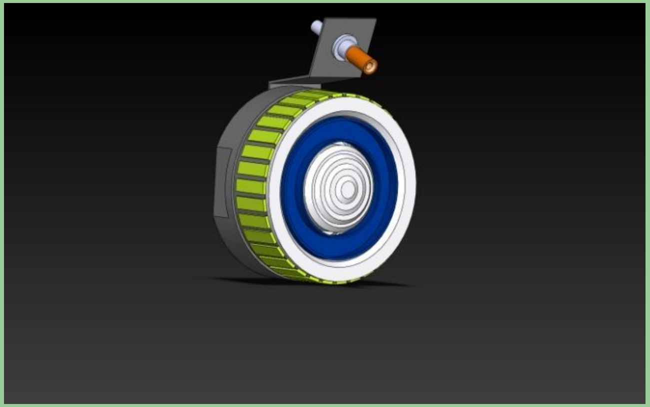
A REVIEW ON THE PERFORMANCE AND DEVELOPMENT OF PERMANENT MAGNET HALL THRUSTERS AT UNIVERSITY OF BRASILIA


PHALL - A HALL PLASMA THRUSTER WITH PERMANENT MAGNETS

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XVI CONGRESSO BRASILEIRO DE DINÂMICA ORBITAL

Serra Negra –SP , Brazil . 26 a 30 de novembro de 2012

PROJECT TEAM AND COLABORATIONS Instituições, equipes, projetos e programas de apoio a propulsão elétrica no Brasil e no exterior

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- Gabriela Possa
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- Paolo Gessini
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- Manuel Barcelos
- Graduate and undergraduate students
- FT – Eng. Mecatronica-UnB
- LARA-Robotic and Automation
- GRACO Automation and Control

- Colaboração Externa:
- LAP-INPE
- DMC-INPE
- FEG-UNESP
- UEFE
- DNU – Universidade Nacional da Ucrânia em Dnipropetrovsk

REDE NACIONAL DE PESQUISAS EM PROPULSÃO ELÉTRICA

Laboratorio Associado de Plasma do INPE
Instituto Tecnológico de Aeronáutica –ITA
UNIVAP

*Propulsão a plasma com Laser no IEAv com colaboração da UFABC

PROGRAMAS:

- UNIESPAÇO –AEB (2004-2012)

-ASTRIUM-INNOVA (Edital recente para parceria com industrias)

- MISSÃO ASTER (proposta com participação de varias universidades e institutos)

INTRODUCTION

The main motivation for Hall Plasma Thruster Development in Brazil is the world wide strong development of electric propulsion and its potential applications on the brazillian space program future missions..

- The main objective of PHALL project and research is to develop a Hall Plasma Thruster with innovative and new concepts, in which, an array of permanent magnets is used to produce and accelerate plasma with efficient propellant mass use, high specific impulse and low electric power consumption.

- - In this presentation we review characteristics and performance of two permanent magnet hall thrusters (**PHALL I and II**) .

- -We will also show the main results of calculations and computer simulations that have been done to show performance and possibles aplications of PHALL family on satellite orbit transfer form LEO to GEO, Lunar polar satellites station keeping and to deep space missions to asteroids (Aster Space Mission).

- This project belongs to the Brazillian Space Program for Universities(UNIESPAÇO) . It is dedicated to introduce and promote space research and development between brazillian universities and space institutes like INPE and CTA.

Development of Several Types of Plasma Sources since 1995.

* TEN YEARS OF RESEARCH AND DEVELOPENT (2003-2013) on Electric Propulsion Systems at PLASMA PHYSICS LABORATORY of UNB

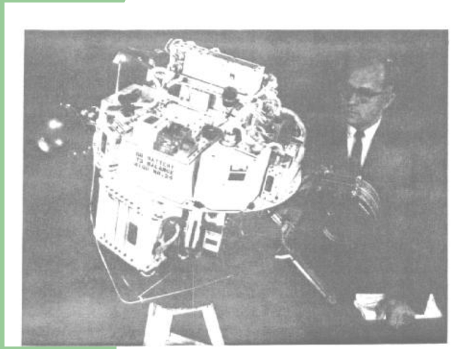
PLASMAS - 4º Estado da Matéria

Homepage Filipe

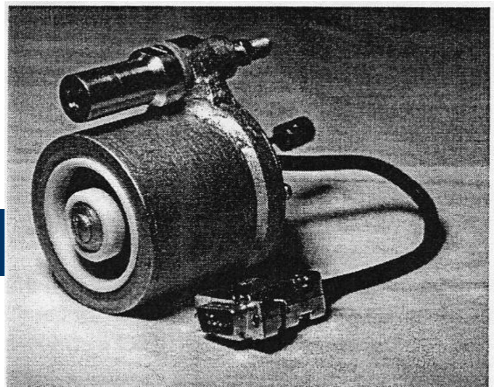
Electric and plasma propulsion * Historical milestones

Robert Goddart(1906) e Hermann Oberth (1922)Werner Von Braun e Ernest Sthulinger (1952)

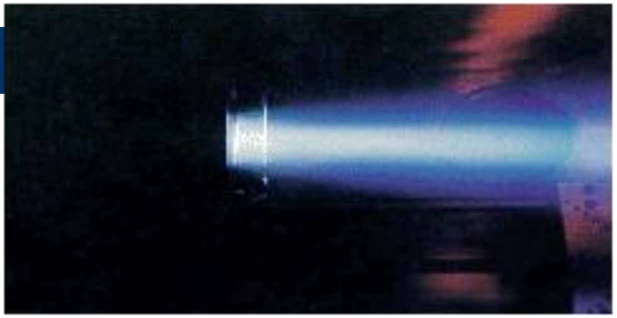
KauffmanPION EUA1960, Zharinov and Morozov HALL URSS1962



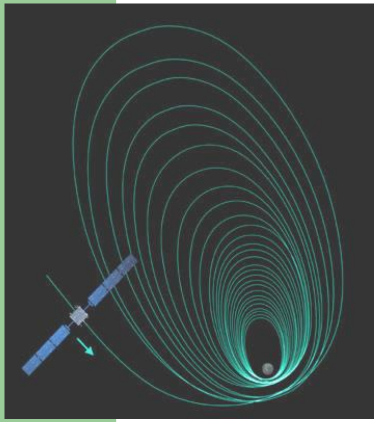
SERT 1 USA 1965



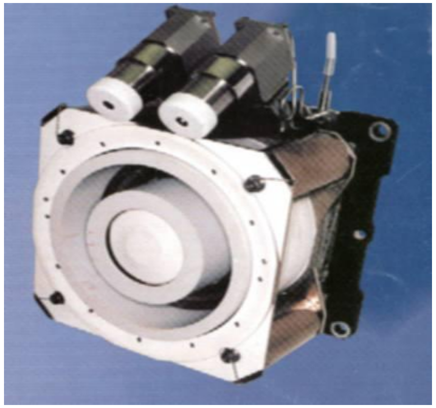
Hall Thruster KM-32 Russia 1970 - 1980



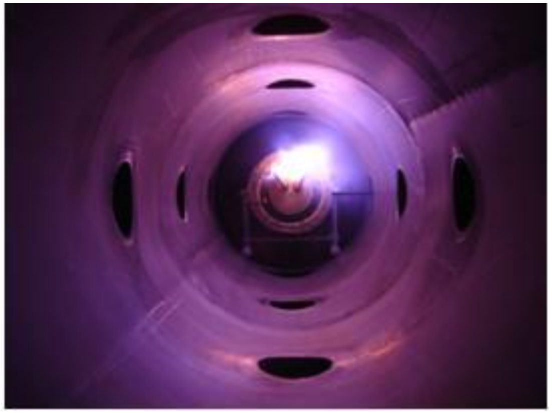
PION LAP/INPE Brasil since 1985



SMART 1 ESA moon mission 2004-2005



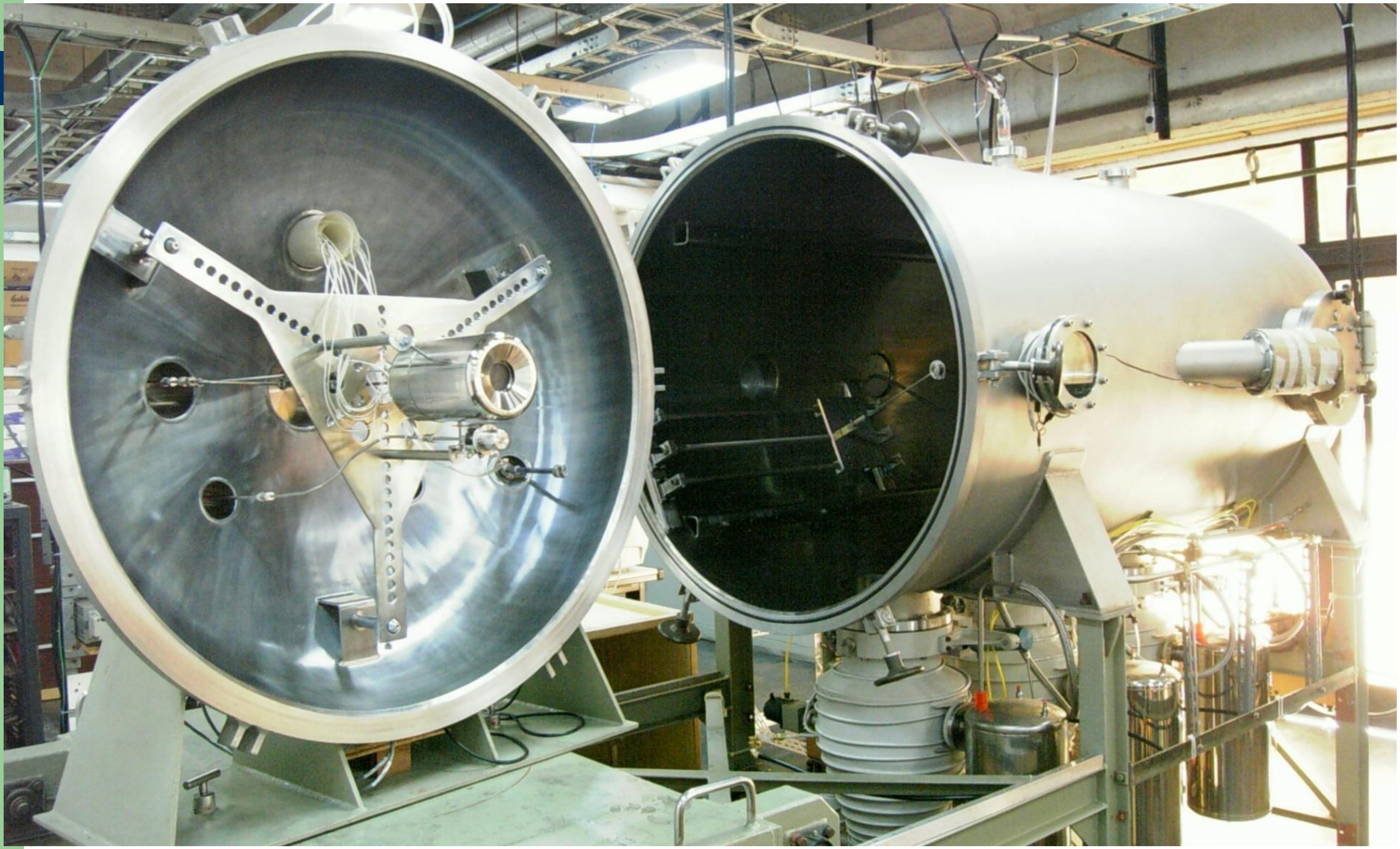
Hall Thruster SPT-100. SNECMA France 2003



PHALL I – Research and development of Hall Plasma Thrusters at LP IF UnB Brasil since 2003

Electric Propulsion LAP-INPE 1985

- It has the biggest facilities for Ion thruster development. The figure below shows PION III inside the D=1,5m X L=3,0m Pumping speed=7500 l/s vaccum test chamber.

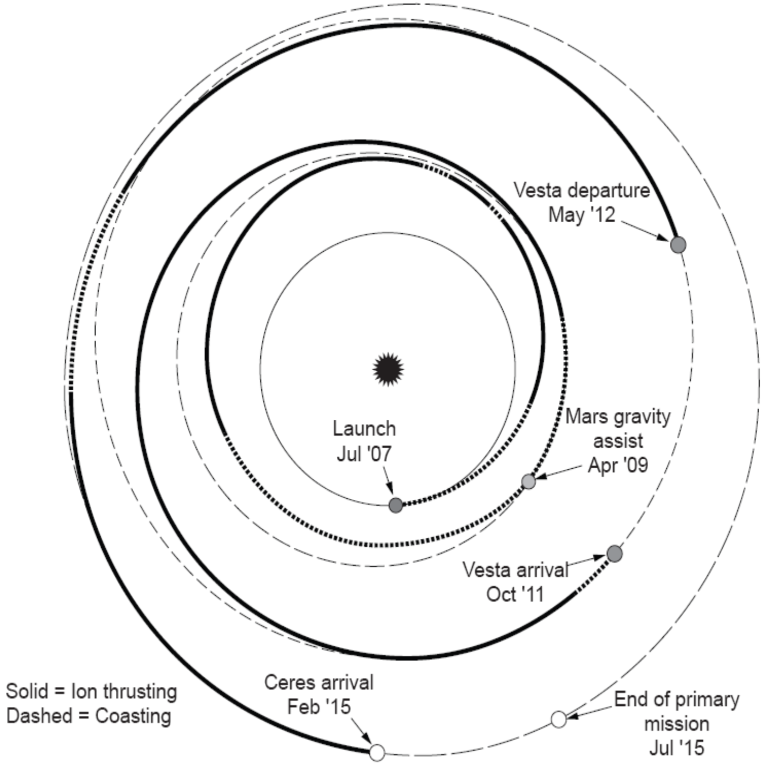


Ion Propulsion Contribution to in situ Solar System Research Hayabusa- Japan Space mission to Asteroid Itokawa(2005)

Ion Thruster with RF ionization source

- The Hayabusa Space Mission landed on an asteroid and collected samples to be studied back on earth. Due to micro-gravity, Hayabusa used plasma propulsion, which allows fine adjustable thrust .

Solar System Dawn Mission(2007-2015) to asteroid Vesta and minor planet (?)Ceres with an ion propulsion. Kauffman type ion source and grid acceleration system



Trajectory

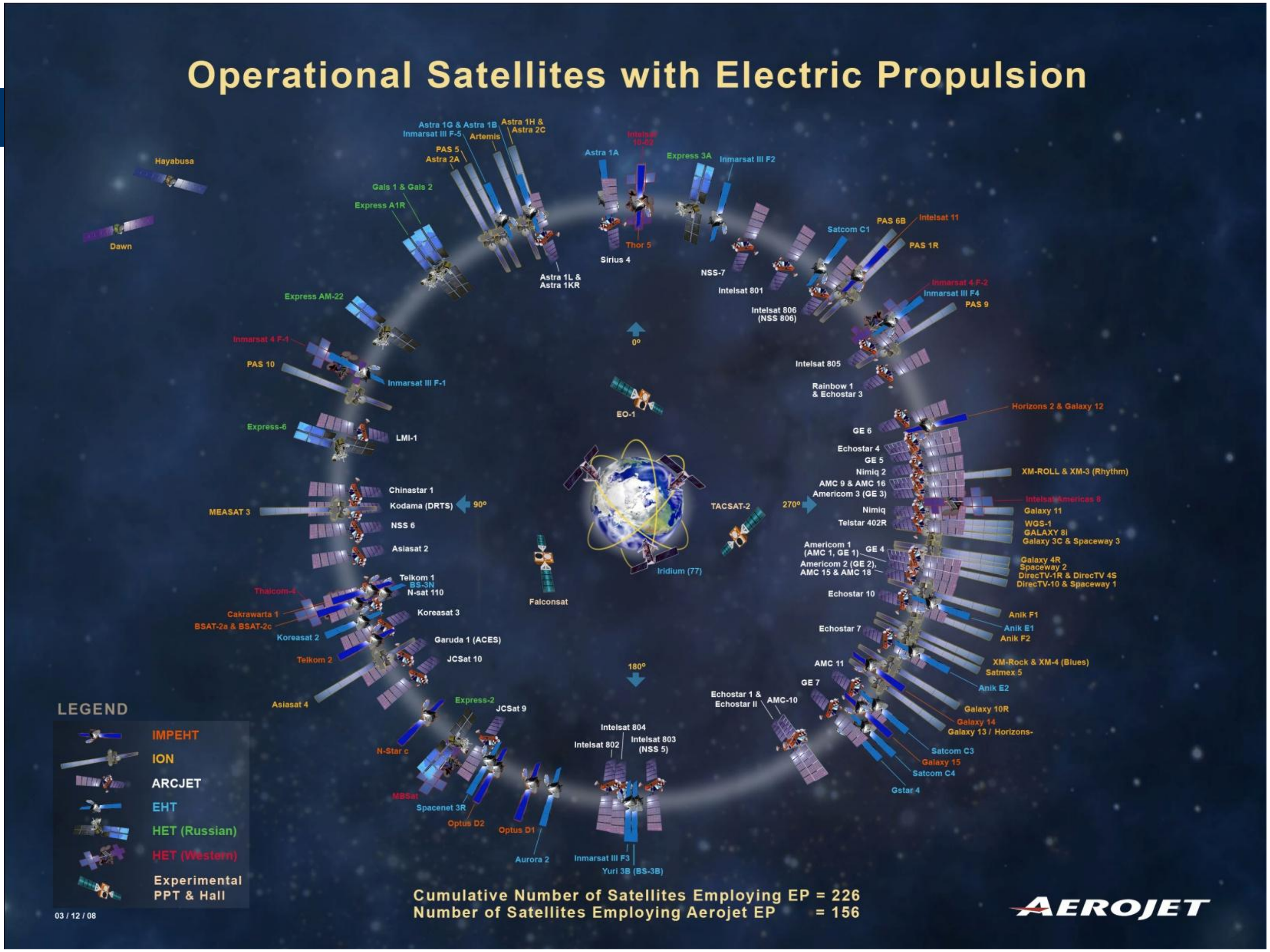
D = 33cm
Ms = 9Kg
Mf = 425Kg
Thrust: 19 to 91 mN
Estimated days of thrusting: 2000

Electric Plasma (EP) Thrusters use since 1965

- Numbers of satellites using EP up to 2008 = 226

- Numbers of Spacecrafts for solar system exploration with EP 1998 to 2012 = 05 .

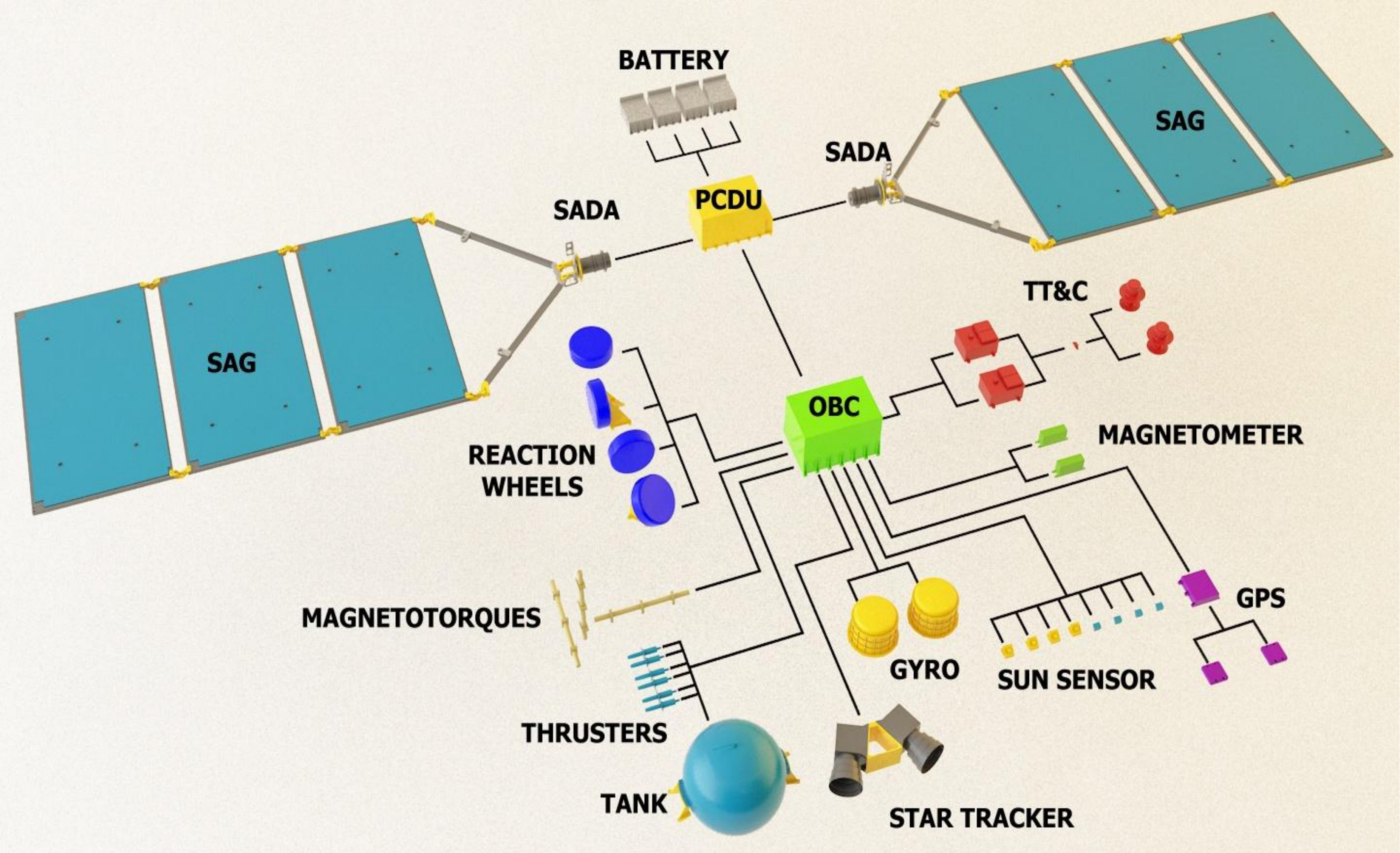
Space agencies and industries are using EPs for comercial Geostationary satellites



Operational Satellites with Electric Propulsion

Cumulative Number of Satellites Employing EP = 226
Number of Satellites Employing Aerojet EP = 156

Electric propulsion is part the satellite structure. It is one of the basic sub systems dedicated to orbit and attitude control. It has to be compactible with satellite mass, size and electrical supply.



Basic parameters of Electric Thrusters and its main atractive features.

Low thrust orbital maneuvering:

$$T = \dot{m} u_e$$

High velocity increment:

$$\Delta v = u_e \ln \frac{m_0}{m_f}$$

Low mass Propellant comsumption:

$$\frac{m_f}{m_0} = e^{-\frac{\Delta v}{u_e}}$$

High Specific impulse (2000s-10000s):

$$I_s = \frac{u_e}{g_0}$$

Advantages of Hall Plasma Thrusters :

High specific impulse and a very efficient use of the propellant gas are basic caracteristics of electrical thrusters .

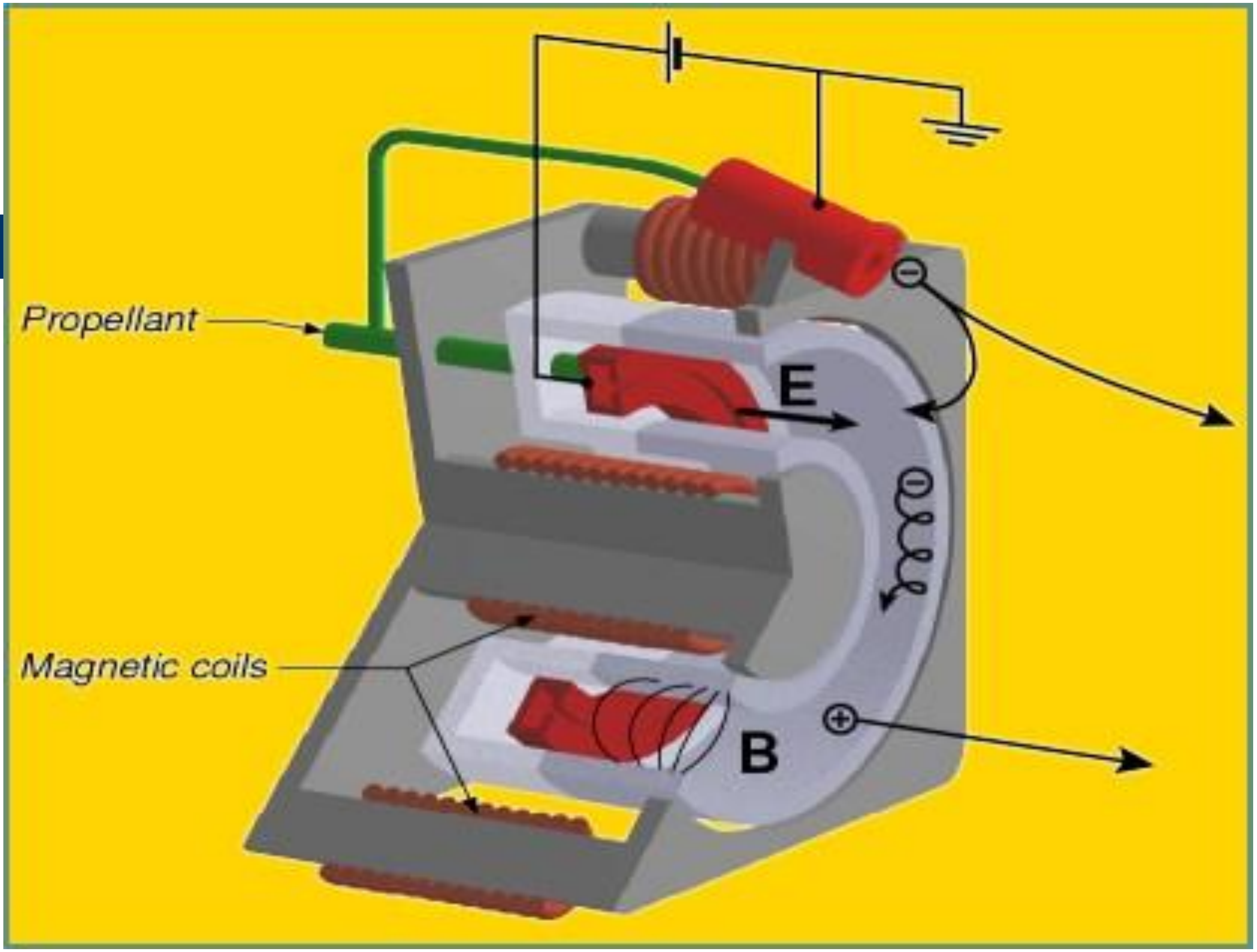
Hall plasma thrusters have aditional advantages:

* Longer life time;

- Easy maintenance due to easy access to all source components;
- Low number of components to be controlled;
- Single cathode;
- Absence of polarized grids;
- Higher plasma flux density;

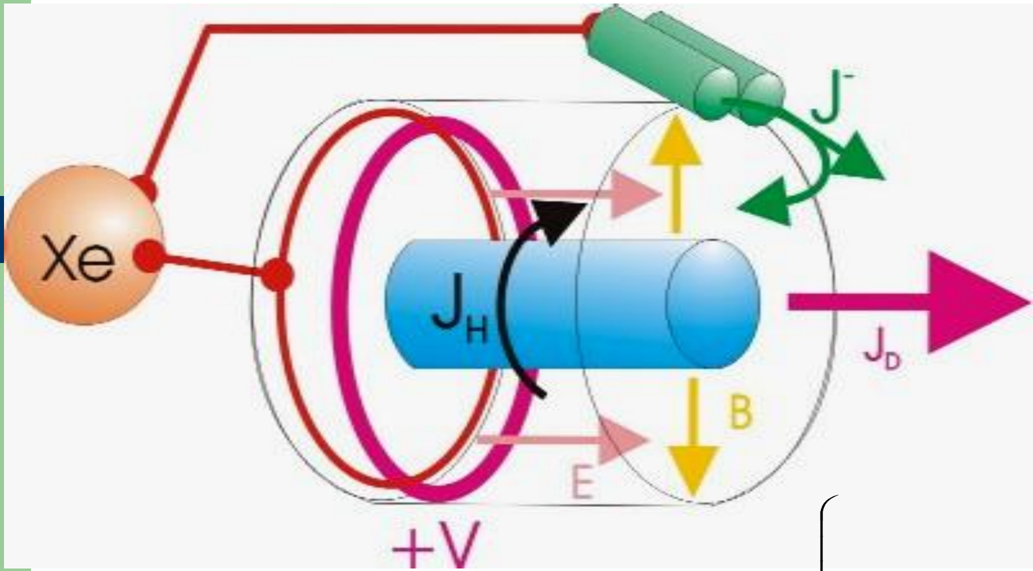
* The Permanent Magnets Hall Thruster(PHALL) developed at UnB can have extra advantages of lower power consumption , simplicity and alternative magnetic field geometries.

Standart HALL THRUSTER-SPT with eletromagnets



Ilustrative scheme of a Closed Drift Plasma (Hall) Thruster showing propellant gas connections in green , hollow cathode and anode in light red and magnetic coils in dark red.

Hall Thruster Principles



Condutivity tensor for the Hall Thruster cilindrical geometry:

Hall

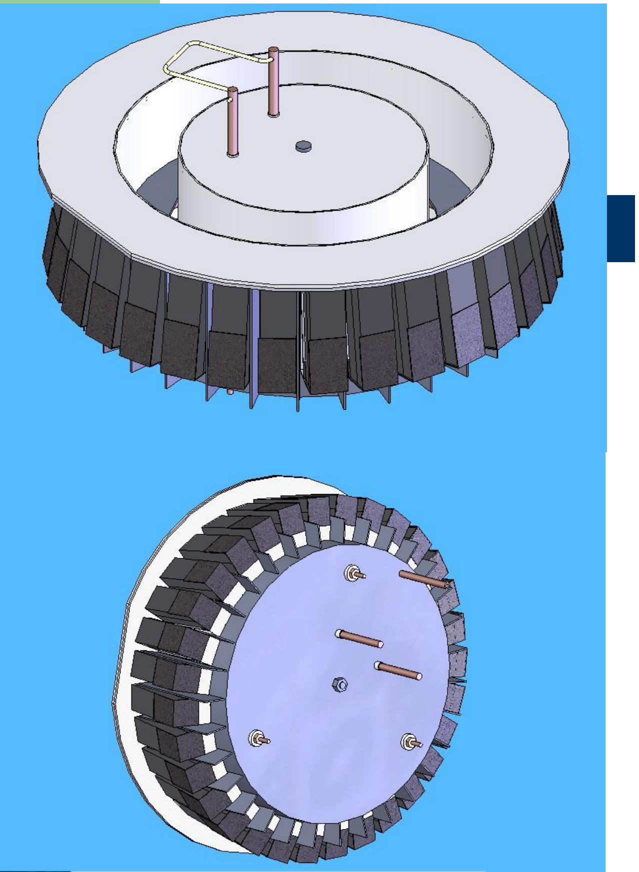
$$\begin{pmatrix} J_r \\ J_\theta \\ J_z \end{pmatrix} = \begin{pmatrix} \sigma_0 & 0 & 0 \\ 0 & \sigma_0 \dfrac{\left(1-\dfrac{\omega_{ce}}{\nu_i}\right)}{\left[1+\left(\dfrac{\omega_{ce}}{\nu_i}\right)^2\right]} & \sigma_0 \dfrac{\dfrac{\omega_{ce}}{\nu_i}}{\left[1+\left(\dfrac{\omega_{ce}}{\nu_i}\right)^2\right]} \\ 0 & \dfrac{\sigma_0}{\left[1+\left(\dfrac{\omega_{ce}}{\nu_i}\right)^2\right]} & \dfrac{\sigma_0}{\left[1+\left(\dfrac{\omega_{ce}}{\nu_i}\right)^2\right]} \end{pmatrix} \cdot \begin{pmatrix} E_r \\ E_\theta \\ E_z \end{pmatrix}$$

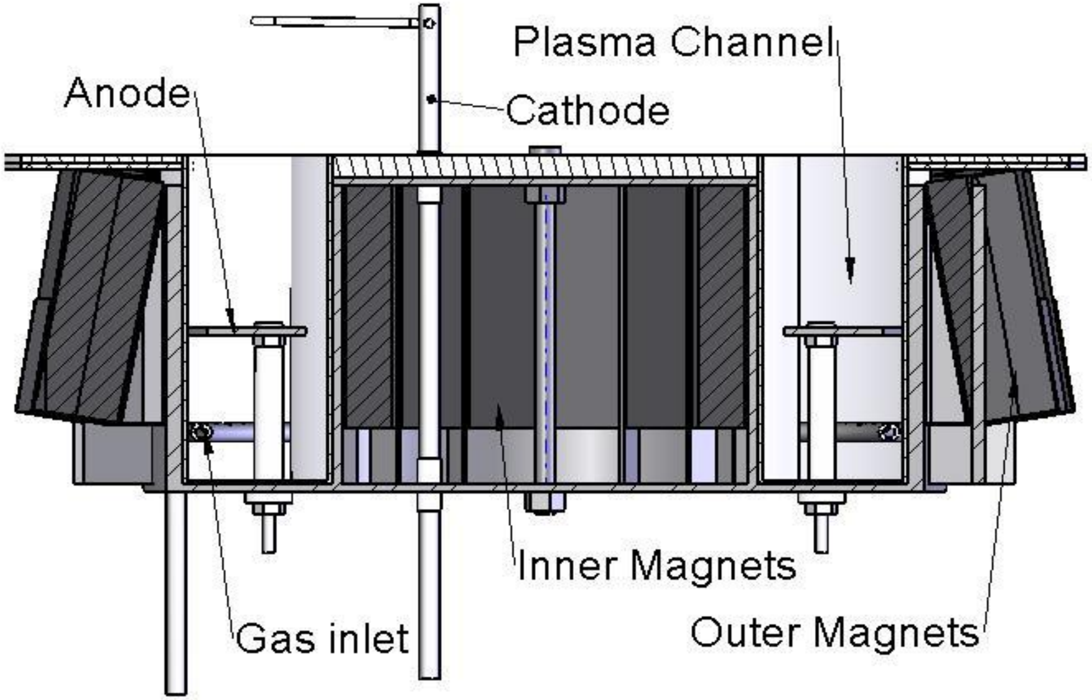
MHD equations and plasma acceleration :

$$\frac{d}{dt}\vec{u} = \frac{1}{n}\vec{J}_H \times \vec{B}$$

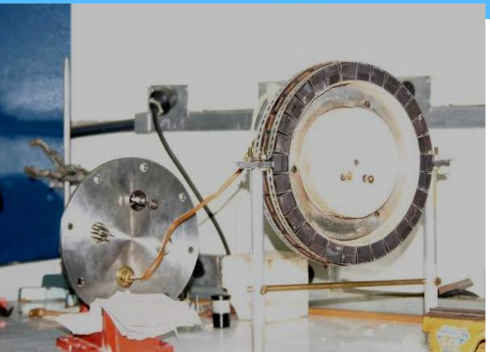
PHALL-1 design,construction,preliminary tests in bell jars.

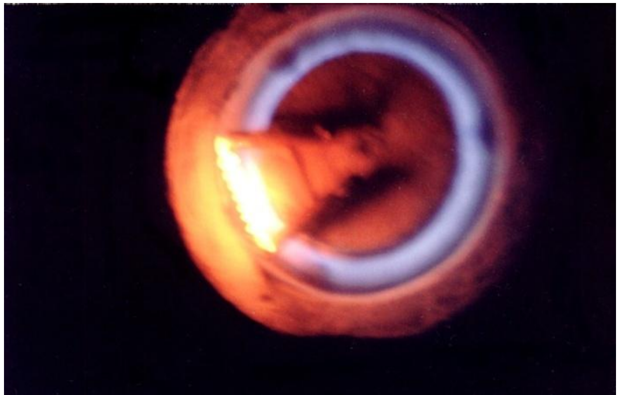
Ceramic permanent magnet arragement . Each magnet has 1.5kGauss and 1cmx2cmx7cm sizes
CHANNEL WIDTH = 3.8 cm D = 30 cm and Cathod made of W with BaO cover. Propellant gas Argon

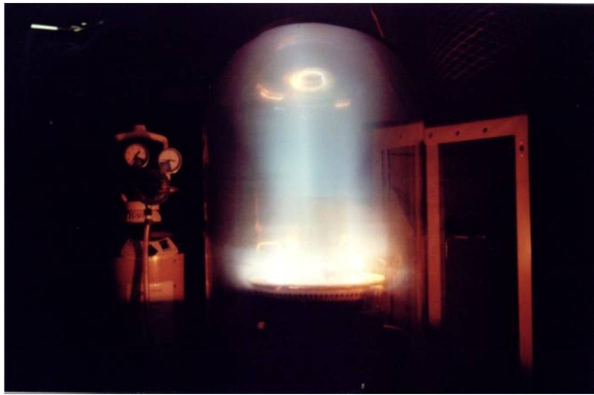




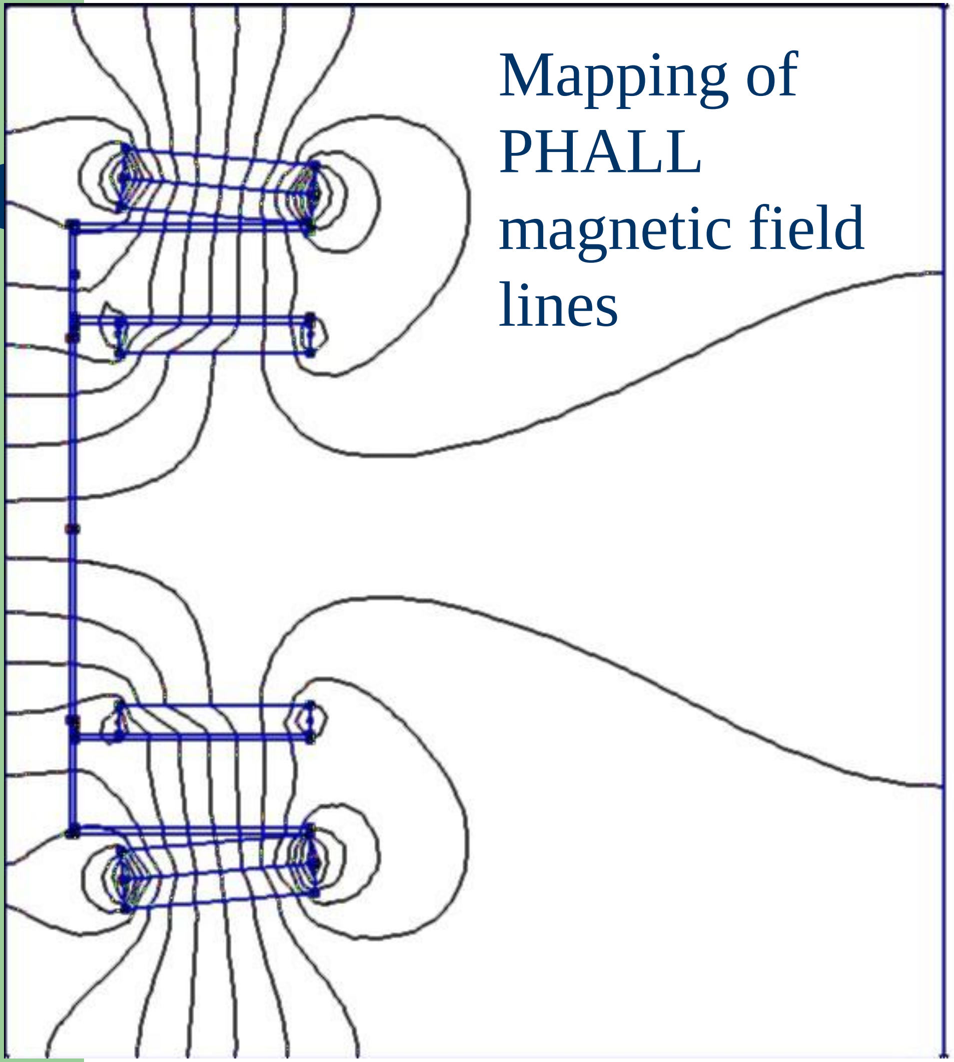
Stainless steel cylindrical body cover by ceramic paste







Computer Simulation of PHALL-I magnetic field lines generated by permanent magnets arrangement in a cylindrical geometry.



Mapping of PHALL magnetic field lines

Relation between magnetic field, Larmor radius and plasma source geometry :

$$\frac{m_i v_i}{eB} > L > \frac{m_e v_e}{eB}$$

$$L \approx \left(\frac{M_{e\perp} V_d}{\nu_i} \right)^{1/2}$$

Phall current channel width

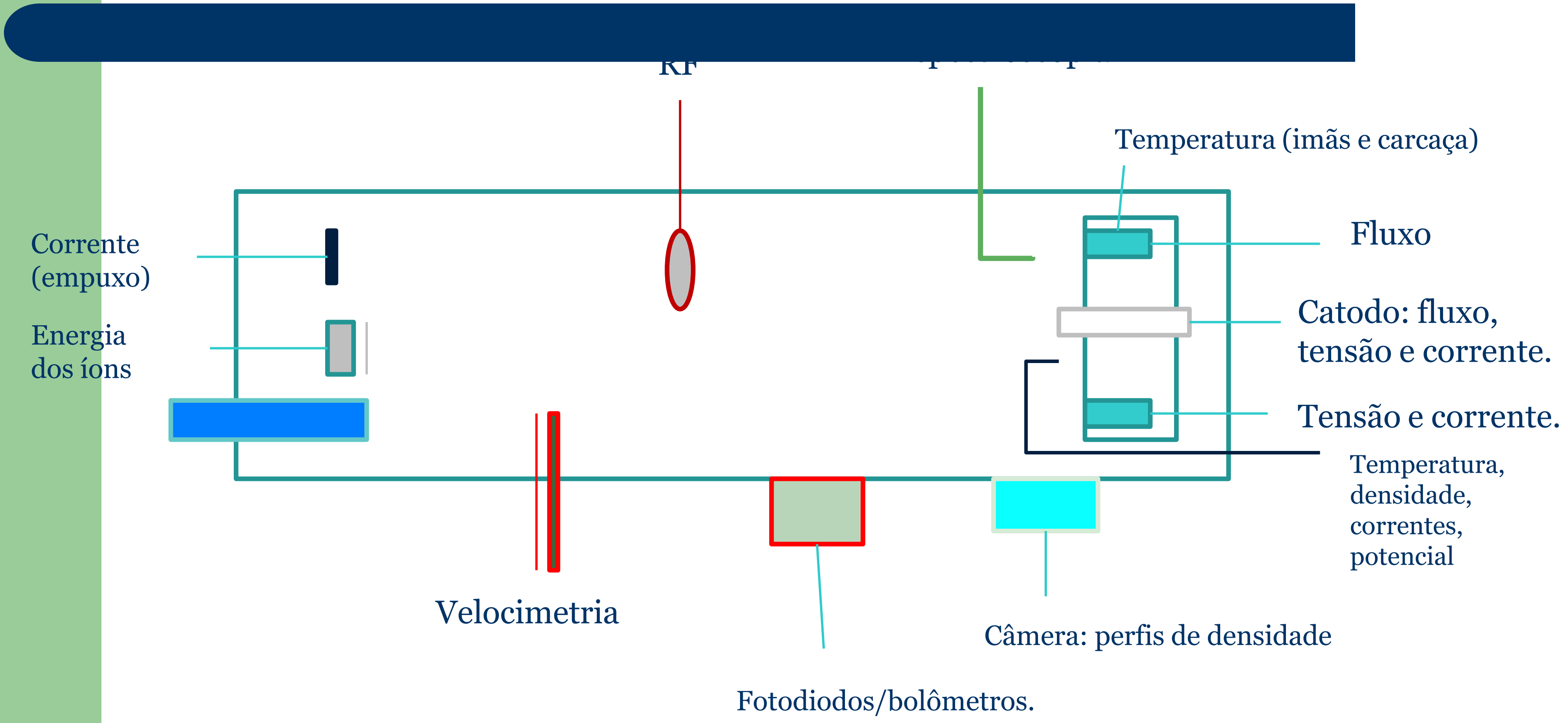
L=3.8 cm

Vaccum test chamber for PHALL plasma diagnostics systems.

Langmuir probes , Ion collector, Electrostatic Ion Energy Analysers, Visible Spectroscopy , RF probes and signals spectrum (6 Ghz) analysers and several multi meters with A-D conversion for computer based data aquisition

Integrated Plasma Diagnostic System - BID

Probes for plasma basic parameters, Doppler broadening spectroscopic ion temperature diagnostics , mass flow rate, CCD imaging of plasma plume and photodiode detection of plasma instabilities.



RF

Temperatura (imãs e carcaça)

Corrente
(empuxo)

Fluxo

Energia
dos íons

Catodo: fluxo,
tensão e corrente.

Tensão e corrente.

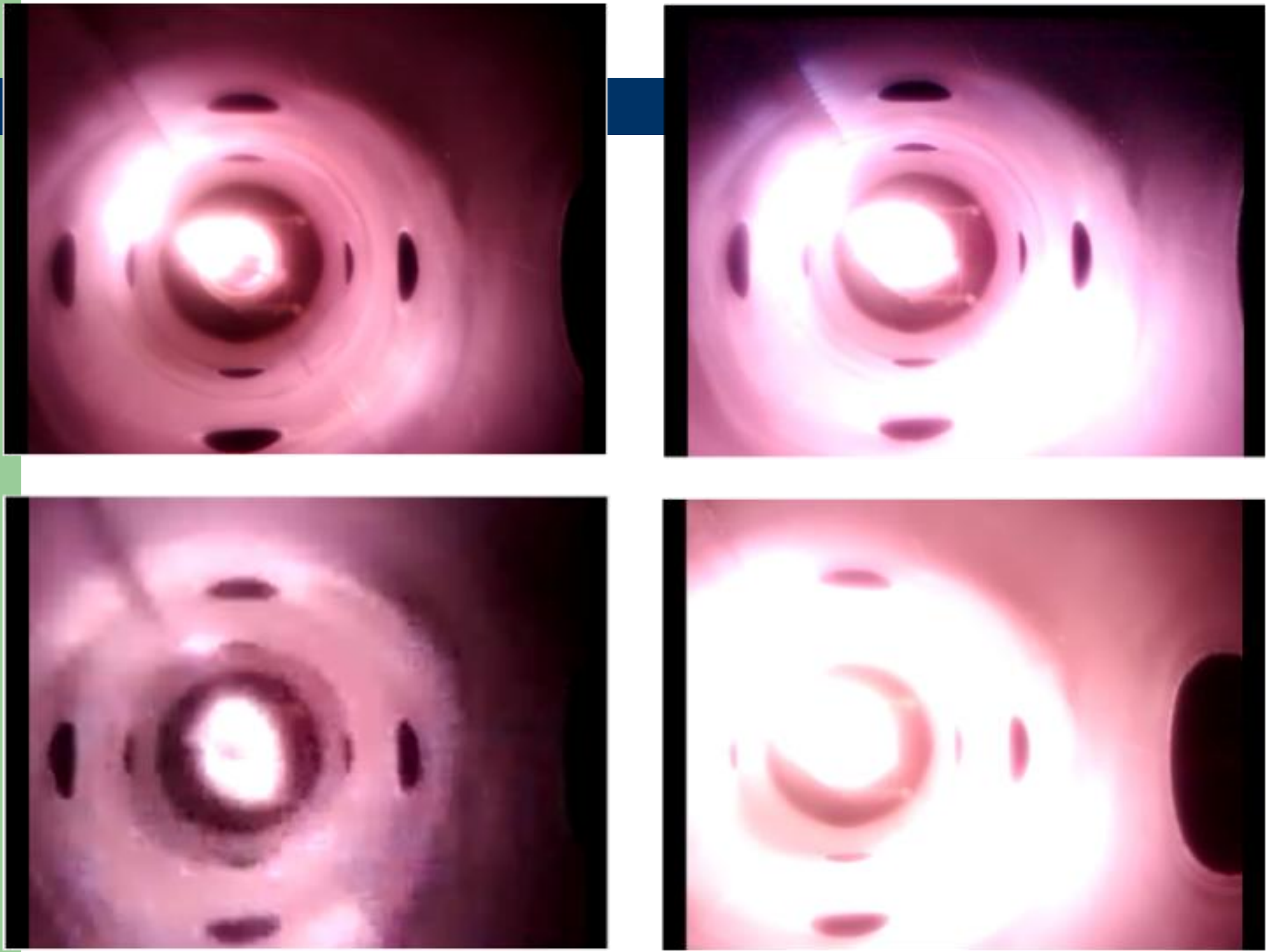
Temperatura,
densidade,
correntes,
potencial

Velocimetria

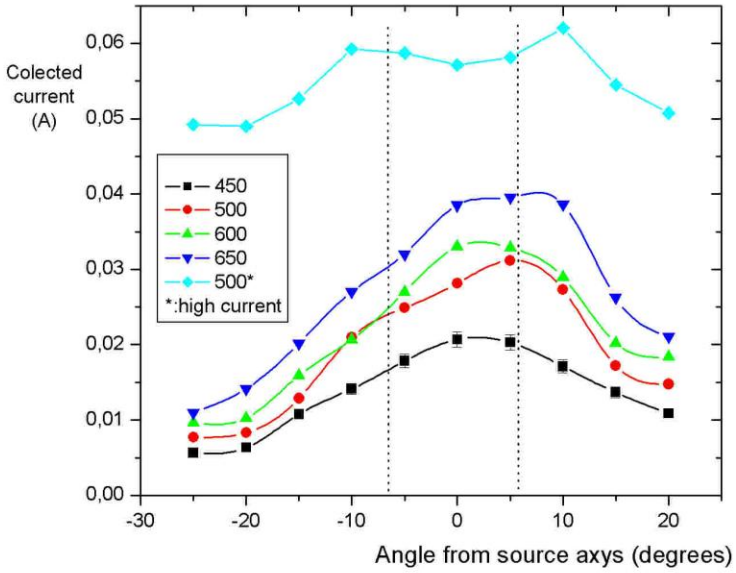
Câmera: perfis de densidade

Fotodiodos/bolômetros.

Exausted beam oscilations during PHALL operation due to plasma instabilities

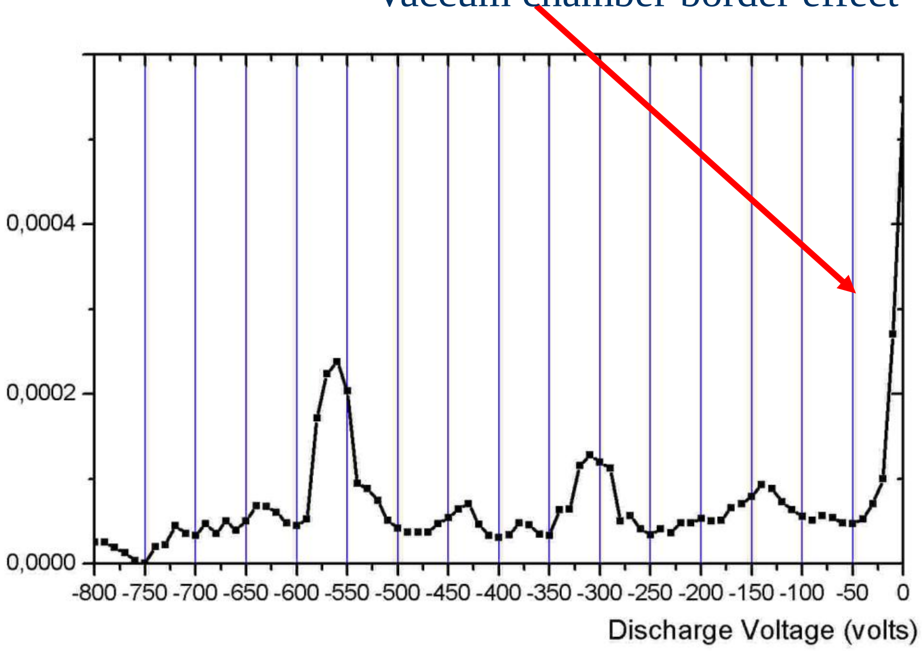


Drift Plasma Plume Characteristics- Ion probes



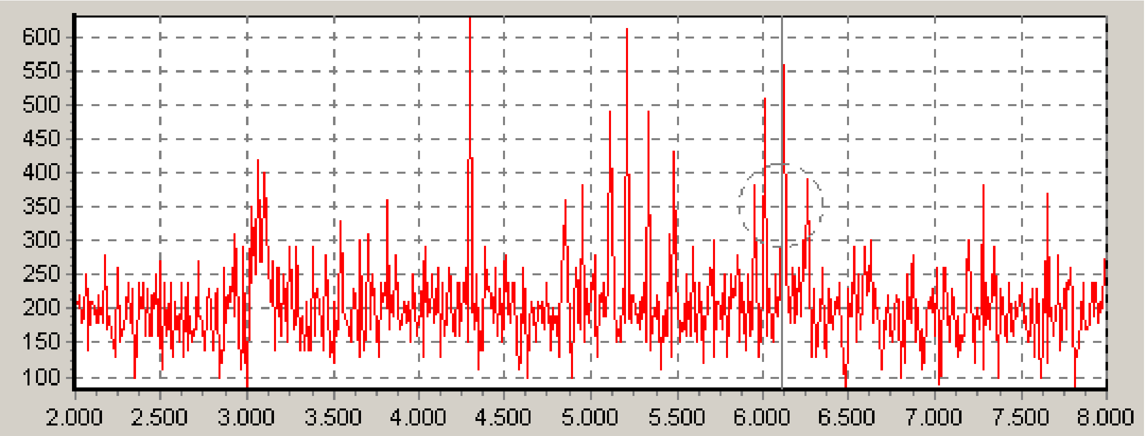
Angular Distribution of the accelerated plasma. Note the assymetric space profile of the accelerated plasma ion current can be adjusted by controlling anode potential.

Vaccum chamber border effect

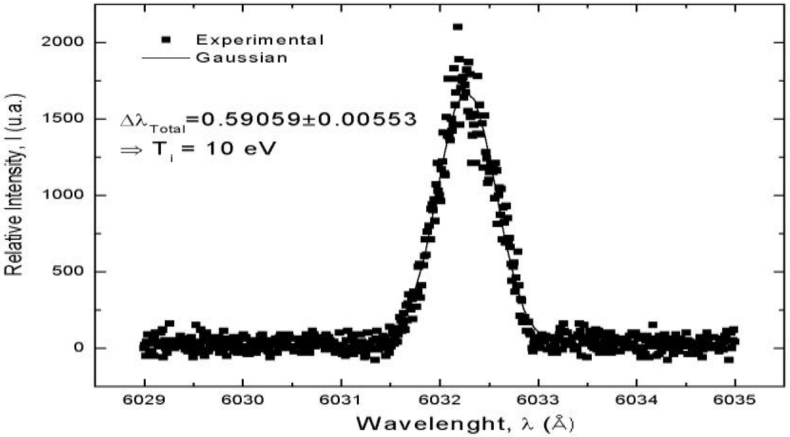


Energy spectrum of the drift plasma ions, for several discharge voltages measured by the electrostatic ion energy analyser

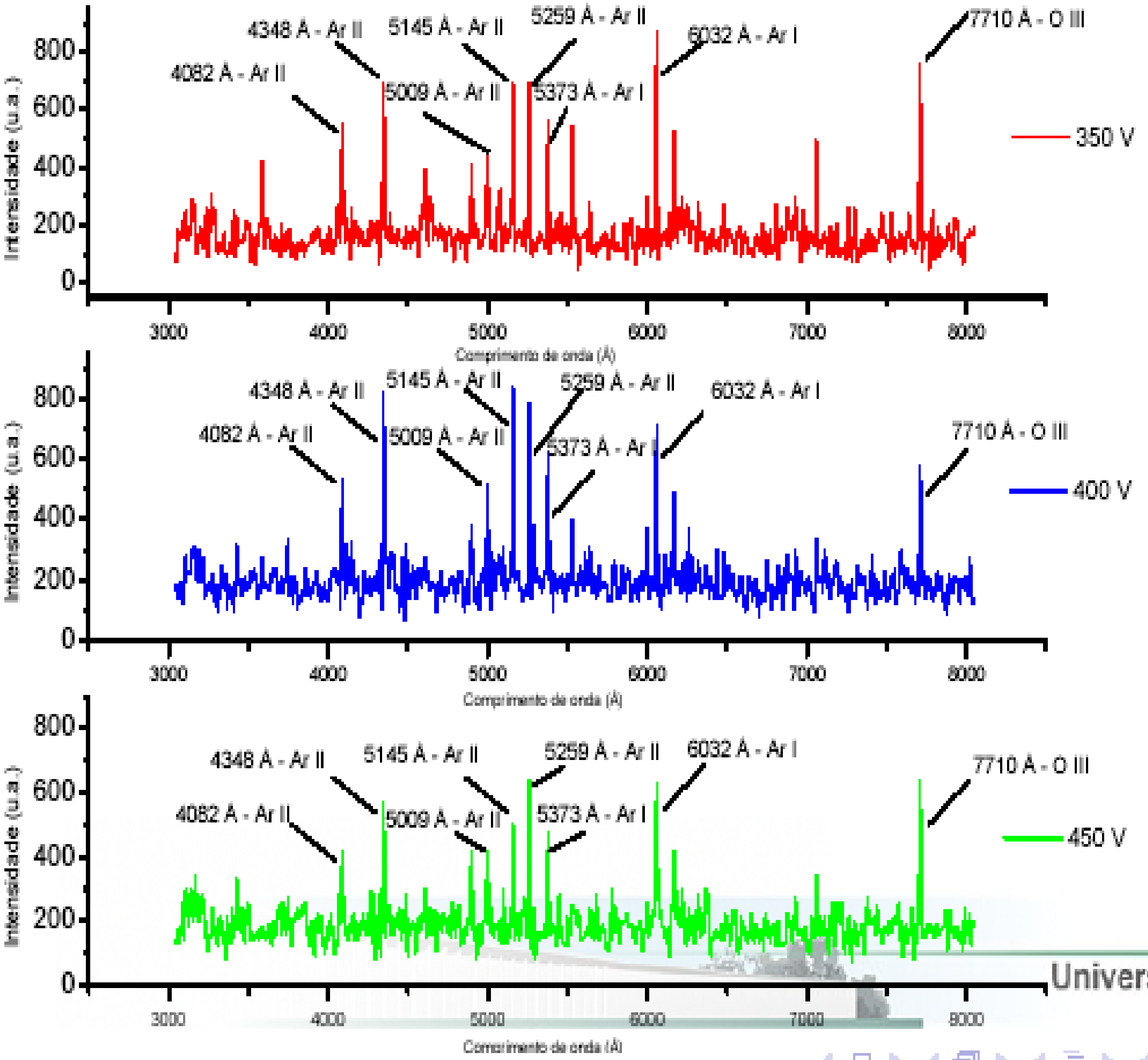
Impurity detection and ion temperature measurement .



- Ion temperature measurement
- from spectral line
- Doppler broadenning



Identificação das Linhas de Emissão do Espectro Obtido:

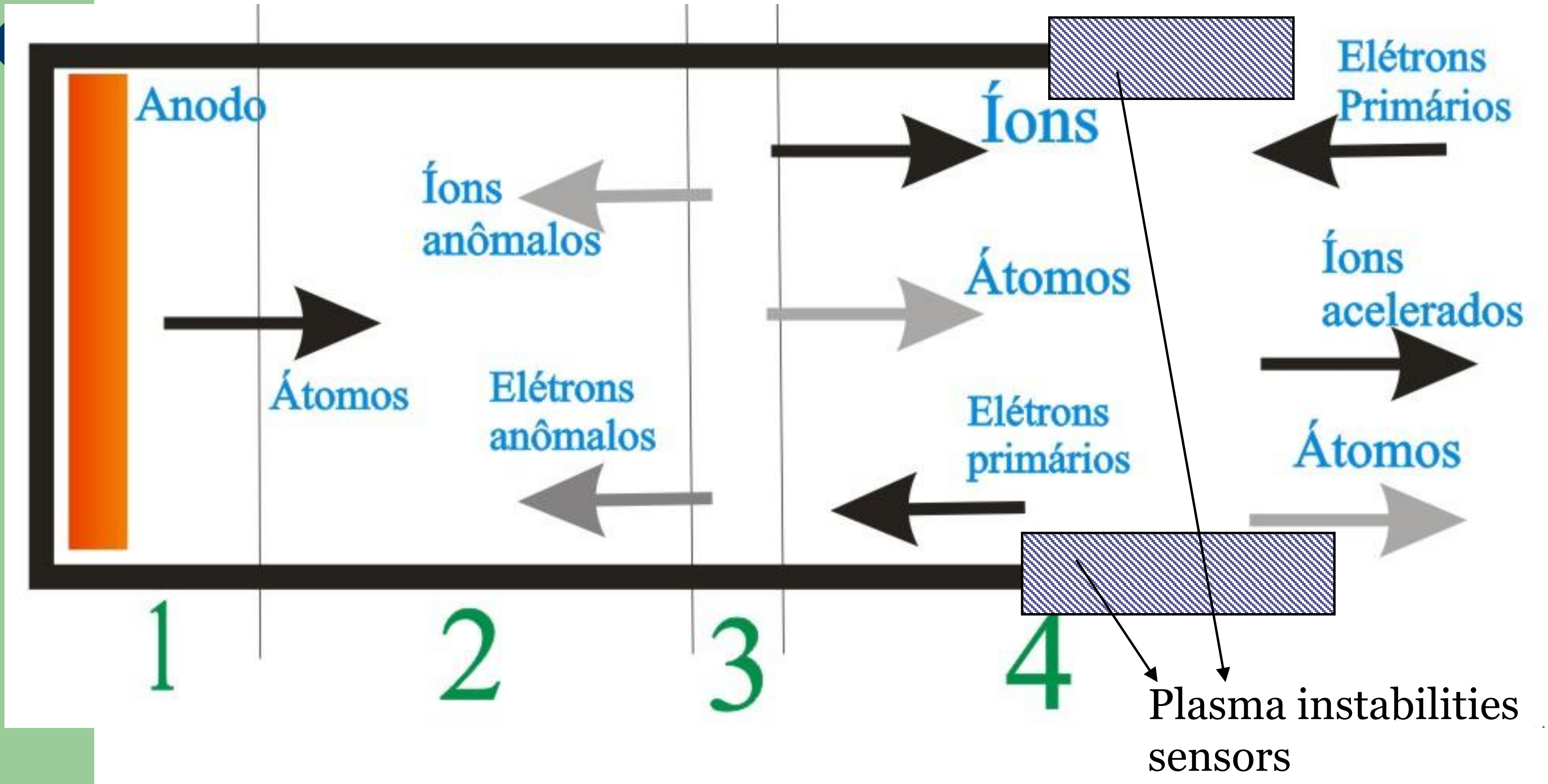


Universidade de Brasília

PC based real time PHALL system control
Transit-time instabilities(fc=40KHz) supression with band pass filters

02 microcomputers with PCI-GPIB boards and c GPIB-USB conversion

PLASMA PHYSICS PROCESSES Plasma in situ non pertubative diagnostics for modelling the Hall Thruster Plasma Physcs such as anomalous particle transport and plasma acceleration.



Anomalous Particle Transport Regime Studies.
PHALL parameters determination for safe PHALL operation

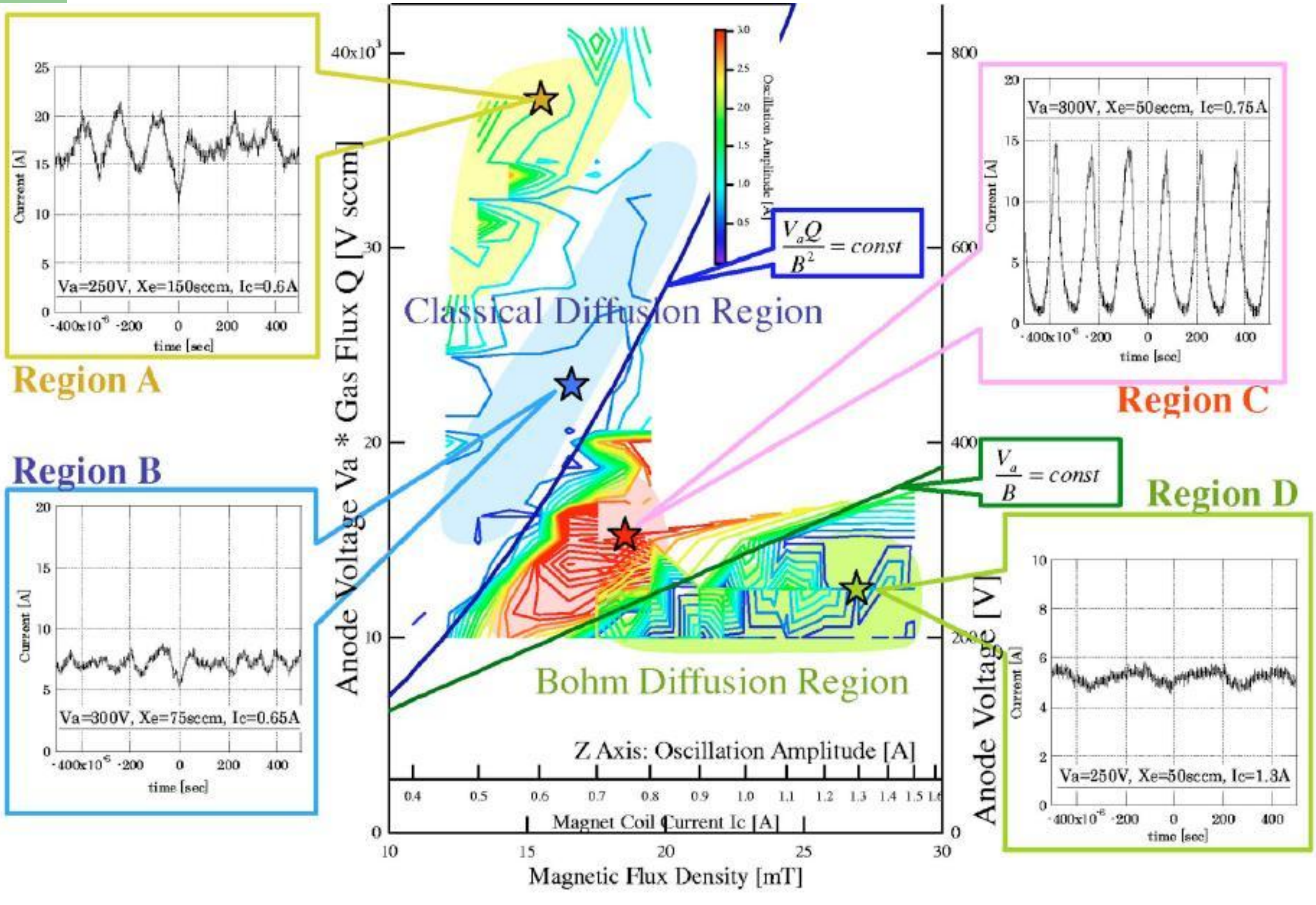
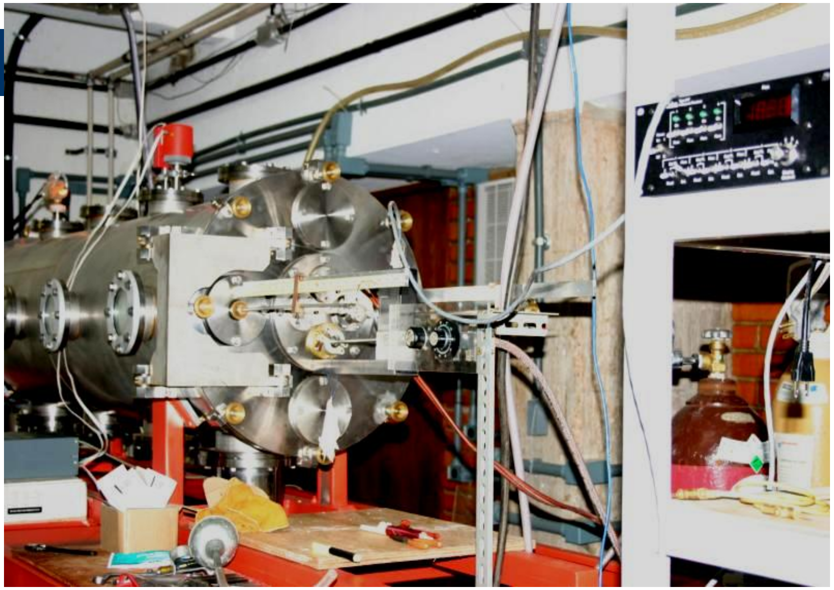
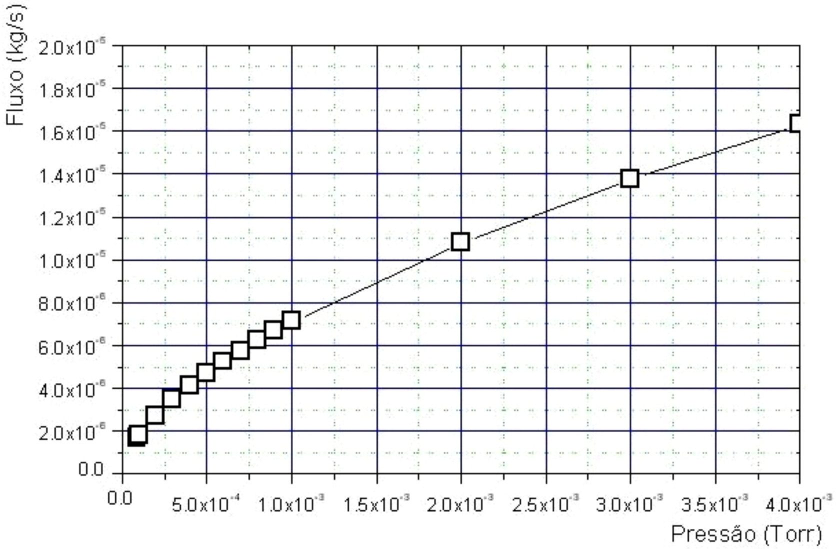


FIG. 8. (Color online) Operation conditions and oscillation mode regions.

PHALL propellant gas flux control system



Mass Flux Control System(MKS) for Argon gas propellant control



Plots of Argon gas fluxe dependence on pressure. Working pressure is between 5,0x10^{-4} Torr and 1,0x10^{-4} Torr.

Mass flow rate = 0,5 – 1,0 mg/s

- This plot is used to estimate the thrust efficience.
- Real time control gas flux system is on the left

PHALL I Operation Performance(merit figure) with typical plasma exaust velocities U=38000m/s – 52000m/s and electric power consumption in the 400W - 600W range

$$\vec{T} = \vec{U}\frac{d}{dt}m$$

$$T = \dot{m}\sqrt{\frac{2Pw}{\dot{m}}}$$

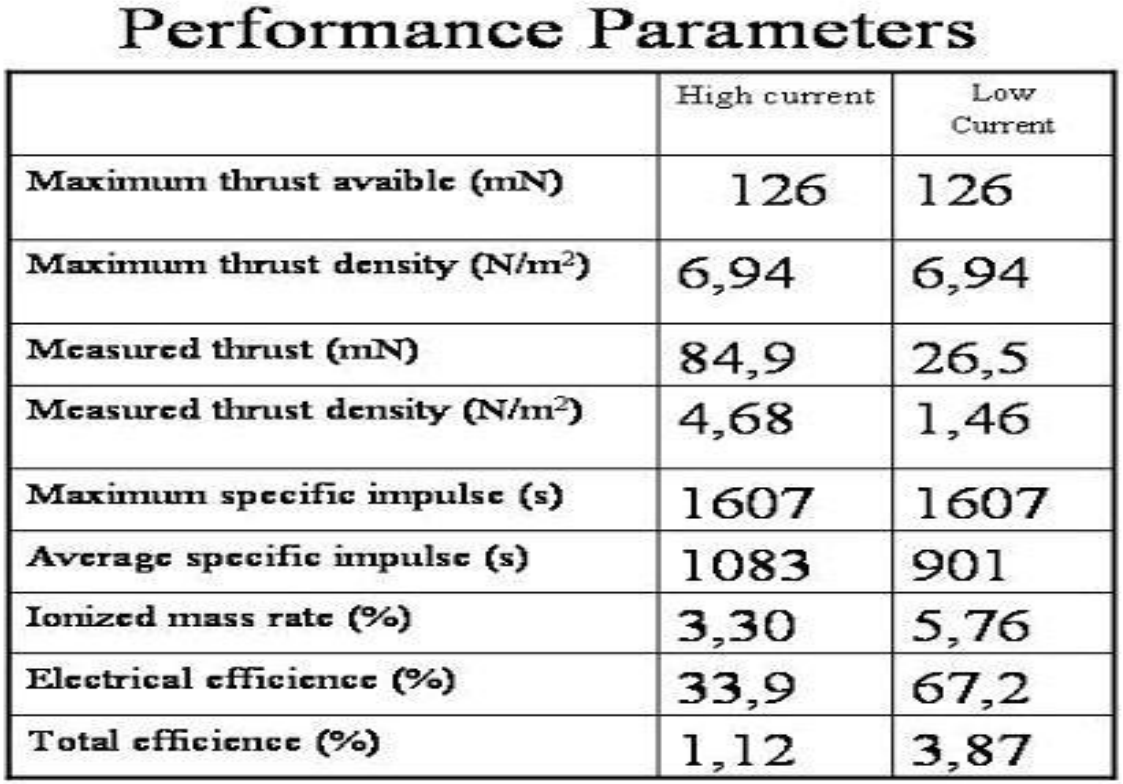
$$T = \dot{m}\frac{i_f}{Aqn}$$

$$I_{sp} = \frac{U}{g}$$

$$I_{sp} = \frac{T}{\dot{m}g}$$

$$\eta_{fmi} = \frac{MAn_i v_i}{\dot{m}}$$

$$mn\frac{d}{dt}\vec{U} = \vec{J}_H \times \vec{B}$$

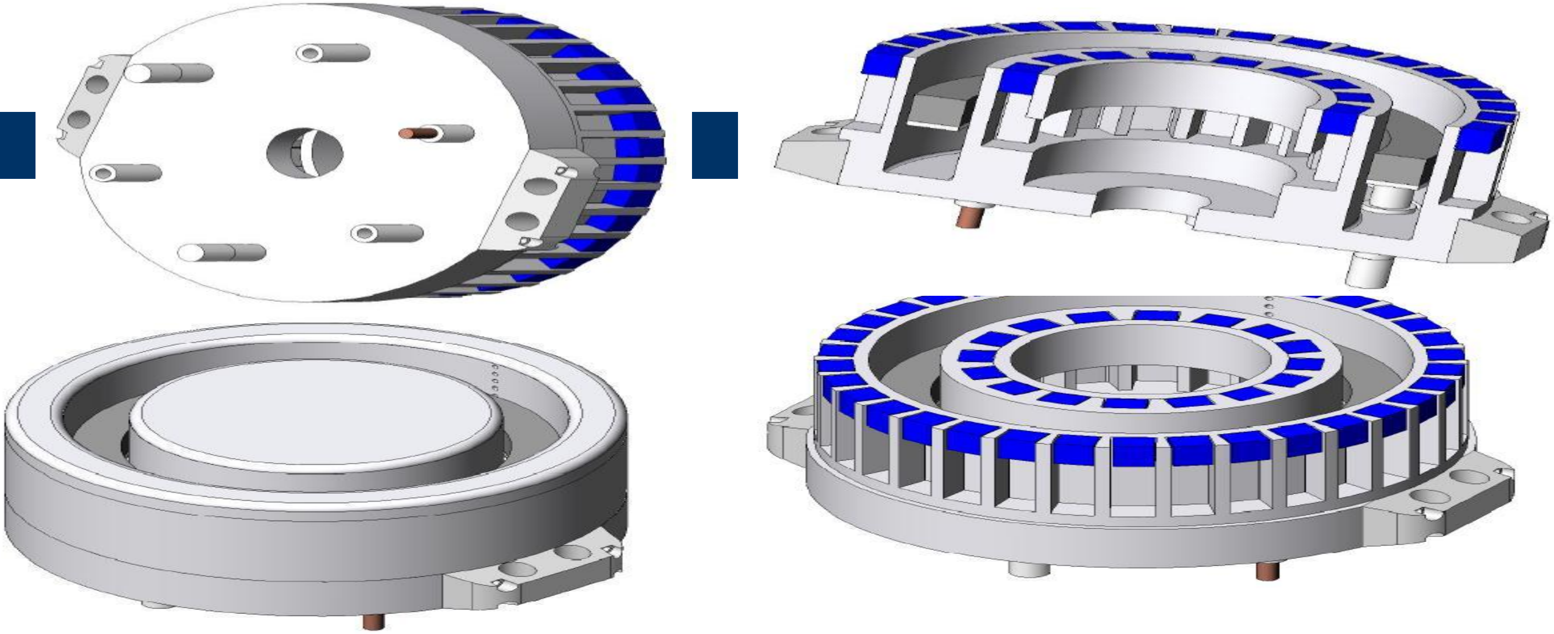


Performance Parameters

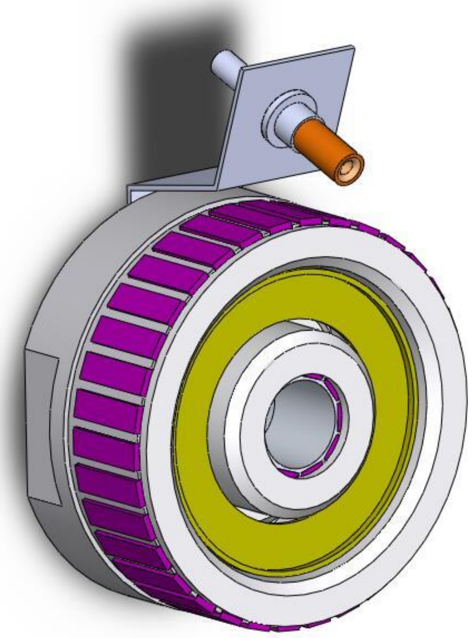
	High current	Low Current
Maximum thrust avaible (mN)	126	126
Maximum thrust density (N/m²)	6,94	6,94
Measured thrust (mN)	84,9	26,5
Measured thrust density (N/m²)	4,68	1,46
Maximum specific impulse (s)	1607	1607
Average specific impulse (s)	1083	901
Ionized mass rate (%)	3,30	5,76
Electrical efficience (%)	33,9	67,2
Total efficience (%)	1,12	3,87

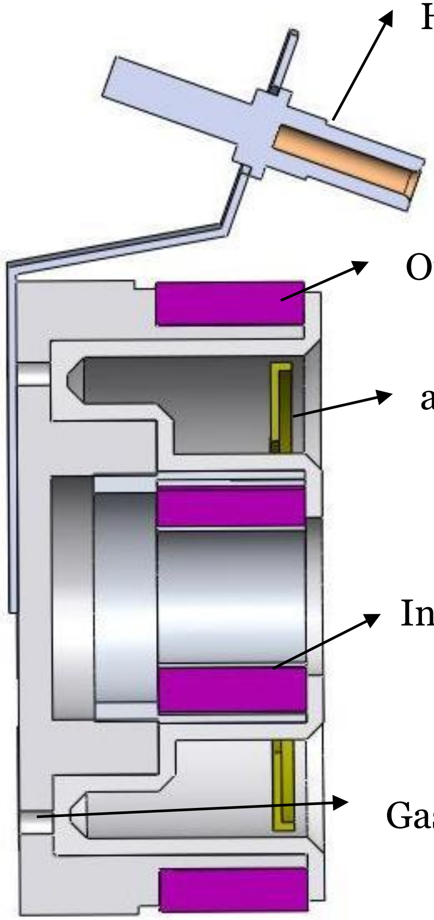
PHALL II Construction , Development and tests at UnB

Nd Fe magnets with 5kGauss at the surface



PHALL-2



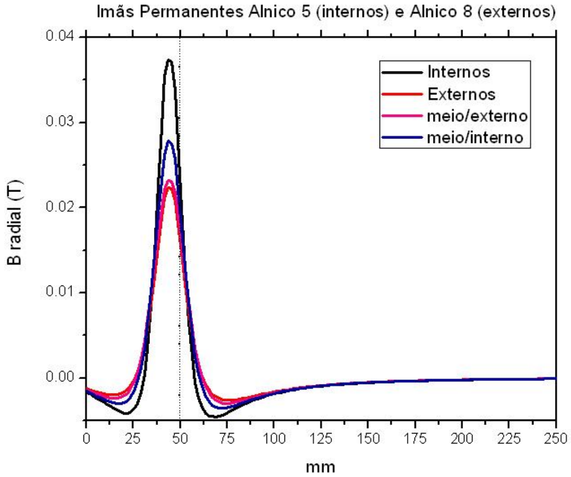

Hollow cathode

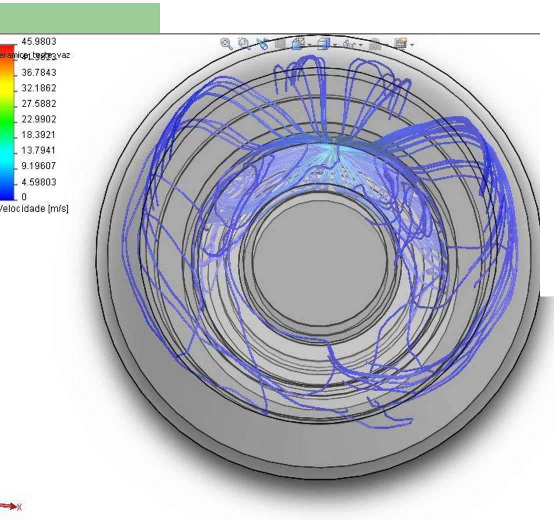
Outer magnets

anode

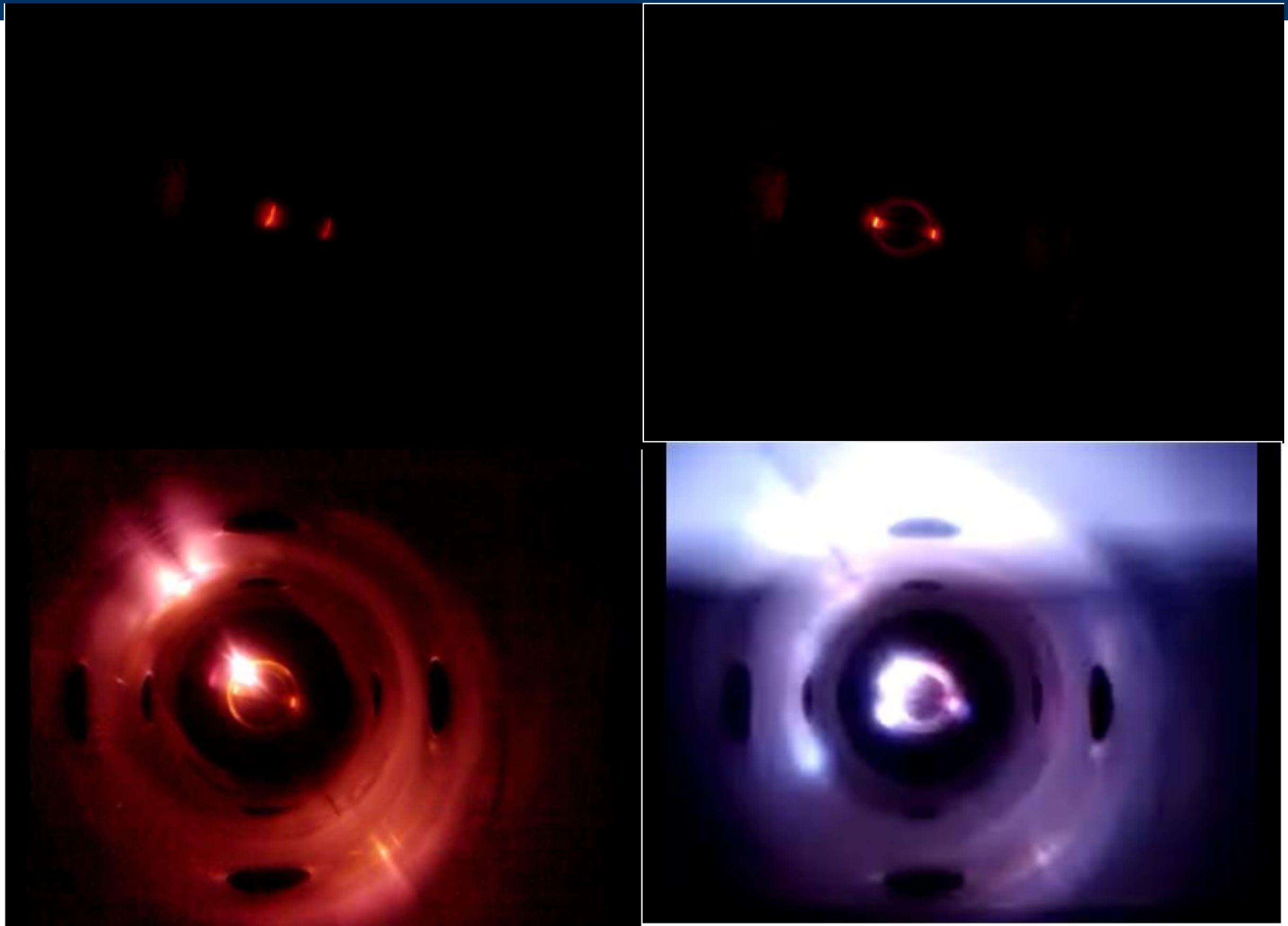
Inner magnets

Gas inlet





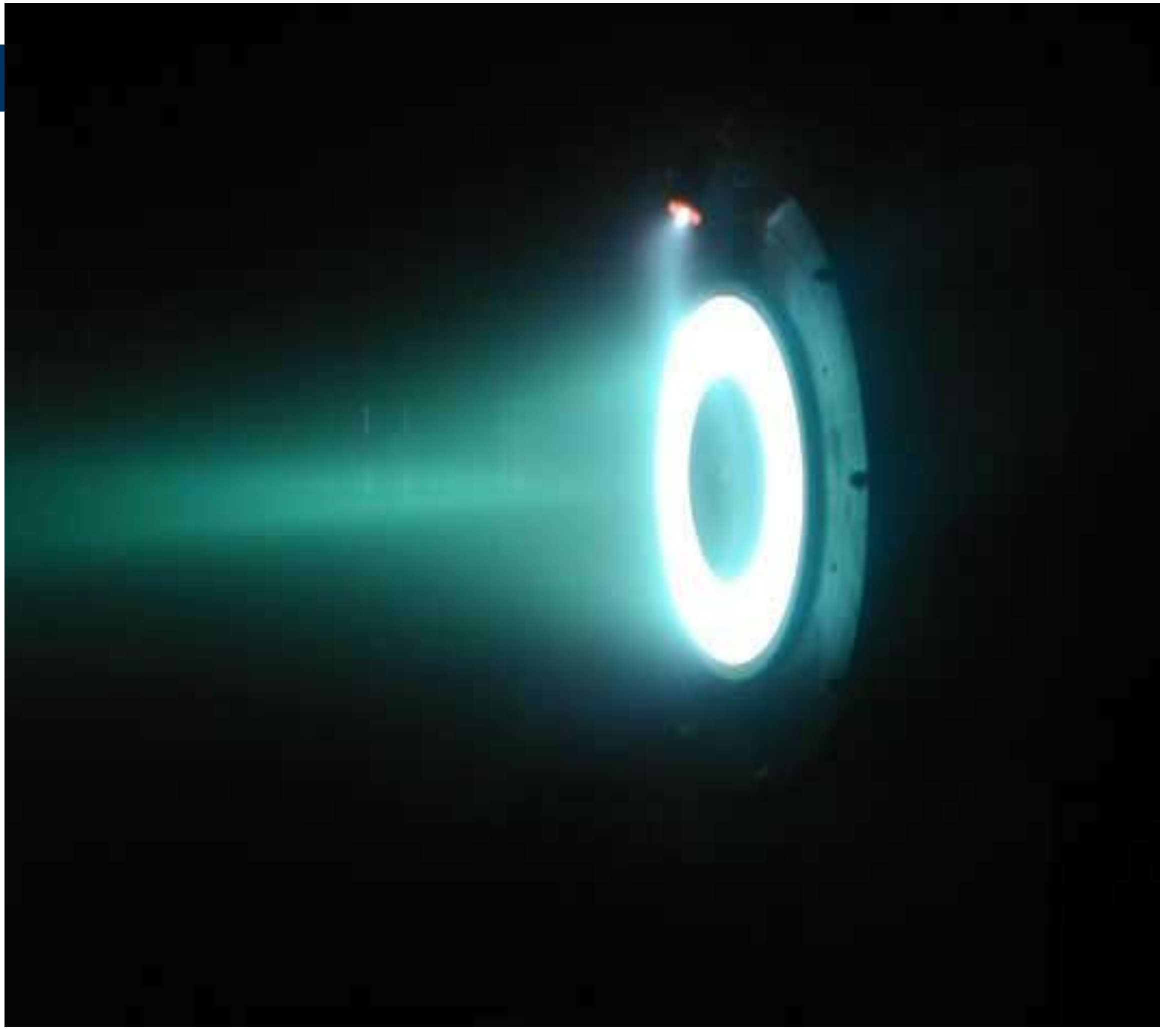
PHALL 2 - Preliminary tests using two redundant cathods



Experimental study of plasma instabilities decreasing by magnetic field increment in PHALL II channel

Medidas de oscilações de plasma de baixa frequência(f=3 Hz) no canal da corrente Hall utilizando câmera CCD com 640x480 pixels 15 frames/seg.

Simulação Computacional de plasmas em sistemas de propulsão elétrica do tipo Hall



Objectives:

-Develop numerical tools to study PHALL plasma formation and acceleration.

-Optimize the Permanent Hall Thruster geometry and working parameters.

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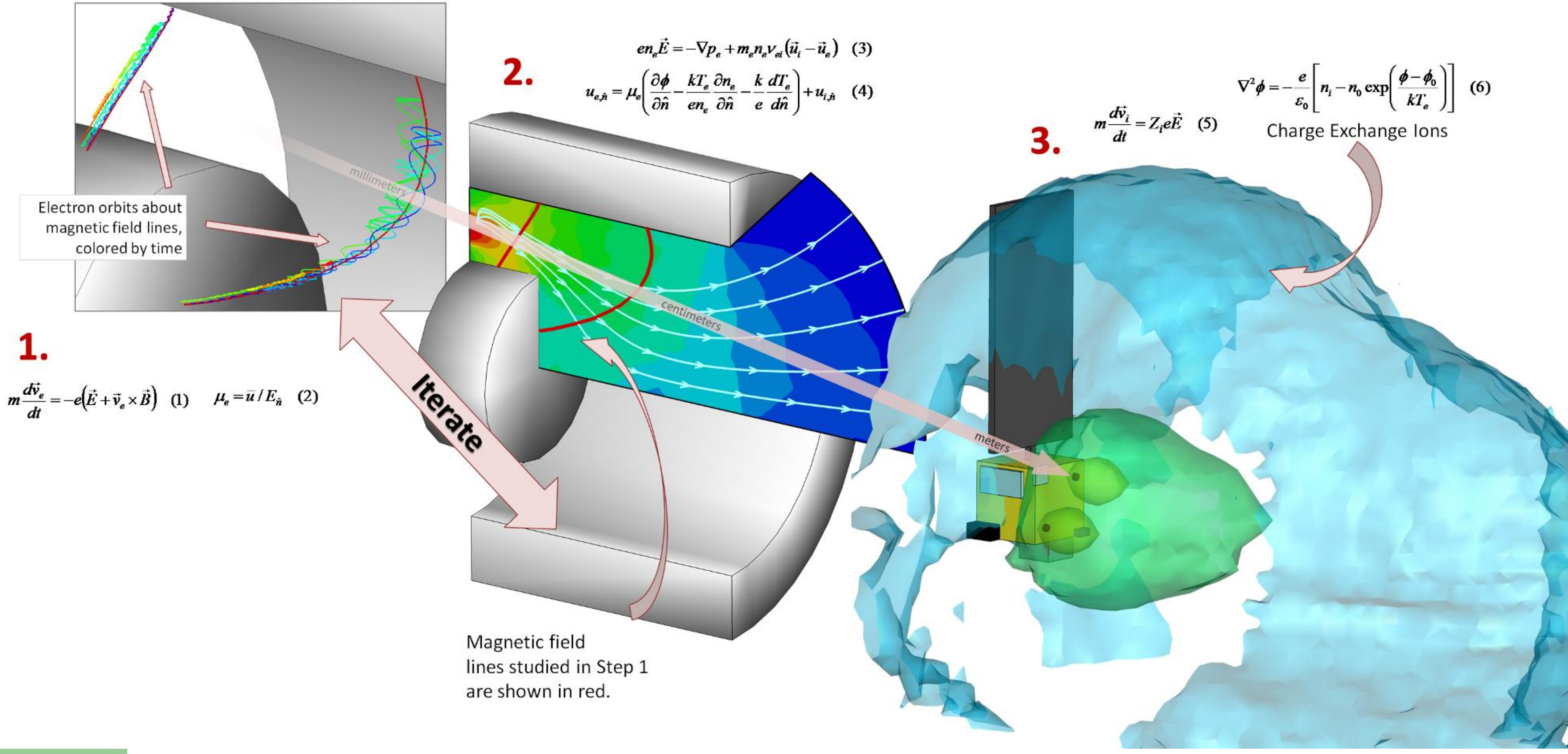
Laboratório de Plasmas
Universidade de Brasília – UnB
(*) Colaborador Curso Eng Aeroespacial FGA-UnB

PHALL plasma source regions to be studied by computer simulations

1. Magnetic field layer

2.Hall current channel

3. Plasma plume exausted region



$$m\frac{d\vec{v}_e}{dt}=-e\left(\vec{E}+\vec{v}_e\times\vec{B}\right) \quad (1) \qquad \mu_e=\overline{u}/E_{\hat{n}} \quad (2)$$

$$en_e\vec{E}=-\nabla p_e+m_e n_e \nu_{ei}\left(\vec{u}_i-\vec{u}_e\right) \quad (3)$$

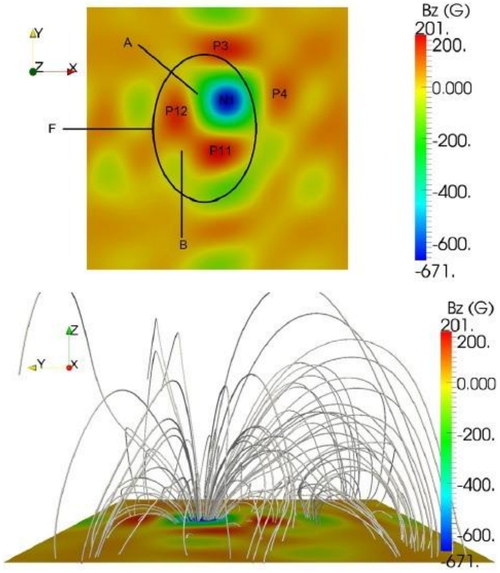
$$u_{e,\hat{n}}=\mu_e\left(\frac{\partial\phi}{\partial\hat{n}}-\frac{kT_e}{en_e}\frac{\partial n_e}{\partial\hat{n}}-\frac{k}{e}\frac{dT_e}{d\hat{n}}\right)+u_{i,\hat{n}} \quad (4)$$

$$m\frac{d\vec{v}_i}{dt}=Z_i e\vec{E} \quad (5)$$

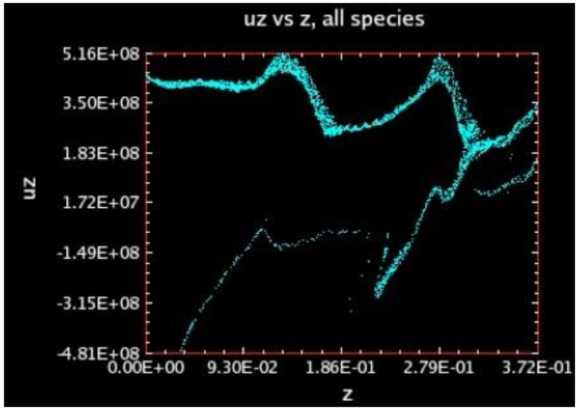
$$\nabla^2\phi=-\frac{e}{\varepsilon_0}\left[n_i-n_0\exp\left(\frac{\phi-\phi_0}{kT_e}\right)\right] \quad (6)$$

Fluid and Particle in cell computer codes

- 3D code with MHD equations also used in solar physics
- OOPIC PIC 2D code Simulate eléctrons, ions and neutral particles for different geometries of electric and magnetic fields

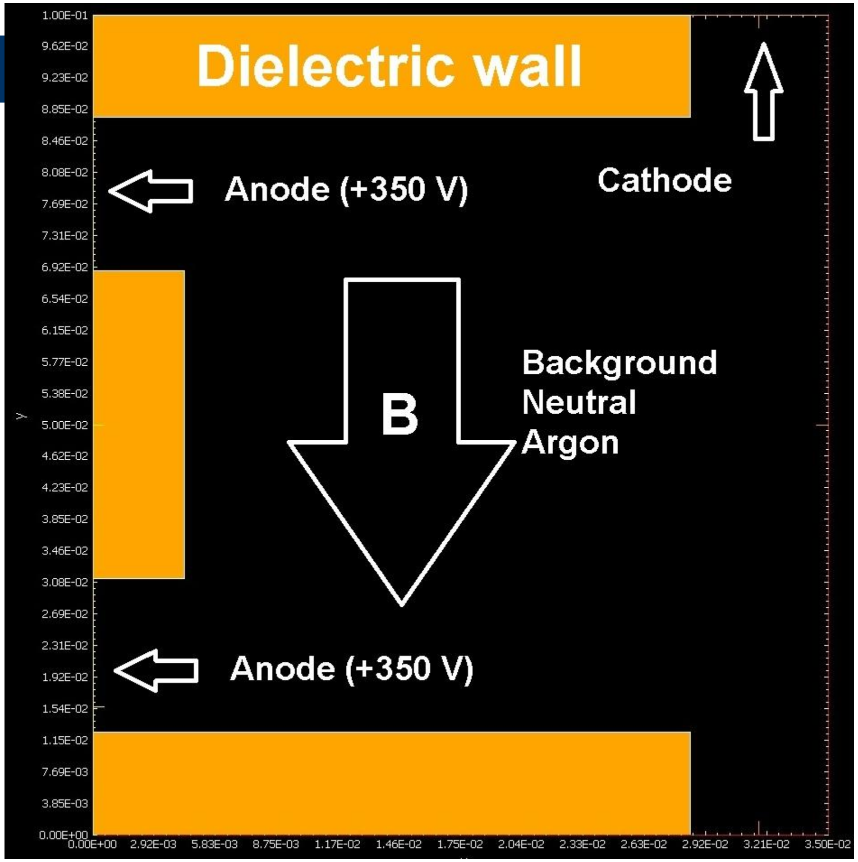


OOPIC Pro



OOPIC Code-Particle in cell computer simulation first results;

- Cross section of PHALL I cylindrical channel cavity with neutral argon atoms.
- Electrons injection and ion formation in the cavity are analysed



Computational particle in cell simulation using BRA Phase space for eletrons(Left)) and for íons(Right) injection in the PHALL 1 cilcindrical channel

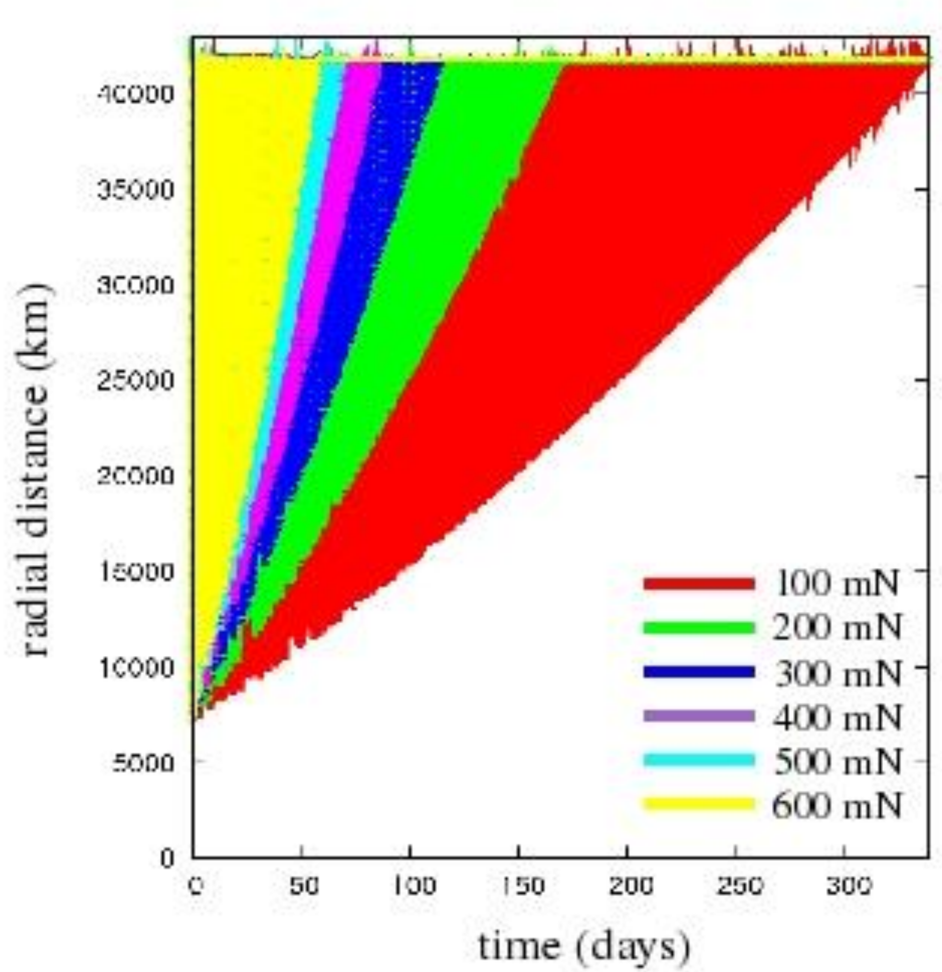
Numerical Computation of Satellite Orbit Transfer

Colaboration with FEG-UNESP and DMC-INPE

Satellite orbit transfer from LEO 700 km to a geostationary position using a Permanent Magnet Hall Plasma Thruster.

- The thrust has a constant magnitude and it is pointed tangentially to the satellite trajectory
- We consider earth flatenning and moon pertubation.
- We follow up: maneuvering time, altitude, semi major axis and eccentricity
- Satellite mass: 0.5 -1.5 T
- PHALL thrust : 100 – 600 mN
- Reverse integration ->we found out the necessary initial conditions in order to obtain a geostacionary orbit location for the satellite (e=0)

Satellite Orbital Evolution for several PHALL thrusts



Optimal orbit maneuvering with PHALL

Computer simulation studies of optimal orbital maneuvers considering the Phall Thruster I and II as the primary propulsion system.

The software used finds the optimal maneuver with the minimum fuel consumption considering the constrains imposed for the maneuver.

The optimal thrust angles presented are the pitch angles. They define the direction of the thrust, witch is the thrust direction perpendicular to the radius vector of the space vehicle trajectory.

The parameters of the PHALL I and II used are:

	PHALL 1	PHALL 2
Average measured thrust (mN)	84.9	120.0
Measured specific impulse (s)	1083	1600

Lunar polar satellite orbit using PHALL .

Main Goal

Maintenance of polar lunar orbits with low eccentricity.

Problem

Earth 's gravitational perturbations **=>** Lidov-Kozai resonance

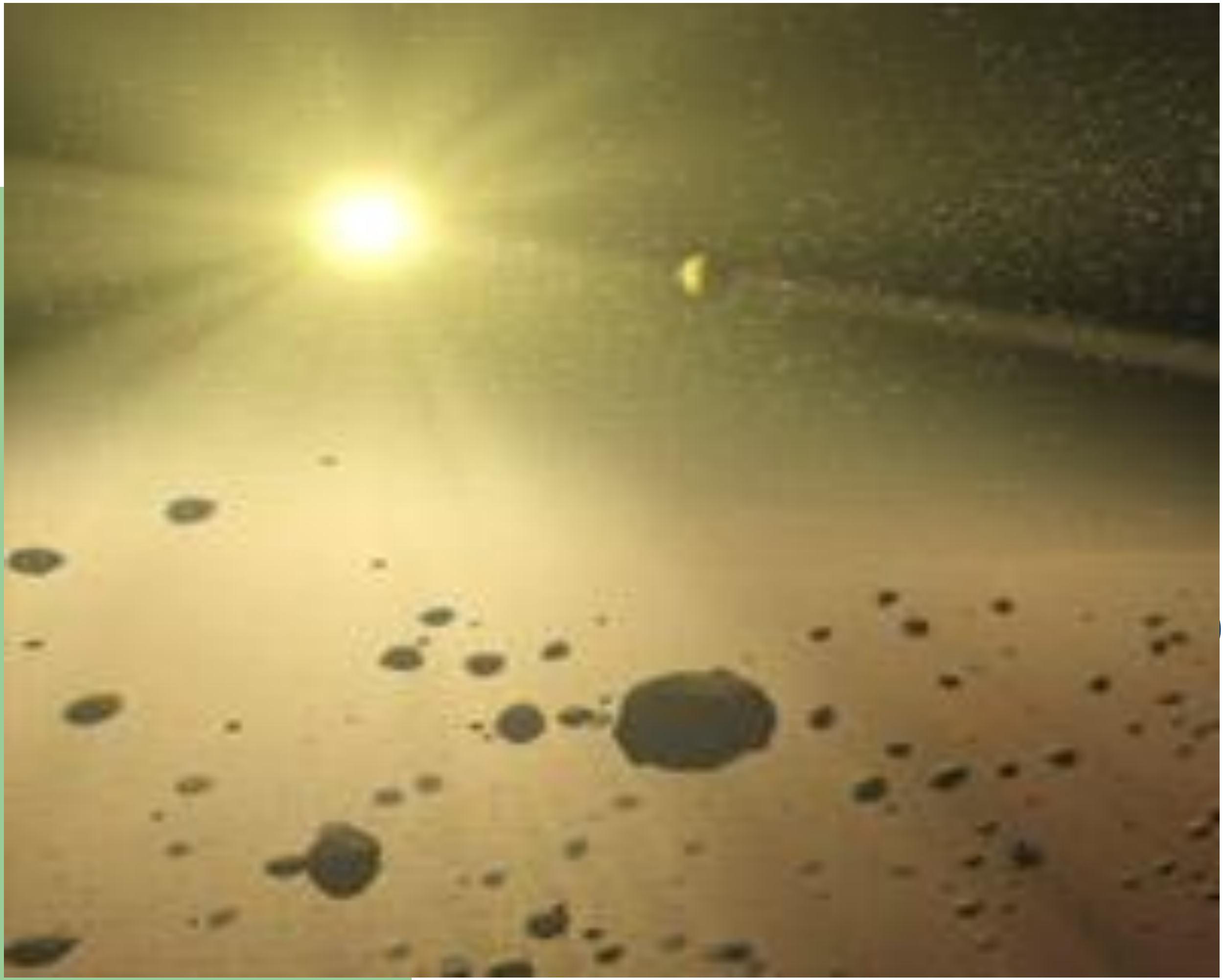
=> **e** increases **=>** shorter lifetime of the satellite due to its possible crash with the moon surface

Proposal

To control the growth of the eccentricity with low thrust propulsion produced by a Hall Plasma Thruster

ASTER PROJECT

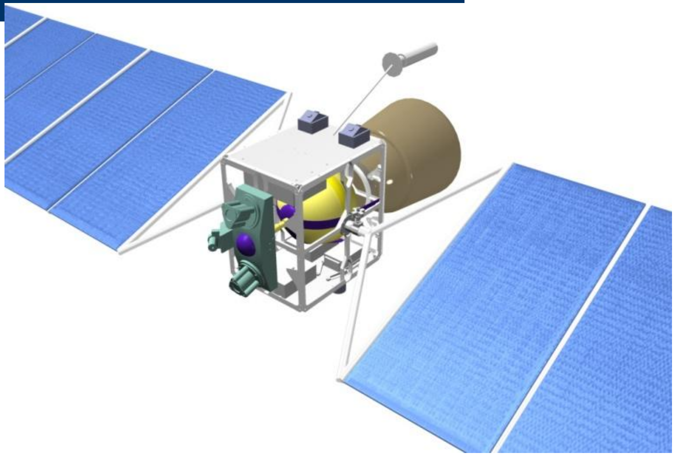
First Brazillian Deep Space Mission to explore a triple asteroid system



International Collaboration
Russian Space Platform from IKI

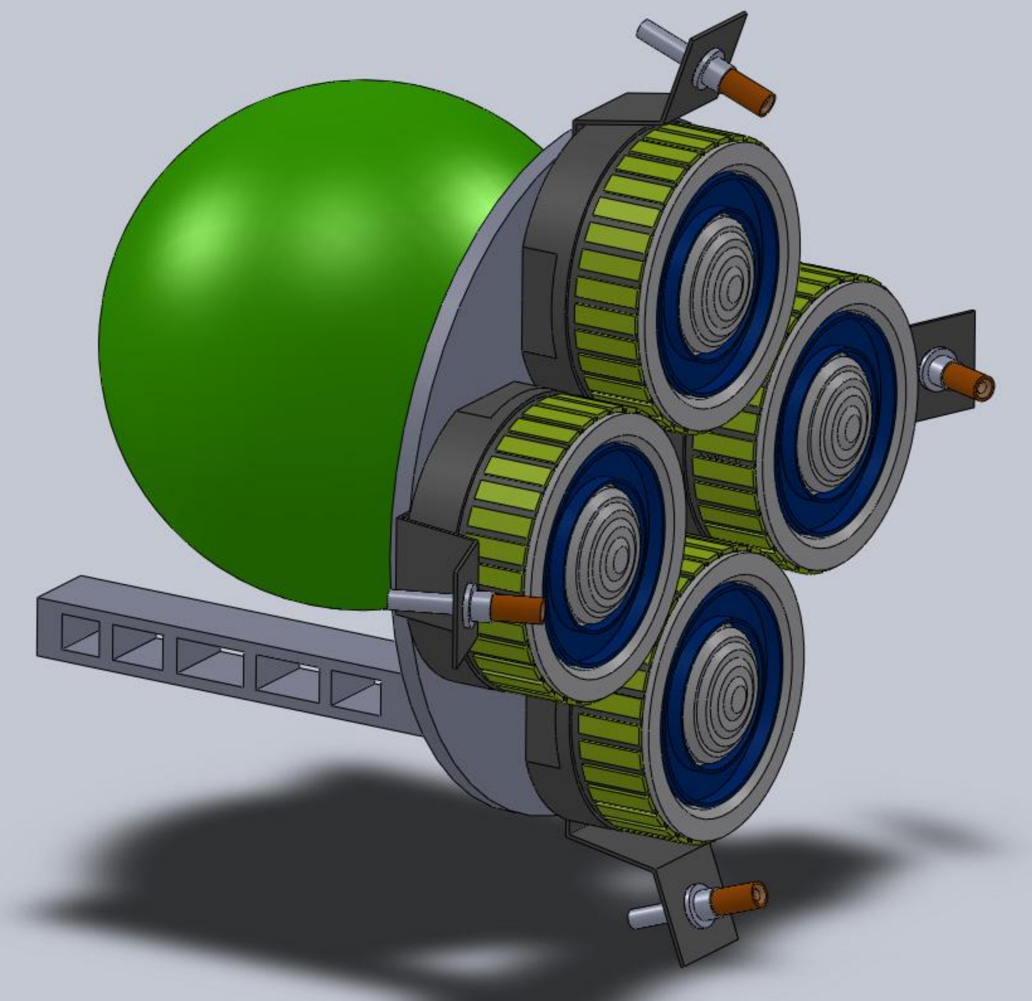
This space platform has been developed for a low-cost Martian mission MetNet

Initial wet mass	120 kg
Scientific payload	36 kg
Propellant (Xe)	43 kg
Nominal power	1.4–1.8 kW
Area of solar panels :	
amorphous silicon film	16–20 m^2
As-Ga	5 m^2
Thrust of 2 Hall thrusters D-55	80 mN

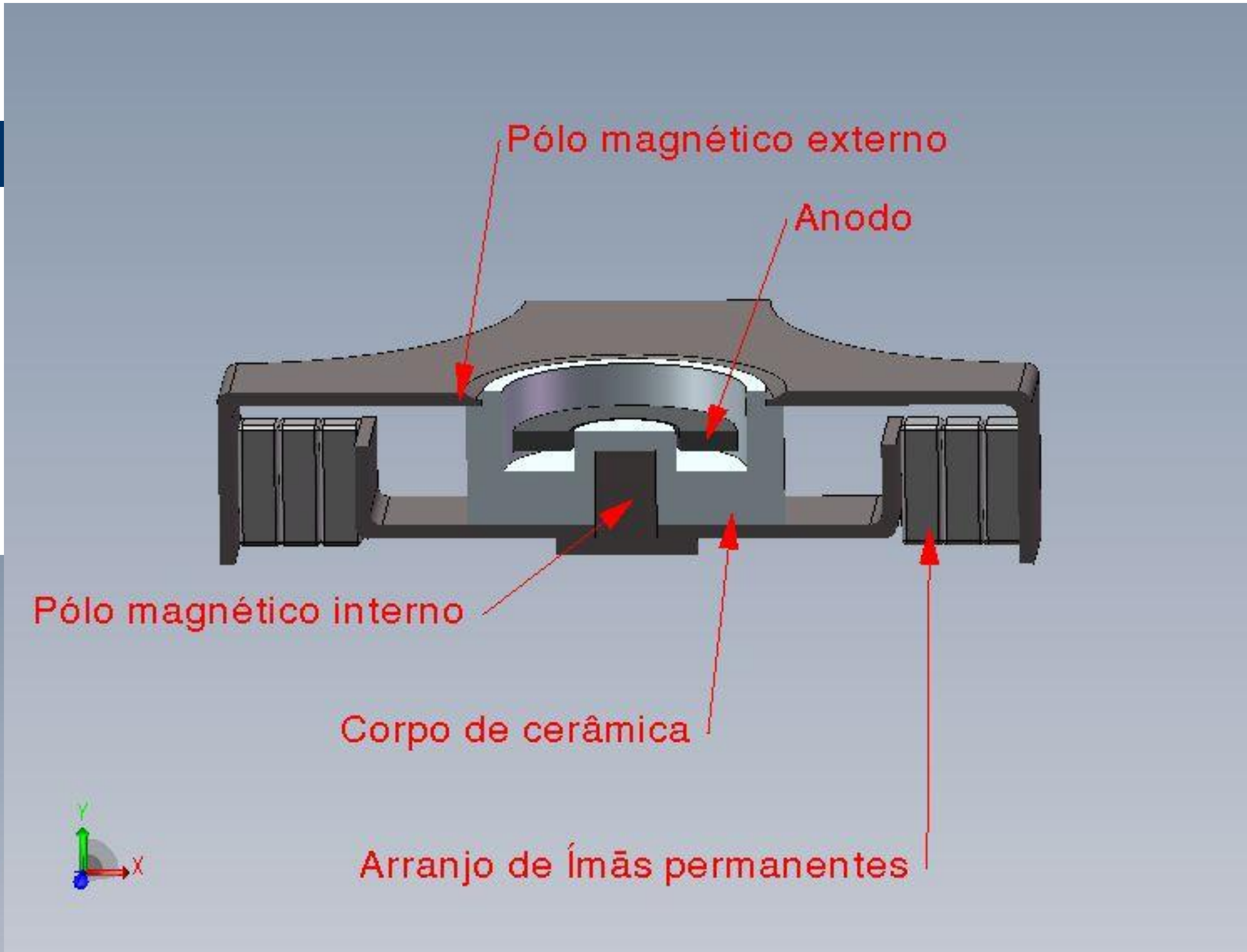


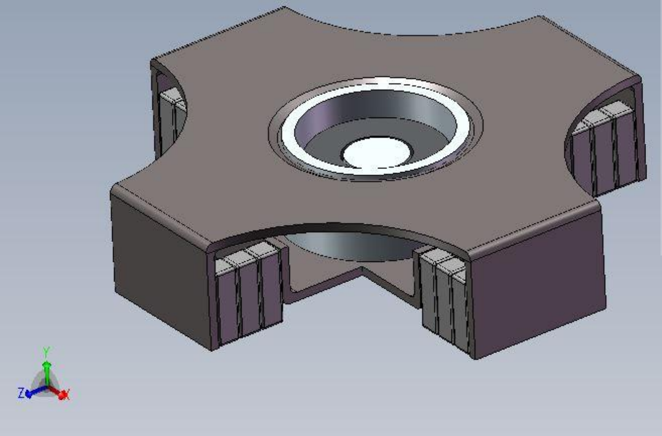
Permanent Magnet Hall Thruster (possible)Configuration for the ASTER Mission

4 Phall advanced with T=85 mN each I=2500s

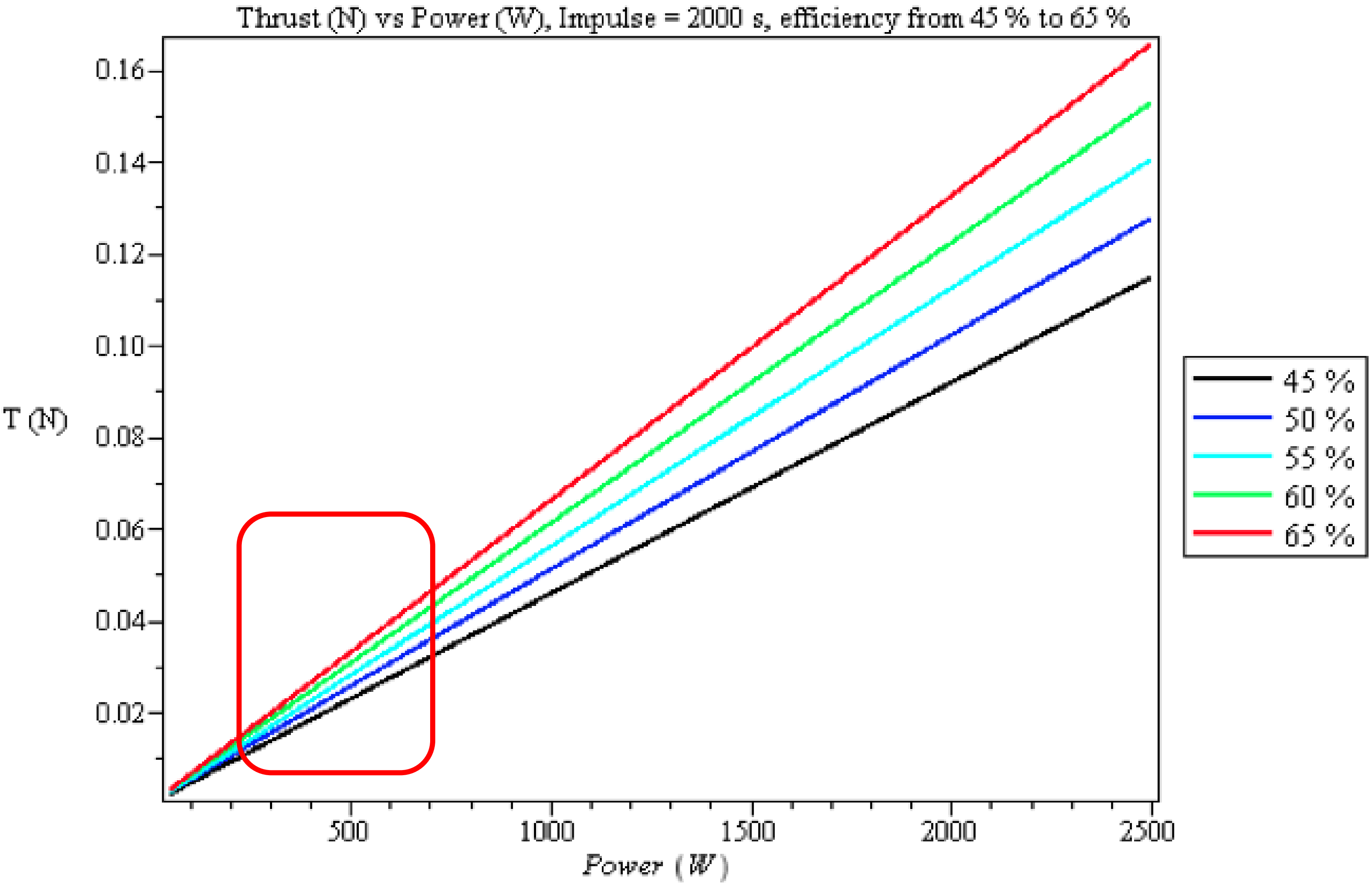


Plans for the near future research- PHALL-IIIa with adjustable permanent magnet fields. A new conception with high performance SmCo magnets.

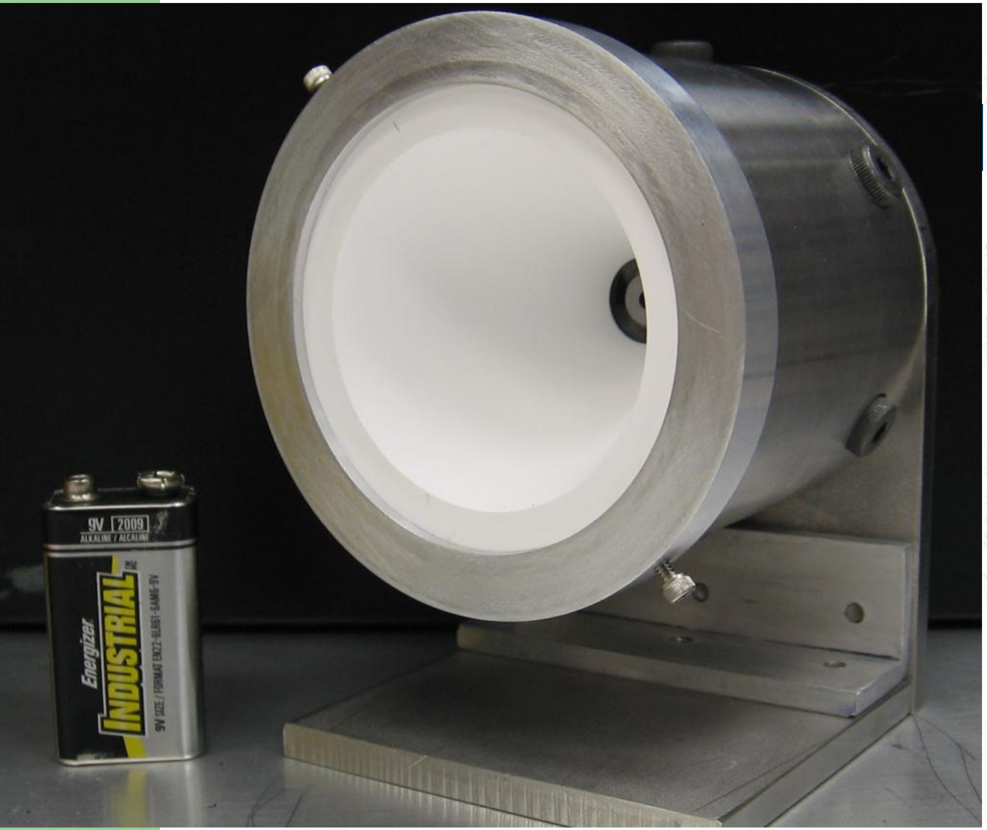


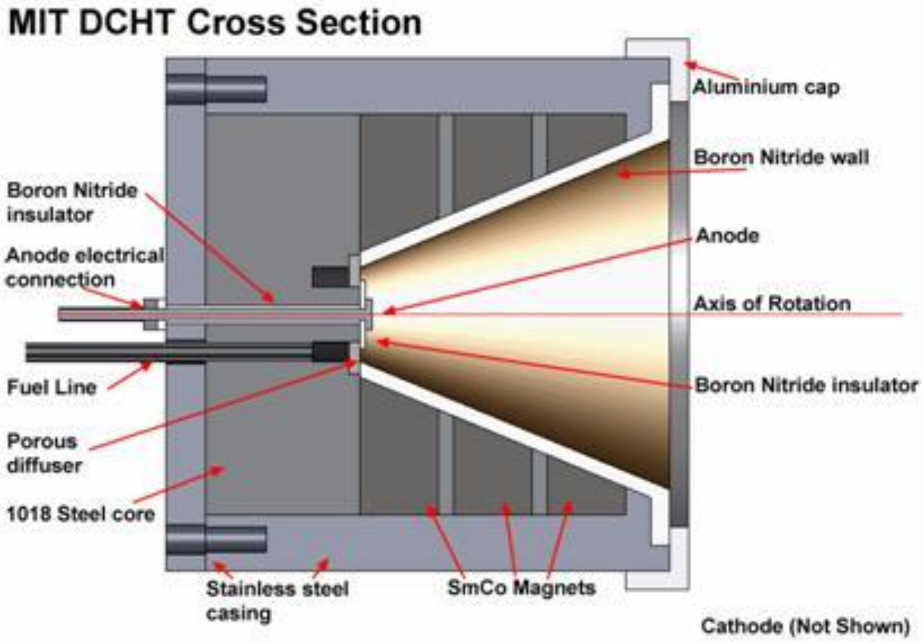


Propulsor PHALL-IIIa

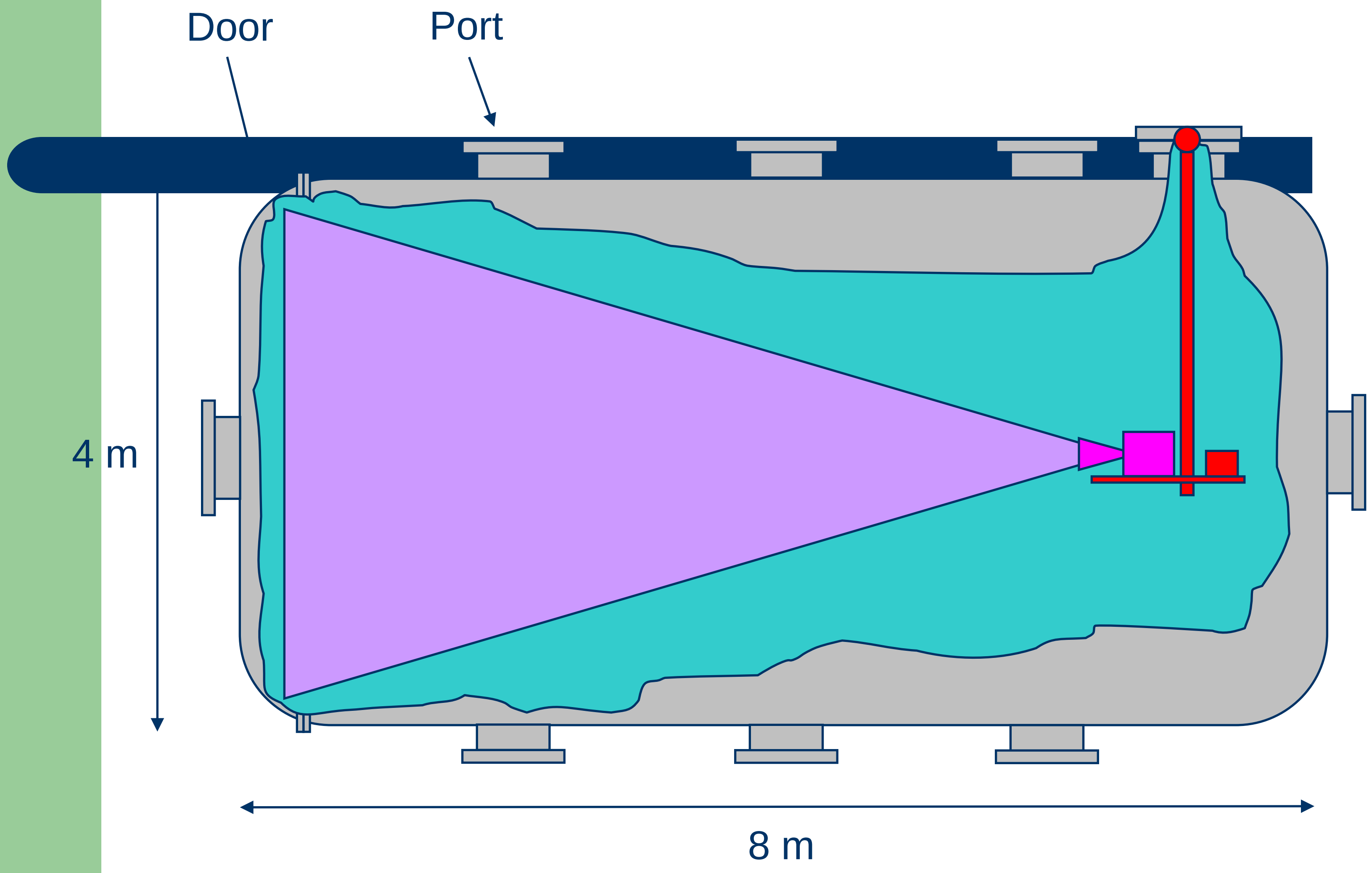


A new generation of compact simplified HALL thrusters(HEMP) (MIT-EUA and Thales Allenia at Stuttgard-Germany)





Vaccum test chamber for space qualification of PHALL (Thrust Balance)



NB: Only approx. to scale

Summary :

We have conducted an extensive experimental study of a Permanent Magnet Hall Thruster performance (PHALL 1 , 1 and PHALL 2) an using several plasma diagnostics technics resulting in the BID developement.

- - PHALL 1 performance shows that it is possible to operate sucessfully permanent magnet Hall Thrusters. They can be used on space missions withe additional advantage of possible saving up 30% of the electrical power supply of the spacecraft or satellite.

- -We have used sucessfully non intrusive plasma diagnostics detection technics to measure plasma instabilities and ion temperature. These measurements are essencial to construct a model for plasma particle transport during PHALL operation.

- - Uptitude figures of PHALL family were constructed to help foressen aplications of permanent magnet Hall thruster for several types of space missions:

- - Satellite orbit transfer from LEO to GTO and satellite de-orbiting(space debris ellimination)

Others future applications:

- -Electric propulsion systems for Station keeping of Future Brazillian Geostationary Satellites
- -Permanent Magnet Hall Thrusters for orbit control of Lunar polar satellites.
- Deep space missions on the solar system.

-Brazillian astronomical society and INPE are suggesting a mission to a, recently discovered, NEAR EARTH triple asteroid system . The Brazillian Space Agency is also studying the mission feasibility.

- Ackowledegments – We thank to **AEB , CNPq , CAPES and FAP-DF**
- **THANKS for your ATTENTION**