THE SHIELD™ SYSTEM FOR SPACECRAFT CHARGE CONTROL

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Abstract

A self-contained, highly miniaturized plasma-based system is introduced as a viable, cost effective approach for mitigating surface charge problems on a wide variety of spacecraft. Details of the SHIELD™ system (Stop High Intensity ELectric Discharges) are presented including: basic design and operational philosophy, specific component design features, mechanical, electrical, and command and control interfaces, plasma emission characteristics, and self-triggering features. Spacecraft mission applications that would benefit from integration of the SHIELD™ system are discussed. Variations of the basic SHIELD™ system are presented in the context of specific plasma emission characteristics designed for unique spacecraft mission application scenarios.

Introduction

The ability to detect and neutralize the hazardous surface charging effects of space plasma environments on a wide variety of spacecraft is important in improving their reliability and overall mission performance. In periods of severe solar activity, detection and neutralization of hazardous surface charging effects can enable these spacecraft to continue operation. Without onboard neutralization capability, severe solar activity can cause high-current, short-duration electrostatic discharges between differentially charged surfaces, which can cause potentially disabling electromagnetic interference levels. For commercial geosynchronous spacecraft, surface discharge anomalies between the spacecraft frame and dielectric surfaces due to space plasma charging environments are a fact of life.[1] It has been estimated that operational anomalies on a typical geosynchronous spacecraft due to electrostatic surface discharges fall in the range of 10^4 annoying events, 10^2 - 10^3 serious events, and 10 critical events.[2] Passive approaches for mitigating these space plasma-induced charging problems are being stressed to their limit as spacecraft become larger, with corresponding increases in solar array size and power, and bus voltage.

The SHIELD™ system shown in Fig. 1 has been developed as a last line of defense for any spacecraft whose passive surface charge bleed-off systems are overwhelmed by an extremely hazardous charging environment. Operational attributes and physical characteristics of the SHIELD™ system are listed in Table 1.

TABLE 1. SHIELD™ System Physical and Operational Characteristics.

Bus Power:	30 W nominal operation (50 W max. for 60 s cold start)
Bus Voltage:	28 ± 6 V DC nominal (other voltage options available)
Gas:	Xenon at 0.03 mg/s
Ion Current:	up to 10 mA
Electron Current:	up to 1000 mA
Ion Energy:	10 - 20 eV
Electron Energy:	≤ 1 eV
Total Operating Time:	15,000 hours
On/Off cycles	10,000 (nominal)
Weight:	6.3 kg (with 1.8 kg of Xenon)
Footprint:	20.3 cm x 30.5 cm
Enclosure:	17.8 cm x 27.9 cm x 12.7 cm

Fig. 1. EPL's SHIELD™ System.

The SHIELD™ system acts like a fire extinguisher, which immediately neutralizes any unbalanced surface charge accumulation that is threatening the spacecraft. Incorporating a built-in surface charge state sensor, and with the ability to operate completely autonomously, the SHIELD™ system quickly detects and responds to spacecraft charging hazards.

A specially designed plasma source within the SHIELD™ system emits a divergent, low electron temperature plasma plume, rich in low energy ions. Figure 2 shows this source and also highlights the plasma plume emitted during operation. The carefully tailored properties of this plasma plume, and its very low energy, enable it to diffuse around the entire spacecraft.   This plasma shield immediately neutralizes, and then prevents, any surface charge imbalance from occurring throughout the duration of the space plasma-induced charging hazard. All normal operating functions of the spacecraft are maintained during the SHIELD™ system activation period. Once the hazardous charging environmental conditions have subsided, the SHIELD™ system is shut down until the next charging hazard is detected.

Fig. 2a. SHIELD™ Plasma Plume.

Fig. 2. SHEILD™ Plasma Source.

Design and Operational Philosophy

Figure 3 shows schematically the basic elements of the SHIELD™ system. These elements include (1) a gas storage and feed system, which supplies a precisely metered xenon gas flow to the plasma source; (2) a power conditioning system, which adapts the user spacecraft power bus to the voltage and current control levels required to operate the various SHIELD™ system components; (3) a plasma source capable of rapid turn on, and capable of emitting a diffuse plume of low energy plasma; (4) a charge state sensor, which continuously monitors surface charge accumulation; (5) and a control system, which interprets the voltage levels on this sensor and monitors inputs from the user spacecraft to determine when and how the SHIELD™ system should be activated to mitigate a particular charging threat to the spacecraft.

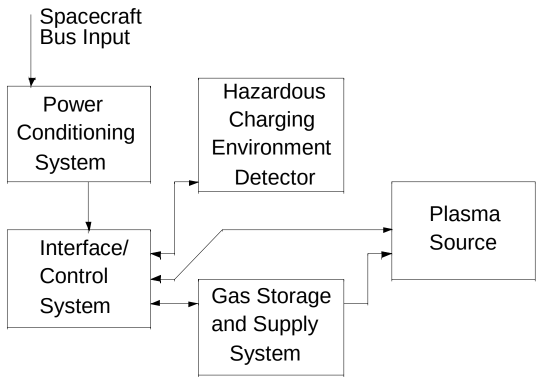

Fig. 3. Elements of the SHIELD™ System.

For most spacecraft applications, the SHIELD™ system would be off for very long time periods during the lifetime of the vehicle. Under these "normal" circumstances, the existing passive charge bleed-off systems would be adequate to control spacecraft surface charging to acceptably low levels. Activation of the SHIELD™ system would be initiated only if either one or more of the following events occurred:

(i) The SHIELD™ system's built-in surface charge state sensor detected a rising out-of-balance potential that exceeded a hazard limit threshold.

(ii) Other sensors on-board the spacecraft detected rising surface potentials, which exceeded the capabilities of the passive charge bleed-off systems.

(iii) The user spacecraft was directed to activate the SHIELD™ system because of up linked commands based on a space weather report that indicated the imminent arrival of a severe solar plasma disturbance.

As previously stated, the SHIELD™ system is designed to be the last line of defense to ensure the continued reliable operation of the spacecraft. Activation of the SHIELD™ system occurs in two steps. Once a surface charging threat to the spacecraft has been detected, the system initiates a cold start process that brings the plasma source to a standby state in a period of a few tens of seconds.

From this standby mode, plasma source activation can occur in less than one second once a command to a full on condition is sent. This standby mode feature is particularly useful since it can be commanded on by prior space-weather-uplink commands, and by charge-state sensor threshold-level responses. The SHIELD™ system may be left in the standby mode for days if required, with no damage to the unit, while the solar activity creating the threat subsides. Similarly, if the SHIELD^{TM} system is fully activated to the plasma-on state, subsequent operation of the unit can be programmed to be either continuous or cyclic. Or, if autonomous operation is not required, the SHIELD^{TM} system can be simply activated to the plasma-on state and left in this mode for however many hours, or days, are required before a space weather report is issued indicating a cessation of solar flare activity.

Neutralization Capability

Severe surface charging environments simulated in ground tests document the effectiveness of the SHIELD^{TM} system for detecting the onset of hazardous charging environments, and responding autonomously to eliminate their detrimental effects. For these tests, the SHIELD^{TM} system was mounted in a 1.2 m dia. x 7 m long vacuum facility as noted in Fig. 4a. In addition to the SHIELD^{TM} system with its integrated charge state sensor, a similar sensor was located on one side of the system, while a Faraday probe was positioned on the other side of the system. The arrangement of these components is identified in the photograph contained in Fig. 4b. During testing, an electron gun positioned at the far end of the test facility was operated at a flux rate of between 1 and 3 nA/cm^2 as recorded at the Faraday probe location. This adjustable and regulated flux rate, and the electron gun energy range capability of 0 to 45 keV, represented a reasonable simulation of geosynchronous substorm conditions.

The integrated SHIELD^{TM} system surface charge state sensor was programmed to respond to various surface potential level trip points as the severity of the charging threat was varied. Similarly, the SHIELD^{TM} system was operated in different modes to demonstrate response time characteristics. Both the integrated charge state sensor, and the isolated charge state sensor displayed nearly identical behavior when exposed to the different simulated substorm test environments. Figures 5a - 5d document test results and verify the neutralization capability of the SHIELD^{TM} system for different charging hazard simulations.

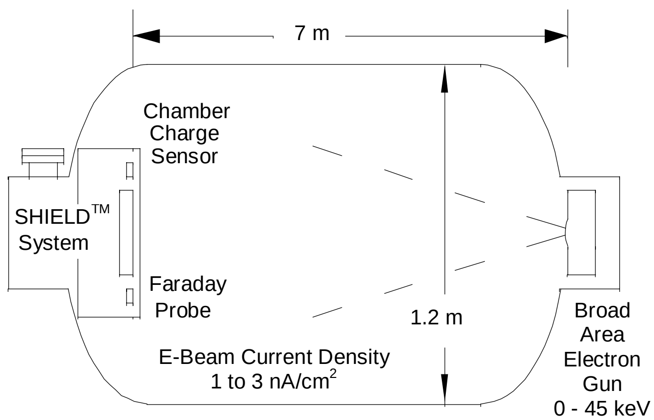

Fig. 4a. Hazardous Charging Environment Simulation Vacuum Facility.

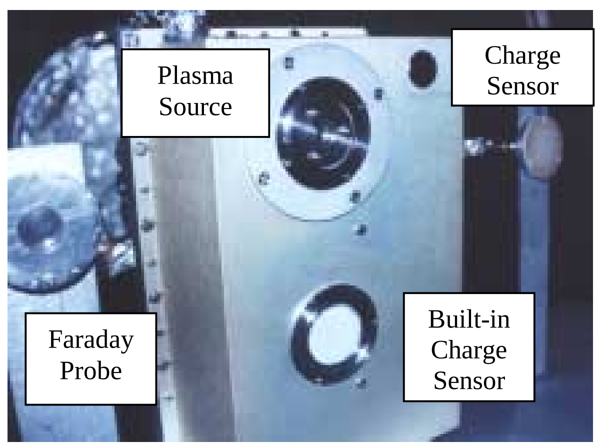

Fig. 4b. SHIELD^{TM} System Installed in Substorm Simulation Vacuum Test Facility.

Of particular interest in these figures are the results of cold start test sequences documented in Figs. 5c and 5d, which show that surface discharging occurs even before the SHIELD^{TM} system plasma source is fully on. This behavior is a result of the thermionic nature of the SHIELD^{TM} system plasma source and indicates that even when initiated from a cold start condition, a measure of protection is afforded the spacecraft after only a couple of tens of seconds.

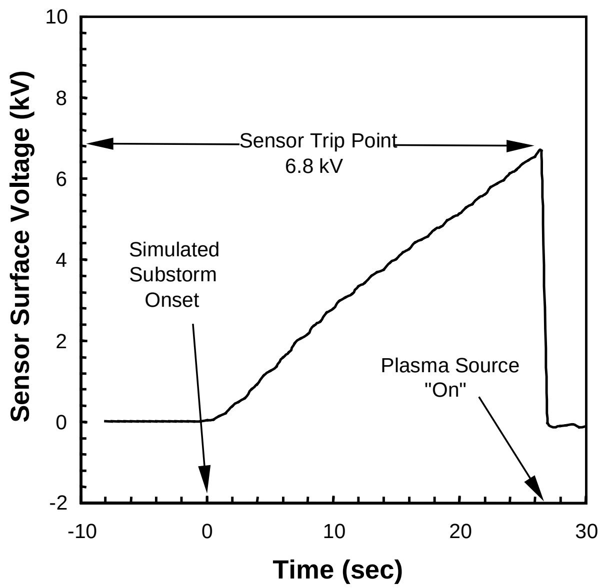

Fig. 5a. Typical Instant Start System Response During Threshold Setting.

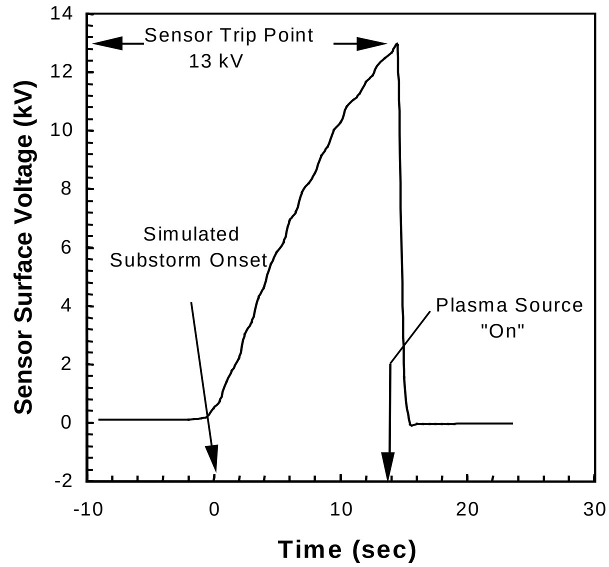

Fig. 5b. Typical Instant Start Performance at Sensor Moderate Simulated Substorm Testing

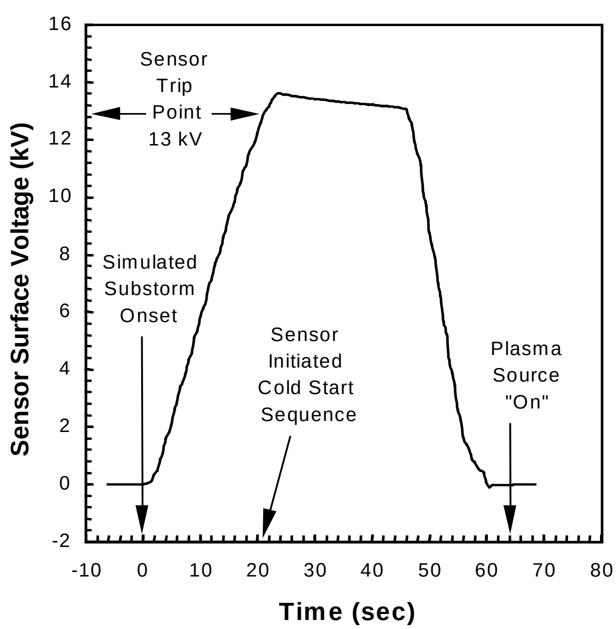

Fig. 5c. Typical Cold Start System Response.

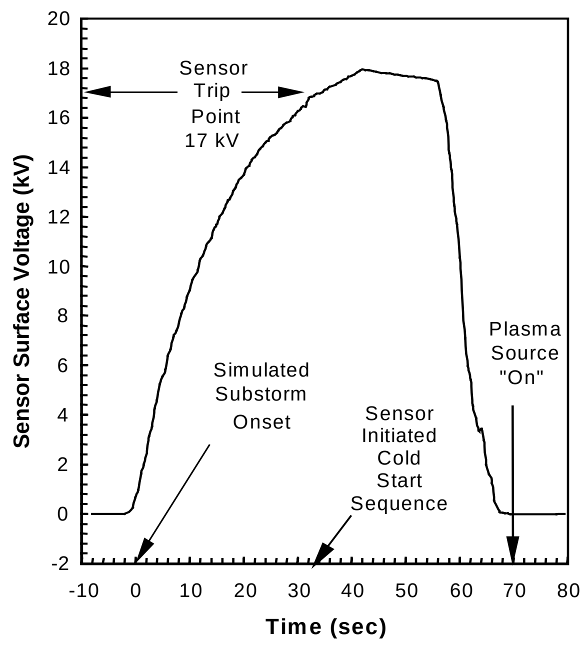

Fig. 5d. Cold Start Performance at High Sensor Threshold Setting.

Interfaces

The SHIELD™ system is designed to mechanically mount on any flat spacecraft surface of minimum area 20.3 cm x 30.5 cm. If permitted by the user spacecraft, the SHIELD™ system is designed for conduction cooling through its mounting plate to the user spacecraft. The steady state power dissipation from the system is about 20 - 25 W during nominal operation. Note that in most applications the SHIELD™ system will be required to function only on a very low and intermittent duty cycle during a normal spacecraft mission lifetime of order 5 - 15 years. Moreover, the duration of each SHIELD™ system operating period is projected to be only of order hours, to a day or two. However, should heat flux to the spacecraft be an issue, the SHIELD™ system can be configured for passive radiative cooling entirely at a system mass increase of about 10 - 20% depending on the specific application. In either mounting configuration, the SHIELD™ system must be mounted with an electrical ground connection directly to the spacecraft bus/structure common. This ground connection can be either through the mounting bolts of the unit, or with a separate strap, or both.

Orientation of the SHIELD™ system is not critical other than that the highly divergent plasma plume emitted by the unit be given an obstruction-free diffusion zone away from the spacecraft. Any direct interception by spacecraft surfaces of SHIELD™ system ions will not cause sputtering damage since the emitted ions are always below sputter threshold levels of the spacecraft construction materials. Similarly, the plasma source does not emit any condensable contaminants because it operates at internal plasma discharge voltages below the sputter threshold levels of the materials used in its internal construction.

Although the baseline SHIELD™ system accepts a nominal 28 $\pm$ 6 V DC bus input voltage, other voltage levels up to 120 $\pm$ 40 V DC can be readily accommodated. Depending on the specific spacecraft application constraints, it may be necessary to maintain a small heater input power to the SHIELD™ system during prolonged off periods. This constant input power requirement of order a few Watts would be required to keep the xenon gas and associated flow system and electronic system components from getting too cold. However, it should be noted that the SHIELD™ system components have been qualified during cold soak thermal vacuum tests to -20 ^{o}C for all gas feed system components, including the xenon gas supply, with no effect noted on the reliability of start-up. Non-operating, cold storage limits are significantly below this level.

In general, xenon is the gas of first choice for the SHIELD™ system due to its high storage density in excess of 1.0 g/cm^3. This high density enables a 15,000 hour supply to be incorporated into a total system mass of only 6.3 kg - where approximately 30% is xenon by weight. However, for unique applications where more severe cold soak temperature limits may be required for reliable system start-up, the SHIELD™ system may also be used with either krypton or argon gas. Use of these lighter weight, and lower operating cold soak limit gases comes at a commensurate reduction in total operating lifetime due to their lower storage densities compared with xenon.

Mission Applications

The SHIELD system has been designed for geosynchronous satellite applications. These spacecraft operate in the magnetosphere, that is above the ionosphere and extends about 10 earth radii on the day side and hundreds of earth radii on the night side. Normally the space plasma at geosynchronous orbit is benign. However, ambient plasma conditions can fluctuate widely due to variations in solar activity that can dramatically alter the magnetosphere. The largest differential charging potentials develop during solar substorms on shaded dielectrics when other regions are in sunlight, or when the spacecraft passes from eclipse to sunlight. In such instances, photoemission of electrons drives the spacecraft frame to near the local space plasma potential, while the shaded dielectric is charged to several kilovolts or more below space potential. Geosynchronous spacecraft with the SHIELD™ system installed would be protected from the differential surface charging extremes, and subsequent electrostatic discharges, of such substorm activity.

Certain planetary spacecraft would also benefit from use of the SHIELD™ system. Specifically, planetary environments known to have energetic plasma regions represent a real risk to these expensive spacecraft due to differential surface charging and electrostatic discharge events that can cause serious operational and data collection anomalies.

A series of highly specialized spacecraft mission applications also exists wherein the spacecraft may be in an unusual earth orbit requiring periodic insertion into a particularly severe space plasma environment. In such applications, an on-board SHIELD™ system can be programmed to be activated at these critical locations of each orbit period to prevent any charging influences of this environment on the functions of the spacecraft.

SHIELD™ System Variations

Certain applications of the SHIELD™ system technology include its application to the future battlespace environment. Specifically, a multi-function charge control system is currently under development at EPL to respond to the unique battlespace charging threats. This system is designed to respond autonomously to a wide range of out-of-balance spacecraft and/or platform charging situations. This response includes the capability to emit a plasma whose flux can be modulated almost instantly to go from milliampere to Ampere levels of plasma electron emission, with microampere to tens of milliampere low energy ion emission, and with the added ability to vary the electron-to-ion flux ratios and the ion and electron energies in this emitted neutralizing plasma in real time. With such a multi-function on-board neutralizing capability, a single system can respond to ambient plasma charging threats, directed charging threats, and spacecraft and/or platform charging threats that would occur if an on-board weapon was discharged.

Another unique variation on the basic SHIELD™ system design currently under development at EPL is called the Plasma Charge Balance System (PCBS). The PCBS is being developed to enable very precise control of the surface potential of scientific spacecraft. Regulation of spacecraft floating potential to a value close to the space plasma potential is important to improve measurements of low energy charged particle spectra by scientific payloads that are exposed to varying space plasma environments. Previously this control has been accomplished using a power supply connected between the spacecraft frame and a plasma contactor derived from electric propulsion technology. To date the PCBS has demonstrated extremely quiet electrical operation with a plasma flow field that is much less environmentally intrusive than conventional plasma contactor systems in terms of plasma production rates field and plasma specie temperature. In addition to tailored emission current capability, the PCBS plasma source does not produce large electric field gradients within its plasma plume footprint. A highly Maxwellian electron population is produced by the PCBS, which expands along with a low energy, streaming ion population. Plasma plume electron temperatures of 0.11 eV and ion energies of 5 eV have been demonstrated at a xenon gas flow rate of only 0.2 sccm.

Acknowledgments

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