An Ultra Cold Photoelectron Gun for the Heidelberg TSR Target Section

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Abstract. We present a cryogenic photoelectron gun, developed for the target section of the Test Storage Ring (TSR) of the Max Planck Institute of Nuclear Physics (MPIK). Cooled to cryogenic temperatures by liquid nitrogen, the photocathode source provides an electron gas with an initial thermal energy spread of around 10 meV. The beam optics of the target section reduce the electron temperatures to much lower values in the comoving frame of the beam. Recently the photocathode source has seen significant improvements regarding its reliability. By controlling several cathode degradation mechanisms, including cryosorption, vacuum degrading leak electron currents, and backstream of ionised restgas particles, cathode lifetime and currents have been subject to substantial improvements. Presently the photoelectron gun can deliver currents of up to 1 mA at lifetimes of about 24 h. The ability of the photoelectron beam to cool slow, heavy molecular ion beams was demonstrated by cooling a 3 MeV CF$_4^+$ beam in the TSR. At an electron cooling energy of only 53 eV and a perveance-limited current of 0.34 mA, a cooling time below 2 s has been achieved, with a very small transverse relative momentum spread of $2.5 \times 10^{-5}$ and final ion beam cross-section of $0.5 \times 0.1 \text{ mm}^2$.

1. The TSR Target Section

The Test Storage Ring of the MPIK is presently the only heavy-ion storage ring equipped with two independent merged electron-ion beam facilities. The so-called electron cooler is normally operated in velocity-matched mode, such that the stored ion beam is continuously phase-space cooled. The second, probe electron beam, hereafter referred to as the electron target, can be detuned in velocity with respect to the ions, and allows electron-ion recombination experiments with unprecedented energy resolution.

To achieve the highest possible energy resolution, the electron target can be equipped with a cryogenic photoelectron gun instead of a thermocathode. The heart of the cryogenic gun is a p-doped GaAs (Cs/O) photocathode. Cooled by liquid nitrogen to about 100 K, it delivers an electron gas with an initial thermal energy spread of around 10 meV, roughly corresponding to the lattice temperature of the cold GaAs crystal [2].

The beam optics of the electron gun greatly enhance the energy resolution in the comoving frame of the electron beam [3]. Adiabatic magnetic expansion by field ratios $\alpha$ of typically 20 to 40 reduces the kinetic energy spread transverse to the beam direction according to

$$k_B T_\perp = \frac{k_B T_c}{\alpha},$$

(1)
Figure 1. The TSR Electron Target and adjacent ring elements: C – cathode position, 1 – accelerator section, 2 – interaction section, 3 – collector section, 4 – toroids merging and demerging the electron/ion beams, 5 – bending dipole magnet, 6 – neutral counting and imaging detectors, 7 – charged fragment detectors.

Figure 2. Schematic drawing of the photocathode vacuum setup (top view): 1 – gun chamber, 2 – preparation chamber, 3 – loading chamber, 4 – atomic hydrogen chamber, M – magnetic manipulators, C – cathode position in the gun, L – excitation laser port.

where $T_c$ is the cathode temperature. Values of $k_BT_c$ as low as 0.5 meV have been observed [4]. Subsequent adiabatic acceleration of the electron cloud kinematically reduces the longitudinal velocity spread in the comoving frame of the beam according to

\[ k_B T_L \approx \frac{(k_B T_c)^2}{eU} + C \frac{e^2 n^{1/3}}{4\pi \epsilon_0} . \]  

(2)

The first, kinematic, term in eq. (2) describes the decrease in longitudinal temperature of the beam related to an acceleration by a voltage $U$. Potential energy relaxation by plasmon emission in the accelerated electron beam leads to a rise in longitudinal temperature described in the second term of eq. (2). $C \approx 1$ denotes the acceleration constant and $n$ the electron particle density. For the TSR target equipped with the photoelectron gun, a value $k_BT_L$ of 22 $\mu$eV has been measured [5].

In low energy operation ($U \lesssim 100$ V) the maximum extractable current $I$ is limited by the gun perveance $P$, which is of around 1 $\mu$Perv for the photoelectron gun:

\[ I = PU^{3/2} = 1 \text{ mA} \frac{P}{1 \mu\text{Perv}} \left( \frac{U}{100 \text{ V}} \right)^{3/2} . \]  

(3)

Guided by a magnetic field of usual inductance 0.04 T, the cold electron beam is then merged with the stored ion beam in an interaction section of 1.4 m length (c.f. fig. 1). Afterwards, the beams are demerged and the electrons dumped onto a Faraday cup in the so-called collector section. Neutral and charged recombination products are separated from the stored beam in the next bending magnet of the TSR downstream of the electron target. Recombination processes can be investigated using counting and imaging detectors.

2. The Photoelectron Source

The heart of the ultracold gun is a transmission mode GaAs photocathode. A surface of p-doped GaAs, activated by a thin (about 1 monolayer) layer of cesium and oxygen, is characterised by a
surface state of effective Negative Electron Affinity (NEA), i.e. the vacuum level lies energetically below the conduction band minimum in the bulk of the crystal. Thanks to the NEA, electrons photoexcited from the valence to the conduction band may escape into the vacuum without further energy supply.

2.1. Photoelectron Emission from GaAs

Excited to the conduction band, electrons quickly thermalise into a Boltzmann distribution, whose spread corresponds to the temperature of the crystal bulk $T_c$. Unfortunately, the emission process itself is characterised by further energy and momentum relaxation through electron scattering at surface states, such that the transverse and longitudinal electron energy distributions in vacuum expand to approximately the span of the NEA which is of 0.1 to 0.2 eV [6]. However, in normal cathode operation the power of the excitation laser beam is set so high that electrons accumulate in front of the cathode surface. Eventually, a space charge builds up, effectively preventing electrons with longitudinal energies lower than about the conduction band minimum to be emitted from the cathode. It has been shown [4] that the effective initial energy spread of the electron gas again corresponds approximately to the temperature of the GaAs bulk, of around $k_B T_c = 10$ meV.

Acting as a buffer, the space charge also defines the effective quantum efficiency of the photoelectron gun which is of about 1% when the space charge potential corresponds to the conduction band minimum [4]. The quantum yield (QY) measured in current-limited mode is much higher – 20% or more for freshly activated cathodes, with a record value of 35%, measured at 635 nm wavelength in reflection mode. During operation in the electron gun, the overall QY of cathodes slowly decreases due to various mechanisms leading to destruction of the Cs/O layer. Thus after a given time of operation a GaAs sample has to be replaced by a newly activated one.

2.2. The Photocathode Setup

The photocathode vacuum setup is designed to allow a fast, all-in-vacuum cathode replacement procedure which takes only half an hour, thereby ensuring a quasi-continuous operation of the electron target. It consists of four distinct vacuum chambers (c.f. fig. 2). Transfer of cathodes among chambers or into the electron gun is done using magnetically coupled manipulators. The so-called gun chamber is flanged to the target’s acceleration section and thus connected to the TSR vacuum. It contains the actual electron gun and features a laser window for transmission-mode excitation of the GaAs samples as well as high voltage and liquid nitrogen feedthroughs. Its base pressure varies around $2 \times 10^{-11}$ mbar, depending on the overall vacuum conditions in the target and in the TSR. The preparation chamber, separated from the gun by a UHV valve, has a base pressure of $5 \times 10^{-12}$ mbar. It can contain up to four cathode samples and features facilities for cesium/oxygen activation as well as ovens for heat-cleaning of samples. In addition the setup features a chamber dedicated to atomic hydrogen treatment of cathode samples after several cycles of heat-cleaning, activation and use [1]. Exposure to free hydrogen radicals removes any traces of activation layer from the GaAs and restores the initial quality of the crystal surface. Last, the setup features a loading chamber, where samples can be removed from or inserted into the setup without disturbing the high vacuum [2].

3. Photocathode Performance in Target Operation

The main drawback of GaAs photocathodes is their limited lifetime, especially in high current operation. While all QY degradation is eventually due to destruction of the Cs/O monolayer on the GaAs surface, we have identified several effects that can lead to such degradation. Carefully monitoring and controlling these effects, we significantly increased the maximum usable extraction current of the photoelectron gun to about 1 mA. This is sufficient for a large number
of experimental needs, especially for slow molecular ion beams, where electron currents are limited by gun perveance anyway (c.f. eq. (3)). As a benchmark for the performance of the photoelectron target at such low energies, a slow beam of CF$^+$ was cooled by an electron beam of energy 53 eV and current 0.34 mA [7].

3.1. Extraction Currents and Lifetimes

At low current drain (several nA), the so-called dark-lifetime of a photocathode is limited by the partial pressures of various chemical agents in the UHV restgas. In the case of GaAs photocathodes H$_2$O and CO$_2$ are especially known to be dangerous [8]. For cathodes operated in the TSR electron target, dark lifetimes are of around one week or longer.

Too strong cooling by liquid nitrogen radically reduces cathode lifetimes, as the cold surface adsorbs restgas such as CH$_4$, CO and CO$_2$ [4]. Undercooling of a photocathode results in an instantaneous, steep drop in the emission current, which can be partially restored by reduction of the cooling power. Formerly the cathode temperature was tuned in a rather indirect way by the liquid nitrogen supply line pressure. In 2007, a nitrogen flow controller was installed, allowing very reliable tuning of the cooling power, thus undercooling is not an issue anymore. Normally used cathode temperatures are estimated to be about 100 K.

At normal operation currents (0.5 to 1 mA) electron emission from the cathode itself degrades the vacuum conditions, as leak currents lead to desorption from gun electrodes and chamber walls. Since the magnetic guiding field effectively prohibits electron propagation transverse to the beam direction, the major part of these leak currents consist of electrons that travel to the collector as normal, but, upon impact onto the faraday cup, produce secondary electrons which can drift back towards the gun and impinge next to the cathode. These leak currents may thus be minimized using the beam optics of the collector section alone, which do not affect the experimentally relevant position of the main electron beam in the interaction section.

Another degradation channel is caused by electron impact ionisation of the target restgas. During target operation, restgas molecules can be positively ionised inside the electron beam. Trapped in the magnetic guiding field, they may drift towards the gun section where they are accelerated and focused onto the cathode surface by the electron beam optics. This high energetic ion bombardment leads to a very localised destruction of the Cs/O layer which is most

**Figure 3.** Electron beam profiles, depicting the current density distribution over the beam cross-section. Shown are a freshly activated cathode (top) and a heavily degraded one (bottom).

**Figure 4.** Extraction current of the photoelectron gun versus time. The current is stable at 1 mA for approximately 23 h, then the cathode would be replaced in normal operation.
prominent in the center of the cathode surface, as depicted in fig. 3. Ion trapping in the target can be prevented using an electric clearing field in the collector section. Additionally, a small positive potential threshold can be added to the acceleration structure of the electron gun. As initial kinetic energies of ionised particles are small, even a very weak positive potential step of 5 to 10 V, which does not affect the high energetic electron beam, is sufficient to prevent ion drift towards the electron gun.

By careful control of the above mentioned cathode degradation channels, we were able to increase the photoelectron gun’s maximum extraction current from about 0.2 mA to 1 mA, while maintaining cathode lifetimes of typically 24 h (c.f. fig. 4). At currents below 1 mA lifetimes of several days have been observed.

3.2. Cooling of Slow Heavy Ion Beams

As can be seen from eq. (2), the quality of an electron beam with respect to its longitudinal temperature degrades at low energies $eU$ as the first term in (2) rises in magnitude. Additionally, the maximum current that can be extracted from the cathode decreases according to eq. (3). The perveance $P$ of the photoelectron gun is of around 1 $\mu$Perv, i.e. at electron energies below 100 eV, the maximum extraction current, and thus the electron density $n$, is limited by perveance rather than by cathode degradation.

A slow beam of CF$^+$, stored in the TSR at a total kinetic energy of 3 MeV (around 90 keV/u), was used as a benchmark for the performance of the photoelectron target at low acceleration voltage [7]. Usage of the TSR’s electron cooler for this beam gave unsatisfactory results, with cooling times of around 15 s and a final width of the stored CF$^+$ beam of typically a few millimeters. Thus, in contrast to the usual operation scheme, the electron target rather than the electron cooler was used to cool the ion beam. The electron cooling energy, matching the velocities of electrons and ions, was only 53 eV, thereby limiting the extraction current to about 340 $\mu$A. The electron beam was magnetically expanded by a field ratio of $\alpha = 20$ to a diameter of about 13 mm, which corresponds to an electron density $n \approx 3 \cdot 10^6$ cm$^{-3}$. A guiding field

\[ P = 1 \mu\text{Perv} \]

\[ eU \]

\[ n \approx 3 \cdot 10^6 \text{cm}^{-3} \]

\[ \alpha = 20 \]

\[ X \text{ mm} \]

\[ Y \text{ mm} \]

\[ \text{FWHM}_x, \text{mm} \]

\[ \text{FWHM}_y, \text{mm} \]

\[ \text{Cooling time, s} \]

\[ \text{Cooling time, s} \]

\[ T_x = 1.8 \text{ s} \]

\[ T_y = 1.4 \text{ s} \]

**Figure 5.** Neutral fragment centre-of-mass distribution of a 3 MeV CF$^+$ beam versus storage time in the TSR, measured by a fragment-imaging detector 12 m downstream of the target section, with the photoelectron target being operated as a cooler. The electron cooling energy was only 53 eV and thus the extraction current of the photocathode perveance-limited to 340 $\mu$A. Still, the cooling time of the ion beam is below 2 s. The figure is taken from [9].
The inductance of 0.04 T was used [9].

The CF$^+$ ion current injected into the storage ring was estimated to be around 100 pA. At such low currents, the TSR’s regular beam diagnostics cannot be used anymore. Thus the molecular fragment imaging detector was used to analyse the evolution of the transverse emittance of the ion beam during electron cooling. 12 m downstream of the position of the electron target, the detector observed the centre-of-mass distribution of the neutral fragments emerging from Dissociative Recombination of CF$^+$. The spread of this centre-of-mass distribution allows to determine the transverse momentum spread and cross-section of the ion beam in the interaction section [9].

The measurement is shown in figure 5. After 6 seconds, the width of the neutral fragment centre-of-mass distribution measured at the detector is of 1 mm in the horizontal (X) and 0.7 mm in the vertical (Y) direction transverse to the beam. This corresponds to a transverse relative momentum spread of the ion beam in the interaction section of around $2.5 \times 10^{-5}$ along both directions. The width of the beam was found to be 0.5 mm along the horizontal and 0.09 mm along the vertical direction. As shown in figure 5, the cooling time was below 2 s for both dimensions, demonstrating a very good cooling performance of the photoelectron beam even at low energies and currents [9].

4. Summary
The target section combined with the cryogenic photoelectron gun features unprecedented energy resolution, as has been demonstrated in both atomic and molecular recombination experiments at the TSR. Transverse and longitudinal temperatures of the electron beam can be as low as 0.5 meV and 22 μeV respectively.

The performance and reliability of the photocathodes have recently seen significant improvements. Carefully controlling various degradation mechanisms, we increased the usable current limit from around 0.2 mA to 1 mA, while keeping lifetimes of 24 hours or more, which is by now sufficient for practically all experimental needs.

Equipped with the photoelectron gun, the target’s cooling capabilities were found to be very good, even at electron beam energies of 53 eV, where the longitudinal beam temperature increases and the electron current is perveance-limited to about 0.3 mA, i.e. significantly lower than the maximum current allowed from the point of view of cathode reliability.

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