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Conceptual design of Dipole Research Experiment (DREX)[*]

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Abstract

A new terrella-like device for laboratory simulation of inner magnetosphere plasmas, Dipole Research Experiment, is scheduled to be built at the Harbin Institute of Technology (HIT), China, as a major state scientific research facility for space physics studies. It is designed to provide a ground experimental platform to reproduce the inner magnetosphere to simulate the processes of trapping, acceleration, and transport of energetic charged particles restrained in a dipole magnetic field configuration. The scaling relation of hydromagnetism between the laboratory plasma of the device and the geomagnetosphere plasma is applied to resemble geospace processes in the Dipole Research Experiment plasma. Multiple plasma sources, different kinds of coils with specific functions, and advanced diagnostics are designed to be equipped in the facility for multi-functions. The motivation, design criteria for the Dipole Research Experiment experiments and the means applied to generate the plasma of desired parameters in the laboratory are also described.

Keywords: DREX, SPERF, dipole, magnetosphere, radiation belt

(Some figures may appear in colour only in the online journal)

1. Introduction

Due to its advantages in simultaneously obtaining global results with multiple point measurements, and as an effective complement to the satellite/ground observations and computer simulations, ground experimental simulation plays a crucial role in investigation of the space environment [1–5]. In recent years, various kinds of terrellas have been built to study the fundamental physical processes in magnetosphere plasmas to understand the geospace environment [6–8]. Of all the terrellas, a dipole configuration is essential to imitate the Earth magnetic field, and plasmas are confined in the capture region after injected or generated by plasma sources. Typical terrellas with a dipole magnetic field have been established to reveal the basic processes in space plasmas and remarkable achievements have been reached, such as the levitated dipole experiment (LDX) for high beta plasma confinement [6, 8, 9], collisionless terrella experiment (CTX) to investigate the basic principles of energetic particle physics in planetary magnetospheres [10, 11], also ring trap (RT)-1, a stable confinement of high beta plasmas produced to simulate 'laboratory magnetosphere' [12], and UCR-T1, which was built to study the interaction between cometary plasma and solar wind [13]. The characteristic parameters and research focuses of the devices are listed in table 1.

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Table 1. Characteristic parameters and related info of typical terrellas.

Devices	Size (m × m)	Plasma density	Electron energy	Research focuses
LDX [6, 8]	Φ5 × 3	10^{10}–10^{13} cm^{-3}	hot electrons: 200–300 keV	(1) Stability and dynamic of high-beta, energetic particles in dipolar magnetic fields by compressibility (2) Plasma confinement in magnetic dipoles. (3) Near steady state evolution of magnetically confined high temperature plasmas. (4) Reliable levitation of a persistent superconducting ring using distant control coils.
CTX [10, 11]	Φ1.4 × 1	∼10^{10} cm^{-3}	15–30 eV	(1) Conditions of excited wave spectrum necessary to induce chaotic radial diffusion. (2) Radial diffusion rates as a function of wave intensity. (3) Evolution of particle distribution during radial transport and comparison of observations to theoretical predictions.
RT-1 [12, 14, 15]	∼Φ2.5 × 1	10^{11}–10^{12} cm^{-3}	⩾10 keV	Research for high-beta plasma confinement and theoretical explanation for the self-organized confinement in a dipole magnetic field.
UCR-T1 [4, 13, 16]	Φ1.3 × 11	∼10^{12} cm^{-3}	15–20 eV	Explanation of cometary tail formation and control of the three-dimensional structure of a comet's magnetosphere by the interplanetary magnetic field.

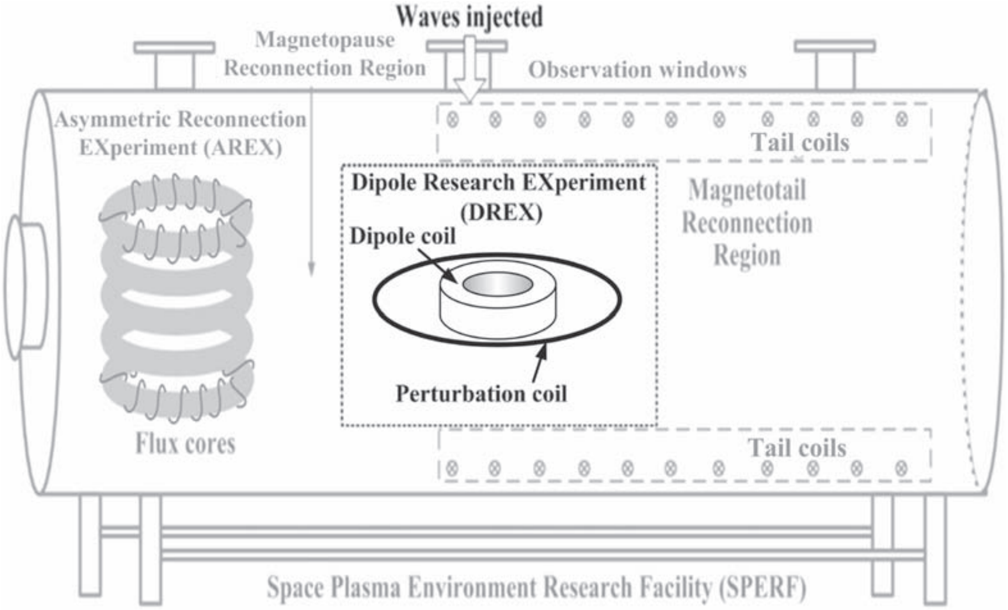

Figure 1. The schematic diagram of SPERF with DREX highlighted in the central region.

However, understanding the energization mechanism and transport characteristics of charged particles, and especially acceleration/loss/redistribution of energetic particles, which are crucially important for terrestrial plasma environment of spacecraft, is still challenging [10, 17–19]. Meanwhile, understanding the energetic particle dynamics is a key issue of geomagnetic storms and substorms. In particular, MeV electrons trapped in earth's outer radiation belt may seriously damage or even 'kill' satellites. Thus, current research interests in space exploration further motivate experimental investigation of the processes responsible for the basic feature of acceleration, transport, and loss of energetic electrons during storm period [20–22]. Specially designed experimental devices with key parameters determined by the scaling law between space and laboratory plasmas are beneficial for such investigations. Recently, China has launched a scientific project for a major state facility of fundamental research, Space Environment Simulation Research Infrastructure (SESRI), at the Harbin Institute of Technology (HIT). The project has three main research directions, namely materials and life-science in the space environment, as well as the space plasma environment. The Space Plasma Environment Research Facility (SPERF) for geospace plasma environment simulation, as a component of SESRI, is designed to investigate the fundamental issues in space plasma environment studies. It has broad experimental parameters and advanced diagnoses, and thus serves as a platform for researchers in space plasma physics to investigate essential space plasma phenomenon, such as energetic particles transport and interaction with waves in magnetosphere, as well as magnetic reconnection at magnetopause and magnetotail, etc. A terrella with a dipole magnetic field configuration, Dipole Research EXperiment (DREX), is used in the central stage of the SPERF to study the mechanism of acceleration/loss and wave-particle interaction of energetic particles in the radiation belt, as well as the influence of magnetic storms on the inner magnetosphere. In this paper, we present the conceptual design of the DREX, including the scientific goals and experimental plans, design criteria, and parameter realization.

2. Outline of DREX

2.1. Apparatus

SPERF aims to provide an international platform for a multifunction scientific research facility for space and plasmas physics. The schematic diagram of SPERF is shown in figure 1. It has a cylindrical vacuum chamber of 10 m in length and 5 m in diameter, with a base pressure of 10^{-4} Pa. The magnetic field configuration is produced by a set of magnetic field coils, plasma sources, antennas for electromagnetic wave generation, and plasma diagnostic equipment. The magnetic field coil set includes two flux cores to generate the simulated magnetosheath field (with other three driving coils) and plasma, a dipole coil for simulating the inner magnetosphere field, a perturbation coil to simulate magnetic storm distortion and exciting Alfvén wave perturbation, and a group of 'tail' coils to simulate the magnetotail and the near earth neutral line. The core part of DREX magnetic field, the dipole coil, is supported by metal frames instead of levitated as in LDX, and is designed to be rotatable in two directions to simulate different tilted positions and various interplanetary magnetic field (IMF) orientations. In DREX the characteristics of Alfvén and whistler waves, as well as their influences on transport of charged particles, are planned to be investigated. In the experiment, Alfvén waves with a characteristic wavelength on the order of meters are excited by a phase control antenna set with a frequency range of 1 MHz and 100 MHz, and a plasma beam injected by a pulse discharge plasma gun. Whistler waves, however, are excited by external antennas in a frequency range on the order of the electron cyclotron resonance (ECR) band. The characteristic wavelength of the whistler waves in DREX is in the order of centimeters. This dipole-like facility with its axisymmetry broken in the 'sun-earth' direction (i.e., the direction of the device axis) can investigate an analogic space plasma environment in a large spatial scale, with broadly adjustable parameters and high diagnostic accuracy. The main characteristics of the facility are as follows: (1) multiple research functions; (2) accurate diagnoses of magnetic fields (with resolutions of 2 mm in spatial and 50 ns in temporal); and (3) simulation of large-scale space structures of an equivalent size of 10–20R_E (the Earth radius) at the axis direction. Two sections in SPERF, Asymmetric Reconnection EXperiment (AREX) and DREX, are shown in figure 1. In this paper we will focus on the DREX section of the facility. The conceptual design of AREX will be presented elsewhere.

DREX aims to study the transport characteristics of energetic particles in dipole-like magnetic field configurations. With arrangements of various coils and plasma sources, it can be operated in three scenarios:

2.1.1. Dipole only scenario. In this case, only the dipole coil turns on to create a dipole-like magnetic field configuration to simulate specified inner magnetosphere plasma environments for radiation belt transport and wave-particle interaction studies.

2.1.2. Reconnection scenario. If both the dipole coil and the 'dayside' flux cores of AREX are on, the analogic solar wind-magnetosphere coupling configuration is then formed. Thus, DREX provides the 'inner' boundary condition for AREX to form asymmetric three dimensional (3D) reconnection configurations, while AREX on the other hand simulates the 'solar wind condition' for fundamental processes in DREX. Also, the dipole coil of DREX is designed to be rotatable in two directions, with a range of ±30°, to simulate the variation of IMF orientations and geomagnetic field tilting.

2.1.3. Storm perturbation scenario. By turning on the perturbation coil with a rapid ramp time, one can explore the inner magnetosphere response to magnetic storm perturbations.

2.2. Scientific goals and experimental plans

In general, the scientific goals of DREX are to simulate the environment of inner magnetosphere, particularly the radiation belt, and to investigate the trapping/acceleration/transport mechanism of energetic charged particles and their interaction with electromagnetic/electrostatic waves and disturbances. Thus, it provides an effective way to establish models of transport/energization/redistribution of energetic particles by ground experiments.

In detail, the scientific aims are as follows:

(1) Investigate the acceleration/transport of energetic charged particles;
(2) Measure the global temporal evolution of the simulated radiation belt;
(3) Explore inner magnetosphere responses to magnetic perturbations generated by the perturbation coil simulated the magnetic storm perturbations.

To achieve the goals listed above, a few of basic experiments can be planned as follows:

(1) Produce background plasma by electron cyclotron resonance (ECR) and hot cathode (LaB_6/BaO) [23] or cold bias cathode with gas injection plasma sources [24], while establishing the magnetic field with a dipole coil;
(2) Generate very-low frequency (VLF) and ultra-low frequency (ULF) waves with different kinds of excitation (antennas/ beams) to investigate the acceleration/transport of energetic particles;
(3) Investigate variations of the magnetic field configurations by means of operating the flux cores and the dipole coil simultaneously;
(4) Simulate the effect of magnetic storms on trapped electrons by perturbation coil disturbance.

3. Physical design

3.1. Design criteria

The parameters of DREX are designed by calibration relation of hydromagnetism between space and laboratory plasmas. It is demonstrated that if the initial conditions of two systems are geometrically similar and certain scaling relations are held, then the ideal magnetohydrodynamics (MHD) description of the systems evolves similarly to one another [1, 25, 26]. This allows us to perform laboratorial simulation experiments to quantitatively interpret the various MHD effects of astrophysical and space plasmas. Our emphasis here is not on the exact scaling of the Earth's magnetosphere to the laboratory but rather on a qualitative understanding of configurations, processes, and their interdependence on the large MHD scale in typical region of the geosynchronous orbit. In fact, the MHD scaling relation used in this experiment aims to determine the equilibrium plasma parameters in a designated magnetic field configuration, such as the plasma density, the electron energy, and the magnetic field strength. The plasma and magnetic field are established by MHD scaling relation and, thus, the basic MHD equilibrium plasma similar to the terrestrial space is obtained. During the experiments that will be carried out in DREX, the kinetic effects will be detected by a series of diagnostic accesses for local plasma parameter measurements and their global profiles. The characteristics of the Alfvén waves in DREX are determined by the MHD equilibrium with scaling relation corresponding to the terrestrial space. In recent years, satellite observations and numerical studies, which are mainly the dominant research methods in studying the space physics, have already made rapid progress and they have given promising results on the dynamic phenomena in magnetospheres, such as reconnection and substorms. DREX is built as an effective supplement research experimental platform. Based on MHD scaling relation, the plasma and waves generated in DREX are qualitatively, similar to the plasma and waves in the geomagnetosphere at the MHD level. Thus MHD waves corresponding to the terrestrial space can be studied and their influence on particle transport/acceleration characteristics can be evaluated.

In the *cgs* system, the ideal MHD equations are written as

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{v})=0, \quad (1)$$

$$\rho\left(\frac{\partial\boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}\right)=-\nabla p-\frac{1}{4\pi}\mathbf{B}\times\nabla\times\mathbf{B}, \quad (2)$$

$$\frac{\partial\mathbf{B}}{\partial t}=\nabla\times\boldsymbol{v}\times\mathbf{B}, \quad (3)$$

where ρ is the plasma mass density, $\boldsymbol{v}$ is the velocity, p is the pressure and $\mathbf{B}$ is the magnetic field. And the equation of state reads as

$$\frac{\partial p}{\partial t}+\boldsymbol{v}\cdot\nabla p=-\gamma p\nabla\cdot\boldsymbol{v}. \quad (4)$$

where γ is the adiabatic coefficient. It can be verified that the set of equations (1)–(4) remain invariant when the initial distributions of the size, density, pressure, timescale, velocity, and the magnetic field in two different systems satisfy the relations of

$$r=ar_1,\ \rho=b\rho_1,\ p=bp_1,\ t=a\sqrt{\frac{b}{c}}t_1,\ \boldsymbol{v}=\sqrt{\frac{c}{b}}\boldsymbol{v}_1,$$
$$\mathbf{B}=\sqrt{c}\mathbf{B}_1, \quad (5)$$

where the subscripts '1' refers to the parameters at the geosynchronous orbit here. Such a design is adapted to several experiments (e.g., UCR-T1 [4]) and also implemented for DREX. Typical parameters for the geosynchronous orbit ($r_1\approx 6.6R_E\approx 4\times 10^9$ cm) are $n_{e1}\approx$ 5–10 cm^{-3} [27], $T_{e1}\approx$ 2–3 keV, $T_{i1}\approx$ 5–10 keV [28] and $B_1\approx 200$ nT [27, 29]. Thus we can deduce that the characteristic velocity of the magnetofluid plasma is $V_A\sim 2\times 10^8$ cm s^{-1} [30] and the characteristic timescale is ~20 s. Therefore, we scale the laboratory system where the initial state is geometrically similar to the geospace to study the effects of the inner magnetosphere phenomena. For the simulated plasma in DREX, the plasma parameters and the strength of the applied magnetic field should be adjusted in such a way that the thermal beta β_e ($=8\pi n_e T_e/B^2$) remains the same for the two systems [4]. Based on the abovementioned scaling relations, the corresponding parameters for the DREX plasma should be $n_e\approx 10^{10}$–10^{13} cm^{-3}, $T_e\approx$ 1–100 eV and $B\approx 500$ G at the typical distance of $r\approx 200$ cm from the axis of the dipole, where the geosynchronous orbit region is simulated. The gyroradius of electrons and protons in such a plasma are ~0.03 cm and ~0.1 cm, respectively, with the ion temperature $T_i\approx 1$ eV; and the electron and ion inertial lengths are about 0.17 cm and 7.2 cm, respectively, which are much smaller than the MHD scale of meters. The characteristic velocity and timescale of the system are ~3×10^7 cm s^{-1} and ~3 μs, respectively, within the accuracy of diagnosis designed for the system (2 mm in spatial and 50 ns in temporal). Therefore, it is possible to investigate the acceleration process. The typical parameters at the geosynchronous orbit and in DREX are listed in detail in table 2.

Table 2. Typical parameters at the characteristic regions.

Parameters	Geosynchronous Orbit	DREX
Radius, r_0 (cm)	4×10^9	200
Plasma density, n_e (cm^{-3})	5	10^{12}–10^{13}
Electron temperature, T (eV)	5×10^3	1–100
Magnetic field at the equator, B (G)	2×10^{-3}	~500
Electron gyroradius, r_e (cm)	8.4×10^4	~0.03
Ion gyroradius, r_i (cm)	3.6×10^6	~0.1
Electron gyrofrequency, f (Hz)	5.6×10^3	1.4×10^9
Electron beta, β_e	0.25	~0.1

3.2. Parameter achievability

To achieve the scientific and experimental goals listed above, it is essential to realize the key parameters in experiments of various scenarios.

For Scenario (1), numerical simulations have been carried out to calculate the magnetic field distribution in the dipole geometry. Based on the analysis, the structure of the dipole coil is designed as a cylinder of the outer and inner diameters and the heights are 96 cm, 68 cm and 28 cm, respectively. Thus, the calculated magnetic field in the *x-z* plane, as the dipole coil operating in its full capacity with a current density of ~20 A mm^{-2}, for a rated total current of ~1.4 MA, is shown in figure 2. As can be seen in figure 2(b), the magnetic field strength reaches a maximum of ~1.0 T at the surface of the coil and fall down to ~500 G at a distance of $r=200$ cm. The high current power supply and water cooling system are also planned to maintain the generated magnetic field for 10 ms in a typical discharge.

For Scenario (2), complete magnetosphere configurations operating together with 'dayside' AREX flux cores as well as the 'tail' coil set are shown in figure 3(a), with all coils working together and both 'dayside' and 'nightside' *X*-lines being formed. The distance between the dipole coil and the flux core set can be adjusted by moving the dipole coil along a track. Also, by changing the axis orientation of the dipole and perturbation coil (with a maximum of ±30 degrees), one can simulate different magnetosphere configurations with various IMF orientations, as shown in figures 3(b) and (c).

For Scenario (3), a magnetic distortion produced by the perturbation coil is applied together with the primary dipole magnetic field to simulate a magnetic storm perturbation. It

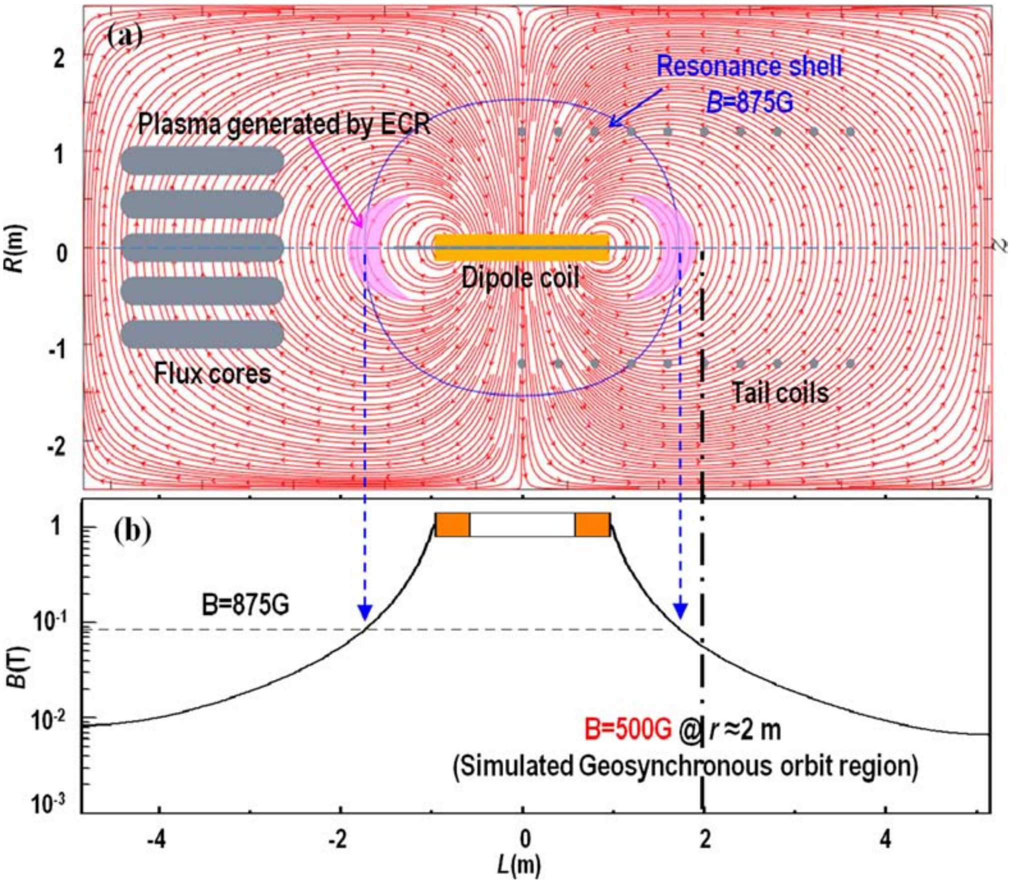

Figure 2. (a) Magnetic field configuration in the x-z plane and the resonance shell of 2.45 GHz ECR corresponding to $B = 875$ G, with other coils (off) also shown; (b) The magnetic field strength along the x axis.

induces a ~20%–30% surge of the local magnetic field at the concerned area when the experiments are carried out.

The radial direction of the chamber, of a radius of 250 cm, is divided in three regions. The region from the dipole axis ($r = 0$) to the inner boundary of the experimental region ($r = 100$ cm) includes the dipole coil and the area close to it, where the magnetic field significantly deviates from the perfect dipole geometry. The experimental region from its inner boundary ($r = 100$ cm) to the 'geosynchronous orbit' ($r = 200$ cm) is designed to be at least an order of magnitude longer than the ion inertial length (7.2 cm) to study the MHD physics. The rest ($r = 200$–250 cm) is left for adjusting ECR antenna, diagnosis distribution, other instruments and coil supporting/steering structures, as well as reducing the conducting wall effect of the vacuum vessel.

To realize the aimed n_e and T_e that are designed as shown above, both ECR and surface plasma sources are applied for DREX plasma generation. The power of ECR source is injected into the resonance area of the dipole field, to generate a background plasma by heating the electrons. A resonance shell of 875 G magnetic field for 2.45 GHz ECR source in DREX is shown in figure 2. Energetic particles are then generated by both ECR heating and the interaction with different kinds of electromagnetic and electrostatic waves generate by wave excitation coils, antennas etc. In the experiments, neutral hydrogen gas injections are applied to stabilize the hot electron interchange modes (HEI's) from energetic electrons produced by ECR and to provide sufficient gas source for ionization. Quasi-stationary high beta plasma discharges are expected to be obtained in the flat part of the microwave heating pulse. On the other hand, the surface plasma source (such as the LaB_6 hot cathode or the bias cold cathode) is equipped at certain position of DREX to generate additional plasmas to increase the number density and so achieve the specified plasma parameters.

It is very important that the device has the capability of monitoring and characterizing the plasma parameters and profiles for DREX experiments. We then plan a series of diagnostic accesses for local and global measurements of plasma parameters, such as density, electron temperature, magnetic field, and etc. For example, the local characteristics of the plasma density are detected by various kinds of electrostatic probes, while the global density profile and fluctuation are observed by fast cameras and interferometers. Also, Thomson scattering is used to perform local measurements of the electron temperature and density and polarized light interferometer is applied to monitor the fluctuation of the magnetic field and plasma density. In addition, the energy of energetic particles will be diagnosed by gridded energy analyzer and multichannel soft x-ray spectrometer. And a movable gridded particle analyzer is employed to study the transport of the energetic particles.

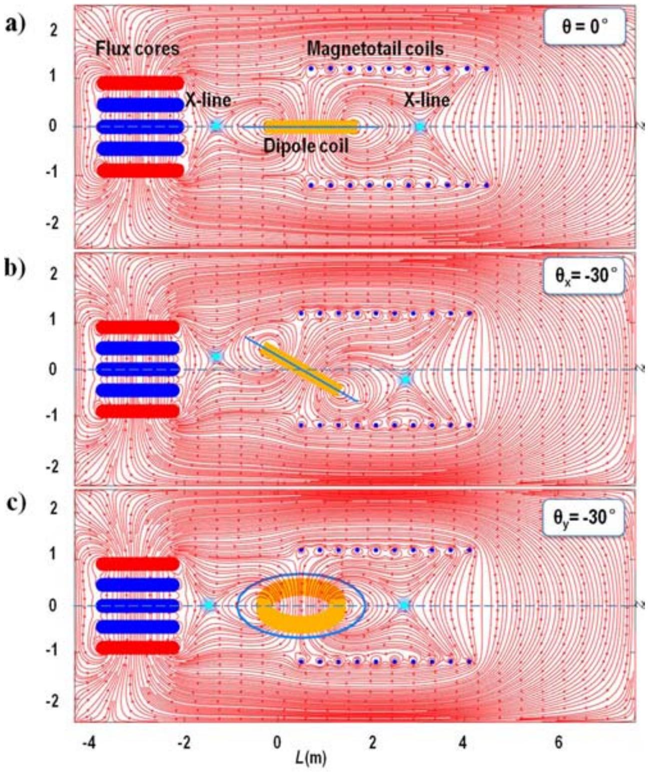

Figure 3. Magnetic field configurations in the x-z plane with rotations of the dipole coil to simulate different IMF orientations: (a) a horizontal dipole coil for the south-towards IMF; (b) the dipole coil rotation around y-axis to simulate the IMF tilt; (c) the dipole coil rotation around x-axis to simulate a southwestward IMF.

4. Conclusion

A new laboratory terrella (DREX) has been designed and planned to be constructed at HIT with aims of investigating the distribution/acceleration/transport of energetic particles, to study their interaction with electromagnetic and electrostatic waves in the goemagnetosphere plasmas, and verify the model of space plasma processes. Based on the MHD scaling relation, the plasma generated in DREX is analog to the plasma in the geomagnetosphere at MHD scales. The device can provide an international research platform for investigation of energetic particle physics and transport processes in terrestrial plasmas. Multiple research functions are also available with widely adjustable parameters and high resolution diagnostics. The designed plasma parameters and the required magnetic field in the concerned area are obtained by means of surface/ECR plasma sources and specially designed coils. The influence of perturbations simulating magnetic storms and solar winds on DREX plasma are simulated in 3D configurations.

References

[1] Schindler K 1969 *Rev. Geophys.* **7** 51
[2] Sheldon R B and Spurrier S 2001 *Phys. Plasmas* **8** 1111
[3] Koepke M E 2008 *Rev. Geophys.* **46** RG3001
[4] Yur G *et al* 1995 *J. Geophys. Res.* **100** 23727
[5] Rypdal K and Brundtland T 1997 *Journal de Physique IV* **07** C4-113-C4-132
[6] Garnier D T *et al* 2006 *Phys. Plasmas* **13** 056111
[7] Garnier D T *et al* 2009 *Nucl. Fusion* **49** 055023
[8] Zhukovsky A *et al* 2005 *Fusion Eng. Des.* **75–79** 29
[9] Kesner J *et al* 2006 First experiments to test plasma confinement by a magnetic dipole *Proc. of the 21st IAEA Fusion Energy Conf. (Chengdu)*
[10] Mauel M E, Warren H H and Hasegawa A 1992 *IEEE Trans. Plasma Sci.* **20** 626
[11] Barnes C W *et al* 1984 *Nucl. Fusion* **24** 267
[12] Yoshida Z *et al* 2013 *Plasma Phys. Control. Fusion* **55** 014018
[13] Minami S *et al* 1986 *Geophys. Res. Lett.* **13** 884
[14] Yoshida Z *et al* 2006 *Plasma and Fusion Research* **1** 008
[15] Saitoh H *et al* 2015 *Phys. Plasmas* **22** 024503
[16] Rahman H U *et al* 1989 *J. Geophys. Res.* **94** 6873
[17] Dragt A J and Finn J M 1976 *J. Geophys. Res.* **81** 2327
[18] Warren H P *et al* 1996 *Phys. Plasmas* **3** 2143
[19] Artemyev A V *et al* 2015 *Nat. Commun.* **6** 8143
[20] Shprits Y Y *et al* 2013 *Nat. Phys.* **9** 699
[21] Chen Y, Reeves G D and Friedel R H W 2007 *Nat. Phys.* **3** 614
[22] Ji H and Zweibel E 2015 *Science* **347** 944
[23] Goebel D M, Hirooka Y and Sketchley T A 1985 *Rev. Sci. Instrum.* **56** 1717
[24] Lehnert B, Hellsten T and Raggi R 1974 *Phys. Scr.* **9** 53
[25] Ryutov D D, Drake R P and Remington B A 2000 *The Astrophysical Journal Supplement Series* **127** 465
[26] Wessel F J *et al* 1990 Fast magnetization of a low-to high-beta plasma beam *OE/LASE'90* (Los Angeles, CA: International Society for Optics and Photonics)
[27] Borovsky J E and Denton M H 2010 *Journal of Geophysical Research: Space Physics* **115** A08217
[28] Birn J *et al* 1997 *J. Geophys. Res.* **102** 2309
[29] Rufenach C L, McPherron R L and Schaper J 1992 *Journal of Geophysical Research: Space Physics* **97** 25
[30] Huba J 2009 'NRL Plasma Formulary 2009': DTIC Document (Naval Research Laboratory)