Parameterization of the Laboratory Performance of the Mini-Magnetospheric Plasma Propulsion (M2P2) Prototype*†

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The Mini-Magnetospheric Plasma Propulsion (M2P2) Prototype seeks the creation of a magnetic wall or bubble (i.e. a magnetosphere) attached to a spacecraft that will intercept the solar wind and thereby provide a high-speed propulsion system with little expenditure and efficient use of propellant. To accomplish this task, plasma is injected onto the field lines of a dipole magnet and when the plasma pressure becomes greater than the magnetic energy density of the dipole an outward expansion or inflation of the mini-magnetosphere will occur. A prototype for testing the magnetic inflation and necessary plasma parameters has been built and tested at the University of Washington. For M2P2 to work it will require a plasma source capable or producing moderate plasma density (10^{18} m^{-3}) with electron temperatures on the order of a few electron volts. A helicon plasma source was chosen because in other laboratory applications it appears sufficient to generate the necessary plasma parameters and is capable of continuous or pulsed operation with 1-2 kilowatts of power consumption. Characterization of plasma parameters in the dipole geometry, where the plasma is injected along the field lines, while maintaining a low neutral gas pressure outside the dipole has been conducted. Plasma densities are found to be similar to other helicon sources with a possible increase in electron temperature at the source region. The helicon source is able to produce a high beta plasma in the dipole equator, expanding the dipole magnetic field. The magnetic field perturbation from this expansion has been measured with magnetic field probes. The amplitude of the perturbation continues to grow even on long time scales as compared to the relevant plasma equilibration times.

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Introduction

Currently NASA's Space Science Enterprise Strategic Plan has proposed several missions to the outer planets to include the Pluto-Kuiper Express, Titan Explorer and Europa Lander. These missions are to begin within the next two decades and will require new technologies if the missions are to be completed in a cost effective manner. With conventional chemical propellant technology, conducting interplanetary and extra solar spacecraft missions is both costly and time consuming. For example, Voyager 1 which was launched in 1977, has not yet left the solar system. New and innovative propulsion concepts are needed to conduct exploratory missions to the outer planets and outside the solar system within reasonable time scales.

Several new systems utilizing plasma propulsion concepts have been proposed and are beginning to be utilized as a viable alternative to chemical propulsion. These systems take advantage of an efficiency gain over that of chemical propulsion by using high speed propellant, thus allowing for a significant reduction in fuel requirements that lowers launch costs dramatically. For ion or Hall thrusters the efficiency gain is realized because exit velocities can be many times that of conventional chemical propellants [1]. The move toward plasma propulsion can be seen from the recent use of the NSTAR ion thruster for the Deep Space 1 mission. Here the NSTAR ion thruster operated continuously for many months with a specific impulse gain of 10 over chemical propellant and with the total power usage for the thruster less that 2.5 kilowatts. Deep Space 1 was be able to provide approximately 20 months of continuous operation with a thrust on the order of 100 mN giving a ΔV of 1.5 km/s. Although the efficiency is greatly enhanced, the main problem with these systems is the limited amount of thrust that can be provided. This limits them to missions of low mass and long operation.

The proposed Mini-Magnetospheric Plasma Propulsion concept, while operating with similar power requirements as ion and Hall thrusters, may be able to couple with the ambient energy of the solar wind to provide enhanced thrust. Simulations conducted by Winglee, et al, predict thrust levels up to 1-3 Newtons with ultimate attainable speeds of 50-80 km/s [2]. This is a dramatic increase in capabilities and would allow for missions to the outer planets and extra solar missions using existing technologies. Coupling to the energy in solar wind particles is not a new idea and has been proposed previously through the use of magnetic sails. These sails incorporate very large superconducting magnets on the order of hundreds of kilometer in radius [3]. Here the large superconducting coils produce a large magnetic field that provides a barrier to the solar wind particles. When these particles encounter the barrier they transfer momentum to the magnetic field providing thrust to the system. The main problem with this scheme is in the manufacturing and launch costs associated with these very large magnets. The M2P2 concept overcomes this problem by using electromagnetic processes to produce a similar size magnetic barrier. The M2P2 prototype utilizes a conventional permanent or electro magnet and a plasma production device common in experimental and industrial applications.

To understand the electromagnetic inflation process and determine the relevant plasma properties, a M2P2 prototype has been built and is currently under investigation at the University of Washington. A half helical, m=1, helicon coil was chosen to provide plasma for the M2P2. Previous studies [4,5,6] of helicon plasma sources have shown that it can provide plasma temperatures and densities in the appropriate range for the magnetic inflation to take place as predicted by Winglee, et al.,(2000). Helicon plasmas are also able to produce plasma in steady state or pulsed modes while requiring only a few kilowatts of power allowing this device to be used with power levels consistent with current solar panel technologies. The viability of helicon sources for use in space propulsion is evident in other plasma propulsion concepts where they have been chosen to be the main source of plasma due to its high ionization efficiency [7]. This paper will discuss the design of the M2P2 prototype with the incorporation of the helicon plasma source in the dipole geometry. Experimental measurements of plasma parameters at the helicon source and the magnetic equator have been made. In addition, measurements of the magnetic field perturbations caused by the injection of plasma along the dipole field line are also shown.

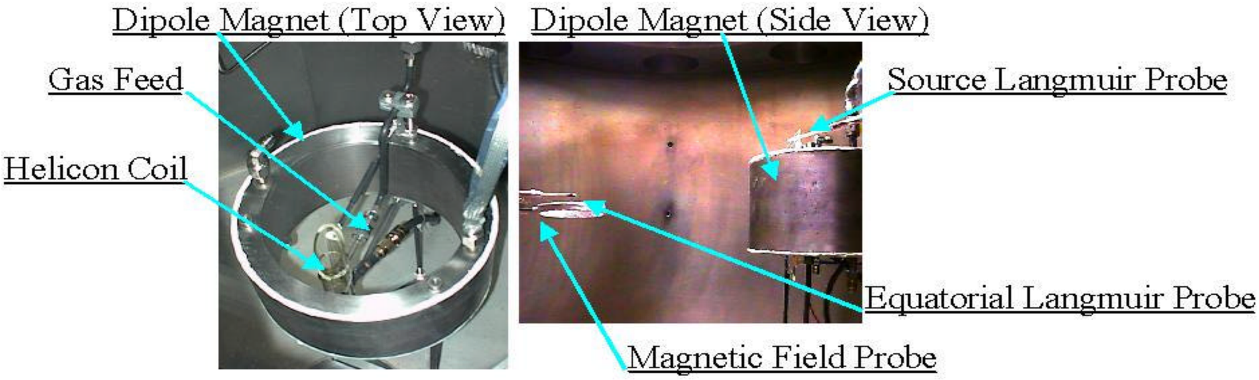

Figure 1. M2P2 Prototype in the 400 liter vacuum chamber at the University of Washington

M2P2 Prototype and Experimental Operation

Figure 1 shows the M2P2 prototype configuration in the 400 liter vacuum chamber at the University of Washington. The M2P2 prototype consists of a 20 cm diameter electromagnet that is used to produce a dipole-like magnetic field. The magnet is capable of producing a steady state 500-2000 gauss field at its center. The prototype is located inside a 400 liter cylindrical vacuum chamber. The vacuum system is capable of a base pressure of 10^{-7} Torr. During normal operation neutral gas is puffed into the source region, where it is ionized by the helicon source, maintaining a high vacuum outside the dipole magnet. This allows for space like conditions to be simulated in the chamber and reduces plasma interactions with background neutrals. Figure 2 shows the neutral chamber pressure as a function of time. The pressure was measured with a capacitive manometer.

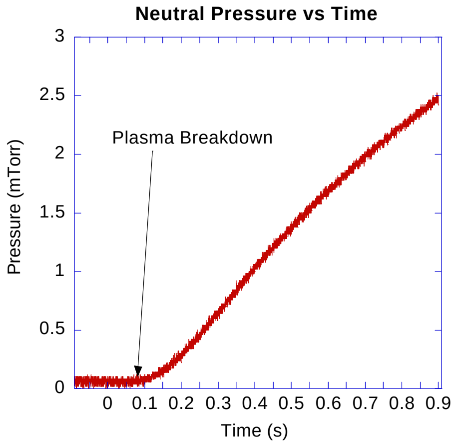

Figure 2. Chamber pressure as a function of time

For a typical plasma shot, breakdown occurs around 80-90 milliseconds after the puff valve is triggered. This delay is due in part to the puff valve solenoid response time and secondly to the neutral flow into the source region where the pressure must come up to the correct value in the Paschen relation for the initial plasma breakdown to occur. The derivative of the pressure profile in Figure 2 leads to an average mass flow rate of approximately 1.5 torr-liters per second or 118 SCCM. This mass flow rate of argon would be a steady state fuel consumption of 300 grams per day.

An estimate of the ion-neutral mean free path can be derived as a function of time from the data in Figure 2. A conservative estimate shows that ion mean free paths are on the order of the distance from the helicon source to the wall of the chamber up to 100 ms after plasma breakdown. That is the plasma essentially maintains a frozen in state on the dipole magnetic field during that time. This estimate assumes a low degree of ionization, while in practice helicon plasmas have been shown to be very efficient in ionizing neutrals [8,9]. Our data also suggest a high degree of ionization within the plasma column with losses due to neutrals playing a minimal role well beyond 100 ms.

To ionize the neutral gas and inject plasma along the dipole field, a half helical helicon coil in the style common to most experimental and industrial applications was chosen. [10,11]. The coil is wound around a 3 cm quartz tube and mounted to the dipole magnet with the coil off axis. The quartz tube protects the coil from the plasma and also contains a ¼ inch connecting tube through which neutral gas is injected directly into the source region. The neutral gas is ionized by the radio frequency excitation of the helicon coil using a 2.5 kW RF amplifier. The coil is matched to a 50 ohm amplifier impedance using a standard capacitive L matching network. Figure 3 shows the prototype in operation using argon. The outline of the equatorial Langmuir probe can be seen coming from the left and entering into the plasma column. Typical operational parameters for the prototype are 1.5 kW RF power at 12.5 or 13.56 MHz with shot lengths varying from one millisecond to several seconds.

Figure 3. Prototype operation in Argon (Side View)

Plasma densities and temperatures are measured at the helicon source and in the dipole equator by two asymmetric double Langmuir probes. Magnetic field perturbations are measured with a 150 turn coil located in the dipole equator. Both the equatorial Langmuir and magnetic probes can be positioned in the radial direction with respect to the dipole magnet axis.

3 cm Heilcon Source Characteristics

Typical helicon source applications use a cylindrical system with a uniform solenoidal magnetic field. The basic helicon dispersion relation assuming plane waves was developed by Boswell and is [12]

$$l \approx 5.6x10^{12}\left(\frac{B_o}{nf}\right)^{1/2}(m) \qquad (1)$$

This dispersion relation assumes a uniform steady state magnetic field in a cylindrical geometry. Equation (1) indicates that for a fixed frequency the plasma density will increase with B_0. There is some evidence that the final density and temperature is determined by the standing waves supported by conducting axial boundary conditions [13].

The geometry for the helicon plasma source in the M2P2 prototype is dramatically different than in most other helicon applications. The magnetic field is designed to be dipole like and is far from uniform, with no cylindrical symmetry. There is also no axial boundary in this system. These changes make modeling of this helicon system difficult and experimental investigation of the plasma source is required to determine its characteristics in the new configuration.

Figure 4 details the plasma density as a function of radial distance across the source.

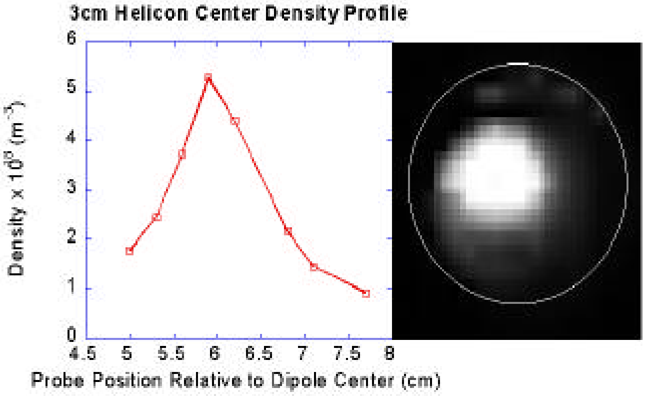

Figure 4. Source density profile with CCD image

It also shows an image of the plasma taken with a CCD camera looking down its axis. Density data was acquired with a RF compensated double Langmuir probe biased into ion saturation. Here a conservative estimate of 4 eV for the electron temperature was used to determine the density. Both the radial density profile and the plasma CCD image show the characteristic central peak produced by a helicon discharge [14]. Here the operational parameters are 1.5 kW RF forward power at 12.5 MHz and a dipole magnetic field of 500 gauss in the center of the dipole coil. The data is in good agreement with other helicon sources of this size. This suggests that the helicon coil is able to produce many wavelengths and couple into the strongest mode as the boundary conditions allow. This is very advantageous for the M2P2, because the boundary conditions change dramatically from dense plasma at the source with relatively high magnetic field strengths (~10^{18} m^{-3}, 500 G) to a low density plasma, at weak magnetic fields (~10^{10} m^{-3}, 10 G) within only a few helicon coil lengths. The helicon radial and temporal density profiles are summarized as a 3D contour plot in Figure 5. The helicon source region begins to produce plasma at peak density within several hundred microseconds and maintains a radial peaked profile for the duration of the shot. At approximately 150 milliseconds, the source region density is seen to decrease by a factor of two. This time scale is long when compared to any relevant plasma time scales and may be cause by two possible effects.

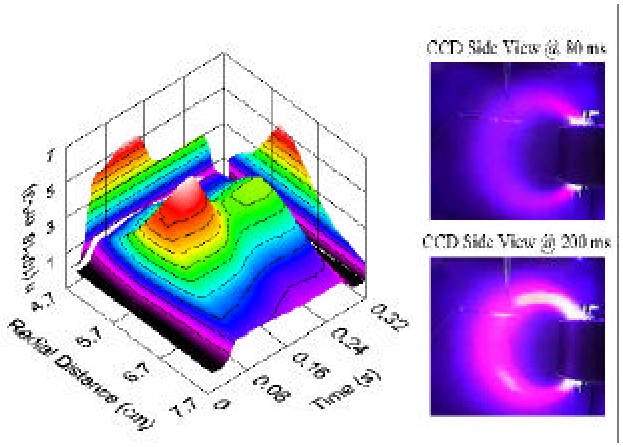

Figure 5. Helicon source radial and temporal density profiles, b. CCD side view of helicon mode change from m=0 to m=1

The first possible cause is the increasing neutral pressure in the chamber enhancing losses. The second cause for could be due to a mode change from the m=0 helicon mode to the m=1 mode. The m=0 mode has axially symmetric plasma production. The m=1 mode has a preferred location for peak plasma production downstream of the antenna in the axial direction. This mode change may be seen from the CCD camera images also shown in Figure 5. The picture at 80 ms shows symmetric plasma generated from the top and bottom of the coil along the axial direction. At 200 ms this has changed to a top preferred production which is in the m=1 direction. Since the Langmuir probe is located directly over the helicon antenna it may see this mode change as a decrease in density at its location.

Measurements of electron temperatures have also been made using a compensated swept Langmuir probe. This data shows the possibility of high electron temperatures for this geometry. Figure 6 is a plot of the electron temperature and density directly over the source as a function of time. Measurements of electron temperature using Langmuir probes are tentative at best, even more so with the addition of a large RF noise source very close to the probe. The swept probe was designed to reduce errors introduced from the RF source by the use of compensation in the style of Sudit and Chen [15]. Even with compensation, errors in electron temperature can still be present. However, it is reasonable to expect that the dipole geometry along with a very low neutral back ground pressure could lead to enhanced electron temperatures due to reduced loss mechanisms.

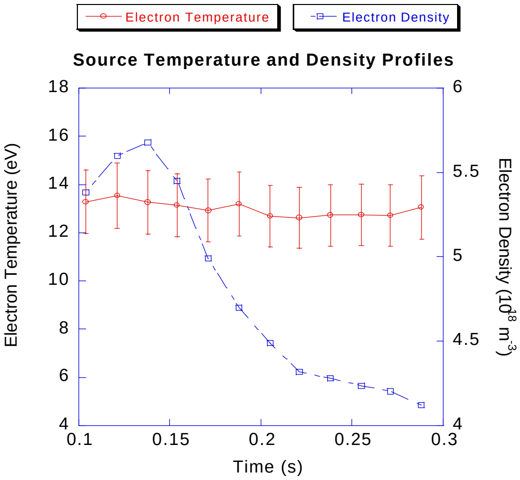

Figure 6. Helicon source electron temperature and density from compensated swept Langmuir probe

To verify this, shots were taken with a continuous backfill of 10 mtorr in the chamber, which is common in most helicon experiments. In this case the measured electron temperature was reduced to approximately 5 eV, which is typical of laboratory helicon. The possibility of increased electron temperatures for the M2P2 prototype indicates efficient power coupling from the helicon source. The dominant losses are due to collisions with neutrals and wall interactions, both of which have been reduced in the M2P2 dipole geometry.

Mini-Magnetoshere Equatorial Profiles

Plasma parameters outside the dipole magnet in the equatorial plane were also measured to determine the performance characteristics of the prototype. Figure 7 shows the plasma density as a function or radial distance from the dipole axis and a CCD image during operation. The radial Langmuir probe can be seen entering the plasma from the right side of the image. The equatorial Langmuir probe is similar in construction to the helicon source probe and could be positioned radially along the equator of the dipole.

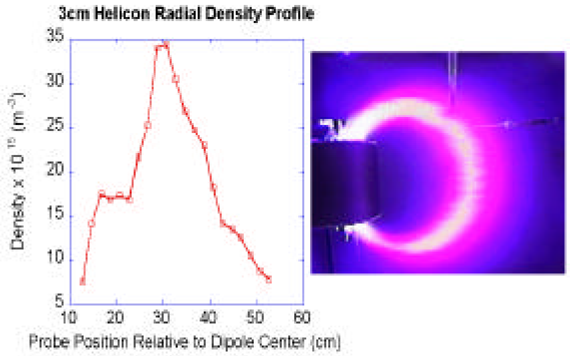

Figure 7. Radial Density Profile and CCD Image of operation showing radial Langmuir probe

For comparison, operational parameters for the M2P2 prototype are the same as in the previous section. From the data in figure 5, the plasma column retains a very peaked profile, which maps back to the helicon source. Peak densities on the order of 10^{10} to 10^{11} particles per cubic centimeter are produced at the equator. The most important feature in the data is that there is good confinement of the plasma even at low magnetic fields as the vacuum dipole magnetic field decreases as r^{-3}. Radial and temporal profiles of the equatorial plasma column are summarized in the 3D contour plot in Figure 8.

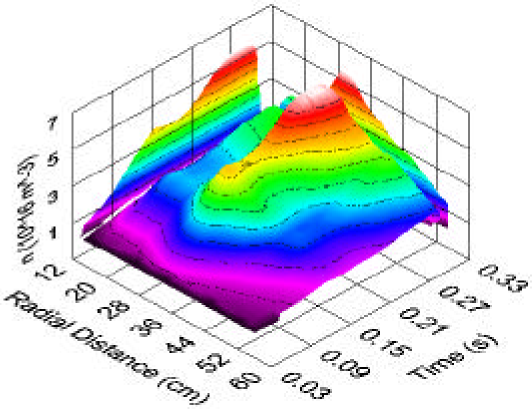

Figure 8. Equatorial radial and temporal density profiles

The figure shows that plasma density increasing in time corresponding to a filling of the flux tube that maps back into the dipole and source region. Additionally, the equatorial density continues to rise even as the source density falls by a factor of 2 around 120 ms. This is consistent with the possible mode change at the source as previously discussed. Plasma temperature and density profiles were also taken with a swept double Langmuir probe in the dipole equator. The density profiles show good agreement with the plasma density measured with the saturated probe with an estimated plasma temperature of 8 eV. Figure 9 contains data taken with the equatorial swept probe.

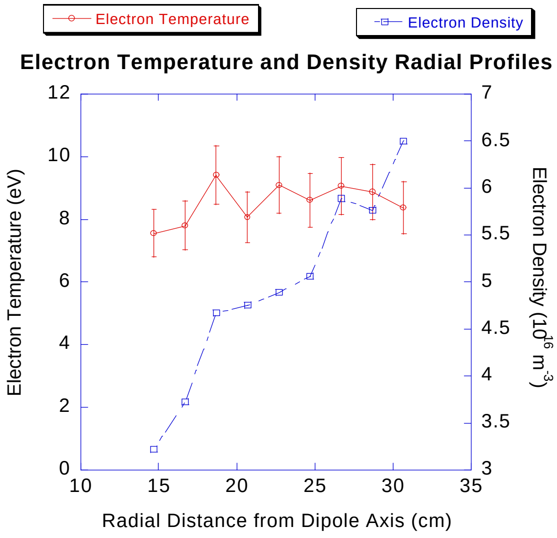

Figure 9. Electron temperature and density as a function of radial position.

The reduction of the electron temperature to 8 eV from the value of 13 eV measured at the helicon coil is consistent with an adiabatic expansion of the plasma as it moves outward along the field lines.

An estimate of M2P2s ability to confine the plasma in the equator can be made by looking at how the plasma density scales as a function of the vacuum magnetic field. Figure 10 is a plot of the ratio of the plasma density to vacuum dipole field strength as a function of the equatorial radial distance at three different times during the discharge. Classical scaling predicts that the plasma density should be proportional to the confining magnetic field strength. Data from figure 10 shows that early in the discharge n/B does maintain the classical scaling with approximately constant values from 30 to 60 cm. During the discharge the n/B ratio begins to increase maintaining proportionally only around 50 cm away from the dipole axis, then falling as the probe comes close to the vacuum chamber wall. The change in the n/B ratio may be indicative of a change in the vacuum magnetic field as the plasma pressure builds expanding the field beyond the original r^{-3} like falloff.

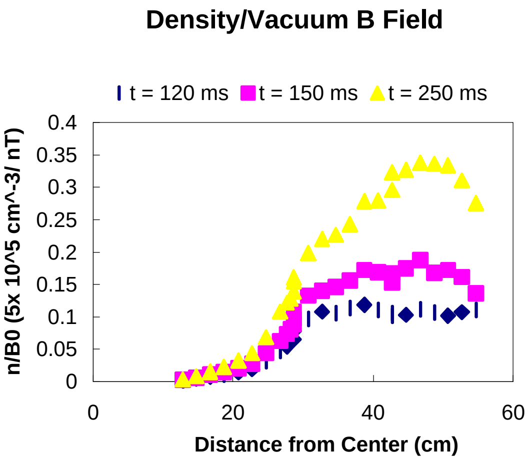

Figure 10. n/B vs Radial position

Plasma Produced Magnetic Field Perturbations

To verify a plasma-induced change in the vacuum dipole magnetic field a 150 turn differential coil was placed in the equator of the dipole. Modeling of the M2P2 prototype conducted by Winglee (et al) shows that there is an initial and rapid expansion of the magnetic field perturbation [16]. After the initial expansion there is a slower (millisecond) build up of the perturbation in time. Slow changes on the order of milliseconds of the low fields strengths (1 Gauss) in the dipole equator are difficult to measure. The RF noise environment caused by the helicon source increases this difficulty. The 150 turn differential coil was therefore designed to measure the initial fast change in the dipole magnetic field. Figure 11 contains data measured with the 150 turn coil and the helicon source density for one shot. The total shot duration in which the RF source was energized was one millisecond. It can be seen that the measured perturbation in the dipole equator is concurrent with the rise of the helicon source density. The perturbation is seen to oscillate and then to maintain a steady state level. Upon shut off of the helicon source, there is a rapid return to the vacuum dipole field level. The plasma density in the helicon source also shows evidence of the inflated field. The helicon shut down at 1 ms occurs very quickly as the power source has a nanosecond response time. The plasma begins to decay as is expected but as the expanded field returns to the steady state value, a rise in the density is seen at the helicon source.

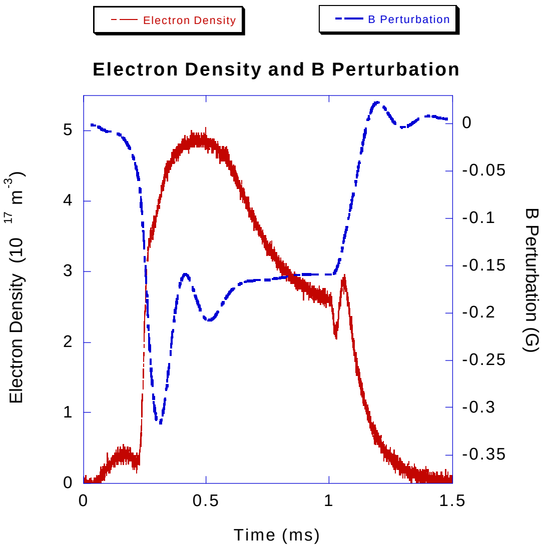

Figure 11. Helicon source density and equatorial magnetic perturbation

The rise in density may be representative of the energy stored in the inflated field being converted to plasma density due to conservation of the first adiabatic invariant. Heating of plasmas by the use of rapidly changing magnetic fields is common in many magnetic confinement fusion concepts. The maximum magnitude of the observed perturbation is around .3 gauss, which corresponds to the magnitude of the earth's field that provides the initial restoring force for the M2P2 to work against.

To study effects of the magnetic perturbation over longer time scales, the perturbation upon RF shut-down was measured. Data for the change in the perturbation for several shot lengths are summarized in figure 12. The magnitude of the perturbation continues to grow even on time scales long compared to the plasma equilibration times. Figure 13 shows a summary of the data in figure 12 as a plot of shot length vs the magnitude of the perturbation. It can be seen that the amplitude is continuing to grow as function of shot length and starts to approach a maximum around 1 second.

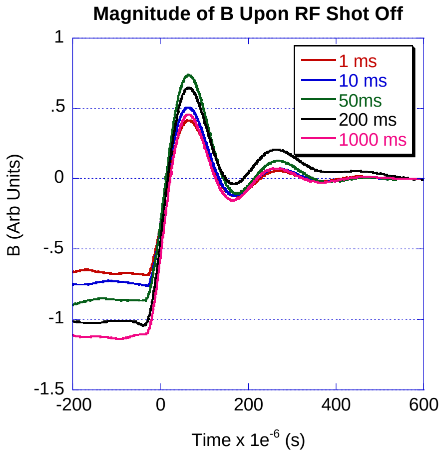

Figure 12. Magnetic perturbation for several shot lengths upon RF shut-down.

It should be noted that on second time scales the neutral pressure in the chamber is coming to a maximum value as shown earlier in figure 2. This implies that the M2P2 prototype is very efficient at ionizing the neutral gas and maintaining the plasma pressure required to hold the field in an expanded state even though losses due to neutral collisions and wall effects are beginning to play a large role.

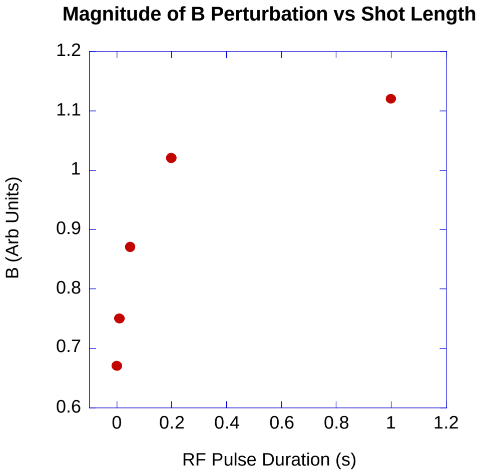

Figure 13. Amplitude of magnetic perturbation vs shot length.

Summary and Conclusions

The M2P2 prototype has been tested to determine its initial performance. The helicon plasma source was tested in the new dipole geometry. Plasma parameters were shown to correspond to those reported for other helicon sources of similar size, with a possible increase in electron temperature. The helicon source was also shown to efficiently ionize the neutral gas introduced into the helicon source and to maintain a well-confined plasma as it expanded radially outward from the dipole. Radial density profiles in the equator show an increase of the plasma density. The radial density profiles do not follow the classical scaling of density proportional to magnetic field strength and is seen as indicative of expanding magnetic field and excellent stability and confinement of plasma within the mini-magnetosphere. Finally, magnetic field perturbations corresponding to the plasma injection along the dipole magnetic field have been measured. The perturbations have magnitudes and time scales similar to those predicted from modeling of the prototype. The perturbations were found to rapidly expand the magnetic field and continue to grow on second time scales. Upon shut-down of the plasma source and the return of the field to the original dipole configuration an increase in plasma density was seen at the helicon source indicating a heating of the plasma by the stored energy of the inflated field.

The results presented above show that the M2P2 prototype is able to produce a high density plasma in the dipole geometry with a low neutral background pressure. The helicon source is able to produce and maintain plasma parameters on the order of those predicted to cause inflation of the magnetic field. Magnetic field perturbations measured in the equator of the dipole indicate a radial field expansion that can be maintained even as the loss rate for plasma is increased due to the increasing neutral background pressure.

Acknowledgments

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