THEORETICAL DESIGN OF A GIGAWATT-LEVEL MPD PLASMA SOURCE FOR STUDIES OF MAGNETIC-NOZZLE CONFINEMENT IN FUSION PROPULSION SYSTEMS

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Abstract

Optimum travel duration for manned interplanetary missions requires propulsion systems that deliver very high thrust, [O(10^3 N)] in conjunction with specific impulse capabilities that exceed 10^4 sec. Theoretically, rocket propellants consisting of fusion reactants intermixed with large masses of hydrogen can be expanded within a magnetic nozzle to meet these requirements. The power levels associated with such systems are attainable by a gigawatt pulser called Godzilla which is adapted for experimental development. The megajoule-level energy available is electromagnetically deposited in cold helium gas to simulate the fusion-heated propellant. The MHD computer code, MACH2 is employed to provide guidelines in the design of this magnetoplasmadynamic (MPD) plasma source. These directions include specifications of the geometric configuration and operating conditions within experimental limitations.

Introduction

The reduced transfer times required for human expeditions within our Solar System demand high thrust-to-weight, high specific impulse propulsion systems. Optimum exhaust velocities for nearly straight trajectories range from 200 km/s to 500 km/s.[1] At present the leading concept that can meet such specifications is thermonuclear fusion power.

Temperatures in neutron-free, fusion systems exceed values for "conventional" D-T fusion concepts by factors of about five (~100 keV vs 10-20 keV). Plasma particles from a D-He^3 fusion reactor would have an average speed of 3000 km/s. Even though these velocities are much higher than the optimum values for fast interplanetary travel, fusion reactants can still be utilized to heat a much larger mass of hydrogen plasma to stagnation temperatures of ~100 eV. This propellant can then be expanded through a magnetic nozzle to provide the optimum speeds.

A gigawatt-level facility at the Ohio State University called Godzilla[2] can provide the necessary energy and power levels to emulate the aforementioned conditions. Godzilla provides 1.8 MJ over a time of 1.8 msec with a maximum current of approximately 0.3 MA. Deposition of this energy in a high density propellant can accelerate it to speeds exceeding 100 km/s. When stagnated within a magnetic "cusp" configuration, this flow will attain temperatures on the order of 100 eV. To create such a high current, magnetoplasmadynamic (MPD) plasma source, we plan to rearrange an existing inverse-pinch switching system[3] used on Godzilla.

The present paper discusses the latest efforts in designing the plasma source, which is fundamentally equivalent to a high power MPD thruster. The challenges associated with such power levels call for rigorous and detailed theoretical design. For this, we have utilized one of the most sophisticated magnetohydrodynamic (MHD) numerical tools currently available.

Inverse-Pinch Switch

Modifications to the inverse-pinch switch that is used to deliver current to the load will provide the desired MPD plasma source arrangement . In its original configuration (see Figure 1), the single output-switch consists of two copper rings, 35.6 cm inner diameter, 1.25 cm thick, separated by an axial gap of 3.2 cm, initially in a vacuum typically of 1-2 mtorr. The ring

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electrodes are held apart by a 10.2 cm long, 28 cm diameter, stepped-conical, insulator.

Gas is delivered from the region interior to the rings by breaking the diaphragm of a shock-tube reservoir. The volume of the reservoir is sufficient to supply gas to the switch during the 1.8 msec current pulse. Addition of gas to the interelectrode region allows the breakdown voltage to drop below the applied voltage. A series of tests[3] has confirmed that voltage hold-off is maintained during charging times (several minutes), with the desired breakdown occurring upon arrival of the high-pressure gas. Current flow interacts with the induced azimuthal magnetic field to create an electromagnetic force on the plasma discharge that is radially outward, i.e an inverse pinch. Gas flow to the discharge region continues to supply new conducting material, so the discharge location does not change. Plasma is accelerated through this region in a quasi-steady fashion, similar to a MPD thruster at high current.

Since the fundamental hardware to provide such type of acceleration is already functional, it is perceived that relatively basic re-arrangements - mainly geometric - can direct the high-speed exhaust gas toward a stagnation chamber. Confinement of such high-temperature stagnated gas can not be provided by solid matter, rather proper placement of magnetic coils will produce confining poloidal magnetic fields in a cusped arrangement. However, potential limitations and compromises associated with such high energies require careful and precise design.

Numerical Simulations

The need for accurate design motivates the present effort toward the numerical simulation of the MPD plasma source, using the state-of-the-art, unsteady, 2½-dimensional, non-ideal magnetohydrodynamic (MHD) code, MACH2.[4] The objectives include exploration of the possibility of designing the equivalent of a MPD thruster that produces speeds of 100 km/s within the geometric constraints of the existing inverse-pinch switch and the hazards associated with gigawatt power levels. Preliminary analysis challenged the theory to produce a configuration that can protect insulating material from the current discharge in terms of radiation and heat conduction. In addition, electrode erosion presents itself as a significant factor in altering the desired performance.

Modeling capitalizes on the diverse capabilities of the code, including thermal non-equilibrium and real equations of state for the helium gas. The geometric design (Figure 2) requires a narrow opening prescribed by the inner and outer electrode radii. Such a configuration would initiate the current breakdown at that location defining the accelerating region. Approximate calculations constrain the possible flexibility of the gap's size to the natural logarithm of the radii ratio for a fixed mass flow rate and current level. One of the earlier benefits of the accurate calculation was to show that this flexibility is even more limited. Expected improvements in the exhaust speed that exceed a factor of 1.5 from increasing the gap by only 1-2 cm were shown by the simulations to be greatly diminished (<10%) due to variations of the current distribution.

The location of the discharge with respect to the insulating material is of great importance as well. It is obviously imperative to confine the discharge at that location and shield the insulators from excessive heat transfer. Numerical simulations were set up to address the issue by introducing a uniform helium mass flow (Figure 2) into a vacuum chamber. Exhaust speed requirements restricted the room-temperature density inflow to $O(10^{-5})$ kg/m^3 for inlet speeds not exceeding 2 km/s. The current level was set to a constant of 0.3 MA to investigate steady state operation. This was proven to be an unsuccessful attempt. Even though the discharge could be easily initiated at the expected minimum area, MACH2 calculated an upstream evolution of the current distribution reaching the vicinity of the insulators. Thermal conduction was more than sufficient to heat the pre-existing gas emulating vacuum conditions (300K,10^{-7} kg/m^3). This in turn increased the electrical conductivity of this very low-density gas allowing current conduction well upstream of the desired location. Convection from the cold inflow was insufficient to contain plasma temperatures (exceeding 2 eV) away from the insulator. In addition, geometric variations could not adequately reduce radiative heat transfer by completely shielding the insulator from view of the discharge.

We recognized that a higher-density gas fill in the chamber prior to the breakdown would ameliorate the situation. The remedy presented a dual potential; decrease in the heat conduction rates balanced by convection away from the insulating surfaces, and shielding from radiation effects. Indeed, simulations with a chamber initial density of O(10^{-5} kg/m^3) proved to confine the discharge in the vicinity of the accelerating region at steady state. (See Figure 3.) This could be accomplished in conjunction with attaining the desired exhaust speeds as shown in Figure 4.

Even though heat conduction rates were greatly diminished they were not completely eliminated. MACH2 calculated that heating of the chamber-gas elevated temperatures in the vicinity of the insulating surfaces above 1000K. (See Figure 4.) Iterative simulations with varying operating conditions did not converge to temperatures that could be tolerated by most insulating materials. Based on this, design of the experimental setup will utilize high-temperature. ceramic insulating material, such as alumina.

Electrode Erosion

In our effort to examine the effects of electrode erosion we have taken advantage of the code's capability to perform multi-material calculations. As a first approximation new routines have been incorporated that model the erosion process in response to the current density distribution. Specifically, this can be accomplished by defining the mass flow rate of the ablating electrode material as

$$\dot{m} = m_c j \, A = \rho \, v \, A \,, \qquad (1)$$

where m_c is the mass loss per charge (kg/C), j is the current density and A is the area. In such manner we can calculate the eroding boundary's inlet speed, v in terms of a specified boundary density of the vaporizing material, ρ. At this stage the effort concentrated in properly developing the numerics within the multi-material scheme. For this, the copper electrode boundary conditions (see Figure 2) simulated a 2840K, 1.5×10^{-6} kg/m^3 vapor, ablating at 1 μg/C. The copper fluid introduced into the flow was also subject to the two-temperature, real-equation-of-state physics mixing with the helium gas under the influence of pressure and electromagnetic forces. (The fluid was modeled as inviscid.) The simulations have been successful with respect to the aforementioned goals. The two-dimensional distribution of the mass concentration fraction depicted in Figure 6 shows that the inner electrode is the main eroding electrode. The ablated material is mixing with the helium flow with part being accelerated downstream. (The legend in Figure 6 should be interpreted as follows: 1.000 = 100% He, 2.000 -> 100% Cu, e.g. B=1.1421 is equivalent to 14.21% Cu, 85.79% He.) Even under this preliminary model the importance of electrode erosion emerged. Interrogation of the pertinent variables has shown that electrode erosion affects the current distribution and subsequently exhaust speed magnitudes.

In our continuing effort to include a full model of electrode erosion, heat transfer to the interior will be taken into account. This will be properly addressed by enhancing our existing ablation model that has been utilized to calculate solid propellant mass loss in pulsed plasma microthrusters.[5] It provides mass loss rates in response to heat transfer to the solid which evaporates based on the material's vapor pressure curve. We plan to augment this ablation model to calculate mass loss based on electrode fall voltages. Cathode modeling will account for electron emission and ion bombardment. Heat transfer to the anode will be enhanced from electron current conduction.

Final Configuration

The series of iterative numerical simulations with the MACH2 code have resulted in a final configuration for the experimental design. Within experimental capabilities MACH2 indicates that the necessary high-power MPD thruster can operate properly. The geometric configuration will utilize a 1" accelerating gap defined by inner and outer electrode radii at the annular gap of 9" and 10", respectively. The distance between the outer electrode (and consequently the location of the discharge) and the vertical insulator is maximized at 4.4". The length of the vertical insulator will be 8" for the initial tests. Figure 7 depicts the geometric alterations to the original inverse-pinch configuration.

For this geometry, operating conditions will utilize a 3.5×10^{-5} kg/m^3 Helium propellant at a mass flow rate of 0.0127 kg/s (Figure 2). For this, currents of 0.3 MA will be confined to the accelerating region (Figure 3) providing the desired speeds of the order of 100 km/s and thrust values exceeding 1300 N (Figure 4). Heat conduction upstream of the accelerating region results in maximum temperatures in the local gas that do not exceed 1700K (Figure 5) a value that should be tolerated by the alumina insulating material.

Conclusions

The theoretical design of a high power MPD plasma source was successfully undertaken by utilizing the MHD computer code, MACH2. Numerical simulations have identified numerous obstacles, but in turn provided avenues to overcome them. The process of upgrading MACH2 to perform electrode erosion calculations has been initiated. In summary, theory suggests that operation of a MPD plasma thruster capable of producing exhaust speeds exceeding 100 km/s is within our present capabilities. In addition, our detailed theoretical approach provides specific directions with respect to geometric configuration and operating conditions for experimental design.

Acknowledgments

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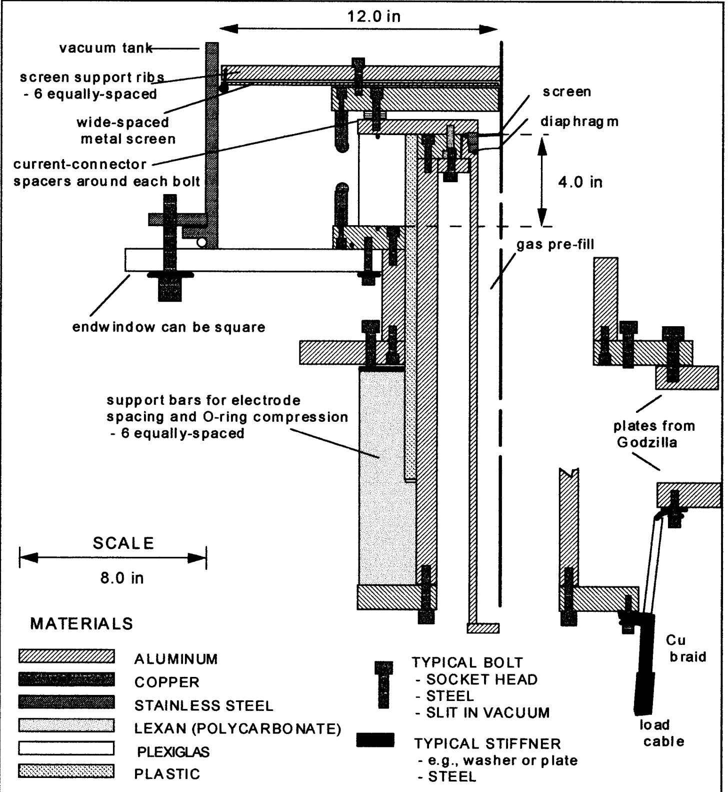


Figure 1. Schematic of the Inverse-pinch Closing Switch

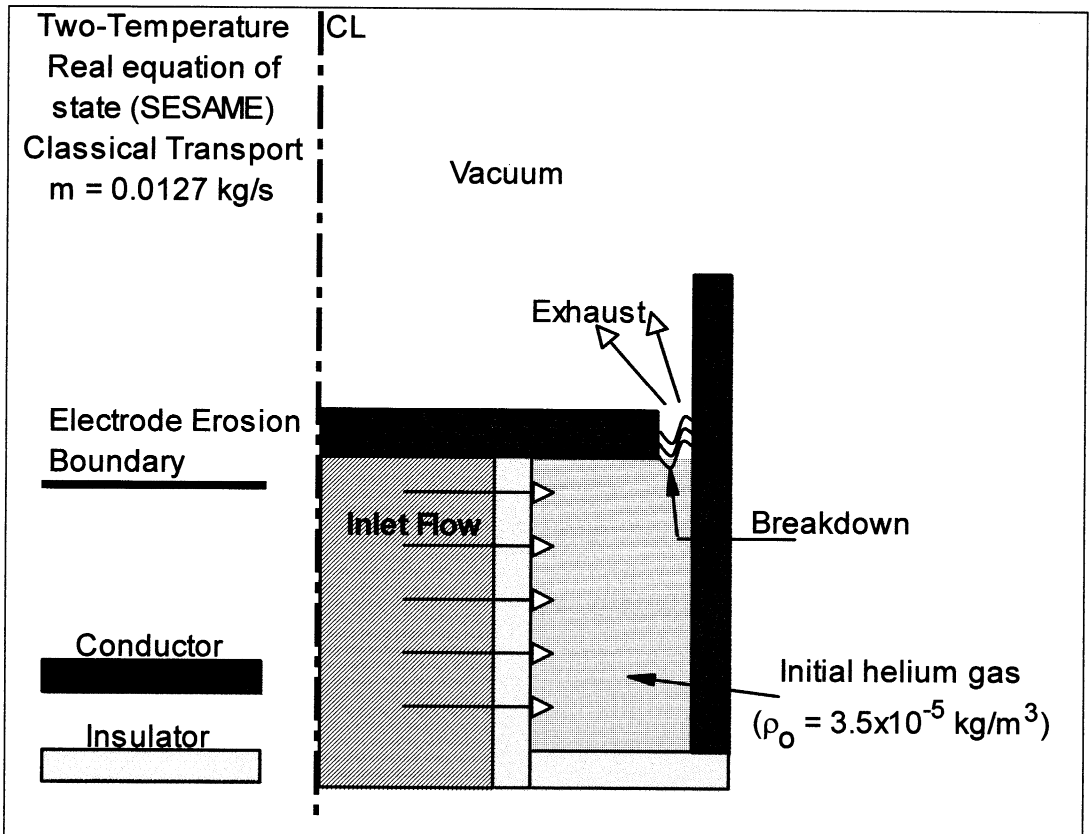
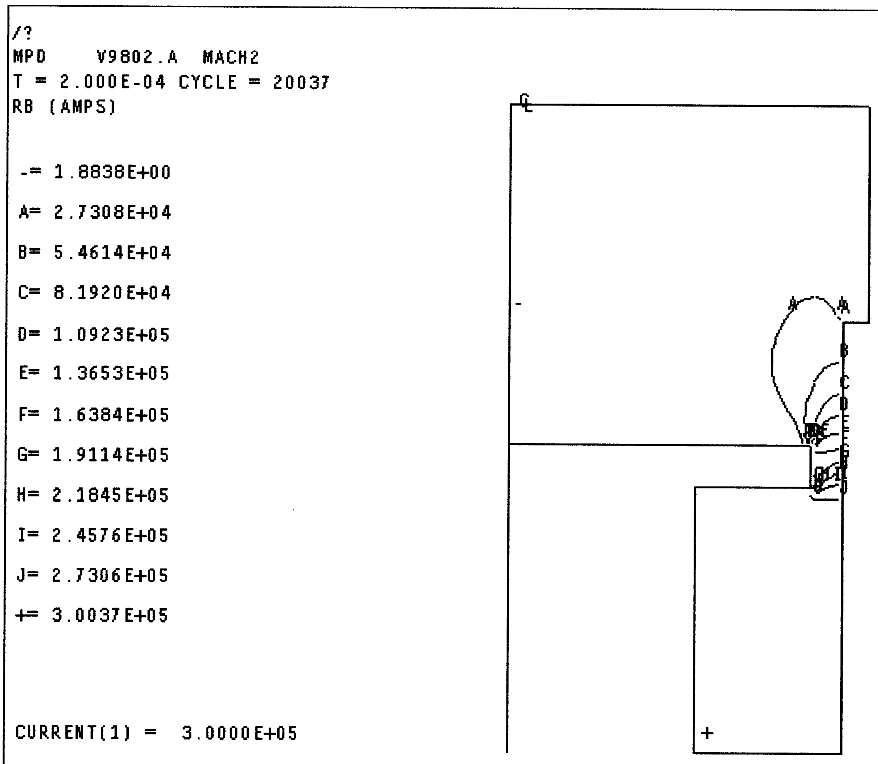


Figure 2. Schematic of the MACH2 simulation setup.



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/?
MPD    V9802.A  MACH2
T = 2.000E-04 CYCLE = 20037
RB (AMPS)

-= 1.8838E+00
A= 2.7308E+04
B= 5.4614E+04
C= 8.1920E+04
D= 1.0923E+05
E= 1.3653E+05
F= 1.6384E+05
G= 1.9114E+05
H= 2.1845E+05
I= 2.4576E+05
J= 2.7306E+05
+= 3.0037E+05

CURRENT(1) =  3.0000E+05
```

Figure 3. MACH2 computed steady-state current distribution.

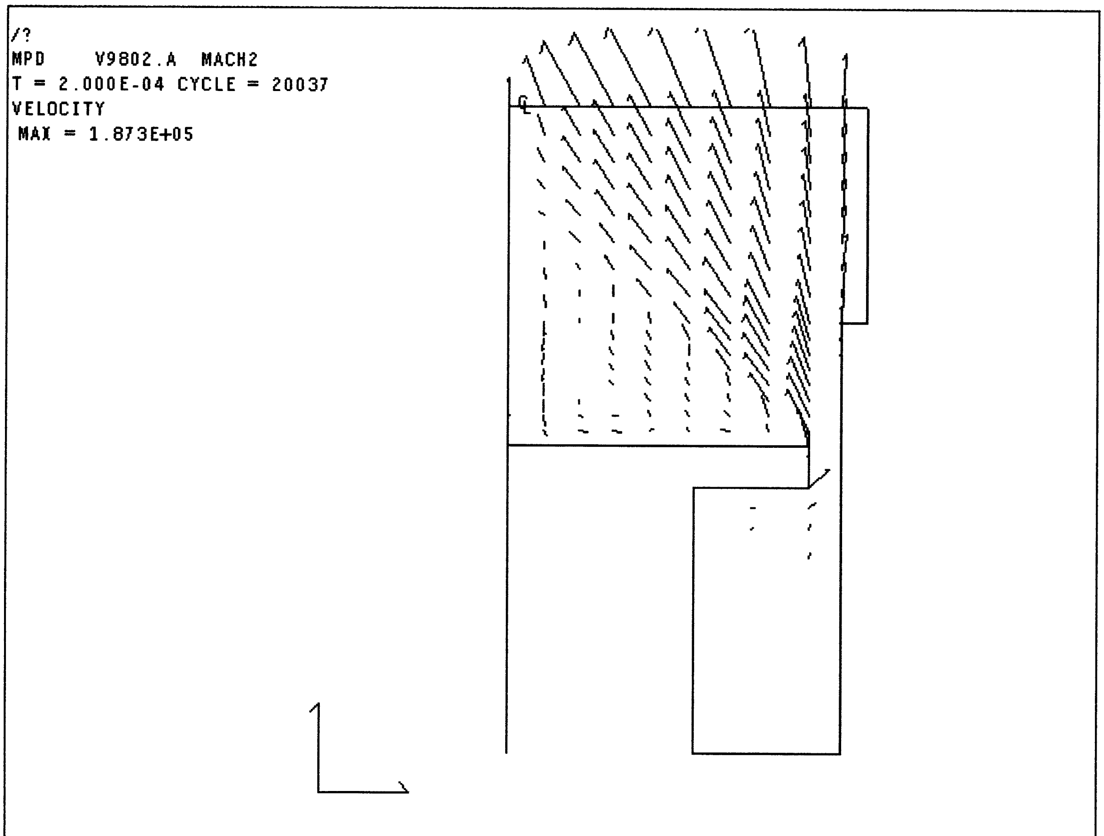

Figure 4. MACH2 computed steady-state velocity vector distribution (m/s)

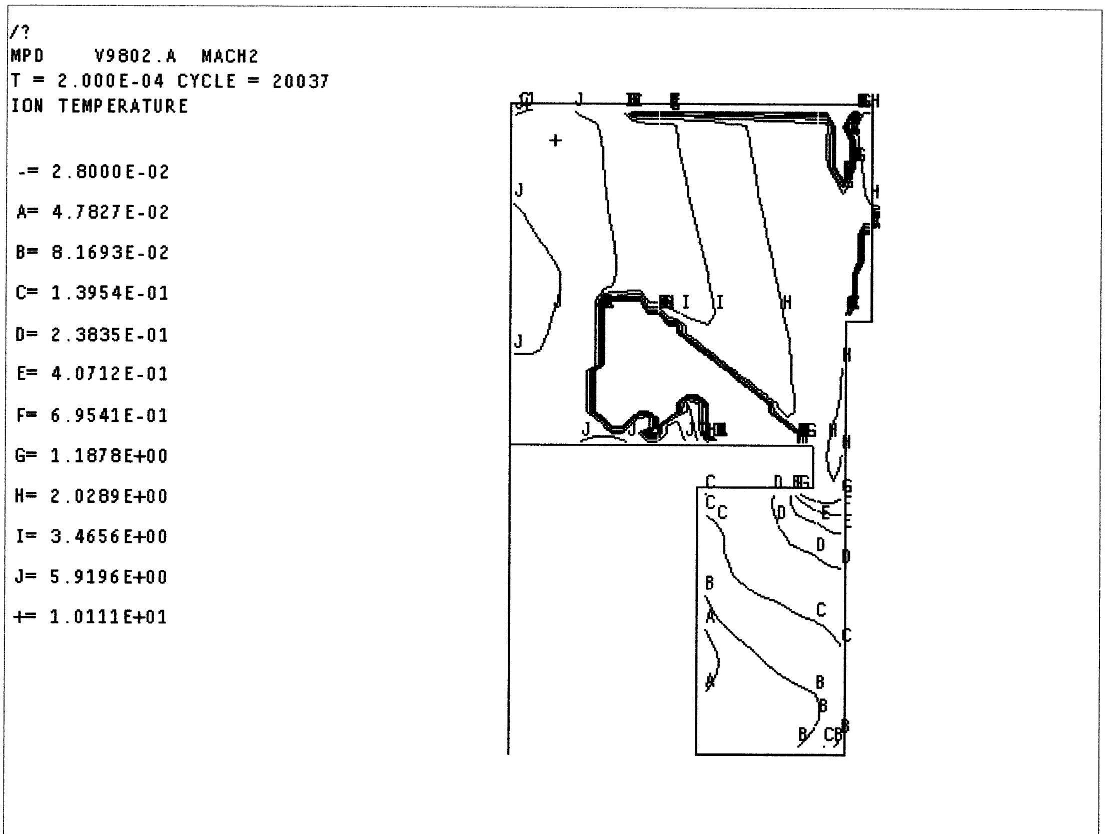

Figure 5. MACH2 computed steady-state ion temperature distribution (eV).

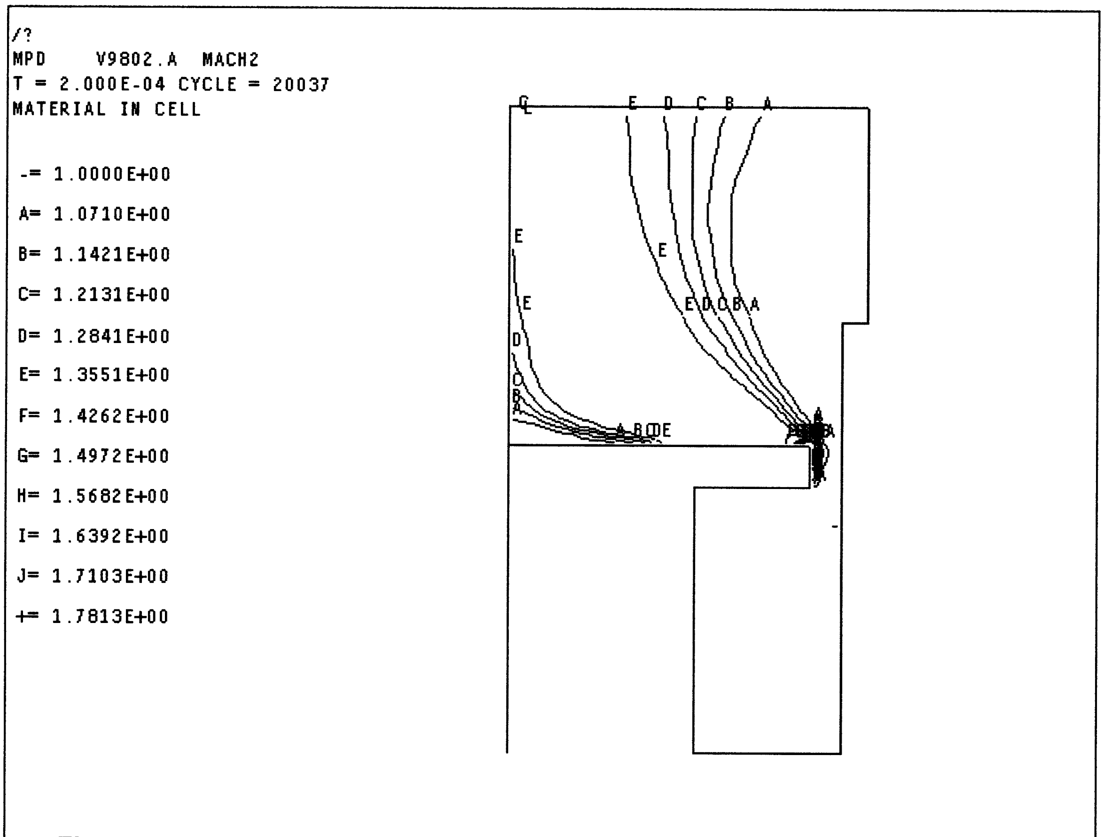

Figure 6. MACH2 Copper Mass Concentration distribution from electrode erosion.

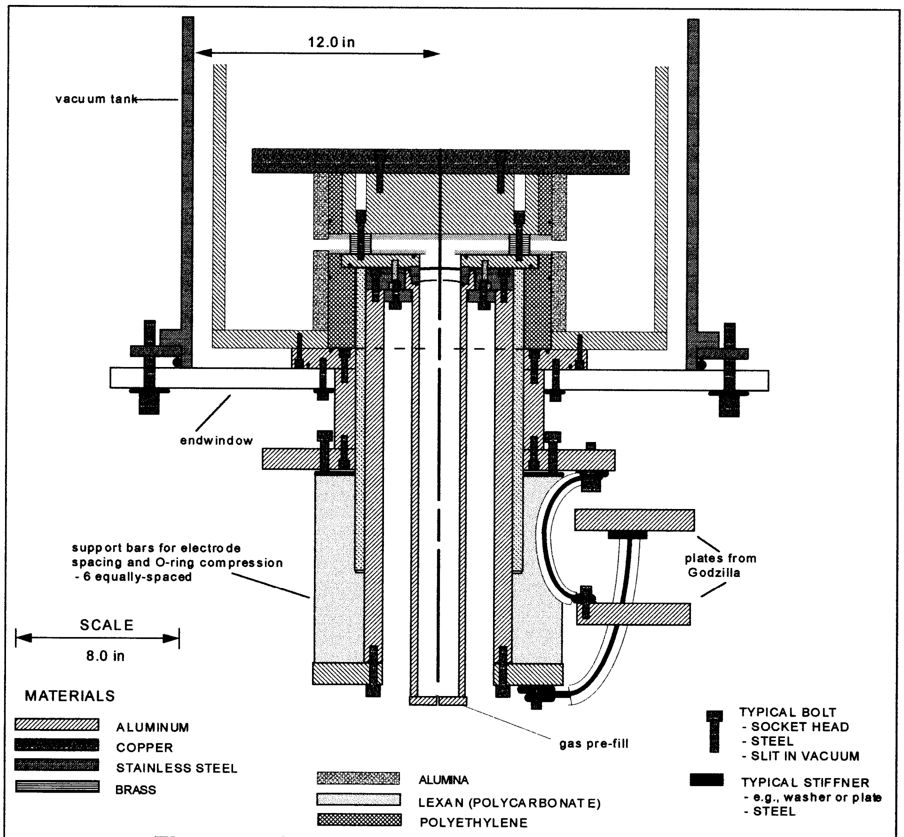

Figure 7. Schematic of the MPD Plasma Source