PLASMA CONTACTOR DEVICE BASED ON HOLLOW CATHODE TECHNOLOGY FOR SPACECRAFTS CHARGING NEUTRALIZATION AND TETHERED SYSTEM APPLICATIONS: REVIEW OF ITALIAN NATIONAL PROGRAM

G.F. Cirri, G. Matticari*, M. Minucci, G. Noci*, A. Severi, P. Amatulli
Proel Tecnologie - Firenze (Italy)

F. Svelto
ASI (Italian Space Agency), Roma (Italy)

Abstract

A Plasma Contactor is a device capable of producing a cold plasma cloud conceived to enhance the electrical contact between a space vehicle and a surrounding plasma environment.

Several applications are presently envisaged for this kind of device, the most relevant being:
- Ion propulsion technology.
- Tethered Systems (power, thrust and wave generation).
- Spacestation / Spacecraft absolute and differential charging prevention / neutralization.

This paper reviews the activity performed by Proel in this field under the supervision of the Italian Space Agency (ASI).

Two fundamental families of plasma contactor devices based on the Hollow Cathode technology have been designed and developed by PROEL:

a) heated plasma contactor;
b) not-heated plasma contactor (based on PROEL patent[10]).

Engineering models of these devices are currently being tested; the preliminary results are presented in the paper and the main characteristics are given as well.

Both the families have the capability of handling electron currents in excess to 10 Amps.

Mathematical modelizations of the emission process are currently under optimization and validation.

The main features of the two families of developed plasma contactors are:

- Low gas consumption.
- Low power consumption.
- High reliability (thousands of hours).
- Low mass.
- Limited size.
- Quick start-up, with not-heated plasma contactors (PROEL patent).

The Plasma Contactor test program includes functional tests in a simulated ionospheric plasma environment (generated by a Kaufman source). However, to verify its behaviour in the real operating conditions, a flight experiment will be recommended.

In-flight experiments, aimed to check the Plasma Contactor working in different situations, have been presented by PROEL and technically approved by ESA.

Introduction

A Plasma Contactor is a plasma producing device conceived to lower the electrical impedance between a space vehicle and the surrounding plasma environment, or to neutralize a charged beam (ion propulsion application).

This kind of device, mounted and properly connected to a space vehicle, will produce a relatively high density plasma cloud through which the ability to exchange ions end electrons with the plasma environment will be improved.

The main applications of this device are related to:

- Ion propulsion technology.
- Tethered Systems (power, thrust and wave generation).
- Spacecraft / Spacestation absolute and differential charging prevention / neutralization.

One important space field application of Plasma Contactors is related to ion propulsion. In this case the Plasma Contactor device works as a neutralizer of the ion beam emitted by the ion engine. The requested currents in this conditions range from fractions of ampere to some amperes.

In Kaufman ion thruster a plasma contactor is also used to produce the discharge plasma from which ions are extracted and accelerated to produce thrust.

Besides, the capability of the Plasma Contactor to develop electron emission and electron collection with

---

* Member AIAA

currents of the order of 10 A is very interesting for Tether System applications. In fact the use of electron guns for 10 A electron emission would require high acceleration voltage, electrical power and mass; while in principle a Plasma Contactor device can feature Tether application requirements with much lower dimensions, power and mass budget[1] [2] [3].

Moreover, the Plasma Contactor can control/prevent space vehicles charging, both absolute and differential. The tendency of space vehicles surfaces to charge has been noted since the beginning of spacecraft flight. This charging effect is particularly severe at Geosynchronous orbit.

Normally a space vehicle charges to few Volts because the plasma to which it is exposed is characterized by low temperatures (about 3 eV), this condition normally doesn't require Plasma Contactor devices.

Occasionally a space vehicle can charge to higher potentials; negative potentials as high as 19kV during eclipse and 2.2kV in sunlight were measured on several spacecrafts (SCATHA, ATS-5, ATS-6, Meteosat et al.)[4] [5].

The capability of a Plasma Contactor to reduce to about -5V high spacecraft potentials up to -3kV, developed during eclipse, has been demonstrated during ATS-6 flight experiments with an ion engine plasma source[6].

The neutral plasma emission from a plasma contactor, among all active methods for space vehicle charge control, has demonstrated to be the most successful in discharging overall and differential charging[5] [7].

The necessary current levels requested by these applications can range from tens or hundreds of microamperes, for a magnetospheric telecommunication satellite[8], up to a current of the order of amperes for a Space Station[9] (e.g. Freedom).

For magnetospheric applications, PROEL has also developed other methodologies, based on electron guns[11] [12], to discharge negatively charged satellites.

This paper describes two families of Plasma Contactor devices, based on hollow cathode technology, capable of handling currents higher than 10 A.

The first family, based on the heated hollow cathode technology, includes devices of different dimensions and consequently different current emission capabilities. Engineering Models of these devices are currently being tested at Proel Laboratories.

The second family is of new conception and it is based on not-heated hollow cathode technology: these devices do not require a heating filament (and its relative power supply), to ignite the discharge. Their technology is based on a Proel patent[10].

The most significant feature of not-heated cathodes is represented by the quick start-up and operation: they do not need a warm-up time to produce plasma.

Plasma contactor principle of operation

To reduce the potential of a space vehicle with respect to the ambient plasma, it is necessary to lower the electrical impedance between them.

An effective way of doing this is to create a high-conductivity plasma plume to allow the positive and negative charged particles exchange through the formed potential sheaths. This plasma plume can be generated with a Plasma Contactor which behaves as an additional source of charged particles to achieve current balance and reduce / prevent space vehicle potential growth.

During operation only the discharge power supply and the gas flow are operative, being the heater (if present) switched off. The discharge voltage between cathode and keeper is 12 ÷ 17V.

The Plasma Contactor can be operated with the cathode (fig. 1a) or the keeper (fig. 1b) connected to the space vehicle ground.

In both cases the produced plasma plume, which is in close contact with the space plasma, maintains the keeper close to space plasma potential.

When the cathode is connected to the space vehicle ground, the Plasma Contactor keeps the space vehicle to a potential, with respect to space plasma, approximately equal to the discharge voltage (12÷17V). The discharge current does not limit the exchange of current with the environment.

When the keeper is connected to the space vehicle ground (fig. 1b), the space vehicle potential, with respect to space plasma, can be lower. The maximum current exchangeable with the plasma is, in this case, limited by the discharge current: high current exchange capability is therefore related to high discharge current, which means higher power consumption.

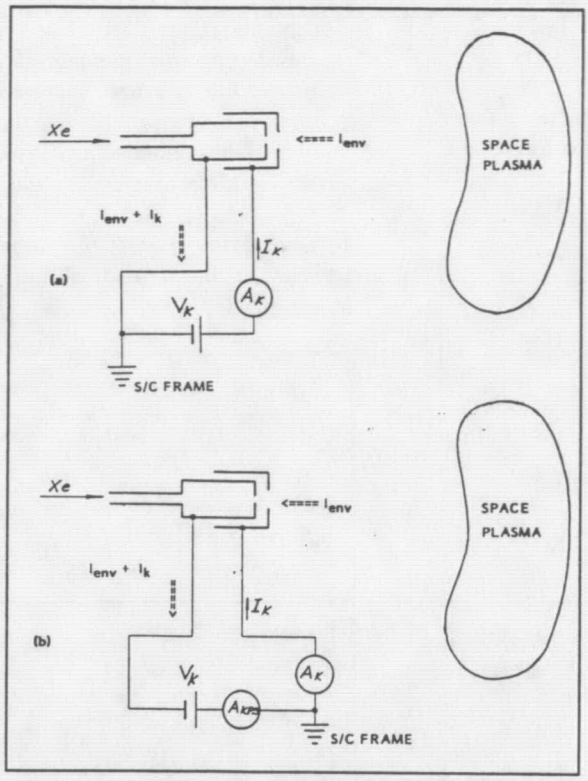

Fig. 1: Possible different connection of Plasma Contactor to space vehicle; a) cathode connected to space vehicle, b) keeper connected to space vehicle

Another important feature of the Plasma Contactor is the capability of self-switch from electron emission to electron collection according to the sign of the potential difference between the device and the ambient plasma. This feature can be exploited in a Tethered Space System.

In a Tether Space System plasma contactors, placed at both ends of the system can be used to generate electrical power (fig. 2) and also to generate thrust (fig. 3). In the latter a reversed current, generated by a suitable high voltage supply, is allowed to flow in the tether thanks to the plasma contactor intrinsic capability to generate particles of different sign.

The interest in plasma contactor applications within Tethered Space Systems has been growing during the last years. Currently PROEL is negotiating the possibility (through Italian Space Agency) to accomodate a plasma contactor on board the Space Shuttle, within the TSS-1 mission re-flight.
Recently a Plasma Motor Generator Experiment, based on a 500 m tether has been successfully flown. Within this experiment (principal investigator Dr. J. Mc Coy - JSC/NASA) two plasma contactors, each mounted at one end of the small Tethered System, allowed a current flow into the tether of some fractions of ampere.

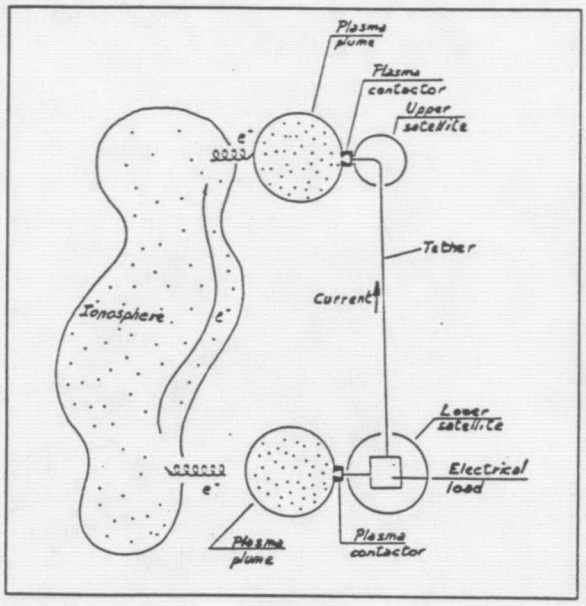

Fig. 2: Plasma Contactors used in a tethered system to generate electrical power

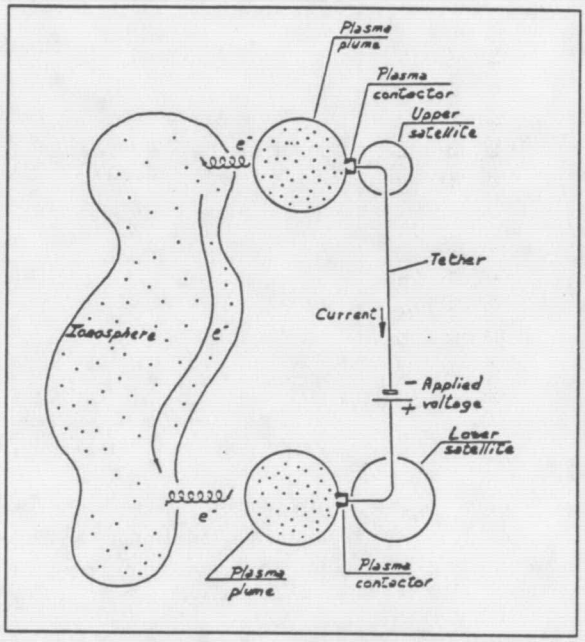

Fig. 3: Plasma Contactors and an High Voltage Generator (HVG) used for tether experimentation as a "motor"

Design characteristics

The basic component of the plasma contactor technology is the hollow cathode.

An orificed hollow cathode is essentially a cavity closed at one end by a disk containing a small orifice.

An inert gas, such as Xenon, flows into the cathode chamber where it is ionized by electrons emitted from a heated emitting insert (heated hollow cathode) or by

the Paschen effect[3] [4] [5] (not-heated hollow cathode).

Fig. 4 and 5 show respectively the schematic drawing and operating principle of heated and not-heated hollow cathode.

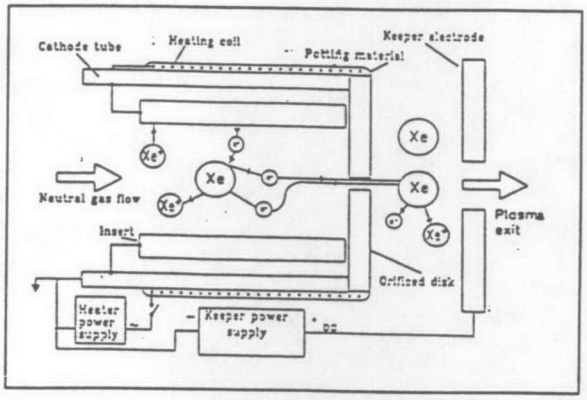

Fig. 4: Schematic drawing and working principle of a orificed heated hollow cathode

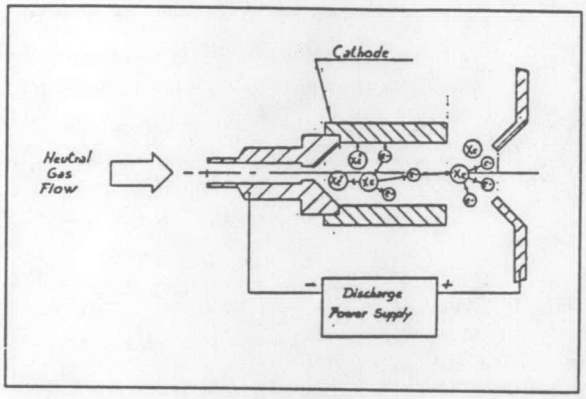

Fig. 5: Schematic drawing and working principle of the not-heated orificed hollow cathode

In the case of heated hollow cathode, a heating filament, wound around the cathode tube, is powered to bring the insert to thermionic emission temperature, which is necessary to ignite the discharge.

Once the discharge has been established, positive ions bombard the insert surface with a kinetic energy suitable to produce a self-sustained discharge, this means that the heater power supply can be turned off after the discharge ignites.

The first time this kind of devices are switched on a special procedure is requested to activate the cathode insert. This procedure generally requires some hours.

PROEL has developed a family of heated plasma contactors, composed by different models (NccA/300, NccA/5000, NccA/10000), capable of providing currents from mA to tens of Amperes.

For the design activity of this type of devices PROEL is developing a computer-code which permits to extimate the plasma characteristics, varying the geometrical parameters and the input power. This code will be validated by Proel during the Plasma Contactor test activity.

In table 1 the general operating characteristics of 3 devices of the heated hollow cathode family are summarized.

	NccA/300	NccA/5000	NccA/10000
Gas Flow rate (sccm Xe)	0.5	1	1 ÷ 2
Discharge Voltage (V)	12 ÷ 17	12 ÷ 17	12 ÷ 17
Discharge Current (A)	0.5	5	5 ÷ 10
Power consumption (W) (running)	7	60÷75	80 ÷ 150
Heater Power Consumption (W) (only at start-up)	20	30	100
Start-up time (s)	60	80	120
Lifetime (h)	>15000	>15000 *	>15000 *
N° of startups	>20000	>20000 *	>20000 *
Ion emission current (mA)	<0.5	-1	-2
Electron emission current (A)	up to 1	up to 5	5÷more than 10
Weight (gr.)	-100	-150	-300

* *To be confirmed by test, currently ongoing*

Table 1: General operating characteristics of some plasma contactors of the "heated" hollow cathode type

A picture of devices NccA/10000 is shown in fig. 6.

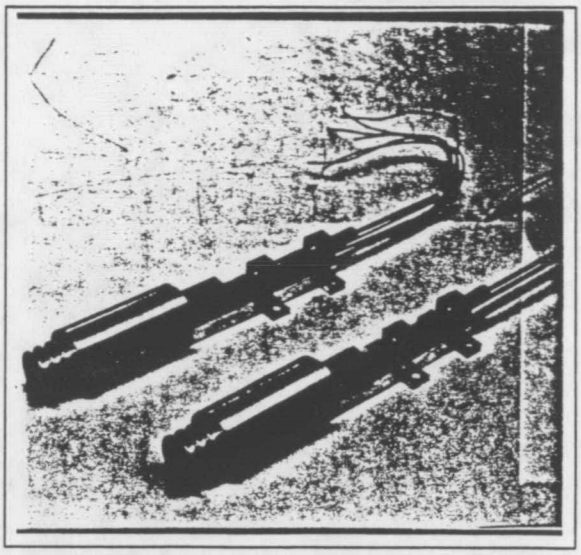

Fig. 6: Orificed heated Hollow cathode devices type NccA/10000

The not-heated orificed hollow cathode devices do not need a heating coil to ignite the discharge. The discharge is ignited applying a suitable voltage between the cathode and the 1st anode of a multi-anode structure[10], in presence of gas flow (Xe or Ar).

The first anode has a calibrated central hole which establishes a pressure gradient between the first discharge chamber and the second chamber.

The second anode acts as the keeper of the other device family (heated) and helps the current extraction from the device.

With a Methodological Model of this device Proel has reached discharge currents of more than 10 A with discharge voltage of 30-35V. Further improvement are ongoing.

On these concepts Proel is developing a family of devices, having different peculiarities.

These devices are of intrinsic simplicity and potentially have a higher reliability, offering also a quicker start-up time with respect to heated devices: their operation is practically instantaneous after receiving the necessary gas flow and electrical power.

The quick start-up may play a key role in the employment of these devices for space application.

For example they could overcome the problem of instantaneous spacecraft charging in the LEO polar environment, due to auroral electrons precipitation.

A picture of the developed methodological model is shown in fig. 7.

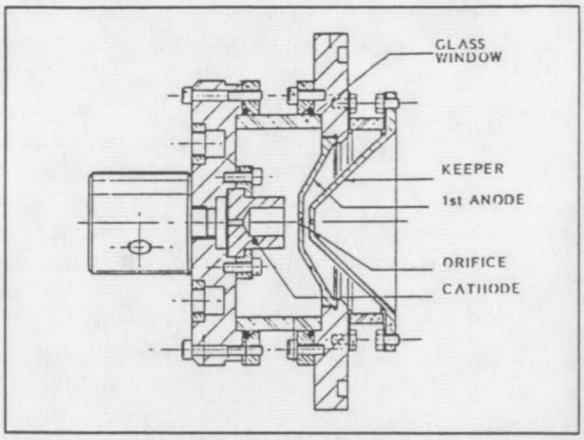

Fig. 7: Not-heated Orificed Hollow Cathode device: methodological model

Plasma Contactor system

For practical operation of a plasma contactor on board of a spacecraft a whole system has to be realized.

A typical Plasma Contactor system is composed by four major subsystems as shown in fig. 8: a Plasma Contactor Device, a Gas Feed Control System, a Power Supply Control unit and a Surface Potential Detector.

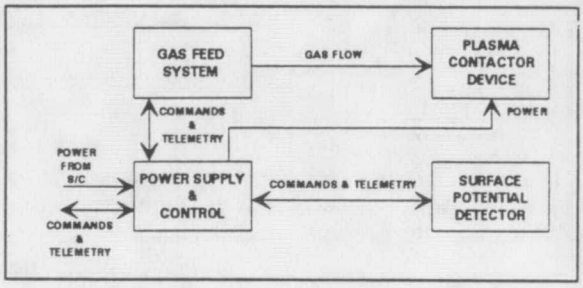

Fig. 8: Block diagram of the Plasma Contactor system

Proel currently has reached an advanced development of the Plasma Contactor device.

The gas feed control system and the Power Supply and Control unit have been developed at breadboard level.

The Surface Potential Monitor, most likely, will be developed in collaboration with an external supplier.

The heated orificed Plasma Contactor requires two power supplies: one for the heater and one for the discharge, while the not-heated Plasma Contactor requires only the discharge power.

The heater power supply is a programmable current controlled power supply which is used only for less than 2 minutes during the device warm-up to heat the insert. The power consumption of this power supply

ranges between 20 and 100 W depending on device size.

For the keeper power supply Proel is working both with programmable current controlled and with programmable constant power systems. Both these types of power supplies have given good results during the test of heated orificed devices. For not-heated sources only the current controlled power supplies have been used.
The power consumption after discharge ignition ranges between 7 and 80 W as a function of device size. Before device ignition (open circuit) a constant 200 ÷ 300V voltage is requested; after ignition the power supply switches automatically to current or power control.

Plasma Contactor Test set-up

To characterize the plasma contactors operation, thus validating on ground their technology, a suitable test set-up has been implemented at PROEL labs.

The main test facilities are here under listed:

- vacuum chambers with relative pumping systems, valves, flanges, fittings and feedthroughs;
- mass spectrometer for monitoring of residual gases due to evaporation and outgassing of heated materials;
- gas feedline with flow controllers, valves, oxygen absorber;
- power supplies and measurement equipment;
- target for the measurement of the emitted current;
- optical pyrometer for perform temperature measurements;
- automatic acquisition system to drive and monitor the fundamental parameters;

Vacuum plants

Two kinds of vacuum chambers have been used for the plasma contactor test activity:

- *Twin glass vacuum chambers*, used for the tests of the NccA/300 devices (see Fig. 9). This double set-up has been implemented to have contemporary experiments running.

- *Stainless steel vacuum chambers*, connectable each other in different ways to reach the maximum flexibility and versatility in the test activity.

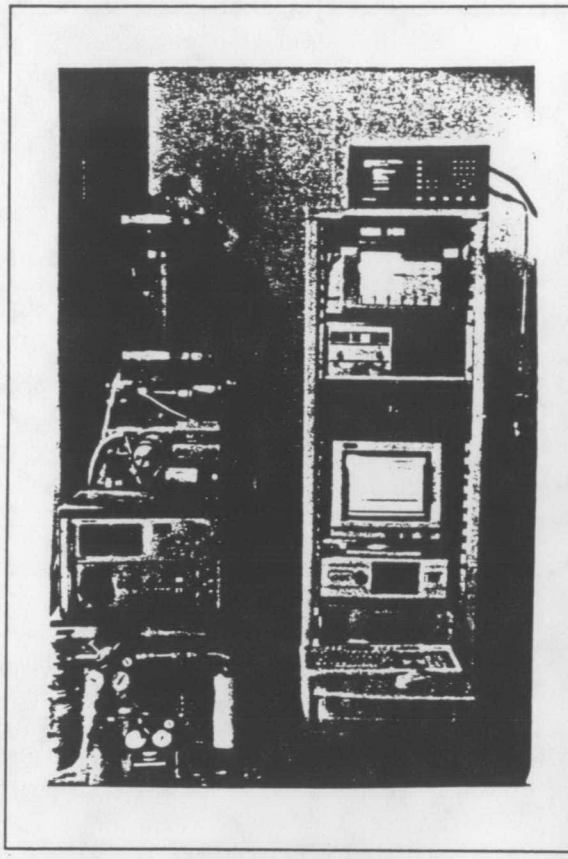

Fig. 9: Glass vacuum chamber facility

The stainless steel vacuum chambers have bee conceived according to a modularity approach. Tw basic modules have been foreseen: a number of the are now available at PROEL labs, with th specifications summarized in Tab. 2.

Module type	Diameter (m)	Length (m)	Pumping speed (lt/s)		# of modules available
			Turbo	Cryo	
A	1	0.9	1500		4
B	1.7	1	1250	50000	2

Tab. 2: Available modules for configuring applicatio taylored vacuum chamber

The modular philosophy allows the realization o various configurations according to the peculia requirements of the considered application.
As an example we show in Fig. 10 the maximum capability of the vacuum plant. It is however eviden that any reduced configuration, obtained combinin the various modules, can be realized.

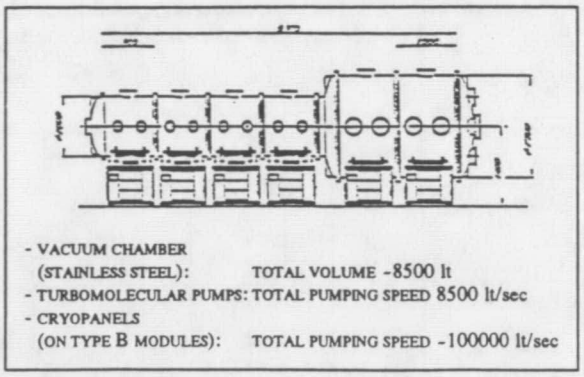

Fig. 10: PROEL vacuum plants: maximum configuration obtained assembling all the available modules

In photographs of fig. 11 and fig. 12 two configurations are shown, respectively assembling two type B modules and three type A modules.

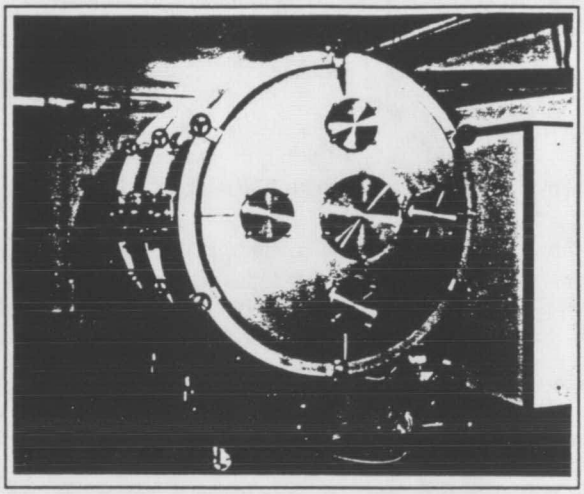

Fig. 11: PROEL vacuum plants: the ϕ 1.7m (type B) stainless steel vacuum modules

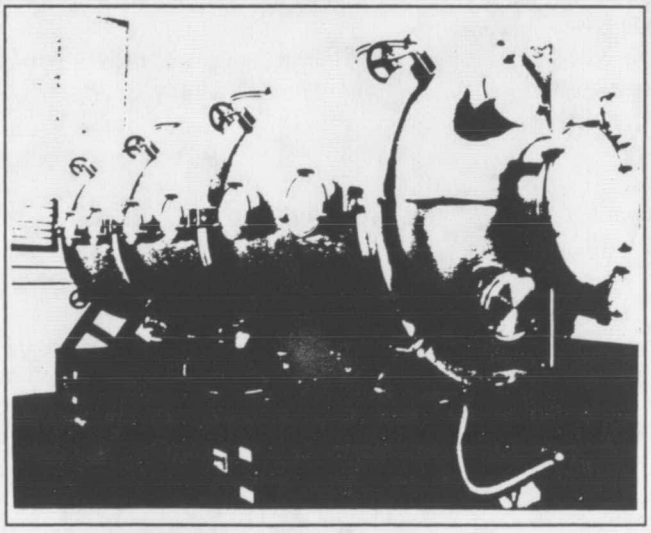

Fig. 12: PROEL vacuum plants: the ϕ 1m (type A) stainless steel vacuum modules

Thanks to the modular approach a wide range of plasma contactor sources, characterized by a gas flow rate from fraction of sccm to tens of sccm, can be tested at PROEL labs.

Gas feedline and flow control

The sketch of the gas feed line is shown in Fig. 13. The flow meter is controlled by the computer as well as the pneumatic valve that allows the regulation of the gas flow into the device under test. The flow meter ranges between 0 and 20 sccm, with about 5% accuracy.
An oxygen absorber is installed in the line to prevent any contamination of the insert due to oxygen and water vapour.

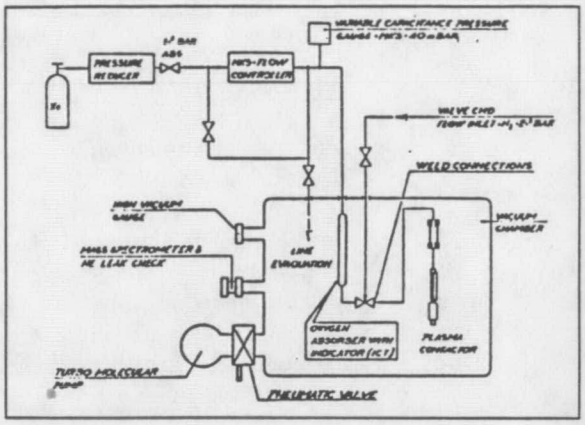

Fig. 13: Gas feed line

Power supplies

3 power supplies are necessary to perform the tests of Heated Orificed Hollow Cathode family devices (see the electrical scheme in Fig. 14): heater, keeper and target power supplies.

The same target power supply was used for NccA/300 and NccA/5000 devices; it has the following characteristics: 1.2 kV DC, 10 A DC.

The heater and keeper power supplies differs with the device models, due to the requested power levels. Therefore for the Heated Orificed Hollow Cathode family we have the following power supplies:

- *Heater power supply*: AC supply, 20 kHz, 1.6 - 6.4 A_{rms} nom, 11-13 V_{rms} nom, adjustable at steps of 0.1 A_{rms}.

- *Keeper power supply*: two types of power supplies have been used:
  * constant power 7-40 W power supply; DC bias of 200-300 V for ignition start
  * a 70 V DC, 30 A DC supply, current driven, controlled at step of 0.1 A.

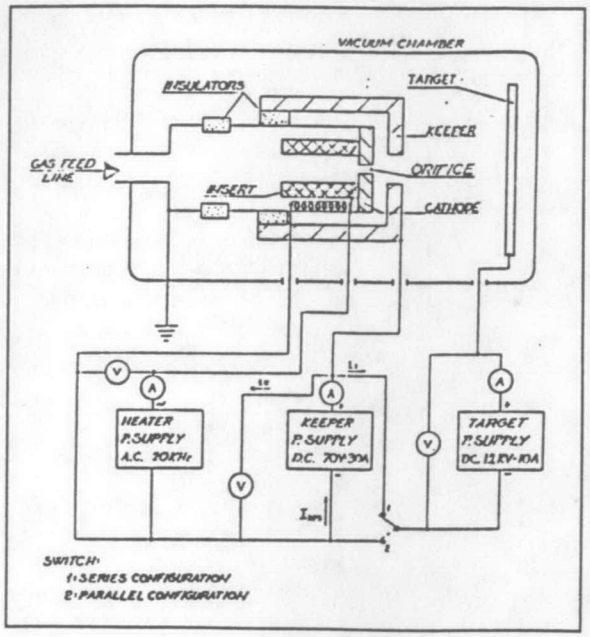

Fig. 14: Power supplies connections to device type NccA/5000

In the case of not-heated plasma contactor test only the discharge (keeper) power supply is used for the device operation. In this case however a suitable switch is foreseen in the electrical scheme to perform the commutation of the discharge from the first anode to the second anode.

Control Unit

A personal computer drives the entire set-up during all operations and performs data acquisition. This function has been done using the Lab Windows (copyright of National Instruments) software and an Electronic Interface Unit manufactured by Proel.

This set-up permits, in fully automation, the igniting of the discharge, the setting of the desired parameters and the performing of current-voltage characteristics internal (cathode-keeper) and onto an external target. The acquired data can be stored in files ready for the analysis.

The block scheme of the system is shown in Fig. 15.

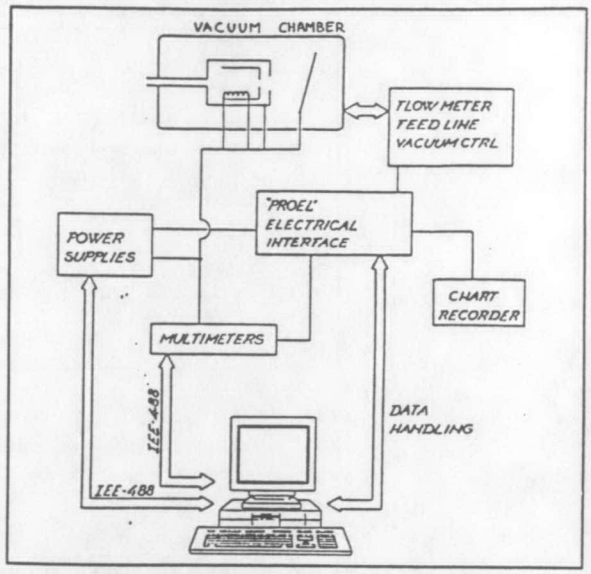

Fig. 15: Block scheme of the Power supply and Control Unit

Plasma diagnostic tools

The tools for investigating and measuring the discharge plasma and plasma plume parameters are basically the following:

- Langmuir probes and retarding potential analyzer, for the qualitative measurement of the plasma density, plasma potential and electron temperature.
- Emission and absorption spectroscopy for the measurement of the electron temperature, the ion/neutral density ratio and the detection of contaminants in the plasma discharge.
- Microwave interferometry for the measurement of the plasma density.
- Multi-element target for the measurement of current distribution in the plasma beam.
- Single target for current-voltage characterization.

All these tools are presently under development / installation in the test facility.

Preliminary results

A consistent test activity is ongoing at Proel Laboratories on Plasma Contactor devices. This activity is performed under a contract with Italian Space Agency and foresees:

a) Plasma Contactor characterization (discharge current/voltage characteristics at different gas flow rates and power consumptions, start-up parameters measurements, operating temperature etc.).

b) Plasma Contactor behaviour respect to a target (electron collection / emission measurements).

c) Test of two Plasma Contactor faced one to the other, one used as electron emitter, the other as electron collector).

d) Test of a plasma Contactor operating in a simulated ionospheric plasma, generated by a Kaufman source.

In the following some preliminary results concerning points a) and b) are presented. The tests c) and d) are currently ongoing.

A typical Volt-Ampere characteristic for NccA/10000 device, orificed heated type, is shown in fig. 16.

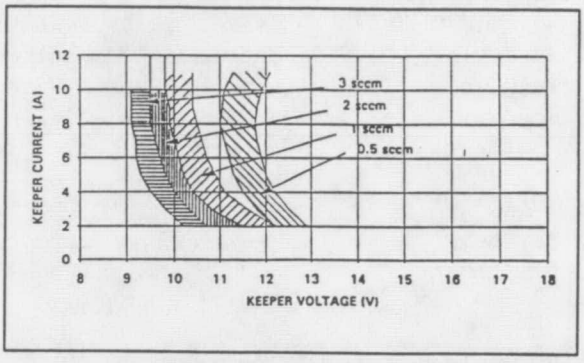

Fig. 16: Volt-Ampere internal characteristic (cathode-keeper) for orificed heated hollow cathode type NccA/10000 at different Xe gas flow rate (0.5 to 3 sccm)

As can be seen, it is possible to obtain internal discharge currents of 10 A, with low voltage drop between cathode and keeper. Controlling the Xe flow rate it is possible to reduce / increase the keeper voltage (at constant current).

The behaviour with respect to a target of the same Plasma Contactor device is shown in fig. 17.

In this figure a comparison is made between series configuration, which means keeper connected to ground and parallel configuration (cathode grounded) at 1 and 2 sccm.

As can be seen that to obtain electron currents of the order of 10 A it is necessary to have a gas flow rate of at least of 2 sccm.

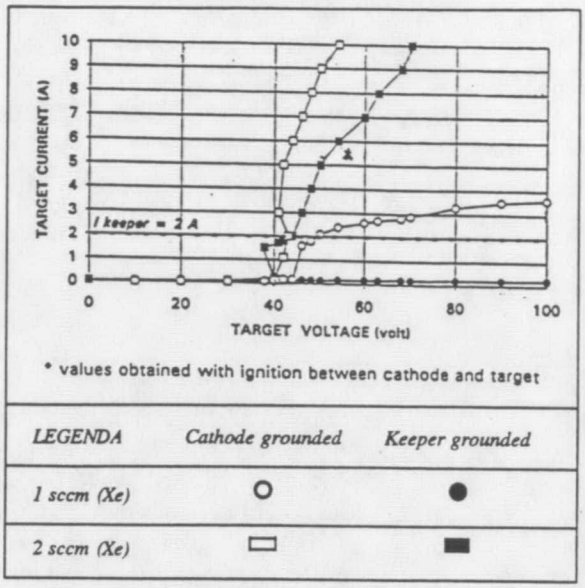

Fig. 17: Comparison between series and parallel configuration. Target distance 15 cm; pressure between 4 10^{-5} and 8 10^{-5} mbar

Flight experiments for technology validation

For the validation/performance characterization of the plasma contactor technology PROEL has proposed two experiments within european in-flight demonstration programmes.

The first experiment (named PLACEX) was proposed within the ESA in-orbit TDP (Technology Demonstration Programme) and was due to be flown on the ARTEP platform. The experiment envisaged the test of the capability of the plasma contactor device to discharge both the spacecraft frame and samples of different materials, typical of to day spacecraft technology. Being the foreseen orbit for ARTEP a GTO (Geosyn. Transf. Orbit) the demonstration of the plasma contactor technology was been conceived for an extremely variable space environment, ranging from LEO to GEO.

The second experiment, named PLEGPAY, was proposed within the Columbus Precursor Flight Programme and was initially studied for installation on EURECA 2. The main goals of PLEGPAY experiment were: the validation of the plasma contactor performances through current-voltage characteristics and the verification of the plasma contactor as a charge control device under artificially induced spacecraft charging (using both a continuous and modulated electron beam emission).

Both PLACEX and PLEGPAY experiments were technically approved and included in the priority list for experiments to be flown.

Unfortunately the TDP programme did not receive the expected economical support from the Italian

Delegation, so at the moment there are not concrete prospectives to fly PLACEX.

On the other side PLEGPAY experiment on EURECA 2 seems to be no more feasible due to the extreme uncertainty of EURECA re-flights, after EURECA 1. However there could be good opportunity for the experiment flight on a different carrier, such as the russian MIR.

Conclusions

A Plasma Contactor family capable of current exchange also higher than 10A has been developed. Engineering Models of these devices, in the heated version, are currently under test showing good results. These Plasma Contactor devices can operate with low gas flow rate (0.5 sccm to 2 sccm as a function of needed current exchange) and low power consumption (7 to 80 W).

Moreover a new family of plasma contactor devices, based on not-heated hollow cathode, has been developed and its operating concept has been successfully demonstrated.

Two flight experiments for the validation of the device operation in the space environment have been proposed by Proel to Italian Space Agency and European Space Agency, all of them have been technically approved.

A flight experiment is expected to take place in the near future on board a russian space vehicle.

References

[1] *M. Martinez Sanchez, D.E. Hastings, " A System study of a 100KW electrodynamic tether", Journal of Astronautical Science vol 35 n. 1 Jan-Mar 1987 pp 75-96.*

[2] *M.J. Patterson, " Hollow cathode based plasma contactor experiments for electrodynamic tether" AIAA 87-0572.*

[3] *G. Vannaroni et al, "Hollow cathode experiments to support electrodynamic tether applications", CNR-IFSI, IFSI-89-5, March 1989.*

[4] *P.A. Robinson, P. Coakley, "Spacecraft Charging, progress in the study of dielectrics and plasmas", IEEE Transactions on Electrical Insulation vol 27 n. 5, October 1992.*

[5] *W.D. Deininger, G. Aston, L.C. Pless "Hollow cathode plasma source for active spacecraft charge control", Rev Sci.Instrum. 58 (6), June 1987.*

[6] *R.C:. Olsen, "Experiments in charge control of Geosynchronous Orbit - ATS-5 and ATS-6", Journal of Spacecraft vol 22 n. 3, 1985.*

[7] *A. Pedersen, "Plasma diagnostics by electron guns and electric field probes on ISEE-1", Space Science Dept. ESA-ESTEC Noordwijk.*

[8] *C.K. Purvis, H.B. Garrett, A.C. Whittlesey, N.J. Stevens, "Design guidelines for assessing and controlling spacecraft charging effects", NASA Technical paper # 2361, September 1984.*

[9] *Ferguson D.C., Snyder D.B., Carruth R., "Evaluation of impacts of Space Station Freedom grounding configurations", Workshop of the Space Station Freedom plasma interactions and effects working group, May 22-24, 1990.*

[10] *"Device with not-heated hollow cathode for the dynamic generation of plasma" Proel Patent FI91A44, 4.3.1991.*

[11] *"Metodo e dispositivo per l'estrazione di elettroni da un veicolo spaziale" Proel Patent pending.*

[12] *"Electron Gun Device for Controlling the Potential of a Body in space" Proel Patent n. 91830525.1 extended to Europe.*

[13] *C. Popovici, M. Somesan, V. Nistor Ann. Physics 19,225 (1967).*

[14] *W.T. Elwell, J.A.F. Gidley "Atomic Absorption Spectrophotometry", Pergamon Press, 1966.*

[15] *C.M. Fevreira, J.L. Delcroix "Theory of Hollow Cathode arc", J. of Appl. Physics 49, 2380 (1978).*