MODIFIED CALUTRON NEGATIVE ION SOURCE OPERATION AND FUTURE PLANS*

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Abstract

Negative ion generation has advanced rapidly by employing the concept of surface ionization. The modified calutron has proven to be a successful tool to explore these concepts and provide solutions to the many problems which must be evaluated. Many features of the SITEX (Surface Ionization with Transverse Extraction) ion source are ideally suited for this exploration. Some of these features are; a ribbon-like plasma, electron control by transverse magnetic fields and the ability to separate the Cs oven parameters from those which control the positive ion generation.

I. Introduction

The advent of the surface ionization concept[1] for the production of negative ions has produced a flurry of ideas for negative ion generation.[2] The modified calutron[3] has shown itself to be a particularly useful and successful vehicle for developing concepts and experimental solutions for the many problems which must be confronted. The geometry of this source is ideally suited to exploitation of the surface ionization scheme. It permits intense bombardment of the cesium surface from a dense plasma which is nevertheless thin in the direction of negative ion escape. Further, the cross-field configuration provides for EXB removal of extracted electrons at low energy, and finally, the plasma generating hardware and the cesium oven hardware are effectively decoupled from the negative ion production region, permitting great flexibility in the design of both of those subsystems. We are contempleting the development of an intense-beam negative ion source based on the calutron, to be called SITEX for Surface Ionization with Transverse EXtraction.

Consider the list of descriptive parameters of a plasma generator for a negative ion based system in Fig. 1: (a) extracted beam current density, (b) CW capability, (c) gas efficiency, (d) electron energy losses, (e) impurity content, (f) optics, (g) grid loading, (h) cesium control and (i) scalability. We have investigated experimentally all of these parameters except grid loading and scalability. However, the calutron concept has been scaled by two orders of magnitude in other applications operating CW. This work is directly applicable to negative ion production. After a brief description of the modified calutron principle, we will discuss the performance of the modified calutron with respect to each of these parameters.

Important Characteristics of a Negative Ion Plasma Generator

- Extracted Beam Current Density
- CW Capability
- Gas Efficiency
- Electron Energy Losses
- Impurity Content
- Optics
- Grid Loading
- Cesium Control
- Scalability

Fig. 1. List of important parameters of a plasma generator for a negative ion based system.

II. Source Operation

A schematic of the modified calutron used in these measurements is shown in Fig. 2. A discharge is ignited between the resistively heated filament and the 0.3 cm slit opening (anode) which is maintained by the power supply V_A. The gas feed, not shown, is in the filament region. Energetic electrons stream along the magnetic field ($\lesssim$1K gauss) and are reflected by the electrically isolated plate labeled reflector. Thus, plasma is produced everywhere along this electron ribbon which is 0.3 cm wide by 1.3 cm high by 15 cm long. A molybdenum converter surface on which cesium is deposited extends along one side of the plasma ribbon and is separated from it by about 0.2 mm. The power supply V_E is used to accelerate positive ions across a sheath onto the cesiated converter which then pass quickly through the thin ribbon to the extraction surface. In this manner of negative ion production, positive ions are produced by V_A and negative ions are produced by V_E in conjunction with an independently controlled cesium supply; negative ion losses are minimized by the geometry of the converter, plasma ribbon and extraction surface. As discussed in the section titled, Future Plans, this geometry may be easily varied to optimize negative ion output. In all extracted current measurements, the values given below are magnetically analyzed, whole beam values along with extracted j_{H^-}. As shown in Fig. 3, the modified calutron ion source and beam collector system are immersed in a uniform magnetic field. This type of test arrangement is well suited to measurements of impurities, beam optics and electron drain.

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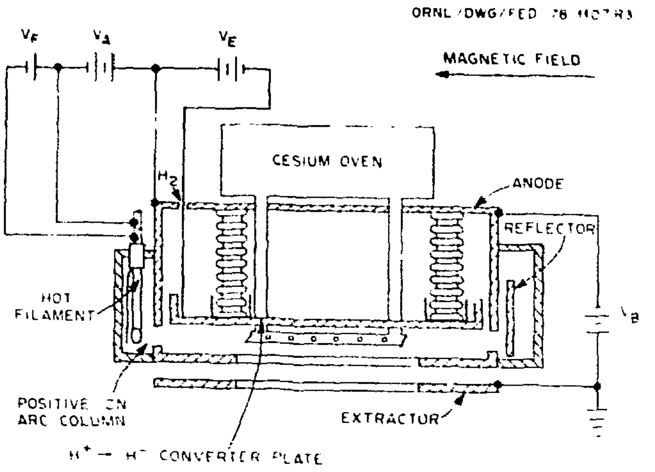


Fig. 2. Sectional view of the modified calutron H^- source.

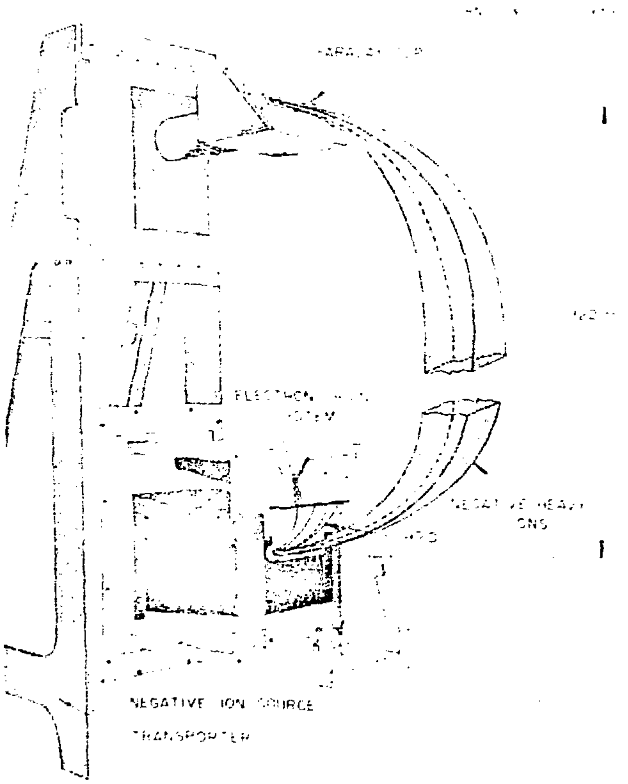
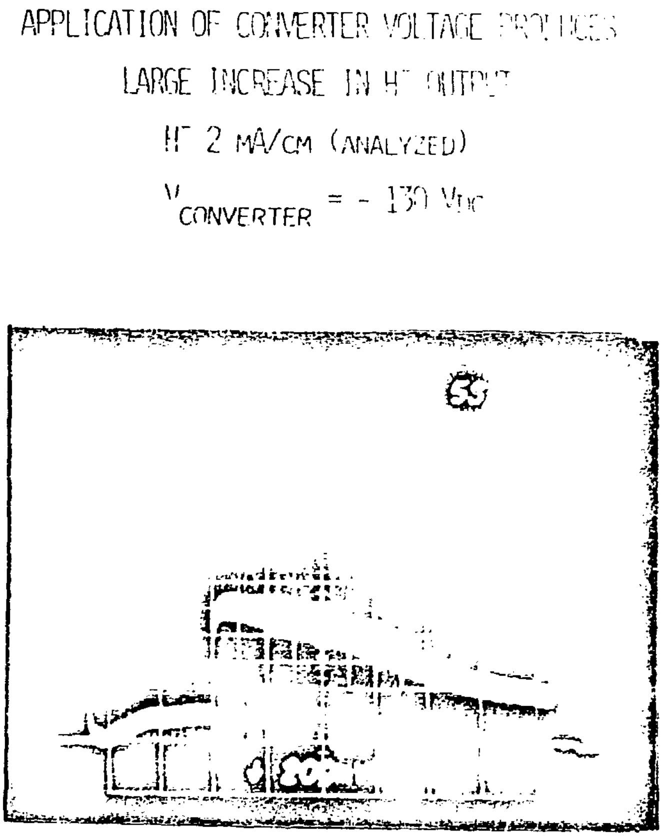


Fig. 3. Calutron ion source and Faraday cup receiver shown illustrated on a carrier in relative operating positions along with ion beam orbits produced by uniform magnetic field.

After considering the questions of positive to negative ion conversion efficiency, extraction geometry and beam transport, we estimate the desired extracted beam current density for beam line applications to be $\sim$100 ma/A^2 at the extraction surface. To date, 90 ma/cm^2 at the extraction slit and 60 ma/cm^2 at the collector has been achieved for 100 msec pulses at 25 kV extraction. As shown in Figs. 4 and 5, current pulses of $\sim$5 sec have been achieved at $\sim$45 ma/cm^2 with a 0.4 cm^2 slit area. Figure 4 shows a current signal which is low initially due to application of the arc voltage alone without the converter voltage. After 10 sec the converter voltage is applied. The output climbs to a maximum and then falls to about one-fifth the maximum before the converter voltage is removed. The decrease is due presumably to depletion of the cesium layer. The gas efficiency measurements for the modified calutron are about 4% which is determined by measured gas flow into the source and analyzed beam current to the collector. Corrections for beam losses during transit have not been included. There has been no attempt to increase the gas efficiency or output current in the manner demonstrated by Dimov and proposed independently by Dagenhart in 1978. A converter surface proposed by Whealton[5] is discussed in Future Plans below. Whealton calculates one order-of-magnitude improvement in gas efficiency for the modified calutron.


APPLICATION OF CONVERTER VOLTAGE PRODUCES

LARGE INCREASE IN H^- OUTPUT

H^- 2 MA/CM (ANALYZED)

$V_{CONVERTER} = -130$ VDC

Fig. 4. Analyzed 25 keV H^- beam.

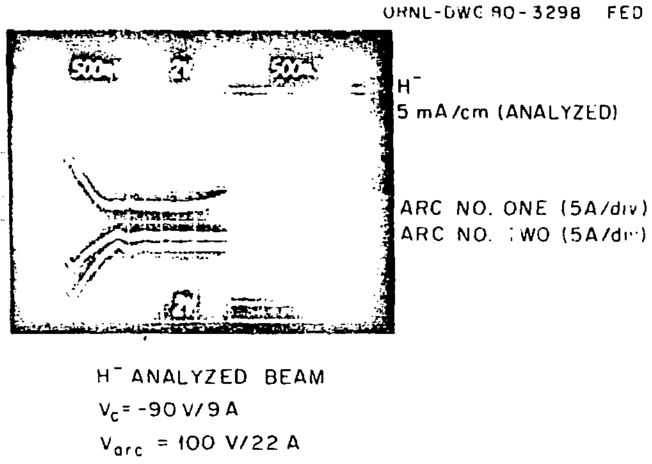


Fig. 5. Analyzed H$^-$ beam.

The power loss due to full energy electron extraction from the source is always undesirable and is intolerable for long pulse operation. The ratio of electrons to negative ions in the modified calutron is typically between four and six. However up to 94% of the extracted electron current has been recovered by the electron recovery system shown in Fig. 6. Electrons which are extracted from the source move up the face of the source due to the EXB drift present in this region. As the electrons approach the top of the source, the collector electrode potential forces the guiding center of the electrons to proceed under the collector electrode, at which point a component of E parallel to B is impressed upon the electrons. The electrons then drain off losing only the small energy supplied by the electron recovery supply. Figure 7 shows the variation of both the accel supply and electron recovery supply currents as a function of collector voltage. At low collector voltage some of the electrons escape to ground potential and are recorded by the accel current meter. Above about 1.5 kV collector voltage, essentially all of the electrons are being collected and the accel current is near zero. This same collection efficiency holds whether or not cesium is used in the discharge.

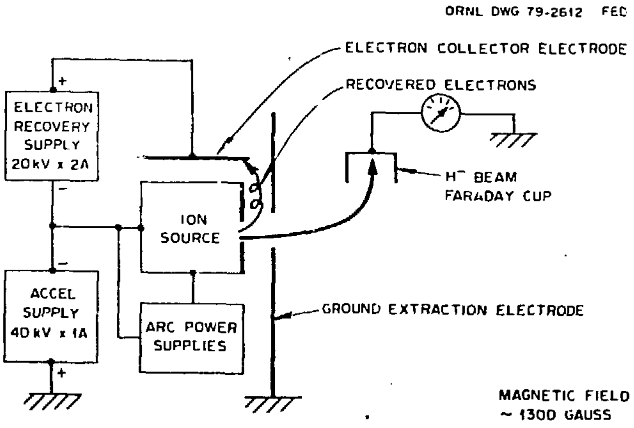


Fig. 6. Electron energy recovery system for the modified calutron H$^-$ source.

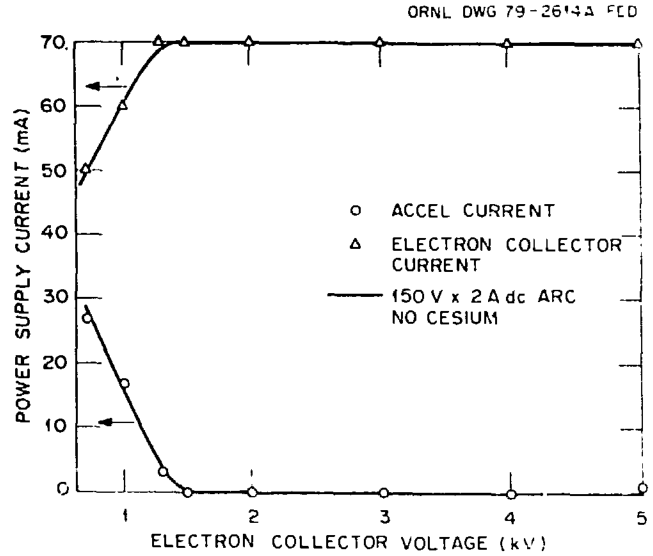


Fig. 7. Electron recovery efficiency variation with electron collector voltage.

The impurity content of the beam, shown in Fig. 8, can be mass identified by sweeping the magnetic field and monitoring the upper Faraday cup shown in Fig. 3. Total beam contamination has been reduced to <1% by careful source conditioning. It is estimated that the required change in magnetic field for mass identification has no more than a 30% effect on the negative ion output over the mass range scanned. In addition, an integral mass 12 → 20 amu impurity current measurement is made continuously during operation without changing the magnetic field. Many of the heavier masses detected are believed to be hydrocarbons arising from diffusion pump oil. Figures 9 and 10 show the variation of the impurity contaminants as a function of time for cesium dichromate and elemental cesium, respectively. The contaminants are summed from mass 12 to 20 amu which accounts for more than 5% of the impurities. A striking difference is the rapid decrease of the contaminant level with time using elemental cesium compared to cesium dichromate. These measurements are uncorrected for charge exchange losses along the path from source to collector; however, the entire beam is analyzed.

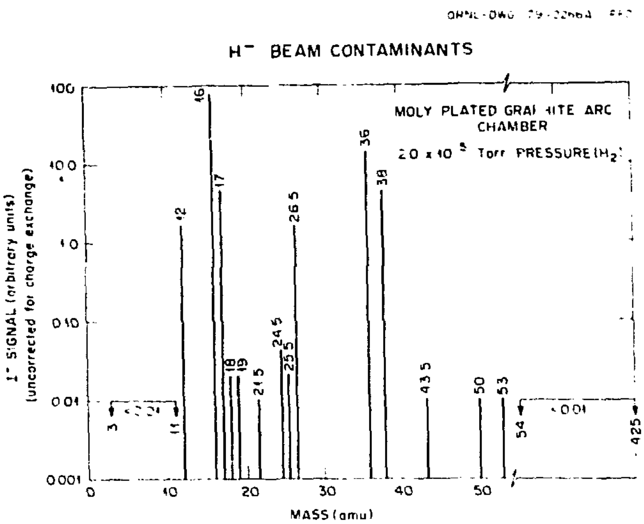


Fig. 8. Negative ion mass spectrum.

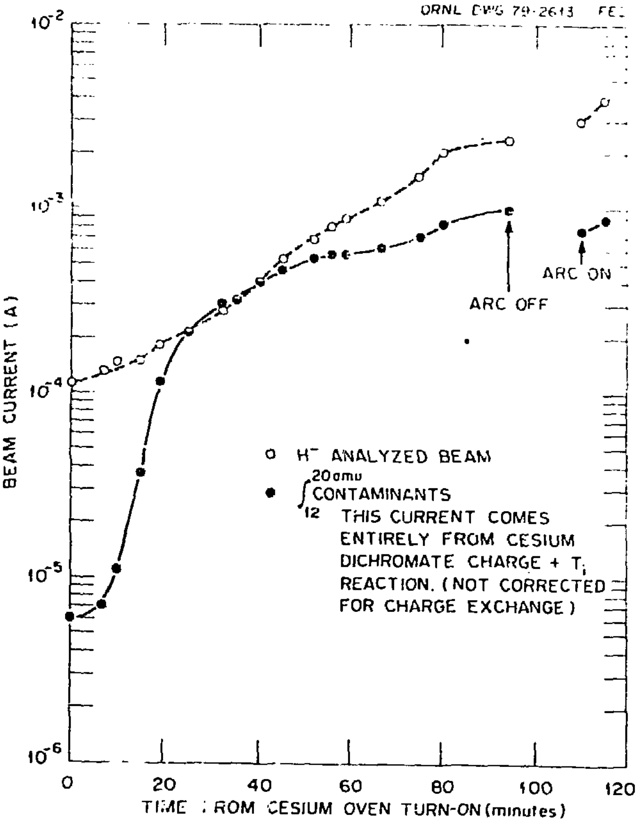


Fig. 9. Variation of heavy mass negative ion contaminants from cesium dichromate.

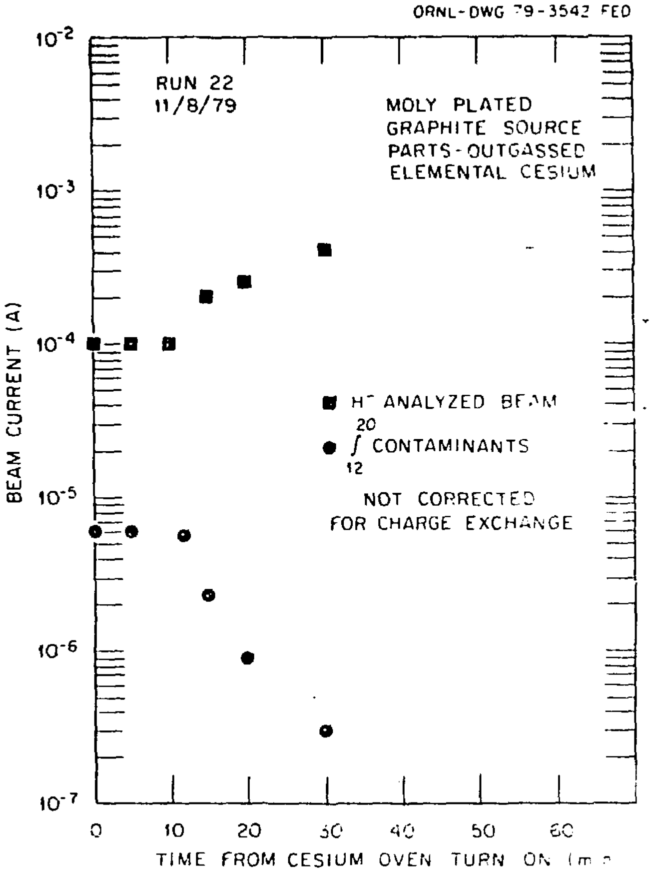


Fig. 10. Variation of heavy mass negative ion contaminants for elemental cesium.

No attempt has been made to optimize the electrode geometry. Existing parts from previous experiments were assembled producing the extraction geometry shown in Fig. 11. The space-charge-limited current density from this electrode configuration is about 95 ma/cm^2 at 20 kV. The only divergence measurement made is the angle subtended by the beam spot on the collector surface. The estimated one-half angle for $\Theta_\perp$ is approximately ± 2°, $\Theta_\parallel$ is very small. A segmented collector with an optimized electrode configuration will be forthcoming.

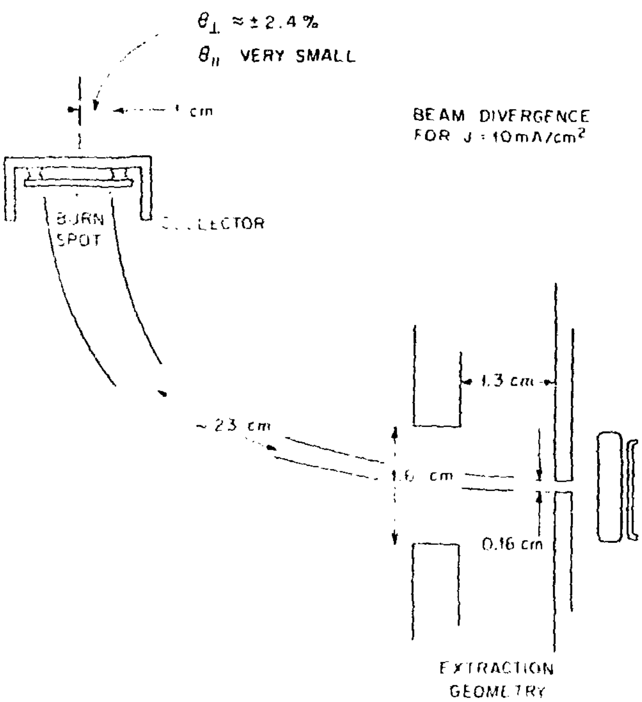


Fig. 11. Early extraction and acceleration geometry for the modified calutron H^- source.

We have started an investigation of the effect of a transverse magnetic field on the deflection and divergence of an ion beam emitted from a two stage accelerator. In these calculations, a TFTR slot geometry is used as a reference design. Two assumptions have been made: (1) the ions approach the meniscus with only about 4 eV and (2) the effect of electron space change in the accelerating gap is unimportant. Fig. 12 shows the deflection of the beam for 0 gauss, 1K gauss and 3K gauss. A plot of deflection versus magnetic field is linear. Figures 12 and 13 show that the divergence of the beam is minimally affected by the beam of the calutrons.

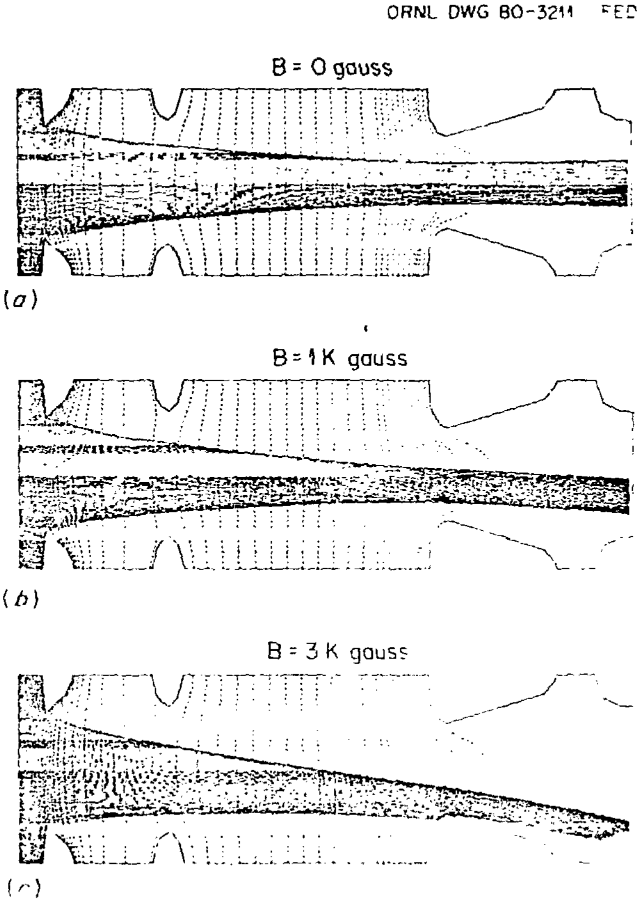


Fig. 12. Angular deflection of the H^- ion beam during acceleration from the modified calutron source.

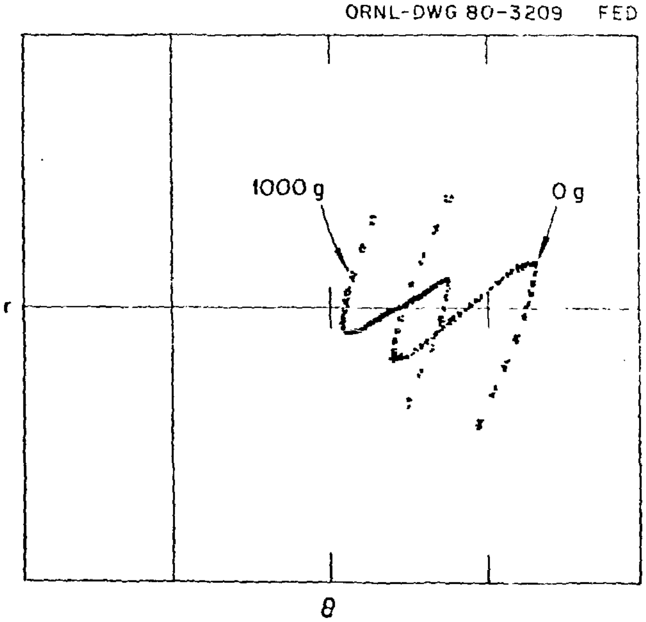


Fig. 13. Emittance plots for the beam acceleration cases of Fig. 12.

The geometry of the source permits great flexibility in the design of the cesium oven. To date, however, little effort has been allocated to the control of cesium deposition on the convertor surface. Since as the data of Fig. 4 indicate, there is depletion of the cesium surface with time using an uncooled substrate, we attempted to water-cool the surface. The temperature was lowered to such an extent that the cesium layer became very thick, thereby greatly reducing the negative ion output.

III. Future Plans

The versatility of the modified calutron and the encouraging experimental results obtained make a magnetically confined plasma with cross-field extraction very attractive for developing a negative ion source. The two major problems remaining in the development are improvement of the gas efficiency and maintenance of an optimum cesium coverage of the converter surface. The former problem relates to keeping beam losses and grid loading low in the accelerator structure. The latter must be solved for truly CW operation or for uniform pulses longer than ∿5 sec.

To improve the gas efficiency, we are studying several ways of generating intense, energetic electron ribbons which can increase the ion density and the ion-neutral ratio in the plasma. In Fig. 14, the anode slit is greatly lengthened compared to that used to date, to reduce neutral gas flow from the filament region. Such a discharge was first developed in 1963[6] in order to produce a plasma column having a plasma density greater than the neutral density of the surrounding gas. This goal was reached in a differentially pumped system. A second electron emitter under development is the hollow cathode shown in Fig. 15. This system has been successfully tested with a 50 V, 1 to 3 A discharge between Cathode 1 and Anode 1, a hollow cylinder of LaB_6. The discharge heats Anode 1 to emission temperature. A second arc supply accelerates an intense electron stream generated at Anode 1/Cathode 2 which will serve as the ionizing medium for the main plasma ribbon. Current pulses of 300 A were achieved. The pulse length varied between 100 and 400 msec due to the excessive current density of 40 A/cm^2. A current limiting device is being added.

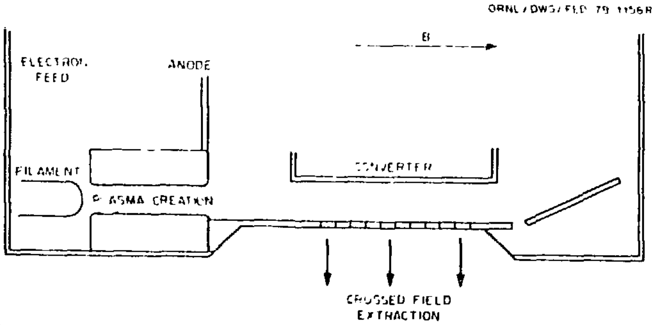


Fig. 14. Long anode high gas efficiency arc discharge.

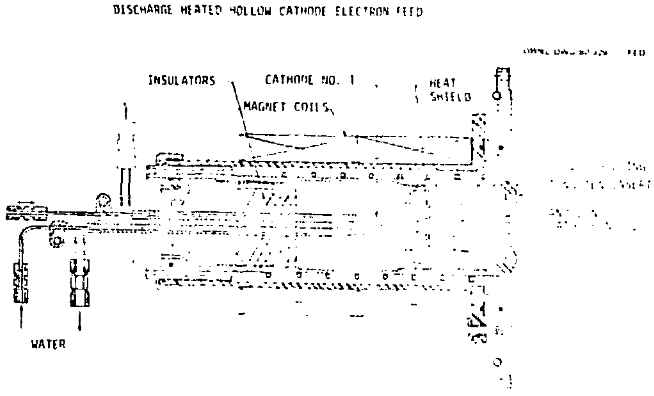


Fig. 15. Hollow cathode.

The idea of Whealton, mentioned above, which is intended as a way to increase the gas efficiency, is depicted in Fig. 16. Figure 16a and 16b shows the improvement due to Dimov. The improvement suggested by Whealton in Fig. 16c is to replace the slot groove in the converter with spherically-shaped dents which focus the negative ions into ciruclar apertures. This design retains earlier improvements with respect to total negative ion utilization and has two advantages. First, the electrons are even more repulsed at the extraction aperture since the negative ions are more highly concentrated due to the extra dimension of focusing. Second, the gas is inhibited from traversing the aperture since the transparency of the aperture is less that of a slot, which passes the same negative ion current.

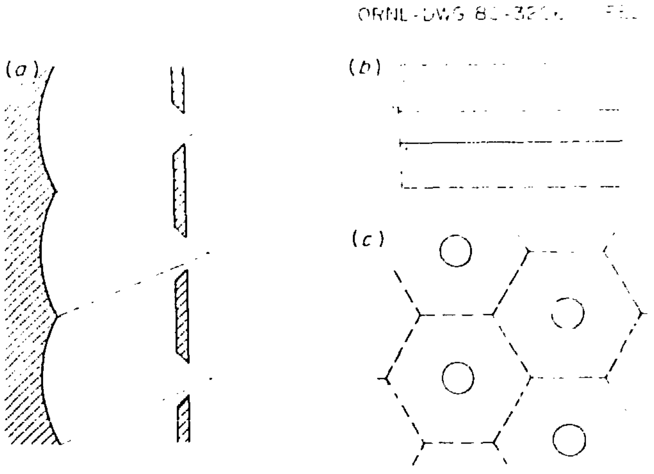


Fig. 16. Spherical focused H$^-$ converter plate.

The problem of cesium control on the converter surface may well be the most difficult of all. Our preliminary attempts to deposit cesium on the surface by controlling oven temperature and by using a cesium flow control valve have not resulted in an optimun surface during long pulses. Even with finer cesium control, ion bombardment may prohibit the use of externally deposited cesium. An alternative measure is to permit the diffusion of cesium through a porous surface. We are starting now to consider the dynamics of such a design.

IV. Summary

The use of the modified calutron to study surface ionization and transverse magnetic field extraction has yielded results which are very promising. A performance summary of the characteristics listed in Fig. 1 are given below:

(a) extracted beam current density — 70 ma/cm^2 at the extraction grid; (b) CW capability — 5 sec pulses achieved and steady state believed to be achievable; (c) gas efficiency — 4% with unfocused converter; (d) electron energy loss — 94% of the electron current is recovered; (e) impurity content — <1% impurity in beam after conditioning; (f) optics — ~±2° subtended by burn pattern; (g) grid loading — not measured; (h) cesium not satisfactory; (i) scalability — a 1 A module called SITEX is in design and a 10 A module is feasible.

From these results, it is readily seen that the modified calutron is well suited to the study of negative ion plasma production.

With the completion of the experiments related to gas efficiency and cesium control discussed under Future Plans, we will be in a position to design a next generation source defined as SITEX which will embody all the concepts and improvements determined from the modified calutron experiments. The first version of SITEX will be an intense 1 A scalable module which will operate steady state at 40 kV extraction potential. An accelerating structure compatible with a 200 kV beam system will be designed with the aid of the 2D[7] and 3D[8] computational code of Whealton.

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