ELECTRON COOLING EXPERIMENTS AT TARN II

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Abstract: A 20-MeV proton beam has been cooled in a synchrotron storage ring TARN II in September 1989 for the first time. Since then, electron cooling experiments have been continued to obtain better cooling conditions and to cool heavier ions. After a brief summary of the electron system and the storage ring, results of electron cooling measurements are described.

Introduction

A strong phase-space compression of ion beams achieved by electron cooling will offer new possibilities for accelerator experiments involving nuclear, atomic and plasma physics. The main reason to study electron cooling at TARN II is R&D of an electron cooling technology of heavy-ion as well as proton beams. The electron cooling device [1,2] produced its first electron beam at the end of 1988: its properties were studied [3] before installed in the ring in early summer of 1989 [4]. The first cooling experiments were performed on 30th September 1989 with 20-MeV protons. Details of the experiments are described in ref. [5]. Systematic cooling studies have then been continued and efforts have been made to improve cooling conditions. Recently cooling experiments for ions heavier than proton have just been tried. In this paper we shall report on the results of cooling experiments performed with 20-MeV protons and also describe briefly on the results for 20-MeV D^+ and $H_2{}^+$ beams.

Experimental Arrangement

Electron Cooling System

Basic parameters of the electron cooler during experiments are listed in Table 1. Controlling the electron cooler mainly consists of setting the acceleration voltage and fine tuning of the electron beam position and direction in the cooling section. A high voltage power supply (HVPS) which accelerates electrons is controlled by a 16 bit DAC and the output voltage is stable within about 0.5 V. The voltage is applied to a high voltage platform where some other power supplies needed for the control of the electron beam are installed. The voltage at the high voltage terminal has a 50 Hz ripple component of about 3 V_{pp}, which is mainly induced by the coupling of an isolation transformer to the high voltage terminal. The stability and the ripple of a gun-anode high voltage power supply which determines the electron current are about 5×10^{-4} and 10^{-3}, respectively. The relative current loss of the electron beam is mostly less than 5×10^{-4}.

Storage Ring

Main parameters of the ring relevant to the electron cooling are listed in Table 2. About 10^7 protons are multiturn-injected and stored in the ring. The electron beam merges with the proton beam in the 1.5-m long cooling section. Horizontal and vertical steering magnets on each side of the electron cooler permit corrections of the deflection of the proton beam in the toroid as well as the beam steering in the electron cooling device. The vacuum pressure was about 1×10^{-9} Torr on the gauge situated at about 1 m upstream of the cooler during the continuous cooling operation.

Table 1. Electron cooler parameters for the cooling experiment of the 20-MeV proton beam.

Acceleration voltage	11.2	kV
Gun perveance	1.1	$\mu AV^{-3/2}$
Typical beam current	0.4	A
Beam radius	2.5	cm
Solenoid field strength	600	G
Length of interaction region	1.5	m

Table 2. TARN II parameters relevant to the electron cooling.

Nominal proton beam energy	20.26	MeV	
Initial momentum spread, $\Delta p/p$	2×10^{-3}		
Ring circumference	77.76	m	
Fraction of orbit occupied by electron	0.019		
Nominal revolution frequency	0.789	MHz	
Rf frequency	1.578	MHz	
	A)	B)	
Horizontal β in cooling section	10.2	11.3	m
Vertical β in cooling section	3.7	2.3	m
Momentum dispersion in the cooling section	4.7	4.6	m
Transition energy, γ_t	1.88	1.99	
Horizontal betatron tune, Q_H	1.71	1.78	
Vertical betatron tune, Q_V	1.80	2.17	

Diagnostic Elements

Electrostatic position monitors distributed around the ring offer the lifetime information as well as the transverse position information for bunched beams. The density fluctuation in the longitudinal direction is measured by a travelling-wave type Schottky signal pickup [6]. The width of the signal is proportional to the momentum spread of the beam. The beam intensity is measured with a beam current transformer.

In order to observe neutral hydrogen beams which are created in the cooling section when cooling electrons are captured by circulating protons, detection systems are mounted at the exit of a thin stainless-steel window (100 μm in thickness) at 4.5 m downstream of the cooling section. The number of neutral beams is measured by a plastic scintillator with a thickness of 5 mm. It also provides fast timing signals for the measurements of the time distibution of bunched beams. The size of the neutral beam is measured by a position-sensitive solid state detector (PSD) with a sensitive area of 47×8 mm^2 and a thickness of 500 μm. It gives one dimensional position information. Both horizontal and vertical beam sizes are measured independently by setting the PSD at positions rotated by 90 deg.

Development in the Cooling Condition

Initial cooling experiments [5] were performed with the working point A) listed in Table 2. The lifetime of the bunched proton beam was typically 20 sec with cooling as shown in Fig. 1a). It is clearly in contrast with the lifetime of 2 sec for the uncooled beam (detuned in electron energy). In the ring, we don't have any elements to cancel the influence of the cooler solenoid field which couples horizontal motion with vertical one.

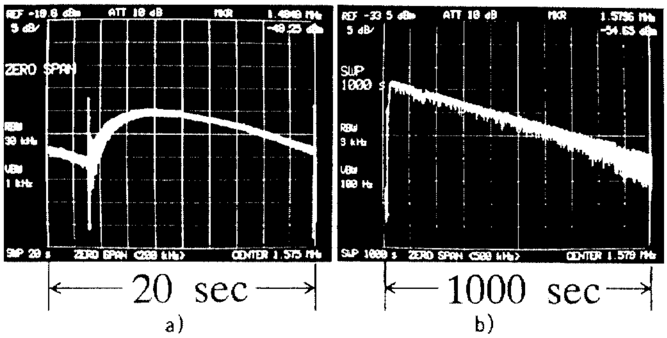

Fig. 1 Evolution of bunched beam signals as a function of time with cooling. The a) and b) are results for the storage ring condition A) and B) in Table 2, respectively.

Therefore it was anticipated that oscillative motions couple strongly at the working point A) which is close to the linear coupling resonance (Q_H-Q_V=0). In fact, the lifetime was much increased by shifting the Q_V from the Q_H. Figure 1b) represents the results of the lifetime measurements for the working point B) in Table 2. The lifetime increased by more than an order of magnitude in comparison with the one for the condition A).

As the injector is an SF cyclotron which is a continuous machine, intensities of injected beams are low even with the pulsed ion source operation, which are in the order of 10^7 particles. In order to increase the beam intensity, cooling was applied during injection: the strong phase space compression due to cooling allows the stacking of repeated multiturn-injected beams. About 20 turn batches were accumulated horizontally resulting in the order of 10^8 particles.

Longitudinal Beam Properties

The change of the momentum width of a beam with cooling can be observed in longitudinal Schottky noise spectra. The proton beam momentum spread was reduced from 2×10^{-3} (after injection) to a value below 1×10^{-4} within a time of a few seconds. Scanned with a high resolution of a spectrum analyzer, the longitudinal Schottky spectra of cooled

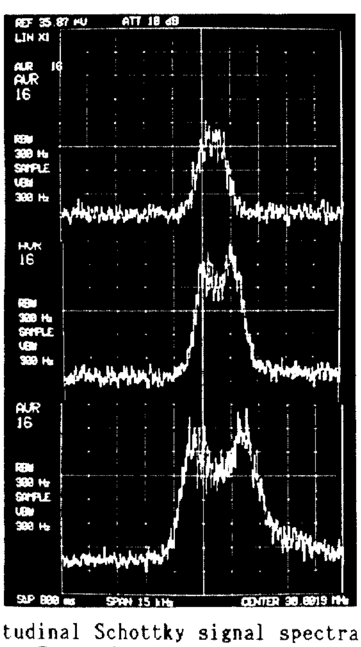

Fig. 2 Longitudinal Schottky signal spectra for coasting cooled beams. From the top, numbers of proton beam are about 3×10^7, 10^8 and 3×10^8.

proton beams have split structures as shown in Fig. 2. The peak splitting increases with the number of stored protons. This behavier is known as a transition from single particle to collective motions and the splitting can be considered as two waves moving with or against the direction of the beam [7]. Spectra for different proton current were fitted by theoretical curves taking account of the collective effects. The momentum spread was then determined from the fit parameters. The results are shown in Fig. 3 as a function of proton current. The momentum spread is typically in the range of 10^{-5} and increases with the number of proton beam due to intrabeam scattering.

The longitudinal cooling force was measured: the acceleration voltage of the electron beam was suddenly stepped up by a certain voltage. Consequently protons were accelerated and their revolution frequencies increased. The cooling force was determined by observing the time dependence of the revolution frequency of the cold beam with the spectrum analyzer and by changing the electron beam energy in small steps. Results for the electron current of 0.4 A are summarized Fig. 4. For drag rates we multiplied observed values by the ratio of the ring circumference to the length of the cooling region. The measurement of the frictional force for a small velocity difference was difficult because of the rapid changes of particle velocities.

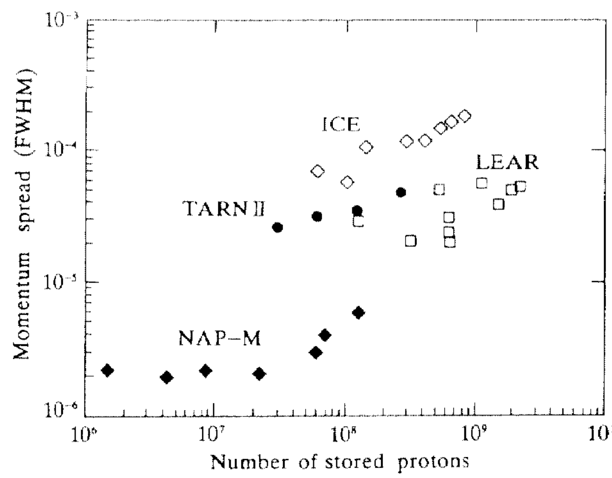

Fig. 3 Equilibrium momentum spread as a function of beam intensity. Results of other experiments [7] are also shown.

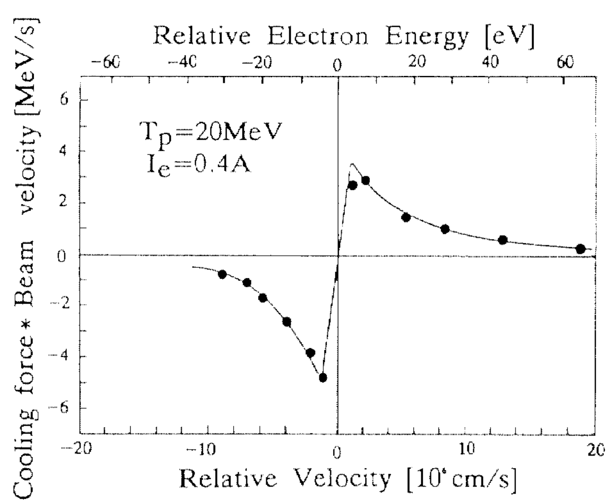

Fig. 4 Cooling force as a function of the proton velocity in the electron rest frame.

Neutral Beam Observation

Neutral atoms are observed at a counting rate of typically 300 s^{-1} for the 0.4-A electron beam. Assuming radiative recombinations and a flattened electron velocity distribution, the dependence of recombination coefficient on the electron temperature T_e can be approximated as [7]: $\alpha_r=0.8\times10^{-12}T_e^{-0.645}cm^3s^{-1}$ (T_e in eV). With the measured electron and proton beam currents, T_e can be deduced as 0.1 ~ 0.2 eV from the count rate. The error comes mainly from the ambiguity of the proton beam current measurement.

The proton beam emittance is deduced from the measurement of the size of neutral beams. The horizontal and vertical distributions measured independently with the PSD are shown in Fig. 5. The cooled beam size at 4.5 m downstream of the cooling section is: $\Delta x=6$ mm and $\Delta y=8$ mm (FWHM). From the lattice parameters listed in Table 2, we have proton beam divergence: $\theta_H=0.21$ mr and $\theta_V=0.76$ mr. From these values the transverse proton beam temperature can be calculated as $T_\perp=12$ eV. We also estimate emittance: $\varepsilon_H=1\pi$ mmmrad and $\varepsilon_V=2.6\ \pi$ mmmrad, and beam radius at the cooling section: $a_H=2.3$ mm and $a_V=1.7$ mm.

For the bunched beam, the reduction of the momentum spread through longitudinal cooling results in the reduction of the bunch length due to the synchrotron oscillation. One can measure the bunch length from the distribution of the arrival times of H atoms. The plastic scintillator signal started a TAC, which was stopped by a signal from the rf. An example of the time spectrum is shown in Fig. 6. The measured time width of 53 nsec corresponds to the bunch length of 3.3 m, which contrasts with the initial one extending for around half of the ring circumference. The bunch length decreases with the rf voltage and it reaches down to 1 m at 400 V.

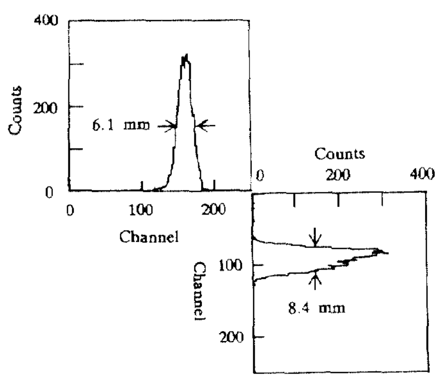

Fig. 5 Neutral beam profile measured at 4.5 m downstream of the cooling section (coasting cooled beam).

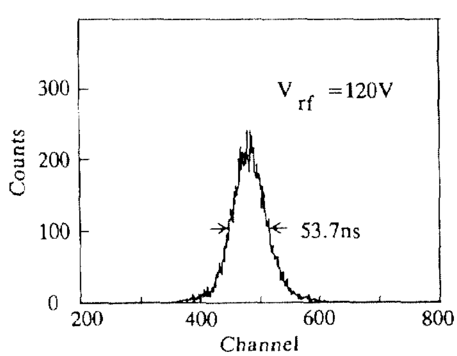

Fig. 6 Time distribution of hydrogen atoms with respect to the rf phase for a bunched beam at an rf voltage of 120 V.

Cooling Experiments on D^+ and H_2^+ Beams

A deuteron beam with an energy of 20 MeV was cooled with a 0.4-A electron beam. The increase of the beam lifetime by a factor of 10 was observed. The stored particle was then changed from D^+ to H_2^+ with the same velocity, keeping the electron cooler and the ring at the same condition. The lifetime of H_2^+ without electron beam was 0.3 sec under the average vacuum pressure of 2×10^{-9} Torr. With electron beam tuned to the H_2^+ beam in velocity, the lifetime slightly but clearly decreased down to 0.2 sec. The lifetime was too short for cooling to be established. In order to study beam loss mechanisms, neutral beams from H_2^+ in the cooling electron beam were measured with the PSD, changing the electron energy in small steps. Energy spectra show two peaks at 10 and 20 MeV corresponding to H and 2H events, respectively. They have a marked electron-energy dependence as shown in Fig. 7. The a) and b) in the figure correspond mainly to the dissociative recombination ($H+H^*$) and the dissociative excitation (H^++H+e) processes, respectively. The results provide a new approach to the research of the atomic and molecular processes at the extremely low relative velocity.

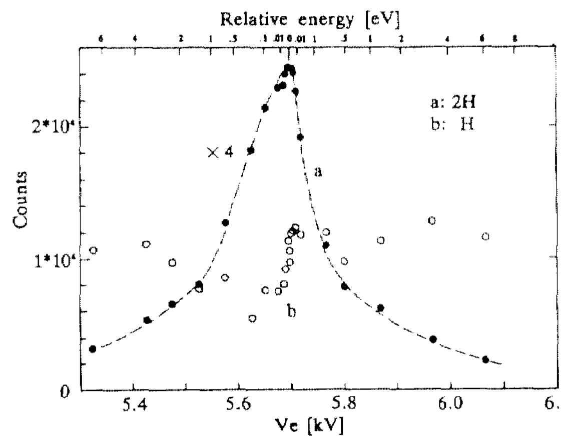

Fig. 7 Electron-energy dependence of neutral beams from H_2^+ in the cooling electron beam. Events due to the residual gas are subtracted. Relative energy is calculated from the electron energy on the beam axis.

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