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Beam Current Limitations due to Single-Beam Collective Effects in the Ion Storage Ring of RIKEN RI Beam Factory Project

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Abstract

Single-beam collective effects limit the beam current when beams are served for colliding experiments in the presently designed ion ring. For the some hundreds MeV/u ion beam making the betatron tune shift -0.2, longitudinal instabilities occur with growth times of 0.02 s, and the transverse resistive wall instability with growth time of 1 s. The electron cooling with cooling time of 0.01 s at the full momentum spread 10^{-3} of the ion beams can damp the instabilities. Then, the luminosity is much less than 1×10^{27} $cm^{-2}s^{-1}$ on the heavy ion side. A proposal about the lattice of the ring is made to improve the luminosity.

1. Introduction

The RIKEN Accelerator Research Facility group has been proposing "RIKEN RI Beam Factory" as a next facility-expanding project [1]. The factory takes the aim at providing RI beams of the whole mass range in a wide energy range up to several hundreds MeV/u. Ion beams from the existing RRC are accelerated and, or qualified as a cooled beam, a high current beam, and, or an RI beam through a superconducting ring cyclotron, an accumulator-booster-cooler ring, and, or an RI beam generator. The beams are injected to the one of a twin storage ring that is called Double Storage Rings (DSR). Electron beams from a 300 MeV linac are accumulated and accelerated in the other one. The colliding experiments are carried out at two interaction sections (IS) in DSR. On the other hand, ion beams are injected to both the rings for ion-ion merging experiments. Both the lattices of the rings have been designed to be the same. Table 1 shows the parameters of DSR.

Table 1: Parameters of DSR.

Circumference of a ring	178.694 m
Max. magnetic rigidity	12.76 Tm
Radius of curvature	8.506 m
Beam energy (injection $\rightarrow$ top)	
ion(Z/A=0.5)	0.4 $\rightarrow$ 1.2 GeV/u
ion(Z/A=0.387)	0.15 $\rightarrow$ 0.82 GeV/u
electron	0.3 $\rightarrow$ 2.5 GeV
Betatron tune ($\nu_x/\ \nu_y$)	6.350/5.763
Momentum compaction factor	0.0424
Natural chromaticity (ξ_x/ξ_y)	-10.81/-7.43
Beta function at IS ($\beta_x^*/\ \beta_y^*$)	0.60/0.60 m
Dispersion at IS ($\eta_x/\ \eta_x$)	0.0/0.0 m
Max. stored electron beam current	0.3 A
Number of bunches (ion/electron)	30/15
Electron rms emittance ($\varepsilon_x\approx\varepsilon_y$)	
at 0.3 GeV	8×10^{-9} $\pi mrad$
at 2.5 GeV	530×10^{-9} $\pi mrad$

Colliding experiments require beams of high luminosity and small momentum spreads. For this, ion beams are intensified and cooled down so that the full momentum spread may become at most 10^{-3} and the transverse emittances may become $1\times10^{-6}\pi mrad$, before the injection to the ring. They are bunched with the full bunch length of 40 cm in the ring. The qualification always does not increase the luminosity, because it makes single-beam collective effects strong and the effects limit beam currents.

Here, current limitations of ion beams and electron beams are estimated which are due to beam-beam effects during the collision, the direct space charge effects, and beam instabilities in the presently designed ion ring, but not in the electron ring. Instabilities are treated of just in the injection energies, because the lower the beam energy, the more easily instabilities occur. Both the lightest ion and the heaviest ion are treaded of in order to watch the dependence on ion species. The luminosity is evaluated for the threshold beam currents. Finally, a proposal is made to improve the luminosity.

2. Electron Beam Current Limitations

In DSR a 15-bunched electron beam circulating in the one ring collides with a 30-bunched ion beam circulating in the other ring at two IS's with zero colliding angle. The linear tune shift of the ion due to the beam-beam effect is described as follows under the assumption where the charge distribution of the electron round beam is Gaussian with the rms σ_{re} in the radius direction [2];

$$\xi_i=\frac{(1+\beta_i\beta_e)\beta_\perp^* N_{Be} r_p\, Z/A}{4\pi\sigma_{re}^2\beta_i^2\gamma_i}, \qquad (1)$$

where β_i and β_e are velocities of the ion and the electron beams normalized by the light velocity c, respectively, $\beta_\perp^*$ the beta function at IS's, N_{Be} the number of electrons per bunch, r_p the classical proton radius, Z/A the charge to mass ratio of the ion, and γ_i the ion mass normalized by the rest mass. The stability of the lattice of the ion ring requires

$$\left|\cos\mu-2\pi\xi_i\sin\mu\right|\le1, \qquad (2)$$

where μ is half the phase advance of the ring. One has the following requirement, reserving a little safety margin;

$$\xi_i\le0.05. \qquad (3)$$

With substitution of $\sigma_{re}^2=\varepsilon_{RMSe}\beta_\perp^*$ to Eq. (1) (the beta function of the electron ring at IS is designed to be equal to that of the ion ring), the threshold number of the electrons per bunch is evaluated as shown in Table 2.

Table 2: The threshold number of electrons per bunch due to the beam-beam effect.

Ion $\times$ electron	300 MeV e^-	2.5 GeV e^-
400 MeV/u $^4He^{2+}$	3×10^9	2×10^{11}
150 MeV/u $^{238}U^{92+}$	2×10^9	1×10^{11}

On the other hand, the stored current of the electron beam is expected to be at least 300 mA, when the beam of 300 MeV is injected in the ring. Then, the number N_{Be} becomes 7×10^{10}. The electron bunch population N_{Be} shown in Table 2 is limited by the value further.

3. Ion Beam Current Limitations

3.1 Incoherent betatron tune shift due to direct space charge

For a round beam whose charge distribution is assumed to be

Gaussian with the rms σ_{ri} in the radius direction and parabolic with the full bunch length ℓ in the longitudinal direction, the incoherent betatron tune shift of ions with small betatron amplitude due to direct space charge is described by [3]

$$\Delta\nu = -\frac{\beta_\perp N_{Bi} r_p Z^2/A}{4\pi\sigma_{ri}^2 \beta_i^2 \gamma_i^3 B_f}, \quad (4)$$

where $\beta_\perp$ is the average beta function of the ion ring, N_{Bi} the bunch population of ions, and $B_f = \ell/(3\pi R)$ the bunching factor, R being the average radius of the ring. Here, one properly uses the equality $4\sigma_{ri}^2 = \varepsilon_i \beta_\perp$ on treating of ion beams whose charge distribution is not Gaussian. When resonance compensation is carried out well, the shift of $|\Delta\nu| \le 0.2$ is tolerable. Then, the bunch population N_{Bi} is limited as follows;

$$N_{Bi} \le \begin{matrix} 1\times10^9 \\ 7\times10^6 \end{matrix} \text{ for } \begin{matrix} 400\ MeV/u\ {}^4He^{2+} \\ 150\ MeV/u\ {}^{238}U^{92+} \end{matrix} \quad (5)$$

3.2 Impedance budget

The lattice of DSR has been being optimized nowadays. The structure of the vacuum chamber and numbers of the elements have not yet determined. Here, the beam coupling impedances with the chamber are estimated under a rough assumption of them.

Longitudinal broad band impedances of bellows and flanges, transition sections, slits of vacuum ports, and clearing electrodes of disk type are evaluated with the theoretically derived equations [4], [5], [6], and [7], respectively. Longitudinal impedances of strip-line monitors are estimated with the equation [8].

A candidate of the RF cavity for the ion ring is a λ/4 coaxial cavity with the use of a perpendicular bias field on the ferrite [9]. The higher order cavity modes are strongly suppressed with the damper [10]. The longitudinal impedance of the RF cavity for DSR is assumed to be like that of the 50 MHz 150 kV prototype synchrotron cavity [11], but the frequencies of HOM are assumed to be just integer times as large as the fundamental frequency. The RF voltage of 700 kV is given with seven cells of cavity in order that the bunch length is reduced to 40 cm.

The longitudinal impedances except the resistive wall one are shown for the injection energies of 150 MeV/u of the heaviest ions and 400 MeV/u of the lightest ions in Table 3. The transverse broad band impedances shown in Table 4 are evaluated with the relation

$$[Z_\perp]^{BB} = \frac{2R}{\beta_i b^2}[Z_L/n]^{BB}, \quad (6)$$

where a round vacuum chamber is assumed with inner radius b=4 cm. It is known that the space charge impedance is dominant in the energy region of DSR.

Table 3: The imaginary parts of the longitudinal impedances $Im(Z_L/n)[\Omega]$ of the ion ring of DSR at the low frequency.

Injection energy	150 MeV/u	400 MeV/u
Space charge	1900	860
Bellows	-1.4	-2.0
Flanges	-0.04	-0.05
Transition sections	-0.1	-0.2
Slits of vacuum ports	-0.002	-0.003
Clearing electrodes	-0.14	-0.21
RF equivalent BB	-1.5	-1.5
Strip-lines	-0.05	-0.07

Table 4: The imaginary parts of the transverse impedances $Im(Z_\perp)[M\Omega/m]$ of the ion ring of DSR at the low frequency.

Injection energy	150 MeV/u	400 MeV/u
Space charge	6600	2300
Broad band	-0.2	-0.2

3.3 Longitudinal instabilities

The microwave instability is undesirable, because it induces bunch lengthening when the bunch population goes beyond a threshold, and the lengthening decreases the luminosity. The threshold peak current I_{pi} is given with Keil Schnell criterion under the parabolic momentum distribution [12];

$$\frac{2I_{pi}e}{\pi m_p c^2 \frac{A}{Z}\beta_i^2\gamma_i|\eta|(\Delta p/p)^2}\left|\frac{Z_L}{n}\right| \le 0.6, \quad (7)$$

where e is electronic charge, η the slippage factor, and $\Delta p/p$ the fwhm momentum spread. The equation (7) shows

$$N_{Bi} \le \begin{matrix} 1.4\times10^9 \\ 1.6\times10^7 \end{matrix} \text{ for } \begin{matrix} 400\ MeV/u\ {}^4He^{2+} \\ 150\ MeV/u\ {}^{238}U^{92+} \end{matrix}. \quad (8)$$

It is known that the microwave instability does not occur for the ion bunch population making the betatron tune shift $|\Delta\nu| \le 0.2$.

When a bunched beam circulates with the angular frequency ω_0 in a ring, it can have following longitudinal frequency components without perturbation;

$$\omega_p = \omega_0(pB + m + n\nu_s), \quad (9)$$

where B is the number of bunches, $p = 0, \pm1, \pm2, \cdots$etc., ν_s the synchrotron tune, m $(=0,1,\cdots,B-1)$ the coupled-bunch mode, and n $(=0,\pm1,\pm2,\cdots$etc.) the synchrotron mode. With perturbation, the frequency is coherently shifted, in the Sacherer-Zotter formalism [13], by

$$\Delta\omega_L^{m,n} = -j\frac{|n|}{|n|+1}\frac{\frac{Z}{A}I_{pi}\omega_0^2\eta}{3(\ell/2\pi R)^3 hV}\left[\frac{Z_L}{n}\right]_{eff}^{m,n} \quad (10)$$

$$\left[\frac{Z_L}{n}\right]_{eff}^{m,n} \equiv \frac{\sum_{p=-\infty}^{+\infty}\frac{Z_L(\omega_p)}{(\omega_p/\omega_0)}h_n(\omega_p)}{\sum_{p=-\infty}^{+\infty}h_n(\omega_p)} \quad (11)$$

where h is the RF harmonic number, V the peak RF-voltage, and $h_n(\omega)$ the spectral power density of the n-th synchrotron mode. The above equations are applicable to the single bunch, also.

Landau damping around the cut-off frequency region is expected if the shift of high-order modes induced through the broad band impedances is smaller than the synchrotron frequency spread coming from a nonlinear sinusoidal RF bucket

$$\Delta(\omega_0\nu_s) = \frac{\pi^2}{16}\left(\frac{h\ell}{2\pi R}\right)^2\omega_0\nu_s. \quad (12)$$

Then, the bunch population is limited as follows;

$$N_{Bi} \le \begin{matrix} 5\times10^6 \\ 5\times10^4 \end{matrix} \text{ for } \begin{matrix} 400\ MeV/u\ {}^4He^{2+} \\ 150\ MeV/u\ {}^{238}U^{92+} \end{matrix}. \quad (13)$$

Therefore, single-bunch and multi-bunch instabilities may be induced for the bunch population making the tune shift $|\Delta\nu| = 0.2$. The growth times of the most unstable mode each n-th mode are shown in Table 5 and Table 6, which are calculated with the program ZAP [14] which has been modified to be applicable for ion beams by the authors.

Table 5: The growth times [s] of the longitudinal single-bunch instabilities.

Energy Ion	400 MeV/u $^4He^{2+}$	150 MeV/u $^{238}U^{92+}$
Mode n=1	0.7	1
Mode n=2	1	-0.3
Mode n=3	10	-4
Mode n=4	30	-0.8

Table 6: The growth times [s] of the most unstable mode(m,n) of the longitudinal multi-bunch instabilities each n-th mode.

400 MeV/u	$^{4}He^{2+}$	150 MeV/u	$^{238}U^{92+}$
Mode(0,1)	0.02	Mode(28,1)	0.07
Mode(0,2)	0.05	Mode(27,2)	0.4
Mode(0,3)	0.3	Mode(29,3)	0.3
Mode(0,4)	0.9	Mode(28,4)	0.6

3.4 Transverse instabilities

As in the longitudinal direction, a bunched beam can have following transverse frequency components without perturbation;

$$\omega_p = \omega_0(pB + m + \nu + n\nu_s). \qquad (14)$$

With perturbation, the frequency is coherently shifted, in the Sacherer-Zotter formalism [13], by

$$\Delta\omega_{\perp}^{m,n} = \frac{j}{|n|+1}\frac{Z/A\, I_{pi} c\beta_{\perp}}{2\, E/e\, \ell}[Z_{\perp}]_{eff}^{m,n} \qquad (15)$$

$$[Z_{\perp}]_{eff}^{m,n} \equiv \frac{\sum_{p=-\infty}^{+\infty} Z_{\perp}(\omega_p) h_n(\omega_p - \omega_{\xi})}{\sum_{p=-\infty}^{+\infty} h_n(\omega_p - \omega_{\xi})}, \qquad (16)$$

where E is the beam energy per nucleon, and ω_{ξ} the chromatic shift $\omega_{\xi} \equiv \xi\omega_0/\eta$, ξ being the chromaticity. The above equations are applicable to the single bunch, also.

Transverse single-bunch instabilities occur when the coherent frequencies of two neighboring low-order modes shift to become equal, for example at $|\Delta\omega_{\perp}^{m,0}| \approx \omega_0 \nu_s$ [15]. They are called mode-coupling instabilities induced through the broad band impedances. The threshold peak current is described by

$$\nu_s \approx \frac{Z/A\, I_{pi}\beta_{\perp} R}{2\, E/e\, \ell\beta_i} Im(Z_{\perp})_{eff}^{BB}. \qquad (17)$$

Then, the bunch population is limited as follows;

$$N_{Bi} \le \begin{matrix} 4\times10^{8} \\ 5\times10^{6} \end{matrix} \text{ for } \begin{matrix} 400\ MeV/u\ ^{4}He^{2+} \\ 150\ MeV/u\ ^{238}U^{92+} \end{matrix}. \qquad (18)$$

Even for the bunch population making the tune shift $|\Delta\nu| = 0.2$, however, the coherent tune shift is

$$\Delta\omega_{\perp}/\omega_0 = \begin{matrix} 0.06 \\ 0.07 \end{matrix} \text{ for } \begin{matrix} 400\ MeV/u\ ^{4}He^{2+} \\ 150\ MeV/u\ ^{238}U^{92+} \end{matrix}, \qquad (19)$$

which is less than the incoherent betatron tune shift. Landau damping is expected to suppress the instabilities.

Transverse coupled bunch instabilities are induced through the resistive wall impedances and RF narrow band ones. Here, as one has no data about the latter, the growth times of the instabilities just through the former are evaluated. The resistive wall impedance contributes mainly the mode n=0 because of its sharp peak at the zero frequency. Without the chromaticity, the most unstable mode is known to be the mode(23, 0) or the mode(24, 0) because of 30 bunches and the betatron tunes on the two sides of 6. For the bunch population making the tune shift $|\Delta\nu| = 0.2$, the growth times are estimated as shown in Table 7. The avoidance of the instabilities is dependent on the chromaticity.

Table 7: The growth times [s] of the most unstable mode(m,n) of the transverse coupled bunch instabilities.

Energy Ion	400 MeV/u $^{4}He^{2+}$	150 MeV/u $^{238}U^{92+}$
Mode(23,0) or Mode(24,0)	1	3

3.5 Electron cooling

The electron cooling is applied to damp the longitudinal and transverse instabilities. The cooling time is required to be less than half the growth time [16];

$$\tau_{cool} \le 0.01\ [s]. \qquad (20)$$

4. Luminosity

The length of the colliding region is two-third of the ion full bunch length, because of the normalized velocity $\beta_i = 0.5$ corresponding to the lowest beam energy. When the detectable collision region is longer than it, the luminosity is described by [17]

$$L = \frac{N_{Be} N_{Bi} f_{REVi} B}{2\pi(4\varepsilon_{RMSe} + \varepsilon_i)\beta_{\perp}^{*}}, \qquad (21)$$

where f_{REVi} is the revolution frequency of the ion beam. When the electron cooling with cooling time of 0.01 s is used to damp the instabilities, the bunch population making the tune shift $|\Delta\nu| = 0.2$ is available. Then, the luminosity is shown in Table 8.

Table 8: The luminosity $[cm^{-2}s^{-1}]$ for the bunch population making the tune shift $|\Delta\nu| = 0.2$.

Ion × electron	300 MeV e^-	2.5 GeV e^-
400 MeV/u $^{4}He^{2+}$	3×10^{27}	2×10^{28}
150 MeV/u $^{238}U^{92+}$	9×10^{24}	1×10^{26}

5. Conclusion

In the presently designed ion ring of DSR, the longitudinal single-bunch and multi-bunch instabilities are induced for the bunch population making the betatron tune shift $|\Delta\nu| = 0.2$ and the bunch length of 40 cm. The transverse multi-bunch instabilities may be induced, which is dependent on the chromaticity. The electron cooling with the cooling time of 0.01 s can damp the instabilities. The luminosity for 150 MeV/u $^{238}U^{92+}$ is much less than $1\times10^{27}\ cm^{-2}s^{-1}$. In order to improve the luminosity, the design of DSR lattice should be modified as follows; 1) the beta function at IS is reduced by one order, 2) the optics of the lattice of the electron ring is variable enough to increase the emittance of the 300 MeV electron beam up to around $0.5\times10^{-6}\ \pi\ mrad$, 3) the number of bunches of both the beams are increased by a few times.

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