Electron Cooling of Ion Beams and Related Applications

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Abstract

A strong phase space compression achieved by electron cooling is now opening a new era for accelerator technology and physics research. In this article, the electron cooling technique including the electron cooling device and results of cooling experiments is described, mainly based on the experiences for the cooler ring TARNII at INS. Then some examples of the applications emphasizing electron-ion collision experiments using the cooler as a target are presented.

I. INTRODUCTION

The great success of phase space cooling originated in Novosibirsk exploited unique fields both in accelerator technology and in physics research. In accelerator physics, the cooling process itself is a very exciting issue. Furthermore, an extension of the cooling technique to heavier ions than protons is attractive as it provides lots of research subjects.. The extreme phase-space compression by electron and laser cooling will ultimately dominate the thermal motion in the beam leading to beam crystallization.

Heavy ions including molecular ions with the electrons of the cooler that can be adjusted to a finite relative velocity cultivated a very interesting research domain of atomic physics. For atomic ions, the process of dielectronic recombination (DR) can be studied with high accuracy. On the other hand, for molecular ions, the dissociative recombination (DiR) can be examined with high luminosity for the ground state ions that can be vibrationally cooled by storage of excited molecular ions. The data thus obtained are of high importance for fusion plasma and thin hot stellar coronae in which energy is released through the photons following the DR. The DiR is also important in determining the composition of molecular fragments in interstellar space.

Proton or light ion cooler rings at higher energy are useful for nuclear physics in precision experiments with thin internal targets. High accuracy can be realized in the balance between the heating of beam in targets due to multiple scattering and the electron cooling. Luminosity in the range of 10^{30} cm^{-2} sec^{-1} is obtainable for gas jet target.

This article reviews the typical results obtained by the electron cooling and the applications of the cooler rings referring to the experiments at TARNII.

II. COOLER RING

At present 9 heavy ion cooler rings listed in Table 1 are in operation. Some of them are equipped with laser cooling and stochastic cooling devices as well as the electron cooling device. The IUCF, CELSIUS and COSY rings are extensively used for nuclear physics experiments. The LEAR is unique in its anti-proton cooling. The ESR is aiming both at atomic physics and nuclear physics. The rest of them are predominantly used for atomic physics.

TARNII is a storage ring for light and heavy ions with beam cooling and synchrotron acceleration capabilities [1]. Fig. 1 represents the layout of the TARNII facility. The ring has a diameter of 24 m and a circumference of 78 m. The light and heavy ions are obtained from PIG or ECR ion

Table 1. Cooler rings.

Name/Location	Injector	$B\rho$ (Tm)	C (m)	Cooling	Ions	First cooling
CRYRING/MSI	CRYEBIS/RFQ	1.4	52.0	ECOOL	HI≤Xe	1992(e)
TSR/Heidelberg	Tandem/Linac	1.5	55.4	ECOOL/Laser	p to J	1988(e) 1989(Laser)
ASTRID/Aarhus	Separator	2.0	40.0	Laser	He,Li,Ne,Ar, Negative ions	1990(Laser)
COOLER/IUCF	Ring cyclotron	3.6	87.0	ECOOL	p,p(pol),He,Li	1988(e)
LEAR/CERN	ECR/Linac, Synchrotron	6.7	78.0	ECOOL Stochastic	p,anti-p,O	1987(e)
TARNII/INS	ECR/Cyclotron	6.1	78.0	ECOOL	p,d,He,HI≤Ne	1989(e)
CELSIUS/TSL	ECR/Cyclotron	7.0	82.0	ECOOL	p,HI≤Kr	1990(e)
ESR/GSI	UNILAC/SIS Synchrotron	10.0	108.0	ECOOL Stochastic	up to U	1990(e)
COSY/KFA	Cyclotron	11.7	184.0	ECOOL Stochastic	p,light HI	1993(e)

sources, accelerated by an SF cyclotron with K-number of 67 and then injected into the ring. The phase space occupied by the stored ion beams is compressed by electron cooling. The average vacuum pressure of the ring is about 1×10^{-10} Torr. The electron cooler is also used for various types of experiments in atomic physics.

III. ELECTRON COOLING DEVICE

Table 2 lists energy (T), cathode diameter(d), cooling length (l) and shape of cooling devices. The maximum energy of existing electron coolers is 320 keV (ESR) which corresponds to the ion energy of about 600 MeV/u. The electron currents are typically less than a few A.

Fig. 2 shows the layout of the electron cooling device at INS [2]. Electrons are emitted from a flat dispenser cathode with a diameter of 5 cm and accelerated to final energy by an acceleration column. Electrons then enter into a drift region and are bent by 45° to the cooling region. The nominal cooling length is 1.5 m which is only 1.9 % of the whole circumference. At the end of the cooling section, electrons are again bent by 45° and are collected after deceleration. A solenoid magnetic field is applied in the direction of the electron beam, preventing it from diverging. The transmission of electron beam is more than 99.9 %, although it depends on the electron energy and current. The closed orbit distortions due to the toroids at the entrance and exit of the cooler are corrected by two pairs of steering dipoles, but there is no element to cancel the influence of the solenoid field.

Table 2. Electron Cooling Devices

Name	T (keV)	d (mm)	l (m)	Shape
CRYRING	20	40	1.1	U
TSR	20	50	1.5	U
ASTRID	3	10	0.54	S
IUCF	270	25	2.7	U
LEAR	27	50	1.5	S
TARNII	110	50	1.5	U
CELSIUS	300	20	2.5	U
ESR	320	50	2.5	U
COSY	100	25	2.0	U

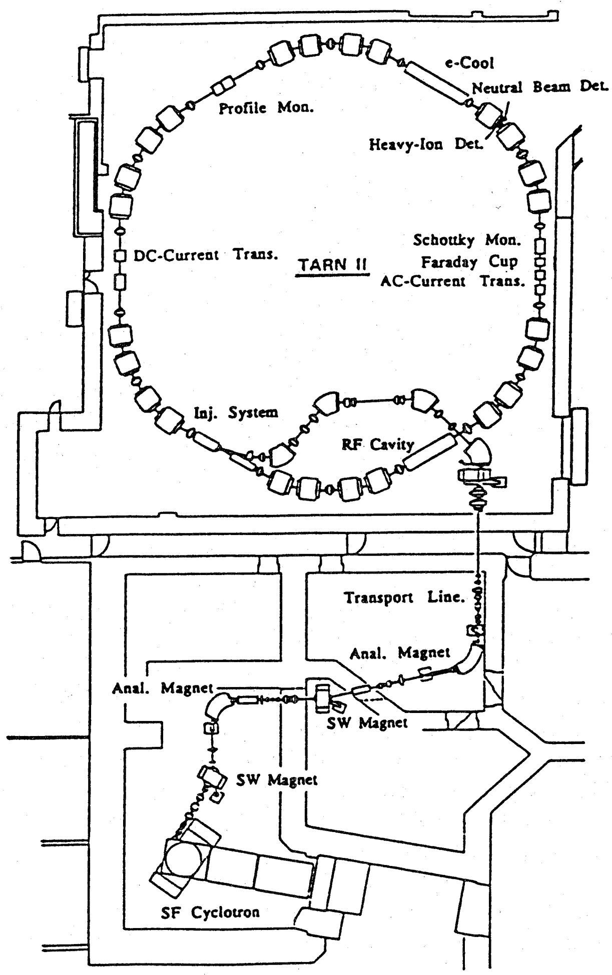

Figure 1. Schematic diagram of TARNII and injector SF cyclotron.

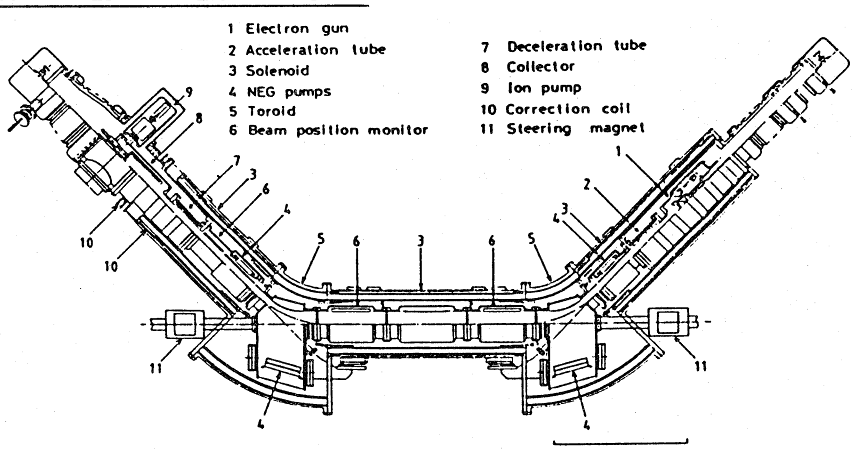

Figure 2. Layout of electron cooling device.

IV. ELECTRON COOLING EXPERIMENTS

Electron cooling is based on the exchange of energy between a hot ion beam and a low-temperature beam of electrons having almost the same velocity as ions. The beams are merged at one of the straight sections as can be seen in Fig. 1. As the ions and electrons interact through repeated Coulomb scattering, the ions experience the friction force and are cooled both longitudinally and transversally within a time of the order of second. The cooling phenomenon can easily be found by observing the beam lifetime. The proton beam lifetime increases by more than one order of magnitude with cooling as the beam divergence due to multiple scattering with residual gas is suppressed. Here we introduce some results of the electron cooling experiments [2].

The change of momentum resolution with cooling was observed by measuring the frequency spread of Schottky signal. Fig. 3 represents the region around the 38th harmonics of the revolution frequency for uncooled and cooled 20 MeV proton beams observed with a spectrum analyzer. The frequency width Δf of the spectrum is proportional 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}. When scanned with a high resolution of the spectrum analyzer, the frequency spectra of the cold beam Schottky signals show splitting as can be seen in Fig. 4. The splitting becomes remarkable with the increase in number of circulating particles. It is originated from two plasma waves propagating parallel and anti parallel to the beam direction with a characteristic frequency f_c that is half the peak distance [3]. If the spectral density of the noise signal is observed near the nth harmonic of the nominal revolution frequency f_0, the characteristic frequency is given by

$$f_c/nf_0 = e[(\eta N_p/pC)(iZ_n/n)]^{1/2}, \qquad (2)$$

where e is electron charge, N_p is number of stored protons, p is proton momentum and Z_n is longitudinal coupling impedance. The momentum widths are deduced by comparing the spectra with theoretical predictions taking account of the collective effects [3]. They are in the range of $\Delta p/p \sim 10^{-5}$, and gradually increase with intensity due to intrabeam scattering.

The change of beam width in the transverse direction with cooling was observed with a non-destructive residual-gas ionization beam-profile monitor. The electron-ion pairs

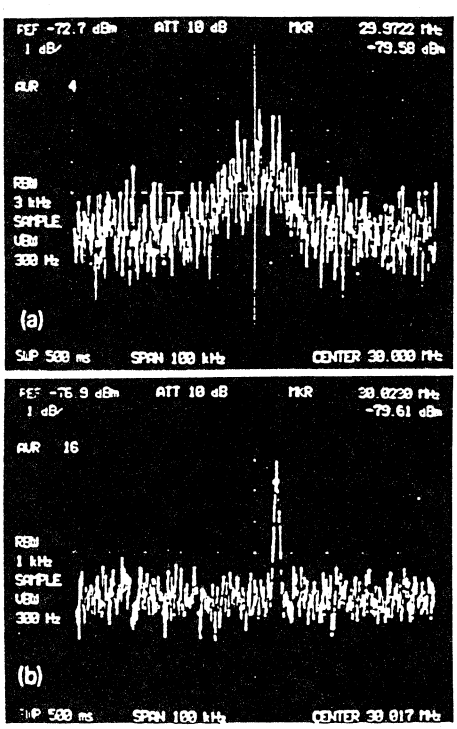

Figure 3. Frequency spectra of longitudinal Schottky signals for (a) uncooled and (b) cooled 20-MeV proton beams.

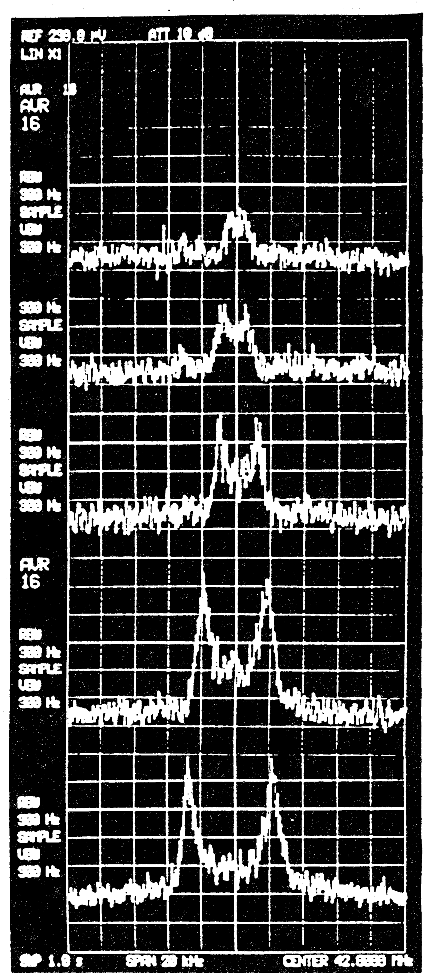

Figure 4. Splitting of frequency spectrum of Schottky signal with increase in stored beam intensity (16-MeV p). From the top, intensities of proton beam are 3, 7, 16, 54 and 90 μA.

produced by the impact of ion beam on residual gas are accelerated in a uniform electric field and ions hit a micro channel plate (MCP). Their positions are read by a resistive -anode encoder. The MCP has a sensitive area of 10 cm (transverse)×1.5 cm (longitudinal) and can measure the horizontal beam profile with a resolution of less than 1 mm.

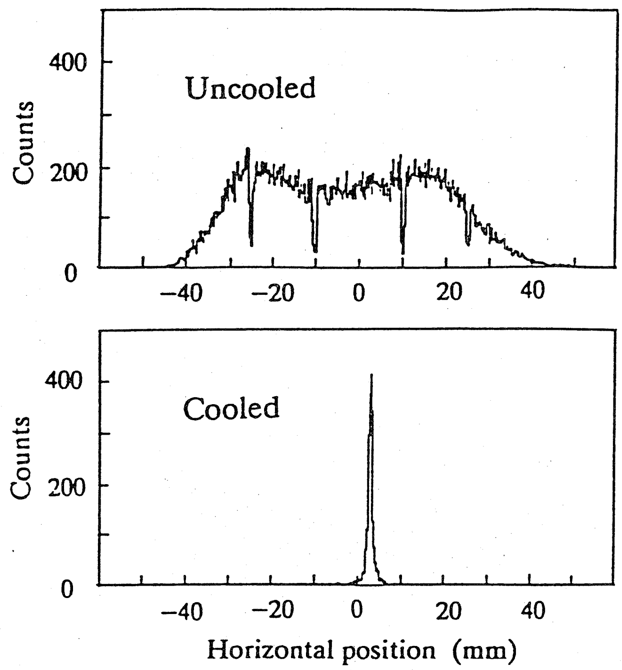

Figure 5. Horizontal beam profiles for (a) uncooled and (b) cooled 85-MeV N^{5+} beams. The dips in the profile result from the shadows of 1-mm thick wires, which are inserted to calibrate the beam position.

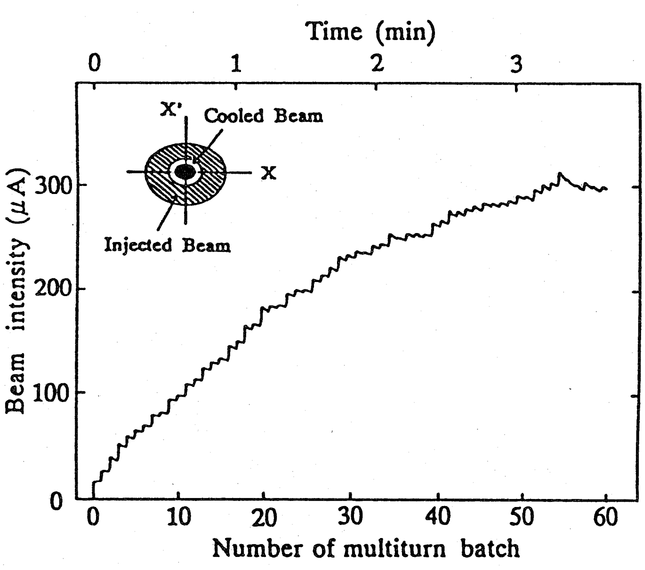

Figure 6. Intensity increase during cool stacking as a function of the number of multiturn batches. The inset shows schematically represented phase spaces for the cooled and stacked beam and for the multiturn injected beam.

As can be seen in Fig. 5 the beam width of 85-MeV N^{5+} beam changed from 60 mm to 1 mm with cooling. This means that the emittance was compressed from 90 π mm mrad to 0.025 π mm mrad. In the cooling, an accurate alignment of electron and ion beam axes is essential for efficient cooling. The beam width in transverse direction is very sensitive to such alignment accuracy. The profiler is thus used for the diagnostics of cooling like Schottky signal.

The beam intensity stored in the ring can be increased by the repeated multiturn injection with cooling, called "cool stacking." In this case, a part of the phase space volume prepared for the multiturn injection is occupied by the cooled and stacked beam. Fig. 6 shows an example of the cool stacking, in which the beam was injected every 4 s and cooled. An intensity multiplication factor of about 30 was reached after 50 injections in a time of 3 min, resulting in the total number of stored particles of 2.4×10^9.

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 beam with the bunch length of the order of 1 m can be obtained by the bunched beam cooling. Such a high density beam localized in space can be used for the study of beam dynamics in phase space when its position and direction are tracked by a transient recorder.

V. ELECTRON-ION COLLISION EXPERIMENTS

The cooler can be used as an electron target with excellent properties due to its high-quality electron beam and the very low residual-gas pressure in the storage ring. A high resolution in center-of-mass energy can be obtained in a setup with merged ion and electron beams. A wide range of collision energies can be realized if the electron energies are changed. In this way the cooler is very attractive in studies of electron-ion collisions. Fig. 7 represents the setup for the experiments.

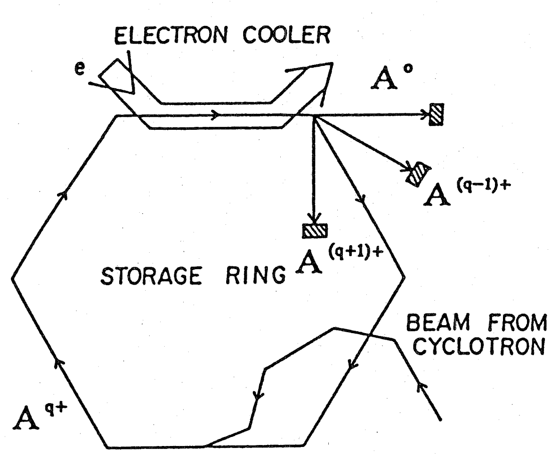

Figure 7. Schematics of the storage ring, the electron cooler and the detection system of charge-changed particles.

A. Dielectronic Recombination of Atomic Ions

Dielectronic recombination occurs in the electron-ion collision when an electron of 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. Owing to energy conservation, the binding energy plus the kinetic energy of the captured electron must be equal to the excitation energy of the bound electron. The formation of the doubly excited intermediate state is resonant for the relative velocities between electrons and ions. 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 (RR) rate by an order of magnitude or more. The DR is thus important also in applications such as nuclear fusion plasma and astrophysics, as well as in fundamental atomic physics. Most earlier experiments were performed on DR process via $\Delta N=0$ excitation (e.g. $2s\rightarrow 2p$ or $3s\rightarrow 3p$ transitions) because of the smallness of the DR cross sections for $\Delta N\neq 0$. The recent development of more intense ion and electron beams in the cooler ring has allowed studies for $\Delta N\geq 1$ transitions. At the TARNII, we have performed the DR experiments on the one-electron (H-like) ion He^+ and the two-electron (He-like) ion N^{5+}. The results on 13-MeV He^+ [4] are shown in Fig. 8. The neutral atoms produced in the electron cooler were separated from the beam by a dipole magnet and detected by a solid-state detector that is sensitive to the total energy associated with the neutral product. The studied DR process is

$$He^+(1s) + e \rightarrow [He^0(2lnl')]^{**} \rightarrow [He^0(1snl')]^* + h\nu .$$

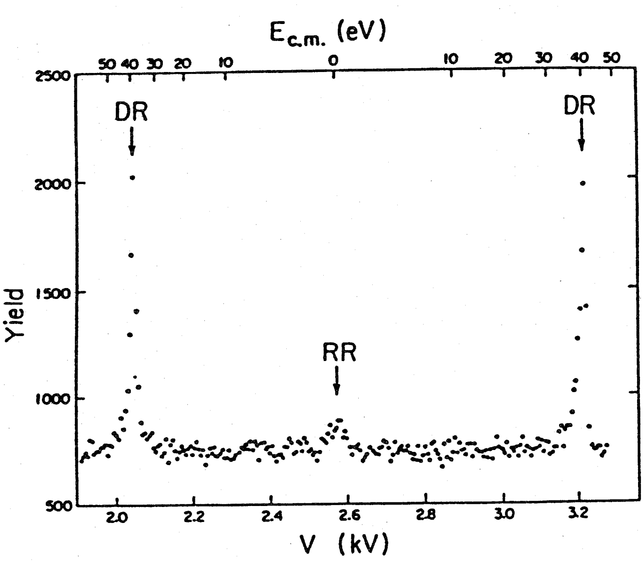

Figure 8. Yield of neutral He atoms formed in the electron cooler as a function of the electron acceleration voltage. The c.m. energy scale is also shown. The maxima on the both sides correspond to DR, while the bump on the center is due to RR.

A small bump from the radiative recombination (RR) also appears at $E_{cm}\sim 0$. Fig. 9 shows the DR results on N^{5+},

$$N^{5+}(1s^2) + e \rightarrow [N^{4+}(1s2lnl')]^{**} \rightarrow [N^{4+}(1s^2nl')]^* + h\nu.$$

Many peaks appear corresponding to the different principal quantum numbers of the captured electron.

B. Dissociative Recombination of Molecular Ions

Dissociative recombination occurs in the electron-molecular ion collisions when an electron is captured by a positive molecular ion to form two or more neutral system,

$$AB^+ + e \rightarrow A' + B'',$$

in which the atoms A and B may or may not be in excited states. This reaction is also important in the upper atmosphere. For instance, the observations of oxygen green line in aurora were attributed to the formation of the excited atom $O(^1S)$ through the DiR of electrons with O_2^+ ions.

Molecular ions produced at ion sources contain many excited states and such excited states have been a bugbear for the electron-ion single-pass experiments. The excited states have mostly finite lifetimes and so, if one can store excited molecular ions longer than their vibrational lifetimes, the ions are expected to be mostly in the ground state. Another advantage of the storage ring technique is much higher luminosity compared with single-pass experiments. On the other hand, the DiR of molecular ions so far reported occurs only around 0 eV center-of-mass energies.

We performed first experimental study of HeH^+ DiR in a storage ring and found a new DiR peak at high energies [5]. HeH^+ ions were produced from a He and H_2 gas mixture in a PIG ion source and accelerated to 9.5 MeV in the cyclotron. The beam was then injected into the storage ring.

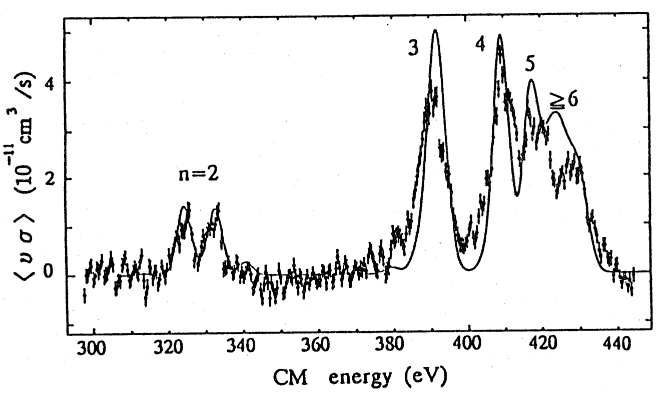

Figure 9. DR spectrum of He-like nitrogen ions in their ground state: $N^{5+}(1s^2)+e\rightarrow N^{4+}(1s2lnl')\rightarrow N^{4+}(1s^2nl')+h\nu$. The data are compared to the preliminary calculations by N.R.Badnell folded with the electron velocity distribution for $kT_\perp=0.5$ eV and $kT_\parallel=0.005$ eV.

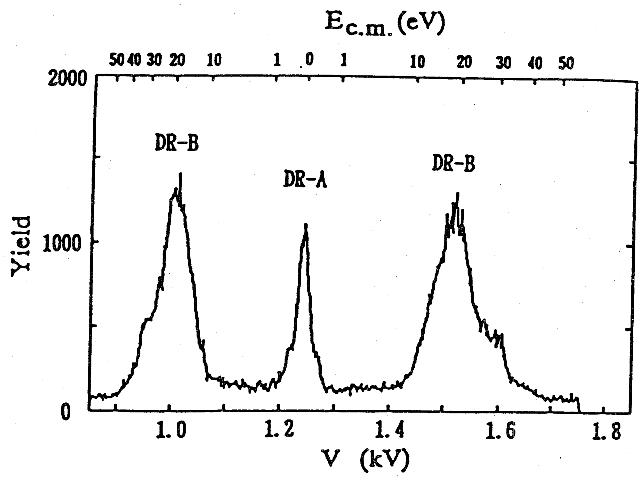

Figure 10. Yield of neutral He+H atoms formed in the dissociative recombination $HeH^{+}+e \rightarrow He+H$ as a function of electron acceleration voltage. The c.m. energy scale is also shown. The time window is 0.92-1.47 s and the electron current is 0.2 A

Experimental DiR results measured for 0.5 s after storage of 0.9 s are shown in Fig. 10. The storage time is long enough to obtain vibrationally cold ion beam. As can be seen in the figure, there exists a large recombination resonance having a peak at around $E_{cm} \sim 20$ eV (DR-B) in addition to the known peak at $E_{cm} \sim 0$ eV (DR-A). Similar high energy resonances have also been found in HD^{+}, H_3^{+} and HD_2^{+}. Such resonances seem to come from two-electron excited states of neutral molecules.

VI. EXPERIMENTS USING INTERNAL TARGET

Nuclear physics experiments using internal target have been studied at IUCF and CELSIUS rings. The first completed experiment that used a hydrogen gas-jet target of 10^{15} atoms/cm^2 and an electron cooler was performed at IUCF for the study of pion production near threshold [6]. The clean experimental conditions were possible only for the cooler ring. At CELSIUS, nuclear physics experiments are now going on by using a cluster-jet target, fiber targets and a pellet target.

VII. CONCLUSION

The electron cooling technique has almost been established through many experimental and theoretical studies. However, some problems are still left; for example, instabilities at high intensities and methods to damp them. An ordered and crystallized beam has not yet been realized so far. For the electron cooling device itself, an ultra cold electron beam with an energy spread of about two orders of magnitude smaller than in present electron cooling devices may be obtained by using a cold GaAs photo-cathode instead of a thermo-cathode [7]. A linear arrangement of the cooler without bending sections is also now in investigation [8]. Such a device will simplify a future electron cooler. The maximum electron energy so far achieved is limited to about 300 keV. In order to cool GeV-region beams, studies of a high energy cooling device have started [9].

Many experiments concerning the application of the cooler have been proposed and some of them have already been realized. Radioactive secondary beams have been stored and cooled in a storage ring at GSI [10]. At the same institute, a new type of experiment, bound β decay of the bare ion $^{163}Dy^{66+} \rightarrow {}^{163}Ho^{66+}$ in the storage ring, has been proved [11]. In Indiana, a bunched high-density cooled beam was used for the experimental studies of non-linear beam dynamics [12]. In future, many new ideas will also be proposed and tested in the cooler rings. In this way, the cooler is nowadays indispensable for accelerator technology and physics research.

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