COLD HEAVY ION BEAMS AT THE HEIDELBERG TSR+

M. Grieser, M. Blum, D. Habs, G. Huber*, M. Jung, E. Jaeschke, C.M. Kleffner, D. Krämer, W. Petrich, R. Repnow, S. Schröder*, M. Steck.
Max Planck-Institut für Kernphysik D-6900 Heidelberg, Germany
* University of Mainz

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Abstract

The Heidelberg Heavy Ion Cooler Ring TSR [1] has demonstrated full performance since the electron cooler, installed in late 1988, allowed the production of high brilliance beams. Using the new method of 'cooler stacking' intensities were enhanced by factors of several thousands compared to single turn injection. The (cooled) phase space volume was reduced by 4 to 5 orders of magnitude limited by the balance of cooling and heating due to intrabeam scattering. Strong collective effects were observed for intense cold beams. Further phase space compression was achieved by Laser-Cooling [2] yielding partially stripped ion beams (Li^+,Be^+) of beam temperatures below 3 K. A comprehensive report on the results of the various machine developments carried out with p, d, Li, Be, C, O, Si, and S beams will be given.

1. Introduction

The Heidelberg heavy ion storage ring TSR [3] is an experimental facility for accelerator, atomic, plasma and nuclear physics at the MPI MP-tandem-postaccelerator combination [4]. Constructed in the years 1985 to 1988, commissioning of the ring started in May 1988. With the installation of an electron cooler [5] the ring has become the first heavy ion cooler ring. It has been used for atomic physics experiments starting already late 1988 [6].
The ring is capable of storing beams of magnetic rigidity up to 1.5 Tm. The electron cooler produces an intense cold electron beam (transversal electron energies of = 0.1 eV) at densities of up to $1 \cdot 10^8$ cm^{-3}, e.g. 1 A at energies of a few keV.
So far many ion species ranging from protons to sulphur at various charge states have been accumulated.

2. Phase Space Compression by Electron-Cooling

Phase space compression of beams by electron cooling allows to generate brilliant beams with extremely small energy spread, independent of the starting conditions. The obtainable equilibrium beam quality is determined by the balance of the friction force of the cooling system and the heating, e.g. by intrabeam scattering, scattering with the residual gas, internal target material etc. As the cooling time scales with A/Z^2, electron cooling of heavy ions is a fast and very powerful tool to create high intensity low emittance and small energy spread beams.

2.1 Noise Spectra Measurements

The properties of the cooled ion beam are monitored by a Schottky pick up which measures the distribution of revolution frequencies of the particles. For low particle numbers this distribution corresponds to the momentum distribution, whereas for higher intensities exceeding a so called threshold intensity (typically some 10^7 particles) a strong interaction of the particles in the beam can be observed [7]. The spectrum (Fig.1) shows two peaks corresponding to two plasma waves which propagate parallel and antiparallel to the ion beam.

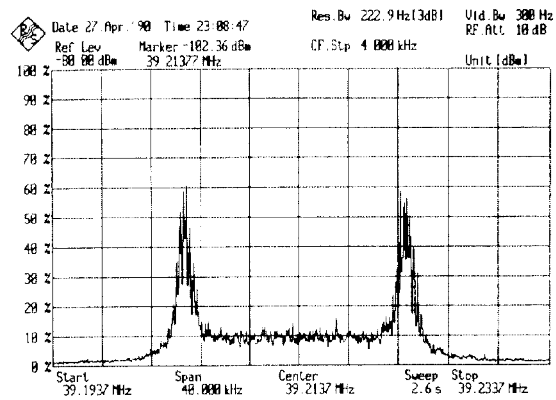

Fig.1: Schottky spectrum of $1 \cdot 10^9$ oxygen ions ($^{16}O^{8+}$ 98 MeV) stored with electron cooling

Schottky spectra for different particle numbers were measured in order to study the effect of mass and charge of the ion. Figure 2 shows a comparison of the momentum spread of the ion beam for deuterons and carbon ions $^{12}C^{6+}$ stored under identical experimental conditions. The momentum spread increases with $N^{1/3}$ which follows from the balance of heating by intrabeam scattering and cooling by electrons. The difference of the momentum spread for a fixed particle number between deuterons and $^{12}C^{6+}$ ions is approximately a factor of 2.1, or expressed for the beam temperature a factor of 25. This is in reasonable agreement with theoretical predictions of an increase of the beam temperature proportional to Z^2.

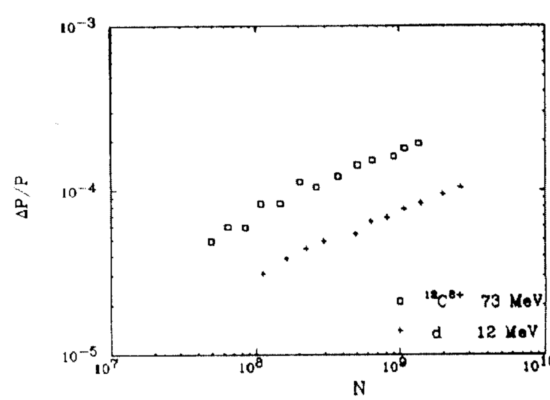

Fig.2: Measurement of momentum spread as a function of particle number for deuterons and carbon ions stored with electron cooling under the same experimental conditions

In Figure 3 a number of additional ions is included showing the same increase of momentum spread with particle number. However, for these measurements the density of the electron beam differs by a factor of up to 2 and also the set up of storage ring and cooler are not identical.

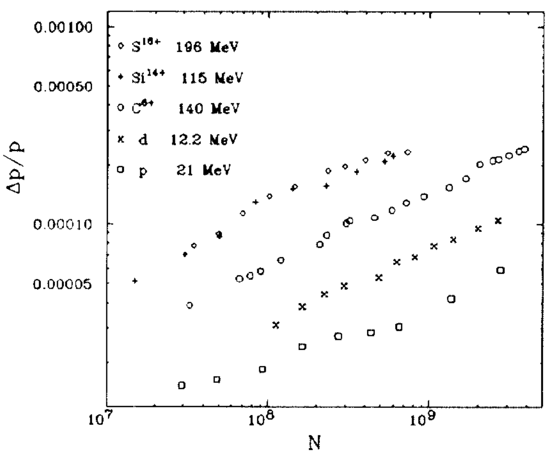

Fig.3: Momentum spread of several ion species which were electron cooled in the TSR

Significant deviations from the theoretical prediction were found for the separation of the two coherent signal maxima at high ion beam intensities. Figure 4 shows measurements of the coherent frequency spread obtained during several experiments with $^{12}C^{6+}$ at 73 MeV. The coherent frequency spread is predicted to scale proportional to $I^{1/2}$ in good agreement with our experimental results for stored currents below 1 mA. For currents above 4 mA a clear deviation from this scaling is observed.

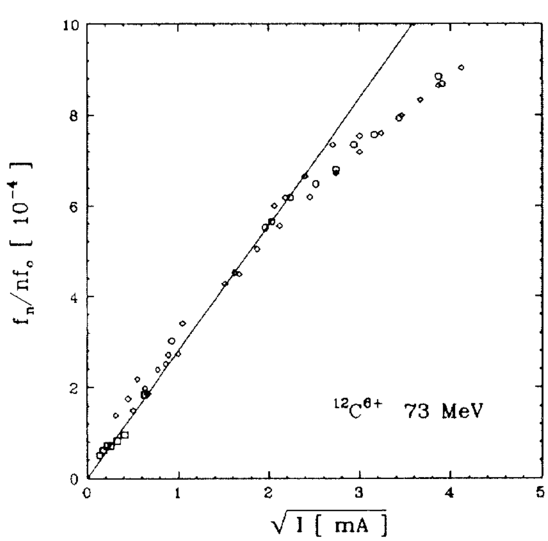

Fig.4: Intensity dependence of the coherent plasma frequency

2.2 ECOOL-Stacking

To study the high intensity behaviour of ion beams systematically a new accumulation technique which employs the electron cooler was developed [1]. The beam is injected with the standard multiturn injection scheme, with simultaneous operation of the electron beam which is slightly detuned towards lower velocity, thus decelerating the newly injected ions. Figure 5 shows a Schottky spectrum of several multiturn batches successively injected and being slowed down to a smaller momentum still within the ring acceptance. The large signal in the spectrum originates from the decelerated particles stored at the velocity of the electrons. With optimized electron cooling currents up to several mA can be stored stably, limited by the onset of transverse coherent instabilities.

Higher intensities can be achieved when applying rf stacking in order to speed up the accumulation process. Intensities as high as 18 mA of $^{12}C^{6+}$ at 73 MeV were stored. Strong coherent signals from the pick ups indicate that this maximum intensity is limited by transverse instabilities.

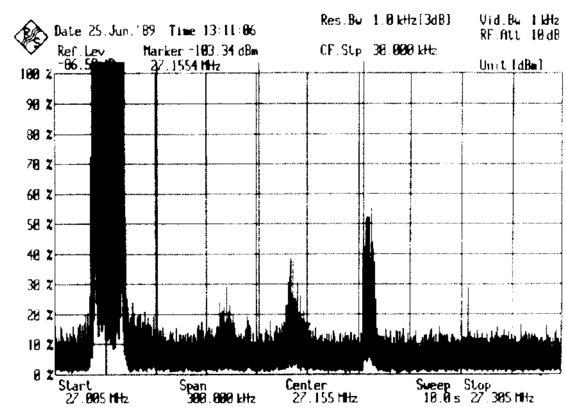

Fig.5: Schottky spectrum during multiturn injection with electron cooling to increase the intensity of the accumulated beam

The method of beam accumulation by electron cooling allowed for the first time simultaneous storage of deuteron and oxygen ions (kinetic energy 6.1 MeV/u). After accumulation and cooling the first stored beam was transferred to a stack position which allowed injection of the second beam without loss of the first. Succesive injection of the two ion species allowed simultaneous storage of $1 \cdot 10^9$ (100 μA) deuterons and $1 \cdot 10^8$ (80 μA) oxygen ions of nearly equal magnetic rigidity. The two beams could be observed (Fig.6) as two well separated signal peaks in the Schottky noise because of the different nuclear masses of the two ions.

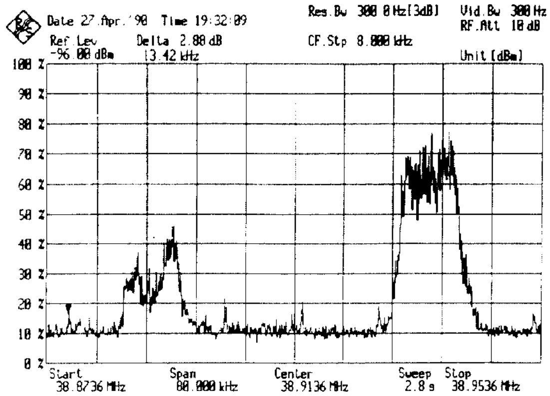

Fig.6: Schottky spectrum with deuteron peak (left) and oxygen peak (right)

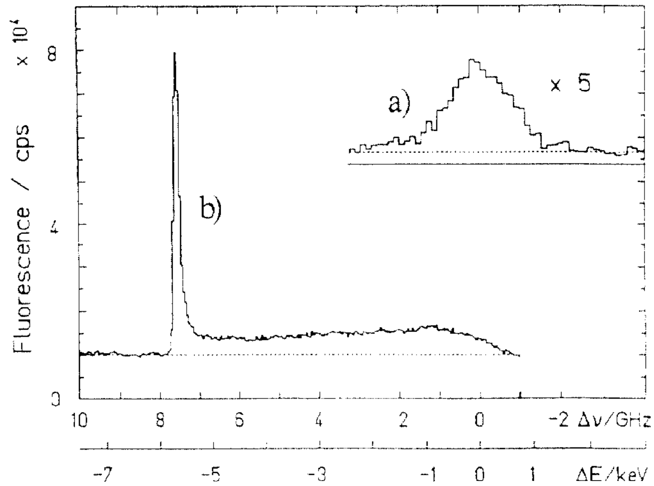

Fig.7: Laser fluorescence signals; a) shows the initial and b) the "compressed" velocity distribution.

3. Laser Cooling at TSR

The method of laser cooling promises even lower equilibrium beam temperatures in the longitudinal degree of freedom than electron cooling.

First successful laser cooling of accumulated $^7Li^+$ and $^9Be^+$ beams at about 5% of the velocity of light has been observed at the TSR [2]. A coasting $^7Li^+$ beam containing about 10^7-10^8 ions was accumulated at 13.3 MeV and stored in the TSR with a lifetime of 8 sec. During the stripping process in the tandem accelerator used to supply the $^7Li^+$ions, about 10% of the ions were excited to the long-lived metastable 1s2s $^3S_1$ state. As an optical electrical-dipole transition of λ =548.5 nm connects this state to the $^3P_2$state and the F-sublevels are sufficiently separated the $^3S_1$(F = 5/2) and $^3P_2$ (F = 7/2) states form a closed two-level system, well suited for laser cooling.

The actual laser cooling was performed in the following way: The frequency of the Ar^+-ion laser was set to be in resonance with ions at the low-energy side of the beam velocity profile and was kept constant. The frequency of the counterpropagating dye laser was set to the corresponding high-energy side and was swept towards lower energies. Ions which came into resonance with the light of the dye laser experienced absorption-emission processes and were therefore decelerated due to the corresponding transfer of the photon momenta. The combined action of sweeping the laser frequency and transfering photon momenta resulted in the accumulation of the ions into a narrow peak in their velocity distribution. Further experimental details can be found in reference [2].

The initial (Fig.7a) and "compressed" (Fig. 7b) velocity distributions were measured by detecting the fluorescent light perpendicular to the ion beam. Figures 7(a) and 7(b) show a compression of the longitudinal velocity distribution, corresponding to a temperature of 260 K in the rest frame of the ions, by a factor of 100 to a final temperature of less than 3 K. Similar results have been obtained for $^9Be^+$.

Acknowledgement

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