Photocathodes as electron sources for high resolution merged beam experiments

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Abstract. An ultra cold electron source was developed for the storage ring TSR in Heidelberg to study electron-ion interactions with high energy resolution. The heart of the source is a GaAs photocathode which emits electrons with energy spreads below 10 meV. Photoemitted electrons are extracted in the space charge mode and then undergo adiabatic magnetic expansion and adiabatic acceleration to obtain an ultra cold electron beam which is overlapped with the stored ion beam in a straight section of the ring. In the first recombination measurements on HD+ unprecedented energy resolution for low-energy resonances was found, demonstrating a transverse and longitudinal temperature of the electron beam of about 0.5 meV and 0.02 meV, respectively.

1. Introduction
Merged beam experiments at storage rings were used successfully to study electron-ion inelastic collisions with high energy resolution (see, e.g., [1]). While the typical energies of the stored ions and electrons are about a few MeV/u and keV, respectively, collision energies below a milli-eV can be realized by small longitudinal velocity detuning between the ion beam and the magnetically guided electron beam. In such experiments the ion velocity is well defined and the collision energy spread is mainly given by the electron energy distribution, being strongly anisotropic in the co-moving reference frame [2]. At zero detuning energy and for typical electron densities $n_e \sim 10^5$–$10^7$ cm$^{-3}$, the longitudinal temperature $kT_\parallel$ of the electrons is mainly defined by potential energy relaxation: $kT_\parallel \sim C n^{1/3} e^2/4\pi e_0$. Here the parameter $C$ describes the quality of the acceleration and can be suppressed by slow acceleration [2]. The longitudinal temperature is typically below 0.1 meV and always much smaller than the transverse temperature $kT_\perp$ which so far has been in the range of 2–30 meV. In recombination experiments, the electron temperatures lead to an asymmetric broadening $\delta E$ of the observed cross-section resonances. The low-energy side of the resonance is broadened by $kT_\perp$, while $kT_\parallel$ broadens the resonance symmetrically by $4(E_r kT_\parallel \ln 2)^{1/2}$, with $E_r$ being the resonance energy [3]. For $E_r$ below 0.1 eV, $\delta E$ is limited by $kT_\perp$. Hence, to improve $\delta E$ in this energy range, $kT_\parallel$ has to be decreased. Initially $kT_\parallel$ is given by the cathode temperature $kT_c$ and can be reduced by an adiabatic magnetic expansion: $kT_\parallel = kT_c/\alpha$, where $\alpha$ is the expansion coefficient [4]. While for thermocathodes $kT_c$ is above 100 meV, semiconductor photocathodes operated at room temperature or below were considered as promising candidates for cold electron sources.

We have developed an electron gun with a cryogenic GaAs photocathode which is suitable for obtaining mA currents of emitted electrons with energy spreads of 5–7 meV [5, 6]. This electron source has been installed into the TSR electron target section which provides adiabatic magnetic expansion.
combined with adiabatic acceleration [7]. Recently dissociative recombination (DR) of HD$^+$ was studied with this setup. In the DR cross section low energy resonances could be seen with unprecedented resolution [8] demonstrating a transverse temperature of the electron beam below 1 meV. In this paper we present the performance of the photocathode source under experimental conditions and show how to realize intense cold electron beams with a GaAs photocathode.

2. Photoelectron emission from GaAs(Cs, O)

In the case of thermocathodes the work function for electrons is about 2 eV. To release electrons into the vacuum the thermocathode must be heated to 1300–1500 K, which results in electron energy spreads of about 110–120 meV. In the case of GaAs photocathodes the situation is different: GaAs with a thin layer of cesium and oxygen produces a state with effective Negative Electron Affinity (NEA) if the vacuum level lies below the position of the conduction band in the bulk [9] (figure 1). Electrons, photoexcited from the valence band to the conduction band, are rapidly thermalized at the bottom of the conduction band and reach the surface with energy spreads defined by the temperature of the bulk, which is in our case about 80 K. Due to the NEA condition, a large fraction of these electrons can escape into the vacuum.

However, during the escape process electrons undergo strong energy and momentum relaxation [5]. As a result they occupy the complete available phase space, enlarging the transverse and longitudinal energy spreads to about the value of the NEA (typically about 150–250 meV). Moreover, in contrast to thermocathodes a decrease of the temperature causes a rise of the energy spreads due to further increase of the NEA [10]. Hence the overall energy distribution from a photocathode is about the same or even worse as compared to thermocathodes. However, it was found that electrons emitted above a suitable longitudinal energy ($\geq E_c$) have transverse and longitudinal spreads of about the bulk temperature [5,11]. For these electrons energy spreads of about 5–7 meV and 25 meV were measured at 90 K and 300 K, respectively [5,10]. The longitudinal potential barrier near the photocathode surface can be produced by applying a voltage to an external electrode or by a space charge barrier. The effective quantum yield for the cold electrons at 90 K is found to be 1–2%, while the total quantum yield is about 20–30% [12]. To get currents in the mA range laser powers of about 1 W have to be applied to the cathode, which imposes strong demands on laser power dissipation from the cathode [13].
3. Setup and photocathode handling

In contrast to thermocathodes there are high requirements regarding vacuum conditions, surface preparation and handling of the photocathodes. To obtain high-performance NEA-photocathodes, the GaAs surface has to be atomically clean. Moreover, GaAs activated with cesium and oxygen shows a very short lifetime in the presence of oxidizing gases in the residual atmosphere of the vacuum chamber.

We use transmission-mode GaAs photocathodes consisting of a two layer GaAs/AlGaAs heterostructure bonded to a sapphire substrate, which has a high thermoconductance at low temperatures. The diameter of the cathode is 6 mm, the emitting \( \text{p}^+ \)-GaAs(100) layer is \( \sim 1.5 \mu \text{m} \) thick and doped with Zn to a hole concentration of about \( 5 \times 10^{18} \text{ cm}^{-3} \). The vacuum setup consists of a loading, a preparation and a gun chamber, separated by all-metal gate valves, with base pressures of about \( 10^{-10}, 10^{-12} \) and \( 3 \times 10^{-11} \text{ mbar} \), respectively. The loading chamber is equipped with a self-made atomic hydrogen source. Inside the vacuum the samples are transferred by magnetically coupled feedthroughs. The first step of the cleaning procedure is performed inside a glove box, flooded with pure nitrogen, where the cathodes are chemically treated in a solution of HCl in isopropanol. Using an airtight vessel, the samples are transported to the loading chamber without contact to the laboratory atmosphere. 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.

After the mounting of the sample in the gun the manipulator is detached from the cathode holder and the pressure unit attached to it. Figure 2 shows the electron gun consisting of a copper cold head (flooded with liquid nitrogen), Pierce and extraction electrodes. The photocathode is illuminated in transmission mode with a 800 nm diode laser capable to apply a power of 1.7 W.

To obtain a good thermocontact the sapphire substrate of the cathode is pressed to the cold head by a spring force of 100 N, applied with the help of a Huntington feedthrough. For different photocathodes a temperature rise of about 15 K/W was measured [13]. The emitting GaAs surface is positioned at a distance of about 0.2 mm from the Pierce electrode which has an opening of 3 mm diameter. A voltage applied to the Pierce electrode allows the difference in work functions of the photocathode and the Pierce electrode to be compensated and the spatial current distribution of the emitted electrons to be controlled. The extraction electrode follows the Pierce electrode at a distance of 2.4 mm. The gun perveance is about \( 1 \mu \text{Perv} \). The electron gun is a part of the electron target described below.
4. Electron target

Recently in addition to the electron cooler an electron target was installed at the TSR, that separates cooling of the ion beam from the target operation. It improves the quality of the electron and the ion beam and hence the resolution in electron-ion collision experiments [7].

The target consists of an acceleration section (including the electron gun), an interaction section, a collector and two toroid sections. Several valves allow the separation of the acceleration and collector sections from the toroid sections. The complete electron target is mounted on precision tracks for easy installation and removal of the setup from the storage ring under vacuum. The magnetic fields used for guiding the electrons amount to 0.04–0.1 T. By increasing the field strength (maximum 3.5 T) at the cathode position, a magnetic expansion of the beam can be achieved. Expansion ratios up to 90 are possible, expanding low-energy electrons adiabatically on a distance of about 0.3–0.4 m. A voltage of about 50–150 V, applied to an extraction electrode, controls the total electron current from the cathode. After extraction, the electron beam enters a drift tube with a length of about 0.2 m, where the electron energy is kept low (100–250 V) during magnetic expansion. Then the beam reaches the adiabatic acceleration section which is about 1.5 m long and includes 77 independent electrodes. After the acceleration (maximum energy is 20 keV) the electrons are bent in a 90° toroid with a radius of 0.6 m and overlap with the ion beam in the interaction section over a distance of about 1.5 m. The interaction section is designed for magnetic-field ∆B⊥/B angles to be smaller than 10⁻⁴ in order to achieve an energy resolution below 0.1 meV in recombination experiments. At the second toroid the electrons are separated from the ion beam and collected by a Faraday cup. At the back of the Faraday cup, a retarding-field energy analyzer with a 50 µm entrance aperture is installed to measure longitudinal energy distributions of the electrons and two-dimensional beam profiles. Clearing electrodes at the toroid sections are used to reduce the back-stream of electrons reflected from the Faraday cup. The recombination processes resulting from electron-ion interactions at the target are observed downstream by direct counting of charge-changed products, which are separated from the stored ion beam at the next storage ring bending magnet. Details of the target setup are described elsewhere [7].

5. Performance of the photocathode source at the TSR target

The photocathode source was installed into the TSR electron target in June 2004. During the following months several measurements were performed with different systems (HD⁺, H₃⁺, F⁶⁺, Sc¹⁸⁺). This time was also used to improve the performance of the cathode (mainly current and lifetime) and to discover problems to be solved. Presently the photocathodes are typically run at emission currents of about 0.2 mA. The current stability is about 5% during 10–15 hours and then the electron current rapidly falls down due to the rise of the work function so that the vacuum level reaches the position of the conduction band in the bulk (see figure 1). Measurements of two dimensional beam profiles did not show changes in the electron density distributions before the dropping of the current. As soon as the cathode starts to show a current decrease it is replaced by another one stored in the preparation chamber. It takes about 5 minutes to change the sample and then about 20 min to cool the cathode down close to liquid nitrogen (LN₂) temperature. The samples were usually re-used 3–4 times by radiative heating and re-activation in the preparation chamber before they lose their performance. Then an atomic hydrogen cleaning technique inside the vacuum setup was used to remove contaminations, as well as Ga- and As-oxides and old (Cs,O) layers. With hydrogen cleaning, we found no degradation of quantum yield and energy spreads even after multiple cycles of heating and (Cs,O) reactivation of a cathode. This allowed us to operate the samples in a closed cycle. In total we had 4 samples which were used for all measurements without removing them from the vacuum chamber.

The increase of the current from 0.2 mA to about 1 mA decreases the lifetime of the cathode to about 1 hour. The degradation at high electron currents is believed due to a back-stream of ions, ionized by electrons in the acceleration section, where the vacuum conditions are not optimal. Measurements of electron current profiles show non-emitting zones, while the rest of the cathode still demonstrates...
Figure 3. (Color online) Dissociative recombination rate coefficient of stored HD$^+$ ions in the TSR observed with the cryogenic photocathode electron gun (dots) [8] compared to the previous high-resolution data from CRYRING [3] (grey/red solid line with stars). For estimating the transverse energy spread, which determines the steepness on the low-energy sides of the three observed structures, a model rate coefficient is shown (——) as obtained from the sum of several components (- - - -), representing a smoothly varying base contribution and three infinitely sharp resonances, broadened with the electron energy distribution for $kT_\perp = 0.5\ \text{meV}$ and $kT_\parallel = 0.02\ \text{meV}$.

Figure 3 shows the DR rate coefficient for HD$^+$ (dots) at energies below 25 meV (in the CM frame), where the transverse energy spread plays a crucial role for the resolution. For comparison the best spectrum obtained before at CRYRING in Stockholm [3] with a resolution of 2 meV is also shown (grey solid line with stars). Aside from a zero-energy peak, the experimental spectra show three additional structures at $\sim 2.5, 8$ and $18\ \text{meV}$. The observed structures are consistent among the two experiments; however, the data obtained with the TSR photocathode gun appear considerably sharper and clearly demonstrate the presence of an even finer structure within each of the three peaks.

To understand the detailed shape of the rate coefficient after convolution with the thermal electron velocity distribution, a theory of the low-energy resonances for HD$^+$ dissociative recombination is required. Unfortunately, the present theory does not describe well this part of the spectrum, where presumably a number of individual ro-vibrational resonances give important contributions. To estimate

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the transverse electron energy spread, it was tried to reproduce the experimental shape at the low-energy sides of the three peaks by a model rate coefficient. First, the baseline of the observed rate was modeled by a smooth function fitting the data in the valleys between the peaks; then, the broadened signals from three delta resonances in the DR cross section were added, where the energetic positions as well as the parameters $kT_\perp$ and $kT_\parallel$ were chosen to obtain the best representation of the experimental peak slopes. As seen in figure 3, a choice of $kT_\perp = 0.5$ meV and $kT_\parallel = 0.02$ meV describes very well the experimental slopes. It should be mentioned that the same procedure (with almost the same base contribution) applied to the Stockholm data gives the previously quoted value of $kT_\perp = 2$ meV [3] for the transverse electron temperature.

Despite a very good energy resolution obtained with a photocathode gun, the measured transverse energy is still higher than could be ultimately expected (0.35 meV). In addition, the increase of the magnetic expansion factor from 20 to 40 (not shown here) unexpectedly had only a small influence on the resolution. Altogether this shows that we reach a limit where other factors give significant contributions to the collision energy spreads. Among these factors could be a misalignment of the electron and ion beams, intrabeam scattering of the ion beam, and nonadiabatic movements of the electrons during the extraction, the magnetic expansion or the bending in the toroid regions. All these problems have to be reconsidered and, where possible, experimentally checked in order to further increase the energy resolution.

6. Conclusions

A new source of cold electrons with a GaAs photocathode was developed for electron-ion merged experiments at the Heidelberg TSR. It provides electrons with energy spreads below 10 meV at currents of 0.2 mA and lifetimes of about 10–15 hours. The photocathode setup allows us to prepare photocathodes and to re-clean them without removing the cathodes from the vacuum setup, thus operating the electron target in an almost non-stop mode. In the dissociative recombination cross section measurements low energy resonances could be seen at unprecedented resolution [8] demonstrating transverse and longitudinal temperatures of the electron beam of $\sim 0.5$ meV and 0.02 meV, respectively. Work to improve currents, lifetimes and energy spreads is in progress.

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