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TITAN project status report and a proposal for a new cooling method of highly charged ions

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Abstract. The TITAN facility for precision mass measurements of short-lived isotopes is currently being constructed at the ISAC radioactive beam facility at TRIUMF, Vancouver, Canada. Current status and developments in the project are reported. A new method for cooling of highly charged ions (HCI) with singly charged ions in a Penning trap, critically needed for precision measurements, is presented. Estimates show that the technique is promising and can be applied to cooling of highly charged short-lived isotope ions without recombination losses.

PACS. 07.75.+h Mass spectrometers – 21.10.Dr Binding energies and masses – 32.10.Bi Atomic masses, mass spectra, abundances, and isotopes – 52.27.Jt Nonneutral plasmas

1 Introduction

Determination of the nuclear masses remains one of the fundamental and important quests of nuclear physics. As the focus of the research shifts further away from stability, going to extreme isospin, hence short life-time, it becomes more important to reduce measurement time further and further, while maintaining high accuracy. One way to achieve this goal is to apply high precision Penning trap measurement methods, but reduce the necessary measurement time by using the highly charged ions (HCI). The resolving power of the Penning trap, whose inverse can be interpreted as the precision of a single mass measurement, can be written as

$$R \approx \nu_c T_{\rm rf} = \left(\frac{q}{m}\frac{B}{2\pi}\right) T_{\rm rf}\,, \qquad (1)$$

where $T_{\rm rf}$ is the time of a single TOF measurement, ν_c is the cyclotron frequency, B is the strength of the magnetic field, q and m is the charge and the mass of the measured ion. The short lived isotopes require short measurement times, which reduces the possible resolving power. This limiting factor can be offset by increasing the charge of the measured ion.

HCI mass measurements on stable, heavy isotopes were first explored at the SMILETRAP facility [1] and are a part of an extensive HCI measurement program for the planned HITRAP facility at GSI [2]. The TITAN facility [3] at TRIUMF is the first experimental facility that will exploit this advantage to measure the masses of short-lived isotopes with a planned precision of $\delta m/m \leq 10^{-8}$. It should be noted that the precision of a series of N mass measurements is better than the precision of a single measurement by the statistical factor $\sqrt{N}$.

In addition to mass measurements, the modular structure of the TITAN facility that includes an RFQ buncher, an EBIT charge breeder and a Penning trap, will allow for a wide spectrum of experiments on trapped highly and singly charged ions produced at ISAC (Isotope Separator and Accelerator) and off-line.

One of the challenges of HCI studies is cooling thereof. The electron stripping methods used to produce the HCI in the EBIT [4,5] invariably increase the energy spread and emittance of the produced ions. For precision measurements it is necessary to reduce the energy spread of these ions. The buffer gas cooling method used for singly charged ions in RFQs and Penning traps is not applicable to the HCI, since they would rapidly recombine. Other methods include resistive cooling [6], and electron/positron cooling [7]. In this article we describe a proposal for using the singly charged ions (SCI) to cool highly charged ions.

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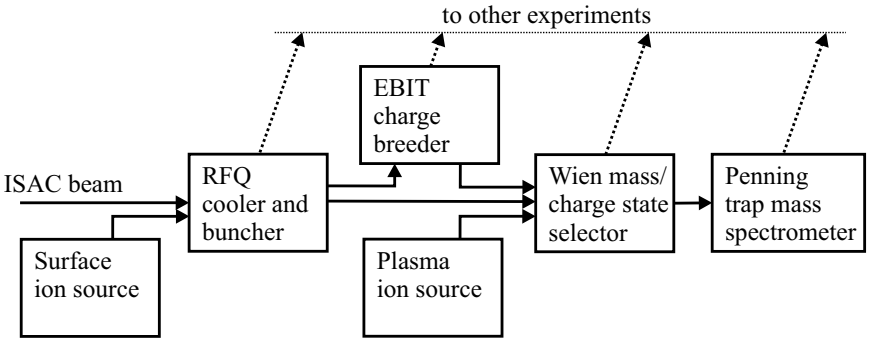

Fig. 1. Block diagram of the TITAN setup.

2 TITAN setup

The overall diagram of the TITAN facility is presented in fig. 1. The radioactive isotopes are delivered from the ISAC ion source by the low energy (30–60 keV) transport beamline. They are first directed into the RFQ cooler and buncher. A pulsed cool beam is sent out of the RFQ either directly into the Penning trap mass spectrometer for experiments with SCIs, or to the EBIT for charge breeding. The second option is a big advantage of this setup. After the charge breeding the HCI can be either studied in the EBIT, or sent to the Penning trap for mass measurements. On the way the HCI are selected according to their charge-to-mass ratio using a Wien filter. There is a capability to add other experiments to the TITAN facility that will be able to accept ions from either the RFQ or the EBIT.

For test purposes we have two different ion sources incorporated into the setup. The RFQ can be loaded with alkaline ions from a 60 keV surface ion source, and also a plasma ion source that can produce a wide variety of different ions at 5 keV energy for tests of the Penning trap mass spectrometer.

2.1 The RFQ cooler and buncher

The first task of the TITAN setup is to accept the radioactive isotope beam (RIB) from ISAC. For that purpose, an RFQ cooler and buncher [8,9] has been designed and built. It improves the beam quality by cooling it with helium buffer gas. The beam is decelerated electrostatically to an energy of a few eV. It is pulled through the area filled with helium buffer gas by a gradient of the DC potentials applied to the RFQ segments. The exit side of the RFQ structure can be closed for beam accumulation, and opened for emission of the bunched beam.

A special cicuit has been designed at TRIUMF, based on fast FET swithes, that can supply square wave rf signal with frequencies up to 3 MHz and amplitudes up to 1 kV, making it suitable for optimal transmission of ions in a large mass range.

The construction of the RFQ is now complete. It is fully integrated into the ISAC standard EPIX computer control system and is currently tested with the surface ion source.

2.2 The EBIT charge breeder

The EBIT will accept the radioactive isotope ions from the RFQ and strip them of most of the electrons. In EBIT, an intense high energy electron beam is compressed in the center of the trap by a strong magnetic field. The electron beam pulls the ions towards the center radially. Along the axial direction the ions are confined by a DC potential well. The major difference of the TITAN EBIT from the previously commissioned EBITs [4,5] is the increase in the electron beam current up to 5 A, compared to typical values of 0.3–0.5 A. This will allow for a faster production of the HCI, which is of high importance when operating with short-lived isotopes.

The TITAN EBIT's 6 T split pair superconducting magnet has been delivered and tested. The 5 A electron gun construction is finished and its comprehensive tests are to be commenced shortly.

2.3 Penning trap mass spectrometer

The Penning trap mass spectrometer system is designed to operate using the well established [1,10] TOF technique [11,12]. The resolving power of such system is given by eq. (1). For unstable isotopes, T_{rf} is limited by the half-life of the ion. The increase of resolving power due to larger magnetic fields is limited by the magnet technology. However, one can immediately see that an increase in resolving power by an order to two orders of magnitude is possible if one is to use HCI. A 4 T high homogeneity superconducting magnet system has been ordered and the design of the various components of the mass spectrometer is underway.

An important issue for the operation of the Penning trap mass spectrometer is the emittance and the energy spread of the ions from the EBIT. It directly translates into signal-to-noise ratio of the TOF spectra. Little is known about the effects that influence emittance of the EBIT, therefore the reduction of the phase space (cooling) of the ions coming out of the EBIT before injecting them into the Penning trap is desired.

3 Cooling of highly charged ions

The ions coming out of EBIT could have the energy spread of up to 50 eV per charge state. For the proper operation of the Penning trap mass spectrometer we need to achieve the energy spread lower than 1 eV per charge. In this section we discuss the known cooling solutions that can be applied to the HCI and propose a new method that is foreseen for the TITAN facility.

3.1 Available methods

The well developed technique of buffer gas cooling is not applicable to the HCI since they will capture the electrons from the buffer gas.

One option is to use electrons or positrons in the Penning trap. These light particles will cool themselves to the environment temperature through synchrotron radiation and cool the HCI via Coulomb interaction. The use of positrons is excluded due to the need for a strong positron source. The electron cooling has been experimentally investigated [7] and is has been evaluated [13] for the HITRAP [2] facility. However, it is only applicable at energies of the HCI higher than 100 eV/q, because at lower energy the recombination rate becomes too high.

The other well developed method is resistive cooling of ions in a Penning trap [6]. The cooling time of this method decreases when the charge state q is increased. However, the requirement to capture the ions with a high energy spread requires the use of a larger catcher trap, and the cooling time increases with the square of the trap size. Additionally, the trap system is currently not cryogenically cold, and therefore prohibits the use of the high quality cryogenic resonant circuits, which further increases the cooling time.

3.2 Proposed ion-ion cooling method

Due to the unique constraints posed by the HCI and the required cooling times, the well-developed methods are not suitable for our purpose at this point. Much like electron and positron cooling methods, our proposed method is based on mixing the HCI into the thermal bath of other charged particles inside a special cooling Penning trap, allowing for energy transfer via Coulomb interaction. In our case we plan to use cold ions (protons) as the bath ions. Unlike electrons and positrons though, synchrotron self-cooling of protons is too slow, and can be disregarded. The protons are to come from the plasma ion source, that can typically produce up to 10 μA of ion beams. We expect a proton beam of at least 10 nA out of this source. The few eV energy spread of the beam will allow the temperature of the proton bath prepared in the first step to be about 1 eV. The proposed cooling method is schematically illustrated in fig. 2.

The DC potential along the catcher/cooler trap axis is envisioned to be a combination of two wells. The bigger well is to contain the bath ions. The smaller well is to accumulate the HCI as they cool down. The catcher trap is initially loaded with protons from the plasma source, while the depth of the main potential well is gradually increased to accomodate larger space charge. The hot HCI are then injected into the trap. They thermalize through Coulomb interaction with the dense proton plasma in the trap and achieve approximately the same temperature as the bath ions. Since the depth of the small accumulator well is proportinal to charge of the ions, it is much more likely to find an HCI ion inside that region than a proton. After the thermalization period the protons will be released from the trap by gradually lowering the trap depth. This way the hottest protons will escape first, effectively cooling the remaining protons and HCIs in the trap (evaporative cooling). Finally, the HCIs are ejected. It is possible that some amount of the coldest protons will be present together with the HCIs in the small potential well. They will be separated in flight by the Wien filter before injection into the measurement Penning trap.

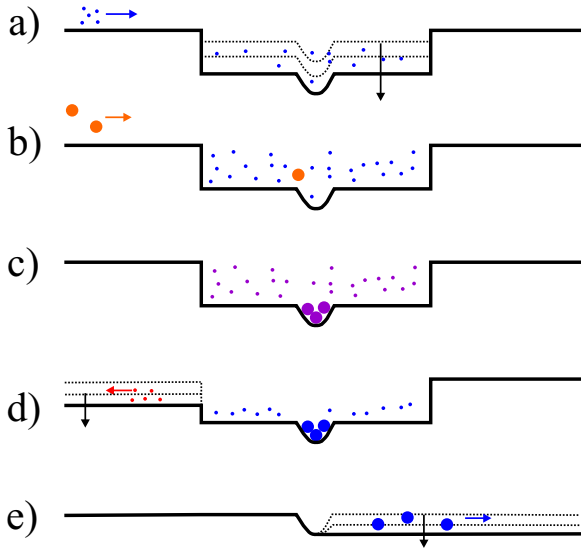

Fig. 2. The step-by-step diagram of the proton cooling method. a) Injection of the proton beam into the cooler trap; b) injection of the hot HCI; c) thermalization of the HCI and bath ions; d) separation of the bath ions/evaporative cooling; e) ejection of the HCI into the measurement trap.

The cooling time of any method applied to short-lived isotopes is of extreme importance. Here we estimate the cooling times that can be reached with this method, based on the Coulomb pair collision picture. It was used by Rolston and Gabrielse [14] to calculate the cooling of (anti) protons by electrons, and, more recently, it was used to calculate the cooling of HCIs by electrons [13]. Here we apply it to the cooling of HCIs by protons. Spitzer has derived a widely used relation giving the thermalization time constant for a two-component plasma of hot (h) and field (b) ions [15]:

$$\tau_{hb} = \frac{3 m_h m_b c^3}{8\sqrt{2\pi} n_b Z_h^2 Z_b^2 e^4 \ln \Lambda} \left(\frac{kT_h}{m_h c^2} + \frac{kT_b}{m_b c^2} \right)^{\frac{3}{2}}, \qquad (2)$$

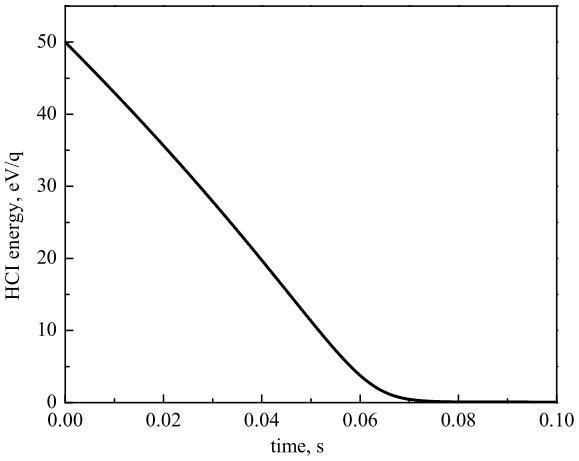

Fig. 3. Time evolution of energy per charge for 10^4 Kr^{36+} ions being cooled down by a cloud of 10^7 protons of 1 eV temperature.

where $m_{h,b}$, $Z_{h,b}$, $T_{h,b}$ is respectively mass, charge, and temperature of hot and bath ions; n_b is the density of bath ions (which should be higher than the density of the hot ions for the expression to be accurate). $\ln \Lambda$ is the Coulomb logarithm, which is the logarithm of the ratio of the smallest and the largest collision impact parameters to be considered. We have employed the same form for the Coulomb logarithm as in ref. [13].

We have calculated the time evolution of the temperatures of bath protons and the injected HCIs, which is governed by the system of two nonlinear differential equations:

$$\frac{\mathrm{d}T_h}{\mathrm{d}t} = -\frac{1}{\tau_{hb}(T_h, T_b)}\,(T_h - T_b)\,, \tag{3}$$

$$\frac{\mathrm{d}T_b}{\mathrm{d}t} = \frac{N_h}{N_b}\frac{1}{\tau_{hb}(T_h, T_b)}\,(T_h - T_b)\,, \tag{4}$$

where $N_{h,b}$ are the numbers of hot and bath ions in the trap.

Figure 3 shows the time dependence for one of the middle range HCI. The number of the HCIs injected into the trap $N_h = 10^4$ is our estimate for a typical number of HCIs in a desired charge state produced by the EBIT. The values of proton density $n_b = 10^7\,\mathrm{cm}^{-3}$, and the total number of protons $N_b = 10^7$ used in the calculation are attainable in a Penning trap. The calculation shows that the HCIs reach the target temperature of 1 eV per charge in under 70 ms, and reach equilibrium temperature of 2.8 eV (0.08 eV/q) in about 100 ms. This example shows that easily achievable densities, numbers, and temperatures of the bath protons are already sufficient to achieve cooling speed fast enough for cooling of HCIs of many short-lived isotopes for precision measurements in the Penning trap. Since the thermalization time scales approximately as m_h/Z_h^2, this method would seem not as powerful for cooling of lighter ions as it is for heavier ones. However, we can easily cool those ions in under 100 ms if the density of the proton plasma stored in the trap is increased. Rotating wall technique allows to reach ion densities close to a fraction of the Brillouin limit (in our case the proton Brillouin density limit is approximately $4 \times 10^{10}\,\mathrm{cm}^{-3}$), and it should be possible to achieve proton densities higher than $10^7\,\mathrm{cm}^{-3}$. In addition, it has been pointed out [16] that expression (2) is not accurate in the case of dense magnetized plasmas. It underestimates the thermalization rate, often by an order of magnitude or more, because in that case the energy is transferred much more efficiently through interaction with the collective plasma modes of the dense plasma. Each of the above factors has the potential to increase the thermalization rate by at least an order of magnitude, which would extend the applicability of this cooling method to the lightest of HCIs and the short-lived isotopes with half-lives of 20 ms or even less.

4 Summary

In this article we have outlined the progress in design and construction of the new TITAN facility at the TRIUMF national laboratory. The components of the TITAN setup are at various stages of completion and the last one (Penning trap) should be operational by the end of 2005. We have also proposed a new cooling technique for preparing hot HCIs for the mass measurement in a Penning trap. The preliminary theoretical estimates show that the proposed method is very promising for many HCI ions, and it will be implemented and studied further.

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