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STUDY OF TRANSVERSE RESONANCE ISLAND BUCKETS AT CESR*

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Abstract

A 6-GeV lattice with the horizontal tune near a 3rd-order resonance line at $3\nu_x$=2 is designed for studying the transverse resonance island buckets (TRIBs) at the Cornell Electron Storage Ring (CESR). The distribution of 76 sextupoles powered individually is optimized to maximize the dynamic aperture and achieve the desired amplitude-dependent tune shift α_{xx} and the resonant driving term h_{30000}, which are necessary conditions to form stable island buckets. The particle tracking simulations are developed to check and confirm the formation of TRIBs at different tunes with clearing kicks in this TRIBs lattice. Finally, the lattice is loaded in CESR and the TRIBs are successfully observed when the horizontal fractional tune is adjusted to 0.665, close to the 3rd-order resonance line. Bunch-by-bunch feedback is also explored to clear the particles in the main bucket and the island buckets, respectively.

INTRODUCTION

Nonlinear resonances are critical topics in the beam dynamics of accelerator physics, which have been studied theoretically and experimentally for many years [1]. Normally a storage ring operates at tunes far away from resonant lines to avoid the negative impact such as instability, poor lifetime, and increased emittance. However, by taking advantage of the resonance nature, one application of the ring operating at the 3rd-order resonance line is to extract particles in multi-turns at CESRN-PS and ELSA [2]. Recently, MLS and BESSY-II have demonstrated the stable two-orbit operation by utilizing the transverse resonance island buckets (TRIBs) [3, 4]. The second orbit for the beam in the island decreased the x-ray pulse frequency by 3 or 4 times which expands the possibilities for timing experiments [5].

TRIBs form in the vicinity of a resonance line, which can be achieved by adjusting the horizontal tune along with the familes of sextupoles (harmonic and normal) to tune the amplitude-dependent tune shift (ADTS) to stabilize the beam [3]. This approach is effective but empirical tuning of the sextupoles may be required. With this method, TRIBs have been successfully observed at MLS, BESSY-II, and MAX-IV [6]. To understand how TRIBs can form at CESR, a relatively high-energy (6-GeV) storage ring, we choose a different approach by designing a lattice with the horizontal tune near the 3rd integer line and a new sextupole distribution, at which TRIBs could form easily by adjusting the horizontal tune only.

In this paper, we discuss the criteria of optimizing the sextupoles for the TRIBs. A particle tracking simulation is developed to demonstrate the formation of TRIBs at different tunes. The lattice is then loaded into CESR and the TRIBs are successfully observed while adjusting horizontal tune to 0.665. Clearing kicks using feedback kicker is explored to clear the particles in the core or island buckets.

LATTICE DESIGN

Cornell Electron Storage Ring (CESR) is a 6-GeV accelerator located on the Cornell University campus. Since 2008, CESR serves as a dedicated light source for x-ray users, namely Cornell High Energy Synchrotron Source (CHESS). In 2018, one sextant of the ring was upgraded with double bend acromat to reduce the emittance and accommodate more compact undulators [7]. The main accelerator parameters are listed in Table 1. CESR magnets including 113 quadrupoles, 12 dipole quadrupoles, and 76 sextupoles are all individually powered, which provides great flexibilty for lattice design and complex nonlinear dynamics studies. Details of CESR lattice are described in Ref [7].

As shown in Table 1, the nominal horizontal fractional tune (Q_x) during CHESS operation is 0.556, far from the 3rd-order line $3\nu_x$=2 (0.667). It is very unlikely that TRIBs would appear by only adjusting the tune near 0.667. Thus, we first optimize quadrupoles to create a linear lattice with the design tunes at (16.643, 12.579) closer to the 3rd-order line while preserving most optics parameters as the normal lattice. Then 76 sextupoles are optimized to meet the conditions of forming TRIBs as well as maxmizing the dynamic aperture (DA).

The formula of the stable fixed points (SFP) have been derived in Reference [1] as shown in Eq. (1),

$$J_{SFP}^{1/2} = \frac{3G_{3,0,l}}{4\alpha_{xx}}\left(1 \pm \sqrt{1 - \frac{16\alpha_{xx}\delta}{9G_{3,0,l}^2}}\right), \quad (1)$$

where J_{SFP} is the particle's action at the SFP, $G_{3,0,l}$ is the resonance strength at the 3rd-order resonance $3\nu_x$=l, α_{xx} is the detune coefficient of ADTS, and δ=$Q_x - \frac{l}{3}$. As Eq. (1) implys, the formation of TRIBs depends on three variables

Table 1: CESR Parameters

Beam Energy (GeV)	E_0	6.0
Circumference (m)	L	768.438
Transverse Damping time (ms)	$\tau_{x,y}$	12.0, 14.6
Longitudinal Damping time (ms)	τ_z	8.2
Synchrotron tune	Q_s	0.027
Horizontal tune	Q_x	16.556
Vertical Tune	Q_y	12.636
Horizontal Emittance (nm·rad)	ϵ_x	~ 28
Energy spread	σ_p	8.2×10^{-4}

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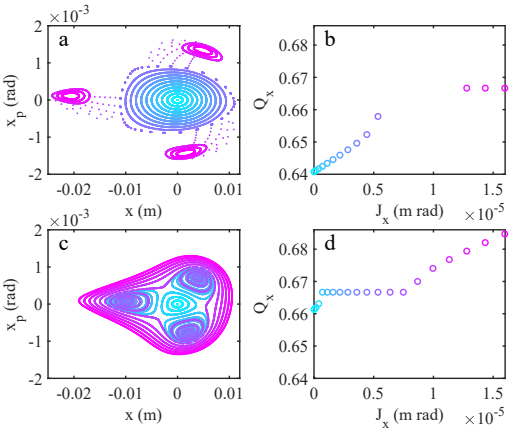

Figure 1: Particles' xx_p plots at two lattice tunes (a) Q_x=0.643 and (c) 0.661. The particle's Q_x as a function of its action in (b) and (d) are calcuated from the TBT data ploted in (a) and (c), respectively.

$G_{3,0,l}$, α_{xx}, and Q_x. Thus, adjusting the tune (Q_x) and the ADTS (α_{xx}) will help the formation of TRIBs.

For sextupole optimization, appropriate target values of $G_{3,0,l}$ and α_{xx} are needed. Suppose we approach the 3rd-order line from below and observe TRIBs at Q_x=0.654 (δ=−0.013) with J_{SFP}=1.0×10^{-5} m·rad, which is within the range that our instrument [8] can measure the TRIBs. Since δ<0, α_{xx}>0 will satisfy the bifurcation condition $\frac{16\alpha_{xx}\delta}{9G^2_{3,0,l}} \leq 1$ more easily. Using Eq. (1) with the above requirements, we obtain one set of values $G_{3,0,l}$=0.1 and α_{xx}=1347 for the sextupole optimization. In the optimization requirement, resonant driving terms except h_{30000} and h_{22000}, which are directly related to $G_{3,0,l}$ and α_{xx}, respectively, are minimized to maximize the DA. The horizontal and vertical chromaticities are fixed at 1.

SIMULATION

Once the linear lattice with desired sextupoles are optimized, simulations are implemented to check the lattice properties. All the simulation programs discussed below are based on BMAD code library [9]. First, 20 particles with different action are tracked through the TRIBs lattice at different Q_x for 1000 turns while RF, radiation damping and excitation are turned off. Figure 1 (a) and (c) plot the xx_p of all particles at Q_x=0.643 and 0.661, respectively. Three stable islands are clearly visible at both tunes in the phase space. From FFT analysis of the turn-by-turn (TBT) x coordinates, the particles' Q_x are calculated and shown as a function of their actions in Fig. 1 (b) and (d). Both plots show that Q_x increases as the particle's action increases, indicating a positive ADTS coefficient (α_{xx}>0). When the particles are in the stable islands, their tunes are exactly 2/3. Several particles are lost while tracking through the lattice with Q_x=0.643 so that their tunes are absent in Fig. 1 (b).

From the xx_p phase space plots in Fig. 1, the action of SFP at different Q_x is extracted and plotted in Fig. 2. The

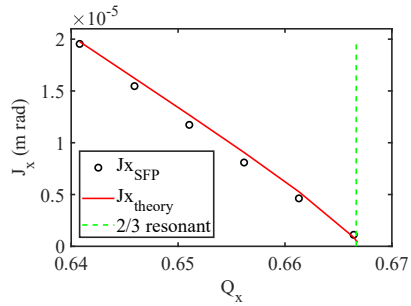

Figure 2: The particle action at the SFP as a function of lattice tune.

extracted Jx_{SFP} decreases as the tune approaches the 3rd-order resonance line, indicating the island sepration in the horizontal plane shrinks. The simulated Jx_{SFP} agrees very well with the calcuated Jx_{theory} using Eq. (1).

Frequency map analysis is performed to check the DA of the TRIBs lattice at different tunes. Figure 3 (a) and (b) show the DA at Q_x=0.643 and 0.661, respectively. It is interesting that both the island and main buckets are visible in these plots. The horizontal DA of the island bucket is much less than the main buckets at Q_x=0.643 while comparable to the main bucket at Q_x=0.661, which is consistent with the phase space plots in Fig. 1.

More realistic tracking simulation including radiation damping and excitation is implemented to check the TRIBs formation in the TRIBs lattice. Starting with an initial distribution with design emittance ϵ_x=30 nm·rad (Fig. 4 (a)), 1000 particles are tracked through the lattice at different horizontal tunes. Since the horizontal radiation damping time in CESR

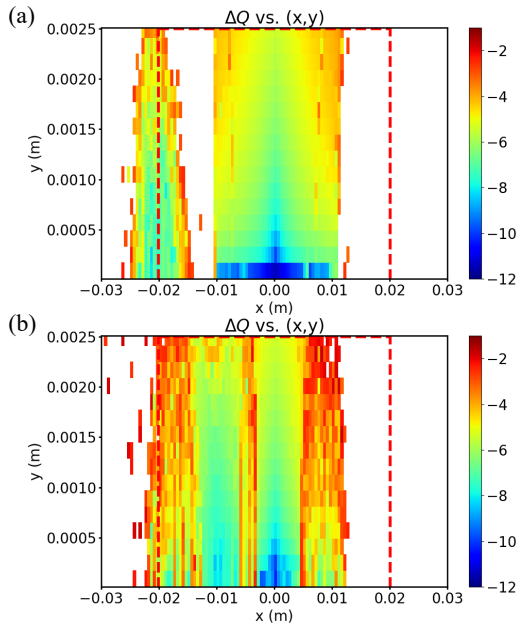

Figure 3: Dynamic aperture at two different horizontal tunes (a) Q_x=0.643 and (b) 0.661. The red dash lines indicate the physical apertures at element 1.

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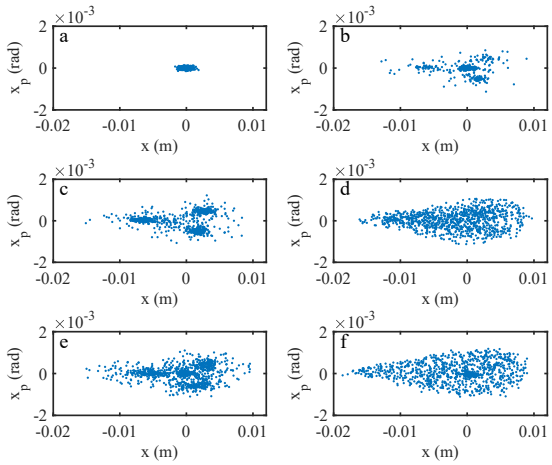

Figure 4: The 1000-particles distribution in the xx_p phase space at Q_x=0.6649 (259.4 kHz) at (a) turn 1 and (b) turn 40000, when applying a sinusoidal kick at f=259.4 kHz with the kick amplitude of (c) 0.5 μrad and (d) 5 μrad at turn 40000, and at f=261.35 kHz with the kick amplitude of (e) 0.5 μrad nad (f) 5 μrad at turn 40000.

is 12 *ms* (~5000 turns), 4×10^4 turns is used for tracking to cover ~8 damping times. When Q_x<0.6613 (258 kHz), the particles remain in the similar distribution through 4×10^4 turns as seen in Fig. 4 (a). When Q_x>0.6639 (259 kHz), the particles diffuse from the core to the island buckets. Figure 4 (b) shows the particles occupy three islands as well as the core after tracking 4×10^4 turns at Q_x=0.6649 (259.4 kHz).

Starting with the distribution in Fig. 4 (b) and applying a sinusoidal kick at f=259.4 kHz same as the core tune, most particles are driven from the core to island buckets (Fig. 4 (c)) after tracking 4×10^4 turns. However when the sinusoidal kick amplitude is greater than 3 μrad, the particles are not clustered in the islands but distributed in the xx_p space evenly (Fig. 4 (d)).

When starting tracking with the initial distribution as in Fig. 4 (c) with the sinusoidal kick at f=261.35 kHz near the island tune (0.667), the particles are converged back to the core bucket but not fully cleared from the islands buckets after 4×10^4 turns (Fig. 4 (e)). When increasing the kick amplitude to 5 μrad, the particles are cleared from island buckets but most of them are evenly distributed in the phase space (Fig. 4 (f)).

EXPERIMENT

After confirming the formation of TRIBs in simulation, we loaded the TRIBs lattice into CESR. Once the optics correction were made (phase and orbit), we adjusted Q_x from 0.6537 to 0.667 while viewing and recording the beam profile from synchrotron radiation using vBSM [8]. The beam profile images from a 1-mA single positron bunch observed at different tunes are shown in Fig. 5. When Q_x<0.663 (258.7 kHz), the beam stays in the core (Fig. 5 (a)). When

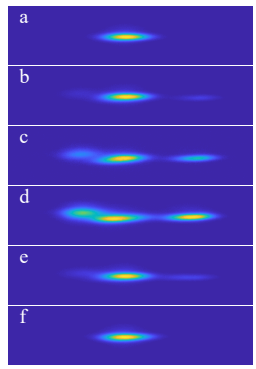

Figure 5: Beam profiles at Q_x= (a) 0.6613 (258.0 kHz), (b) 0.6631 (258.7 kHz), (c) 0.6648 (259.35 kHz), and (f) 0.6700 (261.4 kHz). (d) and (e) are recorded at the same tune 0.6638 (259.35 kHz) but with applying a sinusoidal kick at f=259.35 kHz and 261.35 kHz, respectively.

Q_x is near 0.663 (258.7 kHz), the TRIBs start to form (Fig. 5 (b)) while most particles are still in the core bucket. When Q_x=0.6648 (259.35 kHz), more particles diffuse to the island buckets (Fig. 5 (c)). A bunch-by-bunch feedback was then used to apply a sinusoidal kick (~0.1 μrad) with the same frequency as the core tune 259.35 kHz to the beam. This clearing kick drives the particles from the core to the island buckets (Fig. 5 (d)). If the sinusoidal kick's frequency was set to 261.35 kHz, this clearing kick drives the particles from the islands to the core (Fig. 5 (e)). But there are still some particles remaining in the island buckets. When Q_x is above the 3rd-order resonant line 0.667 (260.1 kHz), all the particles diffuse back to the core island (Fig. 5 (f)). The experimental observation agrees well with the simulation results. The behavior of the clearing kick is consistent with the results reported in Ref [3].

CONCLUSION

We studied the conditions of TRIBs formation near a 3rd-order resonance line and designed a special lattice with optimized sextupole distribution to meet the requirement. Tracking simulation is then developed to confirm the formation of TRIBs. Finally, the lattice was loaded into CESR and the TRIBs were observed at Q_x=0.6648 (259.35 kHz). In addition, the sinusoidal kicks at 259.35 kHz or 261.3 kHz help to clear the particles in the core or island buckets, respectively. In conclusion, we have demonstrated a new approach to design and observe TRIBs in a high-energy storage ring, which provides guidance for future systematic TRIBs study.

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