A COOLER PENNING TRAP TO COOL HIGHLY CHARGED AND SHORT-LIVED ISOTOPES AT TITAN

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Abstract

The low-energy regime of nuclear physics can provide a tremendous insight into the realm of subatomic physics. Precision mass measurements of short-lived isotopes is one such endeavour that can probe the unitarity of the CKM matrix, test the CVC hypothesis, understand the nucleosynthesis path, nuclear structure and help improve nuclear mass models [1, 2]. TITAN at TRIUMF is a facility where precision mass measurement of short-lived isotopes is carried out. The unique feature of TITAN is the combination of three online ion traps that enables mass measurement of short-lived isotopes with very high precision. Presently an EBIT increases the charge state to improve the precision [3]. However, the charge breeding process causes a large energy spread. Accuracy of measured mass is linearly dependent on charge state, while the increased emittance of the beam has a negative impact on trapping efficiency and hence on precision. To overcome this drawback, a cooler Penning trap has been constructed. The trap is designed to use charged particles to reduce the beam emittance by sympathetic cooling, and it is currently undergoing off-line tests. Working principles and updates on the status of the TITAN cooler trap are presented in this paper.

INTRODUCTION

The TITAN experiment at TRIUMF was commissioned with the goal of investigating nuclear landscape's short-lived members. Production, manipulation and mass measurement of these short-lived isotopes within a very short time span is extremely challenging. Only a few facilities worldwide have the necessary expertise to accomplish this goal [4]. TITAN has measured masses of isotopes with half-lives as short as 8.8 ms (^{11}Li) [5] (and [6] for a list of recent achievements at TITAN). The source of radioactive beam at TRIUMF is a solid target which is bombarded with 500 MeV protons. The Isotope Separator and ACcelerator
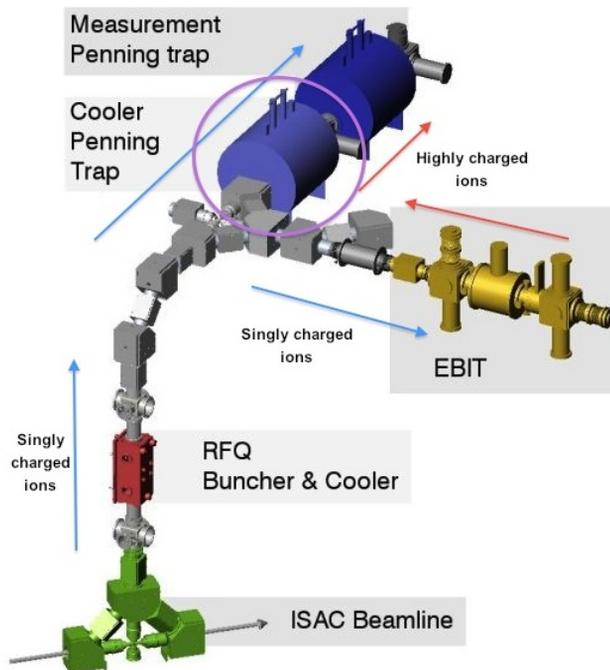
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Figure 1: TITAN beamline. The Cooler Penning trap's final position when included in the beam-line is indicated in the circle.

(ISAC) facility separates the isotopes with a resolution of $m/\Delta m = 3000$ [7]. This continuous beam then enters TITAN's Radio Frequency Quadrupole (RFQ) trap. RFQ is a Paul trap with the facility of sympathetic cooling by He gas. As shown in Fig. 1, for mass measurement of singly charged ions, the cooled and bunched beam is then sent directly to the Measurment Penning Trap (MPET). To perform measurement with highly charged ions, ions from the RFQ are sent to an Electron Beam Ion Trap (EBIT). The charge-bred ions are then sent to MPET for precision mass measurement. The cooler Penning Trap (CPET) will be inserted at the space shown in Fig. 1.

THE COOLER PENNING TRAP

In a Penning trap with magnetic field strength B, if ion motion is excited by applying a radio-frequency potential for time T_{RF} on an ion species with charge q, and N number of ions are used to measure the mass, the uncertainty in mass is given by Eq. (1).

$$\frac{\Delta m}{m} \approx \frac{m}{qT_{RF}\sqrt{N}B}. \tag{1}$$

While increasing precision by means of increased magnetic field (B) is technologically very difficult because of the challenges to maintain the uniformity, the excitation time is limited by the half-lives of the ions. On the other hand, the number of ions (N) is limited by the yields of the radioisotope [7]. The only feasible way to improve the precision is to boost the charge state (q). Another motivation behind charge breeding is that our knowledge of systematic errors is very robust for a certain upper limit of m/q [8]. The charge breeding process facilitates mass measurement of heavier ions by reducing m/q, which implies that the charge breeding is essential for mass measurement of heavier ions. At TITAN this is done by EBIT. Although the charge state is boosted by EBIT, the violent process of charge breeding introduces a huge energy spread among the ions ($10eV/q$) [9]. CPET is a cylindrical Penning trap designed to cool the HCIs and reduce the energy spread by means of sympathetic cooling using either electrons or protons. CPET is comprised of twenty nine gold-plated electrodes made of highly pure oxygen-free high conductivity copper. Figure 2 shows the CPET electrodes assembled with their support structure. Two electrodes have eight segments to facilitate rotating wall compression and cooling (in the inset of Fig. 2, third from the left) while two other electrodes have two segments for isobaric purification (in the inset of Fig. 2, second from the left). Each electrode has a 35 mm inner diameter and is 12.7 mm in length. The whole trap assembly is 400 mm long with a 1 mm spacing between consecutive electrodes [10]. The system is pumped to ultra high vacuum using three 551 L/sec Varian turbo molecular pumps, which are backed by another 70 L/sec turbo molecular pump and a roughing pump. A vacuum of $\sim 10^{-11}$ Torr or better is expected after baking while the current vacuum outside the trap region is $\sim 10^{-10}$ Torr. The trap is housed inside a titanium tube coated with non-evaporable getter (NEG) material and the lowest measured pressure without the trap assembly was below the measuring range of the ion gauges, i.e. below 1.5×10^{-11} Torr. The tube holding the trap assembly is inside a 7 Tesla superconducting magnet with a field homogeneity of $\delta B/B \approx 10^{-5}$ in a region 100 mm along the magnet axis and within a 25 mm radius of the axis. As with any Penning trap, the magnetic field confines the charged particles radially while static electric fields applied to electrodes confine them along the axis of the trap.

Figure 2: CPET assembly and its electrodes on the inset. A Canadian 25 cent coin is shown with the slide callipers.

Working Principles

Sympathetic cooling of charged particles is a well established technique. At CERN antiprotons are routinely cooled by electrons [11]. CPET will use electrons or protons to cool the HCIs. HCI and electrons (or protons) undergo Coulomb scattering and in the process the HCIs lose energy to the lighter particles. However, because of higher electron affinity, for HCIs cooling is more challenging compared to antiprotons as electron-ion recombination will reduce the charge state significantly if the cooling is not accomplished within a certain time window. Considering an ideal condition of a two-component plasma without magnetic field, and defining N_e and N_i to be the number of electrons and ions, respectively (sharing the same volume), the rate at which the electron and ion energy (temperature) changes is given by Eq. (2) and Eq. (3), respectively [12].

$$\frac{dT_e}{dt} = \frac{1}{\tau_i}\frac{N_i}{N_e}(T_i - T_e) - \frac{1}{\tau_e}(T_e - T_{res}), \tag{2}$$

$$\frac{dT_i}{dt} = -\frac{1}{\tau_i}(T_i - T_e), \tag{3}$$

where τ_e is the time constant for electron self-cooling via synchrotron radiation in a magnetic field (which is $\approx$ 0.07 s in a 7 T field [13]), T_e and T_i are the electron and ion energies respectively, T_{res} is the ambient temperature while the time constant for equilibrium in a two-component plasma, τ_i is given by Eq. (4):

$$\tau_i = \frac{3(4\pi\epsilon_0)^2 m_e m_i c^3}{8\sqrt{(2\pi)}n_e q^2 e^4 ln\,(\Lambda)} \left(\frac{kT_i}{m_i c^2} + \frac{kT_e}{m_e c^2}\right)^{3/2}, \tag{4}$$

here, k is the Boltzman constant, m_i is the ion mass, q is the charge of the ion, v_i is the velocity of the ion, n_e is the electron density, and m_e is the electron mass.

In the Coulomb logarithm ($ln\,(\Lambda)$) which carries the appropriate cutoffs for the impact parameters for the electron-ion collision in the plasma, Λ is given by Eq. (5):

$$\Lambda = 4\pi \left(\frac{\epsilon_0 k}{e^2}\right)^{3/2} \frac{1}{q}\sqrt{\frac{T_e}{n_e}} \left(T_e + \frac{m_e}{m_i}T_i + 2\sqrt{\frac{m_e}{m_i}T_e T_i}\right). \tag{5}$$

Similar expressions can be derived for proton cooling [13]. While protons do not self-cool significantly, the advantage

is that there is no decrease of charge states due to electron-ion recombination. However, our initial focus will be to perform cooling of HCIs using electrons. As a result, we will restrict our discussion in this paper to electron cooling.
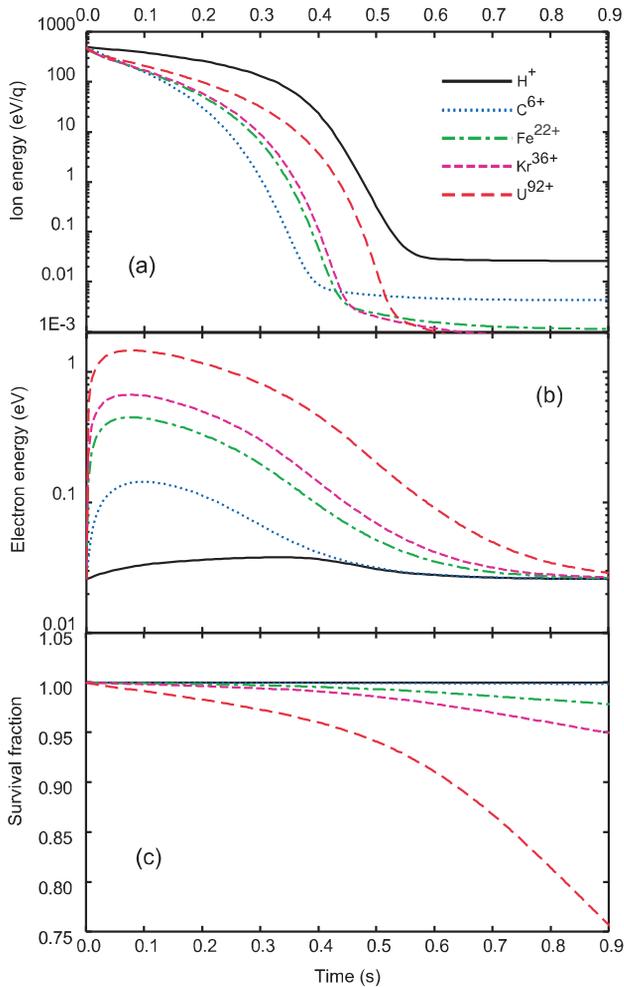

Figure 4: Electron cooling.

CURRENT STATUS

The off-line setup for CPET is complete except for an ion source which is also ready to be installed. Several types of electron sources have been investigated and systematic tests are underway. A TRIUMF made programable pulse generator is used to switch potentials on different electrodes in order to generate a dynamic potential pattern for the different stages of operation as shown in Fig. 4. A LabView interface is currently used to control CPET and its peripherals. As a harmonic potential well ensures longer storage times compared to a square well [15], a resistor chain has been assembled to generate the necessary potential at each trap electrode [16]. For electron trapping, a typical potential profile at different stages are as it is shown in Fig. 5. In the final setup, however, each electrode potential will be adjusted independently. Our methodology

Figure 3: Electron cooling. **(a)** Energy decrease of different ions. **(b)** Electron energy. **(c)** Fraction of ions that survive cooling without undergoing recombination [13].

When working with radioisotopes, it is very important to know time ranges to cool down the ions to a certain energy (T). Simulation of the cooling process for CPET was studied extensively by Ke [13], following the procedure of Rolston, Gabrielse and Bernard [14, 12]. The result from simulations of the electron cooling are shown in Fig. 3. The simulation shows that the ion energy can be reduced significantly within a fraction of second (Fig. 3**a**) without losing too many ions due to ion-electron recombination (Fig. 3**c**). A complete cycle of electron cooling is depicted in Fig. 4. At first the trap will be loaded with electrons which will self-cool via synchrotron radiation. Once the cold electrons are trapped in the so called *nested traps*, HCIs will be injected and trapped. HCIs will undergo scattering with the cold electrons and lose energy which will result in a reduced emittance for extracted HCI beam.
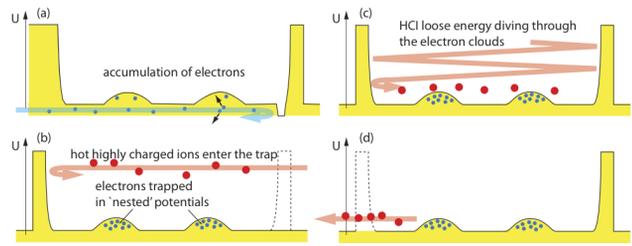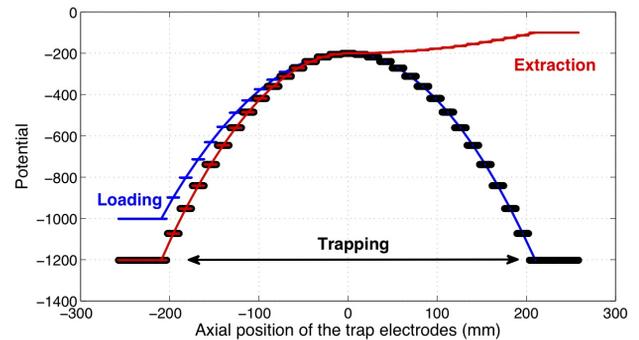

Figure 5: Harmonic potential with resistor.

behind electron trapping is to allow only the electrons that are on axis and with negligible transverse velocity to slip into the trap and reflect back from the opposite end of the trap. While the reflected beam undergoes scattering with incoming electrons, the scattering process causes a reduction in the axial component of electron velocity and thus the electrons remain in the trap. As a result the potential at the entrance has to be adjusted very carefully so that electrons may get trapped by losing some energy because of scattering by the counter-propagating electrons [15].

Results from First Tests with the Electron Source

A prerequisite of successful cooling of the HCIs is to accumulate a high density($\sim 10^7/cm^3$) cold electron

plasma. However, being extremely light weight, the electron's transverse velocity component can easily exceed the critical value to overcome magnetic mirror effect due to the high field gradient which is given by: $\left(v_{e_\parallel}/v_{e_\perp}\right)_{critical} = \left(B_{max} - B_{min}\right)/B_{min}$, where, $v_{e_\parallel}$, $v_{e_\perp}$, are the parallel and perpendicular components of the electron velocity with respect to the magnetic field and B_{max}, B_{min} are the maximum and minimum values of magnetic field. For the first off-line test a Field Emission Tip (FET) was used to test the electron transmission through high magnetic field (7 Tesla) gradient. There is a Farady Cup (FC) on each end of CPET. Electron current is measured at the entrance and exit to investigate the transmission. At first electron current is measured before electrons enter the trap. To test the transmission, the FC at the entrance is withdrawn and electrons are allowed to cross the trap and detected on the other FC. A high transmission efficiency was observed as shown in Fig. 6. The inherent fluctuation of the electron current
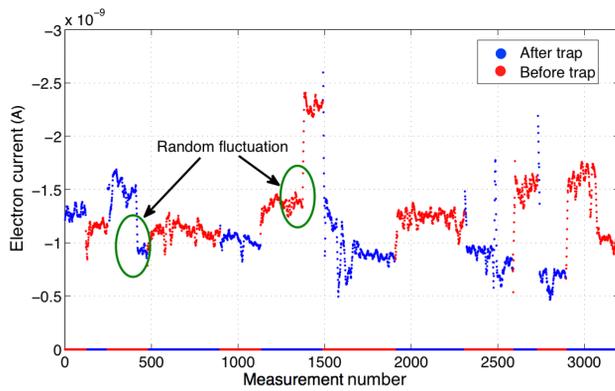

Figure 6: Electrons transmitted through high magnetic field.

only gives a *qualititive* idea of the transmission. Despite the fact that FETs provide a narrow electron beam, they have a number of drawbacks which make them less attractive to be used as a source of electrons in the final on-line experiment. Low current (nA), current instability, long conditioning time and short life span (100s of hours, which requires opening up the UHV vessel frequently) are a few to name. To overcome some of these drawbacks we are currently using a thermionic source. After obtaining a dense electron cloud, the next step will be do trap the electrons in nested traps as shown in Fig. 4.

CONCLUSION

The charge breeding process introduces a large energy spread in HCIs which causes loss of a significant amount of expensive radioactive beam. CPET will improve the situation by providing MPET with an optimized sample of HCIs. CPET will at the same time play a major role in mass measurement, that were previously inaccessible due to the lack of information on systematic errors.

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