INFLUENCE OF ELECTRON ENERGY DETUNING ON THE LIFETIME AND STABILITY OF ION BEAM IN CSRM*

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Abstract

The energy spread of electron beam was artificially increased with the help of the detuning system in the electron cooler. The Influence of electron energy detuning on maximum accumulated intensity, the lifetime and stability of ion beam were experimentally investigated with the beam of 3.7MeV/u $^{112}Sn^{35+}$ in CSRm. The lifetime was derived from the signals of ion beam intensity from DCCT varying with time, and the instability was observed by mean of the longitudinal frequency signals from Schottky probe. The experiments results show that no significant influence of electron energy detuning on the maximum accumulated intensity and lifetime. Due to the limitation of beam intensity from injector, the space charge limitation and saturation condition was not approached, and the obvious evidence for instability suppression by the detuning has not observed in such detuning frequency range.

INTRODUCTION

The accelerator facility HIRFL-CSR [1] is operated for nuclear physics experiments, atomic physics experiments, cancer therapy and other research area. Over 3000 hours beam time was provided in last year, which was mainly used on the research topics of nuclei mass measurements, electron-ion recombination and heavy ion therapy [2-4].

However, the extremely heavy ion beam like Bi and U were successfully cooled and accumulated with very low injection energy and weak intensity [5].

A few times commission for accumulation of proton with the help of electron cooling were performed in CSRm, including instead of proton with H_2^+, these commission were not successfully completed carried out up to now due to the mismatching parameters between injector and storage ring. The accelerator staff was puzzled by this phenomenon. The lifetime of proton beam became shorter when the electron beam was turned on, ulteriorly the proton beam disappeared in the storage ring. No any obvious cooling and accumulation was happened. This was ascribed to the “electron heating” [6, 7]; in this case, the proton beam was not cooled, but heated by the electron beam.

The proton beam disappeared after turn on the electron cooler and electron beam. There was no obvious cooling and accumulation. The lifetime of H_2^+ is very short comparing with the results from TSR and CELSIUS [8, 9].

The instability of high intensity cooled ion beam and electron heating problem were studied in several e-cooler storage rings [10-12]. These are also a challenge of CSRm [13]; the related experimental research work was published on the proceedings of RuPAC 2012 [5]. In order to satisfy higher request on beam intensity, quality and stability, we attempted to improve beam intensity by detuning the matched energy of electron beam.

The motivation of this experiment was to increase the accumulated ion intensity and suppress the ion beam instability after cooling.

Based on the easily implemented experimental methods in literature [14], this paper studied the experimental affect of electron beam energy detuning on ion beam accumulation, lifetime, and instability.

EXPERIMENTS AND PARAMETERS

The Sn beam was generated by the superconductive ECR ion source SECRAL with charge state 26+, turned into about 1ms length bunches after the chopper, rise its energy to 3.7MeV/u by a cyclotron SFC and stripped to $^{112}Sn^{35+}$ by a 33mg/cm^2 carbon film before injected into CSRm. The beam intensity reached approximately 1μA at the injection point of the main synchrotron (CSRm).

$^{112}Sn^{35+}$ beam was injected into the synchrotron through the falling process of four Bumps that have the setting of rising time 1.8ms, platform time 0.7ms, and falling time 1.2ms. Each injection cycle composed of 200 pulse injections with the time interval of 150ms. During the injection, CSRm was set as rigidity 0.889Tm, revolution frequency 0.166MHz, transverse acceptance 200πmmmrad and 30πmmmrad at both directions, longitudinal acceptance ±0.125%, and Betatron function 10m and 16m in horizontal and vertical direction respectively at electron cooling section.

The electron cooling parameters are listed below. The magnetic field at gun section is 1562Gs and 365.5Gs at cooling section. The adiabatic expansion factor is 4.275. The electron beam diameter is 60mm at the cooling section. The electron beam current was 110mA. The hollow profiled electron beam was controlled with the potential ratio between control electrode and anode 0.188kV/1.3129kV.

The lifetime of cooled $^{112}Sn^{26+}$ ion beam was about 7.2 seconds without electron energy modulation. The maximum beam current was 90 μA after 10-second stacking with electron cooling and multiturn injections; the corresponding particle number was 1×10^8.

The lifetime of cooled $^{112}Sn^{35+}$ ion beam was about 5.7 seconds and the maximum stacking current was 39 μA with electron energy modulation, the corresponding particle number was 3×10^7.

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EXPERIMENTS RESULTS AND DISCUSSION

The experimental procedure was begun with firstly setting the modulation waveform width, interval and voltage, and triggering energy detuning system just before the ion beam was injected into the synchrotron. The Next step was to record the experimental process simultaneously by DCCT and Schottky probes. To study the impact of electron beam energy detuning to ion beam accumulation, the injection was sustained even when the synchrotron accumulated the maximum beam intensity. And after inceasing the injection, the effect of detuning on beam lifetime was studied during the whole natural decay of stored beam. Thereafter, the effect of detuning on beam accumulation and the maximum intensity and beam decay lifetime was obtained from DCCT, and beam stability in case of energy detuning was observed from Schottky signal, as illustrated in Figure 1.

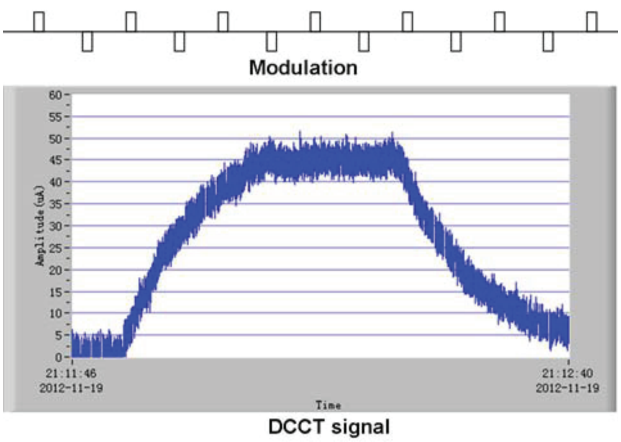

Figure 1: DCCT signal and modulation.

The different pulses width was used in the experiments, for example 100ms, 150ms and 200ms. In addition, three different duty cycles were applied as the time interval of 10ms, 20ms and 50ms. The nine group of energy modulation schemes were used in the experiments as listed in Table 1, in which the maximum amplitude was 0.12% higher than the equilibrium electron beam energy. It was comparable to CELSIUS experiment setting in reference [15].

Table 1: Parameters During Experiments

Relative amplitude of modulation	Amplitude of pulse (V)	Positive Pulse Width(ms)	Negative pulse width(ms)	Interval of pulse(ms)	Repetition
(0~2.5)/2.096kV 0.01%---0.12%	0,0.2,0.4,0.6, 0.8,1.0,1.5, 2.0,2.5	10	10	200	4.76Hz
(0~2.5)/2.096kV 0.01%---0.12%	0,0.2,0.4,0.6, 0.8,1.0,1.5, 2.0,2.5	10	10	100	9Hz
(0~2.5)/2.096kV 0.01%---0.12%	0,0.2,0.4,0.6, 0.8,1.0,1.5, 2.0,2.5	10	10	150	6.25Hz
(0~2.5)/2.096kV 0.01%---0.12%	0,0.2,0.4,0.6, 0.8,1.0,1.5, 2.0,2.5	20	20	150	5.88Hz
(0~2.5)/2.096kV 0.01%---0.12%	0,0.2,0.4,0.6, 0.8,1.0,1.5, 2.0,2.5	50	50	150	5Hz

Ion revolution frequency=0.1656MHz, tune Qx=3.63, Qy=2.61

Experiment Results

The impact of energy detuning voltage change on ion beam lifetime is shown in Figure 2. As can be seen, the lifetime is not sensitive to the amplitude of the modulation voltage. And different modulation modes hardly affect the lifetime of ion beam as demonstrated in Figure 3.

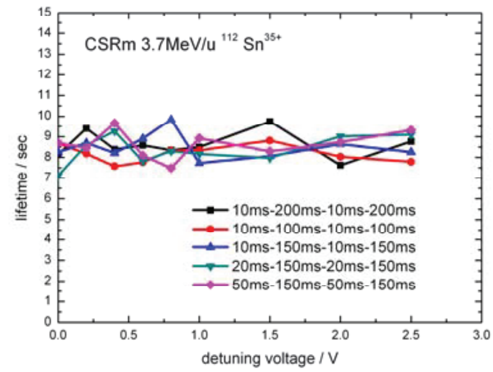

Figure 2: Ion beam lifetime as a function of the modulated voltage.

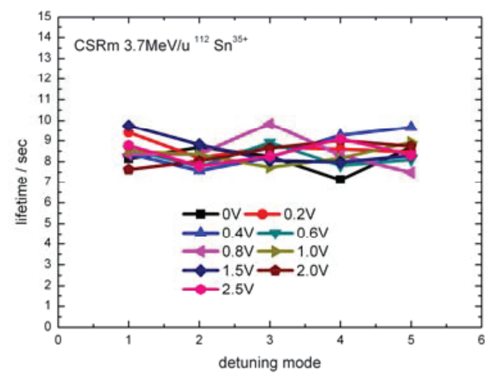

Figure 3: Ion beam lifetime as a function of the modulated mode.

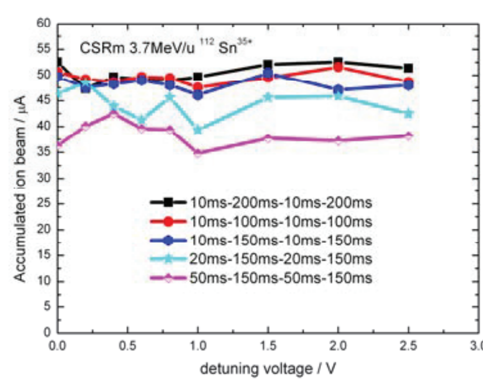

Figure 4: Accumulated ion beam intensity as a function of the modulated voltage.

The maximum accumulated ion beam intensity in Figure 4 and Figure 5 reveal less influence by energy detuning. The reduction of maximum beam intensity in

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Figure 5 was just a consequence of injection intensity decrease by ion source parameters change.

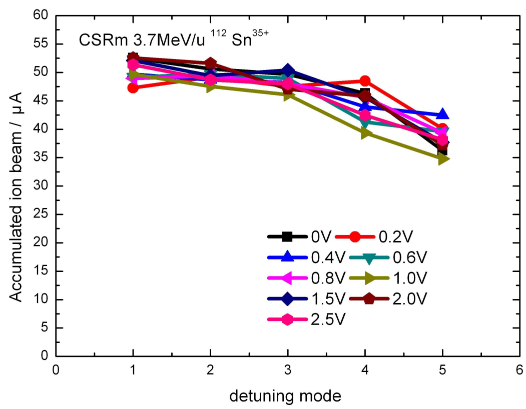

Figure 5: Accumulated ion beam intensity as a function of the modulated mode.

Due to the ion beam intensity gradually became smaller from the injection during the experiment; the accumulated ion intensity became smaller too.

Schottky Signals

However, the longitudinal beam signals from Schottky probe present a quite different result from DCCT. The detuning could pull ion beam off the initial spectrum central position. Comparing between different modulation amplitude, although the modulation was symmetrical, the Schottky signal display symmetrical signal in some modulation, and others were asymmetric. The Schottky spectrum showed an asymmetric revolution frequency response like the examples in Figure 6 – several serious variations on one side than the other. A part of ions was dragged to the lower frequency region with regard to the central frequency, and the portion pulled to the higher frequency region was smaller than the former, therefore the Schottky signal at the higher frequency region was not visible comparing with the opposite side. These results indicated that the ion lost at the higher frequency side, and the ion loss was proved by the signals from the DCCT.

An interesting phenomenon observed by Schottky probe is the separation of beam spectrum by certain amplitude modulation as shown in Figure 7.

The Schottky signal was splitted into two parts in some modulation. The amplitude of modulation was smaller than 2.5V(0.12%).

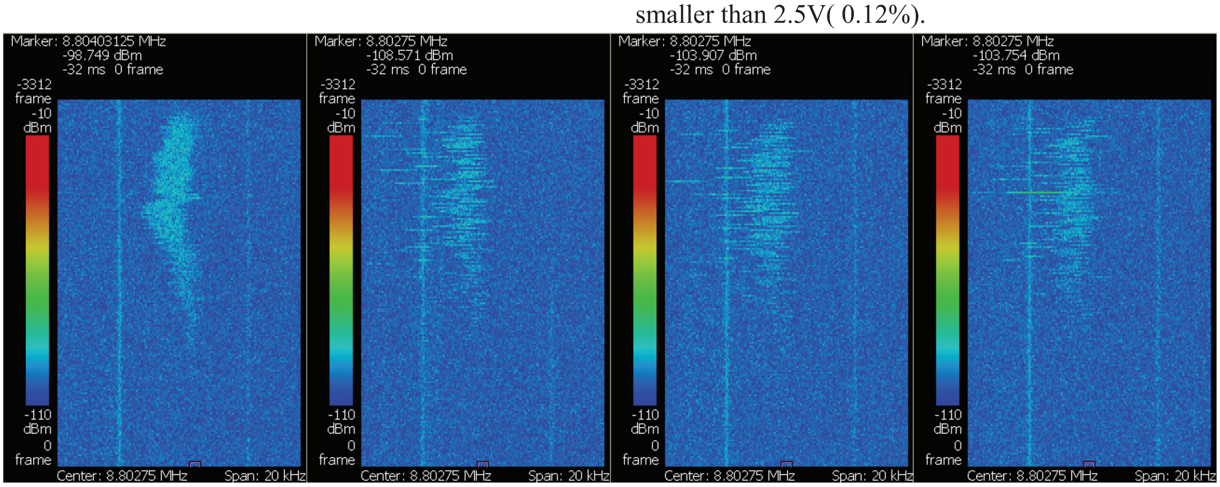

Figure 6: The evolution of Schottky signal with the modulation amplitude.

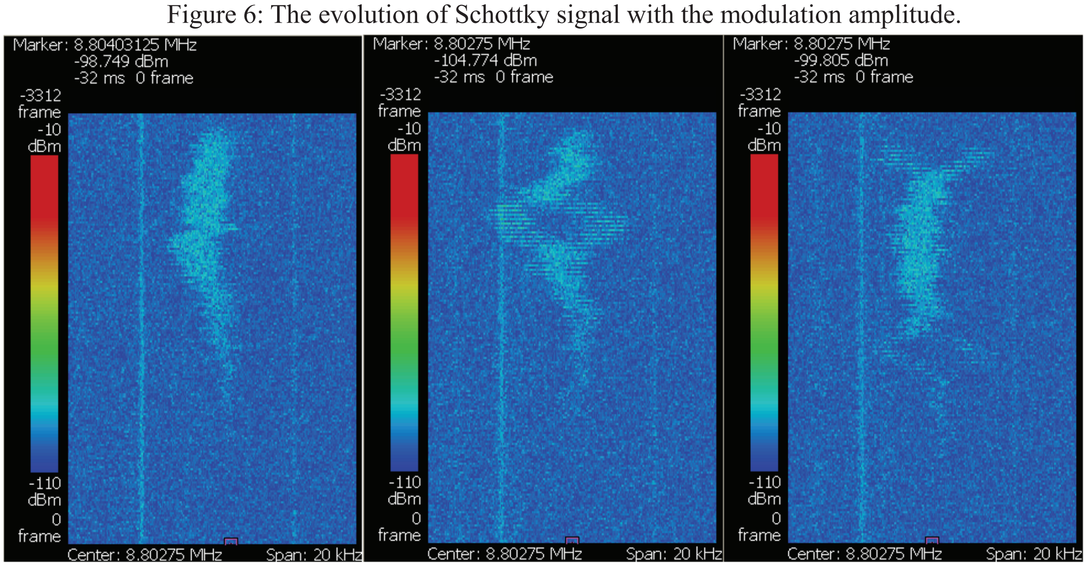

Figure 7: The Schottky signal was splitted into two parts under some modulation The amplitude of modulation was smaller than 2.5V(0.12%).

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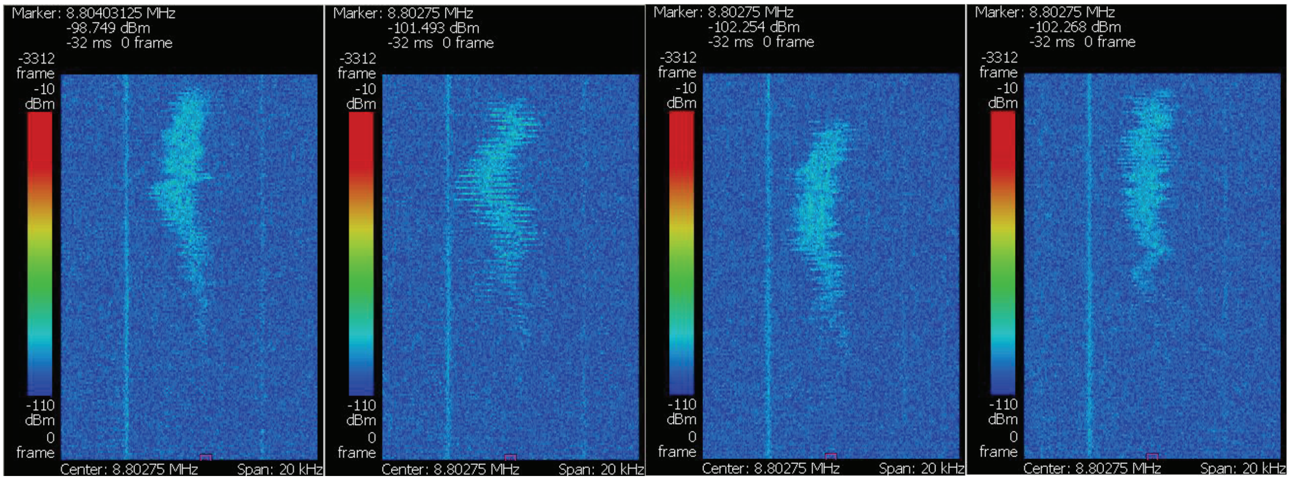

Figure 8: Some Schottky signals in the case of the voltage amplitude of modulation pulse were zero.

Another enigmatical phenomenon, in case of setting the modulation voltage amplitude to zero and switch off the modulation system, is the modulation hysteresis effect in Schottky spectrum as presented in Figure 8. That would appear right after a large voltage modulation.

Another inexplicable beam behavior was demonstrated in Figure. 9. The ion beam suddenly loss when the electron beam energy was modulated. From the Figure. 9 one can see not only the longitudinal signal from Schottky probe presented the oscillation, but also the beam intensity signal from DCCT appeared unexpected drop.

SHORTAGE IN EXPERIMENTS

Since the non-destructive beam profile monitor is not available in CSRm, the evolution of transverse emittance can't be detected and analyzed in this experiment. Additionally, the coasting beam was stored in CSRm without RF bunching; therefore the beam position also wasn't recorded during experiment. Only the ion beam current and the longitudinal momentum were measured by DCCT and Schottky detectors, respectively. The

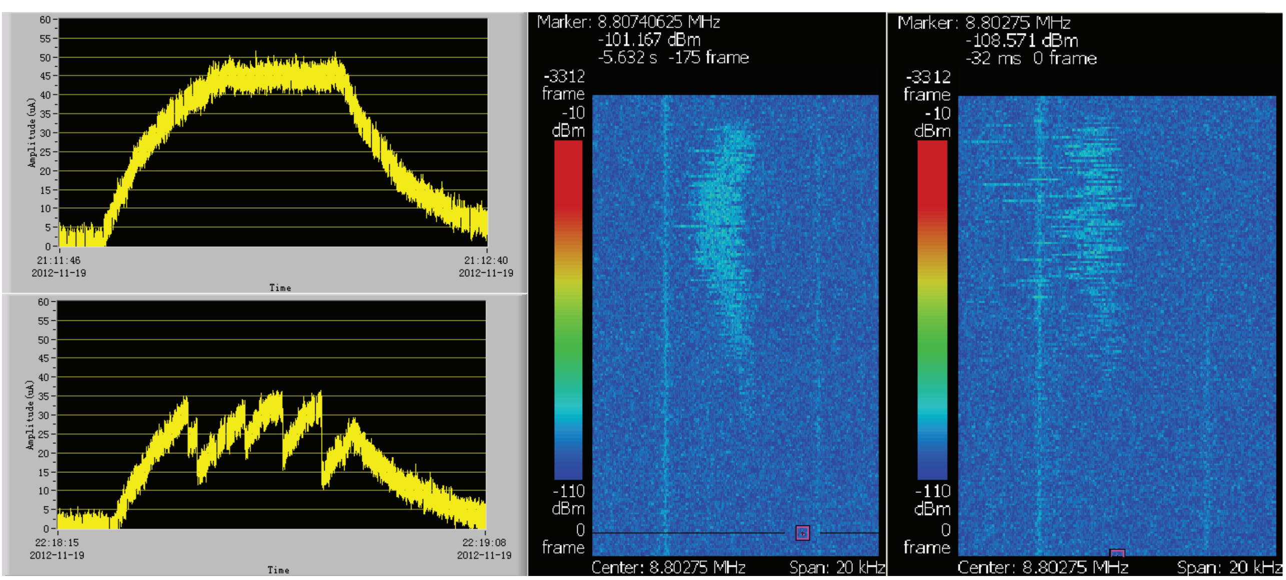

Figure 9: DCCT and Schottky signals at the same time. DCCT signal represents the ion intensity, Schottky signal represents the revolution frequency of ion beam, ion velocity and momentum spread.

This phenomenon was observed more than once, and it did not happen periodically in the time coordinate. This point was not understood clearly. Generally, the ion beam momentum spread was increased due to the electron energy modulations, and the modulated amplitude was not bigger than the longitudinal acceptance. The ion beam was not supposed to loss. In this case, the signal of DCCT should keep invariable. The real reason of beam loss was not understood clearly and revealed completely.

correlation between beam loss and momentum shift was too weak to be analyzed in this experiment, more experimental measurements should be done in the future.

Because of the short machine study time in HIRFL-CSR operation schedule, the electron energy modulation frequency and modulation duty cycle weren't optimized in the experiment. In principle, the cooling time and final equilibrium momentum spread depended on the

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modulation parameters. The influence of modulation parameters on the cooling process will be investigated in the next time.

For an effective electron cooling, the ion beam and electron beam have to overlap coaxially. Due to un-bunched ion beam was stored in CSRm, the ion beam position in the cooling section can't be measured. In this experiment, the ion beam current after stacking was measured for different ion beam orbit correction schemes in the cooling section. The scheme of the maximum stacking ion beam current was used as the perfect orbit correction in the cooling section.

The high voltage stability of the electron cooling system is a key problem of the electron cooling system. According to the results of electron energy modulation simulation [16] and experiment, a limitation of high voltage stability can be described. The results from this experiment also could be useful for the beam stacking and beam loss study with modulated electron cooling. The momentum shift caused by the electron energy modulation is helpful for electron heating study. The influence on the beam lifetime and instability of high intensity beam was not found in the experiment.

SUMMARY

In the condition of this experiments, due to limitation of injected ion beam and its intensity, the accumulated ion beam have not approached the saturation in the storage ring, and the space charge limitation have not reached. At the same time, the proper modulation frequency and appropriate amplitude were not found. As a consequence, there were no obvious evidences for increasing the accumulated ion intensity and suppression of instability by electron energy modulation.

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