HORIZON 2020

EPIC

Report

D2.3 EPIC 1st Workshop report

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EPIC

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1 INTRODUCTION

In the frame of the Electric Propulsion Innovation & Competitiveness (EPIC) project, (grant number 640199) and more concretely its Work Package 2 "Technology Mapping & Application Requirements", a Workshop was held in Brussels, initially as part of Task 2.1 "Survey of available EP technologies and TRL", but with wider objectives.

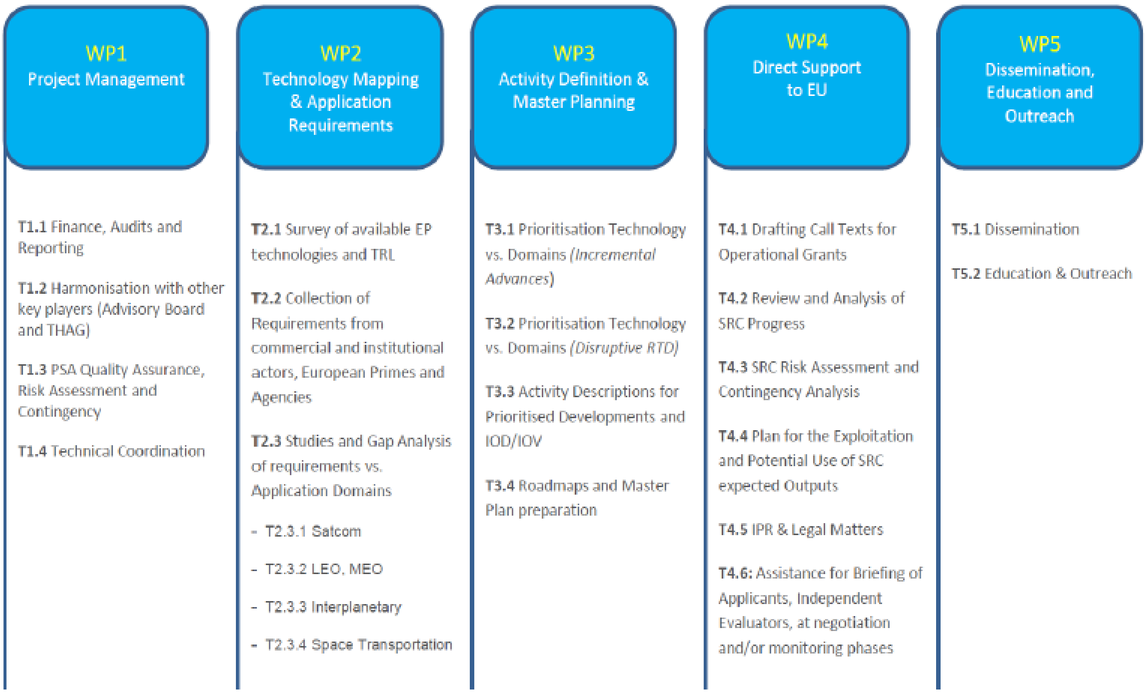


Figure 1-1: EPIC Work Logic

This document provides a report of this first EPIC workshop held in Brussels' Royal Belgian Institute of Natural Sciences on 25th-28th November 2014. Some of the information provided can be found on a dedicated website at the following url: http://www.epic2014.eu/.

2 LIST OF ACRONYMS AND ABBREVIATIONS

Airbus DS: Airbus Defence & Space

EBB: Elegant BreadBoard

ECRA: Electron Cyclotron Resonance Acceleration thruster

ECSS: European Cooperation for Space Standardization

EO: Earth Observation

EOR: Electric Orbit Raising

EP: Electric Propulsion

EPPM: Electric Propulsion Pointing Mechanism

ESP: European Space Propulsion

FCU: Flow Control Unit

FEEP: Field Emission Electric Propulsion

GEO: Geostationary Earth Orbit

GIE: Gridded Ion Engine

GTO: Geostationary Transfer Orbit

HEMP-T: High Efficiency Multistage Plasma Thruster

HEO: Heliosynchronous Earth Orbit

HET: Hal Effect Thruster

IPPLM: Institute for Plasma Physics and Laser Microfusion

LEO: Low Earth Orbit

LIF: Laser induced Fluorescence

MEMS: MicroElectroMechanical System

MEO: Medium Earth Orbit

MIB: Minimum Impulse Bit

MPD: MagnetoPlasmaDynamic

MSL: Mars Space Limited

NEO: Near Earth Object

NGGM: Next Generation Gravity Missions

NSSK: North-South Station Keeping

PCU: Power Conditioning Unit

PCDU: Power Conditioning and Distribution Unit

PIT: Pulsed Inductive Thruster

PPT: Pulsed Plasma Thruster

PPU: Power Processing Unit

PR: Pressure Regulator

PSCU: Power Supply and Control Unit

QCT: Quad Confinement Thruster

R&D: Research and Development

R&T: Research and Technology

RPA: Retarding Potential Analyzer

RF: Radio Frequency

RPA: Retarding Potential Analyser

SPF: Single Point of Failure

SRC: Strategic Research Cluster

TAS: Thales Alenia Space

TED: Thales Electron Devices

TRL: Technology Readiness Level

VAT: Vacuum Arc Thruster

VLEO: Very Low Earth Orbit

XIPS: Xenon Ion Propulsion System

3 SCOPE OF THE WORKSHOP

3.1 Objectives

The EPIC Workshop aimed at the following objectives:

- Collect information with regards to, and assess the TRL of, the following technologies pertaining to in-space electric propulsion:

  1. **Thrusters**: including, but not limited to, Hall Effect Thrusters (HET), Gridded Ion Engines (GIE), High Efficiency Multistage Plasma Thrusters (HEMP-T), Pulsed Plasma Thrusters (PPT), Magnetoplasmadynamic thrusters (MPD), Pulsed Inductive Thrusters (PIT), Quad Confinement Thrusters (QCT), Arcjets, Resistojets, Field Emission Electric Propulsion (FEEP), Colloid or Electrospray thrusters, Helicon thrusters, Vacuum Arc Thrusters (VAT), Hollow cathodes, Ablative Laser Propulsion (ALP).
  2. **Subsystem components**: valves, pressure regulators, flow controllers, power processing units (PPU), mechanisms (e.g. pointing mechanism or deployable arm), tanks.
  3. **Test facilities** (including diagnostics).
  4. **Power generation** (including new power concepts).
  5. **System architecture**.
  6. **Development tools**.

- Collect high-level requirements for the technologies mentioned here-above, based on needs foreseen for the following types of missions:

  1. Low Earth Orbit (LEO)
  2. Medium Earth Orbit (MEO)
  3. Geostationary Earth Orbit (GEO)
  4. Interplanetary missions
  5. Space transportation.

3.2 Programme and participants

The workshop comprised 21 sessions for a total of 90 presentations made by speakers from 12 European countries. The complete programme can be found in Annex 1, while an overview is provided below:

1. Tuesday 25th November:
   a. Mission requirements (14 presentations)
   b. System aspects (5 presentations)
   c. Welcome cocktail
2. Wednesday 26th November
   a. Hall Effect Thrusters, Gridded Ion Engines, HEMPT (16 presentations)
   b. Pulsed Plasma Thrusters, cathodeless thrusters (7 presentations)
3. Thursday 27th November
   a. Other thruster concepts (7 presentations)
   b. EP subsystem components, cathodes (12 presentations)
   c. Test facilities and diagnostics (11 presentations)
4. Friday 28th November
   a. Power Processing Units (9 presentations)
   b. Development tools (7 presentations)

There were 156 registered participants from 16 countries representing more than 75 different companies, institutes or agencies. The detailed list can be found in Annex 2, while all presentations are available online on the workshop's website (http://www.epic2014.eu/test-presentations/) and are provided in a separate zipped archive for convenience (EPIC_Workshop_1_presentations.7z).

4 WORKSHOP SUMMARY

4.1 Session 1 – Mission requirements: GEO

4.1.1 Eutelsat Electric Propulsion perspective – Eutelsat

Eutelsat presented its activities, with two full-electric satellite under procurement (one Boeing 702SP from SATMEX which was acquired by Eutelsat, and one E3000) and one under operation : **SESAT-1, built by Russian NPO-PM**, with 8 SPT-100 and 120 kg xenon (**direct GEO injection in April 2000**), on which more than **6000 hours firing time** have been accumulated over the years.

EUTELSAT 115WB (former SATMEX-7) is expected to launch in Q1 2015, with wet mass of 2200 kg and 8 kW payload. EOR will be performed with 4 XIPS 25, and an expected **duration of 7-9 months**.

EUTELSAT 117WB (former SATMEX-9) is a similar satellite, scheduled to be launched by the end of 2015.

EUTELSAT 172B, based on E3000 EOR platform, expected to launch in Q2 2017 with a wet mass of 3500 kg and 13 kW payload. EOR is expected to last 4 months.

The main design drivers of Eutelsat are: (i) **reduction of cost per transponder** (broken down into : Satellite cost for 45-65% of total, launch vehicle cost for 25-45%, and insurance cost for 10%, with no impact of EOR option), and (ii) timeliness. The main criteria to be considered are:

- **time to orbit**: although an important factor, no clear upper limit has been identified (it depends on how economically attractive the solution is)
- **reliability** (no Single Point Failure allowed)
- **on-board autonomy** to decrease the cost of EOR operations
- **satellite system** compatibility
- **multi-launcher** compatibility
- compliance with **French Space Law**
- **sub-system cost**.

4.1.2 Perspectives for telecom satellites and drivers towards electrical propulsion evolutions – TAS

TAS presented the way forward for telecommunication satellites beyond the NEOSAT programme, by considering several issues related to EP :

- **Power** is sized today by the payload. **Faster EOR** might require sizing the power generation for the EP using HET thrusters in parallel. In that respect, reducing solar panel cost, increasing their efficiency, and reducing losses of power conditioning & distribution is of prime concern for EP.
- **Small payload** is a niche market where EP could enable a shrink in mass and volume, provided that enough power is available on-board to allow EOR in a reasonable duration.
- Telecom missions in **other orbits** than GEO: HEO, MEO, LEO.
- With EP, the definition of the **GTO needs to be revisited** since satellite EP (1500 s) is much more efficient than launcher propulsion (450 s). Leaving more delta-V to the spacecraft should improve the performance of the system launcher-satellite, increasing launchers' capability. Today (with chemical propulsion), GTO requires 1.5 km/s from the spacecraft to reach GEO, and LEO to GEO (same inclination) requires 4 km/s. An optimum has to be determined for this "EP adapted GTO".

As a consequence, TAS proposed to involve satellite primes in the SRC via a **"SAT prime Task Force"** to ensure coherence between technology developments and system studies.

4.2 Session 2 – Mission requirements: General

4.2.1 Airbus Defense and Space: mission and system requirements for electrical propulsion – Airbus DS

Airbus DS made a presentation on mission applications across the board, with a strong heritage in most of them and involvement in all (e.g. in-house studies for EO – both in LEO or GEO –, space transportation, and Galileo 2G). Airbus DS consider the following market segmentation:

- Main segment : **enabling** (mission possible only with EP), and **opportunity** (use of EP is more competitive)
- Sub-segment : **high performance** or **µpropulsion**

Requirements for LEO missions are:

- High Isp for countering air drag or formation flying
- 4-50 mN, 3,000-5,000 s, thrust modulation between 5-100% (main propulsion)
- 500-1500 µN, >1,000 s, thrust modulation 0.1-100%, thrust resolution 0.5 µN (µprop)
- High cycling, 10-20 W/mN, power between 200 W and 2 kW.

Requirement for MEO missions are:

- Reliability >0.997
- Thrust>250 mN
- 1,650<Isp<4,000 s
- 5.5 kW<P<9.5 kW at 50 V or 100 V (TBC)
- Target recurring price: <4 M€

High-resolution EO GEO missions require µpropulsion (requirements similar to that of LEO).

Airbus DS's view about telecom market perspectives is that **more than 50% of telecom satellites will use EP** onboard (either for EOR or station keeping). The roadmap makes a distinction between **competitiveness** breakthrough (i.e. incremental) and **technology** breakthrough (i.e. disruptive):

- competitiveness :
    - low cost EP for station keeping (1.5-2.5 kW HET and PPU, XRFS 2G, mechanisms)
    - low cost EP for EOR (5 kW-class)

    ⇒ synergies are to be found between the two

- technology :
    - it is recommended to have **system studies** to analyse market trends, launcher environment, etc...
    - new approaches are welcome

Here again, Airbus DS **strongly suggested to perform system studies** as soon as possible as a prerequisite for the SRC roadmap.

Airbus DS concluded their presentation by a **multi-mission platform**, that could deal with tugging, debris mitigation, cargo, on-orbit servicing, etc... This is derived from the CNES so-called "EASE" studies, whose main conclusions are that the **concept is feasible** for most mission applications, but the **competitiveness has to be consolidated.** High-level requirements for this type of application are: flexible Isp, high power thruster (20 kW), better efficiency, high total impulse (4 to 10 times as much as today's capabilities), and improved solar arrays' efficiency.

4.2.2 Proposed TAS orientations for electric propulsion technologies considering various satellites applications perspectives – TAS

The **main drivers** for TAS are: reduction of **EOR duration**, improvement of **operational constraints**, decrease of xenon consumption, extension of the **mission duration**, **cost decrease**. Rough figures are provided for the different types of application: telecom, navigation, scientific/exploration, observation and transportation.

- Medium to large satellites :
  - Total available power for EPS may go **up to 30 kW**
  - HET :
    - High power with different operating points : 4-10 kW at 300-800 V
    - >0.6 N at 10 kW and Isp >2500 s at 800 V with Itot>20 MN.s
  - GIE :
    - 5-8 kW, Isp>4,000s and Itot>15 MNs
    - decrease of cost (both thruster and PPU)
- Small to medium satellites :
  - Further development of new technologies
  - Availability of 500 W-class HET for medium satellites & constellations :
    - 200-800 W at 200-300 V
    - thrust level 13-40 mN with Isp>1,300 s

TAS then addressed **innovative power supply design**:

- at PPU level : **different voltages** (up to 800 V), increased power level, 500 W-class PPU, modularity, high voltage switches/connectors/PCB
- at system level : high voltage bus, **direct drive**, unregulated bus for small satellites.

- TAS also insisted on the need for **improved modelling tools**, in particular for EP interactions with the spacecraft and mission analysis (AOCS).

Finally, TAS suggested that there be a dedicated system studies call in SRC earmarked for the 3 primes (Airbus DS, TAS, OHB) covering the following topics: key EP requirements, supporting system analyses, high power PSS architectures, system models/tools

4.2.3 OHB System's vision of the market – OHB

OHB presented their current and future applications with EP :

- Hispasat-AG1 (8 SPT-100)
- Heinrich Hertz (4 or 8 SPT-100 and 4 HEMPT)
- Electra : <3 t launch mass, 10 kW payload, 4.5 kW on booms with a max 6 months EOR phase

Generic requirements are the following :

- Cost reduction (main contributor being the PPU)
- Reliability and autonomy
- Standardization of PPU (multi-thruster compatibility)
- Operating range
- Independence (e.g. avoid ITAR restrictions), yet competition is preferred.

OHB then presented mission-related requirements, notably showing that **HET are best suited for MEO/GEO applications**, while **GIE are more suitable for exploration and station keeping in GEO.** Last, OHB emphasized the fact that space exploration applications require breakthrough in power supply technologies, optimization of mission strategy, or totally new propulsion technologies.

The last slide of the presentation provides a very nice summary of the conclusions and is reproduced below:

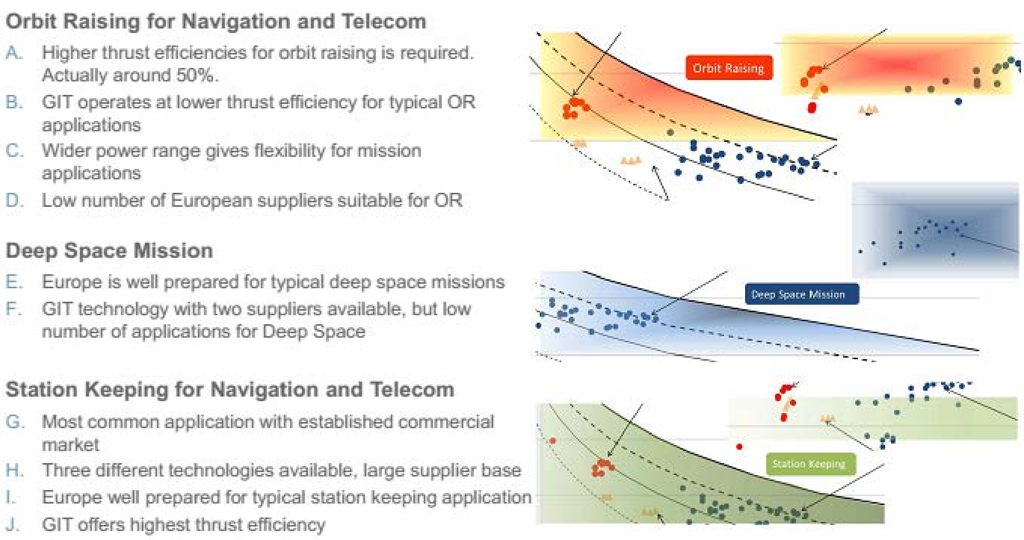


Figure 4-1: availability of European technologies per application (OHB Courtesy)

4.2.4 OHB System's view of propulsion needs – OHB

OHB provided a range of figures (thrust, Isp, total impulse, number of cycles, and power) for the various mission needs, all summed up in the following table (Table 4-1)

	(mN)	(s)	MNs (wo qual margin)	# of (wo qual margin)	W
LEO	10 in orbit, 10000 for reentry	>3000s in orbit, >1000s for rentry	1,5	10 000	50 to 500
MEO	40	2000s	0,2	10 000	1500
GEO	>500 for orbit raising, >80 for Station keeping	>1600 for orbit raising, >1600 for Station keeping	4,5 for OR 1,3 for SK	850 for OR 6500 for SK	4500 for OR 1500 for SK
Interplanetary	10 to 250	up to 4200s	> 20	> 10 000	400 -10 000
Space transportation	10 to 250	up to 4200s	> 20	> 10 000	400 -10 000

Table 4-1: Requirements for different mission types (OHB courtesy)

The **main drivers** are: maturity, cost, specific power, specific impulse, thrust level and stability. The importance of **auxiliary propulsion** was stressed (xenon cold gas costly in terms of propellant consumption), as well as that of **sub-system architecture**.

Constraints that have to be taken into account with EP are : detumbling, collision avoidance, radiation dose, LEO de-orbit and controlled reentry. Propellant storage and management was also mentioned : xenon loading, high accuracy pressure and temperature sensors, mechanical/electronic pressure regulator. Last, the question of ground testing was addressed, with a need for a « thruster simulator » and new, optimized, qualification strategies.

4.2.5 CIRA's R&D Vision in Electric Propulsion – CIRA

CIRA pointed out that future developments will sit at opposite ends of the power range, i.e. at low (<200 W) and high power (> 5kW). Possible orientations in R&D activities have then been discussed : cathode lifetime, decrease of erosion (e.g. through magnetic shielding), improved testing facilities, research on alternative propellants. Besides, CIRA have been working on an **additional VEGA kick-stage based on EP**, as well as advanced exploration concepts in the 100's kW range, considering in this respect that **cryogenic propellant storage** as a « game-changing » technology.
CIRA has expertise in:

- Numerical modeling of ionized gases in electromagnetic field and plasma flow experiments
- Space Qualification Laboratory tests
- Diagnostics

CIRA high level requirements are summarized here:

- Improve Performance and Life of EP systems
- Improve Power Generation Technology
- Reduce EP system complexity and introduce innovative architecture
- Enhance affordability of the EP systems
- Improve research synergy and technology breakthrough
- Develop launcher synergies for LV performance and mission capabilities improvement
- Improve propellant storage and transfer technology
- Increase EP autonomy
- Improve test capabilities and advanced diagnostics systems capabilities
- Incremental steps to steadily build, test, refine, and qualify capabilities
- Extend research on non-conventional propellants and new materials.

4.3 Session 3 – Mission requirements: LEO/MEO

4.3.1 *Very Low Earth Orbit Mission Capabilities using Gridded Ion Engine (GIE) on board PROBA Satellite Platforms: Requirement Definition for the Suppliers – QinetiQ Space*

QinetiQ presented their 400 kg-class **PROBA-NEXT** program, which aims at addressing as wide a mission range as possible (e.g. using 350 km LEO) while building on a standardized platform. As a consequence, **EP has been selected as a part of the propulsion sub-system**, with 400 W available. QinetiQ has already selected the **T5 engine** for this type of application, yet their specific needs are:

- low cost, low complexity PPU and Pressure Control Unit
- 5-150 bars tanks and pressure regulator
- "Constellation phasing using EP" tool needed.

4.3.2 *Electric propulsion needs for LEO satellites – TAS*

TAS pointed out that there are several reasons to aim for an increased Delta-V in LEO: the French Space Act, constellations, and enabling technology:

- **French Space Act**: for 500-1000 kg class spacecraft, there is no need for a controlled re-entry, while it is required for satellites in the 1t-2t range. De-orbit can be achieved with low thrust, but controlled re-entry requires a thrust of 0.05-0.1 N/kg of satellite mass.
- **Constellations**: satellites have to get to their final orbit on their own, which represents a 400-600 m/s Delta-V, which would require a propellant budget of 20% of total mass with chemical propulsion.
- **Enabling technology**: orbit raising, VLEO operation, change of orbit during the mission.

Propulsion **needs and main drivers** for this type of application are:

- Reduction of propulsion tank volume
- Lower power/mass ratio than telecom missions, implying limited power for EP
- Compatibility with a low voltage unregulated power bus (22-38 V)

The main requirements are:

- 250-1000 W
- 20-100 mN
- Isp>500 s, with a target set at 1,500 s

4.3.3 *Electric propulsion need for nano-satellites – TAS*

TAS discussed potential interest for the use of EP on nano-satellites (<100 kg). **High-level requirements** are as follows:

- Delta-V of 50 m/s
- MIB=0.1-0.5 mN.s
- Subsystem mass below 1 kg
- Power below 5 W

- Total cost<20 k€

According to TAS, the **best technology for this type of application is that of Pulsed Plasma Thruster (PPT)**. What should be worked on, however, is the electrode geometry, the use of alternative propellants, capacitors, and system optimization.

4.3.4 Novel mission approaches for electric propulsion – OHB CGS

Two types of maneuvers were addressed in this presentation: orbit transfer (LEO/MEO or GTO/GEO) using either a **transfer module** or onboard propulsion capabilities, and station keeping, with a focus on **VLEO missions**.

As test-cases for the transfer module concept, CGS presented studies for LEO-MEO and LEO-interplanetary transfers. Preliminary design studies consider XR-5, HT-5k and PPS5000 thrusters and, more importantly, US-procured flexible solar array whose efficiency decreases during the transfer phase due to radiation. For VLEO station keeping, mission studies considering a 400 kg-class spacecraft have shown that required thrust is around 20 mN, Isp 1300s and power 300 W.

4.3.5 EP needs of navigation satellites including the GALILEO 2nd generation – TAS

TAS presented requirements with respect to **GNSS applications** in MEO, for spacecraft mass between 1-2 t and available power between 4-5 kW, considering orbit transfer from LEO, which represents a 3-4.8 km/s Delta-V. The added value of EP is to increase the payload mass and enable compatibility with multiple launch (VEGA, SOYOUZ) by maximizing the number of satellites per launch, but it was stressed that tools are necessary to optimize transfer and spacecraft configuration (e.g. plume effect minimization).

4.4 Session 4 – Mission requirements: Space transportation and interplanetary missions (1)

4.4.1 Electric Space Tug – TAS

TAS presented preliminary studies on a space tug concept using EP, with the following targeted applications: orbit transfer, interplanetary missions or exploration, and active debris removal. For orbit transfer, the business model requires that the space tug be **multi-mission** oriented. The required thrust is around 2 N, with a resulting **transfer time around 5-6 months**. High-level requirements are the following: thrust >2 N, Isp >2,500 s, 22,000 h firing time and >20,000 cycles, alternative propellant to xenon, rendezvous capabilities. Last, it was highlighted that such a concept is a **« techno-push »** activity with respect to thrusters, solar arrays, rendezvous & capture, and refueling.

4.4.2 Electric Propulsion Developments for Space Exploration and Science – TAS

Advanced exploration or scientific missions have then been discussed, namely: orbiting infrastructures, future exploration missions (Mars, Moon, Asteroid, NEO), human exploration preparation, and Cosmic Vision or Living Planet programs. Related high-level thruster requirements are:

- thrust >3 N, Isp >3,000 s, Itot>80 MN.s with firing time above 40,000 h.
- Power >20 kW, efficiency >80%, alternative propellant (e.g. CO_2 or iodine)
- **Air-breathing** propulsion capabilities.

Besides, nuclear power generation is mandatory for space exploration (the PPU would be simpler due to the possibility to direct drive by AC current rectification). PPU cost reduction is also a critical challenge for the future. Flexible/versatile PPUs based on building blocks design could be the solution, allowing to support a variety of EP systems.

4.5 Session 5 – Mission requirements: Space transportation and interplanetary missions (2)

4.5.1 EP High level requirement from the perspective of a LEO Launch System Integrator – Avio

The presentation gave an overview of high-level requirements **from a launcher perspective**. EP gives rise to interesting prospects for VEGA, since it allows **extending its mission envelope**, either through increased propulsion capabilities of the payload (i.e. spacecraft) or through the implementation of an **EP upper stage**. The need would be to transfer **1 to 4 tons satellites** from LEO to GEO with a **6 months transfer time**. The requirements analysis has led to recommend the use of HET systems.

4.5.2 EP as an alternative for the JUICE mission – Snecma

Snecma presented an **alternative to the JUICE mission using EP**, illustrating the potential of this technology for **outer solar system science missions**. The gain in propellant mass is significant, decreasing from 2900 kg of liquid bi-propellant to 400 kg of xenon. The required total impulse is 6.2 MN.s, and the proposed system architecture is based on the use of **4 PPS1350-E with 2 PPU Mk2**.

4.6 Session 6 – System aspects

4.6.1 From Smart-1 to Galileo G2, Snecma is designing, developing and operating optimized HET propulsion architectures – Snecma

Snecma presented their know-how, experience and present studies on **EP systems**. They range from the Smart-1 mission, Thruster Module Assemblies (TMA) flying on Eurostar, EP sub-system for SmallGeo (Hispasat-HG1), and **EGEP studies for G2G**. This Electric Propulsion Subsystem is based on 4 PPS1350-E equipped with an improved ceramic material to reach 5 MN.s total impulse, 2 PPU Mk2 from TAS ETCA, and 4 Filter Units (FU). Coupled tests are foreseen in early 2015 **to achieve TRL 6**. Besides, Snecma have performed system studies for EP kick stages. Last, test campaigns have been carried out to investigate the use of **alternative propellants in HET** as well as the possibility of direct drive using 250 V bus and advanced solar cells.

4.6.2 System topologies for HEMP-T systems – TED GmbH

Thales Electron Devices presented advantages of the HEMP-T technology for **dual mode application** (e.g. operation at either high thrust or high Isp), as shown on the figure below:

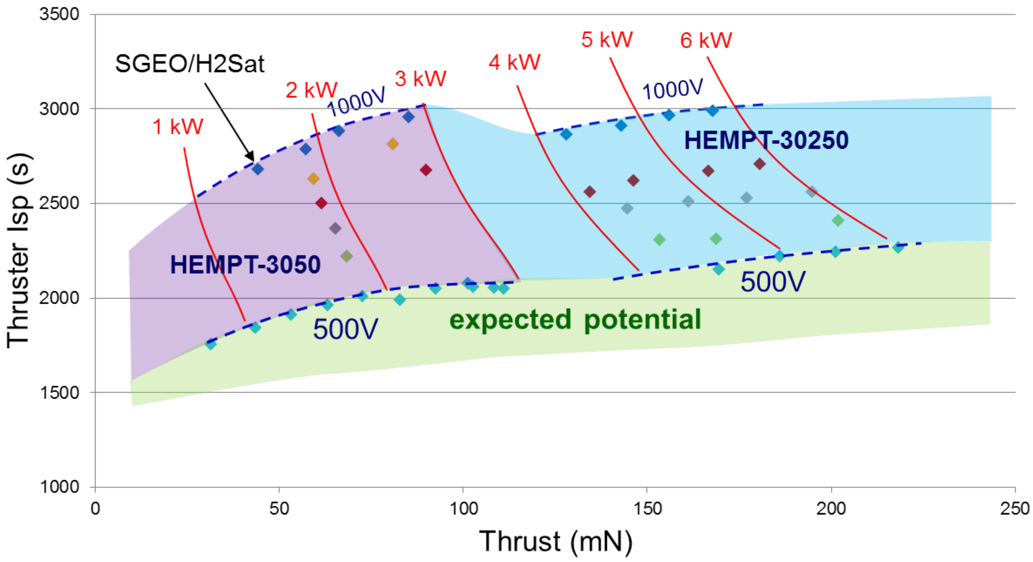


Figure 4-2: HEMPT operational envelope

Various subsystem architectures based on this thruster technology allow EOR and/or station keeping maneuvers, either for GEO or MEO applications. The necessary **transfer time ranges between 7 and 9 months.**

4.6.3 The EPS-500 an innovative and multi-application design (300 W to 700 W) – Snecma

The EPS500 concept is that of an **integrated EP subsystem**, i.e. thruster, PPU and PRU (Pressure Regulation Unit) combined in one single piece of equipment, in the **200-700 W power range.** This concept allows both a

simplification of the propulsion system and a gain in **competitiveness**. The targeted total impulse is 0.5 MN.s, which would cover a wide range of needs for satellites with mass 250 to 2000 kg in LEO or VLEO. Expected performances are:

EPS-500 input power	PPU efficiency	Peak Thrust	EPS Isp
300W	94%	16.7 mN	1208s
500W	94%	28.9 mN	1264s
700W	94%	40.0 mN	1314s

Table 4-2: EPS-500 expected performances

4.6.4 Active Attitude and Orbit control with Liquid µPPT 4 thrusters system – KopooS

System studies concerning **AOCS strategy** using a system comprised of 4 Liquid µPPT on a **cubesat** were presented. Mission requirements were to adapt the orbit altitude up to +/-200 km, representing a Delta-V of 100 m/s. KoppoS point out the fact that misalignment with the COG may lead to significant perturbing torques which necessitate the use of propulsion for 3-axis attitude control. The required **total impulse per thruster is around 100 N.s**. As a conclusion, the PPT-based propulsion sub-system can effectively replace reaction wheels and magnetotorquers.

4.6.5 Shaping an industrial strategy for EP – TAS

TAS discussed advanced future scenarios:

- **Micro-launcher** through **microwave energy transfer**, which necessitates to develop MW-scale MPD thrusters, directed microwave energy, and MW power conversion.
- VLEO Earth observation: down-sized optics, reduced satellite mass, but ATOX concern. **Air-breathing** concept potentially interesting, but for a short period of time.

4.7 Session 7 – Hall Effect Thrusters (1)

4.7.1 High Power Commercial Electric Propulsion – ESP

ESP benefits from Aerojet Rocketdyne's heritage in EP (over 500 EP thrusters flown). The **XR-5** is a 4.5 kW HET that has already demonstrated **10,400 h firing** during on-ground testing (>20,000 predicted) ; 12 thruster strings have flown since 2010. It can either deliver **277 mN at 1840 s Isp or 256 mN at 2050s Isp**. ESP intends to develop its **European counterpart** under ARTES 3-4 funding, coined XR-5E with the aim to gain in **competitiveness**, then develop **high voltage operation**, and finally higher power thrusters (e.g. in the 10-20 kW range). Besides, ESP considers **developing/manufacturing other technologies**, e.g. arcjets (already developed by Aerojet).

4.7.2 Alta Electric Propulsion vision for EPIC – Alta S.p.A.

Alta mentioned the HiPER FP7 project that focused on high power EP technologies (HET, GIE, MPD) and related applications. Alta have starting to develop a range of HET: HT100, HT400, and HT5k over a 200 W-5 kW power range:

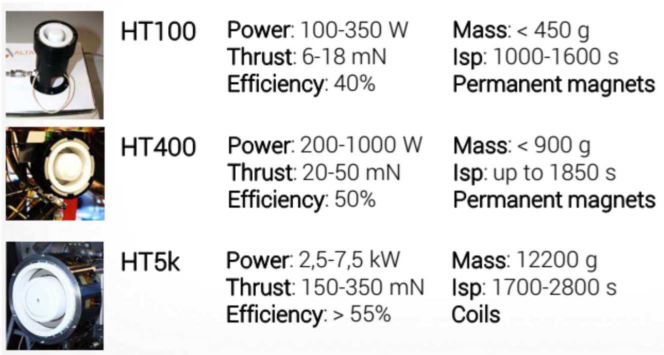


Figure 4-3: ALTA HET family and main performances

The HT5k is currently under qualification, and has been tested with xenon and krypton. Besides, low-current and high-current hollow cathodes are under development as well. Finally, a full sub-system for LEO application is being worked on in cooperation with other European companies (Italy, Greece) as well as with RAFAEL (Israel). Alta also develop MPD thrusters in the 100 kW-1 MW range, resistojets and a 1 kW-class arcjet.

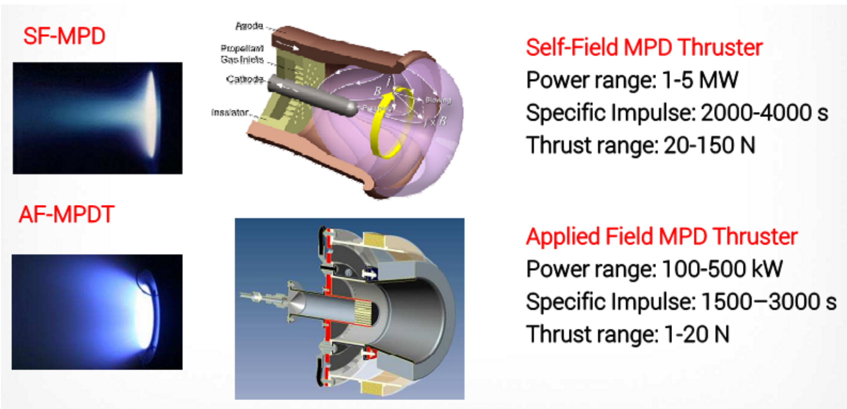


Figure 4-4: MPD thrusters developed at ALTA with their main performances

Figure 4-5: XR150 thruster performance

Alta have several EP test facilities, with up to 1,500,000 l/s Xe pumping speed and 6 m diameter vacuum chambers.

Alta's view of future activities is :

- To increase the power of HET (up to 20 kW)
- Improve **reliability** and **lifetime** of cathode/thruster
- Optimize HET for **alternative propellants**
- Maintain MPD thruster design capabilities
- **Reduce overall cost** for EP system

4.7.3 The PPS®5000 a new generation high power high thrust HET (2,5 kW to 7 kW) – Snecma

Snecma have developed a complete range of HET, with different TRL:

- PPS®500 (200-700 W) : TRL 3
- PPS20k (5-20 kW) : TRL 3
- PPS®5000 (2-4.5 kW) : TRL 4
- PPS®1350-E : TRL 6
- PPS®1350-G : TRL 9

The PPS®5000 thruster's development started in early 2000, with a stop in 2004 due to trade-off in favor of EP NSSK-only on Alphabus, and resumed in 2012, with a qualification for telecom applications (EOR+NSSK) in Q4 2018. This thruster can operate over a very wide range of parameters, which could make it suitable for **dual-mode operation**:

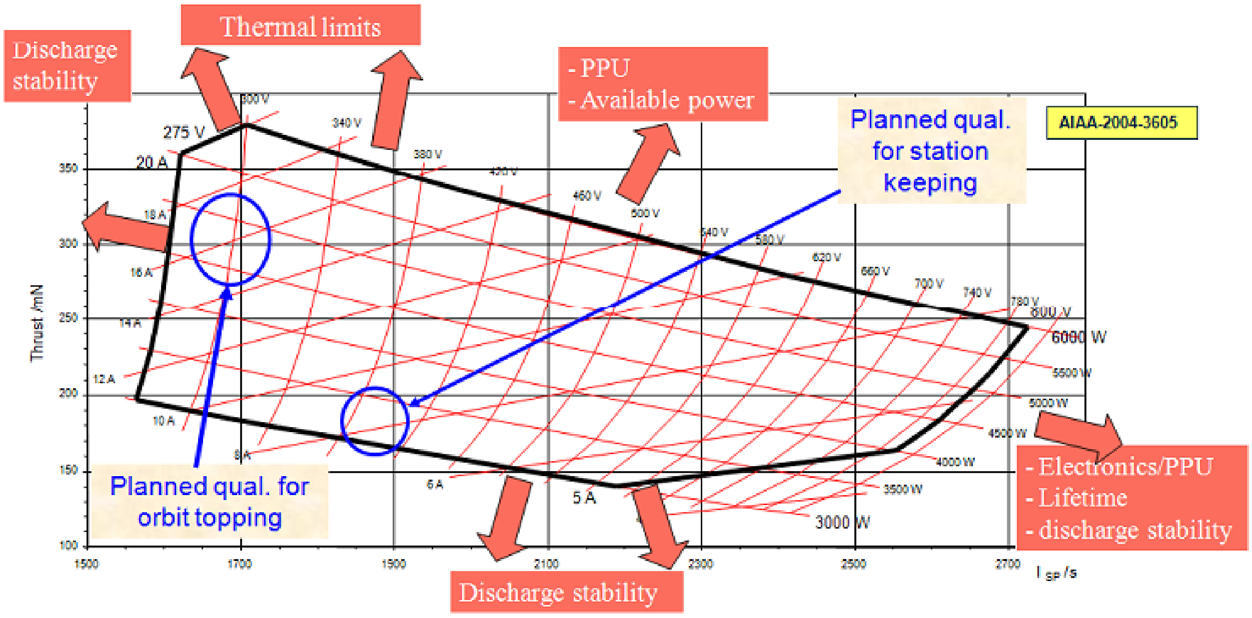


Figure 4-6: PPS®5000 operational envelope

Snecma then presented **future technology improvements**:

- Dual mode operation
- High power
- Throttleability
- Alternative propellants
- Clustered or multi-channel configurations
- Increased total impulse
- Direct drive

The concept of a **multi-mission EP platform** has also been discussed, with a possible use as a satellite module, a launcher upper stage, an exploration module or a service module for active debris removal.

Snecma have already started working on **high-Isp optimized HET** based on a slightly modified PPS®5000 design, in the frame of a 2014 ESA TRP. The optimal voltage seems to sit around 600 V, with about **2,800s Isp** with xenon. On the opposite end, **higher power** (8 kW) operation is also under investigation. Last, operation with **alternative propellants** (Kr, Ar) has been tested on HET, and preliminary system studies for propellant storage are under way.

4.7.4 Development of a 0.5 kW class krypton HET in the Institute of Plasma Physics and Laser Microfusion – IPPLM

The IPPLM are working on a 500 W HET optimized for **krypton operation**. A first prototype has been designed, manufactured, and tested in ESA propulsion laboratory (EPL), albeit only with xenon, with performances in reasonably good accordance with simulations:

***dm/dt* mg/s**	**U_D V**	**P_D W**	**I_D *readout* mA**	***F* mN**	**I_{sp} S**	***η* %**

1	300	245	818	12.1±0.8	1240	30
1	300	247	822	12.4±1.0	1270	31
1.1	300	271	904	14.7±0.9	1370	36
1.1	300	272	907	15.6±0.9	1450	41
1.1	350	322	921	14.5±0.8	1340	30
1.1	450	456	1013	18.2±0.8	1690	33
1.5	200	267	1335	19.1±0.9	1300	46
1.5	250	331	1324	20.3±0.9	1380	41

Table 4-3: KLIMT performances with xenon (Test results at EPL)

The IPPLM has since then procured a test facility, and future tests are foreseen in this vacuum chamber on an improved design of the thruster.

4.7.5 Wall-less Hall thruster – ICARE/CNRS

The wall-less HET concept aims at **extending the thruster's lifetime**. The basic principle is to move the anode toward the outer part of the chamber so as to generate the plasma discharge outside at the exit plane of the thruster, thus limiting plasma/wall interactions. Preliminary testing has been performed on a 200 W prototype, confirming the **validity of the concept**, yet showing an **overall decrease in performance** with respect to a standard configuration. Additional testing was carried out on a 2 kW-class laboratory model with an **optimized magnetic field topology**, which resulted in enhanced performances.

4.8 Session 8 – Hall Effect Thrusters (2)

4.8.1 Characterization of a 100 µN thruster – CNRS

A prototype of a **micro-HET** was presented. The incentive for this development is that of cubesat de-orbit maneuver. The design is based on the use of permanent magnets. Preliminary firing tests have been performed in a small vacuum chamber, yet no measurements were made. Complementary tests are foreseen in summer 2015.

4.8.2 The PPS®1350 family (700 W to 2,5 kW), flight qualified, with growing potential for new applications – Snecma

Snecma presented the PPS®1350 HET family. The 1.5 kW PPS®1350-G is space-qualified (Smart-1, Alphasat), thus reaching TRL 9. The PPS®1350-E, derived from the PPS®1350-G, can operate over a 1.5-2.5 kW range, has reached TRL 6 (successful CDR) and its qualification model is about to undergo the first phase of qualification. Thanks to its design, the thruster has a wide operating range:

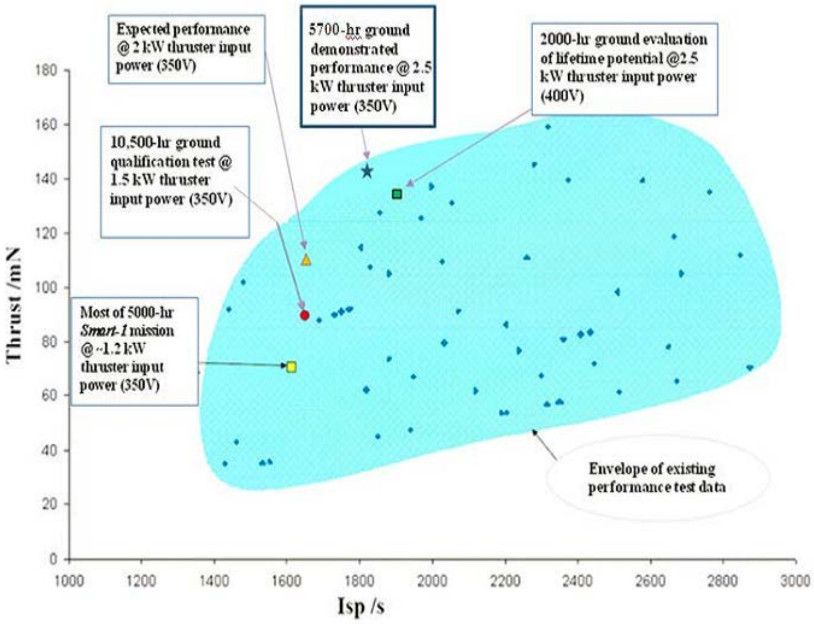


Figure 4-7: PPS®1350 family operational envelope

Proposed improvements for this class of thruster are: **improved ceramic material** with lower erosion rate, **low erosion** thanks to **optimized magnetic topology**. By combining these two activities, a **very long life HET** (i.e. >20,000 h) seems feasible.

4.8.3 High power HET - A target from 7 to 100's kW - The PPS®20k opens the way to space tug and cheaper exploration – Snecma

High power thruster activities at Snecma were presented, with the development status of the PPS®20k that showed the following performances:

- Isp up to 2,700 s at 500 V discharge voltage

- Total efficiency around 60% from 5 kW to 22 kW
- Throttling capability from 350 mN to over 1N
- Power-to-thrust ration down to 14 W/mN

Given advances in solar array technology, **high power SEP (90 kW)** seems feasible in the 2020 timeframe. NASA's related roadmap has identified **three key technology domains** that should be supported by R&D activities: large solar arrays, high power PPU and high power thrusters. To address all of them, Snecma propose to develop a **SEP space tug.**

4.9 Session 9 – HEMP Thruster

4.9.1 Joint Lab Electric Propulsion research at Airbus DS Friedrichshafen, the University of Bremen / DLR Bremen and the Dresden University of Technology – ADS

This presentation was about **joint activities** on EP in Germany between Airbus DS Friedrichshafen, the University of Bremen, DLR Bremen and the Dresden University of Technology, through a Laboratory for Enabling Technologies. This joint lab is involved in µN-HEMP-T development. A lab model was tested and characterized, yielding the following performances: 1-10 W, 21 µN-312 µN, and 87-620 s. Besides, activities on a miniaturized FEEP thruster are on-going, as well as on a MEMS ion thruster:

	Nano-FEEP
Thruster Size	∅ ~13 mm L ~ 21 mm
Mass for 4 Thrusters including Electronics Board	150 g
Specific Impulse	~ 6,000 s *
Operating Time	~ 1,800 h *
Total Impulse (4 thrusters)	~ 60 Ns *
Thrust	0.05 – 22 µN
Propellant	Gallium

	MEMS Ion-Thruster
Field Enhancement	100 – 1000
Grid Distance	10 – 50 µm
Voltage	150 – 400 V
Power	1 – 5 W
Specific Impulse	Up to 2,500 s
Thrust	µN – 400 µN

Figure 4-8: micro- thrusters performances (Airbus DS and partners)

A micro-Newton test facility, including a thrust stand, was designed and set-up, with an aim to test micro-thrusters with a measurement stability compatible with the LISA mission's requirements (thrust noise <40-80 nN, thrust resolution in the order of 1 pN, and thrust measurement capability up to 6 mN).

The joint lab insisted on the necessity to foster the **development of µN thrusters** for future science mission.

4.9.2 HEMP-Thruster technology capability and application – TED GmbH

The HEMP thruster reduces plasma-wall interactions, thus allowing **longer lifetime**. Besides, the ionization and acceleration zones are well separated, which makes **dual mode operation** possible. The HTM-3050 is under qualification (2.8 kW, 40-110 mN, TRL 7) and a prototype of the HTM-30250 has been tested (4-10 kW, 140-320 mN, TRL 3). This technology shows a wide operating range as depicted in Figure 4-9.

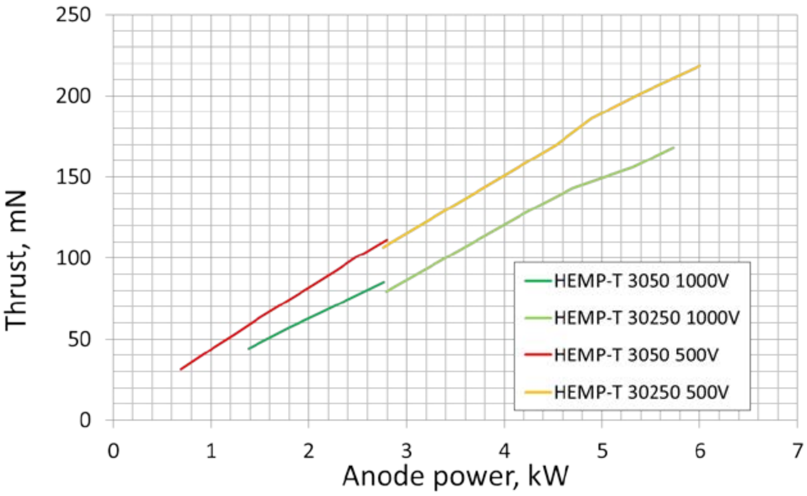


Figure 4-9: HEMP-T 3050 and 30250 operational ranges (TED courtesy)

4.10 Session 10 – Gridded Ion Engines

4.10.1 Innovative Solutions for Next Generation of Hybrid and Full Electric RIT Propulsed Satellites – Airbus DS

Airbus DS presented **market prospects for telecommunications applications**, with a possible share of EP satellites up to 25% according to a recent Euroconsult survey, and down to 4% according to NSR report 2014, due to near-term availability of heavy launchers such as Angara and Falcon 9 Heavy. In this respect, Airbus DS argue that **hybrid systems** may be better suited for future needs, in which case the focus should be on high Isp for station keeping rather than on high thrust for EOR. Airbus DS then presented the **RIT family** covering the 50-5,000 W power range, as well as ongoing developments for this technology up to powers in the range 30-50 kW.

	Thruster			
	RIT-μX	RIT-10/EVO	RIT-15	RIT-22
nominal thrust	50 – 500 μN	15 mN	50 mN	150 mN
extended / on request	3 – 3000 μN	5 – 25 mN [1)]	10 – 70 mN	50 – 200 mN
Isp	300 – 3000 s	> 3300 s	> 3300 s	> 3300 s 4260 s[1)] 4669 s[2)]
max. demonstrated	> 3500 s	> 3500 s	> 4000 s	> 6000 s
nom. power	< 50 W	470 W	1500 W	4580 W[1)] 4740 W[2)]
mass	440 g	1.8 kg	2.8 kg	7.7 kg

Figure 4-10: RIT family thrusters with its main performances

4.10.2 Gridded ion engines development at Mars Space Ltd – MSL

Two different concepts were presented: a **ring cusp** ion engine, and a **dual mode** ion engine. The motivation for a ring cusp GIE is to achieve **higher thrust-to-power ratio** by reducing the energy cost per ion. A first prototype was manufactured, replacing coils with **permanent magnets.** Tests were performed at QinetiQ and NASA JPL, with significant discrepancies between test results. Activities on high-power GIE led to the concept of a **dual-stage 4-gridded GIE** (DS4G) that has so far only been studied numerically. It may enable to achieve higher thrust density with respect to other state-of-the-art GIE:

	Power [kW]	Thrust [N]	Grid A [cm^2]	T/A [N/m^2]	Isp [s]
HiPEP	39.3	0.670	3730	1.8	9,620
NEXIS	23.2	0.475	2550	1.9	7,500
NEXT	6.9	0.237	1020	2.3	4,180
XIPS	4.3	0.166	490	3.4	3,550
NSTAR	2.3	0.093	640	1.5	3,130
RIT XT	8.1	0.218	350	6.2	6,420
T6	4.5	0.145	380	3.7	4,120
DS3G	**25**	**0.400**	**380**	**12.7**	**10,000**

Table 4-4: Comparison of DS3G performance (obtained through computation) with worldwide GIEs (Courtesy: MSL)

4.10.3 Development status of ALPHIE (Adaptable Low Power Hybrid Ion Engine) – UPM / Aernova /CTA

The Adaptable Low Power Hybrid Ion Engine (ALPHIE) is a 200 W thruster intended for application on small satellites. Its basic characteristics are:

- Operation with both xenon and argon
- Low power operation at low voltage (<500 V)
- Throttleability: controlled by potential, mass flow rate, or neutralizing current

The estimated thrust is 2.8 mN with a power-to-thrust ratio around 44 W/mN and an expected Isp of 2,900s. This concept has reached TRL 3-4.

This consortium also investigated **new** (in the space sector) **thermoionic materials** for cathode applications and identified **lithium** as an interesting candidate. However, no experimental confirmation is available yet.

4.10.4 3 gridded ion engine research at the University of Southampton – University of Southampton

The physical principle of DS3G was presented and described. Although extensive numerical simulations have been performed to model and investigate this new concept, a prototype was unsuccessfully tested, due to sparking and arcing issues. Therefore, further work is required on the **experimental demonstration** of the concept.

4.10.5 QinetiQ's T5 and T6 Gridded Ion Engine and Ring Cusp Engine Development – QinetiQ

The T5 and T6 GIE products were presented. The advantages of this technology are: **high Isp** capability, **narrow beam divergence**, **long lifetime**. On the other hand, **the thrust-to-power ratio is rather low**, and the use of high voltage results in **more complex and costly PPU**. The T5 has been successfully operated in space on the GOCE mission for more than 36,000 h (thruster firing time).

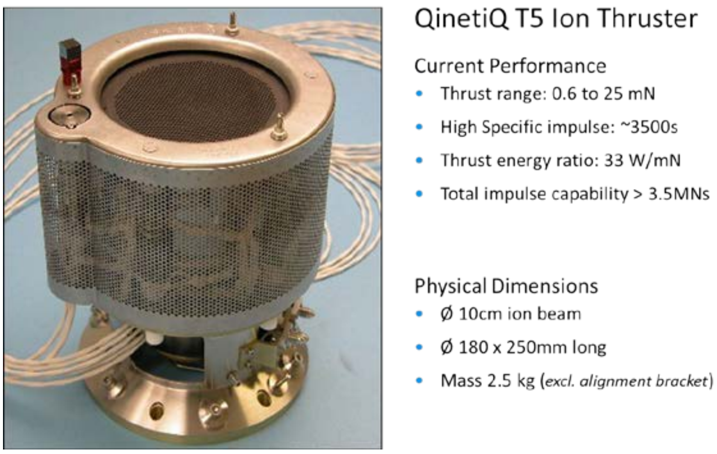


Figure 4-11: T5 ion thruster performance

Figure 4-12: T6 ion thruster performance

QinetiQ also develops **cathodes** for GIE and HET, from low (<1 A) to high (50 A) current, based on **dispenser technology**.

4.10.6 RF-Technology for Space Propulsion – Key for High Specific Impulse Ion Thrusters and Beyond – Airbus DS

Airbus DS presented the development status of the RIT-2X thruster, aiming at reaching **higher thrust-to-power ratios**. Besides, an emphasis was put on the interest of studying hybrid EP systems for satcom applications, e.g. using HET for EOR and GIE for station keeping. Last, the potential of this technology for **very high Isp** was highlighted.

4.11 Session 11 – Pulsed Plasma Thrusters

4.11.1 PPT propulsion system with non-volatile liquid propellant – QuinteScience

The presentation dealt with the L-µPPT FP7 project. The main objectives were to develop a **liquid µPPT system for nanosats** with the following thruster performances: 600 s Isp, 2 J per pulse, 1 Hz, 34 µN.s impulse bit, and 125 N.s total impulse. The propellant used is liquid PFPE, a polymer that has very low vapor pressure, good thermal stability (-50 °C to +150 °C), and properties similar to that of Teflon (e.g. no charring). The first prototype showed good behavior, with an interesting thrust-to-power ratio (36 µN/W). A second prototype achieved 10% efficiency, with a high specific impulse (1,000-1,400 s) and a lower thrust-to-power ratio (18 µN/W).

4.11.2 Micro Propulsion development at Mars Space Ltd – MSL

Two PPT concepts were presented:

- **PPTCUP**: 2.7 W, 40 µN.s impulse bit @ 2 W, 600 s Isp, 280 g mass, 44-60 N.s total impulse, currently undergoing flight qualification (qualification foreseen in late 2015). First flight model has been delivered to the Brazilian Space Agency, and a second one will be delivered in Q1/2015; TRL 6 for now.
- **NanoPPT**: 640 s Isp, 5J discharge energy, 340 g total mass (including electronics), 6.5 W, 188 N.s Isp; TRL 4.

4.11.3 Pulsed plasma thruster modelling at the University of Southampton – University of Southampton

Modelling activities for PPT were presented. The objective is to have a greater understanding of physical processes and resolve the following issues: optimization of the acceleration, reduction of the amount of neutrals left behind, charring.

4.12 Session 12 – Cathodeless Thrusters

4.12.1 ECRA thruster developed at ONERA – ONERA

ONERA started by presenting the work done by a partner CNRS laboratory on the PEGASES and NEPTUNE concepts:

- PEGASES:
  - Based on **ion-ion plasmas** (A+ and A-) generated by an **RF source**.
  - A magnetic barrier traps electrons to prevent them from exiting the thruster.
  - Positively and negatively charged ions are accelerated thanks to a **grid whose polarity oscillates**.
  - **No neutralizer** needed.
- NEPTUNE:
  - No magnetic barrier, but very specific voltage application on the grid.
  - Electrons are ejected at the same rate than the ions. Overall neutral beam.

ONERA then presented the ECR (Electron-Cyclotron Resonance) Thruster principle based on the **ECR-generated plasma** that is then expanded through a **magnetic nozzle**. Ions are effectively accelerated by the ambipolar electric field resulting from space-charge effects. No model is available at the moment.

4.12.2 Helicon plasma Thruster future development Status and future perspectives – Università degli Studi di Padova

A simple **helicon thruster** concept suitable for small satellite applications was presented. It is based on a helicon plasma source whereby thrust is produced through expansion in a magnetic nozzle. Some mission scenarios using this technology with other propellants (e.g. iodine and krypton) than xenon were then addressed. A prototype was tested, yielding the following performances: 0.5 mN; 15 W; 422 s Isp.
The main characteristics of the Helicon Plasma Thruster are:

- The plasma marginally interacts with the structure therefore the erosion is reduced.
- Internal electrodes are absent.
- The exhaust beam is neutral thus an external neutralizer is not needed.
- It can potentially operate with different propellants.
- One feeding line.
- One power line.

Given the very simple and reliable architecture, the Helicon Plasma Thruster can offer:

- High lifetime,
- Throttleability,
- Scalability.

Promising results are being obtained with a 1.7 kW thruster, 94 mN, 2139 s Isp , operated with CO_2.

4.12.3 Benefits of Helicon Plasma Thruster technology development for Space Missions – Sener

Sener presented potential advantages of helicon thrusters for future mission applications:

- High thrust-to-power ratio,
- Longer operating time,
- Throttleability.

Several types of missions were addressed (EO, LEO, GTO-GEO transfer), with what appeared to be positive results for this type of thruster. However, it was highlighted that these figures were **based on expected performances**, which have **yet to be demonstrated**.

4.12.4 Elwing EP technology

Elwing presented their E-IMPACT concept, based on the acceleration of a microwave plasma through the **ponderomotive force**. Expected performance figures were presented for a broad range of products, yet only **very preliminary testing** was performed in 2008, with **no experimental evidence of the proof-of-concept**. Consequently, this technology remains at TRL 1-2.

4.13 Session 13 – Fluidic components

4.13.1 Overview of AST Technologies – Advanced Space Technologies

AST presented their range of products:

- **Miniaturized FCU**, from 0.01 mg/s up to 10 mg/s xenon at 2.2 bar inlet pressure. Coupled EM tests have been performed with the RIT22, thus reaching TRL 6.

Parameter	Value / Range
Flow Range	Models: 0.01 ... 0.15 mg / s Xe @ 2.2 bar 0.1 ... 1 mg/s Xe @ 2.2 bar 1 .0 ... 10 mg/s Xe @ 2.2 bar *Flow may be linearly adapted by changed inlet pressure between 0.8 and 8 bar (abs)*
Independent flow lines per unit	2
Nominal op. pressure	2 bar (may be adjusted: 0.8 .. 8 bar)
MEOP for venting	8 bar
Proof Pressure	12 bar
Random vibration	21.5 g (RMS)

Parameter	Value / Range
Internal leakage	<10^{-6} sccs GHe
External leakage	<10^{-8} sccs GHe
Lifetime	>300 million actuations >1 billion actuations for long life option (equiv. 28 000 hours / 70 000 hours)
Op. temperature	-30°C ... +90°C
Non. op. temperature	-40°C ... +110°C
Mass	62 grams
Size	54 x 46 x 25 mm
Operation voltage	18V .. 24V
Max. op. power	< 5W

Table 4-5: AST miniaturized FCU performance

- **Electronic PRU**: inlet pressure up to 12 bar and outlet form 1 to 8 bar.

Parameter	Value / Range
Inlet pressure	Up to 12 bar (high pressure version under development)
Output pressure	1 ... 8 bar in-flight adjustable
Ripple	<1%
Flow range	0 ... 250 sccm Xe (high flow version for N_2 cold gas under development)
Proof Pressure	16 bar
Burst Pressure	>32 bar
Random vibration	>25 g (RMS) TBC
Shock	>4000 g

Parameter	Value / Range
Op. temperature	-30°C ... +90°C
Non. op. temperature	-40°C ... +110°C
Internal leakage	<10^{-6} sccs GHe
External leakage	<10^{-8} sccs GHe
Pressure sensor	Internal 0 ... 50 bar
Operation method	2-point controller (bang/bang)
Lifetime of valve	Standard: >300 million actuations Long file option: >1 billion actuations demonstrated
Mass	< 100 grams
Operation voltage	18V ... 28V

Table 4-6: AST Electronic pressure regulator performance

- **Cold gas thruster**: 28-140 mN thrust with N2 at an inlet pressure between 1-5 bar; TRL 7

Parameter	Value / Range
Thrust Range	28 mN ... 140 mN (N_2 pressure 1 bar ... 5 bar)
MEOP for venting	5.5 bar
Proof Pressure	8 bar
Burst Pressure	>20 bar
Random vibration	17.5 g (RMS)
Shock	>4000 g
Op. temperature	-30°C ... +90°C
Non. op. temperature	-40°C ... +110°C
Internal leakage	<10^{-5} sccs GHe (typ. <10^{-6} sccs GHe)
External leakage	<10^{-8} sccs GHe

Parameter	Value / Range
Lifetime	Standard: >300 million actuations Long file option: >1 billion actuations demonstrated
Mass	42 grams
Size	D26.2 x 33 plus fluid interface
Operation voltage	22V ... 36V
Pull in time	Min. 5 ms, max. 60 ms
Response time	Open: < 2 ms Close: < 5ms

Table 4-7: AST cold gas thruster performance

- **Particle filter** 5 µm.

It was highlighted that these products are ITAR-free.

4.13.2 MEMS-based components for electric propulsion systems – SSC Nanospace

Nanospace have specialized into **MEMS-based technologies for space applications**, such as micropropulsion, xenon feed system, propellant gauging system, valves. A **micro FCU** in the range 5-50 µg/s xenon has been developed for µRIT thrusters. A larger version is under development, with an aim to deliver flow rates up to 20 mg/s. Its technical specification is as follows:

Flow Control Module Specification	
Media	Xenon
Flow Range	0.5 - 20 mg/s
Flow rate resolution	0.25 mg/s
Mass	65 g (same as low flow version)
Power	<5 W
Dimensions	Module: ∅=43 mm Chip: 8x20 mm

Table 4-8: Nanospace micro FCU specifications

Nanospace also provide 5-10 µm filters, isolation valves with MEOP of 190 bar (resp. 310 bar) for xenon (resp. helium) at flow rates up to 600 mg/s.

Parameter	Xenon feed app	Helium app
MEOP	190 bar	310 bar
Proof	380 bar	620 bar
Burst	760 bar	775 bar
Max flow rate	600 mg/s (Xe @ MEOP)	600 mg/s (Xe @ 190 bar)
Filtration	30 micron	30 micron
Propellant Compatibility	Xe, GN2, He, Ar	Xe, GN2, He, Ar
Internal leakage (before activation)	10^{-5} scc/sec (Xe @ MEOP)	10^{-5} scc/sec (Xe @ 190 bar)
External leakage	10^{-6} scc/sec (GHe @ 10bar)	10^{-6} scc/sec (GHe @ 10bar)
Material	Titanium	Titanium
Mechanical Interfaces	¼ inch tubing	¼ inch tubing
Electrical Interfaces	Flying leads	Flying leads

Table 4-9: Nanospace isolation valves specification

A **colloid thruster** for cubesat applications is under development (under the FP7 Microthrust project), with a thrust-to-power ratio of 50 µN/W, Isp of 3,000s, and a 13,000 h lifetime.

4.13.3 High pressure xenon mass flow regulator – Air Liquide

Air Liquide presented the ongoing development of a **miniaturized xenon flow controller** able to provide flow rates between 8-20 mg/s xenon with an inlet pressure up to 190 bar, which would suppress the need for a pressure regulator at system level and hence possibly **generate cost savings**.

Some figures about **xenon production** were then discussed, with a worldwide volume of **50 t per year**. The main application is that of **lighting** (ECO halogen, cinema, etc...), which is planned to **decline from 2016 to 2018**. Besides, additional means of production can be put in place in distillation plants so as to increase the yearly yield. Consequently, provided **long term agreements** are set up with customers, these investments can be made, and a stable retail price guaranteed by suppliers.

4.13.4 Moog's products for Electrical Propulsion – Moog

MOOG presented their products, ranging from latch valves, pressure regulators, proportional flow controllers, flow control valves, mechanisms, damping systems, resistojets, cold gas thrusters, flexible piping for deployment mechanisms:

- Pressure regulator:
  - 310bar inlet pressure demonstrated
  - Wide range of flow rates and regulated pressures, suitable for:
    - helium bipropellant system pressurisation (0 – 500 mg/s helium)
    - xenon EP applications (0 – 200 mg/s)
    - cold gas applications (0 – 5 g/s xenon)
- Flow control units

Performance Characteristics	
Operating media	GXe
Test media	GN_2, GHe, GAr
Inlet filter rating	2 µm absolute filtration
Inlet pressure range	2.50 to 2.85 barA
Maximum expected pressure	10 barA
Proof pressure	15 barA
Burst pressure	25 barA
Main line flow	0.8 to 3.0 mg/s ± 1.0 %
Cathode line flow	0.6 to 0.8 mg/s ± 1.0 %
Neutralizer line flow	0.10 mg/s ± 10 %
Outlet pressure main line	0 to 300 mbarA
Outlet pressure cathode line	0 to 200 mbarA
Outlet pressure neutralizer line	0 to 100 mbarA
Flow rate initialization time	≤ 1 min
Response time	≤ 1 min
Temperature feedback accuracy	< 0.2 °C
Pressure feedback accuracy	< 0.3 %
External leakage	$< 3 \cdot 10^{-8}$ scc/s GHe
Internal leakage	$< 3 \cdot 10^{-5}$ scc/s GHe (≥ -20 °C)
Mass	≤ 1160 g
Overall size	184 x 144 x 76 mm
Operational temperature range	-30 to +65 °C
Non-operational temperature range	-40 to +75 °C

Table 4-10: MOOG Flow control units performance

- Orientation mechanism

Specifications	
Physical Characterisitics	
Dimensions	8.75 x 5 x 5 inches
Weight	< 11 lbs
Payload Weight	50 lbs (externally supported)
Performance	
Total Rational Range of Travel	±36° in both X and Y axes
Angular Resolution	0.01125°/step
Angular Velocity	3°/sec minimum
Incremental Angular Accuracy	± 0.003° maximum
Absolute Angular Accuracy	0.03° maximum
Operating Temperature Range	-20° to +80°C
Power Requirements	
Power Consumption	22 watts max. per actuator/axis

Table 4-11: MOOG Orientation mechanism performance

- Resistojet:
  - with ammonia: 200 s Isp, 40 mN at 70 W
  - also suitable for nitrogen, xenon
  - up to 500 mN thrust

- Flow control valves

Performance Characteristics		
Operating Media	Butane, Propane, GN_2, Xenon	
Operational Temperature	-35°C to 95°C	
Operating Pressure	4 bar	
Coil Resistance	To Suit Customer Power Requirements	
Opening/Closing Response	< 5 msec	
External Leakage	$< 1 \times 10^{-6}$ scc/s GHe	
Internal Leakage	$< 1 \times 10^{-4}$ scc/s GHe	
Operating Voltage	24 - 32 V_{DC}	
Minimum Cycle Life	1,500,000	
Construction	Body & Magnetic Components	Stainless Steel 304L/Radiometal 4550
	Seal	Silicone, EPDM Viton Rubber
Mass	< 35 g	
Interfaces	Weldable Tubing/Thread – per Customer Requirement	
Maximum Body Length	21mm (individual valve)	
Outside Diameter	16mm	

Table 4-12: MOOG Flow control valves characteristics

4.14 Session 14 – Other EP sub-system components

4.14.1 Large volume xenon storage for EP – ADS

ADS presented their capabilities in **high pressure tanks**, mostly for bi-propellant applications (pressurant tanks) on satellites, and for high pressure He storage on Ariane launchers. Besides, a 69L **xenon tank** was qualified and flown on the Stentor satellite, reaching TRL 8.

The discussion then focused on the **specificities of xenon tanks**:

- High xenon density (1.5-1.8kg/L between 150-190bar), which will generate higher constraints on mechanical interfaces.
- **Variety of capacity requirements** (needs between 100-500 or 800L), which entails cost optimization difficulties

Polar attachment is not possible for high mechanical loads, which means that **skirt attachment** (either metallic or composite) is mandatory. As regards tank versatility, the approach is that of a family of products with a variable central cylindrical part. The qualification of the whole range of tanks is then performed through testing for the most dimensioning tank, and by similarity for the other configurations.

4.14.2 Mechanisms for Electric Propulsion from RUAG Space – RUAG

The presentation highlighted the **EP-specific challenges for mechanisms**: shocks and vibrations, harness and piping, hold-down and release mechanism, and thermal environment. Mechanical constraints require the use of **dampers** to attenuate loads on thrusters. Harness and piping generate torques that have to be taken into account in the assessment of the mechanism's kinematics, as well as cycling issues which will get worse with greater angular mobility requirements. RUAG presented a range of pointing mechanisms, with a focus on deployable arms for EOR applications.

Application	Mechanism Designation	Thruster	Supported Mass	Mechanism Mass	Pointing Angle	Eigen - Frequency (stowed)
Telecom Satellites						
	Thruster Pointing Mechanism TPM	PPS 1350 or ROS 2000 or SPT 100 (2 off)	14 kg	10.6 kg	± 6.5° half cone	80 Hz
	Thruster Orientation Mechanism TOM-100	SPT 100B (2 off)	11 kg	16 kg	-15°....35° ±15°	86Hz
	Thruster Orientation Mechanism TOM-140	SPT 140 (1 off)	11 kg	16 kg	-15°....35° ±15°	78Hz
	Electric Propulsion Pointing Mechanism EPPM	QinetiQ T6 (2 off)	18 kg	21 kg	120° (depl) ±15° ±15°	75 Hz
Scientific Satellites						
	Ion Thruster Alignment Mechanism ITAM	RIT and EIT	7.5 kg	4.3 kg	±6° half cone	85 Hz
	Electrical Propulsion Mechanism EPMEC	PS-1350	5 kg	10 kg	±9.5° half cone	40 Hz
	Thruster Pointing Assembly TPA	QinetiQ T6 (4 off)	9 kg / TPM (4 off)	11.6 kg / TPM (4 off)	±15° half cone	55 Hz

4.14.3 *Non-mechanic thrust pointing system with steerable magnetic nozzle – Universidad Carlos III de Madrid*

A possible **alternative to mechanisms** (trying to decrease complexity and weight) was presented, namely, a steerable 3D magnetic nozzle. It applies to devices akin to helicon thrusters, with small changes in the magnetic design. No proof-of-concept has been performed yet, with **only modelling activities** to investigate the basic physics principle. The corresponding TRL is consequently low (TRL 1-2).

4.14.4 *Cathodeless rf neutralizer - state of the art possibilities and first results – IOM Leipzig*

The cathodeless RF neutralizer is based on a **high-density low pressure plasma generated by inductive RF coupling**. The peak current obtained so far on a breadboard model is 1A at 1 sccm xenon and 80W of RF power, and even 1.8A at 150W RF power. The device was also operated with **argon**, with **significantly degraded performances** (max current of 520mA at 200W RF power and 2 sccm argon). Overall, such a neutralizer is much less efficient that hollow cathode technology.

4.15 Session 15 – Other thruster concepts

4.15.1 Resistojet development at Mars Space Ltd – MSL

The company has two **small test facilities**: MSLC-1 and MSLC-2 equipped with turbopumps whose pumping speed is around 2,000-4,000 l/s. Hollow cathodes HCT5 and HCT6 were tested as resistojet thrusters, yielding Isp around 50s with xenon. Mars space Ltd are now developing a **Very High Thrust Resistojet** with the following requirements: compatible with Xe, Ar, Kr, N2; total impulse 10kN.s; thrust >100mN; Isp >80s (xenon); 50% efficiency; mass below 250g. The main technology issues are the **heater** and the use of **high temperature materials**.

4.15.2 Propellantless electric propulsion/Coulomb drag devices for interplanetary propulsion and LEO deorbiting – Finnish Meteorological Institute

The presented concept is based on the **Coulomb drag effect**, that generates a transfer of momentum between a stream of ions (electrons) with a positively (negatively) **charged tether**. As an example, a 1N e-sail would require one hundred **20-km long tethers** (total mass of 100-200kg). The related power-to-thrust ratio is very low (0.7W/mN).

4.15.3 A new concept of ion engine for low thrust electrical propulsion – Sodern

The idea is to derive **µN thrusters from neutron sources**. These sources make use of deuterium/tritium fusion, whereby deuterium is accelerated as ions to then collide with tritium-based electrically biased targets, thus generating a neutron flux. These devices may be adapted for thruster application while implementing minor changes (i.e. implementing accelerating grids). They have **high ionization efficiency** thanks to the implementation of a **Penning ion source.**

4.15.4 VAT Propulsion System for a Single-CubeSat – Universität der Bundeswehr München

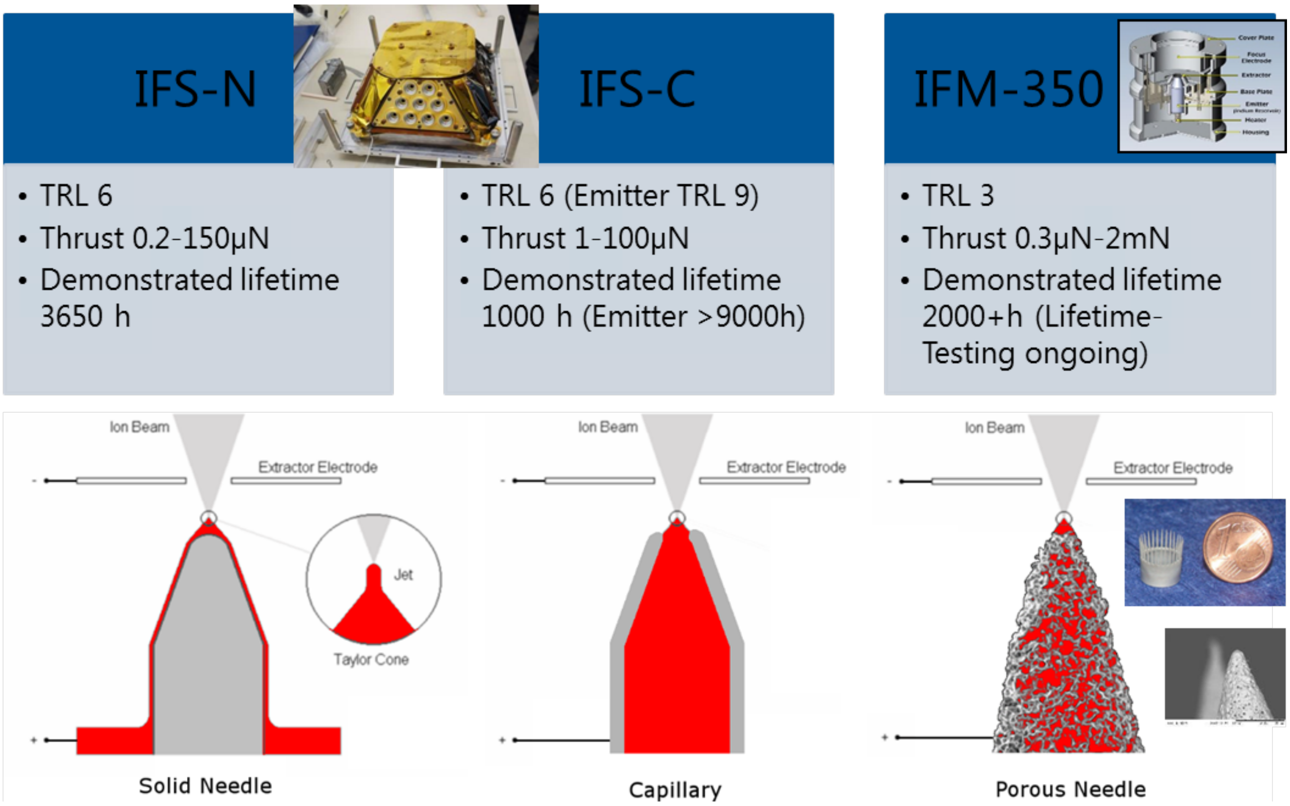
This presentation dealt with the development of a **VAT for cubesat applications**. The principle is based on **plasma arc spots from a solid cathode**. Ignition is obtained at low voltage (100V) thanks to a thin conductive layer between the two electrodes. This technology is presently facing **lifetime, reliability and repeatability** issues. Performances achieved are: 1-30µN.s impulse but, Isp ranging from 139s (Sn) to 1,666s (Cr) and a thrust to power ratio of 1-20µN/W. The PPU development is running in parallel, with difficulties in reaching mass objectives.

4.15.5 Electric Propulsion in Austria - Current Developments and Outlook – FOTEC

FOTEC have a strong Liquid Metal Ion Sources heritage. The propellant used their EP thrusters is Indium. Three different types of technology have been investigated:

- **Solid needle** with liquid metal film and a Taylor cone forming at the tip: IFS-N, tested for 3,650h in the frame of Lisa PF, but needle manufacturing issues have stopped the development (TRL 6)
- **Capillary needle**: IFS-C, tested for 9000h at emitter level, and 1000h at thruster level (TRL 6)
- **Porous needle** technology:
  - IFM-350 Nano: 0.3µN-1mN; TRL 4

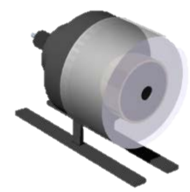
- o IFM-3000: 0.05-600mN, based on a 2D-array of needles (TRL 1)

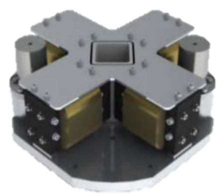
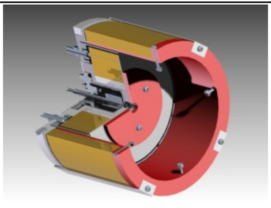
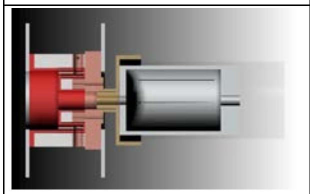
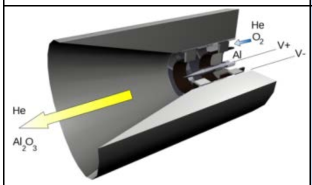


FOTEC have also developed tools for the modeling of EP plume and spacecraft. Last, they have several testing facilities up to 2.5m diameter and 4 meter long.

4.15.6 Electric Propulsion for Small Satellites within the Surrey Space Centre – Surrey Space Centre

SSC insisted on the need to bear in mind **system aspects** form the start in any new EP development. The **QCT** is based on using a magnetic quadrupole to confine the plasma. This enables thrust vectoring, but it also results in the cathode's position having a significant influence on performances. The **Halo thruster** concept was also presented, whereby ions are accelerated between two virtual electrodes that are created thanks to magnetic null points in an axisymmetric discharge chamber.

	Technology	Target Performance	Commercial need
	**QCT-40**	• Input power: 40W • Propellant: Various (Xe, Butane, H2O, etc) • Specific impulse: 250s • Thrust: 3.3mN • Thrust efficiency: 10% • Power/Thrust: 12.1 W/mN	Candidate technology for replacement of the heritage Xenon resistojets on SSTL 50kg - 200kg platforms.

	**QCT-200**	• Input power: 200W • Propellant: Xenon • Specific impulse: 1200s • Thrust: 10.2 mN • Thrust efficiency: 30% • Power/Thrust: 19.6 W/mN	Low cost and low power EP alternative for the growing small satellite industry (100kg - 500kg platforms).
	**QCT-1500**	• Input power: 1500W • Propellant: Xenon • Specific impulse: 1600s • Thrust: 95.6 mN • Thrust efficiency: 50% • Power/Thrust: 15.7 W/mN	Low cost alternative to Hall effect thrusters and gridded ion engines for GEO platforms.
	**DC Halo Thruster**	• Input power: 200W • Propellant: Xenon • Specific impulse: 1600s • Thrust: 7.6 mN • Thrust efficiency: 30% • Power/Thrust: 26.3 W/mN	Low cost and low power EP alternative for the growing small satellite industry (100kg - 500kg platforms).
	**RF Halo Thruster**	• Input power: 1500W • Propellant: Various (Xe, Butane, H2O, etc.) • Specific impulse: 1600s • Thrust: 95.6 mN • Thrust efficiency: 50% • Power/Thrust: 15.7 W/mN	Low cost alternative to Hall effect thrusters and gridded ion engines for GEO platforms, with the added benefit of being able to operate on exotic propellants such as hydrazine.
	**Electrochemical Thruster**	• Input power: 1000W • Specific impulse: 600s • Thrust: 100 mN • Thrust efficiency: 30% • Power/Thrust: 10 W/mN	The UK alternative to the arcjet thruster: Mid-range power, moderate Isp, high thrust device

4.16 Session 16 – Test facilities

4.16.1 QinetiQ's EP test facilities – QinetiQ

Test facilities at QinetiQ are used for development activities, system qualification and acceptance testing, and EMC measurements. EP test capabilities encompass various types of engines: GIE, HET, cathodes and systems (T5 for GOCE, T6 for Bepi Colombo). Several vacuum chambers are available:

- LEEP2: 3,8 m diameter x 9 m length, up to 80,000l/s xenon pumping speed
- Thrust balance: 1-500mN, +/- 0.75mN, thruster mass up to 15kg.
- LEEP 3: 3m diameter x 8m long, up to 200,000l/s xenon. Coupling tests (T5 test on GOCE, T6 for Bepi Colombo
- LEEP 1: 3mx 3m x 4m, with anechoic properties for EMI testing
- Small chambers

4.16.2 The Plasma Testing Facility of the Technical University of Madrid – UPM

The UPM presented the following facilities and diagnostics:

- ARGES vacuum Tank (0.8m diameter x 2m long), used for ALPHIE
- Electric probes (Langmuir or emissive probes, RPA which are less sensitive to stream velocity)

4.16.3 Electric Propulsion Test Facility at DLR – DLR

DLR presented the recently completed STG-ET large test facility:

- 5m diameter x 12m long
- Up to 25-50kW thruster power
- Back pressure less than 10^{-5} mbar
- Equipped with a beam diagnostic (Faraday cups and RPA mounted)

Besides, DLR Göttingen cooperate with the University of Giessen, where the Jumbo vacuum chamber is located (2.6m diameter x 6m long).

4.16.4 Test facilities and advanced diagnostics for electric propulsion – Aerospazio

Aerospazio offer two main facilities for EP testing:

- o LVTF-1: 3.8m diameter x 11.4m long; >180,000 l/s xenon pumping speed
- o LVTF-2: 3.8m diameter x 12.5m long; >180,000 l/s xenon pumping speed; connected to an anechoic chamber for EMI/EMC testing

Besides, smaller test chambers are also available:

- SVTF-1/2/3
- MVTF-1: 1.3m diameter x 3m long; >10,000 l/s xenon

Last, Aerospazio offer a wide range of diagnostics, such as beam probe arm (with 34 Faraday probes and 2 RPA), Langmuir probes, emission spectroscopy, LIF, ExB probe.

4.16.5 System integration and end-to-end test capability at THALES Ulm – TED

TED presented the ULAN test facility: 2.4m diameter x 4m long; up to 120,000 l/s xenon pumping speed. It is equipped with a thrust balance (for thrust measurements up to 800mN with a resolution of 50µN and an accuracy of 300µN), RPA, mass spectrometer, and a probe arm for beam characterization. It has been used extensively for HEMP thruster qualification as well as end-to-end tests.

4.17 Session 17 – Diagnostics

4.17.1 Laser-aided diagnostics for EP – ICARE/CNRS

The ICARE lab has three **test facilities**:

- Pivoine (2.2m diameter and 4m long)
- NExET (0.8m diameter and 1.8m long)
- EPIC (0.5m diameter and 1m long)

Besides, the team has developed a complete range of **plasma diagnostics** (emissive, ExB, and Langmuir probes, RPA, Faraday cup, CCD imaging, emission spectroscopy, laser-induced fluorescence, Fabry-Pérot interferometry, etc...). A focus was made on **laser-based diagnostics**, that provide high spatial and temporal resolution while being weakly intrusive, at the price of complexity, volume, and cost. **LIF diagnostics** enable the measurement of the ion velocity distribution function. **Coherent Thomson Scattering** can give insight into the small-scale dynamics of the plasma discharge by measuring fluctuations such as micro-turbulence. A **photo-detachment technique** is under development for the characterization of negatively charged ions.

Possible developments for EP are: incoherent Thomson scattering (electron energy distribution function), Stark spectroscopy (electric field), and two-photon LIF.

4.17.2 Electric propulsion at ONERA: test facilities and diagnostics – ONERA

ONERA have **three vacuum chambers** (µN bench (0.5x0.7m, 1000 l/s), B09 (0.8x2, 2500 l/s), B61 (1x4, 4000 l/s)) and provide specific diagnostic services:

- ONERA is developing, under an ESA TRP, a **3D LIF diagnostics** that allows a complete mapping of the ion velocity in the thruster's plume.

- The **µN balance** can measure thrusts from below 1µN up to more than 1mN, with a resolution of 0.5µN and an error around 0.06µN.

- The **electron beam fluorescence diagnostic** can measure the neutral density for, e.g., cold gas thruster or neutral injection in HET.

4.17.3 Force Probes for Thruster Plume Diagnostics – University of Kiel

The concept of a **force beam probe** was presented. The principle is to measure the transfer of momentum between ions or neutrals and a planar surface. One of the difficulties is to take into account the effect of sputtering. The minimum level of thrust currently measurable is 1µN/cm2.

4.17.4 THALES test facility and diagnostics for EP in Ulm – TED

TED have several test facilities:

- a neutralizer-specific test facility

- a 2.4x4m with pumping capability up to 200000 l/s xenon

The latter facility is equipped with a thrust stand mounted on a rotating table, fixed beam diagnostics, a thermal interface allowing cold or hot testing, and, in the near future, a rotating probe (RPA) arm for plume characterization and thrust pointing measurement (with an accuracy <0.5°).

4.17.5 AEPD II a new standard for EP-thruster characterization – IOM Leipzig

The institute developed an **in-situ diagnostics package** for EP, with an aim to characterize the plume, the thermal behavior of the thruster as well as its possible erosion. As a consequence, several diagnostics were implemented in the **AEPD II** (Advanced Electric Propulsion Diagnostic) onto a 5-axis moving device: a Faraday cup, an energy-selective mass spectrometry, a pyrometer, a thermocamera, a telemicroscope, and a laser head.

4.18 Session 18 – Hollow cathode

4.18.1 *Hollow cathode development at Mars Space Ltd – MSL*

The company developed several cathodes:

- a very high power dispenser cathode in the frame of the FP7 HiPER project, with a current capability up to 180A
- a high current LaB6 cathode in the range 15-45A
- a lab-model dispenser cathode, HC40

Besides, they tested a laboratory model of a Hollow Cathode Thruster (HCT) with the following performances:

- cold gas mode: up to 25mN thrust; 20s Isp
- resistojet mode: up to 60s Isp at 60W heating power
- arcjet mode: 1.8mN; 320s Isp at 200W

4.18.2 *THALES cathode technology for space applications – TED*

The **HCN5000** was presented. It is a mixed-metal (osmium, tungsten and molybdenum) hollow dispenser barium-impregnated cathode. This piece of equipment underwent a **successful qualification** (environmental and life testing), with a lifetime in excess of 8,000h and predictions **up to over 300,000h**.

4.18.3 *The development of heaterless hollow cathodes at the University of Southampton – University of Southampton*

The possibility of **heaterless cathode** was then addressed. The motivation is to do away with reliability issues, start-up delay and additional power. On the other hand, current issues with heaterless technology are repeatability, lifetime, and high voltage. Research activity in this field is only starting at the university of Southampton.

4.18.4 *High current hollow cathode development at the university of Southampton*

A **100A hollow cathode** for HET is under development, in collaboration with JAXA. It is based on the Barium oxide insert technology, but it is also planned to develop a LaB6 cathode. The lack of a suitable **modeling tool** in Europe for cathode design was highlighted.

4.19 Session 19 – Power Processing Unit (1)

4.19.1 Power Processing Unit Activities at Thales Alenia Space Belgium – TAS

TAS presented their **heritage in the PPU market**:

- PPU Mk1 (1.5kW-class): **30 FM delivered** (of 16 for NSSK on 8 comsats), 7 in production, 10.6 kg.
- External Thruster Selection Unit: select 1 out of 4 1.5kW-class thrusters, 4.3kg
- Filter Unit for 1.5kW-class thrusters, 0.9kg.
- PPU Mk2: for 1.5-2.5kW-class thrusters, coupling tests performed with PPS1350-G and –E models; **8 FM ordered**, with first delivery in 201511.8 kg
- High-voltage PSCU demonstration module coupled test with RIT-22 and HEMPT-3050

TAS are now developing the **5kW PPU Mk3** that is compatible with all main HET on the market (PPS5000, SPT-140D, and XR-5). The PDR was held in September 2014, and the CDR is planned in Q2/2015. QR is foreseen in Q4/2015 and 8 FM have already been ordered, with first delivery due in 2016.

The implemented technologies are: hybrids, SOC (Soldered On Copper plate), planar transformers, digital control loop (for mass flow regulation).

R&D activities for future PPU Mk4 are ongoing, with the aim to acquire **more flexibility** (multi-thrusters), implement more efficient power modules. Proposed **future activities** are: higher power, high voltage HET, development of **European critical parts**. **To increase competitiveness**, the following ideas were discussed: direct drive, integration of PPU with the PCU, hybrid EP system (PPU to drive multi-thrusters).

4.19.2 PPUs for Hall Effect Thrusters – Sitael

Sitael are involved in the **MEPS** (Micro-Satellite Electric Propulsion System) project for 100-300W propulsion, in cooperation with Rafel (Israel). The corresponding PPU is compatible with both ALTA HT-100D and Rafael CAM-200 HET. The main features are: redundancy to avoid SPF, compatibility with heaterless cathodes, high efficiency, 7kg mass budget, max discharge current of **1.5A and 350W** maximum power.

Besides, a **5kW-class PPU** is under development: **5-19A, 5kW max**, variable voltage. Further work should focus on: use of cots, simplified and innovative architecture, space qualification of new power components (e.g. SiC).

4.19.3 Selex ES capabilities in Electronics for Propulsion – SES

SES experience in the field of space electronics includes:

- **PCU** for FEEP (either Cesium or Indium) at **very high voltage** (12-14kV) and RIT at high voltage (2kV). Four Cs-FEEP PPU FM were qualified and delivered to ADS UK for the Lisa Pathfinder mission, the RIT-10 PPU was flown on ARTEMIS, while the µRIT PPU is available as an elegant breadboard version.
- **Electronics for cold gas applications** for the GAIA and MICROSCOPE missions.
- **PCDU** for spacecraft level up to 8kW.

Besides, SES have developed **neutralizers** which can deliver currents up to 6mA, with a steady state input power of 5W, as well as **higher-current cathodes** from 1-20A. They also propose a range of in-space plasma diagnostics, and have competencies in **electronic pressure or flow regulators.** Last, they can provide **solar arrays** across the board, from nanosat to large science missions.

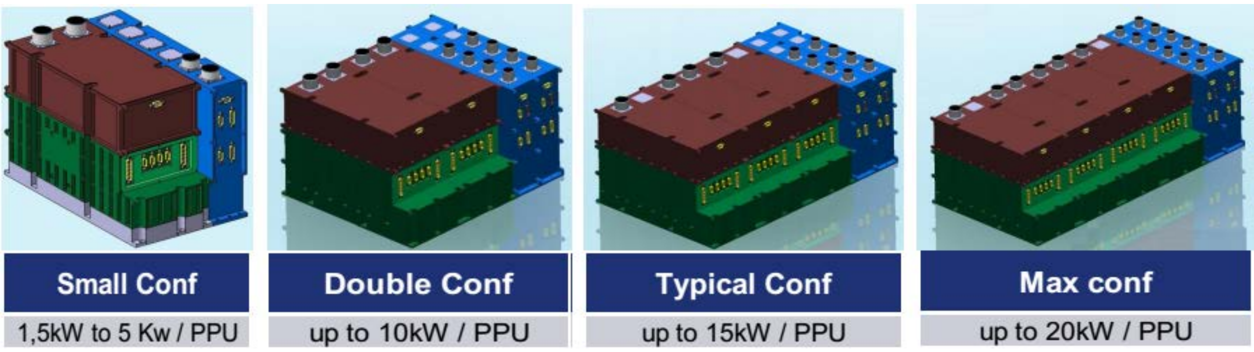
4.20 Session 20 – Power Processing Unit (2)

4.20.1 *Presentation of the PPU activities within Airbus Defense and Space – ADS*

ADS Elancourt presented the ongoing development of the PPU NG for 5kW-class HET thrusters. This piece of equipment features:

- **Modularity** (output power from 1.5kW to 20kW)
- **Variable voltage** (300-400V)
- **Multi-HET** compatibility

The PPU consists of a Heater, Keeper, Ignitor and Sequencer (HKISeq) module than can feed up to 6 thrusters, and up to four 1.5-5kW power modules. These modules can be **accommodated separately on the platform**, and they require to be mounted onto **heat pipes** for thermal management.



The HKISeq can **pre-heat two cathodes at the same time** and then switch on the thrusters one at a time, in sequence. A **breadboard model** has been successfully tested with the PPS5000 and SPT-140D thrusters, and a coupling test with the XR-5 is foreseen in 2015. A PDR was successfully held in Q3 2014, and the CDR is planned in Q3 2015, with a QR in Q1 2016 and a first FM in Q2 2016, on a E3000 platform.

Future proposed activities are: 5kW (instead of 2.5kW) power cell for cost optimization, digital or mixed ASICs, and use of GAN MOSFETs in the anode power cell.

4.20.2 *Power Processing Units for T5/T6 Thruster – ADS*

ADS Crisa presented the **T5/T6 PPUs**. The GOCE IPCU, with a mass of 18kg, provides power up to 520W and voltages up to 1200V. The T6 PPU has been successfully qualified, with coupled test completed with the thruster, and first FM to be delivered in 2015. One PPU can **feed up to four thrusters** (full cross strapping) but can only **power one at a time**. Ongoing activities on the T5/T6 PPUs aim at reducing cost by up to 40%.

4.20.3 *High Voltage Electric Propulsion Electronics for Orbit Raising Application – ADS*

ADS Friedrichshafen and Ottobrunn presented the HEMP-T PSCU that can drive and control four thrusters at the same time with a maximum power of 2.8kW. A 5kW PPU is currently under development, with output voltage <500V, 1000V, 1850V and 2000V, in view of applications with HEMP-T and GIE (both Kaufman/cusp ring and RF types). Future ideas include: **modular PPU**, **European critical parts**, high power-high voltage test facilities, generic high voltage connectors.

4.20.4 An Innovative PPU design for 500W-class thrusters – Sagem

Sagem have worked on a **500W PPU** within the EPS500 concept proposed by Snecma, where the PPU, PRU and thruster unit are all integrated into one single piece of equipment. The **high-level requirements** for this PPU are:

- Low voltage unregulated bus (24-32V)
- Output voltage between 200V and 400V
- Power between 300W and 700W
- No external thermal management
- ITAR-free parts

A breadboard model for the anode module was tested, albeit without the thruster. Next steps of this development require coupling tests as well as testing of an integrated (PPU+HET) system.

4.21 Session 21 – Development tools

4.21.1 *Modeling tools for optimizing design and performance of thrusters – University of Greifswald*

EP modeling is a **multi-scale problem**, and a dedicated code was developed to deal with plasma/wall interactions and anomalous transport in HEMP-T, using PIC, DSMC and similarity scaling. Results were compared with experimental data, with reasonable agreement, especially with regard to ion fluxes at the cusps. Cross-checking with measurements was also performed for the spoke instability observed in cylindrical Hall Thrusters. Last, this code was used for the **modeling of back-sputtering and redeposition** in vacuum chambers.

4.21.2 *Validated dynamic life time modelling and related material investigations – IOM Leipzig*

IOM Leipzig presented a family of modeling tools for the **prediction of grid erosion** based on the implementation of physical models and experimental measurements for sputter yields, as well as for **ion optics optimization**: IGUN, KOBRA3-inp, FLOOD, and DynaSim. The latter was validated through comparisons with experimental data obtained during the RIT-10 qualification, with a good agreement.

4.21.3 *Plume effects Simulation Tool – KopooS*

The presentation started with a recommendation to use more than one tool for modeling, or at least perform **benchmarking and cross-checking** activities. The TdNTriaX code, developed by KopooS presented dealt with plasma **plume and spacecraft interactions**. As an input, it is necessary to provide plume models (current density, ion energy, and ion density). The TurboDESIGN tool, developed by MAI, is based on similar models. A benchmark was performed between the two, showing good agreement for: perturbing torques, erosion rates, RF shift, and re-deposition**, provided the input data was coherent**.

4.21.4 *Official Launch of the ESA European Electric Propulsion Database – FOTEC*

FOTEC presented the **European EP database**, compiling data related to plume, thruster, components and diagnostics. It is intended as a collaborative platform that users can update with their own inputs. The corresponding url is www.electric-propulsion.eu

4.21.5 *HALLMA and EP2PLUS advanced hybrid codes for Hall thrusters, plasma plumes, and SC interaction – Universidad Carlos III de Madrid*

The NOMADS and EP2PLUS codes were presented. NOMADS is used for HET modeling and is a new generation code based on HALLMA and HPHall2 experience. It is a **2D hybrid PIC/fluid** code, with an advanced description of the EEDF, and of plasma-wall interactions. It is currently under development.

EP2PLUS is a **plume modeling** code. It was stressed that the plasma plume is difficult to model, due to the **multi-physics, multi-scale** phenomena at play. This code is based on a hybrid PIC/fluid approach as well, with a renormalization of particles as the plasma expands.

4.21.6 2D DIMAGNO and HELWAVE2 simulators for Magnetic Nozzles and Helicon Antenna Sources – Universidad Carlos III de Madrid

The DIMAGNO code can model magnetic nozzles as found in Helicon, ECR, VASIMR thrusters for instance. It is a **two-fluid, two-dimensional** code of near collisionless **magnetized** plasmas. The MNHyb hybrid code can take into account both magnetized and **unmagnetized** plasmas and collisions.

HELWAVE is a code that describes the **plasma-wave interactions and energy absorption** for helicon thruster applications.

4.21.7 Steps towards a fully kinetic simulation of a HEMP-thruster solving the "anomalous electron transport" problem with a mathematical approach – Kornfeld Consulting

A code based on XOOPIC was presented. It includes a background of neutral gas as well as additional collision phenomena, and multiply-charged xenon ions. In order to achieve acceptable computational time on a typical laptop computer, scaling laws with a factor of 10000 were applied. This resulted in the simulation not being representative of a nominal operation of the HEMP-T, but this approach may be interesting for µHEMP thrusters.

ANNEX 1: WORKSHOP'S PROGRAMME

TUESDAY 25 NOVEMBER

08:00	**Registration**
09:00	**Introduction** *Nicolas ARCIS, CNES*
09:10	**Presentation of the EPIC Projet** *Jose GONZALEZ DEL AMO, ESA*
09:20	**H2020 Space and the Strategic Research Clusters** *Apostolia KARAMALI, European Commission (DG-ENT)*

Session 1► Mission requirements: GEO
Chair/secretary: G. SACCOCCIA / G. MOURY

09:50	**Eutelsat Electric Propulsion perspective** *Cosmo CASAREGOLA, Eutelsat*
10:10	**Perspectives for telecom satellites and drivers towards electrical propulsion evolutions** *Pascal SAINT-GEORGES, Thales Alenia Space / Philippe LAMOTTE, Thales Alenia Space*

10:30 – 10:50 Coffee break

Session 2► Mission requirements: General
Chair/secretary: G. SACCOCCIA / G. MOURY

10:50	**Airbus Defense and Space - mission and system requirements for electrical propulsion** *Nathalie METZGER, Vincent JACOD, Paolo BIANCO, Airbus Defence & Space*
11:40	**Proposed TAS orientations for electric propulsion technologies considering various satellites applications perspectives** *Philippe GARCON, Philippe LAMOTTE, Thales Alenia Space*
12:00	**OHB System's view of propulsion needs** *Alain DEMAIRE, OHB* **OHB System's vision of the market** *Markus PEUKERT, OHB*
12 :40	**CIRA's R&D Vision in Electric Propulsion** *Vito SALVATORE, CIRA – Italian Aerospace Research Center*

13 :00 -14 :00 Lunch with Belgian specialties offered by BELSPO

Session 3► Mission requirements: LEO/MEO

Chair/secretary: G. SACCOCCIA / G. MOURY

14:00	**Very Low Earth Orbit Mission Capabilities using Gridded Ion Engine (GIE) on board PROBA Satellite Platforms: Requirement Definition for the Suppliers** *Julien TALLINEAU, QinetiQ Space*
14:20	**Electric propulsion needs for LEO satellites** *Xavier ROSER, Thales Alenia Space*
14:40	**Electric propulsion needs for nano-satellites** *Piero SICILIANO, Thales Alenia Space*
15:00	**Novel mission approaches for electric propulsion** *Gianluca ASCANIO, CGS S.p.A. Compagnia Generale per lo Spazio*
15:20	**EP needs of navigation satellites including the GALILEO 2nd generation** *Arturo INTELISANO / Massimiliano MARCOZZI, Thales Alenia Space*

Session 4► Mission requirements: Space transportation and interplanetary missions (1)

Chair/secretary: P. LANDIECH / P. LIONNET

15:40	**Electric Space Tug** *Carole BILLOT, Thales Alenia Space*
16:00	**Electric Propulsion Developments for Space Exploration and Science** *Mario PESSANA, Thales Alenia Space*

16:20 - 16:40 Coffee break

Session 5► Mission requirements: Space transportation and interplanetary missions (2)

Chair/secretary: P. LANDIECH / P. LIONNET

16:40	**EP High level requirement from the perspective of a LEO Launch System Integrator** *François BATTIE, Avio*
17:00	**EP as an alternative for the JUICE mission** *Frédéric MARCHANDISE, SAFRAN-Snecma*

Session 6► System aspects

Chair/secretary: P. LANDIECH / P. LIONNET

17:20	**From Smart-1 to Galileo G2, Snecma is designing, developing and operating optimized HET propulsion architectures** *Anthony LORAND, SAFRAN-Snecma*
17:40	**System topologies for HEMP-T systems** *Stefan WEIS, Thales Electronic Systems GmbH*
18:00	**The EPS-500 an innovative and multi-application design (300W to 700W)** *Frédéric MARCHANDISE, SAFRAN-Snecma*
18:20	**Active Attitude and Orbit control with Liquid µPPT 4 thrusters system** *Christophe KOPPEL, Kopoos Consulting Ind.*
18:40	**Shaping an industrial strategy for EP** *Ben OLIVIER, Thales Alenia Space*

19:30 – 21:00 Welcome cocktail

Wednesday 26 November

Session 7► Hall Effect Thrusters (1)

Chair/secretary: N. ARCIS / A. VARINOIS

09:00	**High Power Commercial Electric Propulsion** *Steven AUSTIN, European Space Propulsion*
09:20	**Alta Electric Propulsion vision for EPIC** *Giovanni CESARETTI, ALTA S.p.A.*
09:40	**The PPS®5000 a new generation high power high thrust HET (2,5kW to 7kW)** *Olivier DUCHEMIN, SAFRAN-Snecma*
10:00	**Development of a 0.5 kW class krypton HET in the Institute of Plasma Physics and Laser Microfusion** *Jacek KURZYNA, Institute of Plasma Physics and Laser Microfusion*
10:20	**Wall-less Hall thruster** *Stéphane MAZOUFFRE, ICARE/CNRS*
10:40 – 11:00	Coffee break

Session 8► Hall Effect Thrusters (2)

Chair/secretary: N. ARCIS / A. VARINOIS

11:00	**Characterization of a 100 µN thruster** *Jonathan TANRIN, CNRS*
11:20	**The PPS®1350 family (700W to 2,5kW), flight qualified, with growing potential for new applications** *Gilles TURIN, SAFRAN-Snecma*
11:40	**High power HET - A target from 7 to 100's kW - The PPS®20k opens the way to space tug and cheaper exploration.** *Stephan ZURBACH, SAFRAN-Snecma*

Session 9► HEMP Thruster

Chair/secretary: N. ARCIS / A. VARINOIS

12 :00	**Joint Lab Electric Propulsion research at AirbusDS Friedrichshafen, the University of Bremen / DLR Bremen and the Dresden University of Technology** *Franz Georg HEY, Airbus Defence & Space*
12 :20	**HEMP-Thruster technology capability and application** *Benjamin VAN REIJEN, Thales Electronic Systems GmbH*
12 :40 -13 :40	Lunch (to be confirmed)

Session 10 ► Gridded Ion Engines

Chair/secretary: K. RUF / J. LOPEZ REIG

13:40	**Innovative Solutions for Next Generation of Hybrid and Full Electric RIT Propulsed Satellites** *Farid INFED, Airbus Defence & Space*
14:00	**Gridded ion engines development at Mars Space Ltd** *Michele COLETTI, Mars Space Ltd*
14:20	**Development status of ALPHIE (Adaptable Low Power Hybrid Ion Engine)** *Luis CONDE, UPM / Aernnova / CTA*
15:00	**3 gridded ion engine research at the university of Southampton** *Stephen GABRIEL, University of Southampton*
15:20	**QinetiQ's T5 and T6 Gridded Ion Engine and Ring Cusp Engine Development** *Jonathan HUDDLESON, QinetiQ*
16:00	**RF-Technology for Space Propulsion – Key for High Specific Impulse Ion Thrusters and Beyond** *Hans LEITER, Airbus Defence & Space*
16:20 - 16:40	Coffee break

Session 11► Pulsed Plasma Thrusters

Chair/secretary: K. RUF / J. LOPEZ REIG

Main room

16:40	**PPT propulsion system with non-volatile liquid propellant** *Serge BARRAL, QuinteScience*
17:00	**Micro Propulsion development at Mars Space Ltd** *Michele COLETTI, Mars Space Ltd*
17:20	**Pulsed plasma thruster modelling at the university of Southampton** *Stephen GABRIEL, University of Southampton*

Session 12► Cathodeless Thrusters

Chair/secretary: A. BULIT / I. ALONSO

Side room

16:40	**ECRA thruster developped at ONERA** *Denis PACKAN, ONERA*
17:00	**Helicon plasma Thruster future development Status and future perspectives** *Daniele PAVARIN, Università degli Studi di Padova*
17:20	**Benefits of Helicon Plasma Thruster technology development for Space Missions** *Mercedes RUIZ, SENER, Ingenieria y Sistemas*
17:40	**Elwing EP technology** *Grégory EMSELLEM, Elwing Europe S.A.*

18:00 **End of the day**

Thursday 27 November

Session 13► Fluidic components

Chair/secretary: J. GONZALEZ del AMO / D. RUBINI

Main room

09:00	**Overview of AST Technologies** *Hans-Peter HARMANN, AST-Advanced Space Technologies*
09:20	**MEMS-based components for electric propulsion systems** *Tor-Arne GRÖNLAND, SSC Nanospace*
09 :40	**High pressure xenon mass flow regulator** *Aurélien MOUREAUX, Air Liquide*
10 :00	**Moog's products for Electrical Propulsion** *Patrick Van PUT, Moog Bradford*

Session 14► Other EP sub-system components

Chair/secretary: A. BULIT / I. ALONSO

Side room

09:00	**Large volume xenon storage for EP** *Jean-Louis DODELIN, Airbus Defence & Space*
09:20	**Mechanisms for Electric Propulsion from RUAG Space** *Adreas DERNTL, RUAG Space GmbH*
09:40	**Non-mechanic thrust pointing system with steerable magnetic nozzle** *Mario MERINO, Equipo de Propulsión Espacial y Plasmas (EP2), Universidad Carlos III de Madrid*
10:00	**Cathodeless rf neutralizer - state of the art possibilities and first results** *Franck SCHOLZE, IOM Leipzig*

10:20 - 10:40 Coffee break

Session 15► Other thruster concepts

Chair/secretary: J. GONZALEZ del AMO / D. RUBINI

10:40	**Resistojet development at Mars Space Ltd** *Michele COLETTI, Mars Space Ltd*
11:00	**Electric Propulsion at IRS** *Georg HERDRICH, Institute of Space Systems*
11:20	**Propellantless electric propulsion/Coulomb drag devices for interplanetary propulsion and LEO deorbiting** *Pekka JANHUNEN, Finnish Meteorological Institute*
11:40	**A new concept of ion engine for low thrust electrical propulsion** *Charlie KOECHLIN, SODERN*
12:00	**VAT Propulsion System for a Single-CubeSat** *Mathias PIETZKA, Institut für Plasmatechnik und Mathematik Universität der Bundeswehr München*
12:20	**Electric Propulsion in Austria - Current Developments and Outlook** *Alexander REISSNER, FOTEC Forschungs-und Technologietransfer GmbH*
12:40	**Electric Propulsion for Small Satellites within the Surrey Space Centre** *Aaron KNOLL, University of Surrey – Surrey Space Centre*
13 :00-14 :00	Lunch offered by BELSPO

Session 16: Test facilities
Chair/secretary: N. COX / S. IANELLI

Main room

14:00	**QinetiQ's EP test facilities** *Stephen CLARK, QinetiQ*	
14:20	**The Plasma Testing Facility of the Technical University of Madrid (UPM)** *Luis CONDE, UPM/Aernnova/CTA*	
14:40	**Development Tools and EP Facilities at IRS** *Georg HERDRICH, Institute of Space Systems*	
15:00	**Electric Propulsion Test Facility at DLR** *Andreas NEUMANN, German Aerospace Centre*	
15:20	**Test facilities and advanced diagnostics for electric propulsion** *Fabrizio SCORTECCI, AEROSPAZIO Tecnologie s.r.l.*	
15:40	**System integration and end-to-end test capability at THALES Ulm** *Stephan WEISS, Thales Electronic Systems GmbH*	

Session 17: Diagnostics
Chair/secretary: D. FUTTERER / L. ANSALONE

Side room

14:00	**Laser-aided diagnostics for EP** *Stéphane MAZOUFFRE, ICARE/CNRS*
14:20	**Electric propulsion at ONERA: test facilities and diagnostics** *Denis PACKAN, ONERA*
14:40	**Force Probes for Thruster Plume Diagnostics** *Thomas TROTTENBERG, University of Kiel*
15:00	**THALES test facility and diagnostics for EP in Ulm** *Benjamin Van REIJEN, Thales Electronic Systems GmbH*
15:20	**AEPD II a new standard for EP-thruster characterization** *Carsten BUNDESMANN, IOM Leipzig*

16:00 – 16:20 Coffee Break

Session 18: Hollow cathode
Chair/secretary: N. COX / S. IANELLI

16:20	**Hollow cathode development at Mars Space Ltd** *Michele COLETTI, Mars Space Ltd*
16:40	**THALES cathode technology for space applications** *Benjamin Van REIJEN, Thales Electronic Systems GmbH*
17:00	**The development of heaterless hollow cathodes at the university of Southampton** *Stephen GABRIEL, University of Southampton*
17:20	**High current hollow cathode development at the university of Southampton** *Stephen GABRIEL, University of Southampton*
18:00	**End of the day**

Friday 28 November

Session 19 : Power processing Unit (1)
Chair/secretary: M. GOLLOR / N. COX

09:00	**Power Processing Unit Activities at Thales Alenia Space Belgium** *Eric BOURGUIGNON, Thales Alenia Space*
09:20	**PPUs for Hall Effect Thrusters** *Giovanni TUCCIO, SITAEL S.p.A.*
09:40	**Selex ES capabilities in Electronics for Propulsion** *Aldo POLLI, Selex ES*
10:00	**PPU for Electric for Propulsion Subsystem based on 5KW HET** *Marco MOLINA, Selex ES*

10:20 – 10:40 Coffee break

Session 20 : Power Processing Unit (2)
Chair/secretary: M. GOLLOR / N. COX

10:40	**Presentation of the PPU activities within Airbus Defense and Space** *Fernando PINTO, Airbus Defence & Space*
10:50	**Power Processing Unit NG for HET thrusters** *Guillaume GLORIEUX, Airbus Defence & Space*
11:10	**Power Procesing Units for T5/T6 Thruster** *Ismael GOMEZ HARO, Airbus Defence & Space*
11:30	**High Voltage Electric Propulsion Electronics for Orbit Raising Application** *Nicoletta WAGNER, Airbus Defence & Space*
11:50	**An Innovative PPU design for 500W-class thrusters** *Richard GRANJON, Sagem*

12:10 - 13:10 Lunch (to be confirmed)

Session 21: Development tools

Chair/secretary: N. ARCIS / A/ BULIT

13:10	**Modeling tools for optimizing design and performance of thrusters** *Julia DURAS, University of Greifswald*
13:30	**Validated dynamic life time modelling and related material investigations** *Christoph EICHHORN, IOM Leipzig*
13:50	**Plume effects Simulation Tool** *Christophe KOPPEL, Kopoos Consulting Ind.*
14:10	**Official Launch of the ESA European Electric Propulsion Database** *Alexander REISSNER, FOTEC Forschungs- und Technologietransfer GmbH*
14:30	**HALLMA and EP2PLUS advanced hybrid codes for Hall thrusters, plasma plumes, and SC interaction** *Mario MERINO, Equipo de Propulsión Espacial y Plasmas (EP2), Universidad Carlos III de Madrid*
14:50	**2D DIMAGNO and HELWAVE2 simulators for Magnetic Nozzles and Helicon Antenna Sources** *Mario MERINO, Equipo de Propulsión Espacial y Plasmas (EP2), Universidad Carlos III de Madrid*
15:10 – 15:50	**Steps towards a fully kinetic simulation of a HEMP-thruster solving the "anomalous electron transport" problem.with a mathematical approach** *Günter KORNFELD, Kornfeld Plasma & Microwave Consulting*

END OF THE WORKSHOP

ANNEX 2: LIST OF PARTICIPANTS

	First-name	Last-name	Organisation	Function	Country
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