Conceptual Design of the Tail Research EXperiment in Space Plasma Environment Research Facility (SPERF-TREX)

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Abstract

The Space Plasma Environment Research Facility (SPERF) for ground simulation of space plasma environment is a key component of Space Environment Simulation Research Infrastructure (SESRI), a major national science and technology infrastructure for fundamental researches. It is designed to investigate outstanding issues in space plasma environment, such as energetic particles acceleration, transport, and interaction with electromagnetic waves, as well as magnetic reconnection processes, in the magnetospheric plasmas, etc. Tail-Research EXperiment (TREX) is part of the SPERF for laboratory studies of space physics relevant to magnetic reconnection, dipolarization and hydromagnetic waves excitation in the magnetotail. SPERF-TREX is designed to carry out three types of experiments: the tail plasmoid for magnetic reconnection, dipolarization front formation, and magnetohydrodynamic waves excited by high speed plasma jet. In this paper, the scientific goals and three scenarios of SPERF-TREX for typical processes in space plasmas are presented, and experimental plans for SPERF-TREX are also reviewed, together with plasma sources applied to generate the plasma with desired parameters and various magnetic configurations.

Keywords: SPERF-TREX, wave-particle interaction, magnetic reconnection, dipolarization

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

1. Introduction

Certain fundametal processes in space plasmas are the source of substantial variations in space environment and generation of high-energy particles, by plasma heating, acceleration and deviations of considerable environmental factors (density, temperature, etc.), as major causes of space environmental disturbances [1–6]. Therefore, exploring the evolution of such basic processes in space plasmas is helpful for understanding space plasma environment and providing theoretical and technical supports for the design and safe operation of spacecraft. Magnetic reconnection, dipolarization fronts and high velocity bursty bulk flows (BBFs), waves and turbulence are typical plasma environment processes in the magnetotail [7–11]. In particular, the magnetic reconnection process can convert magnetic energy into the kinetic energy of charged particles (including their thermal motions) in a short time, to play a key role in explosive space environmental processes (such as magnetospheric substorms, etc.) [12–20]. Processes of the dipolarization front, electromagnetic waves, and turbulence are also major causes of acceleration of charged particles in producing energetic particles [21–23].

As an important part of magnetospheric space environment, the magnetotail is a key area to study the physics of magnetospheric substorm [24–29]. Therefore, magnetotail plasma physics has been the focus of space physics for decades. The crucial issues debated among the main magnetospheric substorm models (the Near Earth Neutral Line model, the cross-tail current disruption model, the magnetosphere-ionosphere coupling model, etc.) in international space science community are directly related to the magnetotail plasma process [24–29]. Clearly, most fundametal processes related to the issues have typical multi-scale characteristics for which a single or several point observations of satellites cannot obtain a full picture [19, 20]. It thus brings great challenges to the verification of relevant models. Therefore, ground laboratories have been designed and built to simulate relevant space plasma processes by making use of scaling relations between experiments and the terrestrial space to realize controllable, repeatable, and global simultaneous measurements [30, 31]. With reference to the basic parameters of geospace physics, the Space Plasma Environment Research Facility (SPERF) is proposed and designed for studing magnetosphere processes such as plasma wave generation and propagation, particle accelerationa and transport, magnetic field reconfigurations by three-dimensional magnetic reconnection and dipolarization, and etc [32–40].

The SPERF is a key component of Space Environment Simulation Research Infrastructure (SESRI), a major national science and technology infrastructure for fundamental researches. It consists of three research sections, that is, the Asymmetric Reconnection EXperiment (AREX) [32, 35, 37, 38], the Dipole Research EXperiment (DREX) [33, 34, 36–40], and the Tail Research EXperiment (TREX) [38], for simulating magnetopause, radiation belt, and magnetotail regions, respectively.

Different plasma sources and plasma diagnostic equipments provide the facility of multi-configurations to simulate space plasma environment in a large spatial scale, with widely adjustable parameters and high diagnostic accuracy. In this paper, we present the conceptual design of the TREX, including the scientific goals and experimental plans, design criteria, and parameter realization. The layout of the paper are as follows. In the next section, we briefly describe major functions of TREX and technologies applied. In section 3, we further investigate the design criteria and key parameters of the device. The designed experiment scenarios are analyzed in section 4. Then the paper is concluded in a summary of section 5.

2. Function and technology

SPERF is built to provide international platforms of a multifunction scientific research facility for space and plasmas physics, including the AREX to study asymmetric reconnection dynamics relevant to coupling between the interplanetary and magnetospheric plasmas [32, 35, 37, 38], DREX to study transportation characteristics of energetic particles in dipole-like magnetic field configurations [33, 34, 36–40], while TREX mainly investigates (i) 3D magnetic reconnection of the magnetosphere plasmas, especially in the magnetotail region, (ii) propagation of BBFs in the magnetotail and excitation of hydromagnetic waves, (iii) formation and propagation processes of dipolarization fronts and related spatial environmental effects, and also (iv) the injection process of energetic particles into the radiation belt.

The schematic diagram of SPERF especially TREX is shown in figure 1. As a subsystem of SPERF, TREX shares the vacuum environment and power supply for magnets and plasma sources, as well as plasma diagnostics and data collection with the AREX and DREX of SPERF. As for the diagnostic, two kinds of probes, the electrostatic (resolution 1 μs, 1 cm) and the magnetic (resolution

1 μs, 2 mm) probes, and also interferometers, the HCN (resolution 100 μs, 4 cm) and the polarization (resolution 1 μs, 3 cm), as well as spectroscopy and high-speed camera (max 200,000 fps) are applied to measure the equilibrium and fluctuation parameters of plasma during different experimental processes in SPERF. In addition, the TREX platform includes two plasma sources, the LaB_6 hot cathode source and a plasma gun, and magnetic mirror field coils, etc. The dipole field and its confined plasma are provided by DREX.

The vacuum chamber is cylindrical with 10.5 m in length and 5 m in diameter. A set of magnetic field coils is employed to realize different magnetic field configurations, including a dipole coil for simulating the inner magnetosphere and two magnetic mirror coils for simulating the magnetotail. Different plasma sources are used to produce plasmas with widely adjustable parameters in different research regions.

The roadmap for achieving above research objectives of TREX is as follows.

(1) By combining the TREX field/plasma and the DREX field/plasma, an X-point (X-curve in 3D) and three-dimensional magnetic reconnection configuration can be generated. The TREX main plasma is generated by the LaB_6 hot cathode source and confined by the mirror field, while the DREX background main plasma is generated by a cold cathode plasma source with anisotropic energetic particles in radiation belt generated by an ECR plasma source.

(2) Making use of the high-power plasma gun to generate a high velocity BBF, a dipolarization front can be formed, while also exciting low-frequency electromagnetic waves.

(3) The study of energy particle injection process in radiation belt can be carried out by an additional electron gun.

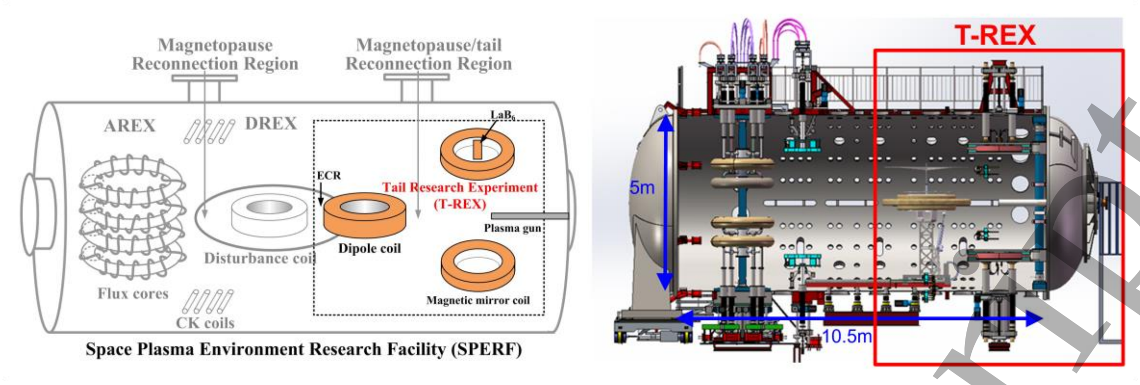

Figure 1. The schematic diagram of SPERF with TREX highlighted on the right.

3. Design criteria and major parameters

Parameters of TREX in the fluid scale are designed by scaling relations between space and laboratory plasmas. It has been demonstrated that if two systems are geometrically similar and the parameters follow certain scaling relations, the description of the systems evolves similarly to one another [33, 34, 36–40]. We thus can perform simulated experiments in laboratorial to quantitatively interpret the various effects of astrophysical and space plasmas.

For the kinetic parameters, however, we can start from Vlasov-Maxwell equations:

$$\frac{\partial f_\alpha}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_\alpha}{\partial \boldsymbol{x}} + \frac{q_\alpha}{m_\alpha}\left(\boldsymbol{E} + \frac{\boldsymbol{v}\times\boldsymbol{B}}{c}\right) \cdot \frac{\partial f_\alpha}{\partial \boldsymbol{v}} = 0, \quad (1)$$

$$\nabla \cdot \boldsymbol{E} = 4\pi \sum_\alpha n_{\alpha 0} q_\alpha \int \mathrm{d}\boldsymbol{v}\, f_\alpha, \quad (2)$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \sum_\alpha n_{\alpha 0} q_\alpha \int \mathrm{d}\boldsymbol{v}\, \boldsymbol{v} f_\alpha, \quad (3)$$

where f_α is the distribution function and α is the particle for ion or electron, $\boldsymbol{v}$ is the velocity, q_α is the particle charge, $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field, and $n_{\alpha 0}$ is the number density. After normalization, we can get

$$\left(\frac{1}{t_0} f_0\right) \frac{\partial \bar{f}_\alpha}{\partial \bar{t}} + \left(\frac{v_0}{l_0} f_0\right) \bar{\boldsymbol{v}} \cdot \frac{\partial \bar{f}_\alpha}{\partial \bar{x}} + \left(\frac{q_\alpha B_0}{m_\alpha c} f_0\right) (\bar{\boldsymbol{E}} + \bar{\boldsymbol{v}} \times \bar{\boldsymbol{B}}) \cdot \frac{\partial \bar{f}_\alpha}{\partial \bar{\boldsymbol{v}}} = 0, \quad (4)$$

with $v_0 t_0 = l_0,\ \omega_{c\alpha} t_0 = 1,\ v_0 = V_A$, and

$$l_0 = V_A/\omega_{ci} = d_i (= c/\omega_{pi}). \tag{5}$$

It can be verified that when the initial distributions of the size, density, pressure, timescale, velocity, and the magnetic field in two different systems satisfy the scaling relations, the equations remain invariant. Typical parameters for the plasma in the magnetotail are magnetic field $B_0 \approx 50$ nT $\approx 10^{-3}$ G, plasma density $n_0 \sim 0.1$–1 cm^{-3}, Alfvén velocity $V_A \sim 10^8$ cm s^{-1}, typical length $l_0 = d_i \sim 10^7$ cm, typical time $t_0 = 1/\omega_{ci} \sim 0.1$ s, and electron temperature $T_e \sim 10^4$ eV [32, 38]. Thus, the corresponding characteristic parameters for the TREX plasma should be $B_0 \sim 10^2$ G, $n_0 \sim 10^{10}$–10^{12} cm^{-3}, $V_A \sim 10^7$ cm s^{-1}, $l_0 = d_i \sim 10$ cm, $t_0 = 1/\omega_{ci} \sim 10^{-6}$ s, and $T_e \sim 1$–10 eV according to the scaling relations [32, 38], and the initial state is geometrically similar to the geospace to study the effects of the magnetosphere phenomena. The gyro-radii of electrons and ions in such a plasma are about 0.2 mm and 1 cm respectively, with the ion temperature is set as 1 eV, and the electron and ion inertial lengths are about 0.2 cm and 10 cm, respectively. The characteristic velocity and timescale of the system are ~ 10^7 cm s^{-1} and ~ 1 μs, respectively, within the accuracy of diagnosis designed for the system. In addition, the electron mean free path in the device is ~ 10^3 cm, with the electron temperature of 10–100 eV and the electron-neutral collision rate of $\nu_{en} \sim 10^5$ Hz (with the working pressure of 0.01 Pa). Clearly, the electron mean free path is longer than the typical device size (a few meters). On the other hand, for typical magnetic field parameter of 500 G, the electron gyro-frequency is $\sim 10^9$ Hz, bounce frequency is $\sim 10^6$ Hz, and drift frequency is $\sim 10^3 - 10^4$ Hz. Thus, for cyclotron and bounce motions, the frequencies are much faster than the collision rate. Therefore, the plasma can be considered collisionless except for taking the drift motion into account.

It is essential to realize the key parameters of the experiment to achieve the scientific and experimental goals. In addition to the dipole coil and its plasma sources in DREX, TREX has its own magnetic coils and plasma sources including two magnetic mirror coils, a LaB_6 plasma source, and a plasma gun.

The two magnetic mirror coils generate the magnetic field in either magnetic sheath or magnetotail region, according to various operation scenarios, to simulate different 3D reconnection configurations with the DREX dipole field. In order to better simulate the near-earth X-line of the magnetotail, the magnetic mirror coil is designed with an elliptical structure to generate an elongated X-line along the direction of dawn and dusk for simulation of the "magnetotail neutral line". The distance between the two magnetic mirror coils is designed to be adjustable within the range of 140–300 cm (corresponding to $z = \pm$ (70–150) cm) to generate a magnetic reconnection configuration similar to the asymmetric magnetic reconnection configuration at the magnetopause or the approximately symmetric magnetic reconnection configuration between the "north-south (up and down) lobes" of the magnetotail. The magnetic mirror coil is elliptical with a rectangular cross-section winded by copper wires. The detailed parameters of the magnetic mirror are shown in table 1. A continuously adjustable magnetic field can be generated by varying the total current of the mirror coils between 90 kA and 480 kA. When the currents of the dipole and the mirror coils are 400 kA and 180 kA, respectively, the magnetic field along the center of magnetic mirror coil (red line in figure 2(a)) is shown in figure 2(b), while the minimum and maximum of the magnetic field along center of the mirror coils are about 145 G and 450 G, respectively.

Table 1. The parameters of magnetic mirror coils.

Parameters	Values
Outer major axis	136 cm
Outer minor axis	90 cm
Inner major axis	106 cm

Inner minor axis	60 cm
Thickness	16 cm
Turns	16×16
Peak current	480 kA
Capacitors	6.23 mF/13 kV
Energy storage capacity	0.53 MJ
Rising period	0.2–1 ms

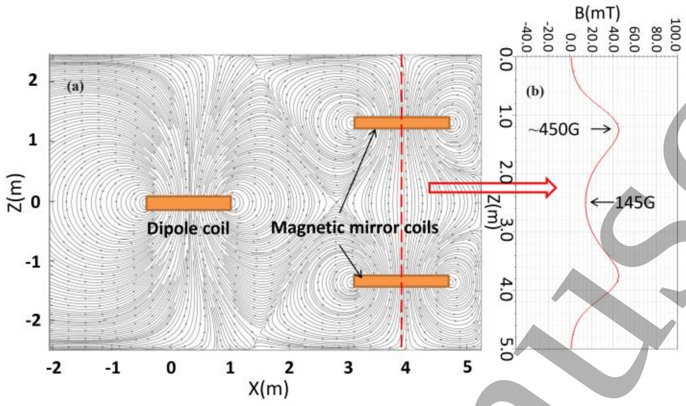

Figure 2. Magnetic configuration of the DREX-TREX system with the local magnetic field distribution along the center line of the magnetic mirror.

As for the plasma sources in TREX, the LaB_6 hot cathode plasma source is utilized to generate TREX plasma which is then confined by the magnetic mirror field. The position of the LaB_6 source near the upper mirror coil is changeable in two directions (*X* and *Z*) regarding to the center of the two magnetic mirror coils. The plasma density produced by the LaB_6 source is 10^{12}–10^{13} cm^{-3}, with at least a region of 30 cm along the major axis (*Y*) and 5 cm along the minor axis (*X*) of the magnetic mirror coil. The plasma in the interested region exists for about 1–10 ms limited by the operation pulse of the magnetic mirror field.

Another plasma source is the plasma gun, injected into the area at the center of the right side of the SPERF chamber. The “shotting” position of the plasma beam by the gun is adjustable by a distance of 1 m toward the dipole coil. The plasma density generated by the gun can reach ~ 10^{15} cm^{-3} while the velocity of the plasma can reach ~ 100 km s^{-1}. The generated high speed plasma beam on one hand can be used to drive the TREX magnetic reconnection process; while on the other hand, it can be used to simulate high-speed BBFs in the magnetotail, form a dipolarization front, or directly excite Alfvén waves in the dipole field region of DREX.

4. Designed scenarios

TREX together with AREX and DREX constitutes a global magnetospheric magnetic field topological configuration and key physical process simulation research system [38]. By arrangements of various coils and plasma sources, it can be operated in three scenarios:

(1) 3D magnetic reconnection scenario

The vacuum magnetic field configurations relevant to the dayside magnetopause and nightside magnetotail reconnection are shown in figure 3. In this scenario, DREX plasma and coils, the LaB_6 generated plasma, and magnetic mirror coils are working together. In the case of magnetopause reconnection (figure 3(a)), the dipole coil together with ECR and bias cold plasma sources are turned on to create a dipole confined plasma and simulate specified “magnetopause” boundary condition to form 3D “dayside” reconnection configurations, while LaB_6 source in TREX simulates the “solar wind” condition for fundamental processes in DREX. Also, the dipole coil of DREX is designed rotatable in two directions of about ±15°, to simulate the variation of the interplanetary magnetic field (IMF) orientation for 3D “dayside” reconnection investigation. In this case, the LaB_6 source is located in the mirror region to provide the “solar wind” plasma. Furthermore, the distance between the two magnet mirror coils is adjustable with the LaB_6 plasma source. On the other hand, figure 3(b) represents the case of magnetotail reconnection. Different from the magnetopause case, the two LaB_6 sources are now located toward the dipole side, across arms (separatrices) of the X-point, to provide the "north/south (upper/lower) lobes" of the magnetotail plasma (in the shaded regions). Therefore, a "nightside" reconnection configuration is produced with the X-point presented "near earth neutral line". Thus, many different fundamental processes of magnetospheric plasmas can be studied in the scenario.

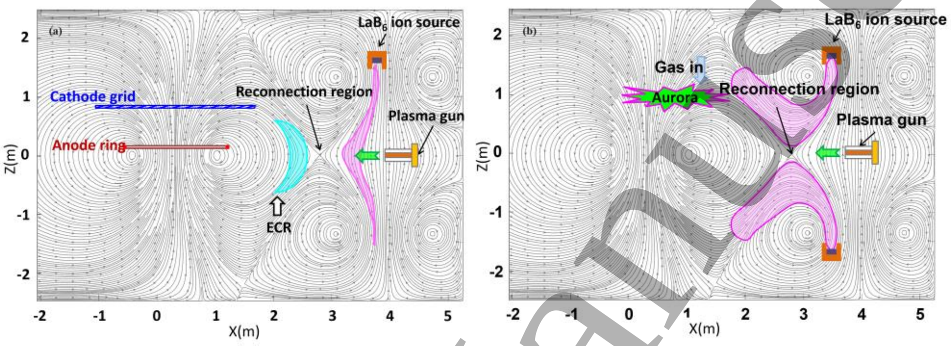

Figure 3. Magnetic field configurations for simulating (a) magnetopause and (b) magnetotail reconnection.

(2) Hydromagnetic waves excitation scenario

The plasma gun can generate high energy density plasma beams with high current density and high plasma density. It can then be used to perturb the magnetic field lines of DREX dipole field to generate fast or slow magnetosonic waves as well as shear or compressional Alfvén waves, as shown in figure 4. According to the scaling law between space and laboratory, at the target region of the "geo-synchronous orbit", the magnetic field is ~ 500 G and the plasma density is ~ 10^{12} cm^{-3}, as well as the cyclotron, bounce, and drift frequencies of the electron are estimated ~ 1 GHz, ~ 1 MHz, and ~ 1–10 kHz, respectively. Also, the wavelength of simulated ULF waves is ~ 10–10^4 cm. The typical size of the plasma body is 2 m. Then, we can study magnetohydrodynamic waves with typical wavelengths of λ ~ 0.2–200 cm (or the angular wave number m ~ 3–300) and frequencies of f_{ULF} ~ 10–10^3 MHz.

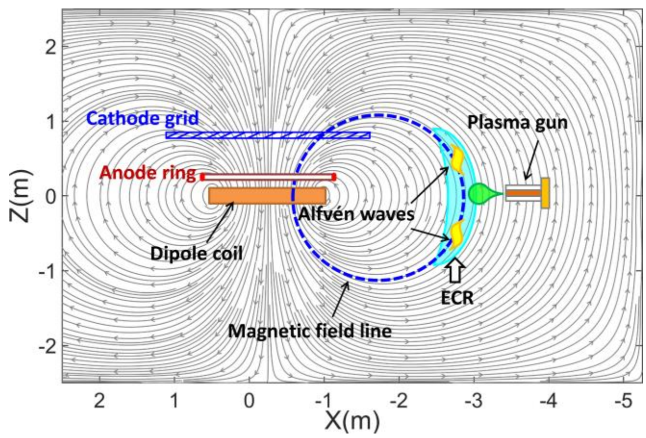

Figure 4. Magnetic field configurations for hydromagnetic waves excitation.

(3) Dipolarization front scenario

The magnetotail BBFs and dipolarization fronts generation can be simulated by DREX dipole field and TREX plasma gun, as shown in figure 5.

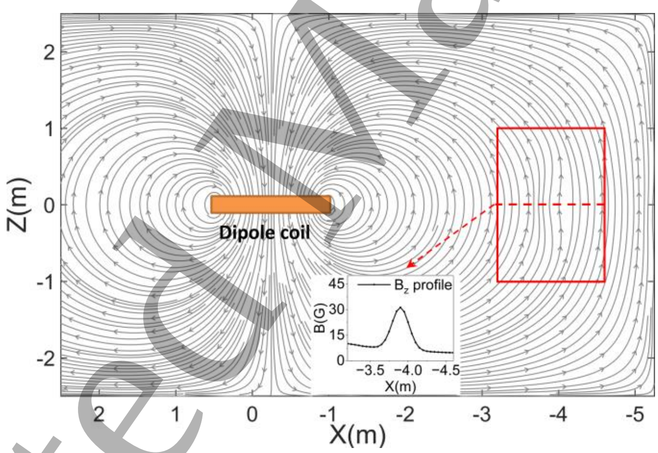

Figure 5. Magnetic field configuration with the plasma gun for hydromagnetic waves excitation.

(i) The burst high-speed flow (BBF) in the magnetic tail is generated by high-power plasma gun, which can also excite the dipolarization front (DF), and excite the low-frequency electromagnetic wave.

(ii) The injection process of energetic particles in the radiation belt can be studied by adding an electron gun (supported by other scientific research projects).

The BBFs can be easily generated by the high speed and high power plasma gun. Also, the dipolarization front formation similar to that in the geomagnetotail can be achieved with particularly chosen parameters.

Furthermore, the comparison between local acceleration by waves and tail injection mechanisms for energetic particle generation can also be done by plasma gun injection with DREX wave-particle interation experiments.

5. Summary

In conclusion, combined with DREX, TREX is a platform for laboratory simulation and research of key physical processes of the earth's magnetotail with high spatio-temporal resolution diagnostics, and its specifications achieve the international leading level, in supporting space environment and magnetospheric physics researches in China. The scientific goals of TREX are: (1) to simulate and study the typical magnetic reconnection process of the magnetotail, (2) to analyze the propagation process and influence of the hydrodynamics waves genenration, dipolarization front formation, and BBFs excitation in the magnetotail, and (3) to explore the propagation process and distribution properties of the injected energetic particles in combination with DREX; so as to provide experimental data and physical basis for exploring and studying the inducing mechanism of space weather processes. The designed plasma parameters, as well as the required magnetic field in the interesting area are obtained by means of different plasma sources and specially designed coils. The results of TREX laboratory simulation research, combined with satellite observation, as well as theoretical and numerical simulation researches, can be applied to study the mechanism of space weather processes such as magnetospheric substorms and the exploration and cognition of space environmental effects, serving space exploration and aerospace industry.

Acknowledgments

This work was supported by State Commission of Development and Reform of China, and National Natural Science Foundation of China (Nos. 42261134533, 11261140326 and 11405038).

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