# EFFECTS OF ACTIVE SPACECRAFT POTENTIAL CONTROL ON CLUSTER PLASMA OBSERVATIONS – FIRST RESULTS

**K. Torkar(1), W. Riedler(1), M. Fehringer(2), C.P. Escoubet(2), K. Svenes(3), B.T. Narheim(3), A. Fazakerley(4), S. Szita(4), and M. André(5)**

*(1) Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria,*
*Tel: +43 316 4120 531, Fax: +43 316 4120 590, E–mail: Klaus.Torkar@oeaw.ac.at*

*(2) Solar System Division, ESA/ESTEC, Postbus 299, 2201 AG Noordwijk, The Netherlands,*
*Tel: +31 71 565 4117, Fax: +31 71 565 4697, E–mail: Michael.Fehringer@esa.int*

*(3) Norwegian Defence Research Establishment, P.O. Box 25, 2027 Kjeller, Norway,*
*Tel: +47 63 807 326, Fax: +47 63 807 212, E–mail: Knut.Svenes@ffi.no*

*(4) MSSL, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, United Kingdom,*
*Tel: +44 1483 274 111, Fax: +44 1483 278 312, E–mail: anf@mssl.ucl.ac.uk*

*(5) Swedish Institute of Space Physics, Uppsala Division, 75121 Uppsala, Sweden,*
*Tel: +46 18 471 59 13, Fax: +46 18 471 59 05, E–mail: mats.andre@irfu.se*

## ABSTRACT

The active spacecraft potential control devices ASPOC onboard the CLUSTER satellites off–set the spacecraft charging induced by the ultra–violet radiation from the sun by emitting positive indium ions. This clamps the spacecraft potential to within a few volts of the plasma potential. The lowering of the potential barrier between the spacecraft and the ambient plasma allows more low energy ions to reach the sensors. Hence, a larger part of the ion distribution is obtained. In addition, most photo–electrons can escape the vicinity of the satellite, whereby the contamination of the electron spectra is reduced. This paper concentrates on some of the first results from CLUSTER, presenting the initial current–voltage characteristics of the spacecraft, and illustrating the considerably improved plasma measurements due to the lower spacecraft potential and the dampening of the potential variations caused by rapid changes in the ambient plasma environment. It is demonstrated that a further stabilisation of the potential can be obtained by varying the emitted ion current in an onboard control loop. The modifications of the sheath around the spacecraft due to the re–distribution of particles and the ion beam are addressed.

## 1. INTRODUCTION

Accurate measurements of space plasma onboard spacecraft require that the velocity vectors of charged particles arriving at the sensor are not modified by any potential well around the spacecraft. In a typical situation in the lobes of the Earth's magnetosphere, which are well shielded from both the solar wind and plasma originating in the ionosphere and therefore may contain extremely tenuous plasma, the electric potential of a satellite may easily reach values of +50 V or higher. This is the well–known result of an equilibrium of currents between the spacecraft and the ambient plasma in such an environment. The electron current from the ambient plasma – roughly proportional to the number density of electrons multiplied by their velocities – is balanced by photo–electrons generated at sunlit spacecraft surfaces. Ions do not contribute significantly to the current balance due to their low mobility. In a low–density environment the total photo–electron current by far exceeds the plasma electron current, which means that equilibrium requires high positive potential of the spacecraft, preventing the escape of all but the most energetic photo–electrons.

The effects of a high positive spacecraft potential are obvious: positive ions from the ambient plasma cannot reach the sensors onboard the spacecraft unless their energy is higher than the potential between the spacecraft and the ambient plasma. Even worse, ions with energies only slightly above this potential will experience significant changes in direction and energy which compromise the measurements. Electrons change direction and energy according to the field around the spacecraft. Although all electrons from the ambient plasma should reach the sensors onboard a positively charged spacecraft, if no regions with negative potential – so–called virtual cathodes – develop around the spacecraft, the measurements suffer from an additional disturbance caused by photo–electrons generated at some surface of the spacecraft which are reflected in the potential structure around the spacecraft and enter the sensors with approximately the energy distribution they had at the time of generation. The presence of differentially charged surfaces complicates the analysis even more. Since the density of photo–electrons generated at typical spacecraft surfaces near the Earth may by far exceed the plasma densities in the magnetospheric lobes, it becomes obvious that even their high–energy tail may produce severe disturbances of the measurements. The high count rates due to photo–electrons may also reduce the lifetime of the channeltron detectors.

## 2. PRINCIPLE OF WORK

The work principle of ASPOC is based on modifying the current balance by emitting a beam of positive ions with energies of 5 to 9 keV. The ions would always easily escape the potential well of some tens of volts and thus add a constant current to the balance, counteracting the photo–electron current. An ion current equal to the total photo–electron current would drive the spacecraft potential to zero or negative values. However, as the bulk of the photo–electrons have low energy (the e–folding energy is of the order of 2 eV), even ion beam currents which are small compared to the total photo–electron current are capable of driving the spacecraft potential values a few times their average energy, in practice below ≈10 V. This is the operating mode for CLUSTER.

The idea to use high–energy ions to control the spacecraft potential has been proposed by Pedersen *et al.* (1983) and was implemented for the first time on the spacecraft Geotail (Japan, launched 1992, see Schmidt *et al.*, 1993). Later on, instruments for the missions CLUSTER (Riedler *et al.*, 1997) and Equator–S (launched December 1997, see Torkar *et al.*, 1999) have been built. As the first attempt to launch CLUSTER failed and Equator-S did not reach the designed lifetime, the re-launched CLUSTER mission is the first to provide an extensive data base of this method for spacecraft potential control.

## 3. SCIENTIFIC OBJECTIVE

The scientific objective of active spacecraft potential control lies in the improvement of measurements by particle detectors achieved by lowering the spacecraft potential without compromising the data of other experiments. Although a reduction of the potential to zero may look desirable, one has to look at the possible consequences: In the absence of a significant plasma electron current, the ion beam current would have to equal the total photo-electron current, which can be estimated from the projected sunlit area of the spacecraft (≈4 $m^2$ for CLUSTER) multiplied by the saturation photo–electron current density for typical materials of the surface, e.g. 30 μA $m^{-2}$ for the indium tin oxide which covers the solar panels to achieve electrical conductivity and a uniform spacecraft potential. The modification of the sheath by a 120 μA ion beam is probably non-negligible. For that reason a compromise was sought, and happily enough it turns out that already beam currents which are an order of magnitude lower can reduce the spacecraft potential to <8 V, which is enough to improve the low energy electron measurements considerably. Some aspects of the effects are to follow in the remainder of this paper.

## 4. ION SOURCE

The instrument is described in detail in Torkar *et al.* (2001). The ion beam is generated in liquid metal ion sources with Indium (stable isotopes with 115 amu and 113 amu to 95.7% and 4.3%, respectively) as the charge material. During operation the metal in the reservoir containing only 250 milligrams is liquid at temperatures above 157°C, but the low vapour pressure of Indium prevents contamination of nearby surfaces.

An ion beam consisting of >90% single–charged $In^+$ forms after applying high voltage of ≈6 to 8 kV between a tip covered by liquid Indium and an extractor electrode. Focusing electrodes narrow the beam to 15° half width, half maximum. The sources are light-weight (a single emitter carrying charge for 4000 hours at 10 μA weighs 1 gram; four emitters combined into a module with electrodes and housing weigh 180 g) and have very moderate electrical power requirements (≈0.5 W for heating, and <1 W for high voltage).

## 5. CURRENT-VOLTAGE CHARACTERISTICS

Figure 1 shows the floating potential of a CLUSTER spacecraft, calculated according to results from the ISEE-1 data by Escoubet *et al.* (1997), as a function of the quantity $\left(n_e\sqrt{kT_e}\right)$ where $n_e$ and $T_e$ are density and temperature of the plasma electrons. The curves are therefore only valid for quiet conditions. For an 1 eV thermal plasma the horizontal scale is equivalent to number density. The figure shows that an ion beam of only 10 μA, which is less than 10% of the total photo-electron current from the spacecraft, can stabilise the spacecraft potential below 10 V. For $n_e > 100\text{cm}^{-3}$ the effect of the ion beam vanishes gradually.

The variation of the spacecraft potential by the ion beam is demonstrated in Fig. 2, showing the potential while the ion beam current is being stepped between 7 and 15 μA. The spacecraft potential is measured by the double-probe electric field experiment EFW (Gustafsson *et al.*, 1997) and transmitted on-board to ASPOC.

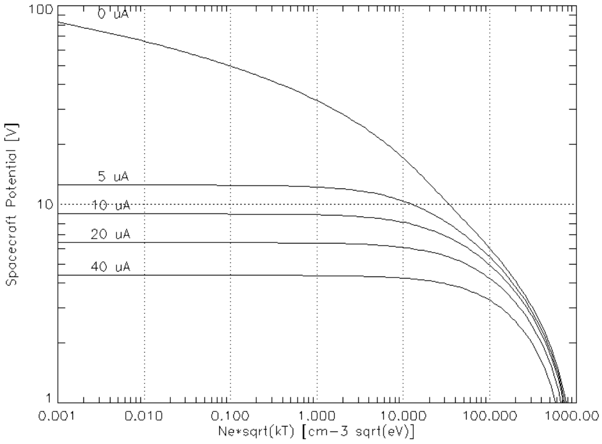

*Figure 1: Estimated CLUSTER spacecraft potential for ion beam currents between 0 and 40 µA.*

Figure 2 shows raw data of the voltage difference between the spacecraft body and the average of two opposite probes at the end of wire booms in 44 m distance from the spacecraft. As the probes themselves acquire a small positive potential relative to the plasma, the full potential between the spacecraft and the ambient plasma will be higher than the plotted values by one or two volts. The spacecraft potential immediately before the turn-on of ASPOC was stable at 20 V. The associated plasma density, estimated according to Pedersen (1995), Escoubet *et al.* (1997), and Ishisaka *et al.* (2001) is 0.21, 0.32, and 0.15 cm$^{-3}$, respectively. From Fig. 1 one can estimate $\left(n_e\sqrt{kT_e}\right) = 6$.

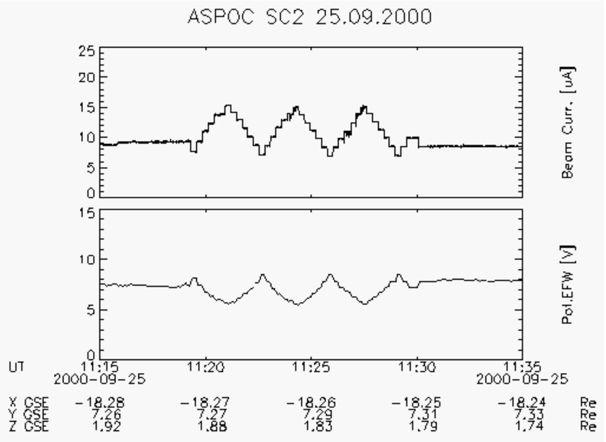

*Figure 2: Ion beam current (top panel) and mean voltage between the spacecraft body and two probes as proxy of the spacecraft potential (lower panel) for CLUSTER spacecraft 2 (Salsa) on 25 September 2000, between 11:15 and 11:35 UT.*

By plotting the raw spacecraft potential against the ion beam current in the time interval from 11:19 to 11:31 UT one obtains the current-voltage characteristics for this plasma environment shown in Fig. 3.

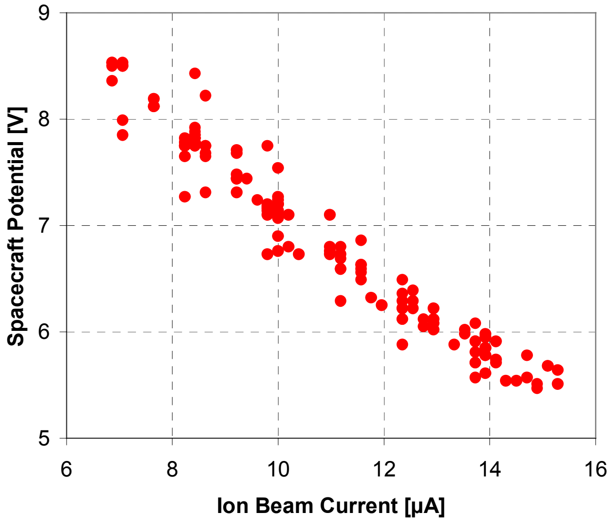

*Figure 3: Current-voltage characteristic derived from Fig. 2.*

In an attempt to calculate the e-folding energy of the photo-electron emission, the logarithm of the sum of the ion beam current and the plasma electron current, the latter estimated with 0.25 µA integrated over the spacecraft surface of ≈20 m$^2$ is plotted over spacecraft potential in Fig. 4, and the slope is determined by a least mean square fit. The thereby assumed plasma electron current is within the range given by the three density models mentioned before. The fit yields an e-folding energy of 4.1 eV. In comparison, the density variations according to these models over the same range of potentials correspond to between 2.6 and 3.7 eV.

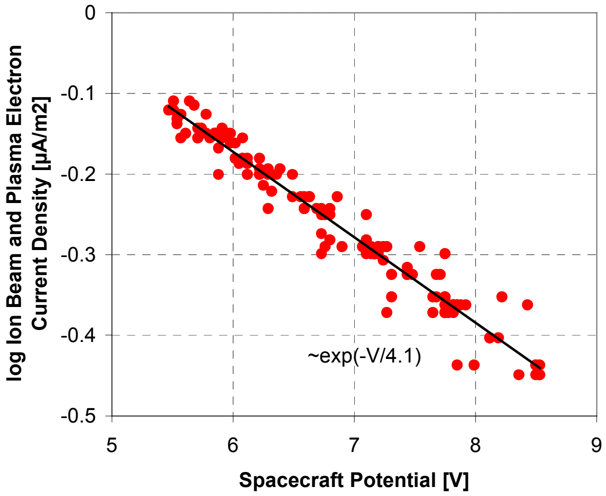

*Figure 4: Derived photo-electron current over spacecraft potential; data as for Fig. 3.*

A similar exercise on another spacecraft (Samba, 22 Nov. 2000, between 13:30 and 14:30 UT), with beam currents between 12 and 37 µA, resulted in potentials between 6.6 and 2.9 V and an e-folding energy of 3.4 eV (equivalent model values between 2.4 and 2.8 eV).

## 6. EFFECTS ON ELECTRON MEASUREMENTS

The plasma electron measurements onboard CLUSTER are provided by the instrument PEACE (Johnstone *et al.*, 1997; Fazakerley *et al.*, 2001), designed to measure the three-dimensional velocity distribution of electrons in the energy range from 0.6 eV to 27 keV. Each of the two sensor systems of this instrument is subdivided into 12 anodes. The configuration on the spacecraft is illustrated in Fig. 5. In principle, a full 3D distribution (4π solid angle) can be measured every half spin.

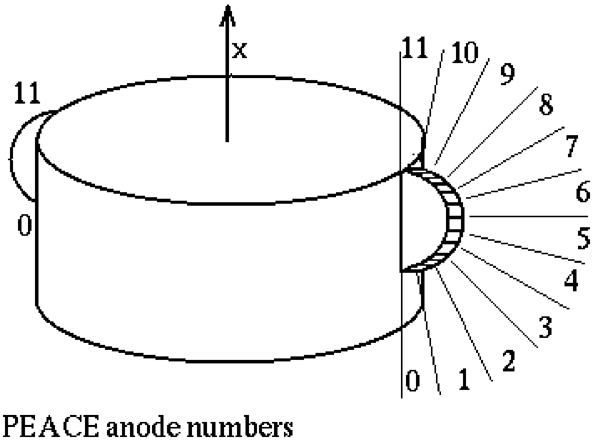

*Figure 5: Orientation of the PEACE sensors on the CLUSTER spacecraft.*

The measurements described here were obtained during the commissioning phase. Several tests of PEACE and ASPOC operating simultaneously were performed on 22 November 2000 on spacecraft Samba. During this period the spacecraft were travelling through the magnetosphere some way inside the magnetopause in the afternoon sector. The undisturbed spacecraft potential was above +20V, but the operation of ASPOC kept it below +10 V. Figure 6 shows the intentional variation of the ion beam current between zero and 40 μA, and the resulting spacecraft potential.

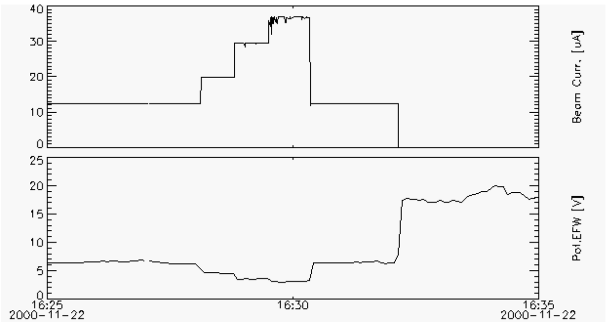

*Figure 6: Ion beam current (top panel) and spacecraft potential raw data (bottom panel) during tests onboard CLUSTER Samba on 22 Nov. 2000, 16:25 to 16:35 UT.*

The simultaneously taken spectrograms in Fig. 7 (showing the low energy electron measurements only), clearly show that the measured photo-electron population is strongly correlated with the emitted ion current. The spacecraft potential is overlaid as black line.

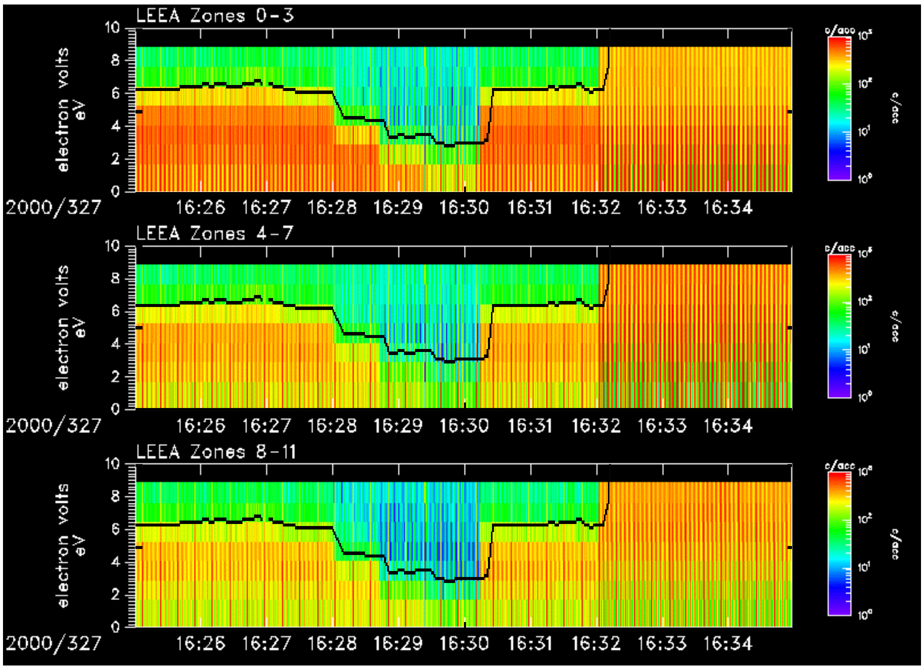

*Figure 7: Energy-time spectrograms of electrons in the energy band from 0 to 10 eV over the time interval of Fig. 6; top panel: anodes 0-3, middle panel: anodes 4-7, bottom panel: anodes 8-11.*

Each current step is clearly seen to lower the count rate in each energy bin. In fact, by increasing the ion current up to 40 μA most of the photo-electrons are allowed to escape the vicinity of the spacecraft. This unambiguously demonstrates the intended positive effect of operating ASPOC on the low energy PEACE observations. Finally, some asymmetry is observed at low energies between anodes pointing towards the solar panels and away from them: most photo-electrons in the anodes (zones 0 to 3) are pointing towards the solar panels).

## 7. SHEATH EFFECTS

The operation of the ion beam did not cause any disturbances in the AC field and wave measurements. However, the quasi-static determination of the electric field by the double-probe instrument EFW showed clear effects when ASPOC was turned on. The magnitude of the effects increased as the plasma became more tenuous. Basically, the fluctuations of the electric field were attenuated, and an offset in the sunward direction appeared. These signatures were initially ascribed to secondary effects of photo-electrons which are no longer trapped in the strong field around the spacecraft. Rather than being reflected onto the spacecraft body from where they originated, the photo-electrons with energies above the - controlled and therefore low - spacecraft potential flow outward. The photo-sheath close to the spacecraft surface is thereby drastically reduced in density (which is the intended effect to improve the response of the plasma sensors), but the overall dimensions of the sheath are enlarged. Very likely the probes of the electric field instrument at 44 m distance from the spacecraft encounter an increased flux of photo-electrons, which leads to the observed effects.

## 8. CONCLUSIONS

The spacecraft potential measured for different ion beam currents corresponds well to standard models. Residual differences may be due to uncertainties to determine the real spacecraft potential and the effective area of the spacecraft.

Ion beam currents of 10 μA reduce the spacecraft potential of the CLUSTER satellites to values well below +10 V, which results in a significant improvement of the plasma electron measurements and a significantly reduced degradation of the sensors otherwise caused by high fluxes of photo-electrons.

Currents of 30 to 40 μA make the photo-electrons almost disappear from the measurements.

The photo-electrons no longer attracted to the spacecraft flow outward, which changes the environment of probes located at a distance from the spacecraft.

## 9. REFERENCES

Escoubet, C.P., A. Pedersen, and R. Schmidt, Density in the Magnetosphere Inferred From ISEE 1 Spacecraft Potential, *J. Geophys. Res.*, **102(A8)**, 17595–17609, 1997.

Fazakerley, A., et al., First results from Cluster PEACE, *Ann. Geophys.*, in press, 2001.

Gustafsson, G., R. Boström, B. Holback, G. Holmgren, A. Lundgren, K. Stasiewicz, L. Ahlen, F.S. Mozer, D. Pankow, P. Harvey, P. Berg, R. Ulrich, A. Pedersen, R .Schmidt, A. Butler, A.W.C. Fransen, D. Klinge M. THomsen, C.-G. Fälthammar, P.-A. Lindqvist, S. Chrinstenson, J. Holtet, B. Lybekk, T.A. Sten, P. Tanskanen, K. Lappalainen, and J. Wygant, The electric field and wave experiment for the Cluster mission, *Space Sci. Rev.*, **79**, 137-156, 1997.

Ishisaka, K., T. Okada, K. Tsuruda, H. Hayakawa, T. Mukai, and H. Matsumoto, Relationship between the Geotail spacecraft potential and the magnetospheric electron number density including the distant tail regions, *J. Geophys. Res.*, **106(A4)**, 6309–6319, 2001.

Johnstone, A.D., Alsop, C., Burge, S., Carter, P.J., Coates, A.J., Coker, A.J., Fazakerley, A.N., Grande, M., Gowen, R.A., Gurgiolo, C., Hancock, B.K., Narheim, B., Preece, A., Sheather, P.H., Winningham, J.D. and Woodliffe, R.D., PEACE: a plasma electron and current instrument, *Space Sci Rev.*, **79**, 351–398, 1997.

Pedersen, A., Solar wind and magnetosphere plasma diagnostics by spacecraft electrostatic potential measurements, *Ann. Geophys.* **13(2)**, 118–129, 1995.

Pedersen, A., C.R. Chapell, K. Knott, and R.C. Olsen, Methods for Keeping a Conductive Spacecraft Near the Plasma Potential, in Spacecraft Plasma Interactions and Their Influence on Field and Particle Measurements, *Proceedings of the 17th ESLAB Symposium*, **ESA SP–198**, 185–190, 1983.

Riedler, W., K. Torkar, F. Rüdenauer, M. Fehringer, A. Pedersen, R. Schmidt, R.J.L. Grard, H. Arends, B.T. Narheim, J. Trøim, R. Torbert, R.C. Olsen, E. Whipple, R. Goldstein, N. Valavanoglou, and Hua Zhao, Active Spacecraft Potential Control, *Space Science Rev.*, **79**, 271–302, 1997.

Schmidt, R., H. Arends, A. Pedersen, M. Fehringer, F. Rüdenauer, W. Steiger, B.T. Narheim, R. Svenes, K. Kvernsveen, K. Tsuruda, H. Hayakawa, M. Nakamura, W. Riedler, and K. Torkar, A novel medium–energy ion emitter for active spacecraft potential control, *Rev. Sci. Inst.*, **64 (8)**, 2293–2297, 1993.

Torkar, K., W. Riedler, M. Fehringer, F. Rüdenauer, C.P. Escoubet, H. Arends, B.T. Narheim, K. Svenes, M.P. McCarthy, K. Parks, R.P. Lin und H. Rème, Spacecraft potential control aboard Equator-S as a test for Cluster-II, *Ann. Geophys.*, **17**, 1582-1591, 1999.

Torkar, K., W. Riedler, C.P. Escoubet, M. Fehringer, R. Schmidt, R.J.L. Grard, H. Arends, F. Rüdenauer, W. Steiger, B.T. Narheim, K. Svenes, R. Torbert, M. André, A. Fazakerley, R. Goldstein, R.C. Olsen, A. Pedersen, E. Whipple, and Hua Zhao, Active Spacecraft Potential Control for Cluster - Implementation and First Results, *Ann. Geophys.*, in press, 2001.