BEAM INSTABILITY PHENOMENA OBSERVED AT HIRFL-CSR IN THE PRESENCE OF ELECTRON COOLER*

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Abstract

Some signal samples acquired from Schottky probes and beam position monitor during operation were presented in this paper, and they were observed in the different operation stages such as during injection, after cooling and cooling force measurement. These signals were considered related with the ion beam instability. The central frequency of ion beam varied with the time. Some were caused by the ripple of hardware, the other were created by ion beam itself. The reasons which caused these phenomena were analyzed. The possible solutions were suggested, and some necessary upgrade and improvements were expected. These results were helpful to attempt the Schottky Mass Spectrometry measurement in the CSR.

INTRODUCTION

The Cooler Storage Ring of Heavy Ion Research Facility at Lanzhou (HIRFL-CSR) has been operating since 2007. The heavy ion beams in the energy range of few MeV/u to few GeV/u can be produced and delivered for the mass spectrometry experiments, the cancer therapy and atomic experiments and so on [1]. The latest results were reported in many papers and conferences [2-5].

In several machine runs the beam instability phenomena has been observed in the different operation stages such as during injection, after cooling and cooling force measurement. Besides this, the beam loss was also happened and investigated for electron cooling force measurements.

The instability resulted in beam loss and emittance growth, thus the achievable beam intensity and experimental precision is however limited. The instability of electron cooled beam has been studied in the different accelerators and reported by several laboratories in the world [6-9]. In this paper, the instability phenomena of electron cooled beam observed at HIRFL-CSR was described, and the Schottky spectra were analyzed.

The Schottky Mass Spectrometry (SMS) [10-12] is one of the high precision mass spectrometers based on storage ring with 10^{-6} or higher precision [13,14]. At HIRFL-CSR, the ultimate relative frequency spread $\Delta f/f$ of about 5×10^{-7} and about 1000s long-term beam stability are necessary for high precision mass measurements.

In order to improve the stable increasing beam intensity at HIRFL-CSR, and prepare the condition for SMS experiments, the mechanisms of instability have to be investigated and different cures methods should be tested.

BEAM ACCUMULATION IN CSRM

The main goal of the electron cooler application at HIRFL-CSR main ring is to increase the beam intensity with the help of stacking-electron cooling procedure at the injection energy [15,16]. A typical longitudinal Schottky signal during stacking-cooling procedure was shown in Fig. 1.



Figure 1: A typical Schottky spectrum of ion beam accumulation in CSRm under electron cooling.

For an effective electron cooling, the ion beam and electron beam have to overlap coaxially, and in principle the relative velocity of the ion beam and electron beam should be zero in the particle reference frame. It's obviously in Fig. 1 that the ion beam was symmetrically cooled down to the central frequency, which means that the injected ion energy, the electron beam energy, the magnetic field of dipole and the RF frequency were matched well. In addition, the deep colour of Schottky signal means the beam intensity increased step by step.

The cooling time obtained from Fig. 1 is corresponding to the simulation result, and there is no obvious sideband signal between the neighbour harmonic. It demonstrated that the HIRFL-CSRm was operated at reasonable workpoint settings. The average velocities of electron and ion were almost equal. Further more, the central frequency shifted to left at the end of stacking procedure because of the changing of beam orbit at injection point.

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INSTABILITY OF ACCUMULATED HIGH INTENSITY BEAM

The betatron oscillation of high intensity cooled beam was observed in several cooling storage rings [17-19]. Fig. 2a was shown the analog signal from one of the BPM electrodes. After few seconds, the signal suddenly becomes very strong. It's clearly demonstrating the transverse oscillations of the high intensity cooled beam. Exactly at the same time the fast beam losses were observed in the DC current transformer. This was the factor which limited the attainable beam intensity. The corresponding beam current signal was shown in Fig. 2b.



Figure 2a: The signal from one electrode of beam position monitor(BPM) during beam instability.





The ion beam intensity during accumulation was not always increased linearly with the continuous injection. The stored beam seriously lost suddenly at some certain beam intensity, but not lost completely. A part of stored beam was remained in the ring. The intensity increased again with coming injections, and the beam loss happened again when the accumulated intensity achieved that certain value. The loss-increase-loss indicated some iterative character.

The space charge fields created by the stored ions in the beam influence its motion and changed the betatron tune value. For designed betatron tune value of CSRm (Qx/Qy=3.63/2.61), the difference resonance would appears and produce the serious beam loss during stacking procedure. The further work should be focused

on the investigation with the tune value measurement and some simulation work.

INSTABILITY DURING INJECTION AND ACCUMULATION

In order to increase the intensity of the stored ion beams, a betatron stacking method in the horizontal phase plane is used at CSRm [20]. The closed orbit at injection point is distorted by means of four bump magnets. From the very beginning the bump is as large as pass close to the septum and then it is gradually reduced to zero within few milliseconds. The electron cooling device was turned on in the whole stacking procedure. The behavior of longitudinal Schottky signal during stacking was shown in Fig. 3. It's clearly that the frequency shift was happened at the beginning of injection.



Figure 3: The Schottky spectra of a complete accumulation and injection under electron cooling. Left - whole, Middle - beginning of injection, Right - end of injection.

SIDEBAND DURING ACCUMULATION

Generally in the synchrotron, the frequency of transverse oscillation of the beam for each signal turn (usually called betatron tune or just "tune") is one of fundamental controllable knobs to avoid the instability phenomena. One of the most popular methods to measure the tune is using the sideband of the transverse Schottky signal with help of the beam exciter [21]. Fig. 4 shows the sidebands around the revolution frequency without any external exciting source. It seems that the transverse oscillation of cooled beam is large enough to make obvious sideband.



Figure 4: The Schottky spectrum with obvious sideband.

BEAM INSTABILITY AFTER ELECTRON COOLING IN CSRE

The ion beam with higher energy was injected into experimental ring after accumulation CSR and acceleration in CSR main ring, it was cooled again by electron at higher energy level in CSR experimental ring. The related physics experiments such as internal target one and ion-electron recombination etc. was carried out in the experimental ring. In the case of lower stored particle number, some investigation on the beam crystallization will be performed [22]. The high precision Schottky mass spectroscope will be carried out in the CSR experimental ring with the help of new developed resonance Schottky probe [23], the high beam instability was necessary to get so high required precision. The Schottky spectrum of 200MeV/u⁸⁶Kr³⁶⁺ ion beam after cooling equilibrium in CSR experimental ring were demonstrated in Fig. 5a, obvious instability was observed from these spectra. The frequency shift range was about ± 25 kHz/243MHz= $\pm 1 \times$ 10^{-4} .



Figure 5a: The Schottky spectra of ion beam after cooling equilibrium in CSR experimental ring.



Figure 5b: The Schottky spectrum of ion beam in the absent of electron cooling at the isochronous operation mode in CSR experimental ring.

The possible reason caused the beam instability were the stabilities of dipole field, quadrupole field, correction dipole field, and the electron energy. Due to lack of the corresponding synchronous beam and field monitoring system, the instability relationship between ion beam and the fields was not correlated with each other, and the source of instability identification was difficult. A special data acquisition system was expected to establish in order to synchronously monitor the ion beam intensity, magnetic fields and the high voltage of electron cooler, obtain the relation between the changes of these parameters, built the contact each other, This system will be helpful to search the reason of ion beam instability.

The Schottky spectrum of 434.8MeV/u ⁸⁶Kr³⁶⁺ ion beam in the absent of electron cooling at the isochronous operation mode in CSR experimental ring was shown in Fig. 5b. From the picture the ion beam instability was observed without electron cooler, but the amplitude was smaller than the above description. The reason maybe came from the operation mode of storage ring, magnetic field level of dipole and the time of data acquisition. Due to the magnets and their power supplies of CSR were not placed the constant temperature circumstance, the temperatures of storage ring channel and power supplies space varied with natural entironment in the different seasons, and also varied with day and night. The stability was higher in the early morning and winter than in the later morning and summer. By the way, the external disturbance of electrical power network had also the influence on the ion beam.

PHENONEMA DURING COOLING FORCE MEASUREMENT

In order to study the difference of electron cooling force between hollow profile electron beam and solid, several experiments was carried on the two cooler storage rings at HIRFL [24]. A typical Schottky spectrum of cooling force measurement process is shown by the left figure in Fig. 6a in measuring the cooling force of 400MeV/u ${}^{12}C^{6+}$ at the experimental ring CSRe. It can be noticed that when cooling action and heating by various factors attains balance, the spectrum peak width and area of cooled ion beam will keep nearly unchanged, i.e. the momentum spread and stored ion number will keep almost invariable. When the electron beam jump to other new energy, the ion beam will be slowly pull away and follow the electron beam for new equilibrium. With a vertical angle existing between ion beam and electron beam in the cooling section in cooling force measurement, Fig. 6a shows the process of electron beam energy jumps from 221.3keV down to 220.9keV by the middle spectrum and from 220.9keV up to 221.3keV by the right one.

It can be seen from the two spectra that: when an angle between the two beam exists, only a certain amount of ion beam was pulled away normally for new equilibrium point while the other part appears unusually slowly shift and tails. The possible causes is that: (1) beams uncoaxiality cause ion beam was only partly pulled away; (2) the distribution of ion beam may be layered or cylindrical, not normal Gaussian, which makes a certain amount of ions subject to a small cooling force; (3) higher transverse temperature of electron beam exists, which makes electron cooling less effective.

Another phenomenon is shown by Fig. 6b in the cooling force measurements of 200MeV/u ¹²⁹Xe⁵⁴⁺ at CSRe. The left one shows a normal cooling force measurement process with an optimized toroid field,

while the middle and the right spectra correspond to the measurement with a smaller toroid field than the optimized one and with the electron energy jump from 108.96keV to 109.16keV and from 108.96keV to 109.16keV respectively. It is shown by the middle and right spectra that only a small part of ion beam was pulled away with the conventional manner and cooled down for the new equilibrium while the other part moves exceptional slowly and contribute to the broadening of attainable momentum spread at new equilibrium. This phenomenon can be explained by the increased transverse electron temperature which was caused by the change of toroid magnetic field from optimized one. The temperature affects the attainable momentum spread at the new equilibrium.



Figure 6a: The Schottky spectra of 400MeV/u during cooling force measurement in CSR experimental ring. Left---zero angle between ion and electron beams, I_{CX6}=1.0A, I_{CY6}=3.0A. Middle---with an angle in vertical direction, I_{CX6}=1.0A, I_{CY6}=3.4A. Right---with an angle in vertical direction, opposite electron energy change, I_{CX6}=1.0A, I_{CY6}=3.4A.



Figure 6b: The Schottky spectra of 200MeV/u¹²⁹Xe⁵⁴⁴ during cooling force measurement in CSR experimental ring. Left---optimal toroid current, I_{toroid}=602.3A, 108.96---109.16keV. Middle---I_{toroid}=584.24A, 108.96---109.16keV. Right--- Itoroid=590.27A, 108.96---108.76keV.

THE ACTION OF RF MODULATION ON THE ION BEAM

A trapezoidal frequency modulation was applied to 200 $MeV/u^{-12}C^{6+}$ ion beam at the experimental ring CSRe by RF station during its performance test [25]. The modulation wave is shown in Fig. 7, of which the voltage is 1 kV, both the rising and falling time are 5s, the plateau time is 50 s, and the center frequency is 6.60895 MHz with a frequency modulation relative width of $\Delta f/f=\pm 3\times 10^{-4}$. The Schottky spectra at the left in Fig.8 indicated that the whole ion beam changes its revolution frequency by closely following RF modulation waveform. But the enlarged momentum spread of ion beam shown by broaden spectrum peak indicates that ion beam is not ISBN 978-3-95450-125-0

well cooled down longitudinally. This can be ascribed to regular velocity mismatch between ion beam and electron beam. The 60 seconds periodically RF modulation brings ion beam a regular velocity change in longitudinal and can be used as a reference of slowly change, analyzing the change in other experiments. This experiment also shows that ion beam can be changed just following the action character of external force.



Figure 7: Waveform of RF frequency modulation.



Figure 8: The Schottky spectra of ion beam under the action of external factor. Left---the action of the change of RF frequency. Middle--- the unilateral change of electron energy. Right--- the bilateral change of electron energy

THE ACTION OF ELECTRON ENERGY **MODULATION ON THE ION BEAM**

In order to carry out experimental research on electronion recombination at CSR, electron beam energy modulation module was added to CSRm electron cooler [26]. Fig. 9 shows the modulation process of electron beam acceleration voltage under optimal cooling and accumulation at CSRm with a rise-time of 20µs, plateau time of 100-1000ms, time interval of 1-2s, and amplitude of 5-1500V. As a typical Schottky spectra of unilateral modulation of electron beam energy, the middle figure in Fig. 8 shows that ion beam shifted its energy quickly corresponding to the change of electron beam energy, however such a plateau like the RF action in previous section was not observed. The right one in Fig. 8, as typical Schottky spectra of bilateral electron beam energy modulation, shows that only small part ions followed closely up to the change of electron beam energy while the majority was still far from new equilibrium location even at the next beginning of reverse direction modulation. The lag of majority ions leads to a momentum spread expansion of ion beam after several modulation cycles. This modulation is always taken as a fast change example.

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Figure 9: Waveform of electron beam energy modulation.

SUMMARY AND PROSPECTS

The beam instability phenomena related with electron cooler in HIRFL-CSR were briefly described and roughly analyzed in this paper. The described phenomena should be carefully investigated seriatim both theoretically and experimentally in order to understand their mechanism and causes. The monitor system will be established for measuring these instabilities in the near future. From the measurement results, the reason and characters will be revealed. The solution for alleviation and suppression should be considered from the technical point of view. The proper and effective methods of instability suppression should be proposed and developed hereafter. The useful and constructive information should be provided for machine improvement and upgrade in the interest of providing the high quality heavy ion beam satisfied the various requirements for high precision physics experiments.

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