INVESTIGATION OF SYNCHRO, BETATRON COUPLINGS AT S-LSR*

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Abstract

Tune couplings of $^{24}Mg^{+}$ beam were observed at S-LSR, Kyoto University. Synchrotron oscillation in the longitudinal direction and betatron oscillation in the horizontal direction was intentionally coupled in a drift tube located at the finite dispersive section. Horizontal and vertical coupling of betatron oscillation was also observed. This fact is a good sign of 3-D couplings to achieve a theoretically predicted crystal beam through the resonant coupling method for transverse laser cooling.

INTRODUCTION

Laser cooling techniques, which achieve the lowest temperature, have been available to cool down the longitudinal temperature of ion beams. This technique, however, cannot cool the transverse direction directly although indirect and not so efficient transverse cooling methods have been reported[1]. Then the resonant coupling method, which transfer a cooling force in the longitudinal direction to the transverse direction, was proposed to achieve the transverse cooling[2]. Horizontal(x) and longitudinal(s) directions are coupled by a regular RF cavity located at the position of a finite dispersion. Two transverse directions, horizontal (x) and vertical (y) directions, are coupled by a solenoid magnet. In this three-dimensional (3-D) couplings of laser cooling, two resonant conditions have to be satisfied,

$$\nu_x - \nu_s = integer,$$
$$\nu_x - \nu_y = integer.$$

where ν_x is the horizontal betatron tune, ν_y is the vertical betatron tune and ν_s is the synchrotron tune of the beam. In this paper, betatron horizontal and vertical couplings, and synchro-betatron (longitudinal-horizontal) coupling are investigated at a resonant point, where the resonant condition is satisfied, for a possible transverse laser cooling to realize a crystal beam [3].

RESONANT COUPLING MEASUREMENT

A symptom of horizontal laser cooling was reported at Small Laser-equipped Storage Ring (S-LSR) at ICR, Kyoto University (Fig.1) [4]. A 40keV $^{24}Mg^{+}$ beam is introduced into S-LSR ring, which is equipped with a frequency tuneable laser system ~280 nm for beam cooling. The cooled beam is diagnosed by a photo multiplier tube (PMT) and a CCD camera at the laser cooling section. S-LSR lattice consists of 6 bending magnets BMi, 16 quadrupole magnets QMij (i is an instrument number $i = 1, 2, \cdots 6$; $j = 1$ for focusing quadrupole, $j = 2$ for defocusing quadrupole) and accordingly it has 6-fold symmetry, which was designed to minimize the beam heating. We used a solenoid magnet of an electron cooler. An RF cavity (drift tube) is located at the position of a finite dispersion (D =1.1 m) where longitudinal cooling force was transferred to the horizontal direction. Table 1 shows the main parameters of S-LSR[5].

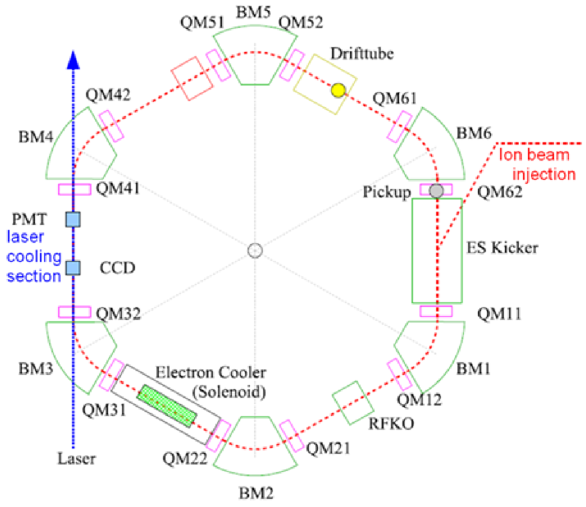

Figure 1: Layout of the S-LSR

Betatron tunes are adjusted by a current of quadrupole magnets QMij in Fig.1. The current of focusing quadrupole QMi1 was varied up to 15A and for defocusing QMi2 was varied up to 25A. The solenoid magnet gives a magnetic field $\vec{B} = 40\,gauss$ (The solenoid current was 16A.) in the s-direction, which was small enough to avoid the lattice symmetry breaking. The maximum RF cavity voltage V_{Cabity} of a drift tube was 100V.

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Table 1: Main Parameter of S-LSR

Circumference	22.557 m
Average Radius	3.59 m
Length of straight section	1.86 m
Radius of curvature	1.05 m
Revolution frequency	25.192 kHz
Super periodicity	6
Ion species	^{24}Mg^{+}
Kinetic beam energy	40 keV
Transition wavelength	280 nm

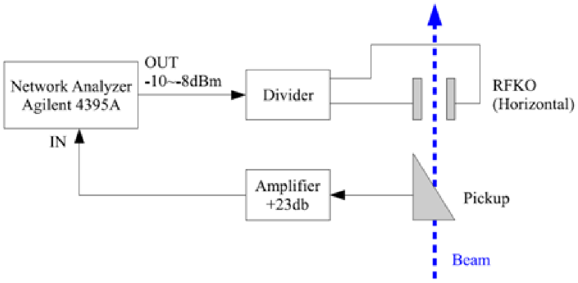

Figure 2: Conceptual diagram of Tune Measurement

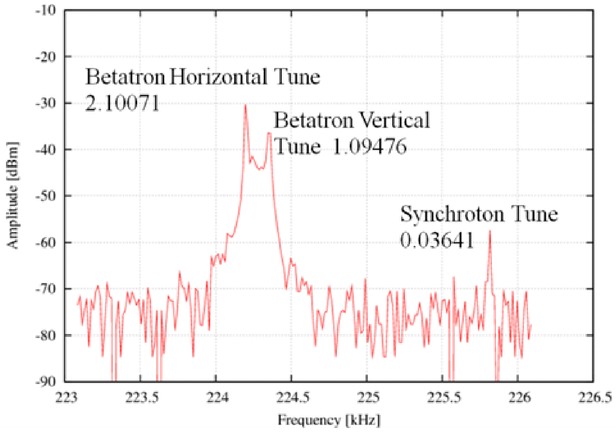

Figure 3: Frequency spectrum of Pickup signal analyzed with a network analyzer.

Betatron and synchrotron tunes have to be measured precisely to reveal the resonance condition. Figure 2 shows the Conceptual diagram of tune measurements. A beam is kicked by parallel-plate electrodes RFKO which is excited by a network analyzer (Agilent 4395A). An example of frequency spectrum of Pickup signal is shown in Fig.3, in which synchrotron , betatron horizontal and betatron vertical tunes were observed. Beam oscillations in longitudinal and transverse direction are detected by Pickup, which is one of beam position monitor triangle-plates. Detected signals are analyzed by the network analyzer, in which we observed sidebands as separations from the longitudinal mode of a fractional part of tune $\Delta\nu$. Sideband behaviors separated the horizontal and vertical betatron tunes. Synchrotron tune, which was varied by V_{Cabity} , was distinguished in the same way.

EXPERIMENTAL RESULTS

We excited the solenoid magnet and investigated betatron horizontal and vertical tunes near a resonant point of ($\nu_x = 2.10$, $\nu_y = 1.10$) . Betatron horizontal and vertical coupling was observed near a fractional part of tune $\Delta\nu = 0.10$ in Fig.4. Two dimensional coupling was confirmed by the beam size measurements[6].

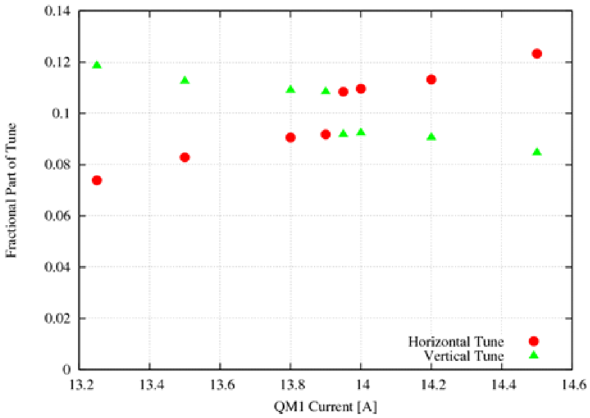

Figure 4: Betatron horizontal and vertical coupling near ($\nu_x = 2.10$, $\nu_y = 1.10$) with a solenoid on .

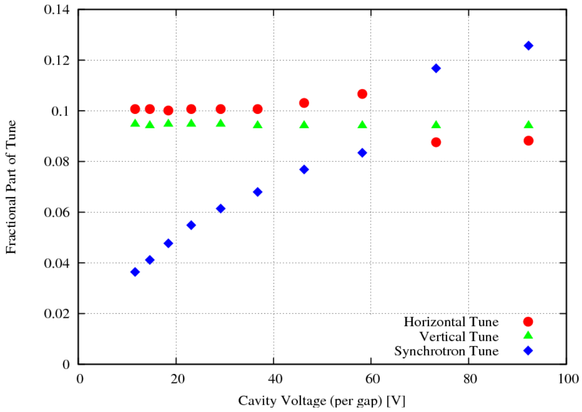

Figure 5: Synchrotron and betatron horizontal tune jumps near ($\nu_x = 2.10$, $\nu_y = 1.10$, $\nu_s = 0.10$) with a solenoid off.

The result near a resonant point ($\nu_x = 2.10$, $\nu_y = 1.10$, $\nu_s = 0.10$) is shown in Fig.5 with a solenoid off. Clear tune jump in synchrotron and betatron horizontal tune were observed near $\Delta\nu = 0.10$, but no jump was observed in betatron vertical tune: This might be an evidence of two dimensional (2-D) coupling near the resonant point $\Delta\nu = 0.10$, which is assumed by our experiment as described later.

Then, a solenoid was turned on in Fig.6

Clear tune jumps in synchrotron tune, betatron horizontal tune and betatron vertical tune were observed. Triple tune jumps were occurred near ($\nu_x = 2.10$, $\nu_y = 1.10$, $\nu_s = 0.10$): This might be an evidence of three dimensional (3-D) coupling near the resonant point $\Delta\nu = 0.10$, which needs experimental verification from now on.

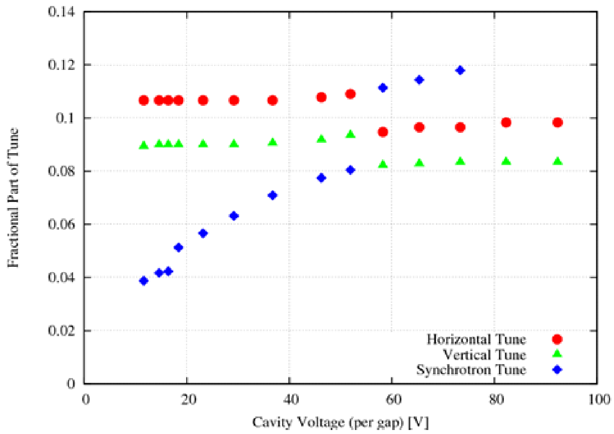

Figure 6: Synchrotron, betatron horizontal and betatron vertical tune jumps near ($\nu_x = 2.10$, $\nu_y = 1.10$, $\nu_s = 0.10$) with a solenoid on. It seems that triple tune jumps were occurred there.

Then the $^{24}Mg^{+}$ beam was laser cooled by the deceleration phase of RF cavity voltage to confirm synchrotron and betatron horizontal coupling in Fig.5: This is 2-D coupling. Beam sizes were measured by the image of a CCD camera looking at the beam upward at the laser cooling section. Beam size measurements were done near ($\nu_x = 2.068$, $\nu_y = 1.105$) [4].

The horizontal beam size was measured for various synchrotron tunes from 0.038 to 0.113 in Fig.7, in which the abscissa represents particle number so time evolves its descending direction (leftward). We chose particle number instead of time since beam decay times were very short for some values of synchrotron tune. When $\nu_s = 0.038$ and $\nu_s = 0.047$, which were far from the resonant point, the initial beam size was 0.9 mm and the beam size blew up due to the intra-beam scattering. When $\nu_s = 0.060$, beam size was remains 0.8mm where an equilibrium of resonant transverse cooling and heating by intra beam scatterings was maintained. When $\nu_s = 0.068$ and $\nu_s = 0.069$, which were close to the resonant point $\Delta\nu = 0.07$, the initial beam size 0.8mm was decreased to 0.55mm. Cooling caused beam size reductions illustrated transferring the longitudinal cooling force to transverse direction near the resonant point; 2-D coupling was confirmed [7].

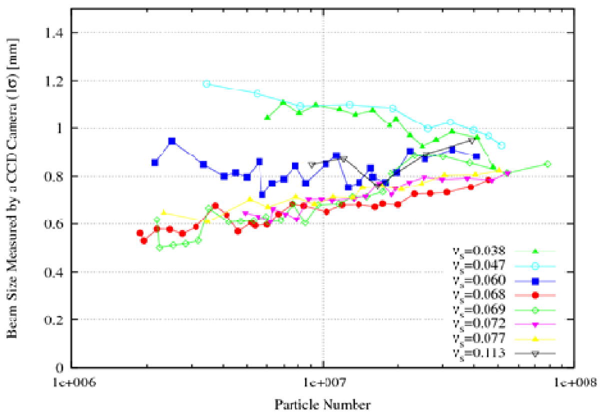

Figure 7: Laser cooled beam size measurements near ($\nu_x = 2.068$, $\nu_y = 1.105$).

The abscissa represents particle number so time evolves its descending direction (leftward).

Beam profiles were measured as an integration of 1 second by a CCD camera and beam sizes were evaluated by 1σ of Gaussian fit.

CONCLUSION

S-LSR, which was constructed to realize a crystal beam, presumes to have 6-fold symmetry to suppress beam instability. In synchrotron and betatron horizontal tune measurements, we confirmed 2-D coupling. In horizontal and vertical, and longitudinal tune measurements, we obtained a good sign of 3-D couplings. However, a confirmation of 3-D couplings needs experimentally observed temperature correlation in three dimensions, which require farther investigation.

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