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Automated test bench for simulation of radiation electrification of spacecraft structural dielectrics

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Abstract. The paper describes the test bench "Prognoz-2" designed in Testing Center, Institute of Non-Destructive Testing, Tomsk Polytechnic University, which can be used: for ground testing of individual samples of spacecraft structural materials (e.g. thermal control coatings or cover glasses for solar batteries) or ceramics of the plasma thruster discharge channel), and whole spacecraft units or instruments (e.g. instruments of solar and stellar orientation or correcting plasma thrusters) exposed to radiation electrification factors; to verify the calculation mathematical models of radiation electrification of structural dielectrics under the impact of space factors in different orbits.

1. Introduction

At present, more and more information, communication and navigation systems make use of Earth-orbiting spacecraft. The development, manufacturing and orbiting of the spacecraft is extremely expensive and developers seek to maximize its active shelf life. However, it is difficult to implement, since the spacecraft is exposed to space factors (SF) such as high vacuum (up to $3 \cdot 10^{-10}$ Torr), temperature difference (from +120° C under sunlight to –130° C when the spacecraft enters the Earth's shadow) solar radiation (energy density of up to 1.38 $kW \cdot m^{-2}$) [1], and ionizing radiation of the Earth's radiation belts. In addition, when a spacecraft approaches the geomagnetic plasma, it provokes radiation charging of structural dielectric materials. Surface and volume electrical fields emerging in structural dielectrics can lead to radiation-induced electrostatic discharge (ESD) that causes electromagnetic interference and pulsed current noise in electrical circuits of the onboard equipment with an amplitude of up to 100 A and the rising edge duration of up to 10 ns. Insufficient protection measures against these electromagnetic interferences and current noise can lead to fatal failure of the onboard equipment. To evaluate the effectiveness of the means protecting the onboard spacecraft equipment from the effects of radiation electrification, ground tests are conducted in conditions simulating significant SF using special test benches. This test bench should provide:

- the study of radiation parameters of electrification of spacecraft structural dielectrics (surface potential distribution, frequency and electrical discharge characteristics) under conditions of space effects (vacuum, electron radiation simulating the energy spectrum in the near-earth orbit, low temperature and solar radiation);
- measurement of interference signals in the circuits providing control of the test spacecraft subsystems (such as the spacecraft correction system) caused by electrostatic discharges;

- development of methods and means of protection from the effects of radiation electrification factors.

2. Experimental techniques

Arrangement of the "Prognoz-2" test bench is shown in figure 1.

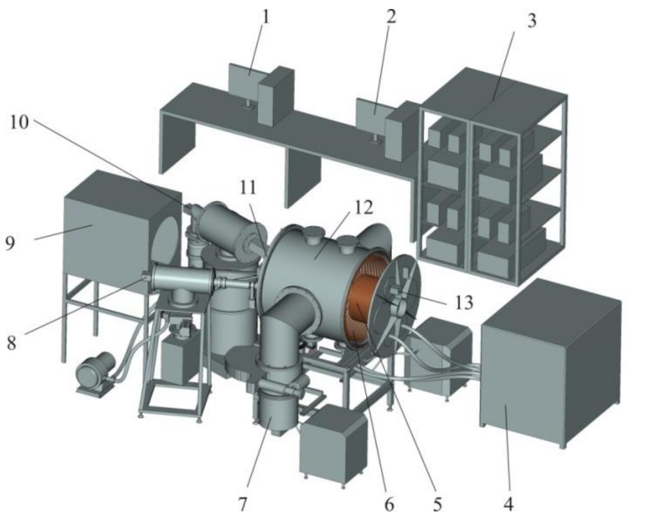


Figure 1. Arrangement of the stand "Prognoz -2".
1, 2 – Controlling and recording PC.
3 – Racks with measuring and control equipment.
4 – Refrigeration plant
5 – Cryo-plate with cryo-shield.
6 – Cryo-jacket.
7 – Cryogenic pump.
8 – Electron gun with energy of up to100 keV.
9 – Optical solar simulator in the range from 200 nm to 1.2 μm.
10 – Electron gun with energy of up to 300 keV.
11 – High-speed camera.
12 – Vacuum chamber.
13 – Vacuum gauge (3 pcs.).

The vacuum chamber of the test bench is a cylinder with a diameter of 1000 mm and a length of 1000 mm. The schematic of the vacuum system is shown in figure 2. Simulation of interaction of electronic radiation with structural dielectric materials of the spacecraft imposes restrictions on the type of the vacuum equipment, and vacuum pumps which do not use oil or air as working medium should be used. To ensure high suction rate during material testing, two high-vacuum cryogenic pumps CRYO-TORR 400 working with helium compressors CRYO-TORR 9600 are used. High suction rate enables: testing of materials having a porous structure; testing of materials with a high rate of gassing upon heating; testing of ion engines with direct inlet of the working material; testing of samples of large geometric dimensions.

A 100 KeV electron gun induces a monoenergetic electron beam with the given energy. A 300 keV electron gun induces a beam with the electron spectrum from 10 keV to 300 keV using a foil system [2]. The results of sample charging by monoenergetic electron beam and by beam with different electron spectrum differ from those obtained in exposure to monoenergetic beam only [3].

The solar simulator and temperature control system allow testing of solar batteries under conditions simulating space effects both in orbital eclipse period and under solar irradiation. The temperature control system has two independent loops for heating and cooling of the cryo-jacket and cryo-plate. The loop for cooling the sample is connected to the refrigeration unit with thermal capacity of 20 kW, which allows cooling of a sufficiently large sample to –80° C. For cooling the sample down to lower temperatures, liquid nitrogen supply in the cooling circuit is provided. An industrial 2 kW fluid heater is used to heat the sample up to +80° C in the heating loop.

The electrical discharges caused by charged dielectric surface are recorded by high-speed video camera.

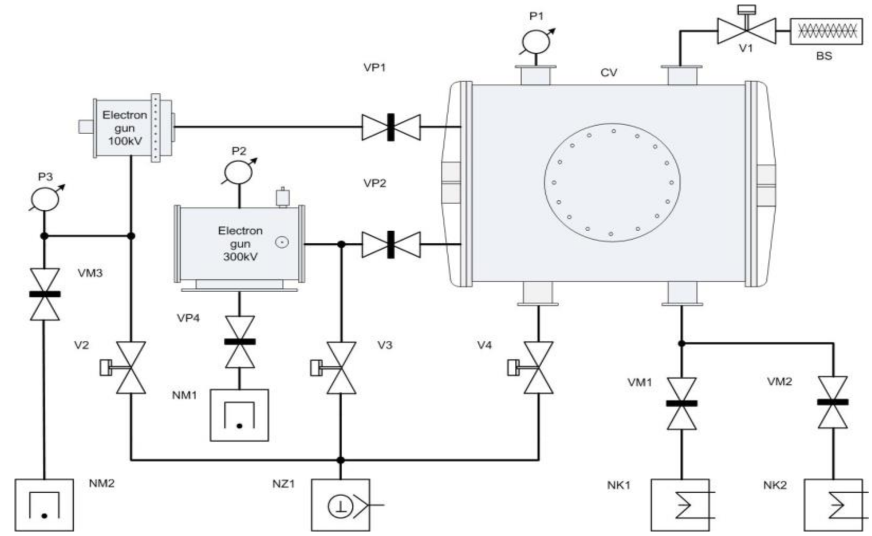


Figure 2. Schematic of the vacuum test bench "Prognoz-2".

VP1, VP2 – gate valves HTC 6VB-SS-KF50-P.;
VM1, VM2 – gate valves VAKMA23V7 – 400;
VP4 – gate valves HTC GVB-SS -ISO-160-P;
V1, V2, V3, V4 – vacuum valves HEC GVB-SS-KF40-P;
NK1, NK2 – high-vacuum cryogenic pumps CRYO-TORR 400;
NZ1 - forevacuum pump Kashiyama NeoDry 30E;
NM1, NM2 – ion water-cooled diode type vacuum pumps NMDO - 0.25 (NORD - 250);
BS – silica gel dehumidifier;
P1, P2, P3 – Granville-Phillips vacuum gauges 354 Micro-ION.

For ease of the control and protection against accidental errors of the operational personnel, the vacuum pumping system was automated. Implementation of the automatic control was performed using a PC, the National Instruments PCIe-6320 module and software created in LabView.

3. Results and discussion

The basic equations describing the dielectric electrification processes under external electron irradiation from the exposed surface follow from Maxwell's equations and include the laws of conservation of energy and electric charge, Poisson's equation and Ampere's law. Ampere's law implies that the total current density of the electric charge transfer (including the initial current of the accelerated electron beam) and the bias current intensity at any fixed time do not depend on the coordinate; it is a function of time. This total intensity of the total current (sum of the conduction and bias current) passes through the metal substrate of the test dielectric, and along with the surface potential, it is one of the main experimentally determined characteristics of dielectric electrification. The electrification parameters are calculated based on the data of the current density distribution and absorbed dose rate of the primary radiation electrons in the test dielectric determined based of the Monte Carlo method. The calculation must take into account the impact of the charged dielectric field on the energy of electrons which reach the dielectric surface.

Figure 3 presents the data acquisition systems required for testing of radiation electrification in dielectric materials. Depending on the aim of the experiment, a number of conventional schemes are used to measure the radiation electrification parameters in dielectrics. To determine the basic physical quantities required for establishment of initial conditions for a mathematical model, which considers the surface and bulk processes of radiation electrification in dielectric samples exposed to low-energy electron beam, the direct measurement is performed. The measured parameters are the current from metal substrate (6) placed on dielectric base (7) on which sample (4) is mounted, and the current from electrode (5) placed on the sample surface. Faraday cup (5) is used to measure electron beam Io (2) that irradiates sample (4). Faraday cup (5) is connected to KEITHLEY 6485 picoammeter (A1). The current from metal substrate (6) and the current from sample surface (3) are measured by KEITHLEY 6485 picoammeter A2, A3 [4]. The study of radiation-induced electrostatic discharges (ESD) implies measurement of the surface charge density by the electrostatic field sensor, which operates on the principle of dynamic capacitor [5] and the Tektronix DMM4040 voltmeter. To prevent failure of the picoammeter input stages during measurement of electrostatic discharges, the amplitude and time values of the discharge pulses are recorded by current shunts PA1, PA2 (Tektronix TCP0030) and high-voltage probes PU1, PU2 (Aktakom ACA-6039) connected to shunts R1 and R2. The current and high-voltage probes are connected to the Tektronix DPO4102B oscilloscope. The oscilloscope is placed in Faraday's cage (9); it has an independent power supply that is not connected to the common electric network to prevent measurement noise. [6] The sample is mounted on the thermoplate connected to thermal cover that allows changing the sample temperature from –80° C to +80° C. All the measuring devices are connected to personal computer (10) via the GPIB interface to measure physical quantities, and process and store the obtained experimental data in automatic mode. The program for measurement synchronization and data processing has been written in LabVIEW.

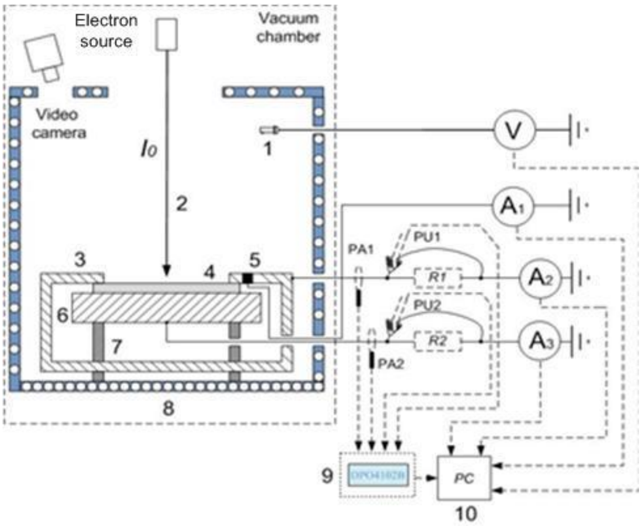


Figure 3. Scheme to measure basic parameters of dielectric charging.

The test bench "Prognoz-2" was used to test the electrification effect on solar battery sample (1) with GaAs-based photoconverters and borosilicate cover glass mounted on thermostat (2 and 3) (Figure 4).

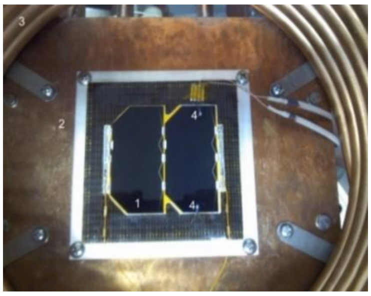


Figure 4. Solar cell sample with GaAs-based photoconverters.

The parameters of sample exposure to simulated magnetospheric plasma for standard tests were: electron irradiation Ee = 70 keV, Je = $1 \cdot 10^{-9}$ A cm^{-2}, beam stability ± 10%, beam non-uniformity across the area ≤10%. Irradiation was carried out on the front side of the solar battery. The angle between the electron beam axis and the sample plane was 90°. The temperature of the solar battery front side was of three values: –70°C, +20°C and +40°C. The temperature was recorded by thermocouples (4) mounted on the sample surface. The sample was in a vacuum P$\leq 10^{-6}$ Torr.

The external field sensor [5] was used to measure the following parameters: the kinetics of the integral charge on the irradiated surface of the borosilicate glass sample; the average frequency of radiation-induced discharges.

Simultaneously, an oscilloscope was used to measure the following parameters with Rm=50Ω: the average and maximum amplitude of the discharge current pulses in the short-circuited electrodes of the borosilicate glass sample grounded through measuring resistance Rm=50Ω: average duration of the discharge current pulses in short-circuited electrodes of the borosilicate glass sample grounded through measuring resistance Rm=50Ω; average and minimum duration of the rising edge of the current pulses in short-circuited electrodes of the borosilicate glass sample grounded through measuring resistance Rm=50Ω. The sample irradiation was recorded by the video camera.

The results obtained in testing the electrification of the solar battery sample with GaAs-based photoconverters and borosilicate cover glass under SF effects are shown in Table 1. In the table, an asterisk * indicates accumulation of radiation charge and hence, potential which is limited to radiation-induced electrostatic discharges on the irradiated surface of the cover glass of the solar battery.

Table 1. Testing results of the sample electrification under various temperatures.

Sample temperature	**Maximum integrated surface potential, kV**	**Maximum charge level of the BF sample, µC**	**Average time of yield of the discharge stationary mode, sec**
- 60°C	12.2*	3.5*	400
+ 20°C	7.9*	2.0*	350
+ 50°C	1.2*	0.3*	200

The electrical discharges presented in figure 5 were recorded on the irradiated surface of the solar battery cover glass within the entire temperature range.

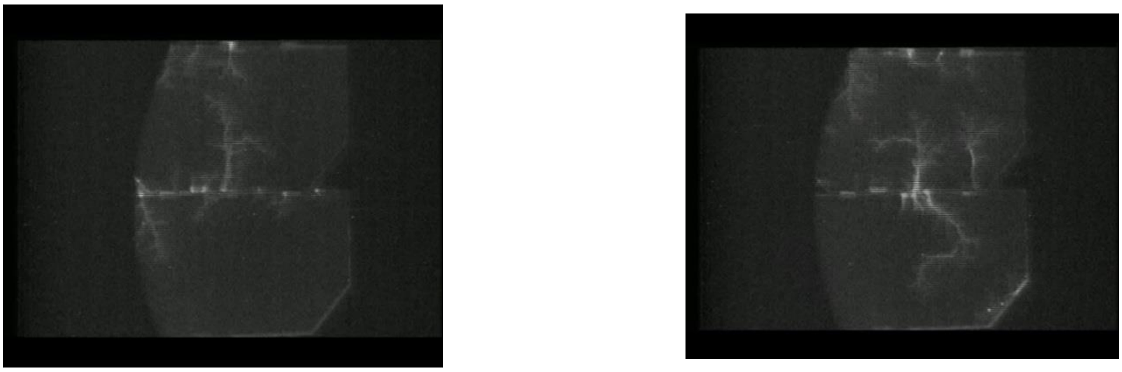
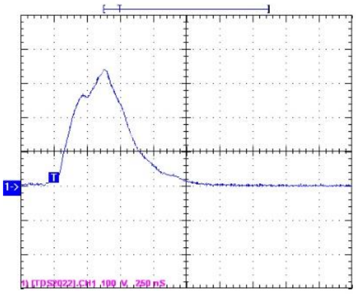


Figure 5. Electrical discharges on the surface of the solar battery cover glass.

The basic parameters of the recorded discharge pulses are presented in Table 2.

The conclusion drawn based on the results of testing the electrification effect on the solar cell sample is as follows. When exposed to electrons with energies up to 100 keV, the borosilicate cover glass accumulates significant radiation charge that causes electrical breakdowns on the cover glass surface within the entire temperature range. As a result, the current pulses with maximum amplitude of up to 12 A were recorded.

Table 2. The shape and parameters of the discharge pulses on the surface of the solar battery cover glass.

Parameter	**Value**			**Form of a typical pulse**
	– 60°C	+ 20°C	+ 50°C	
V_{max}, V	600	540	520	
$T_{ed\ min}$, ns	25	25	50	
$T_{ed\ av.}$, ns	100	250	250	
$T_{dis.}$, ns	1 000	1 000	700	
$\nu_{dis.}$, MHz	37.5	31.0	0.5	

V_{max} — maximum amplitude of the discharge pulse voltage at $R_{vol.} = 50\ \Omega$;
$t_{ed.\ min}$ — minimum duration of the discharge pulse rising edge;
$t_{ed.\ av.}$ — average duration of the discharge pulse rising edge;
$t_{dis.}$ — average duration of the discharge pulse;
$\nu_{dis.}$ — discharge frequency.

4. Conclusions

The developed test bench "Prognoz-2" allowed testing dielectric structural materials of the spacecraft under simultaneous exposure to several space factors such as high vacuum $3 \div 6 \cdot 10^{-6}$ torr, variation of the sample temperature from –130° C to +80° C, spectrum of electrons with energy of 10÷300 keV, solar radiation with a wavelength of 0.2÷1.2 μm.

The dimensions of the vacuum chamber enable testing not only samples with large geometric dimensions and entire spacecraft modules, but micro and nanosatellites.

The test bench was used to test modified ceramics (based on boron nitride) of the discharge channel of the spacecraft correcting plasma thruster in cooperation with JSC "ISS" named after Academician M.F. Reshetnev in the framework of the development work "Katun". The spacecraft solar panels were tested in conjunction with OJSC "Saturn". The spacecraft sun sensor was tested together with JSC "Geophysics-Space".

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