PETRA II: ELECTRON OPTICS, PROTON OPTICS, AND TRACKING STUDIES FOR THE e/p INJECTOR FOR HERA

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Abstract

The electron-positron storage ring PETRA at DESY will be used as the electron-positron (14 GeV) and proton (40 GeV) injector for HERA. Since PETRA's task will be quite different with HERA than during its past e^+/e^- luminosity operation era, considerable lattice modifications as well as different optical solutions are unavoidable. Linear electron and proton optics for PETRA II are presented and design criteria are compiled.

Tracking studies have been performed using experimentally determined multipole coefficients of dipoles. The dependence of acceptance results on the number of tracked revolutions has been investigated. It is seen that the unmodified PETRA arcs yield sufficient nonlinear acceptance for all proton operation modes.

Introduction

The electron-positron storage ring PETRA will be the last element of a chain of accelerators which electrons and protons will have to pass before they can be injected into HERA [1]. It has been the aim from the beginning to restrict the required hardware modifications in PETRA to those absolutely necessary. In fact, it has been shown in a feasability study [2], that PETRA can be used as a proton booster between p = 7.5 GeV/c and 40 GeV/c without any modification of the PETRA arcs and the beam pipe size. Therefore, development of new magnet types is not necessary - provided that the field quality is sufficient. It will be shown in the second part of this report, that this is the case. In the first part, linear electron and proton optics for PETRA II are presented and design criteria are compiled. More detailed information and injection/ejection schemes for electrons and protons can be found in ref. [3].

I. Lattice and Linear Optics

Remember that PETRA has 4 short straight sections (former interaction regions) and four long straight (rf-) sections. Fourfold symmetry is provided and maintained by 4 identical quadrants between the (former) interaction points. Each quadrant is mirror symmetric with respect to the center of the long straight section, i.e. the PETRA optics is fully described by a single octand (the only exception - the proton bypass - is described below).

A) Short Straight Sections

In the short straight sections the low beta inserts are rearranged. The mini-beta quadrupoles (old low beta quads) are replaced by standard PETRA quadrupoles (100 mm bore). In doing so, space is gained for the electron ejection elements in the North-West area, and power consumption is reduced, while the freed large aperture quadrupoles are highly welcome in the HERA interaction regions. Without loss of acceptance this is possible only with an additional quadrupole on the symmetry points (former interaction points), completing a regular FODO structure in the whole short straight sections.

B) Long Straight Sections

The rearrangement of PETRA's long straight sections is governed by the installation of a proton bypass [2], which is needed to prevent protons from traversing the electron cavities. Since the maximum electron energy in PETRA II will be 14 GeV only, it will be sufficient to keep only one (the southern) 2 x 23 m long straight section equipped with rf cavities. The detailed geometry of the bypass is chosen such as to

* yield sufficient horizontal separation between the e^- and p-orbits for installations,
* fit into the existing tunnel building including pipes and cable trays,
* use PETRA standard type magnets only,
* minimize costs of elements and power consumption,
* use PETRA standard drift lengths as far as possible (minimum of new construction),
* allow satisfactory electron and proton optics,
* minimize modifications of the electron lattice in the bypass area, since they must be repeated in all straight sections to keep the fourfold superperiodicity of the electron lattice.

The proton closed orbit is ΔC = 51.4 mm longer than the electron orbit because of the bypass, i.e.

C_e = 2304000 mm		e orbit in PETRA II
C_p = 2304052 mm		p orbit in PETRA II

C_p is the reference PETRA length to be used for the DESY III synchrotron design, and C_e has been used for the DESY II design [4] to permit synchronized rf operation.

C) Electron Optics

The longest and most satisfactory experience with PETRA has been gained with tunes Q_x = 25.2 (horizontal) and Q_z = 23.3 (vertical). Therefore, these tunes have been maintained. The momentum compaction factor $\alpha = 2.52\cdot10^{-3}$ is quite small, since single bunch instabilities due to short bunch length are not to be expected with PETRA II multibunch operation, and small emittance is useful for extraction at 14 GeV ($\epsilon = 91.7\cdot10^{-9}$ Rad·m).

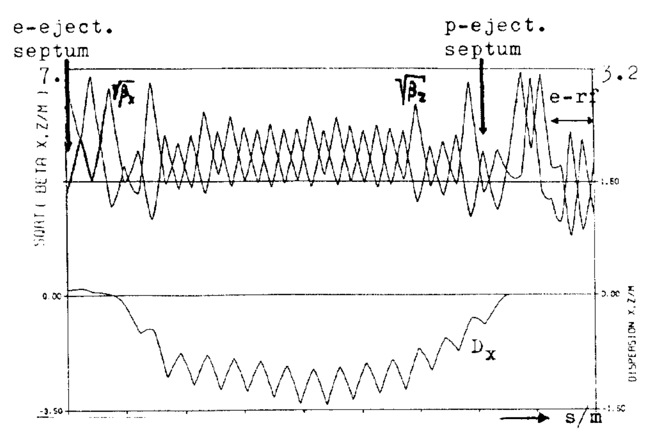

Fig. 1 PETRA II electron optics; octand from short S.S. (former IP) to long Straight Section (rf)

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Special care is taken of electron and proton extraction installations. Small horizontal betas permit the septa to be installed clearly inside the standard vacuum chamber without loss of acceptance. Figure 1 shows envelope and dispersion functions in one octand [5].

D) Proton Optics

For PETRA II proton operation between p = 7.5 GeV/c and 40 GeV/c it is most desirable not to cross the transition energy $\gamma_{tr} = 1/\sqrt{\alpha}$ during energy ramping, the more so as the energy rise must be quite slow in order to avoid large nonlinear (mainly sextupole) field components driven by eddy currents in the vacuum chamber. Therefore, momentum compaction factor values in the intervall

$$\frac{1}{42.644^2} = 0.00055 \leq \alpha \leq \frac{1}{8.0559^2} = 0.0154$$

must be excluded. It has been shown in ref. [6] that very small α values require the amplitude of the periodic dispersion function to be at least 20 m. On the other hand, it has been shown by J. Maidment that $\alpha \geq 0.02$ is possible with the PETRA lattice of the arcs [2] and that satisfactory rf matching between DESY III, PETRA II and HERA is possible then [7].

In principle, $\alpha > 0.02$ (i.e. $\gamma_{tr} < 7.$) is necessary at injection energy only and could be released with increasing energy of protons. On the other hand, for fixed tunes, α cannot be modified by large factors as long as smooth optics (periodic betas and dispersion in the arc) are considered. Since it is very desirable, anyway, to avoid change of optics during energy ramping, the PETRA II proton optics is designed to be suited for both injection at 7.5 GeV and extraction at 40 GeV.

Figure 2 shows envelope ($\sqrt{\beta}$) and dispersion functions in the standard octand (i.e. without bypass). 23 individual quadrupole circuits are necessary to realize both electron and proton optics as shown in figs. 1,2. In addition, six quadrupole circuits have been introduced for the bypass to guarantee not only optics matching but also small betas and sufficient optics flexibility.

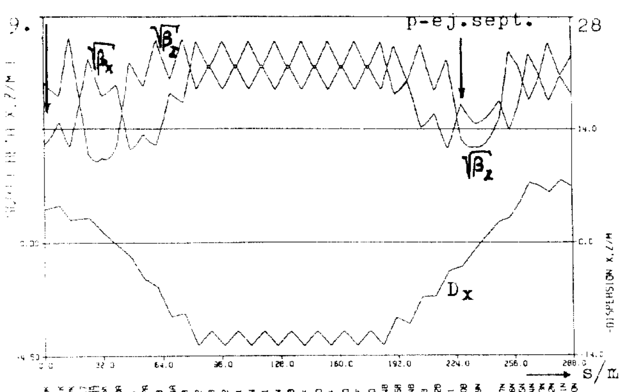

Fig. 2 PETRA II proton optics in the standard octand, i.e. without bypass

The large dispersion value of 12.6 m in the arc is unavoidable due to the large momentum compaction factor α = 0.0233 needed. It has been suppressed partially in the straight sections, especially at the proton ejection septum. Maximum possible acceptance is guaranteed by the fact, that no beta or dispersion function value is larger than in the periodic arc. In order to facilitate construction of e and p septa, the beam envelopes are small at these positions. Tunes are

$$Q_x = 11.405 \quad , \quad Q_z = 11.164$$

which yield satisfactory dynamic acceptance (see section II). Transition energy is $\gamma_{tr} = 1/\sqrt{\alpha} = 6.555$.

II. Nonlinear Acceptance

Due to the large horizontal dispersion, sextupoles for compensation of the linear chromaticity are extremely weak in the proton optics. Therefore, sextupole acceptance is not a problem in PETRA II proton operation. It had to be checked, however, whether magnetic multipoles from field errors in the dipole magnets are tolerable or not.

From field quality measurement for the PETRA quadrupoles [8] and dipoles [9] it is seen that the multipole coefficients of the quadrupole magnets are negligible. Because the acceptance requirement for protons is largest at low energy, tracking calculations have been performed using multipole coefficients as measured for 6 GeV.

Multipole coefficients have been derived from polynomial fits to the field measurements of all 224 PETRA dipoles. The statistics of field quality results in rms errors of multipole coefficients. These errors, however, must be used with care, because the multipole coefficients as given by the fit are highly correlated. In the RACETRACK tracking code [10], however, errors of multipole coefficients can be introduced statistically independently only. Therefore, the effect of errors might be overestimated.

The PETRA dipoles, unlike the curved orbit in the dipoles, are straight. While for beam dynamics the multipole coefficients with respect to this orbit are relevant, the measurements have been performed with respect to a straight line (for technical reasons). Therefore, the multipole coefficients have been transformed into the proper circular reference system [11].

The tracking calculations have been performed with 16 particles distributed on the surface of the four dimensional phase volume with $\epsilon_x = \epsilon_z$ and rectangular distribution with respect to coupling. The latter, although a bit pessimistic, might be more realistic for protons in PETRA than an elliptical distribution, where amplitudes in the z/z' plane become smaller for increasing x/x' amplitudes. The energy deviation $\delta = \Delta E/E_0$ was held constant because the synchrotron frequency is very much smaller than the betatron frequency [12]. A rms closed orbit distortion of 2 mm has been introduced in x and z by two appropriate kicks. The aperture limit has been set on 10^7 mm, i.e. particles are lost due to nonlinear instability only.

Figure 3 shows a tune diagram containing all resonance lines of order less than 7 in the interesting tune region. Two scans across the tune diagram have been performed to identify the most desastrous resonances, see figure 3.

For an appropriate interpretation of tracking results it is worthwhile to investigate the dependence of acceptance results on the number of tracked revolutions. It is seen from fig. 4, that the acceptance result droppes down by approx. 30 % between 300 and 3000 turns but remains nearly constant if the number of turns is further increased. This indicates, that the long term acceptance might be not much smaller than some 60 % of the acceptance results for 300 turns.

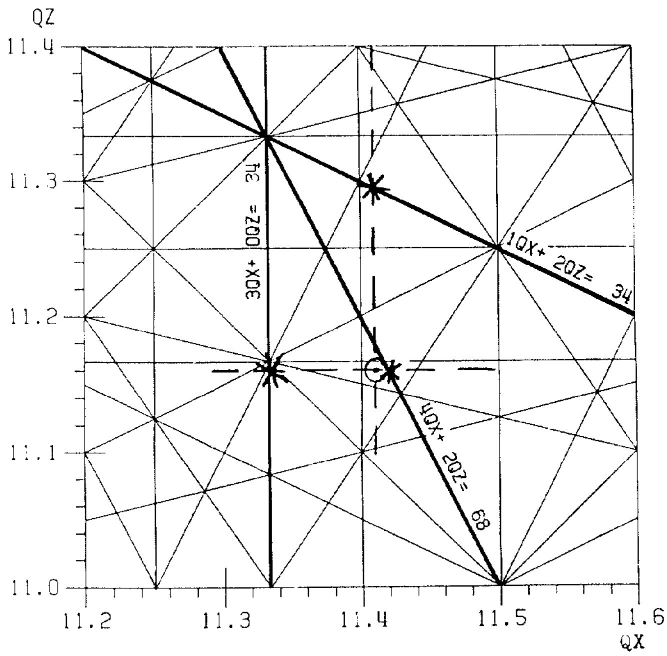

Fig. 3 Tune diagram containing all resonance lines of order less than 7 (because of magnet symmetry resonances driven by skew multipoles are excluded). The broken lines mark tracking scans. The stars indicate significant acceptance reduction due to resonances.

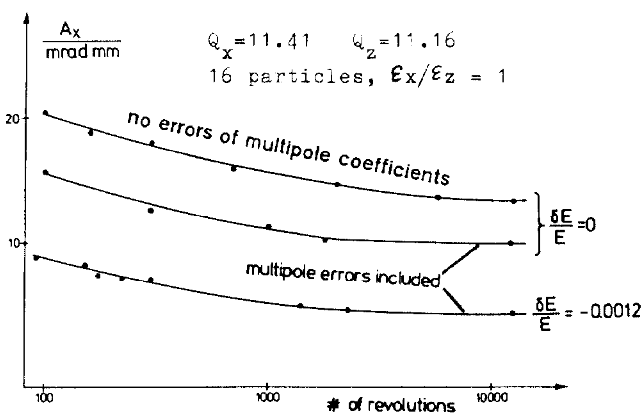

Fig. 4 PETRA II acceptance A_x vs. No. of revolutions; curves are only to guide the eye).

For the proposed tunes $Q_x = 11.405$, $Q_z = 11.164$, fig. 5 shows the acceptance as a function of energy deviation $\delta = \Delta E/E_0$. Three different sets of multipole errors have been used, resulting in error bars for the acceptance as shown in the fig. It is seen that the off-energy acceptance is considerably smaller than the linear acceptance of the vacuum chamber (all the more if one thinks of long term acceptance instead of 300 turns only). Nevertheless, the acceptance should be sufficient for the injected beam.

At extraction, the proton emittance is much smaller. However, in order to synchronize electrons and protons in HERA, one has to compensate for the difference in e and p orbit lengths (ΔC = 52 mm, see section IB). The only way to do that is to shift the proton orbit on an off energy orbit according to $\Delta E/E = \Delta C/(\alpha \cdot C) = 0.97 \cdot 10^{-3}$. As seen from figure 5, the beam approaches seriously the acceptance limit on that orbit.

It has been checked by additional tracking runs, that the acceptance is really considerably larger (some 50 %, not displayed in fig. 5), if no errors of multipole coefficients are applied, i.e. the results shown in fig. 5 might be really a bit too pessimistic, as mentioned above.

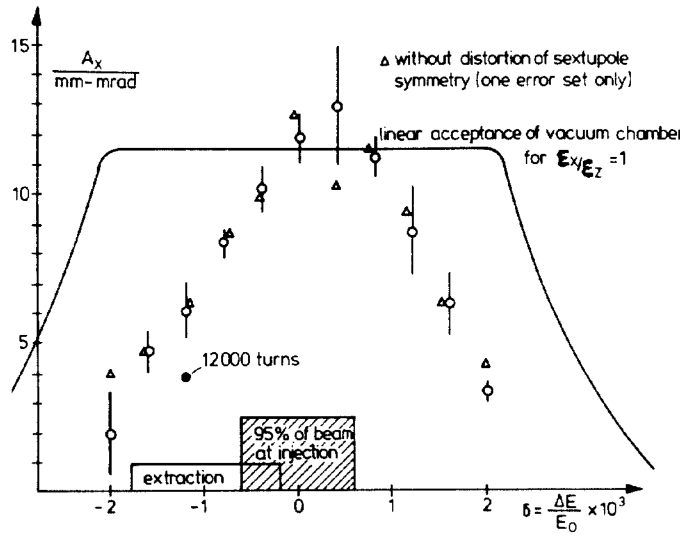

Fig. 5 PETRA II acceptance for protons (RACETRACK results) 300 turns, orbit distortion $\sigma_x = \sigma_z = 2$mm

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