

Radiation shielding produced by mini-magnetospheres

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The deployment of a mini-magnetosphere (or magnetic bubble) around a spacecraft has recently been proposed as a means to couple energy from the solar wind to provide in-space propulsion. In so doing mini-magnetospheric plasma propulsion (M2P2) would have both high specific propulsion and high thrust while requiring only modest (kW/unit) power levels to sustain the mini-magnetosphere. In order to obtain sufficient thrust for a manned mission, the mini-magnetosphere is anticipated to extend out to several 100 km to a few thousand km in radius, possibly supported by several units using a total of ~ 100 kW. At this size, the mini-magnetosphere has the potential for not only deflecting solar wind particles, but also the energetic particles that comprise galactic cosmic rays (GCRs) and solar energetic particle (SEP) events. These energetic particles provide a significant radiation hazard for any extended manned mission in space. This paper presents initial design characteristics for using an M2P2 system as a radiation shield. Each unit consists of a magnet with a radius of 10 – 20 cm, with strength of a few kilogauss to possibly a Tesla. Embedded in each magnet is a plasma source that is used to expand the magnetic field. It is shown that the magnetic field fall off approaches $1/r$ as the plasma energy density approaches the magnetic energy density. The effectiveness in shielding as determined by the integral of $\mathbf{B} \times d\mathbf{r}$ can be more than an order of magnitude larger than the magnet by itself. Pulsed operation of the system is used to prevent modification of spacecraft trajectory and prevent build up of radiation belts within the mini-magnetosphere.

Introduction

As space flights move beyond the Earth's magnetosphere, both crew and spacecraft will be unprotected from energetic particles that fill the interplanetary medium. Some of these energetic particles can reach energies in excess of tens of MeV per nucleon and therefore represent a significant radiation hazard [*Space Studies Board*, 1996; *Wilson*, 1995; 1997]. The two primary sources of the most energetic particles are galactic cosmic rays (GCRs) and solar energetic particle (SEP) events associated with solar flares. GCRs consist of atomic nuclei with about 85% protons, 14% alpha particles, and 1% heavier nuclei [*Wiebel*, 1994]. While the heavy ions represent only a small fraction of the GCRs they are still a significant radiation hazard as their energy deposition is proportional to the atomic number squared. The flux of these GCRs incident on the heliosphere is thought to be approximately constant but there is some modulation during solar maximum due to enhanced shielding provided by the strengthening of the interplanetary magnetic field within the heliosphere during solar maximum.

While the flux of GCRs may decrease during solar maximum, SEPs increase. These events are short lived, lasting from a few hours to several days (depending on the energy of the particles) but their flux can be several orders of magnitude greater than GCRs [Sauer *et al.*, 1990; Shea, 1990]. Fluxes from several large SEPs over the last few solar cycles have been documented by Reames *et al.* [2001]. The SEPs tend to show a sharp decrease above about 100 MeV/n, but at the observed levels will still generate a significant radiation hazard.

There are essentially only two different means for providing radiation shielding. One is to place sufficient material around the spacecraft to stop the energetic particles. However, the amount of material required for adequate shielding can be significant. For example, ~30 MeV protons can penetrate spacesuits and spacecraft walls, while 130 MeV protons required about 20 g cm⁻² for adequate shielding. As such this type of shielding can add significantly to the mass and cost of any mission. In addition, because the energetic particles are stopped by direct interactions with other nuclei, the generated secondaries can also pose a significant radiation risk. The alternative method is to use magnetic or electric fields to deflect the energetic particles. This method has the advantage that no secondaries are produced but has the disadvantage that many of the existing schemes require either very large magnetic and electric fields near the spacecraft that would have large mass and power requirements, or the deployment of a very large field coil which again is not presently feasible.

The problems and potential solution to this problem are very reminiscent to the problems when trying to harness the energy of the solar wind for spacecraft propulsion. The solar wind provides an essentially limitless supply of fast (300 – 800 km/s) ions. These fast particles can be deflected by a magnetic field, but in order to get enough thrust from the tenuous solar wind, a very large (10-100's km) interaction region is required. To achieve this large interaction, Magsail as proposed by Zubrin [1993, and references therein] suggested the deployment of a large (100+ km) superconducting magnet.

A recent advance has been the suggestion of deploying a plasma inflated magnetic bubble or mini-magnetosphere [Winglee *et al.*, 2000a,b]. This scheme called mini-magnetospheric plasma propulsion (M2P2) uses the fact that in a collisionless plasma the magnetic field is frozen in to the plasma. As the plasma expands outwards it will generate the necessary currents to carry the magnetic field with it. For this free expansion to occur the plasma pressure has to exceed the local magnetic pressure (i.e. have a plasma beta greater ~1). Under this free expansion, the falloff in the magnetic field will change from r^{-3} for a simple dipole to r^{-2} . As this expanding plasma moves out work is done on it by the solar wind, and eventually the expansion stops when the pressure of the solar wind is balanced by the total (plasma and magnetic) pressure within the mini-magnetosphere. Because of the compression of the expanding plasma by the solar wind, current sheets can form where the falloff in magnetic field can approach r^{-1} . The fact that the magnetic field falls off as r^{-1} means that the cross-section for the interaction with any type of charged particle would be substantially increased without the need for either intense magnets near the spacecraft surface or the deployment of large current loops in space.

In this paper we examine the potential for using M2P2 units as a potential means for radiation shielding of GeV particles. The system requirements for this application are very much different from the above propulsion application. Larger field strengths (~ 0.1 to 1 T) are required on the magnet, and larger power of the order of 100 kW will be required. While such capabilities are in fact possible with manned flight, the force from the solar wind would be sufficient to significantly modify the spacecraft

trajectory. As such the M2P2 units cannot be run in a continuous manner and the energization of plasma from the solar wind cannot be taken advantage of. Instead pulsed mode of operation must be used. This leads to the detachment of the mini-magnetosphere from the spacecraft, but the magnet field is shown to build up well away from the spacecraft and as each pulse moves out, the ability of the mini-magnetosphere to deflect GeV particles increases.

Extended Magnetic Field Generation by the M2P2 Prototype

The ability to inflate a mini-magnetosphere was initially demonstrated through computer simulations [Winglee *et al.*, 2000a]. In order to show what the inflation looks like this section shows a comparison of model and laboratory results for the prototype being developed at the University of Washington (UW). The simulation model is essentially the same as used in the original application, except that the system size is 2 m with the magnet placed 40 cm from the back wall. The minimum spatial resolution is set to 1 cm in the vicinity of the magnet and is several cm further away from the magnet. The magnet itself is represented by a cylinder that has a radius of 10 cm and a width of 10 cm, similar to the actual experiment. The magnet field everywhere outside the magnet is represented by a point dipole which produces a ratio of 16:1 in field strength at the top of the magnet relative to the equatorial strength at the side, which is comparable to actual configuration. The field strength in all the following simulations is 1.6 kG at the top of the magnet. Superimposed on the magnet's field is the 0.32 G terrestrial field. While this field may appear small it starts to become the dominant field between 0.4 – 0.7 m from the magnet. Figure 1 shows the predicted changes in the magnetic field configuration from the vacuum field (Figure 1a) to the inflated magnetic field configuration (Figure 1b). To see the transition in the field structure, the field lines are color coded with field lines that close on the magnet colored dark blue, those that are open on one end by light blue, and those not connected at either end (i.e. purely terrestrial field lines) are indicated by red. Some pseudo diagnostic probes at fixed positions (black field lines) are used to

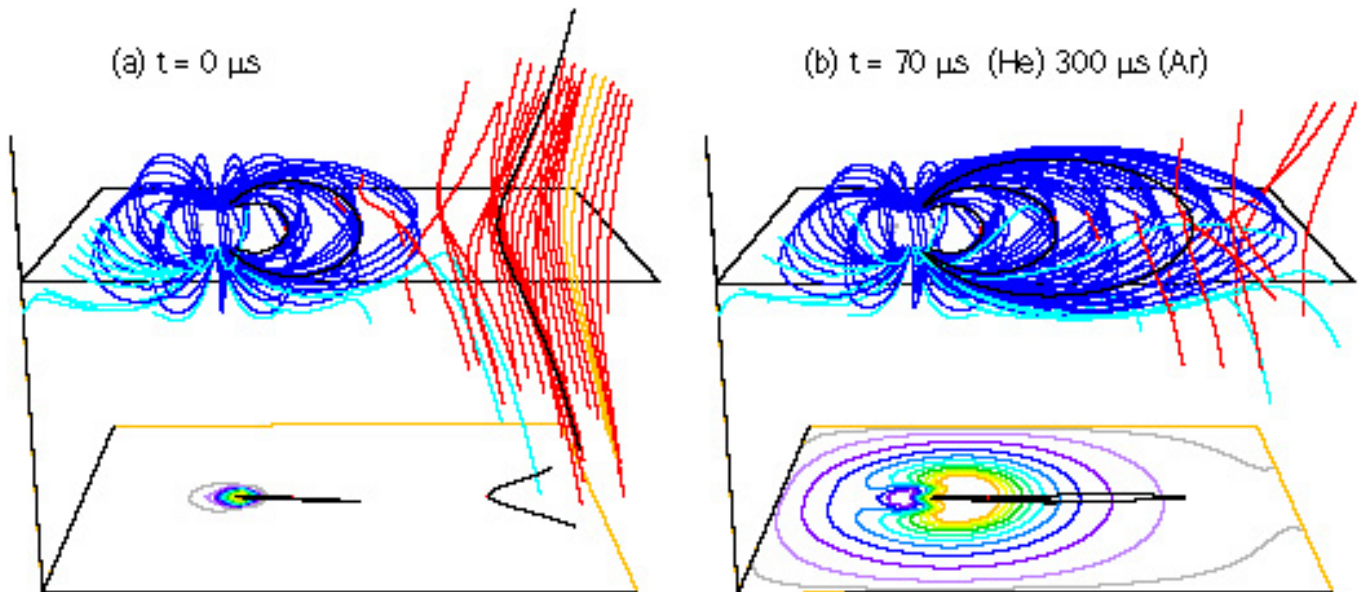


Figure 1. Mapping of the magnetic field (top) during the injection of plasma from within the magnet. Pressure contours in the equatorial plane are shown in the bottom panel. The time of expansion depends on the propellant being used.

continuously sample the plasma and magnetic field characteristics similar to the actual experiments.

In order to drive the plasma inflation a helium plasma of 10^{13} cm^{-3} , and 10 eV temperature is loaded in a 3 cm diameter circle at the top and bottom of the magnet, centered 4.5 cm from the magnet wall. The propagation of plasma and magnetic field are then tracked in time and space using the plasma fluid equations [Winglee *et al.*, 2000]. Similar results are also attained for heavy gases such as argon using the same energy input except that the time scale is correspondingly increased. One of the key signatures of the inflation of the magnetic field is that the region occupied by the closed field lines is seen to rapidly move outwards, and the field lines appear substantially elongated.

This elongation has been seen in a variety of tests of the actual prototype [Ziemba *et al.*, 2001; Winglee *et al.*, 2001]. A recent example is shown in Figure 2 from results taken in the newly installed 2m by 1.7 m diameter at UW. The shape of the optical emissions is very similar to that seen from the simulations. In order to make a more quantitative comparison of the magnetic field perturbations, Figure 3 shows the measured perturbations and the model predictions from tests carried out in the small UW chamber. The laboratory data shows a faster rise time than the simulations, which may be due to the ionization being over an extended region as opposed to the point source assumed in the model. Despite this difference, both show that magnetic flux is removed from the inner region of the dipole (negative perturbations) and transported to the outer regions (positive magnetic perturbations). This flux is seen to pile up such that the outer most regions see the biggest increase. This signature is very distinctive in both the simulations and observations and provides strong proof that transport of magnetic flux has been achieved by the M2P2 prototype.

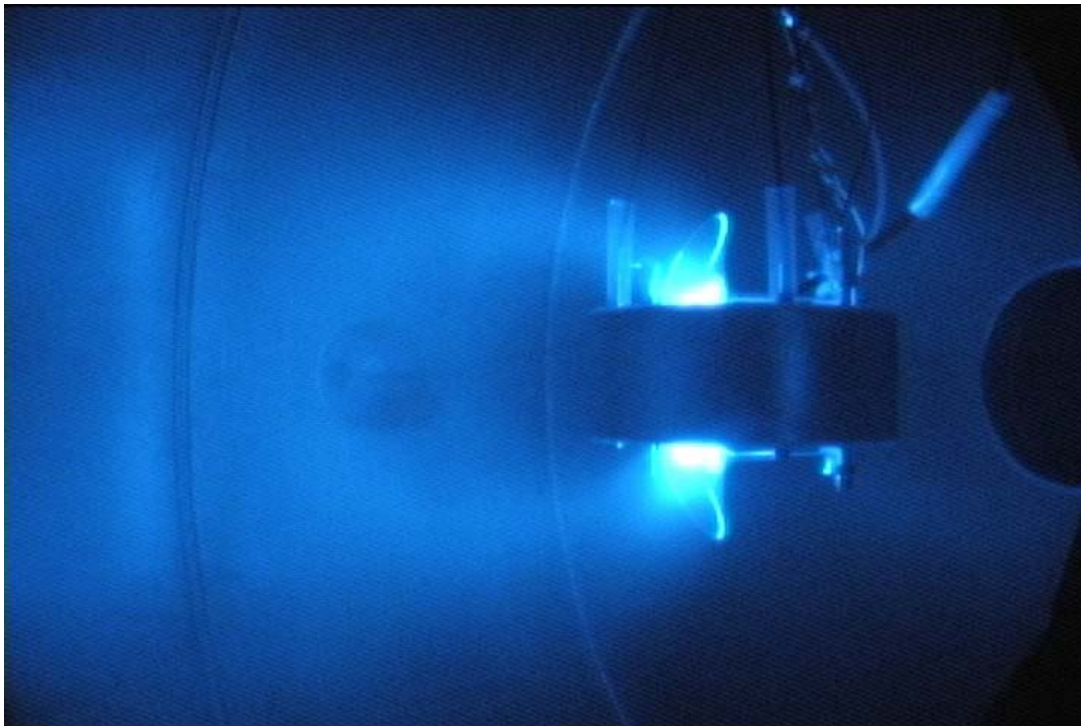


Figure 2. Optical emissions from a 1 ms pulse in the Univ. of Washington chamber. Field of view is ~ 1 m. An elongated flux tube is seen with the plasma reaching the other end of the chamber well within the pulse.

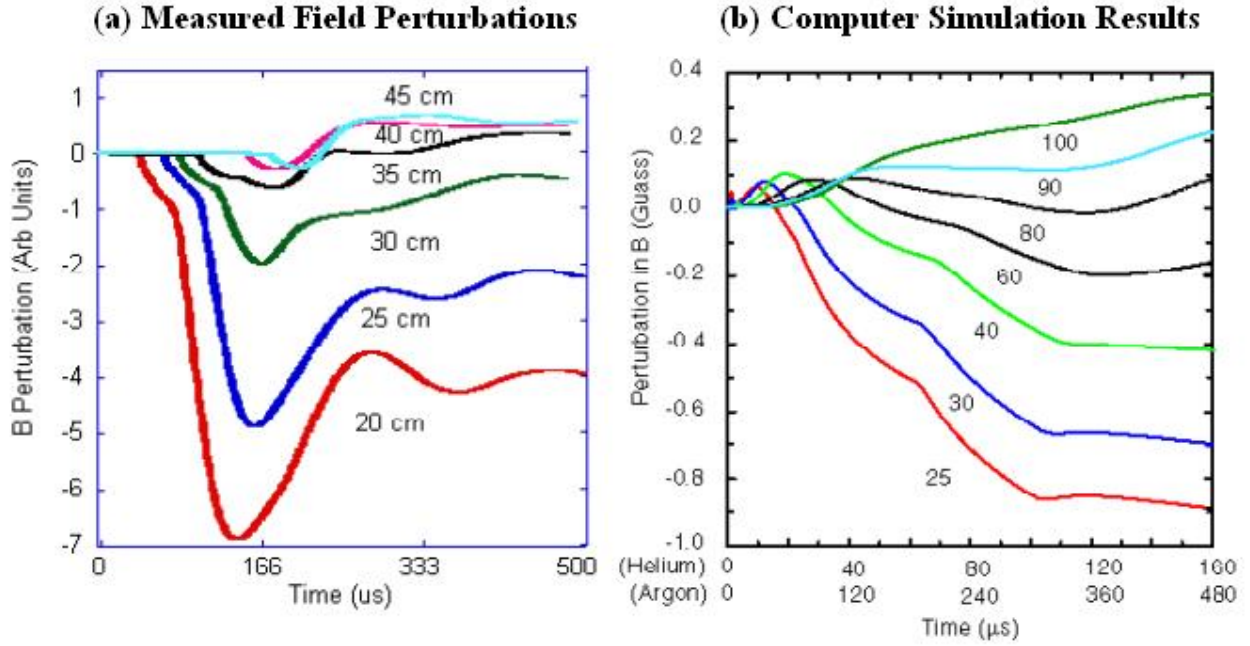


Figure 3. Comparison of (a) the observed magnetic field perturbations in the small UW chamber and (b) the simulations estimates for a 2 m chamber.

Specification for an M2P2 Radiation Shield.

Having demonstrated the ability of the M2P2 prototype to produce a mini-magnetosphere for its initial propulsion applications, the question then becomes what is required for its use as a radiation shield for GeV particles. As a measure of this ability we consider the integral of the magnetic field along a ray path. If the gyroradius of the particle is smaller than the scale length of the mini-magnetosphere then the particle will be deflected. This criterion was also verified by particle tracking of orbits through the magnetic and electric field derived from the simulation model. The above condition is approximately equivalent to

$$v_{\perp,deflect} \leq \frac{q}{m} \int \mathbf{B}_{\perp} dr \quad (1)$$

where any particle with $v_{\perp} < v_{\perp,deflect}$ being deflected. For GeV shielding (1) then requires that $\int \mathbf{B}_{\perp} dr$ be of the order of 1 Tesla meter (Tm). This value has to be achieved around the entire spacecraft for effective shielding.

If the falloff in the magnetic field is specified, then the conditions on the magnet can be readily be determined. In particular, if we assume that the field falls off as r^{-n} , then (1) reduces to

$$v_{\perp,deflect} \approx \frac{q}{m} \frac{B_0 R_m}{n-1} \quad \text{for } n < 1 \quad (2a)$$

$$v_{\perp,deflect} \approx \frac{q}{m} B_0 R_m \ln\left(\frac{L}{R_m}\right) \quad \text{for } n = 1 \quad (2b)$$

where R_m is the magnet radius, B_0 is the field strength at the magnet and L is the size of the mini-magnetosphere. For example, for a simple dipole, the magnetic field falls off as r^{-3} and (2a) reduces to

$$v_{\perp,deflect} \approx \frac{q}{m} \frac{B_0 R_m}{2} \quad (3)$$

If one were to have a freely expanding plasma with a frozen-in field such that the magnetic field fell as r^{-2} , the inflated magnetic field would increase the integral by a factor of 2. The reason for this small increase is that the integral of B primarily depends upon from contributions close to the magnet and the actual size of the mini-magnetosphere is irrelevant.

More substantial enhancements in the integral of B start to occur as the falloff approaches r^{-1} . At this stage the size of the mini-magnetosphere becomes important. For example, for a 20 cm magnet with the field stretch out to 4 km with a r^{-1} integral B would be enhanced by a factor of 20 on the simple dipole, and a large volume would be protected by the mini-magnetosphere. However, because of the logarithmic dependence going out to very large distances produces diminishing returns. For example going out to 40 km, there is only an increase of about 25 in the integral from the dipole case, and at 400 km a factor of about 30 is produced.

Thus, realistically even for the most favorable conditions for inflation of a mini-magnetosphere, the magnet requirements will have to be such that $B_0 R_m$ needs to be of the order of 0.03 – 0.05 Tm. For 20 cm magnets, this requires field strengths of the order of sub-Tesla (several kG) fields. This is in fact achievable with existing magnet technology.

The next issue to be address is the conditions at the source under which an r^{-1} can be achieved. To test for this dependence we ran a series of simulations where the magnetic field strength was held constant and plasma power was increased. Because we wished to test the ability for shielding not at the magnet itself, but rather at a large spacecraft we considered a four unit system, with the units forming a cross and with the spacecraft being at the intersection of the cross. Figure 4 shows the results from two of the cases run. The left hand side shows for a 2 kW/unit system where the plasma speed (V_{plasma}) relative to the Alfvén speed (V_A) is equal to 0.25. It turns out that $(V_{\text{plasma}}/V_A)^2$ is approximately equal to the ratio of the plasma energy density to the magnetic field energy. For this case, the plasma is seen to expand beyond the 100 km range. As it expands the rate of falloff is seen to slow changing from a r^{-3} rate to $r^{-1.5}$ for the last time shown. While this size is extremely important for propulsion aspects it is not sufficiently efficient for shielding applications.

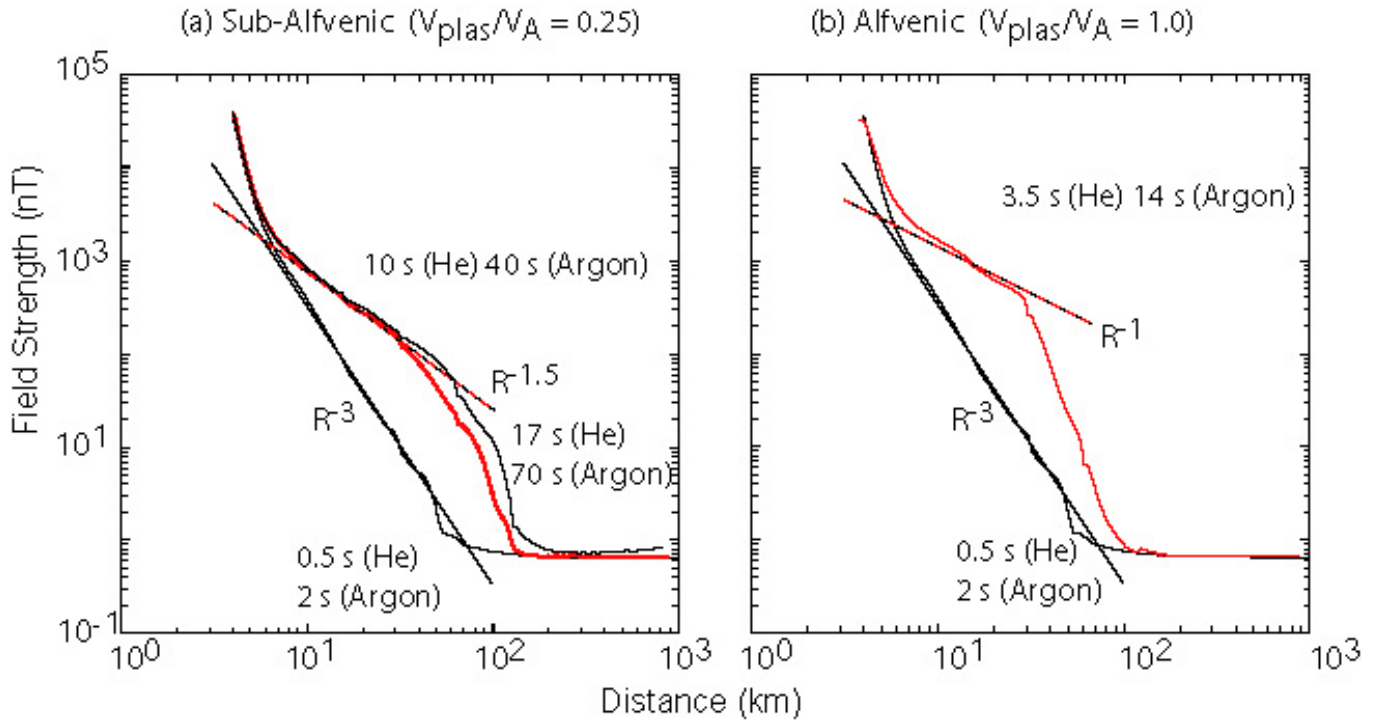


Figure 4. Falloff in the magnetic field in the sunward direction for (a) sub-Alfvénic and (b) Alfvénic inflation of the mini-magnetosphere. As the plasma injection velocity approaches the Alfvén speed a relatively slow falloff of r^{-1} is attained, and provide the strongest shielding over extended distances.

The right hand side of Figure 4 shows the results for a 32 kW/unit system ($V_{\text{plasma}}/V_A = 1$). With the increase plasma power a r^{-1} falloff is attained almost immediately. This means that shielding would be substantially more efficient. The problem is that this mini-magnetosphere will expand to very much larger distances than the low power configuration and thereby intercept kN of force from the solar wind and substantially modify the spacecraft trajectory.

This large-scale expansion can actually be used as an advantage and not a disadvantage for shielding. Specifically, because the expansion will not be impeded by the solar wind for long periods, the M2P2 units can be run in pulsed mode as opposed to CW mode for the propulsion applications. The advantages are as follows. If one has an extended DC magnetosphere, scattering of radiation particles through any type of wave-particle interaction can always lead to the potential formation of radiation belts around the spacecraft. By pulsing the units, one is able to actually detached the mini-magnetosphere from the spacecraft magnets thrust concerns about trajectory modification are removed. At the same time the closed fields lines that would support a radiation belt are removed. In addition, as each pulse moves outwards incoming energetic particles will see an outward propagating wall/mirror which should inhibit inward radial diffusion processes. Pulsing also reduces the net CW power required by the system.

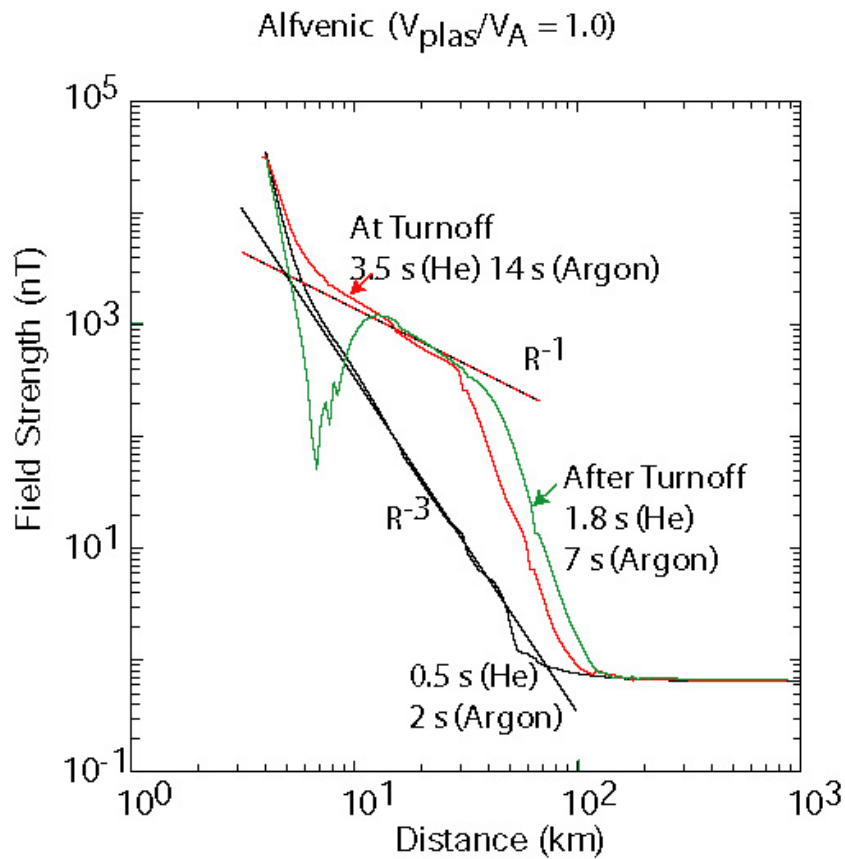


Figure 5. Magnetic profile after turnoff of the plasma source for the Alfvénic case of Figure 4b.

Figure 5 shows an example of the detachment of the spacecraft field from the mini-magnetosphere fields after the plasma source is turned off in the example in Figure 4b. Due to the turnoff of the plasma source the inflation of field in the near vicinity of the spacecraft falls and in fact decreases below the vacuum field strengths. This shape decrease is a consequence of the freezing in of the magnetic field to the plasma. After turnoff, the previously injected plasma has sufficient inertia to keep moving outwards and continues to carry the magnetic field out with it. This outward propagation is seen as a continued presence of magnetic field at large distances. Since this outwards propagating plasma near the magnet is not replaced, a strong reduction in the magnetic field is produced.

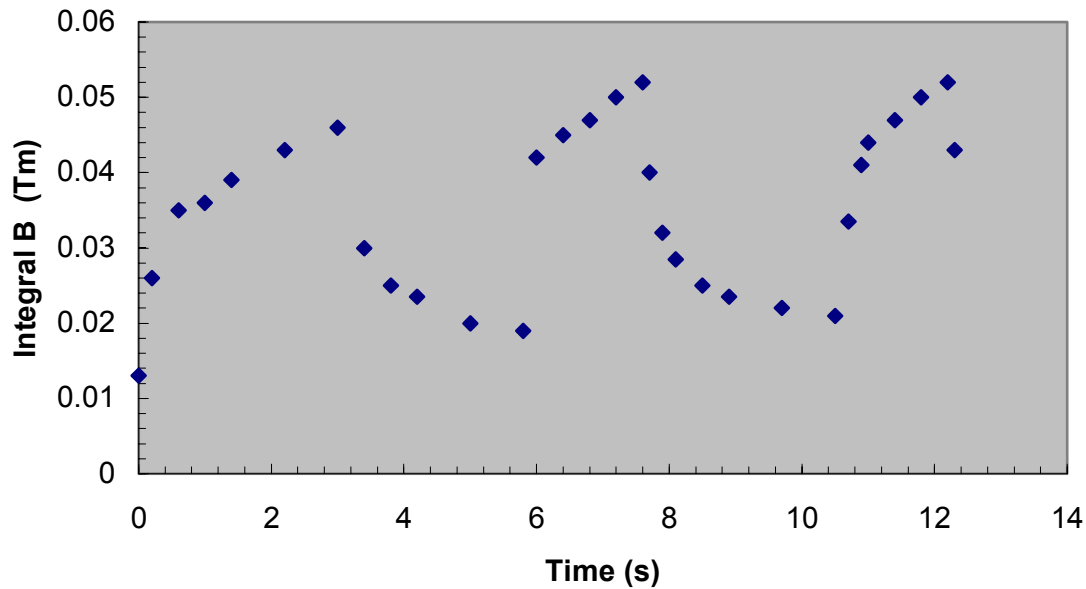


Figure 6. Evolution of integral of B in the direction of the sunward and through the spacecraft position. The pulsing leads to the build up of magnetic field well above the vacuum solution, and with the fields of the mini-magnetosphere detached from the spacecraft.

The time evolution the integral of B through the spacecraft position is shown in Figure 6 during three pulses of the system. As previously noted there is a substantial increase in integral B during each firing. And while there is a reduction in integral B after each turnoff, integral B does not decrease to the vacuum field value. Instead there is a slow build up of magnetic field enveloping the region. This is because the outward pulse is not disrupted by the turnoff of the plasma source. With more successive pulses, it is anticipated that integral B can be built up to the desired value of 1 Tm. This build up is presently being tested with the continuation of the simulations to long times with more pulses.

Conclusion

In this paper we have presented some initial calculations for the use of mini-magnetospheric plasma propulsion (M2P2) units as a means for producing radiation shielding of GeV particles. The strength of M2P2 is that it offers the ability of establish large scale (several hundred km) current sheets and associated magnetic field structures without the need for mechanically deploying large current loops over these same scale. It also offers a system that is lightweight and possibly complementary to any type of advanced propulsion system need for manned missions to the planets.

It shown that the slowest falloff in magnetic field is achieved when the energy density of the injected plasma is comparable to the energy density in the magnets of each M2P2 unit. The required magnetic field at the magnet for GeV shielding requires about 0.1-1 Tesla on the magnet, which magnetic being of the order of 10-20 cm. Under these conditions, the expansion of the mini-magnetosphere is expected to move out to possibly 1000 km, and the force from the solar wind has the potential of modify the spacecraft trajectory. To over come this problem, we have considered pulsed mode of operation.

This mode of operation has several advantages. First, at each turnoff the mini-magnetosphere fields become detached from the spacecraft as the inertia of the plasma carries the magnetic field outwards and new plasma is not available to fill the ensuing void. The second is that the detached of the magnetic fields and the outward moving pulse fronts will inhibit the formation of any type of radiation belt produced by inward diffusion of radiation particles. The third is that the pulses allow a slow build up of the magnetic field so that less power overall would be required.

Further work needs to look at the final solution after multiple pulses to provide that the desired level of magnetic field of 1 Tm can be achieved along the bulk of the mini-magnetosphere. This paper only considers two pulses, but the evidence suggests a continued building of the magnetic field. As such there is potential for providing GeV particle shielding through mini-magnetospheres. This shielding will required about 100 kW continuous power to support the mini-magnetosphere.

Acknowledgements

This work was supported by NASA MSFC grant NCC8-231 to the Univ. of Washington.

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