OBSERVATION OF COUPLING RESONANCE IN HIMAC SYNCHROTRON

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Abstract

Coupling resonance was observed at operating points near to $Q_x - Q_y$=1. The coherent instability was developed at a high-density electron-cooled beam, when the betatron tune was near the resonance line. The instability was suppressed by applying an RF-knockout to reduce the peak density of the beam. The coupling strength was measured without electron-beam. There were residual components of the xy-coupling in the absence of the electron beam. The coupling strength was measured in different methods, with and without cooler-solenoid.

INTRODUCTION

The Heavy Ion Medical Accelerator in Chiba (HIMAC) [1] was constructed in National Institute of Radiological Sciences (NIRS) for cancer therapy and other researches. The accelerator complex is composed of ion sources, two sequencial linacs, main synchrotron-rings, and beam transport lines. In order to increase the circulating beam instensity in the synchrotron, the multi-turn beam injection is applied using the horizontal space. Therefore, the horizontal emittance (260 πmm-mrad) is much larger than the vertical one (10 πmm-mrad). The aperture limit of the vacuum chamber in the synchrotron is also asymmetric. In such an accelerator with asymmetric aperture limit, xy-coupling of betatron oscillations should be minimized, because the narrower (vertical) aperture effectively limits the amplitude of a particle in wider (horizontal) space.

The xy-coupling in the HIMAC synchrotron was first observed during the experiments of electron-cooling(EC) [2]. There, the coherent oscillation was resonantly developed, when the working point was near to the coupling resonance, $Q_x - Q_y$=1.

This paper presents the coupling instability observed in the HIMAC synchrotron. The measurement of the residual xy-coupling component, in the absence of the EC, is also shown.

THEORY OF LINEAR COUPLING RESONANCE

Coupling resonance of a low-intensity beam

The lowest order (linear) coupling resonance occurs when $Q_x \pm Q_y$ is close to an integer. The driving term of the resonance arises from an xy-coupled linear field, such as a skew-quadrupole field and a solenoidal field. The linear theory of the xy-coupled motion of a particle was developed in Ref. [6] in transfer matrix formalism.

There is an essential difference between the sum-resonance ($Q_x + Q_y = n$) and difference-resonance ($Q_x - Q_y = n$) [7]. In a sum-resonance the emittance of a particle grows infinitely large, while it was bounded in the difference resonance.

The strength of the linear xy-coupling, is given by [7]

$$C_n = \frac{1}{2\pi} \oint \sqrt{\beta_x \beta_y}\, [k_{sq}(\phi) + k_{sol}(\phi)]\, e^{in\phi}\, R\, d\phi\,, \quad (1)$$

where k_{sq} and k_{sol} are the normalized strengths of the skew quadrupolar field and longitudinal field, respectively. The normal-mode motion [8] of a particle describes an ellipse in the transverse space, which is inclined in general.

Electron heating

In the presence of electron-beam along the ion-beam, the coherent interaction between ion- and electron-beams causes an instability, which is so called electron-heating [3, 4, 5]. The equation of motion, including the coherent interaction between ion- and electron-beams, can be solved analytically to derive a coupled mode oscillation. With the boundary condition of the electron beam, the ion-motion inside the cooler can be written by a matrix whose determinant is not unitary. Thus, the oscillation of the ion-beam diverges exponentially.

EXPERIMENTAL APARATUS

Our experiments were carried out with the HIMAC synchrotron under the conditions shown in Table 1. The RF was turned off and the coasting beam at injection energy was used. Two dimensional beam-profile in the transverse space were measured with the gas-sheet beam profile monitor (SBPM) [9]. The monitor has the dinamic range of $10^6 \sim 10^9$ Ar^{18+} ions and resolution of $\sim$0.3 mm at σ(standard deviation). The monitor was precisely aligned within around 10 mrad in order to evaluate the inclination of a beam in the transverse real-space. The Twiss-parmeter β at the monitor is around 8 m in the horizontal and 6 m in the vertical directions, respectively.

The conditions of electron cooler is also shown in Table 1. The density of the electron beam is proportional to I_e/R, and corresponds to $n_e = 5.8 \times 10^6$ /cm^3 for

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$I_e = 100$ mA and $R = 3.3$. There are two electrostatic beam-position monitors inside the cooling section. In the experiments, the electrodes of the monitor were connected to a signal generator and used as a dipole-mode shaker.

COUPLING RESONANCE OF A COOLED BEAM

The experiments of beam compression employing the EC was carried out in the HIMAC synchrotron [2]. During cool-stacking, a beam instability was observed when the ion- and electron-beam density became high. Figure 1 shows the waveform of ion intensity and vertical oscillation, when the instability occurred. Here, the electron current was 150 mA and the expansion factor was 3.3. The sudden beam-loss correlated with the bursts of the vertical coherent oscillations.

Figure 2 shows the two-dimensional beam profiles. In this case, the working point was set at (3.71,2.83) and the beam was lost after ∼2.5 s from the injection. Figure 2 shows that the beam was cooled first in the horizontal space (1∼2.5 s), and then the instability occurred in the vertical space. The direction of the amplitude growth due to the instability was slightly inclined, which means that the instability was related to the xy-coupling.

The instability depended on working point. Working points were surveyed along a line between (3.69,2.89) and (3.72,3.13). It was found that the beam was unstable near to the coupling resonances, $Q_x+Q_y = 7$ and $Q_x-Q_y = 1$. The instability was more dangerous around the difference-resonance than the sum-resonance. These results are consistent with the simulation including the electron-beam space-charge field (Fig. 3).

Damping of the instability

Though the instability occurred at high ion-density, it is possible to to suppress the instability by decreasing the peak ion-density. The RF-knockout(RF-KO) [11] was applied at the frequency corresponding to the vertical betatron-sideband frequency in order to decrease the peak density of the ion-beam. With the RF-KO, the coherent oscillation was suppressed and the stacked ion-intensity was improved.

Table 1: Experimental conditions of the HIMAC synchrotron and electron cooler.

parameter	value
Ion specie	^{40}Ar^{18+} ($Z/A = 0.45$)
Circumference	$2\pi R$=129.6 m
Injection energy	6 MeV/u
Aperture limit	±123 mm(H),±32 mm(V)
Twiss β in cooler	8.79 m(H), 9.38 m(V)
Solenoid length	1 m
Solenoid strength	0.05 T
e^- beam current	I_e =0∼200 mA
Cathode temperature	100 meV
Magnetic expan. factor	R =1∼3.8

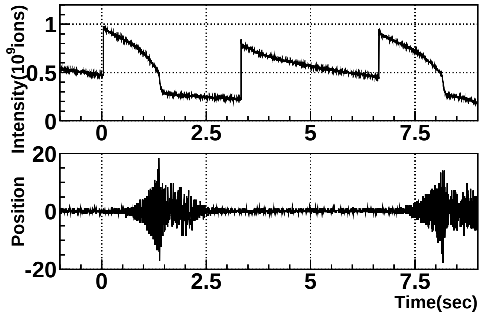

Figure 1: Two-dimensional beam-profiles when instability occurred.

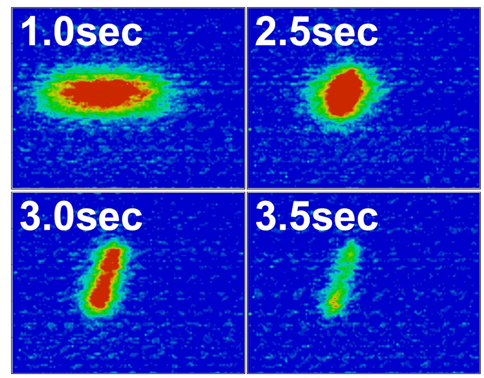

Figure 2: Beam intensity and vertical oscillations in the presence of instability.

The secondary ions, produced by electron beam, are trapped in the cooling section. Those ions neutralize the electron beam, and lead to the electron beam instability [12]. In order to clear such ions, a transverse electric field (shaking) was applied in the cooling section [12]. The ions were cleared at their resonant frequency, and reduced the neutralization factor. By optimizing the cathode voltage of the cooler electron, secondary ion spectrum was obtained. Experimental result (Fig. 4) shows the peaks at 70 kHz(A/Z∼20, H_2O^+ etc.), 100 kHz(A/Z∼9, O^{2+} etc.), and negative peak at 224 kHz.

MEASUREMENTS OF COUPLING STRENGTH

Residual coupling without EC

The HIMAC synchrotron have a residual xy-coupling fields even in the absence of the electron beam. As written in the previous section, it was observed that the principal axis of a beam was inclined in the transverse space when the working point was near to a difference resonance. Here, both of the electron-beam and solenoid in the cooler were switched off. In order to estimate the coupling strength, the beam profiles were measured by the SBPM as a function of vertical tune along $Q_x = 3.62$. Each beam-profiles

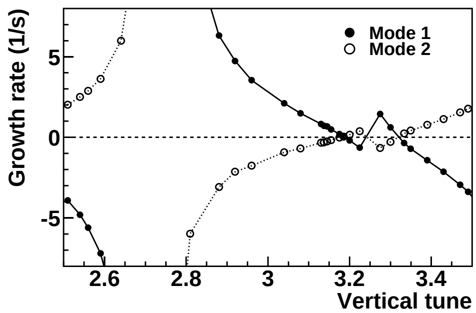

Figure 3: Simulation of transverse instability including the interaction between ion-beam and electron-beam. Horizontal tune is fixed at 3.7.

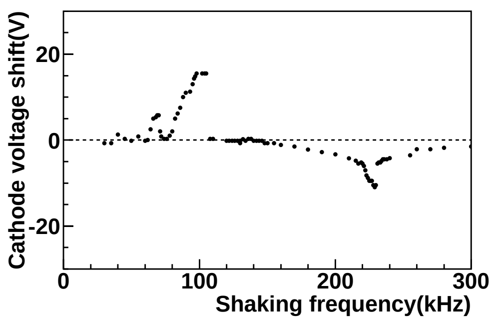

Figure 4: Spectrum of trapped secondary ions.

showed elliptical cross-section which were inclined in the x-y real-plane.

Figure 5 plots the inclination angles of beams as a function of differential tune, $\Delta Q = Q_x - Q_y$. The inclination was larger as the differential tune approaches to zero. This behavior can be explained by the linear theory of the difference resonance. The lines in the Fig. 5 show the analytical results with C_0=0.016, 0.008 and 0.004. The most fitting value of C_0 is around 0.02.

One of the coupling sources can be related to the sextupole components of magnetic field in HIMAC dipole magnets, which corresponds to $B''/B\rho$=0.026 m^{-3}[10]. With a closed orbit distortion (COD) of Δx, the skew component of the magnetic field seen by the beam corresponds to $k_{sq} = (B''/B\rho)\Delta x$. As a result, the total coupling coefficient becomes $C_0 = 0.014$, where $\Delta x = 10$ mm are assumed at each dipoles.

Coupling strength including solenoid

The xy-coupling was also observed by measuring the coupled mode-tunes splitting. In this case, the cooler-solenoid was excited with 0.05 T. The coherent betatron tunes were measured as a function of the current of horizontal defocusing quadrupole (QD). The experimental result is shown in Fig. 6. The measured mode-tune was shifted from linear function (dahed lines in the Fig. 6) at around the coupling condition, and the splitting of the normal-mode tunes is around 0.05. This value corresponds to the coupling strength of C_0=0.006, which is consistent with the cooler-solenoid of 0.05 T.

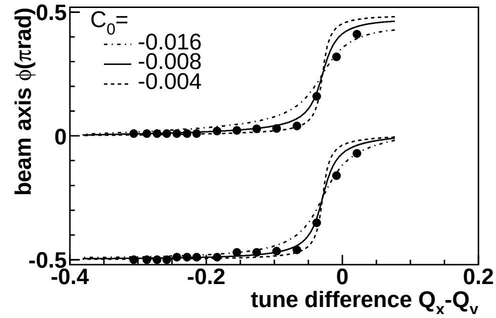

Figure 5: Inclination angle of beam near ΔQ=0 difference resonance.

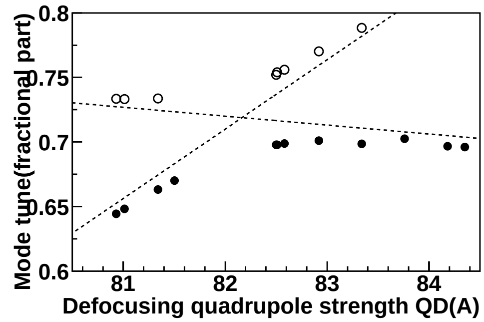

Figure 6: Normal mode tunes including the coupling effect from solenoid.

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