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Analysing the Charge Distribution and Transmission of Carbon and Oxygen in Nitrogen Gas using Tandem Accelerators

Meetha Lal Meena*
Department of Physics, Dyal Singh College, University of Delhi, New Delhi 110 003, India

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This study presents a comprehensive analysis of ion beam transmission and charge state distribution in a tandem accelerator, focusing on the effects of caesium temperature, terminal voltage, and stripper gas pressure. Negative ions ($12C^{1-}$ and $16O^{1-}$) were accelerated and stripped of electrons, resulting in a beam of positive ions having distinct charge states. The energy of these ions was governed by their charge state and terminal voltage (V_T). In transmission of incoming carbon and oxygen ions ($12C^{1-}$ and $16O^{1-}$), which exhibits a maximum with pressure in non-equilibrium region, stripper gas pressure is discovered to have a more intriguing influence than charge state distribution. Our results demonstrate that optimal transmission is achieved within a stripper gas pressure range of 50–70%. At low pressures, we observe non-equilibrium charge state behavior, while at higher pressures, our data quantitatively agree with Schiwietz *et al.*'s empirical model for equilibrium average charge. These findings provide valuable insights for the observed transmission of carbon and oxygen ions behaviour through the tandem accelerator.

Keywords: Accelerator, Ion beam, Charge distribution, Stripper gas pressure

1 Introduction

Tandem accelerators are widely employed for producing energetic positive ions of elements for material science research. The energetic ions have numerous uses, including surface modification, doping, and implantation. These applications are crucial for ion beam analysis, materials science research, and the manufacturing of semiconductor devices. In this study, we optimize multiple parameters to maximize ion beam current while also understanding the operation of 1.7 MeV tandem accelerator. In order to do this, we looked into how ion source operated and how ion beam was transmitted through a high-voltage column. To investigate their impact on ion beam current, a number of parameters were changed, including terminal voltage, stripper gas pressure, lament current, ion source target voltage, and temperature of the caesium oven. The tandem linear accelerator produces positively accelerated ions of various charge states[1]. Its high terminal voltage (V_T) ranges from 200 to 1700 kV. In this tandem accelerator system, negative ions with energy V_n are extracted from an ion source (SNIC), analyzed in an MPI magnet, and then injected into the tandem accelerator, which accelerates ions in two stages. First, injected negative ions are accelerated up to centre of accelerator, where these ions are stripped of one or more electrons through a charge exchange process on collision with a small amount of N_2 gas. Where ionization and excitation occur in bullet itself as well as in target, which goes through excitation, electron loss, and capture.

Charge state distribution of ions is dependent on velocity and atomic mass of ions, and atomic number of stripper target. Cross-section and energy for charge exchange depend on ion energy and ion charge. Consequently, ion beam's average charge varies when target thickness is increased further. State of equilibrium is achieved when average charge and distribution of charge state fractions remain constant following a sizable no. of collisions. Achieving an equilibrium charge state distribution, incident ions must collide with enough targets through a minimum target thickness. Ion's nuclear charge and incident ion velocity (energy) are main factors influencing the equilibrium average charge. The ion beam of carbon and oxygen ions in N_2 gas determines charge state[2,3] distribution and transmission of different energy ranges (0.5-1.3) MV. This study focused on effect of stripper gas pressure (at HE of acceleration column) on transmission and charge state distribution of carbon (12C) and oxygen (16O) ions stripped in N_2 gas in tandem accelerator. Such ion beams were used in numerous material science investigations where the incident ion energy ranged from 0.5 to 1.3 MV[4-6]. We

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*Corresponding author: E-mail: meethalal.physics@dsc.du.ac.in

have performed a critical comparison at different stripper gas pressures between our experimental average charge (q_{avg}) and equilibrium average charge expected by empirical formula created by Schiwietz *et al.*[7] Effect of gearbox (N_2) pressure (That measured pressure of nitrogen N_2 gas in the stripper canal section of the accelerator) from stripper gas is investigated in energy range of current research. We demonstrate that a target can transition from non-equilibrium (e.g. Defined as the conditions where the incident ions have not yet undergone sufficient collisions to reach a stable (equilibrium) charge state distribution) to equilibrium in response to variations in stripping gas pressure. There is also report and discussion of fraction charge state (F_q) distribution at non equilibrium and equilibrium target thicknesses (caused by pressure variations).

2.1 Tandem Accelerator

A high-energy ion beam is obtained using accelerator. An accelerator is a tandem accelerator, meaning it accelerates an ion twice using the same voltage. The primary accelerator tube of a tandem accelerator is segmented and has both ends grounded. Insulators are used to keep some pellets apart. With the core pallet at 1.7 MV, subsequent pallets have higher potentials. Beam's polarity switches to positive when it collides with high-energy gas as soon as it crosses the central pallet. It is then repelled by middle pallet, which speeds it up even further. Consequently, beams with energy up to 3.4 MeV can be obtained using this tandem accelerator. Sulfur Hexafluoride (SF_6) is maintained in order to maintain such high voltages because air degrades at high volts (dielectric breakdown). SF_6 gas can be compressed to 7 bars using a certain unit. An ensemble of electrostatic magnetic lenses, capable of delivering up to 20 kV, is used in the accelerator tube to focus a beam. These lenses have a focal length of two to three meters. In order to use the accelerator effectively, numerous beamlines are necessary, and it is costly. As preparations are being made, experiments can be conducted by directing the beam towards the chosen beamline using a switching magnet. Two dedicated beamlines with parallel plates for adjusting the beam direction are available in the lab for Rutherford backscattering and microbeam studies. When ambient radiation levels exceed permitted thresholds, an online Geiger counter shuts off. The turbo-molecular pumps are used to create a vacuum for ion beams, which operate similarly to jet engines. The annexe was erected to accommodate the microbeam system, which consists of a centimeter-wide beam that is focused down to micrometres.

2.2 Stripper Gas Pressure Calibration

The stripper gas pressure was precisely regulated using a high-accuracy leak valve system, ensuring stable and reproducible gas flow into the interaction region. Pressure measurements were performed with a capacitance manometer, which was carefully calibrated prior to each measurement cycle to maintain accuracy. The reported 50%–90% range corresponds to relative values on the gas flow control unit rather than absolute pressure readings. However, this range has been empirically correlated with the target pressures required to achieve specific charge exchange probabilities, making it a reliable reference for optimizing the stripping process during the experiments.

The stripper gas pressure was controlled with a precision needle valve and metered with a calibrated capacitance manometer. Pressure was adjusted to obtain values of 50% to 90% of the maximum operational range. The Supplementary Information provides a detailed description of the calibration technique and confirmation of pressure settings.

3 Experimental Procedure

3.1 Source of Negative Ions by Cesium Sputtering (SNICS)

SNICS ion origin generates (-)ve ions by sputtering a target material (e.g., metal) with an intense beam of primary ions (Fig. 1). Negative ions are produced in an SNICS source when caesium bottle (Cs reservoir) is heated. Through a pipe, Caesium reaches ion chamber and collides with spherical ioniser, which is maintained at positive voltage with respect to cathode and at a temperature of about 120 degrees. After

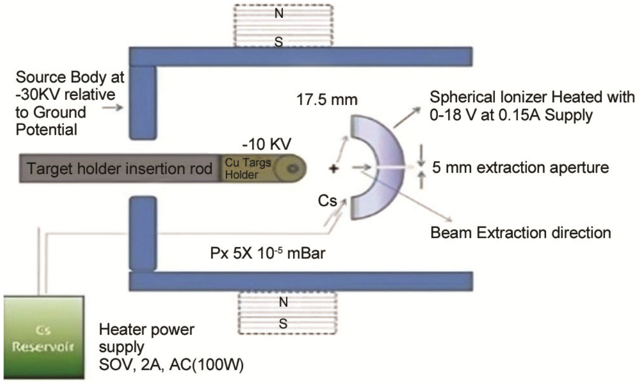

Fig. 1 — A source of negative ions by cesium sputtering (SNICS) source generates the negative carbon and oxygen ions, which are then removed from the source chamber by applying a 30 kV voltage

losing an electron, a specific number of Cs atoms transform into positive ions, which are subsequently focussed and repelled by electric field to collide with target. A thin layer of neutral caesium is produced as caesium vapors condense on target's surface as it cools. Few atoms of target material emerge to surface as a result of collisions inside target (sputtering). Majority of target atoms that make it to the surface are charge-free. Furthermore, atoms of sputtered material turn negative after exchanging an electron with neutral caesium as they pass through Cs layer. Following their repulsive action from cathode potential, these negative target ions accelerate in direction of positive ionizer. In order to further accelerate the negative beam to the extraction electrode's ground potential (-20 to -30 kV), the ionizer has a center hole that is roughly 8 mm in diameter. Energy of outgoing beam is 40keV.

3.2 Negative Ion Beam in Accelerator Tube

Negative ion beam (carbon, oxygen) enters the MPI magnet, where mass and charge selection take place. The beam passes through the MPI magnet, is bent by 90 degrees, and then negative ion beams are extracted from the source by an electric field applied into the tandem accelerator tube. In the tandem accelerator, the ion beam accelerates in two steps. In an accelerator, a positive high voltage is applied at midpoint, and initial point is grounded. The negative ions move towards positive voltage. The ion beam passes through the stripping media, where negative ions change to positive ions. The endpoint of an accelerator is grounded. Positive ions are repelled by positive high voltage and attracted by the ground potential of the other end. Emerging accelerated positive ions with different charge states q have positive energy. $\mathrm{E} = [\mathrm{V_n} + (\mathrm{q}+1)\mathrm{V_T}]\mathrm{MeV}$, where Vn is energy of injected negative ions and terminal voltage ($\mathrm{V_T}$) in (MV)[1]. Hence, energy of accelerated ions depends on charge state. The high voltage is achieved in the Cockcroft-Walton type cascade generator, consisting of capacitors and rectifiers. The ion beam now consists of positive ions with various charge distributions. These positive ions are then accelerated towards the other end HE (high-energy end) of accelerator at ground potential. Ions with different charge states having different energies pass through accelerator tube of tandem accelerator. Average charge of outgoing beam is a function of $\mathrm{q_{avg=\,qF_q}}$. The fraction of charge state is calculated by $\mathrm{F_q} = \frac{\mathrm{N_q}}{\sum \mathrm{N_q}}$, where $\mathrm{N_q} = \frac{\mathrm{I_q}}{\sum \mathrm{q I_q^-}}$ is normalised no. of particles and has charge state (q) of outgoing beam.Two Faraday cups, designated FC1, FC2, FC3, and FC4, are utilized to measure the incident and outgoing beam currents, respectively

2.3 Faraday Cup Working and Calibration

A switching magnet separates several charge states of positive beam. Faraday cup is a device that measures ion beam current of charged particles (Fig. 2). Ion beam is incident on Faraday cup, and a bias voltage is applied on the Faraday cup, which gauges current of an ion beam. Beam current in various charge states was measured in FC-3 port that was connected to ladder target at a 20-degree angle. Following the MPI magnet, FC1 Faraday cup position's negative ion beam current was measured. When switching magnet is off ion beam current is calculated at the FC-4 port. Faraday cups were calibrated with a known proton beam current. Electrostatic shielding, correct grounding, and reproducibility tests over several experimental runs all helped to reduce systematic mistakes. The beam current measurement error is predicted to be ±5%.\

4 Results and Discussion

To optimize the beam current through SNICS source, we measured the intensity of the negative ions at FC-1 as a function of Cs temperature. The data plotted in Fig. 3 measures ion yield for C, O, and H. We can see in the Fig. 3 an exponential dependence for negative C ions, whereas for O and H, the yield is almost linear. The exponential behaviour for negative C can be attributed to the nonlinear dependence of Cs vapor yield on heater temperature.

The ion beam is optimized at FC-3 for positive ions of carbon and oxygen. The ion beam yield for C^+ and O^+ ions as function of terminal voltage at given stripper gas pressure(at 80%). Terminal voltage defines energy of ions before collision with stripper

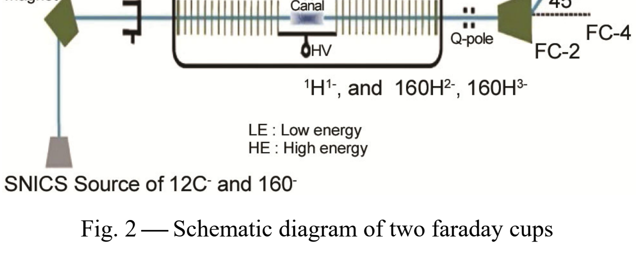

Fig. 2 — Schematic diagram of two faraday cups

gas. Cross section for projectile ionization and electron capture processes depends on velocity of the colliding particles. Thus, shape ion yield at different terminal voltages is a measure of relative dominance of competing ionization and capture processes for a given collision system. As shown in Fig. 4, the C^+ and O^+ ion beam yield is maximum at 700 keV and falls steadily at higher terminal voltage.

When the switching magnet is in on state, ion beam bends by 20 degrees, and ion current of different charge states (carbon, oxygen) is calculated at FC-3 ladder target. Ion beam current is measured for three terminal voltages (0.5, 1.0, 1.3) MV by changing stripper gas pressure.

4.1 Carbon Ion Results

The C^+ results are now primarily discussed in the context, which shows the variation in Cq^+ ion beam current across different stripper gas pressures and terminal voltages. Stripper gas pressure is an important parameter which controls final charge state distribution of ion beam, as shown in Fig. 5. Stripper gas pressure was changed in percentage (50% -90%). The data for C^{q+} ion beam yield as function of stripper gas pressure. One can see that at lower pressure, the ion yield is dominated by the lowest charge state and contribution of higher charge state component increases with increase in stripper gas pressure.

4.2 Oxygen Ion Results

The O^+ results are separately analysed and highlighting differences in ion yield. Experimental data plotted in Fig. 6 for O^{q+} ion beam yield as a function of stripper gas pressure. General behavior is same as earlier we see a drop in overall ion yield at higher gas pressure 90%, which is due to higher probability of charge neutralization.

In Fig. 3, we have compared our experimental work with the theoretical findings published by O. Tarvainen *et al.*[8]. We investigated the relationship between Cs temperature and the intensity of negative ions. It has been demonstrated that ion beam currents increase with increasing Cs temperatures. Our investigation revealed that the cesiated converter electrode causes enhanced sputtering of $1H^{1-}$, $12C^{1-}$, and $16O^{1-}$ when the vapour pressure of caesium increases.

We examine the ion beam current in Fig. 4 and analyze impact of terminal voltage on ion beam within energy range of 300 KV to 1700 K. Incoming charge state, stripping energy, and stripping medium all affect maximum value and width of charge state q = +1 that results from stripping process, which has distributions resembling exponential decay. But in

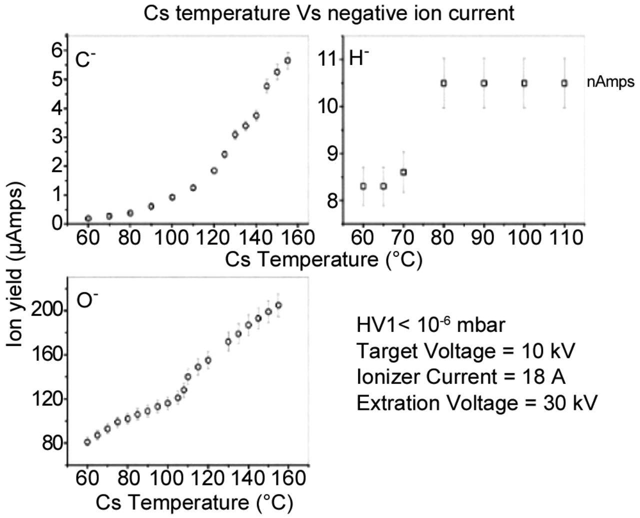

Fig. 3 — The ion beam current is dependent on Cs temperature and measurement at the FC-1 port for negative ions (carbon, oxygen, and hydrogen)

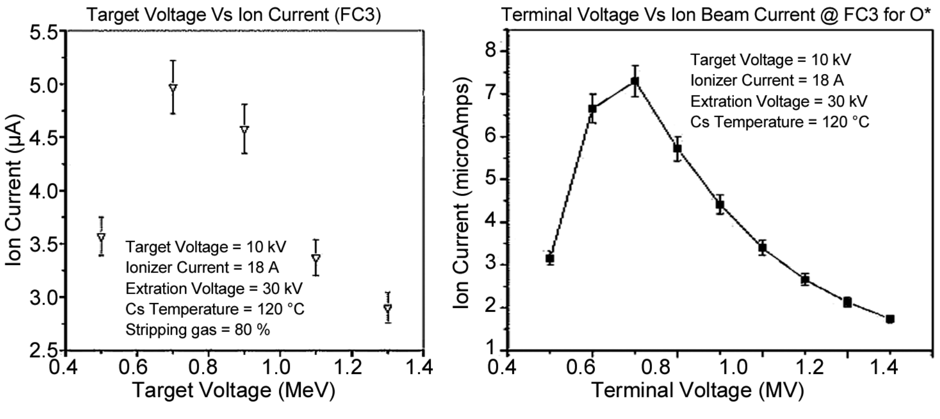

Fig. 4 — The ion beam current depends on the terminal voltage, the ion beam current measured at FC-3, when switching magnet in the off state

Fig. 5 and 6 we have seen that higher charge states q = +2,+3,+4 that are produced during the stripping procedure, have distributions that resemble Gaussian curves. We have observed that numerous scatterings of ions moving through gaseous medium cause alteration in mean square scattering angle. As a result, in residual gas of HE (High Energy End) acceleration column of tandem accelerator, various charge states created in stripper canal will experience elastic scattering in different ways. Gas left over in high-energy end (HE) column will cause more scattering to occur in lower charge states. For a amount of charge state q = +1, change in ion beam current is greatest. Thus, for higher charge states q = +2, +3, +4 ion beam current is not exactly same as distribution for charge state q= +1 in outgoing beam in a tandem accelerator. As a result, in outgoing beam of a tandem accelerator, distribution of ion beam current for charge states q = +1 differs slightly from that of charge states q = +2, +3, and +4.

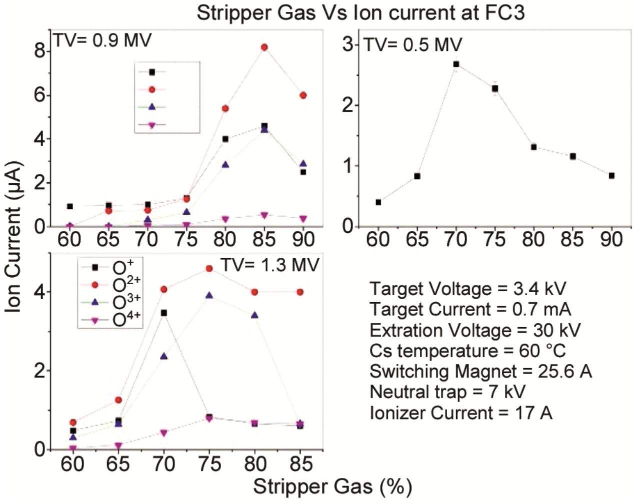

Fig. 5 — The C^{q+} ion beam current is measured for three terminal voltages (0.5, 1.0, 1.3) MV by varying stripper gas pressure

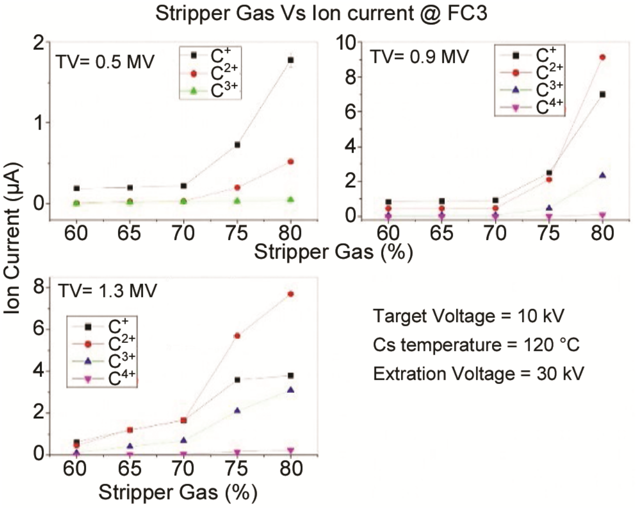

Fig. 6 — The O^{q+} ion beam current is measured for three terminal voltages (0.5, 1.0, 1.3) MV by varying stripper gas pressure

Theoretical and semi empirical formulations developed at different phases by Bohr, Betz, Dmitriev, and Nikolaev can be used to predict the equilibrium average charge state of energetic ions stripped in both solid and gaseous mediums[9-11]. An enhanced empirical formula for the equilibrium average charge of stripped ions in N_2 gaseous media was created by Schiwietz *et al.*[12]. We directly compared the equilibrium average charge expected by recently derived empirical formula by Schiwietz *et al.*[12] with our experimental average charge (q_{avg}) at distinct stripper gas pressures. The average charge at equilibrium is written as Eq 1.

$$q_{avg} = Z_P \frac{x^6+376x}{1428-1206x^{\frac{1}{2}}+690x+x^6} \qquad \dots (1)$$

where

$$x = \left[\frac{V_p}{V_0}\, Z_t^{\,0.03-0.017\, Z_p^{-0.52}\, \frac{V_p}{V_0}}\right]^{1+(\frac{0.4}{Z_p})}$$

The experiment focuses on the impact of pressure at stripper canal on the transmission of incident ions. Stripper canal experiences minimal charge-changing collisions due to the 10^{-6} mbar pressure between the acceleration tube and beam line. Most of the beam entering the stripper canal is negative ions, and charge-changing collisions occur there due to stripper gas raising target density. Transmission of incident $12C^{1-}$ and $16O^{1-}$ beams with various positive charge states is estimated using normalized fractions (N_q). Greater values of experimental average charge compared to expected value for incident ion energy below 1MeV are due to an increased number of neutrals at low energies, which are not considered in the calculation of the qavg experimental value of charge state[13]. Experimental setup used for study only considers charged carbon ions and oxygen ions of outgoing beam. Therefore, to calculate F_q we utilize Eq 2:

$$F_q = \frac{N_q}{\sum N_q} \qquad \dots (2)$$

where,

$N_q = \sum Nq,$

q is from 1 to 4

However, with low incident ion energy, the departing beam will contain a considerable number of neutral carbon atoms, which should be considered when determining proportion of distinct average charge and charge states. We match Schiwietz's empirical value of average equilibrium charge ($q_{emp-avg}$) with average charge formula that includes neutrals, i.e., as stripper canal pressure increases from 50% to 80% for C^{q+} and 50% to 80% for O^{q+}. According to the calculations, raising stripper gas pressure to achieve greater charge state fractions in outgoing beam will significantly increase gearbox costs. In Fig. 5 and Fig. 6, transmission declines with energy at non-equilibrium target thicknesses in energy range (0.5- 1.3) MeV. High-energy transmission side of accelerator decreases in this range because of high velocity of incident ions and low target thickness, which allows many incident $12C^{1-}$ and $16O^{1-}$ ions to escape stripper medium without colliding with anything that changes charge.

5 Conclusion

Within this work, we have compiled the experimental findings regarding impact of Cs temperature, terminal voltage and stripper gas pressure on incident $12C^{1-}$ and $16O^{1-}$ ions stripped in N_2 in tandem accelerator within energy range (0.5-1.3) MeV. Transmission of ion beam current and stripper gas pressure are used to determine single to 5 electron loss and capture cross sections for 12C and 16O in N_2 gas, terminal voltage range of 0.5 - 1.3MeV for positive charge states 1 to 4. A small change in Stripper gas pressure has a noticeable effect on average charge in equilibrium range. Transmission analysis demonstrates maximal transmission of incident ions occurs at desired value of terminal voltage and stripper gas pressure. Analyzing and transmitting charge state distributions can help maximize use of tandem accelerators for high-current applications.

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