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Lattice Design and Dynamic Aperture Optimization for the BEPCII-UP with Crab Waist Scheme

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Abstract

This study employs the SAD program to perform lattice design and dynamic aperture (DA) optimization for the BEPCII Upgrade Plus (BEPCII-UP) collider ring, which adopts the crab waist collision scheme. The lattice design includes the survey, optics parameters, and working point matching. To obtain a sufficient DA for injection, a combined-function magnet scheme (B+S) is explored, and a genetic algorithm (GA) is employed to optimize the strengths of the sextupoles under beam-beam interactions. The optimized lattice preliminarily meets the injection requirement, providing a reliable basis for the BEPCII-UP crab waist scheme.

Introduction

The crab waist collision scheme, featuring a large Piwinski angle, an extremely small vertical beta function (β_y^*), and dedicated crab sextupoles, is widely recognized as the preferred technology for next-generation high-luminosity electron-positron colliders. The BEPCII-UP project aims to upgrade BEPCII into a crab waist beam test facility and a $\varphi - \psi$ factory, achieving an order-of-magnitude luminosity increase in the low-energy region (≤1.89 GeV), while accumulating valuable operational experience for future colliders such as CEPC. However, the strong nonlinearities introduced by the crab sextupoles and beam-beam interactions severely limit the dynamic aperture (DA), which is crucial for injection efficiency and beam lifetime.

Overall Layout & Luminosity Goal

- A new crab waist interaction region (IR) is designed, and a superconducting wiggler (SC Wiggler) is installed in the ring to increase synchrotron radiation damping, reduce emittance, and shorten the damping time. Additionally, a compact damping ring is inserted in the middle of the Linac.

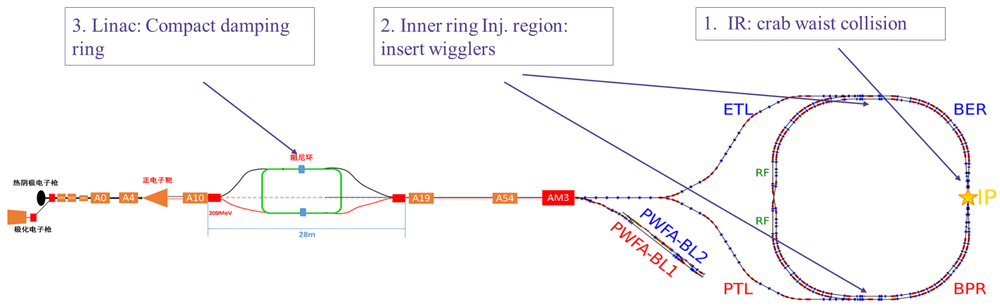


Figure 1. Overall layout of the BEPCII-UP.

- To achieve an order-of-magnitude luminosity enhancement, the target parameters at 1.89 GeV are designed: β_y^* is reduced to 5 mm, the beam-beam parameter ξ_y is increased to 0.09, and the bunch current $I_b$is increased to 12.5 mA.

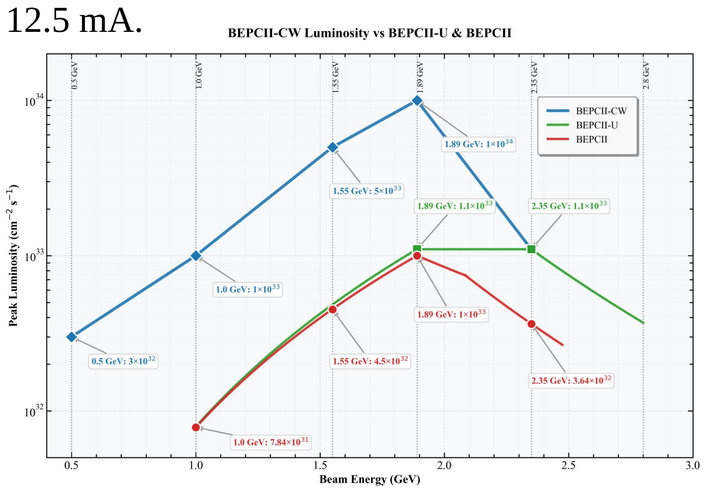


Figure 2. Luminosity performance blueprint for BEPCII-UP.

Lattice Design

- IR Geometry : Two layouts with half-crossing angles of 18.1 mrad and 40 mrad are designed. Modifications are strictly limited within ±23 m (or ±17 m) from the IP to fit the existing tunnel.

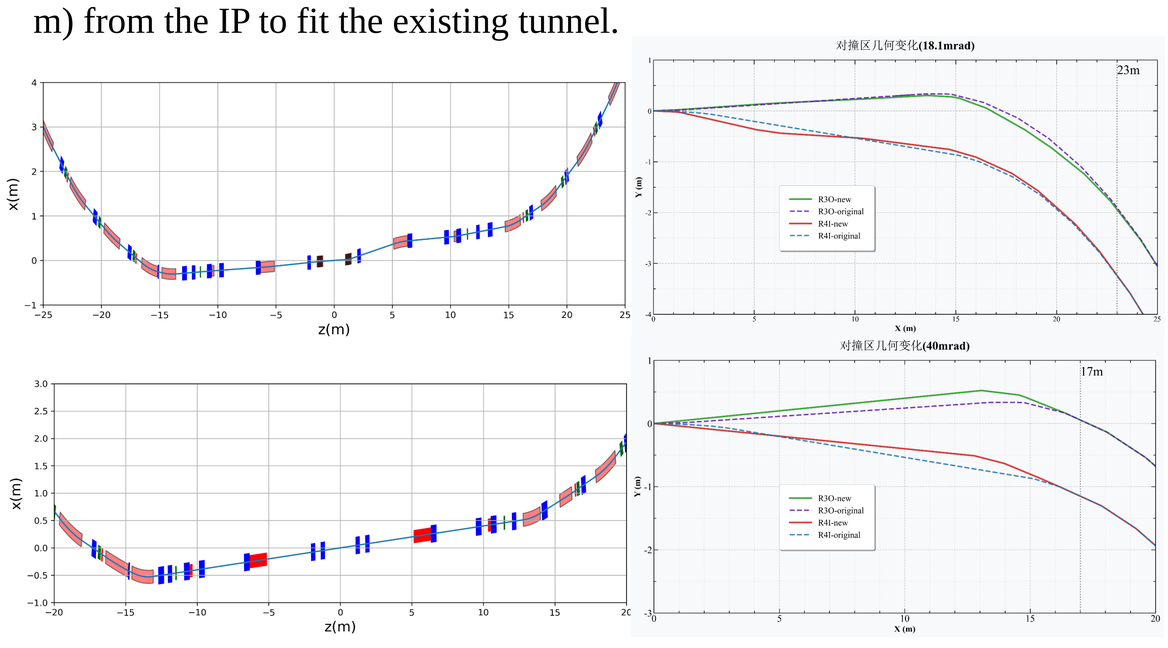


Figure 3: IR geometry for the 18.1 mrad (top) and 40 mrad (bottom) layouts.

Lattice Design

- The crab sextupoles are located at zero dispersion, and the phase advance between the crab sextupoles and the IP is set to (0.5, 0.75).

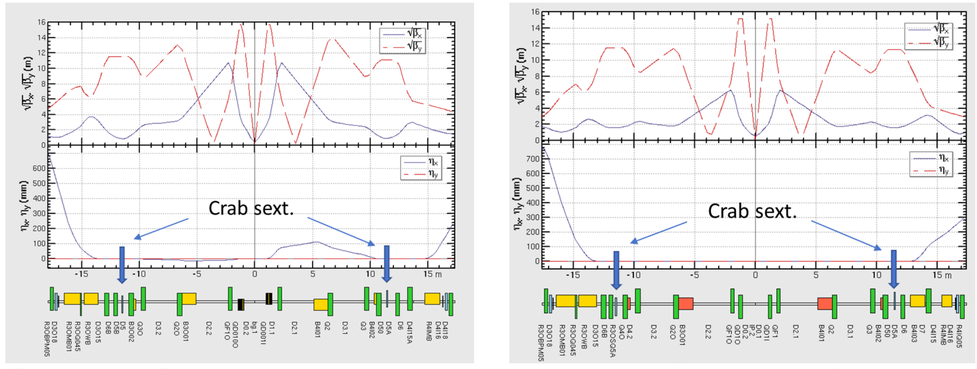


Figure 4: Optics parameter comparison near the interaction region for the 18.1 mrad (left) and 40 mrad (right).

- @0.5 GeV: A relatively large emittance is adopted to significantly improve the Touschek lifetime. This is achieved by lowering the integer part of the working point and increasing the dispersion at the wiggler section.

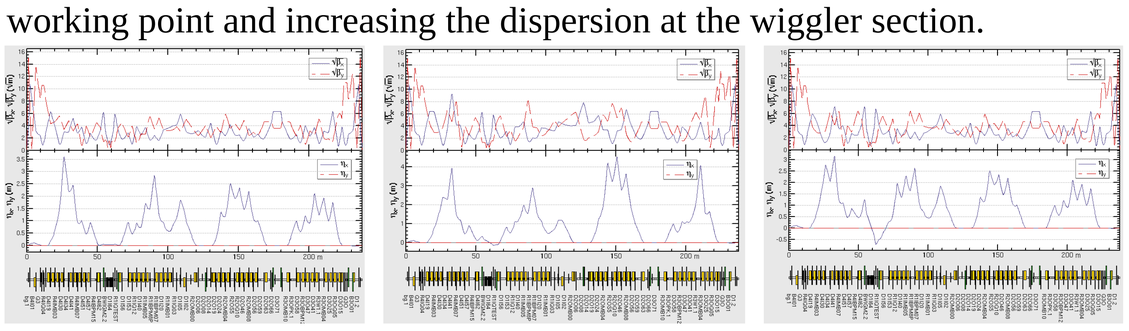


Figure 5: Three matching schemes at 0.5 GeV with emittances of 3.5 nm(left), 9 nm(middle), and 50 nm(right).

Dynamic Aperture Optimization

To enlarge the dynamic aperture, 4 new sextupoles are introduced in the IR (located between the superconducting QD/QF magnets and near the crab sextupoles). A systematic phase pairing strategy is adopted:

- Vertical Pairing: R4IS1 and R4IS5 are paired vertically, with phase advances to the final QD of π and 2π, respectively.
- Horizontal Pairing: R4IS4 and R4IS8 are paired horizontally, with phase advances to the final QF of 2π and 3π, respectively.
- The same pairing scheme is applied to the R3O region.

The best dynamic aperture (@1.89GeV) is significantly enlarged compared with the previous design. Furthermore, the number of B+S combined-function magnets is dramatically reduced from 50 to only 6. These 6 B+S magnets are distributed near the interaction region (3 in the R3O region and 3 in the R4I region), which greatly simplifies the hardware design while still maintaining a sufficient dynamic aperture for injection.

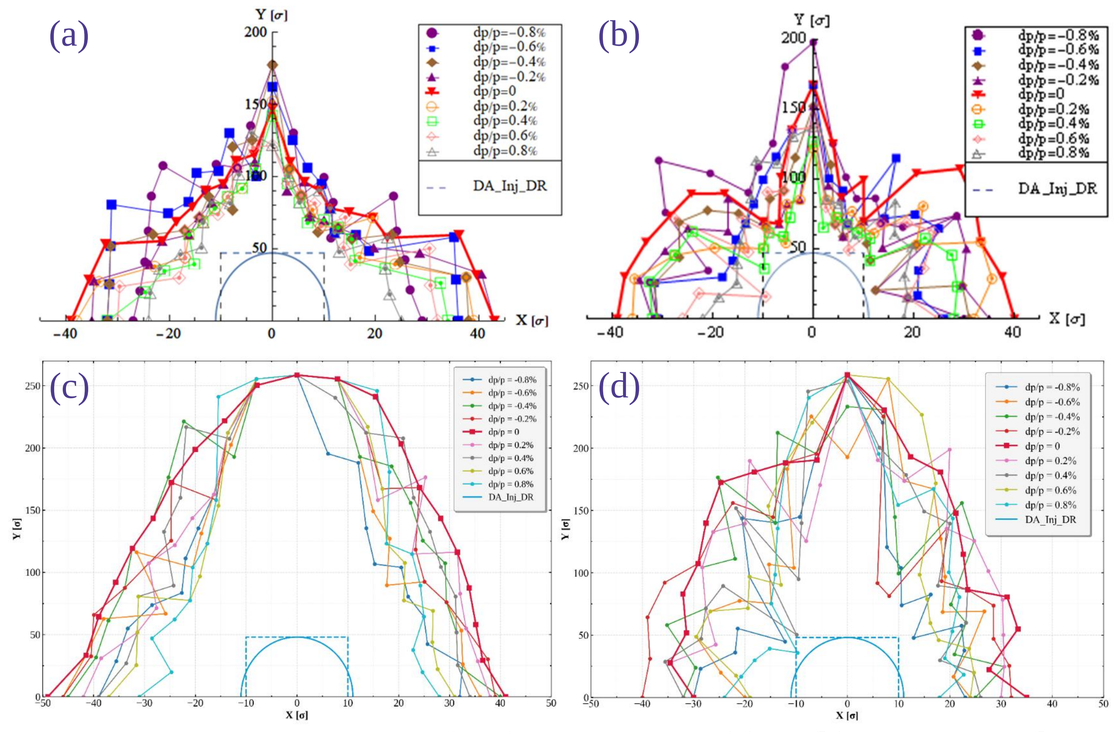


Figure 6: Dynamic aperture (DA) comparison. (a) & (b): Previous scheme consisting of the 36 original sextupoles and 50 B+S magnets, (a) W/O and (b) W/ beam-beam effects. (c) & (d): Optimized scheme containing the 36 original, 4 new sextupoles, and 6 B+S magnets, (c) W/O and (d) W/ beam-beam effects.

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