Study of magnetic field expansion using a plasma generator for space radiation active protection *

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Abstract: There are many active protecting methods including Electrostatic Fields, Confined Magnetic Field, Unconfined Magnetic Field and Plasma Shielding etc. for defending the high-energy solar particle events (SPE) and Galactic Cosmic Rays (GCR) in deep space exploration. The concept of using cold plasma to expand a magnetic field is the best one of all possible methods so far. The magnetic field expansion caused by plasma can improve its protective efficiency of space particles. One kind of plasma generator has been developed and installed into the cylindrical permanent magnet in the eccentric. A plasma stream is produced using a helical-shaped antenna driven by a radio-frequency (RF) power supply of 13.56 MHz, which exits from both sides of the magnet and makes the magnetic field expand on one side. The discharging belts phenomenon is similar to the Earth's radiation belt, but the mechanism has yet to be understood. A magnetic probe is used to measure the magnetic field expansion distributions, and the results indicate that the magnetic field intensity increases under higher increments of the discharge power.

Key words: plasma stream, magnetic field expansion, space radiation, active protection

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1 Introduction

For planetary missions, both astronauts and spacecraft equipment face a significant hazard from the natural ionizing radiation environment. The most significant constituents of this environment are energetic protons and heavy ions during solar energetic particle (SEP) events with energies up to a few 100 MeV, and galactic cosmic rays (GCRs), which consist of protons and heavy ions with energies in the billion electron volt range [1].

Because the protection of the Earth's magnetic field and itself, the mass thickness shielding method has met the need of space radiation protection in the low Earth orbit. However, this method cannot defend against the high-energy SEP and GCR which maybe encountered during the long-term in-orbit flight and interplanetary flight. Hence, an important job is to find suitable active protecting methods for space radiation. An active protecting method uses magnetic or electric fields to deflect the energetic particles, thereby reducing the exposure of space radiation to spacecraft and astronauts. Active shielding concepts fall into four distinct categories: (1) electrostatic fields; (2) plasma shielding; (3) magnetic fields; and (4) Mini-Magnetospheric Plasma Propulsion (M2P2). Over the past several decades, many researchers have proved that the existing level of technology cannot produce a strong enough pure electric field or magnetic field to deflect the high-energy charged particles. The M2P2 proposed by Winglee is considered to be the best one of all possible methods so far [1, 2]. M2P2 seeks the creation of a magnetic wall or bubble (i.e. a magnetosphere) that will intercept the supersonic solar wind which is moving at 300–800 km/s. In so doing, a force of about 1 N will be exerted on the spacecraft while only requiring a few mN of force to sustain the mini-magnetosphere [3]. In this experiment, the creation of a magnetic bubble is focused through the interaction between the plasma and magnetic fields.

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In order to deflect charged particles, the scale length of the magnetic field within the mini-magnetosphere has to be comparable to the gyro-radius of the particle, i.e. [4]

$$V_{\perp,\mathrm{deflect}}=\frac{q}{m}\int B_{\perp}\mathrm{d}r, \tag{1}$$

where q is the charge of the particle, m is the relativistic mass, and the subscript $\perp$ denotes quantities perpendicular to the magnetic field. For any particle with $V\leqslant V_{\perp,\mathrm{deflect}}$, the dipole will be deflected, irrespective of its initial pitch angle. For shielding of MeV protons and <10 MeV electrons, (1) then requires that $\int B_{\perp}\mathrm{d}r$ be of the order of 0.03 Tesla meter (T·m). Deflection of GeV would then require $\int B_{\perp}\mathrm{d}r$ to be of the order of 1 T·m while solar wind particles require 0.001 T·m. So the radius of the M2P2 magnetic field has to be 10 km or more by the inflation of a small-scale (20 cm radius) magnet [2]. M2P2 proposes the idea of injecting plasma into the magnetic field, and then the magnetic field captures the plasma. The plasma spirals around the magnetic field lines and bounces back and forth in the two poles. When the plasma velocity meets certain conditions, the magnetic field lines would be “frozen” in the plasma, that is, the conductivity of the magnetic field becomes higher because magnetic lines capture the charged particles. The attenuation rate of the magnetic field spread will slow down. Therefore, the magnetic field inflates around the spacecraft and can deflect the charged particles, allowing a protection of the spacecraft and astronauts.

The key issues of the magnetic expansion by the plasma include: how to gain the 10 km in radius magnetic field, how to design a high-density plasma generator and how to design the ground experiment to study the interaction mechanism between the plasma and magnetic fields.

The mechanism of magnetic field inflation has been investigated using a variety of simulated techniques, such as full particle, hybrid (particle ions, fluid electrons) and magneto-hydrodynamics (MHD) [5–10] or Hall-MHD [8]. In this paper, a helicon plasma generator has been developed and installed inside a cylindrical permanent magnet. A ground experiment system was built to study the magnetic field inflation caused by a plasma stream. The mechanism of magnetic field expansion is also discussed briefly.

2 Experimental setup

Over the last several years, the ground experiments of the M2P2 have been studied mostly at the University of Washington [2–4]. Laboratory experiments have provided some evidence that the expansion exists. In this paper, a system previously developed in our laboratory is introduced by studying the magnetic field inflation caused by a plasma stream using a 0.1 T cylindrical permanent magnet [11]. It includes a vacuum chamber with diameter of 100 cm and length of 160 cm, a cylindrical permanent magnet is fixed on a holder. The experimental setup is shown in Fig. 1. The magnetic field intensity on the magnet surface is 0.06 T. Its size and shape are as shown in Fig. 2. Such plasma stream is produced using a helical-shaped antenna driven by a radio-frequency (RF) power supply of 13.56 MHz.

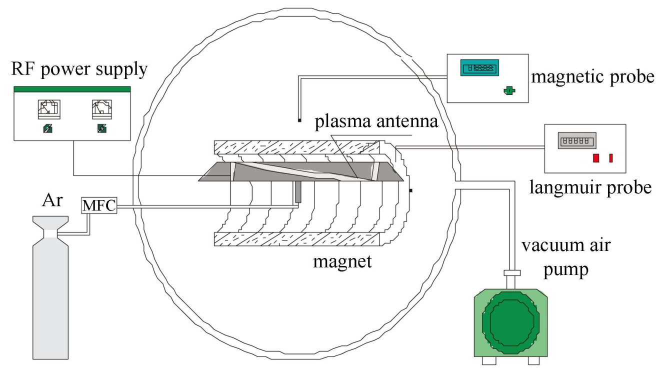


Fig. 1. Experimental setup.

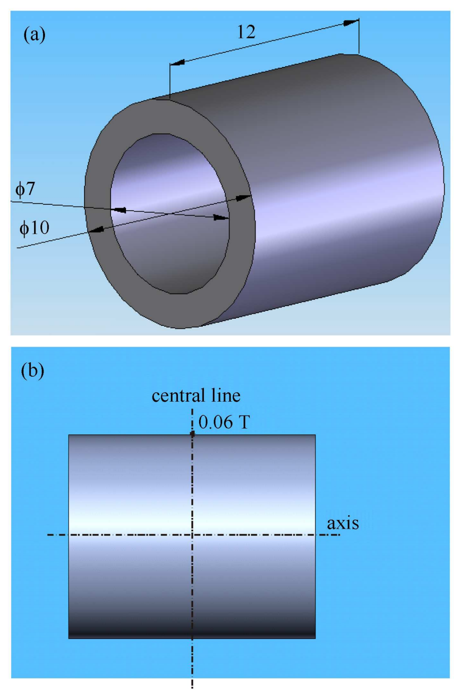


Fig. 2. Dimension of the magnet (unit: cm).

It's a simple dipole magnetic field. The plasma source is fixed offset from the magnet axis, to make the magnetic field expand on one side. In this experiment, the base pressure of the chamber is about 4×10^{-3} Pa, and it rises to 10^{-2} Pa when the working gas (argon) is introduced into the chamber. The discharge is driven by a radio-frequency (RF) power (Dressler, VM 600 W) of 13.56 MHz. A magnetic probe (Teslameter, SG-3-A) is used to measure the magnetic field intensity.

A plasma source with a helical-shaped antenna is developed according to following theoretical calculations.

The length of the antenna is a key parameter, and depends on the diameter of the quartz tube, the frequency of the power and the intensity of the magnet.

The dispersion relation of the helicon waves can be represented as follows: [12, 13]

$$kk_z = \frac{e\mu_0 n_0 \omega}{B_0}, \tag{2}$$

$$k = (k_\perp^2 + k_z^2)^{1/2}, \tag{3}$$

here k is the wave-vector magnitude, $k_\perp$ and k_z are the radial and axial components, whereas e, μ_0, n_0, B_0 and ω are electron discharge, permeability of vacuum, electron density, magnetic magnitude and cyclotron frequency. In the low-density regime, it shows $k_\perp \gg k_z$, from (3), $k \approx k_\perp$, and for m=1 mode, with the limiting values $k_\perp R$=3.83 ($k_\perp \gg k_z$), that is,

$$kR=3.83(k_\perp \gg k_z). \tag{4}$$

In this case, from (2) and (4), the axial wavelength of the helicon mode is calculated by

$$\lambda_z = \frac{2\pi}{k_z} = k\frac{2\pi}{k_z k} = \frac{3.83}{R}\frac{B_0}{e\mu_0 n_0 f}. \tag{5}$$

Here R is the radius of the tube. A quartz tube 2 cm in diameter and 15 cm in length is selected. From Eq. (5), the axial wavelength is evaluated $\lambda_z \approx 0.2$ m= 20 cm (R=1 cm, f=13.56 MHz, and B_0=0.06 T). Considering the coupling effect, l_a=λ_z/2=10 cm is taken as the length of the helical-shaped antenna [12], as shown in Fig. 3.

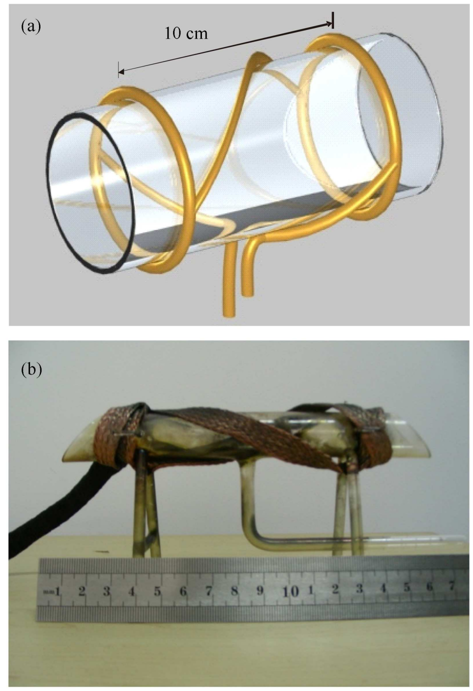


Fig. 3. The antenna configuration and the plasma source generator. (a) the antenna configuration (m=1); (b) the plasma source generator.

3 Results and discussions

Figure 4 shows the pictures of the discharging plasma of different input power, which reveal that the plasma exits from both sides of the cylindrical magnet and also exists on the top of the magnet.

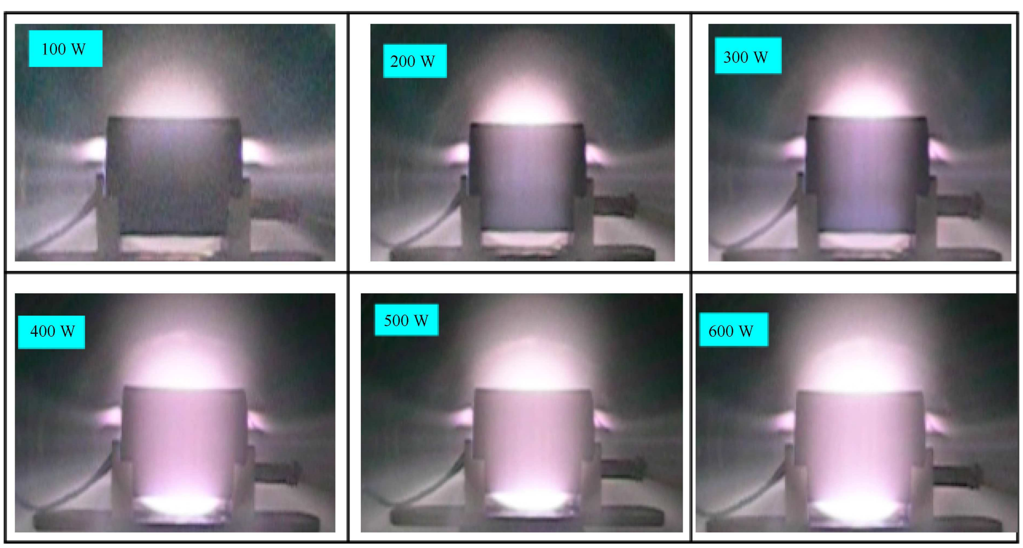


Fig. 4. Picture of the plasma source discharging for different input powers in the vacuum chamber.

The variations of magnetic field intensity on the direction of the central line perpendicular to the magnet's surface is studied with a magnetic probe, and four points, 5, 10, 15 and 25 cm away from top surface of the magnet, are selected, as shown in Fig. 5.

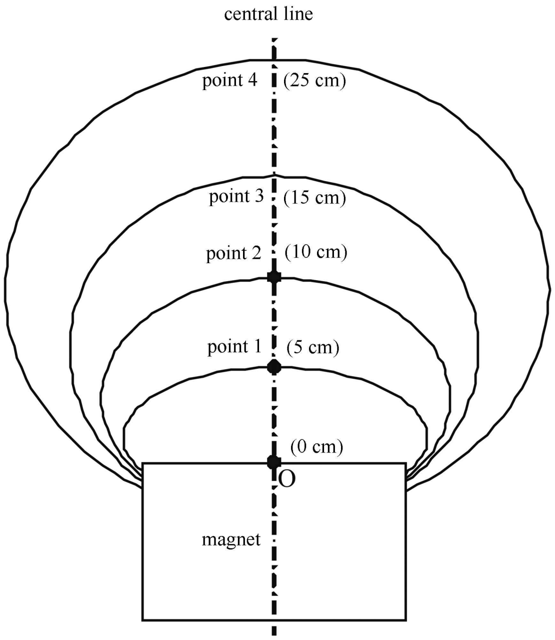


Fig. 5. Schematic diagram of the magnetic probe measurement points.

The magnetic field intensity enhances as the input RF-power increases, as shown in Fig. 6.

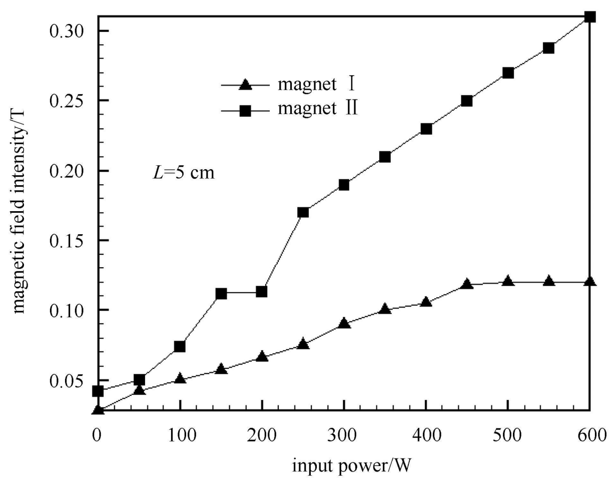


Fig. 6. Magnetic field intensities in different background magnetic fields of different powers (L=5 cm). (magnet Ⅰ: 0.06 T, magnet Ⅱ: 0.1 T).

The magnetic field intensity at point 1(L=5 cm) is only 0.028 T using magnet Ⅰ (0.06 T) as the background magnetic field, without plasma in the magnetic field. It increases linearly with the increases of the input power, and it tends to reach saturation when the input discharge power is over 450 W. The maximum expanded magnetic field intensity at this kind of discharge at point 1 is about 0.12 T. Compared with the magnet Ⅰ, the magnetic field intensity increases linearly with the input power and has not reached saturation using magnet Ⅱ (0.1 T) as the background magnetic field.

Variations of the magnetic field intensity with the input power at different points of the magnet are shown in Fig. 7. The magnetic field intensity climbs linearly at L=10 cm and L=15 cm. The magnetic field intensity at L=15 cm is biggest when the input power exceeds 100 W. The magnetic field intensity at L=25 cm increases from 0.0014 T to 0.0083 T at 100 W then decreases to 0.0024 T at 600 W.

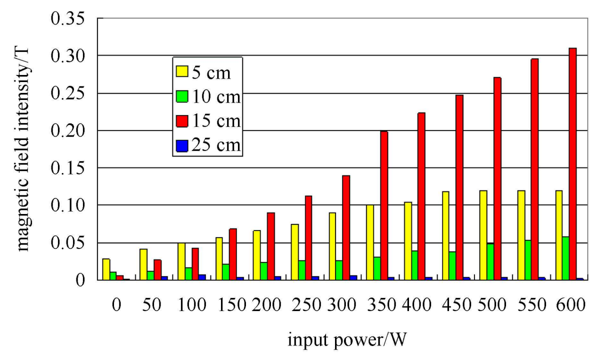


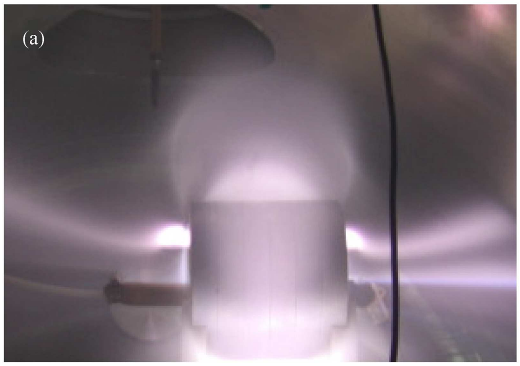
Fig. 7. Variations of the magnetic field intensity with the input power at different points of the magnet.

It is similarly verified that the magnetic field is expanded in the upper side of the magnet by the interaction between the plasma and the original magnet. There are two discharging belts from the experiment data at L=5 cm and L=15 cm which was shown from Fig. 8(a).

The discharging belts phenomenon is similar to the storage ring in Earth's Outer Van Allen Belt. The belt particle populations are determined by a complex superposition of acceleration, transport, and loss processes modulated by their interactions with plasma waves. The mechanism has yet to be understood [14].

The expanded magnetic field depends strongly on the plasma stream, its position in the magnetic field and its discharge manner, electron density, working gas, etc.

The inflated magnetic field intensity is maybe caused by the plasma cyclotron and the particle-magnetic field interaction. Particles will perform in a spiral movement and have a drift velocity when the plasma is injected into the magnetic field. If the velocity of the plasma is equal to Alfvén speed (plasma dynamic pressure is equal to magnetic pressure), the plasma is "frozen-in" magnetic field-lines. For the helicon plasma generator, the plasma



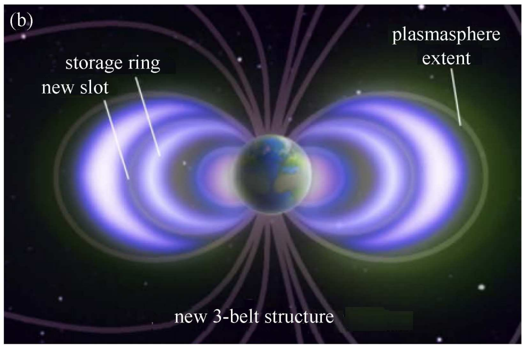


Fig. 8. (a) Discharging belts, (b) The Earth's radiation belts [14].

density and temperature were measured along with the power using Langmuir probe at the jet port. The plasma density is $9.0\times10^{11}/\mathrm{cm}^3$ and the plasma temperature is 7.8 eV in 500 W input power [15]. The plasma "beta"-the ratio of plasma pressure to the magnetic pressure - is $\beta=4.08\times10^{-11}\mathrm{nkT/B}^2$. Using the measured data, the plasma $\beta=7.9\times10^{-4}\ll1$, which allowed the plasma to be confined by the magnetic field.

4 Conclusions

An experimental system is introduced to study the magnetic field expansion. An RF plasma generator with a helical-shaped antenna has also been developed in the work. A plasma stream injected into the magnetic field from both sides of the plasma source causes the magnetic field expansion. The experimental results show that the magnetic field intensity is increasing as the discharge power increases and it reaches saturation in point 1. It is considered that the magnetic field expansion is caused by the plasma rotation, local wave heating, and the interaction between the plasma and magnetic field. The expanded magnetic field depends strongly on the plasma stream, its position in the magnetic field and its discharge manner, electron density, working gas, etc.

A more comprehensive experimental and modeling approach should be employed to investigate the characteristics of the magnetic field intensity, although so far it is still a highly challenging task. The magnetic field expansion scaling, plasma instability and the plasma loss should be researched in the future.

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References

1 Adams J H, Jr Hathaway D H et al. Revolutionary Concepts of Radiation Shielding for Human Exploration of Space. NASA-2005-TM213688
2 Winglee R M, Slough J, Ziemba T et al. Journal of Geophysical Research, 2000, **105**: 21067-21077
3 Winglee R Mt, Slough J, Ziemba Tim et al. Mini-Magnetospheric Plasma Propulsion (M2P2): High Speed Propulsion Sailing the Solar Wind. Space Technology and Applications International Forum-2000
4 Winglee R M. Advances in Magnetized plasma Propulsion and Radiation Shielding. IEEE, 2004
5 Winglee R M, Ziemba T, Euripides P et al. Computer Modeling of the Laboratory Testing of Mini-Magnetospheric Plasma Propulsion (M2P2). IEPC-01-200. 2001
6 Winske D. Journal of Geophysical Research, 93, 4, 2539-2552 (1988)
7 Brecht S H, Thomas V A. Journal of Geophysical Research, 1987, **92**: 2289
8 Funaki I, Yamakawa H, Fujita K et al. Study of a Plasma Sail for Future Deep Space Missions. Toulouse, France, IEPC 2003-89
9 Yamakawa H, Funaki I, Nakayama Y et al. Acta Astronautica, 2006, **59**(8–11): 777
10 Huba J D, Bernhardt P A, Lyon J G. Journal of Geophysical Research, 1992, 97
11 JIA Xiang-Hong, XU Feng et al. Radiation Protection, 2012, **32**(5): 311–315
12 Lieberman M A, Lichtenber A J. Principles of Plasma Discharges and Materials processing. (Pu Y K et al translated into Chinese, 2007)
13 FANG Tong-Zhen. Principle and Applications of Helicon-Wave Excited Plasma Sources. 1998
14 Baker D N, Kanekal S G, Hoxie V C et al. online 28 February 2013 10.1126/Science.1233518
15 JIA Xiang-Hong, XU Feng, WAN Jun et al. Chinese Journal of Vacuum Science and Technolgy, 2011, **31**(4): 481–484