A CHARACTERISTICS STUDY FOR COLD ION BEAM MOMENTUM SPREAD AT HIRFL-CSR*

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Abstract

Two electron cooling devices have been used at HIRFL-CSR in order to provide high quality heavy ion beams for nuclear and atomic research. The momentum spread is one of the most important characteristics of the beam quality. At HIRFL-CSR, the momentum spread is measured directly with the aid of longitudinal Schottky spectra system. In this paper, the measurements for various ion species are presented. At relatively high intensity, longitudinal Schottky spectra is double peak due to collective phenomena and the momentum spread can be obtained by fitting the spectra. The dependence of momentum spread on stored particle number is proportional to N^a.

INTRODUCTION

HIRFL-CSR is a new heavy ion cooling-storage-ring in IMP[1]. It consists of a main ring (CSRm) and an experimental ring (CSRe). The cyclotrons SFC (K=69) and SSC (K=450) are used as injectors. The heavy ions are accumulated at CSRm with the help of electron cooling at injection energy, then, accelerated and extracted to CSRe for nuclear and atomic physical experiments. At CSRe, the electron cooler are used to boost the luminosity even with strong heating effects of internal targets.

Two electron coolers for HIRFL-CSR is the first of a new generation of coolers being operated for fast phase space cooling of ion beams. Electron cooling is a well-established method to improve the phase space quality of ion beams in storage rings [2]. The cooling process is based on the energy loss due to Coulomb interaction of the ions in a superimposed cold electron beam with the same average velocity. After sufficient cooling time, the transverse emittance and momentum spread of beam will be reduced.

The momentum spread was determined using the longitudinal Schottky spectra. Systematic measurements have been made for several species ion beams at HIRFL-CSR. Measurement of Schottky spectra is a direct way to obtain information about the momentum evolution during cooling process. By this method, the collective phenomena of intense cooled beam and crystalline beam were studied in several cooling storage ring [3] [4] [5].

MEASUREMENT SCHEME

Two capacitive pickups are used as Schottky noise probes at CSRm and CSRe respectively. The electrodes have a length of 150mm in beam direction and distances of 170mm and 100mm in horizontal and vertical direction.

Since the ions stack enough, switch off the injector and bump magnets. Then, after a time interval an order of magnitude longer than a typical cooling time during which the stored ions cooled equilibrium, the current and trace of spectra of ion beam were recorded individually.

Fig 1shows the sequence of Schottky spectra for carbon and argon beam at different beam intensity. The spectra were taken around the 100th harmonic of the revolution frequency. A prominent feature of the spectra is their double-peak character at beginning.

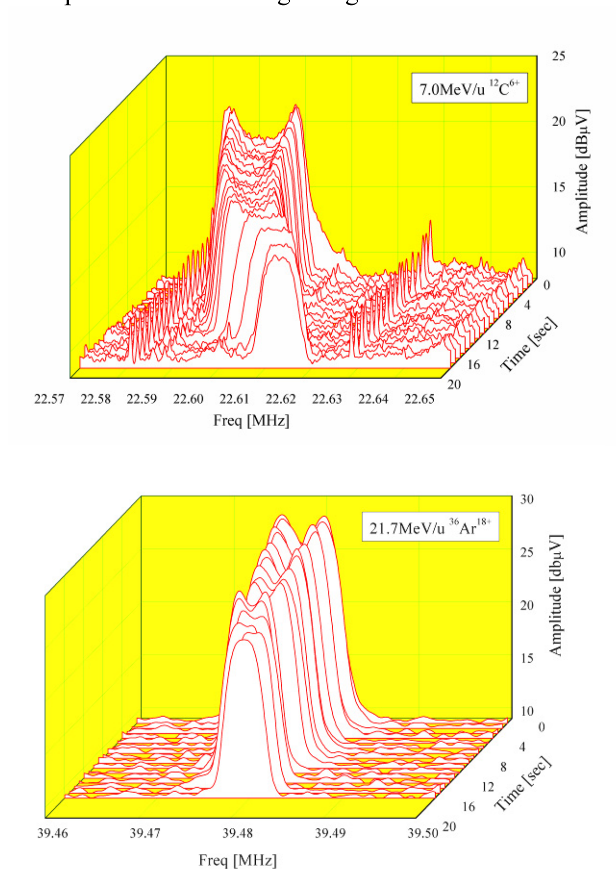

Figure 1: sequence of Schottky spectra for $^{12}C^{6+}$ and $^{36}Ar^{18+}$ at the 100th harmonic of the revolution frequency show a double-peak phenomenon at high beam density.

LONGITUDINAL SCHOTTKY SPECTRA

The signal from pickup can be approximated by a delta pulse each time a particle passes through it. The total signal from N particles with charge Ze can thus be written as [6]

$$u(t) = Ze\sum_{i=1}^{N}\sum_{k}\delta\left(t - \frac{2\pi k + \theta_i}{\omega_i}\right) \qquad (1)$$

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where θ_i is the initial phase of ion i in its motion around the ring and ω_i its revolution frequency. With the help of autocorrelation function, the spectra density of this signal is

$$S(\omega)=\frac{(Ze)^2}{2\pi}\sum_{i=1}^{N}\sum_{k=-\infty}^{\infty}\omega_i^2\delta(\omega-k\omega_i) \qquad (2)$$

It's concentrated in bands around the nominal revolution frequency ω_0 and its harmonics. For coasting beam of N randomly spread particles along the ion orbit in the ring, the revolution frequencies ω_i are distributed according to a function $\Psi(\omega)$, normalized to the particle number, the spectral density can be approximated by

$$S(\omega)=\frac{N(Ze)^2}{2\pi}\sum_{k=1}^{\infty}\frac{1}{k}\left(\frac{\omega}{k}\right)^2\Psi\left(\frac{\omega}{k}\right) \qquad (3)$$

If the number of ions in the beam is not large, so that their interaction can be neglected, this would be the Schottky signal as recorded by a spectrum analyzer in experiments. However, an intense cooled beam develops a collective motion as a result of the interaction between the ions and their environment. In this case, the Schottky bands can be strongly deformed into a double-peak shape as a result of the coherent frequencies caused by the forward and backward running beam plasma waves. The spectral density was calculated by:

$$S(\omega)=G\frac{N(\Delta\omega h)^2}{2\pi\Omega_h^2}\frac{\mathrm{Im}(\varepsilon)}{\omega|\varepsilon|^2} \qquad (4)$$

where G is a constant determined by the gain of measuring system, $\omega=2\pi(f-hf_0)$ is frequency relative to frequency of h^{th} harmonic, ε is dielectric constant, $\Delta\omega$ is spread of revolution frequency, Ω_n is coherent shift on h^{th} harmonic written by:

$$\Omega_n^2=(n\omega_0)^2\frac{Nr_i\eta_t\left(2\ln\left(\frac{a_{vacuum}}{\sigma_{beam}}\right)+1\right)}{4C_{ring}\gamma^3\beta^2} \qquad (5)$$

C_{ring} is circumference of the synchrotron, r_i is classical ion radius, $\eta_t=\frac{d\omega}{\delta p}\frac{p}{\omega}$ and $\Delta\omega$ written by

$$\Delta\omega=\omega_0\eta_t\frac{\Delta p}{p} \qquad (6)$$

Equation of the dielectric constant can be written as expansion

$$\varepsilon=1+2\frac{\Omega_n^2}{(\Delta\omega n)^2}\left[1+\frac{i\omega}{\lambda q-i\omega}\left(1+\frac{q}{1+q-i\frac{\omega}{\lambda}}+\cdots+\frac{q^m}{\left(1+q-i\frac{\omega}{\lambda}\right)\cdots\left(m+q-i\frac{\omega}{\lambda}\right)}+\cdots\right)\right] \qquad (7)$$

with $q=\left(n\frac{\Delta\omega}{\lambda}\right)^2$. $\lambda=\frac{1}{\tau_{cooling}}$ is longitudinal decrement and $\tau_{cooling}$ is longitudinal cooling time.

EQUILIBRIUM MOMENTUM SPREAD OF COLD ION BEAM

The spectra of measured and fitting data at different intensity of $^{12}C^{6+}$ and $^{36}Ar^{18+}$ ion beams are show in fig 2. The double-peak phenomenon was obvious at intense cooled beam but disappeared while ion current small enough, because a distortion of the shape caused by collective particle motions can be neglected and the shape can be approximated by a Gaussian with moderate phase space density.

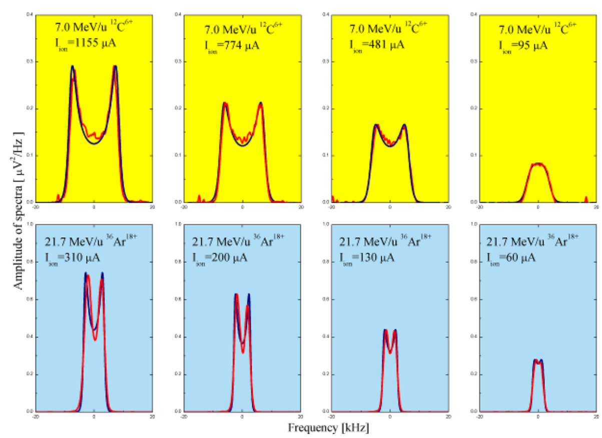

Figure 2: Schottky spectra of measured and calculated for various ion beam currents. Blue line shows the measurement data and red line is simulation result.

The equilibrium momentum spread values as function of stored ion number were obtained and plotted in fig 3. For carbon beam, the momentum spread is proportional $\sim N^{0.16}$ and reaches 2.09×10^{-4} for particle number 7×10^{9}. For argon beam, the momentum spread is proportional $\sim N^{0.31}$ and reaches 5.35×10^{-5} for particle number 3×10^{8}.

CONCLUSION

In electron cooling, the momentum spread of cold ion beam is determined by equilibrium between electron cooling process and energy flux caused by intrabeam scattering. The reduction of the phase space volume by electron cooling is inevitably linked to a growth of the heating rate by intrabeam scattering which grows inversely proportionally to the phase space volume of the ion beam. In general case, the cooling rate depends on phase space volume weakly. Due to this reason, the equilibrium momentum spread increases with stored ion number increased.

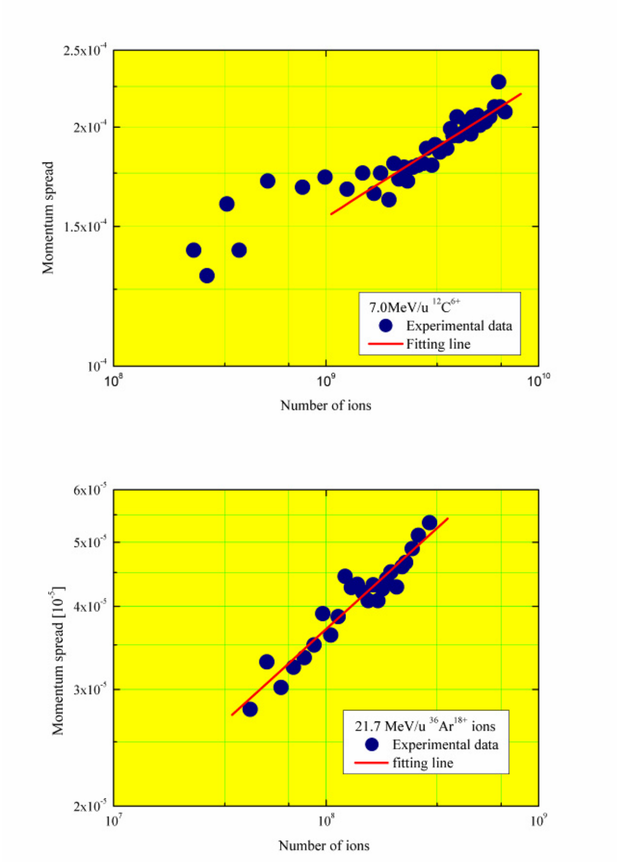

Figure 3: the function of momentum spread depends on stored ion number.

Two capacitive pickups are used as Schottky noise probes at CSRm and CSRe respectively. The electrodes have a length of 150mm in beam direction and distances

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