# AUTOMATED ORBIT CONTROL FOR THE HERA EP COLLIDER

S. Herb, P. Bartkiewicz, F. Brinker, J. Maass, DESY, Hamburg, Germany

*Abstract*

Successful operation of the HERA electron-proton collider requires maintaining stable orbits during the typically 12 hour luminosity runs, as well as during the fill and acceleration procedures. The primary sources of orbit errors for the electron ring are the interaction region magnets, whose support structures are integrated with the experimental detectors and susceptible to thermal and magnetic effects. The orbit correction algorithms are designed to correct these effects locally, while operating with somewhat reduced sensitivity on error sources in the rest of the ring. We describe the correction system and our operating experience.

## INTRODUCTION

The Hera lepton-proton collider consists of two 6 km circumference rings; 920 GeV protons collide with 27.5 GeV longitudinally polarized electrons (or positrons) at two low beta insertions occupied by the Zeus and H1 experimental detectors. In addition the Hermes detector studies collisions between the electron beam and a polarized gas jet target. Hera has operated since 2002 with a mini-beta configuration in which the interaction region (IR) magnets are tightly integrated with the Zeus and H1 detectors [1]. The final focussing, as well as the ep beam combination and separation, is provided by iron-free superconducting (SC) magnets sitting within the tracking detectors and their solenoids, while additional iron quadrupoles are mounted on girders extending into the region of the outer calorimeter iron. The tighter beam focussing provided by this geometry comes at the expense of more complicated support structures for the magnets and interactions between the beam line magnets and the solenoidal field. The limited accessibility also makes accurate measurement of changes in magnet position difficult. Maintaining beam alignment is crucial not only for luminosity, but also because of the synchrotron radiation, with power 20-30 kW, generated by the electron beam in its traversal of the interaction region magnets, which must be dumped cleanly downstream of the detector. This is the basic environment in which the orbit control system must operate; it has turned out that it is an essential part of stable accelerator operation.

## SOURCES OF ORBIT DISTORTION

### *Electron Orbit*

The sources of orbit distortion for the electron beam include several large and well localized contributions, and other less dominant (and less well understood) effects:

- The SC magnets in the Zeus detector tilt during the electron energy ramp due to forces between the solenoid and the ramping SC dipole field, thus introducing kicks from the offset of the SC quadrupole field. The SC magnets in the H1 detector (with a different support structure) move upwards by about 0.7 mm.
- The Zeus detector includes a calorimeter which to minimize irradiation is moved away from the beam for injection, and then closed. The iron in this calorimeter contributes a return path for the field of the SC quadrupole and dipole magnets, with the result that the (uncorrected) bend field seen by the beam changes by up to 20% during closing procedure (and the quadupole field by a lesser amount). The field change is very rapid during the final centimeters of travel.
- There are small motions (up to 0.2 mm) of some of the IR quadrupoles due to long time constant temperature effects during the luminosity runs.
- Orbit bumps for the IR are often not well closed. Contributors to non-closure include beam-beam focussing, coupling from the solenoids (which is compensated ~120 m from the IRs) and magnetic field strengths which differ from laboratory measurements because of the solenoid fringe field or the presence of adjacent iron.
- The energy ramps use widely spaced ‘stepping stone’ files. Non-linear magnet behavior can result in orbit distortions midway between the constrained endpoints.
- There are longer term orbit deviations originating in the arcs due to effects such as tunnel motion.

### *Proton Orbit*

The proton orbit is also affected during the energy ramp by non-linear magnetic behavior between widely spaced energy stepping stones. This is problematic because offsets in the sextupoles modify the betatron tunes and coupling. In addition, slow orbit variations are observed during the luminosity runs.

## ORBIT MEASUREMENT

The rings are equipped with a normal complement of beam position monitors, spaced $90^o$ in phase in the arcs of the proton ring and $72^o$ in the electron ring. Resolution for beam position changes is at the 30 μm level. There are nonetheless inadequacies which make our knowledge of the electron and proton orbits less than ideal. The biggest problems are in the interaction regions, where the measurements are complicated by the limited space available, the motion of the magnets and beam pipes on which the monitors are mounted, and the presence of electron and proton bunches with only nanoseconds of time separation. In addition the proton ring readouts suffer from reliability problems related to the age of the electronics. The practical consequences for the orbit stabilization are:

• Determining the beam trajectories through the IRs requires combining the IR monitor readings, beam-based alignment measurements of the beam position in the quadrupoles, and the beam trajectory from outside the IR [2]. These calculated trajectories are used as operator tuning aids but are at present not fed back into the correction system

• For the proton ring, it is essential to maintain a list of monitors whose readings are not trustworthy.

## LOGIC FOR ORBIT STABILIZATION

The stabilization is used to hold the measured orbit close to a reference orbit during the stationary conditions of injection and luminosity, and during the energy ramp and optics transfer procedures. It also permits operators to insert additional orbit bumps without interference.

### *Reference Orbits*

Machine states are stored in save files containing complete magnet settings for the electron and proton rings and the measured electron and proton orbits; this includes whatever orbit bumps and other corrections have been inserted to achieve a well-tuned machine state. These files serve as stepping stones for changing and restoring the machine state, with the stored orbits used as the correction references. During energy ramps and optics transfers, reference orbits are constructed by interpolating between the reference orbits for the stepping stones.

### *Orbit Bump Compensation*

Setting up and maintaining luminosity and acceptable backgrounds for the experiments in HERA requires tuning by the operators, mostly using standard orbit bumps defined for the interaction regions. There is also occasional polarization tuning using distributed spin harmonic bumps driving 48 vertical correctors. The orbit bumps create desired deviations from the reference orbit which must be excluded from the corrections. A system to do this was suggested by one of the authors (F.B.); as the bump knob is turned by the operator, inserting magnet current increments, the corresponding calculated displacements are summed with the reference orbit. The difference orbit minimized by the orbit feedback is then calculated as [Current Orbit – (Reference + Bumps)]. To the extent that the calculated displacements are equal to those measured by the position monitors, the bumps disappear in the difference orbit, and are not acted upon by the stabilizer. This has the additional merit that orbit ripple resulting from non-closure of the real bumps is removed by the stabilizer.

### *Correction Modes and Algorithms*

The correction systems are designed to distinguish, at least partly, between orbit distortions originating in the inner IR regions and in the rest of the machine. A well known problem with orbit correction is that due to many effects, algorithms rarely succeed in assigning 100% of a correction kick back to its original source. For cases in which we have some knowledge of the source location we use this to help constrain the outcome. At present we operate in two very different modes.

• During the closing of the Zeus calorimeter with its steel support structure, the dominant sources of distortions are the SC bend magnets embedded in the detector. Singular value decomposition (SVD) matrices are calculated for the horizontal and vertical planes which use monitor data from the entire machine but permit only the SC bend magnets to contribute to the correction. These coefficients are used together with the difference orbit to calculate corrector magnet kicks. Because of the rapid field changes, the correction system runs at 4 Hz, the maximum rate for reading out the electron orbit.

• For other operations, a most effective corrector calculation, minimizing the rms value of the difference orbit, yields one horizontal and one vertical corrector per cycle. It is however still the case that most distortions originate in the IRs. This is taken into account by alternating between steps in which only sets of four horizontal and four vertical correctors around each IR are permitted as candidates for correction kicks, and steps in which all correctors in the machine are candidates. Typically four steps with IR-only are followed by one step with all correctors. The usual rate is 1 Hz/step.

A refinement permitting insertion of corrections using more than one magnet per step is to iterate the most effective corrector calculation. This preserves the desirable feature (discussed below) of working much more effectively against global than local orbit distortions.

## IMPLEMENTATION

The stabilization is implemented within the HERA control system framework, based on a lower layer of field bus servers which communicate over Ethernet with the console applications and coordinating middle layer applications. Update rates for the measured orbits are 2-4 Hz, and exchanges between servers typically 1 Hz. The orbit stabilization is built from three cooperating middle layer servers which also interact with the front-end magnet server, the console knob tasks used by the operators for bump tuning, and the HERA sequencer (Fig. 1). The use of separated function servers rather than a monolithic application contributes to the flexibility and maintainability of the system. Included are:

• An optics server, which maintains all optics data and definitions of standard orbit bumps, and is responsible for orbit correction calculations. These include both single shot corrections to submitted orbits, and calculation of SVD coefficients which can be exported to requesting clients.

• A reference orbit server, which makes available the current reference orbits and subtracted difference orbits. It performs the reference orbit interpolation during the ramp and optics transfer procedures.

• The 'orbit stabilizer' server, which performs the feedback between the difference orbits and the magnet settings. Depending on the desired mode of operation, difference orbits are sent to the optics server, which returns the suggested correction, or SVD coefficients are requested from the optics server, and used locally to generate the magnet kick values. These are then sent to the magnet server.

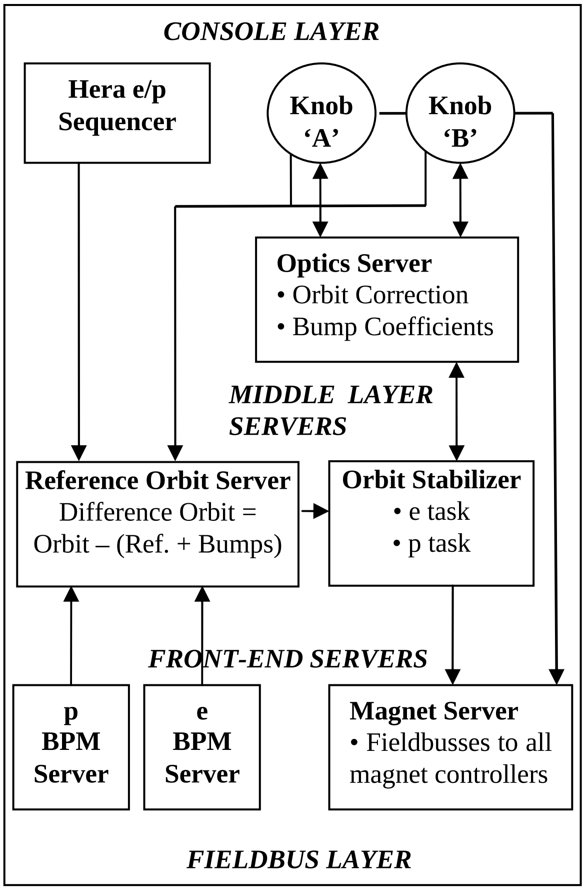


Figure 1: Communications for the orbit stabilization.

## OPERATIONAL EXPERIENCE

### *Electrons*

For energy ramps and optics transfers in HERA pre-2002, it was usually sufficient to clock the magnet currents from one set of saved values to the next without special attention to the orbits. For operation after the upgrade this often resulted in unacceptable radiation during the transfers, which could be mitigated only by active tuning by the operators. With stabilization, the need for such intervention has drastically diminished.

The stabilization has also improved the repeatability for establishing collisions and luminosity, and reduced the frequency with which the operators must re-optimize luminosity using the IR orbit bumps. Typical numbers for steady state operation are that the difference orbit is held to an peak of about 300 μm almost everywhere, and the luminosity optimization is stable over periods of one or two hours.

The stabilization is crucial for the procedure of closing the Zeus calorimeter, since it was established that the limited repeatability of the orbit distortions precludes the use of table driven corrections.

### *Protons*

First tests of the stabilization with the proton machine have shown that is sensitive to badly performing beam position monitors which were not recognized during routine machine operation. We are investigating the possibility of using the stabilization system to tag these monitors and remove them from the fitting procedures.

## DISCUSSION

The use of corrections in a system with incomplete diagnostic information raises the possibility that the correction process will clean up the well measured regions, and worsen the distortions in the less well measured, in this case the regions around the experimental detectors. This an issue in the short term, and also in the long term, as corrections are iterated via periodic updates of the save files. It is unlikely that this situation has a simple solution, and much of the logic of our present system derives from operating experience.

The most important lesson has been the utility of the most effective corrector method, applied iteratively. In a ring with hundreds of position monitors this works preferentially on global disturbances, i.e. orbit ripple due to a single kick. To the extent that the algorithm places the correction near the source of the kick, this benefits the entire orbit, unseen as well as seen. It operates very inefficiently on local distortions, the extreme case being a closed half-wave orbit bump; this discourages insertion of strong local corrections across the IR.

It is clear that if effective, this system can slow the growth of orbit deviations in the under-monitored regions, but will not guarantee long term stability. This depends on additional operator tuning, based on luminosity, detector backgrounds, and auxiliary information such as the position of synchrotron radiation spots on screens, and the calculated IR orbit described above. To the extent that the deviations grow slowly, the operators will be working near a set of local minima in which convergence is likely.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] F. Willeke, EPAC'02, Paris, June 2002, p. 20
[2] F. Brinker, "Online Calculation of the Beam Trajectory in the HERA Interaction Regions", submitted to this conference.