STATUS ON TARNⅡ WITH EMPHASIS ON ELECTRON COOLING AND RELATED APPLICATIONS

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Abstract

Status of TARNⅡ is reported with emphasis on electron cooling development. Electron cooling experiments have been performed on light ion beams. As the cooling electron beam is a good electron target, it has also been used for the study of atomic physics. We aim to extend such studies to heavier ions and now some machine developments towards heavy-ion cooling have been continued. In the texts, the results of experiments so far achieved and the status of the improvement program are described.

General status of TARNⅡ

In 1989, the first electron cooling at INS was done successfully. Since then, 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 1990, the beam acceleration was successfully achieved up to the energy of 120 MeV/u for α beam with fine tuning of beam feedback loops[1]. Efforts have still been continued to raise the beam energy. On the other hand, the NIRS group has recently succeeded in beam acceleration up to 160 MeV/u,[2] which is the highest energy limited by the dipole field at the moment, by using all-digitized RF control system.

In 1991, the slow extraction of the stored beam using 3rd order resonance was successfully performed[3] with reasonable extraction efficiency. Furthermore, the beam was extracted by appling an RF field in the transverse direction.

Also in 1991, aiming to extend the studies of the electron cooling and related applications to heavier ions, some improvements of the machine have been planned and have now been almost completed.

Further details of the electron cooling at TARNⅡ is reported in the following.

Results of electron cooling experiments

The electron cooling is a method to compress the phase space occupied by beams utilizing the long-range Coulomb force acting between electrons and ions. The cooling friction works in the three dimensional space and so the cooling is effective for both longitudinal and transverse directions at the same time. The equilibrium momentum resolution obtained by the cooling is typically in the order of 10^{-5} and the emittance is about 1 π mmmrad or less. Owing to its excellent feature, electron cooling is now bringing fruitful results for the accelerator technology and also for related fields like nuclear physics and atomic physics. The details of the electron cooling device and the electron cooling experiments so far performed at INS have been described in ref. 4.

Here we introduce some of the cooling experiments on the 20 MeV proton beam. First, a beam stacking method utilizing the feature of the cooling is presented. We call this method "cool stacking". The intensity of the beam multiturn-injected from the injector cyclotron is low even with a pulsed ion source operation of the cyclotron and is in the order of the 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 magnet fields for the injection system. Fig.1 shows the neutral beam intensity as a function of number of multiturn batches. The intensity is proportional to the cooled and stacked beam intensity if we assume that the temperature associated with the relative motion between electrons and protons does not change during the process. The intensity increases and gradually saturates with the increase in number of multiturn batches. An intensity multiplication factor 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. This method is very effective in obtaining a high intensity beam when the beam lifetime is long enough in comparison with the cooling time.

Secondly, the results of Schottky scan is described. 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

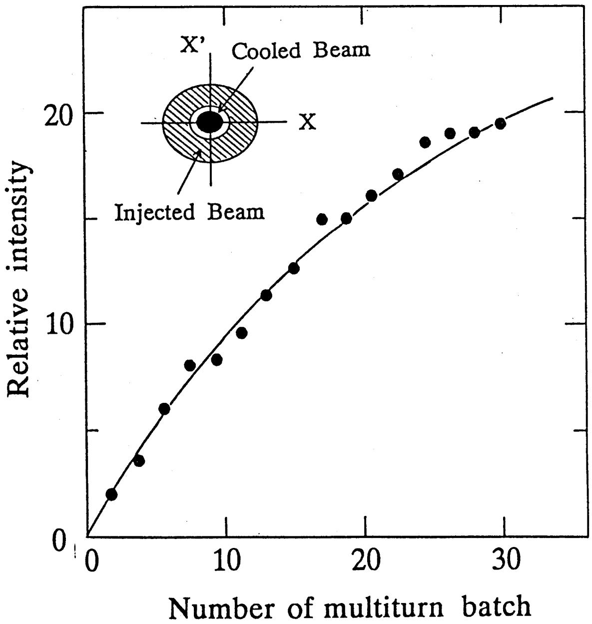

Fig.1 Intensity increase during cool stacking as a function of the number of multiturn batches. The inset shows schematically represented phase spaces for the cooled and stacked beam and for the multiturn-injected beam.

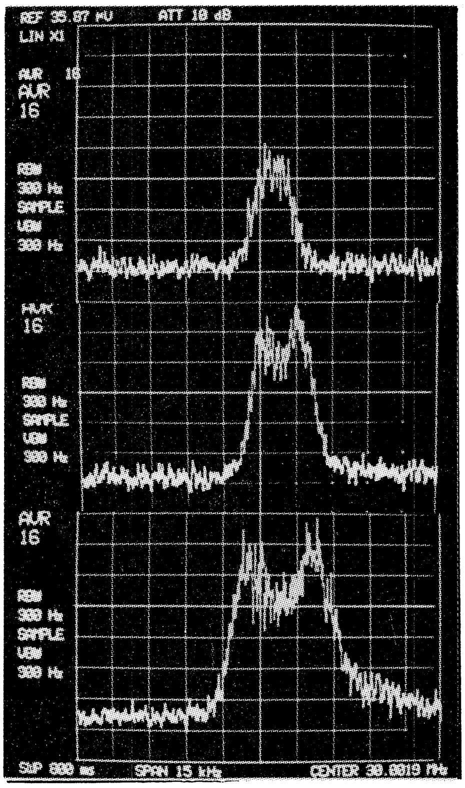

Fig.2 Splitting of frequency spectrum of Schottky signal with increase in stored beam intensity. From the top, numbers of proton beam are about 3×10^7, 10^8 and 3×10^8.

spectrum analyser 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 as can be seen Fig.2. 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_c which is half the peak distance. Such a collective phenomenon begins when the longitudinal temperature of the beam becomes comparable to the interparticle Coulomb energy.

Thirdly, we describe results of neutral beam observation. 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. For the detection of neutral atoms, two detector systems are used independently. One is a plastic scintillator which gives the total number of neutral particles and also provides fast timing signals for the measurements of the time distribution of bunched beams. The other is a position-sensitive solid state detector (PSD). It gives one-dimensional position information.

The horizontal and vertical distributions of neutral atoms were measured at 4.5 m downstream of the cooling section which are 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

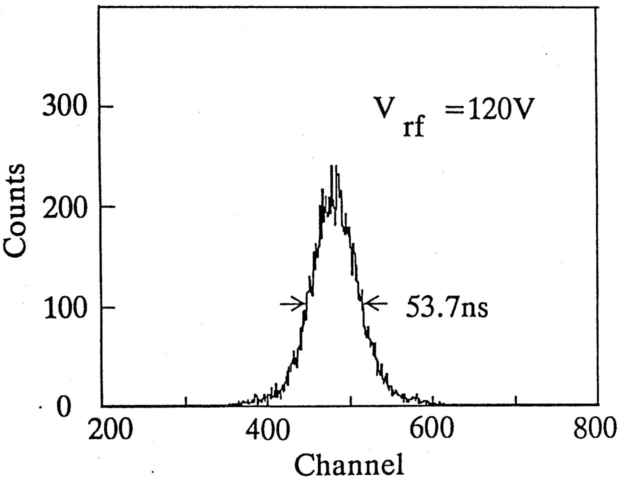

Fig.3 Time distribution of hydrogen atoms relative to the rf phase for a bunched beam at an rf voltage of 120 V.

reduction of the bunch length due to synchrotron oscillation. The bunch length L is related to momentum resolution $\Delta p/p$ 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: a plastic scintillator signal started a time-to-amplitude converter which was stopped by a signal of rf. An example of the time spectrum is shown in Fig. 3. 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.

Application of the electron cooling

Electron capture processes by the ciculatiog ions were studied using the electron cooling device: dielectronic recombination (DR) via 1s→2p excitaton has been measured for 13-MeV ^{3}He$^+$ ion for the first time. 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 state 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. 4 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.5.

Machine development program towards heavy-ion cooling and applications

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 interested ions. The cooling time is generally in the order of a few seconds.

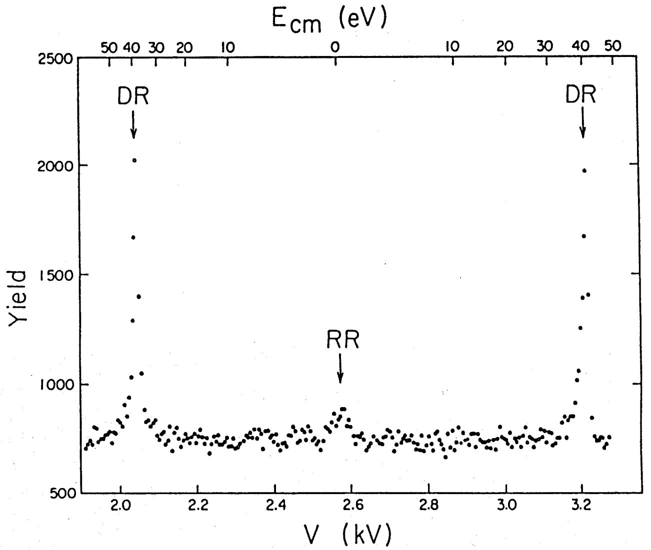

Fig.4 Yield of neutral ^{3}He atoms formed in the electron cooler as a function of the electron acceleration voltage. The c.m. energy scale is also shown. The maxima on the both sides correspond to DR, while the bump on the center is due to RR.

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} 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.[6] 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 26 for Ti sublimation pumps. Now all the pumping system have been installed. We expect that the high vacuum in the order of 10^{-11} Torr will be attained after the bakeout of the vacuum pipes at 300 °C.

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) 6 vertical steering magnets will be installed in the ring for the correction of the COD caused by the misalignments of the dipoles and the quadrupoles. The maximum alignment errors are presently 3 mm and 1.5 mrad. 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 heavy-ion beams.

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.[7] Fig. 5 is a photograph of the residual gas ionization beam profile monitor which consists of ion accelerator electrodes and position sensitive MCP with resistive anode. It has been installed in one of the six long straight sections.

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 line just after the dipole magnet downstream the cooling section as shown in Fig.6. This system gives information on the electron capturing and stripping processes caused by the ion-electron interaction.

Most of the devices have been installed and experiments are expected to start in coming winter.

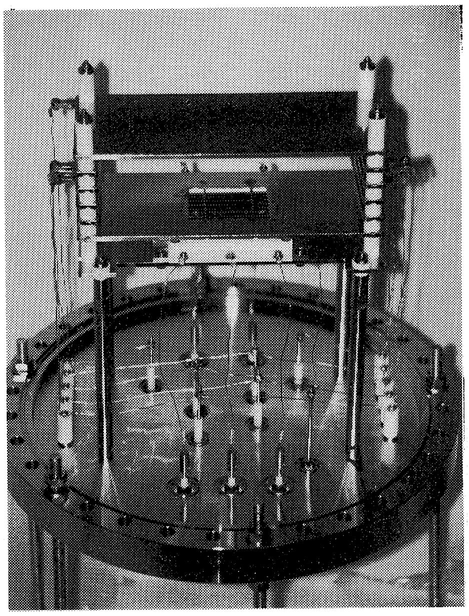

Fig.5 Photograph of the residual gas ionization beam profile monitor.

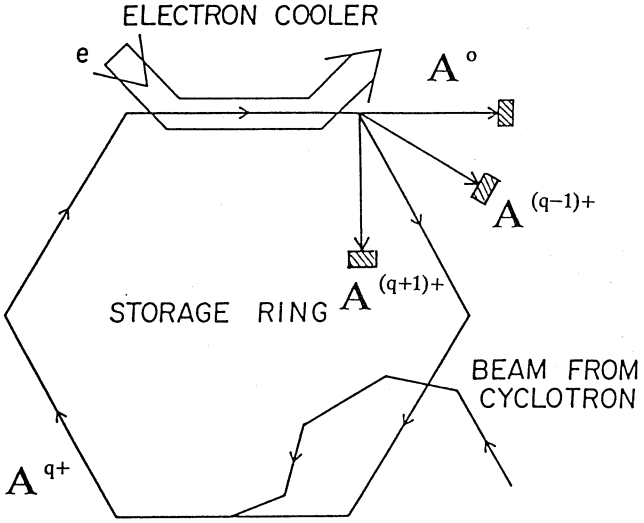

Fig.6 Schematics of the storage ring, the electron cooler and the detection system of charge-changed particles.

References

1. T.Katayama et al., this symposium.
2. M.Kanazawa et al., this symposium.
3. M.Tomizawa et al., this symposium.
4. T.Tanabe et al., Nucl. Instrum. A307 (1991) 7.
5. T.Tanabe et al., Phys. Rev. A, in press.
6. K.Chida et al., this symposium.
7. B.Hochadel, MPI H-1990-V-19.