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DESIGN OF LONG PULSE/STEADY STATE NEGATIVE HYDROGEN ION SOURCES FOR FUSION APPLICATIONS*

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Summary

As part of the program to develop a high energy neutral beam injector based on neutralization of negative ions, several types of negative hydrogen (or deuterium) ion sources for long pulse or steady state operation are being studied at Brookhaven National Laboratory. By using parameters of ion sources when operating in a pulsed mode and without cooling (pulse length < 0.1 s), requirements have been determined for a long pulse (several seconds) or steady state operating mode and two sources have been designed and fabricated. First of the two is a Penning source, designed for a steady state operation with a cathode power density of 1 kW/cm^2. For the range of cathode power densities between 0.2 kW/cm^2 and 1 kW/cm^2, nucleated boiling has to be used for heat removal; below 0.2 kW/cm^2 water flow cooling suffices. Although this source should deliver 0.3-0.5 A of H^- ions in a steady state operation and at full power, the other source, which has a magnetron geometry, is more promising. The latter incorporates two new features compared to first designs, geometrical focusing of fast, primary negative hydrogen ions from the cathode into the extraction slit, and a wider discharge gap in the back of the source. These two changes have resulted in an improvement of the power and gas efficiencies by a factor of 3 to 4 and in a reduction of the cathode power density by an order of magnitude. The source has water cooling for all the electrodes, because maximum power densities will not be higher than 0.2 kW/cm^2. Very recently a modification of this magnetron source is being considered; it consists of plasma injection into the source from a hollow cathode discharge. First experiments are very encouraging and may lead to further reduction of the gas flow by an order of magnitude.

Introduction

Future fusion reactors may require for plasma heating purposes intense neutral beams with energies ranging from about 100 keV/nucleon up to 500 keV/nucleon or more.[1,2] Present neutral beam systems, either in operation or under construction, are based on neutralization of positive ions. However, as the ion energy increases, the neutralization of a positive ion becomes less efficient (Fig. 1). The only way to improve the overall system power efficiency, which is a parameter of crucial importance not only from the beam line point of view but reactor's as well, is through the development of rather complex systems for energy recovery from the remaining charged beam components. Even this method has its limits as the energy of ions approaches 100 keV/nucleon and the required neutral beam power several tens of MW.

Another process to produce high energy neutral atoms is by stripping negative ions. This process is more efficient (depending on the stripping method the efficiency may approach 100%; Fig. 1) and above 50 keV/nucleon the fraction of negative ions which can be converted into neutrals depends little on beam energy. In addition, a negative ion beam has only the atomic component (H^- or D^-), while in positive ion based systems molecular ion components (H_2^+, H_3^+) contribute to fractional energy neutral beam components. Due to their high power efficiency and a single species beam, negative ion based systems are considered an attractive alternative for sources of neutral atoms even at energies as low as 50 keV/nucleon.[3]

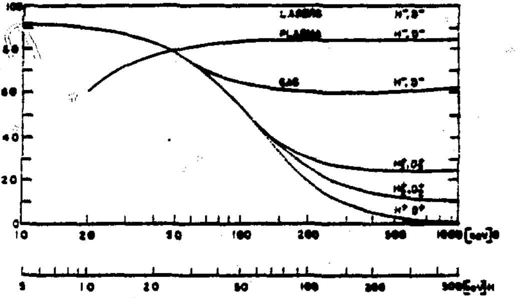

Figure 1. Neutralization efficiency for different ion species and stripping targets, as function of energy.

Presently three methods for production of negative hydrogen ions are being studied: via volume processes, by using double electron capture by positive ions in alkali vapors, or through surface formation processes; the last one seems to be the most promising and has been pursued at several laboratories. The approach adopted at Brookhaven National Laboratory belongs to the systems, where plasma is produced in the vicinity of an electrode having a low work function (surface-plasma sources). Particles, positive and neutral, diffusing out of the plasma bombard the surface and via a combination of surface-particle interactions (desorption, backscattering) may be converted into negative ions; if this electrode has the proper bias with respect to the plasma, most of negative ions will be able to leave the surface and enter the plasma. The simplest sources of this type are Penning and magnetron; their pulsed versions have been described in more detail in Ref. 4. Although the yield from the Penning source was about 0.5 A and from the magnetron close to 1 A, they both had to operate with relatively short pulses because there was no provision for the heat removal from the electrodes. A scaling up of either source type to long pulse or steady state mode of operation showed that cathodes would receive power densities between 1 and 2 kW/cm^2 if negative ion current density of about 0.5 A/cm^2 is desired. Nucleated boiling as the method for heat removal was seriously considered and after some studies a Penning source designed; it will be described subsequently.

Recently an important improvement has been achieved in the performance of magnetron sources.[5] By using geometrical focusing of negative ions, that had been produced on the cathode by surface-particle interactions and accelerated in the cathode sheath, into the extraction slit (Fig. 2 shows a magnetron geometry with three such focusing grooves) it became possible to better utilize the cathode surface and to operate the source with a lower gas pressure.[6] Another change in the design, widening of the discharge gap in the back of the source, contributed further to an improved performance.[5] Based on these results a new magnetron source has been designed, fabricated and put on the test stand; it is expected that it would deliver between 1 and 2 A of negative ion currents, in long pulse or steady state mode of operation, with a gas efficiency of 5-6% and

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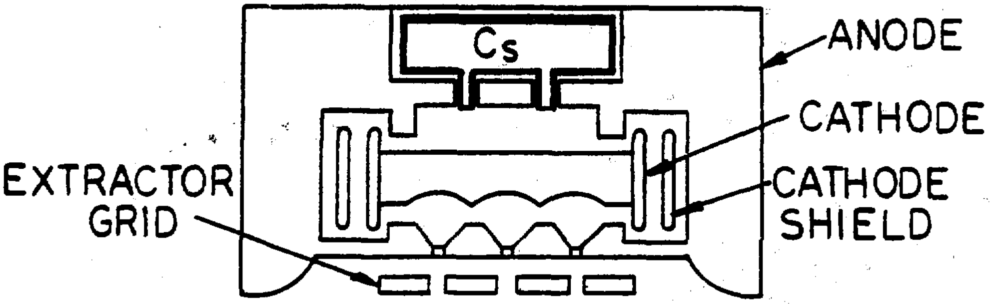

Figure 2: Cross section of the BNL Mk IV magnetron source (without cooling) with three focusing grooves on the cathode and an asymmetric discharge gap.

using water flow as the means for heat removal.

Even this source performance may be marginal for an application in a neutral beam line, where ion currents of several tens of amperes will be required and where the accompanying gas flow might pose serious problems. The only way to improve the gas efficiency (or reduce the gas flow) is by producing a highly ionized plasma outside the ion source itself (i.e. the source electrodes should serve basically to produce negative ions and to lead them out of the source, but not to maintain the discharge) and to inject it into the ion source. First experiments[7,8] with a hollow cathode discharge as the plasma source have been successful and have shown that from the plasma column a high enough positive ion current may be drawn onto a low work function surface. There are indications that a copious emission of negative ions has been obtained from the surface, sufficient to be used in a source. The gas streaming out of the hollow cathode is more than 90% ionized, which may lead to a further improvement in the gas efficiency by an order of magnitude. A modification of the cooled magnetron source so as to include several hollow cathode discharges in parallel, is under consideration. There would, however, be little or no improvement in the overall source power efficiency - a parameter of a lesser importance anyway if the source is to be used in a high energy neutral beam line.

BNL Penning Source With Cathode Cooling

From the first model of a Penning source H^- currents close to 0.5 A were obtained,[9] but the source did not have cooled electrodes and had to operate with short pulses (3 ms). A steady state operation with an extracted current density of 0.5 A/cm^2 would require a cathode power density of 2 kW/cm^2 and cathodes had been designed and studied using nucleated boiling as the method for heat removal. The cooled BNL Penning source has a cathode surface area of 10 cm^2 and an auxiliary electrode situated opposite the extraction slits to enhance the production of negative ions; geometrical focusing of these ions into the extraction slit is contemplated. When operated at full power input, the source is expected to produce about 0.5 A of negative ions, but present tests are limited to levels below 0.2 kW/cm^2 on the cathode. The objective of tests is more to gain the experience with steady state mode of operation and to study some engineering aspects of such sources than to achieve high negative ion yields; for the latter the improved magnetron geometry is more promising.

BNL Magnetron Source With Electrode Cooling

As reported earlier,[4] BNL magnetron sources of the original design (parallel cathode and anode surfaces) and with no electrode cooling had H^- yields up to 1 A but the pulse length was limited to 10 ms. For this type of sources, where the heat developed during the pulse is stored in the electrodes themselves and removed between the pulses by conduction and radiation, there is a trade-off between the yield and the pulse length. Still, for an H^- current density of several hundred mA/cm^2 it is difficult to achieve pulse lengths beyond 0.1 s. A scaling up of standard magnetron sources for steady state operation would result in the requirement that 1 kW/cm^2 be removed from the cathode, therefore nucleated boiling would have to be used. However the magnetron geometry is less favorable for such a cooling method than the Penning source because in the former it is difficult to avoid sharp bends in the water passages.

Fortunately, introduction of geometrical focusing and of the asymmetry in the discharge gap (Fig. 2) has relaxed the cooling requirements. Table I shows a comparison of the results for a standard magnetron source (Mk III, cathode surface area 12.5 cm^2) with its modified version (same cathode surface area, single focusing groove); preliminary results for the geometry as shown on Fig. 2 have also been included. It is evident that for the same negative current density the cathode power density can be reduced because negative ions are collected from an area much wider than the slit itself. An additional gain in the performance results from a lower operating pressure (a lower discharge current requires a lower pressure); the consequence in on one hand a lower gas flow from the source and on the other a longer mean free path for negative ions while travelling from the cathode through the source into the extraction gap.

Based on these results and assuming a linear scaling down of the negative ion current density with source input power, parameters for a larger model, operating steady state, have been determined. The parameters also agree with general guidelines of the neutral beam program, i.e. an H^- or D^- current of about 1-2 A with a density of 0.5-1 A/cm^2, an extraction voltage of 10-40 kV, a pulse length of at least 5 s (thermodynamically this is steady state operation) and the heat removal by a simple method, like water flow. The last requirement limited the maximum power density at any electrode to 0.2 kW/cm^2. Table II shows the parameters of the source and Fig. 3 its cross section. There are five focusing grooves on the cathode surface opposite the extraction slits; total length of the slits is 40 cm and the area 2 cm^2. The shape of the anode cover has been chosen such as to accomodate the cooling channels. Cathode supports serve to feed the cooling water to the center part of the cathode; their shape has been chosen so that in all regions close to the discharge plasma there is a component of the electric field parallel to the magnetic field. Such a shape prevents the diffusion of electrons out of the discharge gap into the support area and an initiation

Table I

	Standard magnetron (Mk III; A = 12.5 cm^2)	Magnetron with 1 groove (Mk III; A = 12.5 cm^2)	Magnetron with 3 grooves (Mk IV; A = 38 cm^2)
H^- current [A]	1	0.6	0.35
H^- current density [A/cm^2]	0.7	2.2	0.35
Pulse length [s]	0.01	0.01	0.1
Cathode current density [A/cm^2]	20	3.6	1.3
Cathode power density [kW/cm^2]	1.6	0.45	0.16
Gas efficiency [%]	1-2	6	-

of sparks or parasitic discharges there. Cathode material is molybdenum, with less than a monolayer of cesium on the surface; this combination has proved to function as a good converter of primary particles into negative ions. The rest of the source is stainless steel. The whole source is immersed in a magnetic field of about 1.5 kG, perpendicular to the grooves (Fig. 3), which is necessary for the operation of a discharge of the magnetron type. Cesium will be injected from a heated cell filled with pure metal and mounted on the side of the source opposite the extraction slits. The design of the grid at this time has not yet been finalized, first experiments will be done with a solid structure and pulsing the extraction voltage (pulse length about 0.1 s). After the shape of the extractor has been optimized, a water cooled version will be fabricated. The schedule calls for grid tests by the end of December.

Table II

H^- (or D^-) current	1 to 2 A
H^- (or D^-) current density (in the extraction slits)	0.5 to 1 A/cm^2
Extraction slit area	2 cm^2
Pulse length	> 5 s
Cathode current density	0.8 to 1.6 A/cm^2
Cathode surface area	60 cm^2
Cathode current	50 to 100 A
Discharge voltage	120 to 180 V
Cathode power density	< 0.2 kW/cm^2
Anode power density	< 0.1 kW/cm^2
Total source power input	< 18 kW
Cathode cooling system (full load)	
inside wall temperature	90°C
water velocity	35 m/s
pressure drop	4.5 kg/cm^2
Anode cover cooling system (full load)	
inside wall temperature	75°C
water velocity	35 m/s
pressure drop	4.5 kg/cm^2
Source power efficiency	0.1 A/kW
Source gas efficiency	6%

BNL Magnetron Source With Plasma Injection

There are basically two drawbacks of the magnetron source as described in the previous paragraph. First, even with the two improvements the gas efficiency was not better than 6% and it is doubtful that it could be increased above 10% by further changes in the design. Second, the energy of primary particles bombarding the cesium covered cathode is determined by the conditions for sustaining the discharge and its value may not be the best for production of negative ions. Both of these drawbacks may be greatly reduced if plasma is injected into the ion source from a separate plasma source. Feasibility experiments have been performed with a 3 mm diameter tantalum hollow cathode[7,8] to see whether a highly ionized plasma with sufficient density could be produced and injected into an electrode configuration similar to the ion source geometry. Table III summarizes the results; they show that it is possible to operate such a hollow cathode at plasma densities above 10^{14} cm^{-3} and to draw between 1 and 2 A/cm^2 of current into a properly biased electrode (-80 V). Covering of the latter electrode (called converter because of processes on its surface) with some cesium resulted in an increase of the current, due to secondary electron and negative ion emission. Simultaneously, a current was observed on a collecting electrode, at the ground potential, situated in the vicinity of the converter. From these measurements it was estimated that 0.3 A/cm^2 of H^- ions or more were produced on the converter surface and transfered through the plasma to the collector. This is more than sufficient for an H^- ion source and a modification of the cooled magnetron to include several hollow cathodes is being studied. It is expected that such a source could deliver more than 2 A of negative ions in a steady state operation, with a gas efficiency of 50%.

Table III

Mode of operation	steady state (> 25 hrs.)
Arc current	
hydrogen mode	22-29 A
hydrogen-cesium mode	4-100 A
Converter current density (at -80 V)	
hydrogen mode	1.3 A/cm^2
hydrogen-cesium mode	2.3 A/cm^2
Estimated H^- yield (Cs mode)	> 0.3 A/cm^2
Operating pressure	(1-3) x 10^{-4} torr
Plasma density (center)	$\approx 10^{14}$ cm^{-3}

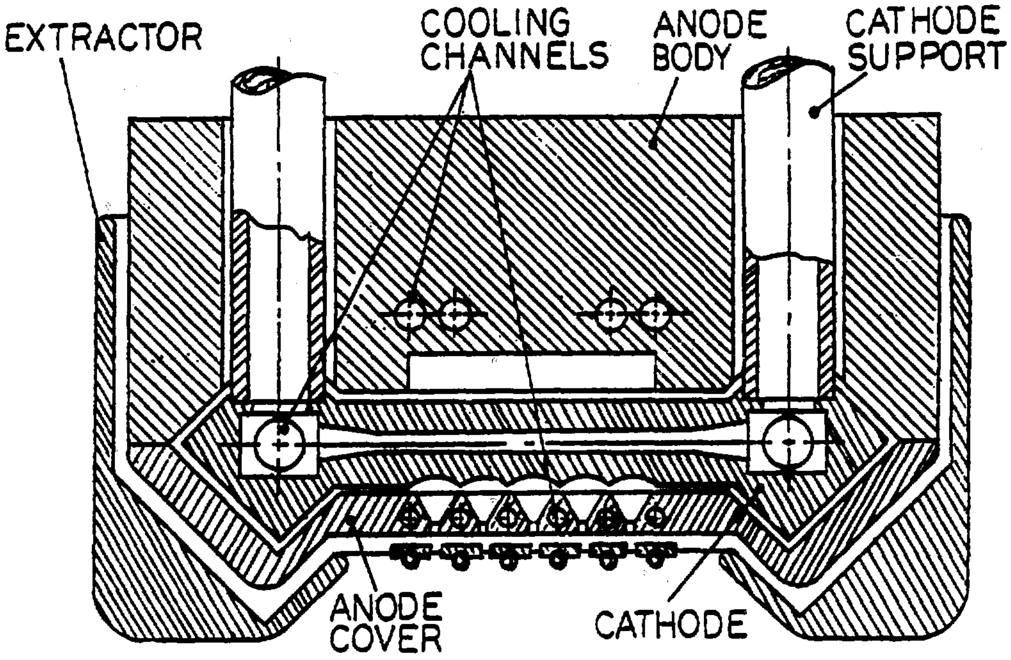

Figure 3: Cross section of the BNL Mk V magnetron source, with electrode cooling.

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