AN ION SOURCE FOR OBTAINING HIGHLY STRIPPED HEAVY IONS

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Abstract

A new technique for the production of highly stripped heavy ions using an extension of the EBIS concept is proposed. In an EBIS configuration, trapping times, charge states, and the yields of high charge states are severely limited because the potential well of the beam gets rapidly filled up and neutralized with a higher density of "unwanted" ions of low charge states which are continuously being formed. It is estimated that the trapped ions will oscillate in the potential well with discrete frequencies proportional to their $\sqrt{e/m}$. By applying external resonant frequencies, it should be possible to throw out the unwanted ions from the well, enabling a selected batch of heavy ions to reach a very high charge state. A high intensity pulsed electron gun system with an ultra high vacuum system has been fabricated to study the technique. Details of the method are described.

1. Introduction

A method of producing highly stripped heavy ions is under investigation at this laboratory. The basic concept used is the same as in the EBIS (electron beam ion source), with suitable modifications to make it practical. The electron beam generates a potential well in which positive ions are trapped, as shown in Fig. 1. Thus the ions cannot escape radially. Positive grids at A and B trap ions axially also. After a containment time τ, the well will get neutralized, and the positive ions will start leaking radially out of the trap. Containment times of the order of a second are required for a trapped ion to receive a sufficient number of impacts with the incoming electrons in the beam to achieve a high charge state of order 25^+. Such a high containment time requires the presence of ultra high vacuum ($\sim 10^{-10}$ Torr). At higher pressures (i.e. 10^{-6} Torr), so many low charge state positive ions (i.e., 1^+ or 2^+) are continuously being formed that the well will get neutralized in milliseconds or less, giving no time for any ion to get 25 or 30 impacts. This is the basic limitation in the present EBIS systems.

A method seems to exist to obtain, in principle, very large containment times at any pressure. Use is made of the fact that the potential well is that of a simple harmonic oscillator in nature, and the trapped ions will oscillate with discrete frequencies proportional to their $\sqrt{e/m}$. Thus by imposing external resonant frequencies, the lower charge states which are continuously being formed in large numbers can be excited and thrown out of the well, thereby increasing the effective well lifetime.

2. Proposed method of increasing containment time

We assume the electron beam is homogeneous in space and pulsed as in Fig. 2. At time $t = t_0$, the well shown in Fig. 3 will be formed. As time increases, some positive ions of charge 1^+ will be formed which will oscillate in the harmonic oscillator potential with frequencies

$$f_z = K.V(t)^{1/2}(Z/A)^{1/2} \qquad (1)$$

where V(t) is the well depth at any instant t, Z = charge state and A = mass number. It is the beam constant and f_z the frequency of an ion with charge state z.

With the passage of time, higher charge states Z = 2, 3 etc. will appear in the well and will oscillate with higher frequencies according to Eq. 1. The relative frequencies are shown schematically in Fig. 4 As the well goes on filling up, the well depth V(t) in Eq. (1) decreases and the oscillation frequencies accordingly slide downwards (shown by the arrows in Fig. 4) towards some frequency f_b.

Two parallel plates across the electron beam (shown in Fig. 3) can be made to introduce an external frequency f_b. Now, as the frequencies of the ions slide downwards, at some time $t = t'$, f_1 will be in resonance with f_b and the 1^+ ions will be excited and "thrown" out of the well. The well depth will remain stationary until all the charge in the 1^+ state has been ejected and replaced by charges in the 2^+ and higher states. This is so because any tendency to decrease the well depth brings f_1 and f_b closer to resonance, increasing the rate of loss of 1^+ ions, which, in turn, causes the frequency pattern to slide up again. After the complete removal of 1^+, the frequencies will slide downwards again until 2^+ is in resonance with f_b and will then start leaking out of the window f_b. This process will continue until all the positive charge required to neutralize the well is concentrated in the highest charge state, when the ion beam must be extracted. To prevent the formation and accumulation of fresh 1^+, 2^+ in the well, whose frequencies will now lie below f_b, the exit frequency window must be wide: between some limits f_a and f_b as shown in Fig. 4c.

The net effect of the exit window is to increase the containment time of the well for the required batch of ions indefinitely, even at relatively higher pressures. Of course, a minimum good vacuum will be required to prevent charge recombination phenomena. For the electron beam parameters of the present system, the ion oscillation frequencies lie in the radio-frequency region. It is proposed to generate the r-f window f_a-f_b using a VCO (voltage controlled oscillator) modulated by a low frequency saw tooth voltage sweep.

3. Estimation of ion source parameters

Some useful order of magnitude expressions can be derived indicating the interdependence of various ion source parameters. The well depth Vo(volts) is related to the electron current and energy by $Vo = 480\ I(A)/E^{1/2}(keV)$ and at $t = t_o$, Eq. (1) can be put in the form

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$$f_z = \frac{48.3\ I^{1/2}}{R_o\ E^{1/4}} \left(\frac{Z}{A}\right)^{1/2}\ \text{MHz} \qquad (1b)$$

where I = electron beam current (amperes)
R_o = beam radius (mm)
E = electron energy (keV).

3.1 Neutralization time

When an electron passes through a gas, the number of collisions per cm of its path length is given by

$$N = S \cdot P \qquad (2)$$

where P = pressure in Torr and S is a factor depending on the electron energy E and the nature of the gas traversed. Fig. 5 shows the measured value of S as a function of electron energy for various gases at 1 mm Hg. pressure[1].

Let the electron current be I(A) and electron energy E(keV). Then the non-relativistic speed of the electrons is given by

$$u = 1.875 \times 10^9\ E^{1/2}\ \text{cms/sec}\ . \qquad (3)$$

The number of electrons per unit length at any instant is

$$N = I/eu = 0.33\quad 10^{10}\ \frac{I(A)}{E^{1/2}\ (keV)}\ . \qquad (4)$$

Let the mean free path of an electron be λ. From (2)

$$\lambda = \frac{1}{SP} \qquad (5)$$

Let the well lifetime, without any external frequency perturbations, be T seconds. The number of electrons crossing any plane in T secs. is

$$N = 0.624\ \times\ 10^{19}\ I(A)\ T(sec) \qquad (6)$$

All these electrons suffer a collision in one mean free length λ. If the well is to be neutralized in T sec., the total number of ionizing collisions (ions) over a length λ in T seconds should be equal to number of electrons present in the beam at every instant over λ. Thus equating (4) and (6) and using (5), the neutralization time T is given by

$$T = \frac{0.53 \times 10^{-9}}{SP(Torr)E^{1/2}(keV)}\ (sec)\ . \qquad (7)$$

Conversely, to get a containment time T, the minimum pressure required is

$$P = \frac{0.53 \times 10^{-9}}{SE^{1/2}\ (keV)\ T(sec)}\ (Torr)\ . \qquad (8)$$

If T $\sim$ 1 sec, E = 10 keV, and using argon for which from Fig. 5, S $\sim$ 0.5, then from Eq. (8), P = 3.3 $\times$ $\times\ 10^{-10}$ Torr.

However, if the unwanted ions are thrown out continuously as described in Section 2, relatively higher pressures can be used to achieve the same neutralization time.

3.2 Containment times

The minimum containment time τ_z required to produce a charge state Z can be calculated by summing over the partial ionization times

$$\sum_{i=1}^{z} \tau_{i-1\to i}$$

$$\tau_z = \frac{e}{j_e} \sum_{i=1}^{z} \frac{1}{\sigma_{i-1\to i}}$$

where $\sigma_{i-1\to i}$ is the ionization cross section for the ion to go from charge state (i-1) to i and j_e the electron beam density. This has been done by various authors[2,3]. The containment time required for stripping an atom to a charge state Z for various elements have been shown in ref. 2 for j_e = 100 A cm^{-2} and E = 10 keV. For uranium, E = 10 keV and $j_e \sim$ 10 A cm^{-2} $\tau(25^+)$ is of the order of 1 sec.

3.3 Ion current estimates

When the well is neutralized, the positive charge formed will be equal to the instantaneous electron charge in the beam over the length of the source. If L(cm) is the length of the ion source, and τ(sec) the required containment time, then from Eq. (4) the positive ion current yield is given by

$$I^+ = \frac{0.53 \times Ie\ (A)\ L(cm)}{E^{1/2}(keV)\tau(sec)}\ (nA)\ . \qquad (9)$$

For a system of our type, $I_e \sim$ 2 A (i.e. $j_e \sim$ 10 A cm^{-2}) for 10 keV and L = 100 cm. If $\tau \sim$ 1 sec for 25^+, then $I^+ \sim$ 33 nA. At GeV energies, this would represent substantial beam power. Higher positive ion current yields can be obtained by using coresponding higher electron beam density guns.

3.4 Recombination of ions

The positive ions formed can recombine either with the neutral gas atoms or the slow secondary electrons. The ion-neutral recombination rate depends on the number of collisions between the ions and neutral gas atoms and is sufficiently low at P = 10^{-8} Torr.

Due to the magnetic field, the slow electrons are constrained to escape axially only. The recombination rate[4] is

$$\frac{dN}{dt} = \rho_e\ N^+N^- \qquad (10)$$

where the recombination coefficient $P_e \propto P^{1/2}$ and for singly ionized argon, $P_e \sim 10^{-7}$ at 15 mm Hg pressure for 0.03 eV slow electrons[5]. If S $\sim$ 0.5, P $\sim 10^{-8}$ Torr and E $\sim$ 10 keV, then from (7)$\Delta T \sim$ $\sim$ 33.6 m sec. In this neutralization time, the number of positive ions ΔN produced per unit length is $\sim 2 \times 10^9$ for I = 2 A in Eq. (4). Thus the rate of slow electron production per unit length $\Delta N/\Delta T \sim$ $\sim 6.10^{10}$, i.e., each unit length of the beam acts as a current source of order 10^{-8} A. Even if these slow electrons have thermal energies ($\sim$ 0.03 eV), then from

Equ. 3 their velocities are high (∿ 107 cm/sec). From (4) with $I_{slow} \sim 10^{-8}$ A and E ∿ 3.1 -5 keV, the instantaneous density of slow electrons along the beam is $N^- \sim 6.10^3$/cm, with $N^+ \sim 10^{10}$ per cc at the time of neutralization. Thus with $P_e = 2.6 \times 10^{-12}$ at 10^{-8} Torr, dN/dt is negligible from Eq. (10), even if P_e increases as Z^2.

Thus, recombination may not be a serious problem at P = 10^{-8} Torr. We note that recombination is also compensated for by the methods of Section 2.

3.5 Effect of the magnetic field on ion frequencies

If a weak axial magnetic field is used to guide the electron beam, the ion frequencies in Fig. 4 will undergo a Zeeman type of splitting and so we may include a term of order ±0.76 B(kG)Z/A(MHz) in Eq. (1b).

4. Experimental set-up

The experimental equipment fabricated to test the techniques described earlier is shown schematically in Fig. 6. The principal subsystems are the ultra high vacuum system and the pulsed electron gun system. The vacuum system consists of two cryo-absorption pumps A and B (Fig. 6) which create a fore-vacuum of ∿ 10^{-3} Torr. The sputter ion pump C is then switched on and brings the pressure down to ∿ 10^{-6} Torr. The system above the table is bakable up to 400°C. After the bakeout the 4" orbitron pump D is switched on and this brings the pressure down to the 10^{-9} Torr region. All these pumps are currently being fabricated by the Technical Physics Division of this centre.

The electron gun system F is based on a Klystron gun design under development at the Tata Institute of Fundamental Research, Bombay. It uses a nickel matrix cathode G heated by a tungsten filament. The electrons are focussed by Pierce electrodes H. I is the beam dump. The design parameters of the present gun are 500 mA electron current at 10 kV with the beam cross-section of about 5 mm diameter. Efforts are underway at TIFR to increase the present beam current. K and L are the high voltage and filament feedthroughs for the gun. M is a solenoid magnet for keeping the electron beam focussed. N is a small mass spectrometer to sample the charge states produced, and utilizes the field of the solenoid. Because of the limited space available within the solenoid, a "cycloidal mass spectrometer" configuration using a crossed electric and magnetic field was adopted which offers high resolution for relatively small orbits and large energy spreads.

5. Conclusions

The existence of "characteristic" frequencies in the potential well for different ion species, which may be excited, is necessary for the working of the "resonance" electron beam ion source (REBIS) system described above. However, the REBIS SYSTEM seems practical and has the advantages of working at gas pressures higher than in the EBIS and concentrating all the positive charge required to neutralize the well in the highest charge state only. Our first experiments will be directed towards searching for the "characteristic" frequencies of the ions in the well. We are grateful to our colleagues in the Technical Physics Division here for providing the technology of the ultra high vacuum system and to our colleagues in the TIFR, for providing the design of the electron gun system.

References

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2) J.D. Daugherty et al. Proc. Part. Acc. Conf. IEE Trans. Nucl. Sci., June 69 NS-19, 2, 125

3) R. Becker, et al. IEEE, April 72, NS-19,2

4) Ref. 1, p 156.

5) Ref. 1, p 161.

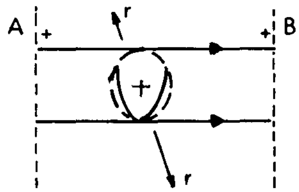

Fig.1 Generation of the potential well in the cross section of the beam.

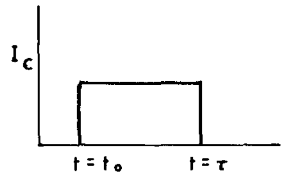

Fig.2 Time variation of the electron beam pulse.

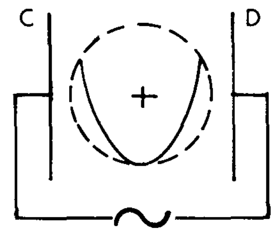

Fig.3 Cross section of the beam showing the potential well. CD are two parallel plates put across the beam.

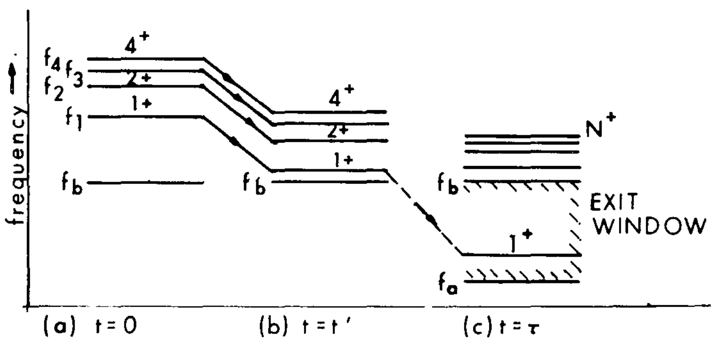

Fig.4 (a) Characteristic frequency levels for different ion species $f_Z \propto (Z/A)^{1/2}$. (b) As time increases, the frequencies slide downwards towards f_b. (c) ion species with frequencies entering the exit window $f_b f_a$ are thrown out of the well.

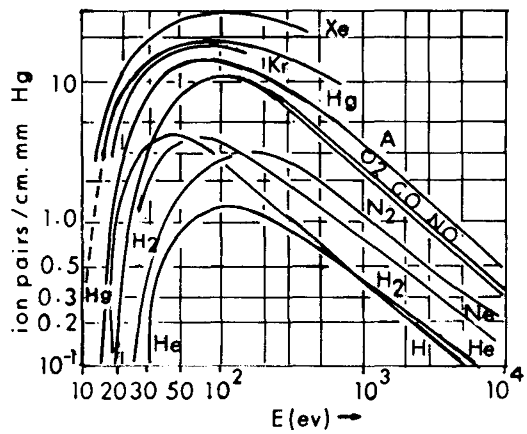

Fig.5 Variation of the ionisation efficiency S with electron energy E for different gases.

Fig.6 Schematic diagram of the experimental set-up.

A,B-sorption pumps
C-Sputter ion pump
D-orbitron pump
E-B.A gauge head
F-electron gun
G-nickel cathode
H-Pierce electrodes
I-Beam dump
J-ion source region
K-high voltage feedthrough
L-filament feedthrough
M-solenoid magnet
N-cycloidal mass spectrometer
V_1 to V_5-isolation valves
O-gas input