A cooler Penning trap for the TITAN on-line trapping facility

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Abstract. The TITAN on-line ion trapping facility at TRIUMF is dedicated to precision experiments with short-lived radioactive isotopes, among them mass measurements. A new approach is to breed the ions into high charge states using an electron-beam ion trap. To counter any increases in energy spread caused by charge breeding, a cooler Penning trap is being developed. Sympathetic cooling mechanisms utilizing electrons and initially cold protons will be investigated. Details of the setup as well as the current status are reported.

1. Introduction

Accurate knowledge of the masses of atomic nuclei is important in numerous fields such as astrophysics, tests of the Standard Model searching for ‘new’ physics, and nuclear structure [1]. TRIUMF’s Ion Trap facility for Atomic and Nuclear physics (TITAN) [2], is an on-line setup interfaced to the ISAC radioactive beam facility at TRIUMF (see figure 1). It currently consists of a radio-frequency quadrupole (RFQ) to cool and bunch the ions, an electron-beam ion trap (EBIT) for charge breeding, and a hyperbolic precision Penning trap where mass measurements are performed (MPET). TITAN is dedicated to high-precision mass measurements of short-lived nuclei with a precision up to $\delta m/m \approx 10^{-7}$ for radioactive nuclei with half-lives as short as 10 ms. Initially, the mass measurement program at TITAN has focused on singly charged halo nuclei, such as $^8$He [3], $^{11}$Be [4], and $^{11}$Li [5].

The on-line Penning trap system at TITAN uses the time-of-flight ion cyclotron resonance (TOF-ICR) method to measure an ion’s mass $m$ in the charge state $q$. In such a measurement an ion’s cyclotron motion at frequency $\nu_c = qB/(2\pi \cdot m)$ is excited by an applied quadrupolar radio-frequency field, and the mass is determined from the measured cyclotron frequency. The statistical uncertainty of those measurements is given by

$$\frac{\delta m}{m} \approx \frac{m}{q \cdot B \cdot T_{RF} \cdot \sqrt{N_{\text{ion}}}},$$

where $m$ is the mass of the nuclide of interest, $q$ the charge of the ion, $B$ the magnetic field strength in the trap center, $T_{RF}$ the excitation time, and $N_{\text{ion}}$ is the number of ions sampled in
Figure 1. (Colour online) The TITAN experimental setup includes an RFQ, a high-precision Penning trap, an EBIT and an off-line ion source. The dotted line labelled ‘SCI’ shows the path of the ions when mass measurements on singly charged ions are performed, the solid paths labelled ‘SCI’ and ‘HCI’ indicate the route for the injection of highly charged ions into MPET.

the measurement [6]. The excitation time $T_{RF}$ is ultimately limited by the half-life of the ions. TITAN aims to boost the precision of the mass measurement by using an EBIT to increase the charge state of the ions. Short-lived, highly charged ions (HCI) extracted from the EBIT are sent to the precision Penning trap. While the higher charge state boosts the precision of the mass measurement by increasing the cyclotron frequency, the breeding process has the potential to significantly raise the energy spread of the HCI extracted from the EBIT. Based on the sparse data [7, 8], we expect spreads of tens of eV/q. This, along with contaminations from the charge breeding of residual gas in the EBIT, disturbs the mass measurement in the MPET which requires energy spreads of $\lesssim 1$ eV/q. To cool the HCI, we are currently implementing a cooler Penning ion trap (CPET) [9] which is designed to use electron cooling and to explore the feasibility of cooling with cold protons [10].

2. Cooling techniques and implementation

Electron cooling has been successfully used for anti-proton trapping and anti-hydrogen production [11]. The electrons self-cool via emission of synchrotron radiation in a strong magnetic field, but electron-ion recombination is potentially a concern, especially for HCI. Cooling with protons would avoid recombination but the synchrotron radiation mechanism is not available requiring larger amounts of initially cold protons. Extensive simulation studies of electron and proton cooling find that with attainable densities of $10^7$ electrons/cm$^3$ and $10^8$ protons/cm$^3$, $10^3$ HCI with initial energy of $\approx 500$ eV/q can be cooled down to 1 eV/q within a fraction of a second [12]. This is in agreement with findings from simulations [13] for the HITRAP system [14]. For electron cooling there is a window of opportunity to extract the cooled ions before electron-ion recombination becomes dominant.

Figure 2 illustrates the procedure. In the case of electron cooling (left side), electrons are first injected, e.g. by scattering electrons into the trap from a back-reflected DC beam as demonstrated by the RIKEN group [15]. After they come to equilibrium with the (room temperature) surroundings by synchrotron radiation emission, HCI are loaded. As the ions traverse the nested wells filled with electrons they lose energy. For proton cooling (right side), a single shot of protons has to be loaded by raising the trap’s entrance gate. The challenge will be to get enough cold protons into the trap. During extraction, the HCI and protons have to be separated by time-of-flight and/or a $q/m$ separation method.
The need for electron self-cooling via synchrotron radiation at a sub-second time-scale sets the requirement for the strength of the magnetic field. In addition, the homogeneous region of the magnet needs to be sufficiently long to accommodate extended bunches of HCI from the EBIT, and a comparatively large number of electrodes is required to implement the nested potential. A 7-Tesla actively shielded solenoid manufactured by Cryomagnetics Inc. has been purchased. It provides a field homogeneity of $\delta B/B = 10^{-5}$ in a cylindrical region of 100 mm length and 50 mm diameter in the centre, and along the axis, the field is constant to $\delta B/B = 10^{-3}$ over a region of 400 mm. In the 7-Tesla field the electron self-cooling time constant is $\approx 0.1$ s.

The main electrode structure shown on the left side of Figure 3 is a cylindrical trap structure based on a multi-ring trap design. It consists of a large number of ring electrodes with identical inner diameter (35.0 mm) and length (12.7 mm, spaced by 1 mm), 29 rings in total. Two longer electrodes form the end caps of the trap. The trap has two regions with an 8-fold segmented electrode, surrounded by two 2-fold segmented electrodes to facilitate RF excitation, plasma diagnostics, and the application of a rotating wall technique for the electron plasma. Figure 3 shows on the right the already machined electrodes displaying the three different types made from high-purity oxygen-free copper, which have since been gold-plated on a silver backing.

The injection and extraction of two species (HCI and either electrons or protons) and the need to dynamically shape the trap potential during the cooling process requires an elaborate switching scheme for the voltages applied to the electrodes, schematically shown in Figure 4. All electrodes external to the trap (Einzel lens, steerers, electron gun) have to be switched between two discrete voltages, on a relatively slow time scale of 1-5 ms. The trap gates (end caps) have to be raised and lowered within 100 ns. As an economical solution, each electrode will be served by a device consisting of two DC power supplies with a high-voltage switch selecting one of the two voltage levels based on a logic signal from the pulse sequencer. In contrast, the electrodes inside the trap will be driven by a multichannel arbitrary waveform generator to dynamically shape the trap potential within a 0 - 200 V range. As the trap floats on a 2 kV platform, the
Figure 3. A view at the cross section of the trap structure shows the arrangement of the electrodes. HCl and protons enter the trap region from the right and electrons from the left, respectively. The main electrode structure is a multi-ring trap design, consisting of 29 cylindrical ring electrodes. Three types of electrodes, the non-segmented (a), the 2-fold segmented (b) and the 8-fold segmented electrodes (c) are used; the latter allow the application or detection of RF.

waveforms will be uploaded via a fiberlink.

3. Integration into the TITAN facility
In order to extensively explore the CPET without disturbing on-going on-line work at TITAN, it will be initially mounted off-line adjacent to the existing TITAN MPET beamline. It will be possible to slide CPET from this position into the beamline using rails. The off-line setup contains optics and diagnostics needed for studying electron and ion injection as well as the two cooling processes of HCl. Figure 5 shows the components of the off-line setup. Along the pathway for electrons, starting at the left hand side, there is the electron source (a field-emission array) placed off-axis and a quad-split steerer to bring the electrons on axis using an $E \times B$ drift. Just before entering the magnet bore, the electron flux as well as the beam location can be monitored with a microchannel plate (MCP) detector [16], consisting of two plates in a Chevron configuration and a phosphor screen. Electron current readings can be made with a Faraday cup. Another diagnostic tool for electrons is located on the other side of the magnet, where another MCP detector with a phosphor screen detects whether the electrons are still on-axis or off-axis, displaying a donut-shaped ring structure. On the right hand side, an ion source will be mounted to provide protons and heavier singly charged ions. To deliver $10^8$ protons in a single bunch (i.e. with a length corresponding to the round trip time in the trap), a source current of $1.6 \mu$A ($\lesssim 10$eV energy spread) is required. An MCP detector is positioned in front of the CPET. In the fringe field of the magnet, the ions pass a quad-split steerer. After passing the trap, alignment with the nominal beam axis can be checked by using an MCP or a Faraday cup.

The off-line stand was designed in order to test optics and diagnostics, as well as for preliminary studies of cooling techniques. This goal will be achieved in a series of sequential steps. First, electrons will be injected, then trapped and extracted. Subsequently, singly charged ions will be trapped and cooled using electrons as a coolant. After characterizing the process for electrons, the same tests will be attempted with protons. Finally isobaric separation methods will be investigated. Once the CPET system is sufficiently understood, it can be moved into the on-line position on the MPET beamline. HCl will be extracted from the EBIT to ground potential with a nominal energy above $2$ keV-$q$ such that the CPET, which floats on a $2$ kV platform, can accept the complete HCl bunch with the lowest possible kinetic energy.

4. Summary and conclusion
The status as well as the perspectives of the CPET project are presented. At TITAN mass measurements on radioactive isotopes increasingly further away from the valley of stability are performed. To keep the precision sufficiently high we plan to use HCl charge-bred in an EBIT.
Figure 4. (Colour online) The switching scheme. The upper part shows the controls, power supplies and the actual electrodes (not to scale). The requirement for the timescale of the HV switches is indicated by numbers. The graphs at the bottom show sample potentials from the CPET cycle.
Figure 5. Outline of the CPET off-line setup, located adjacent to the TITAN MPET beamline. Displayed are optics and diagnostics that will be used. For electron injection into the trap region from the downstream side, the optical elements are shown above the schematic model – for protons and HCl below. The off-line setup will help to perform proof-of-principle tests before inserting the CPET section into the main TITAN beamline.

The energy spread of the HCl from the EBIT suggests the need for cooling prior to injection into the mass measurement trap. The CPET project will investigate electron cooling as well as sympathetic cooling with initially cold protons. As a first step we will set up the system off-line to explore the cooling techniques before inserting the apparatus into the TITAN beamline.

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References
[1] Blaum K 2006 Phys. Rep. 425 1
[2] Dilling J, Baartman R, Bricault P, Brodeur M, Blomeley L, Buchinger F, Crawford J, Lopez-Urrutia J R C, Delheij P, Pouso M, Gwinner G, De Z, Lee J K P, Moore R B et al 2006 Int. J. Mass Spec. 251 198
[3] Ryjkov V L, Brodeur M, Brunner T, Smith M, Ringle R, Lapierre A, Ames F, Bricault P, Dombsky M, Delheij P, Lunney D, Pearson M R and Dilling J 2008 Phys. Rev. Lett. 101 012501
[4] Ringle R, Brodeur M, Brunner T, Ettenauer S, Smith M, Lapierre A, Ryjkov V L, Delheij P, Drake G W F, Lassen J, Lunney D and Dilling J 2009 Phys. Lett. B 675 170
[5] Smith M, Brodeur M, Brunner T, Ettenauer S, Lapierre A, Ringle R, Ryjkov V L, Ames F, Bricault P, Drake G W F, Delheij P, Lunney D, Sarazin F and Dilling J 2008 Phys. Rev. Lett. 101 202501
[6] Graeff G, Kalinowski H and Traut J 1980 Z. Phys. A 297 35
[7] Marrs R E 1999 Nucl. Instrum. Methods B 149 182
[8] Oshima N, Niigaki M, Inoue M, Kojima T M, Mohri A, Kanai Y, Nakai Y, Komaki K and Yamazaki Y 2004 J. Phys. Conf. Ser. 2 127
[9] Simon V V, Delheij P, Dilling J, Ke Z, Shi W and Gwinner G et al, accepted for publication in Hyp. Int. 2011
[10] Ryjkov V L, Blomeley L, Brodeur M, Grothkopp P, Smith M, Bricault P, Buchinger F, Crawford J, Gwinner G, Lee J, Vaz J, Werth G and Dilling J 2005 Eur. Phys. J. A 25 53
[11] Rohs S L and Gabrielse G 1988 Hyp. Int. 44 233
[12] Ke Z, Shi W, Gwinner G, Sharma K, Toews S, Dilling J and Ryjkov V L 2006 Hyp. Int. 173 103
[13] Zwecknagel G 2006 AIP Conf. Proc. 862 281
[14] Kluge H J et al 2008 Adv. Quantum Chem. 53 83
[15] Mohamed T 2008 Plasma Dev. Oper. 16 181
[16] Wiza J L 1979 Nucl. Instrum. Methods 162 587