ACTIVE SPACECRAFT POTENTIAL CONTROL FOR CLUSTER RESULTS FROM THREE YEARS IN ORBIT

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Abstract

The technique chosen to control the potential of the Cluster spacecraft is based on liquid metal ion sources generating an energetic ion beam. The ion current counteracts the photo-electron current and thereby clamps the spacecraft potential to few volts positive even in a very tenuous plasma environment where few other charge carriers exist. This principle and its implementation on the Cluster spacecraft is reviewed from both technical and scientific perspectives. The ion sources are light and require very moderate power resources. Initial results reported earlier have already proven the efficiency of the method and the absence of any interference with field, wave, and plasma measurements. After three years in space further conclusions can be drawn with respect to charging and the efficiency of the control. An overview of the performance of the ion emitters is given, and examples demonstrating the helpful effect on low energy plasma measurements - both electrons and ions - are presented. Finally, the possible application of this technique in future missions is addressed.

Introduction

Active spacecraft potential control has been recognized as a suitable means to ensure accurate plasma measurements on board a spacecraft.

First instruments serving this purpose were designed in the 1980's and flown in the 1990's. The technique which was applied in most cases was the one also used on Cluster: the emission of an ion beam with an energy of several kiloelectronvolt moves the equilibrium potential of the spacecraft into the desired range. Another principle using a plasma source instrument (PSI, Moore et al., 1995[1]) was applied on the Polar spacecraft. This technique brought about quite different results, some of them undesirable.

Two other instruments relied on energetic ion beams:

- Instrument RON on board of the Russian Interball Auroral Probe (Torkar et al., 1998[2]) launched in 1995 into a high inclination Earth orbit
- The Potential Control Device on board of Equator-S (Torkar et al., 1999[3]) launched in 1998 into an eccentric, equatorial Earth orbit

Both instruments can be considered as direct predecessors of the instruments flown in the Cluster mission. The Cluster example provides us with the first long-term data set for studying the effects of active spacecraft potential control. The satellites were launched in July and August, 2000, respectively.

Principle of Operation

Let us review the principle of operation applied for active spacecraft potential control on Cluster. The spacecraft have polar orbits around the Earth with 4 x 19.6 R_E and lead regularly into the polar regions and in the lobes of the magnetosphere, where plasma density may be very low ($<<1$ cm^{-3}). Under these conditions the plasma electron current to the spacecraft surface is small compared to the current of photo-electrons generated at the surface. Therefore the high-energy tail of the photo-electrons suffices to compensate the plasma current, resulting in a highly positive equilibrium potential which allows only these high-energy electrons to escape. By artificially adding another current of the order of the one carried by the bulk of the photo-electrons to this system, one can achieve a significant reduction of the equilibrium potential and a stabilization to values of a couple of volts. The sheath around the spacecraft shrinks due to the reduced spacecraft potential, improving not only the particle measurements, but very often also the electric field measurements by double-probes.

The instruments onboard Cluster are known as ASPOC. The acronym stands for Active Spacecraft Potential Control. A description can be found in Torkar et al. (2001)[4]. The instruments emit an Indium ion beam of 5 to 50 μA, and 5 to 9 keV into the direction of the spin axis. The ion sources are of the Liquid Metal Ion Sources type, where liquid Indium at $T \approx 200$ C covering a needle is ionized in strong E-field. The beam consists of >90% singly charged In^+>90% single charged In^+, and minor contributions of other charge states and clusters. The isotopic composition is dominated by the isotope 115 amu (95.7%), followed by 113 amu (4.3%).

These sources require little electric power: just about 0.5 W for a small heater element and the energy needed in the high voltage system to accelerate the ions into a beam. The mass of the charge material is negligible. One gram of Indium is sufficient for about 4000 hours of operation at 10 μA. The instruments on Cluster contain several emitters in order to increase the total operating time and to have some redundancy, but only one emitter is operated at one time.

Operations on Cluster

After many tests in the commissioning phase of the Cluster, the routine operation of the ASPOC instruments started with the beginning of the nominal mission on February 1st, 2001. Spacecraft potential control on Cluster is still active to date, although the nominal mission has ended on February 1st, 2003, and we are already half a year into the extended mission phase. Active operations is not continuous, but concentrates on key regions:

- the high latitude magnetosphere, with dynamic boundaries, presence of low plasma density regions, occasionally together with the presence of very cold plasma component.
- the lobes of the magnetosphere, in particular the boundaries to the tail plasma sheet.

While the Cluster orbits have their apogee in the tail region of the magnetosphere, the scientific objectives are fulfilled by operating the instruments over

- 7 hours around outbound cusp crossing
- 7 hours centered at neutral sheet
- 7 hours around inbound auroral zone crossing

Seven hours are not a limitation by the technique, but have been chosen as a compromise to allow coverage far into the extended mission. The instruments had also been operated throughout complete Cluster orbits (57 hours).

Table 1 shows a summary of ASPOC operations onboard Cluster, as of August 21st, 2003.

Table 1. Summary of ASPOC/Cluster operations

	Spacecraft			
	Salsa	Samba	Tango	Total
Total operation time (hours)	234	2543	2115	4892
Maximum total operation time of a single emitter (hours)	128	2525	1468	
Number of operations	107	450	373	930
Average duration of single operation (hours)	2.4	5.9	5.8	5.5
Maximum duration of single operation (hours)	7.8	36.4	35.8	

Beam Current and Energy

Figure 1 shows the spacecraft potential of the Cluster spacecraft number 1 and 2, both encountering almost the same plasma conditions. The magenta line indicates the time interval when the ASPOC ion beam was active on Cluster 2, with a beam current of 10 µA. It should be mentioned that this and some following figures show the voltage measured between double probes and spacecraft body as approximation to the real spacecraft potential. The measurements of the spacecraft potential are provided by the double probe instrument (EFW) described in Gustafsson et al. (2001)[5]. The figure shows:

- The potential of Cluster 1 (black) varies strongly, following the variations of density and temperature of the plasma in the changing environment.

- Without potential control at the beginning and the end of the time interval shown, the potentials of the two spacecraft follow each other closely, demonstrating that the conditions were similar on both spacecraft.

- A constant ion beam current is applied on spacecraft 2 between 05:15 and 09:30. It results in a compression of the variations of the spacecraft potential into a narrow band between 6 and 9 V. Some spikes in the raw potential data shown are caused by the operation of the active sounder and should be ignored in this context.

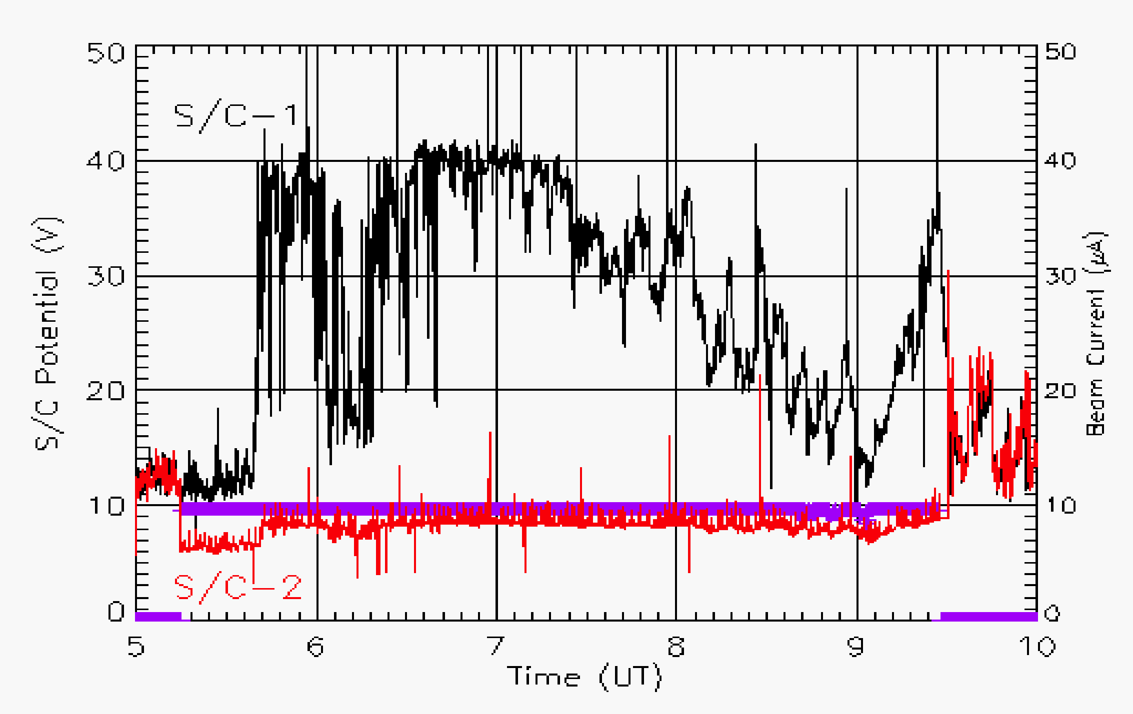


Figure 1. Spacecraft potential on Cluster 1 (black) and Cluster 2 (red), and ion beam current applied on Cluster 2 (magenta).

In summary, the spacecraft potential is very stable during ASPOC operation with constant beam current regardless of how the changing ambient plasma population, enabling better plasma measurements, as will be shown later.

By operating the ion sources in constant current mode, the extraction voltage varies according to the flow conditions of the liquid indium. Furthermore, the typical operating voltage varies between individual emitters due to small mechanical variations. The resulting voltages throughout the first years of the Cluster mission are shown in Figure 2. The horizontal axis refers to operational cycles of an instrument, which implies a typical operating time of 7 hours per cycle.

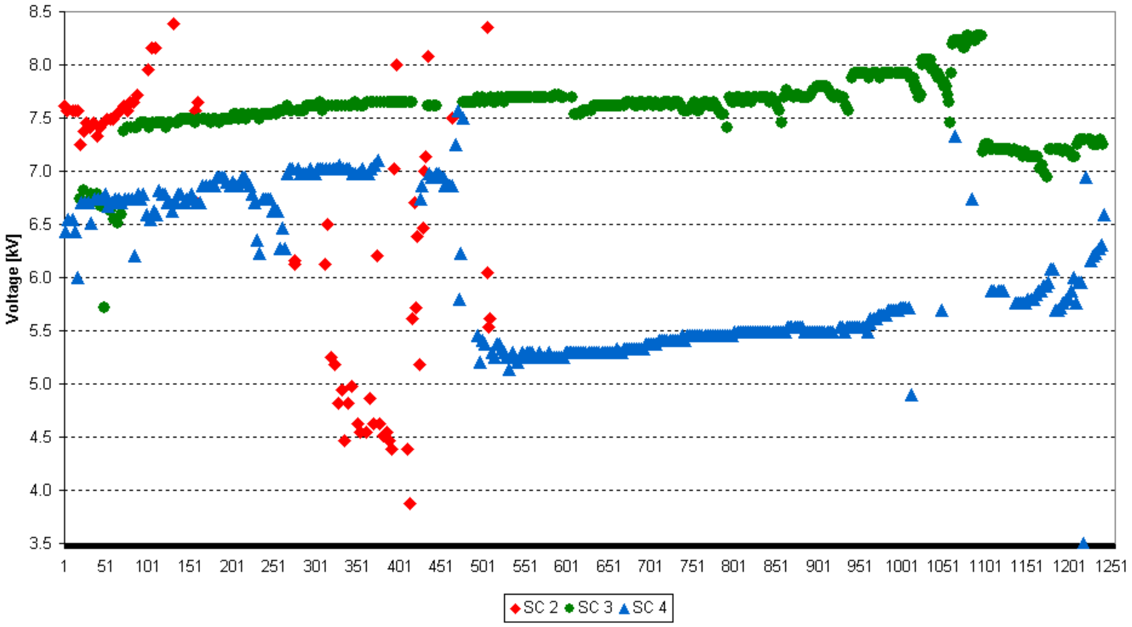


Figure 2. Development of beam energy. Horizontal axis refers to operational cycles of the instruments.

Spacecraft Potential Results

The correlation between the spacecraft potential on the Cluster spacecraft with and without spacecraft potential control has been analyzed on a statistical basis. The following figures display some results for the year 2001. Figure 3 shows a histogram of the spacecraft potential for Cluster 1 and 2, for all times without active spacecraft potential control, confirming that both spacecraft saw similar plasma conditions, and hence both spacecraft have almost identical potentials.

Figure 4 shows histograms, again for Cluster 1 and 2, for all times when the potential control was active, but only on Cluster 2. The peaks around 5 V in the Cluster 1 distribution can be associated to the solar wind and magnetosheath regions. Their position is only slightly shifted to lower voltage when the ion beam is turned on on Cluster 2. However, the range of potentials between 7 V and 45 V measured on Cluster 1 in low density regions in the magnetosphere is converted to a single peak at about 8 V on Cluster 2 due to the ion beam.

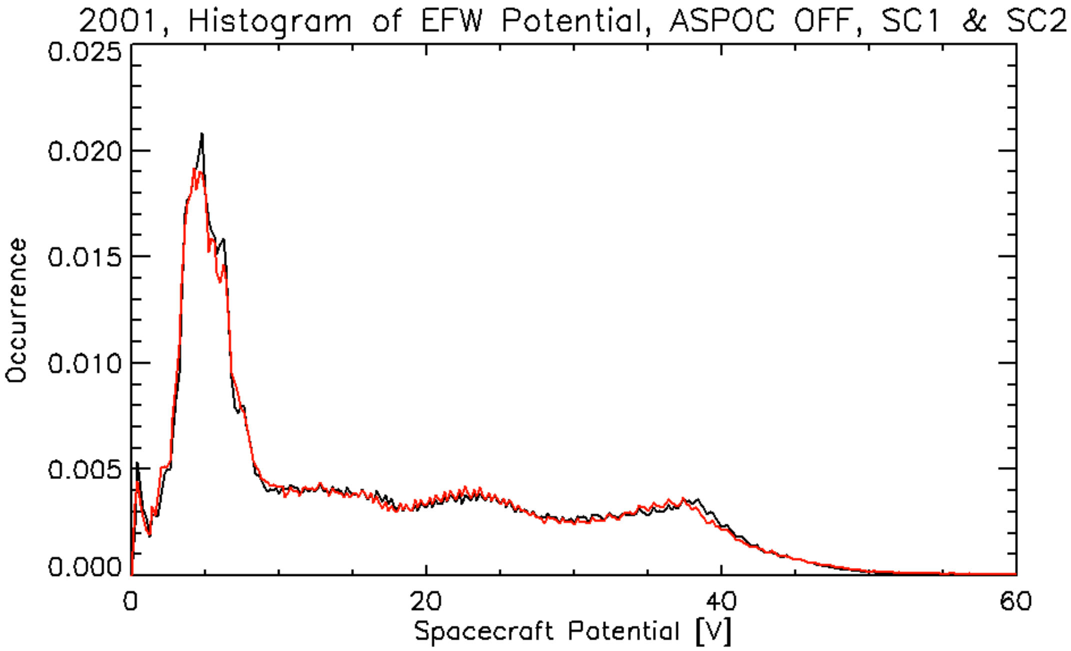


Figure 3. Histogram of spacecraft potential on Cluster 1 and 2 in 2001, for periods without spacecraft potential control

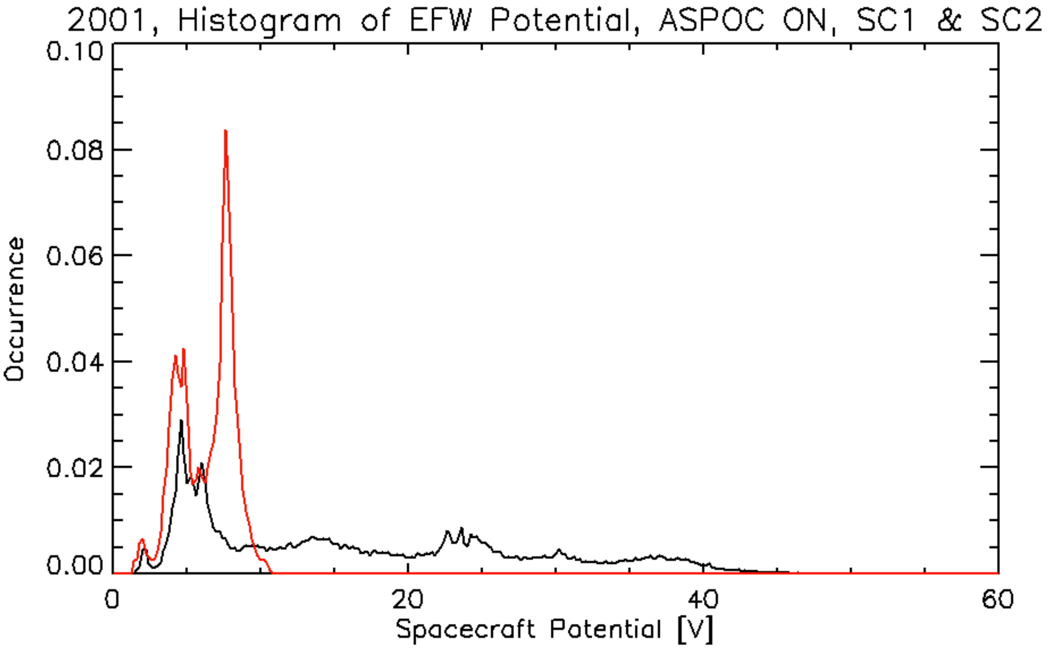


Figure 4. Histogram of spacecraft potential on Cluster 1 and 2 in 2001, for periods with spacecraft potential control

Plasma Electron Measurements

Why is spacecraft potential control so important for a payload dedicated to plasma and field studies in near Earth space? It is shown by examples in this paper that a complete plasma and fields data set is important for many studies. If spacecraft potential reaches several tens of volts positive, which is a common situation in the regions mentioned above, the modifications of the ambient plasma before it eventually can reach a sensor on the spacecraft may introduce severe errors or uncertainties in the measurements and derived quantities.

An essential quantity is plasma density. It can be measured by several techniques which are complementary to each other. Density measurements inferred from particle detectors are necessarily inaccurate if low energies are included in the integration, and if the trajectories and energies of these particles have been severely modified by the spacecraft sheath. Alternatively, if the lower energy limit for the calculation is set to higher energies, then the cold plasma is excluded from the calculation, and a major contribution to the total density is missed.

If the structure of the sheath is known, the modifications of the ambient electrons in the sheath could in theory be calculated and the measurements be corrected. There are, however, major practical limitations. It is difficult to model a sheath around a highly structured spacecraft and its booms, and it is even more difficult if the model has to include plasma density in a self-consistent way. Moreover, the higher the spacecraft potential, the more photo-electrons generated at the spacecraft surface cannot escape into space, and some of them enter the sensors and flood the detectors up to energies comparable to the spacecraft potential.

The abundance of photo-electrons in the sensor data when the spacecraft potential is high makes it difficult to identify ambient electrons: If the spacecraft crosses a boundary from low to higher plasma density, the corresponding sudden lowering of the spacecraft potential has the effect that at energies, where previously photo-electrons were observed, now plasma electrons enter the sensor.

The energy resolution of particle detectors is proportional to energy. Therefore a high potential dramatically lowers the capability to resolve the distribution of the ambient cold electrons. Whereas a typical plasma electron instrument may resolve energies below 10 eV in several bins, these electrons, having been accelerated to 50-60 eV in the electric field of the sheath, would fall into one or two bins only, resulting in a very poor measurement of this component.

Some of the problems with high spacecraft potential are illustrated by Figure 5. Figure 5a shows an electron spectrogram measured by the LEEA sensor of the PEACE instrument (Szita et al., 2001)[6] onboard Cluster 1 in one particular viewing direction (zone 11). One can see the red band of photo-electrons, and the difficulty to distinguish between photo-electrons and plasma electrons in the time interval before 04:30 UT is obvious.

Figure 5b shows the situation onboard Cluster 2, where the ASPOC ion beam was active after 02:20 UT. The distortion of the distribution function f(v) is reduced, and the calculation of moments on-board will be reliable.

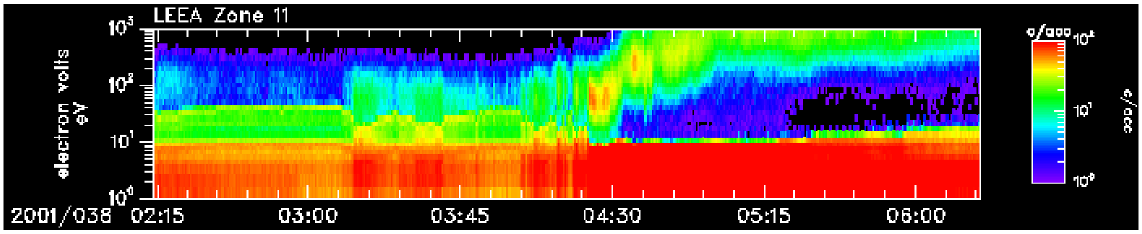


Figure 5a. Electron spectra measured by LEEA/PEACE onboard Cluster 1 without spacecraft potential control.

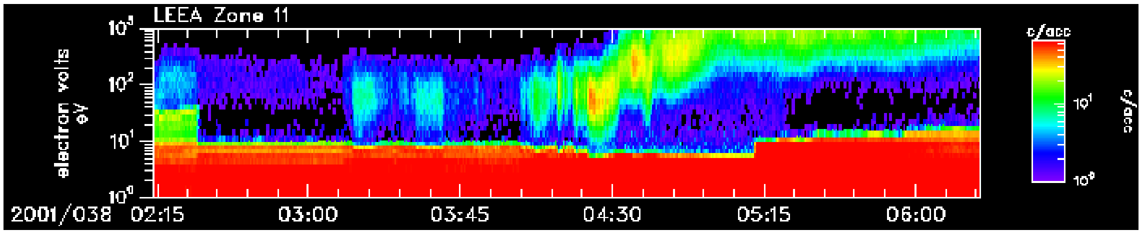
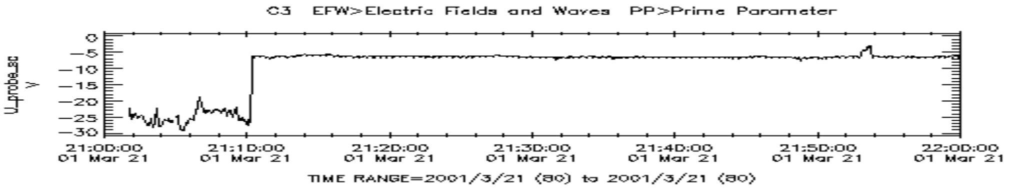


Figure 5b. Electron spectra measured by LEEA/PEACE onboard Cluster 2. Spacecraft potential control sets in at 02:20 UT.

The bottom panel of Figure 6 shows a typical example of Cluster/PEACE electron measurements with active spacecraft potential control. The data are from March 21st, 2001 (AE<50 nT, K_p=1-). Cluster was located in the polar cap (X=-1R_E, Y=2.6 R_E, Z=5 R_E in GSE coordinates). The geomagnetic conditions are quiet.

The top panel shows the (negative of the) spacecraft potential. Before 21:10 UT it fluctuates between 20 and 30 V, which is indicative of low densities in the polar cap. The ASPOC ion beam is turned on at 21:10 UT to a value of 10 µA and clamps the potential to about 7 V. At around 21:53 UT, the ion beam current of ASPOC was increased to 25 µA and then to 30 µA for one minute, and the potential is further reduced to less than 5 V.

Field aligned electrons are present in several bursts until 21:30. When the ASPOC ion beam is turned on at 21:10 UT it permits the measurement of these beams, which otherwise would have partly disappeared in the photo-electrons and shifted to higher energies and to lower resolution. With ASPOC, the features sticking out of the photo-electron baseline are resolved down to about 2 eV, whereas without ASPOC the best resolution is only 10 eV. The features at 21:15 and 21:28 are clearly field-aligned. At around 21:53 UT, when the ion beam current of ASPOC was increased to 25 µA and then to 30 µA for one minute, it removed most of the remaining photo-electrons from the spectrum. There are just a few ambient electrons present at that time, but they remain undisturbed by the beam.



Please acknowledge data provider, G. Gustafsson at IRFU and CSDS when using these data.
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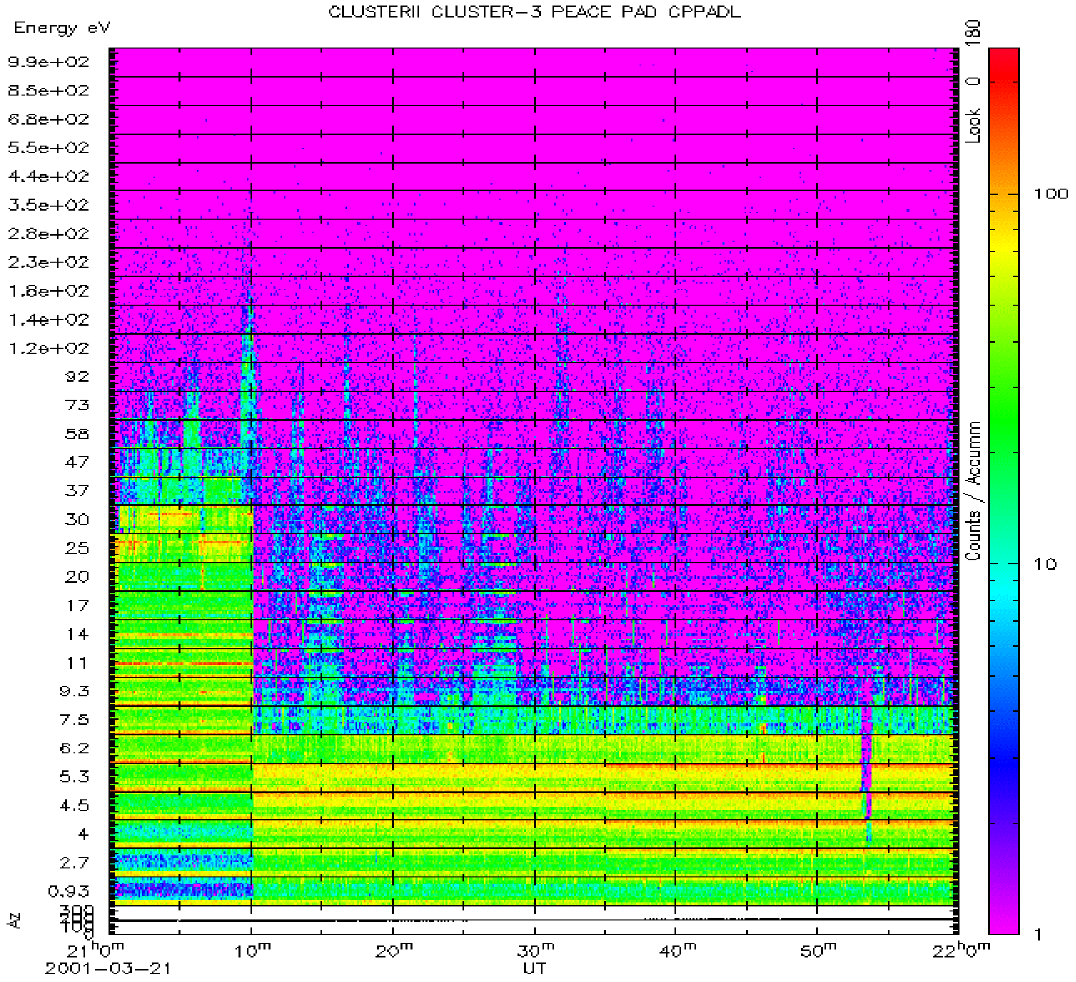

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Figure 6. Electrons from Cluster 3 plotted as function of time and pitch angle on March 21st, 2002, from 21 to 22 UT. Individual panels show look angles increasing in upward direction from 0 to 180° (electron pitch angles from 180 to 0°) for each energy band of the LEEA sensor.

Ion Measurements

For positive ions encountering a positively charged spacecraft, the thermal component is repelled or deflected from the sensors and cannot be measured. This is particularly problematic if the cold component are a major constituent, such as for example in the tenuous plasma of the polar cap region, where cold ion beams occur as a regular feature.

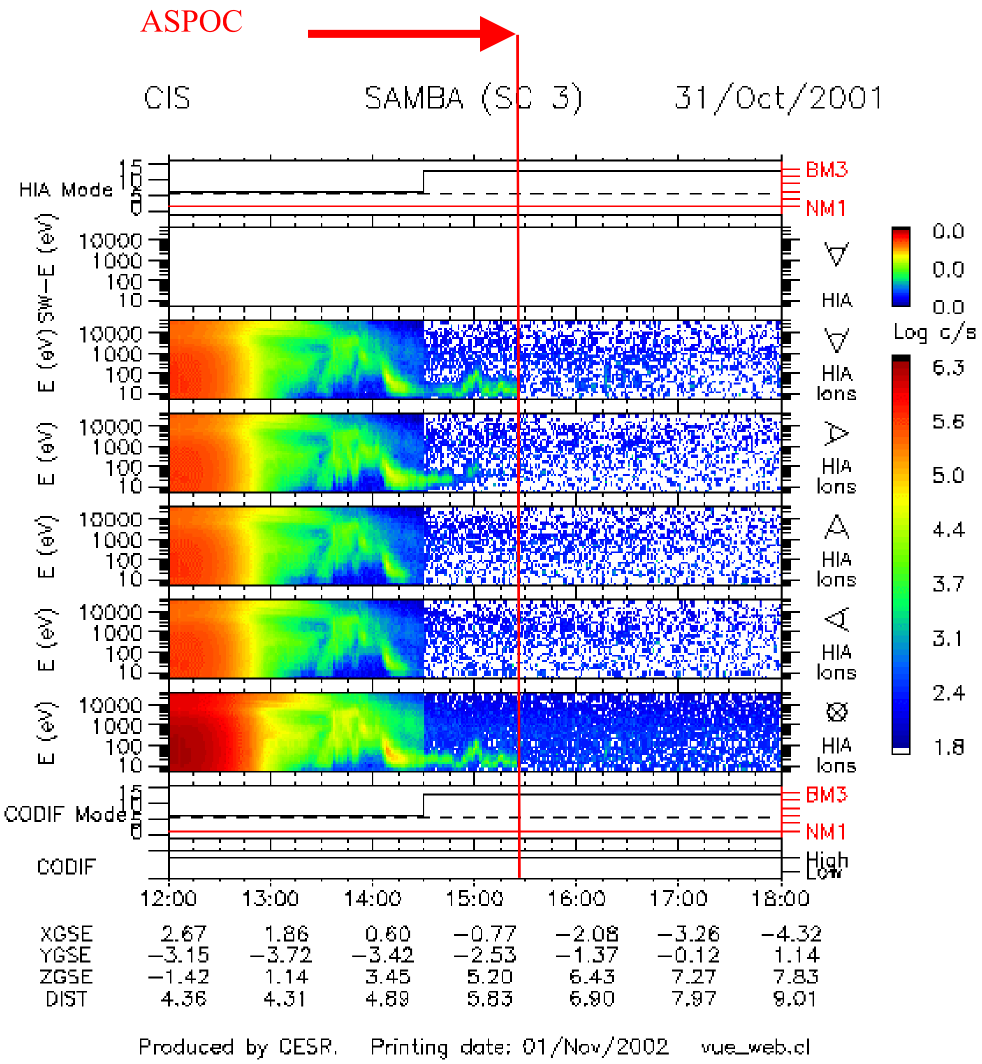

Figure 7. CIS/Cluster data from Cluster spacecraft 3, 31st October 2001. The spectrograms contain from top to bottom: tailward, dawnward, sunward, duskward flowing ions and the total.

Figure 7 shows a measurement of the Hot Ion Analyzer (HIA) as part of the CIS instrument on Cluster (Rème et al., 2001)[7], taken on Cluster 3 on 31st October 2001, between 12 and 18 UT. The five spectrograms show ions in four azimuthal sectors, the uppermost panel showing tailward flowing ions, and the total in the lowest panel. Before 15:25 UT the ASPOC ion beam is active and limits the spacecraft potential to 6.6 V. This allows the measurement of a tailward flowing, cold ion beam. When ASPOC is turned off at 15:25 UT, the potential increases to ≈27

V, and these ions can no longer enter the sensor and disappear from the data. Similar effects can also be seen in H^+, He^+ and O^+ data. A lowering of the spacecraft potential to <10 V clearly helps the measurement of cold ions. By support of ASPOC it could be shown that such beams exist.

Concluding from both electron and ion measurements it becomes clear that only on board of a spacecraft with a low potential the undisturbed measurements of both electrons and ions range down to almost zero energy and thus ensure that (almost) complete distribution functions are measured. This fact is the more important for multi-spacecraft missions such as Cluster or the future Magnetospheric Multiscale mission, where much emphasis is being laid on measuring differences between spacecraft to infer the structure of plasma boundaries and measure currents.

Electric Field Data

So far we have not yet mentioned electric field measurements employing double probes. They have to use long wire booms in order to keep the probes outside the sheath even if the Debye length is large. The high potential region near the spacecraft body and also extending along the wire booms may create a barrier for cold ions, In any case, the further outward any given equipotential surface is located, the more likely it affects the E-field measurement by disturbing the natural plasma flow. On an actively controlled spacecraft the equipotential surfaces move inward and thus reduce any problems the double probes might have to measure in a low density environment. The photo-electrons, however, also encounter a weaker electric field in the sheath if the potential control is working. The size of the photo-sheath grows accordingly. Already simple models show that also any spatial asymmetries of the photo-electron distribution between the sunlit and dark hemispheres grow in size, i.e. the center of their space charge slightly moves in sunward direction, thereby changing the spurious electric field created by them in the double probe measurement.

Side Effects

Is there any undesirable effect of active spacecraft potential control using an energetic ion beam? Absolutely no artificial plasma waves have ever been observed on Cluster, which were related to the ion beam emission. The Cluster wave instruments are very sensitive and cover frequencies from DC to 500 kHz. It had been expected out of theoretical considerations that a beam of heavy ions at the energies and currents applied on Cluster would have negligible growth rates for waves, including electrostatic ion cyclotron waves.

There are two possible effects which deserve some attention in future modeling work, although it must be mentioned beforehand that neither effect could yet be verified by data.

- The cone-shaped plume generated by the ions is readily neutralized at some distance from the spacecraft, which varies with ambient plasma conditions. Certainly at some tens of meters distance the beam charge is neutralized. Close to the spacecraft, however, the ion density in the beam can reach a few 100 ions cm^{-3} at 3 m distance. One should keep in mind that the photo-electron density near the surface reaches comparable values, and an efficient neutralization of the ion beam even at short distances may be possible, but must be studied and modeled in detail.

- Without active spacecraft potential control the negative space charge of the photo-electrons is not important for the overall potential distribution in the sheath, as it will at most create a small sunward-antisunward asymmetry in the potential map of less than one volt. If active spacecraft potential control is applied, the potential of the spacecraft is much smaller, and the space charge of the photo-electrons may drive the potential into negative territories, resulting in a potential barrier. The height of this barrier is difficult to assess numerically. Models range from small fractions of a volt to two volts.

Data from the electron and ion spectrometers on board of Cluster did not show any signature of non-gyrotropy or other effects which might be related to the beam space charge or a potential barrier.

Outlook and Conclusion

Active Spacecraft Potential Control using liquid metal ion sources significantly improves the measurements of low energy electrons and ions onboard Cluster, without compromising wave and electric field measurements. By lowering of the spacecraft potential the characterization of the ambient plasma by on-board sensors becomes more accurate. A low potential also allows the escape of a larger fraction of photo-electrons into space, whereby the wear of micro-channel plates in the electron detectors due to high count rates is reduced. Changes of the s/c potential between <10V and >20V clearly influence the measurements of cold ions. Also the electric field measurements on Cluster, after some initial doubts, have been shown to benefit from spacecraft potential control.

For Cluster operations, there are still on-board resources to continue spacecraft potential control well into the extended mission phase.

While ASPOC is emitting 10 µA ion current, the spacecraft potential does not exceed 8 to 9 V, with 12 to 15 µA => 6 to 7 V. Histograms peak at ≈7 V when ASPOC is active.

Work has to continue on analyzing particle data and modeling the details of the sheath structure when the energetic ion beam is emitted. Up to now, nothing has been found in the electron and ion data which would indicate the presence of any other effects but the desired reduction of sheath effects to all ambient particles. Initial efforts undertaken by some research groups suggest that only minor deviations from an ideal, reduced sheath are present.

Accurate plasma measurements are highly desirable for any spacecraft with plasma physical objectives, but they are particularly essential for multi-spacecraft missions which require reliable data on differences between quantities measured on several spacecraft. The absence of any disturbances from the ion beams applied on Cluster and the moderate resource requirements make this technique a promising candidate for future missions.

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