Title

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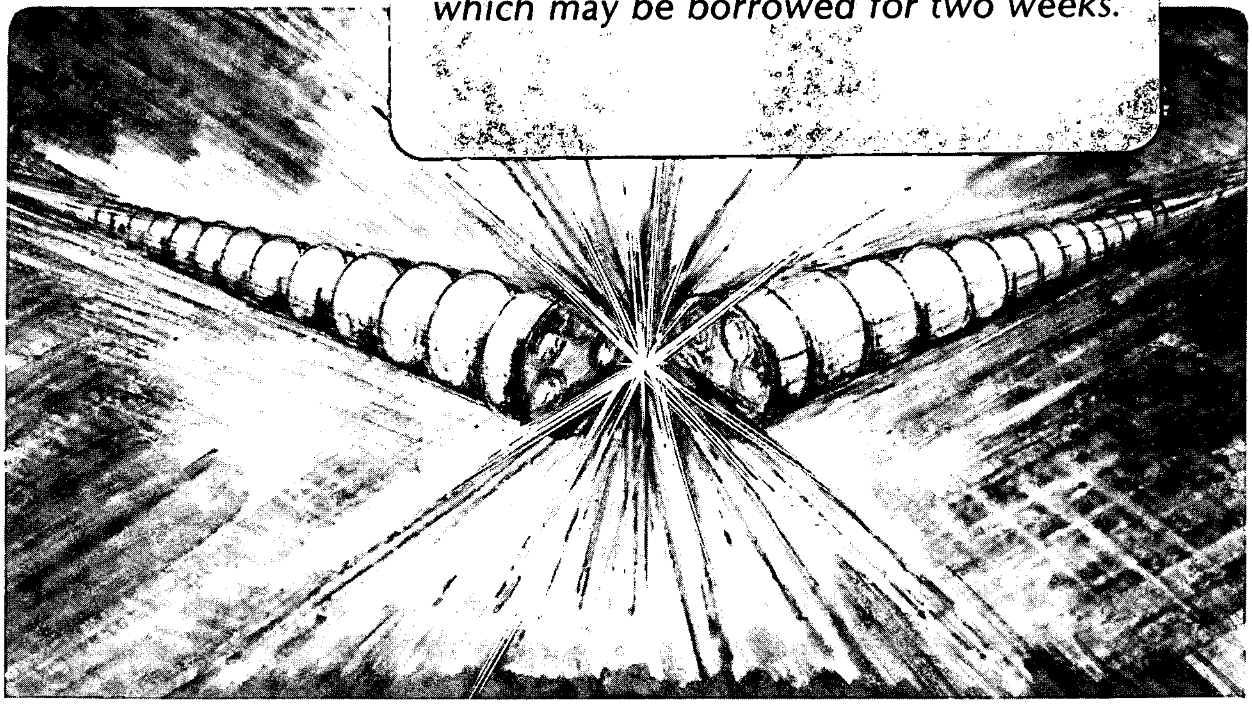

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Steady State Discharge Test of Coaxial LaB_6 Cathode*

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Abstract

Results of steady state discharge test of coaxial LaB_6 cathodes in a multi-cusp plasma generator are described. After single unit test of a compact, 6.4 mm diameter coaxial LaB_6 cathode, a discharge test of two cathodes with one heater power supply was carried out with success. In addition, a new tapered coaxial cathode, which was designed to prevent overheating of LaB_6 due to ohmic heating by discharge current, was investigated. During steady state plasma source operation, a discharge current as high as 180 A was obtained with this tapered cathode.

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Introduction

If the negative-ion-based neutral beam injector is to be used for heating and current drive of the next generation tokamaks such as TIBER in the U. S. and FER in Japan, steady state operation of the ion source is required. Durability of the plasma source cathode is a major problem in the development of CW or long pulse neutral beam injectors. Historically the cathode has been the weakest component of neutral beam injectors. If radio-activation of the injector due to neutrons produced in the torus plasma is considered, the cathode must have as long life time as possible and be easy to maintain and replace.

As described in a previous paper[1], a simple, directly heated coaxial LaB_6 cathode has been developed, which is easily installed and removed from the ion source and can be operated in steady discharge. The coaxial design also minimizes the magnetic field produced by the heater current and therefore minimizes the perturbations on the primary electron trajectories. However, the mounting structure for the cathode was too large and heavy for the electron emission current obtained. Improvements were made on the mounting structure to make it compact and light. Further, in order to reduce thermal stresses and to increase contact resistance, the LaB_6 cylinder was divided into multiple segments.

In this paper, test results of the improved coaxial LaB_6 cathode , and discharge tests of two cathodes with only one cathode preheated are described. A description of the design and test results of a tapered coaxial LaB_6 cathode is presented. This cathode can prevent overheating of LaB_6 due to ohmic heating by discharge current flowing through it. From this cathode, a discharge current up to 180 A was obtained in a steady state discharge operation.

I. 6.4 mm diameter segmented coaxial LaB_6 cathode

Figure 1 shows a schematic diagram of the quarter-inch coaxial cathode and the mounting structure. The cathode is made up of five segments of thin hollow cylindrical LaB_6 (0.6 mm wall thickness, 6.35 mm dia and 3.6 mm long) with two LaB_6 end caps. This multi joint structure was designed to prevent damage due to thermal stresses, as well as to increase contact resistance. A tantalum center conductor runs the full length of the coaxial structure and carries the heater current. The tantalum rod passes through a hole in both cathode caps and is terminated by a molybdenum nut. A boron nitride spacer is inserted between the center tantalum rod and the outer tantalum base to provide electrical isolation. The LaB_6 part is separated from both the molybdenum nut and the tantalum base by rhenium foils as LaB_6 is very reactive with refractory metals at high temperatures.

The LaB_6 cylinder pieces are held in compression by a spring coil and bellows system at the other end of the assembly. The copper bellows is used as the vacuum seal between the center conductor and the external housing and it allows free movement of the parts due to thermal expansion. An adjustable spring coil is installed in parallel with the bellows to compensate for the vacuum load. This spring coil also provides the proper tension on the cathode components, so as to insure good electrical contact. The center tantalum rod and the outer tantalum base are attached to the water cooled copper body. An "O" ring between the glass fiber plastic discs seals the greater part of the structure from the vacuum system.

The cathode assemblies described in this paper have been all tested in a 20 cm diam by 24 cm long multicusp plasma generator. The plasma generator is a round bucket covered by flanges at both ends. Cobalt-samarium permanent magnets are attached on the outer walls of the bucket to form the multicusp magnetic configuration. The bucket is made of copper and is fully water-cooled to allow steady state operation of the source.

In the center of the front plate, a 1 mm diameter hole allows the hydrogen gas to flow to the main vacuum chamber, which is pumped by a turbomolecular pump. In addition the source chamber is pumped through a 3 cm hole by a second but smaller turbomolecular pump. The pressure P_{vac} in the main chamber was measured by an ionization gauge. A rectangular hole is provided in the end flange for insertion of the cathode assembly. Two windows are installed on the side wall of the source chamber for viewing the cathode during heating and discharge. The cathode was positioned in the field free region of the source chamber.

The negative terminals of the heater and the discharge power supplies were both connected to the outer conductor of the cathode. To avoid overheating of central tantalum rod by discharge current, only the positive terminal of the heater power supply was connected to the center conductor.

(a) Single cathode discharge test

The discharge operation of single 6.4 mm diameter coaxial LaB_6 cathode was tested, using a discharge power supply (80 A/200 V,DC) equipped with a current limiting mode. The discharge voltage is first set at a voltage of about 150 V. Hydrogen gas was continuously fed into the source to maintain the desired pressure in the main chamber. Heater power to the cathode was gradually increased until emission was obtained. The heating power required to start the discharge was about 240 watts (40 A at 6 V). Once the discharge was established, the discharge voltage dropped until the current limiting of the power supply became effective. The current limit was then set to give the full output of the power supply. Concurrently with raising the discharge current, the heater current was reduced to zero . After turning the heater power supply off, the discharge remained stable. At this stage, the temperature of the cathode was maintained at an emission temperature by heating due to ion bombardment from the surrounding plasma and by ohmic heating due to the discharge current.

The discharge voltage-current (V-I) characteristics in the absence of a heater current are shown in Fig. 2 as function of the pressure, P_S in the source chamber. P_S is derived from a P_{vac} vs. P_S relationship measured after completion of the discharge tests.. Similar to the previous work[1], the discharge voltage increases as the discharge current decreases. The discharge voltage also increases with increasing gas pressure. At a discharge current of 80 A, the average emission current density is approximately 14 A/cm^2 for a cathode area of 5.6 cm^2.

After this measurement, the discharge power supply was replaced by another one with a larger capacity (200 A/250 V,DC). A discharge current as high as 200 A has been obtained at a discharge voltage of approximately 70 V. However, inspection after the 200 A discharge operation found cracks in the LaB_6 segment which was the closest to the outer tantalum base (negative potential leg). The cracks were probably caused by overheating due to ohmic heating by the large discharge current and the contact resistances around rhenium foil, which was sandwiched between the LaB_6 and the outer tantalum base. To prevent the ohmic heating problem , the tapered coaxial LaB_6 was devised, which will be described in section II.

(b) Two cathode operation with one heater and one discharge power supply

A test was conducted using 6.4 mm diameter coaxial LaB_6 cathodes, with one heater and one discharge power supply. Figure 3 is the schematic diagram of the electrical circuit for this test. A shunt resistor was installed between the #2 cathode and the negative terminal of the discharge power supply so as to measure the discharge current flowing to the cathode.

Procedure of this test was as follows:

1. Hydrogen gas was introduced into the source chamber and adjusted to maintain the desired pressure in the main vacuum chamber.
2. The discharge power supply was set at approximately 150 V.
3. The heater power supply was turned on and the current was gradually increased to the #1 cathode until a discharge was obtained.
4. Once a discharge was established, the #2 cathode was heated by ion bombardment from the surrounding plasma and began to emit electrons. Eventually, a two cathode discharge is established.
5. After the two cathode plasma was established, the heater current to cathode #1 was gradually reduced to zero and the heater power supply was turned off.
6. The discharge continued to run stably.

Figure 4 shows the discharge V-I characteristics in the absence of heater power as a function of the pressure in the source chamber. The data demonstrate that the discharge V-I characteristics for two cathode operation is similar to that for single cathode operation.

Figure 5 shows the discharge voltage vs the discharge currents for #1 and #2 cathodes, respectively. It can be seen that equal discharge currents were obtained from each cathode.

These results show that a high current discharge in an ion source can be obtained from multiple LaB_6 cathodes with the "starter" heating current supplied to only one cathode.

II. Tapered coaxial LaB_6 cathode

(a) Design

During steady-state discharge, in the absence of heater power, the coaxial cathode is heated by ion bombardment, ohmic heating due to discharge current passing through the LaB_6 body, and contact resistance heating. If the value of discharge current is excessive for the cathode size, the LaB_6 will be overheated by ohmic heating and, in the worst case, it will be sublimated at the hottest point.

In the case of our coaxial LaB_6 cathode and electrical connection, the discharge current passing through the cross section is the largest at the tantalum base and decreases along the length of the cathode. Therefore, for the case of a uniform cylindrical cross section, the LaB_6 will become hottest at the tantalum base, provided the heating due to ion bombardment is uniform along the axis.

In order to make the temperature distribution uniform along the axis, we designed a tapered coaxial LaB_6 cathode for steady-state discharge operation. This concept is similar to our previous works on the shaped LaB_6 filament[2] and the tapered tungsten filament[3].

The following subsection describes how the thickness of tapered coaxial LaB_6 was determined.

Let us consider the cylindrical scheme and the electrical connections shown in Fig.6. In the figure, Z is the distance from the narrow end of the tapered section, $r(Z)$ is the outer radius of the taper at the position Z, r_0 the inner radius of straight cylindrical hole in the LaB_6, and L the length of the taper. In the analysis, the heater current I_h is set to zero, and a steady state discharge is considered. Power input to the cathode is by ion bombardment and ohmic heating from the discharge current. Power losses from the cathode are due to thermal radiation from the surface, and cooling due to thermionic emission of electrons . The resistivity, emissivity and heat conductivity of LaB_6 are defined as ρ, ε and λ, respectively. Then the power balance equation at the point Z is expressed as,

$$\frac{\rho I_{arc}{}^{2}(z)}{(r^{2}(z) - r_{o}^{2})\pi} + j_{i}(V_{c.f} + V_{i} - \phi)\, 2\pi r(z) - \varepsilon\, \sigma\, T^{4}\, 2\pi r(z)$$

$$- j_{e}(\phi + \frac{2kT}{e})\, 2\pi r(z) + (r^{2}(z) - r_{o}^{2})\, \pi \frac{\partial}{\partial z} \lambda \frac{\partial T}{\partial z} = 0\,, \qquad (1)$$

where I_{arc} (Z) is the discharge current passing through the cross section at position Z, j_i the current density of ions impinging on the cathode surface, j_e the current density of electron emission from the surface, $V_{c.f}$ the cathode fall voltage, V_i the ionization voltage of hydrogen gas, the work function voltage of LaB_6, σ Stefan-Boltzmann's constant, k Boltzmann's constant, and T is the temperature of LaB_6 at position Z.

Since the purpose of the tapered cathode is to make the temperature distribution uniform along the axis, one should first set $\partial T/\partial Z = 0$. If the temperature is constant at any surface of LaB_6, the resistivity and the emissivity are constant, and one can assume that j_e and j_i are also constant. For simplicity, the cathode fall voltage $V_{c.f}$ is also assumed to be constant. Thus, Eq.(1) can be rewritten as,

$$\frac{\rho\ I\ arc^2(z)}{(r^2(z) - r_o^2)\pi} + j_i(V_{c.f} + V_i - \phi)2\pi r(z) - \varepsilon\,\sigma\,T^4 2\pi r(z)$$

$$- j_e(\phi + \frac{2\ kT}{e})\ 2\pi r(z) = 0. \qquad (2)$$

The discharge current $I_{arc}(Z)$ can be writtren as,

$$I_{arc}(z) = (j_e + j_i)(\pi a(2t + a) + \int_0^z 2\pi r(z)\ dz), \qquad (3)$$

where a and t are the radius and the length of the LaB_6 top cap.

At Z = 0, Eq.(2) becomes,

$$\frac{\rho\ I_{arc}2(0)}{(a^2 - r_o^2)\pi} + j_i(V_{c.f} + V_i - \phi)\ 2\pi a - \varepsilon\,\sigma\,T^4\ 2\pi a$$

$$- j_e(\phi + \frac{2kT}{e})\ 2\pi a = 0, \qquad (4)$$

where $I_{arc}(0) = (\ j_e + j_i\ )\ \ a\ (\ 2t\ + a\ )$.

While at Z = L, Eq.(2) is given by,

$$\frac{\rho\, I_{arc}{}^2(L)}{(R^2 - r_o^2)\pi} + j_i(V_{c.f} + V_i - \phi)\, 2\pi R - \varepsilon\, \sigma\, T^4\, 2\pi R$$

$$- j_e(\phi + \frac{2kT}{e})\, 2\pi R = 0, \tag{5}$$

where R is the radius of the taper at $Z = L$.

Since we intend to design the tapered cathode to match a discharge current of 200 A, we set $I_{arc}(L) = 200$ A. The same values of a, t, r_0 and L as those for the quarter-inch coaxial LaB_6 are used, and these are; a = 0.32 cm, t = 0.52 cm, r_0 = 0.26 cm, and L = 2.3cm.

Although the surface area of the 6.4 mm diameter cathode is smaller than that of the tapered cathode, we use the former to determine the average discharge current density since the latter is not known. Thus, the average discharge current density is given as,

$$j_e + j_i < \frac{200\ \text{A}}{2\pi a(L + t) + a^2\pi} = 33\ \text{A/cm}^2 .$$

It is assumed that $j_i/j_e \sim (m_e/m_i)^{1/2}$, $j_e = 32$ A/cm^2 and $j_i = 0.8$ A/cm^2 . From this value of j_e, the temperature of LaB_6 will be approximately 2040° K, provided the electron emission is temperature limited. Substituting these values as well as V_i = 13.5 V, $\phi = 2.7$ V, $\varepsilon = 0.7$ and $\sigma = 5.67 \times 10^{-12}$ W/cm^2 /deg^4 into Eq. (4) gives $V_{c.f}$ = 190 V. In turn, substitution of this value of $V_{c.f}$ into Eq. (5) yields the equation R, as

$$10.35\, R^3 - 0.7\, R - 2.17 = 0\, .$$

Solving this equation, we obtain R = 0.63 cm as a physically meaningful solution. Using this data, we have designed the tapered coaxial cathode as shown in Fig.7.

(b) Testing

The tapered coaxial LaB_6 cathode has been tested in the same discharge chamber as the 6.4 mm diameter cathode and with the arc power supply of larger capacity (200 A/250 V, DC). During the initial heating of the cathode, only the top cap of LaB_6 looks hot and bright, as expected. A heater power of approximately 300 watts(100 A at 3 V) was needed to start the discharge. Once the discharge starts, the tapered part of LaB_6 is heated and becomes bright. After establishing the discharge, the heater current can be gradually reduced to zero. During steady state discharges without heater power, the temperature of the cathode including the tantalum base mounting appeared uniform.

Figure 8 shows the V-I characteristics of the discharge both with and without the heater power. It can be seen that a stable discharge current as high as 180 A (limited by the power supply) has been obtained at a discharge voltage of ~ 90 V from this cathode. This value of discharge current corresponds to the average discharge current density of 17 A/cm^2 at the LaB$_6$ surface. Discharge voltage increased as the discharge current was decreased, which is similar to the 6.4 mm diameter cathode. The discharge voltage dropped significantly in the low discharge current region when the heater power was turned on, but in the high discharge current region the voltage drop was small. This suggests that as the discharge current (power) increases, contribution of the heater power to the cathode heating becomes small compared with the sum of ion bombardment and ohmic heating.

After several cycles of operation which included the preheating before discharge, the steady state, and the cooling after discharge, some cracks were found on the cap and the taper of LaB$_6$. However, no change was observed in the discharge V-I characteristics even with the presence of cracks. It appears that the cracks were caused by thermal stresses in LaB$_6$ due to non-uniform temperature distribution during the initial heating and the cooling after turning off the discharge. Thus, some further structual, metallurgical as well as operational improvements are necessary to reduce the thermal stresses and lengthen the life time of the cathode.

Acknowledgment

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Figure Captions

Fig.1 Schematic diagram of the quarter-inch coaxial LaB_6 cathode.

Fig.2 Discharge voltage-current characteristics of the quarter-inch coaxial LaB_6 cathode in the absence of a heater current, as a function of the pressure (P_S) in in the plasma chamber.

Fig.3 Schematic diagram showing the electric circuit for testing the two cathode operation with one heater power supply and one discharge power supply.

Fig.4 Discharge voltage-current characteristics of the two cathode operation in the absence of heater power as a function of the pressure in the source chamber.

Fig.5 Discharge voltage vs discarge currents flowing into # 1 and #2 cathodes, respectively , in the absence of heater power.

Fig.6 Schematic diagram showing the concept of tapered coaxial LaB_6 cathode and the electrical connections.

Fig.7 Schematic diagram showing the designed tapered coaxial LaB_6 cathode. The mounting structure is omitted.

Fig.8 Discharge voltage-current characteristics of the tapered coaxial LaB_6 cathode with and without the heater power.

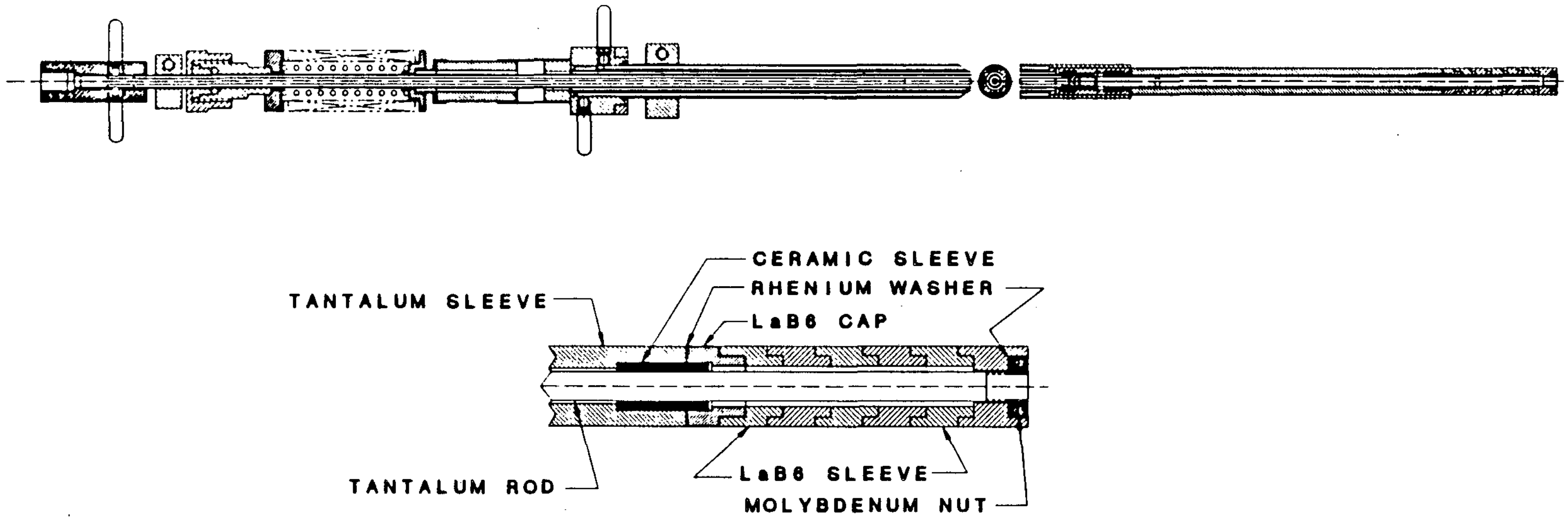

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Fig. 1

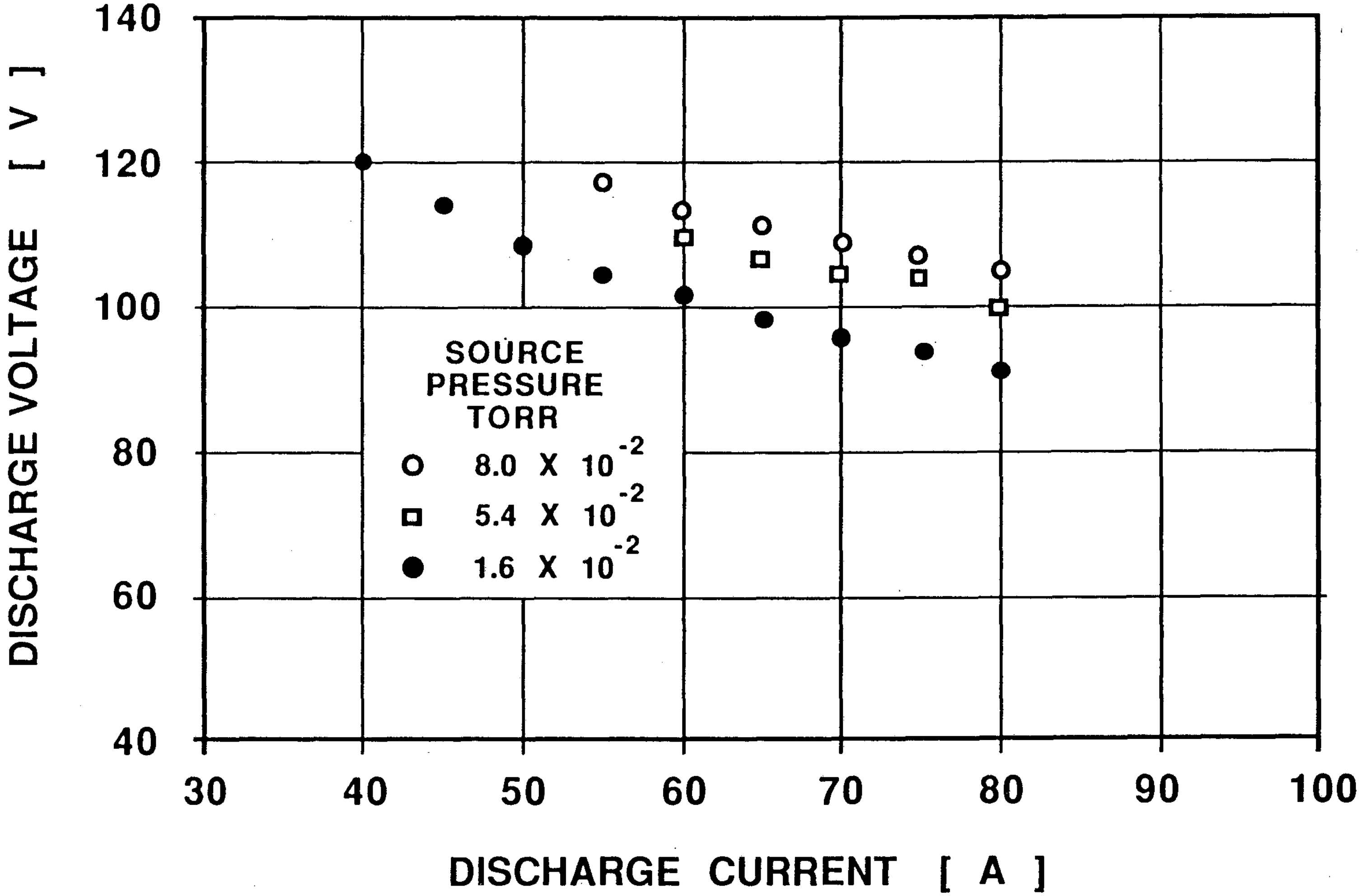

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Fig. 2

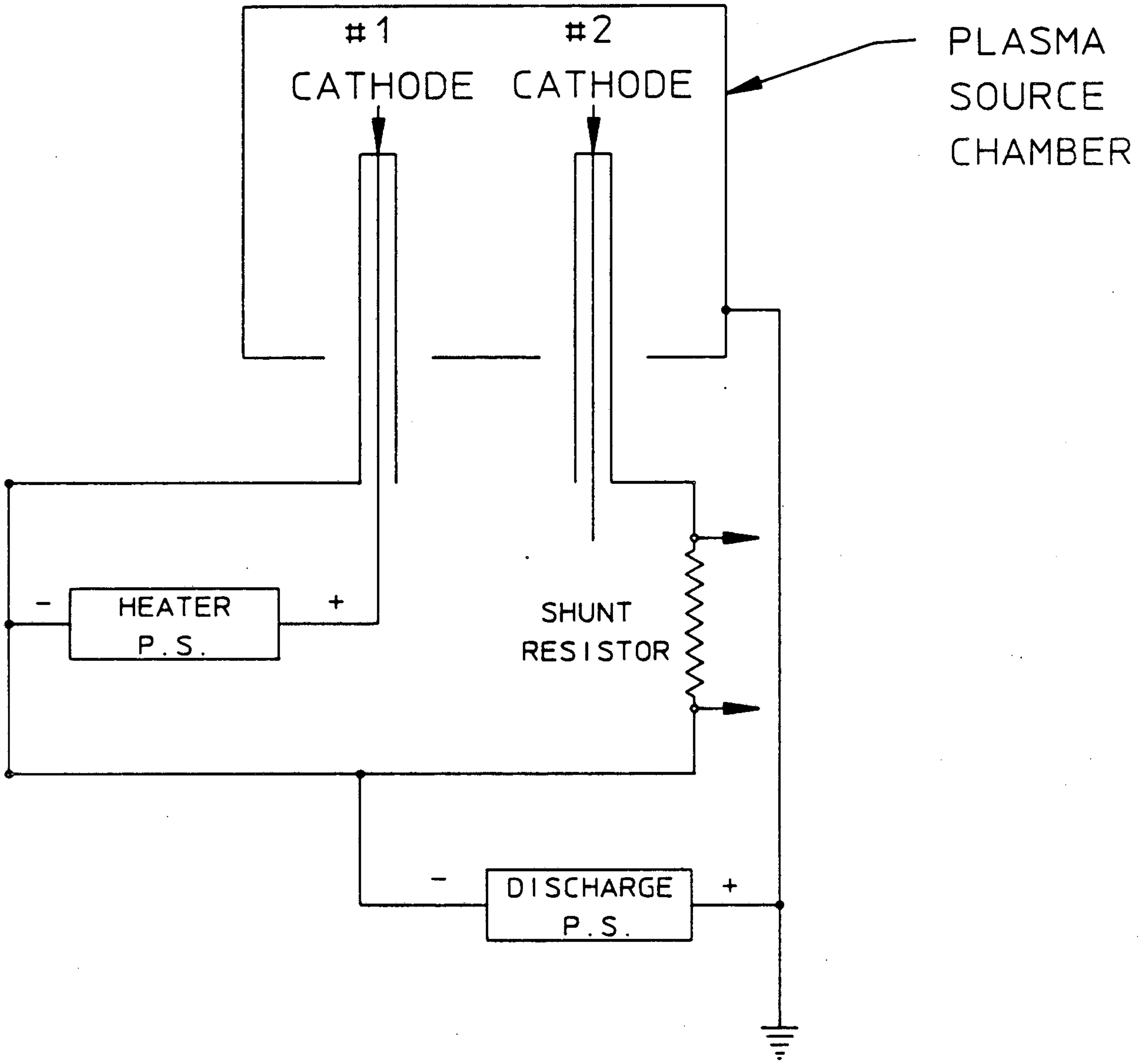

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Fig. 3

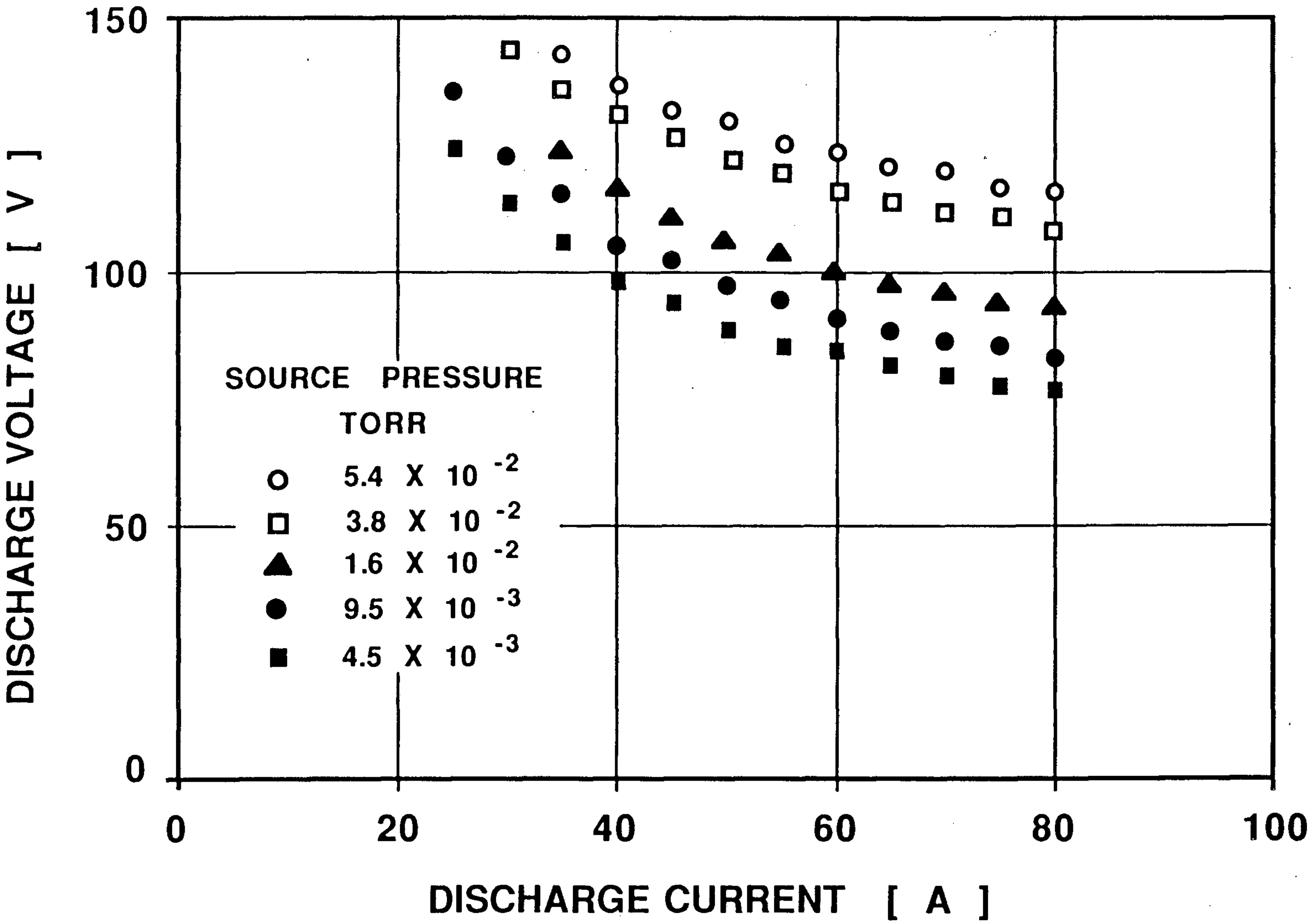

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Fig. 4

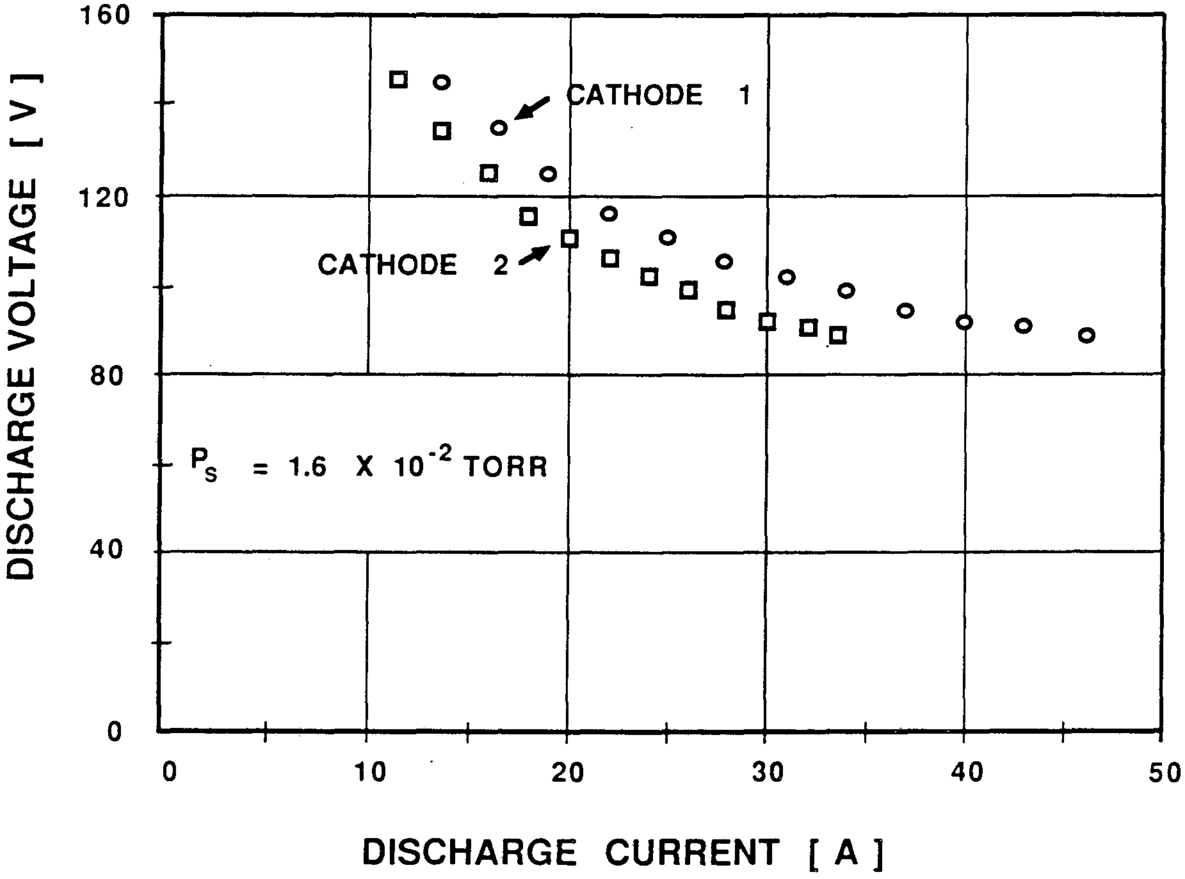

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Fig. 5

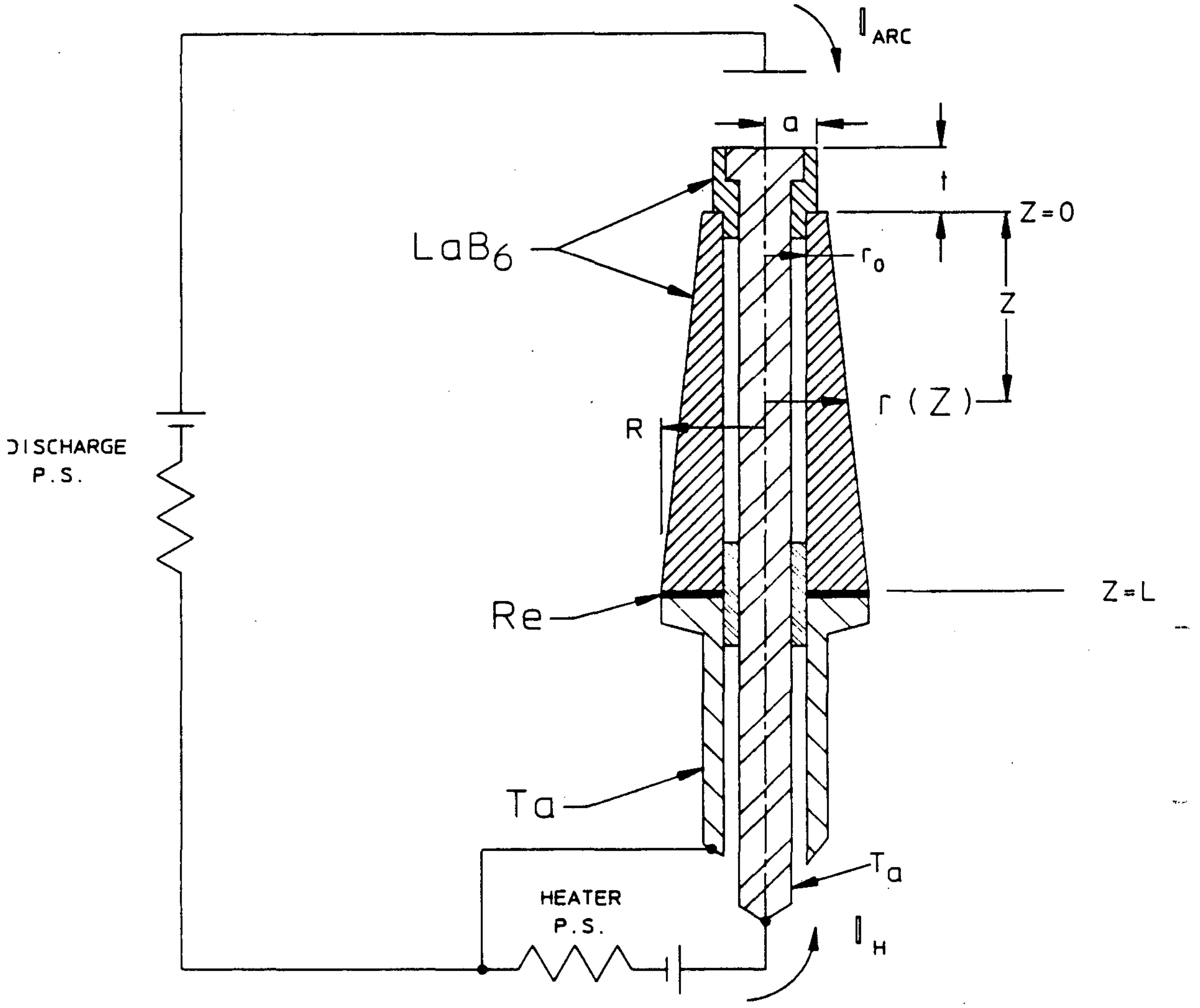

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Fig. 6

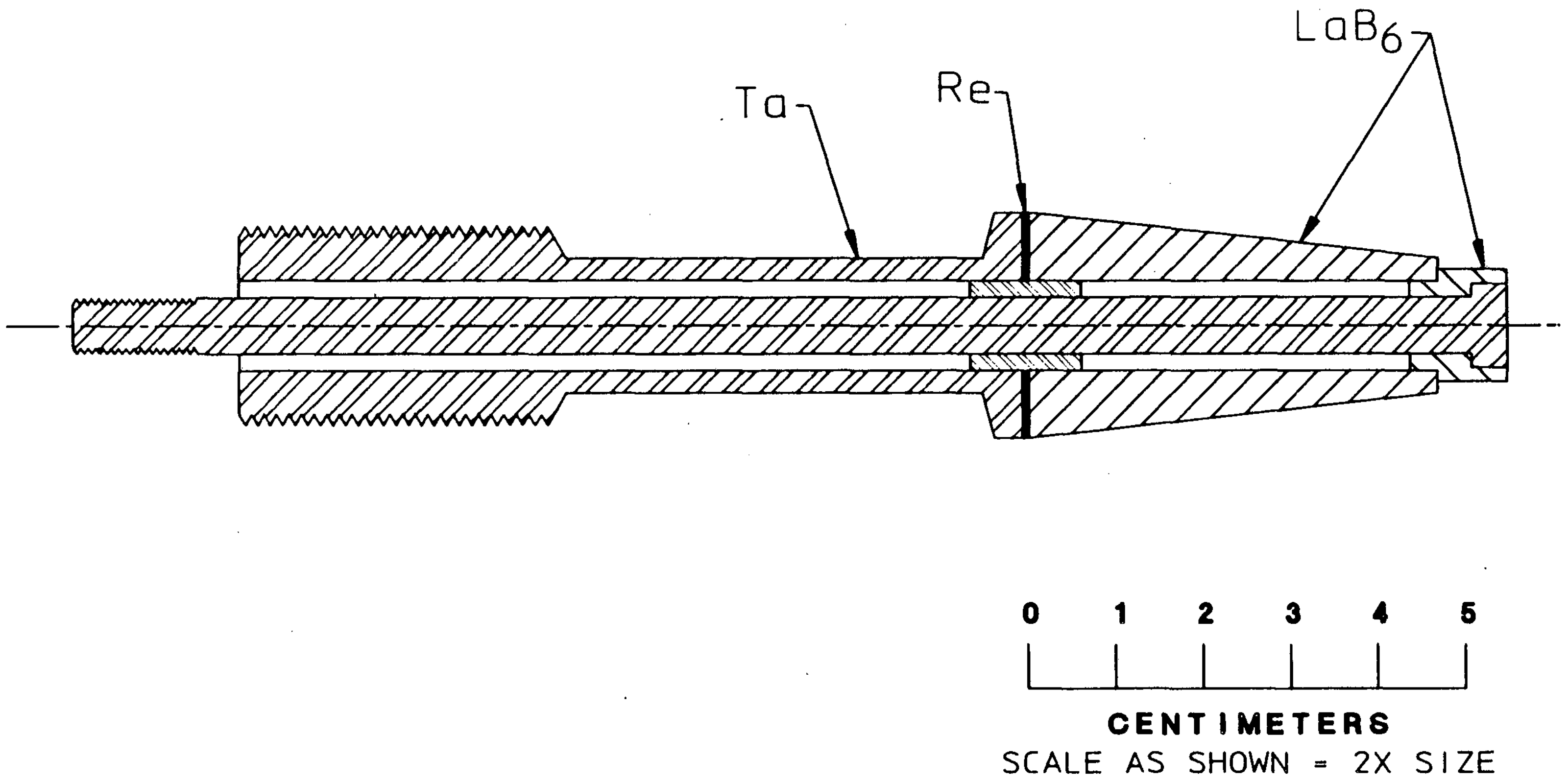

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Fig. 7

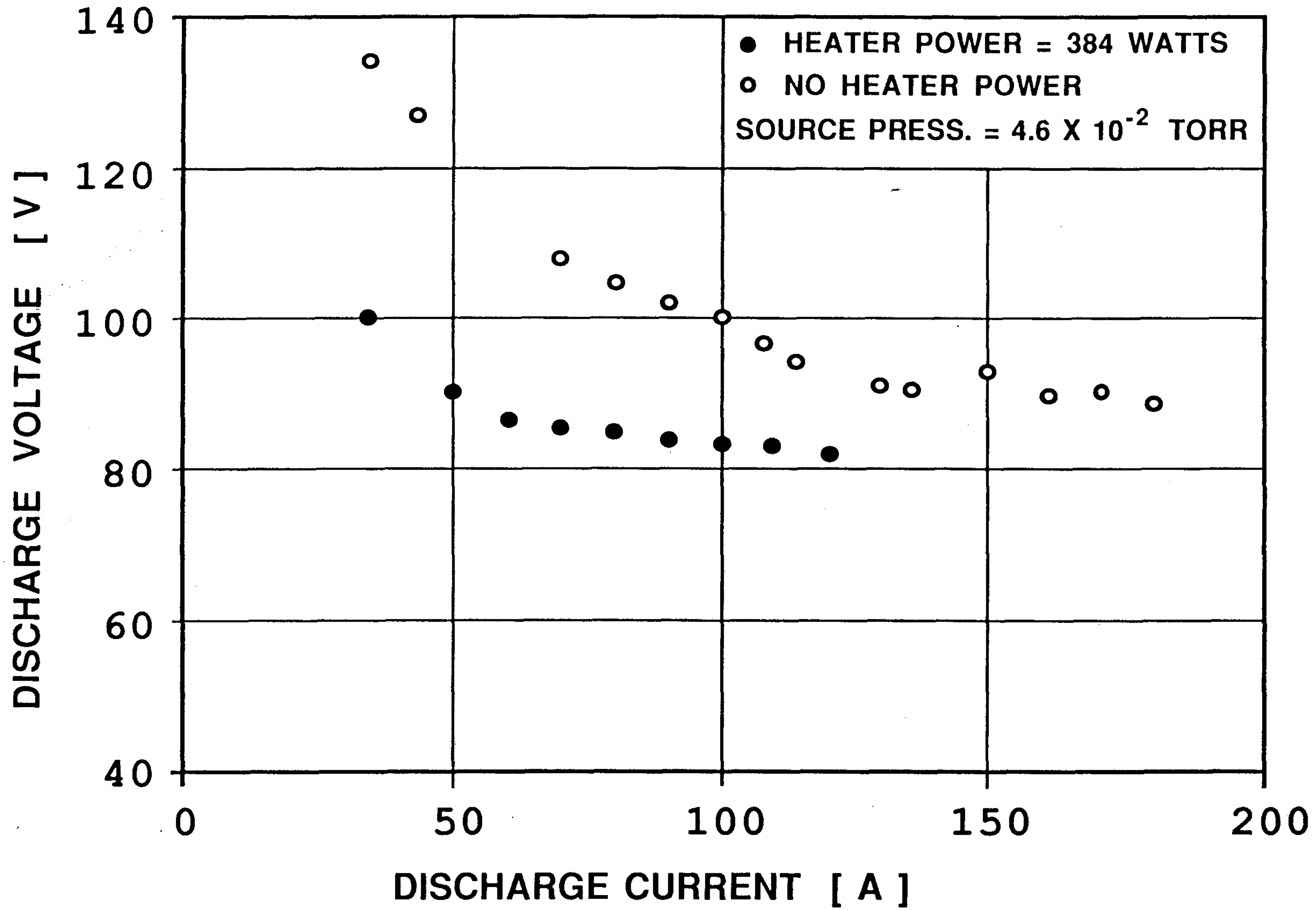

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Fig. 8

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