ELECTRON COOLING WITH PHOTOCATHODE ELECTRON BEAMS APPLIED TO SLOW IONS AT TSR AND CSR

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Abstract

We report electron cooling experiments using a cold electron beam of 53 eV produced by a cryogenic GaAs photocathode. With this device a beam of CF^+ (mass 31) of only 97 keV/u (3 MeV) was cooled down to a very small equilibrium beam size of about 0.04×0.2 mm^2. A transverse cooling time below 2 seconds was obtained.

INTRODUCTION

Cold electron beams at low energies are currently a subject of high interest in view of next-generation electrostatic storage rings where electron cooling of very slow ions as well as high-resolution electron-ion merged beam experiments are planned to be performed. The use of electrostatic rings (instead of magnetic ones normally used for lighter high energy beams) is the only possibility to store heavy molecules, clusters and biomolecules. The energies of stored ions in electrostatic rings are about 20-300 keV (per charge state), limited by the maximum voltage applied to the ring optics. Thus velocities of stored heavy molecules are very low.

An electrostatic Cryogenic Storage Ring (CSR) for ion beams, including protons, highly charged ions, and polyatomic molecules, is under construction at MPI-K [1]. Electron cooling at electron beam energies from 165 eV for 300 keV protons down to a few eV for polyatomic singly charged ions will be applied. The quality of an electron beam with respect of density and longitudinal temperature degrades at low energies. Thus electron beams of low emission energy spreads are needed. For the CSR cooler, the cryogenic photocathode source developed for the Heidelberg TSR target [2] will be used to generate electron beams with emission energy spreads of about 10 meV [2,3], that is at least by a factor of 10 better compared to conventional thermocathode sources. At high energies the main drawback of photocathode coolers is the limited extraction current (at the TSR target a maximum current of 1 mA is presently obtained from GaAs source). At low voltages, however, this disadvantage vanishes as the current becomes limited by gun perveance anyway to about 1-2 mA at 100 V.

Electron cooling experiments of slow CF^+ molecules were performed at the Heidelberg TSR target using an ultracold electron beam of 53 eV, produced by a cryogenic GaAs photocathode. A transverse cooling time below 2 seconds to a very small equilibrium beam size was observed with an electron current of 0.3 mA (corresponding to an electron density of about $3\cdot10^6$ cm^{-3})

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LOW-ENERGY ELECTRON BEAMS

The key parameters of electron beams used for ion cooling and merged beam experiments in storage rings are density as well as transverse and longitudinal temperatures. The transverse temperature of the electrons is not affected by electron acceleration and it can be reduced by an adiabatic magnetic expansion α down to $kT_\perp = kT_c/\alpha$ [4], where T_c is the cathode temperature. The use of a cryogenic photocathode source makes it possible to obtain transverse temperatures below 1 meV [2]. The longitudinal temperature and density of the electron beams, however, degrade strongly at low energies. Indeed, the electron current I and density n_e are limited by gun perveance P (with typical values of about 1-2 μPerv):

$$n_e = \frac{4PU}{\pi D^2 e\sqrt{2\eta}} \approx 6\times10^6\ cm^{-3}\left(\frac{P}{1\,\mu Perv}\frac{U}{100V}\right)\left(\frac{15mm}{D}\right)^2$$

$$I = PU^{3/2} = 1mA\left(\frac{P}{1\,\mu Perv}\right)\left(\frac{U}{100\ V}\right)^{3/2}, \qquad (1)$$

where D is the diameter of the electron beam in the interaction section.

The longitudinal electron temperature $kT_{||}$ of the electron beam is described by the following expression:

$$kT_{||} \approx \frac{(kT_C)^2}{W} + C\frac{e^2 n_e^{1/3}}{4\pi\varepsilon_0}, \qquad (2)$$

where $W=e\cdot U$ is the electron energy and C is the acceleration constant. The first term is due to kinematic transformation of the electron temperature from the laboratory to the co-moving system. It is also taking into consideration that the part of the transverse energy is transferred to the longitudinal temperature during adiabatic magnetic expansion increasing the first term by a factor of about 2 [5]. The second, density term, is connected to a relaxation of the potential energy of the accelerated beam [6]. The acceleration constant C for high acceleration voltages was found to be of about 1.9 [6]. Our studies (work in progress) show, however, that a value of about 0.9 appears to be more appropriate for the C constant. Moreover, for low energies with the first term being dominant the description of the longitudinal temperature for different acceleration energies with a fixed value of C is found to be inaccurate. Figure 1 shows the longitudinal temperatures of electron beams as a function of the kinetic energy calculated for thermocathode (kT_c=100 meV) and photocathode (kT_c=10 meV) electron sources. For the calculations we assumed a gun perveance of 2 μPerv and a beam diameter of 13.5 mm. We see that for the thermocathode the longitudinal

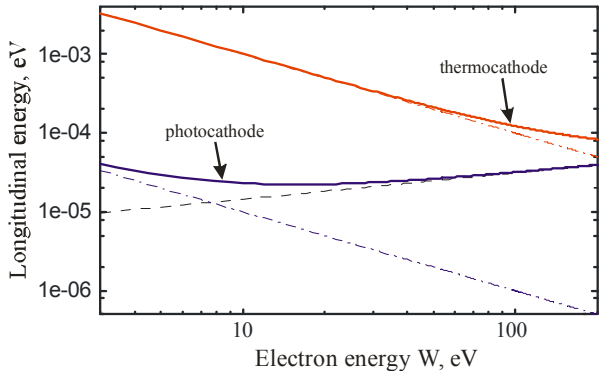

Figure 1: Longitudinal temperature vs electron energy for th ermocathode and photocathode electron beams. The kinematic (dashed-dotted lines) and density (dashed line) terms of the Eq. 2 are also shown.

temperature is dominated by the kinematic contribution over the entire considered range as a consequence of the high cathode temperature. For the cryogenic photocathode, with its small emission energy spread, the kinematic term is smaller by a factor of 100, which yields a much colder electron beam at low energies.

Low transverse and longitudinal temperatures of the electron beam are required for high resolution merged beam experiments. The high cooling force due to low longitudinal temperature also allows to strongly suppress the ion beam scattering and to obtain a small equilibrium size of the ion beam.

The cooling time of the stored ions strongly depends on both the transverse and the longitudinal temperatures of the electron beam as well as on the charge Ze and mass M_{ion} of the ions. The longitudinal momentum spread of the ions as well as the transverse emittance of the ion source is also important to calculate cooling times. However, a first approximation can be done in the model of a non-magnetized electron beam [7] with an electron temperature kT_e identical to the transverse temperature:

$$\tau = \frac{3mc^3(4\pi\varepsilon_0)^2}{8\sqrt{2\pi}e^4}\,\frac{M_{ion}}{n_e\cdot Z^2\cdot L_C}\cdot\left(\frac{k_B T_e}{m c^2}\right)^{3/2}, \qquad (3)$$

where L_c is the Coulomb logarithm. For cold ion beams, injected to the ring with a momentum spread lower than the electron momentum spread, the cooling time can be reduced by a magnetized electron beam with small longitudinal temperatures [8]. Typically, the cross-section of the injected ion beam is few cm which is about the diameter of the electron beam. Ions in the centre or at the edge of the electron beam will see electrons of different velocities, as the space-charge varies across the electron beam. The space-charge induced momentum spread for high perveance electron guns is typically much larger than the longitudinal momentum spread of the electrons. The situation changes at very low energies (≤10 eV) as temperature-induced momentum spread of the electrons approaches the space-charge momentum spread. Thus, the impact of longitudinal electron temperature on the cooling time will be even more important at extremely low energies. The possibility to use electron guns with higher perveance at very low energies also has to be considered.

PHOTOCATHODE ELECTRON SOURCE

An atomically clean surface of p^+-GaAs with a thin layer of cesium and oxygen produces a state with effective Negative Electron Affinity (NEA), where the vacuum energy level lies below the conduction band in the bulk [9] (Fig.2). Electrons photoexcited from the valence band to the conduction band rapidly thermalize to the bottom of the conduction band and reach the surface with energy spreads defined by the temperature of the bulk, of around 100 K in our case. Due to the NEA, a large fraction of these electrons can escape into the vacuum. During the escape process, however, electrons undergo strong energy and momentum relaxation [3]. As a result, the transverse and longitudinal energy spreads of photoemitted electrons are enlarged to about the value of the NEA (typically about 150-250 meV). However, it was found that electrons emitted with a longitudinal energy above E_C (with a potential barrier produced by a space charge) have transverse and longitudinal momentum spreads of about the bulk temperature [3,10]. For these electrons energy spreads of about 7 meV have been measured at 90 K [3].

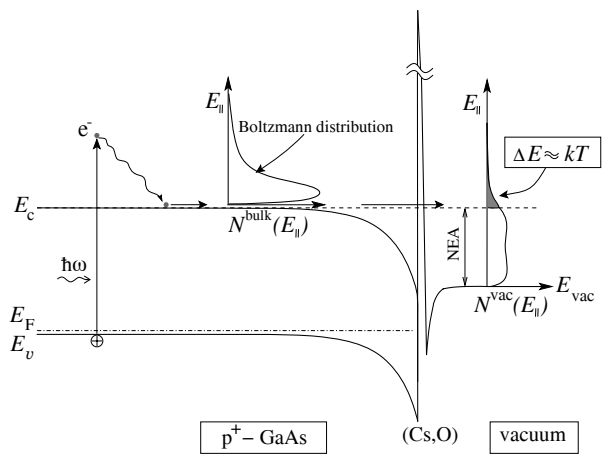

Figure 2: Band diagram of NEA GaAs schematically illustrating the photoemission process.

The vacuum photocathode setup of the TSR target includes a loading (with an attached atomic hydrogen chamber), a preparation and a gun chamber, separated by all-metal gate valves, with base pressures of 10^{-10}, $5\cdot10^{-12}$ and 10^{-11} mbar respectively [12]. Inside the vacuum the samples are transferred by magnetically coupled manipulators. In the preparation chamber the samples are fixed on a carousel capable of keeping four cathodes. The carousel can be rotated into different positions for thermal cleaning and activation of the photocathodes with cesium and oxygen. The effective quantum yield for the cold electrons at 90 K is found to be 1-2%, while the total quantum yield (QY) is about 20-30 % [11]. In the electron gun the sapphire substrate of the cathode is pressed to a copper cold head by a spring force of 100 N in order to obtain a good thermocontact [12]. The photocathode is

illuminated in transmission mode by a 800 nm diode laser with a power of about 1 W. By flooding the cold head with liquid nitrogen an operating temperature of about 100 K is reached. When the QY of the cathode drops down, the degraded cathode can be changed to another one stored in the preparation chamber. It takes about 30 min to change the sample and to cool it down. The samples are usually re-used 3-5 times by radiative heating and re-activation in the preparation chamber before they loose their performance. Then atomic hydrogen cleaning is used to recover the surface properties of the degraded cathode by removing contaminations [13]. Details of photocathode setup and surface preparation techniques can be found elsewhere [12,14].

Using the cryogenic photocathode source ultra cold electron beams were obtained, with transverse and longitudinal temperatures of about 0.5 meV and 0.03 meV respectively [2]. Recently the performance and reliability of the photocathode source have been strongly improved. This was achieved by controlling different degradation effects like cryosorption, back stream of ionised rest gas, pressure raise due to electron induced gas desorption from the chamber walls. Presently, the photocathode can deliver electron currents of up to 1 mA at photocathode lifetimes above 24 hours.

CF^+ COOLING BY 53 EV ELECTRONS

Electron cooling experiments at low energies were performed at the TSR target on a CF^+ beam of energy 3 MeV (about 97 keV/u). The corresponding electron energy was about 53 eV and the electron current was 0.3 mA.

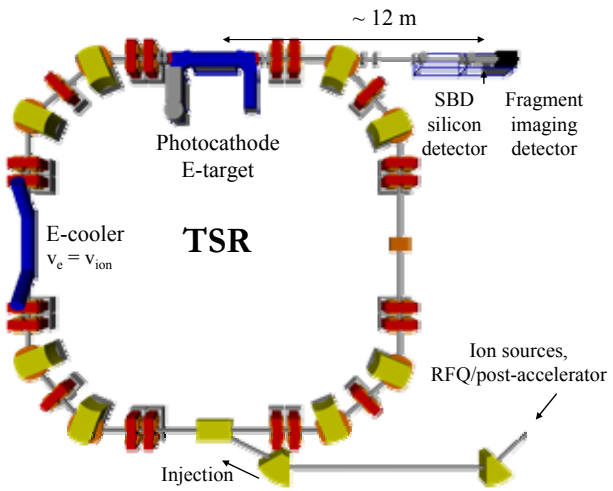

Figure 3: Layout of the Heidelberg Test Storage Ring.

The Heidelberg TSR is a magnetic storage ring with a maximum magnetic rigidity of 1.5 Tm. It is equipped with an electron cooler and an electron target (Fig.3). Typically the electron cooler is used for phase space cooling of the stored ion beams and the photocathode target provides cold electron beams for high-resolution merged beam experiments. However, in the case of the slow CF^+ ion beam the electron target was found to be by far stronger in cooling force providing much shorter cooling times. So, these experiments were performed mainly with the photocathode target serving as both cooler and target. The diameter of the magnetically expanded electron beam was 13 mm (α=20), the electron current was limited by gun perveance to about 0.34 mA (electron density $3x10^6$ cm^{-3}). A magnetic guiding field of 0.04 T was used. The CF^+ current in the storage ring after injection was estimated to be few 100 pA and the lifetime of the ion beam was about 4 s.

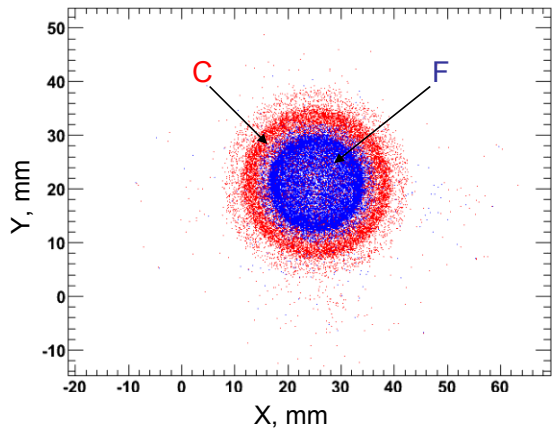

Figure 4: Image of C and F neutral fragments of the cooled ion beam after 12 s.

Imaging detectors 12 m downstream of the electron target are used to measure neutral recombination fragments and to analyze the dissociation dynamics. The transverse momentum of the dissociation fragments is recorded event by event using a spatially resolving multi-hit detector (two-dimensional fragment imaging) [15]. Figure 4 shows a pattern of C and F neutral fragments from dissociative recombination of the stored CF^+ molecular ions in the electron target at zero (cooling) energy, as observed on the imaging detector. Due to the kinetic energy release the neutrals are deflected from the centre. The maximum deflection distance comes from the molecules dissociated transversely to the ion beam propagation with the lighter fragment (C, red) forming the outermost rings on the image and with F atoms (blue) corresponding to inner rings. For CF^+ two different final levels of the C atoms cause two rings each for C and F, respectively, with a smaller branching ratio for the *high* kinetic energy release.

For atomic ion beams the spatial profile of neutral atoms produced by recombination in the electron target directly reflects the angular divergence of the ion beams [16]. For molecules the imaging profile can not be used directly to monitor transverse ion beam properties during the phase space cooling due to the significant kinetic energy release in the dissociation process. However, this can be achieved by monitoring the centre-of-mass of all fragment hit positions for a given recombination event, which reflects the direction of the molecular ion before it captured an electron in the target [17].

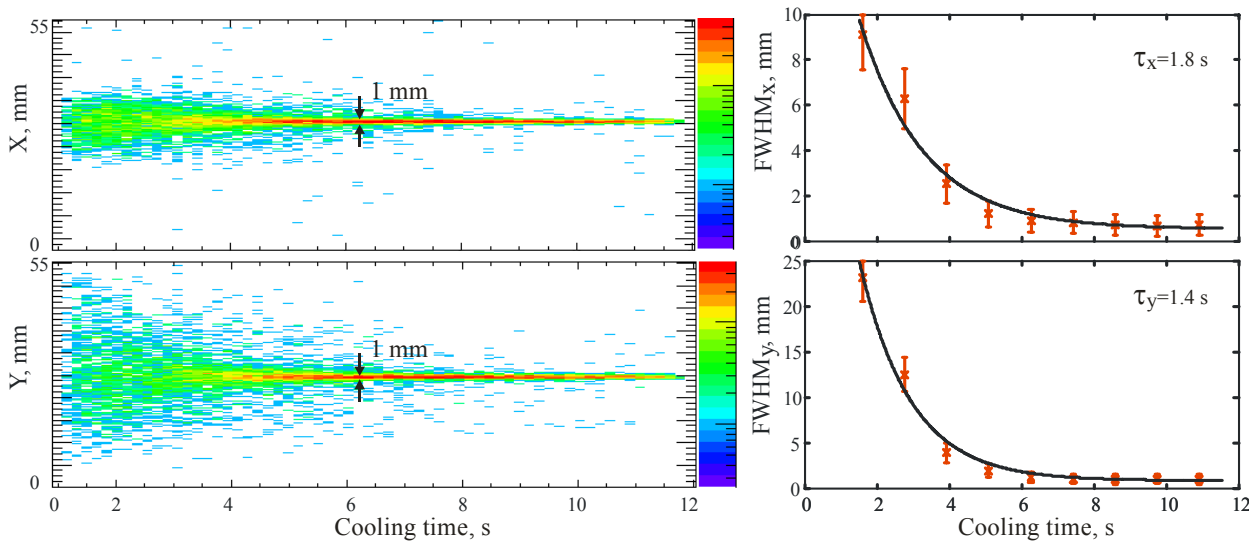

Figure 5: Transverse electron cooling of 97 keV/u CF^+. Centre-of-mass positions of the C and F neutral fragments vs time, recorded 12 m downstream of the electron target by the imaging detector and indicating rms divergence angles of about $3 \cdot 10^{-5}$.

Figure 5 (left) shows positions of the centre-of-mass as a function of the cooling time derived from correlated two-hit events for both transverse directions. The FWHM of the centre-of-mass distribution vs time is also shown in Fig.5 (right). A transverse cooling time below 2 s was achieved, demonstrating a high cooling efficiency of the photocathode beam. An estimation of the cooling time from Eq.3, assuming an isotropic electron beam with 1 meV temperature, L_c=3.3 and the length of the target to be about 2.2% of the ring circumference, gives a value of about 1.5 s for the cold ion beam and 6 s for the hot ion beam (with a diameter of the injected ion beam about 2 times larger than that of the electron beam). After 6 s a FWHM of the centre-of-mass distribution of 1 mm (horizontally) and 0.7 mm (vertically) was measured by the imaging detector 12 m downstream of the target. Assuming a longitudinal ion spread ΔP/P of about $5 \cdot 10^{-5}$ and using the horizontal TSR dispersion of 2 m and the β functions of 3.9 m (horizontal) and 1.5 m (vertical) at the target section, the divergence and size of the ion beam can be derived. The divergence was found to be of about $3 \cdot 10^{-5}$ in both transverse directions and the 1σ size was about 0.04 mm (vertically) and 0.2 mm (horizontally). The larger size of the ion beam in the horizontal direction arises from the ring dispersion and from stability of the power supplies for dipole magnets and cathode voltage.

CONCLUSIONS

Electron cooling of low-energy heavy molecular beams (CF^+, 31 amu) was performed by a cold electron beam of 53 eV delivering by cryogenic photocathodes. An electron current of about 0.3 mA was used. Short cooling times (below 2 s) and a very small equilibrium beam size (0.04×0.2 mm^2) obtained in these experiments demonstrate the high potential of cryogenic photocathode electron beams for electron cooling of slow ions.

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