Resonant Cavity Hollow Cathode Progress

IEPC-2005-007

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31—November 4, 2005

Kevin D. Diamant*
The Aerospace Corporation, Los Angeles, CA, 90009

Abstract: The effect of extraction aperture geometry, cavity internal surface area, and keeper electrode design on the electron current extracted from a microwave resonant cavity discharge is reported. Extracted current increased with increasing aperture area, was largely unaffected by a 41% decrease in cavity sidewall surface area, and was increased by the presence of an enclosed keeper. Peak extracted current was 2.1 A at 60 V with a xenon flowrate of 0.75 mg/s and approximately 60 W of absorbed microwave power.

I. Introduction

The objective of this work is to develop a microwave powered plasma electron source suitable for plasma production and/or beam neutralization in Hall and ion thrusters. Microwave cathodes do not require a low work function electron emitter, therefore failure modes related to the emitter or to the heater required for discharge initiation in conventional thermionic hollow cathodes are eliminated. However, in the absence of a low work function emitter, electron emission from cathode potential surfaces occurs primarily through ion collection, a far less prolific mechanism than thermionic emission.

In Ref. 1, xenon plasma was produced in a cylindrical cavity sized to support the TM_{011} resonant mode at 5.8 GHz, the design frequency of the microwave HiPEP ion engine.[2] Electron current-voltage characteristics were recorded with a flat plate anode placed 2 inches (5 cm) downstream of the cavity. The most notable feature of these characteristics was current saturation at large extraction voltages, indicating a limit imposed by the ion current available for collection at the cavity walls. With approximately 35 W of microwave power absorbed in the plasma, a maximum electron current of nearly 0.5 A was extracted from a 0.100 inch (2.5 mm) diameter aperture at an extraction voltage of 60 V and a xenon mass flowrate of 0.50 mg/s. This paper will describe several modifications to the cavity and their effect on saturation currents.

II. Experiment

A detailed description of the cavity and the test configuration is provided in Ref. 1. For the convenience of the reader, some of that information is repeated here.

Figure 1 is an assembly sketch of the cavity. Microwave power was introduced through the rigid coaxial line labeled "coupling probe," and tuning was accomplished by varying the length of the cavity with the "sliding short," and by varying the depth of insertion of the coupling probe. The tuning elements remained at atmospheric pressure, and were separated from the plasma formation region by a microwave-transparent alumina plate. A photograph of the cavity, with xenon plasma visible through the two rectangular windows, is provided in Fig. 2. The cavity was bolted to an 8-ft (2.4-m) diameter by 32-ft (9.8-m) long cryopumped vacuum chamber with a no-load base pressure of 1e-7 Torr and pumping speed of approximately 2e5 liters/s. Chamber background pressures (corrected for xenon) were between 3e-7 and 1e-6 Torr for flowrates from 0.3 to 1.5 mg/s. The arrangement used to record current-voltage characteristics is shown in Fig. 3. A 4.0 inch (10.2 cm) diameter anode was placed 1 or 2 inches (2.5 or 5 cm) downstream of the cavity, and a keeper electrode was placed downstream of the exit plane of the electron extraction aperture. A wire loop (shown in Fig. 3) and an enclosed keeper were tested. The operating procedure

* Senior Member of the Technical Staff, Propulsion Science and Experimental Mechanics, Kevin.d.diamant@aero.org.

was as follows. The microwave generator was set to a forward power of 100 W, and the cavity was tuned for maximum power absorption in the plasma. A keeper discharge was ignited, and current extraction to the anode was measured at anode voltages up to 50 V, at which point the keeper discharge was turned off. With the keeper off, anode currents were measured as the voltage was increased from 50 to 60 V, and then as the anode voltage was decreased until the anode current became less than a few mA.

III. Results and Discussion

Reference 1 reported current-voltage characteristics with an electron extraction aperture diameter of 0.100 inches and aperture length of 0.125 inches (3.2 mm). Figure 4 plots anode current at 60 V vs flowrate for that and a variety of new aperture geometries with an anode-cathode gap of 2 inches. Figure 5 presents a diagram of the aperture plate and lists relevant dimensions. The wire loop keeper was present, but there was no keeper discharge. These currents were in most cases representative of saturation values, and at 60 V there was a luminous plume present between the cavity and anode.

First to be investigated was the effect of increasing aperture diameter at constant aspect ratio (aperture length to diameter). Each increase in aperture diameter (dimension "A" in Fig. 5) roughly doubled the aperture area. On average, each doubling of the aperture area resulted in an approximately 50% increase in the saturation current. A limit to increasing aperture area (or to decreasing flowrate) was imposed by the increasing difficulty of tuning the cavity as the pressure decreased. Figure 6 partially illustrates this problem by presenting the tuned cavity length and coupling probe insertion depth (1 mil = 0.001 inch = 25 microns) as a function of cavity cold flow pressure. Zero coupling probe insertion corresponded to the tip of the coupling probe flush with the end of the sliding short, as illustrated in Fig. 1. The pressure ranges covered by each of the orifice diameters are shown at the top of the plot. For pressures above about 100 mTorr, the tuned geometry was nearly independent of pressure, but below 100 mTorr the tuned geometry abruptly became quite sensitive to pressure. Furthermore, for pressures below about 150 mTorr there was hysteresis in the tuning. That is, if microwave power was removed from a tuned configuration, then re-applied, the plasma ignited, but power absorption was low. It was necessary to adjust the cavity to improve power absorption, then return to the original settings for best absorption. In most cases it was only necessary to adjust the position of the coupling probe by 0.1 inches (2.5 mm) or less. However, at pressures below about 50 mTorr it became necessary to adjust both the sliding short and the coupling probe, by as much as 0.5 to 1 inch (1.3 to 2.5 cm) each. Below about 30 mTorr, it was still possible to ignite the plasma, but attempts to tune for significant power absorption were unsuccessful. Thus, 0.295 inches was found to be a rough practical upper limit to aperture diameter, barring increases in flowrate that would probably be unacceptable for a thruster cathode (greater than 1 mg/s). Interestingly, the pressure range over which tuning was most difficult was also where it was most fruitful. Figure 6 shows that the best power absorption was obtained below 150 mTorr. Note that due to dissipation in coaxial transmission lines, the power absorbed in the plasma was not 100 W minus the values shown in Fig. 6. Rather, it varied from about 60 W to about 35 W, with an uncertainty of about ±10 W as the reflected power reading increased from 20 W to 40 W. The accuracy of the power meter, and the finite directivity of the dual directional coupler sampling the forward and reverse power contributed to the uncertainty in absorbed power. The extent to which improved power absorption at low pressure contributed to the relative success of the largest apertures was not tested.

Since it was not practical to continue increasing the aperture diameter, the aspect ratio was varied and flares were added to apertures with 0.200 and 0.295 inch minimum diameters. These modifications resulted on average in modest, 10 to 20% increases in current extraction (Fig. 4).

Careful inspection of Fig. 2 reveals that the plasma is brighter near the alumina plate than it is near the aperture. This appearance was typical, and was not anticipated since the theoretical electric field maximum for the TM_{011} mode is at the end of the cavity, just behind the extraction aperture. Nevertheless, it appeared that some benefit might be derived from shortening the low pressure side of the cavity to try to force the high luminosity (and presumably high density) plasma closer to the aperture. A new low-pressure section was fabricated with the distance between the alumina plate and the aperture entrance plane reduced from 3.94 inches (10.0 cm) to 2.32 inches (5.9 cm). The shortened cavity is shown in Fig. 7. Results obtained with the 0.200 inch, 45º flare aperture are shown in Fig. 4, and are very similar to those from the original cavity. This disappointing result was nonetheless revealing, in that a 41% reduction in cavity sidewall surface area had little effect on the extracted current, indicating that the sidewalls did not contribute significantly to net ion current collection. Presumably, this means that electrons created throughout much of the cavity volume were not escaping through the aperture, but were instead recombining with ions in the bulk plasma or at the cavity walls, resulting in wasted power. Logically, further reduction in the volume of the low pressure section, so that most of the electrons are created in the near vicinity of the aperture, should lead to increased efficiency, but it was found that the shortened cavity was more difficult to tune than the original. In fact, attempts to achieve breakdown at a flowrate of 0.3 mg/s were not successful with the shortened cavity, perhaps indicating that wall losses make breakdown more difficult in the smaller volume (for the sake of completeness, the resonant length of the shortened cavity was 4.9 to 5.0 inches at cold flow pressures from 70 to 175 mTorr, with coupling probe insertion depth variations of less than 15 mils around zero). Therefore, experiments continued with the original cavity.

In Ref. 1 it was reported that at extraction voltages greater than about 30 V, a luminous plume appeared in the gap between the cavity and the anode, and the anode current rose with increasing voltage until saturation occurred. This observation suggested that ionization of neutrals escaping the cavity may have contributed significantly to current collection. Hall, Kemp, and Shelton reported that the use of an enclosed keeper dramatically reduced the voltage required to draw a given current from a mercury hollow cathode.[3] They reasoned that the enclosed keeper helped to collimate the escaping neutral flow along the cathode axis, thereby increasing the probability of ionization by electrons extracted from the cathode. This idea was implemented in this work as shown in Fig. 8. A 1.5 inch (3.8 cm) outside diameter by 0.25 inch (0.64 cm) thick insulating washer made of boron nitride was attached to the aperture plate, centered on the extraction aperture. A 1.5 inch outside diameter by 0.063 inch (1.6 mm) thick aluminum washer was stacked on top of the insulating washer to act as the keeper electrode. Keeper electrode aperture diameters of 0.25, 0.50, and 0.75 inches (0.64, 1.3, and 1.9 cm) were used with respective insulating washer inside diameters of 0.75, 0.75, and 0.93 inches (1.9, 1.9, and 2.4 cm). Currents collected at 60 V with the 0.295 inch diameter (aspect ratio 1.27) aperture, and with the enclosed keepers or the wire loop in place, but with no keeper discharge, are shown in Fig. 9 for an anode-cathode gap of 2 inches. For flowrates of 1 mg/s and below, the presence of the enclosed keeper substantially increased the saturation current, particularly for the case of the 0.50 inch inside diameter keeper, for which a peak current of 2.1 A was recorded at a flowrate of 0.75 mg/s (the datapoints labeled "0.50, insert" will be discussed later).

As previously stated, for the data of Fig. 9 there was no electron current collection at the keeper electrode. Figure 10 displays the effect of running a keeper discharge. These data were recorded with the 0.50 inch diameter enclosed keeper and 0.295 inch diameter aperture (aspect ratio 1.27) at a flowrate of 0.75 mg/s, and an anode-cathode gap of 1 inch (Fig. 11 shows that the effect of reducing the anode to cathode gap is to shift the characteristic to lower voltage). At low voltage there was a benefit to running the keeper, but as current collection entered saturation above about 30 V, anode current was reduced by approximately the value of the keeper current. This appeared to indicate that at saturation the total amount of ion current available to be collected at cathode potential surfaces was independent of the keeper discharge, so that if an electron was collected at the keeper, it came at the expense of the anode. This was an unexpected result, given the increases in saturation current observed by simply installing the enclosed keeper, therefore a final experiment was designed to test whether increasing the cathode potential surface area within the enclosed keeper would increase current extraction.

Figures 12 and 13 show how the increase in cathode potential surface area within the enclosed keeper was accomplished. The 0.50 inch aperture keeper electrode was stacked on top of the BN insulator (aperture diameter 0.93 inches), and these were stacked on the part labeled "cathode biased insert" in Fig. 12. The stack was attached to the cavity as shown in Fig. 13, placing the insert in direct contact with the cavity. The insert had a sleeve with an aperture diameter of 0.79 inches (2.0 cm) that extended 0.19 inches (0.48 cm) along the inside face of the BN insulator, leaving a gap of 0.063 inches (1.6 mm) between the top of the sleeve and the keeper electrode. Relative to earlier testing of the 0.50 inch aperture keeper, this arrangement increased the cathode potential surface area within the enclosed keeper by a factor of 2.8, yet current extraction to the anode was not improved, as shown by the datapoints labeled "0.50, insert" in Fig. 9. Running a keeper discharge at 0.1 A reduced the anode current at saturation by approximately 0.1 A, similar to the experience described in the previous paragraph.

The mechanism by which the enclosed keeper increased the extracted electron current is therefore not clear. Actions which presumably increased the plasma density within the keeper (running a keeper discharge), or which increased the surface area for ion current collection within the keeper had little or no positive effect on current extraction. It appears that the presence of the enclosed keeper structure alone somehow influenced plasma properties within the cavity in such a way as to permit increased current extraction.

IV. Conclusion

This paper was a continuation of a study begun in Ref. 1 into the use of a microwave resonant cavity discharge as a plasma electron source. The principal findings of the work described here are as follows. Increased extraction aperture area, as well as reduced aspect ratio (or a flared aperture) increased the extracted current, presumably by increasing the probability that electrons created within the cavity will escape to be collected at the anode, rather than being lost to recombination in the plasma or at a wall. Testing with a shortened cavity revealed that much of the cavity internal surface probably does not contribute significantly to net ion collection, so that increased efficiency should be obtained by limiting plasma formation to a region close to the extraction aperture. The use of an enclosed keeper increased current extraction, but the mechanism by which this occurred is unclear.

Acknowledgments

The microwave generation and transmission equipment was supplied by Gerling Applied Engineering, and the author would like to thank John Gerling and Rex Viney for their outstanding technical and product support. Thanks are also due to Mike Worshum of The Aerospace Corporation for his assistance with test hardware fabrication and assembly, and for many useful discussions on RF engineering. This work was supported under The Aerospace Corporation's Independent Research and Development Program.

References

[1]Diamant, K.D., "Resonant Cavity Hollow Cathode," AIAA 2005-3662.
[2]Foster, J.E., et al., "The High Power Electric Propulsion (HiPEP) Ion Thruster," AIAA 2004-3812.
[3]Hall, D.F., Kemp, R.F., and Shelton, H., "Mercury Discharge Devices and Technology," AIAA 67-669.

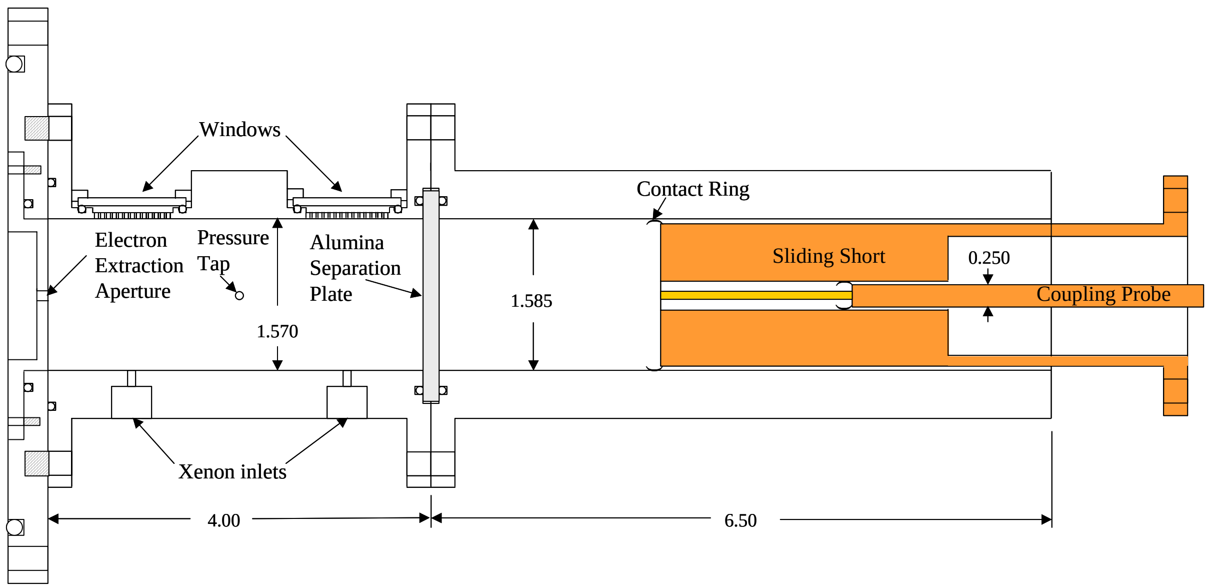


Figure 1. Section view of resonant cavity (dimensions in inches).

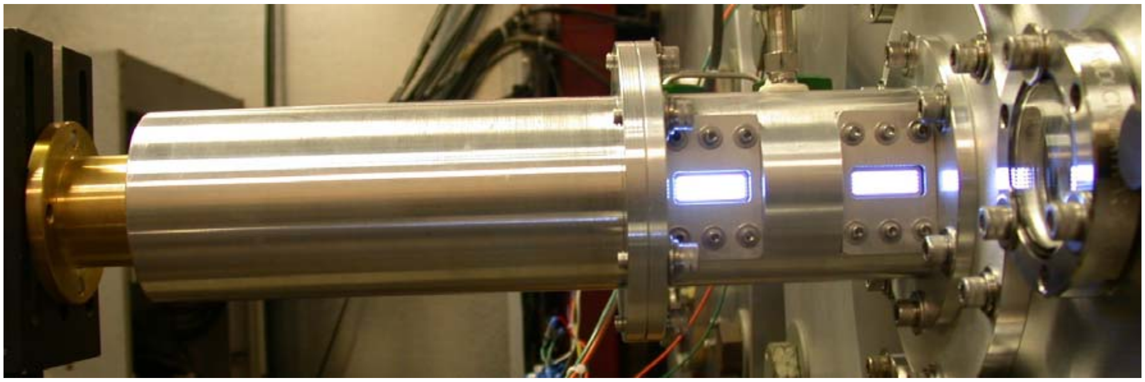


Figure 2. Cavity with xenon plasma.

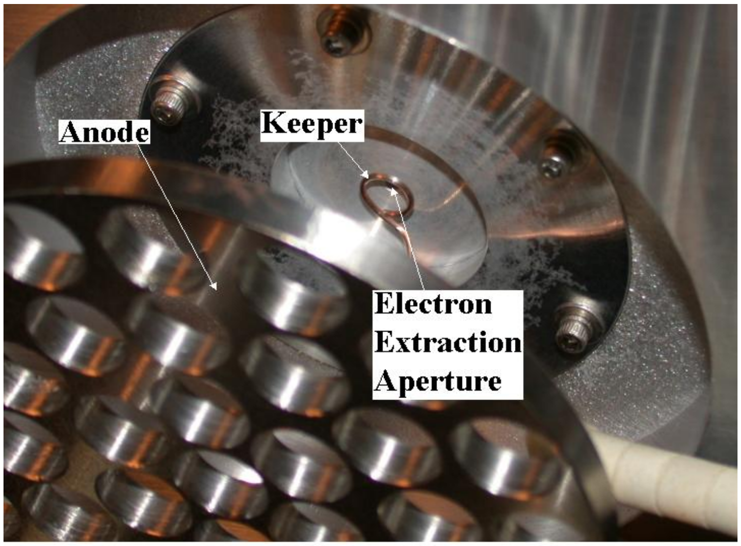


Figure 3. Anode and wire loop keeper.

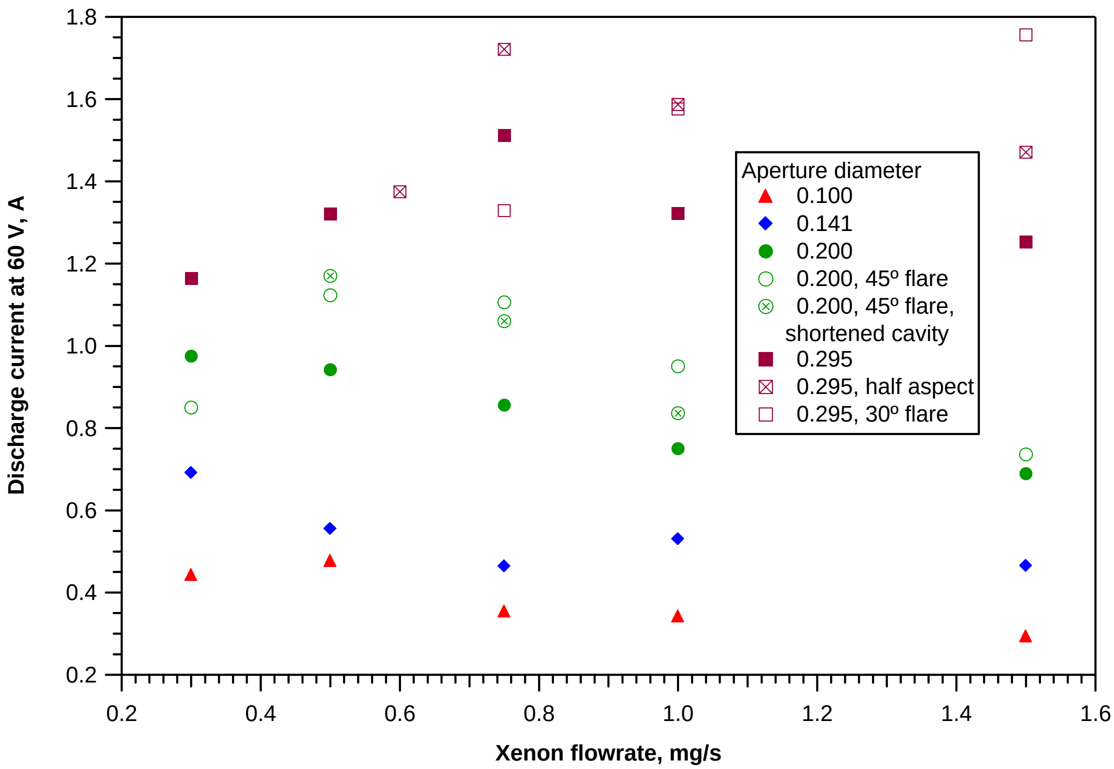
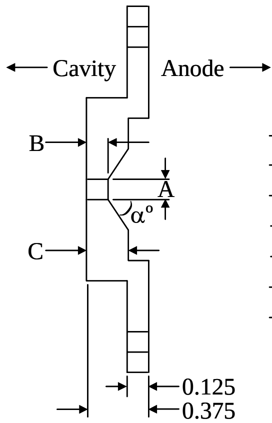


Figure 4. Effect of aperture geometry on anode current at 60 V.



A	B	B/A	C	α
0.100	0.125	1.25	0.125	0
0.141	0.179	1.27	0.179	0
0.200	0.250	1.25	0.250	0
0.200	0.125	0.63	0.250	45
0.295	0.375	1.27	0.375	0
0.295	0.184	0.62	0.184	0
0.295	0	0	0.184	30

Figure 5. Section view of aperture plate (dimensions in inches).

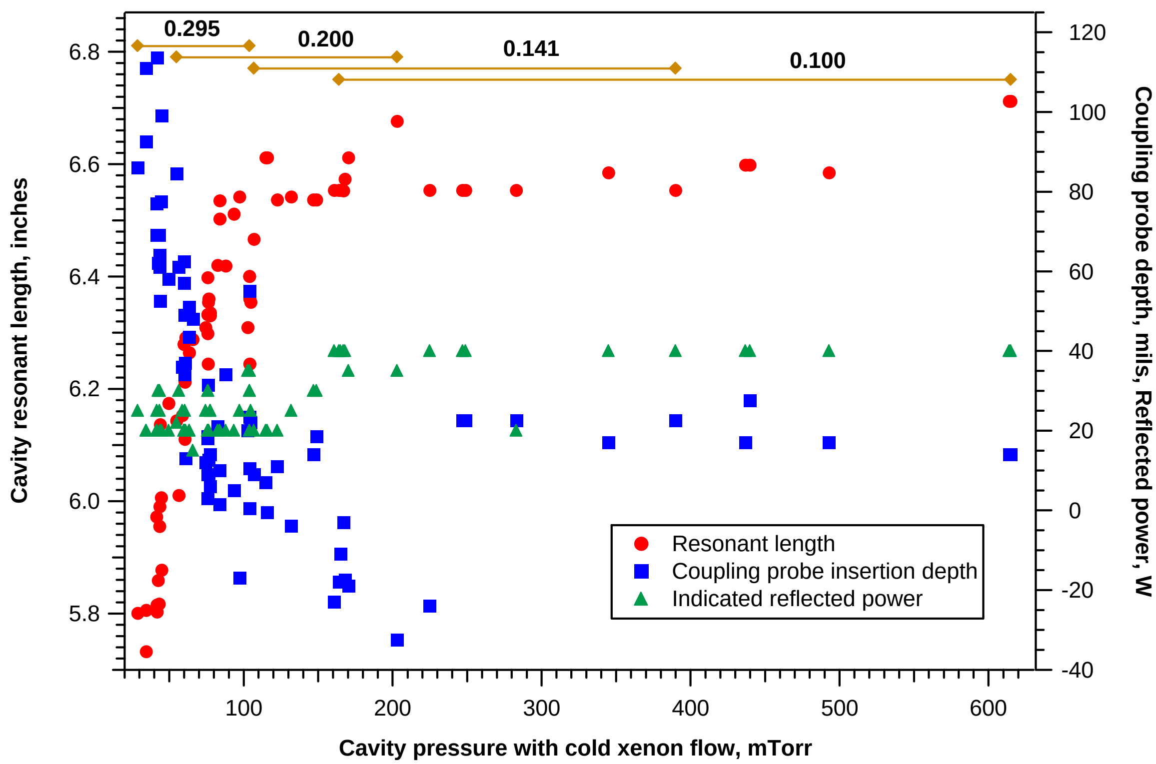


Figure 6. Effect of decreasing pressure on cavity tuning.

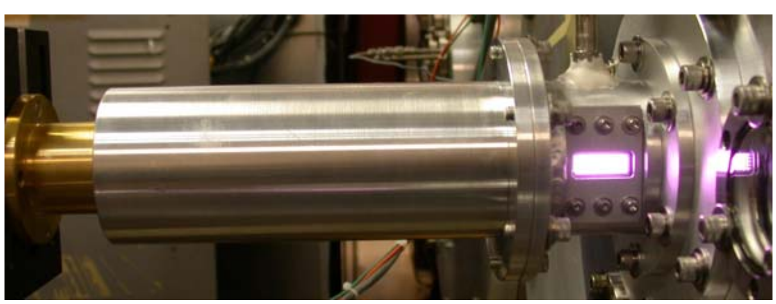


Figure 7. Shortened cavity with air plasma.

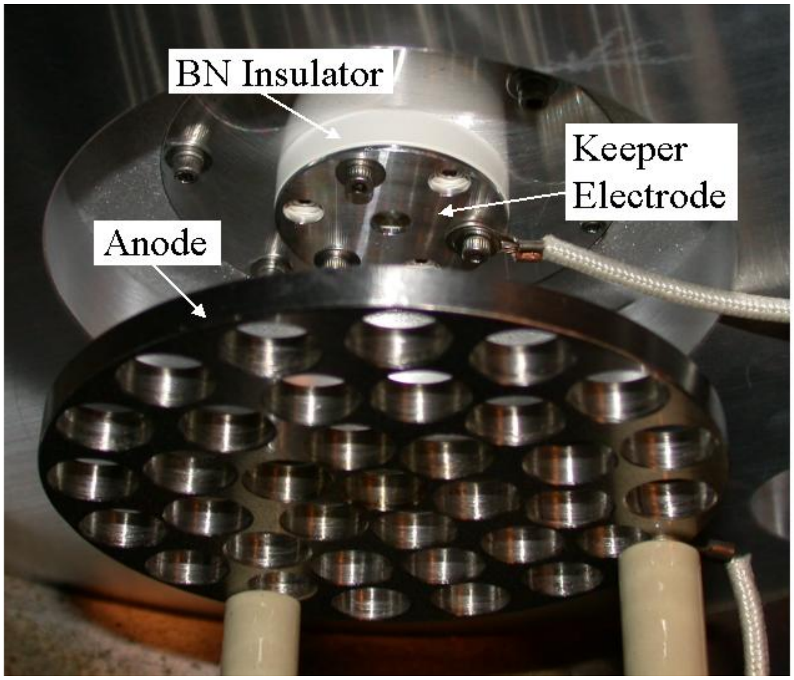


Figure 8. Enclosed keeper.

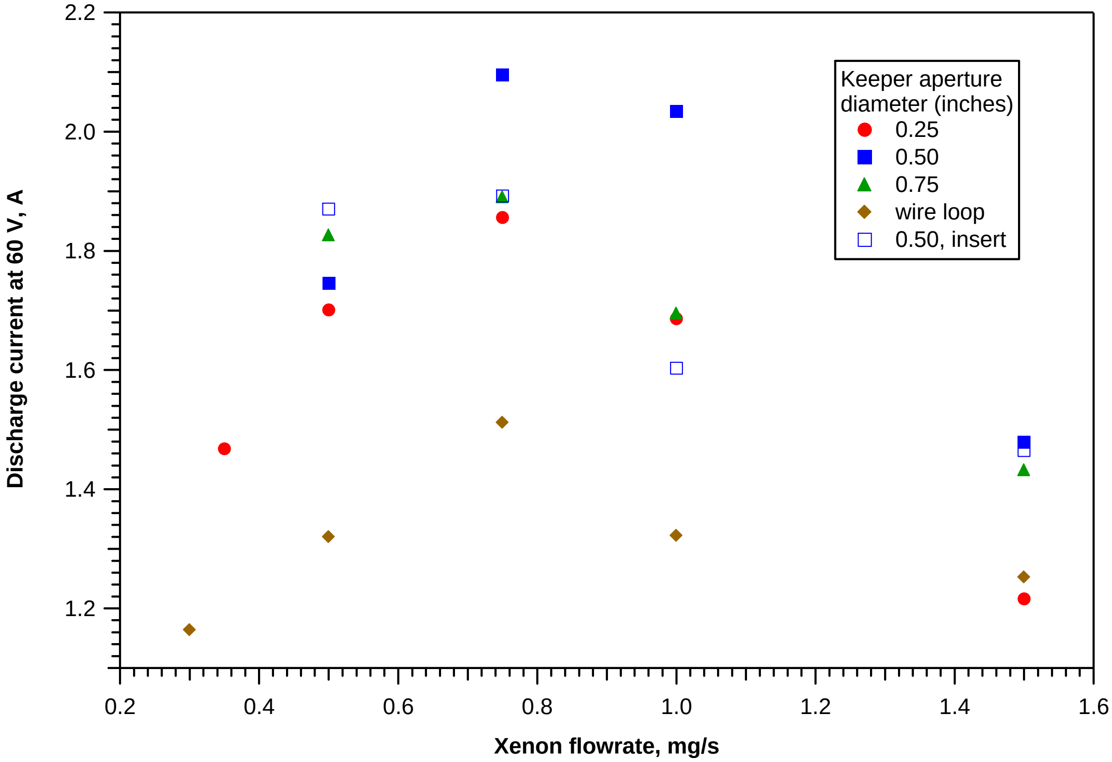


Figure 9. Effect of enclosed keeper on anode current at 60 V with 0.295 inch diameter extraction aperture.

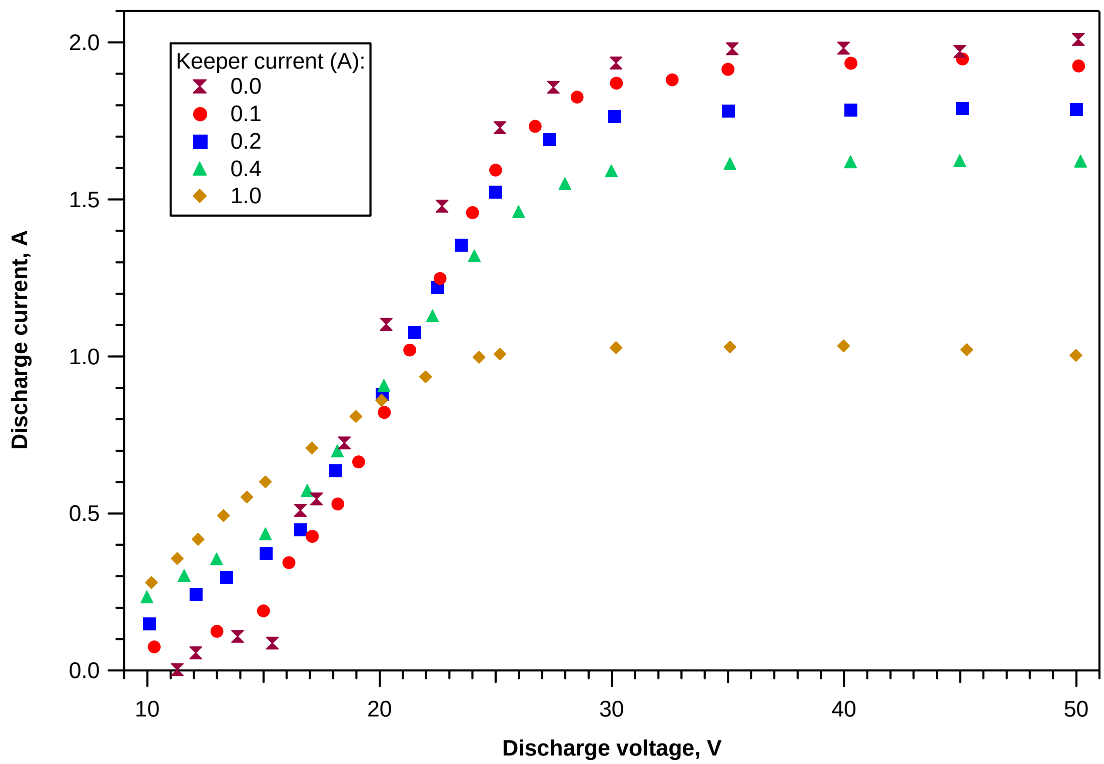


Figure 10. Effect of keeper current, 0.295 aperture with 0.50 enclosed keeper, 0.75 mg/s.

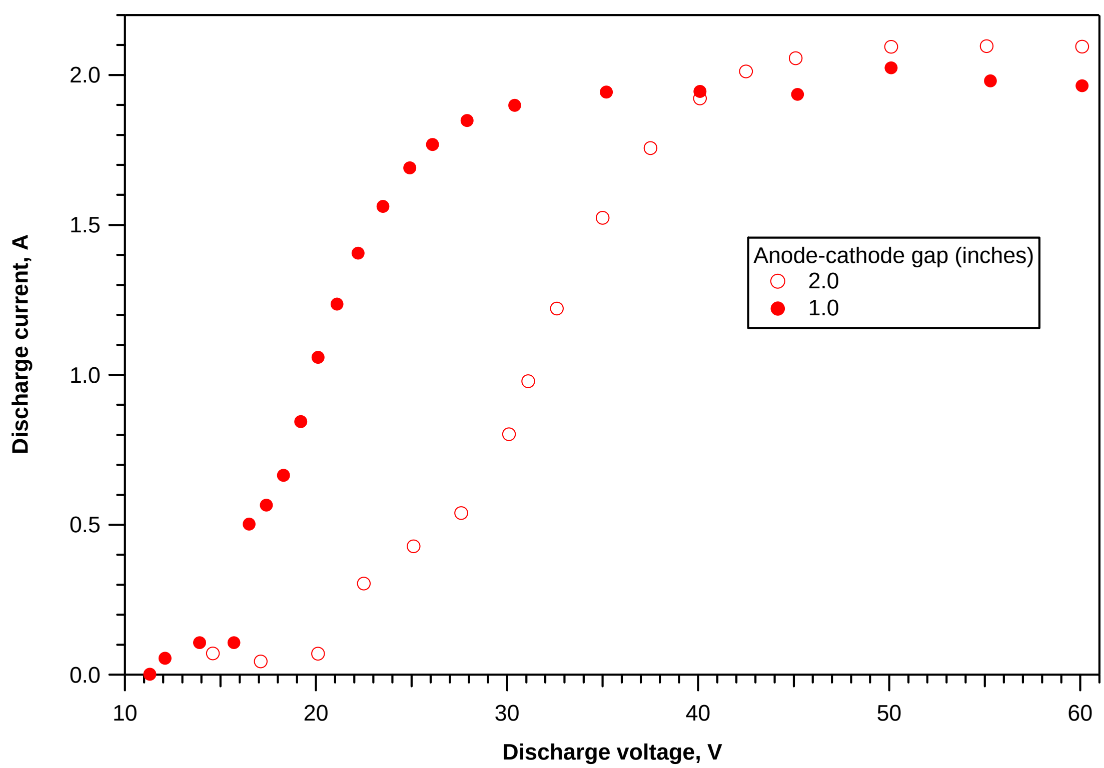


Figure 11. Effect of anode-cathode gap, 0.295 aperture with 0.50 enclosed keeper, 0.75 mg/s, keeper off.

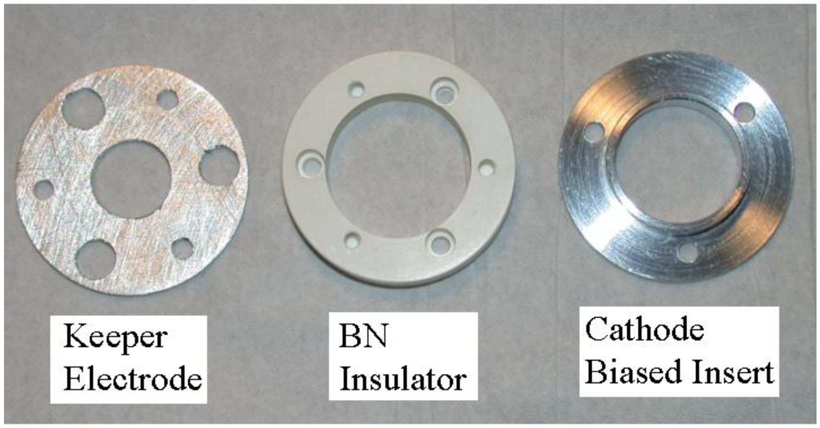


Figure 12. Parts for enclosed keeper with cathode biased insert.

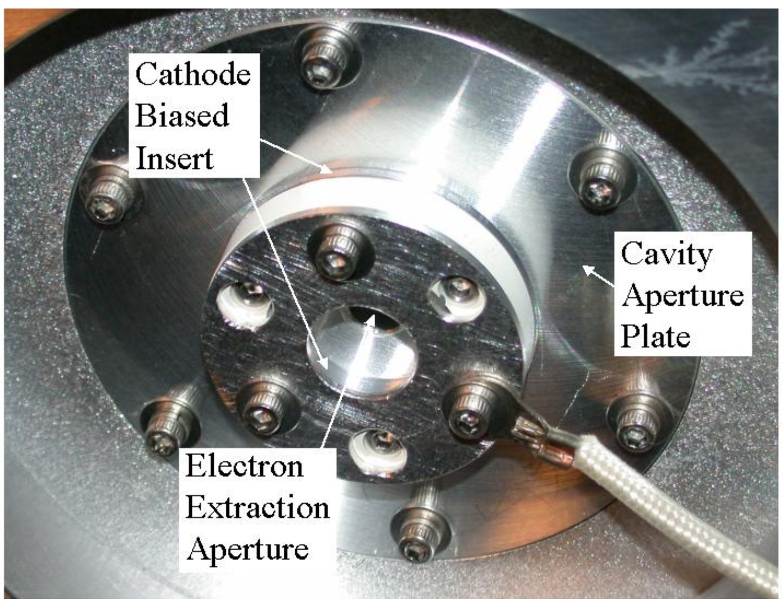


Figure 13. Enclosed keeper with cathode biased insert.