OFF-ENERGY INJECTION INTO NEWSUBARU*

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Abstract

The NewSUBARU electron storage ring temporarily operated with a non-achromatic lattice using chromaticity modulation. In this special mode, off-energy beam injection offers higher injection efficiency. The ring energy (magnetic field strength) was reduced by 0.7%, so that the injected beam energy was higher than the ring energy. The finite dispersion at the injection point reduces the betatron oscillation of the injected beam, while it starts the synchrotron oscillation. Using this technique, it became possible to inject a new beam without losing the stored beam. This was necessary for off-axis top-up operation.

INTRODUCTION

The 1.5 GeV electron storage ring NewSUBARU [1] was constructed in the SPring-8 site in 1998 for research and development on synchrotron radiation technology and its industrial applications. In 2006 the AC sextupole magnet was installed at one of the straight sections for accelerator physics research. When the ring operates with a non-achromatic lattice the magnet produces chromaticity modulation, which suppresses beam instabilities [2]. The research for instability suppression was terminated in 2010, however, new research using chromaticity modulation started in 2011. It would produce oscillating spatial structure in a bunch, which would emit narrowband coherent radiation in the THz region [3].

One of problems of this lattice was poor beam injection because of the small dynamic aperture. At the early commissioning of this lattice, most of the stored beam was killed to inject a new beam. At the present, the off-energy injection enabled sufficiently high injection for off-axis top-up operation.

The off-energy injection enables a small betatron oscillation of the injected beam, utilizing finite dispersion at the injection point [4]. Fig. 1 shows a schematic drawing, explaining the basic idea. The ring parameters are the same for the matched-energy and the off-energy injection. The energy displacement of the injected beam transfers the betatron oscillation to the synchrotron oscillation. In the simplest case, the reduced action of the betatron oscillation J_x is given as

$$2J_x = (x_D - \eta\delta_{INJ})^2 / \beta_x . \quad (1)$$

Here x_D is the displacement of the injected beam position from the injection bump orbit, δ_{INJ} is the energy displacement, and η and β_x are the dispersion and the horizontal beta function at the injection point, respectively.

The trade-off is the synchrotron oscillation produced by the initial energy displacement, δ_{INJ}.

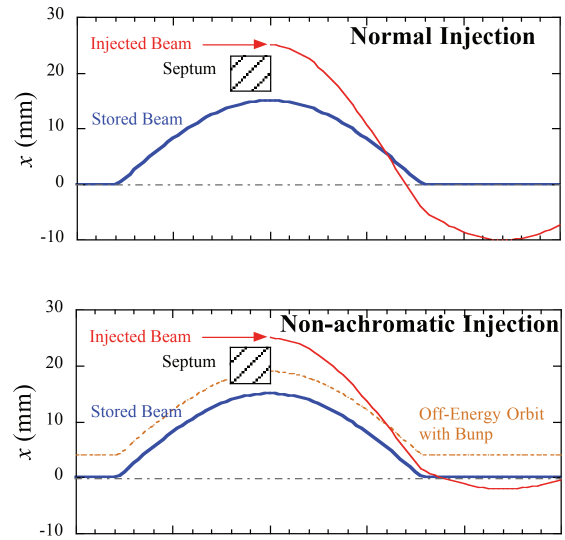

Figure 1: The beam orbit at the injection in cases of the normal (matched-energy) injection (above) and the off-energy injection (below).

INJECTION INTO NEWSUBARU

The Non-Achromatic NewSUBARU Lattice

The main parameters of NewSUBARU are listed in Table 1. The ring is a racetrack type, with a circumference of 118 m., It has two 14 m long and four 4 m long straight sections.

Table 1: NewSUBARU's Basic Parameters

Injection Energy	0.976 GeV
Circumference L_0	117.8 m
Betatron tune: ν_x / ν_y	6.30 / 2.23
Chromaticity: ξ_x / ξ_y	3.4 / 5.8
Synchrotron tune: ν_s	0.0024
Momentum compaction factor: α_p	0.00136
Septum wall from the beam center: x_{MAX}	+21 mm
Septum thickness: Δx_{SEP}	3 mm

Table 2 shows parameters for a normal achromatic lattice and a non-achromatic one. The betatron tuning frequencies (ν_x and ν_y) and the momentum compaction factor (α_P) are the same. Figure 2 shows the Twiss

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parameters (β_x and β_y) and η of the non-achromatic lattice along 1/4 of the ring.

Table 2: NewSUBARU Parameters at the Injection Point at 1.0GeV, for the Achromatic and Non-Achromatic Lattices.

Lattice	Achromatic	Non-achromatic
Natural emittance	50 nm	80 nm
Dispersion	0 m	1.1 m
Dispersion angle η'	0	0.05 rad.
Beta function β_x / β_y	9.36/11.57	10.0/15.9
Alpha function α_x / α_y	-0.035/-0.14	-0.15/-0.19
Horizontal beam size σ_x	0.6 mm	1.03 mm

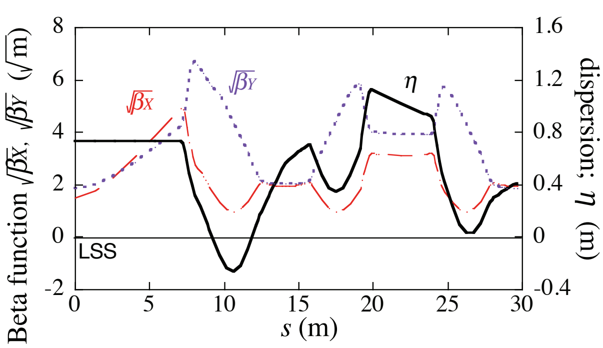


Figure 2: Beta functions and dispersion function of non-achromatic lattice in 1/4 of NewSUBARU. The solid, the dashed, and the dotted lines show η, $\sqrt{\beta_X}$ and $\sqrt{\beta_Y}$, respectively.

Beam Injection System of NewSUBARU

The layout of the injection system of NewSUBARU is shown in Fig. 3. Four pulsed bump magnets produce the injection local bump. Its time width is roughly 1 ms, slightly longer than 2 revolution periods. The pulse septum is an out-of vacuum type, with the septum thickness of 3 mm. The septum wall position of the circulating beam is 21 mm from the duct center. In order to separate the beam from the septum by $4\sigma_x$, the height of the closed injection bump should be less than 17 mm.

The injection bump orbit is not closed during normal user operation. The orbit difference x_D is shared by the injected and stored beam to produce two opposite betatron oscillations. The injection efficiency of 95–100% is realized with a fine parameter tuning.

The beam injection into the non-achromatic lattice is expected to be more difficult than that into the achromatic one, because the circulating beam size is expected to be 1.7 times larger, as listed in Table 2.

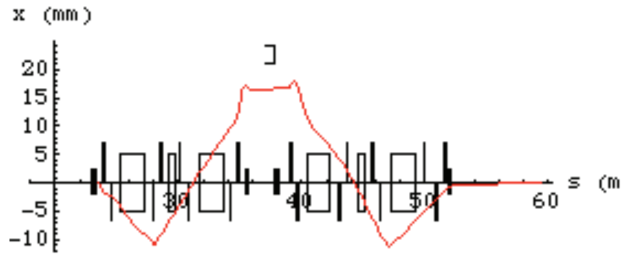
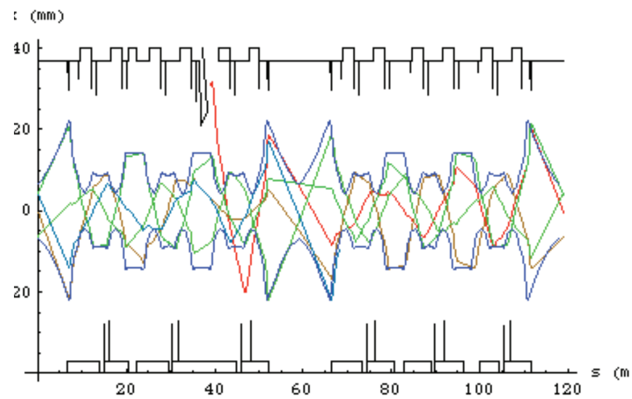
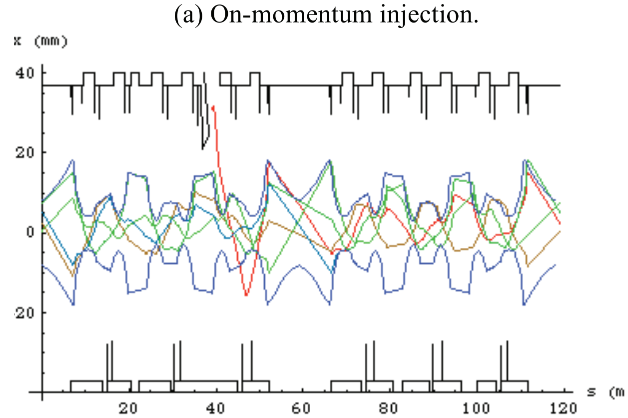


Figure 3: The closed injection bump in NewSUBARU. The height at the injection point is 16 mm. Four small squares indicate the locations of the four pulse-bump magnets. The top clear box shows the location and the thickness of the septum. The stored beam goes from the left to the right.



(a) On-momentum injection.



(b) Off-momentum injection (+0.5%).

Figure 4. Orbit excursion of the injected beam in the cases of (a) matched-energy injection and (b) off-energy injection. The injection point (the exit of the pulse septum) is at s = 38m. The red, brown, light green, dark green, and dark blue lines are the orbits at the 1st–5th turns after the injection, respectively, during which the pulse bump field was active. The two thick blue lines show the envelope of the orbit excursion after the 5th turn, which includes the spread by the synchrotron oscillation, but ignores radiation damping. The black lines on the top and the bottom show the physical acceptance of the ring.

Orbit Calculation

We calculated the beam orbit in a linear lattice, which meant that all sextupoles were turned off. Fig. 4 shows the results — the beam trajectory of the initial few turns and the beam oscillation envelope for the energy-matched and off-energy injection with $\delta_{INJ} = 0.5\%$. The assumed closed bump height was 16 mm at the injection point. The oscillation envelope became smaller with the off-energy injection.

Injection at NewSUBARU

Instead of changing the energy of the injected beam, we changed the energy (magnetic field) of the ring. Fig. 5 shows the injection efficiency for various injection bump heights and the ring energies. A better injection is obtained at around 0.966 GeV, which was about 1% lower than the energy-matched condition. The best energy displacement was larger for a smaller bump height. This was expected from Eq. 1.

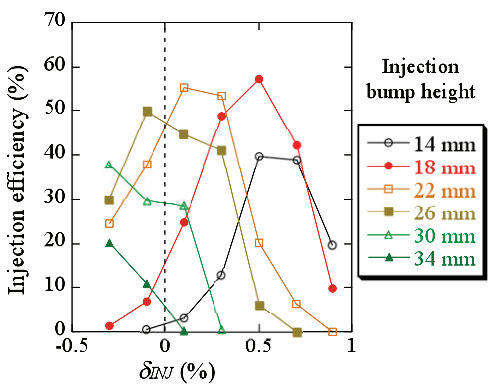


Figure 5: Dependence of the injection efficiency on ring energy for different pulse bump heights.

With additional parameter tuning of the injection bump, we realized the injection efficiency of 40%. In these conditions the pulse bump was not closed, the bump height entering the injection point was 15 mm, and the departure height was 17 mm. Fig. 6 shows the demonstration of the beam accumulation by injection and top-up operation at 100 mA, which was impossible with matched-energy injection.

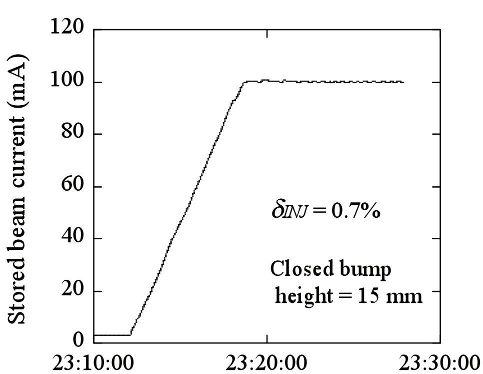


Figure 6: Stored beam current during the test of 100 mA top-up operation using the closed injection bump.

INJECTION INTO A LOW-ALPHA RING

Here we discuss a small effect of the betatron amplitude-dependent circumference shift [5, 6], which should be considered as a special case. The circumference shift moves the equilibrium energy of the injected beam [7] to

$$\delta_0 = (2\pi / \alpha_P L_0)\xi_x J_x. \qquad (2)$$

This means that the synchronous energy of the injected beam is different from the stored energy. Then the initial energy mismatch for the synchrotron oscillation is

$$\delta_{INJ} - \delta_0 \,. \qquad (3)$$

In our case, for $x_D - \eta\delta_{INJ} = 7$ mm, the shift of the equilibrium energy is calculated to be $\delta_0 = 0.03\%$. It reduces the energy mismatch, but the effect is very small.

However, in quasi-isochronous (low α_P) operation, this effect becomes considerable, because δ_0 is proportional to $1/\alpha_P$. There exists a condition for the energy matching (no collective synchrotron oscillation of the injected beam).

$$\delta_{INJ} = (2\pi / \alpha_P L_0)\xi_x (x_D - \eta\delta_{INJ})^2 / (2\beta_x) \qquad (4)$$

At the limit of $\alpha_P = 0$, both the betatron oscillation and the synchrotron oscillation disappear at $\delta_{INJ} = x_D/\eta$. The displaced energy is exponentially damped to zero without oscillation. In a more realistic case, when ξ_x/α_P is small, the matching condition is approximated as

$$\frac{\eta\delta_{INJ}}{x_D} \approx \pi\xi_x \left(\frac{x_D}{\beta_x}\right)\left(\frac{\eta}{\alpha_P L_0}\right). \qquad (5)$$

It should be noticed that the best injection energy is different from the ring energy and may be considerable at low α_P.

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