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Design Considerations of a High Intensity Booster for PETRA IV

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Introduction

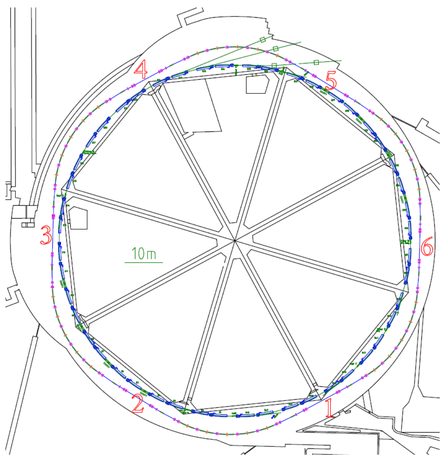
The PETRA IV project toward a diffraction limit synchrotron light source at 6 GeV features an ultra low emittance storage ring and a small dynamic aperture. Whether using on or off axis injection, the emittance of the injected beam must be very low. The current booster DESY II's emittance is 350 nm-rad at 6 GeV, which is too large for PETRA IV's injection. Therefore a new ring accelerator where the beams to-be-injected are prepared is always needed. This ring is named DESY IV.

The required charge to be delivered into the storage ring is as high as 8 nC per bunch. Considering losses during transfers, the single bunch intensity capacity requirement in DESY IV is adjusted higher as 10 nC. An additional challenge comes from the small required emittance.

To be more specific, the proposed operation modes for the storage ring demands the injector to deliver a 10 nC electron beam at 6 GeV with the emittance less than 30 nm-rad at a repetition rate of at least 1 Hz.

The capability to inject and accumulate beams at 6 GeV is optional but it will be included in the design phase.

Layout in DESY Tunnel



DESY II Test beamline, crane, and floor plates in DESY tunnel

- Straight #1, #3, #5 are 8.8-m high beta straights for injection/extraction.
- Straight #2, #4, #6 are 7-m low beta straights for cavities.
- Low energy injection and high energy extraction are in Straight #1
- Straight #3 and #5 are preserved for injections from other sources

Geometric Constraints

- Fit into the old DESY tunnel
- Lift DESY IV's orbit level in order to:

1. **Keeping the Test Beamlines**
   An additional strong constraint is imposed to keep DESY II and its three Test Beamlines dedicated to the detector development. Lifting DESY IV higher can avoid the element conflicts and leave DESY II and all its Test beamlines untouched.

2. **Easy to Install**
   DESY's old tunnel's ground level is composed of many concrete slabs of different heights, making it difficult to install simple girders around. Supporting components from the ceiling seems an easier solution. The existing cranes shall be removed and some tall supports may also be used.

3. **Facilitating the Design of the Transport Line**
   It is crucial for the injection into PETRA IV that the vertical dispersion is avoided. If the booster and the light source are at the same level, the transport line design can be greatly simplified.

Design Strategy

What should be included?

1. Small natural emittance
   * ε_0< 30 nm-rad at 6 GeV
2. Short equilibrium bunch length
   * rms bunch length ≤ 20 mm
3. High TMCI threshold
   * Qth >10 nC at 800 MeV
4. Some achromat straights
   * to eliminate synchro-betatron coupling
5. Low beta straights (length > 6m)
   * for sufficient RF cavities
6. Large DA (>10 mm)
   * for off-axis injection at high energies
7. Large MA (>4%)
   * to accept 4 linac bunches
8. High beta straights (length > 8.5m)
   * enough ports for injections and extraction
9. Efficient orbit bumps (leverage > 5)
   * for beam accumulation at high energies
10. Large magnet apertures and beam pipes
    * to have lower impedance

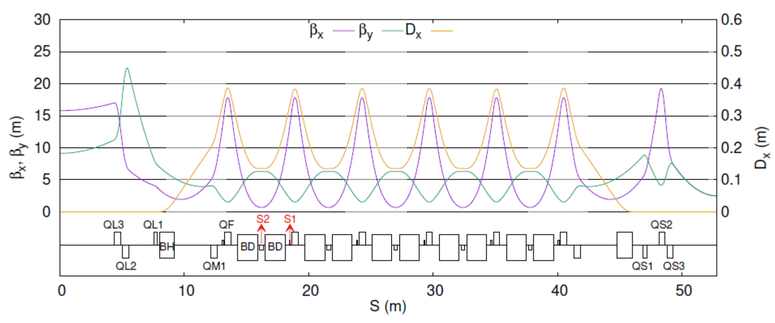
Lattice Parameter

Periodicity	3
Circumference	316.8 m
Harmonic Number	528
Working Tune (H/V)	17.37 / 12.15
Natural Chromaticity (H/V)	-41.8 / -13.8
Momentum Compaction	3.17 E-3
Damping Partition Jx	2.56
At Beam Energy 6 GeV	
Energy Loss per Turn	6.55 MeV
Natural Emittance	19.1 nm-rad
Equilibrium Energy Spread	2.64 E-3
RF Voltage	12 MV
Equilibrium Bunch Length	20 mm
Damping Time (H/V/L)	0.8 / 1.9 / 4.5 ms
At Beam Energy 800 MeV	
TMCI Threshold Qth	11.44 nC

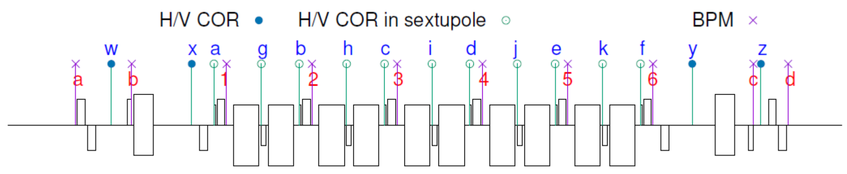
- A guideline formula for TMCI threshold: $I_{th} = \frac{4\sqrt{\pi}(E/e)\sigma_\delta \alpha_c \nu_\beta}{RZ_{tr}}$,
- where E is the beam energy; σ_δ is the relative beam energy spread; α_c is the momentum compaction factor; ν_β is the smaller betatron tune, $R = C/2\pi$ is the averaged radius; Z_{tr} is the effective transverse impedance.
- Z_{tr} =1 MOhm/ mand σ_δ =0.25% as a conservative estimation)

- Uniform beam pipe radii 23mm and 15mm

Linear Optics

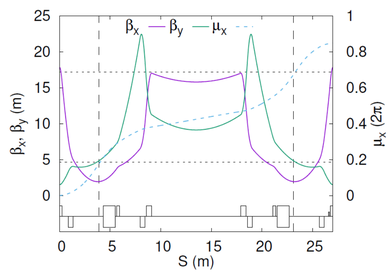


Orbit Correction

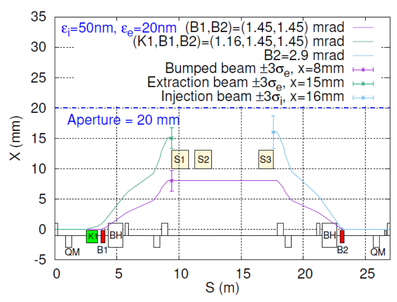


- An efficient configuration is found with
  - 24 BPMs (at position label a, 2, 5, d) and
    24 independent bi-directional correctors (at position label w, x, y, z).
- The max corrector strengths are within 0.5 mrad horizontally and 0.4 mrad vertically.

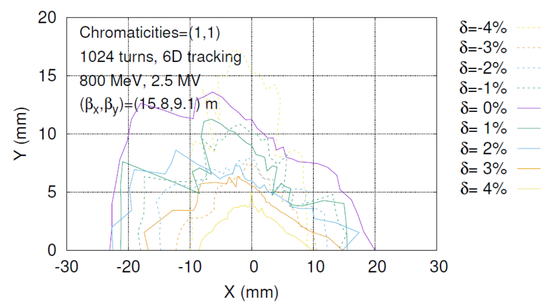
Orbit Bumps

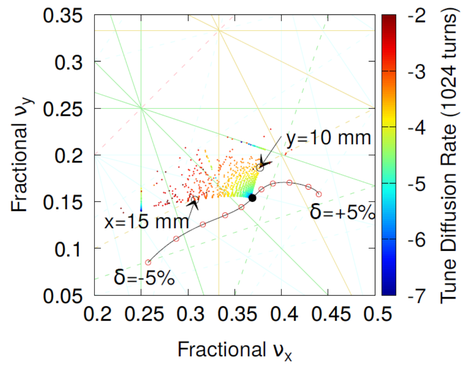


- A horizontal 2-kicker orbit bump is formed by a pair of bumpers at two location with Δμx=π.
- The leverage is 5.5 mm/mrad
- The injection goes vertically to avoid element conflicts
- A tentative configuration of injection/extraction elements are shown



Dynamic Aperture





Summary

The criteria for the injector of PETRA IV are firstly articulated. Following a design strategy, a strong intensity limit booster is custom made for the PETRA IV project. The geometry is well-tailored to fit into the existing DESY tunnel. The orbit level is raised to be the same as PETRA IV so that the existing DESY II and its Test beamlines will not be altered.

Three low beta achromat straights provides enough space for RF modules. In contrast, the other 3 longer achromat straights has higher beta functions. Proper locations for efficient 2-kicker orbit bumps are found. The capability to accumulate the beam at high energies is possible. The low energy injection and high energy extraction can be integrated in one of these straights. In addition, the other two high beta straights are preserved for higher energy injection from other sources.

The input beam energy is raised to 800 MeV to improve the beam stability. The full intensity bunches or bunch trains will be on-axis injected into the storage ring by default. Furthermore, this ring can also be operated as a booster for possible top-up operation or being an accumulator at 6 GeV.