HEAVY-ION COOLING AND RELATED APPLICATIONS IN THE COOLER-RING TARN II AT INS

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An electron cooler-ring TARN II has been used for the studies of accelerator technologies such as electron cooling, beam acceleration and slow extraction. These studies have been performed on light ions. In order to extend the studies of the electron cooling and related applications to heavier ions, some improvements of the machine have been performed. These include the improvement of vacuum and the developments of beam diagnostic elements, ion sources for the injector cyclotron and detectors to measure charge-changed ions for the heavy-ion experiments. The status of the machine and a summary of the experiments so far achieved are described.

Introduction

Since the first success of the electron cooling at TARN II, the electron cooling experiments have been performed on light ions such as proton, deuteron and alpha particles. In these experiments, fundamental data for the cooling technique have been measured. The cooling experiments include the measurements on beam lifetime, cooling time, drag force and momentum resolution. The plasma waves propagating in the cold high-density beam caused by the collective motion of ions have been observed. Furthermore, the beam stacking experiment has successfully been made utilizing the strong phase-space compression due to the cooling. The cooling electrons are also a high-quality electron target. From this viewpoint, the electron capture processes were studied on proton, H_2^+ and He^+. Especially, dielectronic recombination of He^+ has been studied for the first time.

In order to extend the studies of the electron cooling and related applications to heavier ions, several improvements of the machine have been executed in 1991. After the completion of the upgrading works on the machine, heavy-ion beams both for partially and fully stripped ions have successfully been cooled. In the following, the status on the TARN II with emphasis on electron cooling is described after a brief summary of the cooling experiments on light ions.

Summary of the electron cooling experiments on light ions

The details of the electron cooling device and the electron cooling experiments so far performed at INS have been described in ref. [1]. Fig. 1 shows the layout of the electron cooling device. Electrons are extracted from a heated cathode with a diameter of 5 cm and accelerated to full energy. Electrons are then bent by 45° and merge with ion beams. The length of the cooling section is 1.5 m which is only 1.9 % of the whole circumference of the TARN II. The cooling device is located at one of the six long straight sections of the TARN II which has 78-m circumference. The ion beams are injected from a sector focusing cyclotron and stored in the ring.

Here we introduce some of the cooling experiments on the 20 MeV proton beam:

The intensity of the beam multiturn injected from the injector cyclotron is low, which is in the order of 10^7 particles. In order to inject more particles, the electron cooling was applied to the successively injected and coasting beam: the strong phase space compression due to the cooling allows the stacking of repeated multiturn injected beam. Experiments were performed by injecting the beam every 4 s and measuring the beam intensity. About half of the acceptance phase space for the usual multiturn injection was saved for the compressed and stacked beam by weakening the bump magnetic fields for the injection system. The beam intensity increases and saturates with the increase in number of multiturn batches. An intensity multiplication factor

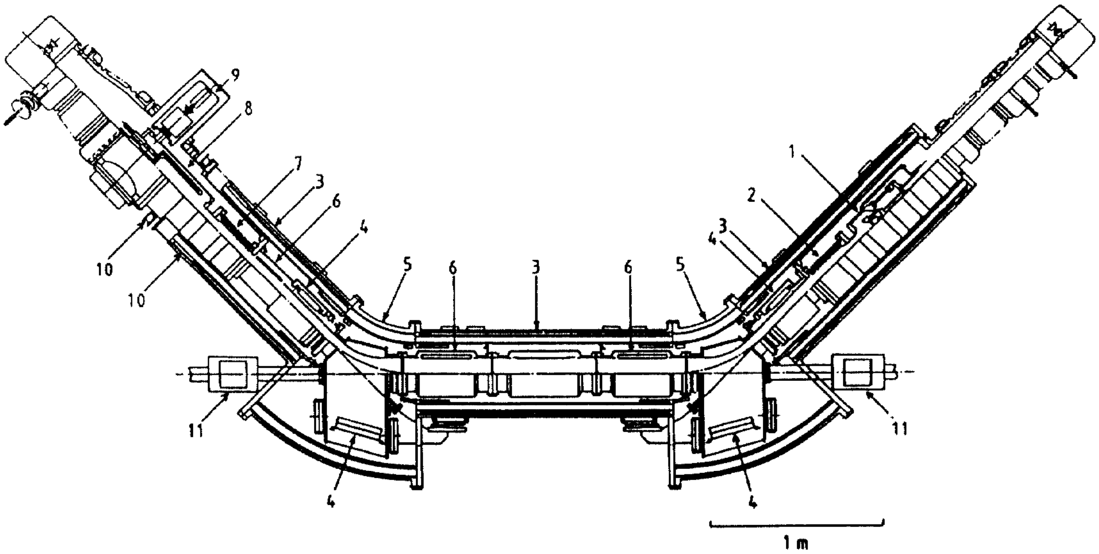

Fig.1 Layout of the electron cooling device. 1:Electron gun, 2:Acceleration tube, 3:Solenoid, 4:NEG pumps, 5:Toroid, 6:Beam position monitor, 7:Deceleration tube, 8:Collector, 9:Ion pump, 10:Correction coil and 11:Steering magnet.

of 20 was reached after 30 injections in a time of 2 min., resulting in the total number of stored particles of the order of 10^{8}.

The change of momentum resolution with cooling was observed by measuring the frequency spread of the higher harmonics of Schottky signals for a coasting beam. The frequency width Δf of the spectrum observed by a spectrum analyzer is related to the width of the momentum distribution Δp by

$$\Delta f/f=\eta \Delta p/p \qquad (1)$$

The momentum resolution $\Delta p/p$ decreased from the order of 10^{-3} to the order of 10^{-5} within a time of a few seconds. When scanned with a high resolution of the spectrum analyser, the frequency spectra of the cold beam Schottky signals show splittings. The splitting becomes remarkable with the increase in number of circulating particles. It is originated from two plasma waves propagating parallel and antiparallel to the beam direction with a characteristic frequency f_o which is half the distance between two peaks. Such a collective phenomenon begins when the longitudinal temperature of the beam becomes comparable to the interparticle Coulomb energy.

Neutral hydrogen atoms produced during cooling provide lots of important information about the electron and ion beams. They leave the ring in the extension of the cooling straight section and are detected outside the dipole magnet just at the exit of the thin window. The horizontal and vertical distributions of neutral atoms measured at 4.5 m downstream of the cooling section were 6.1 mm horizontally and 8.4 mm vertically. From these values and the known beta functions at the cooling section, we can estimate the emittance of the circulating beam. It was about 1 to 2 π mmmrad.

For the bunched beam, the decrease in momentum spread through longitudinal cooling results in the reduction of the bunch length due to synchrotron oscillation. The bunch length L is related to momentum resolution $\Delta p/p$ and and rf voltage V_{rf} as follows,

$$L=k(\Delta p/p)V_{rf}^{-1/2} \qquad (2)$$

where k is a constant. The bunch length was measured from the distribution of the arrival times of hydrogen atoms. The measured time width of 53 ns (FWHM) corresponds to a bunch length of 3.3 m which is much shorter than the one before cooling by a factor of about 10.

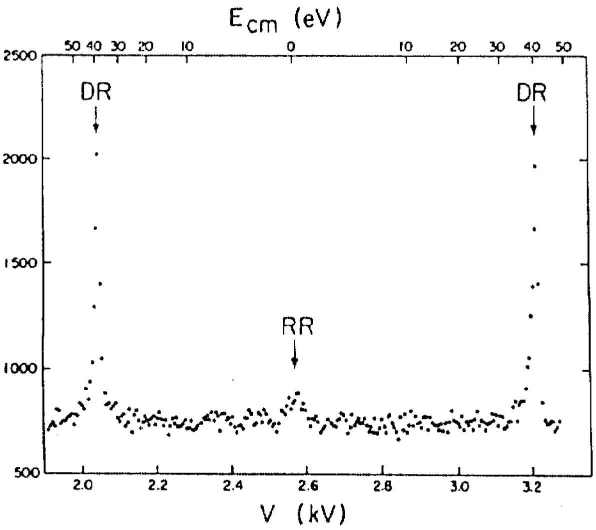

Fig.2 Yield of neutral ^{3}He atoms formed in the electron cooler as a function of the electron acceleration voltage. The c.m. energy scale is also shown. The maxima on the both sides correspond to DR, while the bump on the center is due to RR (see text).

Application of the electron cooling to atomic collisions

Electron capture processes by the circulating ions were studied using the electron cooling device: dielectronic recombination (DR) via 1s →2p excitation has been measured for 13-MeV $^3He^+$ ion. DR occurs in an electron-ion collision when an electron in the projectile ion is excited and at the same time a free electron is captured to form a doubly excited state in the ion, followed by subsequent radiative stabilization. The formation of the doubly excited intermediate states is resonant for the relative velocities between ions and electrons. DR is the principal mechanism in free electron recombination with ions in thin, high temperature plasma. It has been theoretically shown that in the solar corona the DR rate for ($e+He^+$) can dominate the radiative recombination rate by an order of magnitude or more. DR is, thus, important also in applications such as nuclear fusion process and astrophysics as well as in fundamental atomic physics. The most fundamental ion for which DR is possible is He^+. For this process, no experimental data has yet been obtained which permit any meaningful comparison between theory and experiment. Rate of neutral ^{3}He atoms formed in the electron cooler is shown in Fig. 2 as a function of the electron acceleration voltage. The DR maxima were observed for electron velocities both slower and faster than the ion beam velocity almost symmetrically with respect to a small bump due to radiative recombination (RR) located at zero detuning energy ($E_{cm}=0$). Details of the experiments and the analysis are described in ref. [2].

Machine development towards heavy-ion cooling and applications[3]

High vacuum is essential for the long time storage of heavy ions, especially partially stripped ions because the stripping cross sections are much larger than the capture cross sections for most of the related ions. The cooling time is generally in the order of a few seconds. So the lifetime should be longer than this time, at least a few 10 seconds. This requires the high vacuum in the order of 10^{-11} Torr. The vacuum pressure of the ring had been in the order of 10^{-10} Torr which was not enough for the heavy-ion cooling. In order to achieve high vacuum, components with high outgas rate like beam extraction system were temporarily removed. Furthermore vacuum pumps have newly been added around the ring and the injection line. They are 7 ion pumps and 21 Ti sublimation pumps. Total numbers of the pumps along the circumference with the length of 78 m are 17 for ion-pumps and 28 for Ti sublimation pumps. After the bakeout of the beam pipes at around 150 °C, present vacuum is 8×10^{-11} Torr without beam and 1.3×10^{-10} Torr with ion and electron beams. In order to obtain better vacuum, we plan to raise the baking temperature.

The intensity of heavy-ions circulating in the ring should be more than the order of 1 μA for the reliable beam handling and also for the experiments of electron cooling and atomic physics. Some improvements of the machine to increase the beam intensity have been planned and executed: 1) Six vertical steering magnets were installed in the ring for the correction of vertical COD caused by the misalignment of the dipoles and the quadrupoles. The maximum alignment errors are presently 3 mm and 1.5 mrad. With the beam test, an increase of beam intensity of about a factor of two was observed by exciting the vertical steerers. 2) Some beam pipes in the injection line have been replaced by larger ones, as the beam size in the injection line had locally been limited by the small inner diameter of the beam pipes. 3) An indirectly-heated cathode PIG source has newly been developed at the injector cyclotron, which is expected to have a longer lifetime in comparison with the existing source with cold cathode, resulting in the stable and high intensity pulsed heavy-ion beams. A trial to increase the beam intensity from the existing ECR source has also been planned by installing an electron gun made by LaB_6 on the axis of the ECR source.

The alignment between electron and ion beam axes is very important for the efficient electron cooling. But the high accuracy alignment was not easy due to the insufficient sensitivity of the monitoring system. Recently non-destructive beam profile monitor was developed and it was found that the beam profile is very sensitive to the alignment accuracy.[4] Fig. 3 is a photograph of the residual gas ionization beam profile monitor which consists of ion acceleration electrodes, microchannel plate with an area of 5×5 cm^2 and a resistive anode. It has been installed in one of the six long straight sections. An example of beam profiles of 85-MeV N^{5+} during cooling is shown in Fig. 4.

For the atomic physics experiments using the electron cooling system, some devices have newly been installed: 1) In order to define the beam size, a beam scraper has been installed. 2) A Faraday cup was set downstream of the cooling section, which helps the normalization of the injected beam intensity. 3) In addition to the existing neutral beam monitor, a detector system which can detect charge-changed heavy-ions has been installed in the beam pipe just after the dipole magnet downstream the cooling section as shown in Fig. 5. This system gives information on the electron capturing and stripping processes caused by the ion-electron interactions.

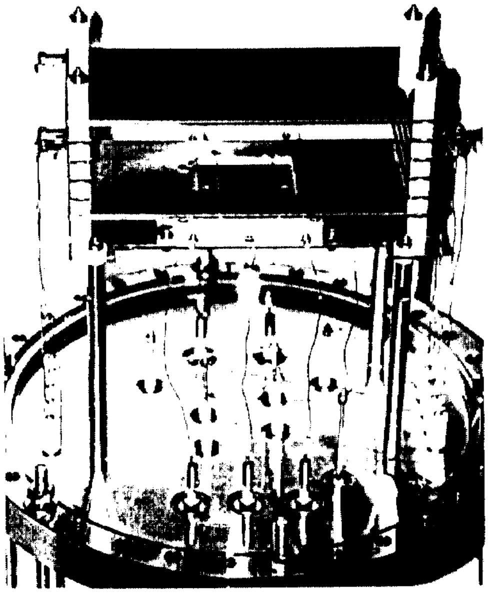

Fig.3 Photograph of the residual gas ionization beam profile monitor.

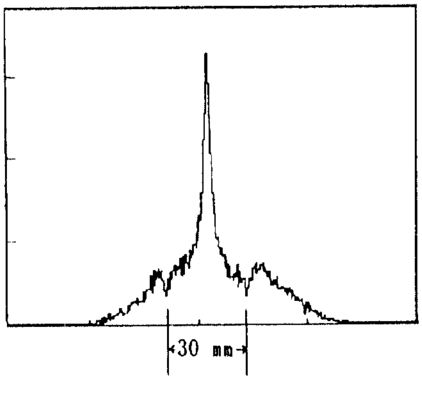

Fig.4 Beam profile of 85-MeV N^{5+} ions during electron cooling (between 1 s and 4 s after injection) measured with the non-destructive profile monitor .

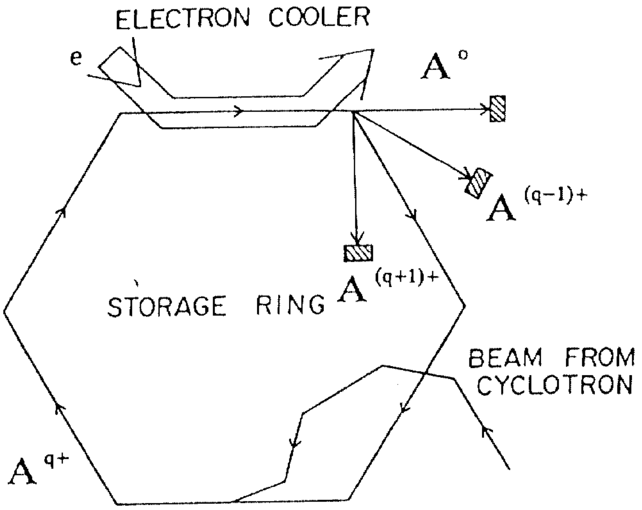

Fig.5 Schematics of the storage ring, the electron cooler and the detection system of charge-changed particles.

Electron cooling of nitrogen beams

After the completion of the improvement works on the ring, the electron cooling experiments on fully and partially stripped nitrogen beams have been performed. The lifetimes of N^{7+} and N^{5+} beams have been measured both with and without electron cooling. Results are shown in Table 1 together with the expected lifetimes assuming the acceptance angle of the ring of 1 mrad and the residual gas content of 50 % hydrogen and 50 % nitrogen. As can be seen in the table, the lifetime of N^{7+} beam is limited by the electron capture process due to the residual gas although the lifetime increases by a factor of 4 with cooling. On the other hand, the lifetime of N^{5+} beam is severely limited by the stripping process.

An experiment to observe the dielectronic recombination processes on the ground state and the metastable states of N^{5+} has just started.

Table 1 Lifetime of nitrogen ion beams.

Ion	Energy	Average Press.	Lifetime (experiment)		Partial lifetime (theory)			
			not cooled	cooled	Mult. Coul.	Single Coul.	Capt.	Strip.
	[MeV/u]	[Torr]	[s]	[s]	[s]	[s]	[s]	[s]
N^{7+}	6.07	2×10^{-10}	40	120	92	1900	198	---
N^{5+}	6.07	1.4×10^{-10}	10	15	250	5200	1050	13

We are indebted to cyclotron crew for improvement of ion sources for this experiment.

References

[1] T.Tanabe et al., "Electron cooling experiments at INS" Nucl. Instrum. Meth. A307, pp.7-25, 1991.
[2] T.Tanabe et al., "Dielectronic recombination of He^+ in a storage ring" Phys. Rev. A45, pp.276-280, 1992.
[3] T.Tanabe et al., " Status on TARN II with emphasis on electron cooling and related applications" in Proc. 8th Symp. on Accelerator Science and Technology, Wako, 1991, pp.19-21.
[4] B.Hochadel, MPI H-1990-V-19.