SIMULATION OF MINI-MAGNETOSPHERIC PLASMA PROPULSION (M2P2) INTERACTING WITH AN EXTERNAL PLASMA WIND

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ABSTRACT

Substantial progress has been made over the last year in the development of the laboratory Mini-Magnetospheric Plasma Propulsion (M2P2) prototype. The laboratory testing has shown that that the plasma can be produced at high neutral gas efficiency, at high temperatures (a few tens of eV) with excellent confinement up to the point where chamber wall interactions dominate the physics. This paper investigates the performance of the prototype as it is opposed by an external plasma acting as a surrogate for the solar wind. The experiments were performed in 5ft diameter by 6ft long vacuum chamber at the University of Washington. The solar wind source comprised of a 33 kWe arc jet attached to a 200 kWe inductively generated plasma source. The dual plasma sources allow the interaction to be studied for different power levels, shot duration and production method. It is shown that plasma from the solar wind source (SWS) is able to penetrate the field of the M2P2 magnetic when no plasma is present. With operation of the M2P2 plasma source at only 1.5 kWe, the penetration of the SWS even at the highest power of operation at 200 kWe is stopped. This deflection is shown to be greatly enhanced over that produced by the magnet alone. In addition it is shown that with the presence of the SWS, M2P2 is able to produce enhanced magnetized plasma production out to at least 10 magnet radii where the field strength is only marginally greater than the terrestrial field. The results are consistent with the initial predictions that kWe M2P2 systems would be able to deflect several hundred kWe plasma winds to produce enhanced propulsion for a spacecraft.

INTRODUCTION

Mini-Magnetospheric Plasma Propulsion (M2P2) [1] seeks to create a mini-magnetosphere or magnetic bubble around the spacecraft and to use the deflection of the ambient plasma to attain energy/momentum to increase the total efficiency and thrust of the system. For example, the solar wind, traveling at 400 to 800 km/s, can provide a limitless source of keV particles to provide high specific impulse propulsion. The main problem in trying to couple to the solar wind is that the solar wind has a low density (~ 6 cm^{-3}) and therefore that interaction/deflection region has to have a size of the order of a few tens of km before a thrust of a few N can be attained. The problem is akin to that of solar sails where the momentum from photons is small (albeit larger than the solar wind momentum flux) and reflecting areas of a few million m^2 are be required to provide N thrust levels. However, solar sails require the mechanical deployment of ultra thin material over large distances and the technical problems involved have yet to be solved. The advantage of the M2P2 system is that the deployment is done by electromagnetic processes and as such does not require the deployment of any large mechanical structures.

M2P2 is able to achieve this electromagnetic deployment due to the fact that when a collisionless plasma is created in a magnetic field, that magnetic field is frozen into the plasma so that as the plasma expands the magnetic field is carried out with it. This transport of magnetic flux can be achieved with low energy plasma and the inertia of the plasma will enable it to expand a few tens of km before being swept downstream by the solar wind. Because only low energy plasma is utilized, the power requirement for the spacecraft is only a few kW [1]. The corresponding mini-magnetosphere will intercept nearly a MW of solar wind energy (some of which produces secondary heating of the plasma of the M2P2) and a thrust of a few N. With this level of thrust a small spacecraft can attain speeds of the order of 50 km/s for little more about 1 kg/day propellant consumption over an acceleration period of about 3 months. Descriptions of the prototype's operational characteristics have been presented in several articles [2-6] and show that the desired operating plasma/magnetic regime can be in fact achieved.

In this paper, laboratory results are presented in the first quantitative treatment of the ability of M2P2 to deflect an external plasma wind that carries a substantially higher energy flux than M2P2 by itself. While the separation between the two sources that can be accommodated in the available chamber is small at only about 1 m, it should be noted that all simulations to indicate that mini-magnetosphere will compress in a self-similar fashion to maintain an almost constant force on it [1]. In addition, if the solar wind source (SWS) can potentially destabilized M2P2 it is most likely to occur when the SWS is close to M2P2 where it energy density is largest. So while these experiments are not exactly representative of space conditions, they are indicative of what be expected from a small magnetized plasma system being able to absorb energy and/or deflect an external wind. Thus, the results are very pertinent to one of the primary objectives of M2P2.

In the next section we give a brief description of the experimental set up, including the setup of M2P2 and the SWS. Following this section we then present Langmuir probe results at the boundary layer well away from M2P2 at nearly 10 magnetic radii distance, where the magnetic field strength is comparable to the terrestrial field strength. The boundary layer measurements show enhanced plasma production at these very large distances. This enhanced plasma production is indicative that M2P2 is able to absorb free energy from the SWS. Results for interior measurements at full power on the SWS are then presented and show deep penetration of plasma if the M2P2 magnet is on without any plasma source. With M2P2 plasma on this penetration of plasma is seen to be essentially stopped for moderate field strengths. A summary of results is given at the end of this paper.

EXPERIMENTAL SETUP

The experimental configuration is shown in Figure 1. 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 5ft diameter by 6 ft long 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, consisting of a 3 cm quartz tube within the magnet where the neutrals are ionized by the helicon source. In the following the rf power into the helicon is 1.5 kWe.

The SWS is placed at the other end of the chamber. In order to accommodate a variety of different experiments at different time scales and power levels, a dual system was developed. This system consisted of an ignitor arc capable of producing a 33 kWe discharge in about 50 μs. This system was placed behind a inductively coupled plasma source that could provide plasma at 200 kWe over time scales of about 1 ms. A small magnet (maximum field strength of 200 G) over the latter source was used to focus or defocus the SWS plasma onto the M2P2 system.

A Langmuir probe was placed over the M2P2 source to monitor its performance. In addition, to this Langmuir probe a second probe was placed in the middle of the chamber. This paper concentrates on the data from this latter probe. The design of the probe allowed it to be swung near the exit of the SWS source or into the interior of the mini-magnetosphere. This enables either boundary layer/SWS source measurements or penetration measurement to be made. In order to identify the different plasma M2P2 was usually run using Xenon (blue-green emissions) and SWS used argon (blue emissions). The SWS source in argon can produce density of ~5×10^{19} m^{-3} at temperatures of 10 – 20 eV.

Boundary Layer Measurements

As a first step we investigate the response of M2P2 with the SWS using only the ignitor running. The experimental configuration is pictured in Figure 2. Because of the large

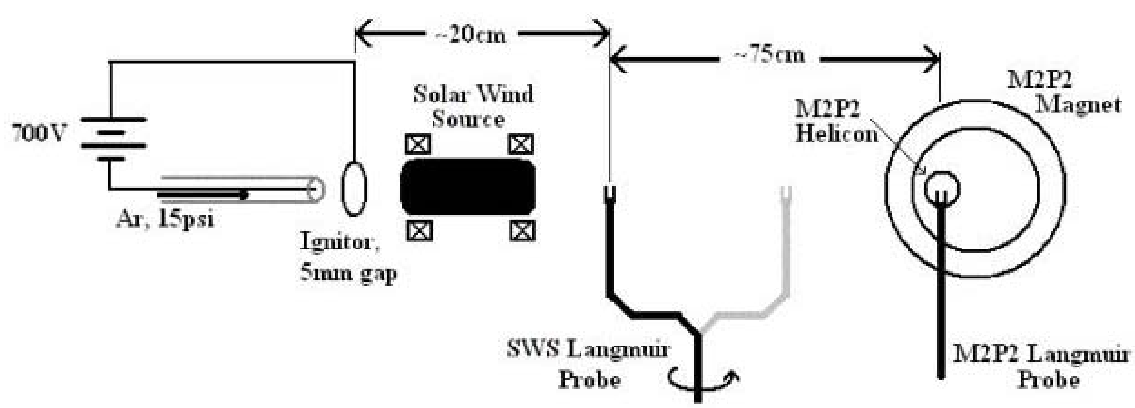

Figure 1. Schematic of chamber configuration of the M2P2/SWS experiments showing relative position of source and Langmuir probes.

distance to the Langmuir probe relative to the magnet radius, the vacuum magnetic field at the Langmuir probe is essentially at terrestrial values for the shots considered here.

In order to see the plasma perturbations produced by the interaction of the two systems, we first identified the plasma profile attain with the SWS source (ignitor only) and the M2P2 magnet on but no plasma from M2P2. The plasma profile attained in this configuration is shown in Figure 3a with the M2P2 magnet set at a fairly low value of 0.4 kG (as measured in throat of the magnet – the outside field strength at the equator is about 1/16 of this value). The ignitor provides a very sharply definite pulse of about 50 μs and produces a peak density of about $1.5 \times 10^{18}\ m^{-3}$ at the probe.

In order to see the effect of the SWS on M2P2 we then run M2P2 for 2 ms and during that period when it is in approximate steady state, SWS was fired. The corresponding density profile is shown in Figure 3b. Prior to the firing of SWS it is seen that M2P2 is able to maintain density of the order of $10^{18}\ m^{-3}$. As noted in [6] the temperatures in this region are of order of 10 eV so that M2P2 is able to achieve one of its objectives in creating an extended high β plasma. It is seen that the firing of SWS leads to even higher densities. The most surprising features is that this enhanced density is present on times scales very much longer than the SWS pulse itself.

The change in the SWS profile due to the interaction with M2P2 is more clearly illustrated in Figure 3c where the SWS only profile is overlaid with the change in density seen while both SWS and M2P2 were operating. It is seen in this overlay that about half the original pulse of SWS is prevent from entering the area. In other words there is about 50% deflection of plasma produced by M2P2 and this deflection cannot be attributed to the magnet alone. In addition, and of equal importance is that there is elevated plasma density for ~250 μs after the shutoff of the SWS. This time scale is a factor of about 5 longer than the original pulse. This means that energy is being taken from SWS and is being utilized by M2P2 to enhance plasma production at very extended distances (1.2 m) from the source. This time scale is of order of the confinement time for M2P2. At the distance from the magnet, the confinement time is mainly set by wall interactions [7].

Figure 4 shows the results for the same configuration but with the field strength on the M2P2 magnet increased by a factor of 2.5 to 1.0 kG. The increase in the field strength does produce some deflection of the SWS pulse, as seen by the lower peak amplitude in Figure 4a relative to Figure 3a. The deflection of the SWS pulse by M2P2 appears relative weak in that there is only about a 20% reduction in the SWS pulse height when M2P2 is operating. This lack of deflection is attributed to the fact that M2P2 has a finite response and in fact at the end of the SWS pulse is amplitude is actually reduced by 50%.

The other way that one can tell that M2P2 with the increased field strength is operating better is that, in comparing the density profiles in Figures 3c and 4c, the density remains enhanced over a longer period to about 400 μs. These results are important as they provide some of the first quantitative evidence for M2P2 ability to absorb energy

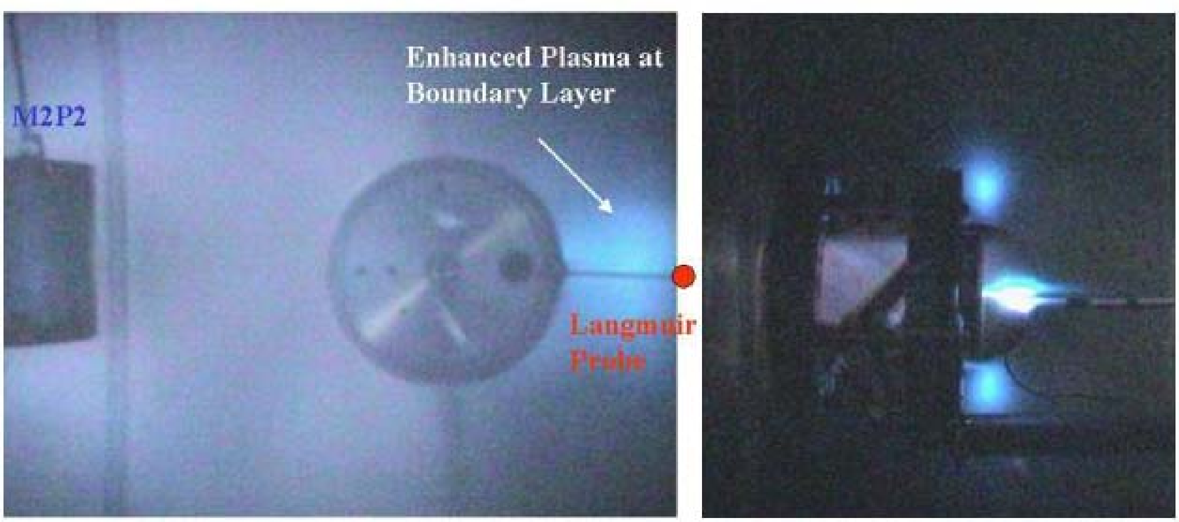

Figure 2. Photographs of the boundary layer configuration. M2P2 (left) and SWS (right) have a separation of about 1.2 m with the middle Langmuir probe about 1 m from the center of the M2P2 magnet. The ignitor discharge is seen on the left, with the two optical emissions above and below being reflections off the back wall. Enhanced optical emission due to the interaction of the two systems is seen in the vicinity of the Langmuir probe.

from an external source, which is one of the primary goals of M2P2.

Superposed on the increased density are coherent oscillations with a period of about 35 μs. There is also some suggestion of oscillations in the lower field strength shots with a period of about 50 μs but the statistics are poorer in the latter case. These oscillations represent ringing of the mini-magnetosphere from the impulse provide by SWS. This ring is important as it indicates that M2P2 is actually coherently/magnetized at large distances from the magnet.

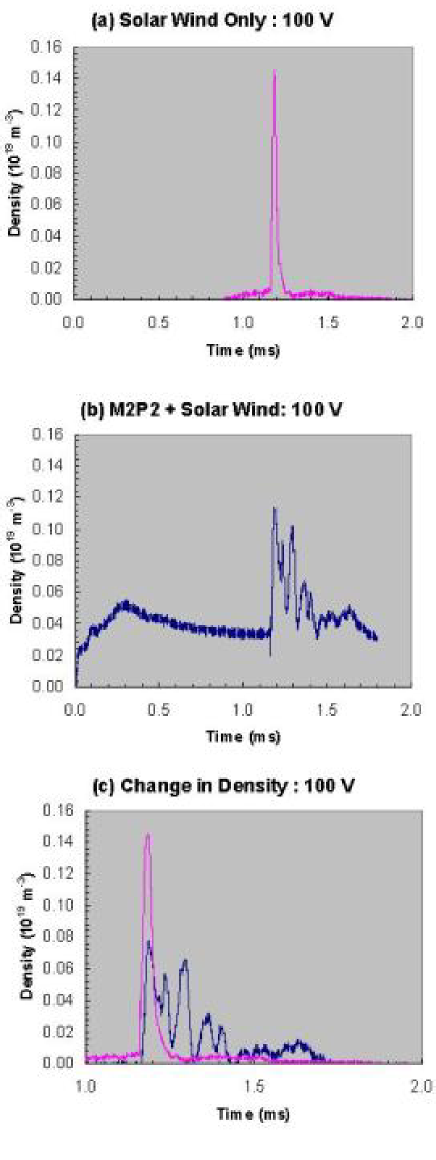

Figure 3. Density measurements from the probe shown in Figure 2 with M2P2 magnet set at 0.4 kG (100 V) for (a) ignitor SWS only, (b) both M2P2 and SWS on, and (c) the change in density associated with the firing of SWS.

INTERIOR PLASMA SHIELDING

Buoyed by the initial results from the low power operation of SWS, emphasis was then placed on the high power operation to determine the maximum power that M2P2 might be able to deflect. To this end, the 200 kWe inductively couple plasma source was switched on. The plasma profile at 2.5 cm from the top SWS magnet are shown in Figure 5 for when the SWS magnet is run at (a) 0 G and (b) 160 G. Without magnetic field a peak density of about 3.5 × 10^{19} m^{-3} with a full width at half height (FWHH) of about 10 cm. With the focusing by the magnets, the

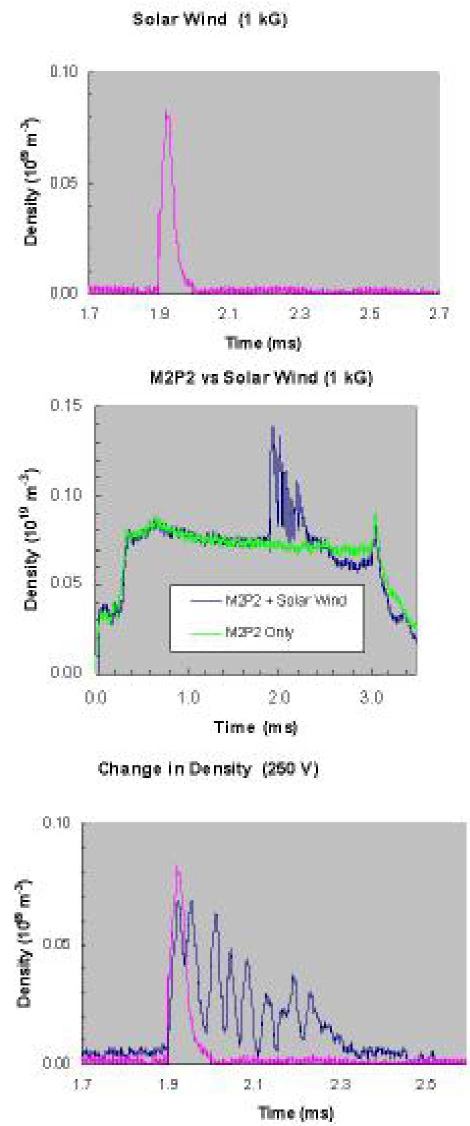

Figure 4. As in Figure 3 except the field strength on the M2P2 magnet was set at 1.0 kG (250 V). Stronger entrapment of SWS energy occurs with increasing field strength.

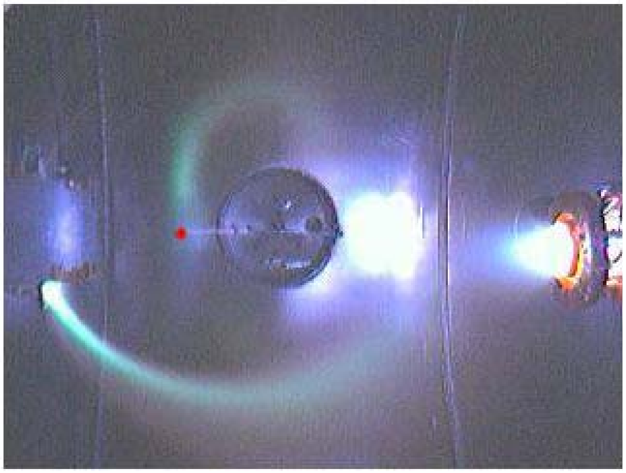

Figure 6. Image of M2P2 (1.5 kWe, 0.8 kG) operating against SWS in high power mode (200 kWe, 160 G). The separation of the devices is about 1 m. The red dot indicates the position of the Langmuir probe for Figure 7.

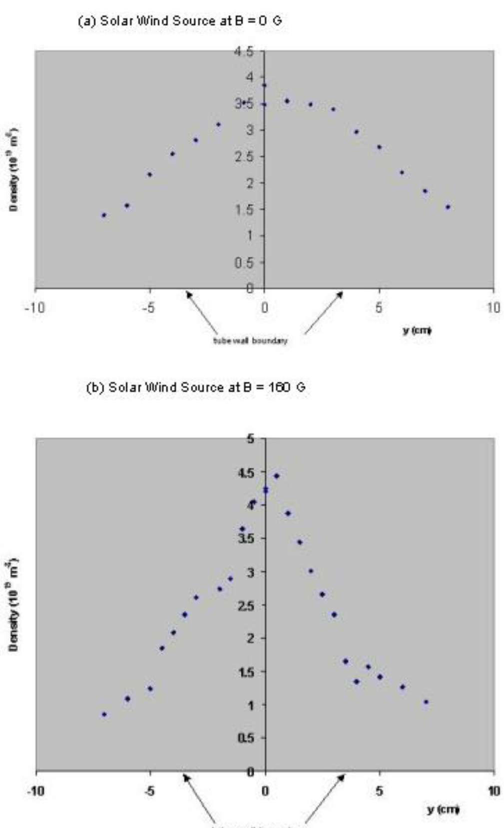

Figure 5. Radial density profile of SWS for (a) 0 G and (b) 160 G on the SWS magnet. The magnet allows focusing of plasma onto M2P2.

device is able to produce peak density of 4.5×10^{19} m^{-3}, and with a reduce FWHH of about 7 cm. Measured temperatures of the plasma are about 15-20 eV. The density here are typically 10-30 times larger than M2P2, so that one would easily expect SWS to overwhelm M2P2.

Figure 6 shows a photograph of the M2P2 (still at 1.5 kWe) operating against SWS at 200 kWe. In order to highlight the sources of plasma we used Xenon for M2P2 which is seen in the figure as emitting blue-green, and argon for SWS which emits in red-blue. For the data in this section M2P2 was run for 7 ms, and when M2P2 was running in steady state, SWS was fired for a 1 ms period. The highly focused beam of SWS is seen on the right hand side extending about 10-20 cm into the chamber. On the left hand side is M2P2. The surprising feature of picture is that despite the overwhelming power in SWS, the Xenon plasma dominates the view, and that it remains coherently on a field line all the way out to close proximity to SWS.

Data from the Langmuir probe (Figure 7, in the same format as Figures 3c and 4c) confirms the fact that M2P2 is able to screen or deflect the plasma from SWS. In Figure 7a, the results when M2P2 has a low field strength of 0.4 kG, and SWS was run without any magnetic focusing. With the M2P2 magnet on but with no plasma source, densities of the order of about 0.4×10^{19} m^{-3} are observed. This density is about 1/10 that observed at the throat and essentially shows no deflection. With M2P2 running, there is a initially only about 20% deflection, but within a few hundred μs the deflection increases to about 50%. This increasing deflection is another sign of M2P2 being able to absorb energy and more efficiently deflect the external plasma (which if on a spacecraft would lead to enhanced thrust).

Figure 7b shows the corresponding results when M2P2 magnet is increased to 800 G and the SWS set at 160 G for magnet focusing. It is seen that with the SWS magnet on one obtains even higher penetration of plasma into M2P2 if its source is not in. In this case densities are nearly a factor of 3 higher than in Figure 7a. Despite the higher penetration of SWS plasma when M2P2 sources in on there is consistently 60% deflection of plasma. If M2P2 magnet is increased to 1.2 kG, SWS can still penetrated into the system at the same level as Figure 7b. However, when M2P2 plasma source is switched on, essentially 100% deflection is attained.

The measured perturbations of magnetic field (not shown) is of the order of 1-3 G in the middle of the chamber. These perturbations are comparable to the vacuum magnetic field, i.e. ΔB/B is of order unity. From the plasma measurements, the thermal pressure generated by M2P2 is also comparable to the magnetic field energy, i.e. we have been able to generate a $\beta = 1$ plasma, and the field perturbations are consistent with this type of plasma beta.

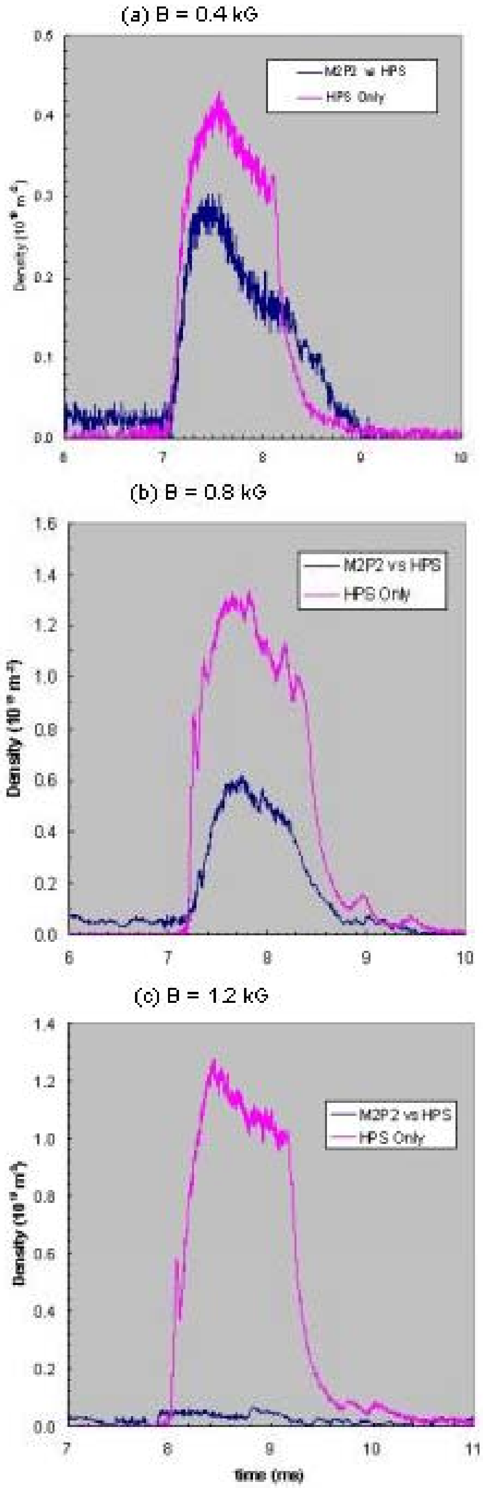

Figure 7. Density perturbations (in units of 10^{19} m^{-3}) measured with (a) M2P2 at 0.4 kG and SWS at 0 G, (b) M2P2 at 0.8 kG and SWS at 160 G, and (c) M2P2 at 1.2 kG and SWS at 160 G.

CONCLUSION

In this paper the interaction of the M2P2 prototype with an external plasma wind (SWS) has been investigated quantitatively for the first time. The M2P2 prototype is the same as previously described [5-7] and was operated at 1.5 kWe electrical. Opposing M2P2 was a solar wind source (SWS) that operated at moderate power levels (33 kWe) and very short times scales of 50 µs. This intermediate operating level was used to demonstrate that M2P2 can absorb energy from the SWS and retain the energy in the form of enhanced plasma density for periods much longer than the 50 µs pulse. The time scale for the retention of this energy is comparable to the confinement time of M2P2 when it is operated by itself. This time scale is a few hundred µs and it appears to be primarily set by wall interactions, given the large size of the gyro-radius of ions in the middle of the chamber.

These results are completed by high power operation of SWS at 200 kWe over ms time scales. The results presented show that in this mode the SWS plasma can cut through the magnetic field on M2P2 essentially unopposed irrespective of the strength of the M2P2 magnet (at least out to 1.2 kG). However, with M2P2 plasma source switched on, very efficient defection of this plasma is seen, particularly at the higher field strength. At 0.8 kG on the magnet about 60% of the plasma is deflected, while at 1.2 kG essentially 100% of the plasma is deflected.

These results demonstrate in absolute terms that the M2P2 is able to achieve all key functions that would enable it to efficiently couple energy from the solar wind to produce enhanced spacecraft propulsion. First we are able to produce a high-beta plasma within a dipole. Second, the M2P2 system is able to absorb energy from the external plasma wind to allow it to sustain higher plasma energy densities than can be afforded by itself. This is required in order to build up the energy density to sustain a *1/r* falloff in the magnetic field. Third, and no less significant is that we have been able to demonstrate deflection of very energetic plasma sources despite the very low energy expended on M2P2. The power in these deflected plasma is comparable to than expected to be deflected if actually deployed in the solar wind. So not only can M2P2 achieve its objective of deflection of the solar wind, it can do so in a stable configuration in probably the worse case scenario of when the overwhelming power of SWS is at point blank range.

In summary, all key features of M2P2 needed for successful operation in space have now been demonstrated in the laboratory.

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