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# Feasibility of Artificial Geomagnetic Field Generation by a Superconducting Ring Network

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**Abstract**

The geomagnetic field shields the Earth from a large proportion of incoming radiation, and has thus played a key role in sustaining life on Earth. Paleomagnetic measurements have shown that the geomagnetic field undergoes many reversals of polarity. Continuous observations of the field intensity have revealed a weakening of approximately 10% over the last 150 years. If we assume that this trend indicates the onset of polarity reversal, the geomagnetic field, particularly the dipole component, may weaken sufficiently over the next thousand years to expose the atmosphere and nearby space to significantly increased levels of cosmic and solar radiation. This may have a serious impact on vital infrastructure such as satellites, air traffic, and electricity networks, as well as on global climate changes, indicating that measures should better be taken in an attempt to support the limited protection provided by the remaining higher-order multipole fields and atmosphere. Here we show that a series of planet-encircling superconducting rings can provide an artificial geomagnetic field equivalent to 10% of the present-day field necessary to prevent adverse effects. A feasible system consists of 12 latitudinal high-temperature superconducting rings, each carrying 6.4 MA current with a modest 1 GW of power requirement.

**Keywords:**
geomagnetic field, polarity reversal, artificial geomagnetic field generation, solar radiation, high-temperature superconductor, superconducting cable, superconducting ring network, fusion

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## 1. Introduction

The geomagnetic field of the Earth shields the atmosphere from a large proportion of incoming radiation, and has thus played a key role in sustaining life on Earth [*1*]. Paleomagnetic measurements have shown that the geomagnetic field has undergone many reversals of polarity [*2*], and theoretical research on the mechanism responsible for establishing such a field has indicated that the geomagnetic field is generated by a self-sustaining dynamo realized by the fluid metal of the Earth's outer core [*3*]. This behavior is a result of the self-organization process of a magneto-hydrodynamic (MHD) fluid with a solid internal core. Simulations have recently demonstrated this self-generation of the geomagnetic field and the intrinsic reversal of polarity [*4-6*].

Continuous observations of the intensity of the geomagnetic field over the last 150 years have revealed a weakening of approximately 10% over that period [*7-9*]. If we assume that this trend indicates the onset of polarity reversal, the geomagnetic field, particularly the dipole component, may weaken sufficiently over the next thousand years [*10*] to expose the Earth to increased levels of cosmic and solar radiation. Though the inspection of the past reversals does not show clear evidence of massive biological extinctions, which might have been mainly due to the protection of the Earth surface by the atmosphere [11], such an event would have a serious impact on vital infrastructure such as satellites, air traffic, and electricity networks, as well as on global climate changes. Paleomagnetic observations suggest that the reversal of the geomagnetic field may take thousands of years to complete [*12*, *13*], indicating that measures should better be taken in an attempt to support the limited protection provided by the remaining higher-order multipole fields [*14–17*] (with much smaller strength than that of dipole field) and atmosphere.

As a means of protecting the Earth should the geomagnetic field weaken dramatically, whether it happens in a thousand years or much later, the present study examines the feasibility of generating an artificial magnetic field by constructing a series of latitudinal superconducting rings around the planet. The magnetic shielding required to protect the Earth from high-energy protons is analyzed by numerical calculations considering reduced geomagnetic field intensities, and a design concept based on high-temperature superconducting (HTS) cables is proposed.

## 2. Structure and magnetic shielding of the magnetosphere

The Earth is protected from direct exposure to high-energy cosmic particles by the magnetosphere, which is formed by interaction between the geomagnetic field and the solar wind [*18*]. MHD simulations have resolved the structure of the magnetosphere in detail [*19–21*]. The typical spatial distribution of magnetic field lines in the present-day magnetosphere is shown in Fig. 1(a), using three-dimensional magnetic field data as obtained by MHD simulation [*22*]. The boundary of the magnetosphere occurs at the location where the magnetic pressure is balanced by the plasma pressure in the solar wind. The radius of this boundary from the center of the Earth ($r$) is approximately given by

$$\left(\frac{r}{r_{\mathrm{E}}}\right)=\left(\frac{B_{\mathrm{E}}^{2}}{\mu_0 N m U^{2}}\right)^{1/6}, \tag{1}$$

where $r_{\mathrm{E}}$ is the Earth radius (~6378 km), $B_{\mathrm{E}}$ is the magnetic field strength at the equator (~$3\times10^{-4}$ T), $\mu_0$ is the permeability of vacuum, $N$ is the number density of protons in the solar wind (~$5\times10^{6}$ m$^{-3}$), $m$ is the proton mass ($1.67\times10^{-27}$ kg), and $U$ is the average velocity of protons (~$3\times10^{4}$ m s$^{-1}$, corresponding to ~500 eV).

Under the present geomagnetic field, the boundary of the magnetosphere occurs at approximately $10R_{\mathrm{E}}$ (~63800 km), as shown in Fig. 1(a). Therefore, if the geomagnetic field weakens, the effective boundary of the magnetosphere will shift closer to the Earth. Although non-dipole components (i.e., quadrupole component and higher multipoles) of the geomagnetic field may persist at a certain magnitude [*4-6*, *20*], only the dipole component is considered here as a first analysis. As the structure of the magnetosphere is determined by the MHD behavior, the structure will be maintained as the geomagnetic field weakens, accompanied by a shortening in spatial lengths.

For example, if the dipole component weakens to 10% of the present-day magnitude, the magnetospheric boundary will be located at approximately $4.6R_{\mathrm{E}}$ (~29600 km), as shown in Fig. 1(b), corresponding to an altitude of ~23200 km from sea level. As this altitude is within the geostationary orbit (~35800 km) of satellites, a large number of present satellites will be at substantial risk to damage by solar wind radiation. Figure 2 shows the movement of the magnetospheric boundary as a function of the geomagnetic field. The boundary will reach the low Earth orbit (~1400 km) if the geomagnetic field decreases to approximately 0.2% of the present-day magnitude (see Fig. 1(c)). Further weakening of the geomagnetic field will progressively expose other craft to radiation damage (e.g., the International Space Station at

~300 km). The boundary will reach sea level at 0.1%, resulting in direct irradiation of the atmosphere, which might cause global climate changes.

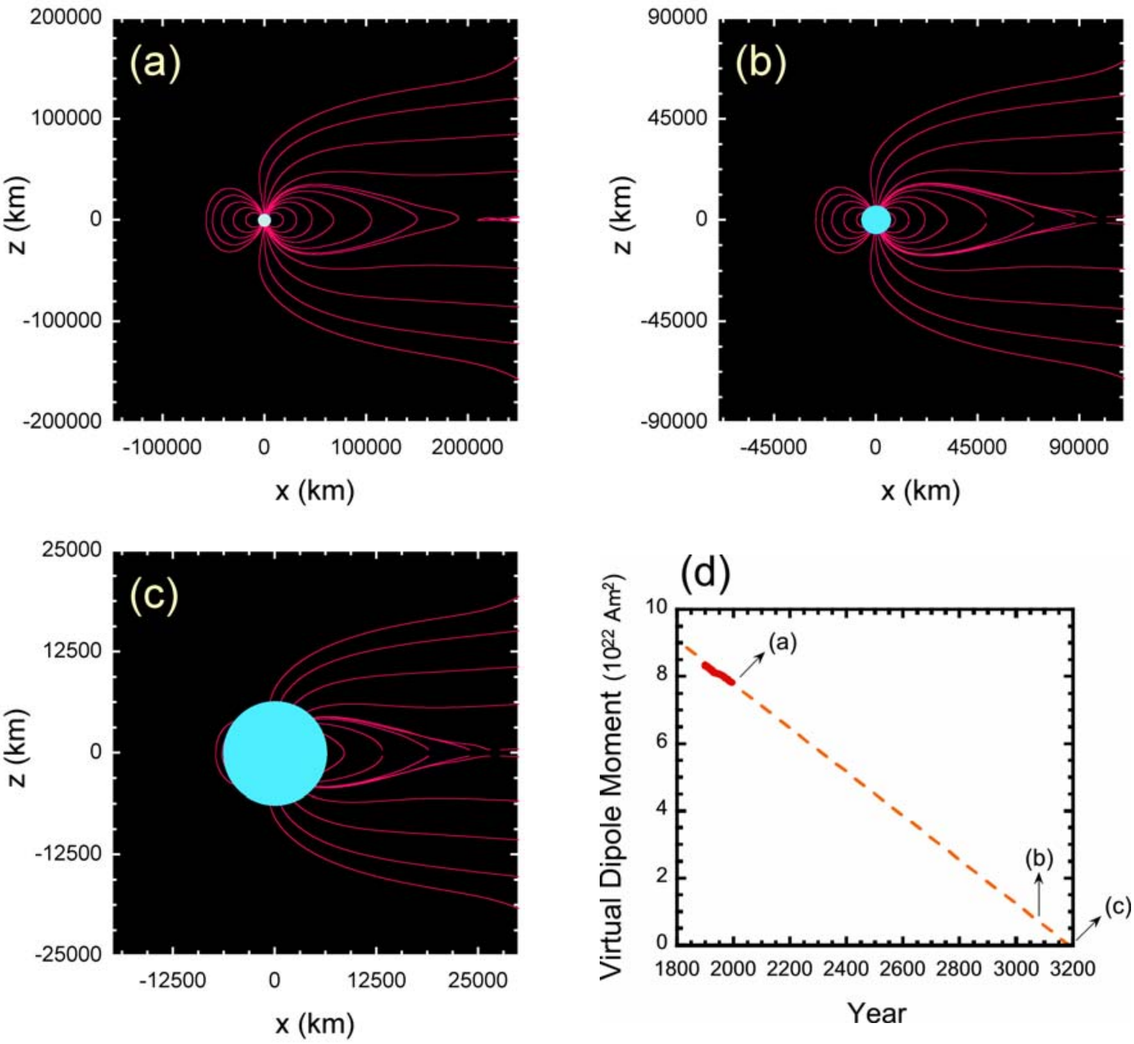


Fig. 1. Spatial distribution of magnetic field lines in the magnetosphere under (a) the present-day geomagnetic field, and (b,c) geomagnetic fields equivalent to (b) 10% and (c) 0.2% of the present-day field. Coordinates are defined with *x* positive from the sun toward the Earth, *y* positive in the direction of Earth revolution, and *z* perpendicular to *x* and *y*. (d) Expected amplitude of the virtual dipole moment based on extrapolation from data in (*9*).

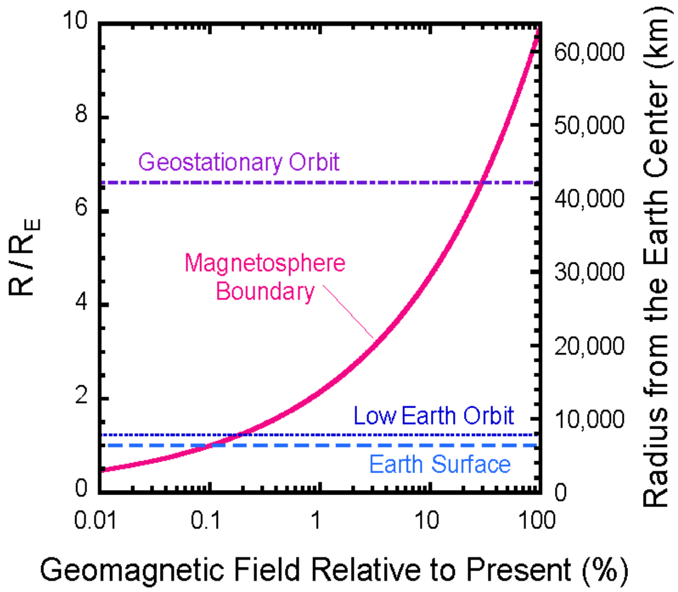


Fig. 2. Location of magnetospheric boundary as a function of geomagnetic field relative to present.

Based on the analysis above, an artificial geomagnetic field of greater than 0.2% of the present-day strength will be required to move the magnetospheric boundary to higher altitude than the low Earth orbit of satellites. It is also necessary, however, to consider the effectiveness of magnetic shielding for high-energy particles entering the magnetosphere. For this analysis, proton orbits can be traced by integrating the full equation of motion for a single particle [*23*], as given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\frac{m\mathbf{v}}{\left[1-(v/c)^2\right]^{1/2}}\right\}=e(\mathbf{E}+\mathbf{v}\times\mathbf{B}) \tag{2}$$

where **v** is the velocity of the traced particle, *c* is the speed of light, *e* is the proton electric charge, **E** is the electric field, and **B** is the magnetic field. The mass of high-energy protons is corrected by the relativistic effect. The electric field is determined by the velocity of bulk plasma in the solar wind satisfying the relation **E** = –**U**×**B**.

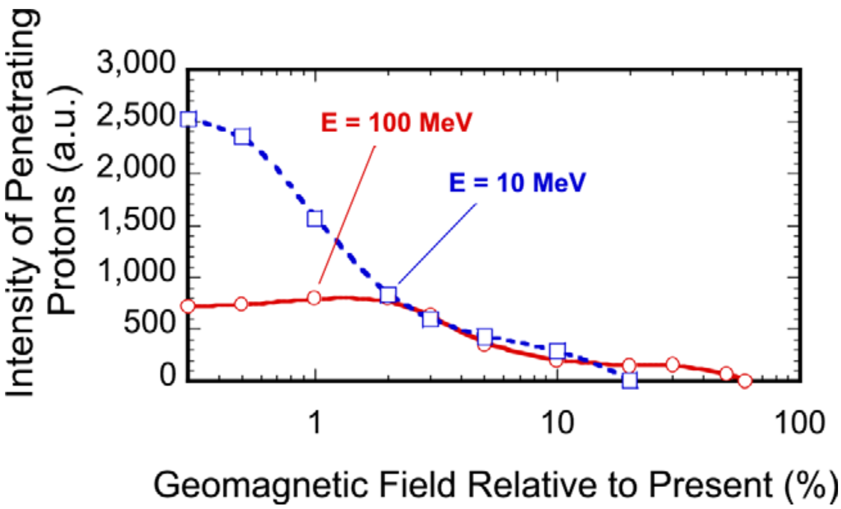


Fig. 3. Intensity of penetrating protons to the Earth's surface (collision with atmosphere ignored) as a function of geomagnetic field relative to present for proton energies (*E*) of 10 and 100 MeV.

The number of particles reaching the Earth's surface has been calculated for proton energies of 10 and 100 MeV as a function of relative geomagnetic field strength. Note that collisions with the atmosphere are not considered in this calculation since our concern is more with proton intensities at high altitude for aircrafts (not at the sea level) as well as with possible heating of upper atmosphere . Figure 3 shows the obtained intensity of the particles penetrating to the Earth surface. In these calculations, 14641 particles are injected from a region delineated by $x = -60000$ km and $-60000$ km $< y, z < 60000$ km with 49 pitch angles at each location. The number of incident 100 MeV protons is adjusted to 3% of that of 10 MeV protons according to the initial distribution function in space [*23*]. A 10% geomagnetic field reduces the intensity of incoming protons by almost one order of magnitude, and this is thus considered to be the minimum field necessary to ensure adequate magnetic shielding.

### 3. Feasibility of generating an artificial geomagnetic field

In the event that the geomagnetic field weakens sufficiently to endanger life and infrastructure, it may be possible to deploy a latitudinal series of superconducting rings to augment the geomagnetic field (see Fig. 4(a)). The feasibility of such a measure is discussed here considering both present-day technology and potential future technologies expected with the progress of superconductors and superconducting magnets associated with fusion and power distribution research.

Using present technology, the superconductors would be installed in a thermally insulated multi-layer metal tube with cooling achieved by passing a liquid coolant through a central channel. Such cables have already been developed and are being used reliably for the superconducting bus-line system of the Large Helical Device (LHD) [*24*, *25*] to transport a nominal direct current of 32 kA from the power supplies to the LHD superconducting coil system. The coils produce a maximum magnetic field of ~7 T with ~0.9 GJ stored energy, which is employed to confine 10 keV plasmas for fusion energy research in a heliotron magnetic configuration [*26*, *27*]. Nine individual bus-lines have been fabricated, with a total length of approximately 500 m. The LHD bus-lines were developed in the mid 1990s and have been operated stably for 10 years. These prototype superconducting power transmission cables are based on NbTi superconductors, and consist of a pair of wires with opposite polarity combined in a single line cable. The wires are separated by an insulation layer, and the cable is housed in the central channel of a five-layer corrugated stainless-steel transfer tube. The cross-sectional area of the cable (for one direction) is 560 $mm^2$, and the outer diameter is 220 mm. Two-phase liquid helium at 4.4 K is supplied into the center channel (68 mm diameter), with thermal insulation provided by a vacuum between the outer layers. The radiation-shielding layer is cooled by helium gas at 40 K, which is effective for reducing the heat load to the center channel.

By applying HTS materials, it is possible to increase the operating temperature, allowing the use of liquid nitrogen (77 K at atmospheric pressure, lower with sub-cooling) as the coolant. This provides a much wider design window. Significant progress in HTS wire technology has been achieved in recent years [*28*, *29*], and a number of projects involving the development of superconducting power transmission cables using HTS materials are being carried out around the world [*30*–*32*]. The use of superconducting transmission cables for dc transmission over long distances as an alternative to loss-affected ac transmission is one potential use of HTS materials [*33*], with superconducting power transmission as a global electrical network being an ultimate goal [*34*]. Such research encourages the consideration of a planet-encircling superconducting ring network for enhancement of the geomagnetic field.

HTS wires, particularly rare-earth metal coated-conductors, such as YBCO or GdBCO, exhibit a much higher current density than that of low-temperature superconducting (LTS) materials under a strong magnetic field at elevated temperatures [*35*, *36*]. HTS conductors with large current capacity are presently under development for fusion magnets, operating under high magnetic fields and at temperatures of 20–70 K [*37*, *38*]. It is possible to consider a cable with a total current capacity of 6.4 MA, 100 times that for the LHD superconducting bus-lines (nominally 64 kA in two wires). A cross-sectional view of the proposed superconducting cable is shown in Fig. 4(b), and the specifications are listed in Table 1. The outer and inner diameters of the superconductor would be 360 mm and 240 mm, producing a maximum magnetic field of 7.1 T. This condition is similar to what is experienced in the superconducting helical coils of LHD (with ~5.8 MA current at 4.4 K), and it can be achieved with coated HTS conductors operating at approximately 65 K.

For a series of latitudinal rings, the maximum length of cable would be close to the circumference of the Earth (~40000 km), and the stored magnetic energy for a single cable would be $2.8\times10^{6}$ GJ. If the maximum voltage is restricted to 20 kV, the nominal operation current of 6.4 MA would require 50 days and 640 MW of electric power to achieve. If the heat load into the cable area is restricted to less than 1 $W\,m^{-1}$, the same as for prototype HTS power transmission cables, the overall electric power required for refrigeration will be approximately 400 MW. Thus, one power plant with 1 GW of electric power output would be sufficient to operate the longest cable of the series.

To produce the required magnetic field strength, it would be necessary to construct 12 such rings at uniform intervals (Fig. 4(a)). As shown in Fig. 5, this configuration can be expected to produce an artificial geomagnetic field equivalent to 10% of the present-day field strength.

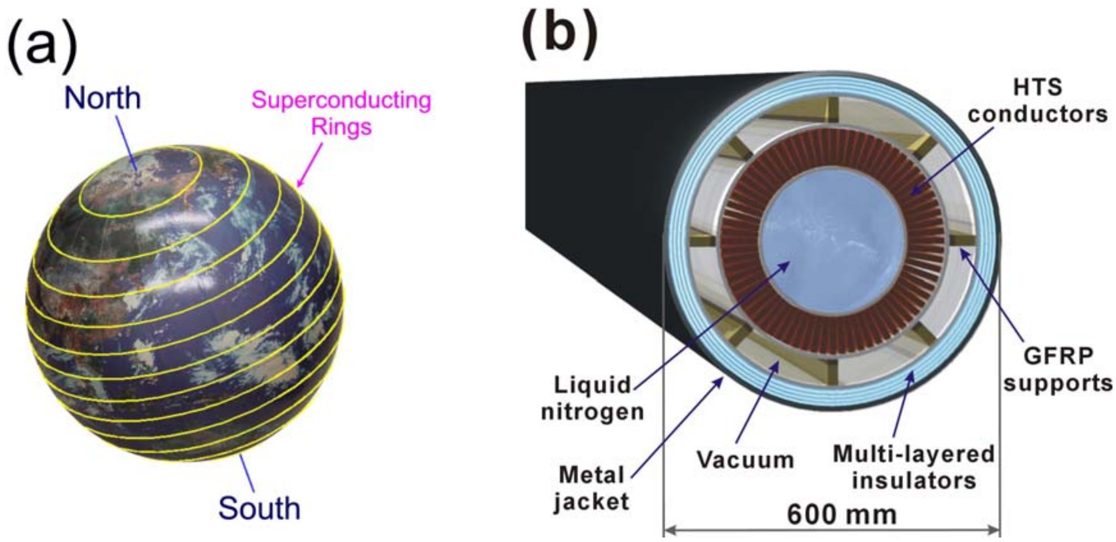


Fig. 4 (a) Layout of 12 latitudinal superconducting cables around the surface of the Earth. (b) Cross-sectional view of proposed superconducting cable.

Table 1. Specifications of longest superconducting cable

| | |
|---|---|
| Superconducting material | YBCO or GdBCO |
| Outer diameter of the cable | 600 mm |
| Outer diameter of the superconducting area | 360 mm |
| Total current capacity | 6.4 MA |
| Number of conductors | 100 |
| Current in each conductor | 64 kA |
| Maximum magnetic field | 7.1 T (outer surface) |
| Current density | 113 A $mm^{-2}$ (average) |
| Coolant | Liquid nitrogen (sub-cooled) |
| Temperature | ~65 K |
| Total length | ~39900 km |
| Total weight | ~15 M tons |
| Total heat load | ~40 MW |
| Stored magnetic energy | ~$2.8\times10^{6}$ GJ |
| Maximum voltage | 20 kV |

## 4. Discussion

The artificial magnetic field is not expected to significantly affect the evolution of the self-sustaining dynamo at the Earth's core. This can be verified by modeling the natural geomagnetic field. For a core modeled as a cylindrical region with inner radius of 1220 km, outer radius of 3480 km, height of 1200 km, uniform current density, and total current of 3.34 GA (see Fig. 5(c)), the natural poloidal magnetic field at the core is roughly 100 times larger (on average with the present strength) than that generated by the superconducting rings (~5000 nT). The large toroidal magnetic field of the Earth dynamo is not considered. Thus, it appears that the artificial field will have a minor influence on the behavior of the Earth dynamo, though the effect of a bias magnetic field on the dynamo process should be fully analyzed by numerical simulation, which could open a new study in the future.

During the reversal of the natural geomagnetic field, that may take thousands of years to complete, the amplitude and polarity of the operating current in the superconducting ring network should be minutely tuned so that the overall geomagnetic field becomes most effective for shielding. Due to the loss of its magnetic field, Mars has a substantially thinner atmosphere at present compared to Earth, which is considered to have contributed to Martian desertification [*39*]. If we think about such a situation to ever happen in the far future also on the Earth (losing geomagnetic field over a longer time due to some failure of polarity reversal), we may consider that the artificial geomagnetic field will have to be turned on even for much longer time. We may think about renewing superconducting rings one by one after a long period of operation.

The finite magnetic field generated by a 6.4 MA superconducting ring would necessitate a 2.6 km safety zone adjacent to the cable to assure that the public exposure limit of 5 G is not exceeded. The routes for laying the cables should thus be chosen carefully to avoid cities and residential areas. For crossing the cables on the ground, one may install magnetic shields around the cables locally. We may also consider another choice of having a larger number of rings to generate the same strength of geomagnetic field with reduced current in each ring. For example, if we deploy 1,200 rings, the current of 64 kA in each ring (the same as for the LHD bus-lines) would give the 5 G limit at 26 m. Though much larger refrigeration power is required for the whole system, this could significantly ease the problems related to the local enhancement of the magnetic field around the cables. Such cables will become more feasible if new superconducting materials with higher critical temperatures are found in the future. We may also use these superconducting cables as one-way high-power transmission lines suitable for integration into a global electrical network. They also serve as a superconducting magnetic energy storage (SMES) system.

The approach of generating artificial geomagnetic shield is also applicable to the moon and other planets such as Mars, where there is no or thin atmosphere and small planetary magnetic field, in order to support the establishment of habitable bases, should the need arise.

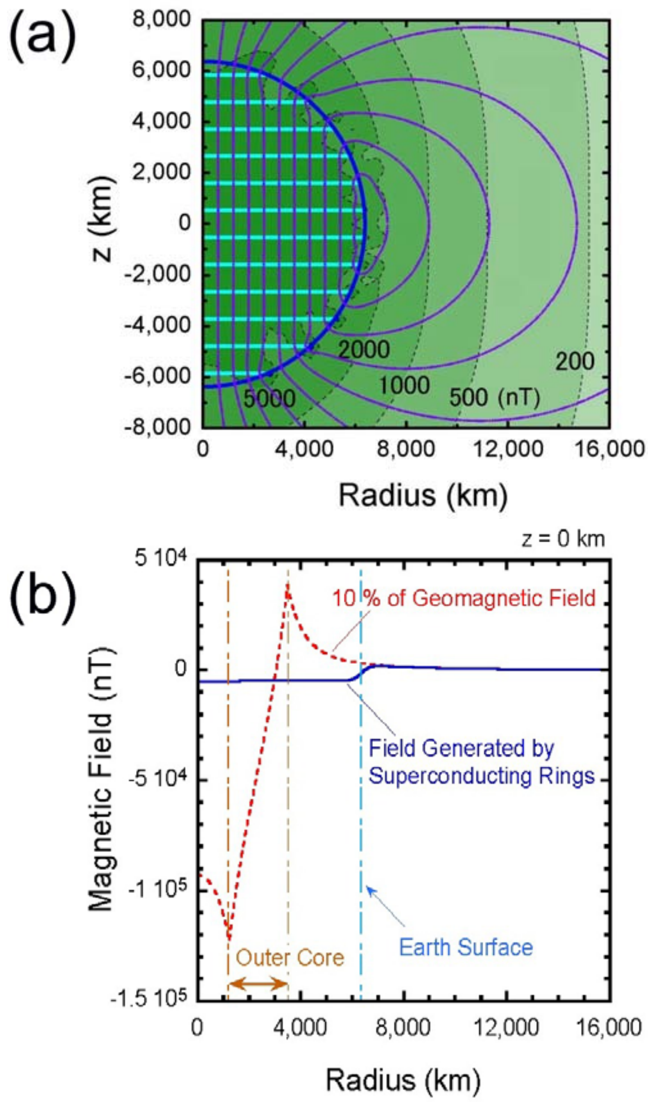


Fig. 5 (a) Spatial distribution of artificial geomagnetic field, showing field lines in purple and field strength in green. Interaction with solar wind is not considered. (b) Comparison of radial variation in 10% natural geomagnetic field with the artificial field.

## 5. Conclusions

A series of planet-encircling superconducting rings is considered as a means of generating an artificial geomagnetic field, which may become necessary should the geomagnetic field weaken in association with polarity reversal. To maintain a geomagnetic field equivalent to 10% of the present-day strength, which is effective to protect the Earth from high-energy radiation, a set of 12 rings carrying a maximum current of 6.4 MA is calculated to be necessary. Using HTS technology, it is considered that such a project is feasible, with modest power requirements. A magnetic field of this strength is also expected to have a minor impact on the behavior and evolution of the Earth dynamo. It therefore appears probable that the planetary magnetic shield, on Earth and on other planets and moons, can be generated artificially should the need arise.


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