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BEAM DYNAMICS ON A COUPLING RESONANCE AT PETRA III

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Abstract

Working on a coupling resonance is a usual way of producing round beams in a synchrotron. The beam dynamics in this regime is however more complicated, and the emittance is sensitive to the working point, coupling correction, and bunch current drop with time, which complicates the operation. We present experience with optics setup for working on a coupling resonance in PETRA III, including linear and nonlinear beam optics characteristics, and the measurement of the horizontal and vertical beam emittances with a 2D interferometer. Beam dynamics on a coupling resonance for PETRA IV, the MBA upgrade of PETRA III currently under consideration, is also presented.

INTRODUCTION

Coupling is a way to create round beams in synchrotrons, where the beams are typically flat when the coupling is small. Round beams can be advantageous for Touschek lifetime, intra-beam scattering (IBS) and synchrotron radiation characteristics in certain regimes. In an uncoupled machine, the skew quadrupole correctors and other sources of coupling are weak, and the tunes need to be brought to a resonance condition to see a significant effect. On the difference resonance the beating of uncoupled actions (invariants) can be calculated with the help of perturbatation approach [1]. The same theory gives the ratio of horizontal and vertical emittances by:

$$g \approx \frac{(|C^-|/\Delta)^2}{(|C^-|/\Delta)^2 + 2}, \tag{1}$$

where C^- is the coupling strength and $\Delta = Q_x - Q_y$ the distance from the resonance, from which it is clear that a round beam is produced whenever the distance from the resonance is small enough for a given coupling.

PETRA III ROUND BEAM OPTICS

The round beam optics for PETRA III is a modification of the standard so-called high beta optics (p3xv19), matched to a working point close to (but not exactly on) the difference coupling resonance. The matching is achieved by using 11 quadrupole cicruits including the main FODO quadrupoles. If only the main FODO circuits are used – the procedure employed in standard operation for tune correction – the optics beating would be noticable and the residual dispersion in the straight sections would influence the equilibrium emittance.

The optical functions are shown in Fig. 1. The nonlinear characteristics of the machine expressed by the dynamic aperture are similar to the uncoupled case, and shown in Figs. 2 and 3. The horizontal dynamic aperture is the key characteristic since it needs to accommodate large injection oscillations during the top-up off-axis injection. It is approx. 25 mm-mrad, a value similar to that of the uncoupled optics. The vertical dynamics aperture is less relevant since in the vertical direction the limitation is due to the physical aperture of the insertion devices.

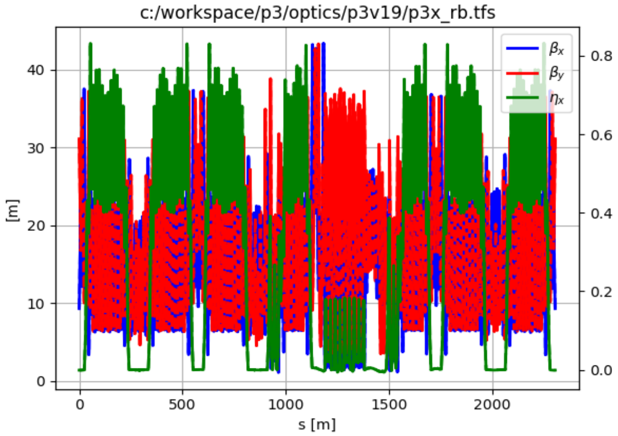

Figure 1: PETRA III optics when matched to the coupling resonance condition.

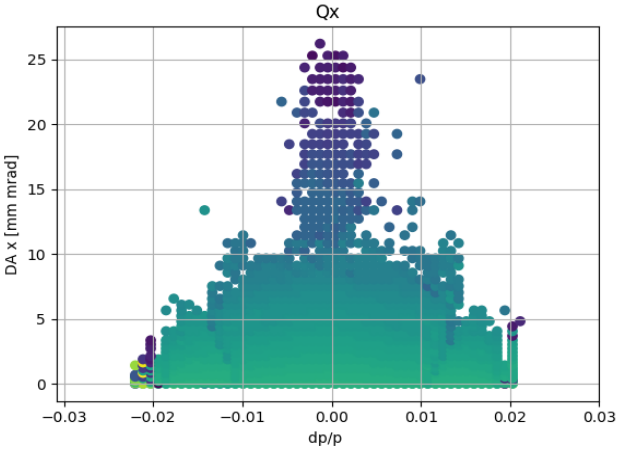

Figure 2: Horizontal dynamic aperture and momentum acceptance, color-coded by the horizontal tune value.

The optics, orbit and dispersion of the machine can then be corrected at this working point. At this point the coupling is small, the beam is still flat, and injection is possible without problems. Then, a very small increase in the coupling (e.g. by using only one skew quadrupole) simultaneously with a slight tune readjustment can produce a round beam. This procedure typically takes several seconds in practice, the limitation coming from the slow response of the strong skew

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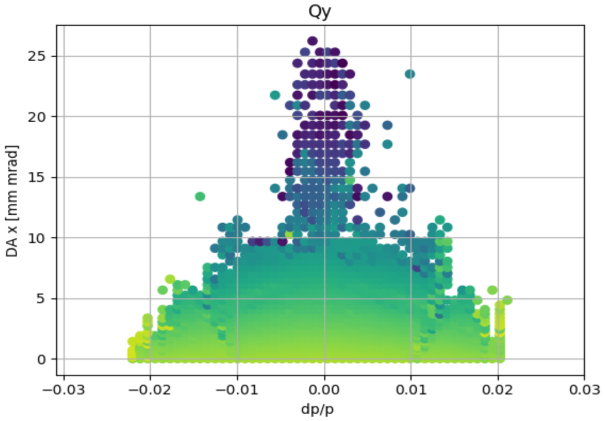

Figure 3: Horizontal dynamic aperture and momentum acceptance, color-coded by the vertical tune value.

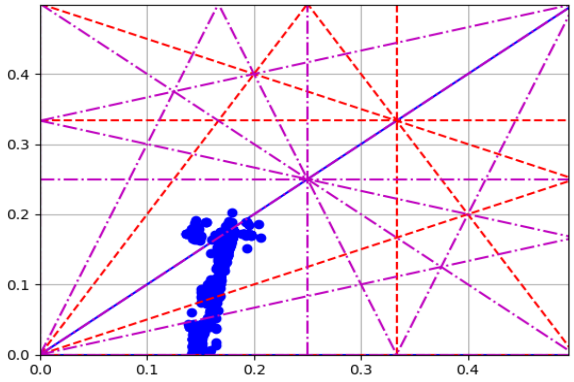

Figure 4: Tune diagram, dependence on horizontal amplitide. The DA limitation of 25 mm mrad is coming from the crossing of the integer resonance.

quardupole magnet. Due to the shape of the detuning with horizontal amplitude (see Fig. 4), the tune at injection should lie slightly below the resonance line.

The optics was set up and tested on 15 November 2017. The 2D interferometer [2] was used to measure the emittance as a function of one skew quadrupole strength, and round beams could be produced for sufficient coupling strength as shown in Fig. 5. For round beam operation the optical functions at the interferometer source point change slightly with respect to the nominal optics (see Fig. 6), which was taken into account.

At the coupling resonance, the detuning with horizontal amplitude is at the angle to the resonance line (see the tune diagram in Fig. 4). Thus, the injection oscillations are initially outside of the resonance bandwidth and the trajectory and emittance damping could outcompete the setting in of the coupling, making the injection possible exactly at the resonance and allowing to bypass the small optics readjustment at the time of injection. Attempts to inject on the resonance using this effect, however, resulted in unacceptably high beam losses. This situation has to be clarified further.

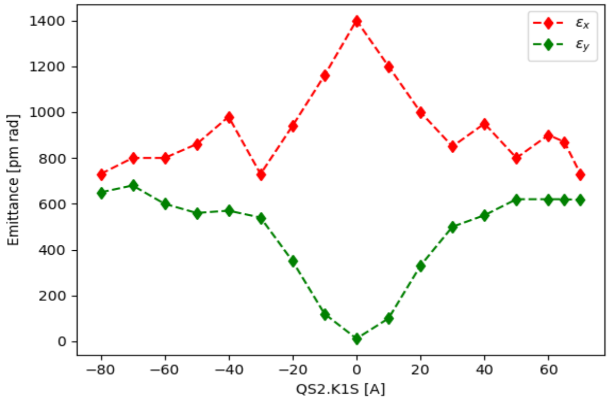

Figure 5: Measurement of the horizontal and vertical emittances as a function of the strength of the skew quadrupole *QS*2.

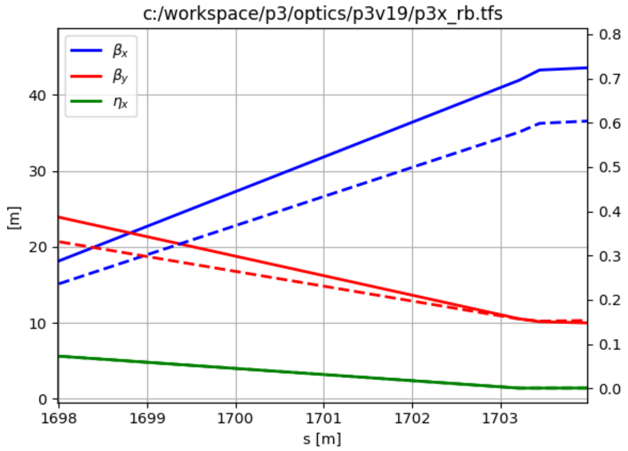

Figure 6: Optics at the source if the 2D interferometer for round (solid line) and nominal (dashed line) operation.

Note that the advantage of working with a broad resonance width is the reduced sensitivity to tune variation, such as when the bunch population is depleted. The emittance was stable for many minutes while the measurement was performed.

ROUND BEAM OPTIONS FOR THE PETRA UPGRADE

For the PETRA upgrade project [3], a round beam lattice based on the phase space exchange principle has been proposed [4]. Such a lattice is however not capable of producing flat beams, so a question arises if an otherwise flat beam lattice can be used for the round beam production. The latest reference lattice for the PETRA upgrade (so-called H7BA optics) is based on a scaled version of the ESRF EBS design [5], and the optical functions of one cell are shown in Fig. 7.

Due to the presence of long straight sections at PETRA, installation of phase space exchange sections is always possible, thus the round beams can be produced via the phase

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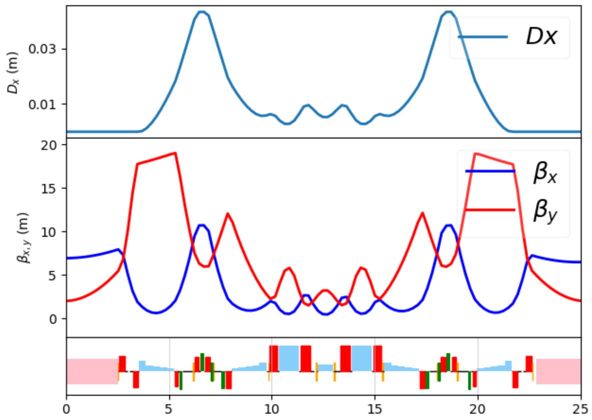

Figure 7: PETRA IV H7BA cell scaled from the ESRF-EBS design.

space exchange principle. The nonlinear characteristics of the lattice, presenting severe difficulties in MBA lattice design, are mostly preserved. So, introducing a phase space exchange into the H7BA lattice and performing no nonlinear optimization whatsoever already yields a dynamic aperture of approx. 6.5 mm at the injection point with β_x = 100 m, a reduction of less than a factor of two from the optimized design, clearly showing the feasibility of this path. The phase space exchange section described in [4] can be easily changed to a 2π phase advance FODO section by means of quadrupole rotation. This, however, requires mechanical intervention which we consider undesirable, and a section design that can alternate between a phase exchange or a fixed or variable phase advance uncoupled optical section by only magnet strength manipulation should be designed if this path to creating round beams is pursued further.

We also explored the possibility of working on the coupling resonance with the PETRA IV reference lattice. When the fractional part of the tune is matched to approx. 0.18 in both planes, the nonlinear characteristics of the lattice do not suffer. The tune footprint is shown in Fig. 8. Both the horizontal and the vertical detuning is at a sufficient angle from the resonance line. Off-axis injection on the resonance could be possible for a sufficiently corrected machine.

Note that very small misalignments or strength errors could already result in significant tune deviation for all PETRA IV lattices considered. This already creates problems for the nominal mode of operation, but will be even more severe if the tune should be locked to the coupling resonance for round beam operation. Advanced feedback mechanisms might be required here. Also note that a number of alternative directions towards round beam production have been suggested (see e.g. [6]), and could be further explored for the round beam operation option at PETRA IV.

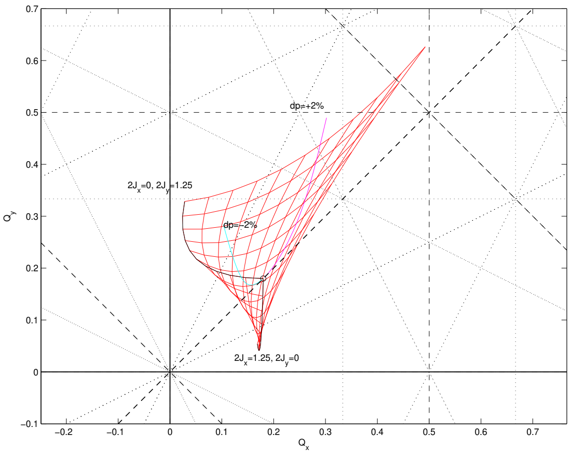

Figure 8: Detuning of the PETRA IV reference lattice for the coupling resonance working point.

CONCLUSION AND OUTLOOK

We set up and tested a round beam optics for PETRA III, and explored the possibility of producing round beams at PETRA IV with the standard approach of working on the coupling resonance. This approach is not difficult to implement, and is compatible with off-axis injection. Avoiding optics manipulation at PETRA III during the injection process altogether at the same time achieving the target transfer efficiency of about 80% is still to be demonstrated.

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