EFFECT OF SOURCE TUNING PARAMETERS ON THE PLASMA POTENTIAL OF HEAVY IONS AND ITS INFLUENCE ON THE LONGITUDINAL OPTICS OF THE HIGH CURRENT INJECTOR

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Abstract

Plasma potentials for various heavy ions have been measured using the retarding field technique in the 18 GHz High Temperature Superconducting ECR ion source, PKDELIS [1]. The influence of various source parameters viz., RF power, gas pressure, magnetic field, negative DC bias and gas mixing on the plasma potential is studied. It is observed that the plasma potentials are decreasing for increasing charge states and a mass effect is clearly observed for the ions with similar operating gas pressures. In the case of gas mixing, it is observed that the plasma potential minimises at an optimum value of the gas pressure of the mixing gas and the mean charge state maximises at this value. The energy spread arising from the plasma potential influences the longitudinal optics of the High Current Injector in terms of increased phase spread which deteriorates the transmission through the RFQ. Details of the measurements carried out as a function of various source parameters and its impact on the longitudinal optics are presented.

INTRODUCTION

Plasma potentials are one of the important figures of merits of an ion source and depicts the degree of stability of a plasma. The ion source stability is one of the main criteria for application in accelerators an ion implanters, besides other applications. In the context of electron cyclotron resonance ion sources, the improved stability results from a lower plasma potential and determines a good confinement of the plasma resulting in a higher mean charge state distribution [2]. On the other hand, if the plasma potential is high, sputtering to the wall is highly probable that results in an unstable plasma. Therefore, the confinement properties of the plasma are worsened and the resulting charge state distribution is a lower mean charge state. The main goal is to tune the source such that that plasma potential is as low as possible, which manifests itself in a stable operation mode. Measurement of plasma potentials is therefore important to get an idea of the source operating conditions. This in turn can be used to infer another important figure of merit called the 'energy spread'. A quick online estimate would suffice to further improve the source tuning and especially for delivering beams to experiments which require good timing information. The importance of the plasma potential shows up in the estimation of the energy spread which is crucial for timing measurements in nuclear physics experiments and other experiments where the pulse width of the bunched beam is of extreme importance. At the Inter University Accelerator Centre, a High Current Injector (HCI) is being installed for delivering a wider mass range of ions with relatively higher beam intensities into the superconducting linear accelerator (SC-LINAC) than what is presently available from the Pelletron-SC-LINAC combination Fig. 1. Due to the wide available mass range, there is a wider charge state distribution and the energy spread of the ion beam will depend on the charge state being delivered. In our earlier experiments, the emittance of various ion beams from an ECR ion source were measured [3] to obtain inputs in the design of beam transport and to match the acceptances of the downstream radio frequency quadrupole (RFQ) and drift tube LINAC (DTL) accelerators of the high current injector being developed [4]. For subsequent acceleration through the RFQ and DTL, the dc beam from the ECR needs to be pulsed and the longitudinal emittance depends on the energy spread of the beam. Due to the pulsed nature of the beam, the timing resolution is very important for various experiments. Since a significant energy spread can influence the longitudinal optics, it was felt necessary to measure the plasma potentials for various ions and its dependence on source tuning parameters. O.Tarvainen et al.,[6] have measured plasma potentials using the retarding field technique and observed the plasma potentials to increase with RF power and gas pressure and the values changed when the negative DC bias was varied. They [7] also measured the effect of the gas mixing technique on the plasma potential, energy spread and emittance of the beam under various source conditions. They estimated that the energy spread due to the plasma potential can influence the emittance of the beam to several tens of percent in the bending plane of the dipole magnet. In Ref 8., they compared the measured values of the emittance and plasma potential using single frequency and double frequency heating modes. In this study we carried out a systematic measurement of the plasma potential and the worst possible energy spread to study the influence on the longitudinal optics. Various methods have been used in the literature to measure the plasma potential. We have used the retarding field method and the instrument used is similar to the one used by the Jyvaskyla group [6] and is described in detail in [12]. In

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our previous experiments, we have measured the effect of the negative bias voltage on the x-ray bremstraahlung and beam intensities of medium and highly charged ions of argon [5] keeping all other source parameters fixed. In this experiment, various source parameters like DC bias voltage, magnetic field, gas pressure, gas mixing [11] and rf power have been tuned to study the influence on the plasma potential. From the measurements, we have estimated the value of the energy spread for the heaviest ion and studied its influence on the longitudinal optics of the High Current Injector. A corresponding energy spread of 0.11 % from the ion source increases the phase spread at the entrance of the radio frequency quadrupole (RFQ) accelerator and thus limits the transmission efficiency through the RFQ to 84 %.

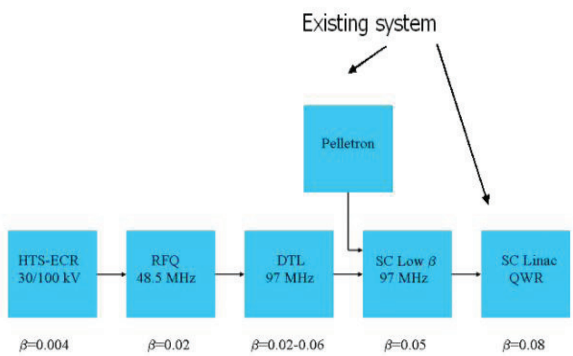

Figure 1: Schematic of the High Current Injector with respect to the existing Pelletron-SC LINAC accelerators.

EXPERIMENTAL METHOD

The compact instrument used for measuring the plasma potential was built in-house. The decelerating system geometry was optimised using TOSCA assuming the system was placed at the image plane of the bending magnet to further minimise the beam blow-up due to deceleration and to filter out unwanted beams. The model further showed that the beam had to enter parallel to the axis of the retarding system to obtain better energy resolution. Details of the system are further explained in [12]. The plasma potential measurement system was installed at the image position of the analysing magnet after the simulations confirmed the validity of the model. The error in the measurements was measured to be +/- 2 V and the repeatability in the measurements was found to be +/- 0.8 V. A typical retardation curve is shown in Fig. 2. The derivative of this current voltage distribution is shown in the inset graph depicting the energy spread information.

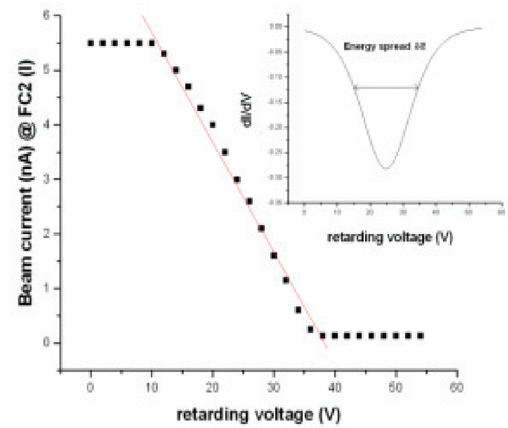

Figure 2: Typical retardation curve and it's derivative ; the inset graph shows the energy spread at FWHM.

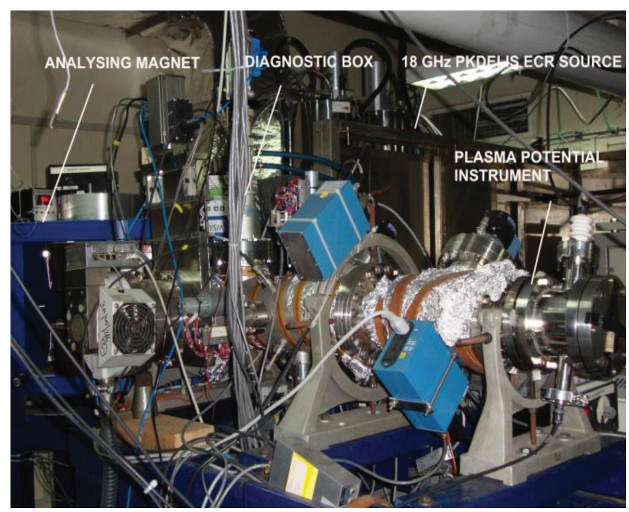

Figure 3: View of the 18 GHz HTS-ECRIS, PKDELIS and low energy beam transport.

EXPERIMENTAL RESULTS

The experimental set-up for measuring the plasma potential is shown in Fig. 3, where the decelerating system was installed at the image plane of the analysing magnet. The measurements have been carried out for oxygen, argon and xenon beams. The influence of the source parameters like rf power, DC bias voltage, magnetic field, gas pressure and gas mixing on the plasma potential has been measured. All the measurements have been recently reported in [12]. Few figures of the measurements will only be shown due to space constraints. In Fig. 4, the plasma potential is shown as a function of charge states of xenon, argon and oxygen, keeping the rf power (500 W), magnetic field (B_{min}/B_{ecr} =0.63) and gas pressure (4.9 x 10^{-6} mbar) fixed. In all the measurements, the dc bias was kept fixed at -100 V, except in the case of Xe where two values of the dc bias

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viz., -100 V and -500 V were used. A mass effect was clearly observed showing that the plasma potential is lower for the lighter mass ions under same source conditions. O.Tarvainen et al., also reported that the plasma which contain lighter mass ions have lower plasma potential [13]. It should be noted that in the present measurements, the plasma potential monotonically decreases with increase of charge states of argon in contrast to that obtained by Higashijima et al [14], where the potential was found to be constant above charge state 5+. A similar variation of the potential was also observed for other ions though it follows the general trend of increase of the plasma potentials for the lower charge states in comparison to higher charge states as observed by others [14,15]. In the case of Xe, application of a higher dc bias voltage of -500 V reduces the plasma potential further, as shown in Fig. 4. The higher dc bias reflects a large number of the electrons which otherwise would be lost, resulting in the decrease of the plasma potential [16]. The plasma potentials of Xe^{17+}, Ar^{9+} and O^{6+} were measured as a function of B_{min}/B_{ecr} with RF power 500W, DC bias -100 V and fixed gas pressure. The plasma potential of Xe^{17+}, Ar^{9+} and O^{6+} decreases with higher values of B_{min}/B_{ecr} up to ~ 0.63 to 0.65 while the normalised beam current is maximum for all three beams in the same range of B_{min}/B_{ecr} due to the increasing value of the electron temperature according to the calculations reported in [17]. Due to the lower gradient at the resonance zone, the electrons gain higher energies resulting in higher beam intensities. It should be noted that the plasma became unstable beyond the value of B_{min}/B_{ecr}=0.73. Our earlier measurements [5] also showed that at a similar field setting of B_{min}/B_{ecr}=0.65, the beam intensities of medium and highly charged ions of argon were maximized. The increase of plasma potential with increase in RF power is consistent with the calculations reported in Ref. 17. This is probably due to the increase of plasma density and density gradients with RF power which results in higher loss of electrons to the wall of the chamber. Therefore, a higher plasma potential is required to compensate the loss rates of electrons and ions [10]. The plasma potential of i) O^{6+}, ii) O^{6+} with gas mixing using He and iii)mean charge state variation of O_2 with gas mixing was measured. In the case of oxygen-helium mixing, the oxygen gas pressure was fixed at 3.5 x 10^{-6} mbar while helium was fed into the plasma. Similarly, the plasma potential of i) Ar^{9+}, ii) Ar^{9+} with gas mixing using O_2 and iii)mean charge state variation of Ar with gas mixing were also measured Fig. 5. In the case of gas mixing studies using the argon-oxygen combination, the argon gas pressure was fixed at 4 x 10^{-6} mbar while oxygen gas was fed into the plasma. The plasma potential increases with gas pressure for O^{6+} and Ar^{9+} due to the decrease in the electron temperature and ion confinement times [17]. The mean charge state variation (open symbols) is shown in Fig. 5 using gas mixing [11] where there is an optimum maximum value corresponding to lowest value (filled symbols) of the plasma potential. It means that the ion confinement time (τ_i) is longer corresponding to higher mean charge state <q> given by ~ $n_e \tau_i$, where <q> denotes the mean charge state and n_e is the electron density. If we compare our experimental result of the plasma potential variation with the mean charge state to the theoretical model developed by N.K.Bibinov et al., [18], and assume cold electron temperatures in the range of few tens of eV with the additional assumption of a Maxwellian electron distribution function (EDF), our experimental values of the plasma potential are of the same order of magnitude as per the calculated values given by the equation $U_{pl} = (kTe/2e)(5.67- \ln\langle q/M\rangle)$ where U_{pl} is the plasma potential, k is the Boltzmann constant, Te is the cold electron temperature and <q> is the mean charge state. The plasma potential as a function of gas injection pressure for Xe^{17+} with and without gas mixing were measured, when the dc bias was kept at -500 V. In the case of gas mixing, the xenon gas pressure was fixed to 4 x 10^{-6} mbar while oxygen was added as a mixing gas. The normalized beam current maximises when the plasma potential attains a lower value. In Fig. 5, it is shown that the addition of a lighter mixing gas lowers the plasma potential and improves the beam intensities and the mean charge state of ions, which has also been observed by Higashijima et al [14] in the case of argon. In our earlier experiments, the emittance measurements using gas mixing [3] also shows that gas mixing reduces the beam emittance of the beam gas and increases the beam emittance of the mixing gas thus demonstrating the ion cooling mechanism [19]. Hence, the reduction of the plasma potential and the beam emittance due to gas mixing are signatures of the ion cooling mechanism.

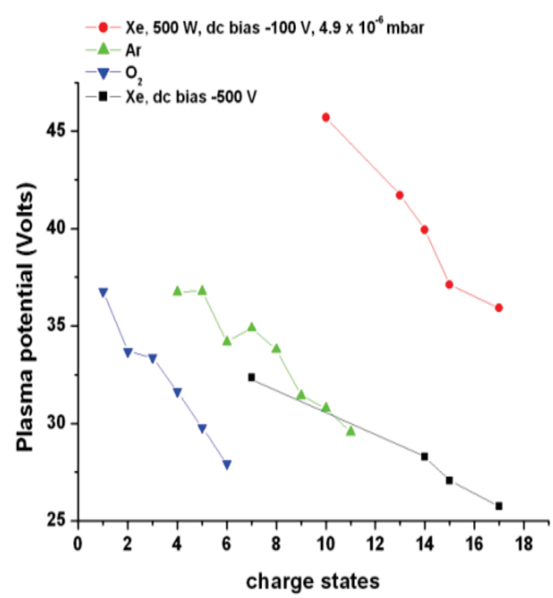

Figure 4:Plasma potentials for various charge states of xenon, argon and oxygen, keeping the rf power, gas pressure and magnetic field fixed.

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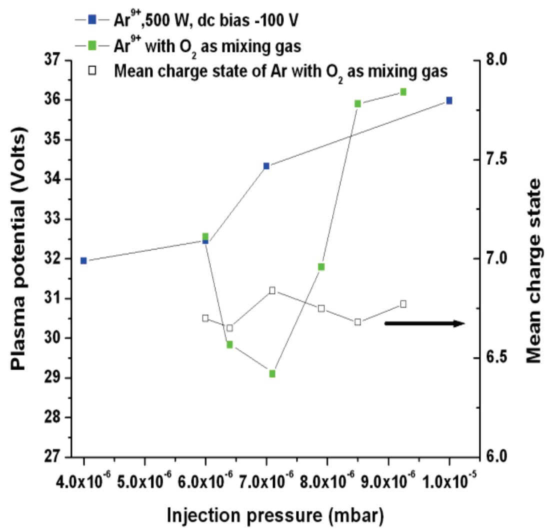

Figure 5: Plasma potentials of i) Ar^{9+}, ii) $Ar^{9+}$with gas mixing using O_2, and iii) variation of mean charge state of Ar with gas mixing using O_2.

LONGITUDINAL OPTICS OF THE HIGH CURRENT INJECTOR

The energy spread of ions coming from an ion source is an important parameter which can influence the bunched width of the beam since ions leaving the ion source with different energies will arrive at the target at different times thus decreasing the effectiveness of bunching. The maximum possible energy spread determined from the plasma potential in the ECR source will therefore have a corresponding influence on the longitudinal optics through the High Current Injector (HCI). The High Current Injector is designed for accelerating beams having A/q ~ 6 and to match to the velocity regime $\beta \sim 0.08$ in the main SC-linac. It mainly consists of the HTS-ECR source (PKDELIS), 48.5 MHz Radio Frequency Quadrupole (RFQ) and 97 MHz Drift Tube Linac (DTL) accelerators. In order to improve the longitudinal emittance of the RFQ, the adiabatic buncher is replaced with external discrete buncher. The transmsision of the RFQ is then equal to that of a conventional RFQ with adiabatic bunching, further reducing the length of the RFQ substantially. Due to this, stability requirement of the pre-injector voltage increases by an order of magnitude and therefore the rf defocussing in the buncher may be significant and use of grids may be necessary or a small beam size should be maintained in the buncher.The dc beam from the source will be accelerated to 8 keV/u using a 100 kV high voltage platform, bunched using a 12.125 MHz multi-harmonic buncher (MHB) before further acceleration by the RFQ to 180 keV/u and finally by the DTL to 1.8 MeV/u. The multi-harmonic buncher used for pre-bunching before the RFQ serves two purposes ; a) most of the DC beam from the source gets bunched close to the entrance of the RFQ to improve the capture efficiency, and b) the growth of the longitudinal emittance at the exit of the RFQ is minimised, following the proposal by J.Staples [20]. The beam having an energy of 1.8 MeV/u will be transported through the SC-LINAC for further acceleration to $\beta \sim 0.08$ In Fig.6, the FWHM of the energy spread at the exit of the ECR source is shown as a function of rf power, calculated from the derivatives of the current versus voltage distribution function of Xe^{17+}. Considering the worst possible case of the heaviest ions being accelerated through the High Current Injector ($^{238}U^{40+}$), an energyspread, ΔE, of 0.11 % would result in a corresponding phase spread, $\Delta\phi$, given by the equation $\Delta v/v = \Delta\phi\beta\lambda/\pi h L_{drift}$ at the entrance of the RFQ (where $L_{drift,}$ distance of 4.0 m from the MHB, considering the length of the MHB and the harmonic number, h = 4) [20]. The model calculations by TRACK [21] using the value of energy spread from the ECR source showed that a significant phase spread $\Delta\phi \sim$ +/- 22.5° arising from the energy spread, would need to be accomodated by the RFQ phase acceptance ellipse. The complete beam-line layout of the High Current Injector is shown in Fig. 7. In Fig.8, the longitudinal phase space plots at the entrance and exit of the RFQ are shown. The calculations show that the transmission through the RFQ is reduced by 16 % due to the energy spread in the beam. The deterioration in the energy spread after the RFQ is minimal and it is expected that the final injection into the main linac would not pose problems for phase matching through the next accelerating elements of the DTL. Since adjustment of the source parameters like gas pressure and rf power play a critical role in deciding the energy spread of the ion beams extracted, it would be necessary to optimise these parameters as determined from the present study for good transmission of the ion beams through the High Current Injector.

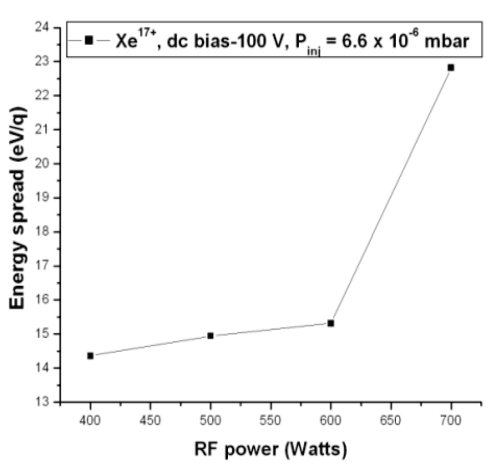

Figure 6: Energy spread at FWHM as function of rf power, calculated from the derivatives of the current versus voltage distribution function for Xe^{17}.

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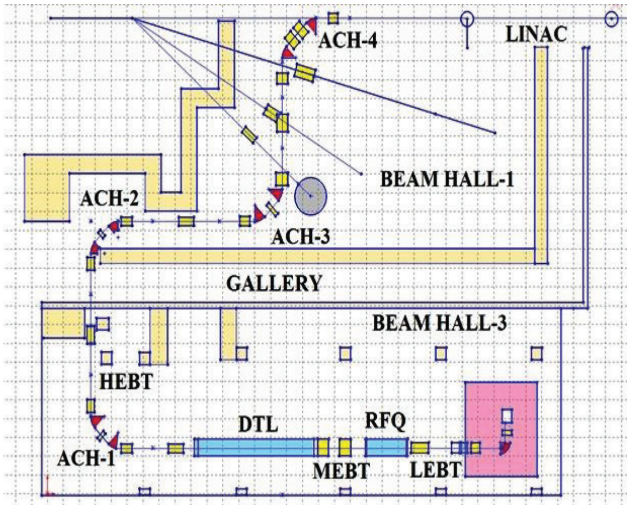

Figure 7: Complete beam-line layout of the High Current Injector.

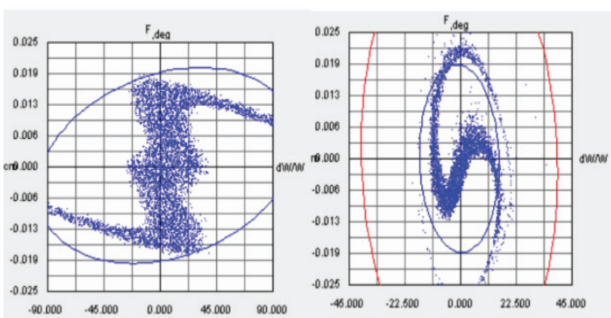

Figure 8: Longitudinal phase space at the entrance and exit of the RFQ situated 4.0 m downstream from the multi-harmonic buncher.

SUMMARY AND CONCLUSION

A systematic study has been undertaken to understand the variation of the plasma potential in an ECR plasma as a function of different source parameters and for several ion beams. These measurements show a mass effect. The measured values of the plasma potential variation with the mean charge state are in accordance with the theoretical model which assumes cold electron temperatures in the range of few tens of eV. The energy spread deduced from the plasma potential measurements influences the longitudinal optics of the High Current Injector in terms of increased phase spread which deteriorates the transmission through the RFQ. This study shows that the energy spread of the ions determined from the plasma potential measurements is a determining factor for the resultant time width of the beam bunches that would be accelerated further by the High Current Injector.

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