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Abstract

The use of ion sources in induction linacs for heavy ion fusion is fundamentally different from their use in the RF linac-storage rings approach. Induction linacs require very high current, short pulse extraction usually with large apertures which are dictated by the injector design. One is faced with the problem of extracting beams in a pulsed fashion while maintaining high beam quality during the pulse (low-emittance).

Four types of sources have been studied for this application. The vacuum arc and the RF cusp field source are the plasma types and the porous plug and hot alumino-silicate surface source are the thermal types. The hot alumino-silicate potassium source has proved to be the best candidate for the next generation of scaled experiments. The porous plug for potassium is somewhat more difficult to use. The vacuum arc suffers from noise and lifetime problems and the RF cusp field source is difficult to use with very short pulses. Operational experience with all of these types of sources is presented.

INTRODUCTION

The use of induction linear accelerators for heavy ion fusion is the chosen path of research for the present U.S. program. Induction linacs offer a technique for accelerating very high peak current short pulse beams at repetition rates that are useful for the fusion application. In an induction linac the current that can be transported in a pulse is dependent on the transport optics and on the pulsers driving the acceleration modules. R.F. linacs by contrast are limited by beam loading effects in the resonant cavities used to generate the electric fields necessary for beam acceleration. For heavy ion fusion drivers one needs beams of very heavy ions such as Pb^+ or Bi^+ or a moderate mass ion such as Cs^+ with current levels of amps per beam for 20-30 μs out of an injector at a few megavolts energy. Low emittance (10^{-7} - 5×10^{-7} π m-rad normalized) is needed if the beam at the end of the accelerator is to be well focused on the target. For scaled beam physics experiments other ions such as Ne^+, K^+, or C^+ can be used with shorter pulse lengths (1-2 μs). The shorter pulse length creates a problem in the extraction dynamics, but it is dictated by the cost of ferromagnetic core material for the machine. The longer the pulse, the more core material is necessary and the longer pulse length provided may not significantly improve the experiment itself. The use of RF linacs would permit the use of small aperture sources feeding beam into an RFQ structure in a steady state fashion. Use of induction linacs however require large aperture – low emittance sources providing very high currents with stable short pulse extraction optics. Three approaches to this problem have been investigated: a carbon vacuum arc source, an RF driven cusp field Ne^+ source, and solid state thermal source of K^+ (two versions). All of these sources were intended to provide beams for scaled beam physics experiments and not for a driver. In some ways the driver problem is actually easier. Long pulse extraction with optical stability is easier than short pulse extraction. Also for a driver, heavier ions, more easily provided in a thermal source are of interest.

From the point of view of engineering a system the plasma sources are interesting because they consume much less energy than the heated sources. However, the extraction problem is more complicated with these sources. Thermal sources in general also restrict one to the use of alkali metal ions. The use of porous plug high work function surface sources such as tungsten and iridium can lead to undesirable metal deposition on insulator surfaces if the alkali metal feed rate is not properly regulated.

SOURCE DESCRIPTION

Carbon Vacuum Arc - The carbon vacuum arc[1] is a pulsed plasma source. It is run using a pulse forming network circuit to drive the arc. Carbon ions from the cathode spot flow toward the extraction region. In order to extract suitable beam two things must occur. First the plasma extraction surface must be kept to a constant shape throughout the extraction so that the particle trajectories will be constant. Second, inherent plasma noise must be removed in order to provide reproducible pulses with constant current in the pulse. Arc sources have been shown to be very noisy at a high frequency.[2] Therefore when one is extracting pulses on a time scale, short with respect to a plasma oscillation, non-reproducibility of the current pulses results. The device for combating this problem and the problem of keeping a constant emission surface is the electrostatic plasma switch.[1] This is an electrostatically biased grid which repels plasma electrons back toward the plasma source and forms a virtual anode layer from which beam can be extracted by applying a voltage pulse to an extraction gap in which the plasma switch grid itself is the anode.

Cusp Field Plasma Source - The cusp field plasma source is shown in fig. 1. The source uses a $2MH_Z$ RF discharge to generate Ne^+ ions. The discharge is initiated by electrons from a small low power hot tungsten filament. In order to get a fixed emission surface, the plasma switch is used here also as shown in fig. 1. In this source gas can be puffed into the source to reduce gas load in the injector accelerating structure and the RF generator can be pulsed for low power consumption. The source can be used with any gaseous element or any element that can be vaporized in an arc discharge. The ions from this type of source are known to be low in temperature(3) thus providing low emittance beams.

Alumino-Silicate Thermal Source (Zeolite Source) - This source is a solid state emitter consisting of a thin layer of alumino-silicate, doped with the desired alkali metal species, melted onto a porous tungsten substrate. The alumino silicate is made by a process devised by Feeney(4). The mixture is stoichiometric and the reaction is $K_2 CO_3 + Al_2O_3 + 4 Si O_2 \rightarrow K_2O \bullet Al_2O_3 + 4 Si O_2 + CO_2 \uparrow$ at a temperture of 1200 - 1500^o C in air. The resultant material is powdered to 400 mesh size mixed with dionized water and painted onto a porous tungsten substrate. The coating is fired in a vacuum furnace at 1550-1575^o C for one hour after very slow heating and then slowly cooled to prevent cracking.

This source has the disadvantage of requiring high temperature (~1000^o C) to get good current density emission, thus requiring considerable power generation in the injector system and also removal of the radiated heat emitted into the accelerating structure. Also the supply of ions available from a source is limited by the amount in the coating. In the case of beam physics experiments, this is not an issue, but for drivers it can be. Finally, one is restricted to alkali metal ions. Offsetting these disadvantages, one gets excellent emission surface control, very low temperature ions, no significant neutral emission, and a simple source electrical system. A high work function porous plug emitter has many of the same characteristics, but without the lifetime limitations. It is also more difficult to produce ions lower in mass than Cs^+ with this type of source, because of the higher ionization energy at lower masses.

EXPERIMENTAL RESULTS

The carbon arc and the cusp field source were both tested on the same test stand using planar extraction optics, Faraday cups for current measurements and double slit emittance scanner.

The carbon source together with the plasma switch provided more than the 25mA/Cm^2 of C^+ ions required for the application for which it was intended. The emission followed the $V^{3/2}$ dependence expected from the Child-Langmuir law. Unfortunately the emittance from the source was approximately 2 x 10^{-6} π m-rad normalized while the required emittance was 5 x 10^{-7} π m-rad from this 5 cm diameter source. The high emittance was attributable to the electric fields in the plasma switch grid. In addition the source would only last for 20-30 x 10^3 shots without failing. The flashover trigger surface would become covered with carbon and the trigger would be shorted The second problem could be overcome by using a gas breakdown trigger, but the emittance problem could not be solved without eliminating the grid.

A cusp field source was designed and tested. This source as intended for scaled beam experiments that would use heavier ions than carbon. The two chosen ions were Ne^+ and K^+, the latter permitting use of a different source described below. The cusp field source was a cylindrical bucket 25.4 cm in diameter and 20 cm deep. This cusps were formed by 14 bar magnets (neodymium - iron) with a peak field at the wall of 1.1 k gauss and less then 20 gauss inside the antenna region. The main discharge came from a helical porcelain coated antenna driven with a 5-13 KW pulsed RF generator with a variable pulse length up to 80 μsec. In these experiments the gas was continually fed into the chamber and ambient pressure was a few millitorr. In order for the ionization efficiency of the source to be high, the end of the bucket where extraction takes place, must be biased negatively to repel electrons but it must also let neutral plasma drift to the plasma switch so that the virtual anode layer can be formed and constant emission optics be maintained. This type of source was tested at various switch conditions, power levels, and operating pressures. The result was that the low ion temperature and resultant low emittance of the source could not be achieved with the use of the plasma switch. One different condition with respect to the carbon source exists here, namely that neutrals from the gas flow are present in the switch region at the time of extraction. The emission from the source using pulsed extraction did not show the Child-Langmuir dependence found with the carbon arc source in either magnitude or slope. This suggests that the plasma switch was not effective in this application and that neutral plasma drifted into the extraction gap. Current measurements with electrostatically biased faraday cups were simply impossible. A magnetically controlled cup using fields up to 450 gauss (900 gauss available, but unnecessary) produced credible results though the failure of the emission to follow the $V^{3/2}$ law indicated that the interaction between the source and plasma switch was not understood. A computer modeling effort did not lead to a solution.

As mentioned above, the stability of emission surface during the short pulse is a very important factor. Solid state sources provide this advantage. Past experiments using alumino silicates(5) had shown relatively low emission of species other than Cs^+. Cs^+ zeolites sources were used in previous LBL experiments routinely. The new coating method described above offered the promise of more durable source coatings and, because no aluminum-oxide cement was used as in the previous design, the promise of higher ion emission. This effect had already been observed in upgrades of the old Cs^+ sources but not with potassium. A 2.54 cm diameter test source was prepared to be tested on the Single Beam Transport Experiment at LBL. A photo of the source, the focus electrode, and the heater assembly are shown in fig. 2. This type of source is operated near 1000° C and the 15 cm diameter source designed for a scaled injector gun will require 3 KW to heat it. The current emitted from the small test source is shown in fig. 3. The plot shows that the obtainable current density is greater than 10 mA/m^2 a factor of two above that required for the large source (4.5 mA/cm^2 K^+). The emission was also found to be very uniform across the surface.

The fact that a large source is being designed into the next step injector implies that the ion temperature must be very low. The emittance specification for the original 5 cm diameter carbon source of 5 x 10^{-7} π m-rad normalized has not been reduced. Therefore since the intrinsic source emittance goes as $\sqrt{\frac{KTi}{Mi}}$ r where r is the source diameter and Ti is the ion temperature, the source temperature must be down by almost an order of magnitude. This implies temperatures of .1-.2 eV. Emittance of the small source is shown in fig. 4. This multishot emittance scan yields a effective source temperature of .2 eV. The source gives a very quiet current signal free of the plasma noise effects in other sources. There seems to be no obstacle to fabricating larger sources. Indeed a 10 cm diameter source is presently under test. One final consideration about the zeolite sources is lifetime and neutral emission. The most urgent concern for the Heavy Ion Fusion program is the next experimental device. The small test source has already produced more than enough charge for one year of machine operation. A driver on the other hand would consume charge about 135 times as fast. Therefore for a driver, another source might be desirable to reduce maintenance shut downs. Measurements of neutral emission from the heated zeolite source showed nothing measurable. If such emission did occur it could result in plating on insulator surfaces. This is a danger in the use of hot surface contact ionization sources where the extracted flux must be balanced to the inflow of neutrals to avoid surface work function degradation. An iridium coated porous tungsten plug source was also tested. Its suffered from long operational equilibration times and a possible pore clogging effect.

CONCLUSIONS

The zeolite source fulfills the near term needs of the HIF program. In addition, cesium is a likely choice for the driver ion because driver studies are moving away from very high masses which require higher particle energy and consequently longer accelerators. Cesium can easily be supplied by the zeolite sources and if lifetime becomes a problem, by hot surface contact ionization sources. Of course the high temperature and potential for neutral emission from surface contact sources present engineering difficulties. If a non-alkali metal ion is required, the plasma source will have to be further developed and the problem of stable, fast pulsed extraction must be solved together with preserving low ion temperature in the extraction process. Injectors requiring smaller emitters would have to be designed to reduce the neutral gas load coming from such plasma sources because charge exchange reactions in the injector caused by background gas are a serious problem with heavy ions.

ACKNOWLEDGMENT

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FIG. 1

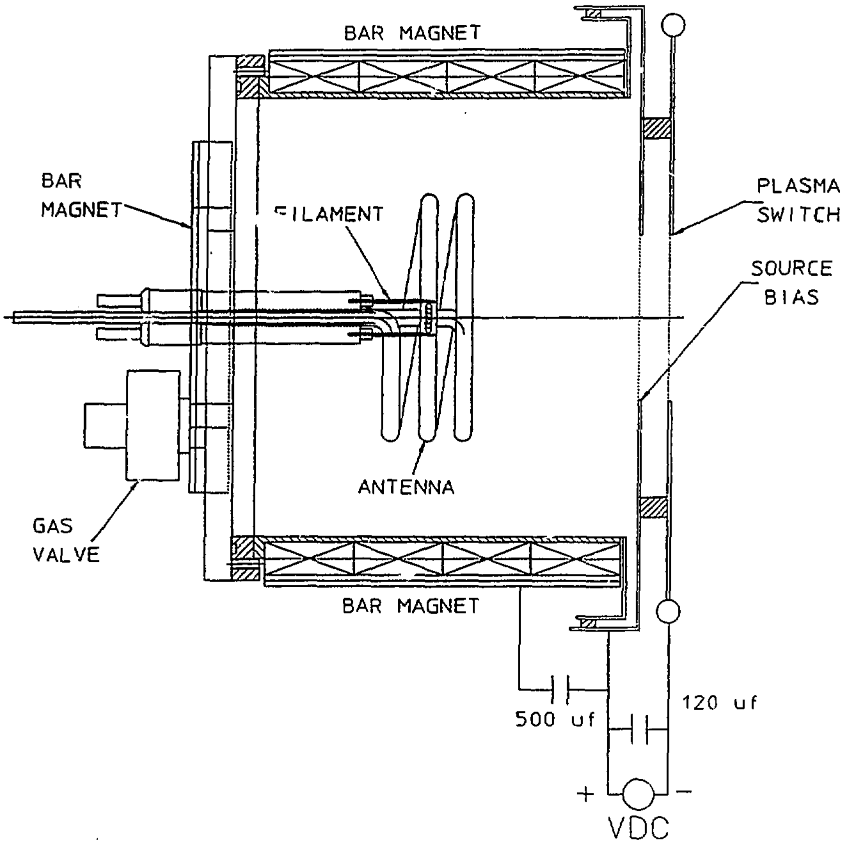

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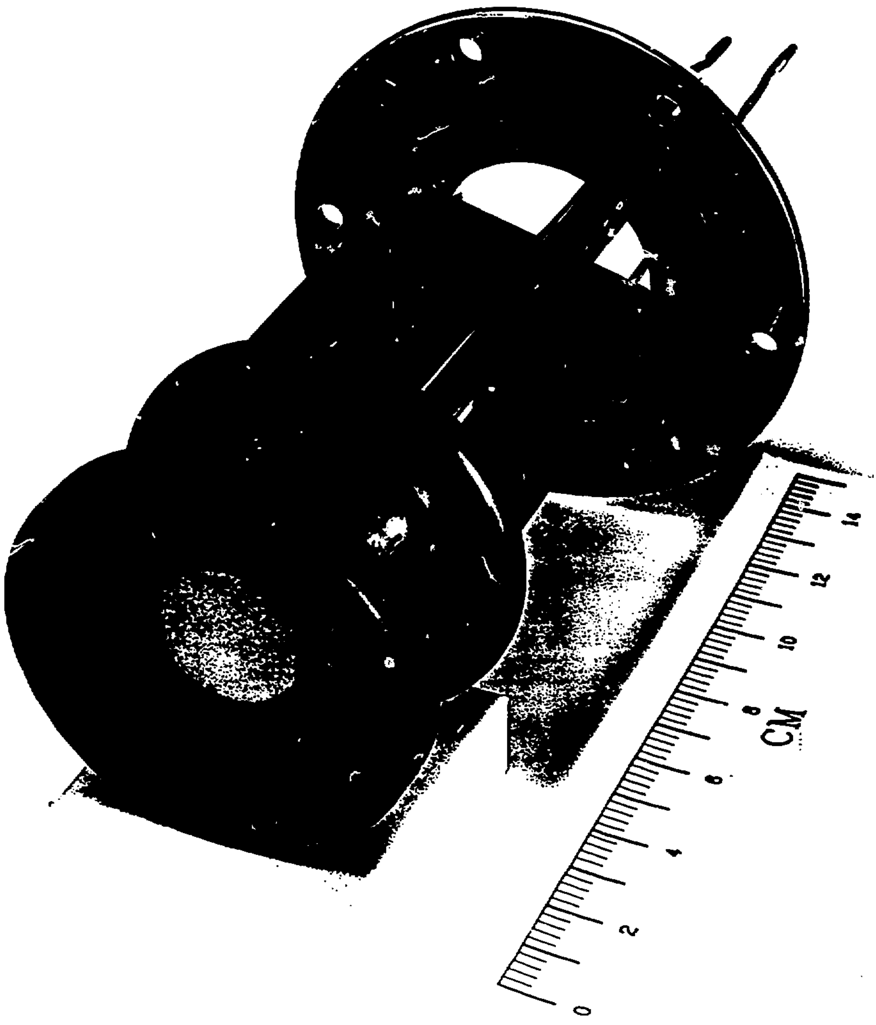
FIG. 2



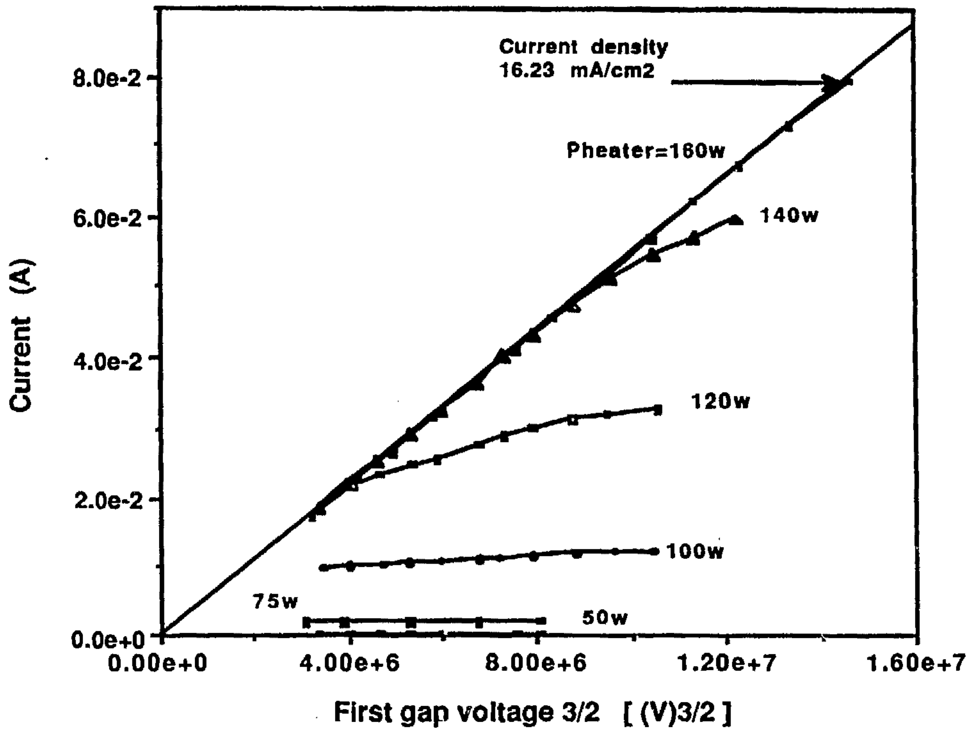


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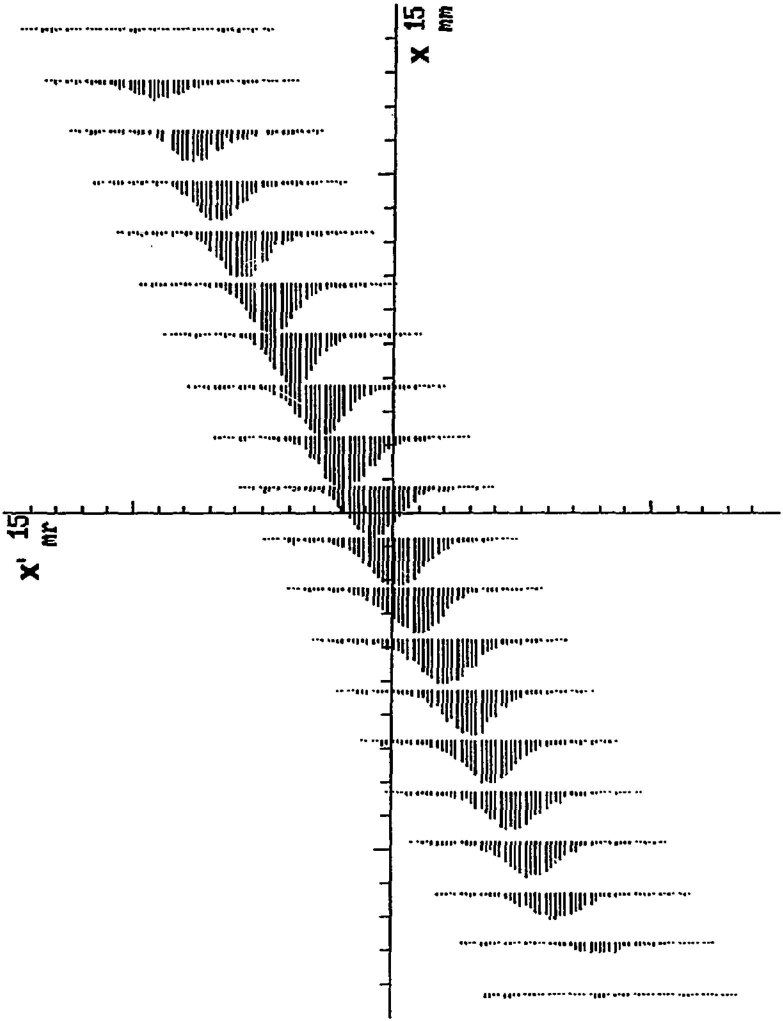
FIG. 3



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