Chapter – 4

4 Ion Energy Spread Measurements

4.1 Introduction

Spread in energy of the extracted ion beam, i.e. $\Delta E$ is an important parameter for an ion source. This point is valid because of various reasons such as: 1). The $\Delta E$ produces a time spread in nanosecond pulsed ion beam after a drift path, 2). $\Delta E$ of ion beam will result in aberrations from the ion-optic system causing an increase in the beam emittance or reduction in focusability. Thus for applications like FIB, it is essential to find out the actual value of $\Delta E$ of the ion beam and try to optimize the source for its minimisation. The importance of $\Delta E$ increases with decreasing ion energy $E$, specifically for the applications where the final spot size of the beam on the target is to be very small. Final spot size is governed by contributions from chromatic aberrations of lenses among other factors, which is directly proportional to $\Delta E/E$ [48]. Since the main aim of this work presented in this thesis is towards the production of micron / submicron ion beams at low ion energies, it is very important to minimize the ion energy spread as much as possible without compromising the ease of operation of the ion source as well as simplicity of the total configuration.

In this chapter, the details of studies on the ion energy spread of ions that are inside the plasma and the ions that are extracted are studied. Energy spread of the extracted ions is always higher than the plasma bound ions due to space charge effects, non uniform penetration of extraction field into the plasma etc which are hard to control. But, the energy spread of plasma bound ions can be minimized by various techniques. In this chapter, the fundamentals and origin of the ion energy spread, experimental set up to measure the ion energy spread of plasma bound ions as well as extracted ions, parameters for optimization and results are discussed.
4.2 Physical cause of Ion Energy Spread.

Depending on the nature of ion source, the physical cause of the energy spread varies. Energy exchanges between particles and existence of any non-uniform potential inside the plasma are the main causes of $\Delta E$ in plasma based ion source. Various elastic and non elastic collisions inside the plasma which involve energy in the range of few eV’s cause the energy spread. Resultant energy spread due to collisions is determined by the dynamic equilibrium between the electron heating and charge transfer cooling. Large energy spread can be generated by large field oscillations in plasma caused by instabilities and plasma oscillations. In many sources, there exists a potential difference between different points in plasma. Thus energy of ions varies depending on the point where they are generated. If ions are generated in plasma sheath they will have an energy spread representative of the sheath potential. If ions are generated near extraction zone, they will have an energy spread approaching the extraction voltage, but the fraction of ions generated in extraction zone is very small. Another serious obstruction for generating monochromatic beam is the lack of the stability of the extraction power supply.

In case of ICP the energy acquired by ions due to collisions are very less and are only slightly higher compared to neutrals. ICP based plasma devices are electrodeless and theoretically there is no sheath created by oscillating plasma. So ideally speaking ICP can produce very small energy spread ion beam, though practically we can see that ion energy spread is in the range of 10’s of eV. This is because that discharges are not ideally inductive and there exists a small capacitive coupling of RF power to the plasma. Voltages on the coil can be as high as 1000’s volts. RF coils form a capacitance with the plasma in the tube. There are two capacitances formed, one is the capacitance between the coil and the plasma sheath and the other is the sheath to the bulk plasma. Sheath capacitance is much larger than the coil to sheath capacitance and these two form a voltage divider and very small voltage is coupled to the bulk of plasma. It is known that ICPs produce high density plasma as compared to other devices. Due to the fact that the ionization is dominant in the periphery of the plasma chamber, there exists a high density plasma at the periphery and hence offer very small skin depth for the
electromagnetic field to penetrate to the bulk of the plasma. Existence of high density plasma, small sheath thickness and the small sheath voltages, ICPs play a very important role in the integrated circuit manufacturing as well as high quality ion source.

The pure inductive discharges can be depicted as shown in Figure 4-1. Ions coming from quasineutral plasma are accelerated in the presheath region, which may be considered to be collisional for almost all pressures considered in this thesis work. The distribution which develops in the collisional presheath has been discussed by Riemann [49] and is shown that the ion energy distribution (IED) at the presheath-sheath transition has a peak at $kT_e$. Having this distribution, the ions enter the thin, collisionless sheath region. The IED observed at the wall is thus simply the distribution at the presheath-sheath transition, which is shifted along the energy axis about the value of the sheath potential. The peak energy of the IED at the wall should thus be equal to the potential drop $\Delta \phi$ within the sheath plus one $kT_e$ for the energy gain in the presheath.

Although the energy distribution is a single peak, it may still be broadened by a few eV due to a small time dependent modulation of plasma potentials by electrons that come under the influence of capacitively coupled RF electric fields between the plasma and the coil [50]. The fundamental limit to the energy spread is typically quoted as $T_e/2$, where $T_e$ is the electron temperature in eV. Since for ICP, electron temperature is 3 – 4 eV an axial energy spread of 1.5 – 2 eV should be possible in the absence of Boersch effect, charge exchange collisions and plasma potential modulations [51].

In practice, the ion energy spread is far from the ideal value listed above. There is also a strong dependence on gas pressure, magnetic field, plasma chamber body material, plasma contaminations etc. Complete elimination of capacitive coupling of RF voltages is not possible and is not desirable since small coupling is required to initiate discharge. However there is a significant scope to further minimize the energy spread by using various techniques. Several works are reported on the techniques such as using magnetic filters at the extraction region [52], using push-pull coil configuration where centre of the coil is grounded [29], using Faraday shield etc. to reduce the ion energy spread in ion sources.
Ion source described in this article, whose size being very small, there is a space constraint to employ the magnetic filters at the extraction region. The antenna size is also small and has only 5 turns offering very low inductance and resistance, so that it is impractical to use push-pull coil configuration. Other parameters such as Faraday shielding, RF power \(P_{rf}\), gas pressure \(P\) and coil orientation that can control the ion energy spread and mean energy which can easily be implemented on such small size ion sources are studied. In the following sections, these techniques and their effects on the energy spread and mean energy of the ions, experimental arrangements and the results are discussed.

4.3 Experiments and results

4.3.1 Retarding field energy analyzers (RFEA) for measurement of \(\Delta E\).

Retarding field energy analysers are the most convenient and most widely used for plasma and ion beam diagnostics [53]. In this and the next section, energy analysis of ions in two regions is dealt with. Ions inside the plasma have energy spread due to collision and due to plasma modulation by capacitively coupled RF voltages from an antenna. The peak energy of ions is determined by the plasma potential which is very low in case of ICP. In our case it is in
the range of 30 – 50V over the wide range of power that have been used in the work presented in this thesis. Y. Zou. et al., [54] [55] have shown that the errors in the measured energy spread is a function of total kinetic energy of the beam.

$$\Delta E = E_0 \sin^2 \theta$$  \hspace{1cm} (1)

Where, $\Delta E$ is the measured energy spread, $E_0$ is the total longitudinal energy of the beam and $\theta$ is the ratio of transverse to total kinetic energy of the ion beam. Since $E_0$ being very small for the ions that are inside the plasma, the conventional RFEA has been used.

Measurement of energy spread of plasma bound ions is important to understand and implement methods to minimize the spread. However, the final focused spot size depends on the energy spread of the accelerated beam which is generally higher than that of plasma bound ions. The measurement of extracted ion beam is complicated by the fact that the ion beam has finite divergence and beam emittance. By proper design of extraction electrodes and operating the ion source with optimized parameters both divergence and emittance can be minimized. However, the conventional RFEA gives errors that are proportional to total kinetic energy of ion beam and the divergence inside the analyzer as seen in Eq. (24). In order to accurately measure the ion energy spread of the extracted ion beam, RFEA that has additional electrode to control the divergence inside the analyzer is designed and will be explained in section 6.6.

4.3.1.1 RFEA for Plasma bound ions.

Since the plasma in the ICP can attain a potential of the order of 30-50V, the total kinetic energy of the ions may be in the range of 30 – 50 eV, a conventional RFEA has been utilized to carry out the measurements. The RFEA utilized in the following experimental investigations is designed based on the work of C. Bohm et al., [56] schematic of which is shown in Figure 4-2. The RFEA consists of four grids and a collector plate, all arranged parallel to each other. Though difficult, efforts were made to align the wires in the grid electrodes as much parallel as possible to each other using a microscope in order to minimize the experimental errors.
The first grid G1 is connected to a stainless steel electrode having an aperture of 2 mm diameter and the plasma to be analyzed is sampled through this. This arrangement minimizes the possibility of perturbation of plasma boundary due to the electric field present in the energy analyzer which otherwise would cause divergence in the ion trajectories resulting in error in the measured energy spread. A negatively biased second grid, G2 is used for preventing the electrons in the plasma reaching the collector. Third grid, G3 is retarding grid to which a variable voltage power supply is connected. Fourth grid, G4 is for suppressing the secondary electrons from the collector plate C, where C is connected to a Keithley pico-ammeter for ion current measurements. Grids are made of stainless steel mesh of 0.08 mm diameter wires providing a transparency of 66% to ions. All the grids are insulated by 1 mm thick Teflon insulators. The energy resolution of this type of analyzer depends mainly on the lens effect caused by the apertures in the grids and for the present set up as shown in equation 2 and it is calculated to be 0.8% of the mean beam energy according to the work by C L. Enloe et al. [55].

\[
\frac{\Delta E}{E} = 1 - \frac{2\pi (d/a) - \ln 4}{2\pi (d/a) - 2\ln[2 \sin(\pi r/a)]}
\]  

(2)

Only those ions which have energy to overcome the voltage applied to the retarding grid shall pass through the grids and reach the collector. The dependency of collector current with retarding voltage represents the integral of ion energy distribution (IED) and full width half maximum (FWHM) of the IED gives the energy spread. The IED, \( f(v_z) \), can be written as
\[ f(v_z) = \frac{e^2}{AM_i} \left( -\frac{dI(V_r)}{dV_r} \right) \]  

(3)

Where \( v_z = \sqrt{2eV_r/M_i} \), \( M_i \) is the mass of ion, \( e \) is the elemental charge, \( A \) is a constant obtained from the transparency of the grid and \( V_r \) is the retarding potential and \( I \) is the current reaching the collector at \( V_r \) [56].

4.3.1.1.1 Experimental results and optimization of the plasma source.

Ideally, the fundamental limit to ion energy spread in the plasma is \( T_e/2 \) as explained in section 4.2 which is < 2.5 eV. However, in most ICP sources, ion energy is different from ideal case. In case of insulating plasma chambers, such as quartz tube or ceramic chambers, there exists finite capacitance between the external helical antenna and plasma inside the chamber. Large RF voltages appearing across the antenna couple to plasma capacitively. By employing a Faraday shield made of vertically slotted thin copper foil, between plasma chamber and the antenna, capacitive coupling of high RF voltages from antenna to plasma is minimized. However, by using Faraday shield of transparency less than 20%, it became increasingly difficult to initiate the discharge. With this arrangement, to initiate the discharge, it was required to operate the ion source with more than 350 W of RF power and at high gas pressure. After striking the initial discharge and before making any measurements, the applied power was reduced and impedance matching unit was readjusted to achieve almost zero reflected power. Power densities in the plasma chamber are of the order of 4 – 8 W/cm³ which are reasonable to produce sufficiently high ion current densities from the ion source.

It is important to have as low RF voltages as possible on the antenna end that is towards the ion beam extraction electrode so that parasitic coupling of RF power is minimized at that region. To achieve this, grounded end of the helical antenna is placed towards the extraction side. To compare the effect of coil direction, IEDs were obtained with different coil configurations. Figure 4-3 shows the ion energy spread obtained while there was no faraday shield and placing the grounded end of the coil away from the extraction electrodes. It also shows a bimodal distribution with large width of the prominent peak. This shows a strong capacitive coupling. Just by reversing the coil and keeping the grounded end of the coil towards...
the extraction side, the ion energy spread reduced from 59 eV to 52 eV while the mean energy ($E_{\text{mean}}$) reduced from 81 eV to 63 eV. This shows that the minimization of capacitive coupling near the extraction region is more effective than that of the bulk of the plasma away from extraction region and also it is evident that the high voltage end of the antenna capacitively couples more energy to plasma making the IED non-uniform throughout the bulk of the plasma along the axis. Same experiments were repeated with the use of Faraday shield made of vertically slotted thin copper foil having 80% transparency and results show a drastic reduction in mean energy and energy spread. A mean energy of 43 eV and energy spread of 10.5 eV were obtained where the ground of the antenna is away from the extraction system and mean energy of 41 eV and energy spread of 8.5 eV were obtained after reversing the antenna. All the distributions are obtained at 50 W of RF power and with argon gas pressure of 0.01 mbar. It is very clear from the distributions that without the use of Faraday shield there is significant capacitive coupling of RF power to plasma inducing large fluctuations in the plasma sheath. These fluctuations in the sheath accelerate ions as well as electrons thereby increasing the mean energy and energy spread. Another consequence of large capacitive coupling of RF power is that, ions with large energies sputter the electrodes causing deposition of thin metallic layer on the inner surface of plasma chamber. This thin metallic film completely shields the coupling of RF voltages that are essential for initiation of plasma and makes it impossible to strike the discharge. It is seen in our initial experiments that with the existence of large capacitive coupling of RF power to unshielded plasma, ion source life was never more than 5-6 hours.

In an effort to reduce the capacitive coupling of RF power to plasma near extraction region, an experiment was carried out by shielding the last two turns of the antenna with very fine slots in the Faraday shield. With this arrangement IED was measured and found very encouraging results. Even though with more than 50% of plasma that is away from the extraction region is exposed to antenna, energy spread was found to be surprisingly low. Figure 4-4 shows $\Delta E = 6$ eV, but the mean energy is still more than 55 eV and a small population of high energy ions is still present. It is also clear that, at the extraction region, fluctuations in plasma sheath are less and sheath thickness is very small resulting in production of nearly mono
energetic ions. With this arrangement, though the discharge initiation was possible at low pressure and low RF power, fine metallic film was formed on the inner surface of the plasma chamber after operating the ion source for over 50 hours. This limitation was due to high plasma potentials of the order of 50 – 60 V that accelerate Ar ions towards the plasma electrode and cause sputtering. For 60 eV Ar ions, the sputtering yield of stainless steel is greater than 0.1 and hence it is essential to reduce the plasma potential further to increase the operating life of the ion source [58].

![Figure 4-3](image)

**Figure 4-3** IED obtained for a configuration with no faraday shield and ground lead of the coil towards the extraction side.

Other major control parameters of ion source to reduce the ion energy spread and the mean energy are gas pressure and RF power. At higher gas pressures, sheath is collisional and though mean energy is low, the ion energy spread is large and shows bimodal energy distribution with low energy population of ions. Figure 4-5 Dependency of pressure on IED obtained at $P_{rf} = 50W$. Figure 4-5 shows the variation of energy spread and mean energy of the ions with gas pressure. As gas pressure is reduced from 0.06 mbar by one order, ion energy spread reduced from 19 eV to 8.2 eV, but there was a steady increase in the mean energy from 33 eV to 43 eV and the low energy tail in the distribution also disappeared. Further reduction in the
gas pressure caused marginal reduction in the ion energy spread, but there was significant reduction in the ion current.

Ion energy spread is markedly dependent on the applied RF power. Measured energy spread reduced 10 eV to 6 eV and showed minima at about 100W as shown in Figure 4-6. These IEDs were obtained with 80% transparent Faraday shield and gas pressure of 0.03 mbar. Occurrence of this minimum in the figure can be explained as follows. At low RF powers, the plasma conductivity is low and hence the quality factor (Q) of the antenna remains equal to the unloaded Q, thereby producing high voltages across the antenna. These high voltages increase the capacitive coupling effect on the plasma and deteriorate the energy spread of ions. At higher RF powers, electrons become more energetic and cause larger ion energy spreads. At optimum RF power, plasma density is high and as a consequence of which the skin depth reduces, attenuating capacitive coupled RF power reaching the bulk of plasma. It is also interesting to note that optimum RF power was different at different gas pressures. In all above experiments it was observed that mean ion energy was still high and it was essential to reduce it further below the sputtering threshold of steel electrode which is about 40 eV.

Capacitance between the antenna and the dielectric wall of the plasma chamber and that between the dielectric wall and the plasma form a capacitive divider network. RF voltages from the antenna are divided by these two capacitors. Plasma sheath, being very thin in inductive discharges, offers high capacitance and thereby small RF voltages appear across the plasma sheath [29]. To reduce the coupling of RF voltages further, antenna diameter was increased from 35 mm (inner diameter) to 55 mm. Increasing the diameter of the antenna demanded higher RF power for initiation of plasma and total ion current reduced as the power coupling efficiency reduced due to increased gap between antenna to plasma. To initiate the plasma and obtain higher ion currents at lower powers, plasma chamber was modified by dividing it into two equal portions by a quartz separator with small aperture for gas flow. This new plasma chamber and its efficacy in triggering the plasma discharge is explained in detail in chapter 2. Low plasma potential obtained due to pure inductive discharge in the lower chamber helped in extending the ion source life. This configuration of ion source has been under use for more than
500 hours and there has not been any deterioration in the performance. It is expected that this ion source will operate with the same performance for still longer time.

![Graph showing IED obtained by providing a Faraday shield for two turns of antenna.](image1)

**Figure 4-4** IED obtained by providing a Faraday shield for two turns of antenna. $P_{rf} = 50W$, $P = 0.01$ mbar. $\Delta E = 6.2$ eV, $E_{mean} = 51.5$ eV.

![Graph showing dependency of pressure on IED obtained at $P_{rf} = 50W$.](image2)

**Figure 4-5** Dependency of pressure on IED obtained at $P_{rf} = 50W$. 
Figure 4-6 Variation of $\Delta E$ with power at $P = 0.03$ mbar. Minimum $\Delta E = 6$ eV obtained at $P_{rf} = 100$ W.

Figure 4-7 V-I characteristics obtained from RFEA at an optimum source configuration and the IED. $\Delta E = 4$ eV, $E_{mean} = 38$ eV

By employing all the optimized parameters such as Faraday shielding, RF power (100 W), gas pressure (0.030 mbar) and coil dimension, very low ion energy spread of 4 eV and low mean energy of 40 eV were obtained. Figure 4-7 shows the plot of ion current with retarding potential and its differential showing the mono energetic IED.
4.3.1.2 Energy spread measurement of extracted beam.

As explained earlier, the beam in practice will have divergence irrespective of any efforts. In case if the beam is considered ideal, conventional RFEA would provide a step like characteristics where all the ions are reflected at one single retarding voltage. Even if the beam is monochromatic, it will have some amount of divergence and thus for extracted ion beam, the simple RFEA did not prove to be very useful. Figure 4-8 shows the V-I characteristics obtained from RFEA for ion beam with two different extraction voltages of 500 V and 1000 V and they have shown an energy spread of 49 eV and 78 eV respectively. Although the extraction process can induce some additional energy spread in the ion beam, the present measurements are abnormally high and show the inefficiency of RFEA measurements for ion beam with higher energies. For improvement of measurement accuracy of RFEA, the beam entering the device has to be parallel. One way to do this is to keep the RFEA far off from the extraction side and perfectly aligned with the beam center, so that the central parallel beam is sampled by RFEA. Another method is to decrease the diameter of the sampling aperture and to increase its thickness and thereby allowing only a collimated beam inside the RFEA.

Figure 4-8 Energy spread of ion beam with two different energies. First graph shows beam extracted by 500 V and second one is that by 1000 V
Although the aperture improves the resolution of the RFEA, the signal to noise ratio deteriorates as significant amount of current is discarded by the aperture. More serious issue with this method is the formation of lens effect by the aperture and the retarding grid, which introduces further divergence to the beam inside the analyzer [59]. This situation worsens as the energy of the incoming beam increases as given by Eq. (24) [12]. Some works have utilized, Hemi-spherical [60] [61], cylindrical [62], etc type of analyzers to improve the resolution, however, although they have better resolution, all of them have common disadvantage of being very bulky. An excellent review on various types of analyzers and the effect of few parameters of beam and analyzers is carried out by N J Taylor [63]. A new type of compact and high resolution energy analyzers based on the works of Y Cui et al [64][65] has been designed to carry out the energy spread measurement of extracted ion beam, which is very compact and offer good resolution. The schematic is shown in Figure 4-9. A suitable focusing field is generated by the focusing electrode shown in the figure to make the diverging beam parallel to the axis of RFEA to improve the measurement accuracy. The only change from the conventional RFEA is the introduction of additional electrode to create a field to create parallel beam inside the analyzer.
4.3.1.2.1 Experimental results

![Graph showing variation of measured energy spread with the voltage on the focusing electrode.](image)

Figure 4-10. Variation of measured energy spread with the voltage on the focusing electrode. Operating parameters of ion source are Vext 2 kV, RF power 100W.

After all the techniques of optimization of energy spread of ions inside plasma as explained in previous section, the minimum energy spread achieved and measured was 4 eV at 100W of RF power. Measurements carried out on 4 kV ion beam using conventional RFEA with a fine aperture and kept at a long distance from extraction system showed that minimum achievable energy spread was about 8 eV. With the same operating parameters, the energy spread of extracted ions is 8 eV while plasma bound ions it is 4 eV. Further reduction in the measured energy spread was not possible due to the limitation of measurements in planar RFEA for divergent ion beam. Ion beam divergence is mainly due to the formation of meniscus in the plasma boundary and the space charge repulsion.

With the use of newly a designed variable-focusing RFEA, the measurements were carried out, minimizing the errors in the measurements and obtained the lowest possible energy spread of 4.2 eV at 100W RF power and 4 kV extraction voltage. It was seen that measured energy spread varies with the voltage on the focusing electrode reaching a minima of 4.2 eV at 80V indicating that the divergent beam is made parallel to the axis of the analyzer. Variation of measured energy spread with the applied voltage on the focusing electrode is shown in the Figure 4-10. When no voltage is applied on the focusing electrode the energy measured energy
spread is about 7 eV and the as the voltage is increased, measured energy spread decreases and reaches a minima where the diverging beam is made parallel to the axis of the RFEA. Further increase in the focusing voltage increases the measurement error once again due to the formation of the crossover of beam trajectories inside the analyzer and introducing the divergence once again.

Experiments were carried to optimize the gas pressure to obtain the minimum energy spread by variation of gas pressure in the plasma chamber as shown in Figure 4-11. It is worth to note that the plasma bound ions showed the minimum energy spread at a gas pressure about 0.03 mbar and the range remains same for the measurements shown on the accelerated beam. This clearly shows the effect of increase in energy spread with energy of ions is clearly minimized by the new type of RFEA. Further experiments were carried out to see the minimum energy spread that could be achieved for minimum practical power, pressure and maximum possible Faraday shielding.

With 20% transparency of Faraday shield, though the initial discharge was difficult, it was easy to maintain discharge upto 50W of RF power and the measurements shows energy spread of 2.6 eV at 2.5 kV extraction potential, gas pressure of 0.02 and 50W RF power as shown in Figure 4-12. Further increasing the Faraday shielding to < 10% transparency, though required more than 200 – 300W of RF power to start the discharge, there was stable plasma at 50W and
energy spread could be reduced to theoretical minimum which is 1.8 eV. The proposed fundamental limit to the energy spread solely due to presheath potential gradient is shown to be about \( \text{Te}/2 \) by K U Riemann et al.\cite{51}. Since electron temperature for ICP plasma is about 3 - 4 eV, the energy spread of 1.5 to 2 eV is possible. However the brightness of the beam is very low at these operating parameters of the ion source.

![Figure 4-12. Measurement on 2.5 keV beam at 50W of RF power and gas pressure of 0.02 mbar.](image)

**4.4 Conclusion:**

Ion energy spread being very important parameter for several applications and in particular for production of focused ion beams. Detailed studies are carried out on the plasma bound and the extracted ions after acceleration. By optimizing various parameters, energy spread of the plasma bound ions were reduced to 4 eV at about 100W of RF power and 0.03 mbar of pressure. Faraday shielding and the coil direction were very effective parameters to reduce the ion energy spread. 80% shielding provided the best results and it was relatively easier to start the discharge. Extracted ion beam was characterized by modified RFEA that was essential for minimizing the errors in the measurements. With the modified RFEA nearly 50% error in the measurement was eliminated. Energy spread of \(~4\) eV was measured on both the
plasma bound and extracted ion beams indicating that there is no additional increase in the energy spread after extraction and acceleration. Further by increasing the Faraday shielding to >90% and operating ion source at low RF power (50 W), the energy spread was minimized to 1.8 eV which is almost the theoretical limit. At these low power and high Faraday shielding the total current available was very low indicating low brightness of the beam. However, at 140 W of power and 7 kV extraction potential and 80% shielding, brightness of beam is measured to be (explained in following chapters) > 7000 Acm⁻²ev⁻¹sr⁻¹. By further optimization of extraction geometry, injecting electrons in the plasma and using several other novel techniques, the energy spread can be reduced to near theoretical limits while operating the source at high power and high extraction voltages. Energy spread of about 4 eV contributes to image blurr of the order of few 10’s nm to the total beam size. This low energy spread is quite sufficient for achieving nm diameter size beams.