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LUNAR LANDER MASS SPECTROMETER

R. F. K. HERZOG W. P. POSCHENRIEDER

GCA CORPORATION

Bedford, Massachusetts

FINAL REPORT
CONTRACT NO. NAS5-9393

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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TABLE OF CONTENTS

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Summary

This report deals with the development of a sputter ion source for the Lunar Lander Mass Spectrometer. The new source utilizes a Penning discharge for producing the primary ions instead of the duoplasmatron which performs very well for the large laboratory instrument but has high power requirements and a susceptible hot filament. A suitable geometry and a mechanical design were determined and the characteristics of the discharge were studied in detail. The duoplasmatron of the large laboratory instrument was replaced by the Penning source to produce the primary beam. The sensitivity obtained in this way compared very well with the sensitivity obtained with the duoplasmatron. This encouraging result concludes the first phase of the contract and renders a firm base for a successful operation of the total instrument to be developed in the following phase.

INTRODUCTION

The first phase of the development contract of a Lunar Lander Mass Spectrometer breadboard model was aimed at the construction and evaluation of a suitable cold cathode ion source. The reasons for the replacement of the duoplasmatron source which operates so successfully in the laboratory instrument were: (a) the high power consumption and (b) the limited life-time of the hot filament. Since the duoplasmatron is the most efficient ion source for gases known so far, the question was, whether a cold cathode ion source would be sufficient to fulfill the sensitivity requirements encountered for the Lunar Lander Mass Spectrometer. The cold cathode discharge geometry finally chosen is well known as the Penning Cold Cathode Discharge which is frequently used for a vacuum gauge. The idea of utilizing this kind of discharge for an ion source dates back to Penning and Moubis [1].* Later, the design was improved by Lorrain [2] and systematically optimized by Keller [3,4]. Another modification of the basic geometry is described in a patent by Gow et al. [5].

The detailed geometry which was finally chosen for this contract bears much resemblance to the design given by Keller. Since this design has been used successfully in the past, sufficient information was available to predict its capability for the present use. On the basis of the knowledge of the principal characteristics of this type of ion source, it was obvious that currents could be obtained quite comparable to those obtained from the present duoplasmatron if a larger ion extraction hole were used. The disadvantages of a larger extraction hole are that a higher flow of neutral gas into the sample chamber is encountered and a larger cross section of the bombarding ion beam on the sample occurs. However, as will be shown later, gas consumption is still very modest, and the higher gas flow is well taken care of by the larger pumping speed in a lunar application. In addition, any pressure increase around the sample is only due to the gas used in the primary ion source, which is of high purity and, therefore, is not expected to interfere with the basic task of the instrument. The larger focus and accordingly smaller current density was expected to cause some intensity loss in connection with our laboratory instrument, particularly when the atomic spectrum is viewed. Experimentally, however, a focus was achieved which was small enough to yield practically the same results as obtained with the duoplasmatron. On the other hand, high spatial resolution is not one of the required features in this project which aims more for the analysis of the average composition of a material of interest. In this light, a somewhat wider focus seems to be more appropriate. Summing up, we may state that the larger extraction hole is of no detrimental consequence within the planned application.

*Numbers in [] throughout text indicate references.

DESIGN AND DESCRIPTION OF THE PENNING SPUTTER SOURCE

The mechanical design of the Penning source was mainly governed by the contractual requirement, to test the performance of this source first with the laboratory analyzer. This necessitated the use of a base flange which could be matched to the top flange of the specimen chamber and to the existing einzel lens which is regularly used with the duoplasmatron.

As a second consideration, the use of an electromagnet instead of a permanent magnet seemed to be a better choice at this investigatory stage. Past experience with comparable structures has shown that stable and optimal performance is only achieved within a limited range of magnetic induction, pressure, and discharge current. Strong plasma oscillations may occur outside of this range and seriously limit the extraction of ions and may cause strong fluctuations in the signal.

Figure 1 shows a cross section of the Penning ion source. The design is essentially rotational symmetrical to the indicated center line. The discharge chamber consists of an anode cylinder which is faced on both ends by the cathode plates. In the middle of the chamber and suspended by a thin wire is a flat ring which is at anode potential. Both cathodes are counterbored in the center and the lower cathode has an additional hole through which the ions are extracted. The magnetic field is generated by a pair of coils, and the base flange, the top plate, and the outer cylinder form the yoke. The inner cylinder is stainless steel and is sealed against the base and top plate by viton O-rings. The anode cylinder is aluminum and is precisely centered by a set of two split brass rings and twelve ceramic balls. The balls are well shielded against sputtered metal and will not become contaminated. Contamination would result in an electrical breakdown since the anode is on a high potential with respect to the cathodes. The anode potential is supplied through a vacuum-tight Alite feedthrough and the gas is admitted via a stainless steel pipe. All parts of the magnetic circuit are machined out of mild steel; however, after some initial experiments, the cathode surfaces had to be clad with a thin liner of aluminum. This was necessary because sputtering of the cathode material under the influence of the magnetic field produced fibers of mild steel which did connect the anode to the cathode. This effect no longer occurred after the aluminum liner had been installed.

No exact theory of the Penning discharge exists. A qualitative description is usually given in the following way. Electrons which are released from the cathode by ion or photon impact and electrons freed by electron impact in an electron-neutral collision at some intermediate potential are confined by the magnetic field. The electrons will oscillate back and forth while also orbiting around the axis until they collide with a gas atom. An electron can only reach the anode by loss of energy in collisions. In this way, the path length and the ionization probability of an electron are considerably increased.

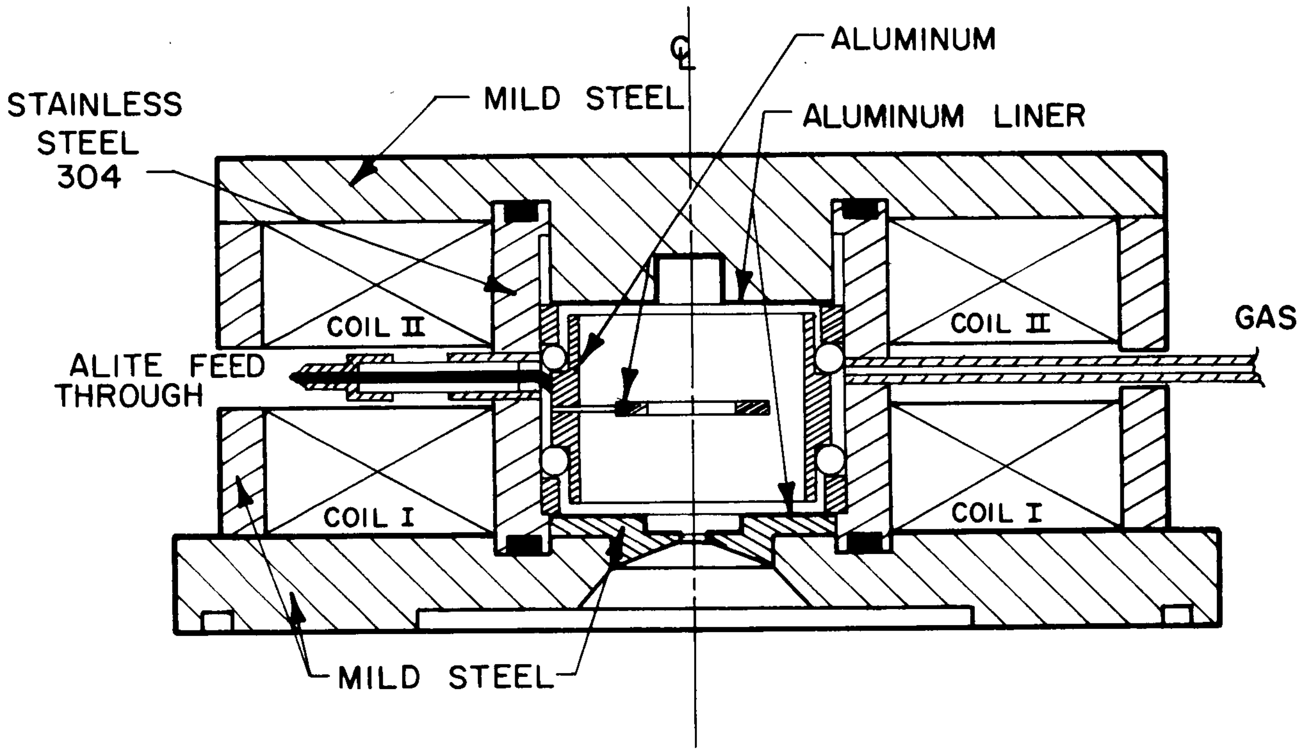


Figure 1. Penning sputter ion source - mechanical outlay sketch.

The main difficulty for a more precise treatment of this discharge mechanism lies in the space charge conditions. Some space charge neutralization occurs at high pressures ($> 1\mu$) where the positive space charge is usually slightly dominant. In this case, the mechanism described above seems to be a fair approximation. At lower pressures, however, the negative space charge becomes so dominant that the original electrostatic field is completely changed. Knaur [6] has shown that in this range, the electric field in the Penning discharge assumes a configuration usually found in the magnetron discharge.

The counterbores in both cathodes produce an inhomogeneity in the magnetic field. This results in an increase in the electron density along the central axis, and consequently, in an equal increase in the extracted ion current. The optimum dimensions for these counterbores and for the whole geometry were determined experimentally by Keller [3].

All ion sources with magnetically confined gaseous discharges have one disadvantage in common: the tendency to plasma oscillations. The frequency of these oscillations covers a very wide range and depends on the geometry and the typical electric and magnetic parameters. Because the modulation frequency of the extracted ion beam is usually high, it rarely causes direct problems, but ion extraction is somewhat hampered and loss of intensity is encountered. More serious are abrupt changes which occur at random in the transition region between two different modes of the discharge. Usually, the different modes are also optically distinguished by a different distribution of the glow within the discharge. This effect is well known from all gaseous discharges and is typical for space charge governed effects. Theoretical prediction of the different mode ranges is extremely difficult if not impossible at the present state of art. A full experimental evaluation is, therefore, still indispensible.

The Power Supply

In order to run the Penning source in connection with the laboratory instrument, it was necessary to construct an additional circuitry. The power source which usually supplies the filament current for the duoplasmatron was used for the magnet coils. However, since a dc field was required, a full wave rectifier with a sufficiently large charge capacitor was put in between. Under full load (6 volts, 8 amperes), the ripple was below 5 percent.

Compared with the duoplasmatron which requires only about 150 volts but 0.5 amperes, the anode supply for the Penning source has to deliver about 1000 volts. However, the current requirement is much smaller and 40 mA were sufficient. Although discharge currents of a few mA are enough to run the source for the planned application, some reserve power was included to evaluate the source also at higher currents. The voltage needed comes from a transformer followed by single wave rectification and a charge capacitor. The primary was directly coupled to the variac which usually serves to regulate the duoplasmatron arc voltage. A schematic is given in Figure 2. The whole circuitry was mounted on a breadboard and accommodated within the duoplasmatron power supply box. This was necessary since the whole circuit is on high potential above ground.

The Characteristics of the Penning Source

Under fixed geometric conditions, the discharge current I_d is a function of discharge voltage V_d, pressure p_d, and magnetic induction B.

$$I_d = f(V_d, p_d, B)$$

Because of the negative characteristic which is typical for self-sustained gaseous discharges, the relationship between I_d and U_d is ambiguous. It is necessary to run the discharge with a series resistor which is large enough to compensate for the negative resistance. A stable condition will be achieved only if the total resistance is positive. With this series resistor R_s(7.5K) an additional relationship between V_s, the supply voltage, I_d, and V_d has to be observed,

$$V_s - V_d = R_s \times I_d$$

The magnetic induction B was expressed by the excitation current I_M of the magnet coils. The relationship between I_M in amps and B in Gauss was determined as:

$$B = 160 \times I_M$$

The pressure p_d cannot be measured directly but may be calculated from the pressure increase Δp_s in the specimen chamber since the conductivity of the extraction hole and the pump speed of the system are approximately known. With a conductance of 0.7ℓ/sec and a pump speed of 280ℓ/sec, one obtains:

$$p_d = \Delta p_s \times 400$$

The characteristics were taken in two different combinations of the various parameters:

(a) The $I_d V_d$ diagram with I_M and p_d constant.

(b) The $I_d B$ or the equivalent $I_d I_M$ diagram with p_d and V_s constant.

The measurements were obtained with an X-Y recorder. The discharge voltage was taken directly, and the discharge current was gained from the voltage drop produced by I_d across a resistor. I_M was determined by the voltage across the magnet coils.

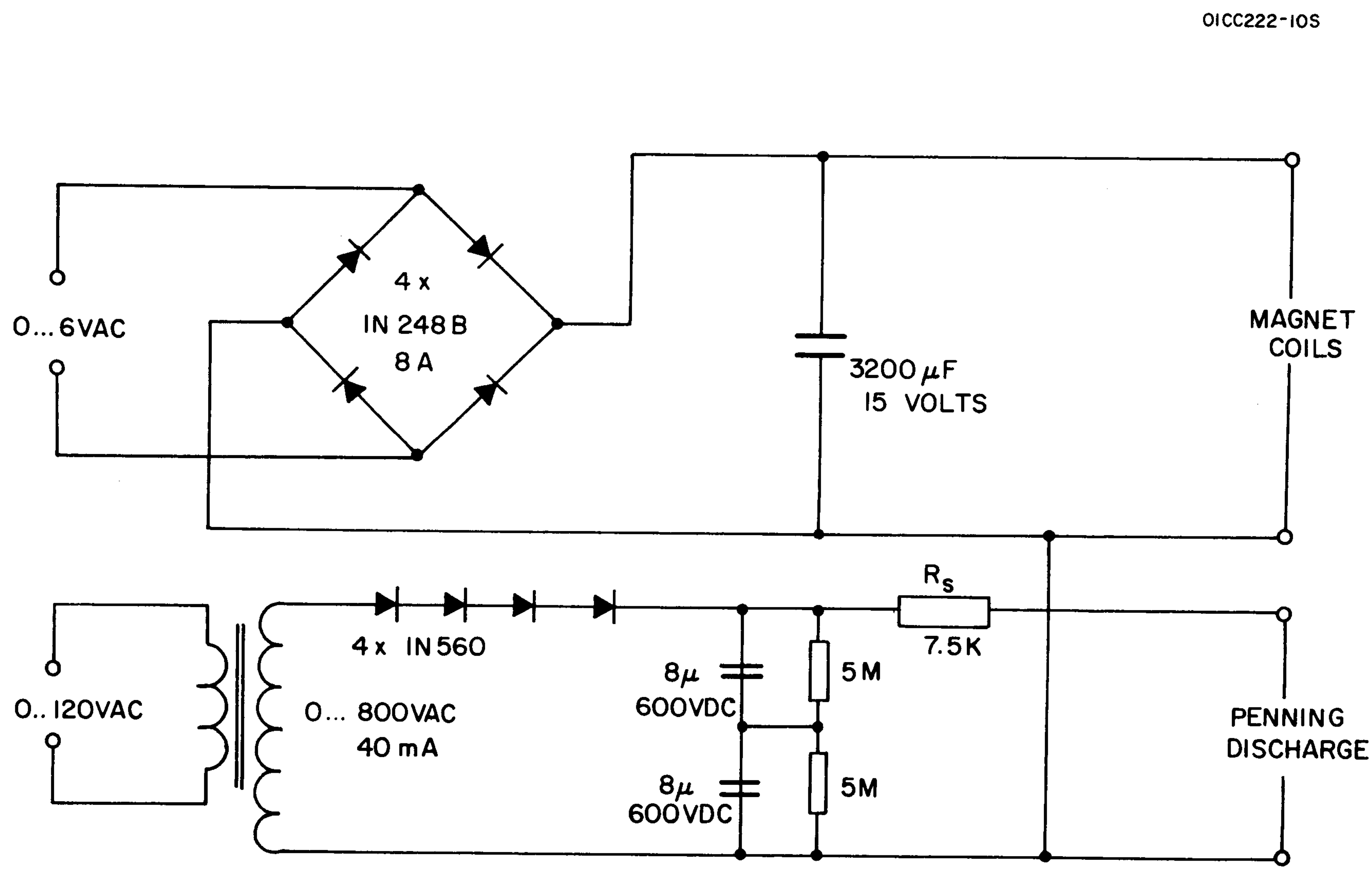


Figure 2. Penning source, power supply.

To characteristics (a): Figure 3 shows typical characteristics which were obtained at a system pressure of 2×10^{-5} which corresponds to a discharge pressure $p_d = 8\mu$. The curves were obtained by continuously increasing V_s. The different curves correspond to different magnet coil currents. One can see that a negative characteristic only develops above a magnet current of 3A (or above a magnetic induction of 480 Gauss). The discharge voltage at a fixed discharge current drops first at a rapid rate with increasing magnetic field, but does not change very much above 5A (800 Gauss). Ranges of instability are easily recognized from the irregular sections of the curve branches. It is possible to reduce the tendency of instabilities by increasing the series resistor; however, as will be discussed later, questions of power consumption have to be considered in this context. (Double traces in Figure 3 were caused by a failure of the recorder to lift the pen sufficiently during the back scan and indicate small hysteresis effects). Similar diagrams were obtained for $p_s = 5 \times 10^{-6}$, 1×10^{-5}, 4×10^{-5}, and 8×10^{-5}.

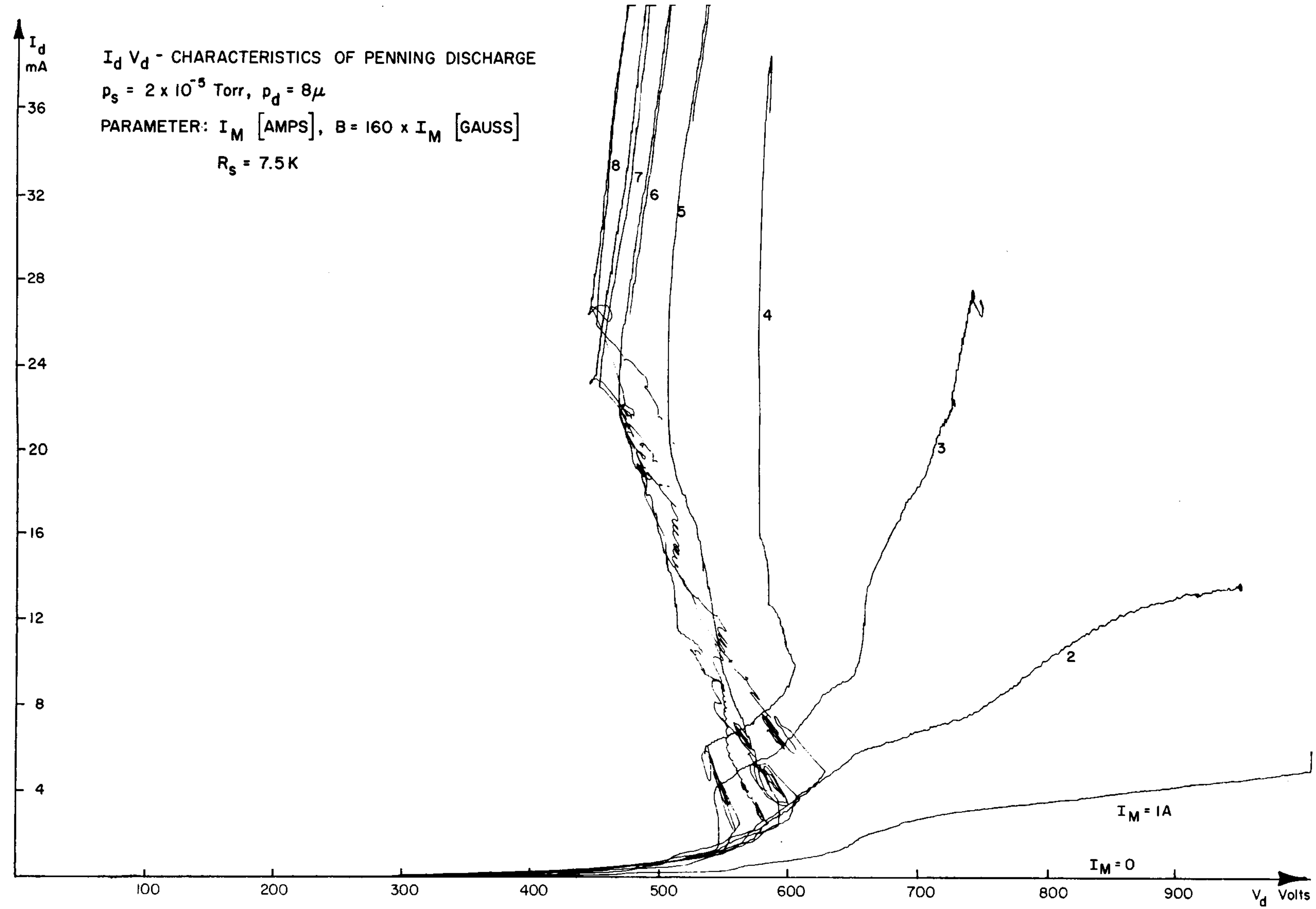
To characteristics (b): Figure 4 gives a typical example of an I_dI_M-diagram. Here, the magnet coil current was increased continuously while p_s and V_d were kept constant. The different curves correspond to different supply voltage values V_d. In the same way, characteristics were obtained for $p_s = 5 \times 10^{-6}$, 2×10^{-5}, and 4×10^{-5}. Figure 5 shows I_dI_M-characteristics, which were recorded with V_d = const. = 1000 Volts and p_s as the parameter for the different curves.

These characteristics were fairly well reproducible within their coarse structure. Details of the finer structure, however, were found to depend somewhat on the pre-history of the discharge. From the characteristics, one can deduce that danger of instability is greatest at low pressures and high magnetic fields. The characteristics show that no instabilities occur at pressures above $p_s = 1.5 \times 10^{-5}$ or $p_d = 6\mu$, within the total range of I_M, i.e., B. Although stable conditions are also found at lower pressure, the higher pressure appears to be the safer choice. Gas consumption at $p_d = 6\mu$ is only 4.2×10^{-3} torr ℓ/sec which is reasonably low. (A 1ℓ bottle of argon under atmospheric pressure will last about 50 hours). The characteristics also show that there is little sense in increasing the field above 800 Gauss. The discharge voltage and, therefore, the power consumption for a given discharge current is only slightly decreasing above this field.

The extracted current does not follow a simple relationship with the discharge current. It depends on the specific mode of discharge, the amplitude and frequency of rf-oscillations, and on the extraction voltage. In Figure 5 is also indicated the current at the target measured at different points of the characteristic with an extraction voltage of 10 kV. This current is not equal to the total extracted current and is also not corrected for secondary electron emission.

The Sputter Source

Secondary ion spectra were easily obtained after the Penning source was put in place of the duoplasmatron. During the initial experiments,



I_d mA
I_d V_d - CHARACTERISTICS OF PENNING DISCHARGE
p_s = 2 x 10^{-5} Torr, p_d = 8μ
PARAMETER: I_M [AMPS], B = 160 x I_M [GAUSS]
R_s = 7.5 K
36
32
28
24
20
16
12
8
4
100
200
300
400
500
600
700
800
900
V_d Volts
8
7
6
5
4
3
2
I_M = 1A
I_M = 0

Figure 3.

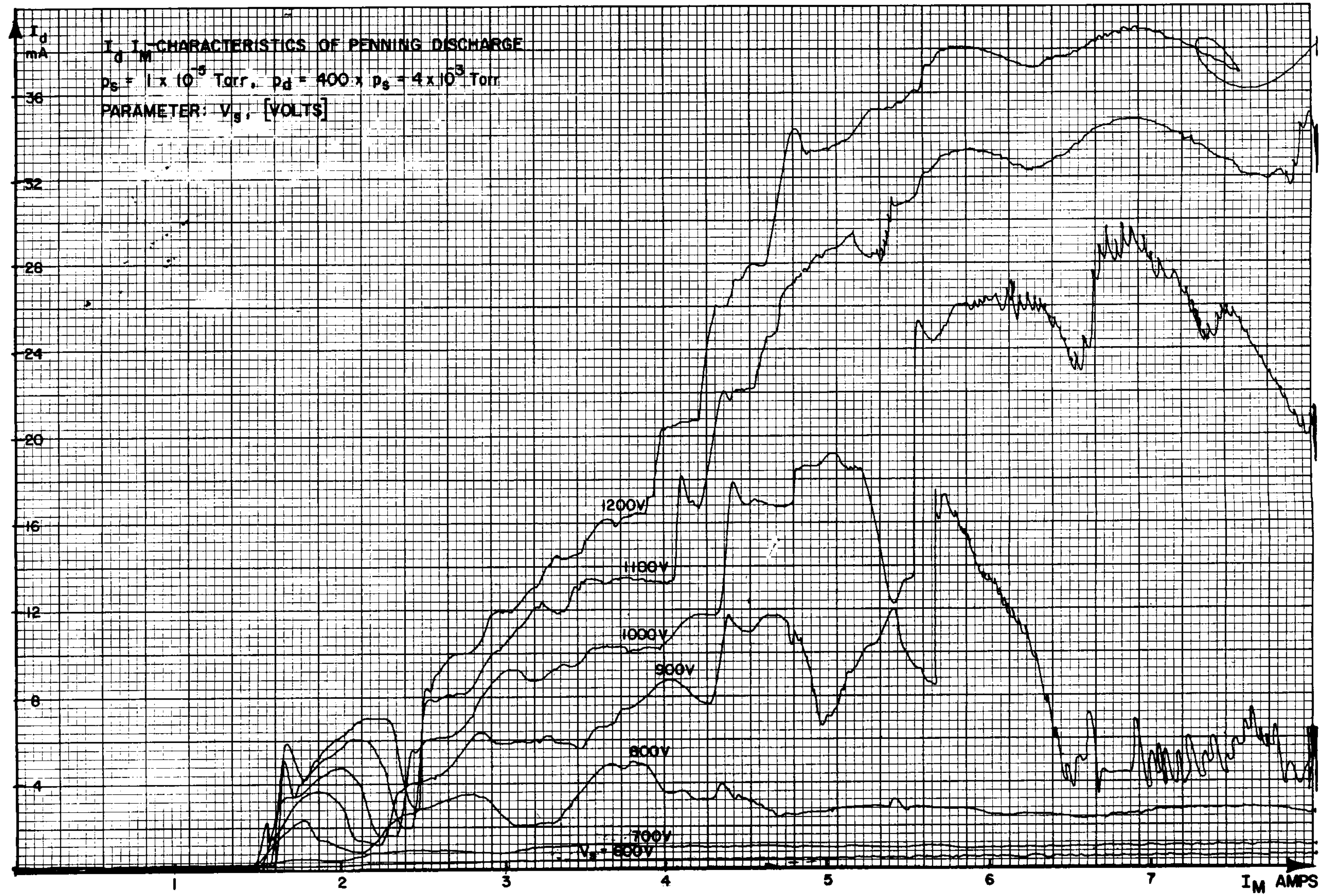
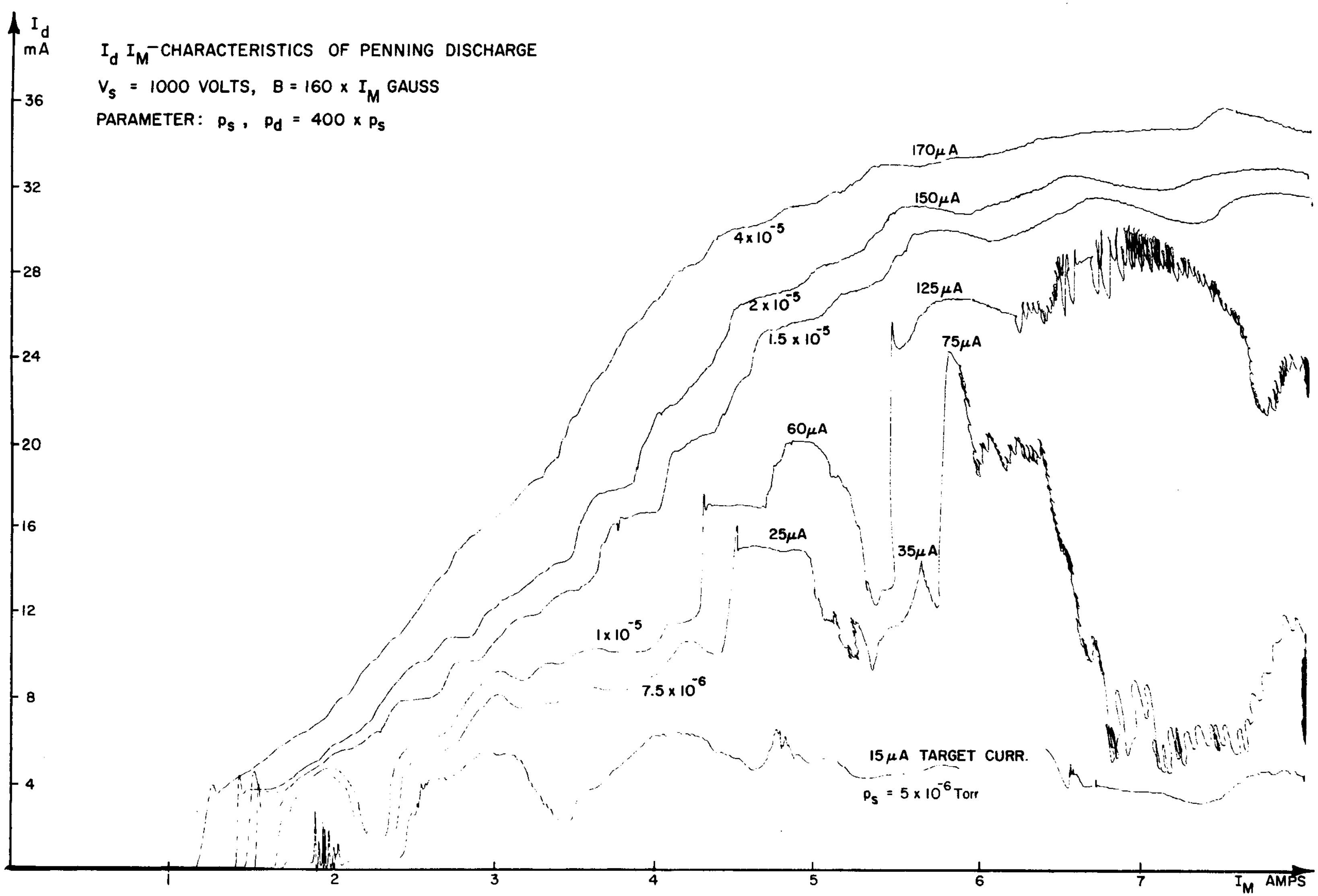

I_d I_M-CHARACTERISTICS OF PENNING DISCHARGE
p_s = 1×10^{-5} Torr, p_d = $400 \times p_s$ = 4×10^{-3} Torr
PARAMETER: V_s, [VOLTS]
I_d mA
36
32
28
24
20
16
12
8
4
1
2
3
4
5
6
7
I_M AMPS
1200V
1100V
1000V
900V
800V
700V
V_s = 600V

Figure 4.



I_d mA
I_d I_M–CHARACTERISTICS OF PENNING DISCHARGE
V_s = 1000 VOLTS, B = 160 x I_M GAUSS
PARAMETER: p_s , p_d = 400 x p_s
36
32
28
24
20
16
12
8
4
1
2
3
4
5
6
7
I_M AMPS
170 μA
150 μA
4 x 10^{-5}
125 μA
2 x 10^{-5}
1.5 x 10^{-5}
75 μA
60 μA
25 μA
35 μA
1 x 10^{-5}
7.5 x 10^{-6}
15 μA TARGET CURR.
p_s = 5 x 10^{-6} Torr

Figure 5.

a focus of about 3 mm in diameter was observed. This rather wide focus caused a considerable loss in intensity when the atomic spectrum was registered. Theoretical considerations indicated the possibility of a smaller focus; therefore, the target was replaced by a phosphor and the extraction gap preceeding the einzel lens was systematically changed. Finally, a focus of less than 1 mm in diameter was achieved, and now the conditions were quite comparable to those known from the work with the duoplasmatron.

Figure 6 gives a spectrum of the Al Mg alloy which has been studied in detail with the duoplasmatron too. The energy window was adjusted to give a molecular spectrum. A comparison with spectra obtained from the same material but with the duoplasmatron (see GCA Technical Report 66-15-N) proves that the Penning sputter source is capable of delivering the same intensities in the spectrum as did the duoplasmatron. The same may be said from the atomic spectrum of Figure 7 which was obtained with an energy window setting of 250 eV.

From these two examples, it can be concluded that the performance of the Penning sputter source is similar to that of the duoplasmatron with any material and at any energy window setting.

The cathodes of the Penning source showed visible signs of sputtering. Sputtering within the ion source can impose some problems as was already mentioned in an earlier paragraph. This effect is not too surprising since in contrast to the duoplasmatron, where arc voltages range between 40 and 80 volts, much higher discharge voltages are involved, and, thereby, ions can gain considerable energies before they impinge on the cathodes. By the choice of materials with a low sputter yield, like Al, this effect can be kept within reasonable limits. In this connection, it was of interest to check the primary beam spectrum particularly with regard to aluminum. Figure 8 shows the primary beam spectrum. Surprisingly, the Al contamination of the primary beam turns out to be very small. The main contaminant is at M-28 which is either N_2 or CO and amounts to about 4 parts per thousand. Further contaminants are H_2O, O_2, H_2, Al, Hg, H, N, O, and some faint indication of hydrocarbons. The contamination with Al is less than 100 ppm. All these contaminants are judged negligible within the contractual requirements concerning the detection limit of trace impurities. In addition, there is some suspicion that part of the peaks at mass M = 28 (N_2?) and M = 32 (O_2) were caused by a small air leak in the Penning source.

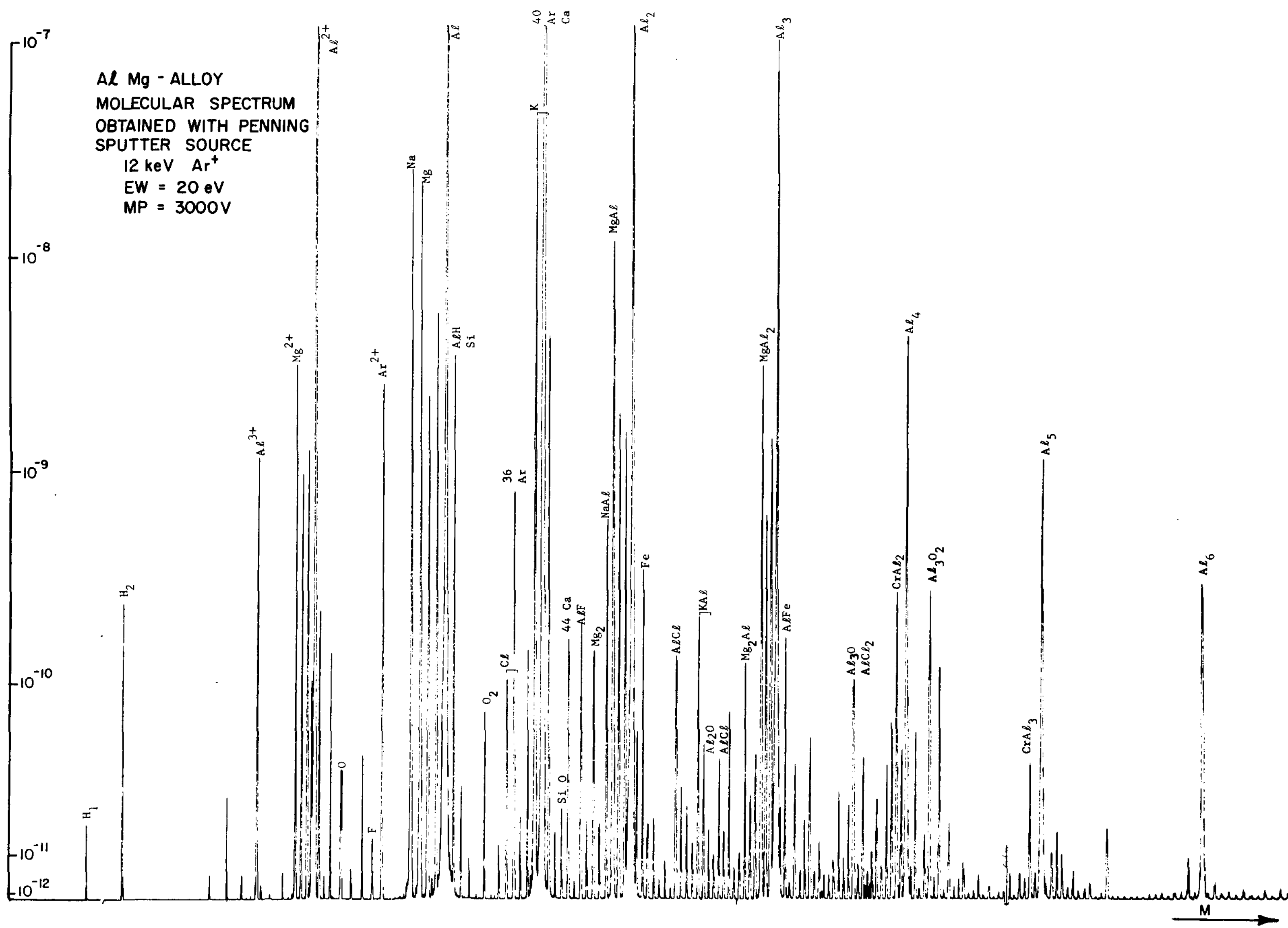
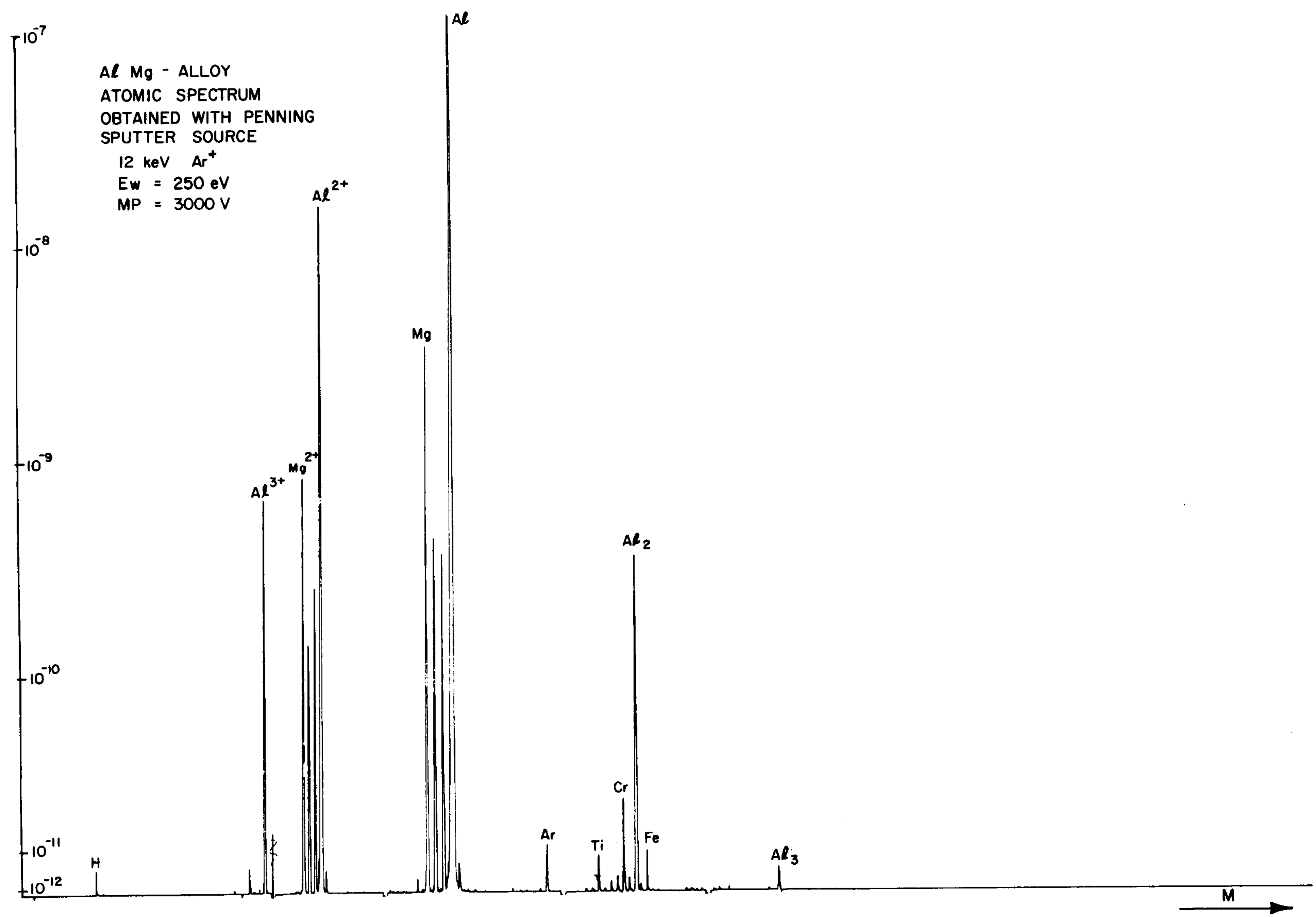

Aℓ Mg - ALLOY
MOLECULAR SPECTRUM
OBTAINED WITH PENNING
SPUTTER SOURCE
12 keV Ar+
EW = 20 eV
MP = 3000V
10-7
10-8
10-9
10-10
10-11
10-12
H1
H2
Aℓ3+
Mg2+
Aℓ2+
O
F
Ar2+
Na
Mg
Aℓ
AℓH
Si
O2
Cℓ
36 Ar
K
40 Ar Ca
Si O
44 Ca
AℓF
Mg2
NaAℓ
MgAℓ
Aℓ2
Fe
AℓCℓ
KAℓ
Aℓ2O
AℓCℓ
Mg2Aℓ
MgAℓ2
Aℓ3
AℓFe
Aℓ3O
AℓCℓ2
CrAℓ2
Aℓ4
Aℓ3O2
CrAℓ3
Aℓ5
Aℓ6
M

Figure 6.



Aℓ Mg - ALLOY
ATOMIC SPECTRUM
OBTAINED WITH PENNING
SPUTTER SOURCE
12 keV Ar+
Ew = 250 eV
MP = 3000 V
10-7
10-8
10-9
10-10
10-11
10-12
H
Aℓ3+
Mg2+
Aℓ2+
Mg
Aℓ
Ar
Ti
Cr
Aℓ2
Fe
Aℓ3
M

Figure 7.

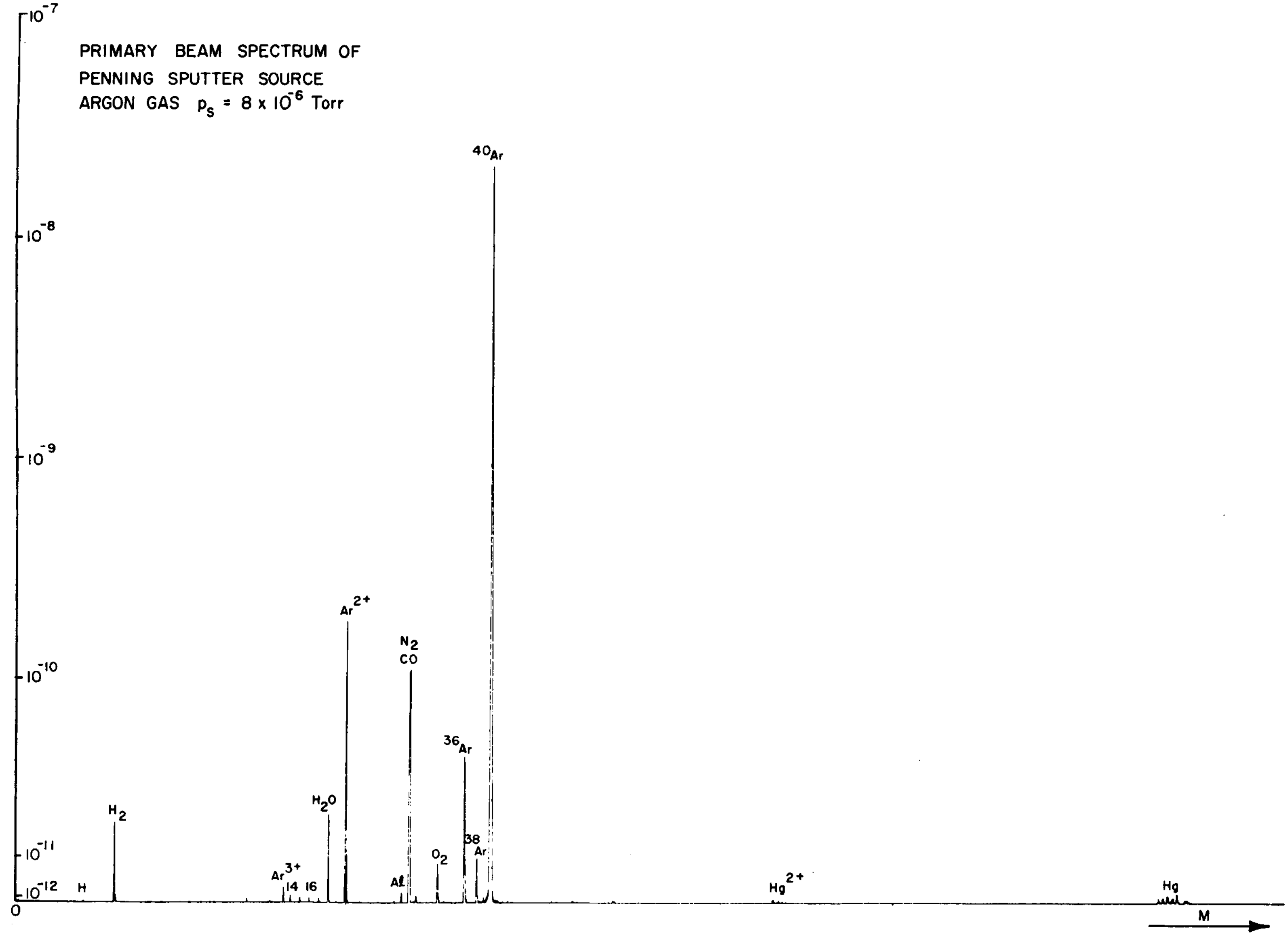

PRIMARY BEAM SPECTRUM OF
PENNING SPUTTER SOURCE
ARGON GAS $p_s = 8 \times 10^{-6}$ Torr
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0
H
H_2
Ar^{3+}
14
16
H_2O
Ar^{2+}
Al
N_2
CO
O_2
^{36}Ar
38
Ar
^{40}Ar
Hg^{2+}
Hg
M

Figure 8.

CONCLUSION

The foregoing sections clearly show the feasibility of a Penning ion source for the production of the primary beam for the ion sputter source. Indeed, considering the advantages of the Penning source - no hot filament, less power consumption and simpler construction - one might almost conclude that the Penning source is superior to the duoplasmatron. This, however, is not quite true. It has already been mentioned that the low arc voltage in the duoplasmatron prevents self-sputtering within the source which can cause a problem at the high sensitivity requirements of the laboratory analyzer. In addition, the ionization efficiency in the duoplasmatron is close to 100 percent while only 5 precent of the gas gets ionized in the Penning discharge. This means that about 20 times more neutrals than ions leave the Penning source through the extraction hole. Accordingly, the plasma density in the duoplasmatron is at least 20 times higher since the working pressure in both sources is about equal. The duoplasmatron plasma density is further increased by the strong magnetic constriction in the extraction region; thus, the same total ion current as in our Penning source is extracted from an extraction hole of only 0.3 mm in diameter. If a hole of 2.8 mm in diameter, as used in the Penning source, were used, a current 80 times higher can be expected. A current of this size, however, would not result in an equal increase in instrument sensitivity since space charge effects would prevent sharp focusing and limit the maximum attainable current density. A sharp focus, as required in the laboratory instrument, is better obtained with a small extraction hole.

Nevertheless, the good performance of the Penning sputter source is a very encouraging pre-condition for the Lunar Lander mass spectrometer. Power consumption of the source can be kept well below 5 watts (V_d = 500 volts, I_d = 10 mA). If a series resistor is used, another 5 watts are lost. This owes to the fact that a voltage drop about equal to V_d is required across this resistor in order to achieve stable operation. Here, however, an electronic circuitry of special design (constant current source) can be used and the total power requirement will only insignificantly exceed the power consumption of the discharge.

In order to save weight and space, it is planned to scale down the momentary source by a linear factor of two. Since the laws of similarity of gaseous discharges are well established, all results gained with the source described herein are readily applicable to a smaller source, and no complications are expected.

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