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METHODS FOR INDEPENDENT PLASMA PRODUCTION AND BEAM INJECTION FOR $H^+ \rightarrow H^-$ SURFACE CONVERSION*

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Abstract

Based on the Oak Ridge National Laboratory (ORNL) source development program, ways to create a uniform and dense plasma are briefly reviewed. The positive ions so created will be accelerated towards a surface convertor for producing negative ions. The convertor will be used for reducing the electrons in the extraction region. The significant results and features of this study are presented.

I. Introduction

The present experimental successes of neutral beam injection heating of tokamak plasmas encourage the use of this heating technique for future fusion devices.[1-3] Considering the penetration of energetic neutrals into the fusion reactor plasma for efficiently depositing the beam power, the required energy of neutrals should be of the order of several hundred kiloelectron volts. At such high energies, neutral beams made from positive ions become ineffective because of the low neutralization efficiency (∿10%). On the other hand, the high stripping efficiencies (65-85%) of negative ions indicate a need for the development of high energy negative ion beams with multiampere beam current. In the last few years, the progress in negative ion beam technology[4-7] is such that ion beam current has increased from a few milliamperes to the 1-A range.

There are two well-established methods by which negative ion beams are generated: (1) direct extraction and (2) two-stage or double charge-exchange extraction. In direct extraction, an electric field is used to extract negative ions directly from the ion source plasma. However, in the double charge-exchange method, relatively low energy positive ions are extracted from the ion source plasma and charge exchange while passing through an alkali vapor cell. The resulting negative ions are then accelerated to the desired energy.

As described in the following sections, the negative ions are created by surface conversion or charge exchange in alkali vapor of positive ions. Theoretically, all positive ion sources can be adopted and modified for negative ion production. After a review of the status of the duoPIGatron ion source, our concepts for creating H^- ions in a duoPIGatron are described and discussed.

II. Direct Extraction

In the direct extraction of negative ions, the creation of the ions via a cesiated surface is still a subject of study.[8,9] However, several general features are recognized. Normally, the prime processes resulting in negative ion creation in the magnetron-type and Penning-type ion sources[4-6] are:

(1) A normal discharge creates a dense hydrogen plasma.

(2) The positive hydrogen ions in the arc column are accelerated into the cathode with an energy about equal to the arc voltage.

(3) The fast ions and neutrals impinge on or reflect from the cesiated cathode surface, thereby creating H^- ions.

(4) The H^- ions are then accelerated through the cathode fall and arc column and reach the extraction region either directly or indirectly by charge exchange with slow hydrogen atoms.

The first two process are essential for positive ion production. Hence, effective positive ion sources such as duoPIGatrons[3] can be modified for the H^- beam. But the last two processes are essentially relevant to the performance of the H^- ion source. These processes control the creation and destruction of H^- ions. Theoretically, the conversion efficiency[8,9] of $H^+ \rightarrow H^-$ on a cesiated surface can be as high as 50%. However, the experimental results[1-4] revealed that only ∿20% of H^+ ions become H^- ions in the extraction region. Thus, the destruction rate of H^- ions is very high. Such a high probability of H^- destruction, dominated by charge exchange with positive ions or collisional detachment with electrons in the main arc column, could result in the poor arc efficiency of H^- ion sources (Table 1). To increase the negative ion output, the discharge is run at a high positive ion flux density (10-50 A/cm^2) with a small spacing between the cathode and extraction electrode. This operation mode may be responsible for the low gas efficiency observed in these sources.

With either the magnetron or Penning source, the arc discharge determines the energy and flux of the impinging ions which in turn determine the temperature of the cesiated cathode surface. In addition, the current density and thereby the negative ion flux are coupled to the discharge parameters. Consequently, the ion velocity, cesiated surface temperature, and negative ion

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flux cannot be individually controlled. Thus, the cesium layer may become depleted with overheating, thereby causing the short pulse operation of these sources.

The problems mentioned above are associated with the particular electrode arrangement in the magnetron and Penning H^- sources. To relieve these problems and improve the performance, the source should be designed in such a way as to achieve high creation rate and low destruction rate of negative ions. Then the source can be operated at a regime with a relatively weak arc intensity. That is, the ion flux on the cesiated surface can be controlled to be about 1 A/cm^2. To optimize the yield of negative ions, the temperature and potential of the cesiated surface should be adjusted separately and be independent of the arc condition. To this end, we propose to develop a convertor with cesiated surfaces for $H^+ \rightarrow H^-$ conversion, which will be used in a duoPIGatron for H^- ion production. The status of the duoPIGatron and $H^+ \rightarrow H^-$ convertor are further described below.

III. Status of DuoPIGatron

To fulfill the need of megawatt neutral beam injectors for plasma heating in fusion research,[1-3] the duoPIGatron ion source originally developed at ORNL has been successfully scaled up with an ion beam current capability of 100 A. During the last ten years, modification and optimization of the electrodes of the plasma generator and ion accelerator[10-17] have been carried out. For example, water-cooled electrodes and multiaperture grids enable the source to deliver a multiampere beam with a long pulse length. Curved grids with programmed apertures for beam focusing improve beam transmission. An axial button and a magnetic multipole line cusp field improve plasma uniformity. Optimization of electrodes, gas feed, and magnetic field results in high arc efficiency and high proton yield. The outstanding performance of other parallel systems,[18-21] such as the electronics of arc and high voltage power supplies, gas feed and cryopumping systems, and beam stop and ion calorimeters, has also contributed significantly to the above sucess. We now describe the characteristics of a 60-A duoPIGatron for the Princeton Large Torus (PLT) injectors.

Figure 1 shows the sketch of a PLT-type source (31-cm-diam chamber for anode 2 and a 22-cm grid diameter). As a conventional duoPIGatron, it consists of a hot cathode (8 off-axis oxide filaments), an intermediate electrode, anodes 1 and 2, and a target cathode (plasma or screen electrode). In addition to the inhomogeneous source field originating from the intermediate electrode, a magnetic multipole line cusp field is added on the sidewall of anode 2. Normally, the arc voltage is applied between the anodes and the hot cathode, while both the intermediate electrode and target cathode are self-biased through resistance connections to the anodes. Under normal operations, the source plasma is composed of a cathode plasma in the intermediate electrode chamber and a PIG plasma in the anode 2 chamber. The particular magnetic field arrangement used effectively guides the electrons from the cathode plasma into the PIG region and then confines these ionizing electrons and the plasma created in the extraction region near the target cathode. Consequently, the source efficiently creates a uniform ($\pm 5\%$ density variation over a 23-cm diameter) and dense (2×10^{12} cm^{-3} at the extraction surface) plasma. This inherent capability enables the source to deliver beams with current up to 70 A, ion energy up to 45 keV, and pulse length up to 500 msec. The source is also characterized with high arc efficiency ($\sim$1 A of beam current per kilowatt of arc power), high proton yield ($\sim$85%), high gas efficiency ($\sim$50%), good beam optics ($\theta_{HWHM} \approx 1^\circ$), long filament lifetime (a few months), high reliability ($\sim$90%), and scalability. The scalability is further supported by the following facts: 15-A sources are used for the ORMAK experiment at ORNL, 30-A sources are used for the ORMAK and the LITE experiment at United Technologies Research Center, and 60-A sources are being used for the PLT experiment at Princeton Plasma Physics Laboratory. At the moment, we have tested a plasma generator capabile of producing 100 A of ion current from a 26-cm grid diameter.

IV. Modified DuoPIGatron with Cesium Convertor for H^- Production

When used for forming a positive ion beam as described in Section III, the plasma generator of a modified duoPIGatron is capable of producing ion densities of 1-2 × 10^{12} cm^{-3} uniformly over about 600 cm^2 with an 85% H^+ beam fraction. Normally, an accel-decel beam formation system with radially water-cooled multiaperture electrodes is used to produce an energetic positive ion beam. For negative ion production, a structure consisting of cesiated tungsten or molybdenum vanes is placed between the source plasma and the extraction surface, as shown in Fig. 2. Each vane in this $H^+ \rightarrow H^-$ convertor is chosen to provide at least one but not more than two bounces of a positive ion being accelerated into it. The cesiated surface can be maintained at a potential with a variable magnitude up to the arc voltage and is negative with respect to the plasma potential. The negative ions are then produced by impinging positive ions, similar to the magnetron or Penning source.[4-6] Electron suppression is achieved by electrostatic repulsion between the convertor and the extraction electrodes and/or by a ~~weal~~ crossed magnetic field between the vanes of the convertor. Progress in this area could improve the extraction efficiency of the negative ion source.

Several advantages are immediately apparent from this design. First, the negative ions do not have to travel through the arc discharge to reach the extraction region. The destruction rate of negative ions should be low and the transport efficiency should be good. Thus, a multiampere negative ion beam could be formed from a source with a low positive ion flux density ($\lesssim 1$ A/cm^2) to the convertor. In addition, the temperature of the cesiated surface in the convertor can be controlled by means independent of the arc discharge. Hence, such a modified duoPIGatron has a high potential for long pulse operation. In fact, the convertor design permits the energy of the impinging ions to be controlled by an external voltage applied to the convertor. Hence, the H^- production can be optimized by adjusting convertor temperature and ion energy, independent of arc discharge. This would result in an improvement in arc efficiency. Together with the inherent high gas efficiency of the duoPIGatron, the convertor will reduce gas conductance and further raise gas efficiency. The estimated performance of a PLT-type source modified for H^- ion extraction is listed in Table I.

A small-scale test of this convertor scheme is being carried out on a 10-cm (or 5-A) duoPIGatron. First tests indicate that this source operates as reliable as a positive ion source. The pulse duration is up to a couple tenths of a second, and pulse rate is up to 1 pulse per second. The temperature of the cesium oven is variable up to 450°C, due to the loading of arc power only. The temperature of vanes of the convertor is up to about 300°C. Hence, a supplementary heating will be provided for proper temperature control of the cesiated surface. The negative ion emission as a function of cesiated surface temperature will be studied. Electron suppression studies will begin hereafter.

Table I

	Magnetron	Penning	DuoPIGatron		
			H^+	H^-	
				10%	30%
Arc Efficiency, A/kW	0.04	0.03	1	0.2	0.6
Pulse Duration, msec	<20	4		Up to 1000	
Gas Efficiency, %	3-5	∿1.1	50	>>5	>>15
Extraction Efficiency (Electrical), %	30-50% ($I_e \approx 1\text{-}2\ I_{H^-}$)	50% ($I_e = I_{H^-}$)	∿100		
Beam Current, A	∿1	0.44	60	6	18
H^- Ion Current Density, A/cm^2	1.5-3	0.25-0.5	0.3	0.03	0.08

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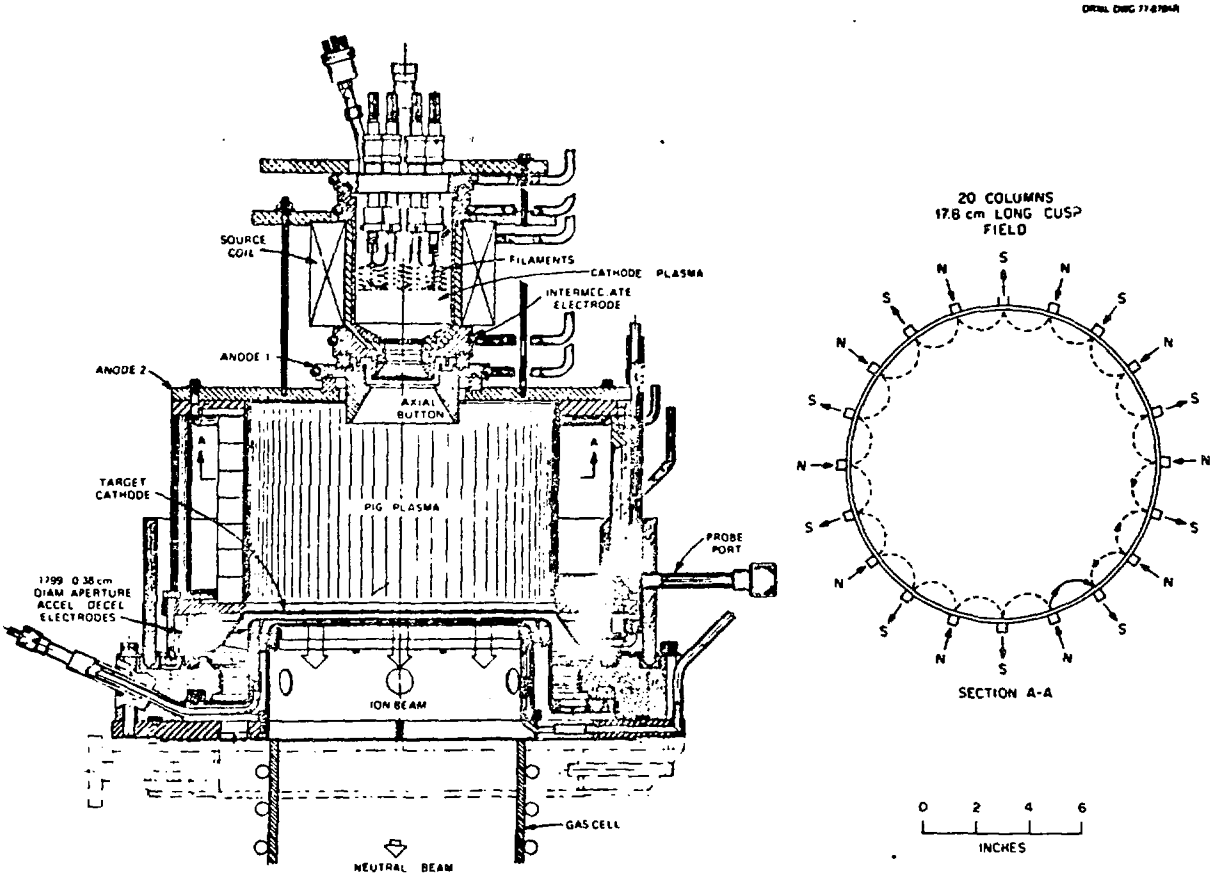

Figure 1 Sketch of a 22-cm duoPIGatron ion source for PLT injectors.

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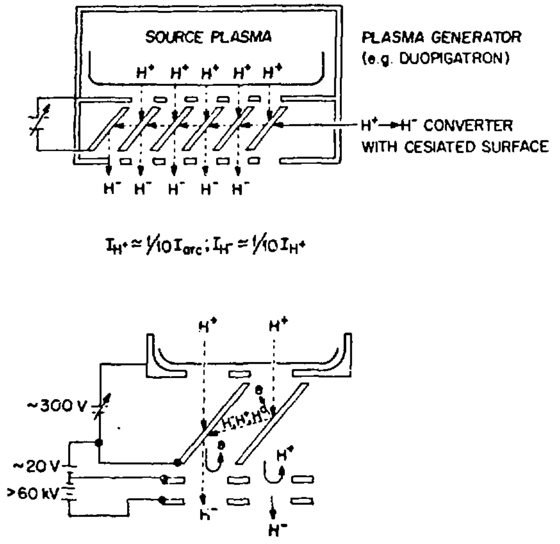

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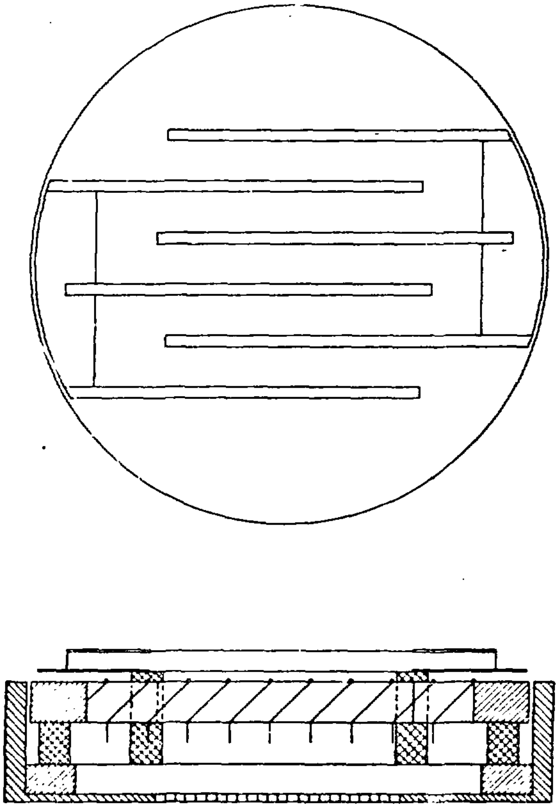

Figure 2 $H^+ \rightarrow H^-$ Convertor for an H^- Ion Source