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Emittance Measurements of the Ion Sources for Induction Linac Driven Heavy Ion Fusion

Heon-Ju Lee
Cheju National University
1 Ara-dong, Cheju 690-756, Korea

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Abstract

The ion sources for induction linac driven heavy ion fusion were fabricated and their emittance characteristics were investigated. For two kinds of ion sources, i. e. a carbon vacuum arc ion source and a cusp field rf ion source, the emittance was measured with a double slit beam scanner. The required normalized emittance of an ion source for heavy ion fusion is $10^{-7}-5\times10^{-7}\pi$ *m-rad*, and the measured emittances of the ion beams from carbon vacuum arc ion source and cusp field rf ion source (Ne^+) were $2\times10^{-6}\pi$ *m-rad* and $4\times10^{-7}\pi$ *m-rad*, respectively.

1. Introduction

The use of heavy-ion accelerators as drivers to initiate inertial confinement fusion(ICF) reactions has been under study since 1975[1]. In order to achieve the heavy ion fusion, the ability of delivering the sufficient energy density to the pellet is critical. The heavy-ion accelerator concepts to provide the desired ion pulse(1 to 10MJ of 5-to 20-GeV ions of atomic mass number between 130 and 238amu) included a rf linac-accumulator system[2], and an induction linac system[3].

In the rf linac/storage-ring method which is progressing in Germany and Japan, the current that can be transported in a pulse is limited by beam loading effects in the resonant cavities used to generate the electric fields necessary for beam acceleration.

The induction linac system, which is mainly studied in U. S. A., can accelerate very high peak current short pulse beams at moderate repetition rates that is useful for the fusion application.

The ion source that can be used with the induction linac should be a large aperture low emittance source providing very high currents with stable short pulse extraction optics. The short pulsed ion beam is preferable because the long pulsed one requires a vast amount of induction core and cost.

To focus the beam well on the target at the end of the accelerator, the emittance should be low. If it is necessary to produce a small radius r of the focused ion beam on the target, the normalized emittance should be

$$\epsilon_n < \beta\gamma\, r\, \theta$$

where θ is the convergence cone half angle, r is the beam radius on the target, β is the particle velocity divided by speed of light, and $\gamma = (1-\beta^2)^{-1/2}$.

The normalized emittance n required at the final lens is below $10^{-5}\pi$ *m-rad* for the typical case ($\theta \simeq 10$*mrad*, r $\simeq$ 3mm, and $\beta\gamma \simeq 0.3$). The required normalized emittance for the ion source is 10^{-7} $10^{-7}\pi$ *m-rad* if we assume the emittance growth through the beam transport in the accelerator is around 10^2.

Two types of ion sources were developed for the induction linac heavy ion fusion experiment and their emittance chracteristics were investigated. One was a carbon vacuum arc source and the other was a rf driven cusp field Ne^+ source. These sources were intended to provide beams for scaled beam physics experiments[4].

2. Source Description

2.1. Carbon vacuum arc ion source

The carbon arc ion source is operated with a pulsed plasma which is produced by microexplosions at the surface of the solid cathode. The vacuum arc is a discharge between two metallic electrodes in a vacuum which is characterized by a low burning voltage (about 20V) and a high current (typically 50-500 A) [5].

This current flow through cathode is restricted to the small cathode spots with a size of the order of μm. Then the current density at the cathode spot is order of 10^6 A/cm^2 or upward, and the cathode spots emit a metal vapor current with a high velocity, up to 1000m/s toward the space between the cathode and the anode. In principle, the metal vacuum arc ion source may produce ions of all metal elements which is used as a cathode.

The structure of the carbon vacuum arc ion source is shown in Figure 1. Under the action of the high voltage triggering pulse, which is applid between the

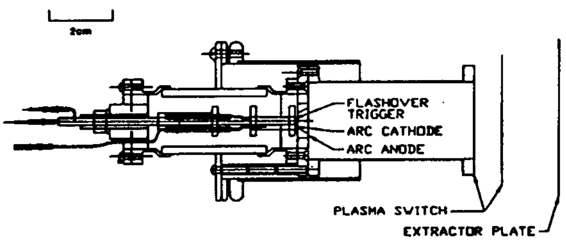

Fig. 1. Drawing of the Carbon Arc Ion Source

trigger electrode and the arc cathode, a surface flashover generates a plasma that drifts out into the main arc gap. This plasma shorts the gap between the arc cathode and an arc anode, and the output of a precharged L-C pulse forming network makes to flow an main arc discharge current up to hundreds of amperes. The metal vapor plasma established in the main arc gap region flows through a central hole of an anode and drifts down to the plasma switch structure.

In order to extract a suitable beam, the electrostatic plasma switch is introduced. The coupling between the properties of the plasma source and the optics of ions in the extraction gap is important for the extraction of high current-density, high brightness ion beams. The plasma source must achieve almost perfect flux uniformity in time and space to generate a low emittance beam.

In a conventional extractor in which ions are pulled directly from the plasma surface, if the plasma flux does not exactly match space charge limited flow, the beam may be over or under-focused. The electrostatic plasma switch is composed of double grids and the downstream grid is biased negatively with respect to the upstream one. The plasma electrons are repelled back toward the arc and the ions flow through this negative grid, forming a virtual anode on the downstream side. In this case, ion flow across the gap is controlled by space charge effect and the high degree of spatial and temporal beam uniformity can be achieved. Then the plasma extraction surface shape is constant through the extraction so that the particle trajectories will be constant. The bias voltage affects the emittance of the extracted ion beam both through the shape of the sheath surface at the anode and through facet-lens-focusing effect [6].

With respect to the electrostatic separation of ions from plasma electrons, the second role of the plasma switch is the removal of plasma noise effect in the extracted current pulse. Arc source have been shown to be very noisy at a high frequency[7]. By providing the plasma switch, the extracted current pulse is effectively isolated from the plasma noise which has the time scale of plasma oscillation and the reproducible result is obtained.

2.2. Cusp Field rf Ion Source

A cusp field source was designed. The source uses a 2MHz rf discharge to generate Ne^+ ions. The schematics of the source is shown in Figure 2. A small tungsten filament supplying the electrons is introduced to reduce the breakdown potential by supplying the electrons. To confine the electrons and enhance the ionization efficiency, the cusp field was formed around the ion source by 14 Nd-Fe bar magnets. The cusp field source is a cylindrical vessel, 4cm in diameter and 20cm deep. The maximum magnetic field strength was 1.1 kG at the wall and the field strength at the antenna region was kept less than 20G to minimize the magnetic field effect on the transverse velocity distribution and emittance of the extracted ion beam.

The main discharge is generated by a glass-coated copper antenna of 10 cm diameter with a pulsed rf generator of 5-13kW. The working gas is introduced through the puff valve whose opening time is 150μs to cw. This kind of valve can reduce the gas loading on the vacuum system.

The ion extraction hole with a diameter of 5 cm, and the ions are extracted through parallel fine meshes (90% transmission each). The distance be-tween anode and cathode is 32.8 mm.

3. Emittance Measurement

The figure of merit based on the effective volume occupied by the distribution of the beam in trace space(x, x') is denoted by the emittance.

The smaller the area occupied by the beam in trace space, the better the quality of the beam, so the beam has good focusability or parallelism.

The x-plane rms emittance is defined[8] as

$$\varepsilon_x = 4[\langle x^2 \rangle \langle x'^2 \rangle - \langle x, x' \rangle^2]^{1/2}$$

where, x' is the gradient of a particle trajectory given by $x' = dx/dz = p_x/p_z$, and the angular brackets, $\langle\ \rangle$, denote an average value over the two-dimensional trace space.

The measurement of a beam emittance was performed with a double slit beam scanner. The schematics of the double slit beam scanner is shown in Figure 3. It is composed of two stepping motor controlled movable plates with 0.1mm width narrow slits in them, a Faraday cup located behind the downstream slit and the signal processing unit.

The longitudinal distance between the upstream and downstream slit is 11cm. The upstream slit slices the beam according to its x position and the angular spread of the beam is analyzed by the downstream

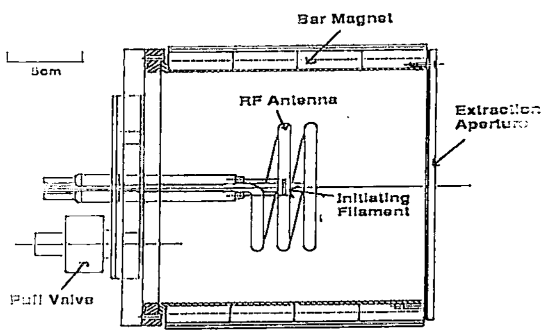

Fig. 2. Darwing of the Cusp Field rf Ion Scurce

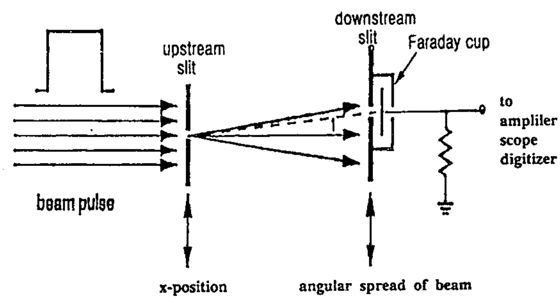

Fig. 3. Schematics of Emmittance Measurement with Double Slit Beam Scanner

slit. The instrument resolution is about $10^{-9}\pi$ *m-rad.*

For a skewed trace-space distribution of the beam, the emittance has to be calculated with the modified equation[9] as

$$\varepsilon_x = 4[\langle (x-\langle x\rangle)^2\rangle \langle (x'-\langle x'\rangle)^2\rangle - \langle (x-\langle x\rangle)(x'-\langle x'\rangle)\rangle^2]$$

And the normalized emittance ε_n is defined as

$$\pi\,\varepsilon_n = 4\pi\,\beta\,\gamma\,\varepsilon_x \text{ is den}$$

where, $\beta\,\gamma$ is the relativistic factor.

4. Experimental Result

The carbon vacuum arc source and the cusp field rf ion source were tested with planar extraction optics. The extraction voltage was supplied by a Marx generator which had a maximum voltage of 200 kV and the peak voltage duration could be varied from 10 s to 100 s by the crowbaring technique. The emittance was measured with the double slit beam scanner and the ion beam current was measured by the Faraday cup which had the negatively biased suppression grid structure for reducing the secondary electron effect. The ion beam current from the carbon vacuum arc ion source was obeyed the Child-Langmuir law given by

$$J = (4\varepsilon_0/q)\ \sqrt{2e/m}\ V^{3/2}/d^2,$$

and measured maximum current density was around $30\mathrm{mA/cm^2}$. The emittance scan for carbon vacuum arc ion source is shown in Figure 4, and the normalized emittance was around $2\times10^{-6}\pi$ *m-rad.* Unfortunately it did not fit the emittance requirement for the heavy ion fusion experiment because the required normalized emittance of an ion source for heavy ion fusion is $10^{-7} - 5\times10^{-7}\pi$ *m-rad.* To reduce the emittance further, the plasma temperature might be decreased. Some detailed characteristics of this ion source was described in reference[10].

The cusp field rf ion source used glass coated copper antenna, and the glass insulating layer was floated electrically at a much negative potential than the

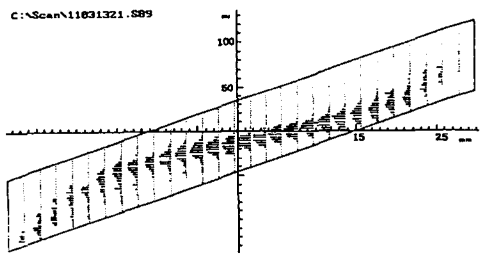

Fig. 4. Measured Emittance of the Carbon arc Ion Source

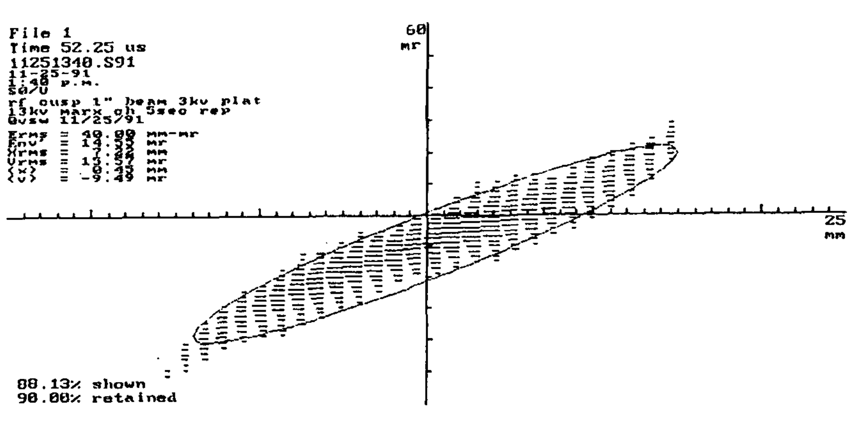

Fig. 5. Measured Emittance of the Cusp Field rf Ion Source

antenna itself. Thus the degree of sputtering was considerably reduced and the source efficiency was increased as mentioned by Leung[11]. The delay time between the opening signal of puff valve and the onset of rf power was optimized at 20ms. According to the ion current measurement,it was found that the minimum pressure for a reliable operation was about 1.1×10^{-4} Torr. When Ne was used as a working gas, the noise level in the extracted Ne^+ ion beam current was low, therfore the plasma in the ion source could be supposed to be very quiescent. The current density emitted was lager and different from the curve given by the Child-Langmuir law. The presence of electrons in the extraction region might be responsible to the discrepancy. To analyze the discrepancy, it would be desirable to study more on the plasma characteristics in the extration region.

The measured maximum current density was up to 37.5 mA/cm^2. The emittance scan for the cusp field rf source is shown in Figure 5, and the normalized emittance was around $4 \times 10^{-7}\pi$ *m-rad.*

5. Conclusions

The emittance of ion sourcec for heavy ion fusion is measured with double slit beam scanner. The normalized emittance of the carbon arc ion source is around $2 \times 10^{-6}\pi$ *m-rad* and that of the cusp field rf (Ne) ion source is around $4 \times 10^{-7}\pi$ *m-rad* .

So the required normalizede emittance for the heavy ion beam physics experiment is $1 \sim 5 \times 10^{-7}\pi$ *m-rad*, the carbon arc ion source has too high emittance and it is not fit for the experiment. The emittance of the cusp field rf ion source is on the border of the necessary value. To apply this ion source in the experiment, the other characteristics including the stability for the prolonged operation has to be checked.

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