Round beams at PETRA IV

I. Agapov* and R. Brinkmann

Deutsches Elektronen Synchrotron,
Notkestrasse 85, 22607, Hamburg, Germany
**E-mail: ilya.agapov@desy.de*

After introducing the PETRA upgrade project and the usual way of producing round beams by working on a coupling resonance at electron sycnhrotrons, we present a non-interleaved round beam lattice based on the phase space exchange principle. Single-particle beam dynamics characteristics (momentum acceptance, dynamic aperture) of this lattice are discussed.

1. PETRA IV – the PETRA III upgrade prpject

PETRA III[1] has been in operation for almost a decade now, with the horizontal emittance of about 1.2 nm rad (1.4 nm rad after the extension project has been completed), and the vertical emittance of less than 10 pm rad. Progress in synchrotron radiation science and technology requires further reduction of the horizontal emittance by up to two orders of magnitude, to the range of 10 to 30 pm rad. A design study for such an upgrade has been ongoing at DESY[2]

Fig. 1. Layout of the present PETRA III machine with the additional hall in the southwest planned for PETRA IV upgrade

PETRA III is a 6 GeV machine of 2304 m circumference (of which however only 1600 m is curved, and the rest is occupied by the long straight sections), these parameters will be preserved for the next incarnation of the facility. The present PETRA III optics is a combination of the double-bend achromat (DBA) cells, initially installed in one octant of the machine and later extended to parts of the two adjacent octants, with the FODO optics remaining from the high energy physics machine PETRA II. For the upgrade the storage ring will be completely exchanged and a new experimental hall will be constructed (see Figs. 1, 2).

Modern ultra-low emittance lattices are based on the multi-bend achromat (MBA) principle[3]. Scaling and modifying one of the more recent MBA designs – the ESRF EBS optics[4] – to the machine dimensions of PETRA readily yields emittances in the 10-20 pm range. Example of cells for such optics are shown in Figs. 3, 4. Moreover, making the arcs fulfil the achromat condition in analogy with the PEP-X design[5] helps to further improve the dynamic aperture. However, the dynamic aperture in all such cases falls short of the roughly 2 mm mrad required for accumulation with the off-axis injection (see Figs. 5, 6). Alternative lattice concepts for improved dynamic aperture are thus under investigation.

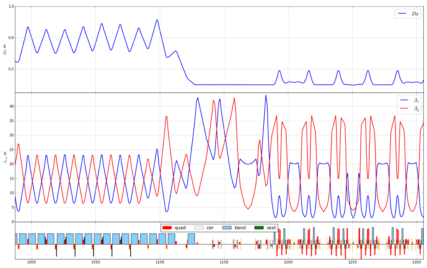

Fig. 2. Current PETRA III optics: a part of the FODO octand and a part of the DBA octant

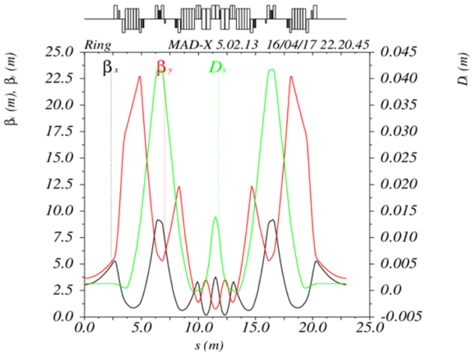

Fig. 3. 6 BA cell, modified from the 7BA cell of the ESRF EBS design

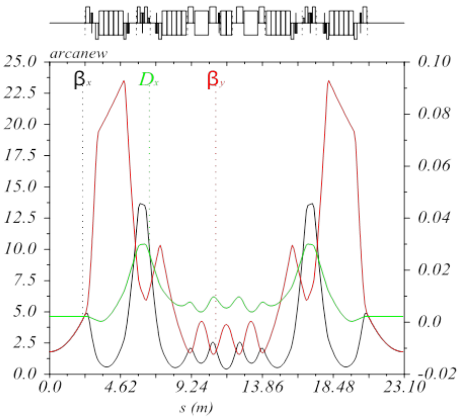

Fig. 4. 7 BA cell, modified from the 7BA cell of the ESRF EBS design

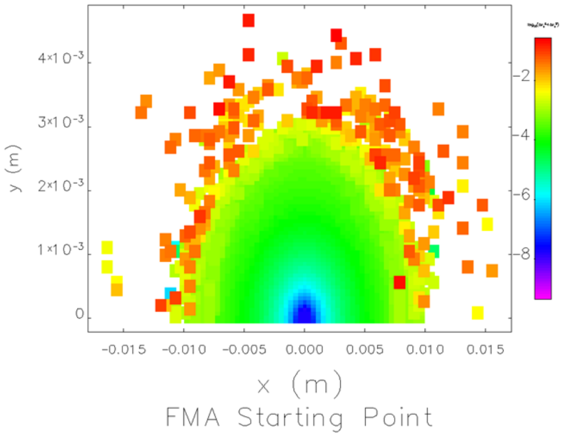

Fig. 5. Frequency map of the 7BA lattice, no errors, β_x=100 m

2. Experience with round beams on the coupling resonance at PETRA III

The natural beam shape in a synchrotron is flat, but round beams have various advantages such as mitigating the intra-beam scattering or improving the brightness at the wavelength where it is restricted by the horizontal beam dimension; the approaches to creating round beams are covered nicely in these proceedings[6]. Here we briefly describe the experience with round beam operation at PETRA III based on the coupled resonance working point, and conclude that such operation mode is not difficult to establish; the drawback is however the increased sensitivity to perturbations, so that e.g. a drop in the bunch current could bring the bunch out

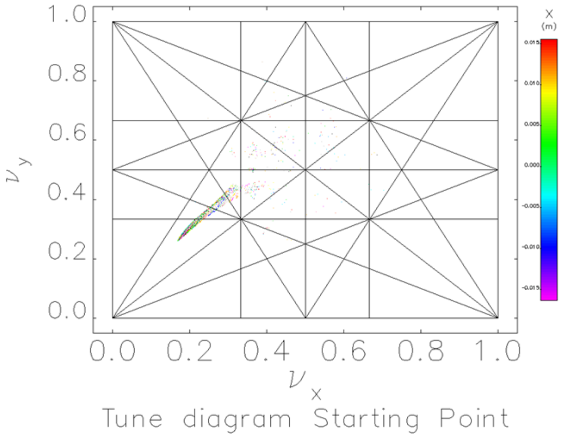

Fig. 6. Tune footprint of the 7BA lattice

of resonance and destroy the round beam shape.

The approach is to establish an optics which is as close to the coupling resonance as possible to still make the injection possible (off-axis injection on the resonance is generally impossible due to the vertical aperture limitation at the insertion devices). The dispersion, orbit, and coupling are corrected at this working point. After the injection one skew quadrupole strength is increased, so that the width of the resonance increases, and the beam becomes round; the emittance ratio ideally satisfies

$$g = \frac{\left(\frac{C}{\Delta}\right)^2}{\left(\frac{C}{\Delta}\right)^2 + 2} \tag{1}$$

where C is the coupling and Δ the distance from the resonance. The optics for this round beam working point is shown in Fig. 7. The difference between the Twiss parameters of the nominal and the round beam optics at the source point of the emittance diagnostics beamline is shown in Fig. 8. The measurement of the horizontal and vertical emittances as functions of the skew quadrupole strength is shown in Fig. 9, and an on-line measurement of the beam spectrum for one particular skew quadrupole setting in Fig. 10. A round beam with horizontal and vertical emittances roughly equal to half the natural emittance is produced for sufficiently large skew quadrupole strength.

Implementation of this scheme for PETRA IV can proceed in complete analogy. The tolerance to tune change and dynamic stability depends on the lattice to be selected and is to be determined.

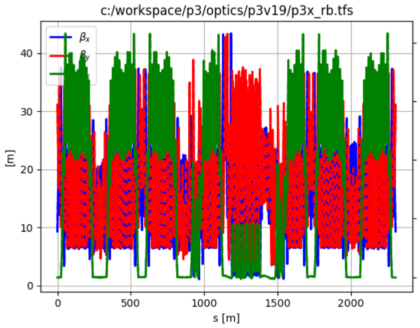

Fig. 7. The PETRA III optical functions close to the coupling resonance

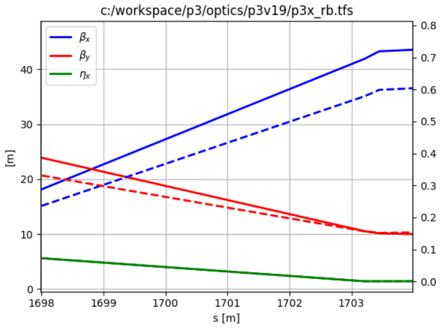

Fig. 8. The difference between nominal (solid) and round beam (dashed) optical functions at the source point of the diagnostics beamline (at 1701 m)

3. The phase space exchange lattice for PETRA IV

For the PETRA IV upgrade project, a lattice with a natural round beam shape which at the same time has a large dynamic aperture has been investigated. It is based on two principles: non-interleaved sextupole arrangement and the phase space exchange.

The so-called non-interleaved sextupole scheme consists in separating two adjacent sextupoles of same polarity by the phase advance of π in both planes (see e.g.[7]). The sextupole aberration in this arrangement cancels almost completely (finite sextupole length produces some small residual). Due to a finite chromaticity of the lattice the phase advance condition does not hold for off-momentum particles. The non-interleaved lattices thus have a large dynamic aperture and a somewhat reduced momentum acceptance.

The phase space exchange swaps the betatron oscillation modes so that the radiative damping and excitation occur uniformly in both planes, resulting in round

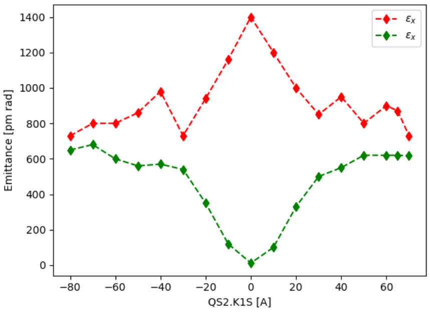

Fig. 9. Horizontal and vertical emittances vs. skew quadrupole strength for the round beam optics at PETRA III

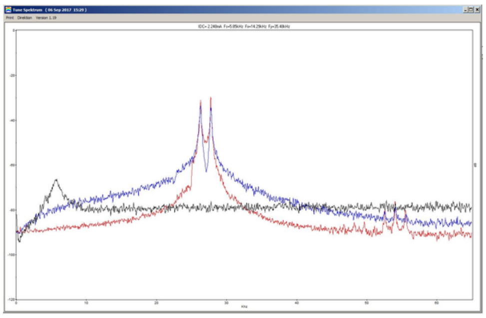

Fig. 10. On-line beam spectrum during round beam operation at PETRA III

beams[8,9]. With the two phase space exchanges per revolution, both the one-turn map and the local optics are uncoupled, which makes the operation easier. Moreover, one could rely on sextupoles of just one polarity (say, focusing) to correct the chromaticity in both planes. A perfectly non-interleaved sextupole arrangement in such a ring is thus possible. A possible non-interleaved 6BA cell and a conceptual scheme of a ring based on the non-interleaved phase space exchange lattice are shown in Figs. 11 and 12.

The PETRA IV layout will be such that only part of the ring (two octants + parts of two other octants) will be occupied by insertion devices, as shown in Fig. 13. There the oscillation modes of a horizontally injected beam are shown, together with two locations of the phase space exchange.

The optics in the arcs without the undulator insertions can be more relaxed due to the fact that the straights for the insertions can be removed. The arc lattice can be made into one long achromat, which is shown in Fig. 14. The long straight sections have a FODO optics, the phase space exchange is realized as a skew FODO section, and the whole ring has the optics shown in Fig. 15. The emittance of the

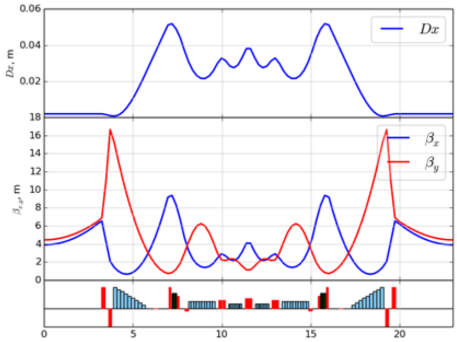

Fig. 11. A possible non-interleaved 6BA cell. Phase advance between two focusing sextupoles (green bars) is π in both planes.

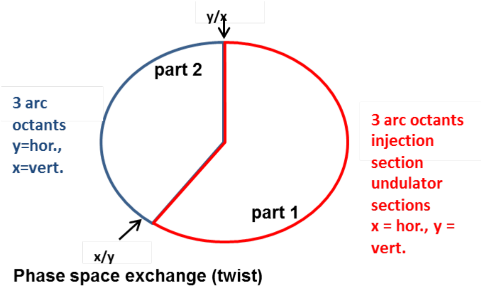

Fig. 12. Schematic of a ring based on the double phase space exchange principle

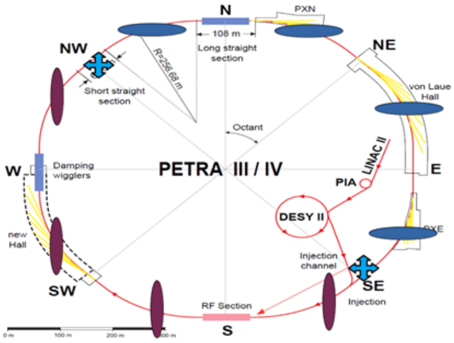

Fig. 13. Possible implementation of the double phase space exchange at PETRA IV

ring is 25 × 25 pm at 6GeV.

The dynamic aperture of a single cell (both of the long achromat and of the un-

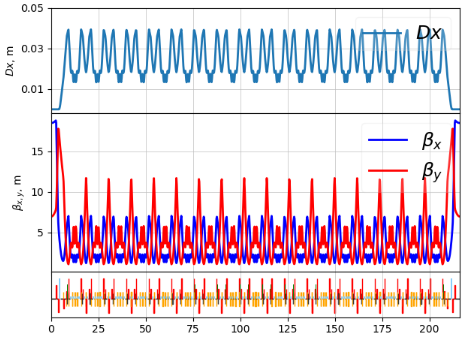

Fig. 14. The potical function in the long achromat arc (without undulators)

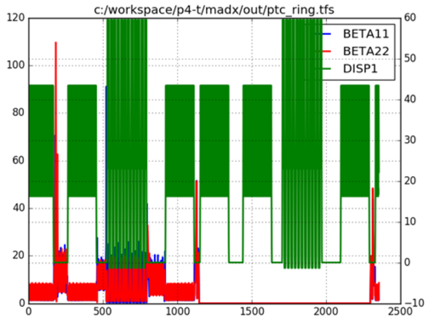

Fig. 15. Ripken (coupled) optical functions for the whole ring

dulator cell) is extremely large on-momentum, and the momentum acceptance is in the 10% range (see Fig. 16). In the full lattice the limitation on the dynamic aperture and momentum acceptance come from the integer and half integer resonances. The amplitude detuning and chromaticity are cumulative properties of the ring. For a non-interleaved cell the amplitude detuning is small while the chromaticity (the nonlinear part) is not; the cumulative nonlinear chromaticity of the ring sets the limit on the momentum acceptance. The situation is shown graphically on a simplified model of two arcs composed of baseline (7BA interleaved) cell in Figs. 20, 18 and 19 (since the chromaticity is corrected over one turn in the phase space exchange lattice, the momentum of single arcs of such lattice is always poor which prevents a similar example with that lattice). The tune dependency on the momentum offset for a 7BA interleaved lattice section composed of two octants is shown. Quadratic and cubic terms in chromaticity are clearly visible and the half-integer resonance sets the limit on the momentum acceptance.

Finally, the dynamic aperture and momentum acceptance of the full lattice

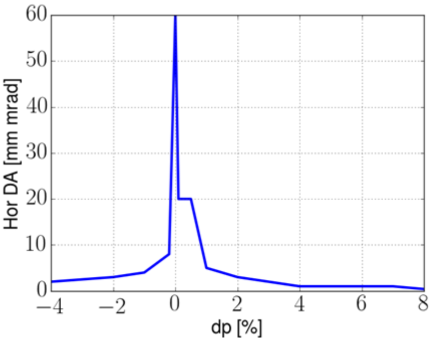

Fig. 16. Horizontal DA and momentum acceptance of the 6BA undulator cell

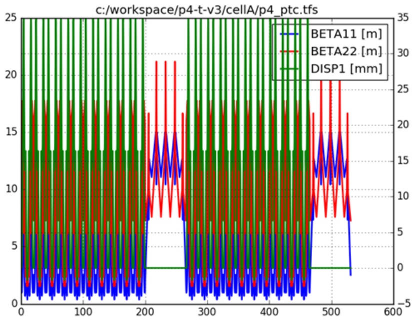

Fig. 17. Two octants of 7BA cells with chromaticity corrected in both planes

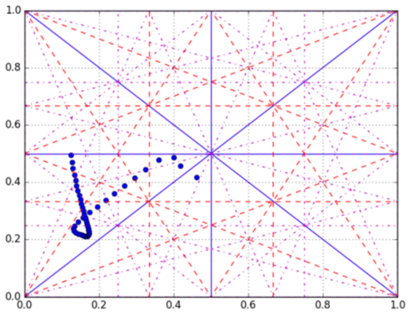

Fig. 18. Off-momentum tune footprint for two octants of 7BA cells with chromaticity corrected in both planes

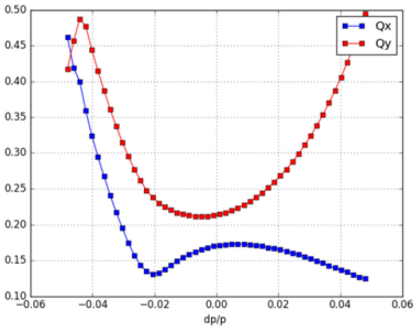

Fig. 19. Tunes for two octants of 7BA cells with chromaticity corrected in both planes

are shown in Fig. 20. The green curve represents the acceptance including the undulator octants, and the blue curve shows the acceptance of a fully symmetric ring made of only long achromat arcs. The latter curve is included for demonstration of the effects of increased sextupole strength needed for additional chromaticity compensation and of the violation of the ring symmetry. The vertical acceptance for this lattice is always larger than the horizontal and is not shown here.

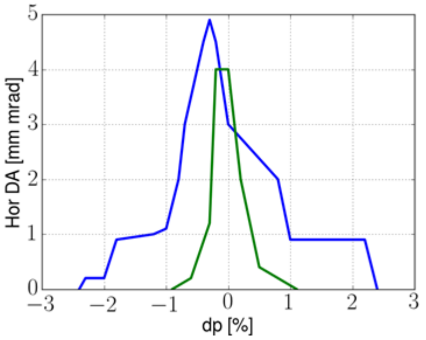

Fig. 20. Green: horizontal DA and momentum acceptance of the phase space exchange lattice. Blue: horizontal DA and momentum acceptance of a ring made of only long ahcromat arcs (no undulator straight sections)

4. Conclusion

PETRA IV design towards an ultra-low emittance hard x-ray source is underway, with several candidate lattices having been studied. Production of round beams is an important feature of the proposed project. A non-interleaved phase space exchange lattice capable of producing such beams has been presented here.

Regardless of the lattice chosen for the upgrade project, the coupling resonance option will be available provided the selected lattice will have sufficient dynamic stability at a working point close to the coupling resonance; the phase space exchange option can also be implemented in any selected lattce – not necessary the non-interleaved one described here – with a relatively short skew FODO section of about 25 m length, for which there is space in the long straight sections of the tunnel.

Acknowledgments

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5. References

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