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NEGATIVE HYDROGEN ION SOURCES FOR NEUTRAL BEAM INJECTORS*

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Abstract

Negative ion sources offer an attractive alternative in the design of high energy neutral beam injectors. The requirements call for a single source unit capable of yielding H^- or D^- beam currents of up to 10 A, operating with pulses of 1 s duration or longer, with gas and power efficiencies comparable to or better than achievable with double electron capture systems. H^- beam currents of up to 1 A have already been achieved in pulses of 10 ms; gas and power efficiencies were, however, lower than required. In order to increase the H^- yield, extend the pulse length and improve gas and power efficiencies fundamental processes in the source plasma and on cesium covered electrode surfaces have to be analyzed; these processes will be briefly reviewed and scaling rules established. Based on these considerations as well as on results obtained with 1 A source models a larger model was designed and constructed, having a 7.5 cm long cathode with forced cooling. Results of initial tests will be presented and possible scaling up to 10 A units discussed.

Introduction

The development of high current H^- ion sources in the period since the last Symposium has gained in importance due to recent studies of several new magnetic fusion devices requiring neutral beam energies of up to and above 1 MeV. The source requirements have been somewhat arbitrarily established, calling for a unit yielding 10 A of H^- or D^- ions, capable of quasi-steady state operation with good power and gas efficiencies. The development of high current H^- ion sources has been pursued at Brookhaven National Laboratory and at the Institute for Nuclear Physics, Novosibirsk, the place where first models of these sources were designed. From sources operating with hydrogen gas and a small admixture of Cs vapors, H^- beam currents of up to 1 A have already been extracted[1,2] and accelerated[3] to energies above 100 keV; pulse length was, however, not longer than 10 ms at these current levels.

Requirements for beams not only an order of magnitude more intense, but quasi-steady state as well have changed our approach in the design of new sources. It has been shown[4] that present magnetrons could be scaled-up for H^- currents up to 10 A, but the pulse length would be limited to less than 100 ms. In such a source the cathode body would absorb the heat deposited during the pulse and release it during relatively long intervals between pulses; the pulse length and the power density would be limited by the allowed cathode surface temperature at the end of the pulse. In the new design, for quasi-steady state operation, the cathode and possibly other electrodes serving as H^- ion emitters have to be cooled so that their surface temperature is maintained at a certain value. As the final beam parameters (e.g. beam current density) will determine the required density of H^- current leaving the emitters, it is of crucial importance to study the processes on the cesium covered surface resulting in the production of H^- ions; a more efficient production or a higher power efficiency would mean lower cooling requirements. Second parameter of H^- ion sources to be investigated and improved is the gas efficiency. It is defined as the relative number of H^- ions leaving the source and it depends, among others, on the surface production efficiency and the ionization degree of the gas in the discharge chamber. Closely related to these two parameters is the problem of H^- losses while traversing the plasma and during the extraction and beam formation processes. All these aspects of the production of negative hydrogen ions in sources will be considered, presently obtained results reviewed and compared with requirements and suggestions given for further developments.

Processes in H^- Ion Sources

There is an agreement that surface phenomena are the reason for enhanced H^- yields from sources operating with a small admixture of Cs vapors. The emission of negative ions from cesium covered metal (W, Mo) surfaces has been treated by several authors,[5-7] but the experimental data are still not available to estimate the contributions of possible processes. Kishinevskiy[5] considers two processes to be of importance: kinetic desorption of surface adsorbed hydrogen in the form of negative ions, under bombardment by particles diffusing out of the plasma, and backscattering of primary particles (atoms, positive atomic ions) from the surface, again in the form of negative ions. By calculating the probability that a negative ion would escape the image field without being neutralized, he has concluded that the coefficient of the secondary ion emission might reach values around 80%, depending on the energy of primary particles. Hiskes et al.[6] have developed a model for H^- ion production, according to which H^- ions would be formed in collisions of energetic hydrogen atoms and protons with adsorbed cesium atoms, electron transfer occurring through the intermediary of the CsH and CsH^- molecular configurations interacting with the substrate. They estimate that the secondary emission coefficient for negative ion production by incident particles with energies of ten to one hundred eV would be in the range between 30 to 50%. Wiesemann[7] has concluded that the kinetic desorption is the most important process for surface production of H^- ions; the most likely adsorption process would be the indirect activated adsorption. There is some experimental evidence, that the effective coefficient of secondary negative ion emission (including all surface processes) as measured in an ion source is indeed high and may reach values above 0.5. It is interesting to note, that the H^- yield of a Penning source may be substantially increased by using a negatively biased electrode opposite the extraction slits and close to the plasma column;[1] if this electrode is placed away from the column, there was little change in the yield.[1,8] This would imply that neutral particles diffusing out of the plasma do not play an important role in the production of H^- ions. Measurements of D^- production in thick cesium films under bombardment by D_2^+ and D_3^+ ions[9] suggest that these particles may also produce negative ions with a high efficiency. For the development of negative ion sources it is very important to know the contributions of possible mechanisms, as function of surface conditions and incident particle parameters. The knowledge of all these parameters may lead to the optimization of the present source performances (e.g. by introducing other emitter materials, more efficient and reliable) and to the development of new source types.

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Related to the processes on the emitter surface is the question of surface heating under bombardment by particles from the discharge plasma. Surface temperature will be one of the factors determining the degree of cesium coverage and, therefore, the efficiency of H^- production. Hiskes et al.[6] have reviewed the processes of Cs adsorption; a surface work function close to its minimum value could be maintained at cathode temperatures up to 600°C if the Cs flux is 10^{16}-10^{17} $cm^{-2}s^{-1}$. Although much higher surface temperatures (up to 1000°C) have been mentioned as possible,[10] there may be another phenomenon limiting the temperature: at high cathode power densities a transition from the normal operating mode into a (probably localized) low voltage discharge was observed, accompanied by a drop in the H^- output to negligible values. There are two thermal regimes of the source operation to be distinguished: transient increase of the surface temperature during the initial part of the discharge pulse and the steady state regime of a source with cooled electrodes. It is possible to estimate the transient increase[4] by using expressions for the temperature distribution in a semi-infinite body, resulting from a constant heat flux input to the surface. As function of the time t after the beginning of the discharge, the change ΔT in the surface temperature follows a simple law

$$\Delta T \propto q_o \sqrt{T}, \tag{1}$$

where q_o is the heat flux input. The validity of this model is limited to $t < 100$ ms in the case of the BNL solid cathode magnetron source, but for such pulses this expression represents a scaling law, showing, for a given ΔT, a trade-off between the power load and the maximum pulse length. For sources operating in quasi-steady state or steady state regimes, the cooling of electrodes, especially those emitting H^- ions, will be one of the most important problems, possibly limiting the current density of the extracted beam. A related parameter, the power efficiency of the source, will become less and less important as the energy of the final accelerated beam increases. The efficiency of the H^- production has been considered in some detail by Bel'chenko et al.,[1] but their estimate of 1-2 keV/ion as achievable seems to be optimistic. Present sources operate with efficiencies of at most 20 keV/ion, or require an input power of 20 kW/A. It may be assumed that about 2/3 of this power would end up as heat on the cathode. The required cathode surface area will be determined by the heat flux that can be removed at a certain surface temperature; e.g. if this value is 2 kW/cm^2, then the area would be about 7 cm^2/A. It is evident that any improvement in the H^- production efficiency will result in a lower heat load and possibly smaller source dimensions (the latter may be determined by the required current density at the extraction aperture).

Processes in the plasma include the production of particles to bombard cesium covered emitting surfaces (positive ions and energetic neutrals) and H^- transport phenomena along the path from the surface to the extraction aperture. The requirements posed on the plasma in a source of this type are to some degree contradictory: on one hand a high plasma density is required so that a sufficient flux of particles, ions and neutrals, diffuses out of the plasma layer and reaches the emitting surfaces and on the other, the density of charged and neutral particles along the way to the extraction slits should not be too high in order not to destroy a large portion of the H^- flux. It is still not very much known about the H^- emission as function of incident particle species (H^o, H^+, H_2^+, H_3^+) and energy, so that from this point of view not much can be concluded about the type of the discharge most suitable for an H^- source. It has to be, however, admitted that for present H^- sources little is known about the composition of the positive ion flux reaching negatively biased electrodes and that even the total positive ion component can only be estimated because the coefficients of the secondary (electron and negative ion) emission are not well known. Once the production mechanism is better understood, it will be possible to optimize the performance of H^- sources; a number of experiments is planned for the near future.[11]

If negative ions, produced on a surface, are to reach the plasma, the surface should be negatively biased with respect to the plasma; it is, however, in principle possible that some negative ions are produced by energetic neutral atoms on surfaces having an unfavorable potential, but still could overcome the decelerating field due to large initial velocities. Depending on the source geometry, primary H^- ions may pass through the plasma with some attenuation and reach the extraction aperture. A part of the extracted beam from the magnetron and the modified Penning (with an emitter) sources will consist of these, high energy H^- ions. Some of them will produce, in charge exchange collisions with slow atoms, slow H^- ions which will then diffuse toward the extraction aperture. The rest of the extracted magnetron beam and probably all of the standard Penning source beam will consist of slow H^- ions. The effect of charge exchange collisions is enhanced by the addition of a small, low plasma density chamber adjacent to the extraction aperture (the idea is to attenuate the diffusion of plasma electrons out of the source). The problem of the H^- transport phenomena through the plasma has been considered in more detail elsewhere.[8,12] For fast, primary H^- ions the most important contributions to the collision frequency

$$\nu_i = \frac{v_i}{\lambda_i} = \sum_k (n < \sigma v >)_k, \tag{2}$$

where v_i is the velocity, λ_i the mean free path and $(n < \sigma v >)_k$ the product of the reaction rate $<\sigma v>$ for a particular collision process k with the density of target particles n, are from collisions with neutral particles,[12,13] if the plasma density is of the order of $10^{13} cm^{-3}$. At higher plasma densities, of the order of $10^{14} cm^{-3}$, the loss due to collisions with charged particles becomes also important. Slow H^- ions will be lost mostly in collisions with charged particles,[12] while drifting toward the extraction aperture. It is interesting to note, that the reported[1] values of H^- current densities of about 3 A/cm^2 from a magnetron source and even higher from a Penning source imply[12] high densities of slow H^- ions (10^{12}-10^{13} cm^{-3}) and neutral atoms (10^{15} cm^{-3}), as well as drift velocities of slow H^- ions up to 10^6 cm/s.

Processes in the extraction aperture and beam forming system have also to be considered. First, there will be a substantial loss of H^- ions during the extraction process itself: the cross section for the reaction

$$H^- + H_2 \rightarrow H + H_2 + e$$

increases with energy up to a broad maximum at 10 keV. These electrons, together with other secondary charged particles produced in ionizing collisions in the extraction gap, contribute to the beam forming system load. For a constant pressure of molecules just inside the extraction aperture the effective thickness of the gas layer outside the source depends mostly on the slit width,[1] a fact recognized early as speaking in favor of the use of multislit geometries.[13,14] The loss itself has not been determined experimentally because of difficulties with the measurement of the neutral particle

TABLE I

Parameter \ Source		BNL Magnetron H_2	BNL Penning		Novosibirsk Magnetrons, H_2		Novosibirsk Penning		BNL cooled cathode source, design values		10 A scaled-up Magnetron
			H_2	D_2			without emitter, H_2	with emitter, H_2	Penning	Magnetron	
$H^-(D^-)$ current	A	0.9	0.44	0.2	0.9	1	0.15	0.2	0.9	1.8	10
$H^-(D^-)$ current density	A/cm^2	0.7	0.44	0.2	2.9	3.3	3	5.4	0.5	0.5	0.5
Pulse length	ms	10	3	6	1	1	0.2		25-50	25-50	dc
Discharge current	A	260	65	40	450	150	180	450(80*)	150	500	2000
Cathode current density	A/cm^2	20	33	20	110	50	300	(90)	20	20	20
Discharge voltage	V	120	220	400	100	120	100	100(100)	200	120	100
Total discharge power	kW	30	14.3	16	45	18	18	45(8)	30	60	200
Cathode power density	kW/cm^2	1.5	4.8	5.3	7.5	4	20	(9)	2.7	1.6	1.3
Power efficiency	mA/kW	30	30	12	20	56	17	3.8	30	30	50

* a. Values in parenthesis refer to emitter parameters.

flow from the source during the discharge,[15] the flow that may be very different from the value in the absence of the discharge. Related to this effect is another ion source parameter, the gas efficiency of the source. Presently quoted values range from 1 to 5% (gas efficiency of 5% corresponds to 3.7 Torr ℓ/As); from the point of view of H^- losses and the gas load in the beam line the gas efficiency should be improved to 10% or better in order for H^- sources to become competitive with positive ion sources. Second, the beam forming system of an H^- source has the role of producing a beam as required by the injection line and of removing the electrons diffusing out of the source perpendicularly to the magnetic field. Narrow slits attenuate the electron component better due to a difference in electron diffusion coefficients in direction along and perpendicular to the field. Finally, the cesium loss through the extraction aperture has to be considered as well. For sources operating with pulses of 10 ms or shorter the cesium loss has been estimated to be about 1 mg/hour, but most of the loss occurs immediately after the discharge pulse,[1] which is very favorable for steady state operation of H^- sources.

Present Source Performance

Parameters of present negative hydrogen ion sources have been summarized in Table I, including the new BNL source with cooled cathodes and a scaled-up version.

Magnetron source was the first high current source to be developed using the surface production of H^- ions[16] and it still remains the most intense and efficient among them. The model developed at BNL[2] has a cathode surface area of about 13.5 cm^2, an extraction aperture area of about 1.3 cm^2, and it yields H^- currents close to 1 A (0.7 A/cm^2) in 10 ms pulses or 0.6 A (0.45 A/cm^2) in 20 ms pulses. Power efficiency of the source is about 30 mA/kW, gas efficiency about 2-3%; corresponding values of the Novosibirsk magnetron source are better by about 50%, but the pulse length was shorter by an order of magnitude. The cathode power load is about 1.5 kW/cm^2, which should be within the capabilities of the future cooling system.[17] Present design of magnetron sources has several weak points. First, there is no independent cesium injection rate control- cesium density in the source is adjusted by changing the temperature of the cathode via discharge pulse amplitude, frequency and length. Second, the pulse length is limited by the initial cathode temperature and by the temperature increase during the pulse (eq. 1) because there was no cooling of the source. Finally, the alignment of the source with respect to the extractor was difficult.

By removing the center part of the cathode the magnetron source was converted into a Penning geometry. A small electrode was added opposite the extraction slits in order to enhance the production of H^- ions,[8] an idea pursued independently at Novosibirsk.[1] From an extraction aperture of 1 cm^2, an H^- current of 0.44 A and D^- current of 0.2 A were obtained. Power efficiency was about 30 mA/kW (12 mA/kW for D^- ions), gas efficiency about 1%, the cathode power density about 5 kW/cm^2. Due to a very small size of the cathodes (1 cm^2 each), the pulse length was limited to 3-6 ms, although the source was capable of operating at pulse lengths up to 50 ms with H^- yields < 100 mA. No substantial enhancement of H^- production was observed when the emitter was biased up to 50 V; however, an improvement by a factor of two was found by the Novosibirsk group when the emitter was put very close to the plasma column. It is possible that in such a geometry a flux of positive ions is required for the production of H^- ions and that a similar increase would have been observed with the BNL source had the emitter been closer to the plasma. Should this prove to be the case, then the power efficiency might reach values of about 50 mA/kW. Same remarks as for the magnetron source apply for the Penning source: there was no independent cesium injection control and no cooling of the electrodes. (The Novosibirsk source has some cooling capabilities through channels in the main body of the electrodes, but due to very short pulses the cooling effect was limited to a faster heat removal between the pulses.) If the power efficiency of the source could be improved by a factor of 2 (e.g. by putting the emitter close to the plasma column), an emission aperture current density of 0.25 A/cm^2 should be achievable with the source operating in the quasi-steady state mode.

BNL H^- Source With Cooled Cathodes

As mentioned before, the BNL approach in the design of the next model of an H^- source had to be changed. It has been decided to incorporate in it not only an independently heated cesium container, but cooling channels in the cathode as well (Fig. 1, magnetron version). This design was still based on previous models, so that the cooling will be effective more between the pulses than during the pulse itself. When operating in the magnetron geometry, the cathode surface area is about 25 cm^2, so that discharge currents up to 500 A should be achieved. With a discharge voltage of 120 V, the discharge power would be 60 kW, and the cathode power density about 1.6 kW/cm^2. If the same power efficiency is assumed as in previous models, an H^- current of about 2 A should be obtained. Figures 2 and 3 show photos of the source. In the Penning mode of operation the cathode surface area is 7.5 cm^2 (cathode length 7.5 cm), and discharge currents up to 150 A are expected. A power efficiency of 30 mA/kW, achieved with the small Penning source, would result in the H^- yield of 0.9 A, a possibly higher value of 50 mA/kW (by using an emitter) would result in the yield of 1.5 A. However, in either case the D^- yield might be appreciably smaller. The source design is flexible and different electrode shapes will be investigated. In order to facilitate the alignment, the source pole tips and the extractor constitute one unit, aligned on the bench and then mounted on the magnet yoke. The source is presently on the test stand and a 50 ms long discharge pulse achieved in the pure hydrogen mode.

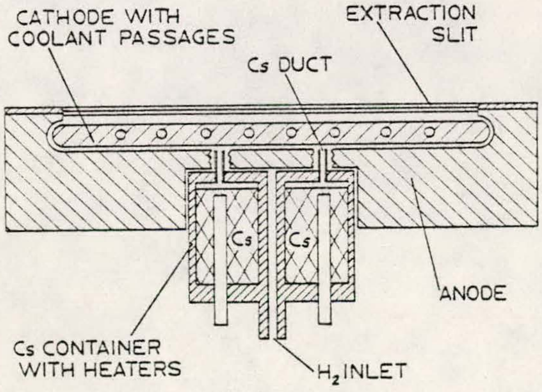

Fig. 1 Cross section of the BNL magnetron source, with a cooled cathode and independently heated Cs container.

Neg. #'s 5-1206-77
9-823-77
10-782-77
10-858-77

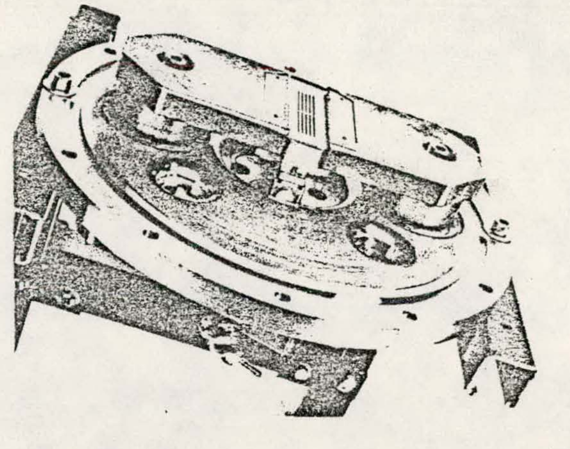

Fig. 2 Photo of the BNL magnetron source; five extraction slits have a total area of 3.5 cm^2.

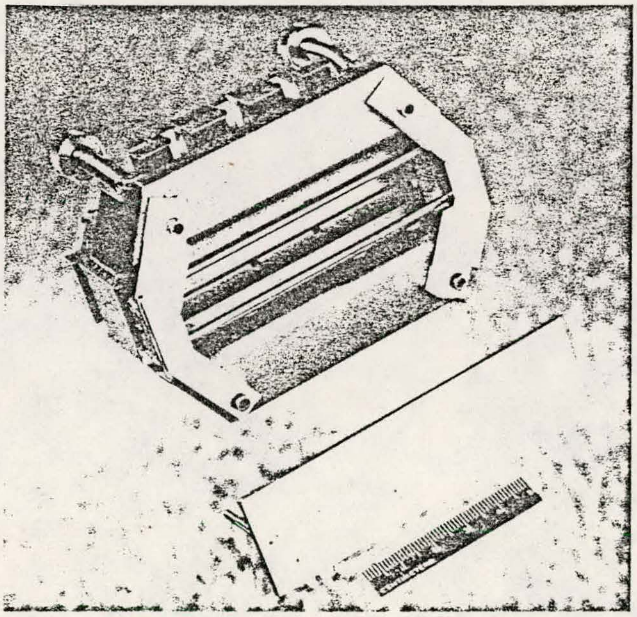

Fig. 3 Photo of the BNL Penning source; emitter electrode is visible inside the source.

The new sources have higher power and pumping speed requirements. A new test stand has been constructed and put into operation (Fig. 4), having a pumping speed of 5000 ℓ/s which is an order of magnitude higher than before. The new extractor power supply can operate at 25 kV, either with 20 A in 100 ms pulses or 3 A dc. The existing discharge power supply, yielding 500 A, 25 ms pulses will be expanded to 50 ms by adding a new 25 ms PFN. Diagnostics has also been redesigned in order to handle longer and more intense pulses of H^- ion beams. Plans for immediate future include continuation of measurements of source parameters (gas flow during the discharge pulse, plasma parameters) and electrode cooling studies with the objective to determine the allowable surface power density for a quasi-steady state H^- source.

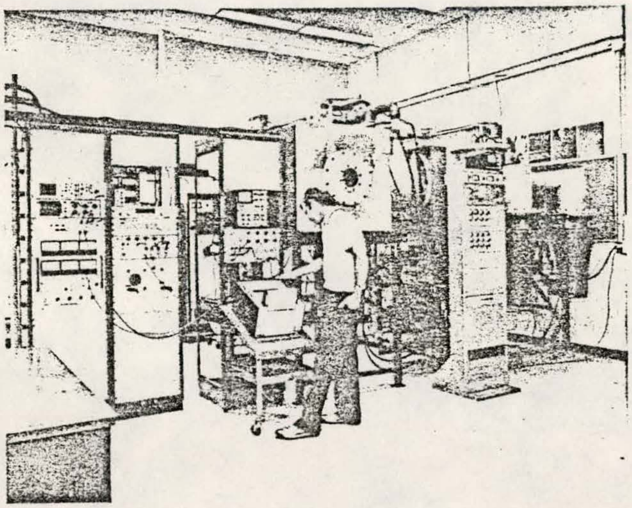

Fig. 4 Ion source test stand.

Finally, one may try to extrapolate present source parameters and get an idea about a 10 A, dc magnetron source (Table I). Assumptions are: a power efficiency of 50 mA/kW, a cathode power density of 1.3 kW/cm^2 and an extracted H^- current density of 0.5 A/cm^2. With a discharge voltage of 100 V the total discharge current should be 2000 A; the maximum cathode power density would limit the cathode current density to 20 A/cm^2, resulting in a cathode surface area of 100 cm^2. The extraction aperture would have an area of 20 cm^2 or 10% of the cathode surface area. Any improvement in the production and plasma transport efficiency would result in a lower cathode power density, but not in a smaller source.

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5. [illegible]