QUANTIFICATION OF THE ELECTRON PLASMA IN TITAN'S COOLER PENNING TRAP*

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Abstract

Modern rare isotope facilities provide beams of short-lived radionuclides primarily for studies in the field of nuclear structure, nuclear astrophysics, and low energy particle physics. At these facilities, many activities such as re-acceleration, improvement of resolving power, and precision experimental measurements require charge breeding of ions. However, the charge breeding process can increase the energy spread of an ion bunch, adversely affecting the experiment. A Cooler Penning Trap (CPET) is being developed to address such an energy spread by means of sympathetic electron cooling of the Highly Charged Ion bunches to $\lesssim 1$ eV/q. Recent work has focused on developing a strategy to effectively detect the trapped electron plasma without obstructing the passage of ions through the beamline. The first offline tests demonstrate the ability to trap and detect more than 10^8 electrons. This was achieved by using a novel wire mesh detector as a diagnostic tool for the electrons.

INTRODUCTION

Nuclear masses serve as critical inputs in models of nucleosynthesis [1] and provide insight into nuclear structure [2], among numerous other applications. Penning trap mass spectrometry presently offers the highest precision and accuracy for mass measurements of radioactive nuclides [3].

Penning traps use a combination of static electric and magnetic fields to confine charged particles in space. A particle with charge, q, precesses in the magnetic field, B, with a cyclotron frequency given by

$$\omega_c = qB/m. \tag{1}$$

Since the cyclotron frequency is inversely proportional to the mass, we can readily determine the mass by measuring this frequency with a Penning trap.

At TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [4] the masses of short-lived isotopes are measured with precisions of 1 part in 10^7 and better. TITAN has successfully performed mass measurements at these precisions for the shortest-lived isotopes ever studied in a Penning trap (e.g. ^{11}Li at $t_{1/2}$ = 8.75 ms) [5].

At the TITAN facility, beams of singly charged, radioactive ions from the Isotope Separator and ACcelerator (ISAC) [6] are cooled and bunched in TITANs Radio Frequency Quadrupole ion trap before being delivered to TITAN's Measurement Penning Trap (MPET) [7] for precision mass measurement.

Precision in MPET is limited by

$$\frac{\delta m}{m} \propto \frac{m}{qBT_{RF}\sqrt{N}}, \tag{2}$$

where $\frac{\delta m}{m}$ is the mass uncertainty, m is the mass, q is the charge state, B is the magnetic field of the trap, T_{RF} is the period over which the ion is resonantly excited in the trap, and N is the total number of ions individually trapped and measured [8]. Therefore, in order to achieve the best possible precision, a stable and homogeneous magnetic field, a long excitation time, and a large number of ions are needed.

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However, the number of relevant ions available is limited by the low intensities of rare isotope beams (down to ~10/s); the excitation time is limited by the half-life of the isotope; and TITAN's magnetic field is fixed at 3.7 T. Therefore, the option exists at TITAN to send the singly charged ions to an Electron Beam Ion Trap (EBIT) [9], where they are trapped and charge-bred before injection into MPET. The charge state of the ions is increased in EBIT using electron impact ionization, and this increases the precision possible within a given experimental duration [10].

However, the possible gains in precision due to the EBIT are counteracted by an increase in the energy spread of the ion bunch that results from its interaction with the electron beam. A large energy spread reduces the precision of a mass measurement. This makes many of the lowest intensity isotope beams produced at ISAC impossible to study. In order to fully utilize the benefits of charge breeding in the EBIT, the energy spread of the ion bunch needs to be minimized, ideally to $\lesssim 1$ eV/q [11]. Therefore, a Cooler PEnning Trap (CPET) is being commissioned to reduce this energy spread by sympathetically cooling these Highly Charged Ions (HCIs) with electrons, thereby enhancing the mass measurement program at TITAN. HCIs are sympathetically cooled as they lose energy, through Coulomb scattering, to a plasma of colder electrons trapped in the same region. In this paper we report on initial measurements of the trapped plasma using a wire mesh detector. This detection method will be able to serve as a long-term diagnostic procedure to monitor the electron plasma in CPET.

THE COOLER PENNING TRAP (CPET)

CPET is a cylindrical Penning trap designed for cooling HCIs. It confines charged particles radially using a 7 T magnetic field, and axially using electrostatic fields generated by two gate electrodes (as well as a series of cylindrical trap electrodes in the future) (see Fig. 1).

A sympathetic cooling configuration is envisioned in which electrons are simultaneously trapped alongside positively charged ions using so called "nested" potentials to create a region in which the hot ions can interact electrostatically with cold electrons. A series of electrodes will be used to trap both the electrons and the ions by using the trap electrodes to create one or more local potential minima for the electrons to reside in within a globally negative trapping potential for the ions. The trap's 7 T superconducting magnet is strong enough for electrons to self-cool by emitting synchrotron radiation with a cooling time constant of 0.07 s [12]. Since the electrons have the ability to quickly self-cool, it is therefore possible to use the same bunch of trapped electrons to cool multiple subsequent ion bunches. This mitigates the system dead-time associated with reloading the trap and cooling a new electron bunch, which would reduce the statistics of an experiment.

CPET will eventually be integrated into the TITAN beamline to reliably cool radioactive ions with electrons on demand.

At the present time, CPET is undergoing tests in order to prepare it for integration into the TITAN beamline for cooling HCIs. Current study is focused on the establishment of a suitable electron plasma for cooling.

Simulations by Ke et al. (see [12]) have established constraints on the cooling plasma. They indicate that ions of 300 eV/q can be cooled to 0.1 eV/q in 0.4 s if $\frac{N_e}{N_i} = 10^4$, N_i being the number of ions and N_e the number of electrons. This gives us an order of magnitude for a reasonable ratio of electrons to ions for a relatively short cooling time of < 0.5 s. Compressing the plasma to greater density could further improve the cooling time.

In the current plasma loading scheme, the hot filament floating at ~1400 V serves as an electron source. Emitted electrons are then accelerated by an anode and sent through optics which are designed to optimize injection into the trap. The trapping region is defined by two gate electrodes ordinarily biased at −2100 V (see Fig. 1). To load the trap with electrons, the injection electrode is lowered to −800 V for 300 ms and then raised back to −2100 V. The electrons then remain trapped between the two electrodes in the trap region biased at −630 V for a chosen period of time until they are ejected from the trap for detection by lowering the ejection electrode to −100 V.

The electrons are not radially centred within the trap by default but rather orbit around the central axis in what is known as the $m = 1$ diochotron mode, a collective motion seen in non-neutral plasmas [13] [14]. The challenge with this radial offset from the axis of the trap is that the radius of the diochotron motion is substantially magnified upon extraction of the electrons from the trap. Due to the rapidly diverging magnetic field lines as electrons move out of the trap, they get farther from the central axis. For this reason, detecting the electrons outside the solenoid magnet is impossible, as they will collide with the components inside the CPET beamline before they can be detected.

ELECTRON DETECTION

To ensure the effective operation of CPET, it is important to be able to establish the presence of electrons in the trap. If the number of electrons in the trap is known, we can then determine the expected rate of cooling the ions. Effectively detecting the electrons will therefore allow us to estimate the capacity of CPET for cooling ions.

Previously, in order to address the diverging electron plasma, we mounted a phosphor screen within the drift tube beyond the ejection gate electrode. The phosphor screen has the advantage of being position-sensitive and able to operate within a magnetic field. Since the detector is still inside the magnetic field, we were able to observe that the radius of the diochotron motion damps over time [15]. The fact that the plasma settles to the centre of the trap is encouraging evidence that it will spatially overlap with the ions, thus enabling sympathetic cooling.

When CPET is integrated into the TITAN beamline it will need to allow the passage of ions under normal operation.

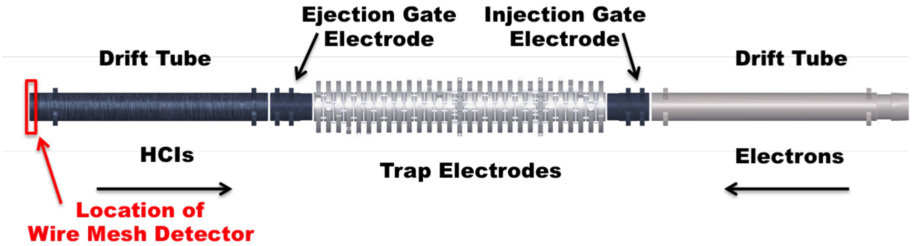

Figure 1: Arrangement of the drift tubes, gate electrodes, and trap electrodes within CPET. Location of the wire mesh detector is shown. Arrows indicate the path of electrons and future HCIs in the trap.

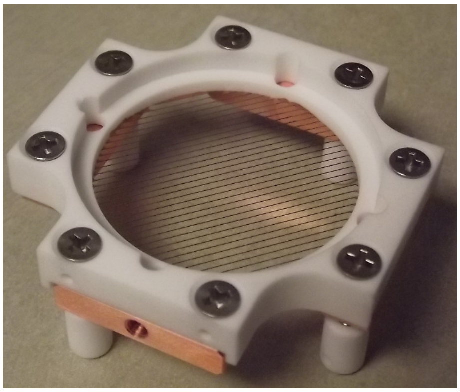

Figure 2: Image of the wire mesh detector.

The phosphor screen blocks the transmission of ions through CPET and space at the mounting location in the drift tube is limited by the size of the magnet's bore. This limits options for detection, and a retractable detector at that location would be impractical due to space constraints. We have therefore designed a wire mesh detector that can either be used as an anode on which to collect electrons, or be biased to drift tube potential to allow regular passage of ions for operation [16]. Detection of electrons is accomplished by grounding the wire mesh and reading out the voltage induced by the electrons collected on the mesh. The mesh sits at the bottom of a potential well made with the electrodes in order to direct the electrons onto the mesh.

The detector is an anode made from a 0.1 mm copper plate with 0.1 mm parallel wires photochemically etched from the material. The circular area of the wire grid has a 34 mm diameter. The wires are spaced with 1 wire per millimeter (see Fig. 2).

The mesh detector is positioned just outside the ejection gate electrode (see Fig. 1). It has been successfully commissioned. This mesh will serve as a long-term diagnostic tool to test the effectiveness of electron trapping.

Measurements with the mesh detector were taken for a range of electron storage times in the trap. The integrated voltage over time on the detector was read out on a oscilloscope which was triggered when the ejection gate electrode was opened. This allowed us to evaluate the total charge deposited on the wire mesh.

An averaged electron signal over 50 trapping/storing/ejection cycles was taken for trapping times of 2, 6, 10, and 14 seconds. We frequently recorded signals for which no electrons were loaded into the trap by using an unbiased Faraday cup as a beamstop. This allowed us to confirm the stability of voltages induced on the wire mesh due to the switching of the trap electrodes and noise from the environment. In this way we ruled out potential systematic uncertainties due to the background on the order of minutes and hours. From one trapping cycle to the next, variations of about 5% in the number of electrons collected on the mesh were seen. These variations were unrelated to the background. No major systematic drifts in the signal over time were observed. Therefore, averaging the measurements was no longer necessary to achieve the required precision; 1 cycle was taken for both the 22 and 30 second trapping times, and 10 cycles for 60 seconds.

Figure 3 summarizes the results of the measurements of the electron number for various trapping times. Approximately 10^8 electrons per ejection were detected on the mesh detector.

We see an initial rise in electron number when the trapping time increases from 2 to 6 seconds. The number of electrons then drops by more than one half over a trapping time of one minute.

One possible reason for the initial increase in the number of detected electrons is the damping of the diochotron motion seen in [15]; as the radial position of the plasma shrinks, more electrons hit the detector. Although 10^8 electrons should be amply sufficient for cooling HCIs in CPET, the gradual decline in electron number over time will necessitate periodic reloading of the trap with electrons.

SUMMARY AND OUTLOOK

CPET is currently being prepared to sympathetically cool HCIs at the TITAN facility. This will require a detector to monitor the trapping of the electron plasma coolant, while still allowing the passage of ions when CPET is incorporated into the TITAN beamline. A novel mesh detector has therefore been implemented to detect electrons in the 7 T magnetic field. We have successfully measured $\sim 10^8$ electrons which were trapped for over 30 seconds in CPET. This is a sufficient number to cool many short-lived isotopes to 0.1 eV/q in a reasonable time of < 0.4 s with potential for

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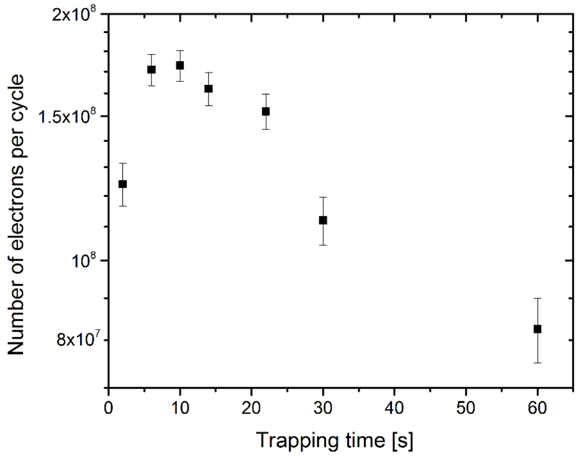

Figure 3: Number of electrons as calculated from the average charge deposited on the wire mesh detector for a range of different trapping durations in CPET. The initial increase in detection number appears to be due to the damping of the diocotron motion.

improvement. To ensure reliable cooling, periodic refilling of the electrons will be required to replace those which are lost over time. Plans are currently in place for CPET to be incorporated into the TITAN beam line with the mesh detector as the standard diagnostic tool for the plasma.

This work demonstrates the mesh detector to be an effective, yet economical solution for many low energy physics applications. Such a selectively transparent, yet robust charged particle detector could be a useful solution in extreme environments like our magnetic field, as well as many other applications.

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