HIGH-INTENSITY SOURCES FOR LIGHT IONS

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The use of the multicusp plasma generator as a source of light ions is described. By employing radio-frequency induction discharge, the performance of the multicusp source is greatly improved, both in lifetime and in high brightness H^+ and H^- beam production. A new technique for generating multiply-charged ions in this type of ion source is also presented.

1. Introduction

Permanent-magnet generated multicusp sources have been developed for neutral beam injection systems of fusion reactors.[1] They have also been used to provide light ion beams such as H^+ or He^+ for particle accelerators, proton therapy machines, neutron tubes for oil-well logging, ion implantation and ion beam projection lithography.[2] Multicusp H^- sources have been used in the injectors of LAMPF, KEK, TRIUMF and CERN. Recently, rf-driven multicusp H^- sources have been developed and operated successfully at the SSC.[3] This new type of ion source will soon be employed at DESY and in cyclotron facilities such as PSI and the University of Jyvaskyla for generating high intensity light ion beams. This paper reviews the latest technology of the multicusp ion source.

2. Ion Source Configuration

A schematic diagram of a typical multicusp ion source is shown in Fig. 1. The source chamber is a thin-walled copper cylinder surrounded by columns of samarium-cobalt magnets which form a longitudinal line-cusp configuration for plasma confinement. The magnets in turn are enclosed by an anodized aluminum cylinder, with the cooling water circulating around the source between the magnets and the inner housing wall. A pair of permanent magnet filter rods can be installed near the first or plasma electrode to enhance the production of atomic H^+, N^+ or O^+ ions and volume-produced H^- ions.[4] The back flange also contains rows of magnets cooled by drilled water passages and contains all the required feedthroughs and ports, including gas inlet, filament or antenna feedthrough, and a quartz rod serving as a light pipe or window. The open end of the source chamber is normally enclosed by a multi-electrode extraction and acceleration system. The shape and separation of the electrode apertures as well as the bias voltage are normally determined by means of ion optics codes.

3. Ion Source Operation and Start-up

The multicusp source can be operated with dc filament discharge or by radio-frequency (rf) induction discharge. In the case of a dc discharge plasma, the entire source chamber wall is served as the anode for discharge. The first or plasma electrode of the extractor is left electrically floating or it can be connected directly to the anode. When rf induction discharge is used to produce the plasma, the filament is replaced with a water-cooled copper coil antenna. The antenna coil is coated with a insulating material to prevent sputtering of antenna material as well as enhancing the source efficiency. Operation of the multicusp source with filament has been described in previous reports.[5] In this section, we will discuss only source operation with rf induction discharge.

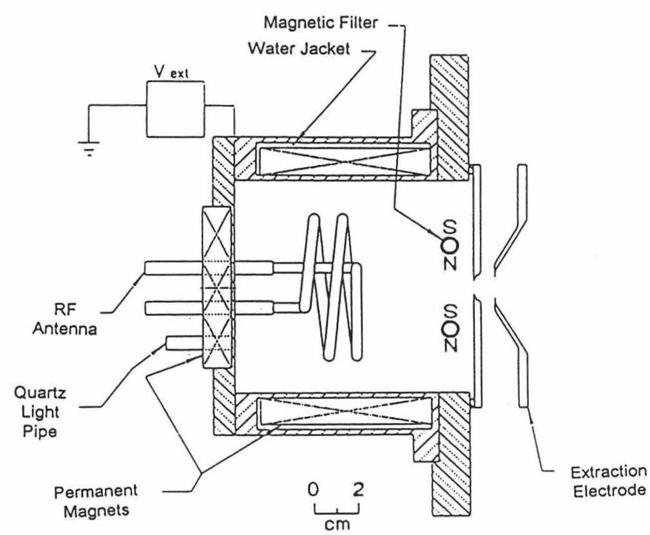


Fig. 1 Schematic diagram of the (rf-driven) multicusp ion source.

When the ion source is operated in pulsed rf mode, a small tungsten filament can be used to generate some free electrons to aid in reliable plasma ignition. However, the filament has a limited lifetime and contributes tungsten impurities to the plasma. It has been demonstrated that the ultraviolet light from a nitrogen laser impinging upon a magnesium target can provide enough photoemission electrons to ignite the plasma.[6] Recently, it is shown that the more expensive laser could be abandoned in favor of an inexpensive xenon flash lamp which has a large ultraviolet spectral component.[7] The pulse width of the xenon flash lamp is about 25 μs with a broadband energy of ~20 mJ. The flash bulb was mounted at one focus of an elliptical mirror and the light pipe was mounted at the other. For maximum transmission of the ultraviolet light, a light pipe made of fused silica was employed. In order to avoid damage by the plasma, the end of the rod was mounted flush with the inner surface of the flange.

In most applications, a two turn copper coil antenna is employed. The antenna is normally coated with a thin layer of porcelain material. For pulsed mode, this porcelain coating can survive months of operation without any significant deterioration. For high duty factor or cw operations, care must be taken to avoid high voltage breakdown across the porcelain coating. A study of the antenna lifetime at high rf powers is still in progress. Currently, the antenna at LBNL has been operated at 10 kW for over 20 h without any pitting or damage to the porcelain coating. For rf power in the range of 4 kW, antenna lifetime in excess of 200 h has been demonstrated at Grumman Corporation in cw operation.[8]

4. Production of High Brightness H^- Beams

H^- ions have found important applications in cyclotrons and tandem accelerators, in fueling storage rings of high energy accelerators, and in generating energetic neutral beams for heating and for current drive in fusion plasmas. In general, two distinct types of H^- ion sources can be identified: (1) surface conversion sources, in which the H^- ions are formed by particle collisions with low work function surfaces, and (2) volume production sources, in which the H^- ions are generated by electron-molecule and electron-ion collision processes in the volume of a discharge plasma. Because of the smaller beam emittance and the fact that they can be operated without cesium, volume H^- sources are now being developed by various accelerator and fusion laboratories in the world.

It has been demonstrated that a multicusp source can be used to generate volume-produced H^- ions in pure hydrogen discharge. The Superconducting Super Collider (SSC) rf-driven source routinely provided 35 kV, > 30 mA H^- beams with normalized rms emittance (en-rms) < 0.1 π mm mrad. The source was typically operated with a 100 μs beam pulse width at a 10 Hz repetition rate.

Attempts have been made to enhance the beam brightness of the rf-driven source by introducing some *cesium* into the source chamber. Since the rf source is operated with a porcelain-coated antenna, a clean plasma can be maintained. Without tungsten or other cathode material contamination, the consumption of cesium should be significantly reduced. A simple cesium delivery system fabricated from small dispensers has been operated quite successfully with the clean rf induction discharge. The effect of applying cesium to different source areas on the extracted H^- and electron currents has been investigated. It is found that the H^- output current can be increased by a factor larger than three if a minute quantity of cesium is applied in the collar around the exit aperture.[9]

Most recently, the SSC rf-driven H^- source was modified to enhance the H^- output for testing a high current LINAC. A collar with eight cesium dispensers was installed at the exit aperture. In addition, a heater wire was placed in the base of the plasma grid insert as illustrated in Fig. 2. This arrangement allowed the control of the collar temperature to be independent of cesium dispensing resulting in a better control over the source operation. With this new cesium dispensing arrangement, high H^- currents can be achieved quickly and maintained. This enhancement in H^- beam current is accompanied by a dramatic reduction of electron current. As a result, H^- beam current in excess of 100 mA and electron to H^- ratios close to one have been observed[10] (Fig. 3). Emittance measurements at 70 mA suggest a 20% increase over uncesiated emittance values.[10]

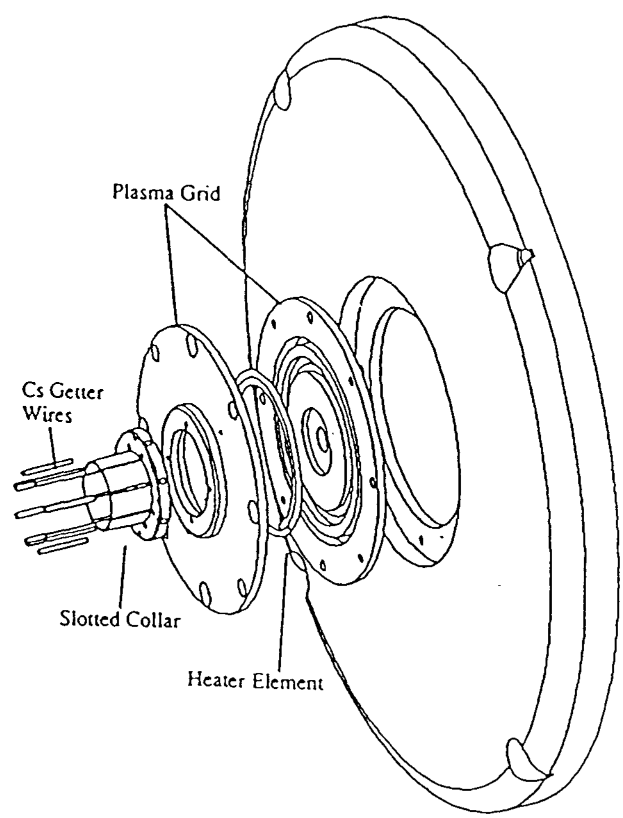
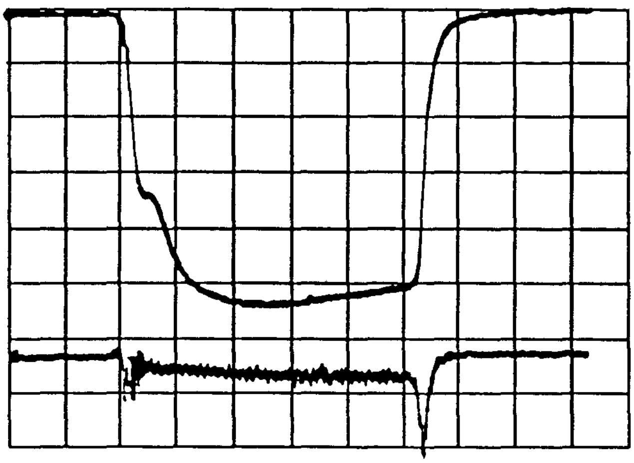


Fig. 2 Exploded view of collar area with eight getter wires and grid heater.



20 μs per division

Fig. 3 Oscilloscope traces showing an H^- current of 100 mA. Top trace: H^- current, 20 mA per division, bottom trace: electron current, 500 mA per division.

5. Production of H^+ beams for injection into an RFQ accelerator

It has been reported that the rf-driven multicusp source can provide high current densities (> 1 A/cm^2) of positive hydrogen ion beams.[11] With a magnetic filter in place, H^+ ion concentration as high as 97% has been observed with an rf power of 30 kW in pulsed mode operation.[11] Thus the use of a bulky magnetic mass separation magnet can be avoided. The H^+ beam can be quite easily accelerated and then matched into a post-acceleration structure such as a radio-frequency quadrupole (RFQ) or an electrostatic quadrupole (ESQ) by a low-energy beam transport (LEBT) system.

A six-electrode double-einzel lens LEBT has recently been designed and fabricated at LBNL. It will extract and transport a 30 - 50 mA, 40 keV H^+ beam from an rf-driven ion source to an RFQ accelerator (Fig. 4).[12] This new electrostatic LEBT is only 11 cm long and it can provide independent adjustment of beam radius and convergence angle at the entrance of the RFQ as shown by the WOLF code computation in Fig. 5.[12] Beam steering to correct misalignment is provided by four-way split electrodes. Unlike magnetic-solenoid LEBTs, the all-electrostatic design avoids the problem of beam neutralization entirely. Testing of the combined rf-driven ion source, electrostatic LEBT and a 410 MHz RFQ system is in progress and the results will be reported in the near future.

6. Multiply-charged ion production with the multicusp source

Permanent-magnet-based multicusp systems can be used to improve the density and uniformity of dc-discharge plasmas. The multicusp fields can confine the energetic primary electrons very efficiently, so the electrical and gas efficiencies of these devices are high. Since the magnetic fields are localized near the chamber wall, large volumes of uniform, quiescent, high-density plasmas can be obtained at low pressure (< 10^{-4} Torr); these conditions are favorable for the formation of multiply-charged ions. The absence of large density fluctuations and of nonuniform potential profiles near the exit aperture also favors the formation if low-emittance ion beams.[13]

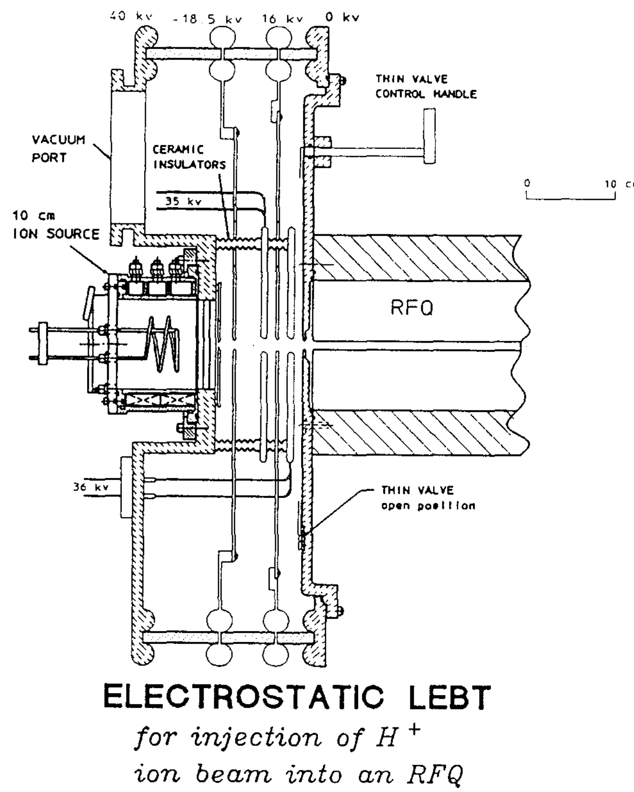


Fig. 4 Rf-driven H^+ ion source, LEBT and RFQ system.

To remove the electrons in the inner shells of an atom, the energy of the primary ionizing electrons must be high. With a modest discharge voltage of ~250 V, it has been demonstrated that Ar or Xe ions with charge states as high as +7 can be achieved from a 25-cm-diam multicusp source.[13] One can further improve the charge state by introducing more and higher-energy electrons into the source. For a steady-state discharge plasma, it is difficult to maintain a high bias voltage on the filament cathode. As the discharge voltage is increased, the ion density increases causing increased ion bombardment of the filament. At some point the ion bombardment dominates the heating of the filament and temperature runaway will occur. This can result in either exceeding the current limit of the discharge power supply causing the discharge voltage to drop or the filament burning out. This has limited the filament driven multicusp source to either pulsed or low discharge voltage in dc operation.

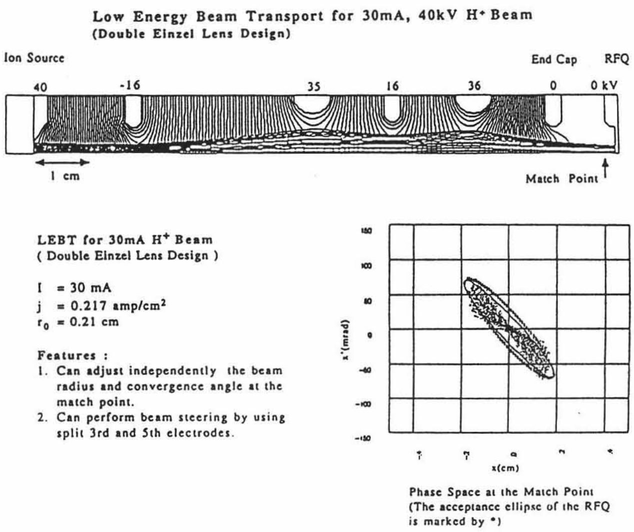


Fig. 5 Low energy beam transport for 30 mA, 40 kV H^+ beam.

A technique for producing a quasi-dc high voltage discharge in a multicusp source has recently been tested at LBNL.[14] The confinement efficiency of the multicusp source is coupled with a high voltage discharge to provide multiply-charged ions. Three tungsten filaments are programmed to provide sequential discharge pulses (Fig. 6). The pulse width and the pulse repetition rate can be controlled by an external pulse generator. The timing and width of these pulses can be adjusted to provide a quasi-dc plasma. Although the plasma discharge is dc, each filament is used for one third of the time. During the other two thirds of the time, the filament is floating which reduces ion bombardment and the resulting heating. Stable, time uniform plasmas were maintained with discharge voltages in excess of 300 volts.

A multicusp source (20-cm-diam and 25-cm-long) with the filament switching arrangement has been tested with xenon and argon discharges. Figure 7 shows the spectrum obtained during xenon operation. Charge state up to 7+ can be identified. The source pressure was 5 x 10^{-4} Torr, discharge voltage was 300 V and discharge current was 16 A. With this pulse filament arrangement, one can inject reasonably high energy primary electrons into the plasma and can therefore optimize the charge state of the ions. This technique is very useful in some applications such as radioactive ion beam production where ions with low charge states (for example: charge state 2+) are required.

7. Conclusions

The multicusp ion source was originally developed for neutral beam injectors in fusion devices. In the last decade, this type of ion source has produced light ion beams for various applications. The recent development of rf-driven multicusp sources has greatly enlarged the field of applications. It is expected that other kinds of ions, including metallic ions, can be efficiently generated by this type of ion sources.

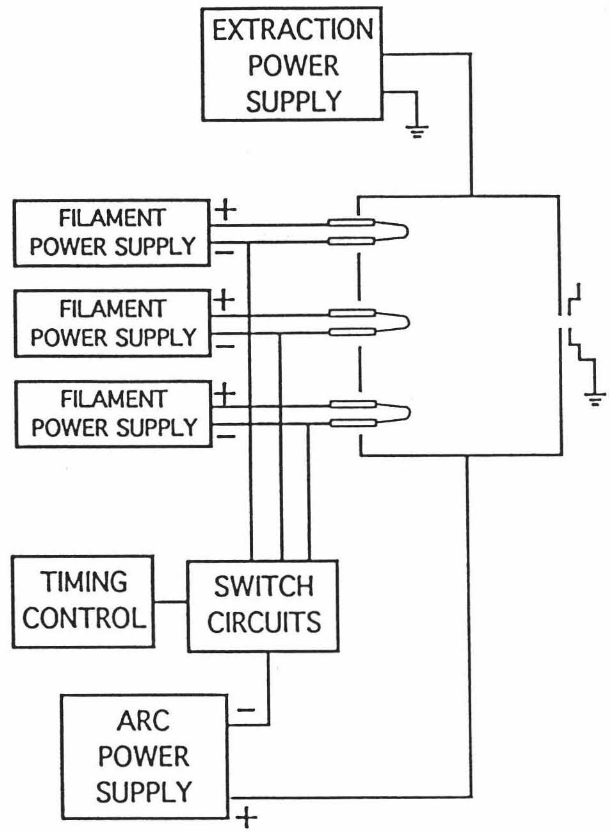


Fig. 6 The electrical block diagram of the operating circuit for multiply-charged ion production.

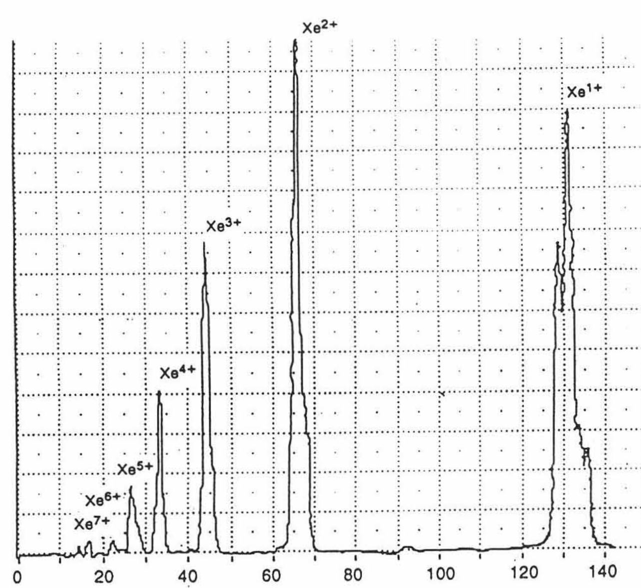


Fig. 7 The spectrometer output signal for xenon operation.

Acknowledgments

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