

# The Plasma Plume of the ISS Plasma Contactor Unit under the Effect of the Geomagnetic Field

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**Abstract:** The process of plasma plume formation on a low orbit was analyzed based on a plume of the plasma contactor operated as ISS standard equipment. It was shown that the geomagnetic field has strong influence on the characteristics of plasma plume expansion that leads to the regular changes of ISS plasma environment parameters. The developed method of plasma plume behavior prediction was described. The correlation with flight data was given.

## I. Introduction

The research of plasma contactor<sup>††</sup> operation as standard equipment of the ISS has shown that the time curve of injection current  $J_{PCU}$  flowing between PCU and the ionosphere has peaks which periodically repeat. [1]. To determine the factors influencing behavior of this curve the large scope of experimental and theoretical work [2 and its References] was conducted. This paper studies an influence of the geomagnetic field on the characteristics of PCU plasma plumes and their impact on electrodischarge processes occurring between ISS elements. This research was conducted as a part of the space experiment program. The space experiment called "Plasma-MKS" has been conducted at ISS since 2005. The experiment is aimed at an investigation of the parameters of ISS plasma environment forming due to the operation of on-board systems which emit gas and plasma. The goal of the investigation is to develop the methods how to predict and minimize interfering and damaging effects of electroplasma processes occurring in spacecraft (SC) plasma environment.

The value of plasma contactor injection current,  $J_{PCU}$ , depends on the potential difference between ISS body galvanically connected with PCU and ISS plasma environment. The electrical field near ISS exists due to the operation of high-voltage solar arrays (HV SA) of American segment (AS) ( $\varepsilon_{SA}=160V$ ) and polarization of the station when it moves across the magnetic field ( $\varepsilon_B \sim 20V$ ). The negative pole of HV SA is shorted to the ISS body and active side of the solar panel is electrically connected with plasma environment through thin conducting side faces of a photoelectric element. Therefore, SA leakage current flows through this plasma between high-voltage edges of the solar panels and ISS body, that means there is constantly ignited discharge. The high-voltage zones of SA strings serve as anodes of this discharge. All conducting areas of outer surface of ISS constitute cathode (including PCU).

PCU unit consists of two plasma contactors (gas-discharge hollow cathode). The unit generates a plume of xenon plasma by means of which the negatively charged body of ISS is discharged. At this, PCU ensures low value of the cathode potential fall ( $\varphi_c < 10 - 15V$ ) even if the current injected by the cathode goes as far as 12A. [3]. When PCU is switched off or the density of plasma environment significantly changes the distribution of spatial charge potential will possibly change and negative bias of ISS body to plasma near  $\varphi_c$  will sharply grow [4].

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<sup>††</sup>Plasma Contactor Unit (PCU) – is mounted on the Z1 module (AS ISS) for active control of surface potential of the station

This poses a hazard for astronauts working outside of SC because their space-suits are shorted to the SC body and present protruding areas of the common cathode surface.

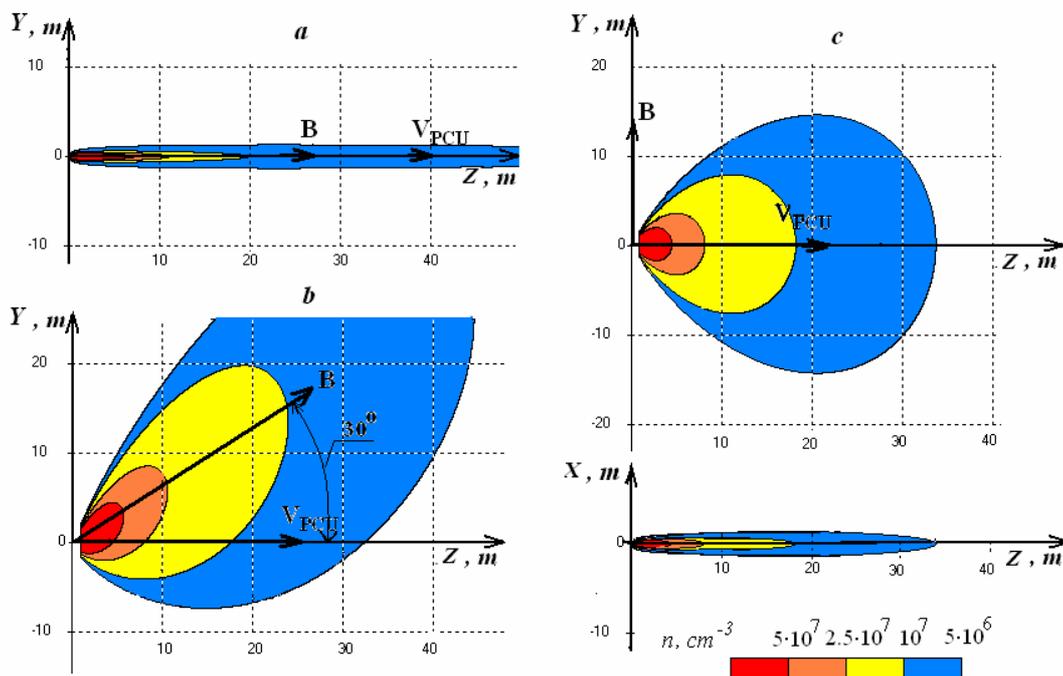
It was shown before [5] that under the influence of the geomagnetic field a plasma plume configuration on low-earth orbit (LEO) changes depending on an angle  $\gamma$  (angle between plasma plume axis and magnetic induction vector). If  $\gamma=0$ , that means the plume effuses along the magnetic field line, the plume is in the form of a spoke elongated along the field line. If  $0<\gamma\leq 90^\circ$ , that means the plume effuses at an angle with the magnetic field lines, the plume is in the form of a petal flattened across the magnetic field lines. The plane of petal symmetry is defined by the vectors  $V_{PCU}$  and  $B$ , PCU plume velocity and the geomagnetic field induction, respectively. The orientation of B vector and plasma petal changes during the ISS orbital movement. Therefore, the parameters of plasma environment near ISS elements also change.

## II. Theoretical background

Taking into account that the plasma plume of PCU is similar to EP plasma plume we used *self-similar model (SSM)* [6] to predict the dynamics of plasma plume and its interaction with the geomagnetic field and charged elements of ISS. Space experiment "Plasma-MKS" [7] investigated electrodischarge processes at ISS. The reference [7] shows that some PCU plume configurations lead to the appearance of plasma bridge when PCU plume is directed towards solar panels due to the influence of magnetic field. At this, the current between PCU and high-voltage zones of SA increases.

The conditions when plasma bridge appears were calculated based on SSM of plasma plume expansion in the geomagnetic field.

The "plasma bridge" phenomenon: PCU generates plasma plume of  $Xe^+$  which parameters are  $\dot{N} \sim 10^{18} s^{-1}$  (flow rate) and  $V_{PCU} = 2 \div 3 km/s$  (velocity) [3]. Not taking into account magnetic field influence the density of this plume is less than the background one at a distance much smaller than the distance to the SA panel serving as an anode ( $L \sim 20 \div 40 m$ ). Due to the influence of the geomagnetic field  $B$  expansion of the plasma plume across the magnetic field lines is strictly confined. As a result, plasma concentration of the plume is much higher than the one of the ionosphere.



**Figure 1. Configurations of PCU plume at different variants of injection: a – along the geomagnetic field ( $\gamma=0$ ); b – at the angle  $\gamma= 30^\circ$ ; c- across the geomagnetic field ( $\gamma=90^\circ$ ) and the cross-section of plasma petal.**

Figures 1 present different variants of plasma plume configuration depending on the angle  $\gamma$ : a) the equal density level surfaces of the plume which is effused along the magnetic field ( $V_{pcu} \parallel B$ ,  $\gamma= 0$ ); b) at the angle of  $\gamma= 30^\circ$ ; c) across the magnetic field ( $V_{pcu} \perp B$ ,  $\gamma= 90^\circ$ ) and the cross-section of plasma petal (below). On the figure the coordinates axis XYZ are related to the plume: Z axis coincides with plasma velocity vector -  $V_{pcu}$ , Y axis lies in the petal plane determined by  $V_{pcu}$  and  $B$  vectors. Taking into account that such values of angles  $\gamma$  are repeated

along one orbit pass the plasma plume configuration is obviously changeable. At this, the dimensions of plasma formation which density is significantly higher than the one of ionosphere plasma at a flight attitude ( $10^5$ - $10^6$   $\text{cm}^{-3}$ ), are comparable with the ISS dimensions.

### III. Orientation of PCU plume and SA panels during ISS orbit pass

Two variants of ISS solar panel arrangements were considered during experimental research. The first variant (figure 2) relates to ISS flight configuration during the period from December, 2000 to August, 2006. The second variant of panel arrangement (figure 3) relates to ISS configuration during the period from September, 2006 till June, 2007. On the figures the scheme of “plasma bridge” realization is shown as plume contours.



Figure 2.

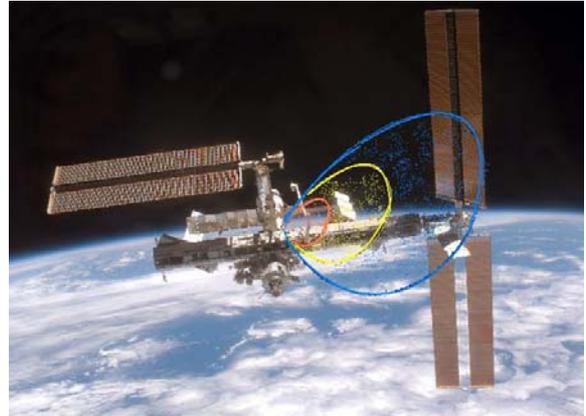


Figure 3.

When the ISS passes an orbit the form and orientation of the petal relative to the station change in accordance with the change of  $\mathbf{B}$  vector direction. The petal plane rotates about the PCU plume axis – angle  $\alpha_p$ . This axis is parallel to  $Z$  axis of coordinate system centered at the service module (SM) of ISS RS (CCS). Figure 4 shows isoconcentration lines of PCU plasma petal located in the plane of solar panel axes for ISS flight configuration 11A. The panels are contoured in the figure. When the ISS passes an orbit the solar panels (Module P6) rotate about their axes to follow the Sun (angle  $\beta$  in figure 4). Two zones of one orbit pass were considered for the analysis. The first one (fig.4a) is the zone locating to the left from the maximum  $J_{H,1}$ , where the plume does not touch the panels due to magnetic field influence, the second one (fig.4b) – to the right from the maximum  $J_{PCU}$ , where almost whole surface of the solar battery is flown by xenon plasma of PCU. Here,  $X$ ,  $Y$ ,  $Z$  axes are parallel to CCS coordinates.

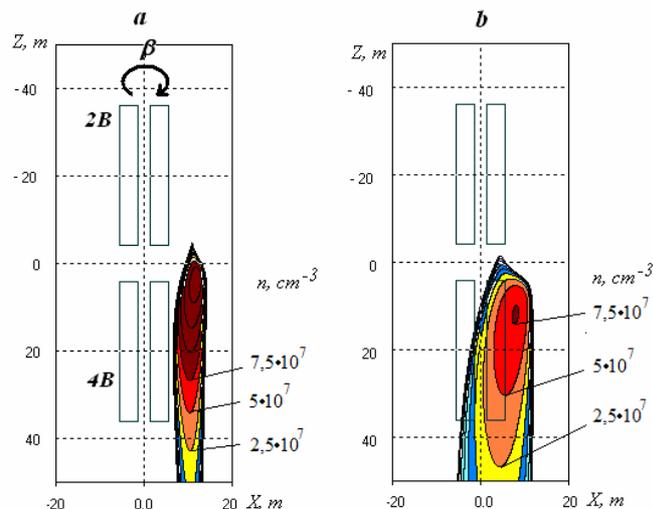
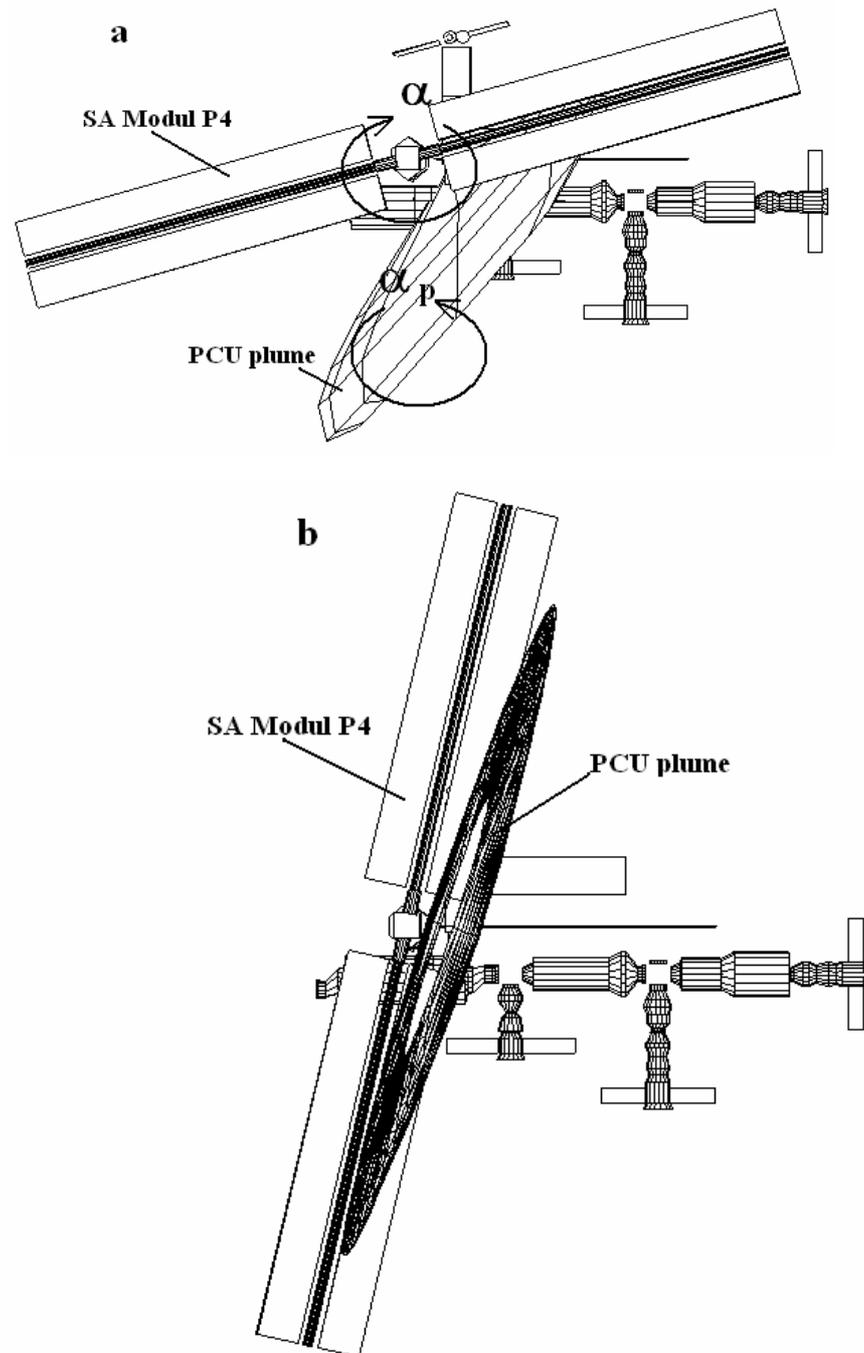


Figure 4. PCU plasma plume cut with SA panel plane depending on the Earth magnetic field direction

Figure 5 shows 12A-1 configuration relative position of the plasma plume and solar panels at two time points. The first one (fig.5a) is the moment when the plasma petal is turned away from the P4 module panel plane. The second one (fig.5b) is the moment when the plasma petal plane coincides with the SA plane.



**Figure 5. Change of relative position of SA plane and plasma petal plane depending on geomagnetic field.**

#### **IV. SPEED method**

The method called SPEED, *Spacecraft Plasma Environment and Electric Discharge* [7], was developed to predict the set of geophysical and orbital conditions when electroplasma processes are to be enhanced. This method allows to predict a beginning moment and duration of such processes as “plasma bridge” when the significant change of PCU current takes place or the jump of the station potential value when PCU is switched off.

This method is based on the following models:

- three dimensional model of plasma plume expansion under the influence of geomagnetic field (*SSM*) [6],

- three dimensional model of SC gas-plasma environment [8],
- mathematical model of ISS orbital motion [9],
- international model of the geomagnetic field [10],
- empirical model of mosaic anode processes [11].

Figure 6 shows an example how the SPEED method works.

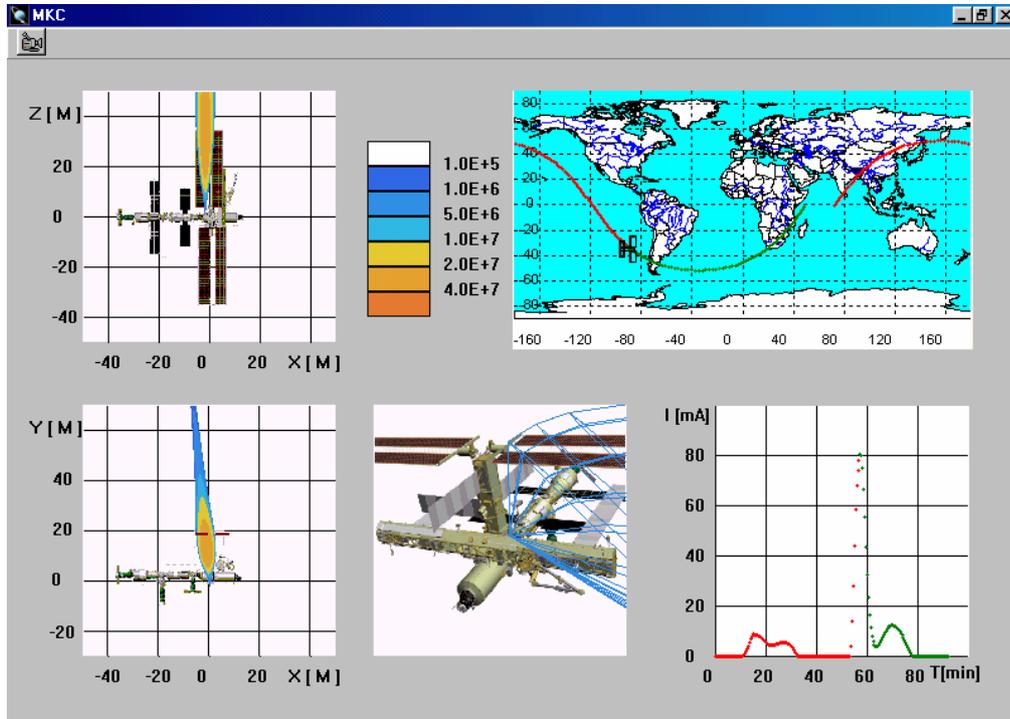


Fig. 6 The example how the SPEED method works (turn # 1667, ISS, 11/04/2004)

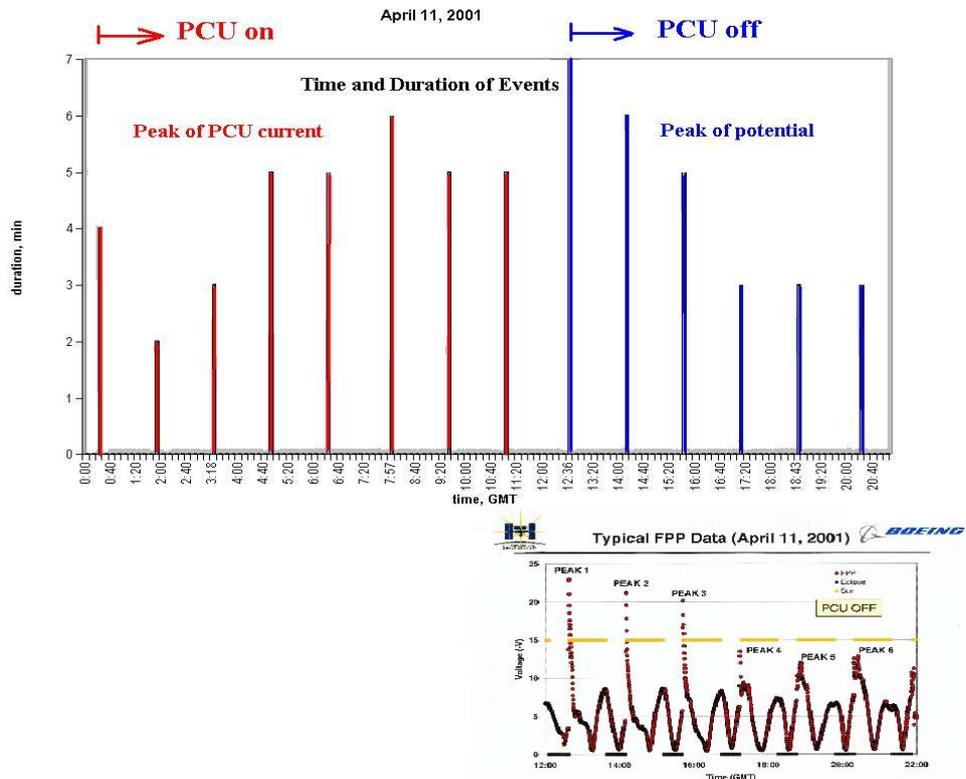


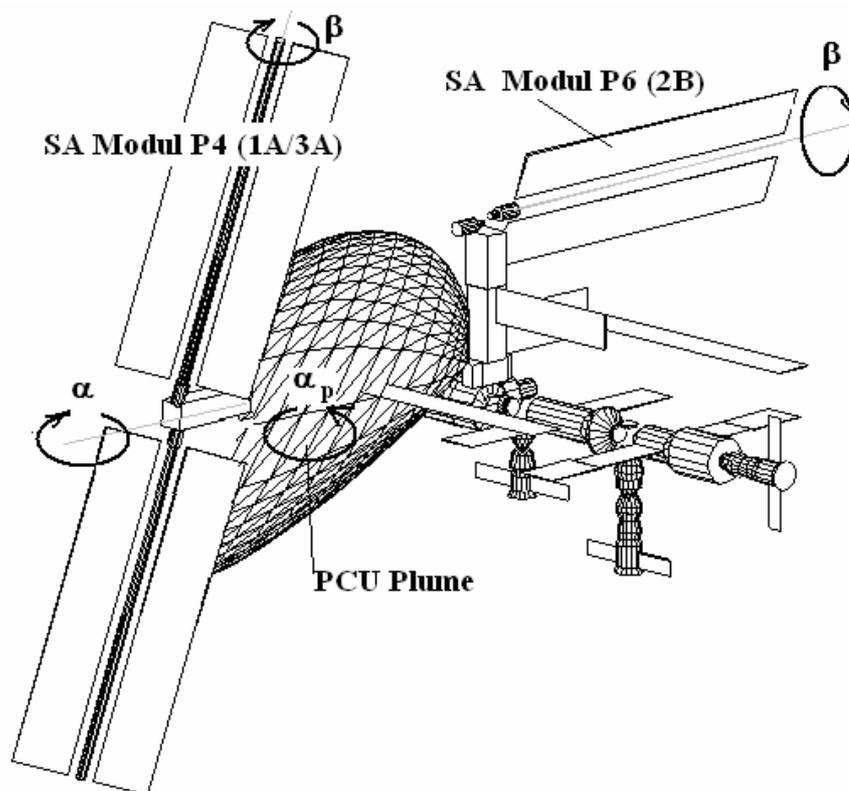
Fig. 7 Correlation between calculated (upper picture) and measured (lower picture [1]) potential peaks, 11/04/2004

The following data are displayed as a result of SPEED method work:

- flight trace of the orbit turn used during the calculation – at the upper right;
- ISS shown in -Y-direction of CCS and isoconcentration lines of PCU plasma petal crossed by the plane where high-voltage solar battery panels lie ( $XOZ$  plane at  $Y=18m$ ) – at the upper left;
- ISS shown in +Z-direction of CCS and isoconcentration lines of PCU plasma petal crossed by the plane by the plane  $XOY$  at  $Z=36$  m which goes through the left extremity of HV SB panel – at the lower left;
- color scale showing the level of electron concentration  $n_e[cm^{-3}]$ ;
- isometrical view of ISS and plasma petal at a level of  $n_e=10^7 cm^{-3}$  – at the middle of lower part of the screen;
- time variation (along the flight trace) of the PCU plasma current which is collected by HV SA panel – at the lower right. A model of metal-dielectric mosaic anode layer volt-ampere characteristics was used in the calculations. The experimental research of this anode is given in Ref. [11].

The PCU current is amplified when the PCU magnetic field line crosses conductive parts of SB. At this time the “plasma bridge” process occurs. Then the current flowing through the plasma environment along the magnetic field line significantly increases due to the fact that the electron mobility along the magnetic field lines is much greater than the one across the magnetic field.

If this occurs when PCU is switched off the ISS surface potential value jumps. American scientists register this effect many times, for an example, at April, 11 in 2001 [12, 13]. The values were measured with the *FPP* unit, a floating potential detector, which registered the floating potential of a station surface point relative to the plasma environment and measured the electron temperature and density of plasma. The measurements were conducted at both states of plasma contactor, when it was switched on and switched off. The measurement results are shown below in Fig. 7. The moments when current (or potential) peaks occur and durations of these peaks calculated with the SPEED method are given above on Fig.7. On the upper and lower fragments of Fig.7 the peaks are given in united time scale. One can see a good correlation between the predicted and registered peaks.

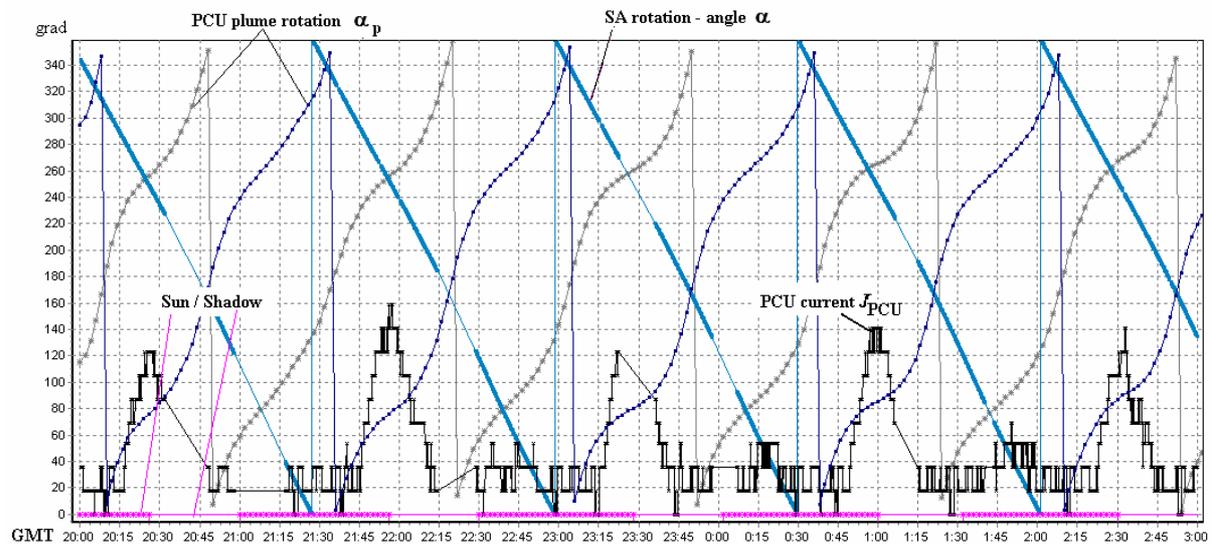


**Figure 8. Relative position of SA and plasma plume at the moment when PCU current peak was registered.**

Figure 8 shows the relative position of solar arrays and the plasma petal for flight configuration A12-1 at the moment, when the current increase was expected according with the SPEED method calculations.

Figure 9 demonstrates that the conclusion about the dominant impact of the magnetic field on PCU injection current was correct. The following data are given in the figure: the PCU current telemetry,  $J_{PCU}$ , and the SA rotation angle,  $\alpha$ . Moreover, the rotation angle of plasma petal  $\alpha_p$  was calculated, sunlit and shadow parts of trajectory are shown on the figure below. All values are given relative to the universal time.

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**Figure 9. Time correlation of PCU current peaks with angular arrangement of plasma petal relative SA plane.**

One can see that the PCU current peaks always coincide with the moments when sunlit panel rotation angle is equal to the petal rotation angle -  $\alpha = \alpha_p$ . This configuration lasts during the period of 3-8 minutes. At that moment the magnetic field ensures the transfer of maximum number of charges to the high-voltage areas of SA like in the previous configuration.

## V. Conclusion

1. The characteristics of plasma plume expansion under actual conditions of ISS flight in low Earth orbit were studied. The plasma plumes were generated by the on-board Plasma Contactors Unit. The following results were obtained:
  - The plasma plume characteristics in LEO are defined by the geomagnetic field and electrodischarge processes developing when plasma interacts with ISS structure elements.
  - Even low-density plasma generated by the PCU unit, a low-power on-board generator, has a great impact on the distribution of electric currents and potentials between ISS surface elements.
2. The method called SPEED was developed to predict the intensity of electrodischarge processes. The influence of geophysical, orbital and electrophysical conditions on the characteristics of plasma environment formed when PCU plume expands is taken into account during the calculation with the use of this method.
3. The results of calculations with SPEED method quantitatively agree with the results of the experimental research conducted during the "Plasma-MKS" space experiment.

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