NUCL SCI TECH (2017) 28:64
DOI 10.1007/s41365-017-0211-1

The charge state distribution of B, C, Si, Ni, Cu and Au ions on 5 MV pelletron accelerator

Ali Awais[1] · Javaid Hussain[1] · Muhammad Usman[1] · Waheed Akram[1] · Kashif Shahzad[1] · Turab Ali[1] · Ishaq Ahmad[1] · Malik Maaza[2,3]

Received: 19 April 2016 / Revised: 23 September 2016 / Accepted: 7 October 2016 / Published online: 29 March 2017

Abstract Stripper gas and terminal potential play a key role for the charge state distribution in a tandem pelletron accelerator. The knowledge of this distribution is important for experiments performed on tandem accelerators. The charge state distribution of B, C, Si, Ni, Cu and Au beams is measured by using Ar as stripper gas, and terminal potential is varied from 0.3 to 3.0 MV on 5UDH-2 tandem pelletron accelerator installed at the National Centre for Physics, Islamabad. The individual charge state is measured after the switching magnet at 15° in high-energy portion. It is observed that the higher charge states are stable in the range of lower and middle atomic masses of periodic table, whereas higher atomic mass (Au) shows beam current instability in higher charge states. For carbon, the charge distribution at 1.7 MV terminal potential by varying stripper gas pressure is also studied, which resulted in decreased overall transmission with good current value for higher charge states.

Keywords Pelletron accelerator · Charge state distribution · Stripper gas · Terminal potential

✉ Ishaq Ahmad
ishaq@ncp.edu.pk

1 Experimental Physics Laboratories, National Centre for Physics, Islamabad 44000, Pakistan

2 UNESCO-UNISA Africa Chair in Nanosciences/Nanotechnology, College of Graduate Studies, University of South Africa, Muckleneuk Ridge, PO Box 392, Pretoria, South Africa

3 Nanosciences African Network (NANOAFNET), iThemba LABS-National Research Foundation, 1 Old Faure Road, PO Box 722, Somerset West, Western Cape Province 7129, South Africa

1 Introduction

Pelletron accelerators are used in today's materials science research, e.g., ion beam analysis, ion implantation, materials modification and radiation testing [1, 2]. In a pelletron accelerator, a negative ion beam is produced and extracted with some initial energy in keV range. This negative beam is then attracted by central terminal of pelletron tank, which is kept at a positive potential of several MV. When the beam reaches at the center of high voltage terminal, some electrons of the negative ions are stripped off to make them positive, and this positive beam is repelled by high positive potential. Stripping can be done either by foil stripper or by the introduction of a kind of gas at low pressure. Due to degradation of the foil stripper with time, the transmission through it changes constantly. On the other hand, gas stripper remains the same all the time under the same experimental conditions. The ion beam, which leaves the stripper medium, consists of different charge states depending on the number of electrons stripped off. The energy of these ions is calculated as $eV(q+1)$, where V is terminal potential, e is electron charge and q is the charge state acquired. The charge state distribution depends on terminal potential and stripper gas pressure. Previous studies on charge state distribution have been performed with energy variation effects on charge states for Be, Cl, Al, Ti, Ni and C ions on various accelerators around the world [3–8].

In this paper, we measure the charge state distribution of B, C, Ni, Si, Cu and Au beams on 5UDH-2 pelletron accelerator installed at the National Centre for Physics [9], Islamabad, Pakistan, so as to qualify our system for measuring the charge state distribution of different beams using Ar as target stripper gas. The knowledge of charge sate distribution is important since beam with higher charge state of an element can have greater energy than lower charge state at the same terminal potential of the machine. The charge state distribution with varying terminal potential (0.3–3.0 MV) is measured while making the stripper gas pressure at constant value. The advantage of choosing terminal potential is that we can cover a good range of energy especially with higher charge state at 3.0 MV potential. A range in atomic mass of elements in the periodic table is covered while studying the behavior of higher charge states, i.e., B, C and Si are low mass elements, Ni and Cu lie in middle range and Au is higher mass element. The stripper gas pressure effect on charge state distribution is studied, too, while keeping terminal potential constant. The results depict that the higher charge states are stable for B, C, Si, Ni and Cu, but some fluctuation are observed in the higher charge states of Au. In the case of C beam, with increasing stripper gas quantity and constant terminal potential, it is also observed that the higher charge states are more preferable but overall transmission of the beam is decreased.

2 Experimental setup

The accelerator has two beam lines at 15° and 30°. The 15° beam line is being used for ion beam analyses such as Rutherford backscattering spectroscopy (RBS), elastic recoil detection analysis (ERDA), nuclear resonance analysis (NRA), and particle-induced X-ray emission (PIXE), as well as ion beam irradiation for material modification, whereas the 30° beam line is dedicated for nuclear cross-sectional measurements of various materials [10].

Schematics of the accelerator setup with 15° beam line is shown in Fig. 1. The negative ion beams are produced by SNICS source and are extracted with initial energy of 61 keV. The beams are then bent to 45° using analyzing magnet (Fig. 1) and injected into pelletron accelerator. The initial current of negative beam is measured at Faraday cup FC2. The negative beam enters stripper housing after passing through accelerating tube.

In stripper housing, Ar gas is allowed to enter into stripper canal at low pressure by opening the gas stripper valve. The gas stripper valve is operated remotely in the control room. The pressure of Ar gas in stripper line, sized at Φ11.5 mm × 966.6 mm, is measured by a thermocouple gauge. Two turbo molecular pumps (navigator TV301) are installed diametrically opposite at stripper housing, used for recirculation of the Ar gas, and create a pressure at the center of stripper canal. Equilibrium between the incoming and recirculation gas is maintained after some time. Opening the stripper valve and switching on the turbo molecular pumps creates a small thickness in $\mu g/cm^2$ of Ar gas at center of stripper canal. The pressure in accelerator tube is measured by the ion gauges at both ends of the accelerator tank. The stripper gas pressure can be estimated indirectly by measuring the increase in pressure at the two ion gauges with increasing stripper gas quantity [8].

The positive beam consisting of all charge states leaves the accelerator tank from high-energy side, and the current is measured at FC 3. Switching magnet bends the accelerated ion beams to the 15° beam line and the current is measured at FC 4.

3 Results and discussion

3.1 Stripper gas thickness measurement

It is difficult to calculate the stripper thickness precisely. It can be estimated by modeling the gas flow through gas lines and stripper canal itself [11]. An alternate way of measuring the stripper gas pressure is to measure the pressure on high-energy and low-energy ion gauges [8]. We have measured the stripper thickness by making a simple assumption. If the average pressure in stripper canal is considered to be one-third or one half of the pressure measured on thermocouple gauge and the effective canal length is assumed to be 100 cm, then the results for stripper gas thickness will be approximately of right order of magnitude. For example, if thermocouple gauge reads the value of Ar gas at 10 µm, then actual value of the pressure

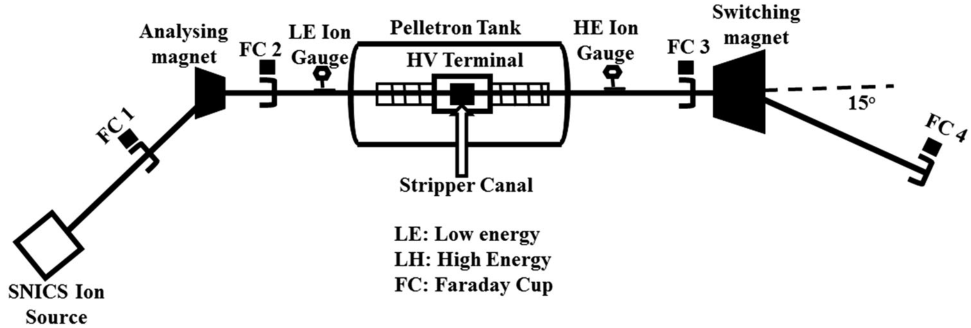

Fig. 1 The schematic diagram of the pelletron tandem accelerator 5UDH-2. The total beam current is measured at FC 3, and the individual beam current is measured after switching magnet at FC 4

will be about 14 µm. This is because according to thermocouple gauge calibration charts it may read up to 40% low for Ar gas. Using above assumption, the average pressure in stripper canal is 7 µm. The density of Ar gas at STP is 40 g per 22.4 L or 1786 µg/cm^3. Therefore, at 7 µm pressure the density is 0.016 µg/cm^3. So the stripper thickness (density × effective length) in 100 cm effective length would be about 1.6 µg/cm^2.

3.2 Charge state distribution

NCP accelerators are utilized for different types of scientific experiments including ion irradiation/implantation and ion beam analysis. Therefore, it is of utmost importance to have a detailed knowledge of charge state distribution of different available ion beams. In this perspective, the charge state distribution of ^{11}B, ^{12}C, ^{28}Si, ^{59}Ni, ^{63}Cu and ^{197}Au ion beams is measured as a function of terminal potential while stripper gas thickness is maintained at approximately 0.6 µg/cm^2.

Figure 2 shows the charge state distribution for ^{11}B with Ar as stripper gas at equilibrium pressure. The +1 charge state decreases with increasing terminal potential, and in terminal potential range 0.3–1.2 MV +2 charge state is dominating while for 1.3–1.8 MV range +3 is dominating charge state. We have also observed good current in 1.5–1.8 MV range for +4 charge state.

Figure 3 shows the charge state distribution of ^{12}C and ^{28}Si as a function of terminal potential with Ar as stripper gas at equilibrium pressure. Here again +1 charge state decreases with increasing terminal potential, +2 is dominating charge state in 0.3–1.2 MV range, and +3 is dominating charge state in 1.3–3.0 MV range. The +4 charge state has shown good current in 2.5–3.0 MV range, and +5 charge state shows reasonable current in 1.5–3.0 MV range for Si beam and in 2.5–3.0 MV for C beam.

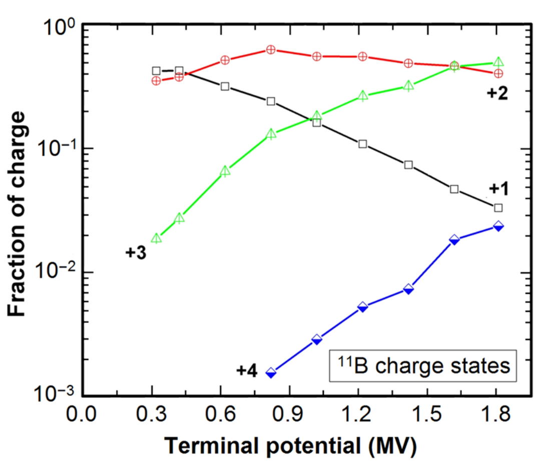

Fig. 2 Charge states distribution of ^{11}B beam as a function of terminal potential. The stripper gas is at equilibrium with thickness of ~0.6 µg/cm^2

Figure 4 shows the charge state distribution for ^{59}Ni and ^{63}Cu. In both cases, +1 charge state decreases with increasing potential, +2 charge state is dominating in 0.7–2.0 MV range, +3 charge state dominates in 2.0–3.0 MV range, and +4 and +5 charge states also have good currents in 1.5–3.0 MV range. A reasonable current is observed for higher charge states as well.

Figure 5 shows the charge state distribution for ^{197}Au. The maximum limit of switching magnet in our accelerator is 1.4 T. So the calculated fields for +1 charge state from above 0.7 MV terminal potential and in case of +2 charge state from above 2.0 MV are beyond these limits. The +3 and +4 are dominating charge states in 1.5–2.5 MV range. The +5, +6 and +7 are showing good currents in 1.0–2.5 MV range. For higher charge states, some fluctuations are observed for Au ions due to unknown reasons.

It seems that there are systematic trends: The beam transmission losses are largest at the lowest and at highest energies. It means, at a given terminal potential, the higher the charge state, the greater will be the energy for a pelletron machine; so for the higher charge states the energy will be higher and for lower charge state the energy will be lower. At low energies, the deviation could be assigned to scattering losses or caused by neutral particles. At the highest energies, the losses might be related to the ion optics. The small angle scattering in the stripper canal can lead to significant beam losses especially at low energies. The transmission through a tandem accelerator also depends on the optics. The losses due to the ion beam transport are related to the focusing properties of the acceleration tubes and following optical system (e.g., magnet and lenses) and depend therefore on the selected charge state.

Figure 6 shows the charge states distribution of ^{12}C, ^{28}Si, ^{59}Ni and ^{63}Cu at 3.0 MeV. The +2 is dominating charge state for all beams, while the +3 is also dominating for C and Si. In Fig. 7, the charge state distribution for C is observed with varying stripper gas pressure while the terminal potential is fixed at 1.7 MV. The stripper gas thickness varies from 0.4 to 1.4 µg/cm^2. The best results are obtained at 0.6 µg/cm^2. The +3 charge state is in good agreement with the measured data previously [5].

The error calculated between different measurements of same beam is approximately within 5%. In case of Au at higher charge states, the error is increased to 10%. This error includes statistical error and error due to slight variations in stripper thickness. The error has also been developed because of different vacuum and operating conditions.

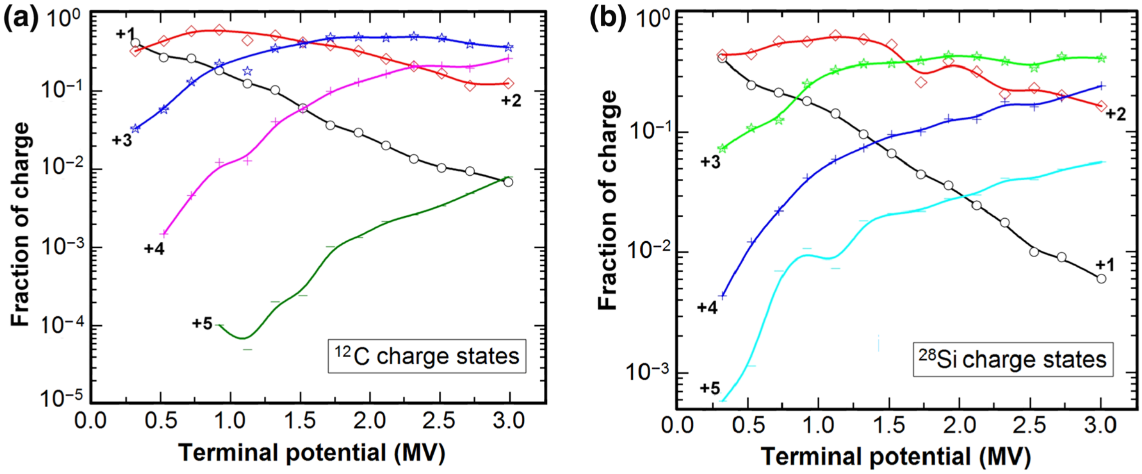

Fig. 3 Charge states distribution of ^{12}C (**a**) and ^{28}Si (**b**) beams as a function of terminal potential. The stripper gas is ~0.6 μg/cm^2 at equilibrium

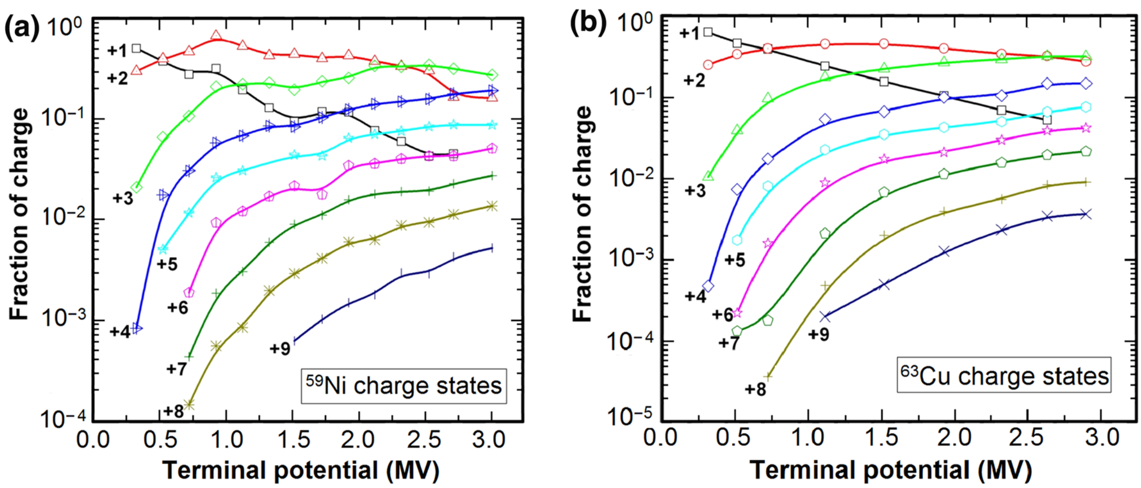

Fig. 4 Charge states distribution of ^{59}Ni (**a**) and ^{63}Cu (**b**) beam as a function of terminal potential. The stripper gas is ~0.6 μg/cm^2 at equilibrium

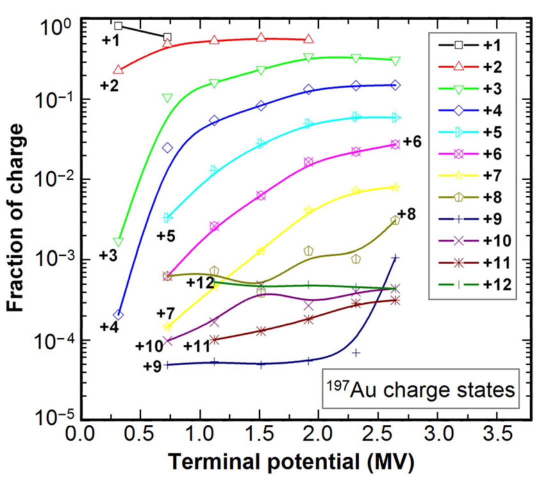

Fig. 5 Charge states distribution of ^{197}Au beam as a function of terminal potential. The stripper gas is ~0.6 μg/cm^2 at equilibrium

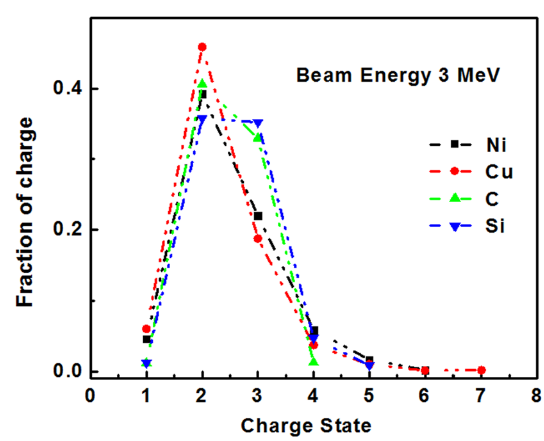

Fig. 6 Fractional distribution of charge states measured at 3.0 MeV beam energy and stripper gas thickness 0.6 μg/cm^2

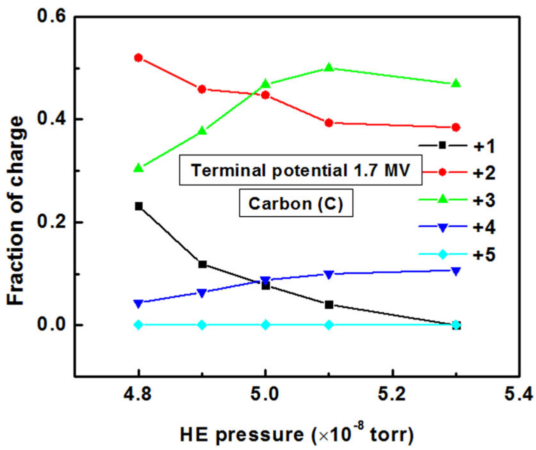

Fig. 7 Effects on fraction of charge with increasing stripper gas pressure while making the terminal potential fix at 1.7 MV. HE pressure shows the reading on high-energy vacuum gauge. The stripper thickness varies from 0.4 to 1.4 μg/cm^2

4 Conclusion

In this report, we have qualified our system for charge state distribution of different beams using Ar as target stripper gas. The previous results for charge states distribution are presented with varying energies. A good range of energies is covered by choosing terminal potential variation instead of energy variation in our experiments. An increase in number of charge states is observed with increasing terminal potential. For C beam, charge distribution behavior is also observed by making terminal potential stable and by varying the stripper gas pressure. With increasing stripper gas pressure, the higher charge states are more preferable, but it affects the overall transmission of the beam by increasing gas pressure in accelerator tubes. The results of C beam are in agreement with the pervious measurements performed by Kiisk et al. [5] and Sarkar et al. [6]. We have presented the results at higher charge states for B, Si, Ni, Cu and Au and at higher energies. In case of B, Si, Ni and Cu, beam current stability at higher charge states is good but for Au fluctuation is observed above +8 charge states.

References

1. W. Akram, M. Madhuku, K. Shahzad et al., Roadside dust contamination with toxic metals along Islamabad industrial area. Nucl. Sci. Technol. **25**, 030201 (2014). doi:10.13538/j.1001-8042/nst.25.030201
2. A. Ishaq, L. Yan, H. Suixia et al., Optical absorption of ion irradiated multi-walled carbon nanotube sheets in the visible to Terahertz ranges. Nucl. Sci. Technol. **20**, 197–201 (2009). doi:10.13538/j.1001-8042/nst.20.197-201
3. A. Wiebert, B. Erlandsson, R. Hellborg et al., The charge state distributions of 0.5–2.9 MeV Be, Al, Cl, Ti and Ni ions measured after carbon foil stripping. Nucl. Instr. Meth. B **114**, 15–19 (1996). doi:10.1016/0168-583X(96)00146-2
4. A. Wiebert, B. Erlandsson, R. Hellborg et al., The charge state distributions of carbon beams measured at the Lund Pelletron accelerator. Nucl. Instr. Meth. B **89**, 259–261 (1994). doi:10.1016/0168-583X(94)95184-5
5. M. Kiisk, R. Hellborg, P. Persson et al., The charge state distribution of Be, C, Cl and Al ions at the Lund Pelletron accelerator with the recently modified terminal pumping in use. Nucl. Instr. Methods Res. A **521**, 299–305 (2004). doi:10.1016/j.nima.2003.11.042
6. M. Sarkar, N. Shukla, N. Banerji et al., Transmission and charge state distribution of carbon ions emerging from nitrogen gas target in a tandem accelerator: impact of stripper gas pressure. Phys. Rev. Accel. Beams **15**, 100101 (2012). doi:10.1103/PhysRevSTAB.15.100101
7. M.A.C. Hotchkis, D. Child, D. Fink et al., Sulphur hexafluoride as a stripper gas for tandem accelerators. Nucl. Instr. Meth. B **302**, 14–18 (2013). doi:10.1016/j.nimb.2013.03.029
8. A. Taniike, T. Shinobu, S. Mochizuki et al., Charge fraction measurement for heavy particle beams generated by the tandem accelerator with MCP system. Plasma Fusion Res. **8**, 2401087 (2013). doi:10.1585/pfr.8.2401087
9. www.pelletron.com
10. K. Gul, K. Shahzad, J. Taj et al., Experimental study of proton scattering on carbon. Nucl. Instr. Meth. B **269**, 2032–2034 (2011). doi:10.1016/j.nimb.2011.06.006
11. R. Hellborg et al., Vacuum in accelerating tubes calculation and measurements. Presented at the symposium of North-Eastern Accelerator Personal XXXVII, Strasbourg, France, pp. 13–16 (2003)