Acceleration of 4+ Ions in an RF Linac Accelerator

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***Abstract*— Axcelis introduced the Purion VXE system, an RF linac-based very high energy ion implanter capable of maximum energies of up to 8MeV for phosphorus and arsenic. To maximize the energy range the Purion VXE accelerates 4+ charge state ions to achieve the highest energies.**

Charge state 4+ fraction after the magnetic mass analysis of the extracted beam from the ion source showed apparent abnormalities, the fraction being higher than that of 3+ ions. With two electrostatic analysis methods, it was confirmed that the mass-analyzed 4+ beam in fact contained a large amount of contaminant, doubly charged ions with the energy of the extraction voltage, which possess the same magnetic rigidity as the 4+ ions.

This paper describes the nature of the contaminant, its population in the mass-analyzed 4+ beam at injection into the RF linac, and how the RF linac successfully discriminates between contaminate and desired ions to produce contamination-free final 4+ beam.

Keywords—high charge state beam, charge state fraction, ion source, contamination, high energy implantation, RF linac

I. INTRODUCTION

Requirement for higher energy ion implantation continues to rise, driven by applications such as CIS devices, for which deeper implants result in increased photon collection efficiencies at longer wavelengths. The top end energies of the implantations are rapidly approaching 10MeV, the range which has been long considered to be nuclear physics territory. In response to this market need Axcelis introduced the Purion VXE a high energy ion implanter, a higher energy version in the Purion XE [1] family, the RF Linac based high energy ion implanter. Purion VXE's extended energy capabilities reach 8MeV for phosphorus and arsenic using 4+ ion charge state.

On most ion sources, the available higher charge state currents decrease almost exponentially by charge states and the final beam currents of the higher charge state beam for implantation are limited by ion source output. The limited amount of the 4+ ions out of an ion source is the reason why the use of the charge state 4+ ions for ion implantation has been very rare. However, use of high charge state ions greatly reduces the size and cost of the accelerator for high energy implantation. The use of the 4+ ions is almost inevitable for the required implantations at the ultra high energies, although the beam current may be limited. Without relying on 4+ ions, the size and cost of the implanters for the energy range would be prohibitive. Fortunately the applications of the very high energy implantation are at low dose, which makes the use of 4+ ions feasible.

An early test for the available P++++ beam current from the ion source was a surprise. The measured P++++ beam current was found to be comparable or even larger than the P+++ current. Given the expected exponential decrease of ion current in particle current by every charge state this was completely unexpected. It was suspected that the mass analyzed P++++ ions might contain a large amount of contaminant.

This paper describes the identity of the contaminant in mass analyzed 4+ ion beam, its population and how the Purion VXE successfully discriminates the effective acceleration on the contaminant to produce contamination-free final 4+ beam.

II. CHARGE STATE FRACTIONS

Low voltage hot cathode arc discharge ion sources are used almost exclusively on most commercial ion implanters, mainly for its long life in adverse environments, like the presence of halogen atoms at an elevated temperature. The ELS-2 ion source used in Purion VXE is one of the low voltage DC arc source with indirectly heated cathode. The electron energy for ionization in these sources is rather low and creation of the higher charge state ions is predominantly achieved by step by step ionizations, or multiple electron impact process, like 1+ ion gets ionized to 2+ and so on. In a crude approximation in which the differences in ionization potentials on charge state is ignored, the multiple electron impact ionizations results in the charge state fractions in the ion source plasma exponentially decreasing with charge state [2]. Actually, ionization to a higher charge state becomes increasingly difficult because of the rapidly increasing ionization potential to higher charge states [3]. Higher charge state fractions are expected to drop more rapidly than exponential, according to the multiple electron impact model.

Fig. 1 shows the measured phosphorus charge state fractions at the injector cup located at the entrance of the RF linac and after the mass analyzer magnet on the Purion VXE. Four different arc power settings were utilized. The vertical axis is the fraction of each charge state in particle current relative to the total current, plotted in logarithmic scale. The abnormality of the charge state 4+ currents is quite apparent. Almost perfect exponential decrease of the charge fractions

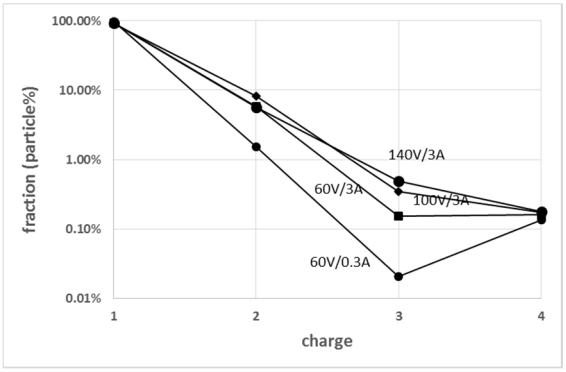

Fig. 1. Measured phosphorus charge state distributions at four arc conditions.

suddenly breaks down at 4+ charge state. At the two lower arc conditions, the 4+ fraction looks larger than that of 3+ ion even though the two higher arc power conditions made the relationship closer to the expected exponential relationship. Presence of a large amount of non-4+ ions are easily suspected from the curves. Also, by extrapolating the curves, the real P++++ fractions should be at the most 0.1%. Fig. 2 shows the same charge state distribution measured with arsenic beam. Abnormality in 4+ fraction is only seen at low arc condition. The graph also tells us that the 4+ fraction of arsenic could be close to 1% at high arc condition, which is considerably higher than phosphorus.

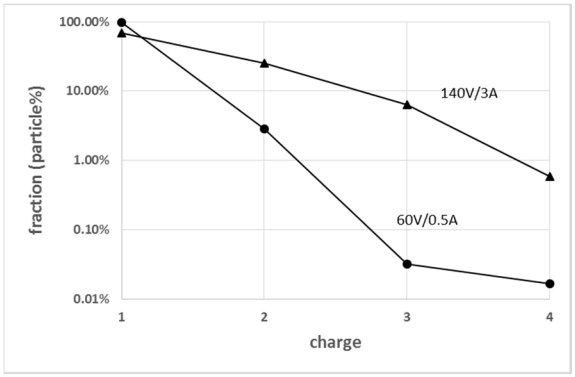

Fig. 2. Measured arsenic charge state distributions at two arc conditions.

III. Identification of the Contaminant

All the commercial beam line ion implanters employ magnetic mass analysis for separation of the desired ions according to mass, energy and charge state after ions are extracted from ion sources. Although it is called a mass analysis, in actuality the analysis is according to magnetic rigidity of ions rather than mass itself, Rm= $\sqrt{mE}$ /q, where m is the mass, E is the energy and q is the charge state of the ion. If there are other ions which happen to possess the same magnetic rigidity as the desired ion, these ions go through the mass analyzer without any hindrance and they will constitute as contaminants in the mass analyzed beam.

For 4+ ions extracted at 80kV extraction voltage, for example, two possible contaminations possess the same magnetic rigidities as the 4+ 320keV ions, 1) 20keV 1+ ions from quadmer breakups, $(X_4)^+ \rightarrow X^+ + 3\ X^0$ since some population of quadmers are possible on arsenic and phosphorus vapor, and 2) 80keV 2+ ions from the charge stripping reaction on ions extracted as 80kV 1+ before mass analysis. Since magnetic mass analysis cannot separate these ions from each other or from 4+ ions, identification has to rely on other analysis methods, like the electrostatic analyzer based on electrostatic rigidity, E/q, of ions, or Time-of-Flight analysis based on the velocity of ions.

As previously described [4], Purion XE and Purion VXE are equipped by Energy Tracking System (ETS) which uses the electrostatic beam scanner as an electrostatic energy analyzer. The deflection angle by an electrostatic beam scanner is inverse-proportional to ion's electrostatic rigidity, Re= E/q at a given deflection voltage. Since the main 4+ beam and the two possible contaminant beams, 20keV 1+ and 80keV 2+ ions, possess different electrostatic rigidities, the ETS system will be able to separate them into 3 individual peaks.

Fig. 3 is the spectrum obtained by the electrostatic analyzer based on ETS, of a P++++ beam at 80kV extraction voltage, plotted against the electrostatic rigidity, E/q values. The desired beam of P++++, with the electrostatic rigidity of 80keV, that has an energy of 320keV 4+, appears as a broad peak of 80keV. The tall peak at 40 keV/q clearly show the large contamination is actually 80keV P++ ions, charge stripped 80keV P+ ions. The peak height in the graph is in electronic current rather than particle current and the actual population ratio of the P++++ would be further reduced by 2. Actually, the author learned later that this P++ contamination in P++++ ions was reported previously [5], and was observed as a large shallower peak in a P++++ SIMS profile. Lack of a peak at 20 keV/q tells us the population of 20keV P+ ions from quadmer breakup, $(X_4)^+ \rightarrow X^+ + 3\ X^0$, is essentially negligible. The shapes of the peaks were affected by a particular setting of the electrostatic quadrupole doublet located upstream of the scanner.

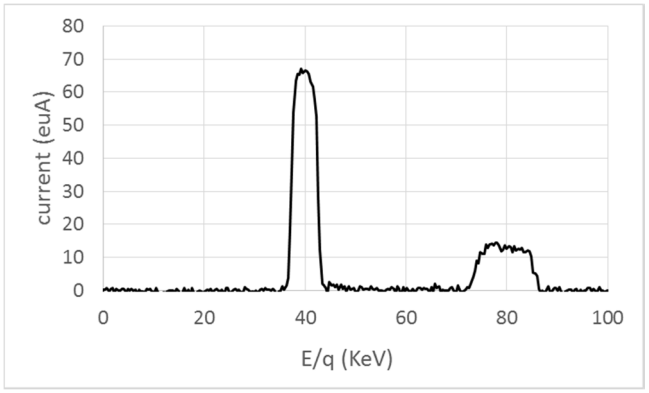

Fig. 3 Electrostatic rigidity spectrum of P++++ beam.

Fig. 4 is a similar measurement on As++++ at the highest arc current condition shown in Fig. 2. Quite interestingly, with the high arc current condition there is no sign of the 80keV As++, the charge stripped As+. The absence of the 80keV As++ is expected from the charge state fraction distribution of the high arc condition, which shows a steeper than exponential decrease toward high charge states (Fig. 2).

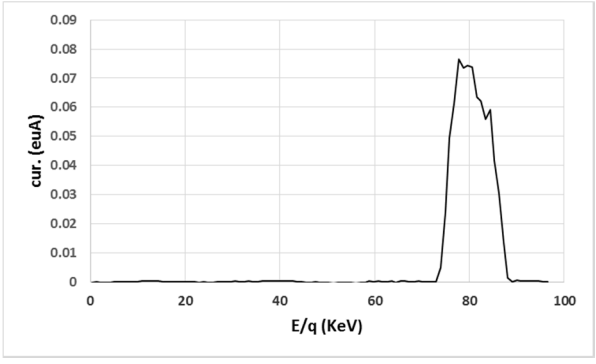

Fig. 4. Electrostatic rigidity spectrum of high current As++++ beam.

Another electrostatic method can be used to identify the contaminant. A retarding potential analyzer creates a retarding potential barrier, a positive barrier for positive ions,

to block any ions with energies or electrostatic rigidities, E/q, less than the potential barrier. Some ion implanters incorporate a filter based on the retarding potential barrier to block the dimer breakups in 2+ ions [6], and the retarding potential filter is often referred as a dimer filter. In the case of the mass analyzed 4+ ions with 80kV extraction, the two possible contaminants, 1+ quadmer breakup with E/q =20keV and 80keV 2+ from charge stripped 1+ with E/q=40keV, would show up as stepwise drops in the transmitted beam current at the filter voltages which create +20kV or +40kV on the "axis" of the beam path. Fig. 5 shows the result of a simulation for the E/q=40keV beam being repelled by a positive potential barrier created by the center electrode held at 42kV above ground. Two outer electrodes are utilized for electron suppression held at -2kV.

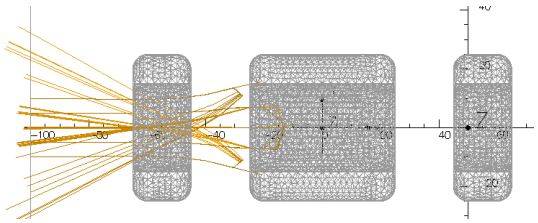

Fig. 5. E/q=40keV beam into retarding filter at 42kV.

Fig. 6 shows a comparison of the transmitted beam current through the retarding potential filter for P++++ and P+++ beams at 80kV extraction. As seen there is a large amount of 80keV P++ ions in the P++++ beam. With this particular source setting, the transmitted current of 4+ ions was roughly the same as 3+ at a zero filter voltage, but as the filter voltage increased the P++++ current rapidly decreased. After a sharp drop at 42kV, the minimum blocking voltage predicted by the simulation, the transmitted current reaches a plateau which is believed to be the real 4+ beam current. The sharp peak before the cutoff must be from the very strong focusing by the filter to E/q=40keV beam which is decelerated to only 2 or 3 keV at the filter.

Although quite effective in filtering out lower E/q contaminant ions in a rather simple configuration, the retarding filter poses some difficulties either for analysis or for filtration, because the fact it is essentially a very strong Einzel lens. Even an ion beam which does not contain any contaminants of lower E/q values, the transmitted beam current is affected by the variation of the focal property of the lens. Especially in the configuration in which the filter is located immediately upstream of the mass slit and the transmitted beam has to go through a narrow slit. The curve for P+++ in Fig. 6 represents the variation of the focusing effect since P+++ is considered to contain negligible amounts of contaminants, the trimer breakups, if any at all. In fact, if the filter voltages of P++++ data in Fig. 6 were doubled the P+++ and P++++ curves up to 44kV a near-perfect match was obtained as shown in Fig. 7. Since the lens effect from the retarding potential acts as twice as strong for a E/q=40keV beam as for E/q=80keV ions, the match is another proof that the contaminant of E/q=40keV is the overwhelming majority in the beam.

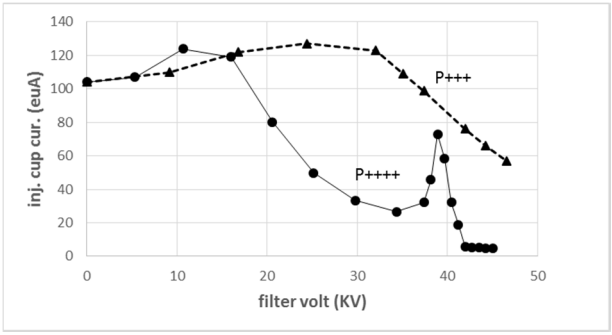

Fig. 6. Transmitted ions through retardation filter.

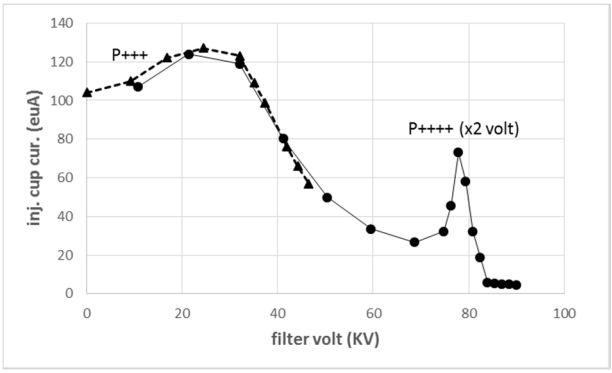

Fig. 7. Transmitted ions through retardation filter with doubled voltage scale on P++++ data.

The effect of activating the retarding potential filter on the charge state fractions of the arsenic beam is seen in Fig. 8 at a low arc power condition. After removal of the As++ contaminant in As++++ by the filter, the charge state fractions fits quite nicely to a single exponential decrease with charge states.

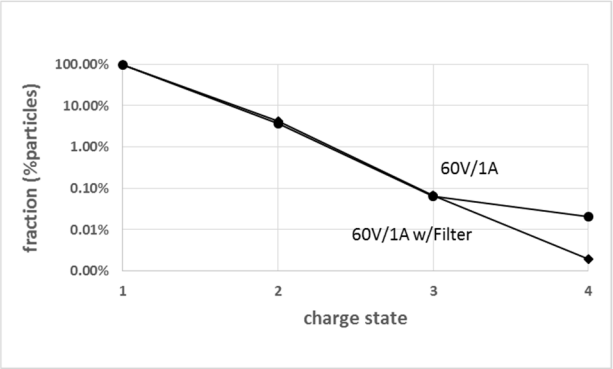

Fig. 8 Arsenic charge fractions. With and without the filter.

IV. Acceleration by RF Linac

RF linac is a very effective velocity filter. Ions of different m/q values from the main beam get "detuned" because of the phase mismatch on the arrival at 20+ RF acceleration gaps and the final energies will be far less than the energies expected by the differences in charge states. Once the energy of the contaminant is well separated from the main beam, a 2nd magnetic analyzer after the RF linac, Energy Magnet, can easily filter out the contaminants after acceleration. The velocity filtering of the RF linac can be

seen by running a simulation code, like Parmela [7] by injecting the 80keV P++ contaminant beam into the RF linac configuration optimized for P++++. A simulation showed the final energies of the 80keV P++ injected into the linac for 8 MeV P++++ would end up with broad spectrum below 1 MeV, which are easily rejected by the following magnetic analyzer.

Direct proof of the filtering by the RF linac came from several SIMS depth profiles of high energy 4+ ions. Fig. 9 shows one of the P++++ and As++++ depth profiles, 8 MeV P++++ and As++++. without the retarding potential filter [8]. No hints of energy contamination by the 2+ contaminant have been found so far, which proves the inherent velocity filtering of the RF linac is sufficient to remove the contaminant in the final beam.

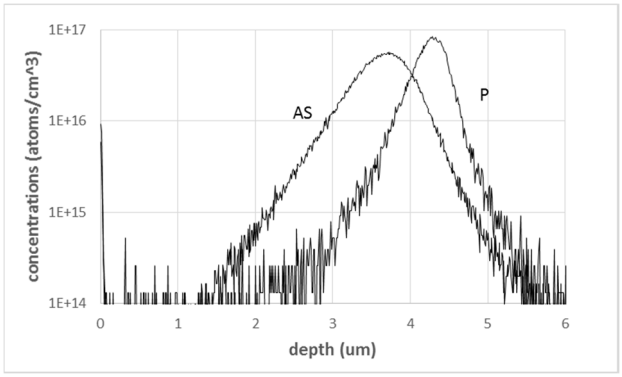

Fig. 9. SIMS profiles of 8 MeV As++++ and P++++.

V. Discussion

The amount of the 2+ contaminant ions in 4+ beam can be estimated if the cross sections for the charge stripping reaction on 80keV P+ and As+ beam are known. Assuming the cross section of $5x10^{-17}$ cm^2 in the vacuum of $5x10^{-5}$ torr over the distance of 30cm, 0.3% of 80keV 1+ ions would become 80keV 2+ ions, which is already larger than the measured 3+ ion fraction (Fig. 1). Absence of the 80keV As++ ions in As++++ beam at high arc condition suggests the stripping cross section for the 80KeV As+ ion is much smaller, probably by one order, than the value because of the lower velocity.

The large difference in the observed charge state fraction distributions between phosphorus and arsenic, both in the magnitudes and in the general trends, is interesting noting that the ionization potentials, even to high charge states, are not as different between the two elements [4]. Arsenic fraction shows the downward deviation from straight exponential at higher charge states which is more consistent with the increasing ionization potentials with charge states.

VI. Summary

Although mass analyzed 4+ injection beam, especially P++++, can contain a large amount of contaminants, the filtering by RF linac was found to be enough to filter out the contaminant in the final 4+ beam, the presence of the large amount of the contaminants in the injection beam poses some practical inconveniences. First, the possibility of creating a wrong linac data set which may accelerate the contaminant instead of the desired 4+ beam. Second, it is possible, although remotely, the ion source operation may be optimized for the contaminant ions instead of the 4+ ions. To prevent the possible confusions, Purion VXE is equipped with the built-in retarding potential filter which can be used to check the E/q of the injected ion beam into the RF linac by simply turning it ON.

VII. Acknowledgement

The author would like to thank Serguei Kondratenko for the SIMS profiles and Axcelis Purion High Energy Product team for all the help and the continued support.

[1] S. Satoh, J. Ferrara, E. Bell, S. Patel and M. Sieradzki, “Optima XE single wafer high energy ion implanter”, Proceedings of the 17th Int. Conf. in Ion Implantation Technology, p. 273-276 (2008)

[2] T. S. Green, “Intense ion beams” in Rep. Prog. Phys. 1974 37 1257-1344..

[3] T.A. Carlson, C. W. Nestor, Jr., N. Wasserman and J. D. McDowell, ORNL-4562 (1970)

[4] J. David, S. Satoh, K. Wu, C. Geary and J. Deluca, “Beam energy tracking system on Optima XEx high energy ion implanter”, Proceedings of the 19th Int. Conf. in Ion Implantation Technology, p. 364-367 (2012)

[5] H. Ryssel, M. Current and L. Frey. “Contamination control for ion implantation”, Ion Implantation Science and Technology, 6th ed. J. F. Ziegler (ed.) (1996)

[6] B.B. Adibi, M.L. Turner, T. Marin, G.T. Lecouras, R.J. Macklin, W.J. Boyd, D. Wagner, W.J. Wriggines, “Development and application of beam energy filter for the PI9200XJ high current implanter”, in Ion Implantation Technology-92 (1993) 601

[7] L.M. Young, “Parmela, A particle dynamics code for electron linacs” LA-UR-96-1835 (2002)

[8] S. Kondratenko, L. Rubin, and E. Webster, “Analysis of very high energy implantation profiles at channeling and non-channeling condition”. This conference.