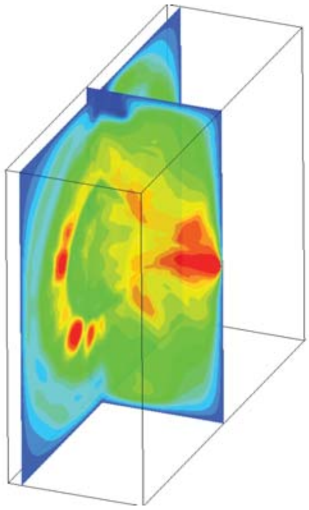
BOOK of ABSTRACT



International Workshop

IPAIA2017

Ion Propulsion and Accelerator Industrial Applications

CNR Research Area Bari

Sala Congressi

March 1-3, 2017

SCOPE OF THE MEETING

This workshop will provide a forum for the presentation and discussion on the progress in methods and technologies used for the research, development and industrial applications of ion propulsion (IP) for satellite and spacecraft.

Special emphasis will be given to possible ion propulsion applications to different technological fields such as energy (accelerator and ion sources for fusion) and material science (ion implantation, surface treatment, nanoparticle synthesis). Subtopics include: Modelling and simulation, Progress made on the different IP configurations, Plasma-wall interaction, Ion source physics, Accelerator Industrial Applications.

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International Workshop on Ion Propulsion and Accelerator Industrial Application

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Book of abstracts

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High Power Hall Thruster Design at SITAEL

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The increase of available power on board of modern spacecraft is paving the way to the use of very high power electric propulsion systems for a variety of deep space exploration missions to cislunar space, asteroids and planets of the inner solar system, as well as private commercial space missions. Hall thruster technology offers a favourable combination of performance, reliability, and lifetime for such applications. For these reasons, the attention of the electric propulsion community to the development of high power Hall Effect Thrusters (HETs) has been gradually increasing.

SITAEL is currently engaged in carrying out preparatory activities in the field of very high power HET-based electric propulsion. In the frame of the ESA TRP "Very High-Power Hall-Effect Thruster for Exploration", SITAEL has developed and tested a new 20kW class Hall Thruster, the HT20k, together with the associated high current cathode, the HC60.

The HT20k Hall Effect thruster is designed to operate at a nominal discharge power of 20kW. The thruster design is based on the extensive experimental and theoretical heritage of SITAEL in this field. A theoretical scaling methodology developed in past years, along with detailed numerical analyses conducted with a dedicated model have been used to size the HT20k and to estimate its performance envelope. The HT20k was expected to perform thrust levels of 1 N with efficiencies of about 60%. This prediction has been confirmed by the experimental characterization carried out in SITAEL's IV10 Vacuum Facility.

In the usual design of a HET, channel dimensions (in terms of length and height) are scaled so as to keep the involved physical processes unchanged with respect to the reference thruster (e.g. the Russian SPT 100). However, in the frame of the present project it was decided to opt for a different approach resulting in higher densities. This choice permitted to reduce the overall dimensions by about 20% with respect to a conventional-design thruster of the same power level. [figure 1]

The development of the HT20k also includes the assessment of non-standard magnetic field topologies aimed at drastically increasing the thruster lifetime. In its "magnetically shielded" variant which presents chamfered channel ceramics, the magnetic field is shaped to be almost tangent to the chamber edges. A preliminary numerical and experimental assessment of the magnetically shielded thruster showed that the erosion can be effectively reduced by more than two orders of magnitude, whereas performance, even though affected, remain close to those of the standard configuration.

The HT20k Hall thruster features an internally mounted hollow cathode, the HC60, located inside the inner pole of the magnetic circuit. Based on past experience with lower current applications, the thermionic hollow cathode configuration with a lanthanum hexaboride (LaB6) emitter was selected as the baseline configuration of the HT20k Hall effect thruster. The design was carried out through a dedicated numerical model previously developed at SITAEL and validated against experimental data of lower current class devices (from 1 to 20 A of discharge currents).

In the characterization campaign, systematic investigations aiming at optimizing thruster performance over an extended operating envelope were carried out. The HT20k was tested from 10 to 20kW on Xe, demonstrating a peak of anodic efficiency of 67% at 800V of discharge voltage and 12.5kW of discharge power. At power levels of 20kW, a maximum anodic efficiency of 64% was reached at 800V. The HT20k demonstrated anodic specific impulses greater than 2000s even at low voltages (300-350V).

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Small rf plasma generator for air

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Complex plasma devices as thrusters or ion sources for fusion and their physical models at reduced size, as the negative ion source NIO1 developed by Consorzio RFX and INFN-LNL, rely on several accessories, like coil shielding, cesium vaporizers, probes and bias electrodes, which needs to be separately tested , both to avoid delays in the major source schedule and to better understand features of those accessories. A simple plasma generator developed at INFN-LNL can be installed on standard pumped vacuum chambers. Air is used as feeding gas for economy; moreover spectroscopy of nitrogen allows for a determination of electron temperature Te in much simpler and direct way than in the other gas cases. Simple and direct diagnostics are described. Even in the present limitation of rf power level, reasonable dense (10^16 m^-3) and bright plasma can be produced, with a large degree of inductive coupling and Te about 4 eV (+/-1 eV) according to the still compelling scaling laws from global ionization balance models. On the other hand, oscillation of the plasma potential (possibly much larger then Te) can be studied as a function of the coil and bias configuration, and may indicate some residual capacitative coupling. Effect of these fluctuation on electron and ion flows inside plasma is worth investigation.

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Carbon-based materials for cathode neutralizers in electric propulsion

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Neutralizer cathodes used as electron sources represent a key component of electric propulsion (EP) systems for spacecrafts. In EP systems such as electric propulsion thrusters, ion engines and hall thrusters, a positive ion beam is ejected at high speed to produce thrust. Over time, the ion beam expands and becomes fuzzy for the space charge formation that reduces the thrust and causes arcing and back-ion bombardment that damage onboard instruments. Thus, neutralizer cathodes are needed to obtain an electron emission current equal or greater than the ion beam, so to maintain ion beam neutralization and restore spacecraft charge balance.

Typically, neutralizer cathodes utilized in Hall thrusters [1] are hollow cathodes that are not suitable for satellite stations because they require a limited number of ignition cycles and a long heating time for each ignition. For this reason, field emission (FE) cathodes with Spindt geometry [2] are presently considered as alternative to hollow cathodes. However, Spindt type cathodes made of microfabricated Mo [3] and Si [4] tips are predicted to malfunction in a simulated thruster environment due to the excessive ion-sputter damage.

Recently, innovative carbon-based materials, such as carbon nanotubes arrays [5, 6] and thin films of nanocrystalline graphite [7], are tested as field emitters featuring a current density of 1 A/cm2 and an ion-sputter resistance higher than that of Mo and Si. Among carbon-based materials, diamond exhibits superior chemical and physical properties, such as high hardness, corrosion resistivity, chemical inertness and excellent photo-, thermo- and field-electron emission. This, thanks to its negative electron affinity if the surface is hydrogenated and low work function if it is doped.

In this contribution a number of emissive measurements of nanocrystalline diamond (NCD) and N-doped diamond films produced by the microwave plasma enhanced chemical vapor deposition (MWPECVD) technique starting, respectively, from CH4-H2-Ar and CH4-H2-N2 gas mixtures, and of nanodiamond (ND) layers deposited by the pulsed spray technique using nanoparticles of about 250 nm dispersed in solvents, are illustrated.

The NCD films were grown at different values of the deposition temperature that affects the shape and size of grains and, as a consequence, the fraction volume of grain boundaries with the amount of incorporated hydrogen that modulates the surface electron affinity. The NCD films grown at the highest deposition temperature featured the highest photo- and thermoionic emission currents [8].

The N-doped diamond films were produced by using variable N percentages, i.e. 0, 0.2, 0.5, 1, 3.5, 5 and 6 %, to the CH4-H2 gas mixture. The quantum efficiency (QE) of photocathodes was assessed in the UV range from 140 to 210 nm for all samples, before and after plasma treatments in pure H2 and H2-N2 (25-75%) plasmas. Both the hydrogenated and hydro-nitrogenated films showed an enhancement of the QE up to 38% at 140 nm, with respect to the untreated aged ones [9].

Two types of ND powders with particle size of about 250 nm and having different sp2 (graphite phase) and sp3 (diamond phase) C contents were examined. The photoemission results showed that the QE values depended on the type of NDs. In particular, the rich-graphite ND layers are more photoemitting (QE=47% at 140 nm, [10-12]) than the rich-diamond ones, for both as-received and hydrogenated ND powders. The values obtained represent the highest QE achieved by diamond-based devices in the current literature, and encourage the application of these films and layers as neutralizer cathodes in small aerospace thrusters.

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Vibrational Kinetics of Electronically Excited States in H2 Discharges

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The evolution of atmospheric pressure hydrogen plasma under the action of repetitively ns electrical pulse has been investigated using a 0D state-to-state kinetic model that self-consistently couples the master equation of heavy particles and the Boltzmann equation for free electrons. The kinetic model includes, together with atomic hydrogen states and the vibrational kinetics of H2 ground state, vibrational levels of singlet states, accounting for the collisional quenching, having a relevant role because of the high pressure. The mechanisms of excitations, radiative decay and collisional quenching involving the excited H2 states and the corresponding cross sections, integrated over the non-equilibrium eedf to obtain kinetic rates, are discussed in the light of the kinetic simulation results, i.e. the time evolution during the pulse of the plasma composition, of the eedf and of the vibrational distributions of ground and singlet excited states.

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Electron drift instability and secondary electron emission in Hall effect thrusters: An insight from bidimensional particle-in-cell simulations

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Despite electric propulsion (EP) having its beginning in the 1960's, its full potential has only been realized in the last few years, with all-electric communication satellites and large small-satellite constellation projects. Since Hall effect thrusters (HETs) are one of the most successful EP technologies, there is an increasing need for accurate and predictive models, in order to develop more effective, more powerful, and more energy efficient thrusters.

Typical HETs consist of three main components: (1) An external hollow cathode, providing electrons to sustain the plasma discharge and to neutralize the ion beam. (2) An annular ceramic channel where the propellant gas is injected through an anode, ionized, and accelerated (due to a potential difference applied between the anode and cathode). (3) A specially designed magnetic circuit used to produce a predominantly radial magnetic field to trap electrons in the channel region.

Numerous studies have shown that the electron mobility across this imposed magnetic field tends to be anomalously high in comparison to the predictions from classical diffusion theories. Historically, multiple mechanisms have been proposed to explain this anomaly: Intense secondary electron emissions (SEE), sheath instabilities, gradient driven instabilities, or electron drift instabilities.

The effect of these latter drift instabilities on the electron mobility has been recently investigated theoretically, and since unscaled 3D PIC simulations are still out of reach, r-theta simulations using a 2.5D PIC simulation model where used to investigate this correlation. However experimental as well as simulation studies show that walls materials, and thus secondary electron emissions, do play an important role in the plasma discharge behavior. Hence the model was extended with a well-known linear SEE model in order to investigate their effects on the electron anomalous transport through a parametric study.

These model improvements enabled a deeper look into the thruster operation, and allow us to differentiate the relative importance of some of the mechanisms producing enhanced electron transport as well as identifying plasma discharge regimes.

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Helicon Propulsion Technology perspective for Minisatellites

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Propulsion technology based on helicon thruster was always considered promising because in principle it allows for long life time and versatility in using different type of gases. It is relatively compact with respect to other thruster technologies and thus is also considered promising for high power applications.

Moreover, helicon thruster technology has some remarkable features which makes it cheaper with respect to other propulsion technologies and thus attractive for very small satellites.). Most relevant features are: (i) simple structure, (ii) no neutralizer, (iii) PPU does not need to provide high DC output. Such a technology would introduce mobility to small spacecrafts, providing new unconventional opportunities for low cost missions.

However, to be implemented, reasonable performances need to be achieved in the range 15-50 W, which is a challenging target considering that most of the other electric engines have a performance-drop below 50W.

To achieve such demanding results, a strong research effort has been initiated in 2008 at University of Padua through an international consortium (HPH.com), which led in 2012 to the development of a first engineering model operating at 50 W. After four more years of development, a completely new miniaturized unit based on a helicon thruster has been developed and characterized with extensive performance test, showing remarkable results in the power range between 15-50 W.

In this presentation, the numerical and experimental work performed is presented and the achieved results are described.

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ESA Perspectives on Electric Propulsion

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Today electric propulsion is considered or being used for several applications such as orbit raising/orbit topping and station keeping of telecommunication satellites, orbit maintenance and deorbiting of constellations of small satellites (OneWeb, LEOSAT, SpaceX, etc.), for transfer manoeuvers (e.g. BepiColombo transfer to Mercury), formation flying of satellites, etc. The required thrust levels for all these applications span over a wide range from several micro-Newton up to hundreds of milli-Newton which means that a large variety of thrusters is required to cover the different needs.

In the commercial area, the strong completion among satellite manufacturers is a major driver for advancements in the field of electric propulsion, where improved performance together with reduced costs are required. New scientific and Earth observation missions dictate new and challenging requirements for propulsion systems. Moreover, new interplanetary missions in the frame of exploration will require sophisticated propulsion systems to reach planets such as Mercury or Mars and in some cases bring back to Earth samples from these planets. Finally, electric propulsion might also be used in the Galileo 2G programme to perform orbit raising in order to increase the payload capability and reduce launch costs.

ESA is supporting European Industry in order to be able to provide competitive product. Therefore, ESA is involved in activities related to spacecraft electric propulsion ranging from basic research activities and development of conventional and advanced concepts to the manufacturing, Assembly, Integration and Verification (AIV) and flight control of propulsion subsystems of several European satellites. The exploitation of flight experience is also an important activity at ESA in order to help mission designers to implement the lessons learnt in the development of new propulsion systems.

ESA mission such as Artemis, Smart-1, GOCE and Alphabus have paved the way for the use of electric propulsion in future ESA missions: BepiColombo, Neosat, Electra, LISA, etc.

In the last years, electric propulsion has also been identified by European actors as strategic technology for improving European competitiveness in different space areas such as in-space operations and transportation. For this reason the European Commission has set up the "In-space Electrical Propulsion and Station-Keeping" Strategic Research Cluster (SRC) in Horizon 2020 with the goal of enabling major advances in electric propulsion in order to contribute to guarantee the leadership of European capabilities in electric propulsion at world level within the 2020-2030 timeframe, always in coherence with existing and planned developments at national, commercial and ESA level. The "Electric Propulsion Innovation & Competitiveness" (EPIC) is the Programme Support Activity (PSA) for the Electric Propulsion SRC. ESA is the EPIC project coordinator. In the frame of EPIC a total of six the operational grants have been awarded: three for incremental technologies and three for disruptive technologies.

ESA is also coordination research activities in the field of plasma-spacecraft interactions with the goal to provide an improved modelling tool for electric propulsion induced plasma-spacecraft interactions.

Furthermore, ESA is working on standardization of electric propulsion testing and qualification. Standardization is necessary in order to meet the need for cost reduction that can be achieved through optimised production and verification programmes. This optimisation requires reliable testing, comparability between test facilities and defined qualification standards.

Testing activities for electric propulsion systems can be performed at the ESA Propulsion Laboratory (EPL), that is an operational facility located at the European Space Research and Technology Centre (ESTEC) of the European Space Agency (ESA). The EPL provides test services to the ESA Propulsion and Aerothermodynamics Division, which is responsible for R activities and support to projects in the areas of chemical propulsion, electric and advanced propulsion as well as aerothermodynamics.

Since 2004 the EPL holds an ISO 17025 accreditation. Accredited mass-flow, thrust (down to the micro Newton level) and electrical power measurements for electric and cold-gas thrusters and components are performed at the EPL. Furthermore a number of electrostatic probes are available at the EPL for the investigation of plasma parameters in the plume of electric propulsion devices. The EPL also offers support to ESA projects and technology development activities in the field of propulsion. Currently the EPL is involved in activities linked to the standardization of electric propulsion testing. EPL activities have been expanded to chemical propulsion

(cold-gas and other non-toxic propellants) and propulsion component (pressure drop characterisation and waterhammer tests) testing as well as aerothermodynamics (sloshing bench).

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Kinetic modeling of electrostatic ion thrusters

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The development of optimized electrostatic ion thrusters for space propulsion is until now a trial-and-error procedure. The need for expensive prototypes, extensive testing and iterative improvements is non-optimal in terms of time and costs. In other fields of research modeling is used to minimize the number of iterations, replacing real prototypes by virtual prototypes tested in numerical test environments. A typical example for this is car industry and the development of new car models, where numerical wind tunnels replace more and more real tests. Based on integrated models, combining self-consistent kinetic plasma models with plasma-wall interaction modules a new quality in the description of electrostatic thrusters can be reached. These open the perspective for modeling in this field. This will be discussed for the example of the HEMP (High Efficiency Multistage Plasma) thruster patented by Thales Electron Devices. HEMP thrusters represent a new type of grid less ion thrusters with a particular magnetic confinement of the plasma electrons. In the HEMP thrusters the specific magnetic field topology provided by a sequential arrangement of magnetic stages with cusps efficiently confines the plasma electrons and minimizes plasma-wall contact. Electron movement towards the thruster anode is strongly impeded by this magnetic field topology to form steep electrical field gradients for effective ion acceleration. As a consequence, the HEMP thruster concept allows for a high thermal efficiency due to both minimal heat dissipation and high acceleration efficiency, and for a wide range of operational parameters.

2

High thrust-over-power collisional Hall thruster

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The possibility of realizing a high thrust-over-power collisional Hall thruster will be discussed.

A major figure of merit in propulsion in general and in electric propulsion in particular, is the thrust per unit of deposited power, the ratio of thrust over power. We have recently demonstrated experimentally and theoretically [1-5] that for a fixed deposited power in the ions, the momentum delivered by the electric field is larger if the accelerated ions collide with neutrals during the acceleration. The higher thrust for given power is achieved for a collisional plasma at the expense of a lower thrust per unit mass flow rate, reflecting what is true in general, that the lower the flow velocity (and the specific impulse) is, the higher the thrust for a given power. This is the usual trade-off between having a large specific impulse and a large thrust. Broadening the range of jet velocities and thrust levels is desirable since there are different propulsion requirements for different space missions. Operation in the collisional regime therefore can be advantageous for certain space missions.

I will review our experimental results that show the increase of thrust-over-power due to collisions. The increase is found to be proportional to the square root of the number of collisions. The configuration used was of a crossed electric and magnetic fields, as in the Hall thruster, so that the source of the thrust is the magnetic pressure. Tailoring the magnetic field profile in order to modify the electric field will be examined.

Sources of inefficiency will be discussed. The electron cross-field transport is increased as the gas pressure in the acceleration channel is increased. As a result, the current utilization is reduced. The energy utilization is reduced as the spread in energy of ions and neutrals is increased by ion-neutral collisions.

Momentum delivery to neutrals on the few eV level should be examined for other industrial applications in addition to electric propulsion.

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HYBRID MODELLING OF SINGLE AND DOUBLE STAGE HALL THRUSTERS

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Hall Thrusters (HTs) – also referred as Stationary Plasma Thrusters (SPT) in the literature – are now a mature technology to be used on board satellites to maintain a spacecraft on a geostationary orbit and for scientific probe missions able to explore the solar system. In a HT, a heavy gas, most often xenon, is introduced through an anode plane and is ionized by an electron current coming from a cathode located outside the thruster channel. In order to increase the ionization mean free path, a radial magnetic field – maximum in the exhaust plane – is applied to impede the axial transport of the electrons. The discharge takes place in an annular channel between two concentric cylindrical walls. The channel walls are composed of dielectric materials that serve to protect the magnetic circuit from ion erosion. The applied voltage between the anode and the cathode, concentrated in the region of low conductivity/large magnetic field, serves to heat the electrons and to accelerate the ions in the axial direction that supply the thrust.

The mission domain of HTs has recently enlarged since they are also possible candidates to replace chemical thrusters for orbit transfer. The dual-mode operation of a HT consists to firstly operates at high thrust and low ion velocity to minimize the orbit transfer duration and to secondly operates at ion velocity and low thrust to minimize the propellant consumption. Nevertheless, for a given electric power, the use of a Single Stage HT (SSHT) is not able to fulfill these two missions. Double Stage HT (DSHT) concepts have been proposed and tested. Two-dimensional transient hybrid model results for SSHT and DSHT concepts will be presented.

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EXPERIMENTAL AND THEORETICAL STUDY OF ION BEAM NEUTRALIZATION BY PLASMA

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Producing an overdense background plasma for neutralization purposes with a density that is high compared to the ion beam density is not always experimentally possible. We show experimentally [1] and making use of particle-in-cell simulations [2,3] that even an underdense background plasma with a small relative density can achieve high neutralization of intense ion beam pulses if enough electrons are available to neutralize the ion beam space charge on plasma boundaries. Using particle-in-cell simulations, we show that if the total plasma electron charge is not sufficient to neutralize the beam charge, electron emitters are necessary for effective neutralization but are not needed if the plasma volume is so large that the total available charge in the electrons exceeds that of the ion beam [2]. Several regimes of possible underdense/tenuous neutralization plasma densities are investigated with and without electron emitters or dense plasma at periphery regions, including the case of electron emitters without plasma, which does not effectively neutralize the beam. Over 95% neutralization is achieved for even very underdense background plasma with plasma density 1/15th the beam density. We compare results of particle-in-cell simulations with an analytic model of neutralization and find close agreement with the particle-in-cell simulations.

We present experimental results on charge neutralization of a high-perveance 38 keV Ar beam by a plasma produced in a Ferroelectric Plasma Sources (FEPSs) discharge [1]. By comparing the measured beam radius with the envelope model for space-charge expansion, it is shown that a charge neutralization fraction of 98% is attainable with sufficiently dense FEPS plasma. The transverse electrostatic potential of the ion beam is reduced from 15V before neutralization to 0.3 V, implying that the energy of the neutralizing electrons is below 0.3 eV.

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Concepts in Low Power Hall Thruster Design - A Personal Perspective

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Following the general trend in miniaturization of technology there is a growing interest in using microsatellites (< 100 kg) and nanosatellites (< 10 kg) to replace larger and more expensive platforms. To enable these capabilities, small, low mass, and efficient electric propulsion systems are required. Due to their inherent propellant mass economy, Hall effect thrusters (HET) are an obvious choice. However, the current generation of HETs are optimized to operate at power levels above 300 W. Scaling HETs to lower power levels causes a rapid decline in performance, rendering them unusable for smaller spacecraft with limited available power. In this presentation I will review the basic principles that govern HET efficiency and mass utilization in particular. Two non-conventional HET architectures that enable lower power operation will be discussed: the Co-Axial Magneto-Isolated Longitudinal Anode (CAMILA) Hall Thruster and a very low power Thruster with Anode Layer (TAL). Both systems are currently another study at the Technion.

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Development of IPPLM's krypton HET

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Since the first launch on board of the Russian satellite of Meteor series Hall effect thruster (HET) has become a serious competitor for the classic rocket technology as far as station keeping and positioning, orbit rising or even deep space mission driving is concerned. Despite of the fact that lasting more than 50 years development of HET resulted in the matured and well optimized design, there is still a need to resolve such issues as mission economy (e.g. in terms of mass budget, duration and overall costs), thruster miniaturization, throttling and extension of the thruster lifetime which is limited mostly due to erosion of the discharge channel. In response to these problems, increasing thruster specific impulse, modification of magnetic field topography and the use of various propellants have been suggested. For the new implementations (scaled-up or down) the well known SPT-100 flight model is regarded as a state-of-the art reference HET. The majority of these implementations use xenon which is an almost perfect but extremely scarce in the Earth's atmosphere and consequently expensive propellant, what makes searching for other thruster driving materials an urgent need. On the other hand, operating a HET with a noble gas has so many advantages that krypton is considered as an indeed attractive alternative propellant, in spite of its slightly less favorable propulsive characteristics than those of xenon. Here, higher ionization energy, smaller ionization cross section and lower atomic mass could be mentioned however, the indisputable advantage of krypton is its price which is several times lower than the cost of xenon.

Even though the use of krypton propellant to feed a HET has been already investigated for more than 15 years in several laboratories, usually the experiments were performed with thrusters optimized for xenon. In the Institute of Plasma Physics and Laser Microfusion (IPPLM) it was decided to kick-off electric propulsion (EP) studies by designing of a new 0.5 kW-class HET dedicated to operate primarily with krypton. This new thruster was geared as a laboratory/research model aiming at assessment of krypton as a propellant for relatively small HET and compare its performance in relevance to xenon. Therefore, keeping in mind the operation of current thruster mostly with krypton, such problems as increased heat loads and magnetic field topography were addressed from the ground-up of the design phase. Extensive modeling with simulating tools for temperature distribution in the thruster body and B-field topography prediction were performed. Additionally, the parametric calculation with time dependent 1D hydrodynamic code for thruster characterization were completed for both gases. Within the frame of ESA/PECS project (under the acronym KLIMT - Krypton Large Impulse Thruster) three subsequent versions of the thruster were designed and tested for its gradual improvement. The final version of the thruster appeared to be thermally steady and operated stably for both propellants as long as it was necessary. In the paper the guidelines for the design, its optimization, results of modeling, testing procedure as well as resulted characteristics of the thruster as measured in ESA /ESTEC and IPPLM's laboratories will be presented.

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Ion Acceleration Mechanism in a Quad Confinement Thruster

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The Quad Confinement Thruster is a DC magnetized plasma propulsion system invented and developed within the Surrey Space Centre (University of Surrey). The QCT contains a square discharge channel with the anode located at the closed, upstream end. An external hollow cathode neutralizer provides primary electrons for triggering the ionization process (via electron-neutral collisions) and neutralizes the ejected ion beam. The magnetic field is characterized by cusps at the four lateral walls, which enhance plasma confinement and electron residence time inside the device. The magnetic field topology is manipulated using four independent electromagnets on each edge of the channel, tuning the properties of the generated plasma and steering the ion trajectories. This peculiar feature enables to perform active thrust vector control.
We characterize the plasma ejected from the device applying a non-intrusive laser-based technique. In particular, Laser-Induced-Fluorescence measurements map the 2-D ion velocity field throughout the plume for multiple plasma discharge conditions. Measurements show a free-space ion acceleration layer located 8 cm downstream of the exit plane with an observed ion velocity increase from 3 km/s to 10 km/s within a region of 1 cm thickness or less. Moreover, the ion velocity field is investigated with different magnetic configurations, demonstrating how ion trajectories may be manipulated in real time.

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Improvements in global modelling of gridded ion thrusters

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PEGASES is an ion-ion thruster concept developed at LPP for over ten years. The neutralization of the plume by alternate negative and positive ion extraction leads to a thruster design where no external neutralizer is required anymore. Formerly simulated with an electropositive Argon plasma [1], a first 0D fluid model of this thruster was developed including more complex molecular iodine chemistry [2]. Recently, neutral gas heating by ion acceleration in the sheath was added to the model, which has a very large influence in the neutral power balance.

Following the description of collisionless heating in inductively coupled RF plasma provided in [3], stochastic heating was also taken into account both through an effective collision frequency, and a heating term in the electron power balance. Refining the global model leads leads to a better predictability of the thruster efficiency.

Both numerical PIC simulations and expertiments are in progress to validate the analysis that were conducted in this paper.

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A first review of facility effects on electric thruster testing

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Evaluating a thruster performances in a representative operational environment is a key milestone towards its use in space. However, the limited size and pumping speed of currently available test facilities limit the validity of most performance measurements, from the plume divergence to the thruster lifetime expectancy. Based on a literature review, this poster features a panel of the different effects related to the vacuum facility that apply to the thruster itself, the measurement devices and the plume. Several comments are made about how these effects differ between HET and GIE thrusters, large and small thrusters, and between classic Xenon propellant and more recent innovative propellants such as the use of iodine in GIEs.

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The Hall thruster technology: from the classical design to the wall-less concept.

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The Hall thruster (HT) is a gridless positive ion accelerator used for spacecraft propulsion. The original idea of ion acceleration in a quasi-neutral magnetized plasma discharge was introduced in the mid-1960s. The first HT was successfully operated in space in 1972 aboard the former USSR Meteor satellite. Since that time numerous works have been performed, the technology has greatly evolved with an increase in thrust level and efficiency and an extension of the operating envelope. Over the last decacdes, HTs have equipped tens of commercial and military satellites for attitude control, trajectory correction and, nowadays, for orbit topping and orbit transfer maneuvers. This contribution mostly focuses on the technological aspect of HTs with only a brief overview of the underlying physics. After a description of the classical HT annular architecture, which rests on an ExB discharge confined into a dielectric cavity, we will present the current state of the technology in terms of sizes, power and thrust, including constraints and limits. Then we will discuss the magnetic shielding configuration, which, by strongly reducing plasma/surface interaction, leads to an extension of the thruster lifespan with, in addition, the possibility to operate at larger voltages. Finally, the last part of the contribution will deal with Hall thruster variants and new architectures that offer interesting characteristics for low power and high power applications. In particular we will describe nested-channel HTs, cylindrical HTs, double-stage HTs and the wall-less HT.

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Modeling magnetized plasma jets in electric propulsion

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Understanding the expansion of the plasma plume produced by an electric propulsion system into vacuum is a fundamental problem for predicting the thruster performance, improving thruster design, and flagging any potential spacecraft integration problems due to plasma-surface interaction.
This talk covers, firstly, the key challenges of modelling a magnetized plasma jet in a divergent magnetic field or magnetic nozzle (MN). A MN is the main acceleration stage in several electrodeless plasma thrusters such as the helicon plasma thruster (HPT), the electron cyclotron resonance thruster (ECRT), the VASIMR, and the applied-field MPD thruster.
A two-fluid, steady-state model with fully-magnetized electrons but partially-magnetized ions is used as the basis to understand the magnetized plasma expansion. Ion acceleration, thrust generation, and plasma detachment are analyzed as a function of the parameters of the problem. The possibility of using a 3D MN to obtain contactless thrust vector control capabilities is also presented.

Secondly, the talk comments on other aspects related to magnetized (and unmagnetized) plasma plumes:
In HPTs and ECRTs an electromagnetic wave is used to create and heat the plasma in the thruster chamber. The propagation and absorption pattern of this wave is essential for the operation of the device. An approach to understand plasma-wave effects in the MN region of these thrusters and optimize thruster design is presented.
Then, a kinetic model that integrates directly Vlasov's equation to explore the EVDF response in the collisionless plasma is discussed, with the main goal of understanding collisionless electron cooling mechanisms and its effect in setting the total electric potential drop and the final energy of the supersonic ion beam. The unmagnetized counterpart to this kinetic model is also presented to compare the analogies and differences that exist with magnetized plasma plumes.

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Hall Thruster numerical tool - Demo

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A software methodology implemented through an extremely user-friendly UI, able to simulate an Hall Effect Thruster, starting from its physical dimensions up to specific material and atomic species data, will be showcased.

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Low Power Electric Propulsion Activities at Sitael

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Low power electric propulsion is an enabling technology for a number of future missions, especially the ones involving mini- and micro- satellites. Currend trend is to launch many low-cost spacecraft to accomplish a wide variety of tasks, ranging from Earth monitoring to communication. A brilliant example of it is the idea of developing a constellation of small satellites placed in LEO and capable of granting full internet coverage all over the world. In such a case an efficient propulsion system is extremely beneficial in order to save propellant and maximize the payload mass. Lightness is privileged, while internal redundancy is not strictly required (as it is implicitly provided by the large number of satellites constituting the constellation). Another relevant application is the de-orbiting of small satellites, a task that has now to be mandatory accomplished by each spacecraft operating in LEO.

To respond to these market needs, Sitael is actively operating in the field of low power Hall Thrusters, developing in house devices that operate at different power levels, small cathodes and all the necessary diagnostics to validate and qualify them.

The present work describes the main ongoing activities, presenting the development status of HT100, MSHT100, HT400 and small heated cathodes.
HT100 underwent an intensive series of tests in order to investigate its structural behavior and to better assess its expected lifetime. The thruster has also been successfully coupled with a PPU BB, showing solid performance in an extedend voltage and power range. Tests with alternative propellants have been carried out as well.
MSHT100 (magnetically shielded HT100) has been tested at the end of 2016, showing promising results in term of expected lifetime.
Results obtained from recent experimental campaign are here presented, illustrating also the short-term roadmap towards the full space qualification of the thruster units.

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Development of Hollow Cathodes for Electric Thrusters: Theoretical and Experimental Results

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Hollow cathodes are sources of electrons to ionize the propellant and neutralize the ion beam exhausted by ion and Hall effect thrusters. A complete understanding of the operation of hollow cathodes is hindered by the complexity of their driving physical processes along with the difficult plasma diagnostics due to the small size (typically a few millimeters in diameter) and high operating temperatures (above 1000 K). Nevertheless, a deeper study of hollow cathodes is important to improve the entire propulsion system, whose performance and lifetime are both affected by their operation.
The talk illustrates the main features of state-of-the-art hollow cathodes for space applications and the critical issues relevant to their operation and technological development. Recent theoretical and experimental results on hollow cathodes developed by Sitael and JPL (in collaboration with the University of Pisa) are shown. The cathodes have been designed to operate with xenon and krypton fed Hall effect thrusters ranging from 100 W to 200 kW, corresponding to current levels from 1 A to 300 A, with an expected lifetime of tens of thousands of hours.

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CIRA IMP-EP project: Development and validation of a 1D model for hollow cathode analysis and design

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The development plan of CIRA Electric Propulsion Program financed by PRORA, called IMP-EP1, is structured in three main lines and will develop according to:
I. design and realization of the facilities (MSVC, LSVC) including the improvement of test definition and competences;

II. development and improvement of basic and advanced diagnostics methodologies;
III. development of design methodologies and technologies for electrical thrusters, including the set-up of a preliminary design tool, improvement of numerical modeling and post-test analyses and laboratory models manufacturing.
In the frame of line III the development of a low power Hall thruster to be tested in the MSVC facility is currently ongoing. In order to design the cathode for this thruster, a preliminary numerical design tool describing the physics of orificed Hollow Cathode devices with low work function insert has been developed, combining relevant literature models2-6 with some different customized relations.
A time-independent, volume-averaged model has been developed to determine plasma properties in the emitter, orifice regions.
The model includes a current density equation, an ion flux balance, a plasma power balance and a plasma pressure equation. The systems of equations are solved to compute self-consistently the plasma number density, the electron temperature, the cathode voltage fall and the neutral number density.
The code employs the fsolve MATLAB routine with dedicated Graphical User Interface (Figure 1) and a convergence check is performed at each iteration by comparing the evolution of the relative error until the stop condition is met.
Simulated parameters have been compared with the available experimental data and trends found in the literature on existing devices2-7, showing good agreement.
This parametric study of the cathode performance has assessed the dependence of the average plasma parameter on discharge current and mass flow rate, as well as on the geometry.

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Hall thruster virtual lab

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A realistic three-dimensional fully kinetic particle simulation of a Hall-effect thruster discharge and plume regions has been attempted.
The model consists of a Particle-in-Cell (PIC) methodology tracking electrons and propellant ions in their self-consistent electric field. A detailed secondary electron emission representation is also implemented in addition with electron-atoms and ion-atoms volume collisions. The model is able to capture the start-up transient phase and the most relevant features of axial, radial and azimuthal behaviors of the steady-state phase detecting sheath instability and azimuthal fluctuations in the acceleration region. Ion-induced erosion and plume divergency are aestimated from code output. The model has the potentiality to adapt to the different HET configurations (cusped-field, magnetic shielded, wall-less, cylindrical, etc.) and to single out the different mechanisms contributing to electron anomalous cross-field transport and to investigate on the proper incidence on it.
The model contains a Graphical User Interface (GUI) from where the user can select the configuration (geometrical, electrical, magnetic and propellant/wall material parameters) to be studied.

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Hall Thrusters used as dissociator for fusion application

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It is well known that negative ions used for neutral beam injection in thermonuclear fusion reactor are mostly produced by conversion of hot atoms on caesiated surface. In this contribution we are investigating the possibility to produce hot atom by molecular dissociation process in HT configuration, i.e. finding the best operative conditions to increase the molecular dissociation in place of ionization. The study is supported by Particle-in-Cell models of plasma-gas phases taking into account the vibrational kinetic of molecular hydrogen.

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Wall interactions in Hall Effect Thruster, investigation with bidimensional Particle-in-cell model and simulation

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Hall effect thrusters (HET) are one of the main technology used and studies for spacecraft propulsion. Grid-less, they present net advantages, resulting of an increasing need for predictive and accurate models, and a better understanding of the complex behavior of the plasma.

HETs consist of three main components : a magnetic circuit used to produce a mostly radial magnetic field; an external hollow cathode to sustain the plasma discharge and to neutralize the ion beam; an annular ceramic channel where the neutral gas is injected from the anode, and ionize before being accelerated.

One of the main characteristic of the thruster is its lifetime, limited by the ceramic channel eroded by the plasma. However long experiments are costly, and erosion diagnostics and measurements are difficult to perform.

A bidimensional r-theta particle-in-cell simulation is therefor developed to investigate the plasma interaction with the ceramic walls. The dielectric aspect is emphasized, concerning the model, its implementation, and results compared to dielectric walls. Secondary electron emissions are also implemented, to better understand the material effects on the plasma.

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Status of NIO1 negative ion source and acceleration system

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Neutral Beam Injectors (NBI) are fundamental to increase the plasma temperature in magnetic confinement fusion devices. In the perspective of dense and large plasmas foreseen in advanced experiments, the use of negative ions is needed to efficiently produce neutrals in MeV energy range, able to penetrate the plasma core. In the framework of the accompanying activities in support to the ITER NBI test facility a relatively compact radiofrequency (RF) ion source, named NIO1 (Negative Ion Optimization phase 1) is being developed and tested in Padua, Italy, in collaboration between Consorzio RFX and INFN. Negative hydrogen ions are formed in a cold, inductively coupled plasma with a 2MHz, 2.5 kW external antenna.

The negative ions are extracted by means of a set of gridded electrodes to form 9 beamlets, arranged in a 3x3 configuration. The nominal beam current is 135 mA and the final beam energy 60 keV. After the first test in Air and Argon doped Oxygen plasmas, the source is now routinely operated in Hydrogen, at an average RF power <1200W. The set of diagnostic used include infra-red calorimetri, Langmuir probes, beam and source spectroscopy and linear CCD detectors. This contribution describes the main features of the experiment as well as its current status. Future improvements to the extraction system are discussed.

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MODELING THE ELECTROMAGNETIC FIELD IN ANISOTROPIC INHOMOGENEOUS MAGNETIZED PLASMA OF ECR ION SOURCES

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We present a numerical approach to solve the 3D Maxwell-Lorentz system with the aim of investigating the interaction of the electromagnetic waves with the magnetized non-homogeneous plasma produced inside Electron Cyclotron Resonance Ion Sources. The FEM COMSOL Multiphysics® software was used to compute the electromagnetic field in a cavity filled by the anisotropic-inhomogeneous plasma, described by a full non-uniform dielectric tensor in "cold plasma" approximation. The full-wave solution is then coupled to an “in-Matlab” developed kinetic code based on a PIC – Particle-In-Cell strategy, solving the Newton-Lorentz equation of motion for plasma electrons. Our model explains the experimentally observed frequency sensitivity and gives a relevant contribution to the challenging goal of predicting the electron/ion dynamics in ECR plasmas.