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OPERATIONAL EXPERIENCE WITH THE BNL MAGNETRON H^- SOURCE*

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ABSTRACT

A magnetron H^- source with a grooved cathode has been in operation at the BNL Linac for over 18 months. The source has run at 5 pps with a 600 μsec pulse width for periods as long as 5 months. Its development and performance will be discussed.

INTRODUCTION

The H^- source which was installed in September 1982 in Pit II of the BNL linac was based on the original magnetron source reported by Dimov et al.[1] and further developed by Sluyters[2] and Prelec at BNL. This design served as a starting point for Schmidt[3] at FNAL who brought it to full operational capability for accelerator use. While retaining the basic physical parameters the FNAL design provided a more durable configuration. A 90° bending magnet was added to select the H^- beam and focus in both planes. A cold-box cryopumped the cesium which left the source, preventing plating of the column components. The cesium delivery system was redesigned using a boiler to allow long term operation. The result was a truly operational source which ran at 15 pps with a 0.1% duty factor and 40-50 ma H^- current. This source was installed in the FNAL preinjector in late 1977. A second preinjector was adapted to H^- operation a year or so later.

Based on the success with H^- injection at Fermilab, Brookhaven started planning for a similar modification[4] using the magnetron source which had performed so well at FNAL. It was hoped that little modification and no development would be required since both machines operated at the same duty factor.

The actual mating of the source to the accelerating column was an obvious problem. The FNAL high gradient column used SF_6 gas in a liner to provide insulation between external electrodes, allowing close spacing. The BNL column design operates in air so the external electrode separation had to be much wider. Inside the BNL column, long conical sections were used to connect the actual accelerating electrodes with the external portions. The shallow cones in the Fermilab column allowed the source to be placed close to the first electrode. The source sits above the beam line, with the beam bent onto the axis by the 90° magnet, requiring considerable radial clearance. To get sufficient voltage hold-off, the BNL source had to be moved to the back-plate of the column. At this location the beam had to travel about 0.5 M from the 90° bending magnet to the first electrode.

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An estimate of the emittance at the extractor was made from FNAL data and used to redesign the bending magnet to reduce aberration terms and increase the focussing normal to the bend plane. This higher magnet gradient (n = 1.35) when coupled with a downstream quadrupole doublet allowed the production of a double waist at the aperture of the first electrode. To keep these pulsed quadrupoles at dome reference potential, a quartz cylinder was used to insulate them from a drift tube which is at extractor voltage. The calculated beam transport is shown in Figure 1. A schematic of the complete source assembly is presented in Figure 2. The difficulty in moving the source forward is clearly evident in this drawing. Note also the location of a beam toroid at the end of the extraction tube.

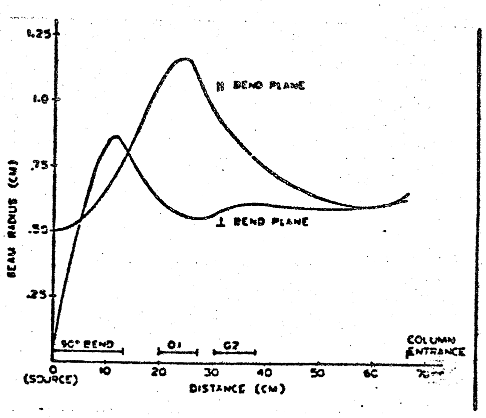

Fig. 1. 20 keV transport plot.

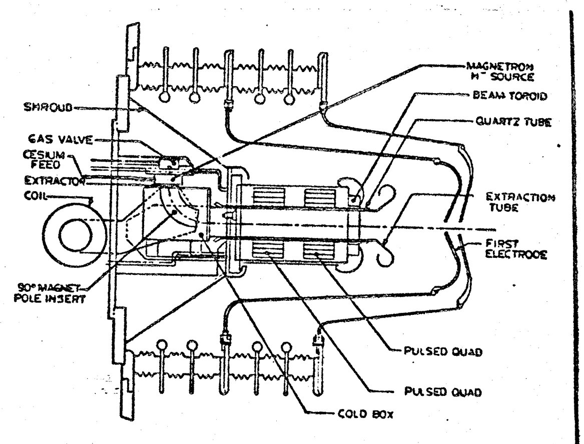

Fig. 2. Source assembly in BNL column.

SOURCE EVALUATION

Tests of the FNAL design source showed it could operate at the 5 pps and 200 sec pulse width required by the BNL linac. The discharge parameters were the same as reported by Schmidt[3], but the source was being stressed thermally. After several weeks of running, the source was disassembled and inspected. The MACOR insulators appeared to be melting away at the front of the source. The source temperatures were higher than that at Fermilab but seemed to be below the manufacturers limit. The thermocouples read only the average temperature of anode and of the cathode. Even though the duty factor for both sources is the same, the longer pulse at BNL probably caused the peak temperature to rise higher than at FNAL, reaching the point where the MACOR would break down and melt away. To counter this problem, a set of alumina insulators was installed. After two weeks of around-the-clock running, there was no melting or physical damage evident.

The emittance of the magnetron source was measured after the 90° bending magnet.[5] The results are shown in Table I for beams of 40 mA.

TABLE I
Emittance of the flat cathode magnetron source
for two bending magnet designs

Magnet Type	Narrow Plane $(\varepsilon\beta\gamma)_{90}$	Wide Plane $(\varepsilon\beta\gamma)_{90}$
FNAL (n=1.0)	0.07π cm-mrad	0.20π cm-mrad
BNL (n=1.35)	0.035π cm-mrad	0.14π cm-mrad

The improvement made by the new magnet is clearly seen. In addition, for the same source parameters, 30-50% more beam was observed after the magnet. During the course of these tests, improvements were made in some of the electronic support equipment. One area of improvement was in the operation of the pulsed gas valve, which uses a piezoelectric crystal to allow a burst of gas into the source. A voltage pulse of fixed amplitude (~ 100 V) was varied in width to control the gas setting. The long-term stability was found to be poor, with the output varying as the source heated. An adjustable bias voltage had been used to compensate for this variation. Short term drift was also observed. These problems (and the bias adjustment) were eliminated by redesigning the gas valve pulser to provide higher voltage pulses (> 150 V) and designing a regulator circuit which automatically adjusted the pulse width to keep the average vacuum readout constant.

Controlling the cesium boiler temperature was another problem area. The cesium delivery system consisted of a copper boiler topped by a mechanical valve. This was connected to a feedtube which delivered the cesium vapor to the source. The valve and feedtube are heated to prevent cesium condensation. Only the heater on the boiler is adjustable. It was found that ambient temperature variations and drift of the valve and feedtube temperatures affected the boiler temperature. A local servo-loop was put around the boiler heater and thermocouple, which eliminated this problem. Variations of tens of degrees in the valve or ambient temperature produced only a fraction of a degree change in the boiler.

INSTALLATION IN PIT II

The source was installed in the second preinjector pit (Pit II) at the linac for testing at 750 kV. Figure 3 shows a photograph of the source assembly with the vacuum baffle removed. A beam transformer at the end of the quadrupole can measure the net current leaving the drift tube. Figure 4 shows the column back plate with the source and turbomolecular pump installed in pit II.

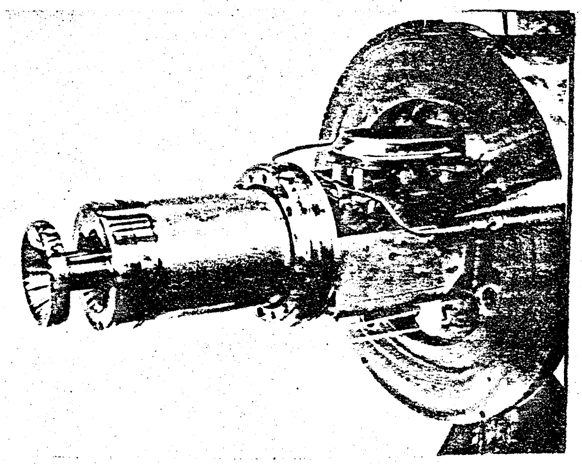

Fig. 3. Source assembly mounted on column back plate with vacuum shroud removed.

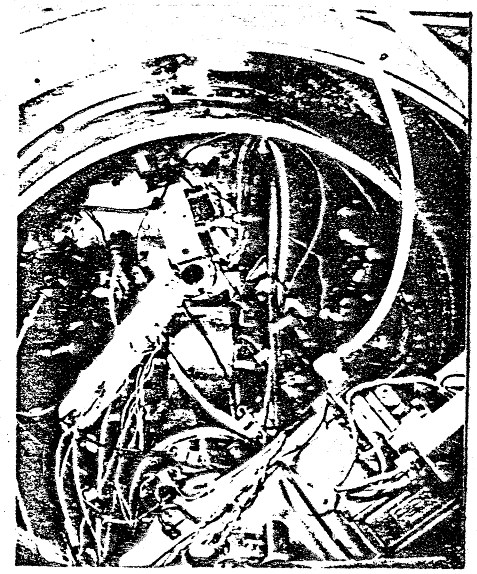

Fig. 4. View of column back plate mounted on Pit-II column. Insulated cesium boiler is angled item in center. Dome-turbomolecular pump is in the foreground.

Some initial problems with column conditioning were overcome by cleaning the ceramics and electrodes. The commissioning of the remaining support hardware went smoothly. However, after 6 months of trying, it was never possible to reproduce the stable operation of the test box for more than 8-10 hours. In the test box the source had run at 150 V and 150 amperes discharge, in the column it would run at 220 V, 70 Amperes. The extracted current was only about 18 mA, barely enough to meet the minimum AGS needs.

In an effort to get stable source operation, many substitutions of source components were made but without success. The alumina ceramics were replaced by the original MACOR insulators but no improvement was seen. Most suspect was the cesium delivery hardware. Cesium was introduced by breaking a 5 gm glass cesium ampule within the evacuated copper boiler by externally crushing the boiler tube and glass ampule. Occasionally, it was necessary to re-crush the boiler to prevent glass pieces from capping the cesium. Several times a copper colored film was found over the cesium when the boiler was removed and inspected.

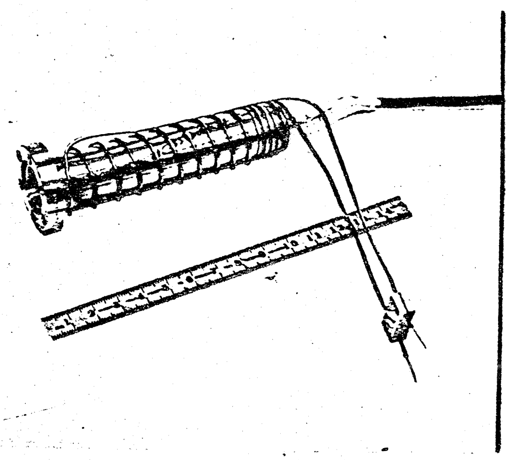

Fig. 5. Stainless steel cesium boiler with armored heater wire in place. Temperature is monitored by a thermocouple mounted at the bottom.

Because of the problems with the copper boilers, a re-usable stainless steel boiler was developed. This unit features a carefully placed heater winding which keeps the temperature constant to within 1 degree Centigrade throughout the volume of the cesium pool. The temperature is then graded uniformly up to that of the valve (Figure 5). The cesium is put into the boiler in an Argon atmosphere glove box. A special fixture breaks the ampule letting the cesium filter through a heated mesh into the boiler. About 70-80% of the cesium reaches the boiler with this technique. The new boiler was much more convenient to use but made no improvement to the ailing discharge.

The feedtube was suspected of being blocked because the internal heater element occluded much of the tube. This was redesigned using a larger diameter tube to greatly increase the conductance. The net result was a lowering of the required boiler temperature from 190°C to ~ 140°C, to maintain the same cesium in the source.

After all the changes and refinements to the source and its support hardware, the behavior was the same. Returning the source to the same configuration and components used in the test box still gave poor results. It was suspected that some contaminant existed in the column which had not been present in the test box. The early difficulties in voltage conditioning of column had been traced to oil contamination from a prior vacuum pump failure. This had been cleaned up well enough to hold high voltage on the column but perhaps was still the cause of the poor source operation.

THE GROOVED CATHODE

It had been suggested by Sluyters and Alessi[6] that a groove in the magnetron cathode could produce more H^- current at lower discharge current density. With the poorly operating source a 70 A discharge produced only 15-18 ma of accelerated H^- beam. Since the groove in the cathode would increase the surface area contributing to the extracted beam, it was felt that such a modification might result in acceptable current even with the poorly operating source.

In April of 1982 a groove was machined into a molybdenum cathode. The arc length was 4 times the height of the anode slit. The cathode was put into a source body and installed in the column. Conditioning and performance were the same as for prior flat cathode designs: dying out after about 8 hours of high discharge current operation (120-150 A). Beam current was similar to that observed for the flat cathode.

At this point the discharge power supply voltage and the pulsed gas were reduced. The beam current soon rose above its original value. This procedure was repeated until the H^- arc conditions peaked at ~ 150 V, 50 A. The pulse width, which in the high discharge current mode was thermally limited to 200 μsec, had to be continually increased to keep the source from getting too cold. It soon reached the 320 μsec limit set by the PFN in the Discharge Pulser. Under these conditions 40-45 mA was observed in the Dome of which 90% could be transported through the column to the Low Energy Beam Transport (LEBT). Up to 85 mA could be obtained in the Dome by lowering the gas, but the LEBT beam current never exceeded 50 mA.

Emittance measurements were made at 760 KeV in a viewing box about 5 M from the column. The normalized values at 90% for a 35 mA beam are:

Narrow plane - 0.19π cm-mrad   Wide Plane - 0.26π cm-mrad

These values are for the grooved cathode, but the flat cathode gave about the same result when extrapolated to this current. These data are about twice that reported by FNAL[7], possibly due to space charge growth in the 20 KeV transport.

The PFN was modified to allow a pulse width of nearly 600 μsec at a 3-Ohm impedance. The source was run at 5 pps at a duty factor of 0.3% around the clock for 2 and one-half months. When it was inspected no damage was found on the MACOR ceramics. Some small black flakes of molybdenum were present, but less than after a 2 week run in the high current mode. These flakes, which were also found on the extractor, probably caused the observed 10% current drop-off by obscuring the slit.

The cathode was eroded by about .020" on the side nearest the cesium inlet, and half that amount on the other side. A sharp image of the anode slit .010" deep was found in the center of the groove, caused by high energy protons which had been stripped in the extractor region.

Due to the good lifetime and reliability of the source and successful acceleration of 25 ma of H^- to 200 MeV, the AGS was shut down for complete conversion to H^- injection. During this period the source was cleaned and reinstalled with a new grooved cathode but with the original boiler and cesium. Work was begun to convert the main preinjector (Pit I) to an H^- source.

The second grooved cathode conditioned much like the first. With this source new peak intensity and integrated beam records were set for the AGS in a short time. The source ran a little over 2 months until a short circuit in its heater required replacement of the feedtube. This was done without disassembling the source by keeping it in a plastic argon-filled bag while the feedtube was replaced.

This same source was kept running for another 3 months while Pit I conversion was completed and commissioned. In total, it operated for 5 months without disassembly. The source had performed well during this period, showing no deterioration in its output at the end of the 5 months. This is to be contrasted to the flat cathode source which drops to half its output in 2 months.[8]

Figure 6 shows the source as the anode cover plate was removed. Some of the molybdenum flaking can be seen. Part of the image of the anode slit is visible. Figure 7 compares the cathode with a new grooved one. The ablation on the cesium inlet side is clearly displayed.

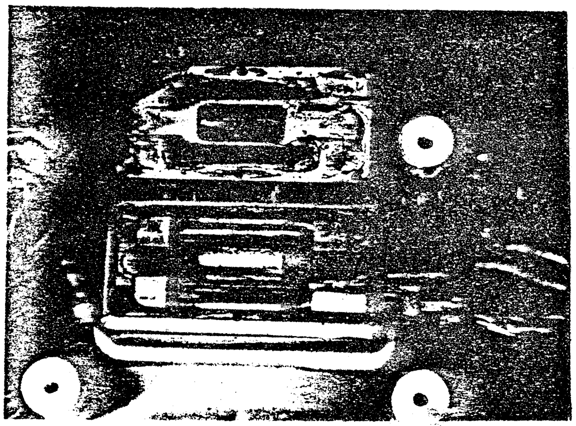

Fig. 6. Opening grooved cathode source after 5 months operation.

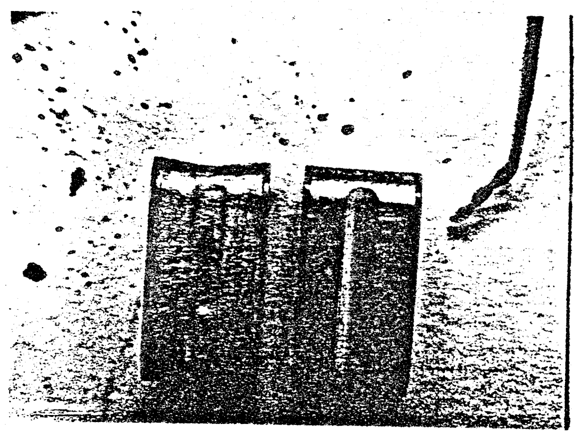

Fig. 7. Grooved cathode after 5 months (left) vs. new one.

The cesium boiler was found to be nearly empty when it was opened. There was no residue of any kind observed. This cesium had lasted for over 8 months of full time operation for an average rate of 0.6 mg/hr. After cleaning and charging with a new load of cesium, the boiler was re-installed on the source, which had been cleaned and fitted with a new grooved cathode.

The temperature at which the cesium pool is maintained has varied as the source and cesium delivery system changed. After increasing the conductance of the feedtube, the boiler temperature had to be lowered from 190°C to 140°C. When the stainless steel boiler was installed, the temperature went up to 160°C. This was partly because the stainless is an inferior thermal conductor to copper and because the thermocouple had been placed too close to a heater wire. When the grooved cathode was installed, the temperature was still measured in this manner, but now had to be set at 120°C. Later the thermocouple was moved to a recess in the bottom of the boiler where the temperature was measured to be 8°C cooler than the cesium pool. The temperatures read by the thermocouple indicated a cesium temperature of 105°C.

PIT I--OPERATION

Operation from Pit I begin in late April 1983. Table II shows typical parameters for the source.

Table II
Source parameters

Function	Name	Readback Nominal	Readback Range	Units
Discharge PS Voltage	DISP	255	250→270	V
PFN Voltage	PFNV	190	185→205	V
Extractor PS Voltage	EXTV	17.5	17→18	kV
Dome Vacuum	DVAC	8	7→10	μTorr
Cesium Boiler Temp.	CSTP	99	98→100	°C
Cesium Boiler Current	CSBI	480	450→520	mA
90° Magnet Current*	90DI	7.50	7.00→8.00	A
Discharge Current	DISI	40	38→50	A
Discharge Voltage	DISV	135	125→150	V
Cesium Valve Temp.	CSVT	300	280→330	°C
Cesium Feedtube Temp.	CSFT	330	300→340	°C
Source Anode Temp.**	SANT	200	160→220	°C
Source Cathode Temp.**	SCAT	380	350→400	°C
Cold Box Temp.	CBXT	−30°C	−40→−15	°C
Extractor Delay Time	EXTD	1830	1830	μsec
Extractor Pulse Width	EXTW	400	300→500	μsec
Gas Delay Time***	GASD	930	700→1130	μsec
Discharge Delay Time***	DISD	900	1130→700	μsec
End of Discharge	EDIS	500	400→600	μsec
Dome Beam Current	DMBI	40	35→60	mA

* Current shown for Pit I. Magnet in Pit II 1 A less.
** Depends on many conditions, especially EDIS.
*** Sum of these must equal EXTD.

Figure 8 shows the discharge voltage and current in the Dome and the beam current measured in the first LEBT transformer. The beam current is always quiet, in contrast to the high current mode in which high frequency noise was often seen. The ripples in the beam current may be due to mismatch problems in the PFN.

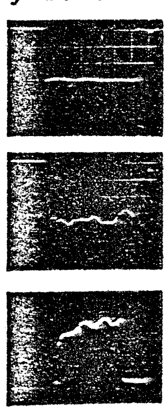

Fig. 8. Source discharge voltage 130 V, 500 μsec.
Source discharge current 40 A, 500 μsec.

Figure 9 shows a long time plot of source parameters. The data is taken every 20 minutes by the AGS PDP-10. The microprocessor in the Dome sends the readbacks of all parameters, which are then logged on a disk file. Operating personnel can then print the history of 10 parameters for a period of up to 1 week. Using this tool, long term drifts with time constants of hours to days become apparent, as does the effect of parameter change.

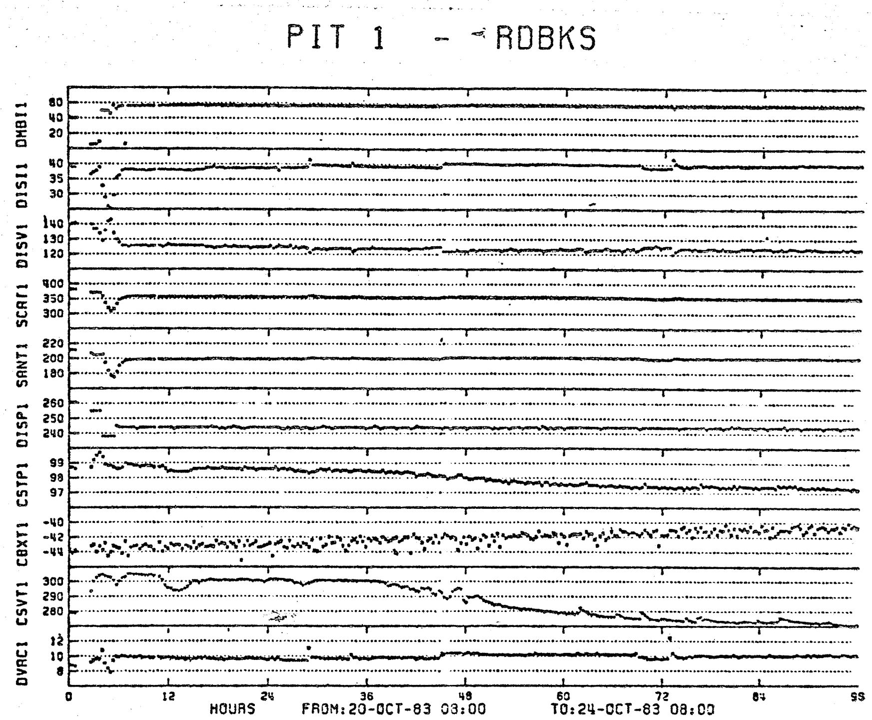

Fig. 9. Source parameters over a 4-day period.

During the summer 1983 shutdown, the source was cleaned and reassembled with the original cathode. A new design pulsed gas valve (Figure 10) was used which greatly simplifed the valve calibration process by using a 10:1 lever arm to extend the adjustment range. The new valve appears to be stable and reliable in operation.

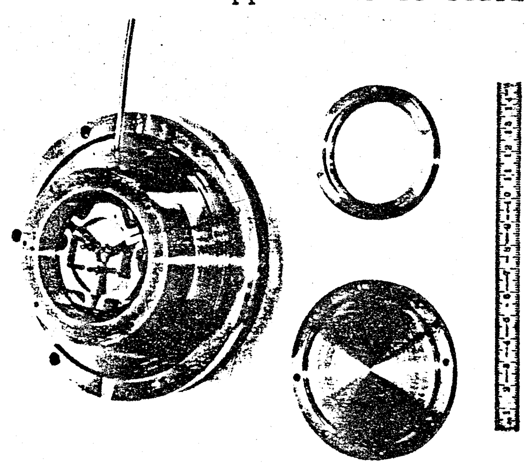

Fig. 10. New pulsed gas valve. Levers give 10:1 mechanical gain in settability.

The source start-up was interrupted by a direct lightning strike during a storm. One of the pulsed quadrupoles developed a short circuit to ground. Floating the quad pulser allowed the source conditioning to continue but the source showed only very slow improvement. After several weeks of effort the Dome beam current was only 25-35 mA and the source impedance about 4 Ohms. Most disturbing was the very limited range of stability. Changing the gas by 0.1 μTorr or the Discharge Power supply by 2 volts, or the boiler temperature by 0.5°C would cause the current to drop below 20 mA and the impedance to go to 5 Ohms or more.

Because of the quadrupole failure, poisoning of the source by Freon 113 coolant was suspected. A mass spectrometer installed at the ground side of the column showed a Freon 113 signature. The source was removed and given a minor cleanup. The quadrupole short was repaired and all Freon connections redone. The mass spectrometer, now installed in the Dome on the pumpout port, indicated that the Freon-113 had been significantly reduced, but a trace was still discernable.

The source was started up and conditioned very well. The beam current seen increased until over 50 mA was obtained in the Dome. The ranges of parameters which could be tolerated were back to their previous points.

NEUTRALIZATION PHENOMENA

Emittance measurements in the 20 KeV Test Box had shown distinct space charge influence on the early portions of the beam.[9] For the first 50-100 μsec, changes were seen in the phase space area and orientation of the beam normal to the 90° bend plane. This was shown to be greatly reduced by the increase of the background gas pressure, until stripping occurred. Similar effects have been seen by others.[10]

When the source was moved to the column, the same effect was observed. In the column, however, increasing the background gas is not a desirable option. An alternate method is to make the beam as late as possible after the gas pulse, letting the neutrals flow into the beam transport channel. The effect upon the rise time of at 760 KeV is quite apparent in Figure 11. The benefit of improved rise time must be balanced against the loss of peak current due to stripping at later times. As the beam pulse width is made longer, the start must occur earlier to assure sufficient gas in the source for proper discharge.

The transport line from Pit II to the Linac is about 15M long. The vacuum in the line is normally in the low 10^{-7} Torr range. A chopper located 3 M from the column produces fast rise and fall times or completely inhibits the beam in case of a malfunction. It was observed that beam chopped from a flat portion of the pulse acquired a tilt by the end of this line. To test if this was a neutralization effect, various vacuum pumps along the line were turned off, changing the background pressure. The results are shown in Figure 12. It is clear that the slope is reduced, then reversed, and finally the whole beam is lowered in intensity as the background ion concentration increased.

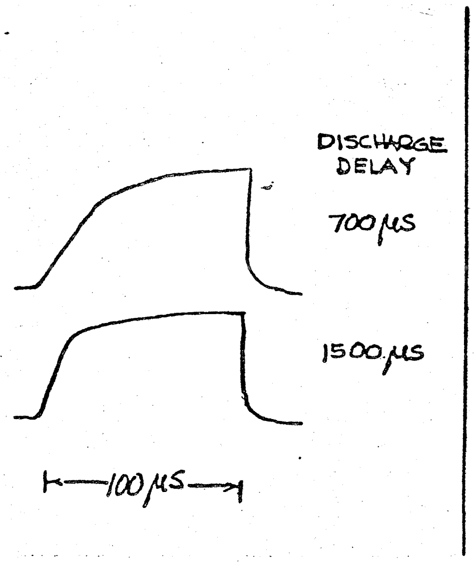

Fig. 11. Effect of background gas on source current rise time.

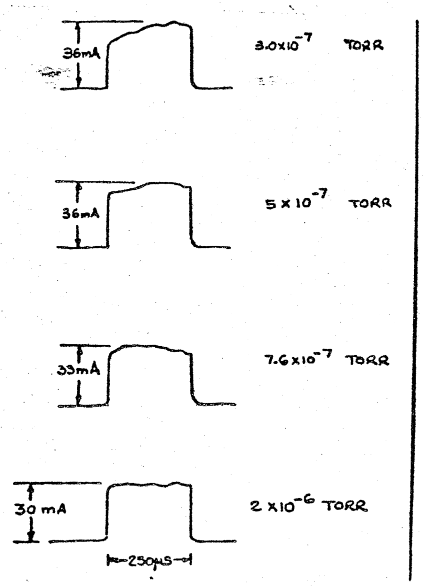

Fig. 12. Variation of beam current in LEBT with background pressure.

SUMMARY

The use of a curved cathode magnetron H^- source has been very successful at BNL. The lower dissipation requirements have allowed extension of the duty factor by at least a factor of 3 beyond the flat cathode source. By lowering the stress on the source, the stability seems improved as well.

The durability of the source is such that it can easily run 3 months with little or no loss of intensity before maintenance is performed, and has been run up to 5 months.

The use of a 20 KeV beam transport line in the column has been successful although it appears emittance growth may have occurred.

ACKNOWLEDGEMENTS

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