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Operational Experience with HERA

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On behalf of the HERA team

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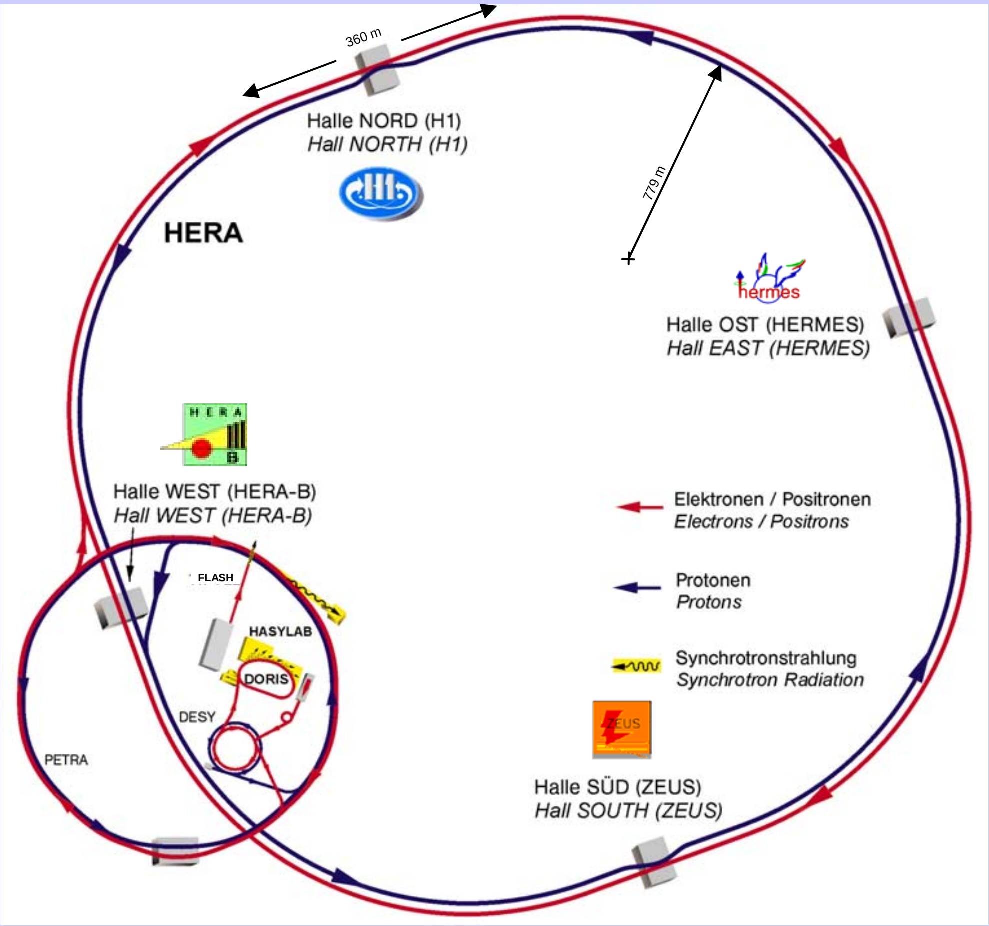
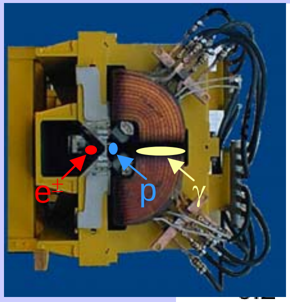
Layout of HERA

<u>H</u>adron <u>E</u>lectron <u>R</u>ing <u>A</u>ccelerator

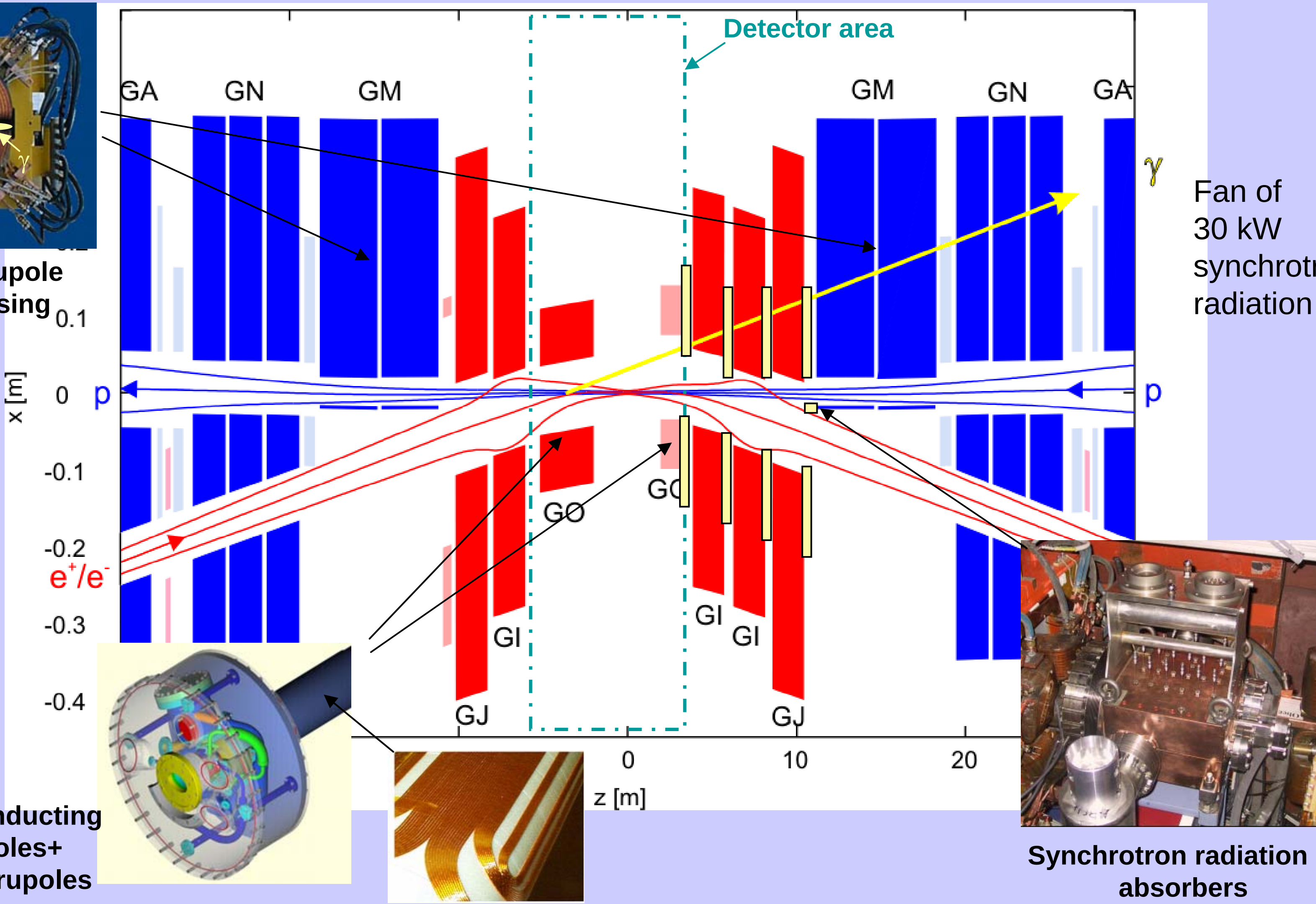
- Double ring $e^{\pm}$/p collider, circumference 6.336 km
- 920 GeV protons
- 27.5 GeV electrons/positrons
- Polarized $e^{\pm}$ beam
- Experiments:
  - **H1, ZEUS**: protons on electrons in two IPs
  - **HERMES**: electrons on internal polarized gas target
  - **HERA-B**: protons on internal wire target (until 2003)



HERA e/p Interaction Region



Half quadrupole for p focusing



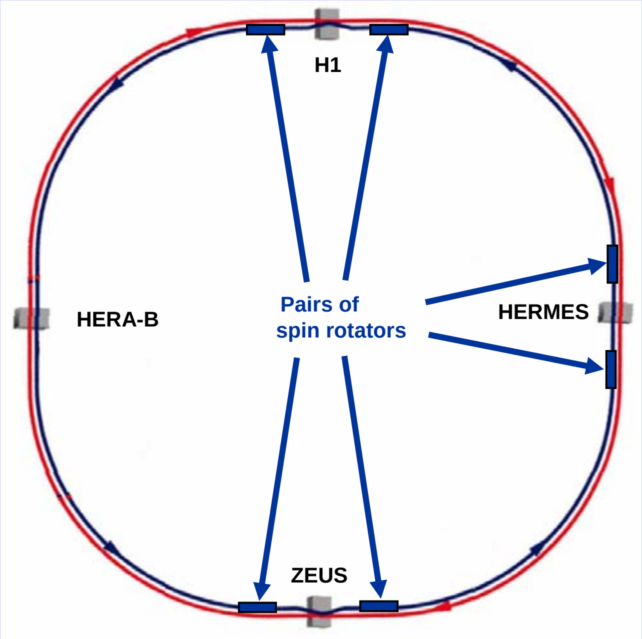
Fan of 30 kW synchrotron radiation

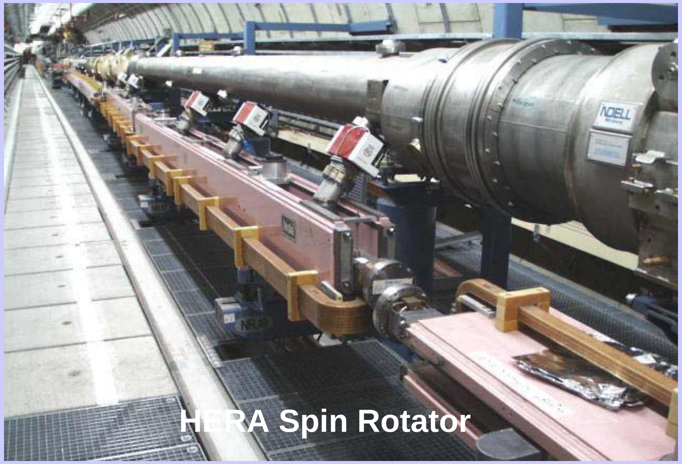
Superconducting dipoles+ quadrupoles

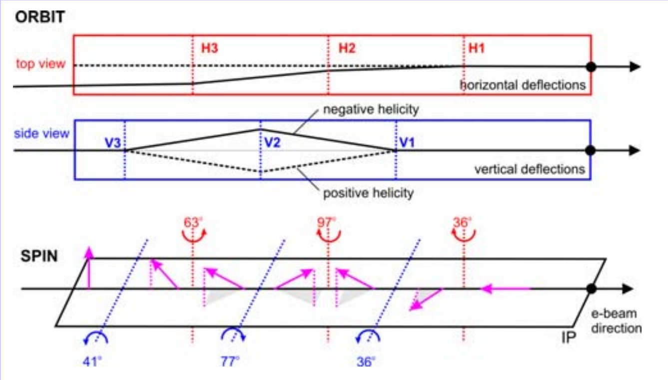
Synchrotron radiation absorbers

Polarized Lepton Beam

- HERA experiments need **longitudinal polarization** at the IPs
- Equilibrium polarization in vertical direction in the arcs is balance of
  - Radiative **self-polarization**
  - **Spin diffusion** (non flat machine, uncompensated solenoids of experiments,…)
- Pairs of spin rotators turn vertical spins into longitudinal before the IPs and back







90° Spin Rotator

HERA Parameters

Parameter	Unit	Positrons	Protons
Energy E	GeV	27.5	920
Max. current I	mA	44	112
Number of (colliding) bunches n_b		180 (173)	180 (173)
Horizontal emittance ε_x	π·nm·rad	22	3.8
Vertical emittance ε_y	π·nm·rad	3.0	3.8
Horizontal beta function at IP β_x^*	m	0.63	2.45
Vertical beta function at IP β_y^*	m	0.26	0.18
Bunch length σ_p	cm	1.03	13
Hourglass factor R		0.95	
Specific luminosity L_s	$mA^{-2}\cdot cm^{-2}\cdot s^{-1}$	1.6 – 2.1	
Peak Luminosity L	$10^{31}\ cm^{-2}\cdot s^{-1}$	5.1	
Beam lifetime in collisions τ	h	10-15	200
Polarization P		40-50%	---

Limitations:

For e^+: RF power

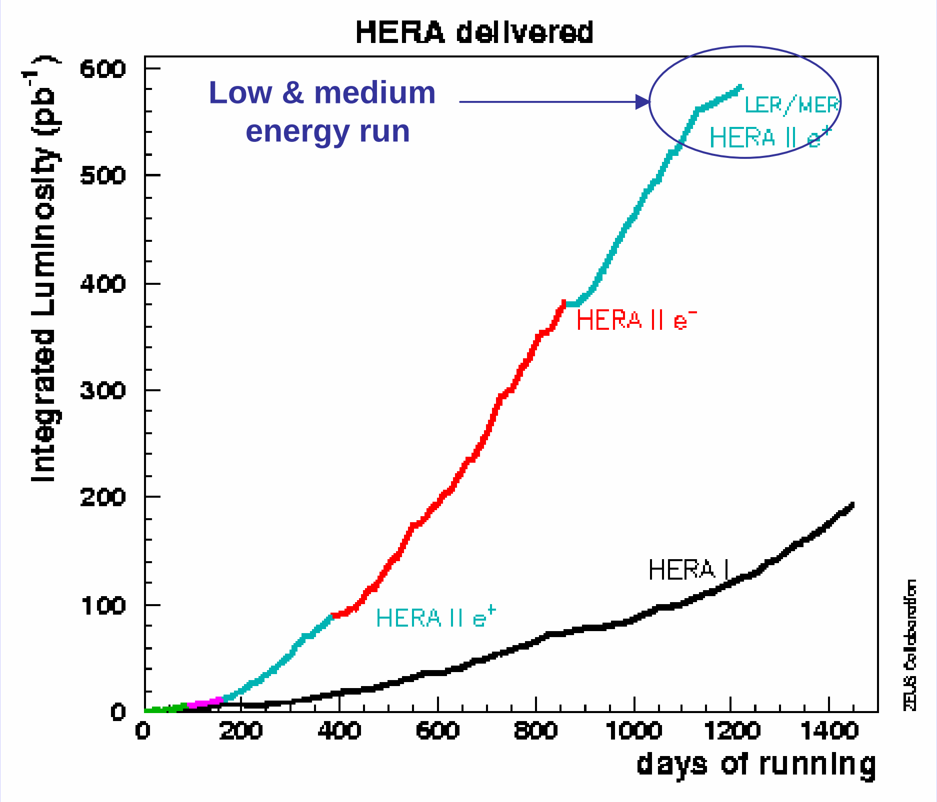
For p : pre-accelerators

For e^+: without dynamic beam-beam beta-beating

Design: 1.82

HERA II Luminosity Production

- The HERA II run has delivered 600 pb^{-1} to the experiments
- The integrated luminosity was equally split between e^+/e^- operation
- The luminosity production has increased during the years
  - 2002/03: current limitations by background conditions
  - Make use of dynamic beta beating effect
  - Higher availability
- At the request of the experiments HERA has been operated in the last 3 months with reduced proton energies
  - E_p=460 GeV for two months
  - E_p=575 GeV for one month



Critical Issues of HERA Operation

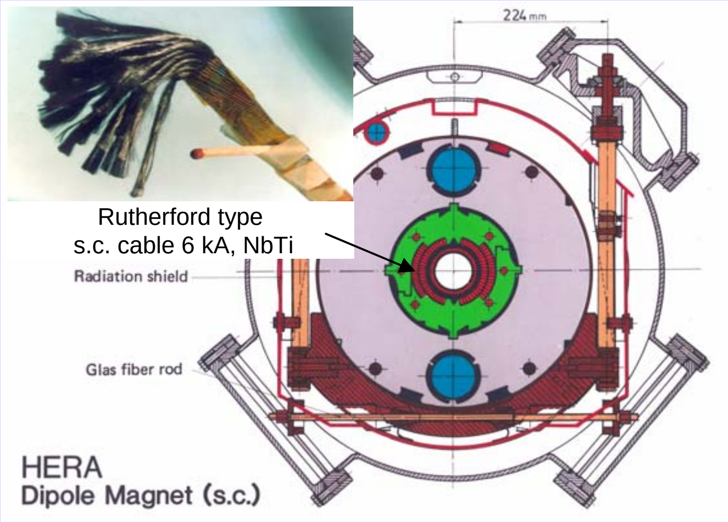
- **HERA-p**:
  - **Sextupole field distortions** at injection (persistent current in s.c. magnets)
    ⇨ small dynamic aperture at 40 GeV; head-tail instability
  - **Ground vibrations** and **power supply ripple** ⇨ proton background
  - **Longitudinal multi bunch instability** ⇨ proton bunch lengthening
  - **Matched beam sizes** ⇨ otherwise low p-lifetime
  - **Vacuum conditions** in the IR are critical
  - **Luminosity** limited by p-**beam brightness** (injectors, BB-limit of leptons)

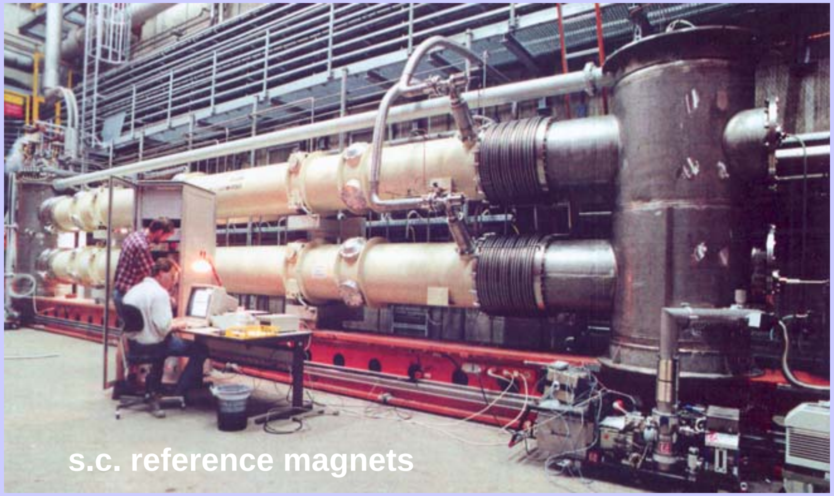
- **HERA-e:**
  - **Synchro-betatron resonances** limit space in tune diagram
  - **Good orbit control** (global + local at IP) necessary (synchrotron radiation)
  - **Lifetime disruptions** for **e^-**-operation (''dust'')
  - **Beam-beam interaction** has strong influence on **polarization**
  - Luminosity limited by **RF power**

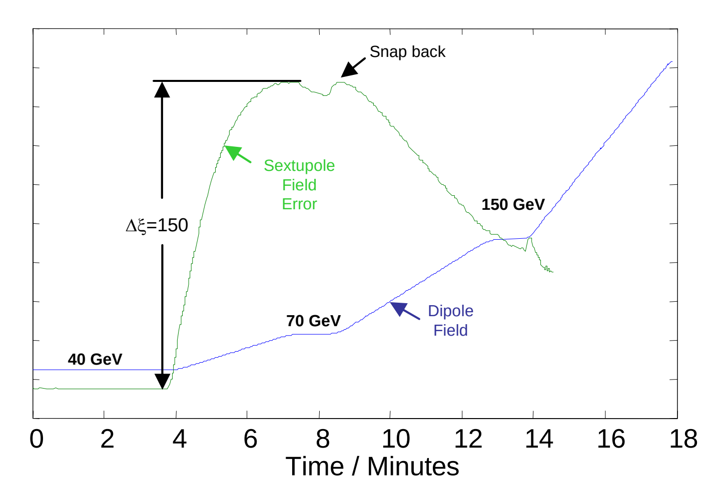
Persistent Current Effects

- **Sextupole field distortions** during proton acceleration
  - **persistent currents** induced in 400 s.c. magnets
  - First part of ramp: fast change of chromaticity
  - If $\xi < 0$: Head tail instability
  - If $\xi > 5$: Dynamic aperture small

- To **correct** this effect HERA uses
  1. Measured field in two reference magnets
  2. Additional empirical correction (ramp table)
  3. Optimization 'by hand' using the tune spectrum





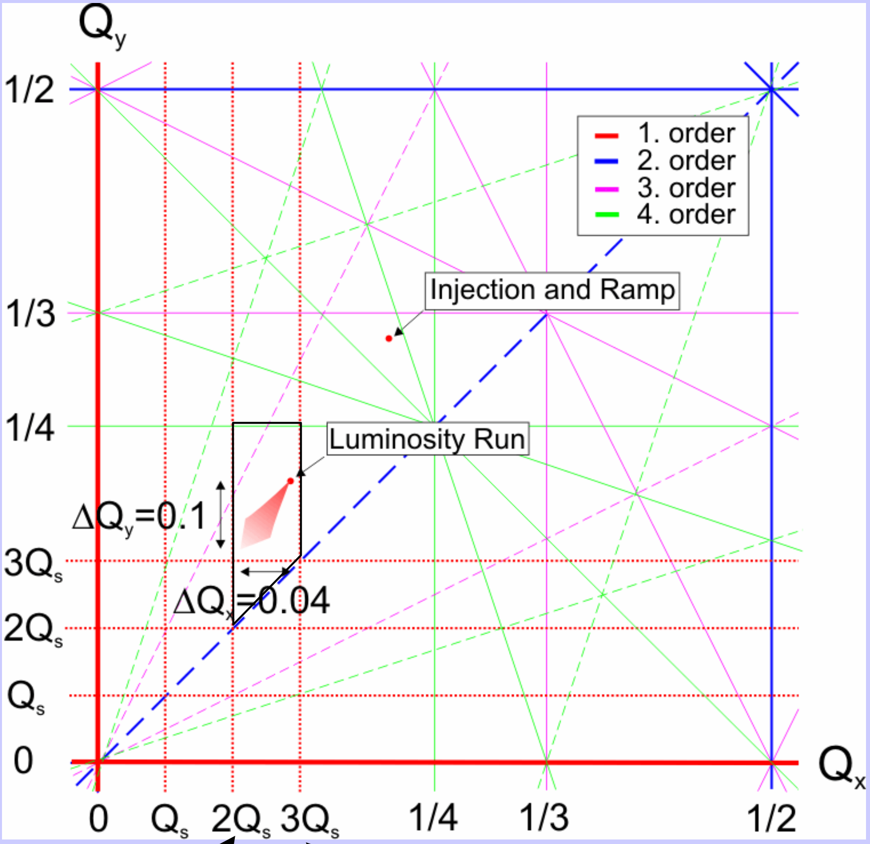


Persistent current sextupole field error

Synchro-Betratron Resonances of HERA-e

Operating tunes for HERA-e:

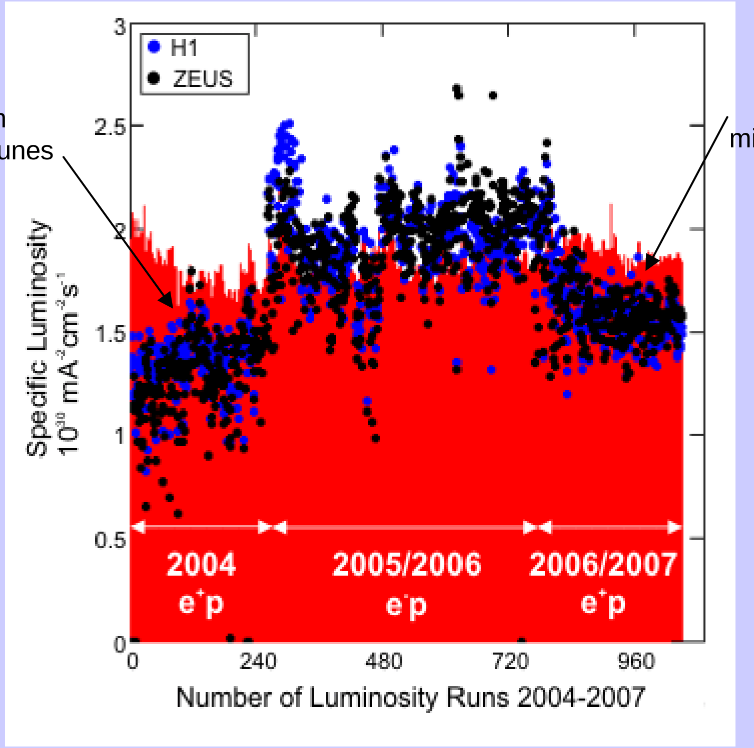
- **Injection and Ramp**
  - Sufficient dynamic aperture
  - No polarization
- **Luminosity Run**
  - Resonance free region to accommodate beam-beam tune shift ($\Delta Q_x \leq 0.04$, $\Delta Q_y \leq 0.10$ with 2 IPs)
  - Space limited by strong 2nd and 3rd order synchro-betatron resonances, coupling resonance Q_x-Q_y and $4Q_y$ resonance
  - Small betatron tunes are necessary to maximize distance between intrinsic depolarizing resonances

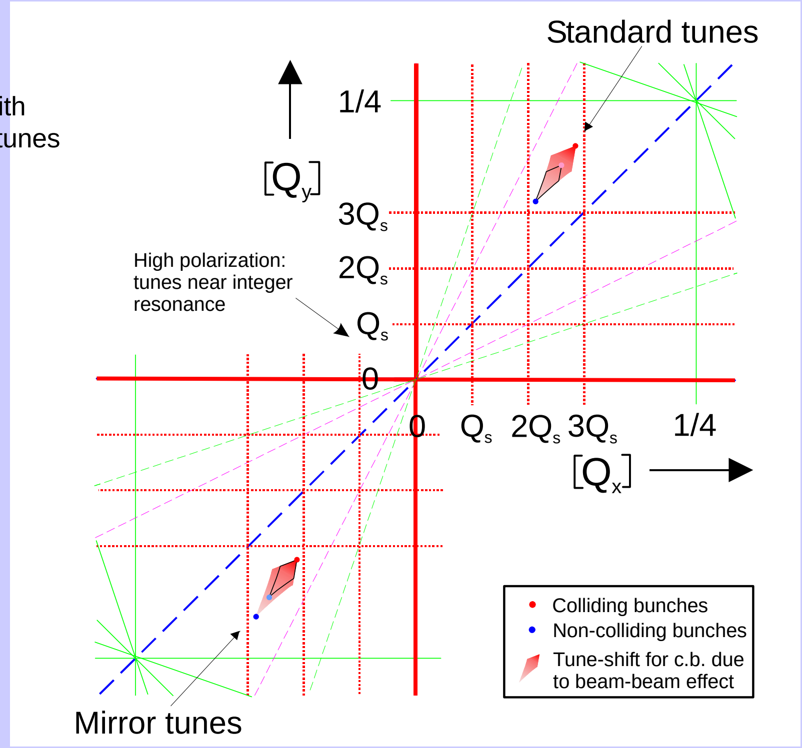


Cure for $2Q_s$ resonance:
Orbit and dispersion control, orbit feedback

Cure for $3Q_s$ resonance:
Optics with intrinsic compensation of nonlinear chromaticity contributions from the 2 IPs

Peak and Specific Luminosity

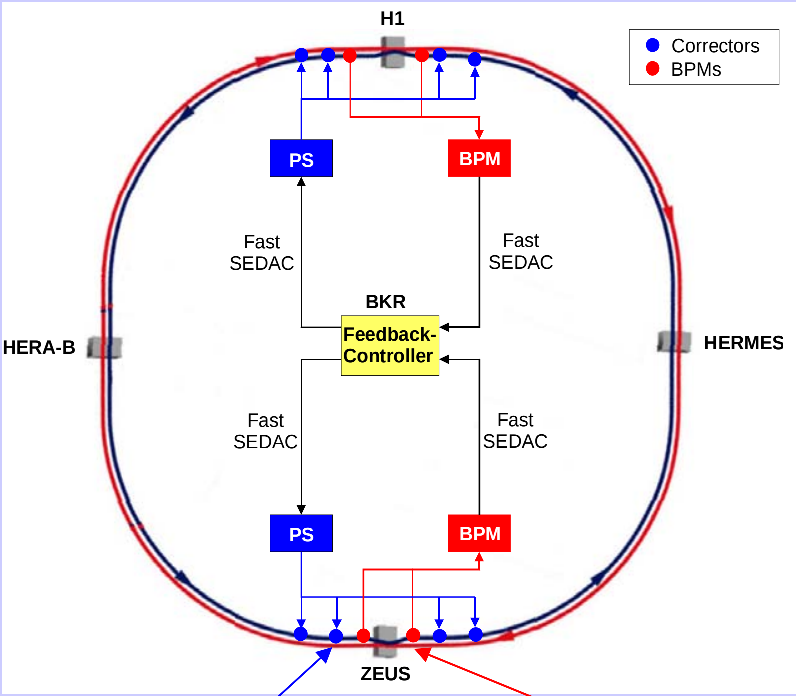


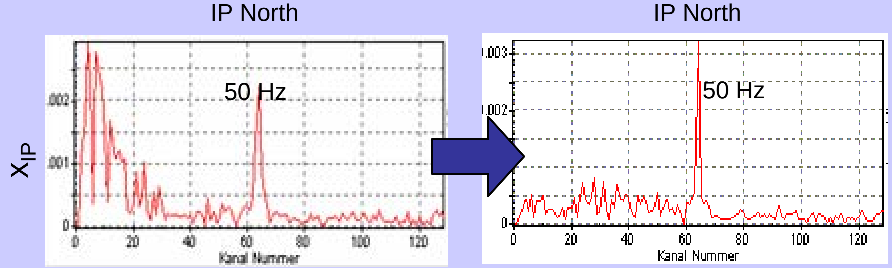


- Since e$^-$ operation in 2005: Take advantage of beam-beam beta beating to get smaller beta functions at the IPs: standard tunes for e$^-$, mirror tunes for e$^+$
- Max. specific Luminosity: L_s=2.2·10^{30} cm^{-2}mA^{-2}s^{-1} (with e$^-$)
- Peak luminosity achieved: L=5.1·10^{31} cm^{-2}s^{-1}

Control of e-Orbit Oscillations at IPs

- Orbit oscillations of the electron beam relative to the p-beam can increase
  - the proton beam **emittance**
  - the proton **halo** production
- The HERA orbit spectrum is dominated by frequencies between 0-20 Hz + harmonics of 50 Hz
- A **local IP feedback** was implemented in short time using local symmetric bumps (16 new air coils) and 8 BPMs (new electronics) to stabilize the e-orbit positions x_{IP} & y_{IP} at the IPs between 0-20 Hz
- The sampling frequency is 800 Hz
- The bandwidth is limited by eddy currents in the HERA vacuum chamber to B < 35 Hz





Feedback off

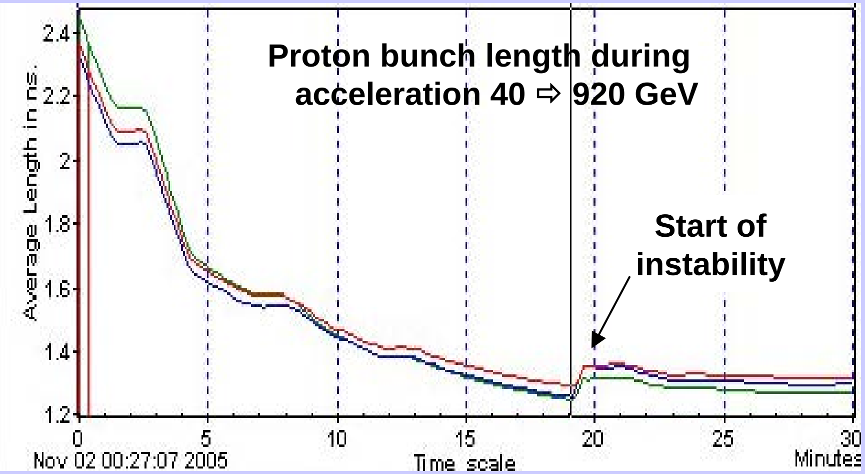
Feedback on

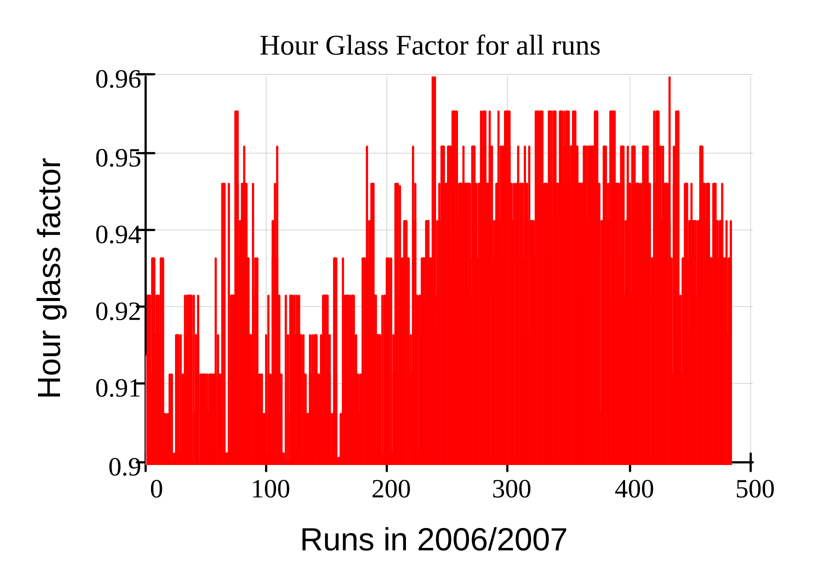
4 hor.+4 ver. air coils at each IP

4 BPMs at each IP

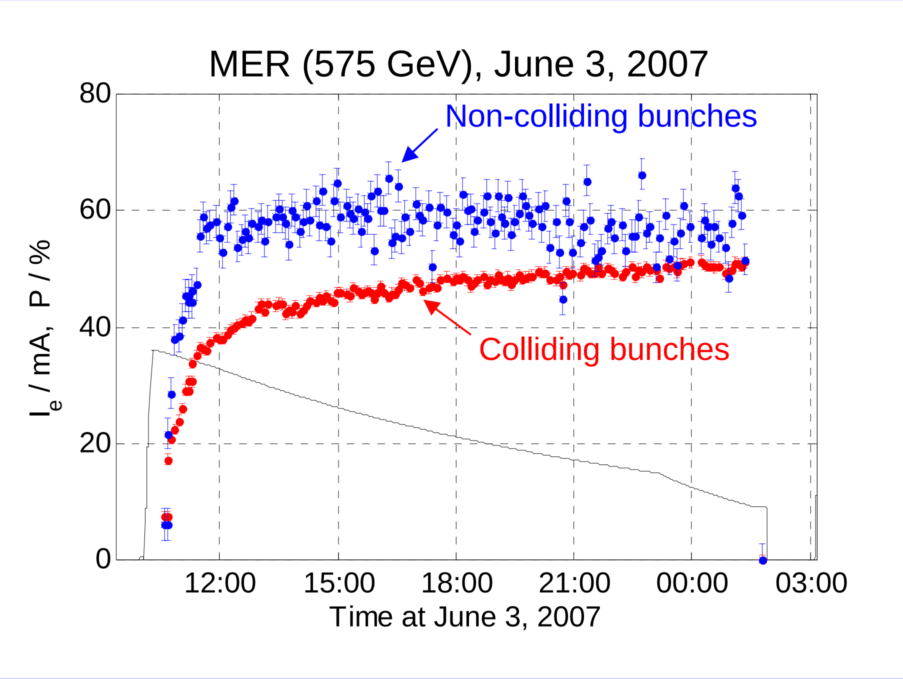
Control of Proton Bunch Length

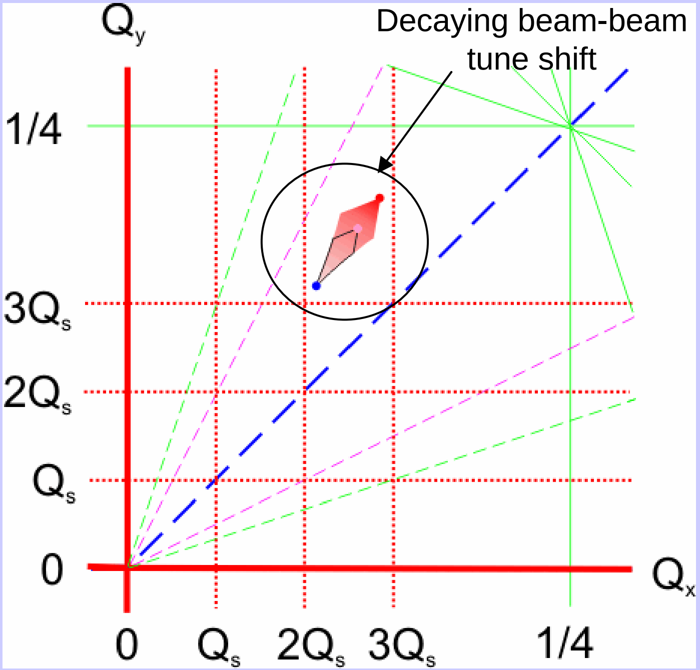
- P-bunches get longer during acceleration due to longitudinal multi-bunch instability
  ⇨ Reduction in luminosity
- Cure: feedback system
- System is running routinely and provides initial proton bunch lengths corresponding to the design value
- Poster: J. Randhahn et al., MOPANI018





Polarization with e^+/p Collisions





- Strong influence of **beam-beam effect** on polarization observed
- Polarization grows slowly during run
- Reason: proton emittance growth
  ⇨ decaying beam-beam tune shift

After optimization of energy, vertical orbit, dispersion functions and harmonic bumps:

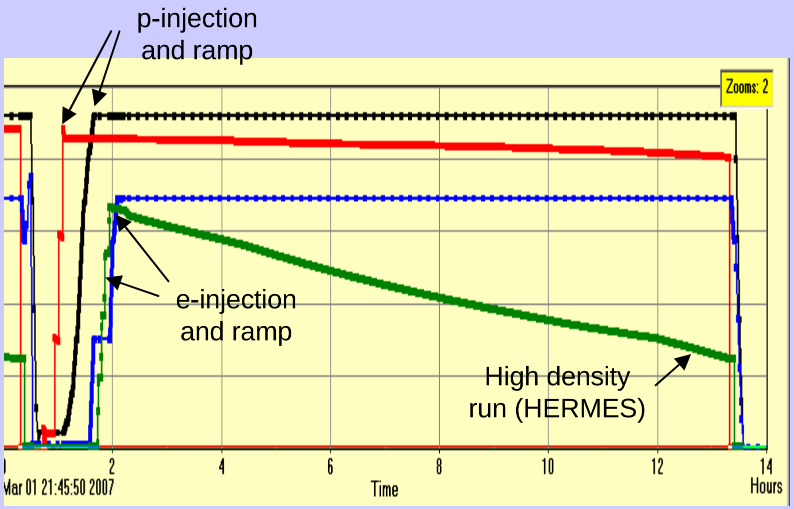
- Polarization of **non-colliding bunches**: 50-60%
- Polarization of **colliding bunches**:
  - HER (920 GeV): 40% (e^-), 45% (e^+)
  - LER (460 GeV) & MER (575 GeV): 50% (e^+)

HERA Operational Efficiency

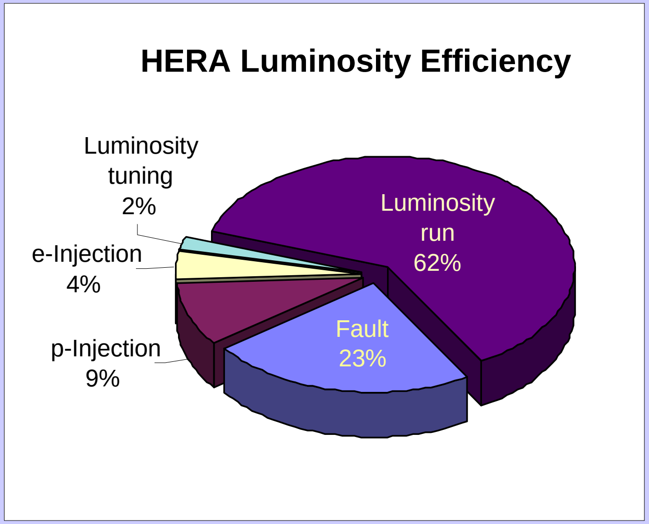
- HERA availability is a major issue
- HERA is a slow ramping machine
  - P-injection + p-ramp: 1 h
  - E-injection + e-ramp: 0.5 h
  - Magnet cycling + setup of luminosity: 0.5 h
  - ⇨ at least 2 hours lost if a beam loss happens during a luminosity run

- HERA availability has increased to ~80% in 2006/07 due to
  - **Preventive maintenance** (all power components)
  - **More fault diagnostics** (transient recorder)
  - **Improved controls** (tune controller using wavelets analysis, etc.)
  - **Organizational measures** (on-call service, operator training)

- Main technical problems
  - RF transmitters
  - Power supplies
  - Vacuum leaks



Typical HERA run



Summary

- The operation of HERA will end on June 30, 2007.
- The HERA II run has delivered an integrated luminosity of 600 pb^{-1} in 6 years (HERA I: 200 pb^{-1}) equally split between e^+/e^- operation.
- An average luminosity production of 1 pb^{-1}/day has been achieved for HERA II.
- The peak luminosity of the HERA II run was $5.1 \cdot 10^{31}$ $cm^{-2}s^{-1}$
- A polarization of the lepton beam between 40-50% has been achieved.
- For the last three months HERA has been running for a dedicated experiment with reduced proton energy of 460 and 575 GeV to measure the longitudinal structure function F_L
- The rich physics program of HERA gave a deep insight in the structure of the proton and the polarized gluon contents.

Many thanks to

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… and of course to the HERA technical groups!