ARCING ON SOLAR ARRAY SURFACE IN SPACE AND LABORATORY

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Low Earth Orbit (LEO):

H=250-500 km, plasma N_e=10^3-10^6 cm^{-3}, T_e=0.05-0.2 eV, O^+ ions, V_{sc}=8 km/s

Polar Earth Orbit (PEO)=LEO + Aurora precipitation

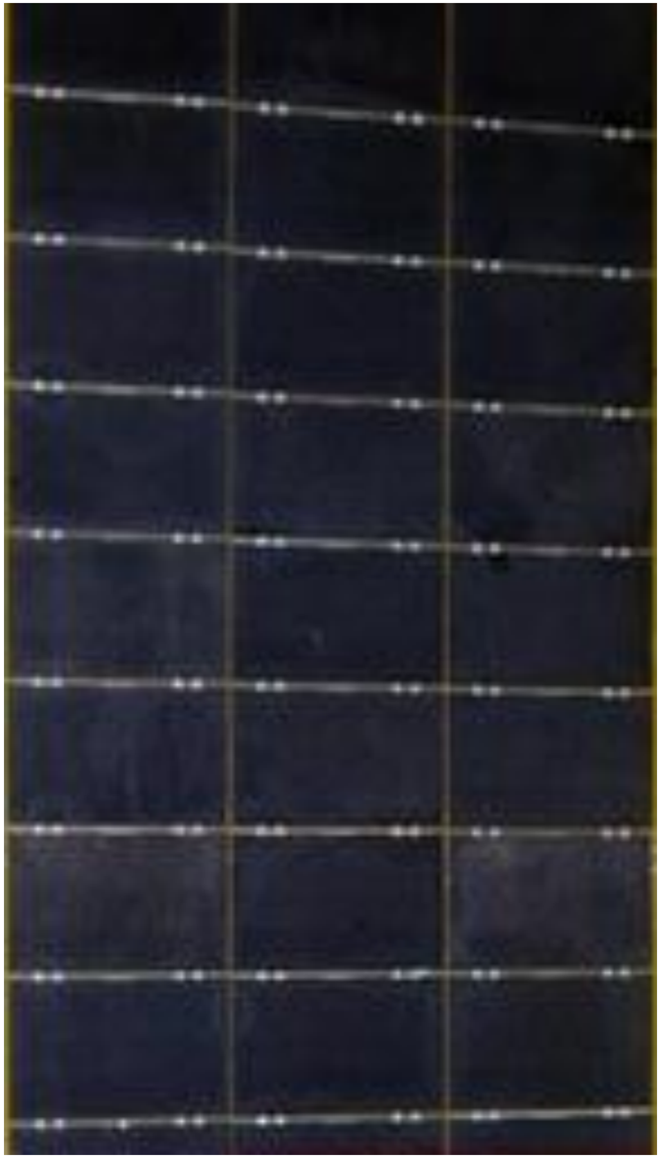
Geosynchronous Orbit (GEO):

H=36000 km, plasma N_e=0.1-1 cm^{-3}, T_e=0. 5-10 keV, H^+ ions, V_{ion}=400 km/s,
X –rays, UV, and CR

Important factors: S/C orientation and temperature variations

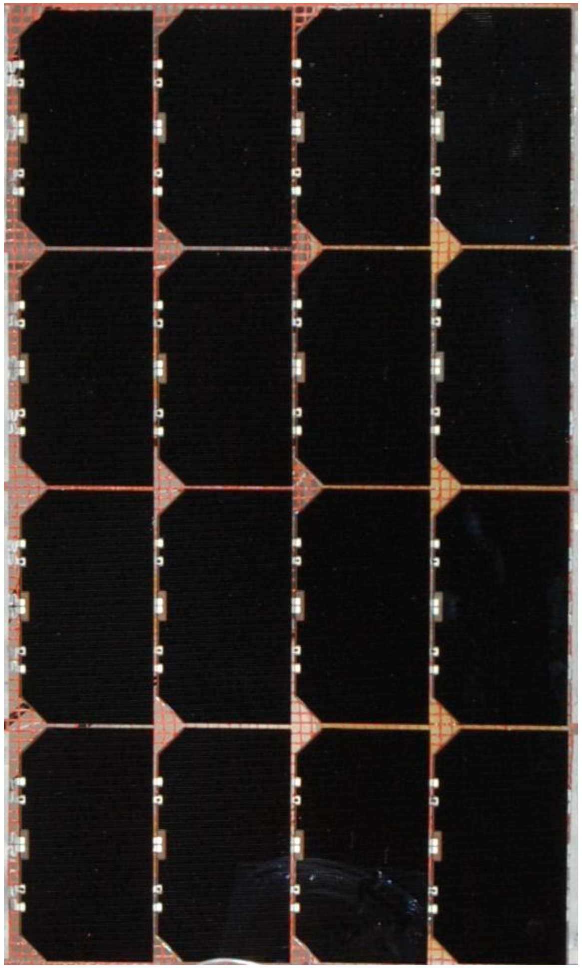
Other missions: planetary, deep space, solar, L2, etc.

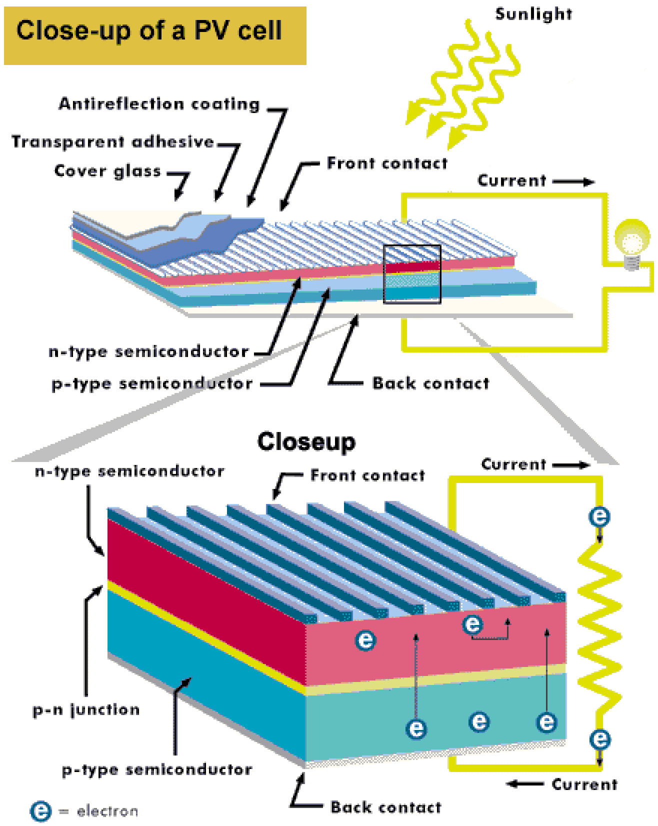
TECSTAR

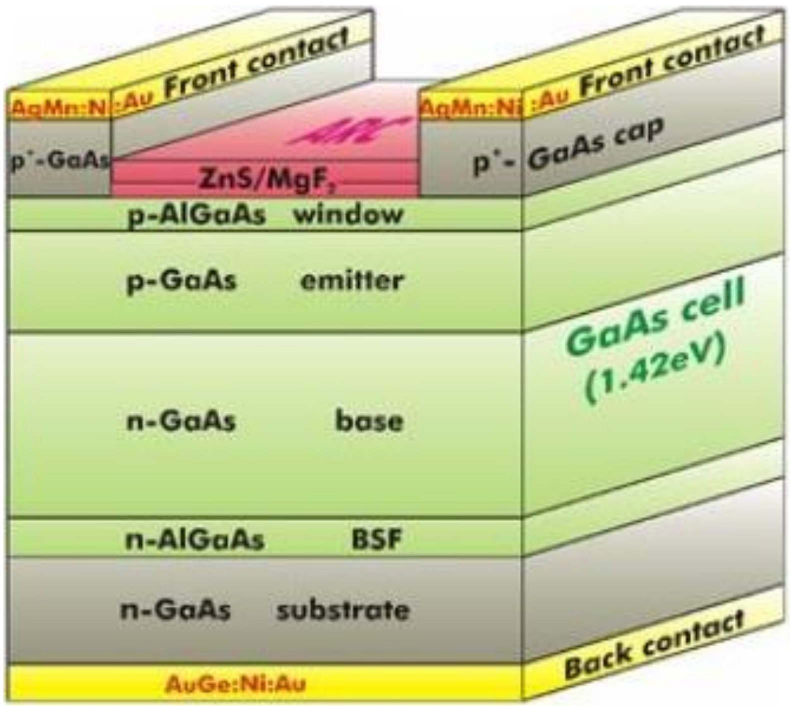


ISS

ORION

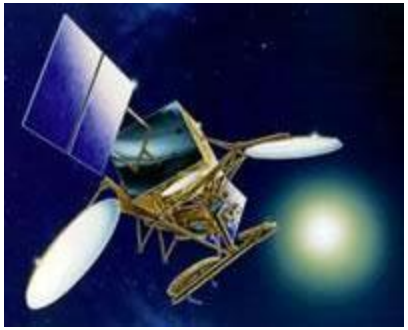




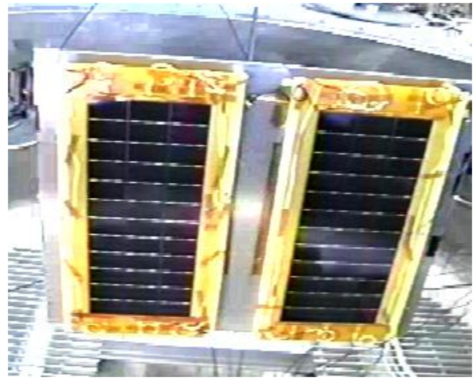


Si cells-robust, low efficiency (0.6 V)

3J (GaAs) –high efficiency (1.2 V)

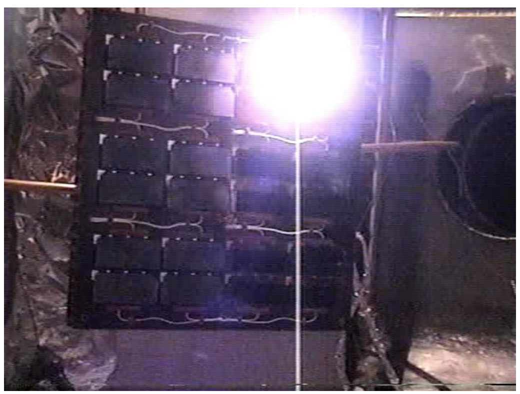


Spacecraft is charging negatively in surrounding plasma

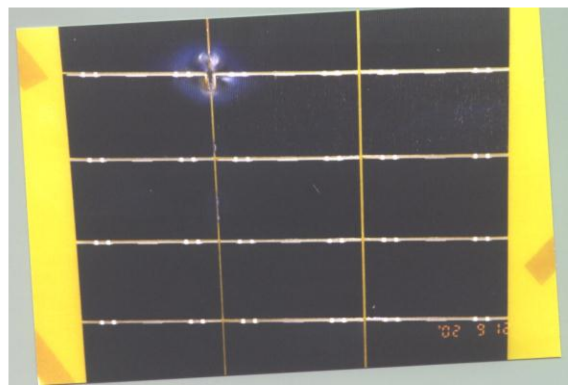


Differential charging is simulated in plasma chamber (PIF, NASA Glenn)

Primary arc on triple junction

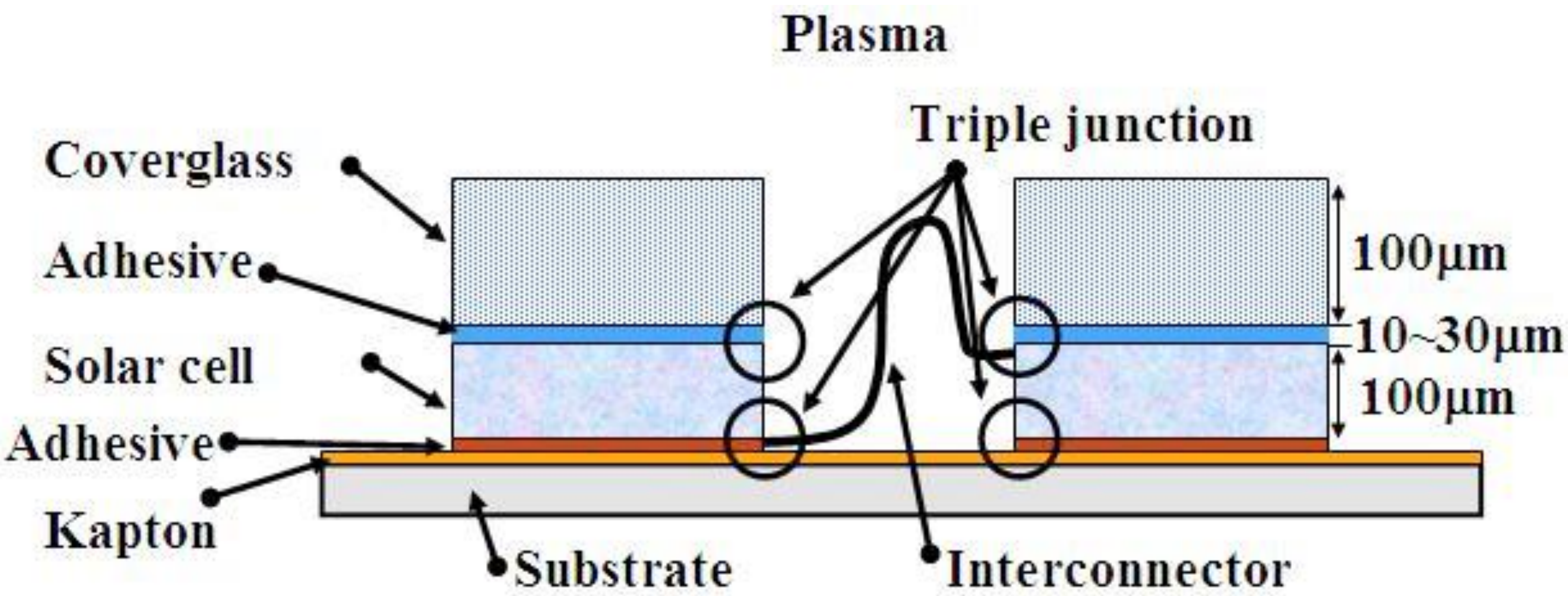


Sustained arc between strings



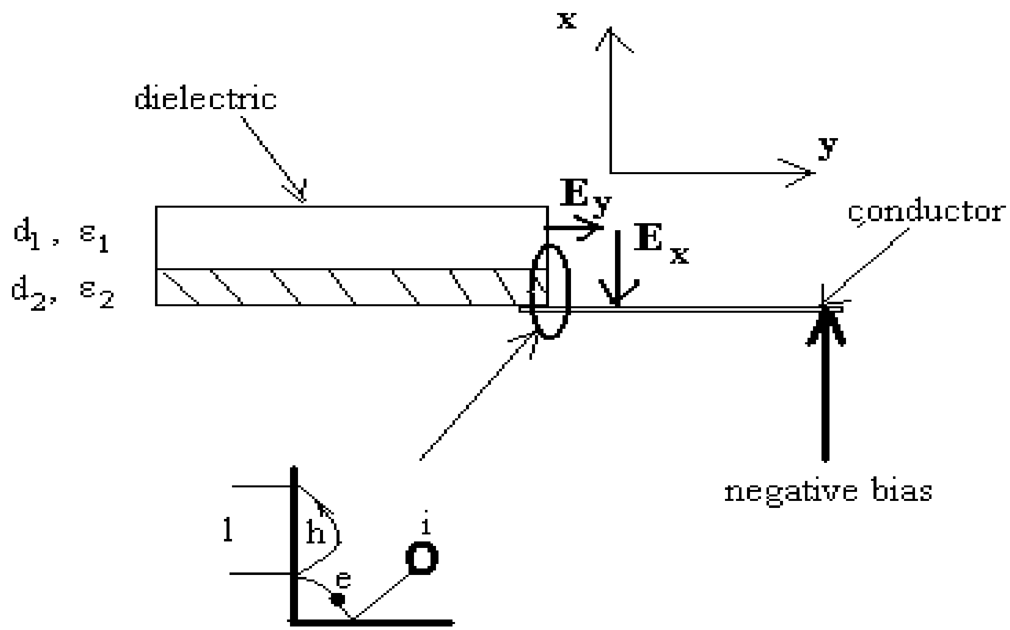
Damage induced by sustained arc

$$E_{2x} = \frac{\varepsilon_1}{\varepsilon_2 d_1 + \varepsilon_1 d_2} U$$



Solar Cell Design

Arc inception on triple-junction



In LEO:

$$U_{fl} = (0.8 - 0.9)U_{bus}$$

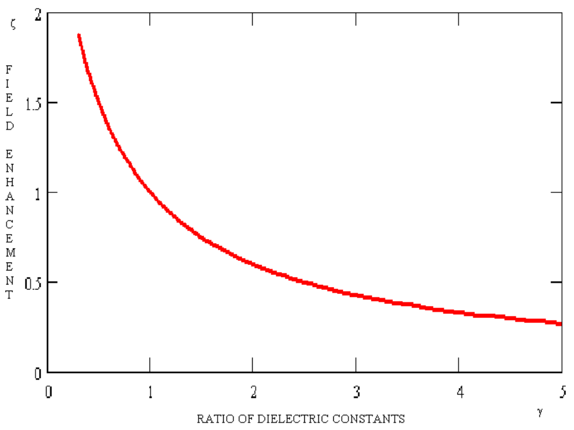
E=(1-5) MV/m

In GEO:

$$U_{cg} - U_{fl} \approx 1kV$$

$\beta = \beta_1 \beta_2 \beta_3$

Field enhancement vs. ratio of dielectric constants

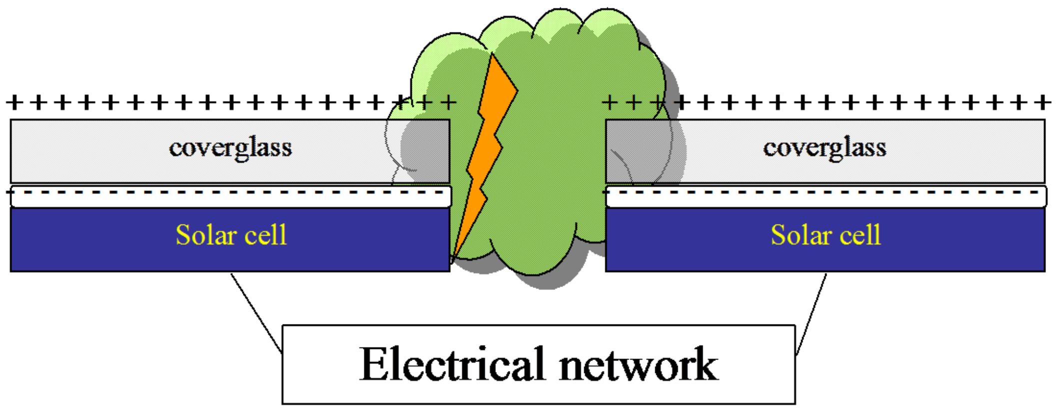


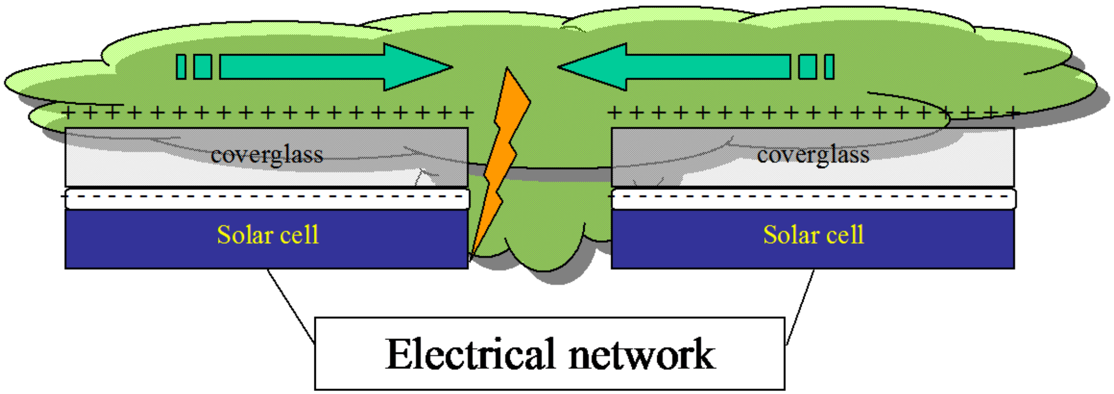
DOW CORNING ® 93-500
SPACE-GRADE ENCAPSULANT

ASTM D149 Dielectric Strength, t volts/mil……………………………….. 570
ASTM D 150 Dielectric Constant,
at 100 Hz………………………………………………………………..2.75
at 100 KHz………………………………………………………………2.73
ASTM 150 Dissipation Factor
at 100 Hz………………………………………………………………0.0011
at 100 KHz……………………………………………………………0.0013
ASTM D 257 Volume Resistivity, ohm-cm……………………………6.9 x 10^12
ASTM D 412 Tensile Strength, die C, psi…………………………………….790

GLASS

Chemical Composition	Physical Properties
SiO_2 = 80.6%	Coefficient of expansion (20°C-300°C) 3.3 x 10-6 K-1
B_2O_3 = 13.0%	Density 2.23g/cm3
Na_2O = 4.0%	Refractive index (Sodium D line) 1.474
Al_2O_3 = 2.3%	**Dielectric constant (1MHz, 20°C) 4.6**
Optical Information	Specific heat (20°C) 750J/kg°C
Refractive index (Sodium D line) = 1.474	Thermal conductivity (20°C) 1.14W/m°C
Visible light transmission, 2mm thick glass = 92%	Poisson's Ratio (25°C - 400°C) 0.2
Visible light transmission, 5mm thick glass = 91%	Young's Modulus (25°C) 6400 kg/mm^2


coverglass
coverglass
Solar cell
Solar cell
Electrical network


coverglass
coverglass
Solar cell
Solar cell
Electrical network

Floating Potential:

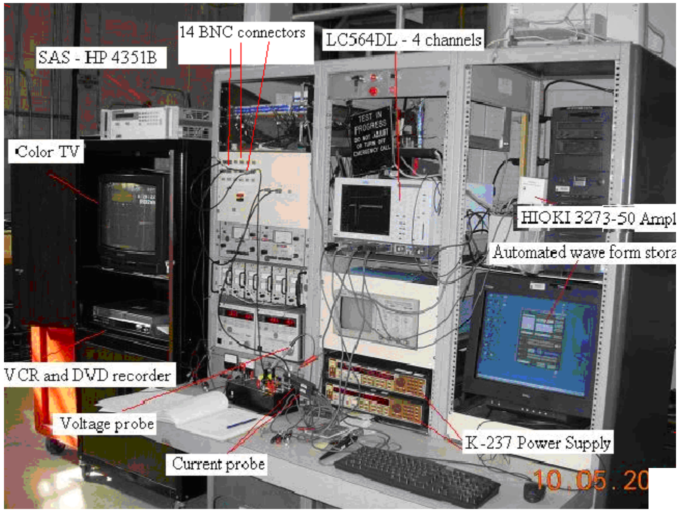
Steady-state is determined by current balance $I_{tot} = I_e + I_i + I_{\sec} = 0$

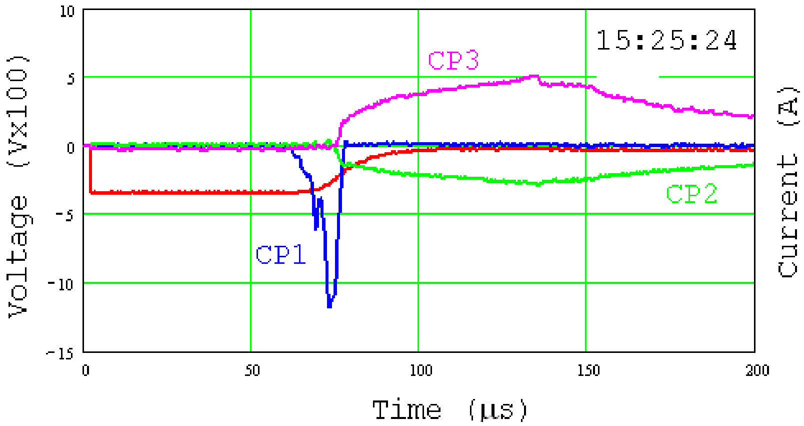
For metal ball in equilibrium plasma $U_{fl} = -T_e \ln \frac{V_e}{V_i}$

Absolute charging is important for scientific measurements but differential charging may result in S/C malfunctions and catastrophe.

S/C external surface is not homogeneous. Special computer programs are developed to compute potential distribution (EWB and NASCAP in USA, MUSCAT in Japan, and SPIS in Europe).

Sun provides 1.4 kW/m^2, solar array efficiency is 20-25%, and modern S/C needs in 3-20+ kW electric power→high voltage solar array

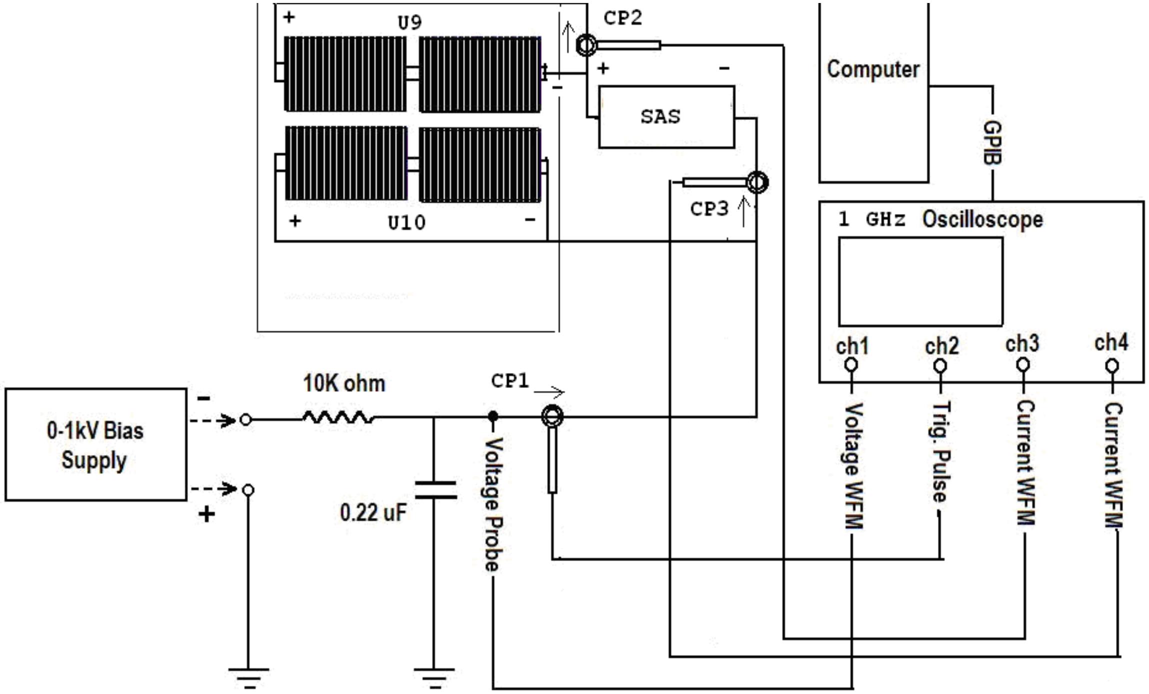




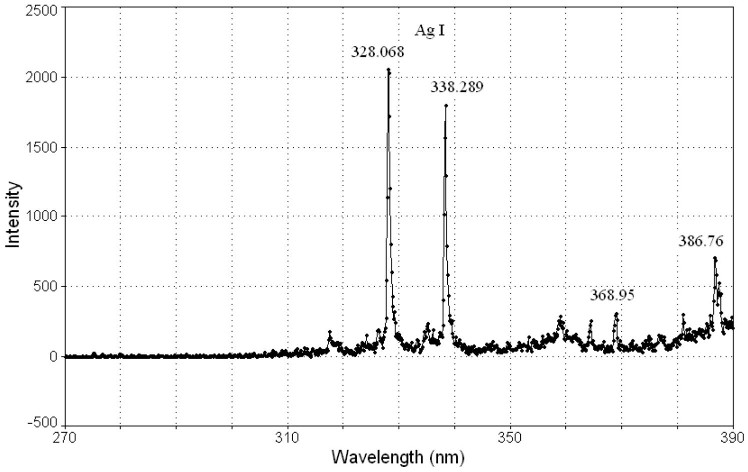
P=30 μTorr (Xe)

Arc in LEO plasma

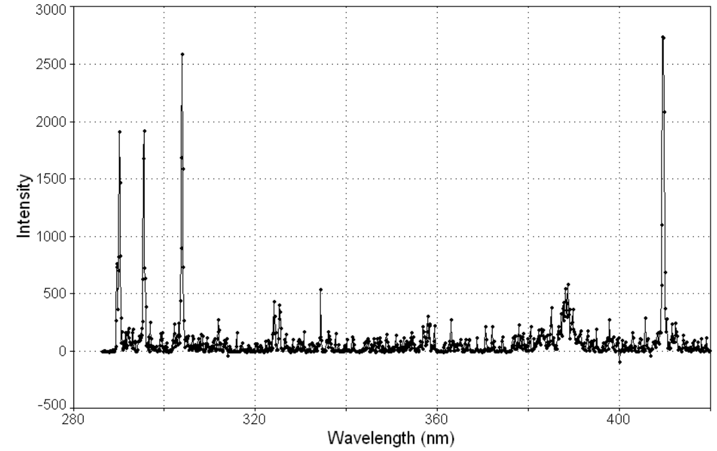
T_e=0.2-0.5 eV; n_e=10^5-10^6 cm^{-3}



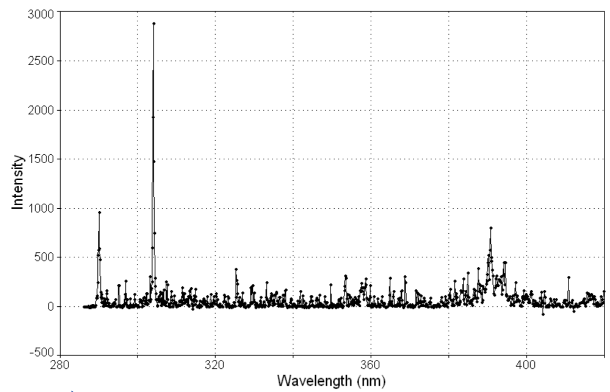
Circuitry diagram for arc parameter measurements.



a)



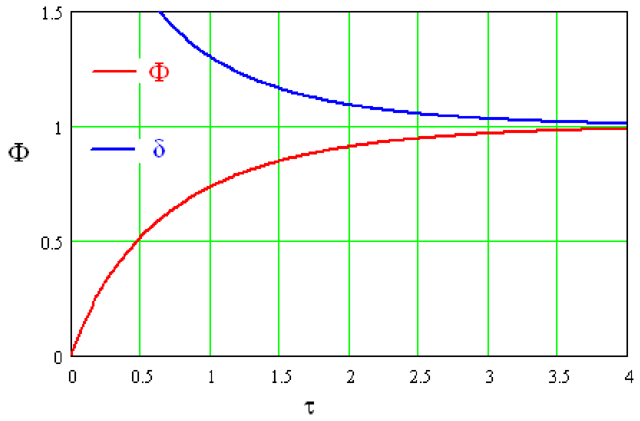
b)



c)

Resolution 0.12 nm/px

Emission spectra of arc plasma: a) arc on interconnect; b) arc between strings U3-U4; c) temporary sustained arc (>500 µs). Spectral lines of Ge I (303.9) and Si I (390.6) are identified.



For example, a typical beam of 1 nA/cm^2 provides a coverglass charging time of a little over 120 s. If the second crossover energy is 2.0 kV, the bias voltage is -2.5 kV, and the beam energy is 3.3 kV, then the surface potential at steady state is U_g= -1.3 kV, and differential charging reaches U= 1.2 kV.

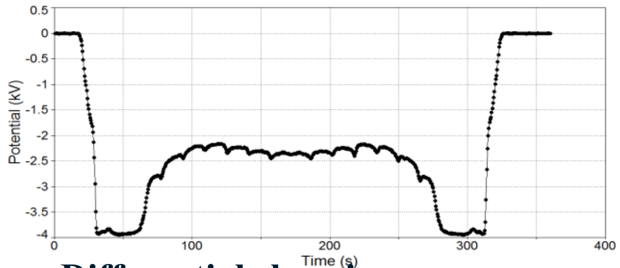
In GEO

$$C_s \frac{dU}{dt} = j_b(1-\delta(U))$$

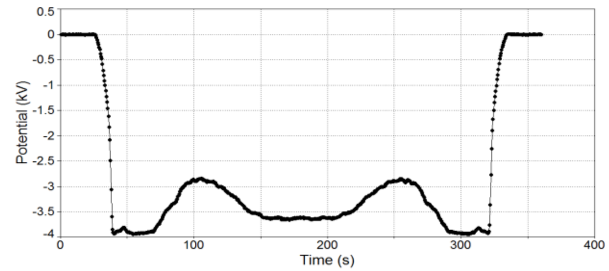
j=1 nA/sq.cm R=1 MOhm

$$\delta(U) = \delta_m \exp\left(-\frac{U}{E_{sc}}\right) \qquad \tau = \frac{j_b}{C_s E_{sc}} t \qquad \Phi = \frac{E_b + U_g}{E_{sc}}$$

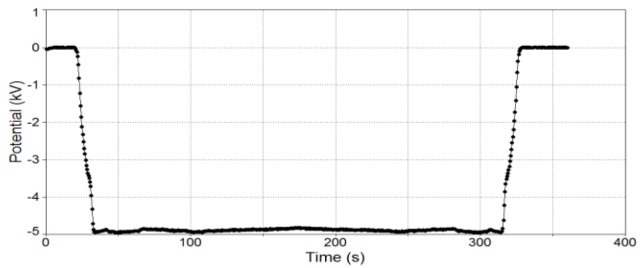
GEO SIMULATION



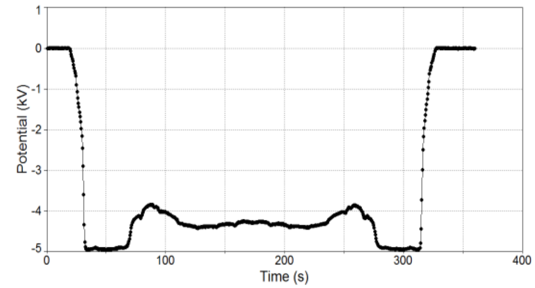
Differential charging



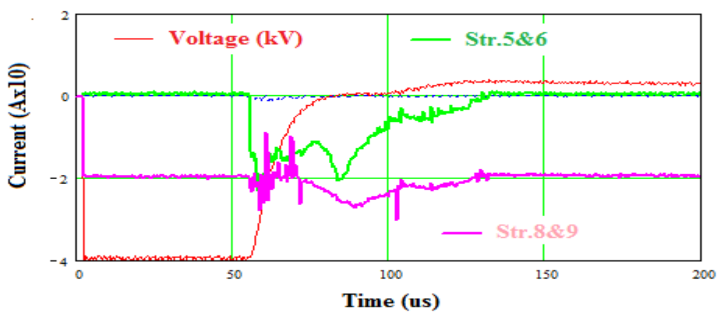
TREK scan of str.8 after five arcs at bias voltage of -4 kV

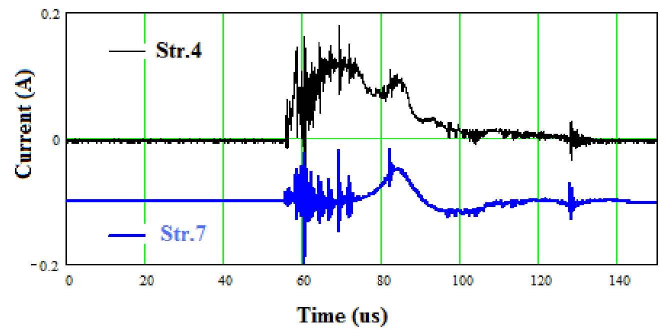


TREK scan of str.8 biased -5 kV



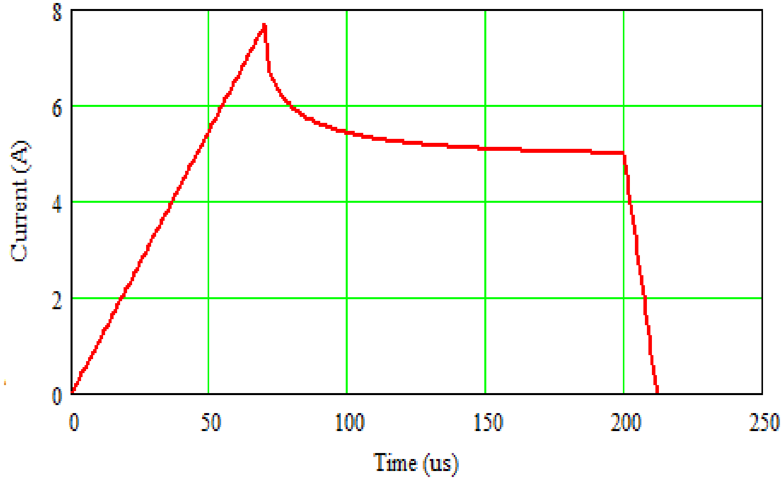
TREK scan after last arc



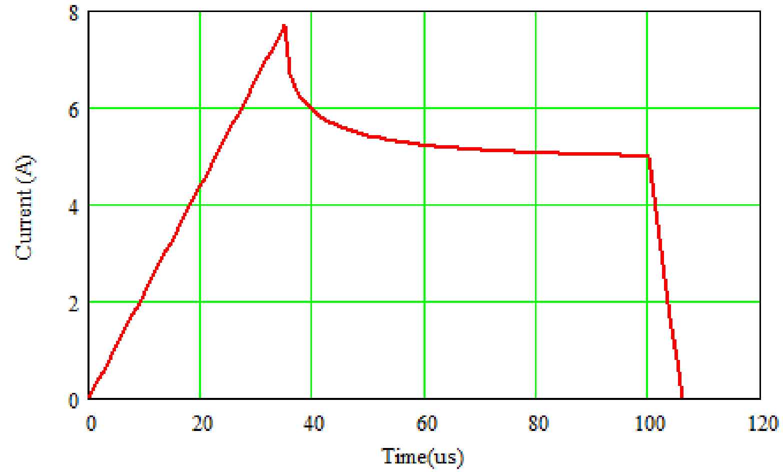


Discharge current

$$I(t) = CU \frac{dS}{dt}$$



Current pulse wave form: coupon dimensions 1.4x4 m², arc in the middle point, v=10 km/s. U=800 V



Pulse wave form for the same sample: expansion speed v=20 km/s, and U=400 V

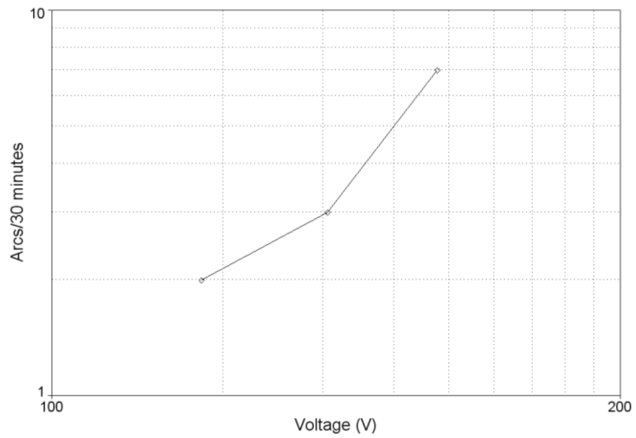
$$I(t) = 2\pi C U v^2 t; \quad t \le \frac{H}{2v}$$

$$I(t) = 4 C U v^2 t \cdot a\sin\left(\frac{H}{2vt}\right); \quad t > \frac{H}{2v}$$

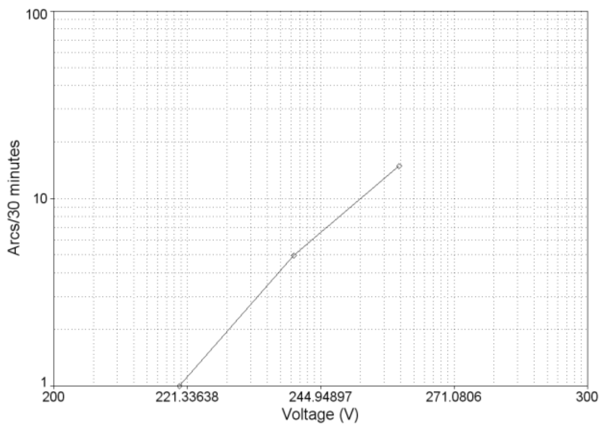
C=0.25 μF/m²

V=Const; full discharge

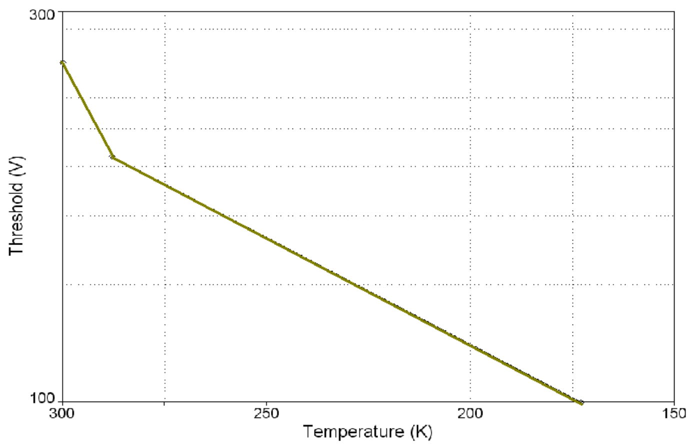
LEO



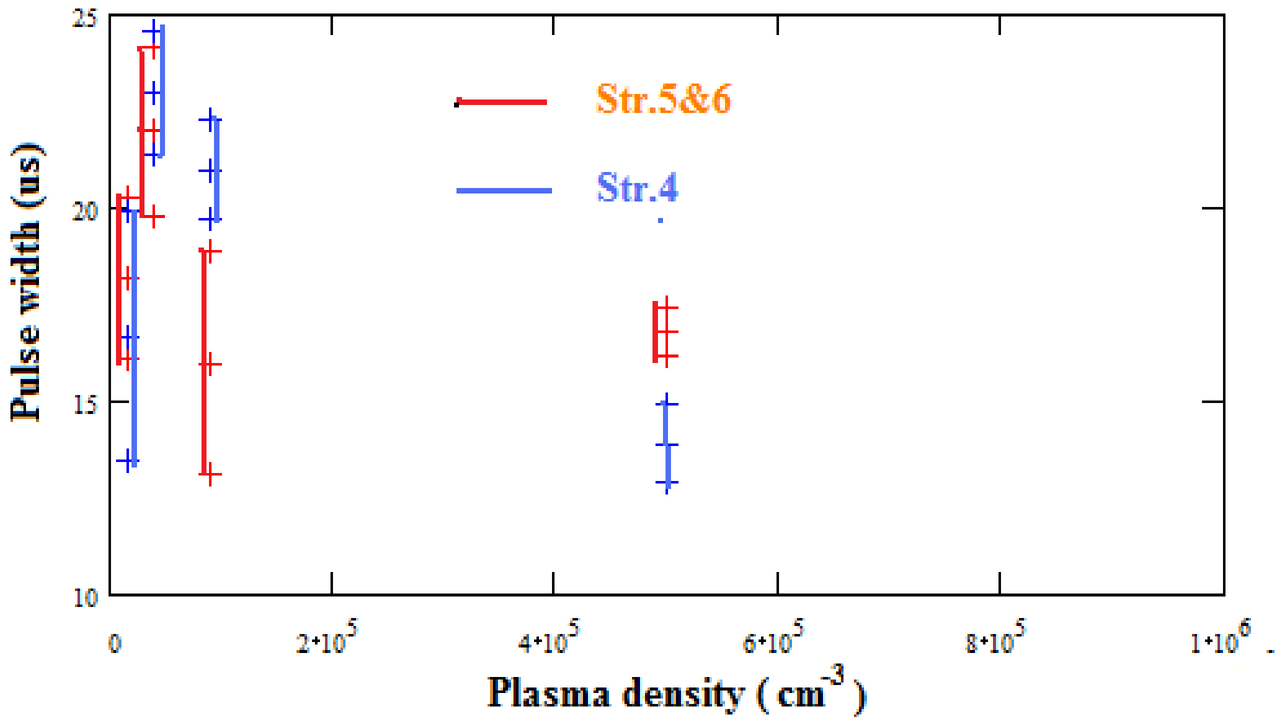
Arc rate vs. bias voltage at low temperature (-100 C).



Arc rate vs. bias voltage at the temperature +10 C



Arc threshold vs. sample temperature



Pulse width vs. plasma density is shown for two cases: two parallel strings and one separate string.

PROBLEMS:

Peak and width of Arc Current pulse vs. dimensions
Arc Inception Voltage and Threshold current for SA
Damage to cells
Electromagnetic Interference (EMI)
Interaction with Thruster Plume Plasma

Continuously changing design and materials

References:

Vayner, B., Galofaro, J., and Ferguson, D. “Interactions of High-Voltage Solar Arrays with Their Plasma Environment: Physical Processes”, ***Journal of Spacecraft and Rockets***, Vol.41, No.6, 2004, pp.1031-1041.

Vayner, B., Ferguson, D., and Galofaro, J. “Emission Spectra of Arc Plasmas”, IEEE Transactions on Plasma Science, Vol. 36, No.5, 2008, pp.2219-2227

Vayner, B., and Galofaro, J. “Inception and Prevention of Sustained Discharges on Solar Arrays”, *IEEE Transactions on Plasma Science*, V.40, No.2, 2012, p.388-393