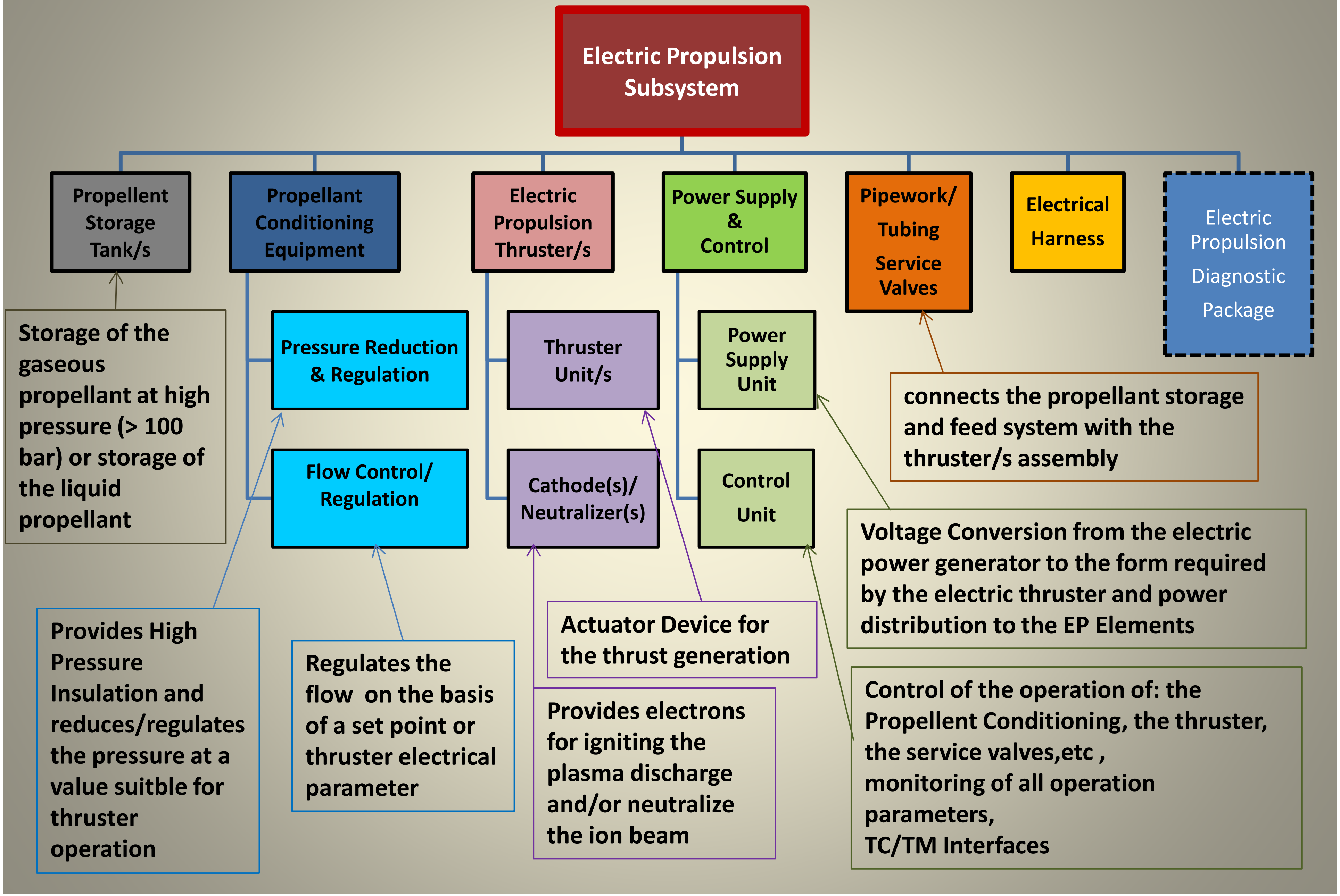
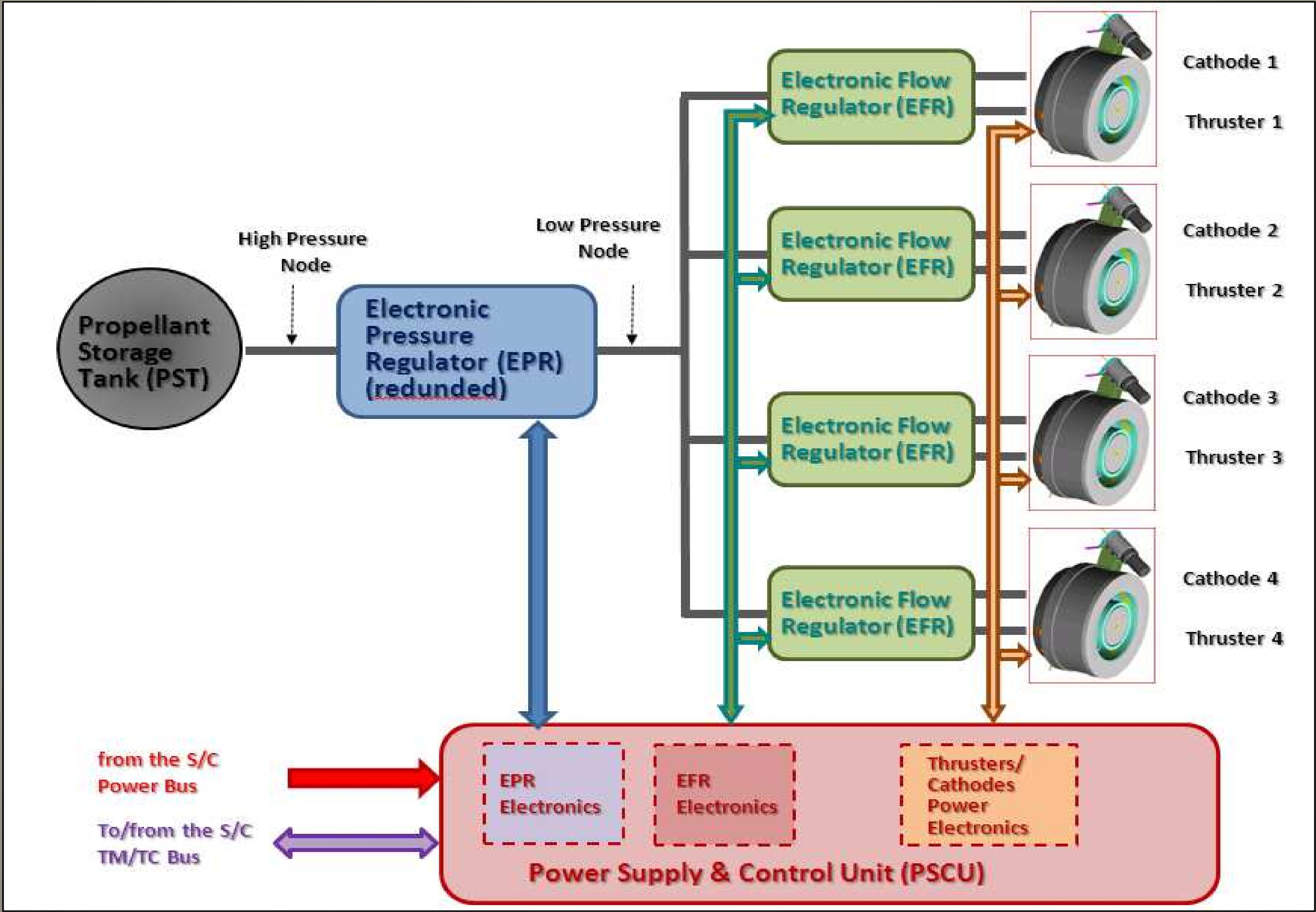
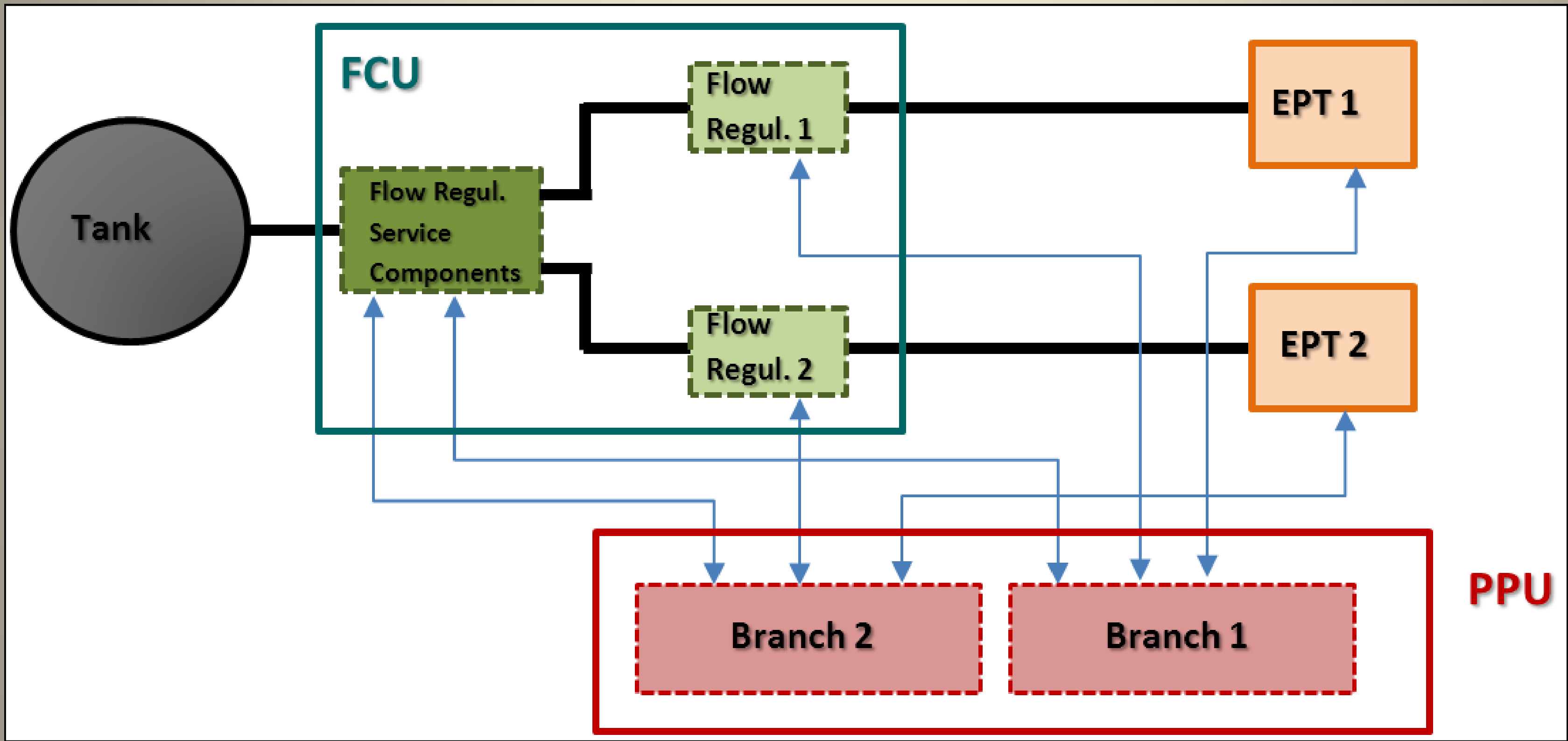
Major Elements/Units of an Electric Propulsion (EP) Sub-System



Possible architectural schemes fo an EP sub-system: 4 thrusters configuration with double stage propellant conditioning

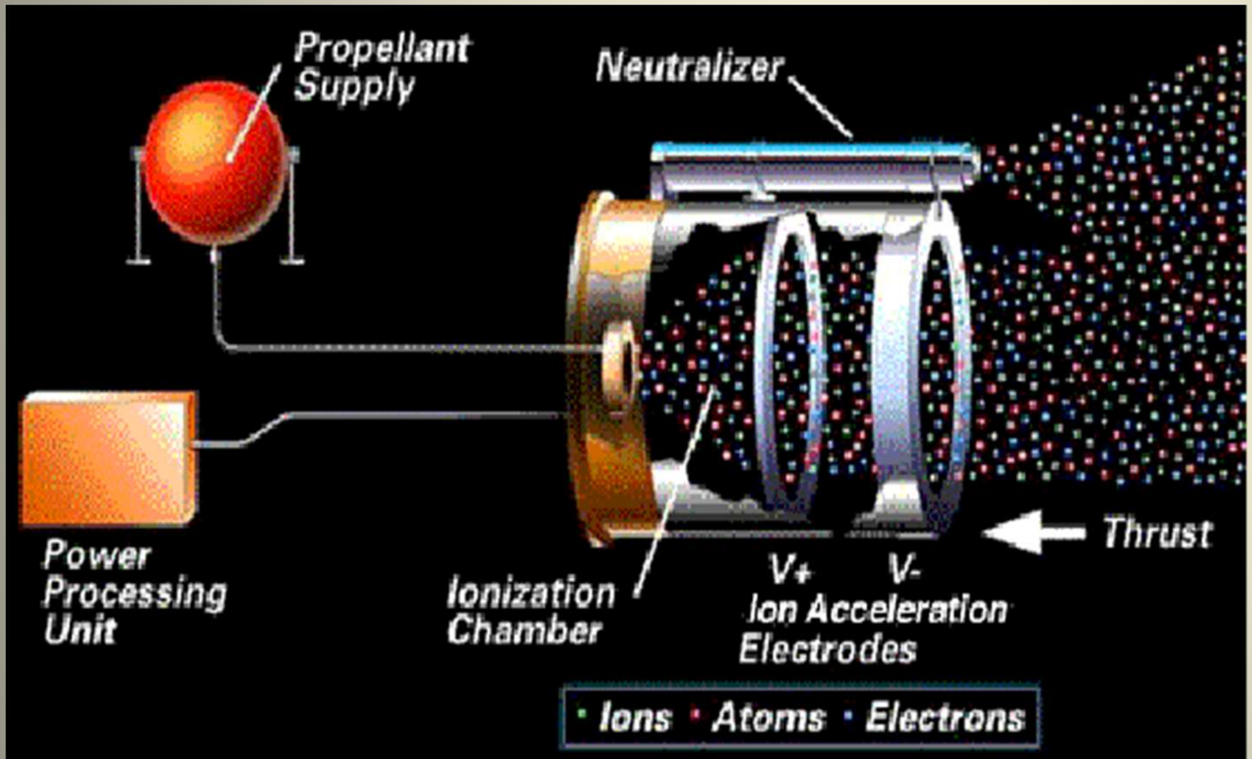


Possible architectural schemes for an EP sub-system: 2 thrusters configuration with flow regulation directly interfaced to the high pressure (single-stage regulation)



Electrostatic Propulsion: Gridded Ion Engine (GIE) Concept

In a GIE the propellant is ionized within a "Ionization Chamber" and then accelerated by electrostatic fields generated by High Voltage Biased Grids. Ions in the beam are neutralized by an electron cloud provided by the "neutralizer"



The thrust density is limited by space charge limited current density:

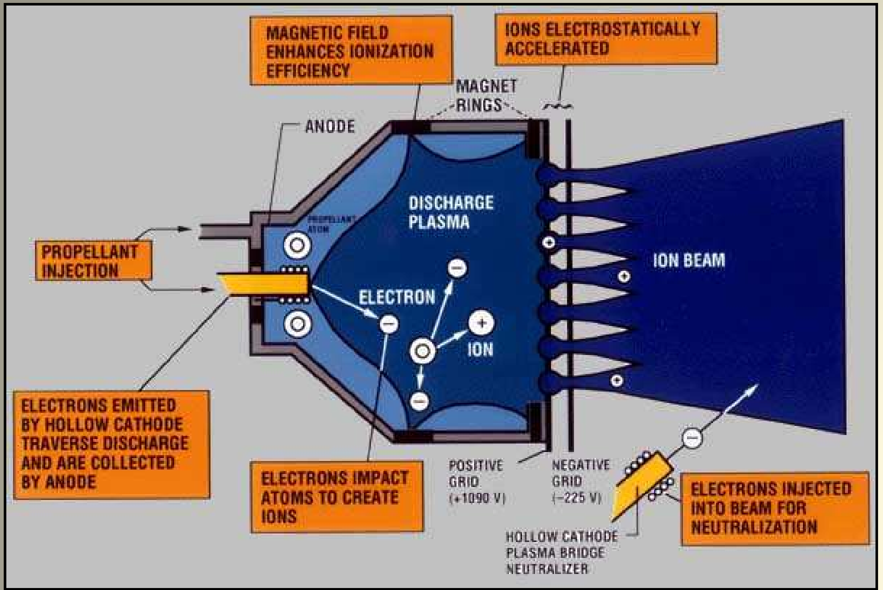
$$j = \frac{4\varepsilon}{9}\left(\frac{2q}{M}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

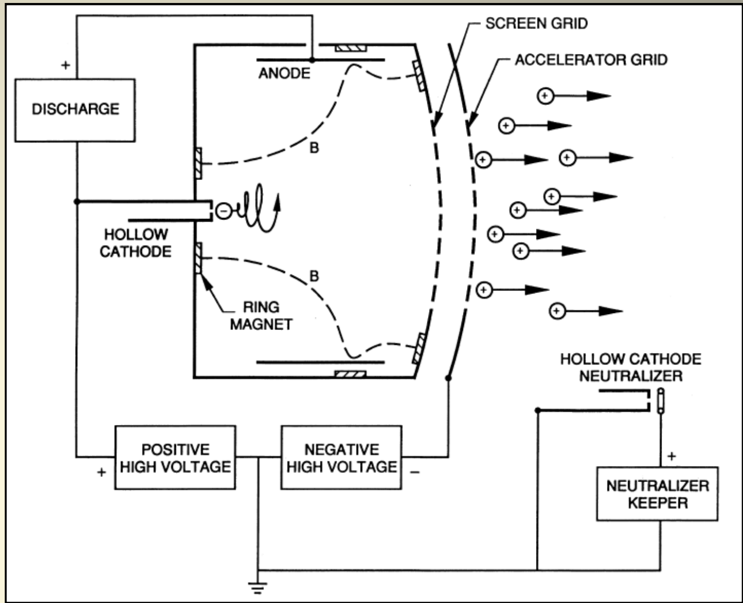
Is is proportional to √V
typical Is range from 1500 to 5000 s
efficiency is from 40%to 60%

Typical propellants: **Xe, Ar, Kr**

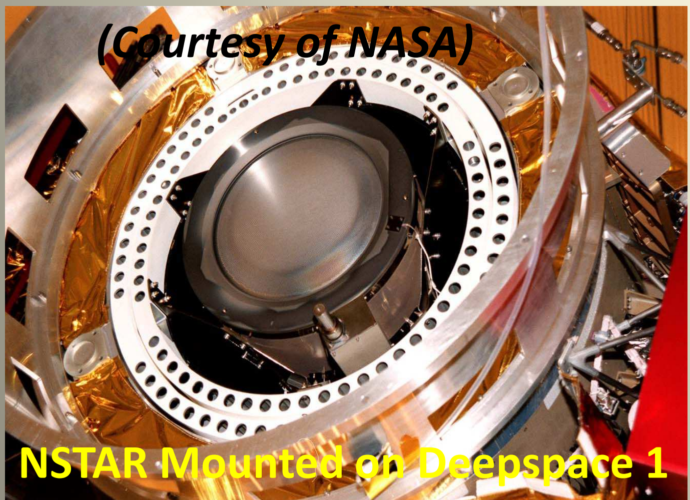
Electrostatic Propulsion: GIE, Kaufman type

In a GIE Kaufman the propellant is ionized by a DC discharge established between a cathode and an anode in the discharge chamber





Magnetic conditioning is necessary to increase the electron mean free path and thus ionization probability


(Courtesy of NASA)
NSTAR Mounted on Deepspace 1

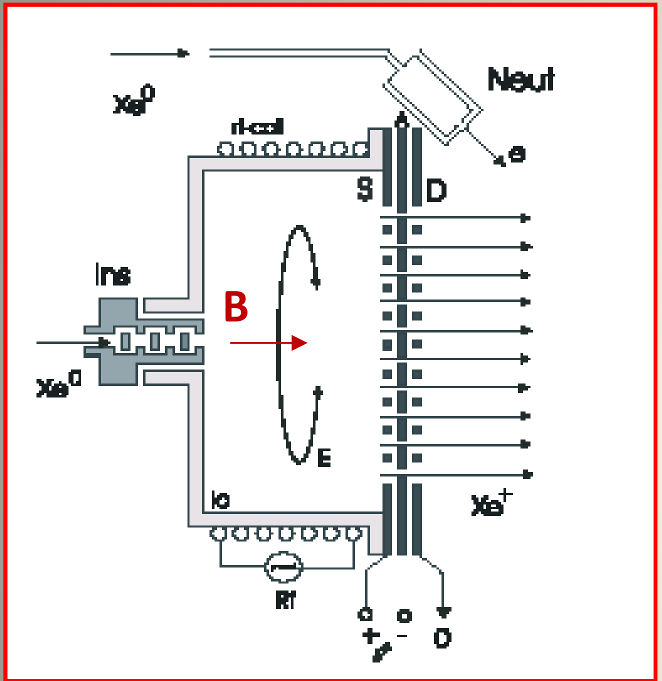

(Courtesy of Qinetiq)
T6 Ion Thruster (QinetiQ)

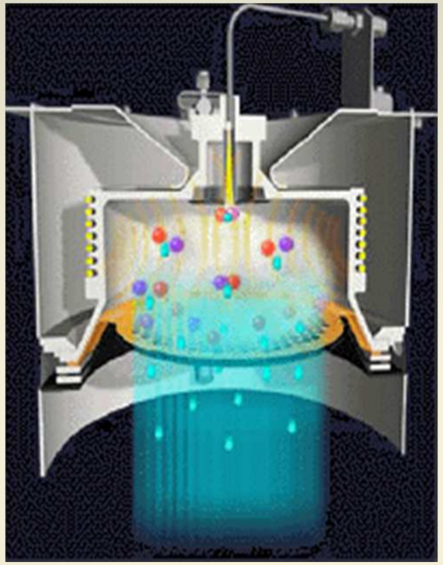
Flown on:
- BSC satellites (HS-601) and Deepspace-1
- Japanese ETS VI, COMETS, ETS VIII
- ARTEMIS;

will fly on BepiColombo

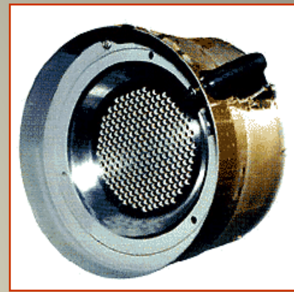
Electrostatic Propulsion: GIE, RF type

In a GIE RF ion creation is achieved by pumping a RF radiation into the discharge chamber





RIT-22



RIT-10 flown on ARTEMIS

Typical frequencies used in RF ion thrusters are in the range of **1 MHz**

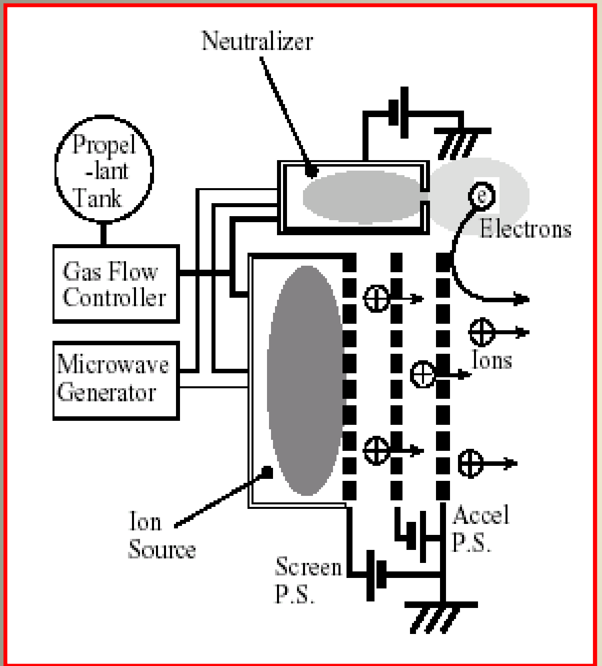
(Courtesy of EADS Astrium)

In the RIT systems a RF coil induces an axial magnetic field. The primary magnetic field (axial) induces by Maxwells Law a secondary circular electric field (azimuthal) from which free electrons gain the energy for impact ionization

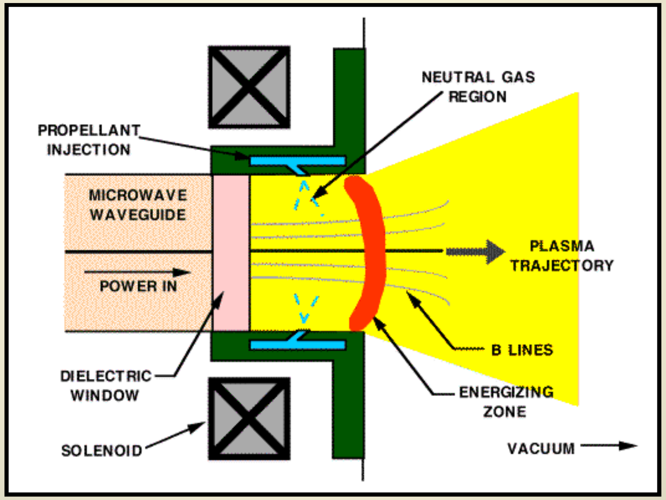
The electrons, however, don’t see the oscillating component of the electric field

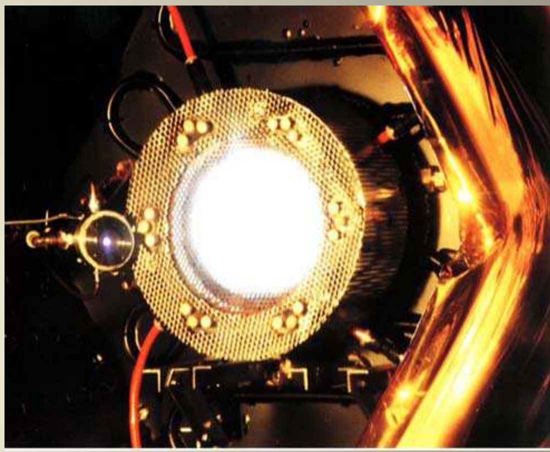
Electrostatic Propulsion: GIE, ECR microwave

In a ECR (Electron Cyclotron Resonance) microwave ion creation is achieved by pumping a microwave radiation into the discharge chamber



Electrons trapped in the magnetic field rotate at a frequency: $\mathbf{f = eB/(2\pi m_e)}$





(Courtesy of MELCO)

μ-Wave Ion Thruster for MUSES-C

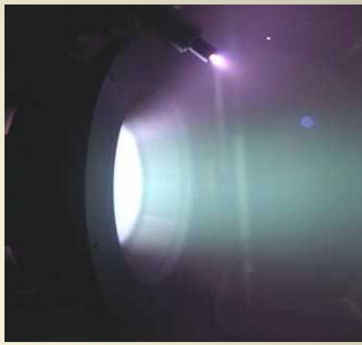
Plasma production relies heavily on an energizing process of electrons trapped by the ECR process (magnetically trapped electrons resonantly absorb electric field oscillation perpendicular to magnetic field and energize the gyro motions)

Electrostatic Propulsion: RMT Radiofrequency with magnetic Field Ion Thruster

The RMT technology (thrust range **2-12 mN**) uses a RF discharge, in the **VHF** range, (≈**150 MHz**) in conjunction with a low level (~ **100 Gauss**) **static magnetic field**. This configuration allows the excitation of resonance phenomena in the plasma, which are exploited to enhance the ionization efficiency,

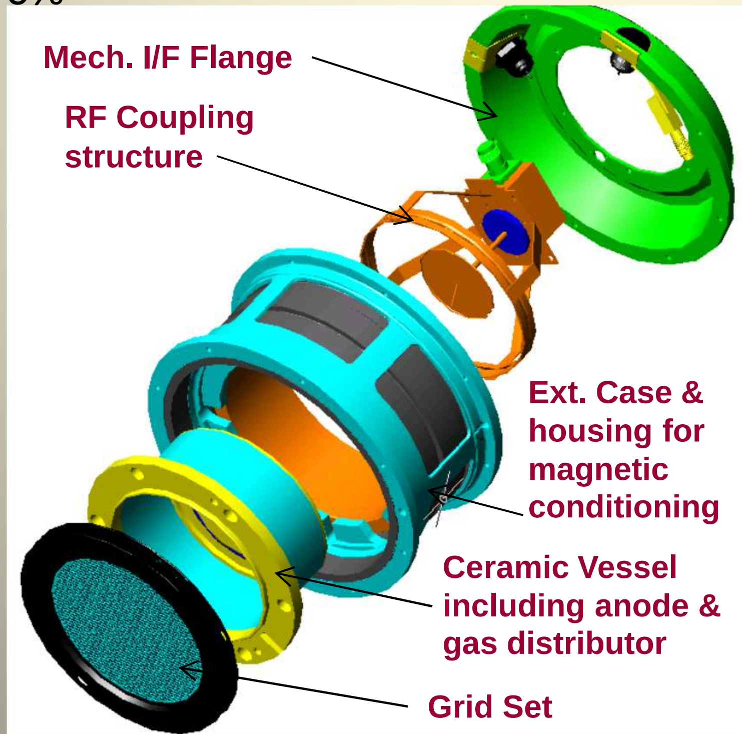
Radiofrequency Generator Unit RFGU

- Output power up to 90 W
- Frequency range: 146 to 154 MHz
- Control voltage: 0-28 V
- Efficiency : 70%



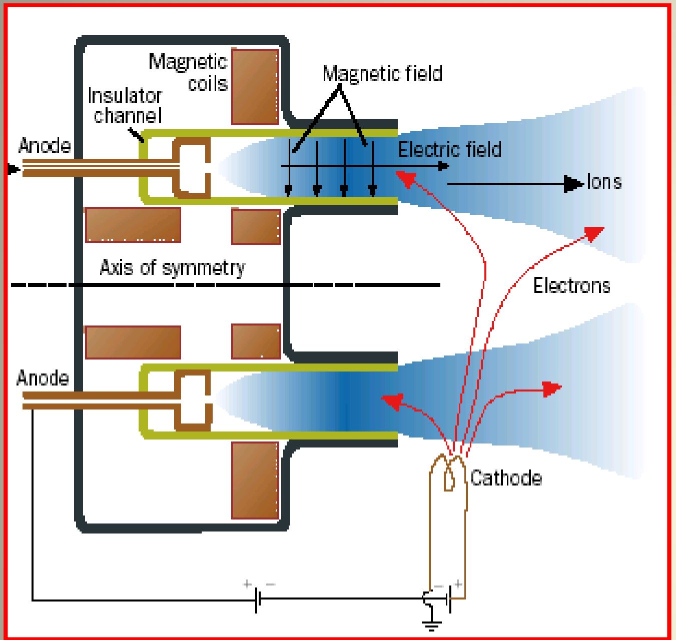
Courtesy of former LABEN/Proel

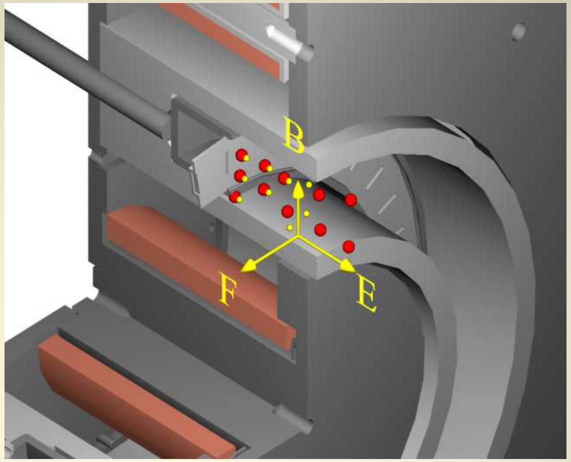
Development performed with strong cooperation with the University of Florence Electronics Dept **Laboratiorio Ultrasuoni e controlli non distruttivi**

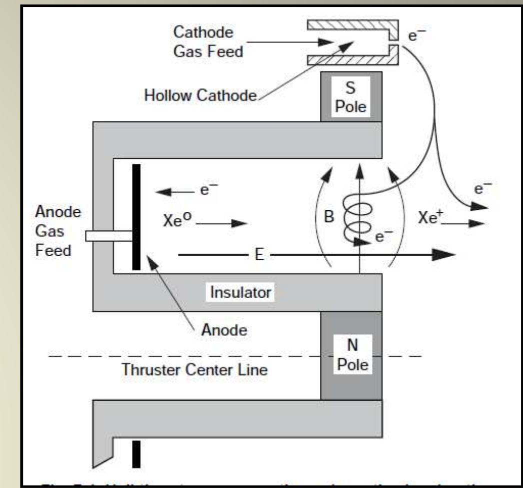


Electrostatic Propulsion: Hall Effect Thruster (HET) (1/2)

In a HET the neutral plasma acceleration is due to the interactions between magnetic fields and "Hall" currents







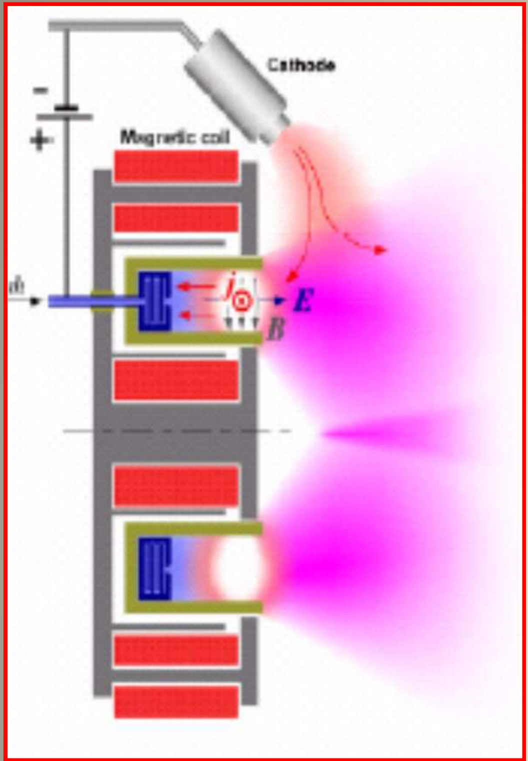
Ion acceleration occurs in the plasma region near the channel exit, space charge does not limit the ion current density and the thrust density can be higher than that achievable in gridded ion thrusters.

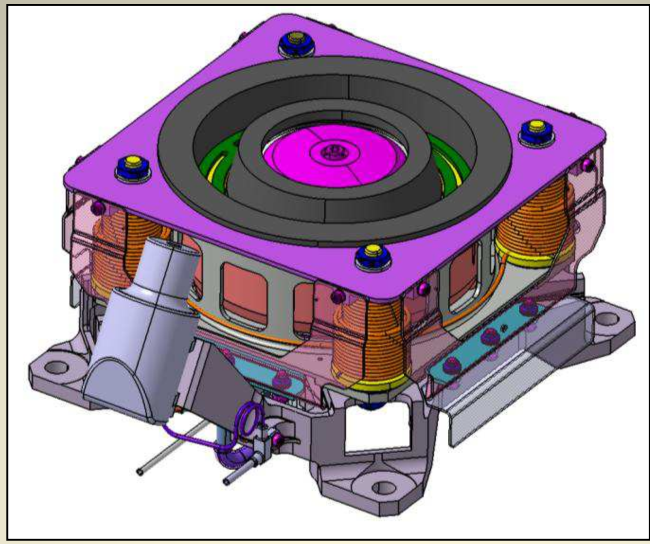
$$\underline{v}_{e\theta} = \frac{\underline{E} x \underline{B}}{B^2} \qquad \underline{j}_{e\theta} = n_e e \underline{v}_{e\theta}$$

In a HET, due to a radial magnetic field electrons, are forced to execute an Azimuthal drift (Hall Current). The magnetic field acts as an impedance to the flow of electrons to the anode, resulting in an electric field in the plasma (perpendicular to both the Hall current and the magnetic field) and points axially out of the thruster

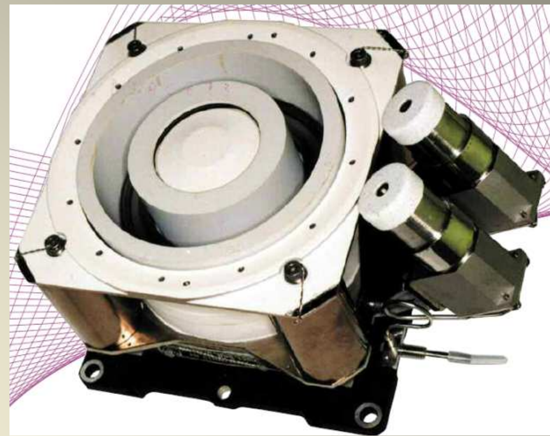
The plasma acceleration is established by a body force arising from the **interaction of the magnetic field with the Hall current** (ions are unaffected by the magnetic field are accelerated along the axis)

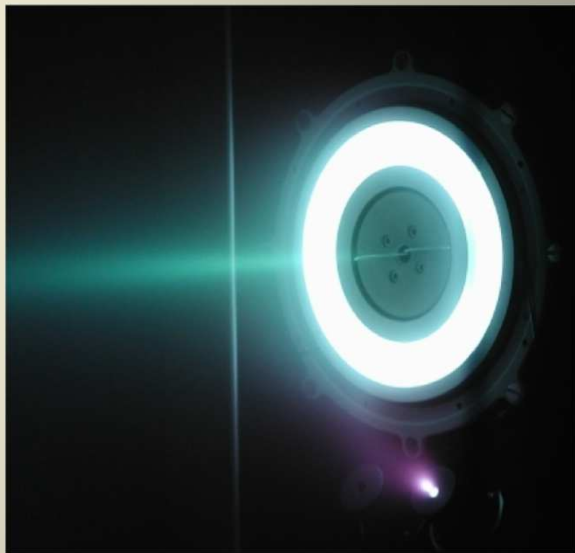
Electrostatic Propulsion: Hall Effect Thruster (HET) (2/2)





3D view of the PPS®NG thruster
(Courtesy of SNECMA)





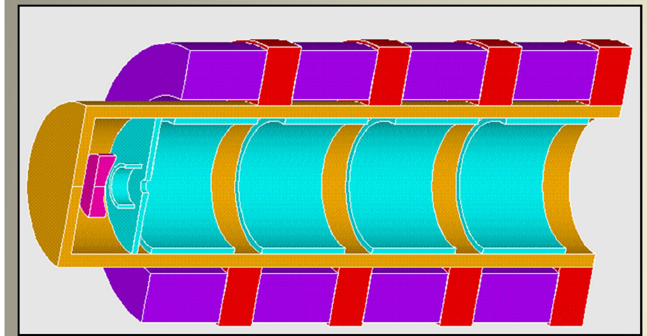
Flown on a large number of Russian satellites sice 80's (Meteor, Kosmos, Gals, Express)and on SMART-1
It is flying on Alphasat and will fly on Small GEO

In a traditional HET the discharge chamber is made of insulating material; this material should be able to provide secondary electrons to enhance the plasma discharge

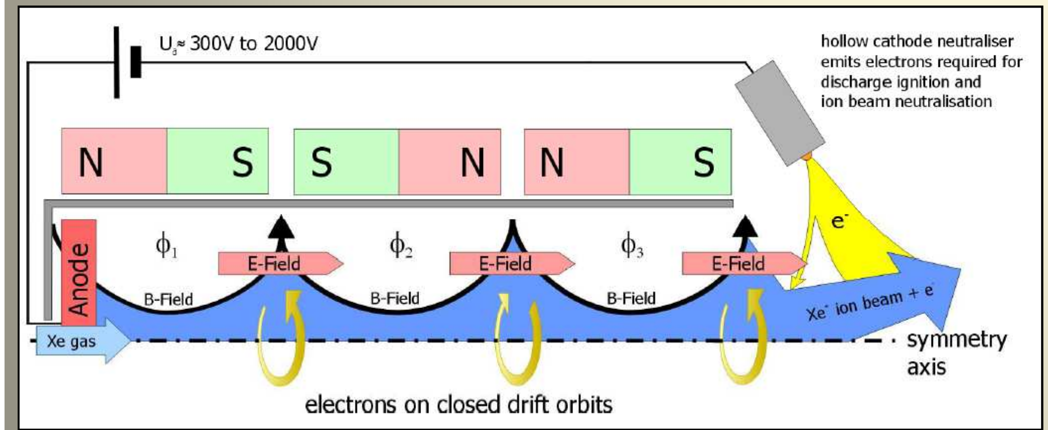
Electrostatic Propulsion: High Efficiency Multistage Plasma Thruster

A periodic permanent magnet structure focuses the Xe plasma, on the axis and thus prevents losses on the ionisation chamber wall.

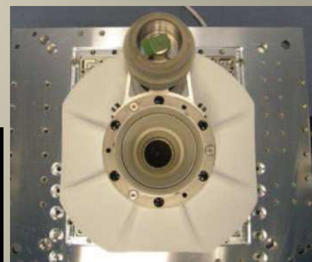
- **The applied plasma potentials ϕi between the Cusps decrease towards the exit. The resulting electrical fields accelerate the Xe ions.**
- **A neutraliser provides at the exit the electrons for neutralisation of the ion beam current**



Electron movement towards the thruster anode is strongly impeded by the magnetic field topology to form **steep electrical field gradients** for effective ion acceleration



Radial magnet fields; axial electric fields



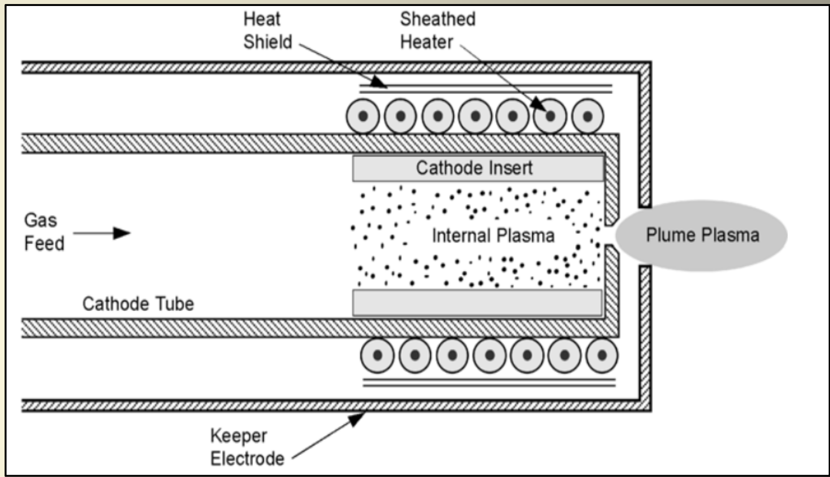
Cathode/Neutralizer: Functions & Features

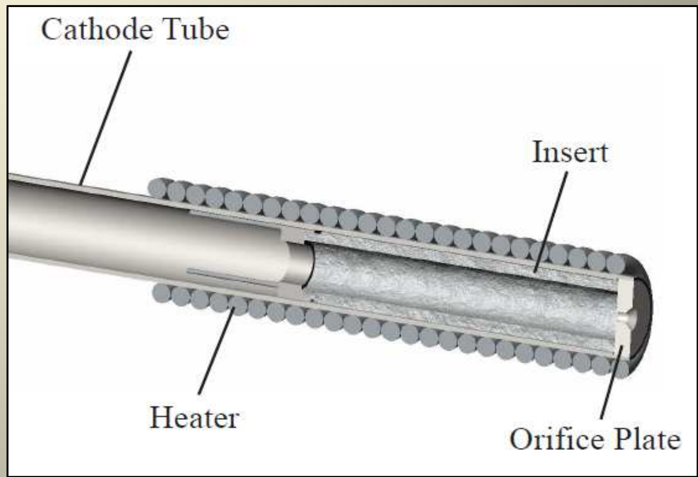
Cathode/Neutralizer within an EP system: what for?

- Provide neutralization electrons to **counter-balance positive charge in the ion beam**
- Provide primary electrons for **igniting the Ionization RF discharge in RF GIE**
- Provide electrons **to ignite and sustain the plasma discharge in a HET**

Requiered features

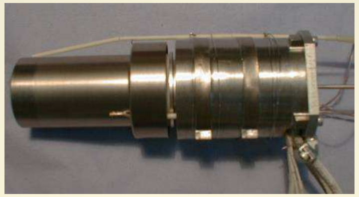
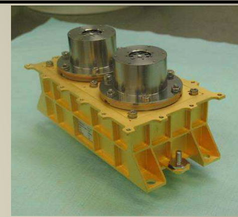
- **High Lifetime** capability and high reliability (avoid redundancy).
- Provide the required electron current at a propellant **mass flow rate** (into the cathode) **as low as possible** (impacts on the Is of the thruster)
- Limit the "**floating potential**" which affects the net accelerating voltage (and again the **Is**)
- **Low heating power** for containing the complexity and cost of the Power Supply & Control Unit
- **Limited hardware complexity**, which, impacts the overall EP system competitiveness and reliability.



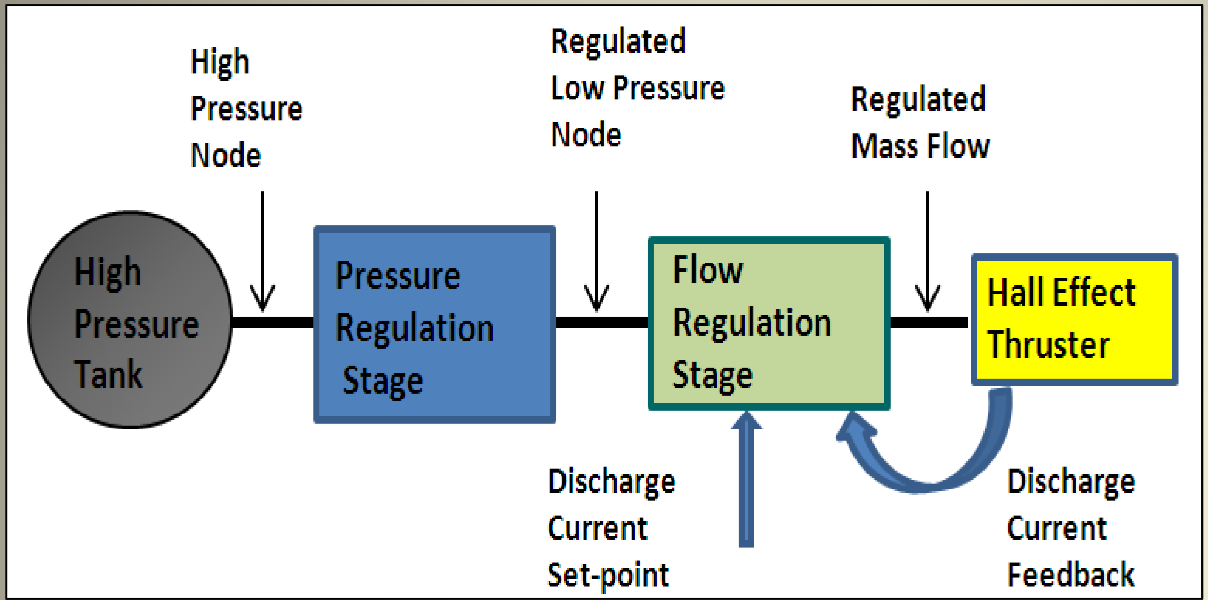


Cathode/Neutralizer Product Family *(Courtesy of TAS-I and Selex ES)*

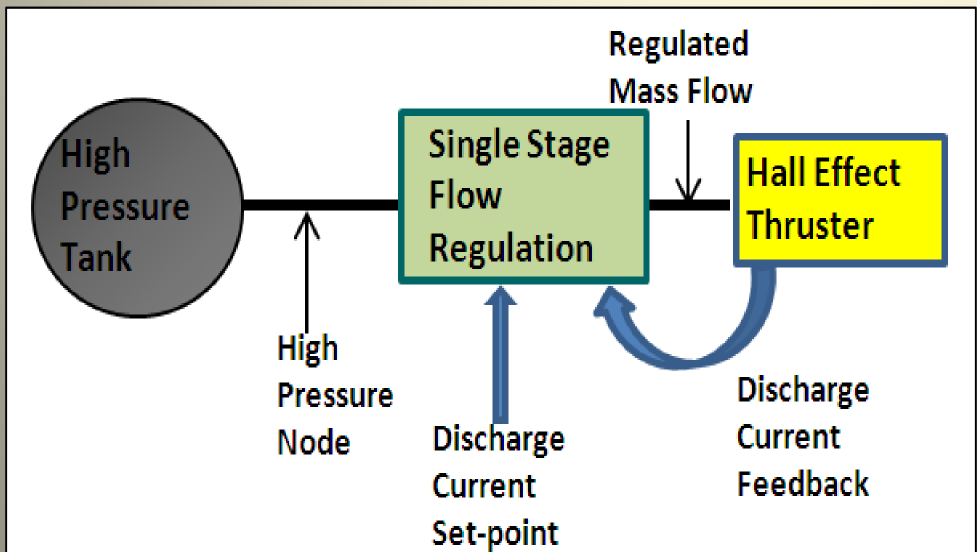
A family of Cathode/Neutralizer Devices has been developed in Italy over a time frame of about 20 years

NccA 1000 model	NccA 5000 model	NccA 15000 model	Mini HET HCA	Neutralizer Ass.y
RIT-10	**PPS 1350, SPT 100**	**PPS 5000, RIT XT**	**100-400 W HET**	**Cs and In FEEP**
Flown on ARTEMIS	Flown on the ISS	Tested in Lab	Tested in Lab	Developed FM
				
Heating pow.: < 20 W	Heating pow.: < 60 W	Heating pow: < 100W	Heating pow: < 20 W	Heating pow: < 7 W
Heating-up time: < 3 min	Heating-up time: < 6 min	Heating-up time: < 10 min	Heating-up time: < 5 min	Heating-up time: < 10 min
Gas flow rate: 0.02-0.1 mg/s	Gas flow rate: 0.1-0.5 mg/s	Gas flow rate: 0.3-0.8 mg/s	Gas flow rate: 0.1-0.2 mg/s	No gas Flow Thermionic Emission
Discharge curr.: 0.5 to 1 A Electron current: up to 0.8A	Discharge curr.: 2 to 5 A Electron current: up to 4 A	Discharge curr.: 5 to 20 A Electron current: up to 8 A	Discharge curr.: 0.3 to 2 A Electron current: up to 1.5A	Extracted Electron Current: 6 mA
Mass: 60 g	Mass: 110 g	Mass: 130 g	Mass: 90 g	Mass: <150 g
Dimenions: 105x37x37 mm	Dimenions: 82x32x32mm	Dimenions: 90x42x42 mm	Dimenions: 100x40x40 mm	Dimenions: ϕ 40 x 45 mm

Propellant Management/Conditioning: Double Stage vs. Single Stage flow regulation



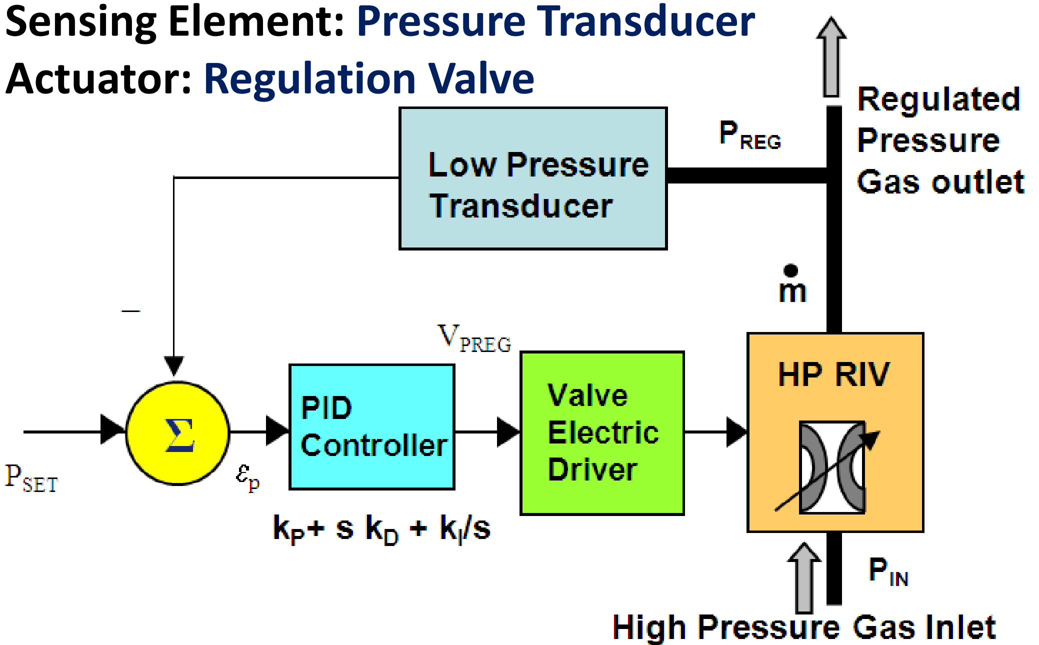
Propellant management line based on an upstream **Pressure Regulator** and on a downstream **Flow Regulator** operating with a regulated low pressure at its inlet port



Propellant management line based on a **Single Stage Flow Regulator** operating with a high pressure at its inlet port

Pressure and Flow Electronic Regulation Control Loops

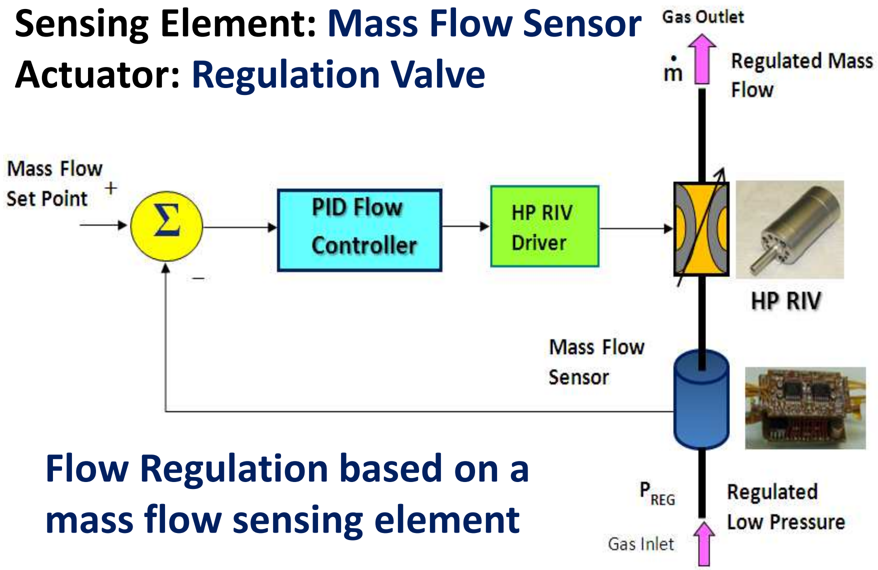
Sensing Element: Pressure Transducer
Actuator: Regulation Valve



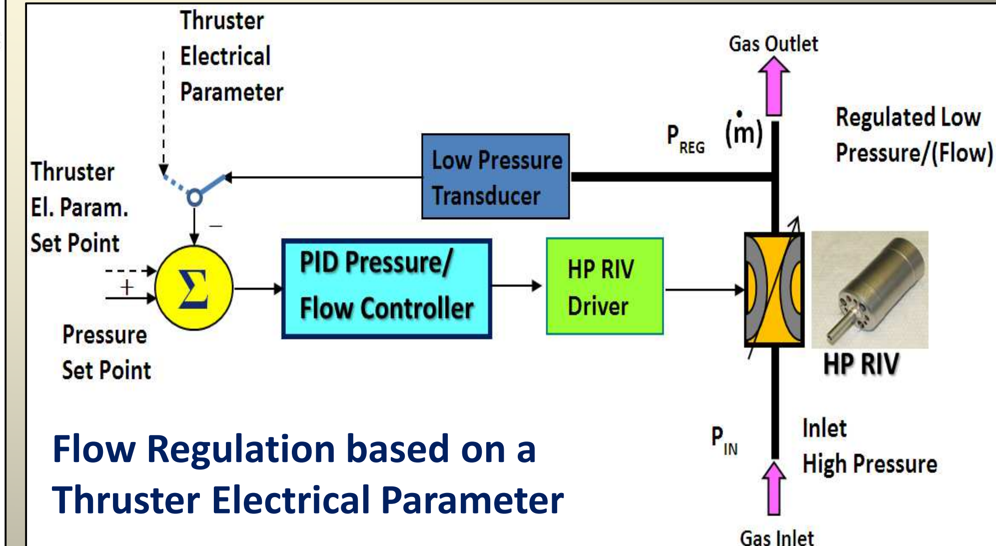
Regulation Valve:
It is a valve for which the actual exit orifice can be progressively varied from valve fully closed to valve fully open

Sensing Element: thruster parameter (e.g. beam current)
Actuator: Regulation Valve

Sensing Element: Mass Flow Sensor
Actuator: Regulation Valve



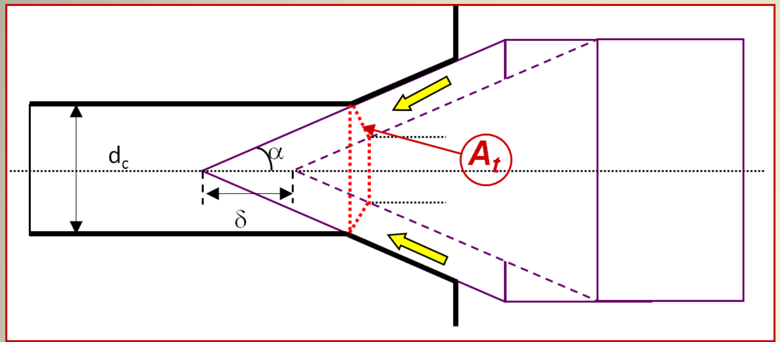
Flow Regulation based on a mass flow sensing element



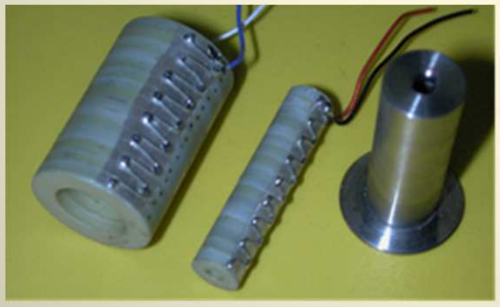
Flow Regulation based on a Thruster Electrical Parameter

Key Element of the Electronic Pressure and Flow Regulator: High Pressure Regulation & Insulation (Piezo) Valve (HP RIV) *(Courtesy of TAS-I and Selex ES)*

Normally Closed when powered off
Compatib. with Xe, N_2; Ar, Kr, He



$$A_t = \pi \cdot \delta \cdot \sin\alpha \cdot (d_c - \delta \cdot \sin\alpha \cdot \cos\alpha)$$



Component qualified in the frame of a Contract with ESA

HP RIV used as actutor of the control whose Sensing Element is:

- **Pressure Transducer for Pressure Regulation**
- **Mass Flow Sensor or I_D for Flow Regulation**

HP RIV main elements:

- Actuator: **Piezo -ceramic** stack
- **Antagonist S-shaped spring** & piezo "return" spring
- **Plunger** moved by the piezo mechanism
- **Polymeric Seat** containing the exit orifice
- **Heating provisions** (for Xe at P_{IN}> than 40 bar)
- Electric /Fluidic I/Fs

Power consumption:

Pin > 40 bar (Xe):	2.54 W (heater) + 0.3 W (piezo)
Pin < 40 bar:	0.3 W (piezo)

Mass flow rate:

0 25 mg/s GXe

Inlet pressure (P_{IN}) :

Nominal operating pressure:	150 bar abs.
Proof pressure:	225 bar abs.
Burst pressure:	375 bar abs.

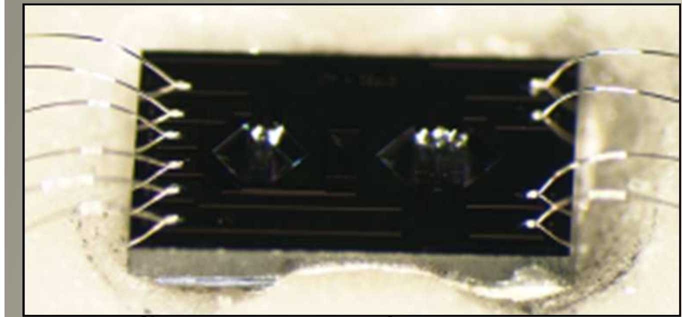
Leakage:

Internal leakage @ nom. P_{IN}:< 10^{-6} sccs
External leakage @ nom. P_{IN} :< 10^{-7} sccs

Main dimensions & mass:

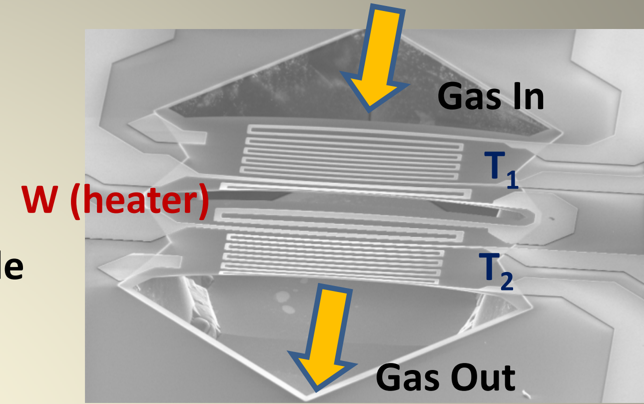
Dimensions	33 Φ mm x 61 mm
Mass:	<200 g

Flow Sensing Element: Mass Flow Sensor (MFS) *(Courtesy of Selex ES)*

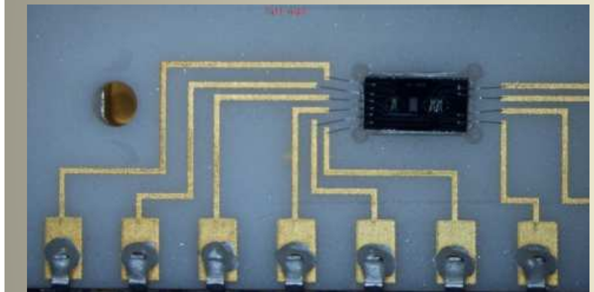


MFS flow sensing element (collaboration with FBK Trento)

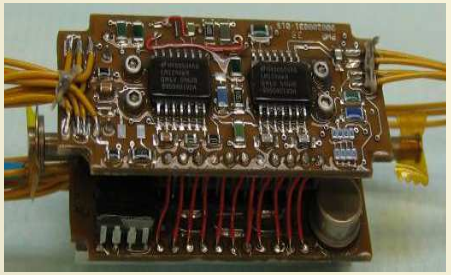
Mass Flow obtained from the measurement of the "ΔT" in presence of the mass flow, between two temperature sensors, while a constant amount of power is provided in between.



$$W = m_{dot} C_p \Delta T,$$



Sensing element mounted on the Al_2O_3 support



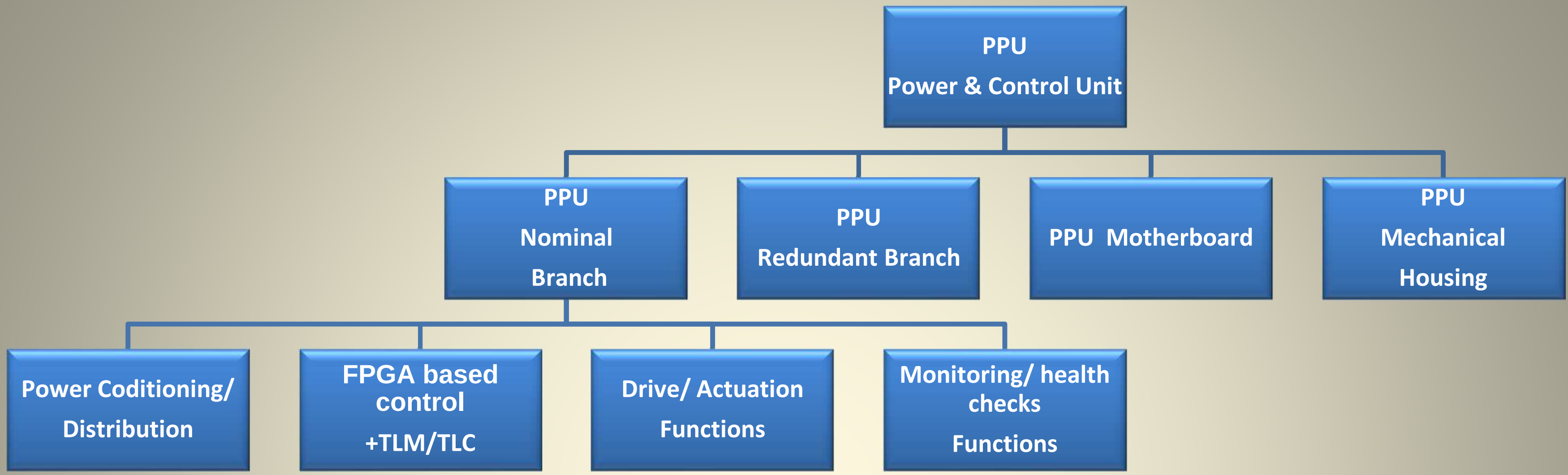
MFS assembly with Front End Electronics (FEE)

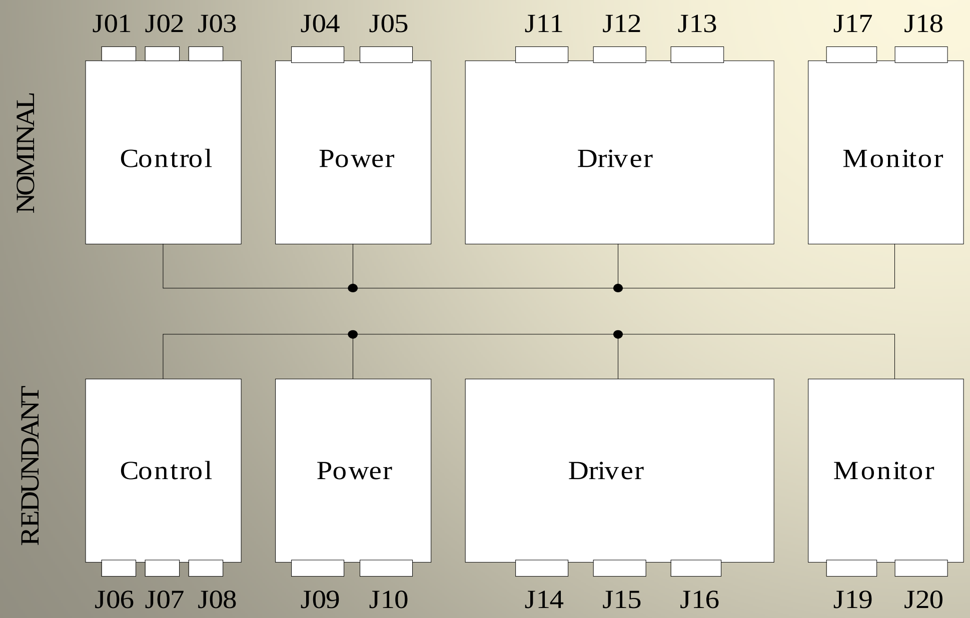
The major elements of the MFS are:

- **Si chip, packaged and bonded on the Al_2O_3 support**
- **Al_2O_3 support with Au tracks,**
- **Fluidic assembly with a plastic cover glued on top in order to provide a closed path for the gas flow**
- **Input/output fluidic connections**
- **Double Board FEE for the MFS electronic conditioning**

Inlet pressure
Nominal Operating (MEOP) : 0 to 2 bar
Proof : 6 bar
Burst : 12 bar
Leakage
External leakage @ nom. inlet pressure :< 10^{-6} sccs GHe
Flow rate @ nominal inlet pressure
For CGP Applications with N_2:0.005 to 5 mg/s
For EP applications with Xe: 0.05 to 25 mg/s
Main dimensions & mass
width: 34 mm
length: 57 mm
mass: < 90 g
Power Consumption. few mW
Tme response about 10 ms
Sensitivity 0.1 sccm
Accuracy 1% of flow

Power Supply & Control Unit (PSCU) or Power Processing Unit (PPU)

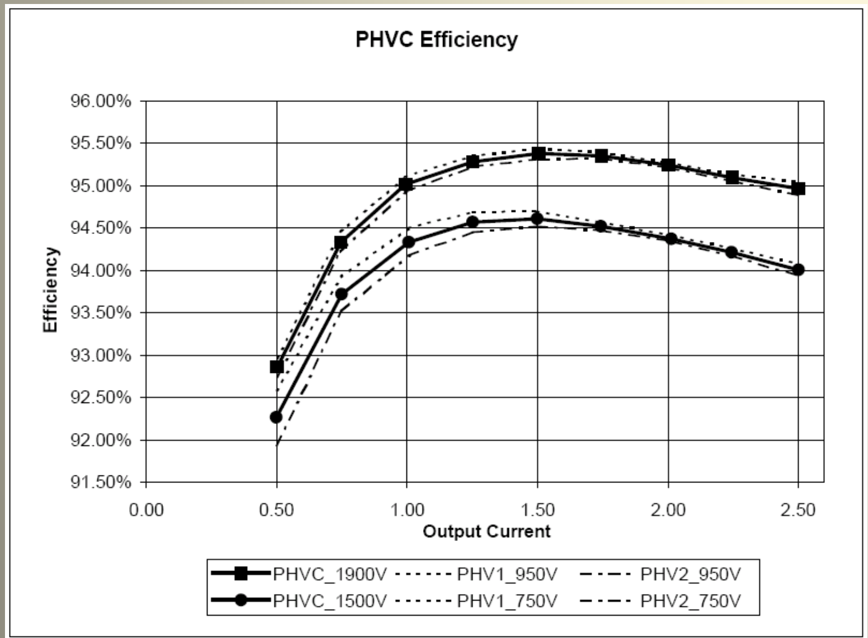


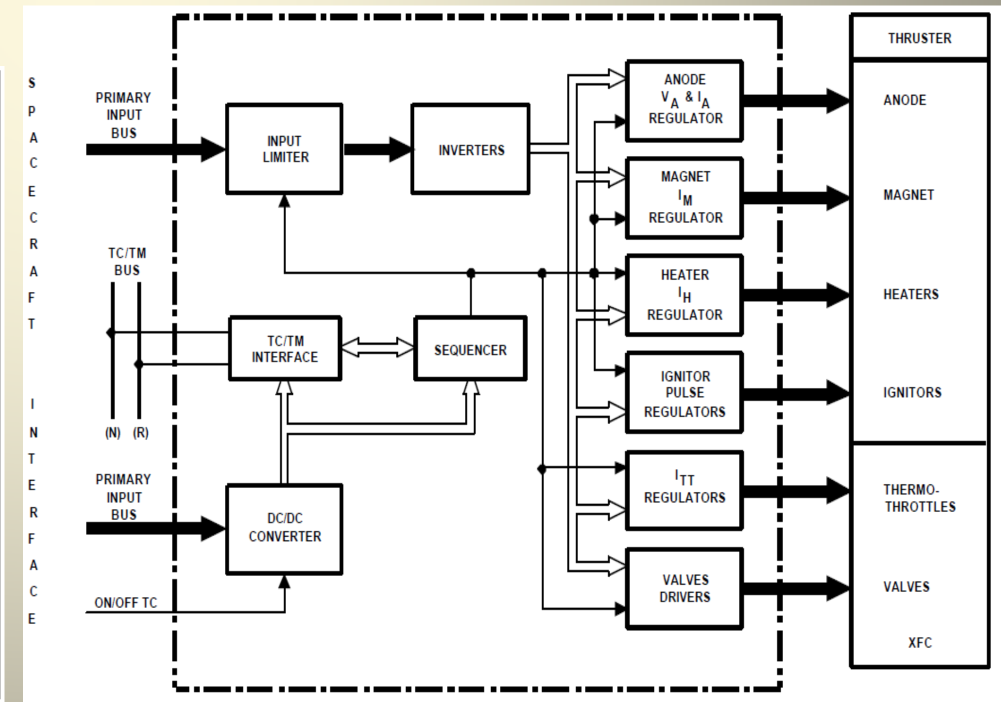


- Key equipment of an EP Sub-system EPSS)
- **Each class of thruster** presents **its own specific demands** (e.g. high currents and low voltages or viceversa or any combination of the two)
- **Ion thrusters** require a **broad range of voltages and currents** for their anodes, hollow cathodes, and accelerating grids and must be protected against high-voltage shorts and insulator breakdowns
- General rule: for handling of the same amount of electrical power **PPU masses increase when increasing the voltage level** (mainly due to insulations provision mass)

Main PSCU/PPU Functions

- Interface the **Primary input power bus**, insure main bus protection, voltage level conversion and galvanic isolation
- **Thruster power supplies**: the thruster different electrodes (anode, magnet, cathode heater, ignitor, grids, discharge, etc) are supplied according to their specific power requirements.
- **Pressure/Flow regulation power supplies** opens or closes the valves and controls the pressure/flow regulation closed loop control
- **Controller** (Processing Section) insures the automatic control and the survey of the thruster operation: start-up, stop, stand-by, regulated thrust, failure recovery
- **TC/TM interface** with the satellite communication bus.
- **Switching Unit** allows the swiching to the redounded resources in case of failure



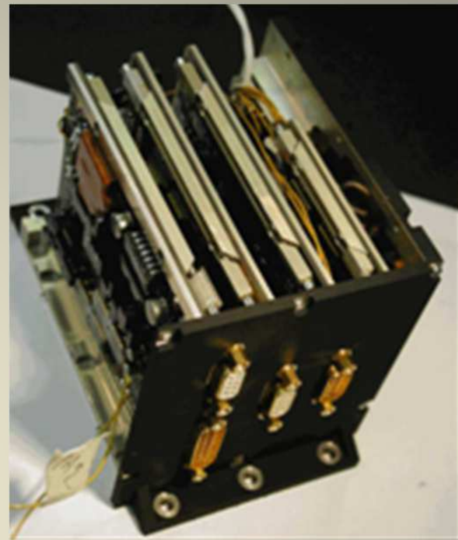


General PSCU/PPU Design & Development Criteria

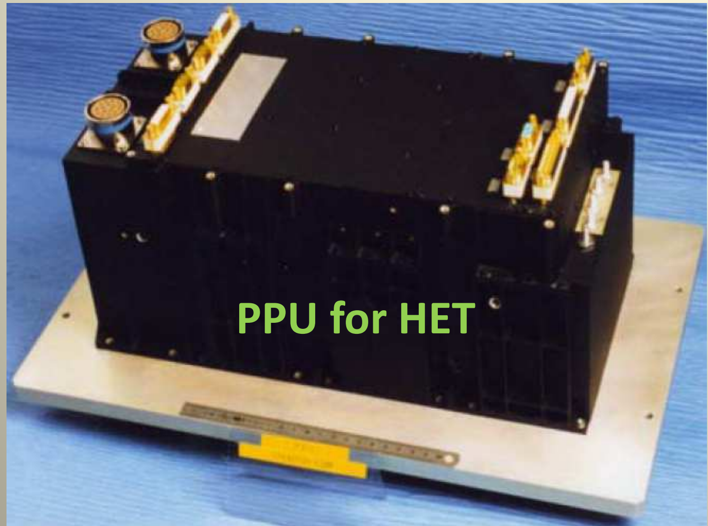
- Present needs for EP require the necessity to operate the thruster/s on board different S/C and in different operating ranges, at a **max. degree of flexibility**
- Power architectures with **configurable voltage power supplies** need to be therfore conceived and developed.
- A key point is the identification of a **scalable (modular) topology**, with the capability of providing a highly throttleable output voltage to sustain the thuster variable range performance
- Architectures can be based on **modules** or **building blocks** characterized by a certain voltage and current (and therefore power handled at module level)
- Modules can be arranged is **series/parallel configurations** for different PPU power sections , depending on the needs
- Implementation of a broad output operating range provides **higher average efficiency** than a single point architecture focused on pushing peak efficiency
- For what concern the Control Unit a trade-off on a case by case basis has to be performed between the approach with a **microprocessor + SW** and a solution based on a **FPGA** approach (this latter for sure cheaper)

Examples of PSCU/PPU Practical realizations

Courtesy of Thales Alenia Space



Courtesy of ETCA



Courtesy of Selex ES

The stages/steps of development of a product at space std level

- Proof-of-Concept (PoC) → Definition and assessment of the physical «operating principle» of the device
- Breadboard (BB) → Development Tests
- Engineering Model (EM) → Engineering Tests
- Qualification Model (QM) → Qualification campaign
- Flight Model (FM) → Acceptance Campaign

- Elegant Breadboard (E-BB) → Development and functional Tests
- Engineering Qualification Model (EQM) → Engineering and (partial) environmentl test
- Proto- Flight Model (PFM) → Proto-qualification Campaign

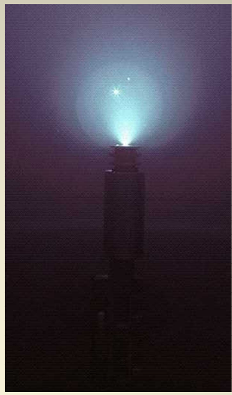
(Reference: ECSS standards)

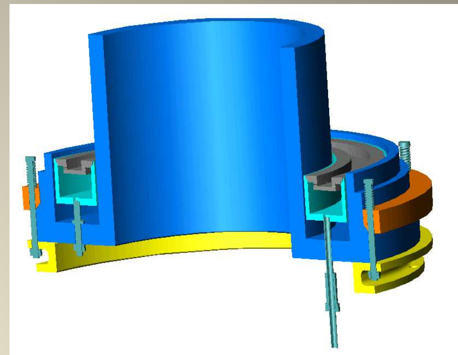
Resources to support EP technologies development & qualification

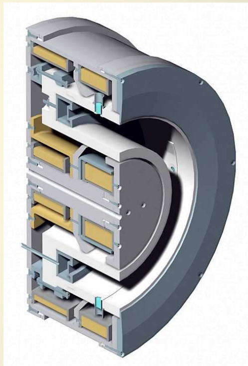
- **Design & Development**
- **Analyses, Simulation and Modelization**
- **Engineering and Manufacturing**
- **Assembly, Integration and Test**
- **Product/Quality Assurance**

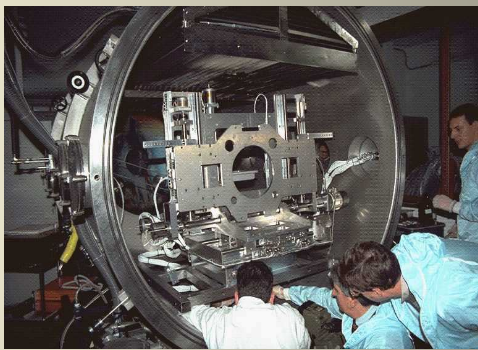
Design & Development

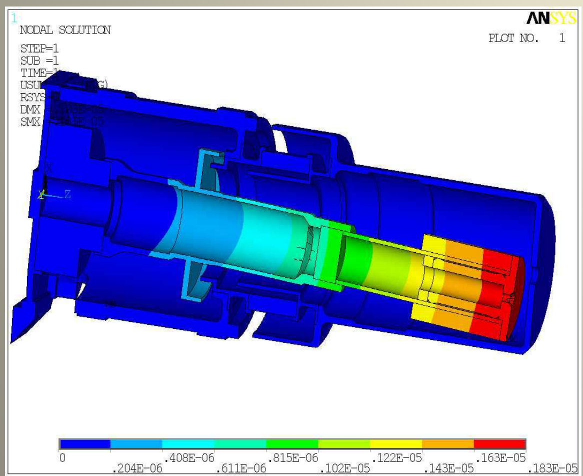
- Plasma physics/diagnostics
- Charged particles generation/acceleration
- Plasma and ions extraction processes
- Magnetic conditioning of plasmas
- High vacuum technologies
- Precision electromechanical positioning systems in vacuum
- Mechanical and thermal design
- Electric/electronic design
- Chemistry of materials

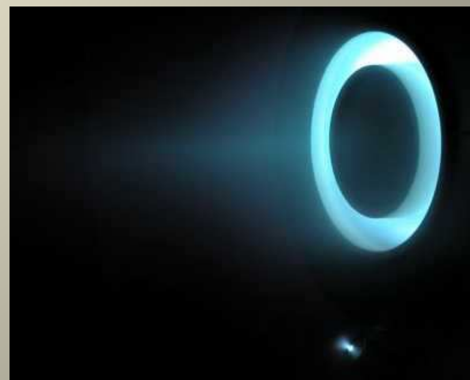




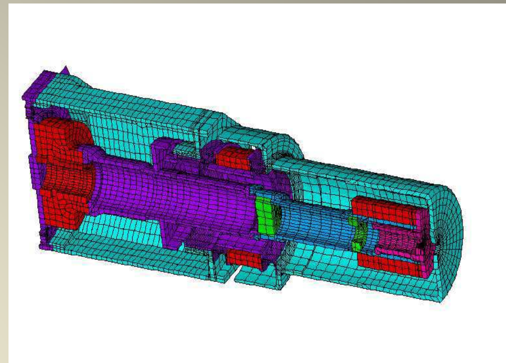




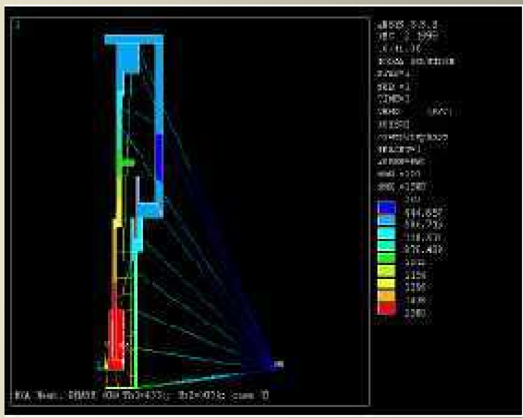


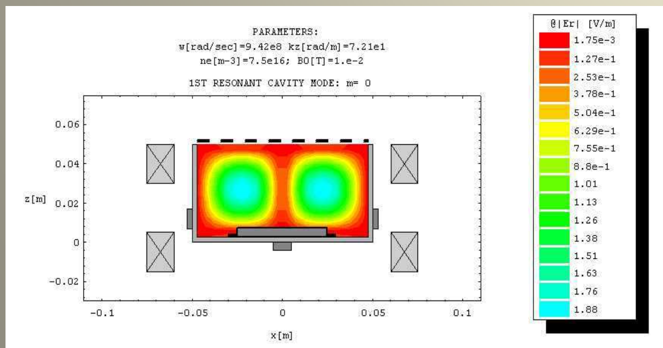


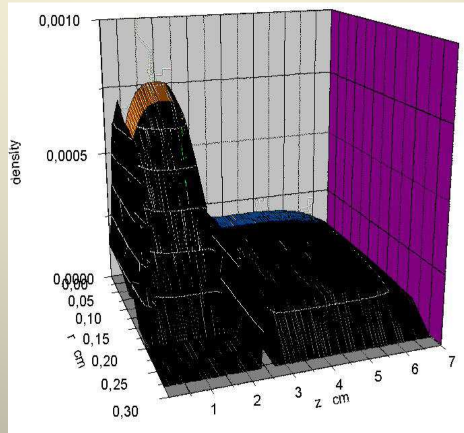
Analyses, Simulation & Modelization

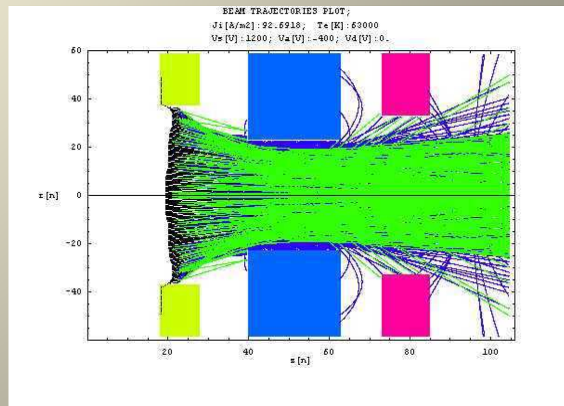


- Modeling of plasma generation and expansion processes with commercial and in-house developed codes
- Simulation of charged particles trajectories in electric and magnetic fields
- Particle-In-Cell (PIC) models (e.g. Montecarlo, etc.)
- Simulation of erosion processes
- FEM thermal/mechanical analyses
- Modelization of magnetic fields
- Electric Thtruster performace/functional models
- CAD (3D/2D), Structural Analyses, Graphical pre & post-processing
- Radiation analyses
- Fluid-dynamic modelizations







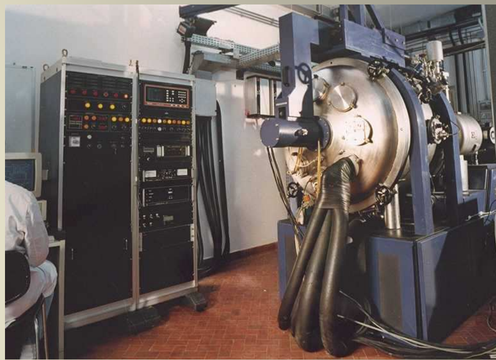


Engineering & Manufacturing *(Courtesy os Selex ES)*

- **Vacuum-tight joinings:**
  - **metal-to-metal and metal-to-ceramic brazing at controlled temperature and atmosphere**
  - **Plasma/RF welding**
  - **spot welding**
- **Chemical, electrochemical, thermal treatments on materials**
- **Mechanical precision workings;**
- **Laser cutting, drilling, marking and welding**
- **Materials processing, baking and outgassing**
- **Annealing and Thermal/Mechanical pre-conditioning**
- **Mounting of PCB's at Space standard level**
- **Special (vacuum-tight) Bonding /gluing**

Assembly, Integration & Testing *(Courtesy of Selex ES)*

- High precision tridimensional mechanical control
- Flight units assembly in controlled atmosphere (clean room)
- Thermal mapping and analysis with infrared video system
- Process/material analysis with SEM and radiography
- Corona /partial discharges characteriz. In shielded Chamber
- Vacuum tight joints verification through the leak detector
- Mechanical / chemical characterization of materials
- thermo-vacuum chamber at NASA/ESA standard;
- vacuum chambers with cryo-panel pumping for EP test
- Instruments automatic control in Labview environment
- Plasma environment simulation
- Simulation of materials outgassing and gas analysis
- Plasma particle beam in-situ diagnostics.



Wrap-up

- Thank you for your attention
- Bibliography/references available
- Appendixes with additional info available
- Questions ??