SIMULATION OF ORBIT CORRECTION AND SYNCHROTRON RADIATION ASPECTS IN THE UPGRADED HERA INTERACTION REGIONS

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Abstract

In the upgraded HERA interaction regions, about 30 kW of synchrotron radiation have to be passed safely through the high energy physics detectors. At a distance of about 11 m from the interaction point a fraction of this synchrotron radiation is absorbed, while the remaining part is passed further on through the separated beam pipes. To protect the vacuum chamber between the IP and the 11 m absorber against accidential mis-steering of the synchrotron radiation fan, four emergency absorbers are installed. On the other hand the HERA detectors are very sensitive to backgrounds from backscattered synchrotron radiation photons. The aperture of absorbers and other elements in the downstrem beamline have to be chosen such as to guarantee acceptable background conditions even with moderately missteered electron beams. To investigate the feasibility of this scheme, extensive simulations have been carried out taking into account realistic machine errors, such as magnet misalignments, monitor errors, optics distortions, etc. It is shown that under realistic conditions the synchrotron radiation fan can be safely controlled.

1 INTRODUCTION

To increase the luminosity of the e-p collider HERA, the interaction regions at the two colliding beam experiments ZEUS and H1 will be upgraded in the near future. To keep the β-functions in the low-β quadrupoles of the electron ring within reasonable limits when the β-functions at the interaction point (IP) are reduced by a factor of about 4, these final magnets will be installed at a distance of about $2\,\mathrm{m}$ from the IP. Thus the electron low-β quadrupoles also have to provide the required separation of the two beams. Figure 1 shows an overview of the upgraded interaction regions.

The final focus magnets of the electron ring will be installed inside the high energy physics detector. Since the electron beam will be deflected by $8.8\,\mathrm{mrad}$ using these low-β quadrupoles to provide for the necessary separation of the two beams, about $30\,\mathrm{kW}$ of synchrotron radiation will be generated and have to be safely transported through the detector and about $11\,\mathrm{m}$ of beam pipe on the downstream side of the experiment, see figure 1.

At a distance of about $11\,\mathrm{m}$ downstream of the IP, the common beam pipe for the three beams (protons, electrons and synchrotron radiation photons) splits into three separated beam pipes. At this location a synchrotron radiation absorber is foreseen to avoid heating of the three beam pipe ends by perpendicular hits of synchrotron radiation photons.

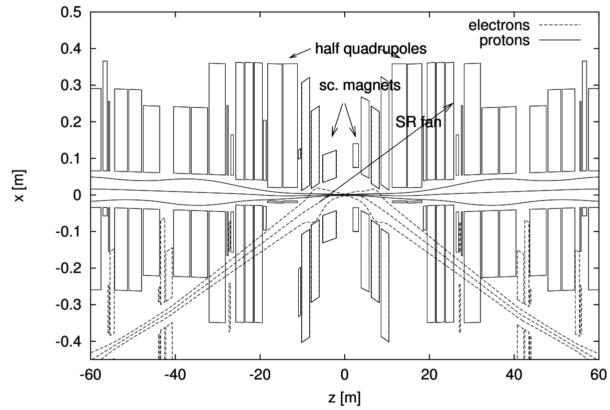

Figure 1: Overview of the new HERA interaction regions.

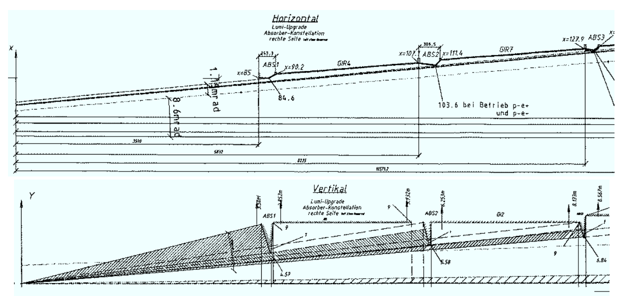

Figure 2: Locations of emergency absorbers downstream of the interaction point.

Since the beam pipe between the detector and the $11\,\mathrm{m}$ absorber will be made of stainless steel for stability reasons, any direct hits of the synchrotron radiation fan within this area must be avoided very carefully. It is therefore foreseen to install 4 so-called emergency absorbers in this beam pipe, as schematically shown in figure 2. The dimensions of these emergency absorbers are chosen such that under any circumstances they protect the stainless steel beam pipe. Figure 3 shows a cross section of the beam pipe with the emergency absorber ABS1 at a distance of $4.6\,\mathrm{m}$ from the IP.

Since high energy photons hitting these emergency absorbers would be backscattered into the detector, thus leading to high background rates, this has to be avoided carefully.

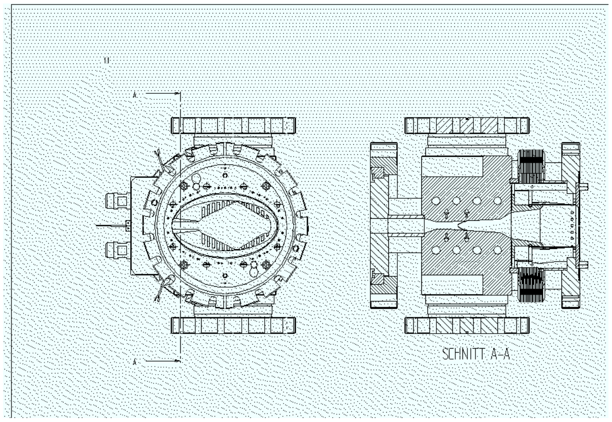

Figure 3: Cross section (left) and side view (right) of the vacuum pipe with an emergency absorber.

2 LOCATING ERRORS

Standard orbit correction algorithms try to minimize the effect of orbit distortions without locating the true position of the errors (e.g. MICADO [2]). This has been a good approach in most cases but might not be sufficient if other issues besides orbit distortions have to be considered. Missteered synchrotron radiation in the upgraded HERA interaction regions can be more harmful than larger orbit deviations along the ring. For these reasons an algorithm capable of locating errors has been developed.

Based on the principles of linear beam optics, phase jumps in the orbit can be used to detect misaligned quadrupoles. Additionally errors in quadrupole strength and sextupole misalignment will lead to similar effects if orbit deviations are present [3]. The orbit $Y(\varphi)$ is a superposition of oscillations generated by kicks of the form $\Delta x' = k\, l\, \Delta x$ produced by off-center quadrupoles of strength k and length l:

$$\begin{aligned} Y(\varphi) &= A(\varphi)\, \cos\left(\varphi + \delta(\varphi)\right) \\ &= \sum_i B_i\, \cos\left(\varphi + \psi_i(\varphi)\right) \end{aligned}$$

The amplitude $A(\varphi)$ of the orbit and also its phase angle $\delta(\varphi)$ depend on the position in terms of betatron oscillations φ. The amplitudes B_i and phase angles $\psi_i(\varphi)$ vary with the kicks. All amplitudes and BPM-values are divided by $\sqrt{\beta(\varphi)}$ to exclude the influence of the β-function.

At the position of an error there will be a phase jump in the corresponding oscillation and therefore also in the superimposed orbit oscillation. Moreover a change in amplitude will normally occur. By calculating phase angle $\delta(\varphi)$ and amplitude $A(\varphi)$ from the BPM-values it is possible to locate these phase jumps and amplitude changes and thus locate errors. But as $Y(\varphi)$ is a superposition of many oscillations the size of the phase jump and amplitude change depends not only on a single kick but on many. A small change in phase angle and amplitude is not necessarily caused by a small error.

The calculation is done by fitting $A_i\, \cos\left(\varphi + \delta_i\right)$ to every two consecutive BPM-values y_i and y_{i+1}. By solving the system of two equations and considering the different cases one finds solutions for amplitude and phase angle :

$$\begin{aligned} A_i &= \frac{\sqrt{y_i^2 + y_{i+1}^2 - 2 y_i y_{i+1} \cos\left(\varphi_{i+1} - \varphi_i\right)}}{\sin\left(\varphi_{i+1} - \varphi_i\right)} \\ \delta_i &= \begin{cases} \arccos \frac{y_i}{A_i} - \varphi_i \\ -\arccos \frac{y_i}{A_i} - \varphi_i \end{cases} \end{aligned}$$

The results can be plotted against the betatron phase φ (Figure 4). Every kick will show up as a step in the graph of the phase angle, whereas they can be absent in the amplitude. In a similar way it is also possible to detect localized sources of coupling and focusing perturbations as is shown in [3].

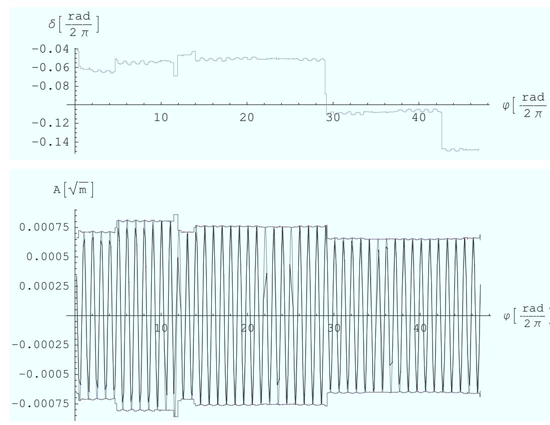

Figure 4: In the upper plot the phase angle δ is plotted, the lower plot shows the amplitude A, the calculated oscillation (dashed) and the BPM-values (solid). In this simulated data for the HERA electron ring seven errors were built in. They can be found as steps in the phase angle δ at $\varphi = 0.5, 4.7, 11.6, 12.1, 14.0, 29.2, 42.7\, \frac{\text{rad}}{2\pi}$. The step at $\varphi = 42.7\, \frac{\text{rad}}{2\pi}$ is absent in the amplitude.

3 THE SIMULATION PROGRAM

To study orbits and synchrotron radiation fans in the upgraded HERA interaction regions under realistic conditions including any kind of machine imperfections, a simulation code has been developed. In addition to quadrupole misalignments and beam position monitor errors, it also includes optics distortions caused by deviations in the actual quadrupole strengths. In the entire code, all error distributions are gaussian without any truncation of large values.

Since only the interaction regions are simulated, closed orbit distortions caused by quadrupole misalignments in the rest of the machine were treated as follows. The entire machine with misaligned magnets was simulated with different random seeds using the PETROS code. After application of a global orbit correction using 5 correctors, the

Courant-Snyder invariant of the resulting orbit at the upstream end of the interaction region was calculated for each seed. For the simulation of the interaction region the worst case, i. e. the case with the largest Courant-Snyder invariant, of these simulations was taken as the orbit entering the interaction region from the arc. The corresponding initial betatron phase for this orbit is chosen randomly.
The distorted β-functions at the interaction point are assumed to show a gaussian distribution for different random seeds. Starting from the IP, the distorted optics parameters are calculated for each seed, taking into account the respective quadrupole strength errors.
The closed orbit distortions in the interaction region are calculated from the orbit entering the interaction region from the arc, and from quadrupole misalignments in the interaction region, using the distorted optics. Then this orbit is corrected by standard methods and closed orbit bumps, according to the BPM measurements which themselves show a certain error. For the calculation of the necessary corrector strengths the design optics are used, while these ideal corrections are applied to the distorted optics, as it is the case in a real machine.
To calculate the position and direction of the synchrotron radiation fan, the individual orbits of 20 particles with different initial betatron phases but the same emittance are calculated. For each of them the tangent to the resulting corrected orbit is computed at ten equidistantly distributed longitudinal locations within each lattice element.

4 SIMULATION RESULTS

The simulations were performed using 1000 different random seeds for the calculation of the various individual misalignments and optics errors. Besides different rms misalignments of quadrupoles and beam position monitors the following set of parameters was used:

$$\text{quadrupole strength}: \left(\frac{\Delta k}{k}\right)_{\text{rms}} = 1 \cdot 10^{-4}$$
$$\beta\text{-function at the IP}: \left(\frac{\Delta \beta^*}{\beta^*}\right)_{\text{rms}} = 5 \cdot 10^{-2}$$
$$\text{quadrupole misalignment in the arcs}: \quad \sigma_{\text{arc}} = 3 \cdot 10^{-4}\,\text{m}$$

When the rms alignment error of the beam position monitors equals the rms misalignment of the quadrupoles in the interaction region, the probability of synchrotron radiation hits from the central particle at the emergency absorbers is found to increase almost linearly with the rms alignment error, fig. 5.
To simulate the effect of beam based calibration of beam position monitors and/or empirical orbit correction using closed orbit bumps, the rms alignment error of the beam position monitors was set to zero. In this case, the probability of synchrotron radiation hits from particles having a betatron amplitude of 3σ is roughly independent of the rms quadrupole misalignment in the range $100 \ldots 300\,\mu\text{m}$, fig. 6.

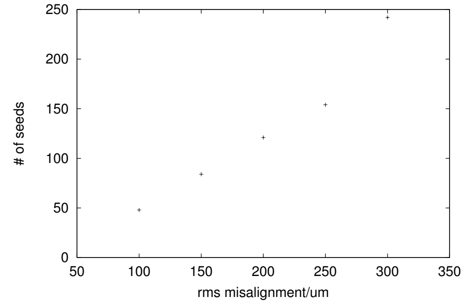

Figure 5: Number of seeds leading to hits at the emergency absorbers from particles on the closed orbit, with the total number of seeds being 1000, as function of the rms alignment tolerances of quadrupoles and beam position monitors.

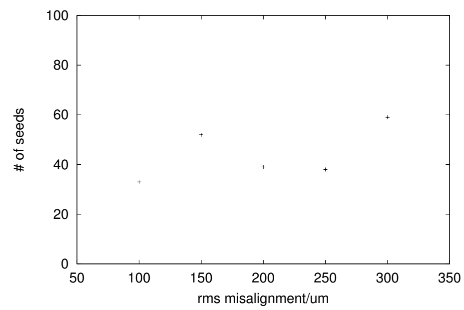

Figure 6: Number of seeds leading to hits at the emergency absorbers from particles at 3σ around the closed orbit, with the total number of seeds being 1000, as function of the rms alignment tolerances of quadrupoles. The monitor error is set to zero.

5 CONCLUSION

Simulations show that for a realistic machine with optics distortions and alignment errors the synchrotron radiation in the interaction region can be safely controlled using beam-based alignment techniques and/or empirical orbit bumps. Unsually large misalignments of a small number of magnets can be detected using BPM data.

6 REFERENCES

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