INITIAL ELECTRON COOLING STUDIES IN THE TARN II

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Abstract

Proton beam with energy of 20 MeV has been cooled in the TARN II with electron beam current of 0.3 A for the first time. After a brief summary of the electron system and the storage ring, the results of electron cooling measurements are described.

Introduction

Strong phase-space compression of ion beams achieved by electron cooling will offer new possibilities for the experiments in nuclear, atomic and plasma physics. The TARN II [1] is one of many cooler rings under construction in the world and its main aim is in the study of accelerator technology. The initial commissioning of the ring began in December 1988. On the other hand, the electron cooling device produced its first electron beam at the end of 1988 and its properties were studied before it was installed in the TARN II. Details concerning the design of the cooling system and the results of electron beam test have been presented elsewhere.[2-7] The cooling device has then been installed in the ring in early summer of 1989.

In this paper, we shall report the results of the first cooling experiments performed with 20 MeV protons on 30 September 1989, during 1.5 days of beam time.

Electron cooling system

The basic parameters of the electron cooler during the experiments are listed in Table 1. The control of the electron cooler mainly consists of setting the acceleration voltage and of fine tuning the electron beam position and direction in the overlap region with the proton beam. The vacuum pressure was about 5×10^{-10} Torr before turning the proton and electron beams on. During continuous cooling operation at 20 MeV, the pressure was about 1×10^{-9} Torr on the gauge situated about 1 m upstream of the cooler. Collection efficiency of electron beam is typically better than 99.95 %. The high voltage power supply (HVPS) which accelerates electrons was controlled by a 16 bit DAC and the output voltage was stable to within about 0.5 V. The ripple component of the HVPS is less than 0.5 V. The output voltage at the high voltage terminal had, however, a 50 Hz ripple component of about 3.5 V_{pp}, which was mainly induced by the coupling of the isolation transformer to the high voltage terminal. The stability and the ripple of the gun-anode high voltage power supply which defines the output electron current were about 5×10^{-4} and 10^{-3}, respectively.

Storage ring and its main parameters

Protons accelerated to 20 MeV in the SF cyclotron were injected into the ring in multi-turns. Number of injected particles was about 10^7. The electron cooler is situated in one of the six straight sections. 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 permitted the correction of the deflection of proton beam in the toroid and also steering of the beam in the electron cooling device. Details of the correction was described in ref. 8. A pair of electrostatic position monitors installed at the cooling section allowed the position measurements of both electron and proton beams in the horizontal and vertical directions. The other position pickups distributed around the ring offered the transverse position and lifetime information of bunched beams. Density distribution of the protons in the longitudinal direction was measured by using a travelling-wave type signal pickup.[9] In order to observe the neutral hydrogen beam which is created in the cooling section when cooling electrons are captured by circulating protons, a detection system was mounted at the exit of a thin window (100 μm in thickness) downstream of the cooling section. It consists of a large solid state detector with aperture of 4 cm which has a thickness of 1 mm. In order to obtain better magnetic field regulation for the dipole and quadrupole magnets of the TARN II ring during cooling, usual thyristor-regulated power

Table 1 Electron cooler parameters for the cooling experiment

Acceleration voltage	11.168	kV
Typical beam energy on axis	11.035	keV
Corresponding velocity	0.20	c
Gun perveance	1.1	$\mu AV^{-3/2}$
Typical beam current	0.3	A
Beam radius	2.5	cm
Electron density	1.5×10^7	cm^{-3}
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
Corresponding velocity	0.20	c
Initial momentum spread, $\Delta p/p$	$\sim2\times10^{-3}$	
Ring circumference	77.76	m
Fraction of orbit occupied by electron	0.019	
Nominal revolution frequency	0.789	MHz
RF frequency	1.578	MHz
Horizontal β in cooling section	10.2	m
Vertical β in cooling section	3.7	m
Momentum dispersion in cooling section	4.7	m
Transition energy, γ_t	1.88	
$\eta=1/\gamma^2-1/\gamma_t^2$	0.676	
Horizontal betatron tune	1.71	
Vertical betatron tune	1.80	

supplies exciting these magnets were replaced by the other transistor-regulated power supplies. Typical field regulation including ripple components was about 0.01 %. Experiments were started with relatively poor vacuum condition, primarily because beam pipes are still unbaked. The vacuum pressures were about 10^{-9} Torr at the cooling section and about 10^{-8} Torr at the opposite section in the ring during operation. The TARN II machine parameters relevant to this experiment are summarized in Table 2.

Initial cooling studies

Measurements of the cooling were made with 20 MeV proton beam. Much of our data on cooling is still preliminary as they have not been critically analyzed or reproduced due to limited beam time.

Before switching-on the electron beam, the proton orbit deformation due to the toroidal field and the dipole field in the cooler was corrected by exciting horizontal and vertical steering magnets. The correction was optimized by observing the proton beam lifetime. The lifetime at the solenoid field of 600 G was about 60 % of the one without solenoid field. The short lifetime with solenoid field on seems to be due to the coupling between horizontal and vertical motions induced by the solenoid field since the difference of tune values between both directions is small as listed in Table 2.

The positions of the electron and proton beams at the cooling section were then measured. The accuracy of the position measurements for protons was not enough in comparison with that of the electron beam because of the low and fluctuated beam intensity of the proton beam. So it is not certain that the proton and electron beam axes in the cooling section were properly aligned.

With 0.3 amp of electron beam on (but detuned in energy) proton beam lifetime was reduced by a factor of about 3 even after the correction of the tune shifts due to electron space-charge. The reason of the short lifetime with electron beam on is not well known, but it appears to be caused by stray electrons bound in the solenoid field and ions trapped in the electron space charge cloud. The lifetime is improved by sweeping these charged particles. The increase of lifetime by a factor of 2 was actually observed by applying voltages in the transverse directions to the split drift electrodes. The situation will also be improved after attaining better vacuum.

If the electron cooling acts effectively, the oscillation damping of protons introduced by electron cooling causes beam contraction in the transverse and longitudinal directions and suppresses the expansion due to multiple scattering. With the electron and proton beams well matched in velocity (to about 4 parts in 10000), increase of lifetime of bunched beam was immediately observed. A typical mean life of about 20 sec was observed for the cooled beam, which contrasted with the lifetime of about 2 sec for the uncooled beam, as shown in Fig. 1. After the beam was injected in a stationary rf bucket with height even lower than the energy width of injected beam, the decrease of momentum spread caused by the cooling increased the beam density in the bucket and consequently increased the signal amplitude of the beam pickup as can be seen in Fig. 1, a). After reaching equilibrium, the signal then decreased gradually due to the scattering of the beam with the residual gas. This lifetime increase for the proton beam was the first effect observed in experiments on electron cooling. The lifetime increased with decreasing rf voltage. It was also sensitive to the beam axes alignment. With the change of the steering field of 0.5 G in the cooler, the increase of beam lifetime by a factor of 2 was observed. Data shown in Fig. 1 are the results which have not yet been optimized. The absolute value of the acceleration voltage of electrons under the cooling condition was consistent with the one expected neglecting the electron-beam space-charge compensation, within an error of 10^{-3}.

a)

b)

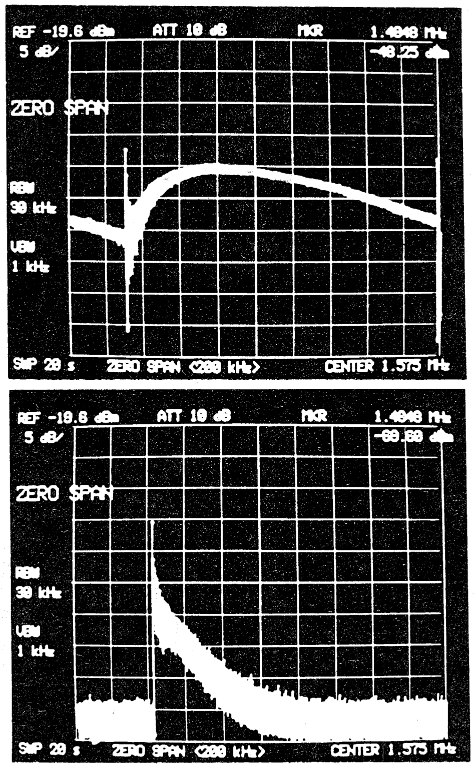

Fig. 1 Evolution of bunch signal as a function of time observed by position pickups (sum signal) with electron beams a) tuned and b) detuned to proton beams in velocity. Spikes represent injection points. Horizontal scale: 2 sec/div and vertical scale: 5 dB/div.

Time evolution of cooling process was observed by measuring the bunched-beam frequency spectrum. Figure 2 shows frequency spectra of the 38th harmonic of the bunch signal from the longitudinal beam monitor. The decrease of the momentum spread, caused by the cooling, reduced the bunch length and increased the signal amplitude. The frequency width which reflects momentum width decreased rapidly with time after beam injection. The time dependence of the frequency spread is also plotted in Fig. 3. It gives an estimate of the cooling time at about 1.4 sec for bunched beam. The final width is narrower than the initial one by a factor of 10. These results bring an outlook on the cooling process, although the accurate value of the cooled-beam momentum spread has to be measured by observing the coasting-beam Schottky signal and this has not yet been tested.

Increase of neutral beam production rate under the cooling condition was observed. The rate was about 10 counts/s. Neutral beam was also detected even in the uncooled condition without electron beam. This may be produced by protons grazed the chamber wall due to the poor alignment of the circulating beam and also by interaction of protons with the residual gas. In order to do quantitative analysis related to the deduction of electron temperature, the background has to be eliminated as well as the accurate measurements of neutral particles and of number of stored particles in the ring.

Periodic change of bunched beam density with a period of about 5 sec was observed at a higher harmonic of the

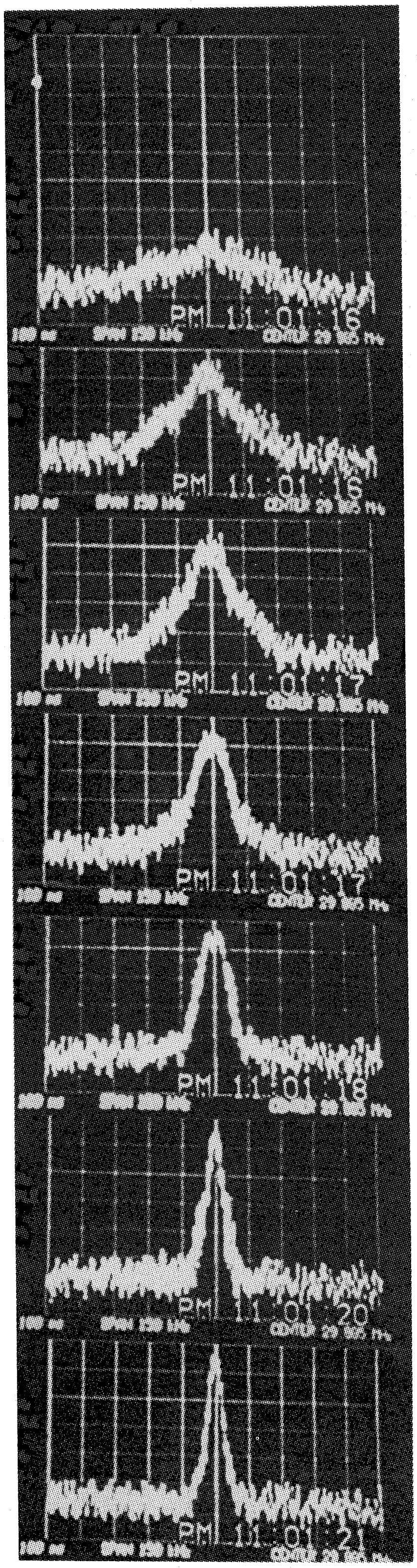

Fig. 2 Time evolution of frequency spectrum of bunched proton beam after injection with cooling. Horizontal scale: 15 kHz/div, vertical scale: 5 dB/div and center frequency: 29.985 MHz.

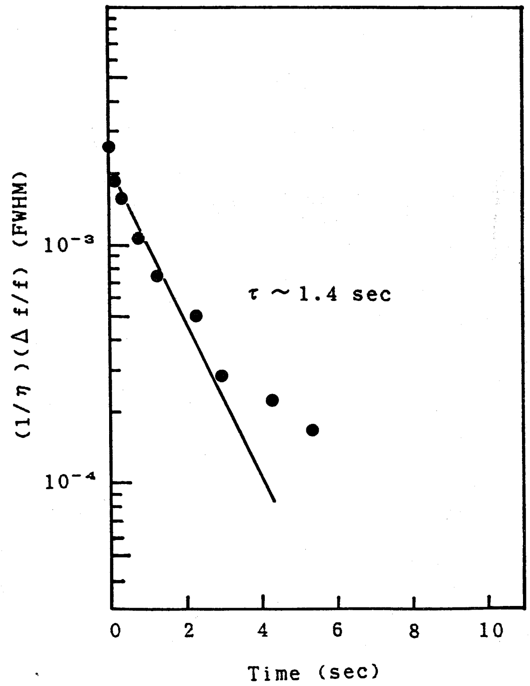

Fig. 3 Time dependence of the frequency spread of 38th harmonic of beam signal.

longitudinal frequency spectrum. This seems to be related to some instability as observed in the LEAR[10]. Transverse side-bands observation is necessary for the reasonable understanding of this phenomenon.

Systematic cooling studies have just begun and effort will continue to obtain better cooling conditions and to clearly observe subtle effects.

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