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DEVELOPMENT OF NEGATIVE ION BASED NEUTRAL BEAM SYSTEMS IN THE USA*

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Advanced fusion devices will require very long pulse neutral beams with currents of several hundreds of amperes and energies up to and above a thousand keV.[1] The mirror program at Lawrence Livermore Laboratory already calls for a high current, 200 keV neutral injector prototype to be ready as early as 1982,[2] and for higher energies soon afterwards. This trend leads to the development of neutral injectors based on negative ions because their neutralization efficiency does not depend much on the energy and may exceed values of 60-90%, depending on the stripping target. If such systems are realized, considerable savings would result in project costs.

Two approaches are presently being pursued to develop usable beams of negative ions. The first approach is to extract negative ions directly from a surface source and then to accelerate them to the high energy. The second approach is directed to the production of negative ions from positive ions in a double charge exchange cell; the beam is then accelerated and neutralized in a similar way as in the first approach. Figure 1 shows schematically the principles and basic components of both systems.

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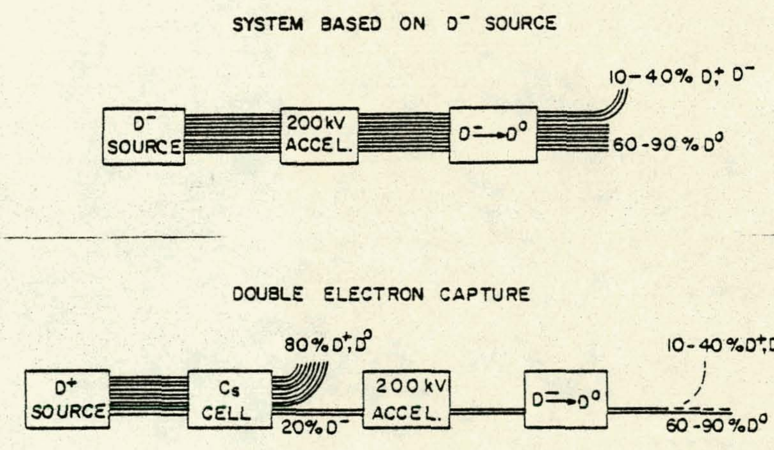

Fig. 1 Principles of the direct and indirect production of negative ions.

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Preliminary experiments with both systems have resulted in the production and acceleration of negative ion beams. It is, however, not clear yet which principle will be more practical, because in both experiments the beam current and the beam energy are still too low and the pulse length too short and a considerable scaling-up will be required before a decision can be made. In the paragraphs below we shall discuss the progress of a double electron capture system under development at the Lawrence Laboratories, a direct extraction system based on negative ions from magnetron and Penning sources at Brookhaven National Laboratory and the negative ion production by laser irradiation of alkali hydride or deuteride targets pursued at TRW Inc.

Neutral Beam Systems Based on Double Charge Exchange

The main advantage of the production of negative ions using double charge exchange is the application of well developed, reliably operating positive ion sources, which in principle can be scaled to arbitrarily large beam currents.

The experiments have been concentrated on studies on production and transport of pulsed (10-25 ms) negative ion beams. So far, beam currents around 0.1 A were accelerated to energies of 60 keV using a cesium charge exchange cell.[2,3] Figure 2 shows a schematic of the experimental arrangement.

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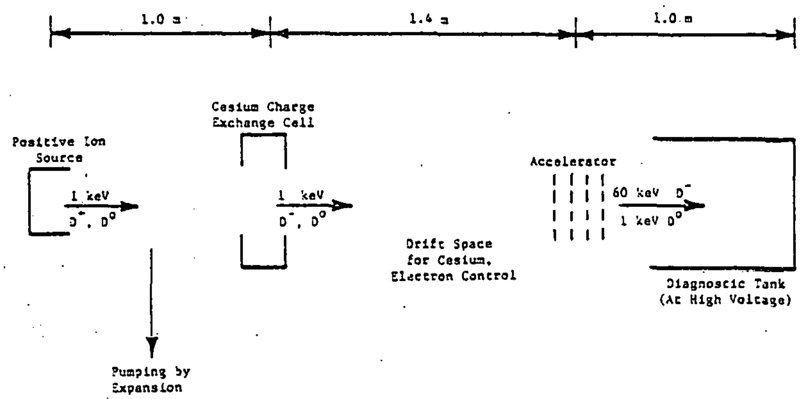

Fig. 2 Schematic of double charge exchange experiment.

The positive ion source is a "10 A" LBL source with a special accel-decel grid array for low energy extraction and beam formation. Electron emitters are installed near the grids for improved space charge neutralization. An important fraction of the beam, which enters the charge exchange cell, has already been neutralized by the relatively high background pressure, estimated to be 5×10^{-3} Torr, limited by the source vacuum chamber. Another component of the extracted beam (5%) are energetic (up to 10 keV) neutrals formed by charge exchange within the extraction grids. This component can only be avoided by lower gas pressure in the grid structure.

The charge exchange medium used in this experiment is cesium, which has the highest negative ion equilibrium fraction among the alkali vapors namely 24% at 1 kV.[4,5] With special care in the design of the pulsed, single slot jet the loss of cesium along the beam line has been reduced to a tolerable level. Further reduction of cesium loss may be expected with a double nozzle system and a central guiding surface.[5] Angular scattering during charge exchange collisions is small. However, the charge exchange process, $D^- + Cs^+ \rightarrow D + Cs$, with a theoretical cross section of about 10^{-14} cm^2, may limit the beam current density.[6]

The transport of the low energy negative ion beam to the accelerator is not a trivial task, in particular if the distance is large in order to avoid cesium contamination of the accelerator. The transport is based on an initial quasi parallel beam which is space charge neutralized by a plasma generated by the primary beam.[7] Electrons from this plasma and electrons from the stripping process cause a non-negligible current drain on the accelerator (10-20%) at a background pressure of about 5×10^{-5} Torr. It was found experimentally that unstable beam propagation occurs below a pressure of 4×10^{-5} Torr for a current density of about 3 mA/cm^2.

The six electrode 60 kV high voltage accelerator structure is shown in Fig. 3. The first electrode with a 6×12 cm^2 aperture defines the beam size; the second electrode is a correction electrode and the main accelerating gap is between the third and fifth electrode with a field gradient of about 8 kV/cm. With the Faraday cup 1 meter downstream a 100 mA negative ion beam was measured with a density of about 2-3 mA/cm^2 and a 2.4° beam divergence.

The main merit of these results at Livermore is that for the first time a well defined negative ion beam of 0.1 A has been delivered on a target 2.5 m from the source. The efforts in the near future will be concentrated to increase the total current, the current density and the energy. These objectives may be achieved by further development of highly directional cesium jets, or the development of directional intense plasma beams (replacing the proton sources) to avoid space charge limitations.[6] It is also possible that other charge exchange targets such as sodium with lower conversion efficiency (10%), but higher initial energy (10 keV) may become a more practical choice.[5,8]

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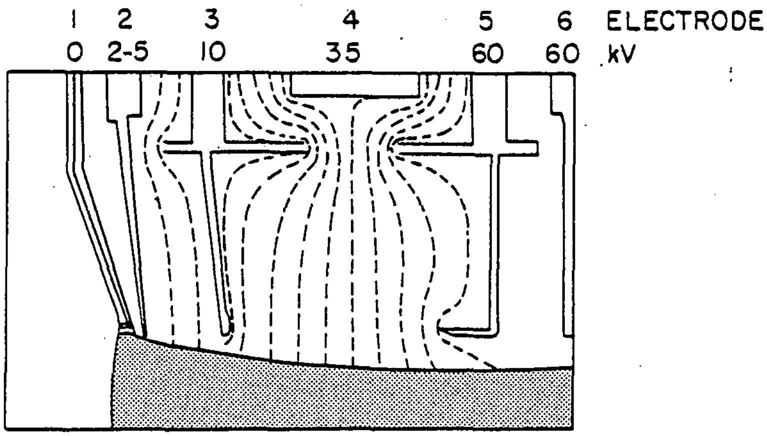

Fig. 3 High voltage accelerator.

Neutral Beam Systems Based on Direct Extraction Sources

Development of surface plasma (SP) sources for neutral beam systems is mainly concentrated at BNL. It is interesting to note that the application of these sources in electrostatic preaccelerators is now actively pursued in high energy physics laboratories such as FNAL (Batavia) and LASL (Los Alamos).[10,12]

As for the double charge exchange method there are advantages and disadvantages for the use of SP sources in neutral injectors. The advantages are: a compact structure with the high density source of primary particles adjacent to the cathode, a high efficiency of negative ion production, a low diffusion rate of electrons in the crossed E × B field and the production of low negative ions, which may provide a small beam emittance. The disadvantages of these sources are in particular the low gas efficiency and the heating of the converter surface during long beam pulses or in general the yet unknown art of scaling these sources to multiampere, dc units.

a) Ion Sources

Several models of magnetron and Penning sources were constructed and tested. The BNL MK III magnetron with the cesium compound in the cathode cavity (Fig. 4) is still the most intense and efficient source among the surface sources. Table I shows the parameters of the BNL and FNAL sources.[9,10] The pulse length and extracted current are limited by the removal of heat from the cathode without outside cooling means.

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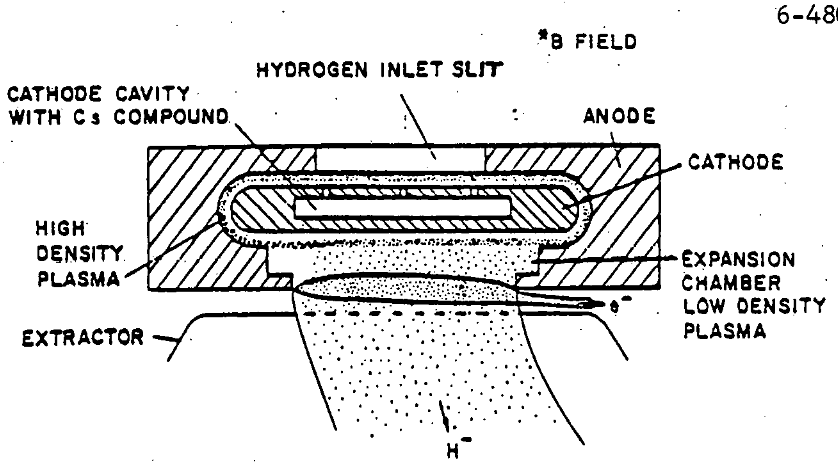

Fig. 4 Magnetron (MK III)

Table I

MAGNETRON PARAMETERS

Parameters \ Source		Fermilab 15 Hz H_2	BNL (MK III) H_2
H^- (D^-) current	A	≈ 0.1	0.9 (0.6)*
H^- (D^-) current density	A/cm^2	≈ 1	0.7 (0.45)
Pulse length	ms	0.09	10 (20)
Discharge current	A	150	260 (180)
Cathode current density	A/cm^2	15	20 (14)
Discharge voltage	V	175-200	120
Total discharge power	kW	26-30	30 (22)
Cathode power density	kW/cm^2	1.8-2	1.5
Power efficiency	mA/kW	3.0-4.0	30 (20)
Gas Efficiency	%	---	2-3

*Parameters for 20 ms pulses are given in parentheses.

Penning discharges (Fig. 5) have been investigated at BNL[11] and LASL.[12] Achieved H^- currents are generally lower than from magnetron sources, see Table II, due to smaller dimensions of presently operating sources. At BNL a pronounced isotope effect was found: D^- yields and power efficiencies were considerably lower. It seems that a Penning source with a separate emitting electrode opposite the extraction slits may improve the performance by a factor of 2. If this is so, these sources would have characteristics comparable to those of magnetron sources and might be scaled-up to much larger sizes.

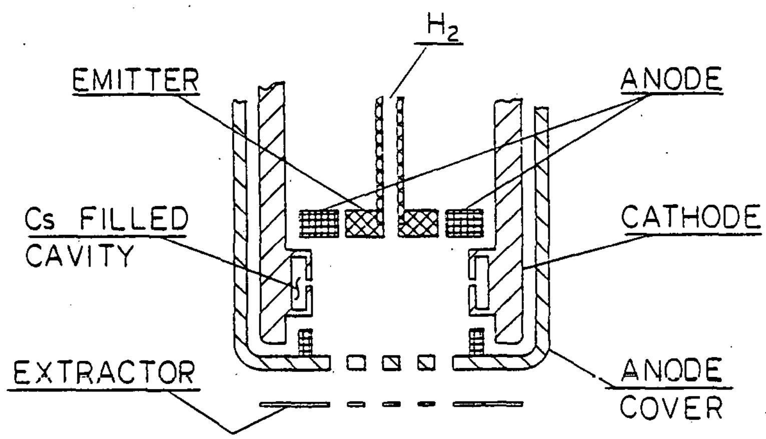

Fig. 5 Penning with emitter (MK III).

There are several proposals to improve the gas efficiency in surface plasma sources. For instance, a wider gap in the back of the source may facilitate the start of the discharge and maintain it at a lower pressure.[13] Another approach, under investigation at BNL, is the jet source, as shown in Fig. 6 in which the primary gas flow is directed towards a pump manifold located in the back of the source.[14] In the molecular flow situation with a mean free path length of several millimeters inside the discharge chamber, it is expected that the excess gas will be mainly removed in the back of the source instead of through the emission slits.

Another drawback of the described SP sources is the lack of efficient cooling during the discharge pulse. Recent studies at BNL have shown that it should be possible to keep the cathode surface temperature around the optimum temperature, which is between 300-500^{o} C, under a heat flux of 1 to 2 kW/cm^2, by using pressurized water cooling.[15] The larger BNL MK IV model, that may operate in both magnetron and Penning modes, has some

Table II

PENNING SOURCES

Parameters	Source	LASL H_2	BNL (MK III) H_2	BNL (MK III) D_2
H^- (D^-) current	A	0.11	0.44	0.2
H^- (D^-) current density	A/cm^2	2.2	0.44	0.2
Pulse length	ms	0.7	3	6
Discharge current	A	60	65	40
Cathode current density	A/cm^2	[100]*	33	20
Discharge voltage	V	80	220	400
Total discharge power	kW	4.8	14.3	16
Cathode power density	kW/cm^2	[4.8]	4.8	5.3
Power efficiency	mA/kW	23	30	12
Gas efficiency	%	0.8	1.1	

*Values in [ ]: expected or not confirmed.

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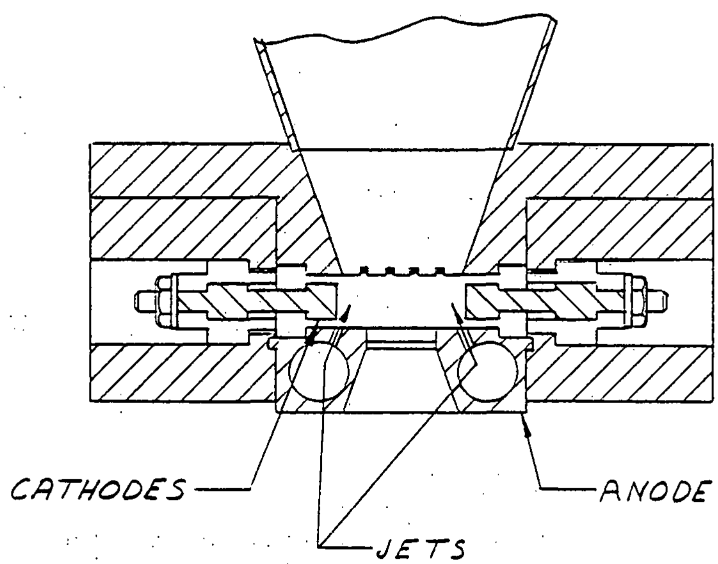

Fig. 6 Jet source.

cooling capability (cooling canals in the cathode); the method of cesium injection has been changed as well (see Fig. 7). Instead of placing the cesium compound into a cavity inside the cathode, a separately heated container will be used, resulting in a better control of the cesium diffusion rate. Currents up to 2 A in the magnetron are expected. The source is presently being tested and normal operation of the discharge in the hydrogen mode was achieved with pulses 50 ms long. To our knowledge, there are no other sources of either magnetron or Penning type designed for long pulse or steady state operation.

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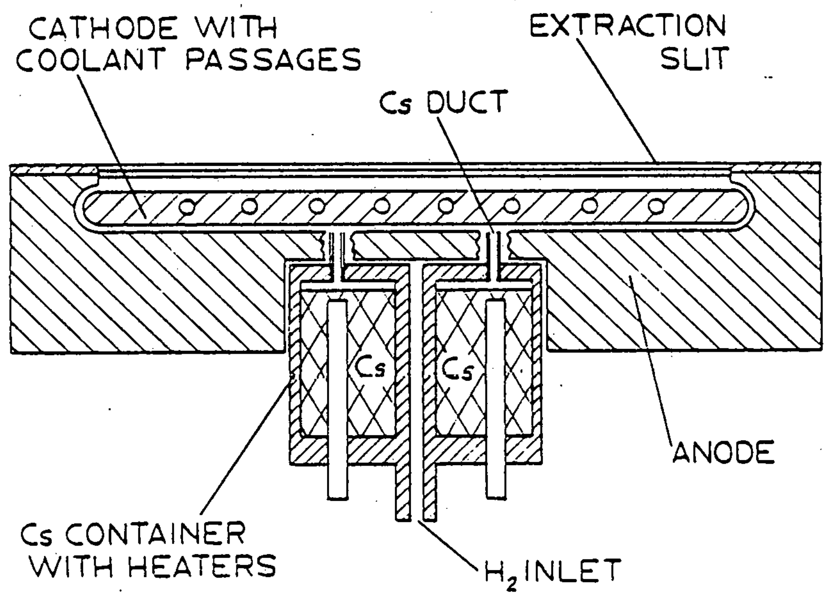

Fig. 7 MK IV magnetron.

The future source development at BNL will be concentrated around the scaling up of either the magnetron of Penning source to the multiampere dc range. Parallel to this effort, a study is underway on how to stack several sources in order to reach the higher beam currents.

Finally, at ORNL there is an effort underway to modify duopigatrons to serve as intense negative ion sources; plans are to use perpendicular magnetic fields in the extraction aperture to remove the electrons. This program is still at a very early stage of investigation.[16]

b) Extraction and Acceleration

The extraction of negative ions from the source, removal of accompanying flux of electrons, transport and focus of ions into the accelerating system have been achieved so far in a close coupled, single gap accelerator system. Figure 8 shows the experimental arrangement. The two main advantages of such a system are the compact source-accelerator structure and low beam losses during fast acceleration of the ions. The disadvantage of the close coupled structure is: the closeness of the accelerating electrodes to the source, which causes an unreliable operation of the high gradient accelerator due to the high density gas background, the large beam halo from the source and the contamination of the electrodes by cesium in between beam pulses. Without quadrupoles H^- currents of about 1 A have been accelerated up to energies of 120 kV in beam pulses of 3 ms at an initial current density of 0.8 A/cm^2. At 15 cm downstream the density was about 25 mA/cm^2 in a divergence of 10-15°. In preliminary low beam current transport experiments with a 3" diameter magnetic quadrupole doublet, a 150 mA negative ion beam was focused on a Faraday cup, located 75 cm downstream. This focused beam was limited by the acceptance of the quadrupoles, located 20 cm downstream the single aperture accelerator.

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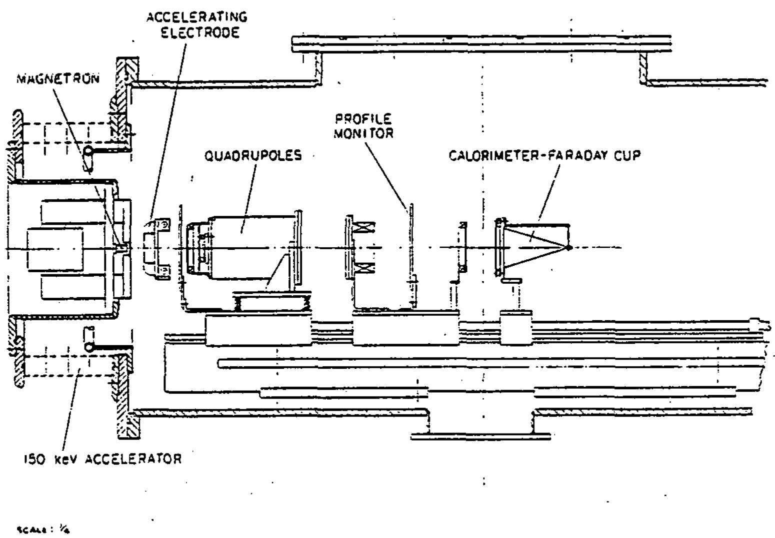

Fig. 8 Close coupled accelerator arrangement.

An attractive alternative to close coupled acceleration is separating the extractor from the accelerator by a bending magnet. The advantages of this approach are the operation of the source with high current densities (therefore better source gas efficiency), the efficient removal of electrons and heavy ion impurities, differential pumping of the space between source and accelerator, and absence of cesium contamination of high voltage accelerator electrodes. In addition, the bending magnet, with strong focusing properties in the plane perpendicular to the emission slit, provides some control of the beam entering the accelerator. Disadvantages of this additional beam line component are that it becomes bulky for large beam currents and that the beam losses due to collisional detachment are not negligible. Table III summarizes the performance of such a system with a small, 8 cm radius, bending magnet as measured in Novosibirsk,[17] LASL[12] and FNAL.[10]

Table III

Parameters \ Source		Novosibirsk Penning	LASL Penning	Fermilab Magnetron
Extracted H^- current	mA	100-150	≈ 120	100
Extracted H^- current density	A/cm^2	2-3	≈ 2	≈ 1
Extraction voltage	kV	20	18	20-25
Output H^- current	mA	100	110	50
Output H^- current density	mA/cm^2	125(10*)	> 15	20
Transport efficiency	%	80-90	90	50
Post-acceleration voltage	kV	--	--	700
Field index		1	0.85	1

*Noisy discharge.

A neutral beam system based on this principle of post acceleration is under investigation at BNL.[18] Figure 9 shows a schematic layout of a 1-2 A, double gap 250 kV injector with single acceleration apertures; the pressures in the bending magnet, the accelerator chamber and the neutralizer are independently controlled.

c) Neutralizers

So far, experimental investigations of neutralizers for negative ions are limited to a) the metal vapor cesium jet as applied in the double

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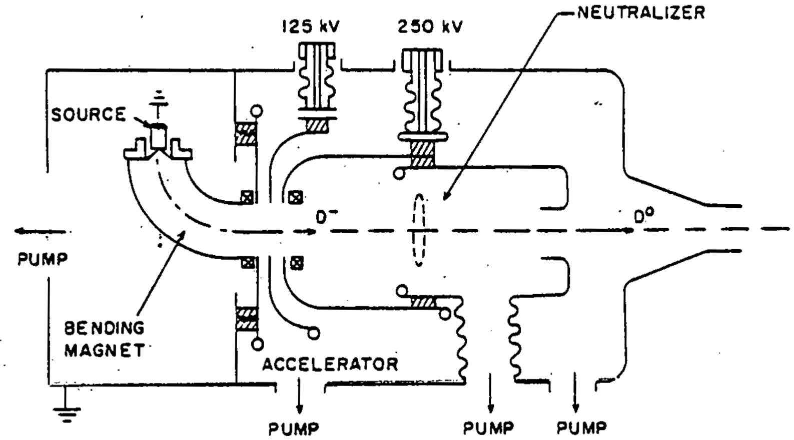

Fig. 9 A 250 kV neutral beam system.

charge exchange experiments in LLL[3,6] and b) a H_2 and CO_2 gas jet in BNL.[19]. The neutralization efficiency at the optimum target thickness ranges from 40% for CO_2 to about 60% for Cs and H_2. The choice of the target is a compromise between the efficiency on one hand and the required target thickness and ease of pumping on the other. Recent experiments on the gas profiles of a low pressure effusive CO_2 jet show good correspondence with theoretical predictions.[20]

In conclusion, it appears reasonable to assume that with adequate cooling of the cathode and independent cesium control a multiampere, quasi steady state negative ion surface plasma source can be realized. The application of post acceleration with bending magnet(s) seems to have more future for multiampere high energy neutral injectors than close coupled systems.

Laser Induced Negative Ion Production

There is a study underway on the performance of a negative deuterium source based on direct plasma production from solid alkali deuteride illuminated by a short (100 ns) laser pulse of about 1 Joule.[21] Figure 10 shows a schematic of the experimental set-up. A carbon dioxide or ruby laser irradiates a solid NaD target mounted in a vacuum chamber. This radiation evaporates some of the solid material and produces a multispecies plasma, which expands into the vacuum chamber.

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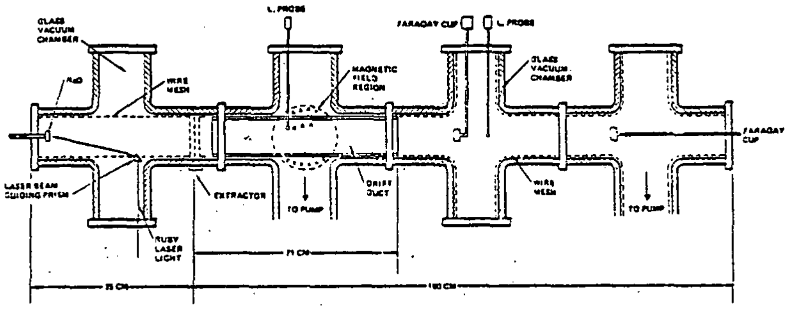

Fig. 10 Laser-NaD target experiment.

Ratios of $D^-/D^+ \approx 0.2$ at about 1 m from the target have been measured. Negative ions are extracted by a multiple grid structure. It is assumed that in the first two grids of the extractor a magnetic field, produced by opposing currents, separates the electrons from the ions, while the third grid provides the acceleration gradient. Other extraction techniques with crossed E × B field are under investigation. Preliminary results measured current densities of 15 mA/cm^2 at about 1 m downstream the extractor grids.

If successful, such a system has the advantage of low background pressure; however, the problems surrounding beam formation and scaling these sources to long beam pulses are not trivial.

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