TRAPPED ION SOURCE

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Abstract

In this paper it is shown the design and the mechanical construction of a Trapped Ion Source (TIS). TIS is a new type of source capable, in principle, of producing very highly charged ions and, at the same time, it is a radio frequency quadrupoles linear trap suitable to study the interaction of the trapped ions (or charged microparticles) with electrons, high energy particles or laser beams. In practice, it is a modified version of an Electron Beam Ion Trap (EBIT) recently developed in some laboratories mainly to study X and UV rays spectroscopy for "hydrogenic" and "helium-like" ions. Among the goal of TIS, other than the production of highly charged particle, it can be foreseen the production and trapping of radioactive isotopes, ion cooling, analysis of macromolecules and also "dust targets" for high energy accelerators.

1 INTRODUCTION

The ability to produce very highly charged ions in a small laboratory apparatus at a small fraction of the cost of producing them at a large accelerator represents a great opportunity. In fact new EBIT are being built in several laboratories around the world, and the initial operation of two of them has recently been reported [1].
Highly charged ions play important roles in hot plasmas physics, controlled fusion devices and x-ray lasers.
Production of a very highly charged ion is extremely difficult, requiring successive collisions having center-of-mass energies greater than the binding energies of the electrons to be removed. One can achieve such type of collisions either by directing a relativistic heavy ion beam from a large accelerator into a stationary foil target or by directing an electron beam a thousand folds less energetic into a stationary ion target. The latter method is used in an EBIT. Although the EBIT was initially developed for X-ray measurements of trapped ions, one can change its mode of operation to provide an efficient source of very slow, very highly charged ions.
In this paper we present the design and the construction of a Trapped Ion Source (TIS) that can be seen as a modified version of an EBIT and an EBIS. One can foresee that TIS could overcome some drawbacks of the EBIT and EBIS making it a more flexible device. In fact an EBIS presents the following problems:
In an EBIS (or EBIT) a continuous electron beam is used to produce and contain the ions. The highly charged ions can be obtained by electron bombardment ionization in two different ways:
i) single-step ionization
ii) multi-step ionization
i) in the single step-ionization the incident electrons must have an energy of at least the sum of all the ionization potentials of the removed electron;
ii) in the multi-step ionization, for the incident electrons, it is required only the energy of each electron removed from the atom or ion.
The multi-step ionization process is, greatly, the most probable way to obtain high charge state ions [2] but this process, of course, takes time. This time depends on the plasma density and on the ionization cross-section. It must be shorter than the ion life-time in the plasma if one wants obtain significant number of highly charged ions.
As an example, one can consider the effective cross sections for sequential ionization of a given element by electron impact, $\sigma_{k\to k+1}$, then the ionization time can be given by

$$\tau_i = \frac{1}{j}\sum_{k=1}^{Z-1}\frac{1}{\sigma_{k\to k+1}}$$

where j is the electron current density and Z is the ion charge state.
Applying this equation, to generate N^{+7} with a current density of $1.8X10^{20}$ el/cm^2/s (30 Amp/cm^2) at an energy of 3 keV, an ionization time of 50 ms is obtained. Such a long ionization time, requires a residual gas pressure of 10^{-10} - 10^{-11} Torr (very high pressure) in the trap region. In fact only under these conditions the replacement of working gas ions by the residual gas can be practically excluded, and the ionization will be effective. In other word the potential well generated by the electron beam must not be leveled by the ions issued from the background gas. This problem imposes very high density electron beam to reduce the interaction time and the residual gas pressure constraint [2]. On the other hand the use of high density electron beam can induce plasma instabilities [3].
In fact the other problem related is the ion losses. Three possible ways for losing the highly charged ions are: a) transverse ejection (due to elastic collision with the continuous eb); b) electron recombination (that in this condition can be neglected [2]); c) plasma instabilities (that prevent the increase of eb density and of the ion trap length).
In TIS the utilization of a rf quadrupole field to contain the ions in a selective way allow to use a pulsed electron beam and in this way these kind of problems could be overcome (see below).
Applications that can be foreseen for TIS are in the following.
1) Development of cooling methods and eventually production of Wigner crystals. Most of the existing ion traps are of the static type. Cooling can be also applied in large storage rings, where ordered forms of relativistic ions

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can be obtained. TIS is designed mainly to allow cooling experiments on ion groups in slow controlled linear motion. The ions will be contained in a potential well nearly flat in the longitudinal direction, with potential barriers of a few keV at the extremities, while the rf quadrupole field produces a transverse harmonic potential. Several forms of filtering can select the trapped ion type, since by suitable bias TIS works as quadrupole mass spectrometer, or by pulsing some electrode it can work as a time of flight spectrometer in the longitudinal direction.
2) Dating with Long Lifetime Isotopes (LLI). The method of dating with isotopes of long lifetime (e.g. C^{14}) has been used for many years by measuring the residual radioactivity of the specimen to be dated. However the method is insensitive and time consuming, since only a very small fraction of the nuclei to be detected decay during the measurement. More recently the atoms to be detected were accelerated with tandem accelerators, fully stripped, and their charge verified by magnetic analysis and by nuclear detectors. The ability to highly strip and isotopic selection with different methods allows to TIS a similar performance using much less expensive apparatus.
3) Use as a target for high energy ion or particle beams. TIS can suspend powder particles or macromolecules that can be exposed to a high energy ion beam. The molecular recoil can be detected, allowing the measurement of very low energy loss and momentum transfer.

2 ION SOURCE DESIGN

In fig.1 is shown the operation scheme of the device. In that figure one can see the electron gun that generates the electron beam needed to ionize the atoms. Since an electron gun designed and built for another experiment is intended to use for TIS experiment a couple of iris are been used to match the electron beam emittance to the acceptance of the TIS transport channel.

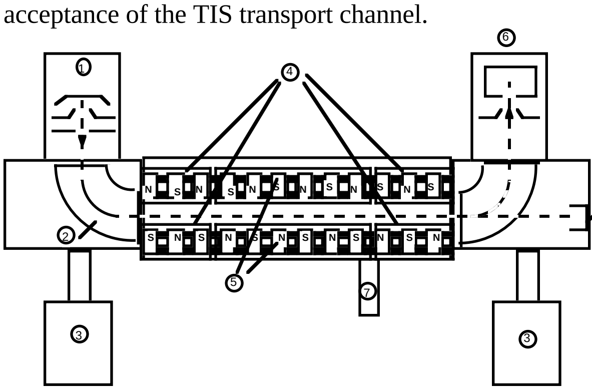

Fig.1 Operation scheme of TIS: 1) electron gun, 2) bending magnet, 3) vacuum pump, 4) static potential electrodes U_0 for longitudinal ion trapping, 5) rf quadrupole electrodes with inside the focusing magnetic quadrupoles, 6) electron collector, 7) gas-inlet, 8) ion collector.

The transport channel that drives the beam until to the electron collector and the electron beam envelope is shown in fig.2. The main new feature of TIS, with respect to an EBIT (or EBIS), is the adding of radial ion confinement of the rf quadrupoles to the potential well of the eb space charge when it is on. When the eb is off (the eb will be pulsed) only the desired ions will remain trapped.

2.1 Ion confinement

The ion containment in the transverse direction can be obtained by a rf quadrupole field or by the same electron beam needed to produce ions (like in a EBIS or EBIT). In the longitudinal direction the containment is obtained by two repelling electrodes placed at the edges of the quadrupole electrodes. These electrodes can be pulsed to pull-out the trapped ions for external use (e.g. acceleration).
In TIS The rf radial ion confinement is obtained by applying a time varying potential to the rf cylinder shaped electrodes. This results in a harmonic pseudo-potential well of the form [4]:

$$\Phi_p = \frac{qV_0^2}{4m\varpi_{rf}R^4} r^2 = \frac{m}{2q}\Omega^2 r^2 \qquad \text{with } \Omega = \frac{qV_0}{\sqrt{2}m\omega_{rf}R^2}$$

where R is the radial position of the cylinder shaped electrodes (fig.1), and V_0 is the voltage amplitude applied. Ω is, of course, the oscillation frequency in the radial direction of the trapped ions. The condition to be satisfied for the formation of a pseudo-potential well is: $\Omega \ll \omega_{rf}$.
In fig.2 are shown the depths of the pseudo-potential well, at 1 cm from the axis, for different ion mass and different ω_{rf} values. In those figures the pseudo-potential well has been put to zero when the previous condition on the "secular" frequency Ω was not satisfied.

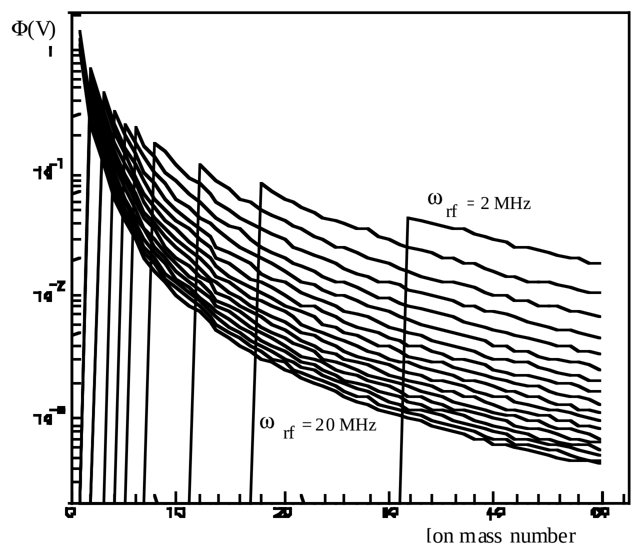

Fig.2 Potential well depth *vs* ion mass numbers at 1 cm from the axis for different rf frequency.

As mentioned before in the EBITs the ions are contained transversally from the eb space charge and longitudinally from the potential set by the electrodes on the edges. In this situation residual gas ions can be trapped together with the wanted ions. In this way all these ions can easily fill the pseudo-potential well and then reduce the ion containment capability.
In order to avoid this drawback a pulsed electron beam will be used in such a way that the transversal ion containment

is maintained only by the rf quadrupoles. In this way by adding to the rf field a continuous quadrupole field it is possible to select the ion type to be contained in the pseudo-potential well (as is done in a common mass spectrometers). In meanwhile, the slow electrons generated form successive ionization's are swept away because the rf period is much less than the electron transit time of the quadrupole field. For this reason multipacting phenomena should be avoided.

In this condition the stable (trapped) ion trajectories , in both planes, are given by the Mathieu equation solutions). From these solutions , one can see that, once fixed the rf and the continuous quadrupole potential, the stability region for the ion trajectories depends only on the charge to ion mass ratio [5].

As an example, one can take an ion mass number A= 40, it has a charge to mass ratio (for one charge) e/m_A = $2.4X10^6$, fixing ω_{rf}=6 Mhz , V_0=100 V and U=7 V, the stability region obtained for e/m_a is in the range $2.4X\ 10^6$-$5.4X\ 10^7$, then, this ion can be ionized for 20 times (e/m_A=$4.8X10^7$) and remain in the stability region.

For the confinement along the longitudinal axis a static voltage U_0 is applied to the electrodes placed at the edges of the quadrupole electrodes in the longitudinal direction (see fig.1). It can be seen that the radial potential well is slightly weakened by the axis potential U_0 [4]. In its normal operation, an electron beam pulse is injected transversally in the trap and then bent in the axial direction. Transversally, in the center of the trap, gas, vapor or powder jet can be injected by a valve, then it is ionized and confined by the rf quadrupole field.

The ion extraction will be done by changing the axial static voltage U0 (on the left of the trap) to a negative value to eject the ions towards a Faraday cup placed on the axis to collect the ions (about -100 V).

The rf quadrupoles electrodes have a cylinder shape that approximates near the symmetry axis the pure quadrupole field generated by hyperbolic shape electrodes. An optimization of this approximation, given for a particular ratio between the distance from the axis and the cylinder radius, is shown in fig.4, where a value of A_4/A_6 = 2.7x 10^4 has been found for the ratio of the Fourier quadrupole coefficient with the sextupole coefficient. The other multipole fields Fourier coefficients are practically negligible.

2.2 The electron beam transport channel

The electron beam will be generated by an electron gun with a Pierce design originally built for an electron cooler and then modified for our needs. To get a pulsed electron beam the first electrode will be connected to a Bloomlein type pulser. The density electron current obtained in the simulations is about 80 mA/cm^2 with a perveance of 0.11 μP. The couple of iris have a radius of 2mm and are placed at a distance of 210 mm to give at gun exit an emittance of about 50 mm x mr. To make the operation more easy, the gun cathode is set at high voltage and the transport channel at ground.

From the exit of the gun the electron beam will be transported till the collector trough two 90° electron bending magnets (BM) and a new kind of magnetic quadrupoles (see below) inserted inside the rf quadrupole electrodes. The eb envelope in the horizontal and vertical plane along a 1 m long transport channel is shown in the computer simulations of fig.3. The BM curvature radii are 95 mm, The Quadrupole gradient values are symmetric with respect the center of the transport channel.

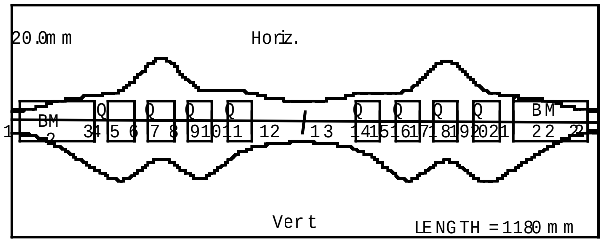

Fig.3 Beam envelope transportation along the trap, from the entrance of the first bending magnet to the entrance of the electron collector. The central region is the trapping region.

A mechanical design of the new type of magnetic quadrupoles that we think to utilize for the eb focusing is also shown in fig.1. This quadrupoles will be built by turning four iron bars, alternating a section of larger to one of smaller diameter. Around the smaller ones are wound the excitation coils with alternating polarity from coil to coil.

After the second bending magnet the eb will be decelerated and then recovered by a collector placed at a voltage about 1kV less than the high voltage of the gun cathode to recover all the electrons.

3 CONCLUSION

The mechanical design and the computer simulations of the device has been concluded. The vacuum chamber, the electron gun, the electron collector and the cylinder shaped electrodes for the rf quadrupole field are already available.

The construction and the test of the new type focusing quadrupoles for the eb are under way.

In the first phase of the experiment pick-up electrodes will be used as sensors for the electromagnetic signals given by trapped ions and in a second phase they will be used to apply a stochasting cooling to the trapped ions.

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