The Development of the ESA-XX Ion Thruster

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ABSTRACT

The ESA-XX ion thruster is a large (25 cm diameter) ion thruster designed to operate at high thrust (200 mN) for deep space and orbit raising applications. The current version of the thruster is based on a re-design of the previous Phase 1 thruster and makes use of a number of design improvements, most noticeably in the geometry of the extraction grid system. This paper summarises the results of the Phase 1 test programme, showing the performance potential of the thruster. The paper also describes the re-design of the thruster, its current status and the future test programme.

1. INTRODUCTION

The ESA-XX ion thruster is being developed jointly by a number of European companies under the auspices of the European Space Agency. The thruster is designed to provide the propulsion requirements for future interplanetary space missions as well as for applications in Earth orbit where substantial thrust is required. The thruster is a synergy of two European ion propulsion technologies, combining the discharge chamber of the radio-frequency ionisation thruster, the RIT-35, with the extraction grid system of the electron bombardment thruster, the UK-25. This combination has the advantage of replacing the discharge hollow cathode with the electrodeless discharge of the RIT-35 while keeping the higher perveance of the UK-25's molybdenum extraction grids.

In the first phase of the development programme the thruster successfully demonstrated operation over a wide range of thrusts up to 200 mN. In addition, this operation was achieved with low discharge power losses and high ion extraction efficiency and propellant utilisation. Typically, the thruster operated with an electrical efficiency in excess of 80% at a spezific power of 30 W/mN. Examination of the thruster after operation during this phase of the programme, however, showed that considerable erosion of the extraction grid system had occurred. This erosion was a consequence of direct ion impingement on both the accelerator (accel) and decelerator (decel) grids and was particularly severe near the edges of the grids, where the discharge plasma density was relatively low.

At the start of the second phase of the development programme the thruster was substantially re-designed. This re-design included a change in the thruster discharge chamber material and a modification to the extraction grid system. The grid system was modified in order to eliminate the direct ion impingement observed in previous tests as well as grid arcing that had affected the performance of the grids. The re-design of the ion optics characteristics of the grid system was performed using a computer code, *SAPPHIRE*, that could model in detail the ion extraction and transport processes. In addition, the code was used to calculate the expected grid lifetime resulting from erosion by charge exchange ions.

The paper will start by summarising the performance of the Phase 1 ESA-XX thruster. It will then describe the design and the expected performance of the Phase 2 ESA-XX ion thruster. In particular it will describe the computer calculations used to design the extraction grid system and the results of the lifetime analysis. The paper will also describe the design and fabrication of the thruster discharge vessel and the other thruster subsystems. A detailed description of the Phase 2 test programme will also be given.

2. PERFORMANCE OF THE ESA-XX PHASE 1 THRUSTER

In this section some results from the test of the Phase 1 thruster are briefly reported [1]. The basic performance of radio-frequency ion thrusters is determined by the RF-power consumption as a function of the propellant consumption for different levels of extracted ion beam current. These relationships are shown graphically in Figure 1 for the Phase 1 ESA-XX thruster at thrust

levels of 50, 100, 150, and 200 mN. The dotted lines at the left hand side of the curves are the borderlines for 100 % propellant efficiency. The plasma ion production cost is in the range of 3.1 to 3.5 W/mN.

One should note that, due to the extraction grid design, the nominal beam voltage of 2.0 kV was applied only for the 150 and 200 mN thrust levels. At the lower thrust levels beam voltages of 1.75 kV and 1.5 kV were used. These lower beam voltages, of course, lead to lower specific impulses for these thrust levels.

An important operational parameter is the accel grid drain current since it is a measure of the likely sputtering of the accel grid. This is important since accel grid erosion is one of the main lifetime limiting aspects of the thruster. The accel grid drain current is composed of two parts, of defocused ions which impinge directly on the grid and of charge exchange ions which are generated in the downstream part of the grid system. The latter are attracted by the negative potential of the accelerator grid. The first part is determined more by the grid geometry, the extraction grid voltages and the plasma density but the rate of generation of charge exchange ions depends mainly on the neutral gas losses and the extracted ion current. In the tests accel grid drain currents of about 2% of the beam current were observed. These increased to about 3% with increased flow rate. These values are somewhat lower than normally experienced by RF ion thrusters but greater than that seen on the UK-25 thruster.

In order to reduce the number of charge exchange ions hitting the accel grid, the influence of a small decel grid bias was studied by applying voltages of up to -50 V to the decel grid. The result of this was that the accel grid drain current fell significantly since some of the charge exchange ions were now attracted to the negative decel grid. A reduction of about 40% to 50% in the accel grid current was observed. It could also be shown that the fall in accel grid current led to a more or less commensurate increase in the decel grid.

The thruster's total power consumption is the sum of the beam power, the discharge power and the neutraliser power but excludes any power conditioning efficiency. The total power consumption is shown in Figure 2 for thrust levels of 50, 100, 150, and 200 mN as a function of the propellant consumption. It can be shown that the measured values e.g. 6.2 kW for the production of 200 mN at a propellant flow of 40 sccm or 3.85 mg/sec are well below the scheduled data. The ESA-XX thruster demonstrates very good efficiencies which are reflected in a beam ion production cost of 30 to 31 W/mN. These values were achieved for thrust levels of 100 to 200 mN whilst at a thrust of 50 mN a value of 26 W/mN was achieved.

Looking in more detail at the thruster's efficiency it turned out that the electrical efficiency depended only weakly on the flow rate and was always well above 80%. The mass utilisation efficiency decreases with increasing flow rate from 90% to 60% depending on the specific thrust level. This gave a total efficiency for the thruster of about 80% for a propellant flow rate of 3.85 mg/sec. Table I summarises the performance characteristics of the ESA-XX Phase 1 thruster at 200 mN thrust.

Table I *ESA-XX Phase 1 performance charasteristics at 200 mN thrust.*

Thrust	200 mN
Beam Voltage	2000 V
Total Power	6.2 kW
Beam Current	2.71 A
Total Efficiency	ca. 80%
Specific Impulse	4500 s
Beam Ion Production Cost	31 W/mN
Propellant Flow Rate	3.85 mg/s
Ion Production Cost	3.1 W/mN
I acc / I beam Ratio	1.5% - 3%

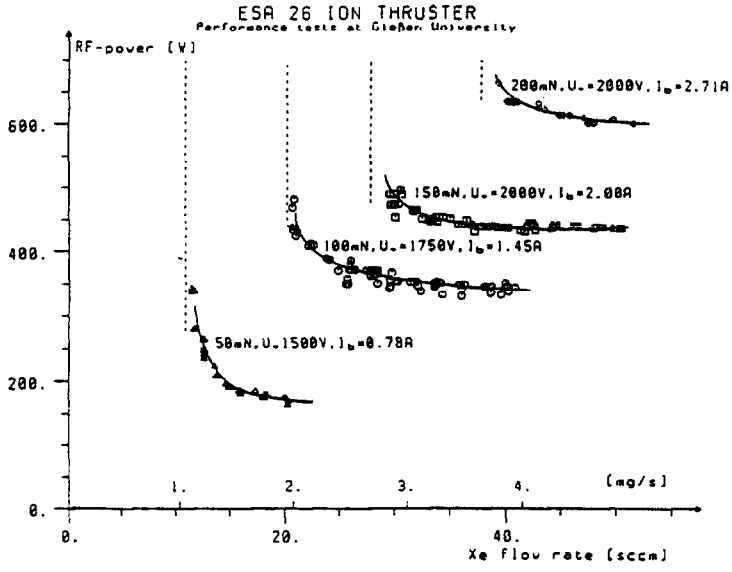

Figure 1. *Basic thruster performance at different thrust levels*

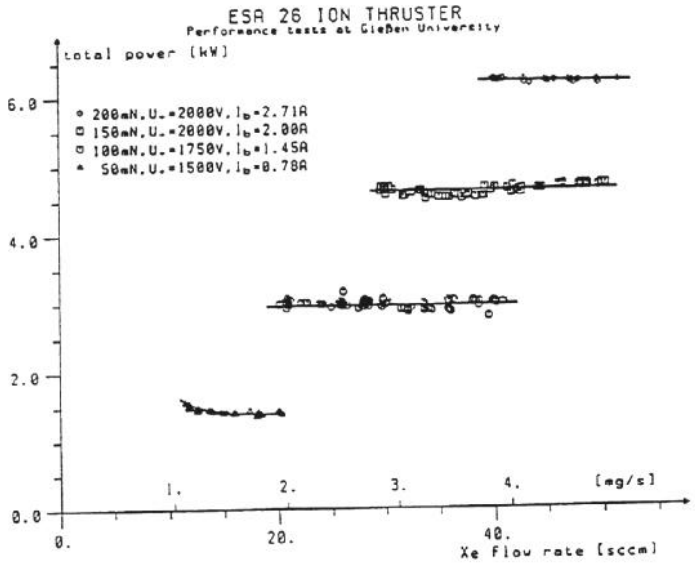

Fig. 2. *Total Power Consumption of the ESA-XX phase 1 engine*

3. PHASE 2 EXTRACTION GRID DESIGN

The results of the Phase 1 experimental programme indicated some problems with the operation of the extraction grid system. The first of these problems was the occurrence of inter-grid arcs at the rim of the grid system which led to the formation of molten 'beads' of material, reducing the screen/accelerator grid gap. The reduction in screen/accelerator grid gap prevented the thruster operating at higher thrusts and eventually curtailed the experimental programme. In the Phase 2 extraction grid design this problem was addressed by increasing the grid separation and making the individual grids of different diameter, thus substantially increasing the breakdown path. Severe arcing is, therefore, not expected to be a problem with the re-designed Phase 2 grid system.

The second problem that occurred with the Phase 1 extraction grid system was grid erosion by direct ion impingement. Examination of the accelerator grid showed very substantial erosion, which increased moving out from the centre to the edge of the perforated area. This took the form of the removal of molybdenum from the downstream part of the barrel and, quite unexpectedly, showed a six-fold symmetry pattern indicating that the effect of neighbouring apertures had clearly influenced the erosion. Figure 3 shows a photograph of the most seriously effected region at the periphery of the accelerator grid. The operating time of the thruster had been short so that charge exchange erosion would have been negligible and the erosion was, therefore, the result of direct impingement. No such impingement has been seen on the 200 mN UK-25 thruster, which was operated for several hundred hours in total. However, similar patterns were reported from a Japanese long duration test [2] and, more recently, evidence of a hexagonal erosion pattern at the periphery of the gird system has been seen on a UK-10 triple grid thruster after operation at very low thrusts of 1-5 mN. Similar erosion was also observed on the decel grid.

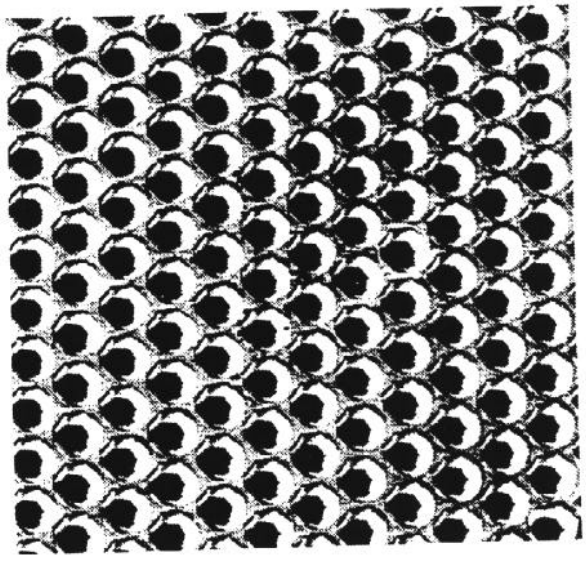

Figure 3. *Photograph showing the erosion of the ESA-XX Phase 1 grid system (down-stream face).*

In order to understand why the Phase 1 extraction grid system was eroded, a series of computer calculations were performed using the ion beam extraction code *SAPPHIRE*. This analysis confirmed that the erosion was due to direct ion impingement and also showed that this occurred largely at low thrust with the full beam voltage. The six-fold symmetry of the eroded distribution was also shown to be due to the interaction of the ion extraction sheaths of individual beamlets at the periphery of the grid system. This effect is described more fully in [3].

Using the *SAPPHIRE* code an optimisation study of the extraction grid system was performed as input to the design of the Phase 2 grid system. This optimisation study was designed to eliminate the effect of direct ion impingement on the grid system as well as attempting

to maximise the lifetime of the system. Figure 4 shows a typical simulation of multiple apertures of the grid system. Because the discharge chamber plasma density profile varied across the discharge vessel it was necessary to perform a series of calculations with different input plasma densities. Determining the plasma density profiles for different thrusts was an important part of the analysis. Table 2 provides a summary of the Phase I and Phase 2 extraction grid parameters. One should note the increase in screen/accel grid separation and the reduced accol grid voltage of the Phase 2 grid design. Figure 5 is a photograph of the Phase 2 grid system.

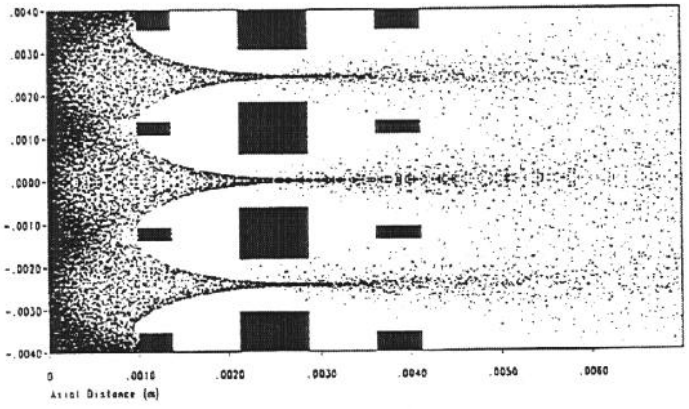

Figure 4 *The primary ion distribution for a multi-aperture simulation of the extraction grid system, calculated using the model.*

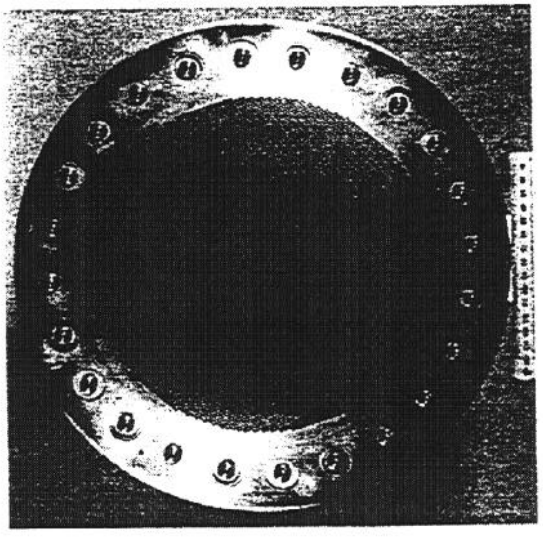

Figure 5. *A photograph of the ESA-XX Phase 2 extraction grid system.*

Table 2 *ESA-XX Phase I and Phase 2 extraction grid characteristiss at 200 mN thrust.*

	Phase 1	Phase 2
Number of Apertures	9097	9097
Beam Voltage [V]	2000	2000
Accel Grid Voltage [V]	-500	-250
Decel Grid Voltage [V]	-50	-50
Screen Thickness [mm]	0,375	0,5
Accel Grid Thickness [mm]	0,75	0,75
Decel Grid Thickness [mm]	0,5	0,375
Screen/Accel Grid Sep. [mm]	0,75	1
Accel/Decel Grid Sep. [mm]	0,75	0,5
Screen Grid Hole Diam. [mm]	2,15	2,15
Accel Grid Hole Diam. [mm]	1,25	1,25
Decel Grid Hole Diam. [mm]	2,15	2,15
Compensation	No	Yes

Calculations of erosion rates for a molybdenum grid system predicted relatively high rates of accelerator grid erosion, which cannot be avoided by acceptable changes in the grid geometry. While the mechanical integrity of the grid system may be secure for more than 8,000 hours of operation, the quantity of sputtered molybdenum which will enter and coat the inside of the discharge chamber is a serious cause for concern. This is because the conductivity of the deposited layer is estimated to be substantially higher than an equivalent mass of carbon, as conventionally used in RF ion thrusters. Calculations were, therefore, repeated for a carbon (graphite) accelerator grid. The rates of erosion are predicted to be some 3-6 times less than equivalent values for the molybdenum accelerator grid. Some caution is needed in considering the predictions because of the experimental uncertainties in the energy and angular variation of the sputter yields which are the basis of the *SAPPHIRE* sputter model.

For a flight version, therefore, a graphite accelerator grid is the preferred option. This grid would be geometrically similar to that used in the Phase 2 grid design but would have a substantially stiffened rim in order to allow for launch vibration. A preliminary vibration analysis has been performed and a feasible manufacturing route has been identified.

4. DESIGN AND MANUFACTURE OF THE PHASE 2 THRUSTER

Figure 6 is a photograph of the ESA-XX thruster and shows the extraction grid system mounted on the alumina discharge vessel (without the RF coils attached). The discharge vessel material was changed from quartz to alumina for Phase 2 because an alumina vessel was easier to fabricate and has much better mechanical properties. Figure 7 shows a cross-section of the thruster system.

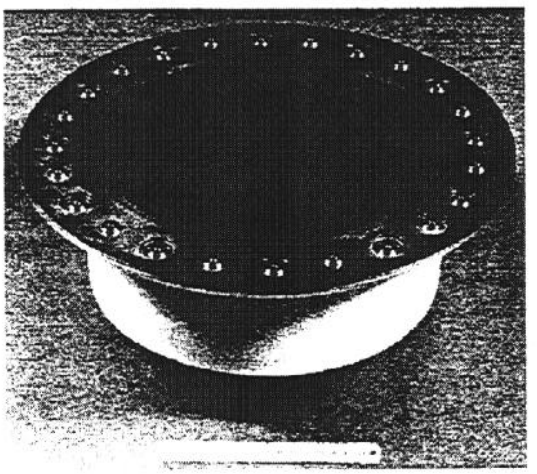

Figure 6 *Photograph of the ESA-XX thruster chamber and attached grid system*

The discharge vessel was manufactured to its basic dimensions before the sintering process was performed. After this the final vessel shape was achieved using a combination of grinding and drilling. The discharge vessel is fixed to the rear flange of the thruster by means of six metal stand-offs which are soldered to the alumina vessel using a special procedure. The extraction grid system is attached to the discharge vessel by means of 24 titanium bolts, fastened at the rear of the vessel flange. Titanium was used for these bolts to minimise differential thermal expansion with the molybdenum grids and the alumina discharge vessel. The electrical connections to the grids are provided for by metal connecting rods, isolated from inside the thruster cavity by alumina tubes.

The ESA-XX ion thruster is a radio-frequency thruster where the plasma source discharge is generated using a radio-Frequency field (of 0.5 MHz frequency) produced by an external RF coil. This coil, which was fabricated by the University of Gießen, is attached to the discharge vessel by Vespel spacers and clips.

5. THRUSTER SUB-SYSTEMS

In the current phase of the development of the ESA-XX ion thruster the emphasis is on the design and development of the thruster system, including the neutraliser supplied by Proel Technologie. At the end of this phase it is anticipated that a detailed understanding of the ope rating and performance envelope of the thruster will have been achieved.

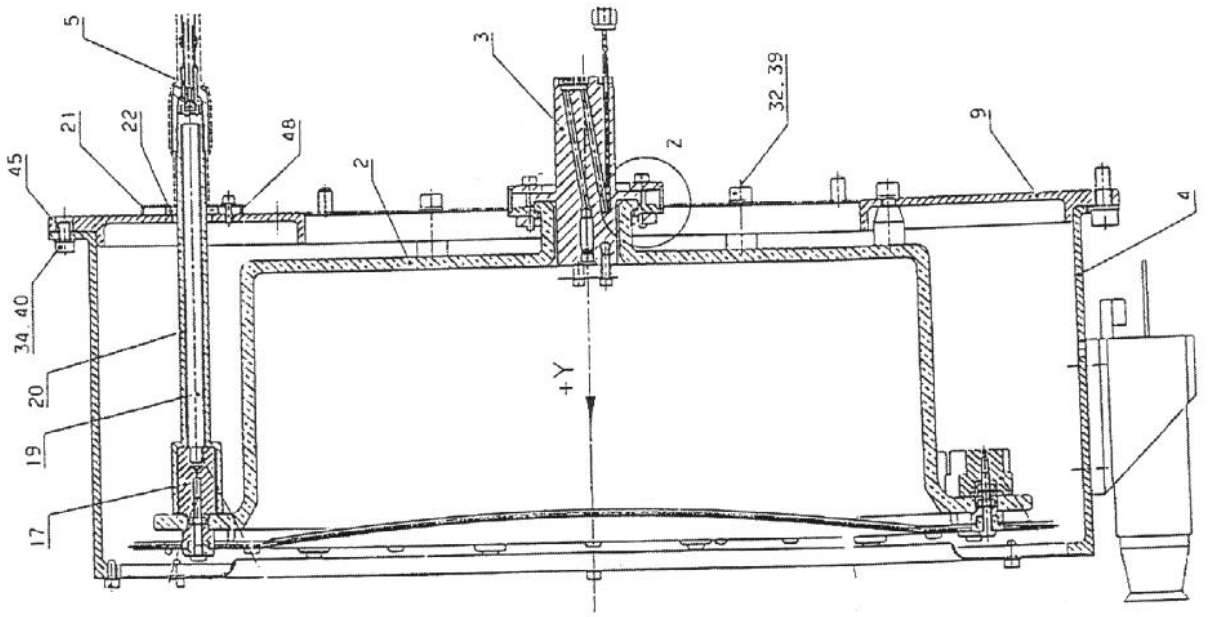

Figure 7. *A cross-section of the ESA-XX thruster.*

In the next phase of the development of the ESA-XX ion propulsion system a number of sub-systems will need to be developed for incorporation into a flight version. For such a version the following sub-systems will be required:

- Power Supply and Control Unit (PSCU), connected to the main spacecraft bus and to the telemetry and command systems. This unit provides the power to the ion beam supply, the discharge RF generator and the extraction grid system.
- RF Generator Unit (RFG). This produces the RF power and feeds the RF coil surrounding the discharge vessel.
- Flow Control Unit (FCU). This provides the xenon propellant feed to the thruster and neutraliser.

Figure 8 is a block diagram of the complete ESA-XX sub-system layout.

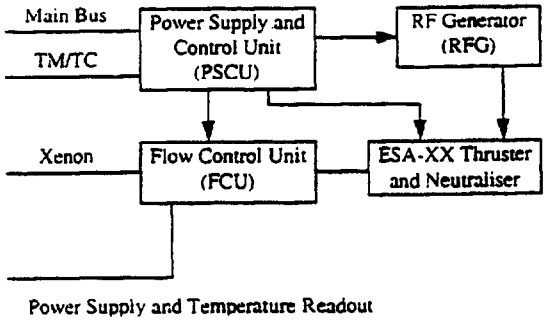

Figure 8. *ESA-XX sub-system block diagram*

The characteristics of the ESA-XX power supplies are shown in Table 3. A schematic of the power system is shown in Figure 9.

6. PHASE 2 EXPERIMENTAL TEST PROGRAMME

The tests on the Phase 2 ESA-XX thruster will be performed in the "JUMBO" Test Facility of the University of Gießen as for the previous tests on the Phase 1 thruster. The ESA-XX thruster will be mounted in a hatch, which can be separated from the main chamber via a gate valve. This allows easy access to the thruster without requiring the complete facility to be brought to atmospheric pressure.

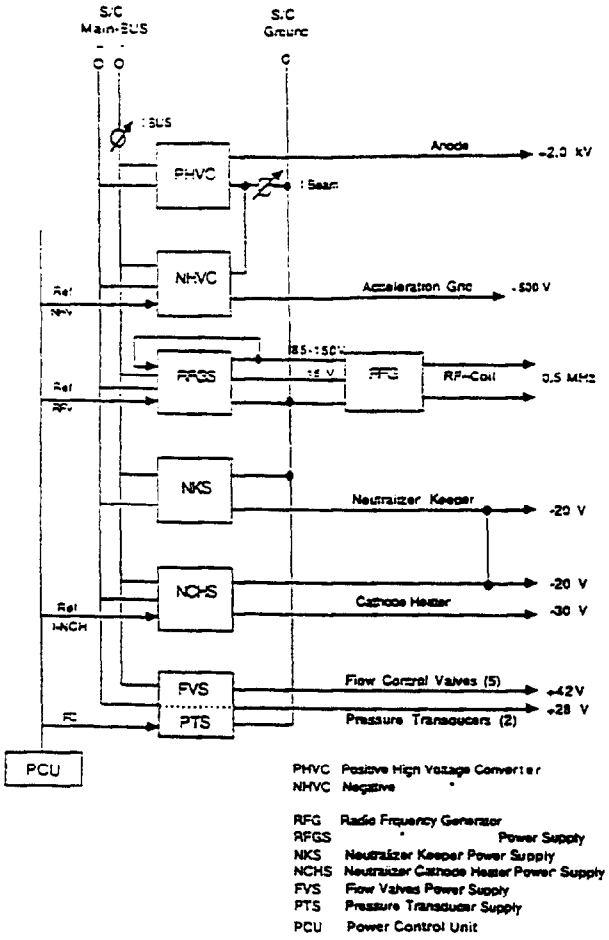

Figure 9. *ESA-XX power system schematic.*

Table 3 *ESA-XX power system characteristics for operation at 200 mN thrust.*

System	Oper. Characteristics
Pos. High Voltage Converter	2000 V 3.5 A
Neg. High Voltage Converter	-200 to -600 V 60 mA
RF Generator Power Supply	85 V to 150 V 1100 W
RF Generator	1000 W 0.5 MHz
Neutralizer Keeper Supply	200 V 3.5 mA/5 W
Neutral. Cath. Heater Supply	11 V(ac) 4 A
Valve Supply	42 V
Pressure Transducer Supply	28 V

A block diagram of the test facility used for this test is shown in Figure 10 indicating the position of the thruster in the thruster hatch and the position of the beam diagnostic system in the main chamber. For the operati-

on of the ESA-XX thruster laboratory power supplies will be used for the high voltages, the RF power and neutraliser supply. For the propellant supply commercial flow controllers will be used for the main and the neutraliser branch fed by a common high pressure xenon supply tank. The performance data will be monitored and recorded by a purpose-built data acquisition system which takes all relevant thruster parameters, the measured temperatures and the values of the beam diagnostics. Figure 11 is a sketch demonstrating the power and propellant supply setup which will be used for the tests on the ESA-XX.

The tests programme envisages the following steps:

- A grid conditioning phase at the beginning of the tests.
- Complete performance mapping at different thrust levels.
- Study of the temperature distribution / thermal properties of the engine
- Ion beam diagnostics to determine the beam characteristics.

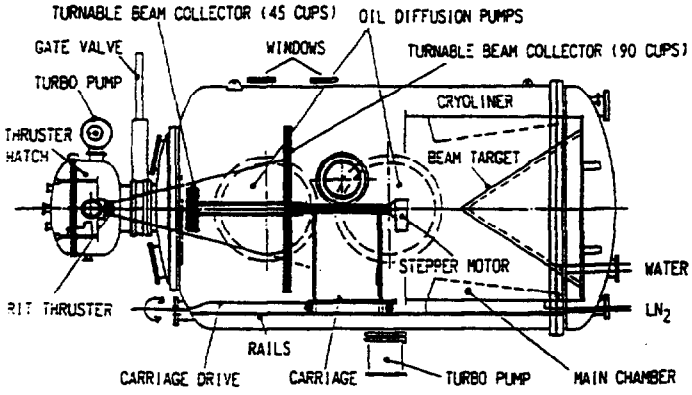

Figure 10. *Sketch of the Giessen Ion Thruster Test Facility.*

The grid conditioning will be carried out only once when the new thruster is put into operation for the first time. A special procedure will be applied increasing the high voltages to the grid system step by step until the grids keep the full voltage.

After this phase, the regular performance mapping will be started measuring the ion beam current, the accel

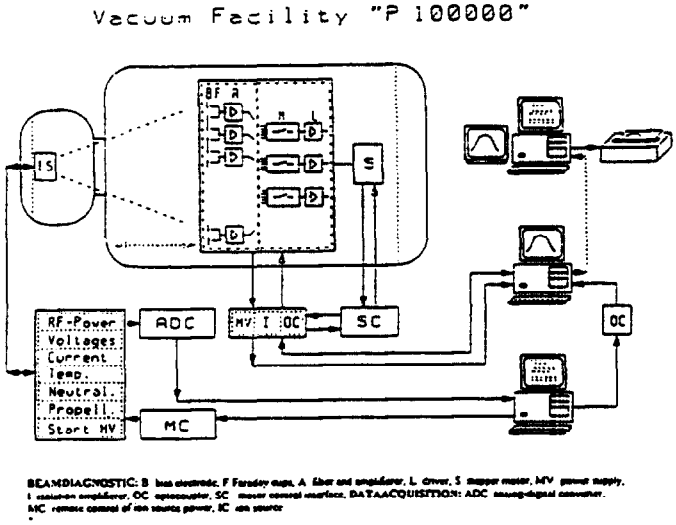

Figure 11. *Power and propellant supply circuits and diagnostics for the tests on the ESA-XX thruster.*

grid drain current and RF-power consumption as a function of the propellant consumption. This procedure will be repeated for different thrust levels which are presently planned at 50, 100, 150, and 200 mN.

Partly in parallel to the performance mapping, partly separately the temperature distribution in the thruster at different power levels will be determined. For that, 8 temperature sensors are placed e.g. at the grid system, the discharge vessel, the RF-coil and the neutraliser. Equilibrium temperatures at different thruster power levels will be recorded as well as some temperature gradients.

The available beam diagnostic device will be used to determine the mechanical beam parameters as there are the beam divergence and the thrust vector. These parameters will be studied for different thrust levels and it will be checked whether the thruster temperature influences the thrust vector.

The goal of this test programme is to evaluate the properties of the Phase 2 ESA-XX engine completely.

9. SUMMARY AND CONCLUSIONS

The development of the ESA-XX ion thruster is now well into its second phase. Lessons from the Phase 1 programme have been learnt and modifications have been made to the Phase 2 design. A detailed experimental programme will start in the next few months

where the operation of the thruster will be investigated in detail. This will allow the performance envelope of the thruster to be full characterised and its potential advantages for future missions to be understood. The ESA-XX development programme will provide Europe with an ion thruster propulsion system of high specific impulse and thrust for applications in future deep space and earth orbit missions.

10. REFERENCES

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