# ONLINE CALCULATION OF THE BEAM TRAJECTORY IN THE HERA INTERACTION REGIONS

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*Abstract*

During the HERA luminosity upgrade the new super conducting mini beta quadrupoles have been placed inside the experiments for final focussing and separation of the lepton and proton beams. The synchrotron radiation of about 12 kW produced in these magnets passes through the detector and is absorbed behind the experiments. In order to avoid background events from synchrotron radiation it is a mandatory to adjust precisely the beam trajectory before and inside the detector. A procedure has been developed to calculate the trajectory in the interaction regions. With a beam-based alignment (bba) the offsets of the beam with respect to the quadrupoles is measured. From this measurement the offsets of the quadrupoles and of the beam position monitors are fitted. With the knowledge of these offsets the trajectory of the beam is calculated with high precision. The display of the trajectory is online available as an operational tool for beam steering and background optimization.


## INTRODUCTION

The proton-electron storage ring collider HERA has gone through a major modification in 2001. A complete redesign of the interaction region increased the design luminosity to $7\cdot10^{31}\text{cm}^{-2}\text{s}^{-1}$ [seid]. Part of the concept are the new superconducting final focus quadrupoles, which are partly build inside the experimental detectors. These magnets are combined function magnets which also start the separation of the electron and the proton trajectory. An unavoidable drawback of this design is that the synchrotron radiation (SR) produced in these magnets by the electrons or positrons of about 12 kW cannot be absorbed before the detector. The SR fan has to pass the detector until it reaches the absorbers at 11 m and 26 m downstream of the interaction point (IP). In the same machine upgrade the detectors have also been improved by adding new silicon micro vertex detectors [ zeus ] close to the beam pipe. The combination of these facts enforces a precise steering of the beam though the interaction region to allow save operation of the vulnerable detectors. For save operation it was necessary to install an orbit feedback which controls the particle trajectory in all operating modes, especially during the energy ramp [herb]. To find the optimal beam trajectory we developed a system to calculate and display online the beam trajectory through the IP region and in addition the direction of the SR fans. This has been proven as a useful operational tool for optimizing the background conditions for the experiments.

## MEASUREMENT OF ABSOLUTE BEAM POSITION AND ONLINE DISPLAY

The calculation of the beam trajectory w.r.t. the design orbit can be done in linear approximation with

$$x(s) = a(s)\cdot x(0) + b(s)\cdot x'(0) + \cdots$$
$$+\sum_{i=1}^{n}\sqrt{\beta_i\beta(s)}\cdot\sin(\phi(s)-\phi_i)\cdot\delta_i\,;\,\phi_i<\phi(s)$$
$$with: \tag{1}$$
$$a(s)=\sqrt{\frac{\beta(s)}{\beta(0)}}\cdot(\cos(\Delta\phi)+\alpha(0)\cdot\sin(\Delta\phi))$$
$$b(s)=\sqrt{\beta(0)\beta(s)}\cdot\sin(\Delta\phi)$$

Here α and β are the Courant Snyder functions and φ the phase advance calculated for the machine optic. The start values are x(0) and x'(0) for the position and slope of the trajectory. The $\delta_i$ are kicks deflecting the beam which are here kicks from the correction coils, which are known, or kicks from transverse offsets of the quadrupoles which are a priori unknown. They produce a beam kick of $\delta=\Delta x_q\cdot k\cdot l$ for a quadrupole with strength k and length l and offset $\Delta x_q$. Please notice that we calculate here the IP region like a transport line and forget about the rest of the ring. This means that we have to fit the starting conditions x(0) and x'(0) from the position monitor readings.

So to calculate the orbit one has to know the settings of all involved correction coils and the transverse offsets of all quadrupoles in the region of interest. At points about 70 degrees apart the position of the beam is measured with capacitive position monitors. These monitors have a relative precision of about 30 μm, but with an a priori unknown offset due to mechanical, electronical and alignment tolerances of up to 2 mm. The magnetic axis of the quadrupoles is aligned with an rms precision of 0.3 mm. In the tunnel these positions are fixed in good approximation. Between the tunnel and the detectors there are bridges which support the final focus triplets including one side of the superconducting mini beta quadrupoles. The magnets on these bridges are moving about 0.3 mm depending on the temperature of the support structure. The mini beta quads themselves are moving by about 0.4 mm due to magnetic forces of the detector solenoids on the conductors of the quadrupoles. These forces increase with the quadrupole current on each energy ramp. In addition there are rather large displacements whenever the magnets are warmed up to room temperature and cooled down again. These displacements are not perfectly reproducible. The movements are well known but not to a precision necessary for our goal to plot the absolute orbit.

To come to a practical solution we use a three step procedure:

1. Do a beam based alignment by changing the quadrupole strengths and measure the beam position w.r.t. the quadrupole axis. Find the most probable distribution of quadrupole and BPM offsets consistent with these measurements [ bba,bba2 ] This is done once and repeated for example after a shutdown period.
2. Use the results from this analysis together with actual BPM readings and correction coil settings to fit the offset and angle of the beam trajectory at one point in the region of interest plus some quadrupole offsets which are known as not reproducible.
3. Use the found offsets and known corrector settings to calculate the trajectory through the IP region as well as the direction of the synchrotron radiation fans.

If step 1 shows quadrupole offsets which are exceptionally large these are corrected and the bba is repeated. The steps 2 and 3 are done every 4 seconds for both IPs and displayed in the accelerator control room.

The merit function for the fitting routines in step 1 and 2 is (2), where the $y_i$ are the beam displacements measured with BPMs or with the bba method and the $K_m \cdot \Delta x_m$ are the kicks acting on the beam from quadrupole offsets.:

$$\chi^2 = \sum_{i=1}^{N} \left[ \frac{y_i - a_i \cdot y(0) - b_i \cdot y'(0) - \sum_{m=1}^{M} A_{i,m} \cdot K_m \cdot \Delta x_m}{\sigma_i} \right]^2 \cdots$$

$$+ \sum_{m=1}^{M} \left[ \frac{xoff_m - \Delta x_m}{\sigma_m} \right]^2 \qquad (2)$$

The second term inserts into the equation our knowledge about the precision of the quadrupole alignment and of known offsets $xoff_m$. The matrix element $A_{i,m}$ is the effect of a kick *m* on monitor *I* calculated with (1) This function is minimized by finding the optimal set of parameters Δx, y and y' by using the singular value decomposition [num]. with bba data. Several bba measurements are combined for the initial fit. Measurements with the same optic just reduce the uncertainties of the measurement by averaging, whereas measurements with a different optic give us additional information since the matrix elements $A_{i,m}$ are different.

A comparison of the beam position calculated at the IP with the reconstruction of the interaction point by the H1 detector shows that it both measurements are in agreement within 60 µm horizontal and 30 µm vertical.

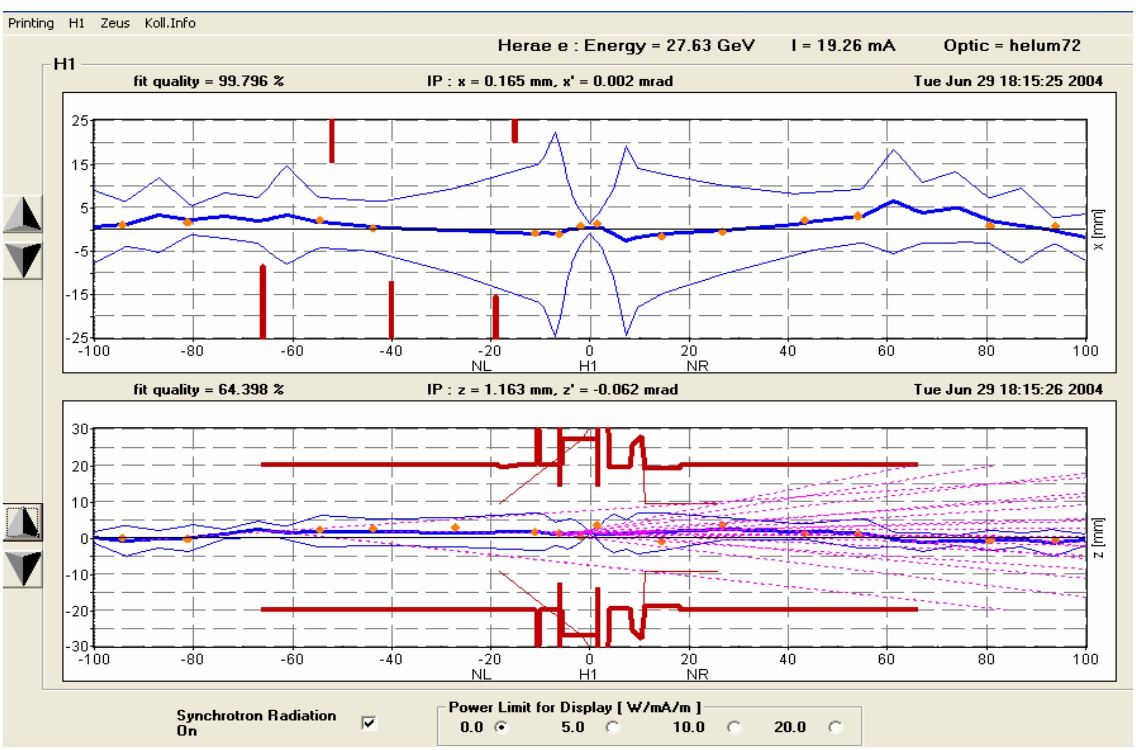


Figure 1 Online display of the positron orbit near the H1 detector in HERA. The lines are the best fit orbit with its 10 sigma envelope and the dots the values from the BPMs. Drawn in the lower half are the vertical chamber dimensions including absorbers and the positions of the movable collimators as well as the direction of the synchrotron radiation fans (dashed lines).

## CALCULATION AND DISPLAY OF THE HERA PROTON ORBIT

It is not necessary to control the proton orbit in HERA with the same precision as for the positrons, since the effect of SR can be neglected. Nevertheless we decided to do a similar analysis for two reasons. First it is helpful in the daily operating to see the orbit not only at the BPM positions but also at other locations, especially when for instance the maximum bump amplitude lies in a final focus quadrupole with huge beta functions. For instance the display has been used to adjust the slope of the beam at the collision point to optimize the luminosity.

The other point is that the HERA proton BPM electronic shows significant ageing effects. There are significant changes of offsets or calibration constants which are not at once visible as invalid values. By fitting the trajectory to the BPM values using the known corrector currents, it is possible to find critical positions in the ring where either strong distortions are located or where the monitor has a problem. In striking cases a detailed examination with local bumps is done.

A beam based alignment has not been done for the protons since all proton quadrupoles are arranged in families and can not be changed individually. Instead an iterative procedure has been used. One kick per corrector-monitor pair is fitted with the constraints to keep the additional kicks and the differences from BPM values to the fitted trajectory as small as possible. This is done with different orbits and optics. Offsets of monitor values or kicks which appear in all cases are then assumed to be real and are used for the next iteration. In this way one obtaines a self consistent picture which has proved to be quite helpful on several occasions.

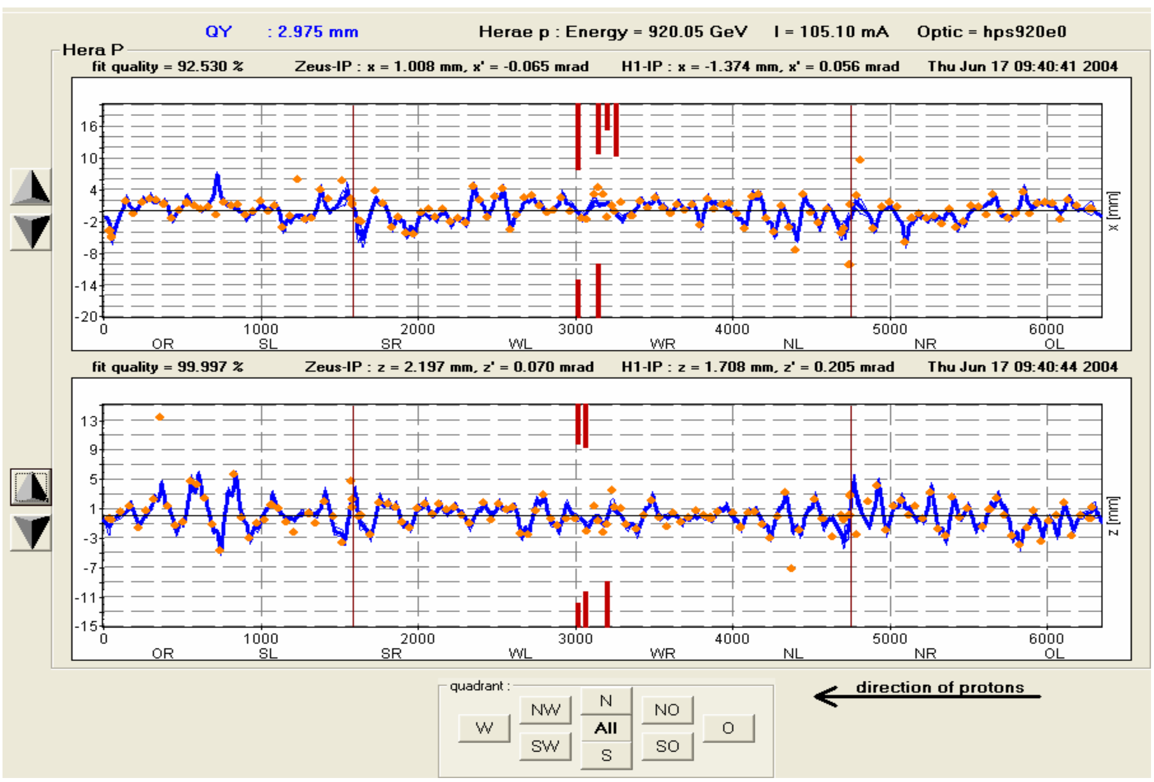


Figure 2 Online display of the fitted proton orbit in HERA. The line is the trajectory, the dots the BPM values and the bars the positions of the movable collimators. Some monitors lying far apart from the trajectory are removed from the fit as they are recongnised as unreliable.

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