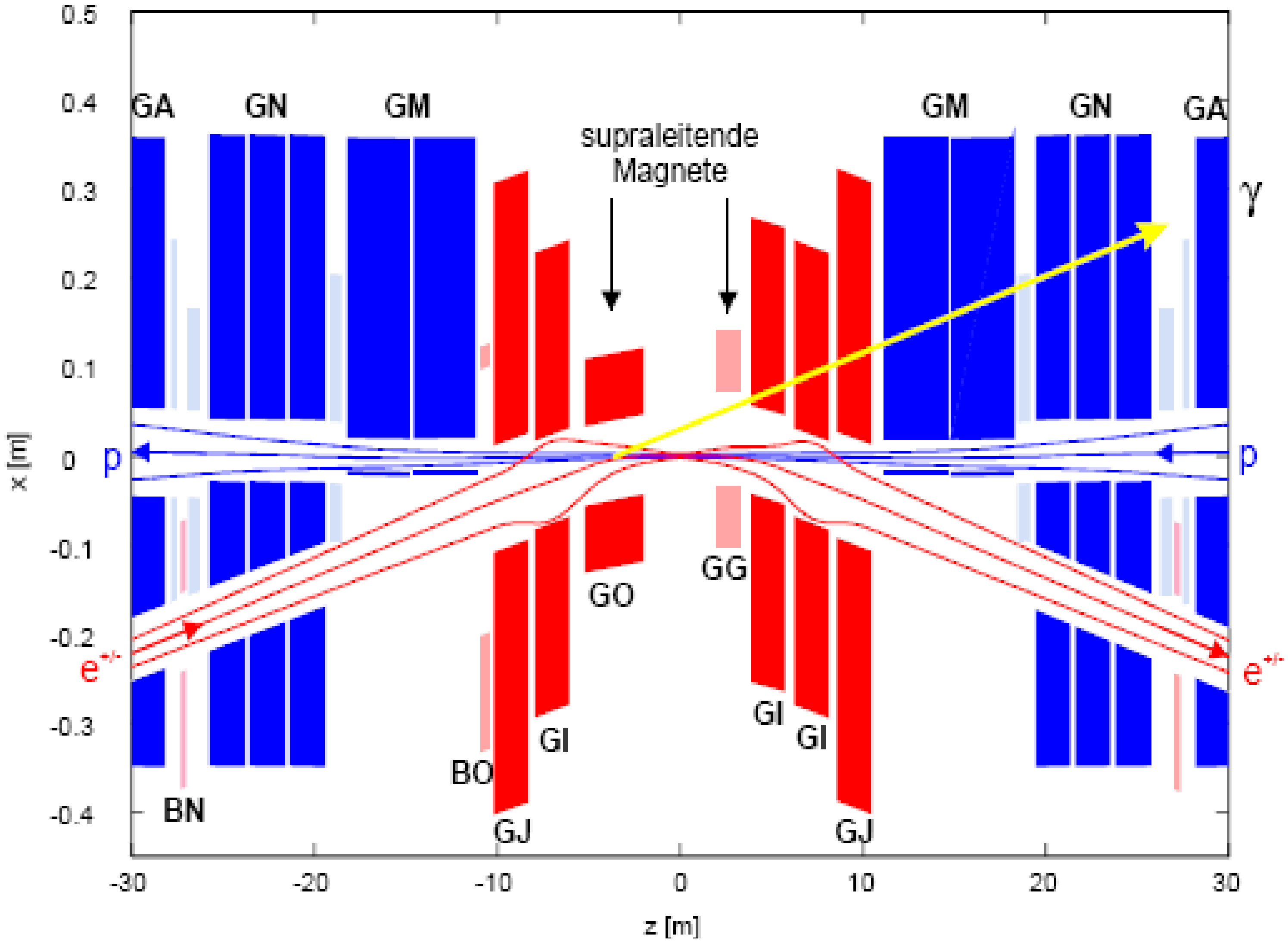
S.C. Reference Magnets



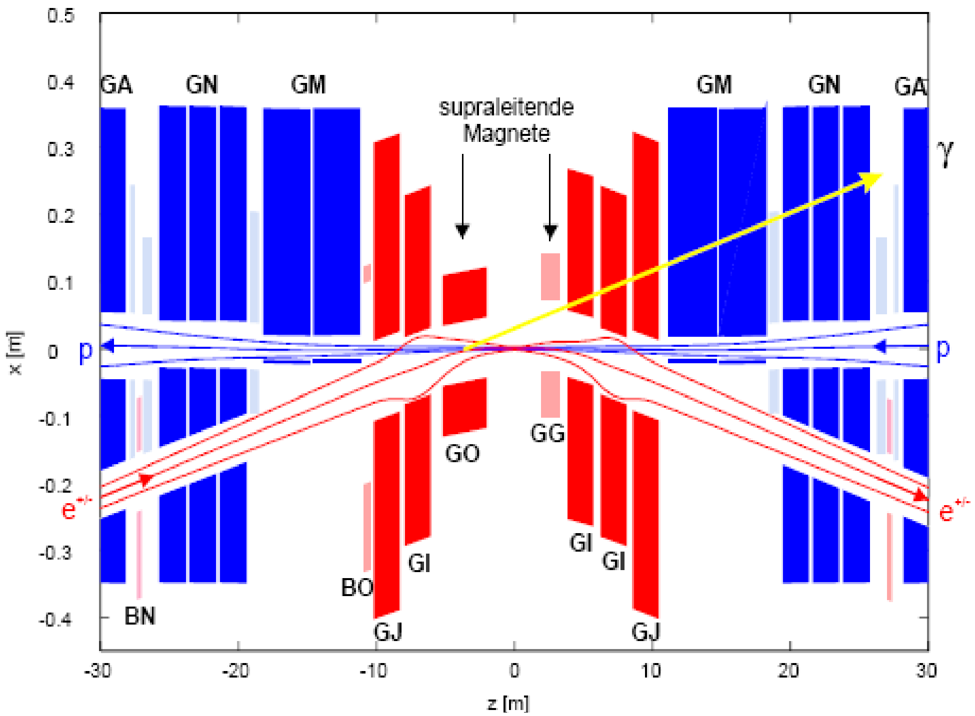
Persistent Current Sextupole Field Error



The HERA–II Interaction Region (Overview 1)



The HERA–II Interaction Region (Overview 2)

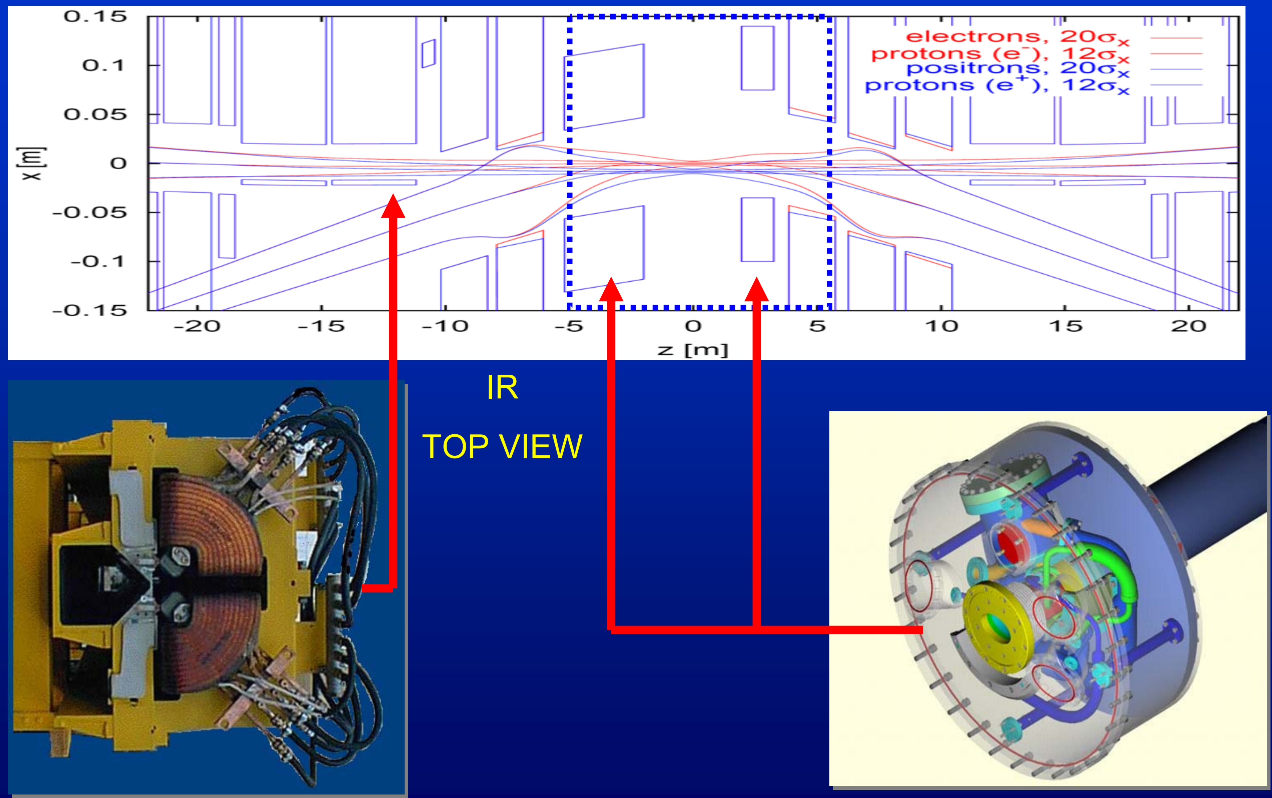


- $e^{\pm}$: Triplet upstream=[GJ,GI,GO] downstream=[(GG),GI,GI,GJ]
- GO : 3.2m long **s.c.** quadrupole with H-dip, V-dip, sextup, Sk-quad windings added
- GG : 1.4m long **s.c.** H-dip, V-dip, sextup, Sk-quad
- p : double doublet [GM+GN, GA+GB, QR10, QR14]
- GM : mirror quadrupole to accommodate $e^{\pm}$-beampipe

- p: pass through complete $e^{\pm}$–triplet
- Separation : design trajectories off center in quads ($e^{\pm}$: all / p: triplet, GM,GN) & GO/GG-H-dipoles
- switching between e^{-} and e^{+} requires shifting of magnets !

The HERA–II Interaction Region (Special Magnets)

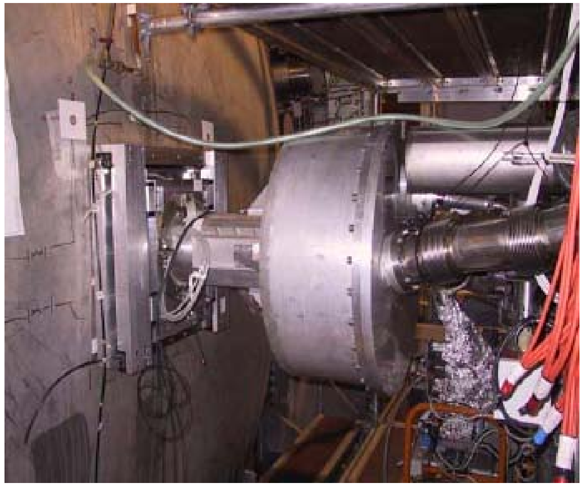
Basic Concept: low β Quadrupole Magnets closer to the Interaction Point, using novel magnet technology

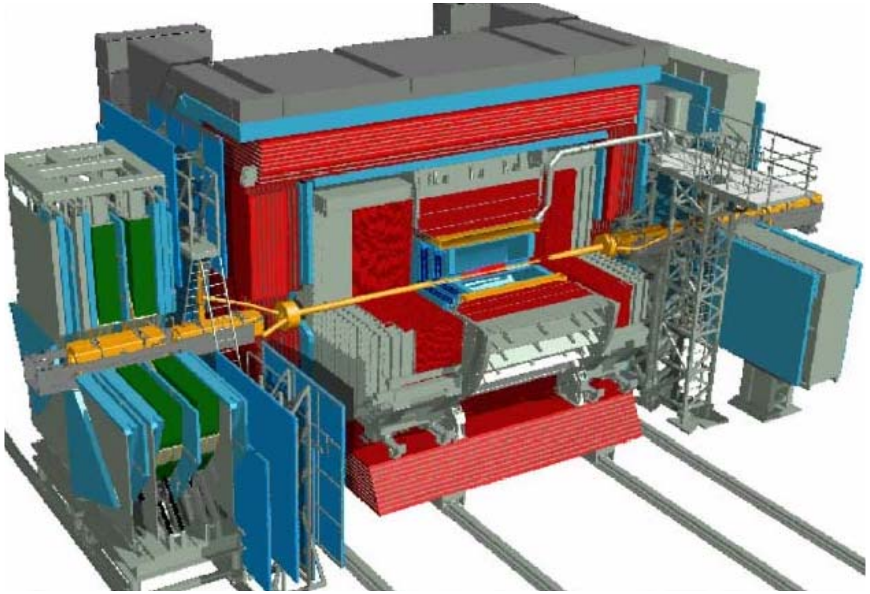


Half Quadrupoles for p-focusing

Superconducting Separator/Quads

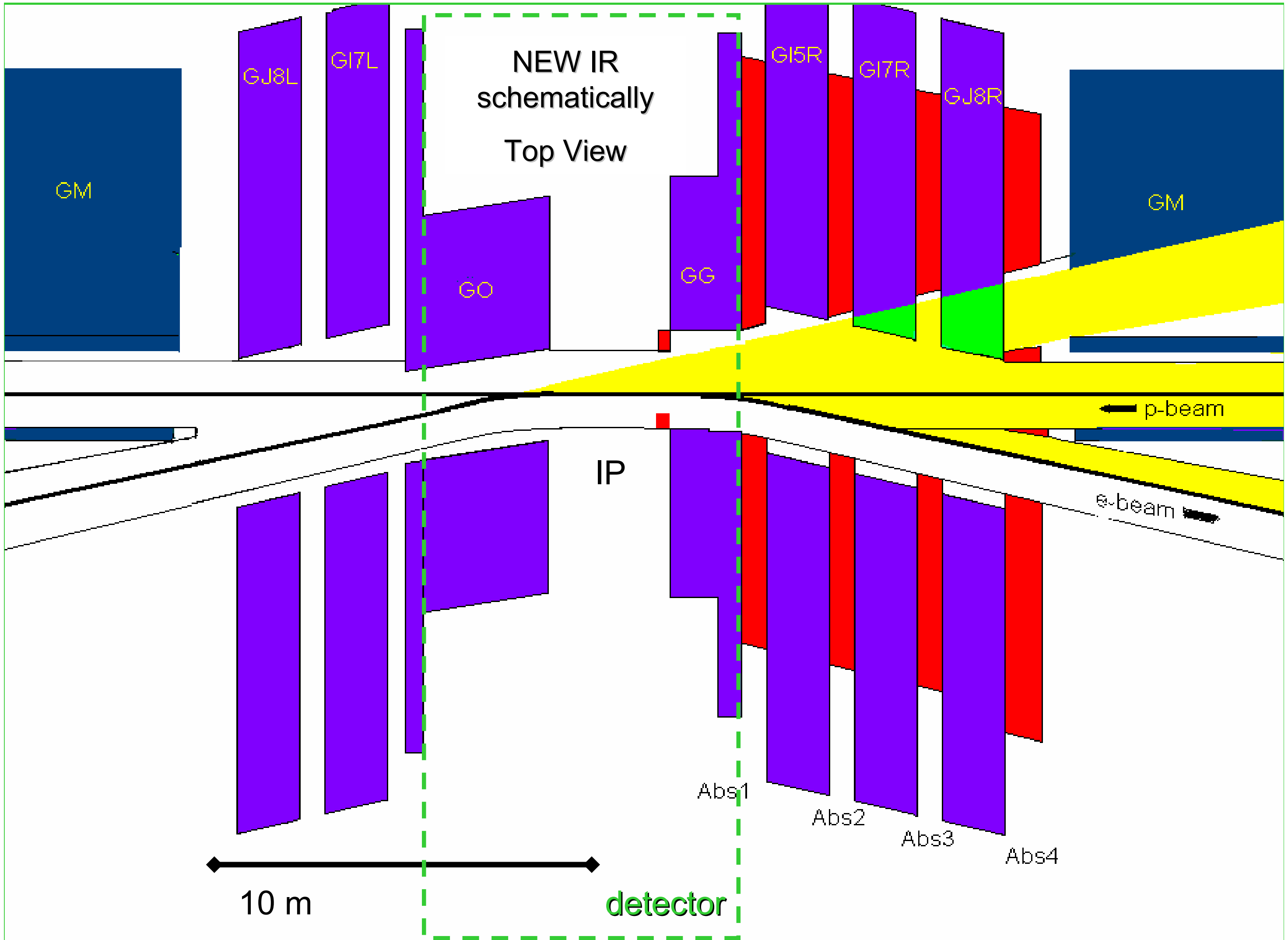
$e^{\pm}$–Triplet : GO & GG **inside** central detector





- H1 : GO cold box ↑ and H1-calorimeter
- ZEUS : detector with ↑ GO and GG ("yellow")
- magnet support in detector and on bridge to tunnel : mechanically extremely challenging
- magnet cooling in detector environment : an issue ! (icing observed)

The HERA–II Interaction Region (SynRad 1)

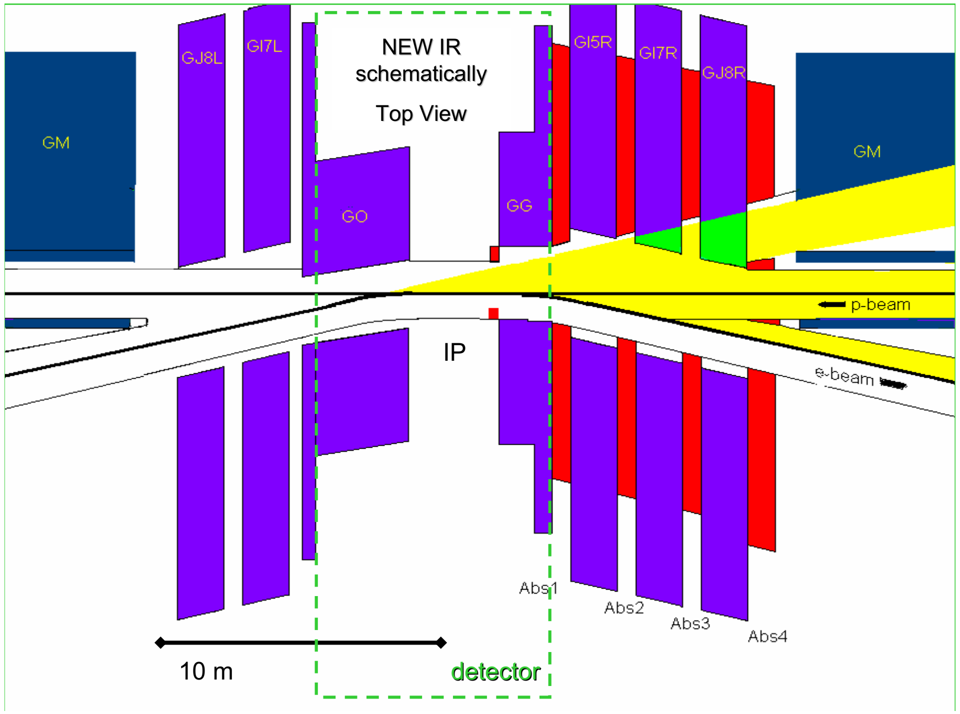


The HERA–II Interaction Region (SynRad 2)

- powerful SynRad from GO/GG
  → protection for experiment, beam pipe, magnets

⇒ absorbers C5 (experiment), 1,2,3,4

- at absorber-4 (right 10.8m): common beam pipe splits :
  SynRad (pic. → top)
  p (pic. → middle)
  $e^{\pm}$ (pic. → bottom)



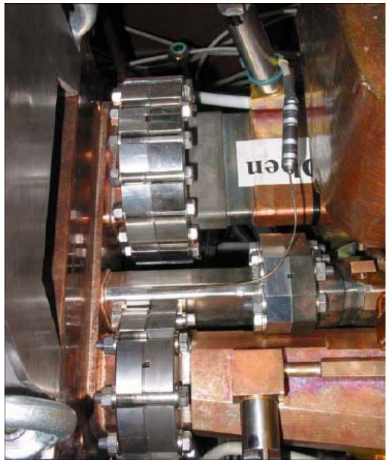
- Abs-4 : avoid backscattered SynRad into experiment ⇒ complicated geometry

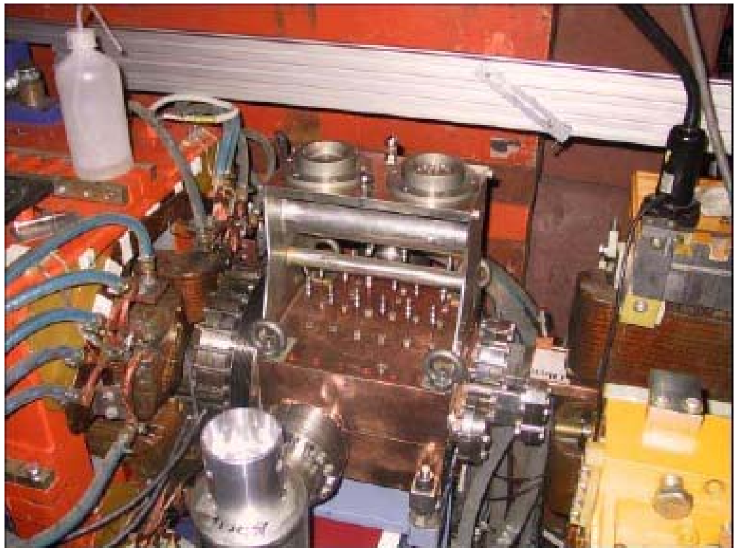
⇒ careless beam steering (or component failure) ⇒SynRad hitting flanges

- cause of several ventings of IR (p–upstream !!!!) → see next slide

SynRad-Absorber-4 : right 10.8m

- between last $e^{\pm}$–triplet quad GJ and first p–quad GM
- heavy water–cooled copper block
- lots of temperature sensors attached
- 3 beampipes (γ, p, $e^{\pm}$)





- **port** $\uparrow$: original design: p–pipe connected through flange (too fragile)
- **starboard** $\nearrow$: modif. design: p–pipe soldered onto absorber (no failure so far)

p mirror quadrupole

- mirror plate strongly cut to accommodate $e^{\pm}$–beampipe

$\Rightarrow$ mechanically challenging

- p–mini–β $\longrightarrow$ aperture limit

common GI chamber

- stainless steel $\Leftarrow$ bad thermal conductivity

$\Rightarrow$ has been "fried" twice (beam–steering!)

- several extra–thin thermal sensors $\longrightarrow$ $e^{\pm}$–beam–interlock

p–Issues

p during Acceleration

- 40GeV $\longrightarrow$ 920GeV : 20–30 min
- s.c. dipoles & large energy range $=$ 23 $\longrightarrow$ persistent eddy currents $\longrightarrow$ sextupole $\longrightarrow$ **chromaticity**

$\Rightarrow$ **head–tail instability**

$\longrightarrow$ beam–loss or emitt. blow–up

$\Leftarrow$ automated sextup. correction

$\longleftarrow$ (reference magnets)

$\Leftarrow$ sextup. tables

$\Leftarrow$ **operational skills!!!!**

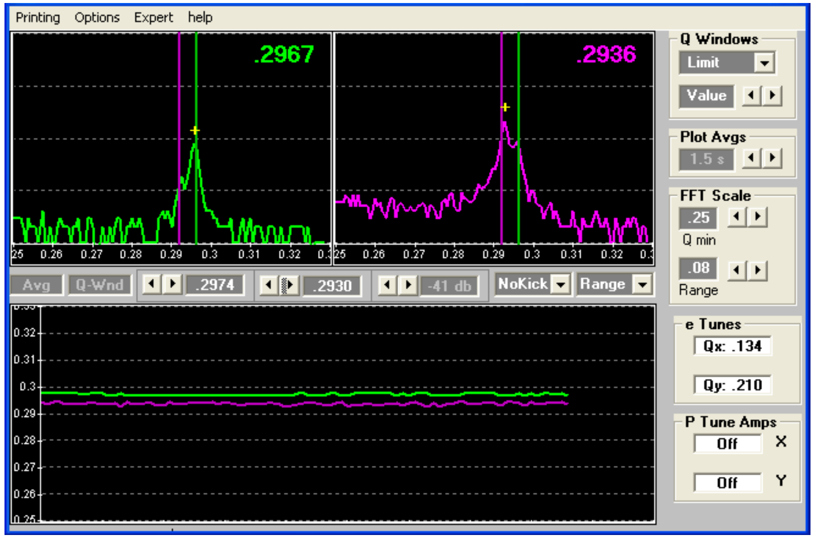
- transv. multi bunch FB tried ('96) $\longrightarrow$ large tune excitation needed to control Q_x, Q_y on ramp $\Rightarrow$no overall gain in $\mathcal{L}$
- recently : automated tune FB (before: purely manually)

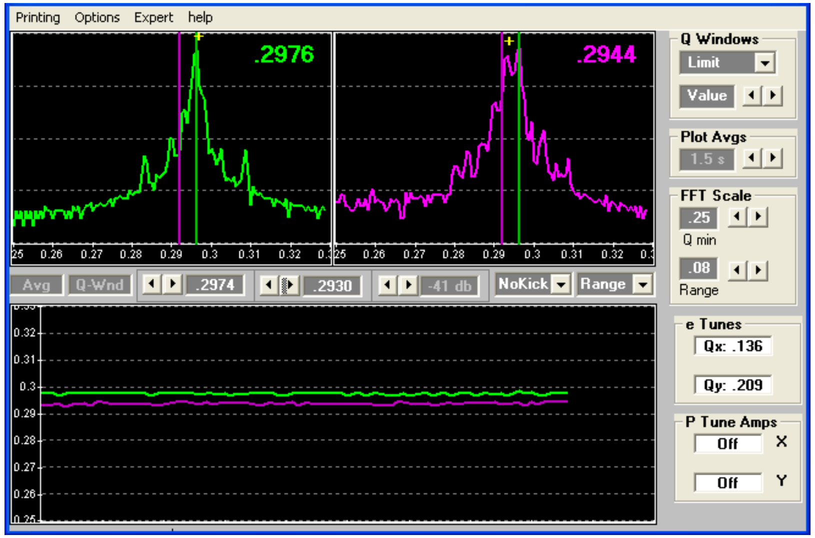
p under Collisions

- minimal β_y^p limited by hourglass effect
- action diffusion enhanced ($\approx \times 10$)
- aperture limits close to IP (GM,GN)
- orbital stability :
  $\longrightarrow$ short term fluct. $\approx \pm 150\mu$m
  $\longleftarrow$ also at collimator section $\Rightarrow$ Bckg!
  $\longrightarrow$ reference orbits stable over weeks
- p–collimation (West–hall):
  $\longrightarrow$ for each plane
  $\longrightarrow$ two indep. sets of 3 collimators
  $\longrightarrow$ [primary, $2\times$ secondary]
  $\longleftarrow$ careful adjustment needed from time to time
- long. emittance growth through IBS ($+$ RF noise?)

p–Tunes

- p tune measurement by chirp excitation and extremely sensitive pick up
- most essential diagnostic tool for p–operations
- p lifetime & diffusion rates extremely sensitive to (Q_x, Q_y)





- **nice signal**
- |chromaticity| through peak width
- manual control or tune FB

- **tune peaks enhanced $\Rightarrow$instability**

  here : during set up of collisions :

  $e^{\pm}$–tunes to close to synchro-β sideband

$\Rightarrow$ most likely transverse p emittance blow up (typically $\times 1.5 - -2$)

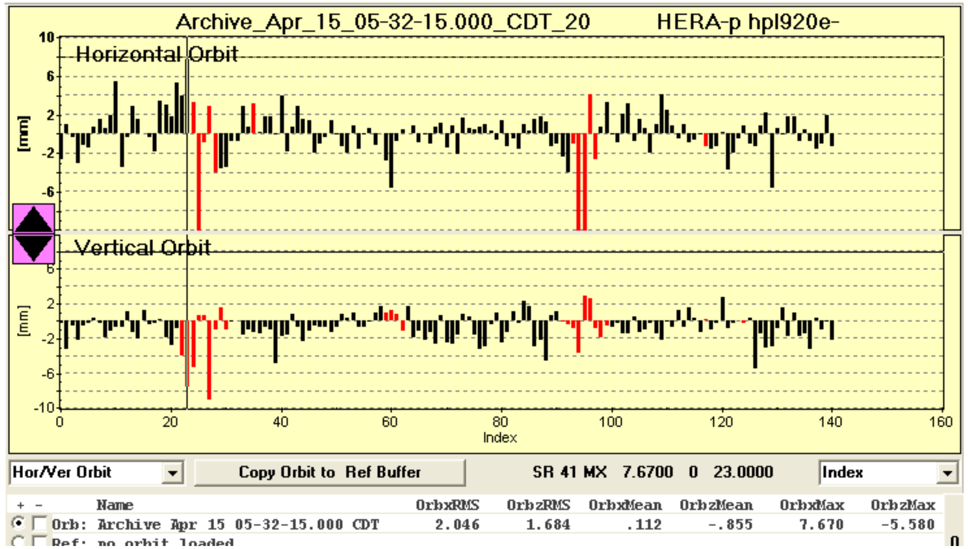
p–Orbit

+ strip line BPMs with high dynamic range

– unfortunately overheated for last 15 years
  ⇒reliability suboptimal

- typical absolute RMS : 1.5–2.0 mm

- orbits can be reproduced over a decent number of runs
  only slow drifts



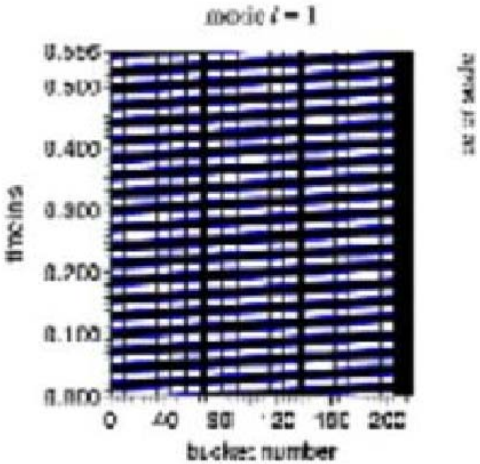
- ground motion, intrinsic mechanical noises (e.g. water pumps), PS–ripple → fluctuations $\approx 150\mu$m

- lifetime and diffusion rates relatively sensitive to orbit

- experimental background extremely sensitive to orbit in mini–beta's

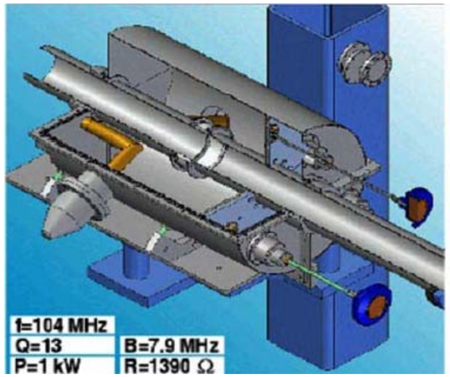
p Longitudinal Multi–Bunch Feedback

- at HERA–II : further β–squeeze limited by hour glass effect (p–bunchlength already comparable to β_y^p)
- observed longitudinal multibunch instabilities ($m = 1, \ldots, 10$ and $m = 162$) $\Rightarrow$blow up of longitudinal emittance



- **FastLongitudinalDiagnostics** $\uparrow$
- horizontal : bunch positions, vertical : time, color : phase$-$average

$\Rightarrow$ nearby mode $l = 1$



- **new long. multi bunch FB** $\uparrow$
- bunchlengths at 920 GeV reduced from 1.7–2.0ns to 0.9–1.2ns
- need more RF–Voltage to counteract IBS

$e^{\pm}$–Issues

$e^{\pm}$: Injection / Acceleration

- off–axis injection (accumulation)
- tunes at inj. set for maximum dynamic aperture
- 12GeV $\longrightarrow$ 27.6GeV : 10min
- $e^{\pm}$–tunes & orbit automatically controlled during acceleration
- beta–squeeze on ramp
- SynRad fans through IR must be carefully controlled
- working point at inj. can **not** accommodate beam–beam footprint + has lousy polarization

$e^{\pm}$ under Collisions

- Working point between 2-nd and 3-rd horizontal synchro–beta sideband
- with brilliant p: footprint barely fits
- sidebands must be well compensated

$\longrightarrow$ dispersion beating

$\longrightarrow$ chromatic beta–beat

- for special working points: beam–beam beta–beat adds to beta squeeze

$\longrightarrow$ e^- : above integer

$\longrightarrow$ e^+ : below integer

- hard to maintain good conditions for luminosity **and** polarization

$e^{\pm}$–Tunes

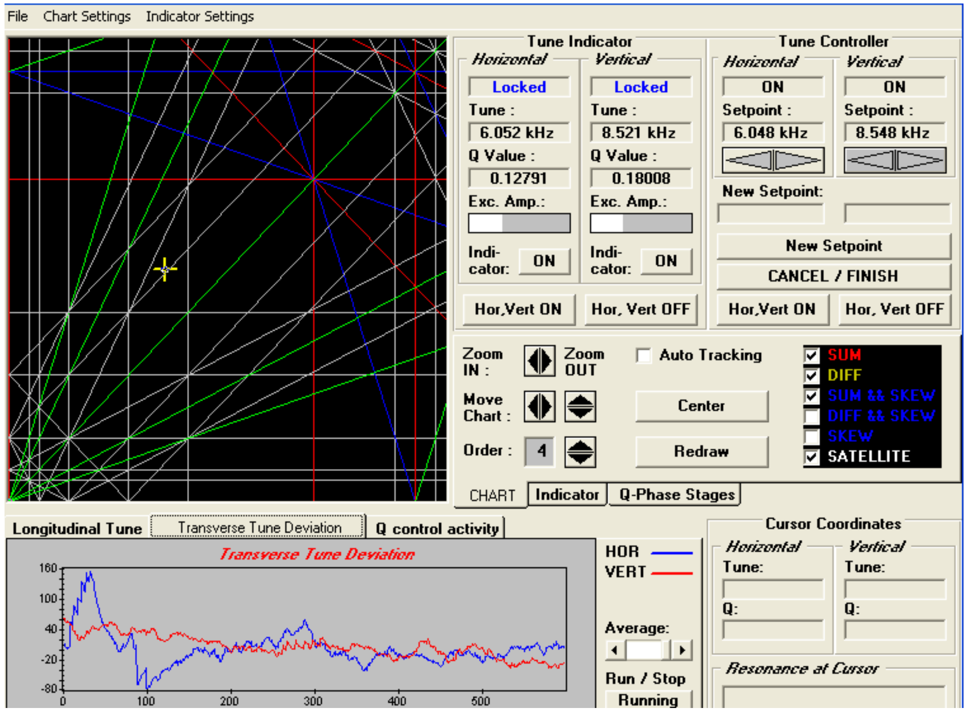
- $e^{\pm}$tune controller : PLL added to transverse multi bunch feedback
- luminosity working point $\rightarrow$
- careful of (Q_x, Q_y) adjustment needed (adapted to $e^{\pm}$–orbit & p–brilliance)

$\rightarrow$ $e^{\pm}$–lifetime

$\rightarrow$ experimental background

$\rightarrow$ polarization

$\rightarrow$ p–excitation has been observed for $e^{\pm}$–tunes too close to 3-rd sideband



$e^{\pm}$ Dynamic Aperture under Collisions

(1) uncompensated chromatic beta–beat drives

$$2Q_x \pm 1Q_s = n$$

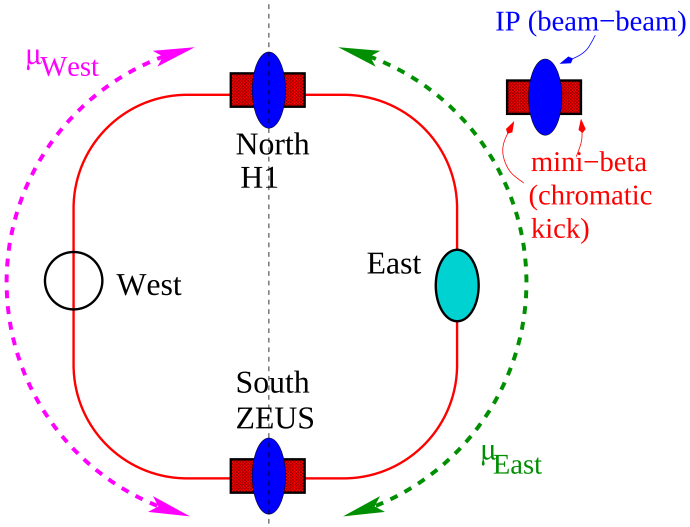
(2) oscillatory closed orbit drives

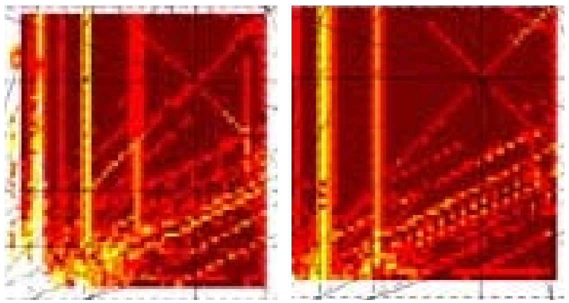
$$Q_x \pm 2Q_s = n$$

$\longrightarrow$ interference of the above drives

$$Q_x \pm 3Q_s = n$$

$\Rightarrow$ **not enough space for footprint**





- cure (1) : optic with intrinsic compens. of beta–beat from the IP's (special choice of $\mu_{\text{West}} - \mu_{\text{East}}$)
- cure (2) : orbit & dispersion control
- left $\leftarrow$: tune–map for uncompens. optic
- right $\leftarrow$: tune–map for compensated optic

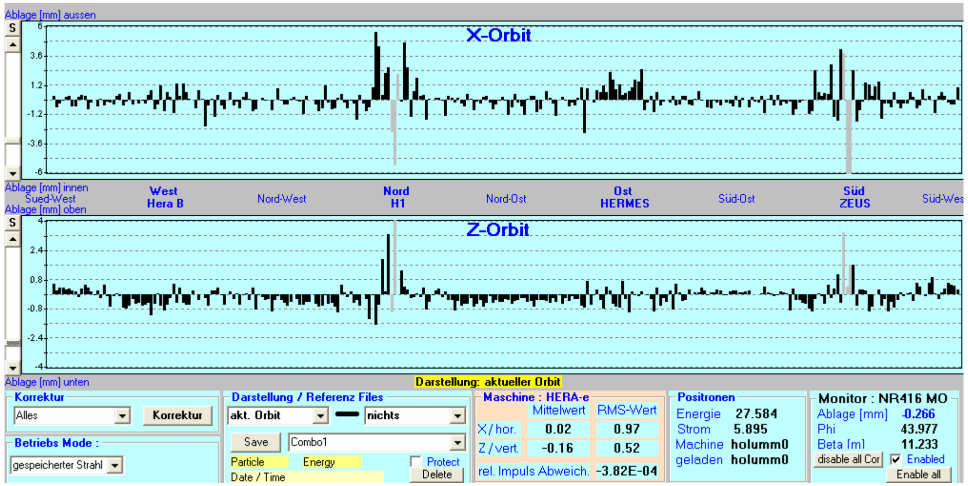
$e^{\pm}$–Orbit

- knob BPMs with recently updated electronics
- in general reliable

$\leftarrow$ except when hit by SynRad

$\leftarrow$ except in chamber with "exotic" geometry (IR)

– experiments extremely sensitive to $e^{\pm}$–orbits !!



$+$ automated orbit feedback (timescale 1 to 10 sec)

- BPM failures can easily expose sensitive parts to SynRad

$\leftarrow$ experiments connected to beam–interlock

- temperature sensors connected to beam–interlock
- decent polarization conditions require y–RMS < 1mm

Special $e^{\pm}$ (Orbit)–Bumps

- each IP : x, x', y, y' "Lumi–Bumps"

$\leftarrow$ same for p

- each IP : background bumps (8) to steer SynRad through experiment
- $8\times$ $\Re$ and $\Im$ of harmonic bump (polarization)
- vertical dispersion bumps (to match vertical beamsize to p)
- global decoupling bumps (vertical orbit through sextupoles)

$\leftarrow$ same for p to assist skew-quads

Quad–Bumps

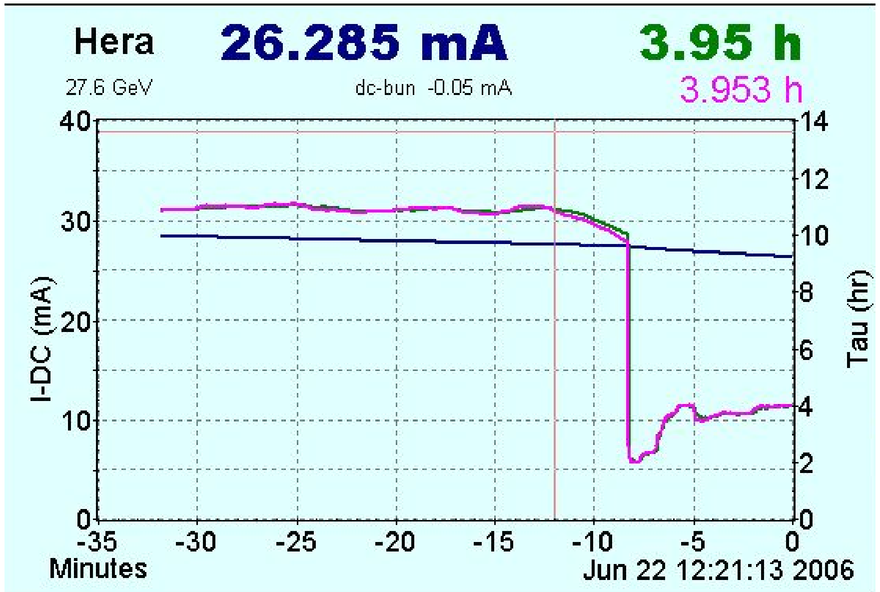
- decoupling bumps (SumRe, SumIm, DiffRe, DiffIm) for experimental solenoid (4 skew-quads each)
- tilt–bumps to change (x,y) ellipse at IP
- α- & β–bumps at each IP
- x and y phase trombone $\rightarrow$ $\mu_{\mathrm{West}} - \mu_{\mathrm{East}}$

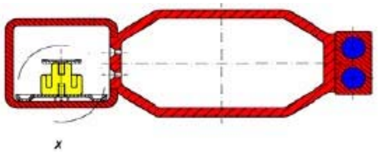
"SuperBumps"

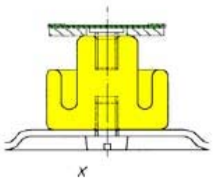
- program to create arbitrary 3, 4A, 4S bumps using all available correctors

e^- Dust Trapping

- HERA–I : electron operation severely limited
- positively ionized dust–particles get trapped in periodic field of stored e^- bunches
- major source of dust : integrated ion–getter–pumps







- 1998 : **all integrated getter pumps replaced by NEG pumps**

$\Rightarrow$ improvement : typical $\tau_{e^-} \approx$ 8–12h compared to $\tau_{e^+} \approx$ 12–20h (at 27GeV)

- severe lifetime breakdowns ($< 5h$) only rarely)

Experimental Backgrounds

p–related

- vacuum upstream IP !!!

$\leftarrow$ cold magnets inside detector

$\leftarrow$ SynRad desorption ($e^{\pm}$)

- aperture limit (mirror quad)
- halo population
- orbit fluctuations at p-collimators

$e^{\pm}$–related

- direct SynRad
- backscattered SynRad
- off-energy particles

$\leftarrow$ enhanced by : dust–trapping

cures

- vacuum : more pumping power at IR, better pumping slits, regular warm-up (cold magnets) and NEG–regeneration
- SynRad : optimize $e^{\pm}$–collimators upstream experiment, careful orbit steering and interlock, improved SynRad masks inside experiment
- halo build up and orbit fluctuations : continously search and remove sources (PS-ripple,. . .)

$e^{\pm}$–Polarization at HERA–II

- longitudinal polarization at all 3 experiments

\+ **radiative self–polarization** (Sokolov–Ternov)

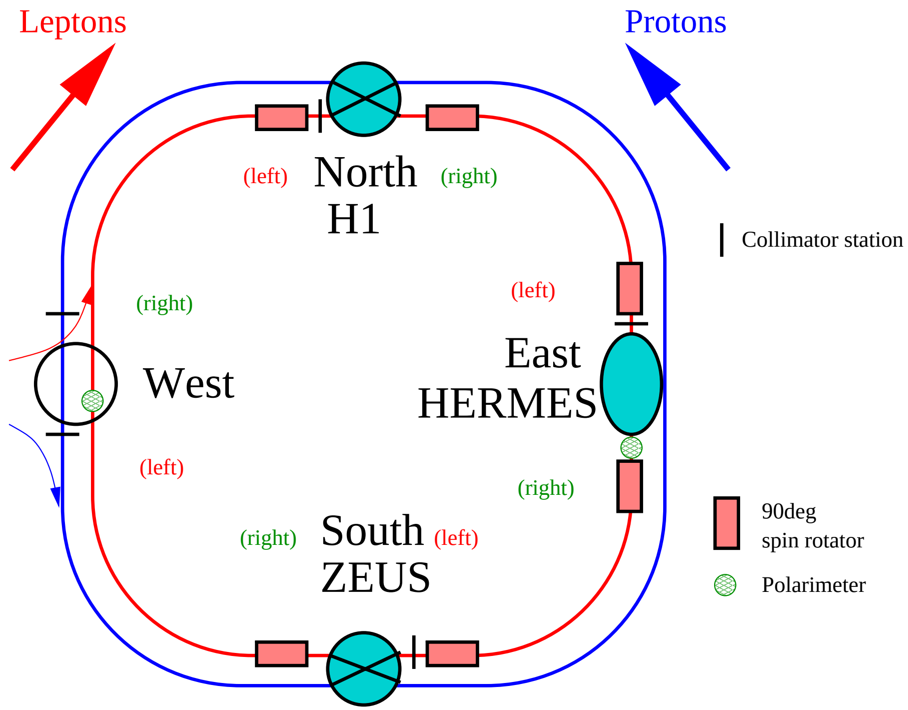
⇒ vertical equilibrium polarization in the arcs

— **spin–diffusion**

→ non–flat machine (spin rotators)

→ uncompensated experimental solenoids

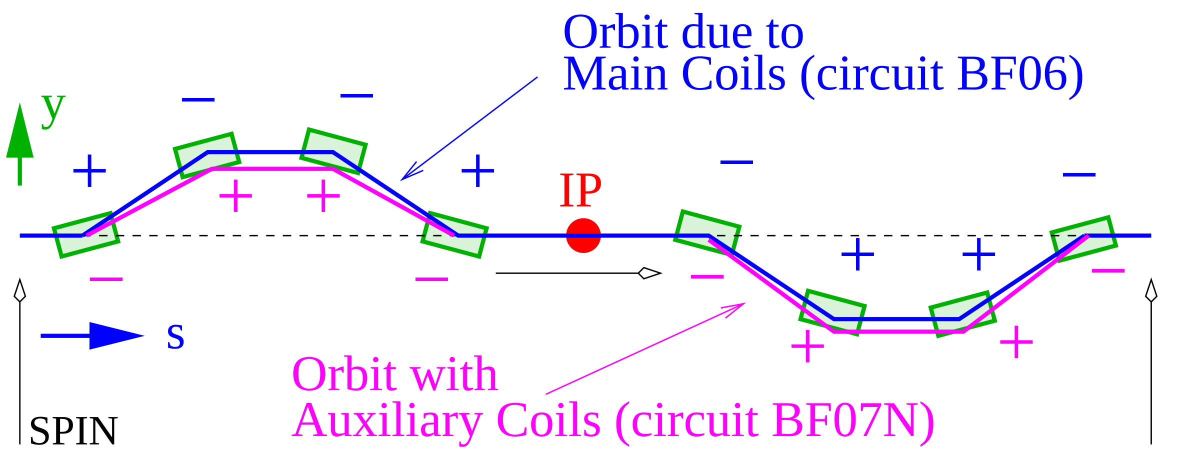
→ . . .



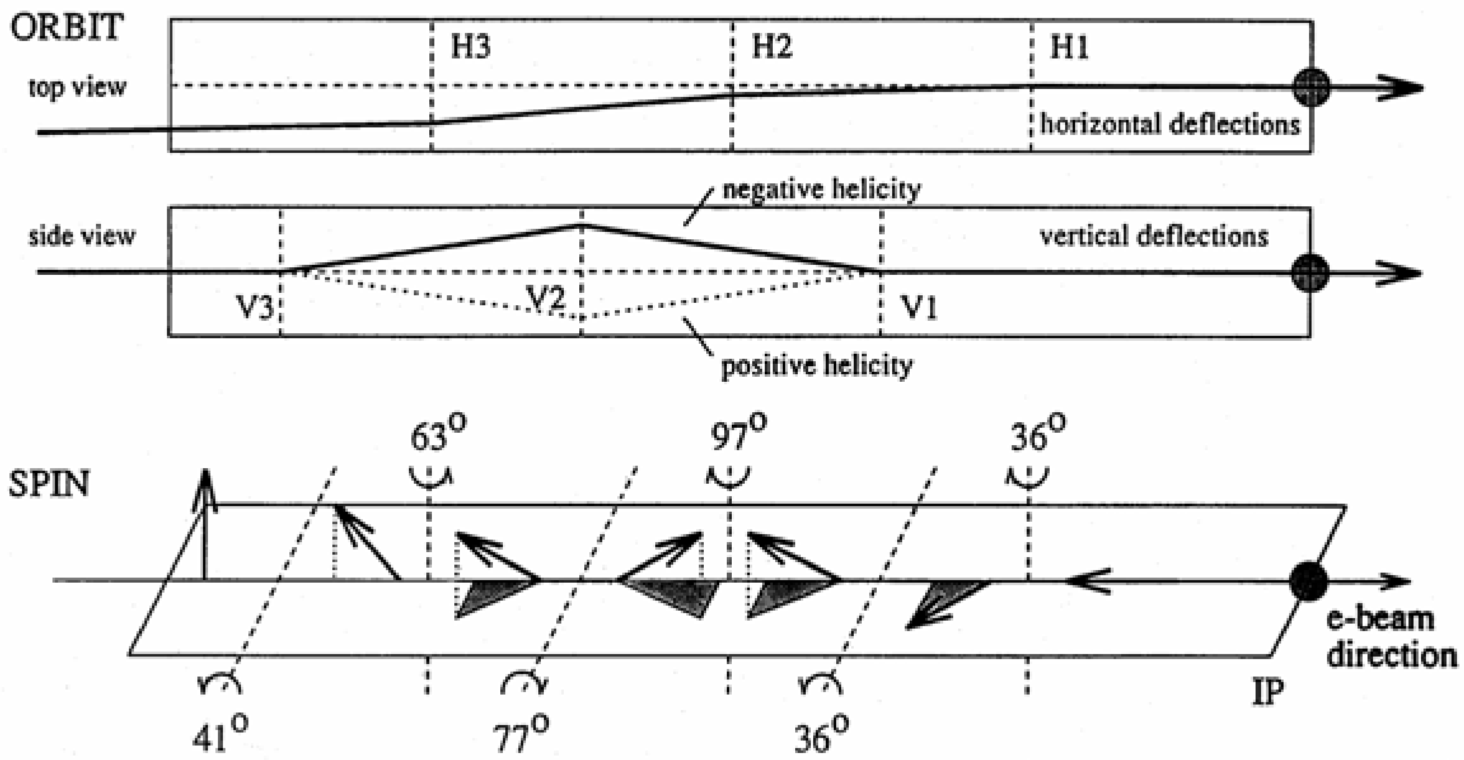
- three pairs of rotators turn vertical spins into longitudinal before each IP . . .
- . . . and vice versa after each IP

The HERA Rotators (1)

- Polarization direction vertical in the arcs but longitudinal at the IPs
- Needed for experimenters (**O,N,S**) **but also to maintain Polarization** because of the uncompensated Solenoids in **N** & **S**
- **In particular:** H1-Solenoid (long. spin–rot.) overlaps with horizontal combined function magnet (vert. spin–rot.) (energy dependent!)
  $\longrightarrow$ **special rotator setting needed for compensation!** $\boxed{\leftarrow \textbf{helicity dependent}}$
- Interleaved **vertical (↓ figure ↓)** and horizontal bends
  $\longrightarrow$ `BF06` and `BF07N` used to change rotation axis

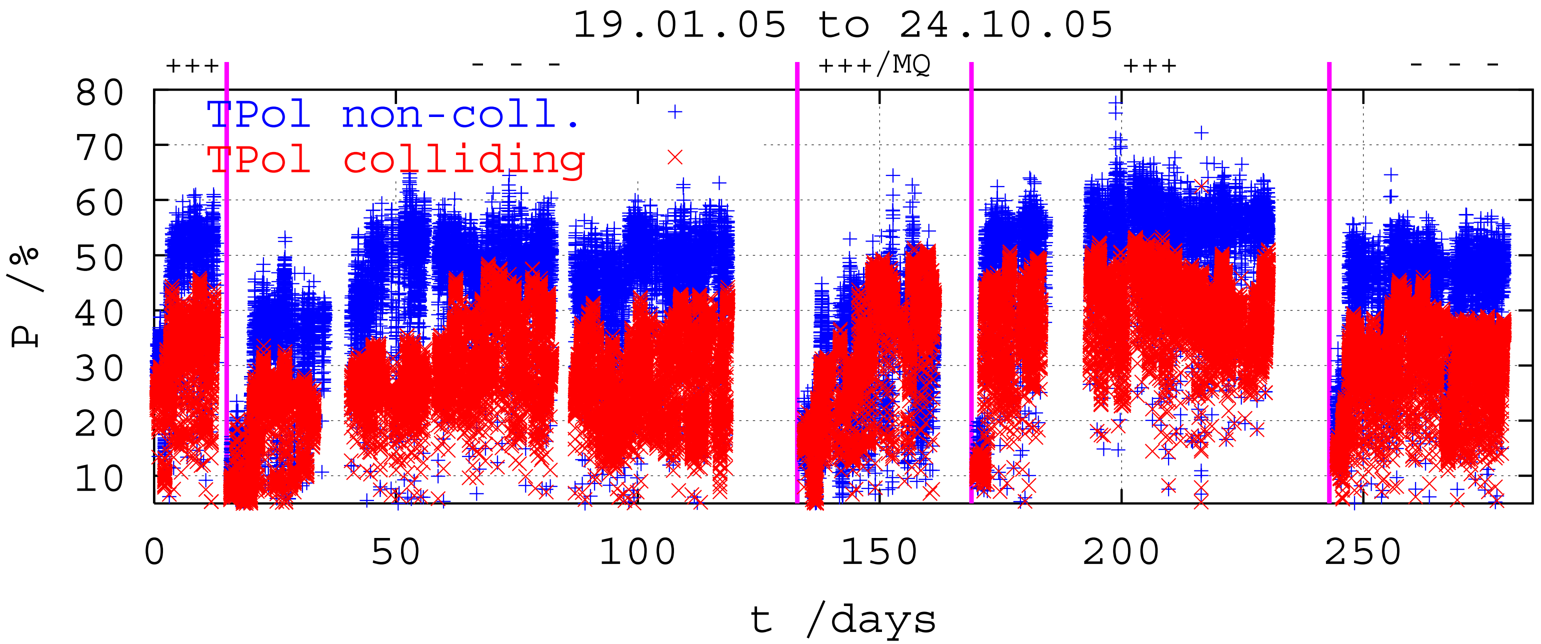


A 90°–"down"–Rotator (+ "up" on other side of IP)



Overview of e^- Runs in 2005

(TPol=Transverse Polarimeter; typically 146 colliding and 6 non–colliding bunches)



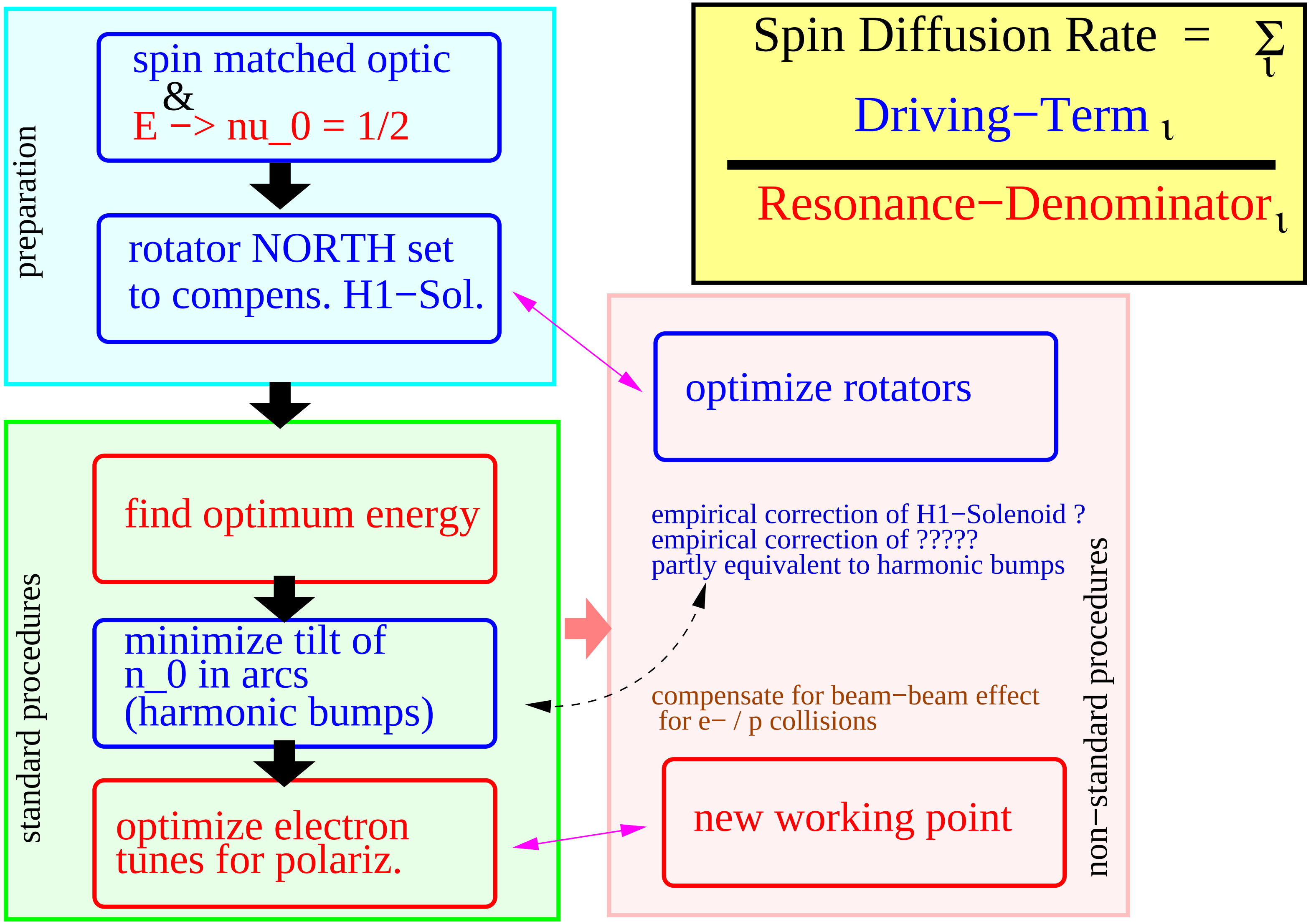
Main Issues

- Beam–beam effect on coll. bunches
- Asymmetry w.r.t. rotator polarity (not yet understood)

Typical Polarizations

HERA-I	HERA-II e^+	HERA-II e^-
55%	45%	40%

Polarization Strategy

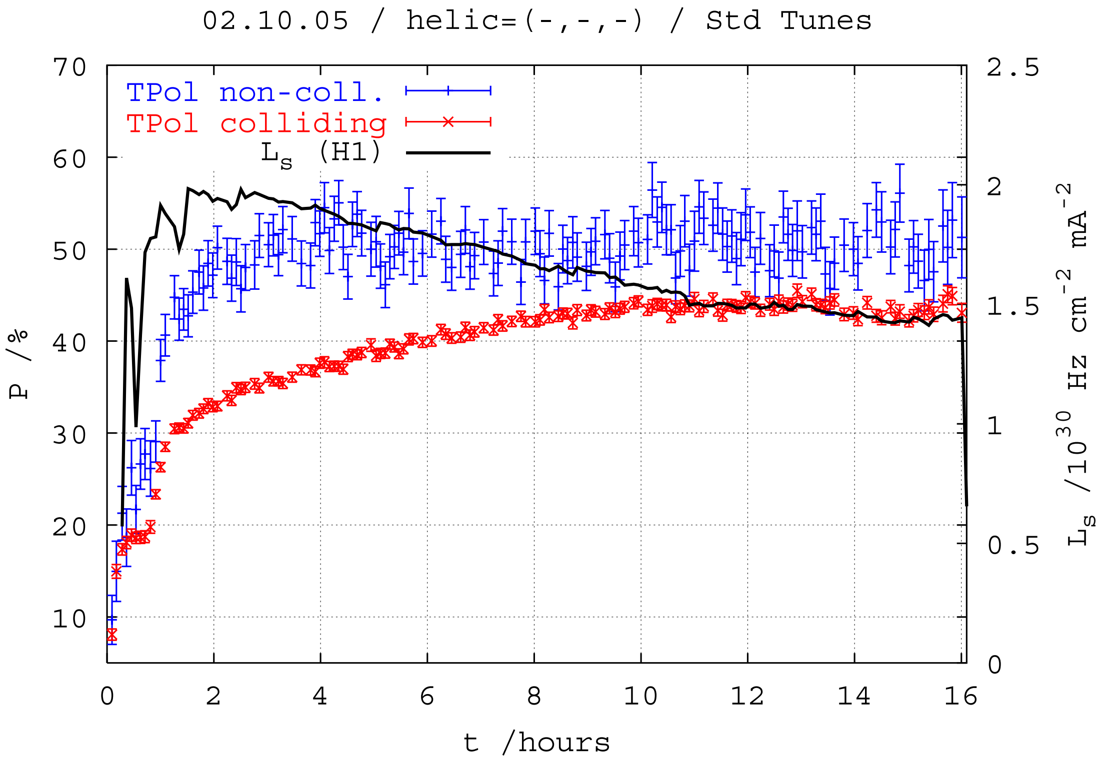


Polarization with e^-/p Collisions

- Non-colliding bunches:

$\longrightarrow$ $P_{\mathrm{non-coll}} \approx$ 50%

$\longrightarrow$ reach stationary state $\Rightarrow$ equilibrium–polarization $\approx$const.

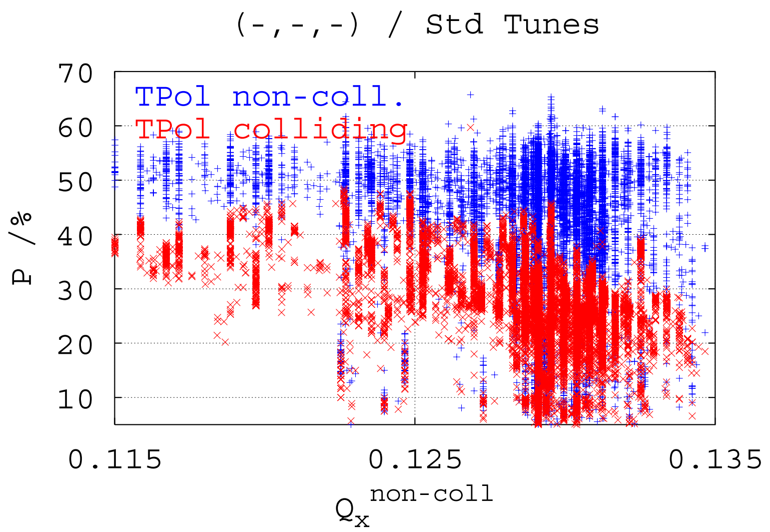


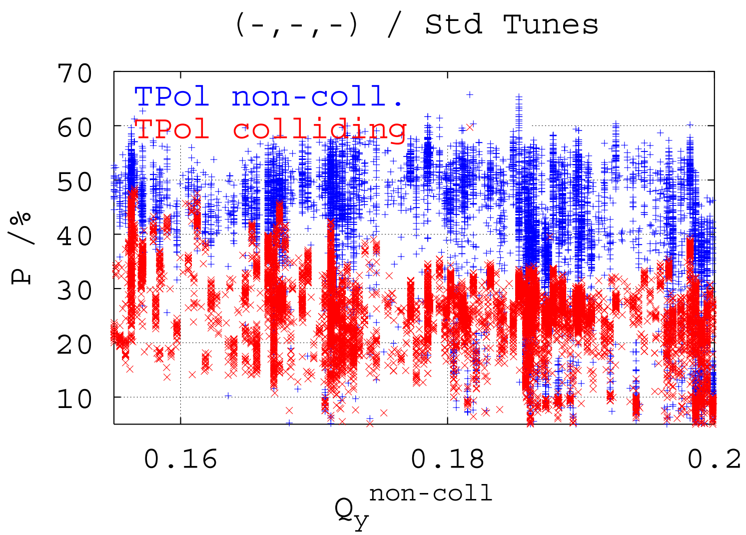
- colliding bunches:

$\longrightarrow$ $P_{\mathrm{coll}} \approx$ 35 – 45 %

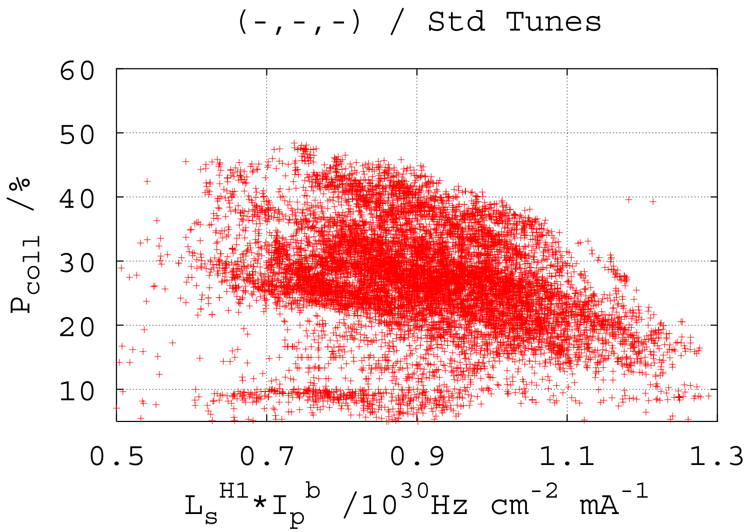
$\longrightarrow$ equilibrium polarization grows slowly $\Leftarrow$ decaying $\mathcal{L}_s$ $\Leftrightarrow$ decaying beam–beam tune shift

Tunes and Beam–Beam Effect



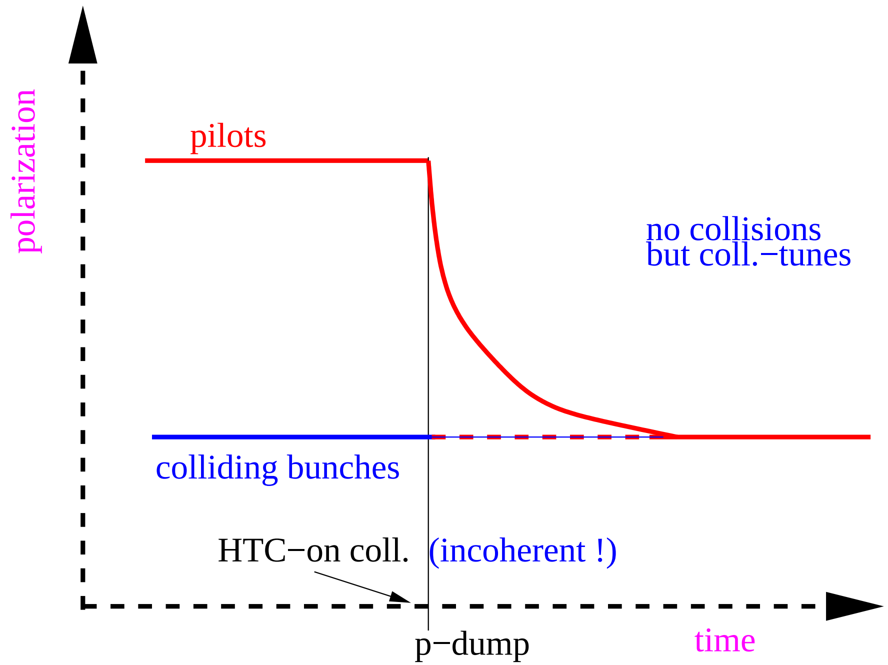


- Polarization favors $\boxed{\text{tunes close to the integer}}$
- For **matched beams** and **fixed** $R := \sigma_y/\sigma_x$ $\rightarrow \xi_x^e \propto \mathcal{L}_s I^p \frac{R}{1+R}$ and $\xi_y^e \propto \mathcal{L}_s I^p \frac{1}{1+R}$
- Beam Beam moves the tunes of the colliding bunches



Beam–Beam Experiment

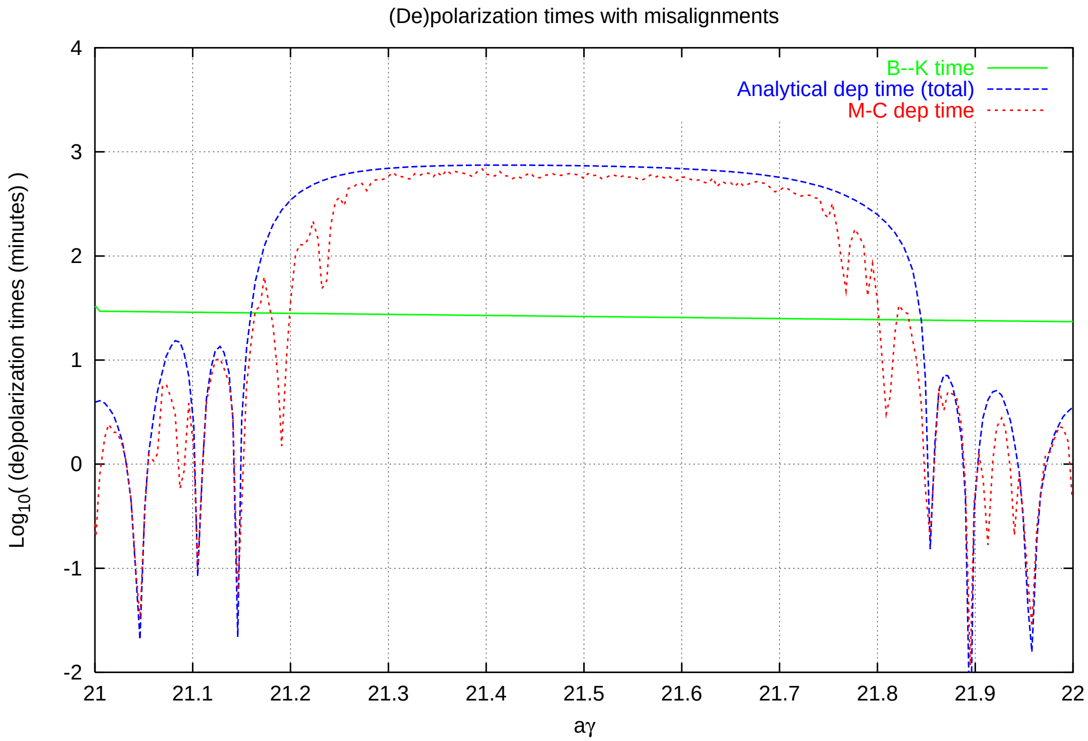
- 23.03.05 : end-of-run:
- measure coherent ΔQ^e's
- p–dump
- move incoherent Q^e's to $Q^{e,coll}$
- wait for equilibrium



- **Main reason for b–b depolarization seems to be tune shift**
- ... at least for **moderate** beam–beam tune shifts

$\longrightarrow$ residual non–linear effects $\Rightarrow$ non–linear polarization **simulation** $\Rightarrow$

Non–Linear Radiative Tracking



- New code `SLICKTrack` by D.Barber $\longrightarrow$ **today 17:15**
- Will replace old and "buggy" `SITROS`

$\Leftarrow$ Example : e-RHIC τ_{dep} vs. $a\gamma$ $\longrightarrow$ nonlinear sidebands

- Does include weak–strong beam–beam
- HERA Simulation (much longer ring !!!) : coming soon

Electron Tune Space Above and Below the Integer

- **Above** the Integer:
  Limited by

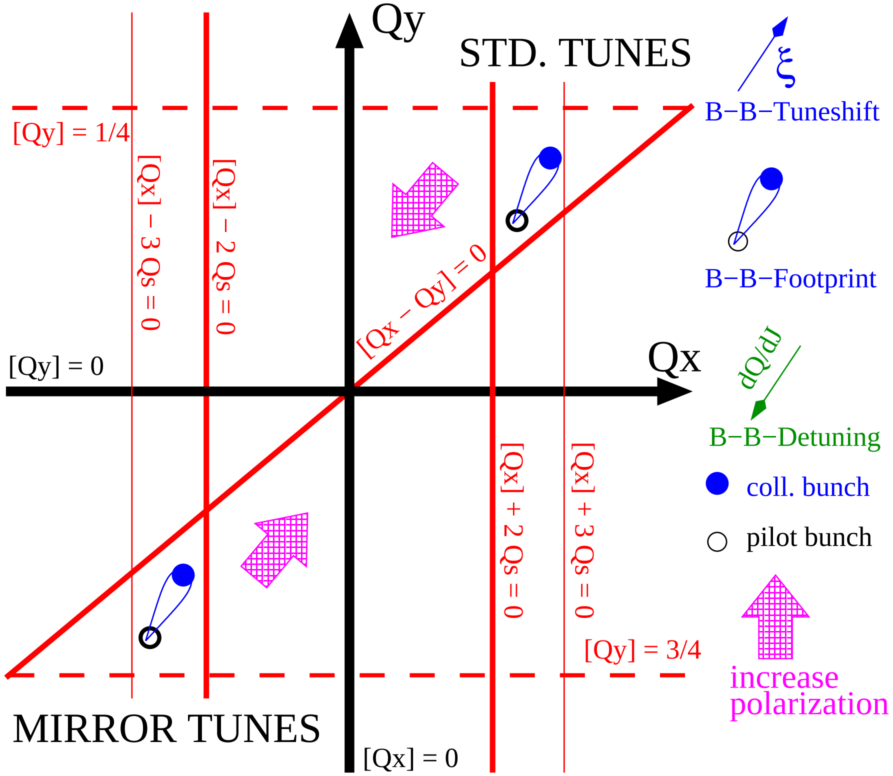
→ 2-nd and 3-rd satellite (x)

→ coupling resonance and 4-th integer (y)

- **Below** the Integer:

→ x: 2-nd and 3-rd satellite interchanged & sum →difference

→ y: coupling resonance and 4-th integer "interchanged"



- **Electrons Above** the Integer : beam–beam tune shift pushes tunes of colliding bunches **up away from integer**
- **Electrons Below** the Integer : beam–beam tune shift pushes tunes of colliding bunches **up towards integer**
- **Unfortunately:** coupling and satellite resonance degrade $\mathcal{L}_s$ ⇒**back to std.Q**

Mirror Tunes for Positrons ?

- beam–beam tune shift reverses sign under lepton charge reversal

$\Leftarrow$ positron operation (2002–2004) with tunes **above** the integer produced
$\mathcal{L}_s \approx 1.7 \cdot 10^{+30}$ Hz cm^{-2} mA^{-2}

$\Leftarrow$ electron operation (2005–2006) with tunes **above** the integer produced
$\mathcal{L}_s \approx 2.1 \cdot 10^{+30}$ Hz cm^{-2} mA^{-2}

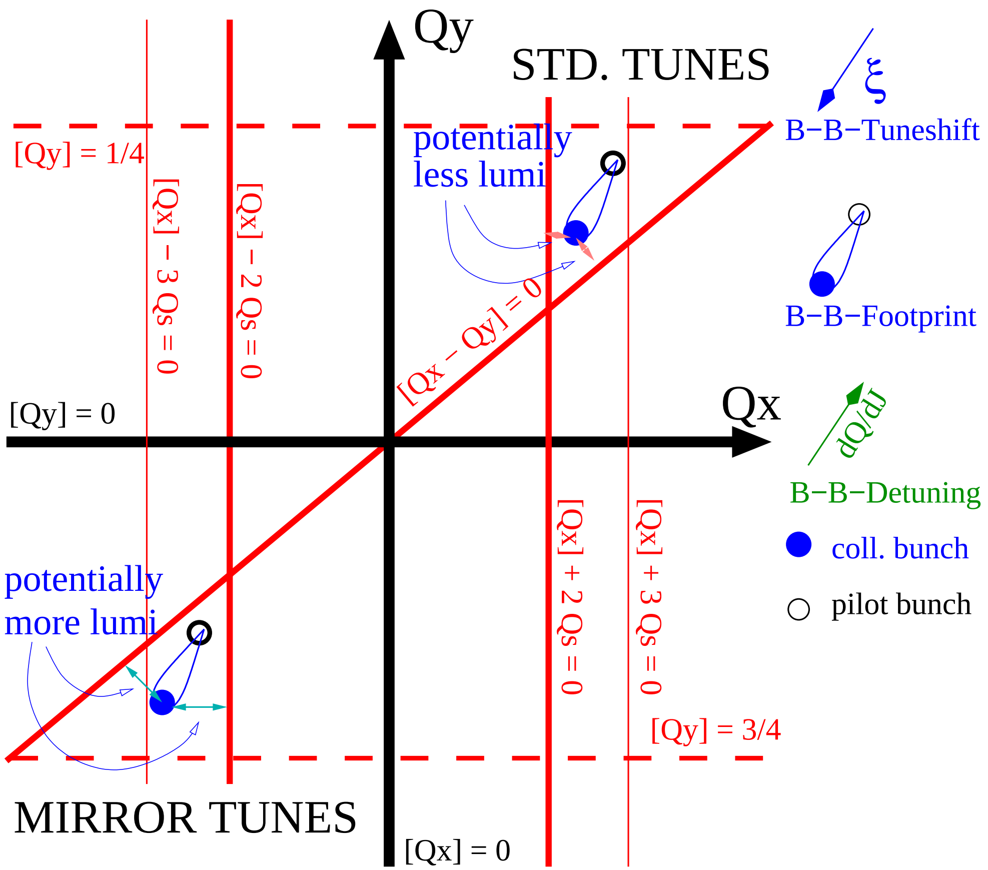
$\Leftarrow$ electron operation (06/2005) with tunes **below** the integer produced
$\mathcal{L}_s \approx 1.7 \cdot 10^{+30}$ Hz cm^{-2} mA^{-2}

$\Rightarrow$ try positron operation (2006–) with tunes **below** the integer and hope for
$\mathcal{L}_s \approx 2.1 \cdot 10^{+30}$ Hz cm^{-2} mA^{-2}

- first indications are that this might actually work . . .
- . . . most likely at the cost of lower polarization

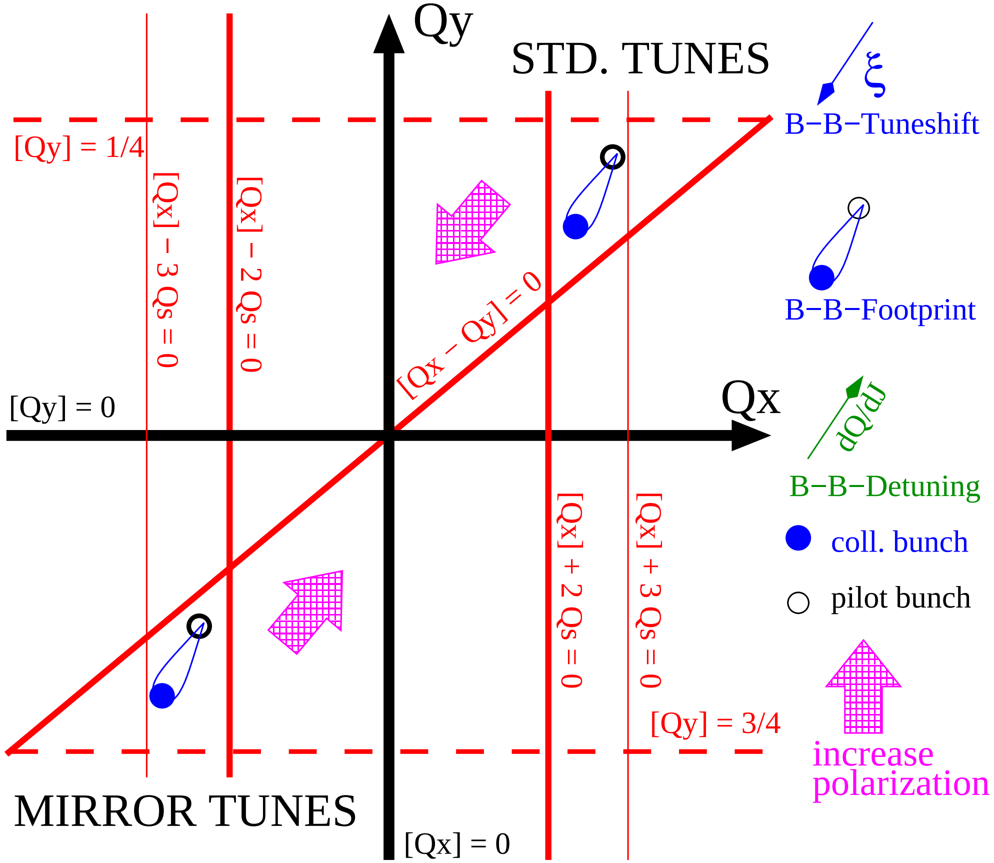
e^+/p–Collisions : Mirror Tunes for Luminosity

- e^+/p–collisions : beam–beam tune shift is **negative**
- **Mirror Tunes :**
- colliding bunches : further away from dangerous/lumi-degrading resonances
- beam–beam beta beat decreases β at IP
- **Standard Tunes :**
- colliding bunches : closer to dangerous/lumi-degrading resonances
- beam–beam beta beat increases β at IP



e^+/p–Collisions : Standard Tunes for Polarization

- Polarization likes tunes close to the integer (below or above)
- **Mirror Tunes :**
- colliding bunches : further away from integer $\Rightarrow P_{\text{colliding}} < P_{\text{non-coll}}$
- **Standard Tunes :**
- colliding bunches : closer to integer $\Rightarrow P_{\text{non-coll}} < P_{\text{colliding}}$



Conclusion

HERA is as asymmetric as an accelerator can be ! Not only the energies are greatly different, but HERA deals with hadrons and leptons which brings on the "goodies" from both worlds. However, it has been done so why should it not be done again ?