

Spacecraft Potential Control Using Indium Ion Sources – Experience and Outlook Based on Six Years of Operation in Space

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Abstract. The conditions for measurements by particle instruments at low energies are significantly improved by stabilizing and reducing the high positive potentials sunlit spacecraft acquire when they are embedded in tenuous plasma. Among the many techniques employed for this purpose the emission of a beam of positive ions with energies from 5 to 8 keV is considered to be the most efficient approach. Its feasibility has been demonstrated by two instruments on board the spacecraft Geotail and Equator-S launched in July, 1992, and December, 1997, respectively. The ion emitter instruments onboard these spacecraft use liquid metal ion sources with indium as the charge material. Already small and lightweight due to carrying the charge material as a solid, these ion sources feature very high electrical and excellent mass efficiency. The reliability of these ion sources has been demonstrated in space by the flawless operation on board the Geotail spacecraft over six years. The second instrument on board Equator-S has been operating on a routine basis for four months throughout the active lifetime of the spacecraft. The efficiency of the method is shown by overviews and examples from the missions. It can also be demonstrated both in theory and experiment that this technique produces only few, if any, undesirable side effects. The outlook of this type of instrument is focused on the mission Cluster-II.

Introduction

Spacecraft irradiated by the Sun charge up to positive voltages when they are embedded in tenuous and not too hot plasma. Photo-emission from sunlit surfaces amounts to typical current densities of several tens of microampere per m², creating a cloud of photo-electrons around the spacecraft. The equilibrium of currents dictates that electron currents leaving the sheath around the spacecraft must be compensated by currents from the ambient plasma. With ambient densities below some 100 electrons per cm³ this equilibrium can only be achieved by a positive potential of the spacecraft which attracts the bulk of the photo-electrons back to the surface. The equilibrium potential often reaches several tens of volts in the outer magnetosphere, particularly in the lobe regions (see, *e.g.* Lindqvist [1983], Pedersen [1995]). Escoubet *et al.* [1997] compiled ISEE-1 data and found that densities below 10⁻² cm⁻³ result in potentials >30 V. Such potentials obscure any measurement of the core of the ion distribution function, which has a thermal energy comparable to the spacecraft potential (see, *e.g.* Olsen [1982]). Also, the low energy portion of the electron spectra is contaminated by photo-electrons from the spacecraft surface, trapped by the positive spacecraft potential.

Technical Principle

In order to improve the measuring conditions for plasma instruments a number of spacecraft have been equipped with

devices to control and reduce the floating potential to values at or below the energy window of the instruments. The most widely used techniques include plasma sources, such as for the Polar spacecraft (*Moore et al.* [1995]), and emitters for positive ions at energies of several kiloelectronvolts. The present paper focuses on the extensive flight experience that has been obtained using the latter technique.

Ions actively emitted from the spacecraft at energies of several kiloelectronvolts remain largely unaffected by variations of the floating potential of some tens of volts. When their current reaches a sizeable fraction of the total photo-electron current emitted from the surface, and provided that other currents from and into the ambient plasma remain small, the resulting equilibrium potential of the spacecraft relative to the ambient plasma becomes comparable to the mean energy of the photo-electrons. A beam of 10 to 15 μ A, applied on board a spacecraft with a sunlit surface of a few m², results in a sufficiently small potential to ensure that particle distributions measured by instruments on board remain unaffected.

After the proposal for this method had been made (*Pedersen et al.* [1983]) it took several years to implement it. 'Solid needle' - type liquid metal ion sources previously described in the literature (*e.g.* Mahoney *et al.* [1969]) have been chosen. Already small and lightweight due to carrying the charge material as a solid, these ion sources feature very high electrical and excellent mass efficiency. The sources have been developed further in an extensive program to qualify them for space use.

Figure 1 shows a schematic plot of a needle type liquid metal ion source which is used for spacecraft potential control. In that design a sharpened tungsten needle is mounted in the center of a cylindrical indium reservoir. During operation the indium in the reservoir is molten and a thin indium film covers the needle. A high voltage of about 6 kV is applied between the emitter tip and an accelerator electrode which is mounted opposite to the tip. Due to the small radius of curvature at the tip apex the local electric field reaches values in the order of volts per nanometer, high enough to enable field ion emission.

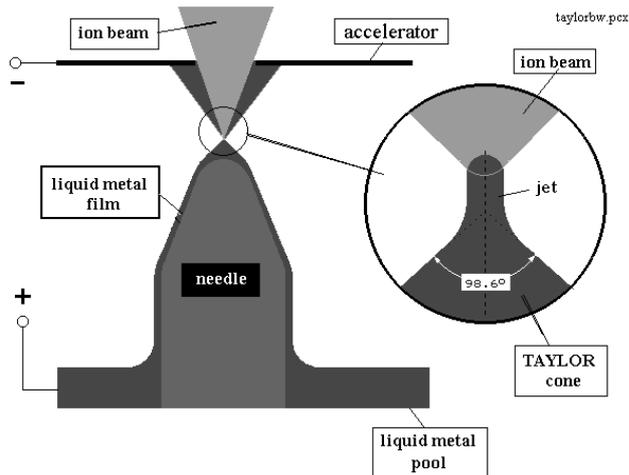


Figure 1. Schematic plot of the principle of a needle type liquid metal ion source.

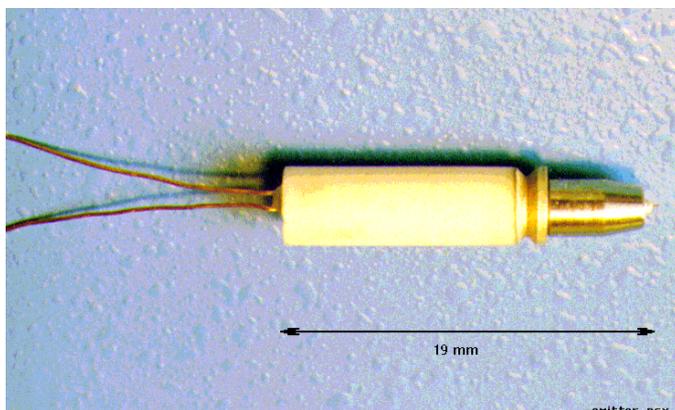


Figure 2. Photograph of an indium emitter as it is being used in the spacecraft potential control instruments.

Rüdenauer *et al.* [1987] showed that the beam consists of >90% single-charged In^+ with minor fractions of double- and triple-charged ions and single-charged indium clusters. The average charge number per emitted charged indium particle is 0.98, and the mass efficiency, *i.e.* the fraction of the total mass taken by single-charged ions, at $10 \mu\text{A}$ is about 80%.

Indium (stable isotopes with 115 amu and 113 amu to 95.7% and 4.3%, respectively) has been chosen as the ion-source charge material because of its low vapor pressure, which prevents contamination of the source insulators and ambient spacecraft surfaces. On the other hand, the melting point at 156.6°C is high enough to prevent melting of an unheated source charge.

Figure 2 shows a photograph of the standard indium ion emitter as it is used in space. Depending on the size of the reservoir, up to 4000 hours nominal operating time at $10 \mu\text{A}$ emission current can be achieved with a single emitter. In comparison, the best commercially available liquid metal indium ion source at the start of the space development program in 1987 had a guaranteed lifetime of 150 hours only, and its mechanical design was not adequate for flight. In order to achieve a total operating time of the instrument of 10000 hours, and to provide some redundancy, eight emitters were combined into one instrument, grouped into two so-called emitter modules powered by separate supplies. Figure 3 shows a schematic cut through a complete emitter module.

The obvious advantages of the liquid metal ion source principle are:

- high electrical and mass efficiency,
- low power consumption – mostly determined by the heater power ($\approx 0.5 \text{ W}$) to keep the indium in molten state, in addition to the beam energy,
- compact design and low mass: a single emitter carrying charge for 4000 hours at μA weighs 1 gram; four emitters combined into a module with electrodes and housing weigh 180 g.

The total mass of the instrument including housing, electrical supplies and the control unit is below 2 kg. The maximum power consumption including electronics is 2.7 W.

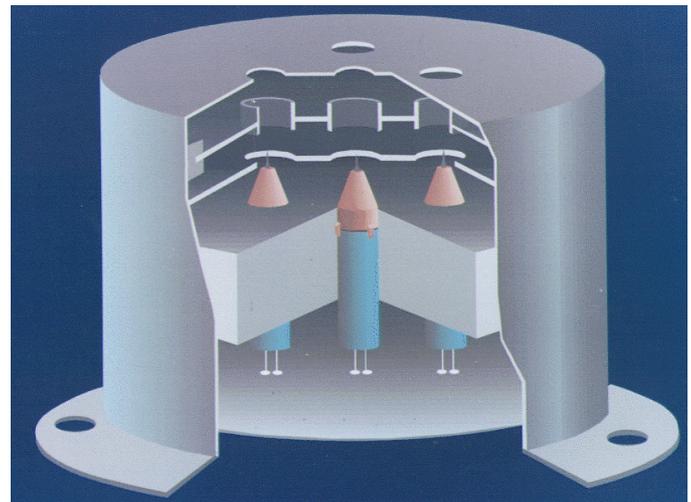


Figure 3. Schematic cut through an emitter module containing several indium liquid metal ion sources.

Experience in Space

The reliability of these ion sources has been demonstrated in space by the flawless operation on board the Geotail spacecraft over six years beginning in July, 1992. A second, similar instrument on board Equator-S (launched in December, 1997) has been operating on a routine basis for four months throughout the active lifetime of this spacecraft. It is shown in the remaining part of this paper that the objectives to reduce the positive spacecraft potential and to improve the plasma measurements were fulfilled, and that the ion beam – in compliance with theoretical predictions (Schmidt *et al.* [1992]) – did not produce any significant disturbances of the wave measurements.

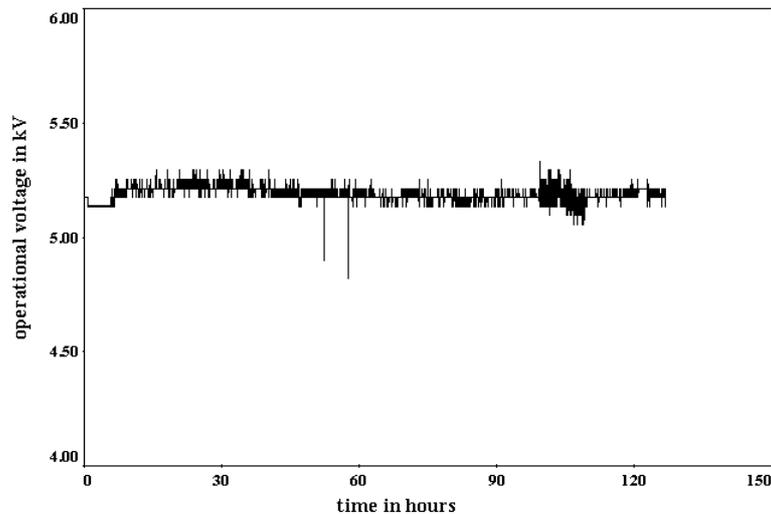


Figure 4. Complete set of high voltage data points of 40 individual operations of one single ion source covering 125 hours.

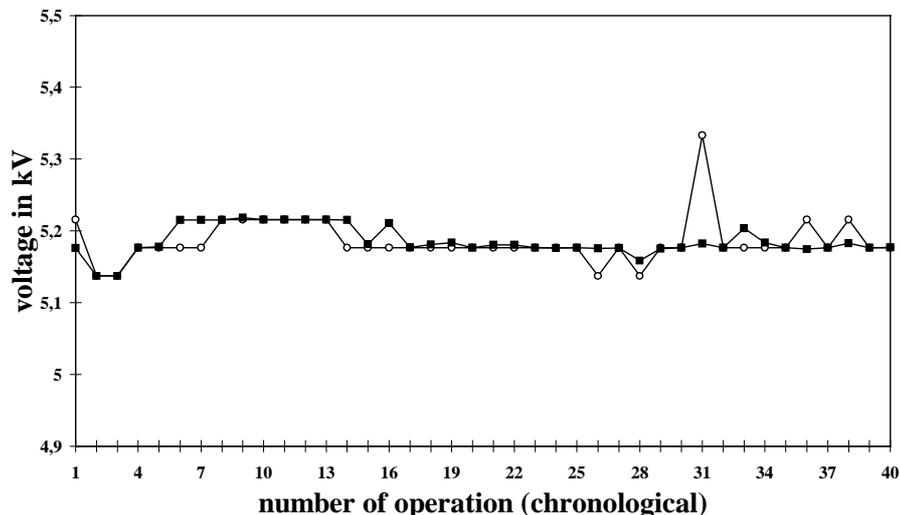


Figure 5. Startup- and operational voltage of all 40 operations of the same emitter shown in Fig. 4 (squares: operational voltage, circles: ignition voltage).

Operation on board the Geotail spacecraft

The ion emitter instrument EFD-iE on board the Geotail spacecraft formed part of the electric field instrument EFD (PI: T. Tsuruda, ISAS). Technical details can be found in *Schmidt et al.* [1993]. EFD-iE constituted the first and very successful test of the new technique in space. The instrument has been in operation from 1992 to 1997 without any single problem ever. It has accumulated about 600 hours of flawless operation during these years. This instrument also confirmed the well substantiated assumption that it would operate better in space than it does in the laboratory due to the lack of vacuum chamber walls which are the biggest contributors to sputtering of material back to the surface of the source.

Figure 4 shows the complete data set of the operational voltage of one single ion emitter from the Geotail instrument, its standard deviation is 11 V. Figure 5 plots the ignition voltage and the mean operational voltage of every single operation of that same emitter. There is practically no difference between these values. This fact confirms that the

emitters operate very reliably in space, without any sign of contamination or deterioration. Data proving the same quality in operation are available for all the other five emitters in that instrument. Two emitters were not active already on the ground before launch. The total emitted charge exceeds 6000 μAh .

Scientific Performance

One of the primary objectives of the Geotail mission relates to the exploration of the Earth's distant magnetotail, where low plasma densities and – hence – high spacecraft potentials are common features. Figure 6, from *Schmidt et al.* [1995], demonstrates the clamping effect the ion emission exerts on the spacecraft potential. When the ion current is held constant, natural variations of the ambient plasma density no longer influence the equilibrium potential. It is not even necessary to vary the ion current in a feedback loop with on-board measurements in order to achieve a stable potential.

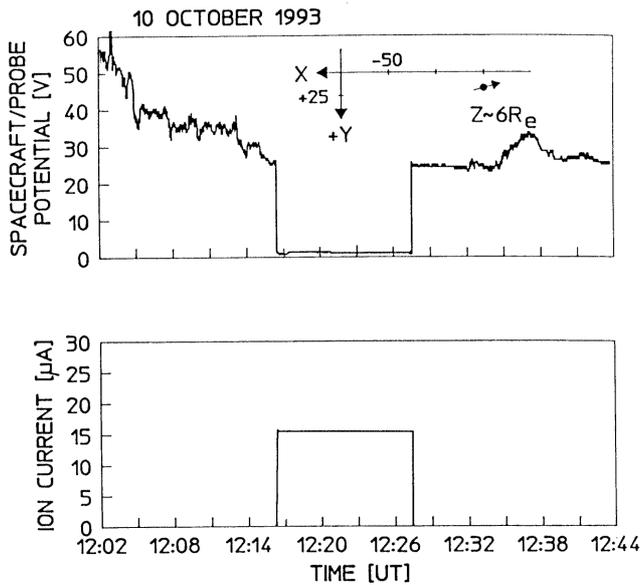


Figure 6. Ion emitter operation on Geotail on 10 October 1993. The ion emitter was turned on at 1216 UT with 15 μA emission current (lower panel). The spacecraft potential (upper panel) drifted between +56 V and +24 V in the uncontrolled state, but remained at about +1.7 V with the ion emitter on. The location of the spacecraft in GSM coordinates is indicated.

The absence of plasma waves induced by the ion beam clearly distinguishes this method from plasma sources. The

Plasma Wave Instrument (PWI) on Geotail instrument does not show any features, neither in the magnetic nor in the electric components, which might be related to the ion beam, apart from a very minor increase of the noise level below 15 Hz.

On the other hand the effect on the electron measurements is dominated by the complete disappearance of photo-electrons, which in the uncontrolled state always clutter the lower energy part of the spectra. As an example, Figure 7 shows Key Parameter data of the Low Energy Particle instrument (LEP, PI: T. Mukai, ISAS) which are available through CDAWeb. The absolute values of the electron flux are not important, as the main point is to show the effect of turning on the ion beam between 11 and 19 UT. At this time the broad trace of photo-electrons at low energies disappears almost completely. Only a faint trace of photo-emission remains in the tailward flux. Thereby the detailed features in the electron flux from the ambient plasma become visible.

Conclusion from Operations on Geotail

- The technical and scientific objectives have been achieved.
- As the most noticeable feature the flawless operation of all ion sources over 600 hours and 6 years in space must be mentioned.
- The operation resulted in the successful verification of the operational principle, the reduction of the spacecraft potential and the subsequent improvement of particle measurements.
- The absence of noticeable side effects was demonstrated.

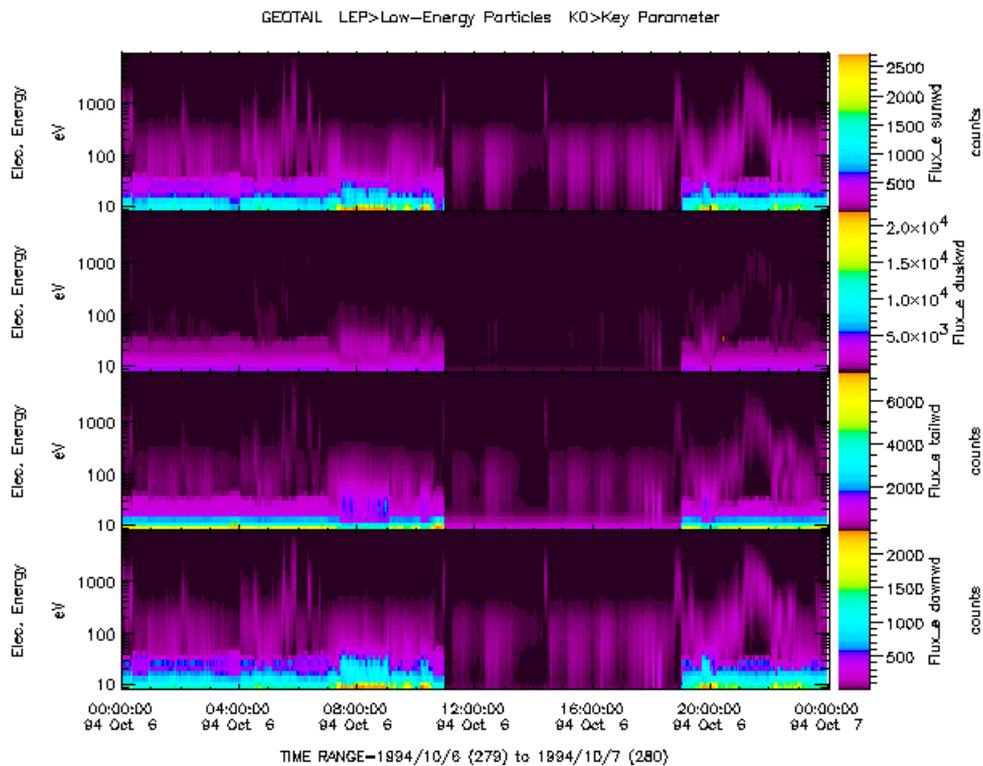


Figure 7. Electron flux from the Low Energy Particle instrument (LEP, PI: T. Mukai, ISAS, Key Parameter data from CDAWeb) for October 6, 1994 in sunward, duskward, tailward, and downward direction (top to bottom).

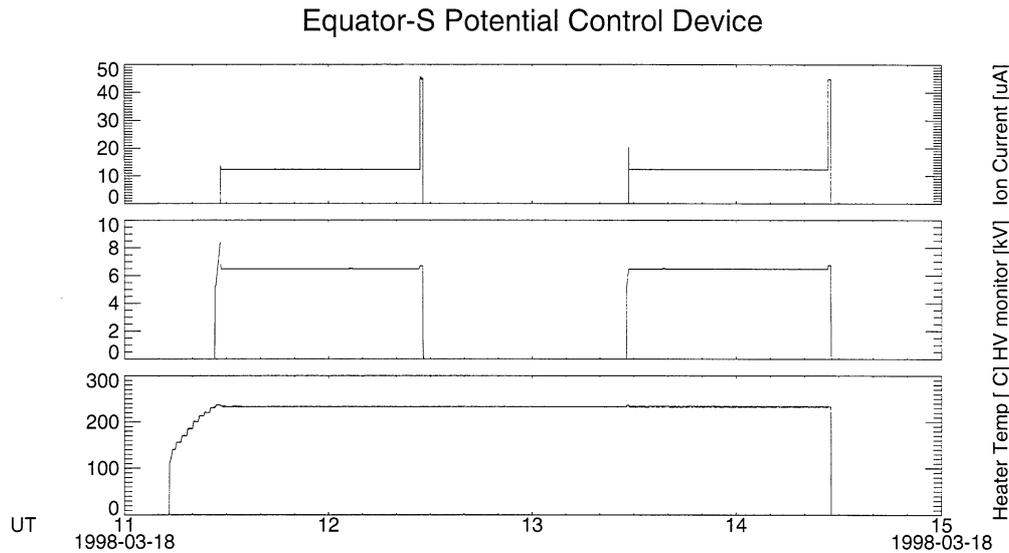


Figure 8. Routine operation of the instrument PCD. From top to bottom: voltage and current of the ion beam, heater temperature.

Operation on board of Equator-S

A similar instrument (PCD for Potential Control Device) has been flown on the Equator-S spacecraft in a $500 \text{ km} \times 10.3 R_E$ equatorial orbit. The objectives to fly this instrument were similar as for Geotail. Additional emphasis was given to testing the slightly modified design in view of the forthcoming mission Cluster-II, where identical instruments (Riedler *et al.* [1997]) will be flown to support one of the most ambitious missions in the Inter-Agency Solar Terrestrial Science Program. For a summary of the instrument PCD see Torkar *et al.* [1998].

All mechanisms (covers), electronics, and software worked without anomaly. The instrument again carried 8 individual emitters with nominally 4000 h operation time each. Although the commissioning of the instrument in orbit was hampered by operational difficulties, four emitters were operated successfully. Due to the increased nominal lifetime of the emitters compared to Geotail already two emitters would have been sufficient to fulfil the requirements of the mission.

In simultaneous operation with the 3D Electron Analyzer instrument (3DA) the advantageous effect on electron measurements by controlling the spacecraft potential was successfully verified. An early failure of 3DA, however, impeded the further scientific exploitation. Until the end of the mission in April, 1998, the ion emitter was turned on routinely for 2 hours at each orbit, as shown in Figure 8 with a typical ion beam current of $12 \mu\text{A}$. More than 250 hours of single emitter operation time were accumulated. Again, the operating parameters of the ion source were very stable and unchanged with time. The short current pulses visible at the end of each operation were applied for test purposes and as a precaution against contamination of the source. It is well known from laboratory use of liquid metal ion sources that short impulses at high emission current can remove obstacles in the liquid flow that might have accumulated. The attempt to assess the long-term behavior of an emitter over a much

longer period was, however, terminated by the early failure of the spacecraft.

As a conclusion from Equator-S, the instrument worked well, and ion emission was achieved with good stability throughout the whole routine operation phase. Overall, it was a technically successful test for similar instrument on Cluster-II. Among the lessons learned for this mission is the observation that the operating voltage of the emitter should be monitored, and small deviations from the nominal value should be taken to trigger a preventive cleaning procedure. This procedure has already been implemented in the four similar instruments which are being built for Cluster-II.

Conclusion

The successful tests of liquid metal ion sources for spacecraft potential control on board the Geotail and Equator-S spacecraft have demonstrated the capabilities of this method. With the experience gained from these missions the operation of similar instruments on the four Cluster-II spacecraft is likely to become a further demonstration of the advantages of this technique.

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