Active Spacecraft Potential Control by Emission of Weak Ion Beams

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State-of-the-art plasma and electric field measurements in space require that the electrostatic potential of the spacecraft body be kept close to the ambient plasma potential. In particular, the tenuous plasmas in the outer magnetosphere force the spacecraft potential to values in excess of +50 V in sunlight. For scientific spacecraft, it is advantageous or even mandatory to actively control the surface potential and maintain it close to the ambient plasma potential. This requires conductive surfaces and active control of the potential by emission of charged particles.

Two ion emitter concepts are presented that are presently under development and will be flown in the early and mid 90's on a number of scientific space missions. The saddle field ion source ionises a gaseous substance in a chamber with a particular configuration of the internal electric field. A rather complex gas flow control system is required. The liquid metal ion source is based on field emission of In^+ from a sharp tip. A cartridge containing the liquefied metal supplies indium to the tip where ion extraction due to extremely high electric field gradients takes place. This concept allows for a small and light-weight design with enough redundancy to achieve the desired lifetime.

The instruments are designed to allow control of the beam current in an on-board control loop with measurements of the spacecraft potential.

1. INTRODUCTION

Accurate low energy plasma and electric field measurements in space require that the electrostatic potential of the spacecraft body be kept close to the ambient plasma potential. In steady state a spacecraft will charge to an equilibrium potential where the sum of the currents to the spacecraft vanishes so that there is no net transfer of charge between the spacecraft and the environment (see *Grard* [1973] or *Whipple* [1981] for reviews). Outside the plasmasphere where the plasma density is low, and as long as the electron temperature is not too high (less than a few keV), current balance to a spacecraft with conductive surfaces is usually between the plasma electron current and photo-emission, and spacecraft potentials are a few volts positive. It has been shown for GEOS-2 and ISEE-1 (see e.g. *Schmidt and Pedersen* [1987] and *Lindqvist* [1983]) that the potentials for these spacecraft were determined by the quantity ($n\sqrt{T}$), where n is the plasma electron density and T the electron temperature. In extremely low density plasmas such as in the lobes of the Earth's magnetotail, the resulting potentials can be as high as +50 V and more. Such potentials not only degrade but occasionally even render impossible cold ion and electron- as well as quasi-static electric field measurements. For scientific spacecraft it is advantageous or even mandatory to actively control the surface potential and maintain it close to the ambient plasma potential. This requires conductive surfaces and active control of the potential by emission of charged particles.

A number of methods for charge control can be envisaged (see e.g. *Pedersen et al.*, 1983). A reliable long-term behaviour, combined with realistic mass and power requirements has to be sought in the technical realisation.

This paper deals with two related experiments where high energy ion beams with emission currents of typically 10 μA are generated by two different systems: One system ionises nitrogen in a so-called saddle field ion source (SFIS) while the other one is based on a liquid metal ion source (LMIS). The instruments described in the following are presently under development and will be flown in the 90's on a number of scientific space missions with eccentric magnetospheric orbits and apogees of about 20 R_E and above. The basic concepts have been described by *Schmidt et al.* [1988] and *Riedler et al.* [1988]. Although the designs are widely different, they have a few common features: both instruments apply ion beams in the range 4–7 keV to reduce high positive potentials and they control the spacecraft potential by a feedback loop with on-board measurements of the potential.

2. SCIENTIFIC OBJECTIVES

A perhaps over-simplified but nevertheless basic picture of the current–voltage characteristics of a spacecraft is given in Fig. 1. It shows

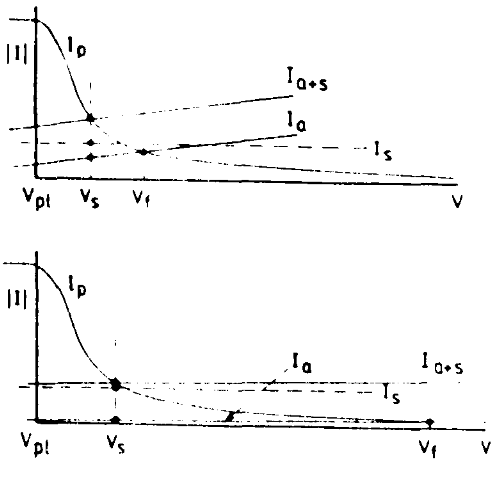

Fig. 1. Simplified current–voltage characteristics of a spacecraft, showing the effect of active ion emission in dense (top panel) and tenuous (bottom panel) plasma. V_f ... floating potential for $I_s = 0$, V_s ... potential with ion emission, I_a, I_p, I_s ... ambient electron, photo–electron, and ion source currents.

the currents flowing from and to a sunlit sphere in a plasma. This figure shall, however, just illustrate the basic approach to the active control of the spacecraft potential by an energetic ion beam, taken in the experiments described below.

The floating potential is in first approximation determined by the equilibrium between photo-electron current, the current due to incident ambient electrons and ions, and the actively emitted ion current. The photo–electron current is essentially determined by the surface properties. The mean photo–electron temperature can be assumed with about 1.5 eV [*Grard*, 1973]. The saturation current density is of the order of nA cm^{-2}, and the photo-current in saturation for an average size spacecraft is some 100 μA. The variations of the ambient plasma current in space and time are not fully predictable. It varies with density and temperature as indicated by the top and bottom parts of the Fig. 1.

The method for active potential control in regions where the photo–electron current dominates is twofold: At first the potential must be clamped somewhere in the steep part of the photo–emission characteristics of the spacecraft. In this way the effects of irregular variations of the ambient electron current on the spacecraft potential are very much reduced. In a second step the actively emitted ion current shall be adjusted to compensate for all natural current variations and to clamp the spacecraft potential at a fixed value. The corresponding modes of operation are described in section 5.

The advantage of a controlled electrostatic environment for other experiments in the fields of low energy plasma and electric field measurements is obvious.

The feedback from on-board measurements of the spacecraft potential is a requirement for full operation of the system. It has been shown that double-probe electric field experiments such as the one flown on GEOS–2 can provide a reference at about 1 V above the local plasma potential [*Schmidt and Pedersen*, 1987]. Double–probe experiments will also be flown e.g. on the Interball, Geotail, and Cluster [*Gustafsson et al.*, 1988] spacecraft. Low energy electron measurements [*Johnstone et al.*, 1988] also gain from a spacecraft potential close to zero, because high positive potentials would accelerate ambient electrons too much. The distribution would become highly compressed and difficult to resolve in an analyser. Below the energy corresponding to spacecraft potential the sensor would detect photo–electrons. The spacecraft potential will appear in the energy spectrum as a minimum in the flux. This information, distributed via an on-board data link to the ion emitter experiment, can also be used for controlling the potential.

The following sections describe the technical realisation of the ion sources and the envisaged modes of operation.

3. THE SADDLE FIELD SYSTEM

3.1. The Saddle Field Ion Source. The saddle field ion source (SFIS) is a type of cold cathode source, based on the effect that electrons describe long oscillatory paths in the presence of an electrostatic saddle potential field. This configuration increases the probability for ionising the gas in the source. Pure nitrogen is used in the application described here. A discharge can be maintained at considerably lower pressure than in conventional cold cathode tubes without a magnetic field, which makes the design easier for magnetically clean scientific spacecraft. General properties of such ion sources have been described e.g. by *Franks* [1979]. A cross-section of the SFIS is shown in Fig. 2.

By differential pumping and by the special configuration of the SFIS a relatively high pressure of 10^{-1} to 10^{-2} mbar can be achieved that is required to maintain the discharge. At the same time scattering of the beam is avoided by a low pressure of 10^{-3} to 10^{-4} mbar in the environment. The electrostatic field has a saddle point in the centre of the source. The positive ions formed in the discharge are accelerated towards both cathodes. A beam of hot ions emerges through the cathode aperture. The ionisation efficiency of the beam is dependent on the beam current drawn. Ions accelerated to the bottom-side in Fig. 2 hit the deflecting plate and are diffused to the cylindric cathode wall. This electrode may be isolated from the housing of the emitter and serve for monitoring the beam current. The ratio between the current flowing through this electrode and the emission current is constant over a wide range of currents.

The diameter of the cathode opening is determined by a trade-off between electrical efficiency, discharge voltage, and stability of the beam in the low-current region. For a given inlet pressure a larger opening would increase the fraction of the beam current relative to the total discharge current, but also increase the discharge voltage because of the lower pressure in the discharge region. The diameter used in the present design is 1.5 mm and takes into account the gradual widening of the hole by erosion.

Fig. 3 shows the beam current which can be extracted from the source as a function of the total discharge current for some values of the gas pressure. For a fixed geometry the current efficiency increases with decreasing gas pressure, together with obvious benefits for the gas consumption. On the other hand with decreasing pressure the discharge voltage soon reaches an upper limit determined by the electrical design of the source.

The selection of suitable materials for the source was lead by the design goal of a lifetime of 5,000 hours. The major limitations encountered were erosion of the cathode disc by sputtering and subsequent deposition of sputtered material on the walls. Both processes change the electrical properties of the source. Sputtered material is likely to form thin layers at the walls which lose contact and short-circuit the source when it is subject to thermal variations. The erosion of a usual cathode after some 1,000 hours operation may also be severe. Apart from its influence on the gas flow the resulting roughness of the surface is unwanted from the stand-point of high voltage safety. In previous tests it was found that cathodes made of stainless steel were subject to unacceptably strong degradation after a few hundreds of hours operation time. A harder material (a car-

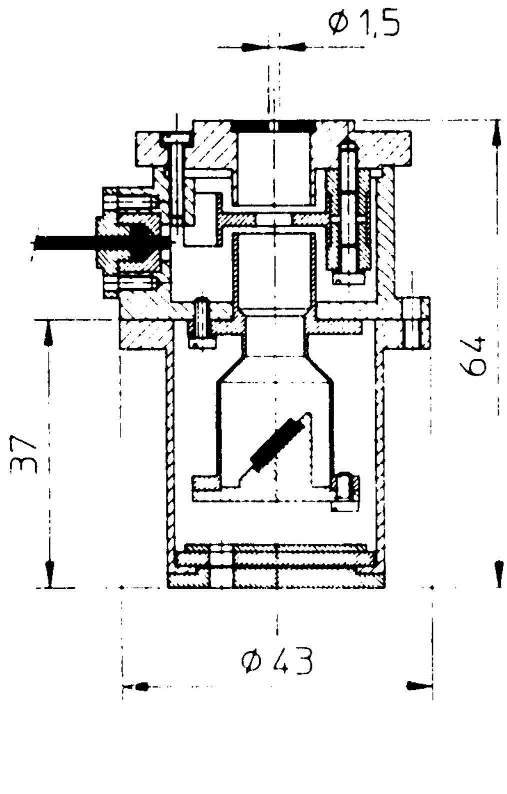

Fig. 2. Cross section of the saddle field ion source.

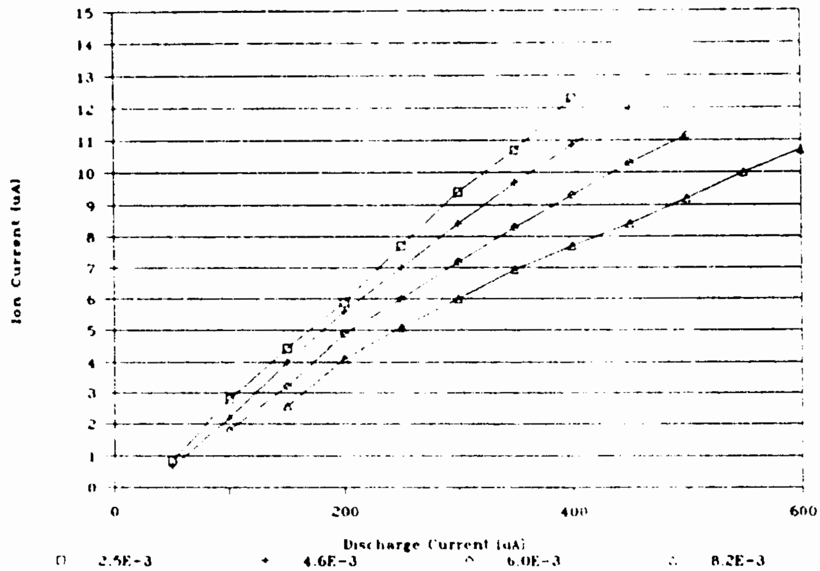

Fig. 3. Beam current extracted from the SFIS as a function of total discharge current for some values of the gas pressure (in bar).

bide) with low sputter yield was chosen for the final design of the cathode disc and the rear deflection plate. Titanium is the material used for the cathode walls to save some mass. As a side-effect the layers of sputtered material formed in a titanium–nitrogen environment consist of a considerable fraction of titanium nitrite, which in contrast to most other nitrites is conductive. This avoids the accumulation of charges on the walls and subsequent secondary effects.

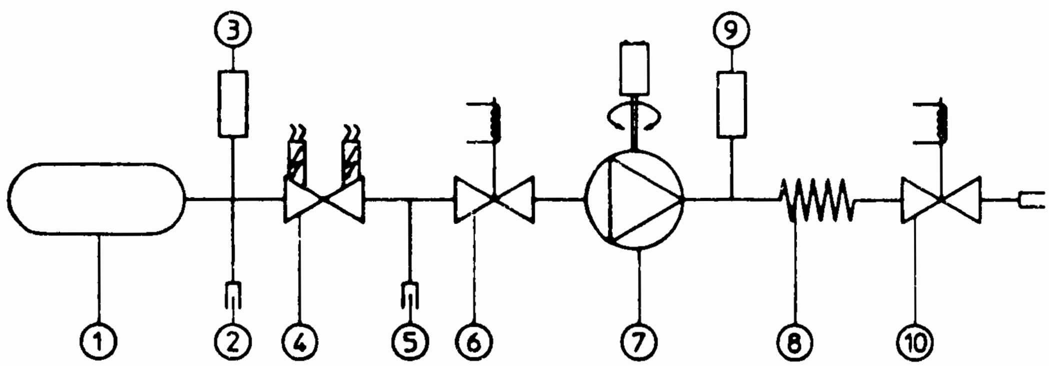

Fig. 4. Scheme of the gas flow control system for the SFIS. (1) gas bottle, (2) filling nipple, (3,9) pressure transducers, (4) pyro–valve, (5) test port, (6,10) latching valves, (7) pressure regulator, (8) constant impedance.

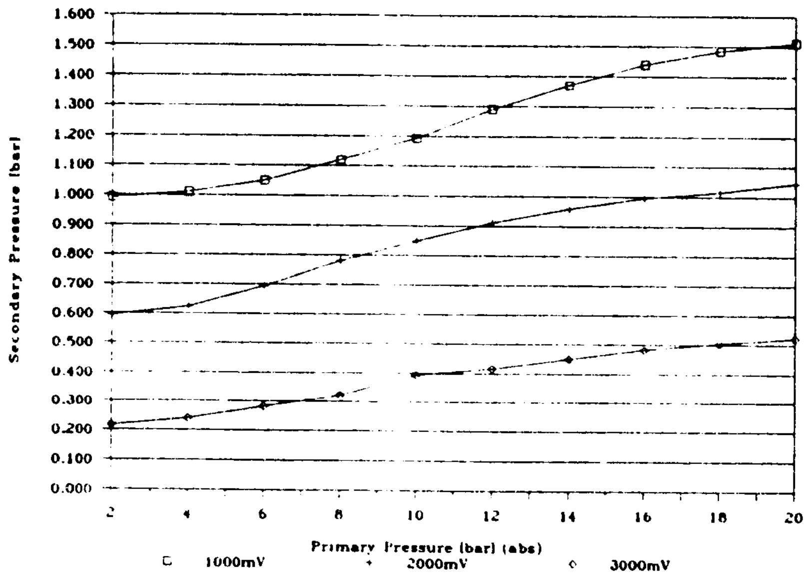

Fig. 5. Variation of secondary pressure with changing primary pressure at different settings of the pressure regulator.

3.2. <u>The Gas Flow Control System</u>. A gas flow control system (GFCS) had to be constructed that reduces the high gas pressure inside a bottle to a constant low value by means of a pressure regulator for very small flows. The system has been described in full detail by *Arends and Scheper* [1989]. A scheme is shown in Fig. 4.

The starting point for the design of the GFCS was the optimum gas pressure at the source, which was found to be 2.5×10^{-3} mbar, and the corresponding gas flow of 1.6 N cm^3 $hour^{-1}$. A gas bottle (1) with 0.5 l volume, initially filled with pure nitrogen at 18 bar was found sufficient for 5,000 hours of operation.

The gas pressure is measured by two pressure transducers (3,9). Their output is used by the on-board microprocessor to adjust the pressure regulator (7). The pressure regulator will keep the secondary pressure constant almost independent of the primary pressure. Only small corrections are needed when the bottle is emptied. The valve (4) secures a hermetically sealed volume of gas and can be opened by a redundant pyrotechnic piston actuator. The latching valves (6,10) take over the function of the pyro valve after this has been activated. The drift of the secondary pressure with changing primary pressure, i.e. the supply effect of the source is depicted in Fig. 5. It amounts to 25 mbar bar^{-1}, and a few turns of the motor valve are sufficient to compensate for large variations from 18 down to 2 bar of the pressure in the gas bottle. The effect of ambient temperature is as small as −1 mbar/K.

The most delicate element in this system is the constant impedance (8), a glass capillary with a leak-rate of 6×10^{-4} mbar ltr s^{-1} for air at 1 bar. The scheme in Fig. 5 gives an idea of the complexity of the system which is its major drawback. Both the SFIS and the GFCS of the engineering model have undergone the usual environmental tests (sine vibration, shock test, etc.).

4. THE LIQUID METAL ION SOURCE

4.1. <u>Operating Principle</u>. The alternative approach to achieve a high energy ion beam is based on the liquid metal ion source. This ion emitter is a solid needle – type liquid metal ion source, previously described in the literature using indium as charge material [*Evans and Hendricks*, 1972; *Wagner and Hall*, 1979; *Dixon and Engel*, 1980]. A solid needle, made of tungsten, with a tip radius between 2 and 15 μm is mounted in a heated reservoir containing the charge material (Fig. 6). A potential of 5–7 kV is applied between the needle and an extraction electrode. If the needle is well wetted by the metal, the electrostatic stress at the needle tip pulls the liquid metal towards the extractor electrode. This stress is counteracted by the surface tension forces of the liquid. One of the equilibrium configurations the liquid surface can assume is that of a so-called Taylor-cone [*Taylor*,

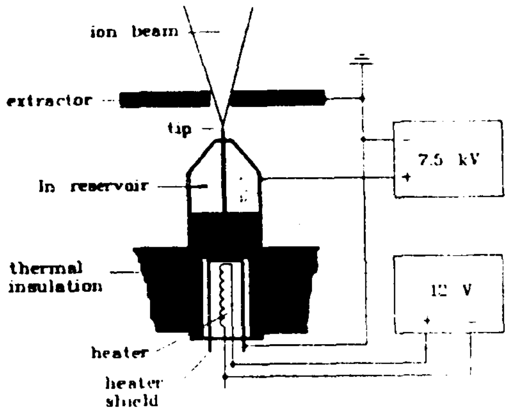

Fig. 6. Individual liquid metal ion emitter.

1964] with a total tip angle of 98.6°. The apex of the Taylor-cone in practice reaches a diameter of 1 to 5 nm [*Kingham and Swanson*, 1984]. The field evaporation of positively charged metal atoms in the strong apex field leads to emission of a high brightness external ion beam from this cone apex with a beam brightness of the order of 10^6 A cm^{-2} sr^{-1} at 10 keV beam energy.

Since the emission zone is in the liquid state, ions leaving the surface can be continuously replenished by hydrodynamic flow of liquid metal from the reservoir to the needle apex so that a stable emission can be maintained.

Due to the extremely high source brightness, the LMIS is particularly suited for formation of microfocused ion beams and has found wide application in microelectronic technology: ion beam lithography, writing ion implantation, ion microfabrication, and microanalysis [*Rüdenauer*, 1984]. The advantages of the LMIS principle are:

- low power consumption; mostly determined by the heater power to keep the indium reservoir above 429 K;
- high mass efficiency;
- compactness and low mass; one individual emitter has a volume of 170 mm^3 and a mass < 5.2 g.

Indium has been chosen as ion source charge material because of its low vapour pressure. This prevents contamination of the source insulators and ambient spacecraft surfaces. On the other hand, the melting point is high enough that melting of an unheated source charge cannot occur even at the maximum expected elevated environmental temperature.

The individual emitters (Fig. 6) are of cylindrical geometry. The indium and the needle are kept at high tension. The sources are individually and indirectly heated by a thick film resistor embedded into a ceramic insulator tube. Al_2O_3 was chosen for superior high voltage insulation characteristics. This scheme enables the source to be heated from a grounded power supply and the tip itself still being kept at high voltage.

4.2. Design of the LMIS Module. Figure 7 shows the schematic design of an ion emitter module. One such module consists of an array of 5 individual ion emitters which are operated one at a time. They are mounted in a slab of porous ceramic with extremely low heat conduction ($< 5 \times 10^{-4}$ W K^{-1} cm^{-1}). All emitters have a common extraction and focusing lens arrangement consisting of a grounded extractor electrode, a focusing electrode at beam potential and a second ground electrode. These electrodes constitute a unipotential lens with the tip apex located in one focal point. The divergent ion beam (opening angle < 30°) emitted from the tip is focused by this lens into a nominally parallel beam after passage through the ground electrode.

Due to the wide-angle nonparaxial rays entering the electrode system, the lens aberrations actually will produce a divergence of 15° (half maximum)

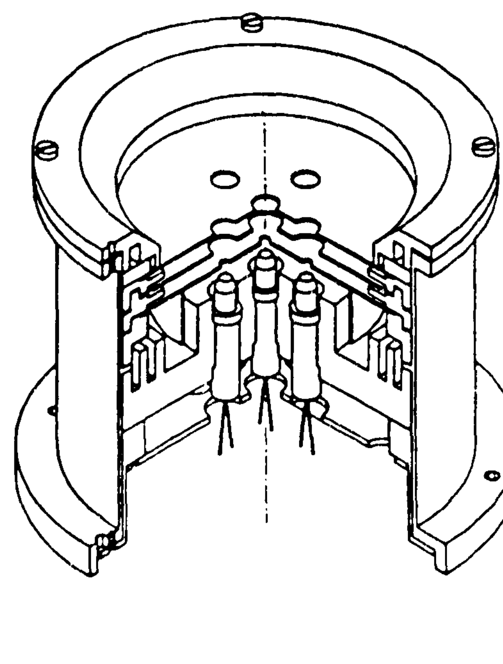

Fig. 7. Schematic of the LMIS module.

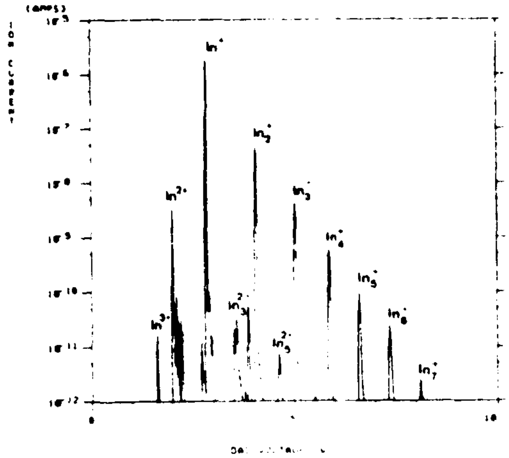

Fig. 8. Mass spectrum of the LMIS at 10 μA extraction current.

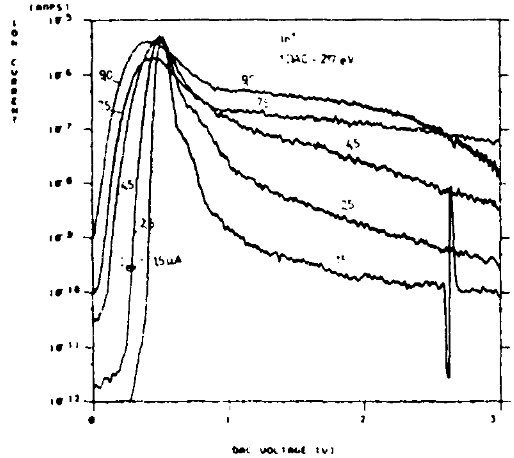

Fig. 9. Energy spectrum of the In^+-peak with the currents at the extraction electrode as parameter (1.5, 2.5, 4.5, 7.5, and 9 μA).

in the outgoing beam (11). Tip and focusing electrode are on the same potential so that no additional power supply or voltage divider is required for beam focusing. Since the beam shaping and focusing optics is purely electrostatic, the lens properties and the beam shape remain unchanged if the tip voltage (which is identical to the focusing voltage) changes.

All outer surfaces are electrically connected to spacecraft ground. The cold secondary side of the high voltage supply, which is connected to the inner shield and focusing system inside the emitter housing, is floating at <0.5 V because of a beam current monitor circuit.

4.3. Performance of the LMIS module. The energy spread and the composition are important properties of the ion beam. Fig. 8 shows a mass spectrum of the extracted ion beam for typical operating conditions. Various peaks of different indium molecules and clusters with single, double and triple charges are visible, but singly charged In^+ with 115 amu dominates all other species by a factor of 40. The average charge number per emitted charged indium atom is 0.976. The emitted In^+ ion current shows some broadening of the energy spectrum with increasing currents at the extraction electrode from 1.5 to 9 μA, as shown in Fig. 9. At an emission current of 10 μA the energy width is 150 eV, but a low intensity, low energy tail down to more than 500 eV below nominal beam energy can be expected.

Major efforts were put in the design of the thermal isolation of the source because of its immediate effect on the total power consumption. Whereas the 50-90 per cent of the energy provided by the high voltage supply that go into the emitted ion beam require <1 W primary power going into the supply, the additional power for the heating of the indium is about 0.8 W.

5. FLIGHT OPERATIONS

The operation modes in flight have to be optimised with respect to the requirements of the low energy plasma and electric field experiments and have to avoid interference with other experiments on plasma waves, high energy particles, and optical experiments. The effects on the environment must be well-defined and preferably synchronised with scans, sampling intervals etc. of other experiments. The electrical paramcters of the ion beam must be known to all experimenters to facilitate their data reduction. For the same reason rapid variations of the beam current are undesirable except for very short periods of so-called active experiments as described below.

Two operation modes are foreseen on a regular basis:

In the feedback mode mentioned before a measurement of the spacecraft potential is supplied by either the electric field experiment or the low energy electron analyser and this information is then used to adjust the emission current sufficient to reduce the spacecraft potential to within some predetermined value, as described in the discussion of Fig. 1. The required ion current would be the order of a few tens of μA. In the case of plasma current domination, the required emission current would be smaller.

It may be a difficult problem to use the on-board software to select either the electric field or the electron analyser data if the signals differ from each other. It is planned to analyse the first orbits and to uplink some decision rules for the on-board processor. Robustness against spurious commands and on-board memory errors is another important software requirement.

In case no on-board data on spacecraft potential from any experiment is available, the stand-alone mode involves setting the emission current to some predetermined value based on the spacecraft current-voltage characteristics, and perhaps a measure of the ambient plasma density and temperature. In this mode, the emission current must be set to a level to insure that the spacecraft potential is not driven negative. The control of the potential would not be as good in this case as in the feedback mode, but could still be used to reduce the spacecraft potential to a few volts positive relative to the ambient plasma potential.

In a so-called active mode scientific investigations of the photoelectric characteristics, dependence of the spacecraft potential on plasma parameters, and of spacecraft charging in different plasma environments can be carried out. In accordance with the scientific operation plan for the spacecraft and in agreement with other experimenters the optimum ion current will be varied in a defined way for a short time to enable the co-operating plasma experiments to calibrate their response to spacecraft potential variations between the unregulated and the clamped, near-zero values. The current-voltage characteristics of the spacecraft will be determined as well. Such experiments will be carried out at large, but regular intervals.

If the uncontrolled spacecraft potential is negative with respect to the ambient plasma, any ion beam emission would lead to an even greater negative potential and should be avoided. In feedback mode the on-board software of the instrument will switch off the ion beam in such a case. In stand-alone mode the beam current should be set to a predetermined value derived from theoretical considerations and preceding in-flight tests. This value can be preprogrammed to vary according to the expected plasma environment along the trajectory including a safety margin to avoid beam-induced negative charging under abnormal conditions.

6. DISCUSSION

6.1. Comparison of the SFIS and LMIS systems. The main instrument data are listed in Table 1. The first column contains the numbers for a combined SFIS-LMIS instrument to be flown on an Interball spacecraft. Its mass and power are governed by the requirements of the gas system. The second column is for the experiment flown on Cluster (ASPOC, Fig. 10), which contains two independent LMIS modules for redundancy or for an extended operation time.

The SFIS has a low efficiency (3–5 per cent) and a requirement for short-time power to operate the valves. The LMIS has a higher efficiency in the high voltage circuit itself: about 50–90 per cent of the total current go into the beam, the remaining fraction is diverted to the focusing system.

Experiment Name Spacecraft Ion Sources	RON Interball SFIS + LMIS	ASPOC Cluster 2 LMIS
Mass [kg]	7.5	1.5
Size [mm]	300x250x250	180x125x140
Power (max.) [W]	10.5	3
Telemetry Rate [bit s^{-1}]	20-200	100
Beam Opening Angle [deg]	± 10	± 15
Design Lifetime [h]	10,000	10,000
Ion Species	N_2^+, In^+	In^+

Table 1. Instrument data summary

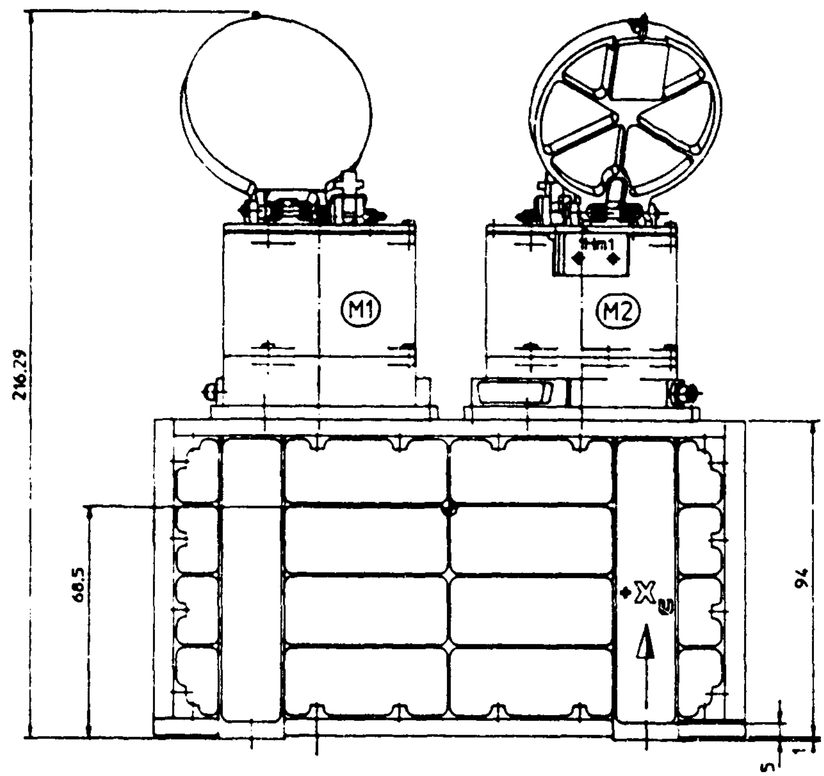

Fig. 10. Drawing of the experiment ASPOC (Cluster spacecraft) with two LMIS modules on top of an electronics box.

However, additional heating power for the charge material is required (typically 600 mW).

The other major differences between SFIS and LMIS beyond mass and power resources relate to the ion species, chemical cleanliness, and ground operations.

6.2 Electromagnetic Compatibility. Any harmful effect on any other experiment by actively controlling the spacecraft potential is unlikely if the emission current is kept within reasonable limits. However, the necessity of operating the emitter in close consultation with all the other experimenters is acknowledged.

The emission of a charged particle beam into a plasma is a potential source of electromagnetic noise. The extent of this possibility for the present applications is not yet well understood, especially since a dedicated active potential control experiment using an ion beam has not yet been operated on a spacecraft. Theoretical work on the triggering of activity by beams with current densities as low as in the present experiments and at 4–7 keV is practically non-existent in the literature. Ion beams with two orders of magnitude higher current densities were injected into the ionosphere and generated waves around the lower hybrid resonance frequency. Other experiments found increased emission in the magnetic field around the local electron cyclotron frequency. In this case the electric field antenna did not measure any effect. It is known that a small opening angle of a beam tends to increase the probability of wave generation. For this reason the beam focusing system is designed for a large opening angle of 15° half width.

6.3. Chemical Contamination by the Ion Beam. Chemical interaction that could be considered as potential concerns to the spacecraft or instruments covers:

- condensation of neutral indium in the vicinity of the LMIS emitter,
- return of ions to the spacecraft after one or more gyrations,
- interaction of the ion beam with spacecraft surfaces.

The condensation of neutral indium on cold surfaces is extremely unlikely. The vapour pressure of indium is only 1.1×10^{-19} Torr at the melting point and the total surface from which indium evaporates is in the order of 1 mm^2 for the active, hot emitter and about 9 mm^2 for the surfaces at the environmental temperature. Neutrals that penetrate through the orifice are expected to drift freely into the ambient plasma. Their return to the spacecraft skin can only occur through two processes which have been found very unlikely [*Riedler et al.*, 1988]: collision with other neutrals and photo-ionisation.

6.4. Constraints. The advantage of low mass and high efficiency of the LMIS is balanced by some constraints for active ion beam emission and handling on ground. It is not possible to operate the LMIS at total pressures $> 3 \times 10^{-6}$ Torr for extended time periods ($>$1 hour), and the LMIS must be stored in dry nitrogen to avoid oxidation. This makes the instrument subject to similar purging requirements as for a number of other experiments. A third constraint, namely the restriction to control only positive spacecraft potentials, applies to both positive ion sources and has been mentioned in section 5.

7. SUMMARY

Two widely different designs for ion sources to control the spacecraft potential have been presented along with a short description of their application in two instruments and the anticipated modes of operation. Each system has its advantages. The first test in orbit with both systems combined into one instrument is to be carried out in the early nineties. Experience collected in this mission will help to improve the design and operation of the LMIS system that has been selected for the Cluster spacecraft.

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