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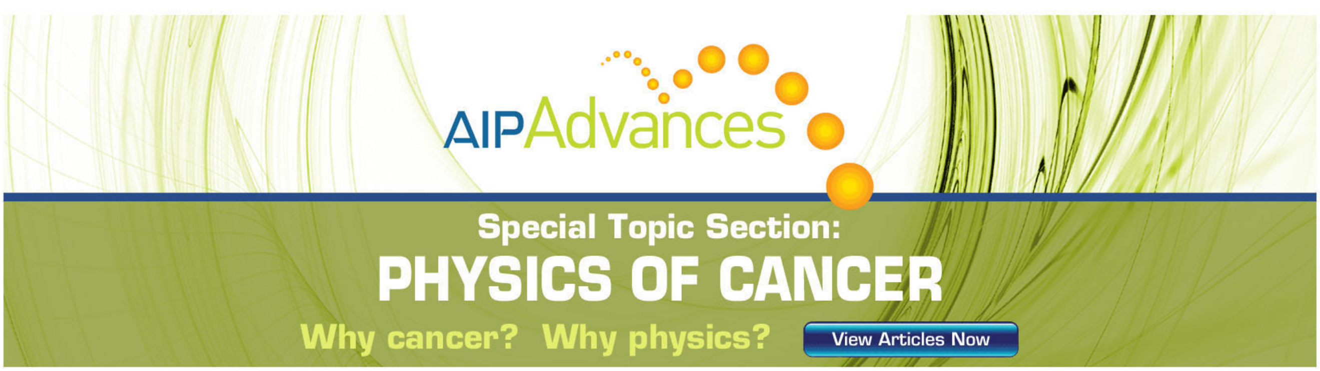

Effect of source tuning parameters on the plasma potential of heavy ions in the 18 GHz high temperature superconducting electron cyclotron resonance ion source

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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 [C. Bieth, S. Kantas, P. Sortais, D. Kanjilal, G. Rodrigues, S. Milward, S. Harrison, and R. McMahon, Nucl. Instrum. Methods B **235**, 498 (2005); D. Kanjilal, G. Rodrigues, P. Kumar, A. Mandal, A. Roy, C. Bieth, S. Kantas, and P. Sortais, Rev. Sci. Instrum. **77**, 03A317 (2006)]. The ion beam extracted from the source is decelerated close to the location of a mesh which is polarized to the source potential and beams having different plasma potentials are measured on a Faraday cup located downstream of the mesh. 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. The study helped to find an upper limit of the energy spread of the heavy ions, which can influence the design of the longitudinal optics of the high current injector being developed at the Inter University Accelerator Centre. 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 minimizes at an optimum value of the gas pressure of the mixing gas and the mean charge state maximizes at this value. Details of the measurements carried out as a function of various source parameters and its impact on the longitudinal optics are presented. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3695004]

I. INTRODUCTION

Measurements of the plasma potential give an important figure of merit determining the degree of stablility of a plasma. The plasma stability is found to be better when the plasma potential is low in the range of few tens of volts. This gives rise to higher beam intesity of the highly charged ions[2] due to better confinement in the case of electron cyclotron resonance (ECR) ion sources. 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 (HCI) being developed;[4] additionally, we have measured the effect of the negative bias voltage on the bremstraahlung x-rays and beam intensities of medium and highly charged ions of argon[5] keeping all other source parameters fixed. This study helped us to have a strong diagnostic tool to tune the ion source for the production of medium and highly charged ions. 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. The energy spread coming from the ion source is dictated mainly by the source instability, high voltage platfrom instability, and the inherent energy spread of the ions. The contributions from the first two are minimal as compared to the energy spread determination from the decelerated ion beam technique. In addition, the thermal energies of the ions can also influence but their values are in the range of few electron volts and can be neglected. This is especially true for the heavier ions since their measured beam emittances are much lower.[3] Therefore, the total beam energy coming from the ion source is the product of the charge state and the sum of the extraction voltage and the plasma potential assuming a uniform potential difference between the plasma and the chamber wall. Since a significant energy spread can influence the longitudinal optics, it was felt necessary to measure the plasma potentials for various ions and its dependance on source tuning parameters. 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. Tarvainen *et al.*,[7] also measured the 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

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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, viz., Langmuir probe, retarding field energy analysers,[9] magnetic rigidity analysis,[10] etc. The retarding field method is chosen since it does not disturb the plasma stability and a quick estimate can be obtained online during the source tuning. The instrument used for the retarding field method is similar to the one used by the Jyvaskyla group[6] which has the advantage of having a single electrode raised to the source potential and makes the system compact and easy to use. A linear dependance of the reduction of beam intensity as a function of the decelerating voltage allows a linear fitting of the falling part of the current versus voltage distribution function and the value of the intercept gives the value of the plasma potential. The energy spread at FWHM is then calculated from the derivative of the distribution. In 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 such as 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 RFQ accelerator and thus limits the transmission efficiency through the RFQ to 84%.

II. EXPERIMENTAL METHOD AND DETAILS

A schematic view of the compact retarding system used for the plasma potential measurement is shown in Fig. 1 where the beam enters from the left side. The compact instrument used for measuring the plasma potential consists of two grounded collimators, A, B, having an aperture of 5 mm followed by a mesh, C, polarised to the source potential. A Faraday cup, D, with an electron suppression sitting further downstream is used to measure the beam current. Due to the small gap between the high potential and ground potential, the operating source voltage was limited to 6 kV in all the measurements. A variable power supply was used for further deceleration in the range 0–70 V which was kept floating at the source potential. A linear dependance of the reduction of beam intensity as a function of the decelerating voltage allows a linear fitting of the falling part of the current versus voltage distribution function and the value of the intercept gives the value of the plasma potential (Fig. 2). It should be noted that the ion temperature (thermal energy) influence on the measurement at the saturation part of the voltage distribution function is neglected since its maximum value is in the range of few electron volts. The energy spread at FWHM is calculated from the derivative of the distribution shown in the inset graph of Fig. 2. In this case, the energy spread was calculated to be 14.946 q eV for Xe^{17+} measured at 500 W of RF power. The plasma potential measurement system was installed at the image position of the analyzing magnet to further minimise the beam blow-up due to deceleration and to filter out unwanted beams. The error in the measurements was measured to be ±2 V and the repeatability in the measurements was found to be ±0.8 V.

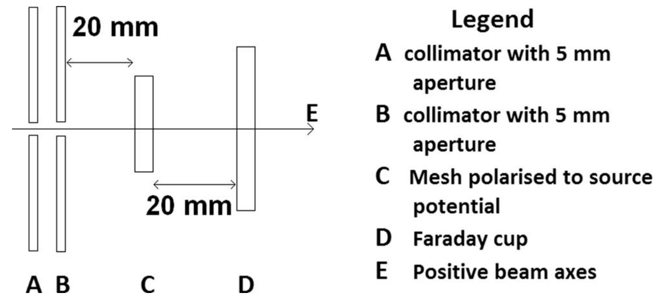

FIG. 1. Schematic of the compact retarding system installed at the image plane of the analyzing magnet.

III. EXPERIMENTAL RESULTS AND DISCUSSION

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. In Fig. 3, 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 (4.9×10^{-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, viz., −100 V and −500 V were used. This mass effect, that the plasma potential is lower for the lighter mass ions under same source condition, is clearly seen in Figure 3. Tarvainen *et al.*, also reported that the plasma which contain lighter mass ions

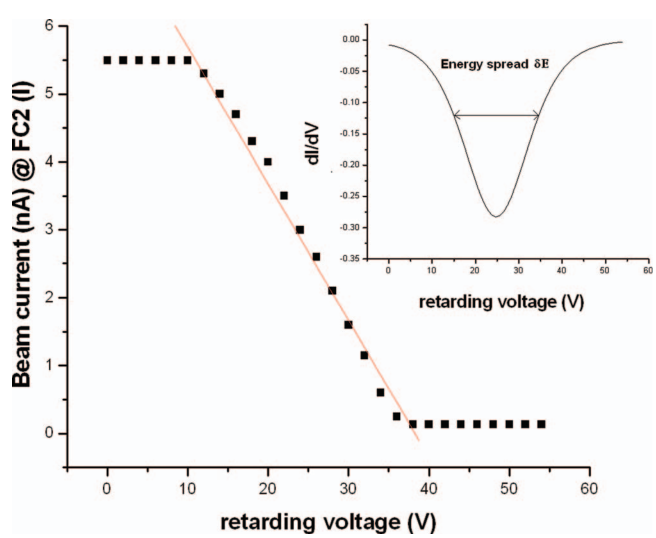

FIG. 2. An example of a typical retardation curve showing a linear fit and it's derivative, dI/dV (shown in inset graph) showing the energy spread at FWHM.

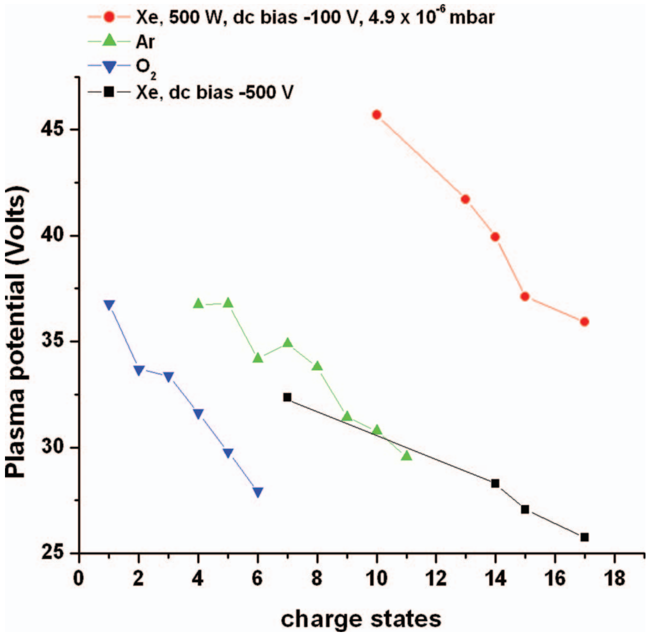

FIG. 3. Plasma potentials for various charge states of xenon, argon, and oxygen, keeping the RF power, gas pressure, and magnetic field fixed.

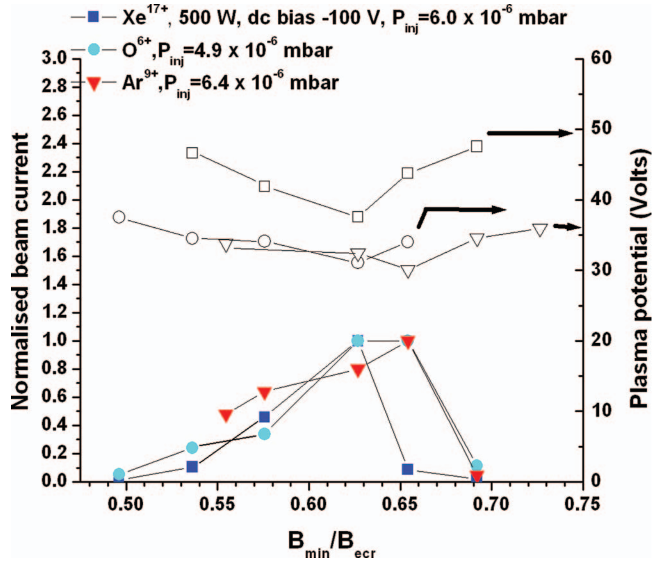

FIG. 4. Plasma potential variation of Xe^{17+}, Ar^{9+}, and O^{6+} as a function of B_{min}/B_{ecr} keeping RF power, dc bias voltage, and gas pressure fixed. Filled symbols represent the normalized beam current and the open symbols represent the plasma potentials.

have lower plasma potential.[12] 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.*,[13] 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.[13,14] In the case of Xe, application of a higher dc bias voltage of −500 V reduces the plasma potential further, as shown in Fig. 3. The higher dc bias reflects a large number of the electrons which otherwise would be lost, resulting in the decrease of the plasma potential.[15]

The plasma potential variation of Xe^{17+}, Ar^{9+}, and O^{6+} as a function of B_{min}/B_{ECR} is presented with RF power 500 W, dc bias −100 V, and fixed gas pressure (Fig. 4). The plasma potential of Xe^{17+}, Ar^{9+}, and O^{6+} decreases (open symbols) with higher values of B_{min}/B_{ECR} up to ∼0.63–0.65 while the normalised beam current (filled symbols) 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 Ref. 16. 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 variation of the plasma potential as a function of RF power is shown in Fig. 5. The increase of plasma potential with increase in RF power is consistent with the calculations reported in Ref. 16. This is probably due to the increase of plasma desnsity 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] It should be noted that in the case of different operating gas pressures for the various ions (compare to the case in Fig. 3 where all the beams having similar gas pressures shows a mass dependance), the mass effect is obscured. It shows that the plasma potential is strongly dependant on the gas pressure variation. 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 are shown in Fig. 6. In the case of oxygen-helium mixing, the oxygen gas pressure was fixed at 3.5 × 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 are shown in

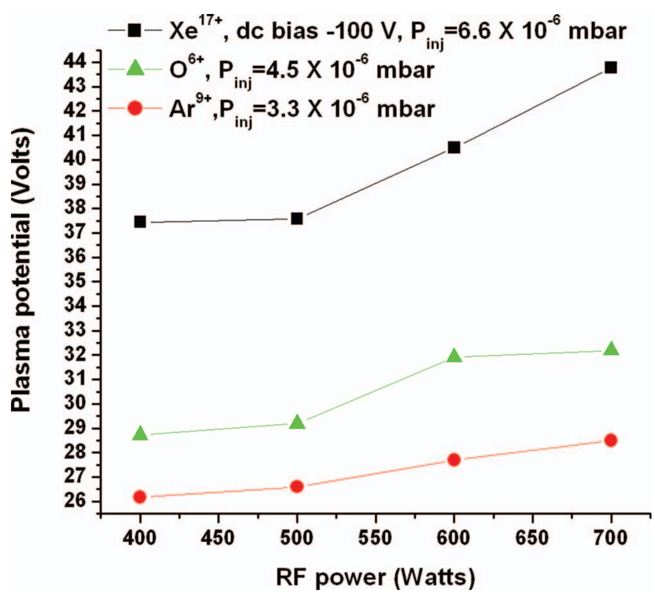

FIG. 5. Plasma potential variation of Xe^{17+}, Ar^{9+}, and O^{6+}, as a function of RF power keeping gas pressure, dc bias voltage and magnetic field fixed.

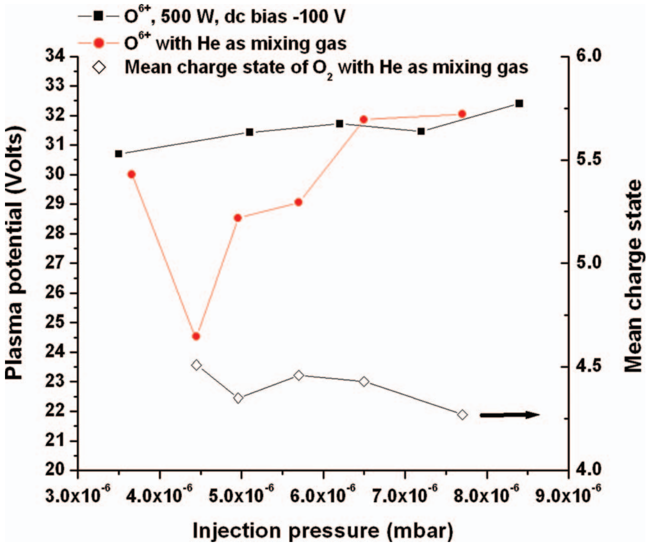

FIG. 6. Plasma potential variation of (i) O^{6+}, (ii) $O^{6+}$with gas mixing using He, and (iii) variation of mean charge state of O_2 with gas mixing using He.

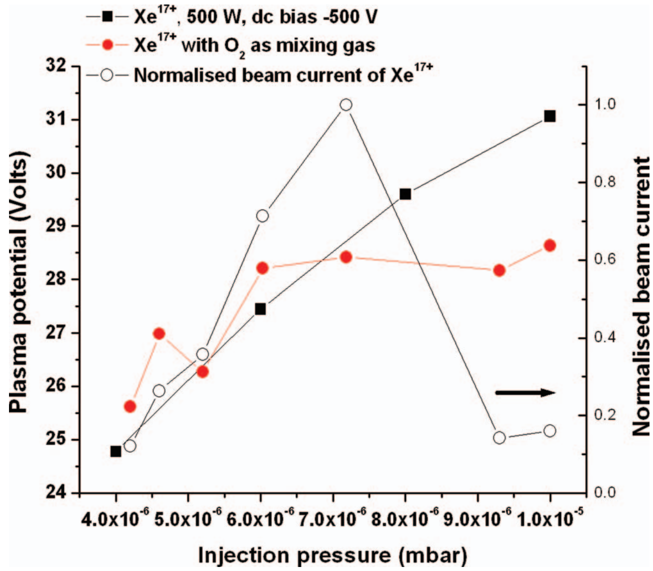

FIG. 8. Plasma potential variation of Xe^{17+} with gas pressure and gas mixing, and normalized beam current with gas mixing.

Fig. 7. In the case of gasmixing studies using the argon-oxygen combination, the argon gas pressure was fixed at 4×10^{-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.[16] The reason for this behaviour is attributed to the fact that due to the increased plasma density, the electron losses to the chamber wall become higher and a higher potential is required to compensate for the losses.[10] The mean charge state variation (open symbols) is shown in Figs. 6 and 7 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 $\langle q\rangle$ given by $\sim n_e \tau_i$, where $\langle q\rangle$ 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 Bibinov *et al.*,[17] and assume cold electron temperatures in the range of few tens of eV with the additional assumption of a Maxwellian electron distribution function, our experimental values of the plasma potential are of the same order of magnitude as per the calculated values given by the equation $U_{pl} = (kT_e/2e)(5.67 - \ln\langle q/M\rangle)$, where U_{pl} is the plasma potential, k is the Boltzmann constant, T_e is the cold electron temperature, and $\langle q\rangle$ is the mean charge state. The plasma potential as a function of gas injection pressure for Xe^{17+} with and without gas mixing are shown in Fig. 8, when the dc bias was kept at −500 V. The increasing trend with gas pressure seen in Figs. 6 and 7 without using mixing gas is shown also in Fig. 8. In the case of gas mixing, the xenon gas pressure was fixed to 4×10^{-6} mbar while oxygen was added as a mixing gas. The normalized beam current (open symbols) maximizes when the plasma potential attains a lower value. Due the addition of a lighter gas, the plasma potential is lowered. In Figs. 6–8, 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.*[13] in the case of argon. In our earlier experiments, the emittance measurements using gas mixing[3] also show 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.[18] Hence, the reduction of the plasma potential and the beam emittance due to gas mixing are signatures of the ion cooling mechanism.

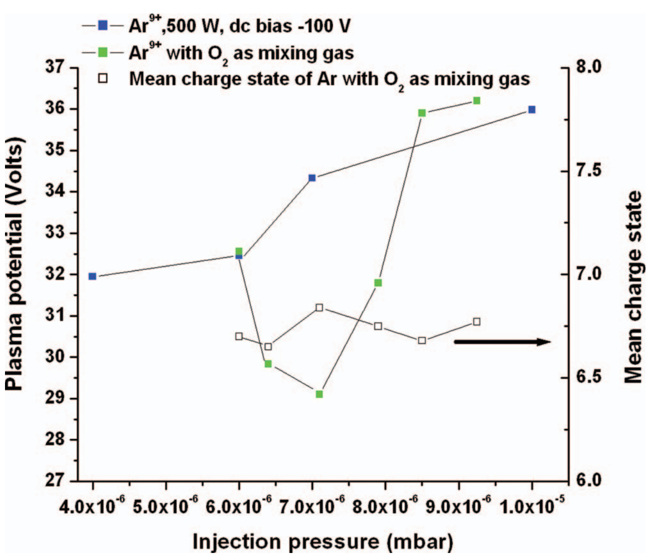

FIG. 7. Plasma potential variation of (i) Ar^{9+}, (ii) Ar^{9+} with gas mixing using O_2, and (iii) variation of mean charge state of Ar with gas mixing using O_2.

IV. INFLUENCE OF THE PLASMA POTENTIAL ON THE LONGITUDINAL OPTICS

The energy spread of ions coming from an ion source is an important parameter which can influence the bunched

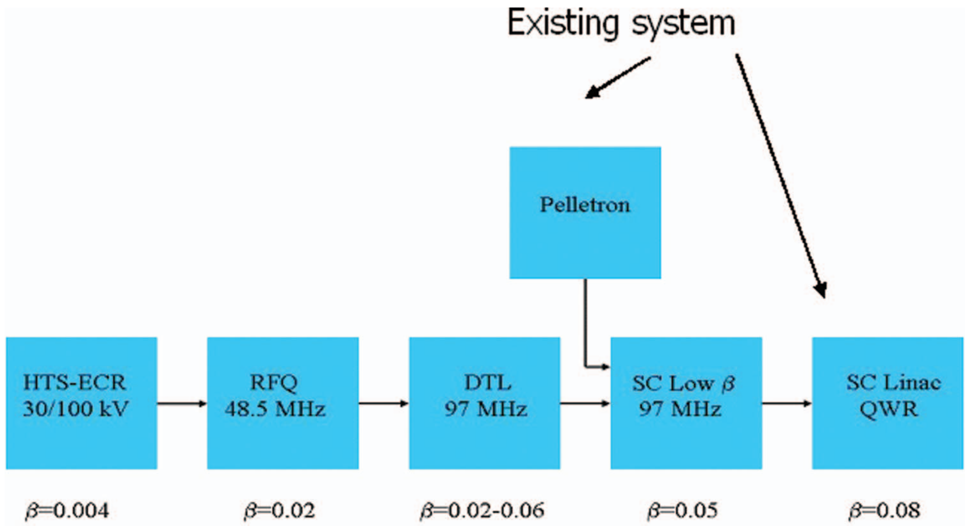

FIG. 9. Schematic of the associated accelerator systems showing the existing accelerators and the HCI under development.

width of the beam since ions leaving the ion source with different energies will arrive at the target position at different times thus decreasing the effectiveness of bunching. The maximum possible energy spread determined from the plasma potential will therefore have a corresponding influence on the longitudinal optics.

At the Inter University Accelerator Centre, New Delhi, a 15 MV Pelletron and the superconducting linear (SC-LINAC) accelerator combination delivers ion beams with low beam currents (approximately few enA) for experiments. A HCI programme for the SC-LINAC is being developed in parallel to obtain higher charge states and higher beam intensities. A schematic of the associated accelerator systems depicting the existing Pelletron–LINAC and HCI under development is shown in Fig. 9. The high current injector is designed for accelerating beams having A/q $\sim$ 6 and to match the velocity regime $\beta \sim 0.08$ in the main SC-LINAC. It mainly consists of the high temperature superconducting (HTS)-ECR source (PKDELIS), 48.5 MHz RFQ, and 97 MHz DTL accelerators. The dc beam from the source will be accelerated to 8 keV/u using a 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 minimized, following the proposal by J. Staples.[19] 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. 10, 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 energy spread, 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).[19] The model calculations by TRACK[20] using the value of energy spread from the ECR source showed that a significant phase spread $\Delta\phi \sim \pm 22.5^\circ$ arising from the energy spread, would need to be accomodated by the RFQ phase acceptance ellipse. In Fig. 11, 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 such as gas pressure and RF power play a critical role in deciding the energy spread of the ion beams extracted, it would be

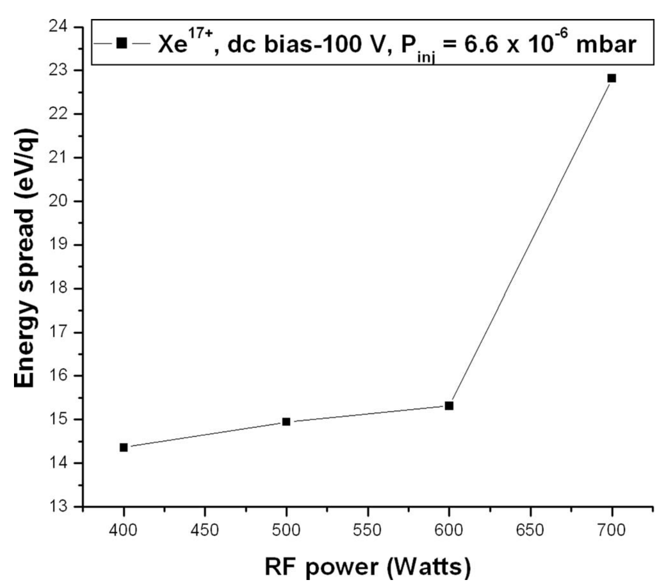

FIG. 10. Energy spread at FWHM as function of RF power, calculated from the derivatives of the current versus voltage distribution function for Xe^{17+}.

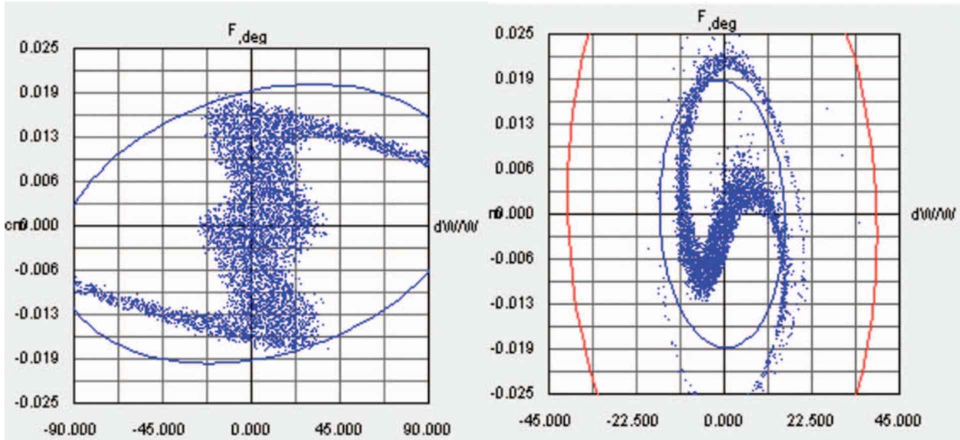

FIG. 11. Longitudinal phase space at the entrance and exit of the RFQ situated 4.0 m downstream from the multi-harmonic buncher.

necessary to optimise these parameters as determined from the present study for good transmission of the ion beams through the high current injector.

V. SUMMARY

The variation of the plasma potential in an ECR plasma has been studied as a function of different source parameters and for several ion beams which clearly shows a mass effect. Operating the source at higher gas pressures and high RF power increases the plasma potential. In case of gas mixing, it is observed that the plasma potential reaches a minimum at an optimum value of the pressure of the mixing gas and the mean charge state maximizes at this value. On the other hand, the dc bias and gas mixing reduces the plasma potential. The energy spread arising from the plasma potential measurements influences the longitudinal optics of the high current injector in terms of increased phase spread that deteriorates the transmission through the RFQ. It is shown that tuning of the ion source parameters such as dc bias and gas mixing can bring about a reduction of the energy spread of the ions. 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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[20] See http://www.phy.anl.gov/atlas/TRACK/ for further information on the code TRACK used for beam dynamics simulation in accelerators and transport lines with 3D electric and magnetic fields.