QUADRUPOLE SCAN MEASUREMENTS IN THE BEAM TRANSPORT LINE BETWEEN DESY II AND PETRA III

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Abstract

PETRA III is a 6 GeV third generation synchrotron light source in Hamburg, Germany. The storage ring is operated with a typical beam current of 100 mA and is running in top-up mode. The beam delivered to PETRA III is accelerated by a fast cycling booster synchrotron (DESY II), extracted in a 203 m long beam transport line (E-Weg) and injected afterwards into PETRA III. In the framework of PETRA IV upgrade scenarios the potential for decreasing the extracted emittance from DESY II has been investigated which can be achieved by lowering the extraction energy to 5 GeV and increasing the focusing in DESY II. In addition measuring the emittance of the extracted beam from DESY II and the optics in the beam transport line can help to better understand and improve the injection efficiency of PETRA III. By changing the quadrupole strength and measuring the beam size downstream on a screen monitor in the E-Weg the emittance of DESY II and the Twiss functions at a quadrupole in the E-Weg have been determined. Measurements at different energies of DESY II will be shown and compared with calculations.

INTRODUCTION

The third generation synchrotron light source PETRA III [1] is now in user operation since 2010. Two new experimental halls were built to get space for 10 additional beam lines in a one year break in 2014. For the future a major upgrade of the facility is planned which makes use of the technology of multi-bend-achromats (MBA) to reach ultra-low emittances in the range of some 10 pm·rad and is called PETRA IV.

In the context of the PETRA IV project it has been considered to operate the facility at a lower energy of 5 GeV. This would allow to reduce the strength of the magnet gradients in PETRA by 20 % compared to 6 GeV. Because of the very strong focusing of the quadupoles in the MBA-lattice the dynamic aperture of PETRA IV is expected to be small. This requires also a smaller emittance delivered from the pre-accelerator. As the emittance scales with E^2 lowering of the energy together with a stronger focusing could be a way to reach a smaller emittance in DESY II.

EMITTANCE REDUCTION IN THE BOOSTER SYNCHROTRON DESY II

DESY II was built in the year 1987 as an injector for the storage rings DORIS and PETRA I [2]. The lattice of DESY II consists of 8 supercells with a length of 36.6 m; the circumference of the machine is 292.8 m. Each supercell is made of 3 FODO cells. DESY II is a rapid cycling synchrotron with a repetition frequency of 12.5 Hz and accelerates electrons from a LINAC on a sinusoidal curve with an injection energy of 450 MeV up to a maximum energy of 7 GeV. By changing the extraction time on the rising slope different extraction energies can easily be realized. At an energy of 6 GeV the natural emittance for a damped beam is $\epsilon_x = 335$ nm·rad and at 5 GeV it is 241 nm·rad. The emittance coupling of DESY II is < 10 %.

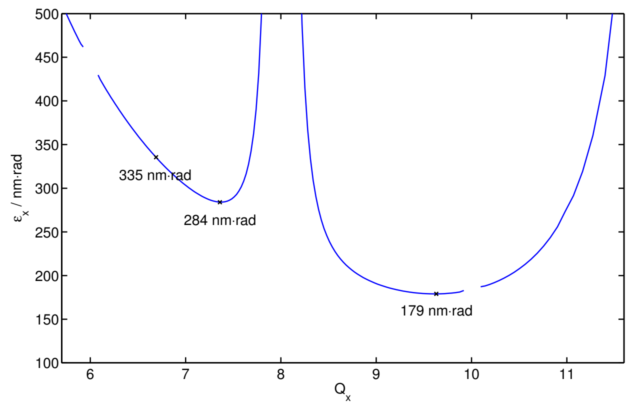

Figure 1: Natural emittance of DESY II as a function of the horizontal tune for a vertical tune of $Q_y = 5.44$ at 6 GeV.

One possibility to reduce the emittance of DESY II is to increase the focusing in the FODO cells. It is well known that the FODO cell has a global minimum of the emittance near a phase advance of 137° [3]. During normal operation a horizontal tune of $Q_x = 6.7$ is used which corresponds to a phase advance of $\Delta\phi_x \approx 102°$ per cell. Calculations with MAD-X [4] for the lattice of DESY II have shown that the global emittance minimum is at a tune of 9.63 with 179 nm·rad (Fig. 1). Due to the growth of the emittance near the resonance $Q_x = 8$ the tune has to be chosen either below ≈ 7.6 or above ≈ 8.3. During test measurements at 6 GeV it was possible to store the beam with $Q_x \approx 7.2$. The emittance in this local minimum is 284 nm·rad. A tune $Q_x > 8.3$ is only possible at 5 GeV because the current limit of the DESY II power supplies would be exceeded. Also the natural chromaticity of the lattice increases and requires stronger sextupoles. A third possibility to decrease the emittance is shifting the RF frequency. A shift of +50 kHz would provide an emittance of 252 nm·rad at 6 GeV.

BEAM TRANSPORT LINE E-WEG

The E-Weg is the beam transport line between DESY II and PETRA III and has a total length of about 203 m (Fig. 2).

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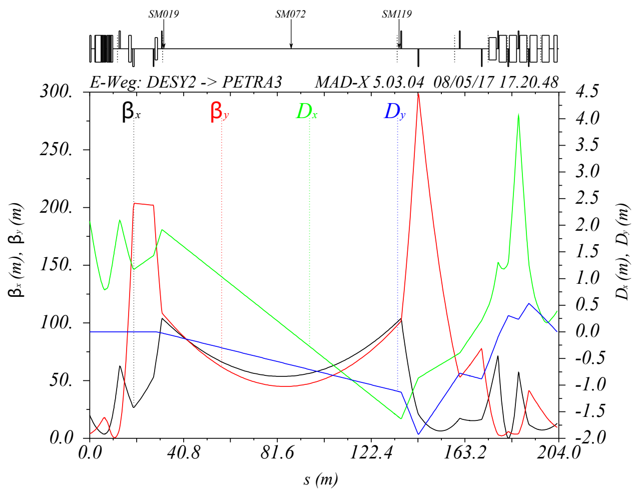

Figure 2: Optical functions of the E-Weg.

The extracted beam from DESY II has to go through two dipole magnets, a quadrupole and a sextupole magnet downstream of the DESY II septum before it enters the E-Weg. After a matching section a 100 m long drift space without quadrupoles suitable for emittance measurements is following. Several horizontal bending magnets at the end of the E-Weg deflect the beam by ≈ 90° towards the injection septum of PETRA III. The midplanes of the accelerators have a difference in height of 1.28 m. To compensate this a vertical bending magnet is installed before the long drift space and the first horizontal bending magnet downstream of the long drift has a small longitudinal roll angle. The E-Weg is equipped with 8 BPMs and 10 screen monitors. Three screen monitors are installed in the long drift space at 19 m, 72 m and 119 m and were used for the optics and emittance measurements.

EMITTANCE AND OPTICS MEASUREMENTS

Because of the lack of diagnostics for emittance measurements in DESY II the size of the extracted beam was measured in the E-Weg. The quadrupole scan method and the multiple screen method have been used [5].

Both methods determine the beam matrix Σ which is composed of the 2nd order moments of the distribution in position, angle and the correlation between them:

$$\Sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

The elements of Σ are proportional to the Twiss parameters α β, and γ, and the emittance ϵ and can be propagated using the transfer matrix M between point 1 and 2

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

to the sigma matrix Σ_2 at point 2 using the relation

$$\Sigma_2 = M\,\Sigma_1 M^T$$

As screens can only measure the beam size the dependency of the square of the beam size at point 2 on the matrix elements of M can be written as

$$\Sigma_{2,11} = M_{11}^2 \Sigma_{1,11} + 2M_{11}M_{12}\Sigma_{1,12} + M_{12}^2 \Sigma_{1,22}$$

This equation can be used together with the transport matrix M to compute the complete Σ-matrix at position 1 and with (1) also the Twiss functions and the emittance. For an uncoupled beam line both planes can be treated independently.

Quadrupole Scan Method

For the quadrupole scan method measurements with one screen monitor downstream a quadrupole is already sufficient. By changing the focusing strength k of a quadrupole upstream of the screen all elements of the Σ_1-matrix at the entrance of the quadrupole can be determined. One screen is sufficient because the total transfer matrix $M = M_q(k) \cdot M_d$ will change with k.

The N measurements of the beam size σ_j^2 at the screen at position 2 can be written in matrix form as

$$\begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \cdots \\ \sigma_N^2 \end{pmatrix} = \begin{pmatrix} M_{1,11}^2 & 2M_{1,11}M_{1,12} & M_{1,22}^2 \\ M_{2,11}^2 & 2M_{2,11}M_{2,12} & M_{2,22}^2 \\ \cdots & \cdots & \cdots \\ M_{N,11}^2 & 2M_{N,11}M_{N,12} & M_{N,22}^2 \end{pmatrix} \cdot \begin{pmatrix} \Sigma_{1,11} \\ \Sigma_{1,12} \\ \Sigma_{1,22} \end{pmatrix}$$

and can be solved (if $N > 3$) for the vector on the right side by using a least-squares fit minimizing the χ^2-function

$$\chi^2 = \sum_{j=1}^{N} \left(\frac{\sigma_j^2 - M_{j,11}^2 \Sigma_{11} - 2M_{j,11}M_{j,12}\Sigma_{12} - M_{j,22}^2 \Sigma_{22}}{2\sigma_j \Delta(\sigma_j)} \right)^2$$

with the errors of the beam size measurements $\Delta(\sigma_j)$ taken from a 2D-fit of the beam profiles.

For the measurement the strength of the quadrupole QE019 upstream of the long drift space was changed. The screen at 72 m was chosen as the beam size change is neither too big (screen at 119 m) nor too small (screen at 19 m).

A typical measurement of the square of the beam size σ_x^2 for the 6 GeV case is shown in Fig. 3 for the horizontal plane. An error of $\Delta(\sigma_j) = 0.4$ mm for the fitting of the profiles was assumed. The reconstructed beam ellipse at the entrance of QE019 is shown in Fig. 4 (red curve) together with the beam ellipse (black curve) computed from the theoretical optics model of the E-Weg and initial optics parameters from DESY II. The blue lines are the back propagated measurements which are tangents touching the beam ellipse.

Multiple Screen Method

Beam size measurements at multiple screens can also be used to determine the sigma matrix Σ_1 at a location upstream of the screens. For this kind of measurement all transport matrices $M^{(1)}, M^{(2)}, \ldots, M^{(N)}$ are different between point 1 and point 2 (one of the N screens). From N beam size measurements $\sigma^1, \sigma^2, \ldots, \sigma^N$ the Σ_1 matrix at a point upstream

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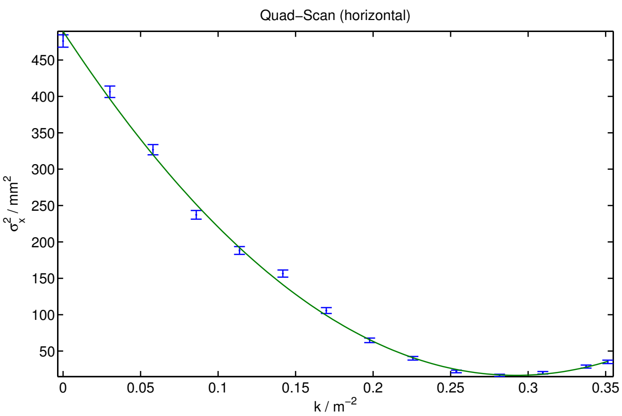

Figure 3: Square of the horizontal beam size as a function of the focusing strength of quadrupole QE019.

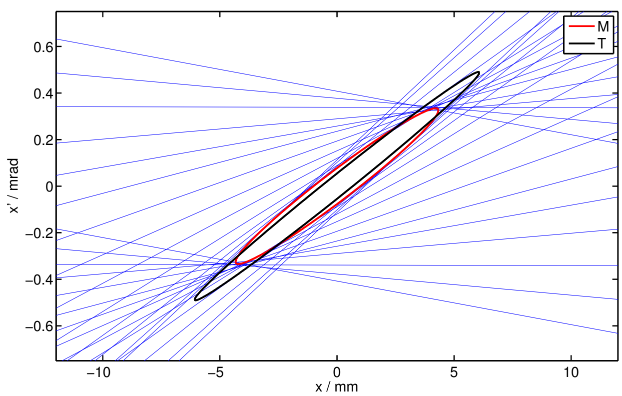

Figure 4: Reconstructed ellipse in the horizontal phase space (x, x') at the entrance of quadrupole QE019 (red: measurement, black: theory).

can be determined using a least-squares fit from N equations in a similar way as discussed above for the quadrupole scan method.

The screens at 19 m, 72 m and 119 m have been used for a measurement at 6 GeV and emittances of $\epsilon_x = 358$ nm·rad and $\epsilon_y = 12$ nm·rad have been fitted. The Twiss functions are $\beta_x = 76$ m, $\beta_y = 83$ m, $\alpha_x = -6.0$ and $\alpha_y = 7.7$ at the entrance of quadrupole QE019. The theoretical values are listed in Table 1. Because the number of screens is equal to the fit parameters no error can be given.

Results

The measurements of the horizontal emittance and the coupling of $\approx 3.6\%$ are in good agreement with the expectations (Table 1). The emittance at 5 GeV is substantially smaller compared to 6 GeV. However the measured optical functions are in disagreement with theoretical values which was also observed with the three screen method. The phase space plot (Fig. 4) shows a disagreement between the measured beam ellipse (red) and the expected ellipse (black). It was also observed that the measured dispersion function

Table 1: Results of the Quadrupole Scan Measurements

	Theory		**Measurement**	
	5 GeV	**6 GeV**	**5 GeV**	**6 GeV**
ϵ_x / nm·rad	241	331	253 ± 6	335 ± 12
ϵ_y / nm·rad	24	33	10 ± 0.5	15 ± 0.5
β_x / m	111	111	53 ± 2	56 ± 2
β_y / m	120	120	56 ± 4	56 ± 3
α_x	-8.9	-8.9	-3.8 ± 0.1	-4.2 ± 0.2
α_y	11.9	11.9	6.2 ± 0.4	5.9 ± 0.3

is not in agreement with theory already at the first BPM in the E-Weg [6]. The reason for the discrepancy might be the insufficient model of stray fields of the DESY II magnets the beam has to pass downstream of the DESY II septum.

SUMMARY

For the PETRA IV project different options for emittance reduction in DESY II have been studied. Increasing the focusing in DESY II can reduce the emittance to 284 nm·rad. A further reduction to reach the minimum of 179 nm·rad is not possible at the moment without changes at the power supplies. A second method would be lowering the energy of PETRA IV and DESY II to 5 GeV. The decrease of the emittances has been measured with quadrupole scans in the E-Weg and are in good agreement with the theory. The coupling at both energies is about 3%. Nevertheless it was also found that the optical functions are in disagreement with theory. This may be caused by an incorrect model of the stray field of the DESY II dipole magnet which the beam has to cross when extracted. This discrepancy in the optical functions needs further investigation.

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