

DYNAMIC APERTURE TRACKING FOR HIGH-INTENSITY PROTON ACCELERATORS

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Abstract

Dynamic aperture tracking is an widely employed and effective method in the design of circular accelerators. However, in high-intensity proton accelerators, the pronounced space charge effect induces substantial tune shifts, which can severely compromise the accuracy of nonlinear dynamics analysis. In this study, we present a novel dynamic aperture tracking code tailored for high-intensity proton accelerators, which explicitly accounts for space charge-induced tune shifts. The CSNS/RCS synchrotron serves as a case study to validate the code's efficacy.

INTRODUCTION

Dynamic aperture (DA) tracking is a fundamental tool in the study and optimization of nonlinear beam dynamics for circular accelerators. It provides quantitative insight into the stable region in transverse phase space and is crucial for maintaining beam quality and minimizing losses during operation. For electron storage rings and low-intensity proton machines, single-particle tracking with multipole field errors is generally sufficient to describe the nonlinear behavior of the beam.

However, in high-intensity proton accelerators, collective effects, particularly the space charge effect, introduce significant complications. The space charge force generates a substantial tune spread across the particle distribution, with the maximum tune shift even reaching several tenths. Such a large tune spread makes particles interact with many resonance conditions, which are not well represented in standard single-particle nonlinear dynamics analysis. As a result, conventional DA tracking tends to misestimate beam stability and fails to reflect the actual loss mechanisms in high-intensity machines.

To address this issue, it is essential to incorporate space charge effects into the dynamic aperture tracking framework. Full self-consistent multi-particle simulations can achieve this, but they are computationally expensive and not well suited for systematic nonlinear optimization studies. Therefore, a simplified yet representative model that accounts for the influence of space charge on the tune distribution is highly desirable.

In this work, we develop a dynamic aperture tracking code specifically designed for high-intensity proton accelerators, in which the space charge-induced tune shifts are included analytically. The method allows efficient evaluation of the nonlinear dynamics under realistic space charge conditions. The Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS) [1] is used as a practi-

cal example to validate the approach and demonstrate its potential applications for the CSNS-II upgrade and similar high-intensity machines.

METHOD

In conventional DA tracking, particle motion is evaluated under the influence of static magnetic fields, including multipole components, while collective effects are neglected. This approach assumes that each particle follows a fixed tune, determined by the linear optics and magnetic nonlinearities. However, in high-intensity proton accelerators, strong space charge forces cause tune shifts and spreads that vary with particle amplitude and longitudinal position. These effects significantly alter the resonance structure and must be incorporated into the analysis.

To efficiently include space charge effects in DA studies, we applied a simple model that modifies the particle tunes according to their transverse amplitudes and the instantaneous beam current. The model assumes a Gaussian beam distribution and computes the incoherent tune shift using the linearized space charge formula:

$$\Delta Q_{x,y} = -\frac{r_p N_b}{2\pi \beta^2 \gamma^3 \varepsilon_{x,y}} F_{x,y},$$

where r_p is the classical proton radius, N_b is the number of particles per bunch, β and γ are the relativistic factors, $\varepsilon_{x,y}$ are the transverse emittances, and $F_{x,y}$ are form factors depending on the beam aspect ratio. The tune shifts are then mapped to each tracked particle based on its action variables, effectively generating an amplitude dependent tune spread.

This modified tune distribution is embedded into the DA tracking algorithm. At each integration step, particle motion is updated with the effective tune shift corresponding to its instantaneous amplitude. The resonance driving term (RDT) analysis is also adapted to include the space charge induced tune modulation, enabling a consistent evaluation of resonance strength and location under collective effects.

The calculation code is based on the code in [2]. The resulting code maintains computational efficiency comparable to traditional single-particle tracking, while providing a more realistic estimation of the stable phase space region in high-intensity machines.

RESULTS

The developed DA tracking code has been tested using the RCS of the CSNS as a representative case study. The CSNS/RCS accelerates protons from 80 MeV to 1.6 GeV at a repetition rate of 25 Hz, corresponding to a beam power

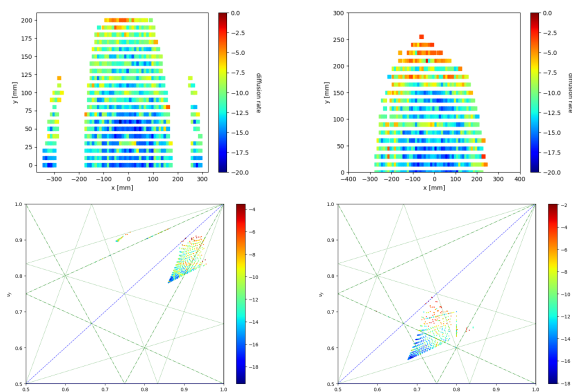


Figure 1: Dynamic Aperture of CSNS/RCS with (right) and without (left) the Space Charge Effect.

of 100 kW in routine operation. In the CSNS-II upgrade, the linac energy will be increased to 300 MeV and the beam intensity to 7.8×10^{13} protons per pulse, resulting in a significant enhancement of space charge effects.

For the simulations, a realistic lattice model including sextupole fields was employed. The entire ring consists of four periods, with each period containing four chromatic sextupole magnets. To minimize the beam loss caused by the frequency shift from the space charge effect, a relatively large Tune value (4.86, 4.78) is adopted. According to our other work [3], chromaticity has a significant impact on beam instabilities. To suppress beam instabilities, the horizontal and vertical chromaticities of the ring are corrected to $(-9, -9)$.

The space charge-induced tune shift was set according to the operational beam parameters, with the maximum incoherent tune shift reaching approximately 0.2. The DA was evaluated for 1000 turns, and the results were compared with those from conventional single-particle tracking without space charge effects.

Figure 1 compares the DA computed with and without the space charge effect using the present code. Contrary to the common expectation for generic lattices, the CSNS/RCS lattice was originally optimized with space charge in mind; as a result, including the space charge-induced tune shifts yields a larger DA than the tracking that neglects space charge. In other words, single-particle DA estimates (which ignore space charge) underpredict the stable region for this machine because the lattice and nonlinear corrections were tuned to the operational tune footprint including collective effects. RDT analysis indicates that the designed working point and multipole settings reduce the influence of low-order resonances once the realistic tune spread is applied, effectively

increasing the usable phase-space area. The proposed semi-analytical approach captures this behaviour while retaining a computational cost comparable to standard single-particle DA tracking, making it suitable for rapid lattice studies that must account for space charge.

These findings demonstrate that the presented method can efficiently predict dynamic aperture degradation in high-intensity proton rings. It provides a practical and fast tool for lattice optimization and nonlinear correction studies under realistic collective conditions, supporting the design and upgrade of next-generation high-power synchrotrons such as CSNS-II.

CONCLUSION

A novel DA tracking approach has been developed for high-intensity proton accelerators, explicitly incorporating space charge-induced tune shifts. The method provides an efficient semi-analytical treatment of collective effects, allowing realistic estimation of the stable phase space region without the computational cost of full multi-particle simulations.

Application to the CSNS/RCS synchrotron demonstrates that space charge significantly reduces the dynamic aperture, particularly at injection energy, and enhances resonance overlap. The proposed method accurately captures these effects and offers a practical tool for lattice optimization and nonlinear dynamics studies under high-intensity conditions.

This approach can be readily applied to the design and upgrade of next-generation high-power proton rings, such as the CSNS-II, providing a reliable framework for predicting beam stability and guiding corrective measures to mitigate beam loss in high-intensity operation.

In the future, we plan to refine the space charge model to better reflect actual beam conditions, enhancing the algorithm's realism and predictive power. Additionally, multi-particle simulations using PyORBIT and Pyheadtail will be performed to cross-validate the results, ensuring the reliability of the approach before its deployment in operational optimization of high-intensity machines.

REFERENCES

- [1] J. Tang *et al.*, "Physics design and technology development of CSNS accelerator", *Institute of High Energy Physics*, 2010.
- [2] <https://github.com/wei0852/simplestoragering>
- [3] L. Huang *et al.*, "Beam coupling impedance and collective effects in rapid cycling synchrotron of CSNS-II", *J. Instrum.*, vol. 20, no. 07, p. P07004, 2025.
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