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DEVELOPMENT OF H^- SOURCES AT BROOKHAVEN NATIONAL LABORATORY*

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Abstract

Negative hydrogen ion sources have been developed at Brookhaven National Laboratory for several years, with the initial goal to design a source for accelerator applications and later on to design a large unit for applications in neutral beam injectors of magnetic fusion devices. Three types of sources have been investigated, a hollow discharge duoplasmatron yielding H^- currents up to 60 mA, a Penning source yielding H^- currents up to 440 mA, and a magnetron source yielding H^- currents up to 1 A. All sources operate with a mixture of hydrogen gas and cesium vapors, and H^- ions are most likely produced on cesium covered electrode surfaces. A larger model of a Penning/magnetron source has been constructed and will be tested soon; it incorporates among other new features a system for the cooling of the cathode.

I. Introduction

Development of negative hydrogen ion sources for accelerator applications at Brookhaven National Laboratory started on a modest scale sometime in 1972, but very soon afterwards the information obtained from laboratories in USSR on new source designs[1,2] showed that the field of applications could be extended to include the production of intense neutral beams for fusion devices. Since then the program to develop intense negative hydrogen ion sources has been pursued vigorously both at the Institute for Nuclear Physics, Novosibirsk and at Brookhaven National Laboratory. The work at Novosibirsk has been reviewed in several reports[3,4] and this paper will cover the work at Brookhaven National Laboratory. All three types of sources being investigated, a hollow discharge duoplasmatron, a Penning and a magnetron source (in USSR, the name planotron is used for the latter), operate with a mixture of hydrogen gas and cesium vapors, resulting in an order of magnitude higher H^- yield than without cesium. Negative hydrogen ions are dominantly produced on cesium covered electrode surfaces under bombardment by particles from the discharge plasma. This is the reason that the name surface-plasma source (SPS) has been proposed and accepted for this type of sources.

Processes of importance for the production and transport of negative ions will be reviewed first, followed by a discussion of requirements for a large H^- source operating in a quasi-steady state mode. Results of measurements on the three types of SP sources will then be presented, compared with requirements, and further plans outlined.

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II. Fundamental Processes and Requirements

Consideration of fundamental processes will be limited to those resulting in production/destruction and transport of negative ions, although for the operation of an SP source the plasma production of primary particles to bombard cesium covered surfaces (neutral and positively charged particles) is of equal importance. Formation of negative ions by collisions of hydrogen particles, positive and neutral, on cesium covered surfaces of refractory metals (W,Mo) has been treated theoretically by several authors.[5,8] There is an agreement that the initial charge state of the impinging particle is of little importance, that the degree of cesium coverage should be such that the work function of the surface is in the region around its minimum, and that for a reasonable survival probability of negative ions the energy of impinging particles should be at least several eV, up to one hundred or so eV. Conversion efficiencies of up to 30 to 40% and even higher could be expected. It is not clear yet what the contribution is of another possible process for the surface production of negative ions: sputtering of surface adsorbed hydrogen particles in the form of negative ions. There are other open questions as well, e.g. the role of molecular ions, isotope effect, etc. Experimental data on the secondary negative ion emission (coefficient of the emission as function of the impinging particle species, energy and angle of incidence, surface conditions, etc.) are still scant; estimates have been reported[7] showing values of up to 20%, decreasing fast to a few percent when the discharge voltage increased from 100 V to 400 V (corresponding to different degrees of cesium coverage).

Related to the processes on the 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. According to Ref.6, where data on cesium adsorption have been reviewed, a minimum work function of about 1.5 eV could be maintained at the surface temperature of about $500^\circ C$ with a cesium flux of $10^{16} cm^{-2} S^{-1}$ and at about $630^\circ C$ with a flux of $10^{17} cm^{-2} S^{-1}$. Our estimates of the optimum surface temperature[8] in a magnetron source tend to agree with this range of temperature, although values up to $1000^\circ C$ been mentioned as still assuring a normal operation of the source.[9] There may be, however, another reason for maintaining the surface temperature below 500° to $600^\circ C$. At higher power densities SP sources show a tendency for a sudden transition from a normal operating mode into a (probably localized) low voltage discharge, accompanied by a drop in the H^- output to negligible values. It may be necessary, in order to avoid this phenomenon in quasi steady state sources, to keep the cathode temperature lower than otherwise possible. There are two thermal regimes of source operation to be distinguished: transient increase of the surface temperature during the initial part of the discharge and the steady-state regime of a source with cooled electrodes. By using expressions for the temperature distribution in a semi-infinite body, resulting from a constant heat flux input to the surface, it is possible to estimate the transient increase.[10] As function of time t after the beginning of the discharge, the change ΔT in the surface temperature follows a simple law:

$$\Delta T \propto q_o \sqrt{t} \qquad (1)$$

where q_o is the heat flux input. The validity of this model is limited to $t < 0.1s$ in the case of the BNL 1 A magnetron source, but for pulses shorter than that Eq. (1) represents a scaling law, showing, for a given ΔT, a trade-off between the power load on the cathode 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, limiting possibly the current density of the extracted beam. Our estimates show that up to 3 kW/cm^2 could be removed. It is not clear yet whether at these power densities a sufficient flux of H^- ions may be produced at the cathode. Present sources operate with an efficiency of at best 50 mA/kW (20 kW/A of the extracted H^- beam), out of which power about 2/3 end up on the cathode. With a maximum heat input of 3 kW/cm^2 the required cathode surface area would be about 5 cm^2/A. The power efficiency of H^- production has been considered in some detail by V. G. Dudnikov[13] but the quoted values of 500 to 1000 mA/kW (1-2 kW/A) seem to be optimistic. However, if such an improvement by an order of magnitude becomes feasible, sources of negative ions would successfully compete with sources of positive ions.

Processes in the plasma determine the transport efficiency of H^- ions from the producing surface to the extraction slits. In SP sources the requirements posed on the plasma are to some degree contradictory: on one hand a high plasma density is required so that a sufficient flux of particles 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. Processes occurring in the space between the emitting surface and the extraction slits may be summarized as follows. Primary H^- ions reach the plasma either by gaining energy in the field adjacent to the electrode (cathode, a biased emitter) or by leaving the surface with an initial energy sufficient to overcome a decelerating field (possible emission from the anode). They pass through the plasma with some attenuation toward the extraction aperture or may transfer the charge to a slow atom which then as a secondary slow H^- ion diffuses toward the extraction aperture. The latter process is the dominant one in Penning and, probably, in hollow discharge duoplasmatrons. Penning and magnetron sources have also a region of much lower plasma density adjacent to the extraction slits,[4] with the idea of attenuating the diffusion of plasma electrons out of the source. It is in this region where a large part of extracted secondary slow H^- ions is produced. Processes of H^- ion transfer through the plasma have been analyzed for both, Penning and magnetron sources.[13,15] Calculations have been done by taking into account the collisions leading to the loss of an H^- ion, charge transfer collisions leading to the production of a slow H^- ion and the diffusion of slow H^- ions across the magnetic field under the influence of an electric field in the plasma. It seems that for the Penning source, values reported in Ref. 7 for the surface conversion efficiency of H^+ into H^- are too low to explain the achieved H^- beam current densities, that neutral particles and molecular ions may play an important role, and that a relatively strong electric field (e.g. several tens of V/cm or more) may exist in the plasma adjacent to the extraction slits, facilitating the diffusion of slow H^- ions across the magnetic field.

The region consisting of extraction slits themselves and of the adjacent volume on the outside of the source, will not only serve for the removal of accompanying electrons and the initial beam formation but cause some H^- loss as well. It has been suggested very early[2] that the electron component would be substantially attenuated by using long, narrow extraction slits perpendicular to the magnetic field because of the difference in electron diffusion coefficients in directions along and perpendicular to the field. Loss of H^- ions occurs because of their collisions with molecules of the neutral gas, streaming out of the source. Under normal operating conditions of SP sources there is enough gas coming out of the source to cause a substantial loss of H^- ions before they enter the high vacuum region further downstream. It is clear that the gas efficiency of SP sources should be improved from presently quoted values of 1-5%, (gas efficiency of 5% corresponds to 3.7 Torr ℓ/As), for this as well as for the reason of a lower gas load in the beam line. At this point it may be mentioned that the use of multislit extraction geometry, proposed at an early stage of Brookhaven National Laboratory source development,[15,17] is preferable to a wider single slit of the same area because of a smaller effective gas layer thickness and a smaller electron beam component.

The following requirements may be established when designing a multiampere source for quasi steady state or steady state operation. First parameter is the H^- current density at the extraction aperture. It seems, on the basis of computer calculations,[13] that values between 0.5 and 1 A/cm^2 would still be manageable, i.e., that at these densities a low divergence beam could be achieved. The objective of the source design is then to optimize the production and minimize the losses of H^- ions so that the necessary power loss on H^- emitting surfaces is below the limit set by the cooling system.

An overall power efficiency of 50 mA/kW should be achievable; for a given total H^- current this parameter determines the total power used in the source and, together with the maximum allowable emitter power density, the required emitting area. Any improvement in the power efficiency will, of course, be reflected in the total consumed power and the emitting area. If, on the other hand, the power loss becomes too high for the capabilities of the cooling system, it will be the latter to determine the maximum H^- current density. The second parameter to be taken into account is the gas efficiency. As an objective a value of 10% may be stated or 1.7 Torr ℓ/As; the difficulty with this parameter is an accurate measurement of the gas flow during the pulse.[19] Different designs will have to be developed if present models of SP sources show that an improvement of the gas efficiency is not possible.

III. Hollow Discharge Duoplasmatron

The observation that in a duoplasmatron, operating as an H^- ion source, more H^- ions are obtained from the periphery of the discharge, has led to the design of the hollow discharge duoplasmatron (HDD).[1] The center rod in such a source creates a hollow cylindrical discharge and H^- ions are extracted from its inner periphery. In the BNL version of the source, the center rod was replaced by a tube, serving as the cesium container[19] (Fig.1). Although the source operated satisfactorily in the pure hydrogen mode (H^- beam currents of 11 mA were obtained, corresponding to a density at the extraction aperture of 0.23 A/cm^2), it is with cesium that the best results have been achieved. Maximum H^- yield was 60 mA, from a circular aperture with a 2.45 mm diameter, which corresponds to an H^- current density of 1.27 A/cm^2. Some source parameters are given in Table I. In contrast with the pure hydrogen mode of operation, best results in the hydrogen-cesium mode were obtained with a cold cathode. The surface processes are most likely the dominant source of H^- ions; all metal surfaces covered with a monolayer or so of cesium and exposed to bombarding positive and neutral particles may, in principle, serve as emitters of negative ions. However, in the complex HDD geometry, only those surfaces that are close enough to the extraction aperture may contribute to the final H^- beam; they are the center rod, the intermediate electrode and the anode. Measurements of H^- ion energy spectra[21] indicate that the center rod is the source of H^- ions.

TABLE I

Parameter	Source	BNL HDD	BNL Penning H_2	BNL Penning D_2	Novosibirsk, Penning No emitter	Novosibirsk, Penning Emitter	BNL Magnetron	Novosibirsk Magnetrons		10A Scaled-up
$H^-(D^-)$ current	A	0.06	0.44	0.2	0.15	0.2	0.9	0.9	1	10
$H^-(D^-)$ current density	A/cm^2	1.27	0.44	0.2	3	5.4	0.7	2.9	3.3	1
Pulse length	ms	0.9	3	6	0.2		10	1	1	dc
Discharge current	A	145	65	40	180	450(80)*	260	450	150	2000
Cathode current density	A/cm^2	-	33	20	300	180	20	110	50	45
Discharge voltage	V	80	220	400	100	100(100)	120	100	120	100
Total discharge power	kW	11.6	14.3	16	18	45(8)	31	45	18	200
Cathode power density	kW/cm^2	-	4.8	5.3	20	12	1.5	7.5	4	3
Power efficiency	mA/kW	5.2	30	12	17	3.8	30	20	56	50

*a. Values in parenthesis refer to emitter parameters.

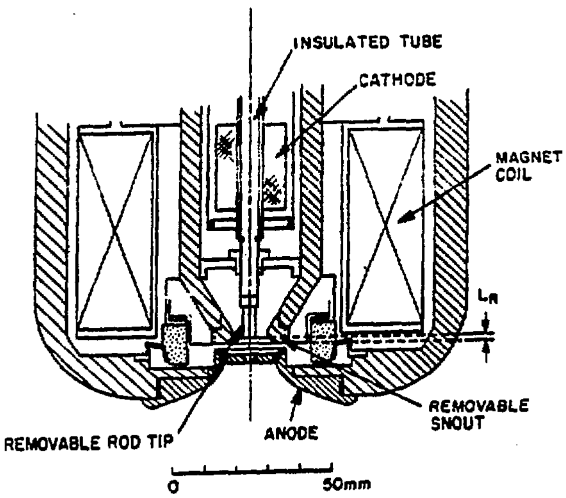

Fig. 1. Cross section of the hollow discharge duoplasmatron.

The HDD has attractive features for application in high energy accelerators because of a high brightness at a sufficienctly high H^- beam current. The fact that almost 2 A of electrons are extracted and have to be accelerated to the 45 kV level before being removed from the beam is not so important for accelerator applications because of a short pulse length and low duty factors. There have been proposals to investigate an HDD source[22,23] (as well as some positive ion sources) with larger multislit apertures in order to increase the H^- yield and power efficiency but the difficulty with the removal of electrons from the beam at a low enough energy (e.g., by the use of localized perpendicular magnetic fields) was one of the reasons against the plan. The conclusion is that in its present form an HDD source is not useful for applications in neutral beam lines because of a very low power efficiency.

IV. Penning Source

Penning discharges have been used as sources of negative hydrogen ions for quite some time, but it was only after the discovery of the enhanced production of H^- ions on cesium covered surfaces[24] that these discharges have been considered for neutral beam applications. The Penning source developed at BNL[13] includes a small electrode (emitter) opposite the extraction slits (Figs. 2,3); this idea for an increased production of H^- ions on the properly biased, cesium covered emitter was independently applied at Novosibirsk.[25] As shown in Fig. 2, both cathodes of the source were hollow and cavities filled with the cesium-containing mixture. The total cathode surface area was 2 cm^2. The purpose of the experiment with this relatively small model was to acquire the information necessary for the design of a scaled-up version for substantially higher currents and pulses longer than 100 ms. Table I shows some of the source parameters; for comparison parameters of two Penning sources developed at Novosibirsk are also shown. The effect of the emitter bias was not investigated outside the range ± 50 V; due to an unsatisfactory design breakdowns occurred at higher values. In this bias range H^- yield did not change by more than 10%, possibly because the emitter was too far from the discharge. Extraction geometries with 3,5 or 7 slits, 0.5-0.7 mm wide, have been used (Fig 3 shows a cover with five slits). The H^- current density was about 0.5 A/cm^2 for H^- ions, the total H^- current 0.44 A; a pronounced isotope effect was observed and D^- currents of only 0.2 A have been obtained.

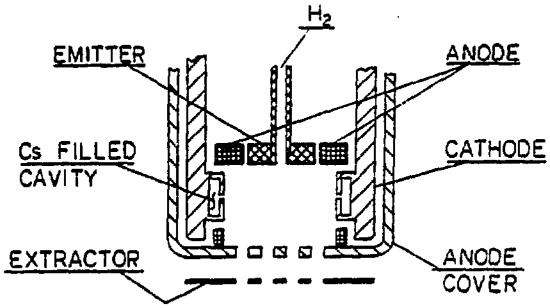

Fig. 2. Cross section of a Penning source with emitter.

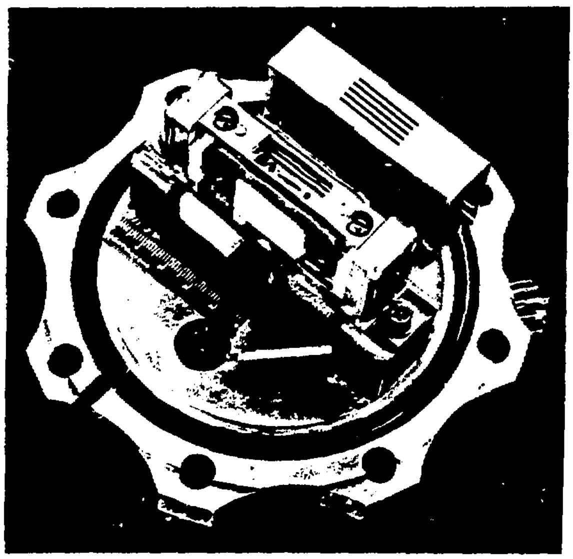

Fig 3. Photo of the BNL Penning source, with 5-slit cover removed. The emitter electrode with the gas injection slit is visible at the bottom of the discharge chamber.

While H^- ions are produced on both cathodes of the source, under bombardment by positive particles diffusing out of the plasma, it is not excluded that other electrodes (anode,emitter) contribute to the H^- beam as well. As mentioned before, analysis of experimental results[13] leads to the conclusion that the observed H^- yields cannot be explained by the values of the secondary negative ion emission coefficient quoted in Ref. 7, assuming that H^- ions are produced from protons and on the cathodes only. Neutral atoms produced by reflection of protons from cathodes may also play a very important role in a Penning source. However, it would be difficult to determine contributions of different electrodes to the final H^- beam because almost no fast primary H^- ion, originating on a cathode, can reach the extraction aperture: the final beam consists mostly of slow, secondary H^- ions produced by charge transfer.

Gas efficiency of the BNL Penning source was estimated to be about 1%, this is in accordance with values reported by other authors. A substantial improvement in this parameter is necessary if Penning source is to compete with other sources. It has to be noted, however, that presently used methods[13] for gas flow measurements are relatively inaccurate and limited to the source with gas pulse only, without the discharge.

Penning sources at the present stage are within the reach concerning the required power efficiency (30 vs. 50 mA/W), but the gas efficiency is still too low. The new model of the source with an improved geometry of the discharge chamber, which is to be tested soon, may result in a gas efficiency improved by a factor of 2 or so; further improvements would require a redesigned source. However, scaling-up of a Penning source for currents of 10 A does not seem feasible,[13] because the achievable linear (per cm of the cathode length) H^- current densities are about 0.2 A/cm; even by assuming an improvement to 0.5 A/cm, this would require a source cathode longer than 20 cm. Therefore, this type of sources would be limited to units for currents below 5 A.

V. Magnetron Source

Magnetron source was the first SP source to be developed[35] and it still remains the most intense and efficient among them. Figure 4 shows the cross section of the source and Fig. 5, the BNL 1 A model. The discharge chamber of magnetrons is ribbon-shaped, in the form of a race track. The distance between the cathode and the anode in the BNL source is 1 mm, the cathode surface area (center part) about 13.5 cm^2. Cesium containing mixture filled the cavity in the cathode; the rate of cesium diffusion into the discharge was regulated by the average discharge power (i.e., pulse amplitude, length and repetition rate). Results are shown in Table I, with two sets from Novosibirsk[3,36] for comparison. The BNL source had a multislit extracting geometry, with the total area of about 1.3 cm^2; number and width of slits varied. Extraction voltage was 18 kV and the excess current in the extractor circuit about two times higher than the H^- current. The excess current consists of H^- ions falling on the extractor and of charged particles emitted from electrodes and produced in the extraction gap. If an accelerating field exists immediately after the extraction, the excess current is much smaller. Gas efficiency was estimated to be around 2-3%, which is somewhat lower than quoted by the Novosibirsk group (5-6%), but it has to be noted again that the flow measurement accuracy has to be improved.

Magnetron source is the most promising SP source to be developed for neutral beam applications. Power efficiencies of 50 mA/kW have already been achieved,[9] at cathode power densities of 4 kW/cm^2; the BNL source, operating with an order of magnitude longer pulses, has reached values of 30 mA/kW at 1.5 kW/cm^2 which should be well below the limit of the cooling system. If the gas efficiency could be improved by a factor of two or so, magnetron sources would become very competitive. In contrast with Penning sources, where the scaling-up is basically possible in one direction only (by lengthening the cathodes), magnetron sources may be scaled-up in two directions. Power-wise, a scaled-up magnetron source yielding 10 A of H^- ions, assuming a power efficiency of 50 mA/kW, would require 200 kW of discharge power. About 2/3 of it will end up as heat on the cathode or about 130 kW. If 3 kW/cm^2 can be removed by forced cooling, the cathode should have a surface area of 45 cm^2 or 3-4 times more than the present BNL source. With a discharge voltage of 100 V, the discharge current would be 2000 A, or 45 A/cm^2. Cathode current densities of this order of magnitude should be sufficient for the required H^- ion current density at the cathode. Parameters of this hypothetical source are also given in Table I.

VI. Recent Results and Future Plans

As the next step in the development of SP sources at BNL, a larger model was designed, constructed and will be tested shortly (Fig 6). It is a very versatile source, incorporating several important changes. It may operate in both modes, magnetron and Penning, by exchanging a few parts only. In the magnetron mode, the cathode side shields are isolated from the center part, so that current distribution may be investigated. The center cathode area is about 25 cm^2, so that discharge currents up to 500 A should be achievable. In the Penning mode the effect of an emitter will be studied in more detail than before. In the latter mode the cathode surface area is about 7.5 cm^2. In both modes cathodes can be cooled by pressurized water; however, the source design is such that by cooling the cathode only the average source power will be increased and the operating regime will not approach the quasi steady state one. A second novel feature is an independently controlled cesium injection from a separately heated container. The whole source together with magnet pole pieces and the extractor has been built as a unit, which should facilitate the alignment. By scaling up H^- yields from present BNL sources it is expected that in the Penning mode of operation H^- and D^- currents around 1 A should be achieved, while in the magnetron mode yields of about 2 A are expected. Due to the cooling of the cathodes, sources should be capable of operating with pulses of 50 ms duration.

The new sources have higher power and pumping speed requirements. A new test stand has been constructed and put into operation (Fig.7), 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 future work include also continuation of measurements of source parameters (gas flow during the discharge pulse, plasma parameters) and electrode cooling studies with the objective to eventually design a quasi steady state H^- source.

Fig. 5. Photo of the BNL 1 A magnetron source.

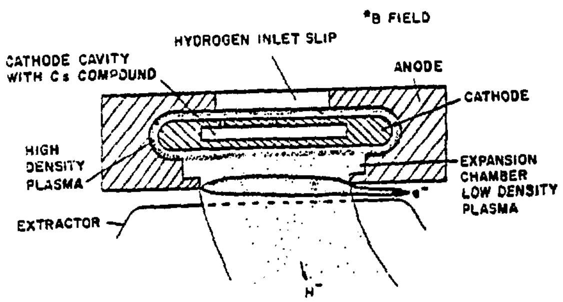

Fig. 4. Cross section of a magnetron source.

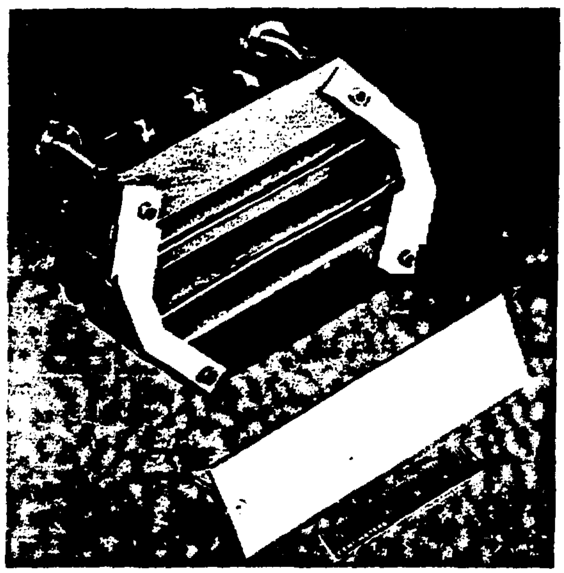

Fig. 6. Photo of the large BNL source, Penning mode of operation. Front anode parts have been removed to show the cathodes and the emitter.

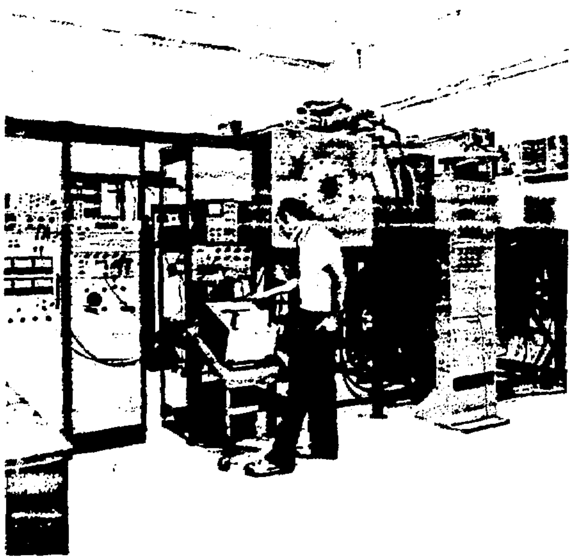

Fig. 7. Ion source test stand.

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