MINOTOR

Magnetic nozzle thruster with electron cyclotron resonance

MINOTOR H2020 project for ECR thruster development

D. Packan, P.Q. Elias, J. Jarrige, T. Vialis, S Correyero, S. Peterschmitt, *ONERA*

M. Merino, A. Sánchez-Villar, E. Ahedo *UNIVERSIDAD CARLOS III DE MADRID*

G. Peyresoubes, A. Thorinius, *THALES MICROELECTRONICS*

K. Holste, P. Klar, *JUSTUS-LIEBIG-UNIVERSITAET GIESSEN*

M. Bekemans, T. Scalais, E. Bourguignon (*THALES ALENIA SPACE BELGIUM*

S. Zurbach, *SAFRAN AIRCRAFT ENGINE*

M. Mares, A. Hoque, P. Favier, *L – UP*

Content

- **Consortium**
- **MINOTOR technology: ECRA**
- **Objectives and structure of MINOTOR**
- **Achievements of Work Packages**

Experimental investigations:

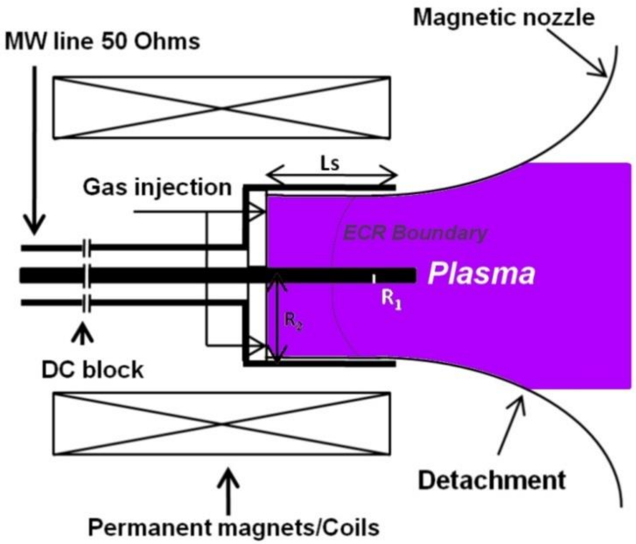
- Waveguide thruster
- Magnetic trust measurement
- LIF measurements
- Facility effects: JLU tests

Consortium

Participant no.	Participant organisation name	Participant short name	Country
1 (CO)	Office National d'Etudes et de Recherches Aérospatiales	ONERA	France
2	Universidad Carlos III de Madrid	UC3M	Spain
3	Thales Microelectronics SAS	TMI	France
4	Justus-Liebig-Universitaet Giessen	JLU	Germany
5	Thales Alenia Space Belgium SA	TAS-B	Belgium
6	Safran Aircraft Engines	SAFRAN	France
7	L-UP SAS	LUP	France

MINOTOR technology

ECRA thruster configuration



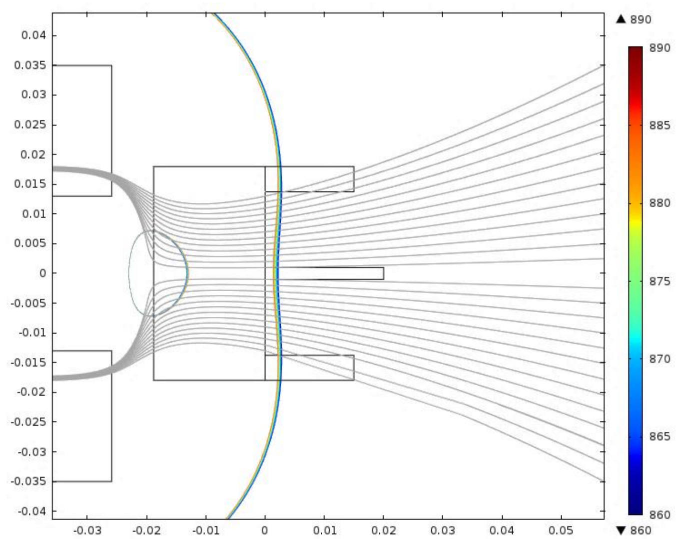
Current tested conditions and dimensions

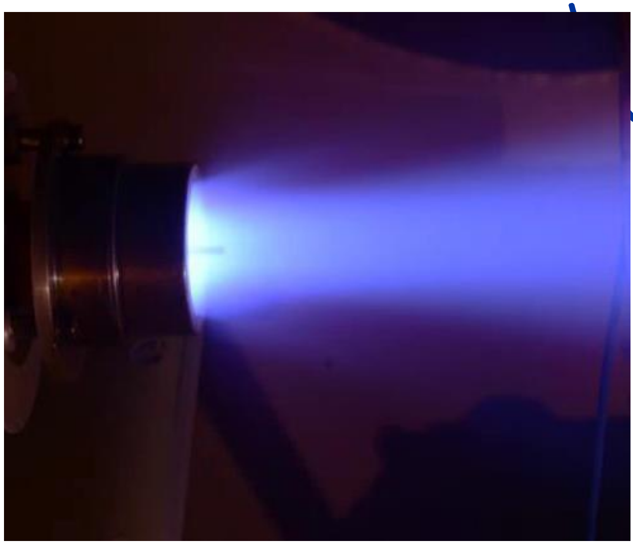
- MW Frequency = 2,45 GHz
- ECR conditions at 875 Gauss
- 0,1 to 0,4 mg/s of Xenon
- 10 to 50 Watts currently tested
- 2-3 cm diameter current dimensions

Scalable to lower and higher power (kW)

- Plasma expansion (driven by T_e)
- Diamagnetic effect in the divergent $\vec{B}$ (Magnetic Nozzle)

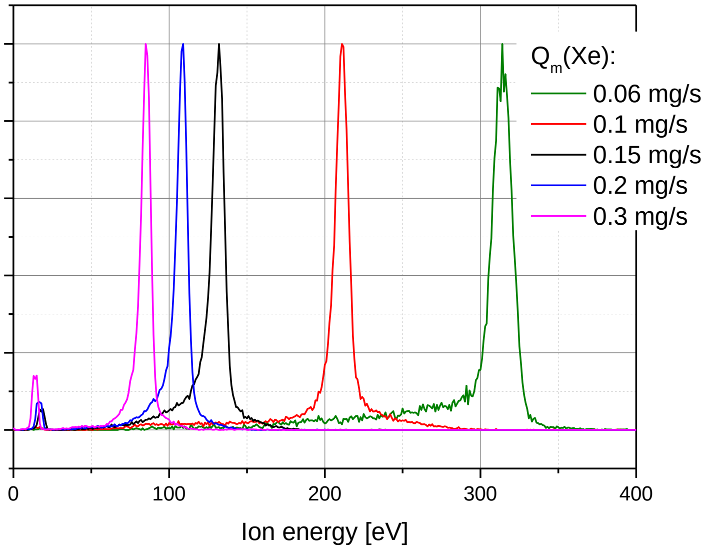
‹#›

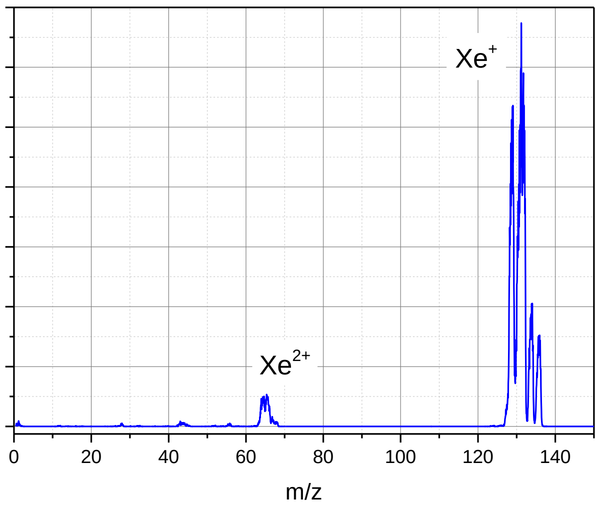




MINOTOR

Experimental measurements





Gas	Xenon
Mass Flow Rate (mg/s)	0.1
Power absorbed (W)	30.0
Ion energy (eV)	250
Ion ideal Isp (s)	1950
Ion current (mA)	45
Thrust (mN)	0.98
Isp (s)	993
Mass utilization efficiency (%)	61
Power efficiency (%)	38
Divergence efficiency (%)	83
Thruster total efficiency (%)	**16**

ECRA technology characteristics

Advantages:

- Cathodeless (no neutralizer) → simple design (including at system level: only one power supply, naturally isolated)
- Easy to start
- Insensitive to pollutants, compatible with alternative propellants
- B field→ shielding, thrust vectoring
- Low cost

‹#›

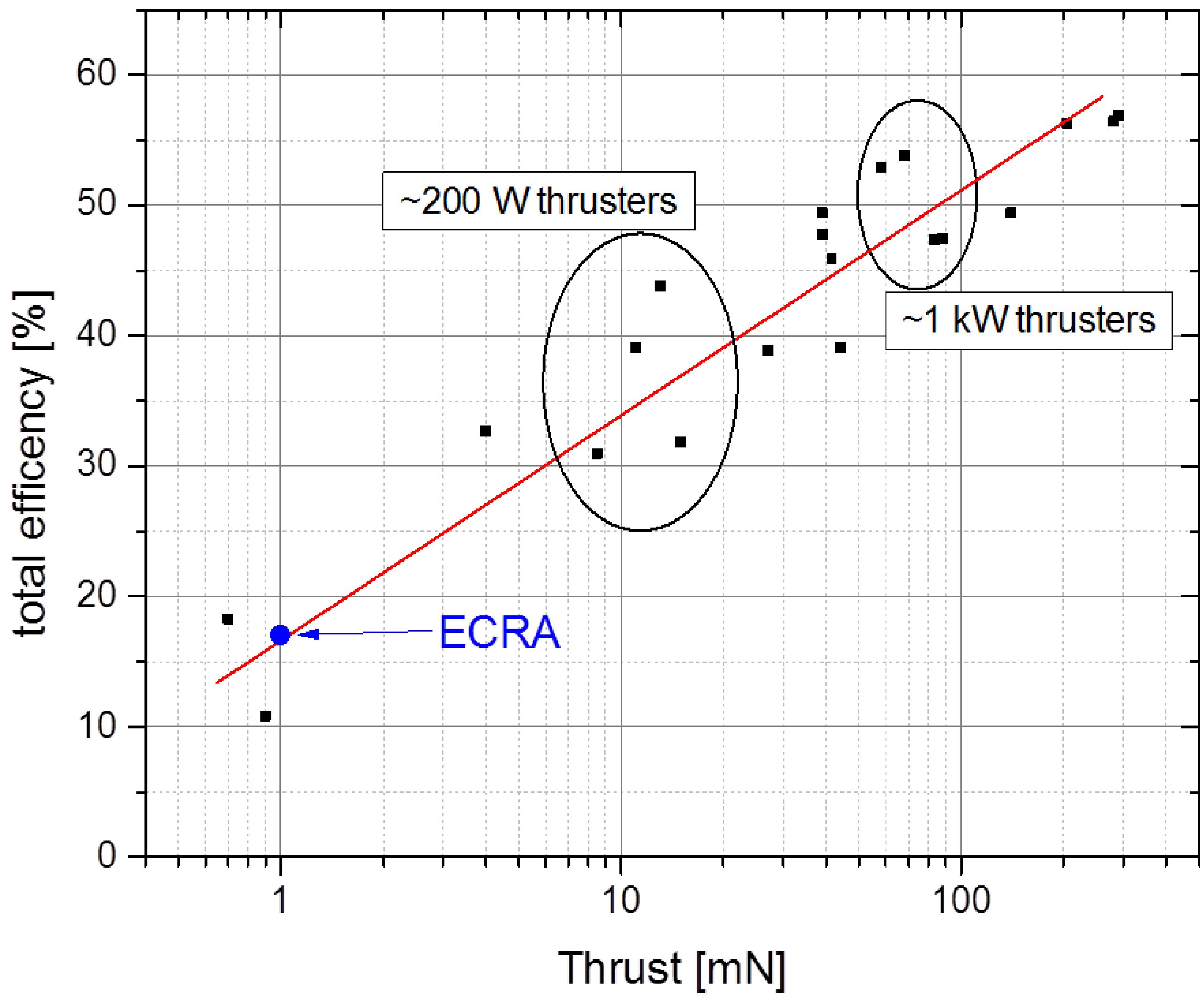
Challenges:

- Plasma physics more complex than other thrusters: wave/ionisation/acceleration coupling. Full model not yet available. Magnetic nozzle challenging.

- No direct knowledge of the total current and of the ion energy: need for ion beam probes and very refined experimental characterization, in an unfamiliar plasma environment.

- Good vacuum levels needed: need to be < 10-5 mbar (HET can work up to 10-4 mbar)

Performance perspectives



Objectives and structure of MINOTOR

‹#›

Objectives of MINOTOR

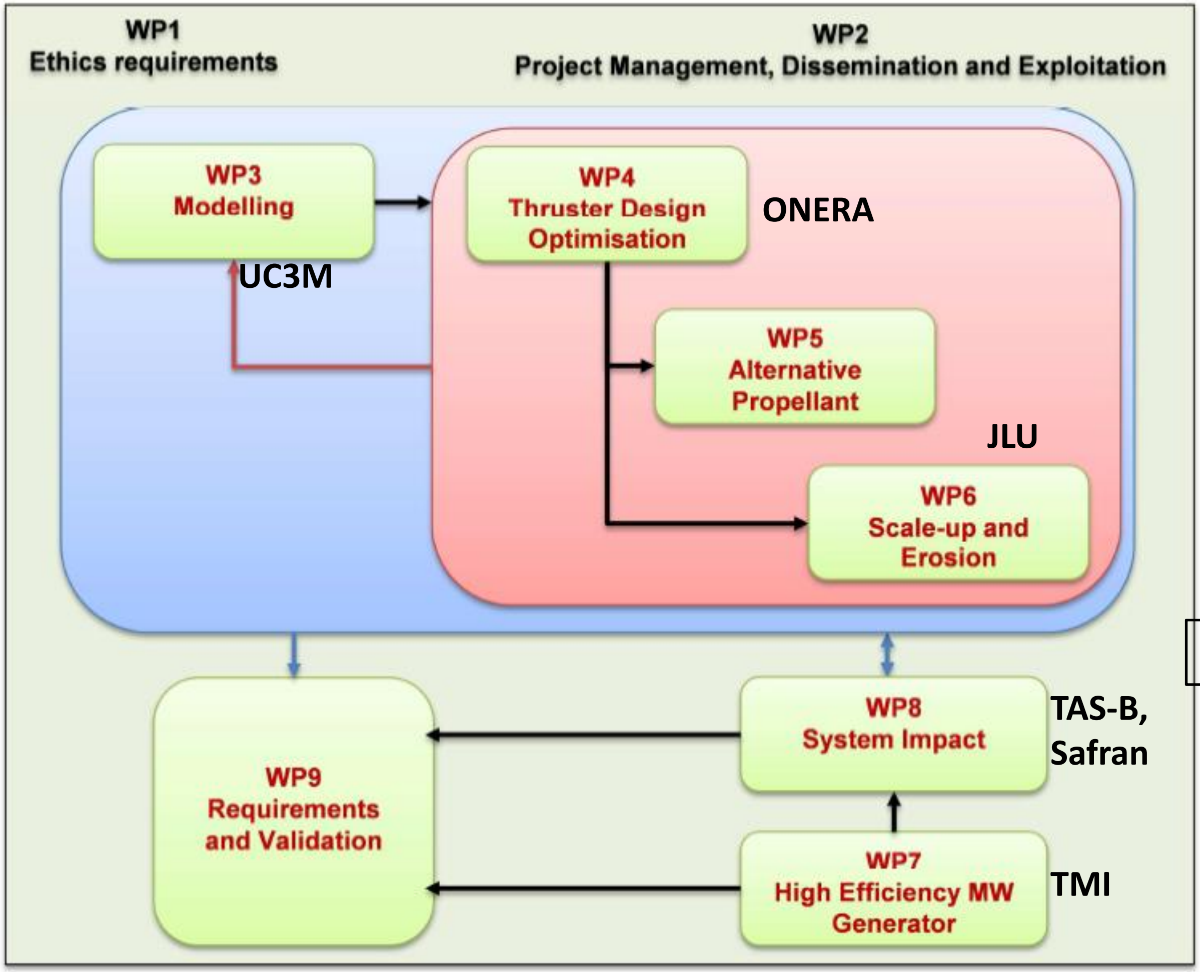
Status at start of project: TRL 3, short tests at 30W, a few configurations tested

Main objectives (thruster and PPU):

- Understand the physics
- Demonstrate performances, and extrapolate
- Determine possible uses: GO/NO GO
- Prepare development roadmaps

~ Go to TRL 4

Relations between WPs



Management: LUP

Work package achievements: middle of second year

WP3: modeling

Modeling strategy

The strategy is to develop two codes :

- The main code is the SURFET hyrbrid code from UC3M (fluid + PIC), will be able to efficiently model the whole thruster.
- A 3D full PIC ROSEPIC code is developed by ONERA, and will look at specific setpoints for the refined physics.

Two different regions, with different challenges:

- The inside of the thruster (the so-called "source"), with high density plasma
- The magnetic nozzle, with high longitudinal gradient.

The codes will become operational at the end of the year, in line with expected schedule.

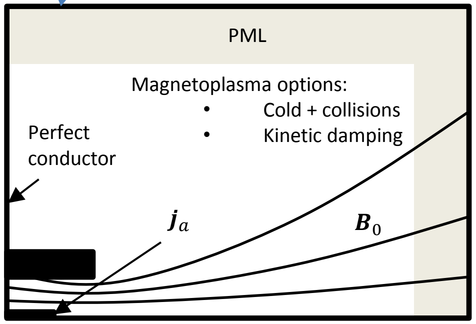
In parallel, a global (simple) model si being developed, fed by experimental results.

WP3 Modeling: SURFET hybrid code

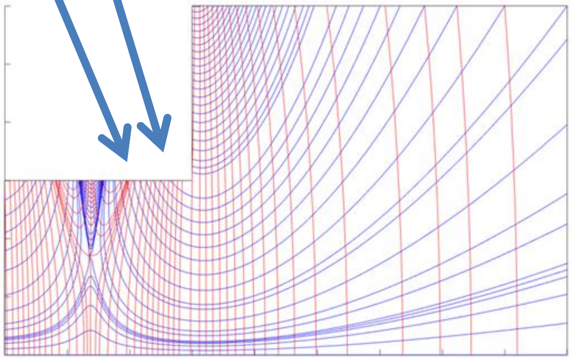
The hybrid code (fluid+PIC) tailored to the ECR thruster is being developped by UC3M.

The SURFET code is subdivided in 4 modules:

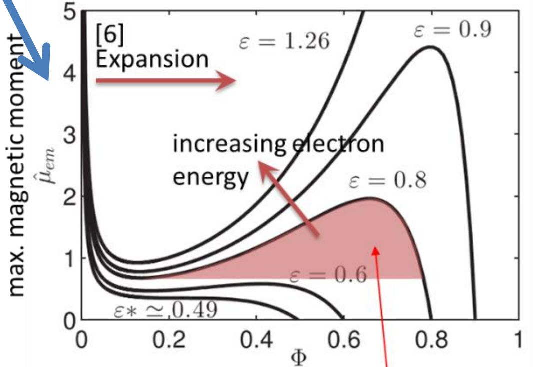
- **Plasma-wave interaction module**: 2D cold-plasma dielectric tensor code (module #1 of SURFET). Kinetic submodels and/or information from ROSEPIC will be used to model accurately the resonance regions.
- **Ion/neutral PIC-DSMC subcode**: 2D quasi-structured Particle-In-Cell code based on magnetic grid. Will include ionization, recombination, excitation and transport dynamics
- **Electron fluid subcode**: magnetized electron fluid with energy balance. Fluid electrons (instead of PIC) reduce substantially the computational complexity, at the expense of a minor loss of physical detail
- **Magnetic nozzle module**: two-fluid, 2D code of the plasma expansion in the magnetic nozzle



IEPC-2017-105



Ongoing work



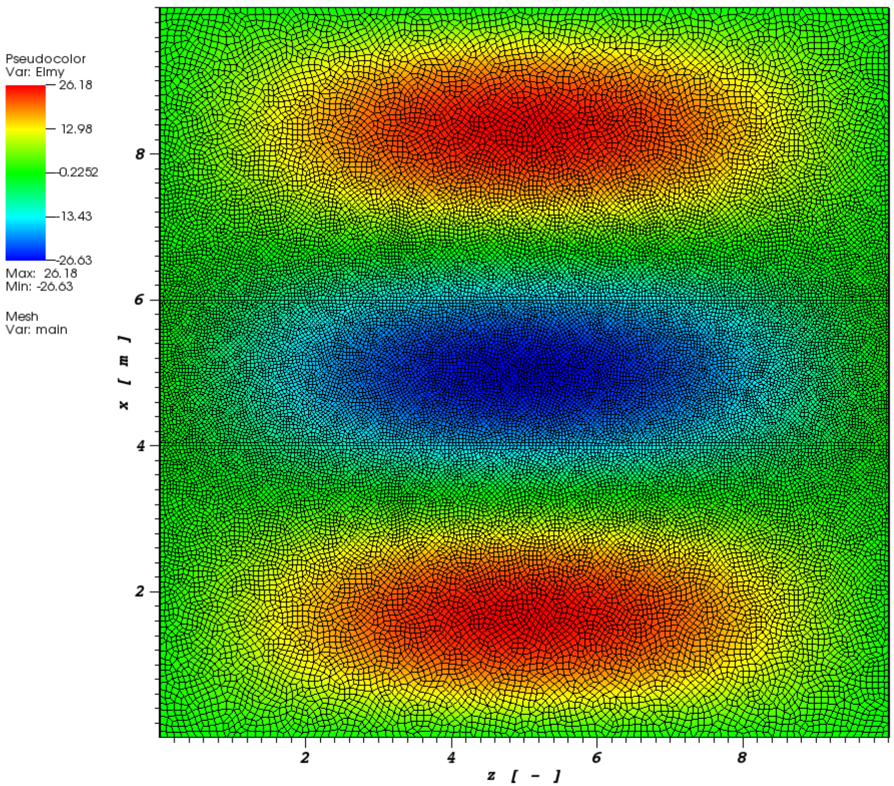
IEPC-2017-106

trapped electrons

Ongoing work

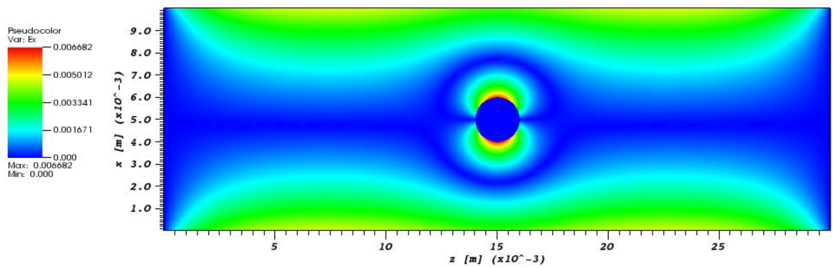
Key Technical Points : Plasma-Wave Module validation

Use of non-triangular cells validated:

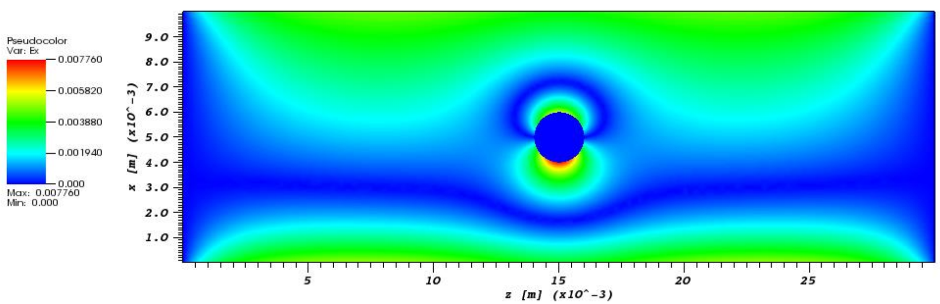


Successful handling of mesh subdomains, each with different properties.

Vacuum:



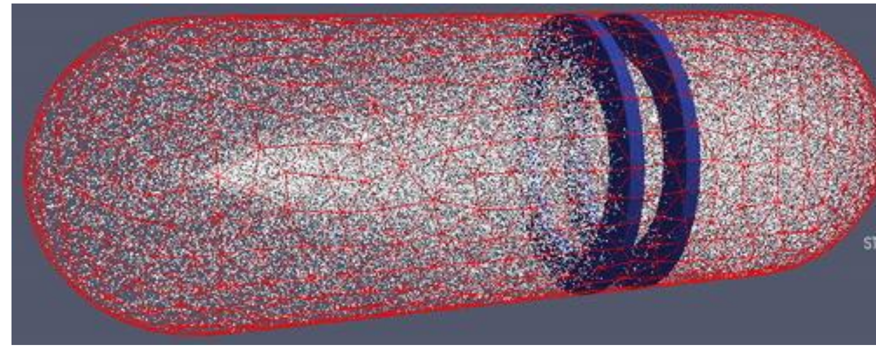
With magnetized plasma:



MINOTOR

WP3 Modeling: PIC code

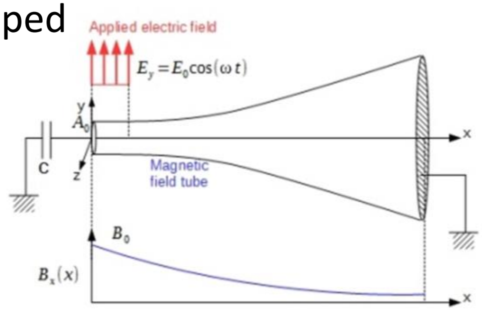
- **Development of a PIC/MCC code**
  - ES-PIC for Low pressure plasma modeling
  - DSMC capability: vacuum chamber analysis
  - EM-PIC for ECRA

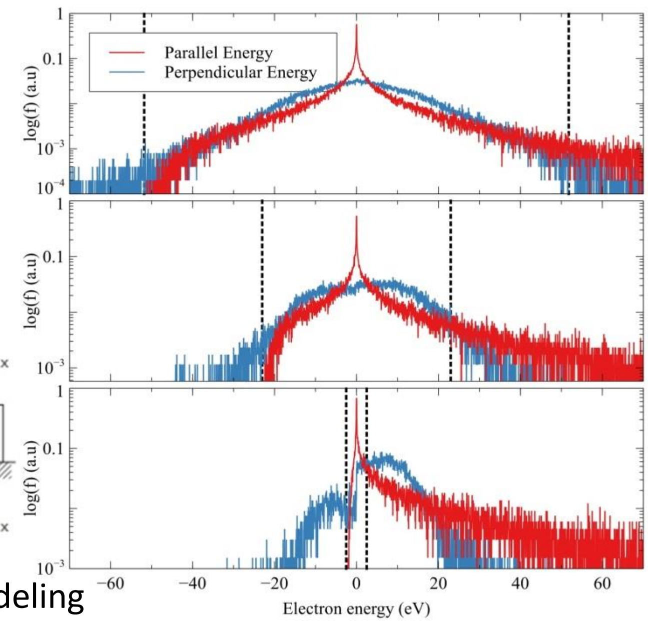


Vacuum chamber simulation, 72 cores ~ 7.10[6] particles

- Features :
  - Serial / 2-level parallelism (MPI/ OpenMP)
  - Block – cartesian mesh
  - Arbitrary geometry : immersed boundary method
  - Tiled structure

- Status of the Code
  - All particle modules developed
  - 3D DSMC test done
  - Maxwell Solver : 1D done
  - 2D 3D parallel version under development





1D PIC modeling

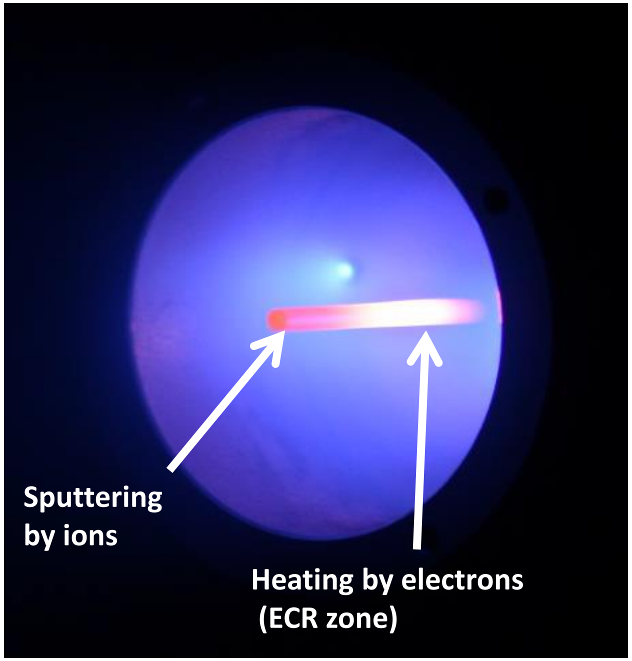
WP4: experimental investigation

ECR coaxial thruster: antenna limitation

Coaxial design allows independance on frequency, and near complete (> 90%) power coupling, but:

•The antenna is a source of power loss from impact (heating)

•The antenna shows sputtering after several 10s of hours (lifetime limitations)



<u>Solutions:</u>

- **Improve on the antenna concept (ongoing)**
- **Design an antenna-less thruster**

19

MINOTOR

Roadmap of experimental investigations

Antenna thruster (30 W)

Geometry: antenna diam., source length
Source matérial / coating
Thrust balance development
Diagostics: faraday, LIF
Magnetic vs pressure thrust
Magnetic field topology
Antenna material / coating
Wave frequency
Erosion

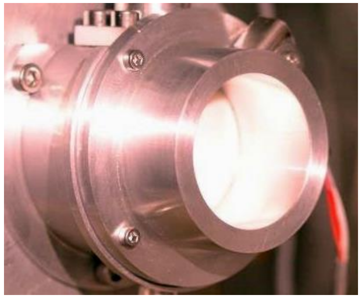
30W Test in another facility,
Jumbo at Giessen:
Facility + vacuum effect

Hybrid and PIC codes
Global models

Frozen upscaled design
(3rd year)

Test of different propellants

Waveguide thruster (30W)



First test
Vaveguide filling material
Coupling theory

200 W test + several 100hs

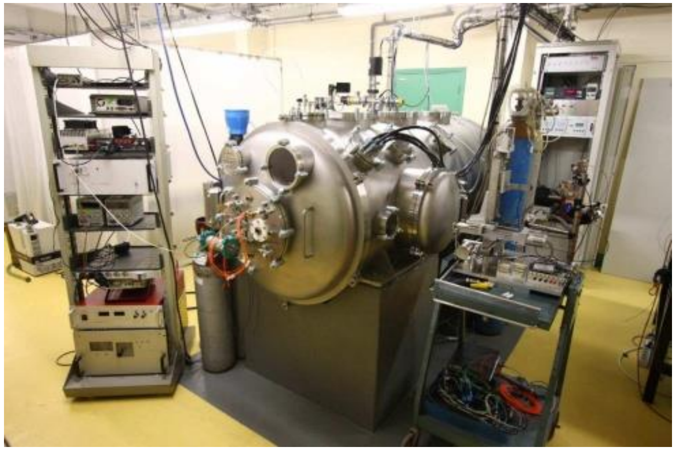
1 kW test

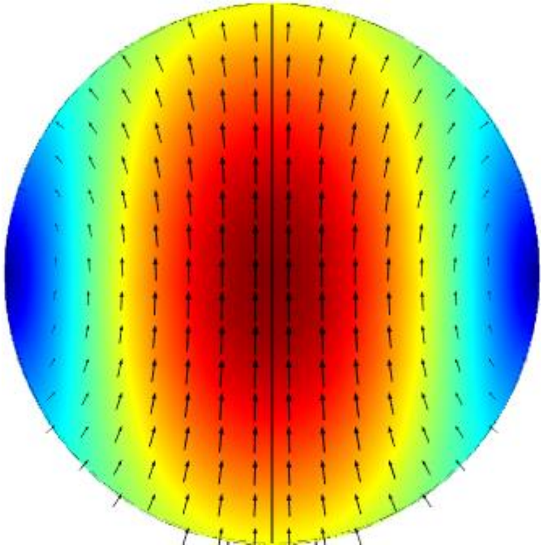
Low power waveguide coupled ECR thruster

- New design of the thruster , keeping the same source dimensions
- Same magnetic field
- ~30W
- ~1sccm Xe

Tested at ONERA B09 facility

- 10 000 L/s for Xe
- 0,8 x 2 m
- Operating pressure ~3 10^{-6}





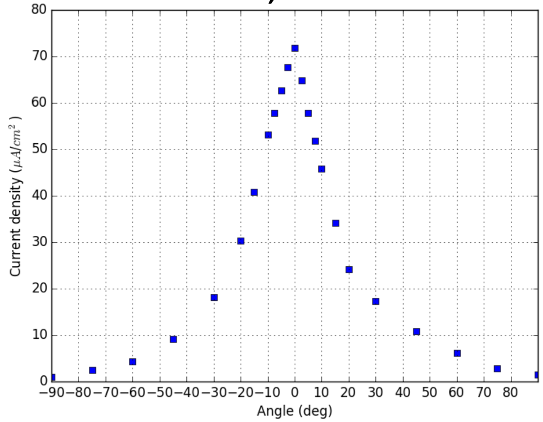
Front view of the electric field in the source

Waveguide coupled ECR thruster : first results

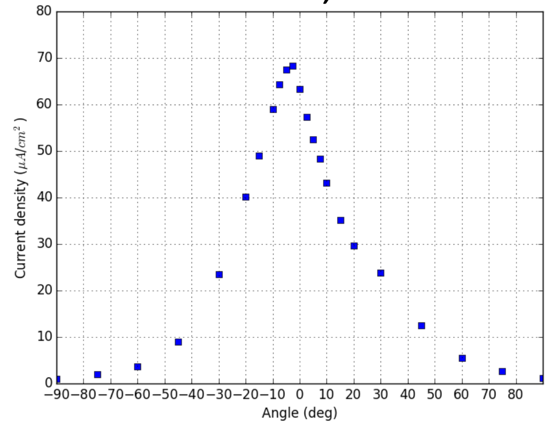
MINOTOR
Magnetic nozzle thruster with electron cyclotron resonance

First test performed in May:
successful startup!

Metal source
1sccm, ~ 24 W

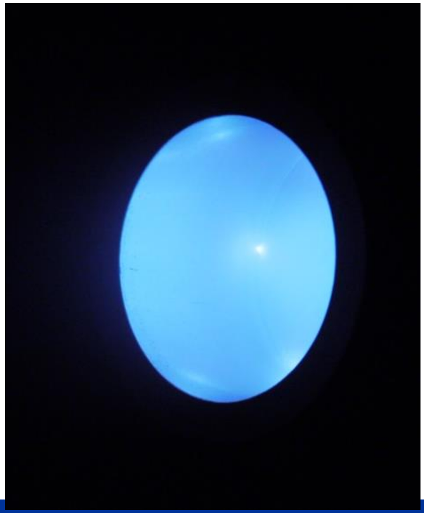


Boron nitride (BN) source
1sccm, ~ 24 W



Angular current density + mean ion energy measurement (gridded faraday)

	Metal	BN	Coaxial thruster
Mass utilisation efficiency	0,49	0,54	0,61
Divergence efficiency	0,76	0,79	0,83
Ion energy (eV)	65 eV	65 eV	**250 eV**
Thrust (µN)	360	400	900
Total efficiency	2,7	3,5	17



Conclusion on waveguide thruster

MINOTOR
Magnetic nozzle thruster with electron cyclotron resonance

The experimental work on ECR thruster is ongoing.

Results have been presented:

- Improvement of the MW circuit: paving the way to high power
- First tests of a new thruster type (preliminary results), the waveguide ECR: design, sucessful startup, good mass efficiency

Still to be done experimentally:

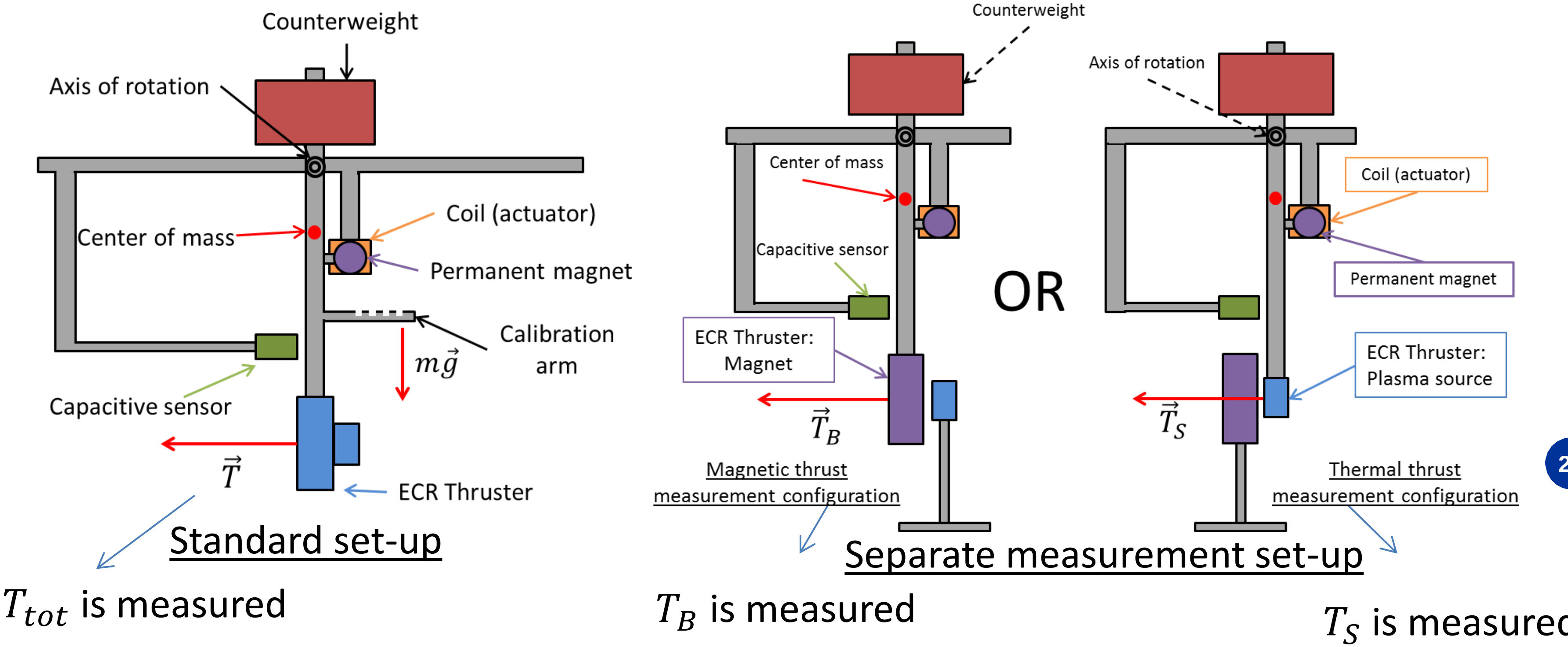
- Work on antenna protection
- Wavecoupling to waveguide ECR: ceramic losses, impedance matching, …
- Improve ion energy: distance of ECR zone to the wall, etc…
- Test different frequencies on coaxial design (1-4 GHz)
- Test different magnetic field topologies (started already)

23

MINOTOR

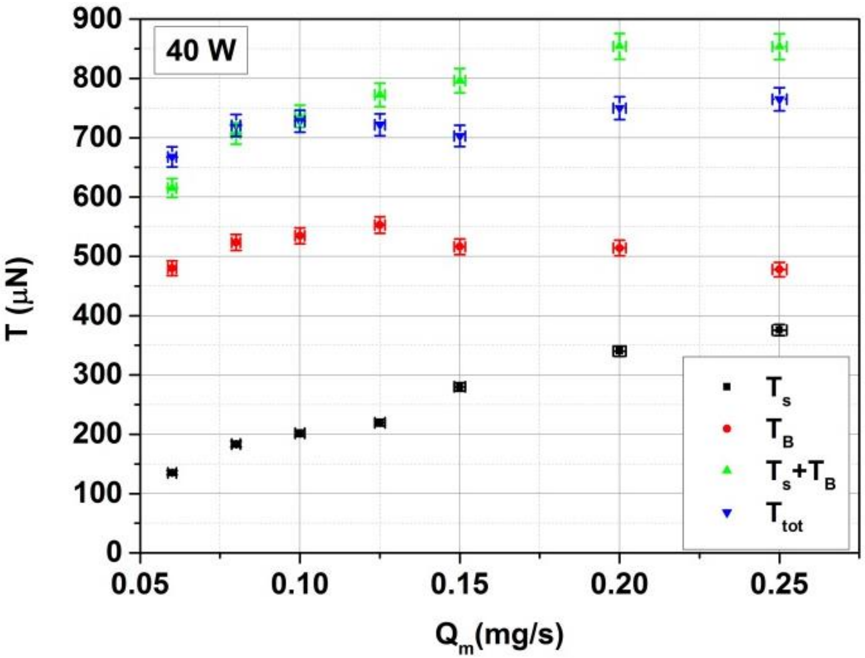
MAGNETIC THRUST MEASUREMENT

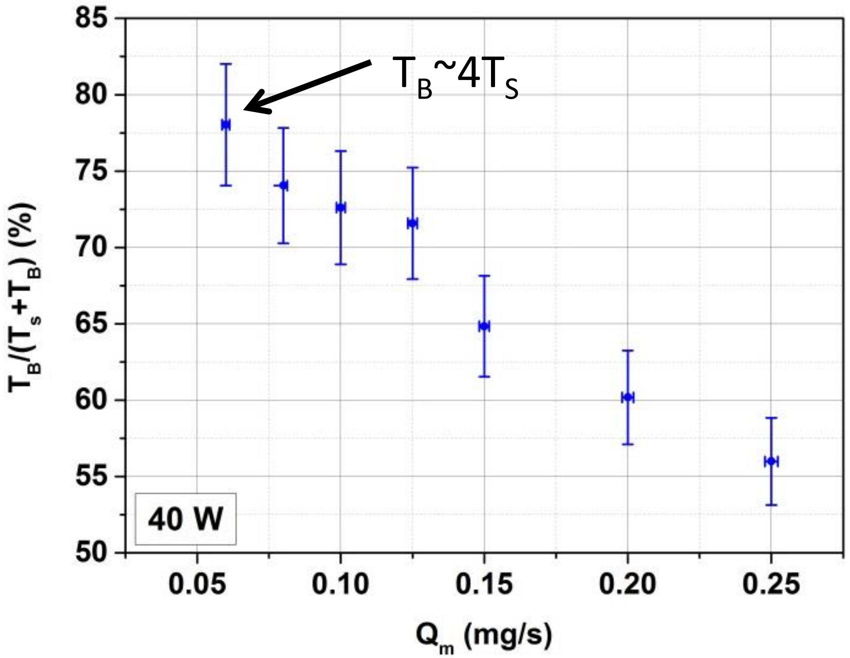
Experimental Set-up: Direct thrust measurement



- Standard setup: measures Total thrust T_{tot}
- Modified setup: measures the two contributions of the thrust:
  - electron pressure (thermal thrust) acts directly on the plasma source
  - the diamagnetic effect (magnetic thrust) acts on the magnet

Results: effect of xenon mass-flow rate at 40 W





- Again, $T_S + T_B$ approximately equal to T_{tot}
- 1st observation: T_S increases with respect to the mass-flow rate
- 2nd observation: T_B increases of low mass-flow rate but decreases for higher mass-flow
- The proportion of T_B goes from 80% to 55% when the mass-flow goes from 0.06 to 0.2 mg/s

Conclusion

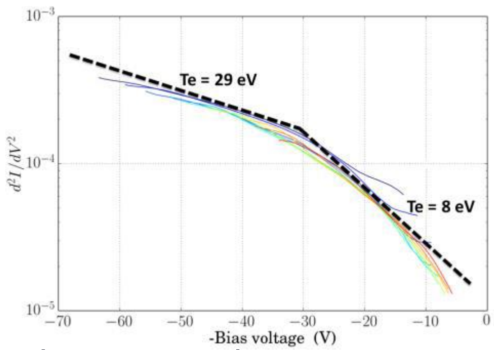
- Direct thrust measurements have been performed to measure separately, for the first time, the magnetic thrust and the electron pressure thrust of an ECR plasma thruster.

- The magnetic thrust represents up to 80% of the total thrust, and always more than 50%: magnetic nozzle thrust is dominant.

- Power variation does not affect the ratio, but mass-flow rate has a big effect on the ratio.

LIF and diamagnetic measurements

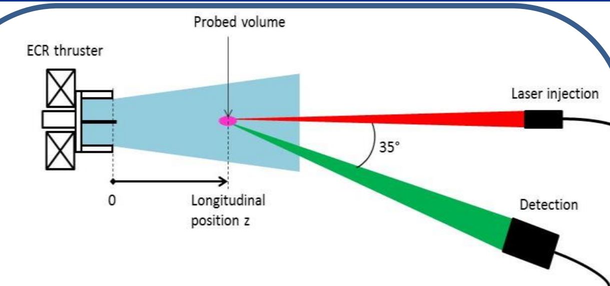
- Measurement of plume properties, with Langmuir / Faraday probes

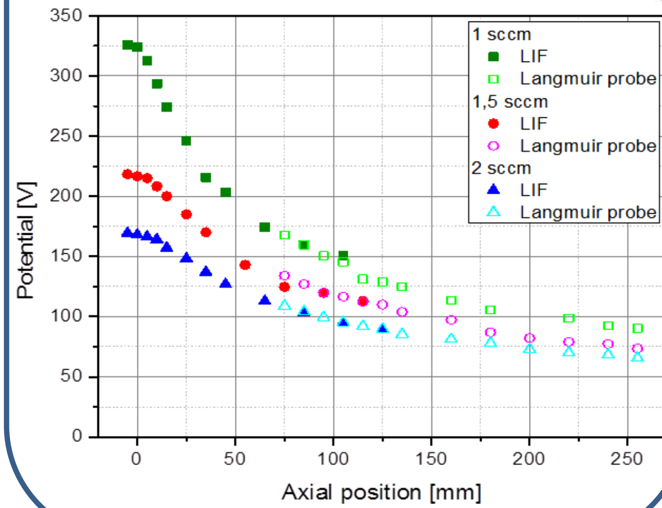


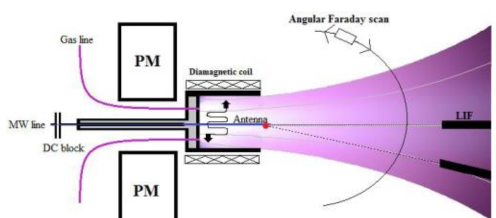
- Combination with LIF measurements

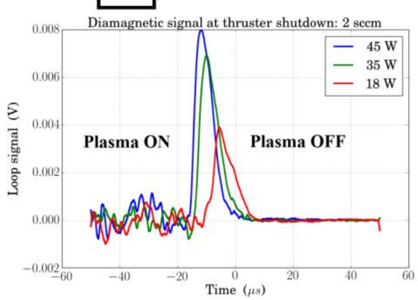
Achievement:
Measurement of acceleration voltage profile

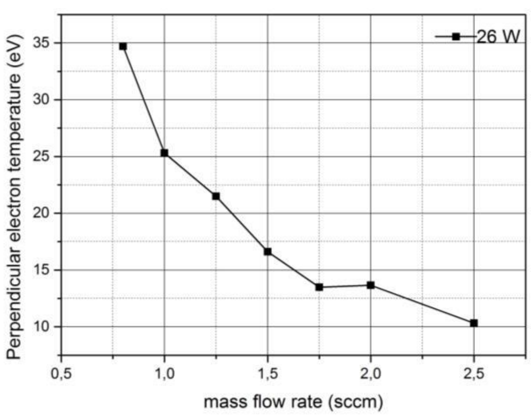
- Development of new techniques: plasma diamagnetism











Achievement:
Measurement of perpendicular electron temp. (anisotropic distribution) and longitudinal acceleration

30W tests at JLU

Interest:

- Test effect of vacuum level on ECRA performance: facility effect

- Independant assessment of thrust / performance

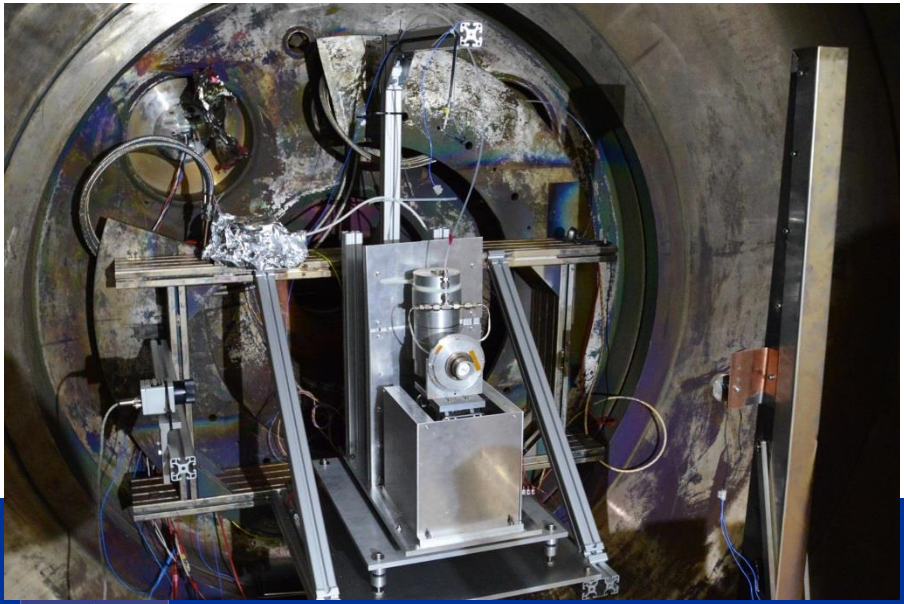
- Comparison of probes (current , energy) from ONERA and JLU at the same facility: harmonization of hardware and practices

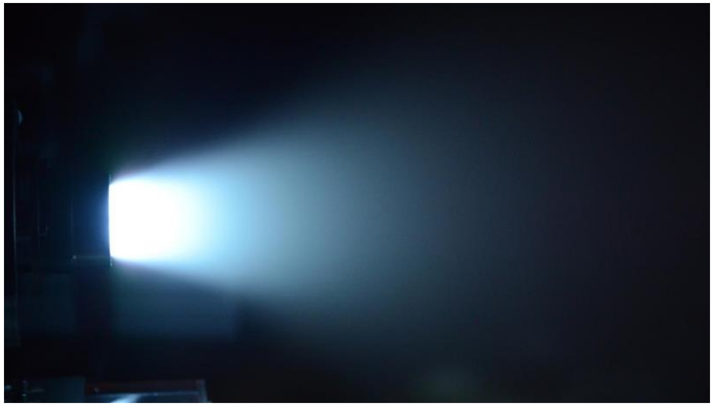
The campaign was successfully performed last week: facility, thruster, thrust balance and probes showed compatibility, and were well performing.

Analysis ongoing, first results presented.

Experimental setup

JUMBO facility
2,6m x 6m
150 000 l/s
(ONERA: 10 000 l/s)

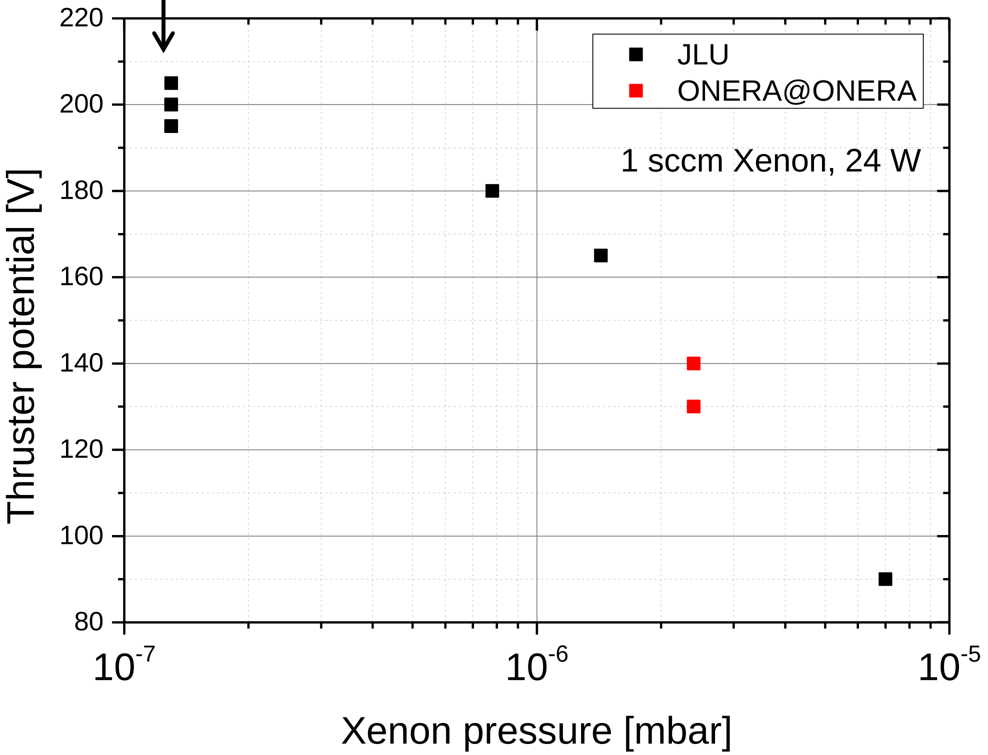




Thruster potential and ion energy

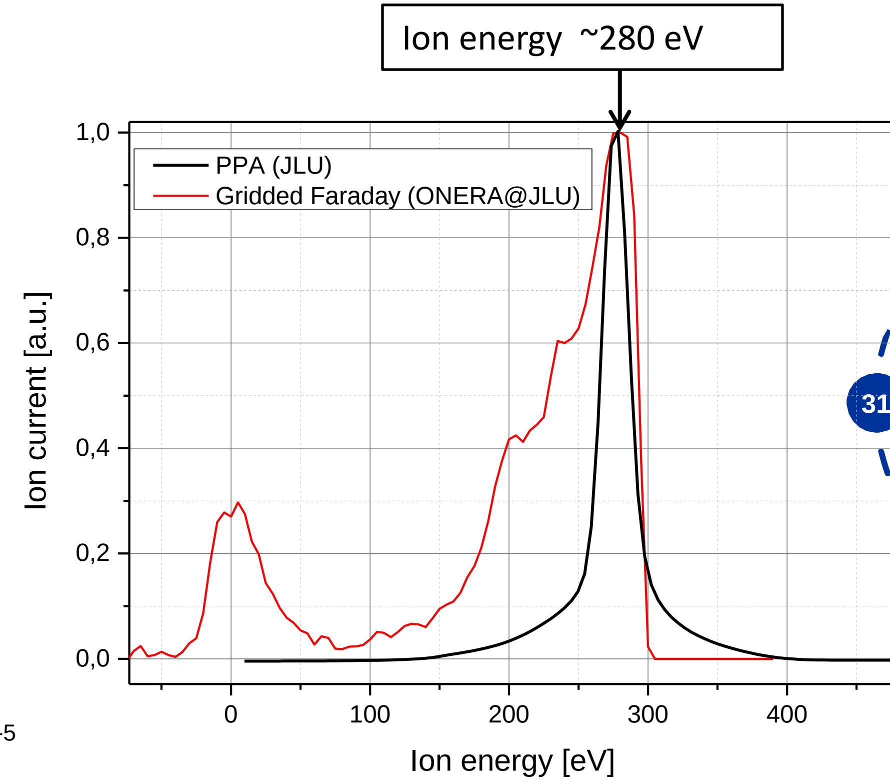
Magnet thruster 17% total efficiency, highest obtained

Thruster potential versus Xe pressure



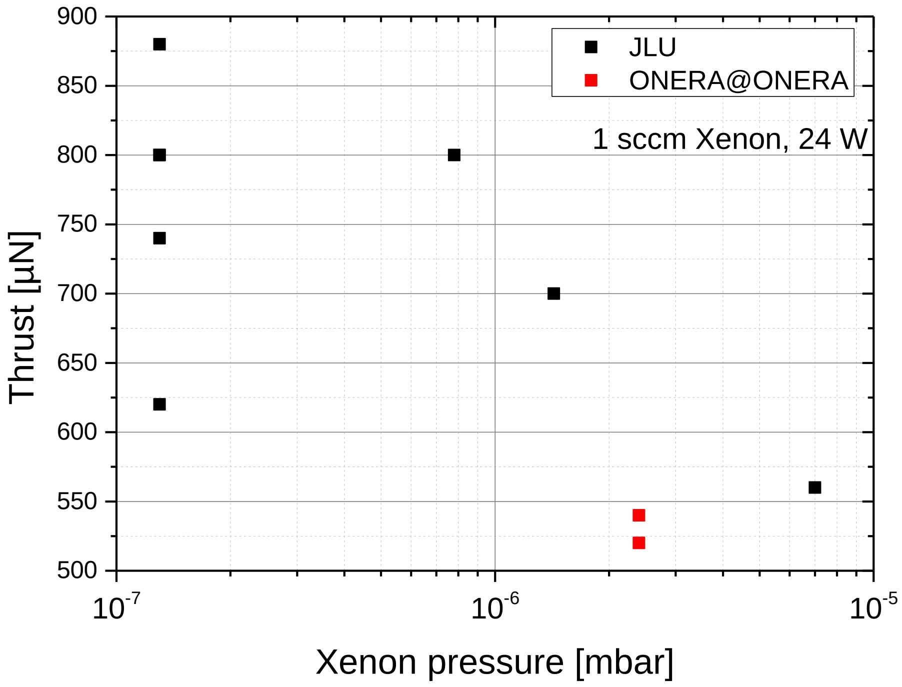
Confirmed trend (unexplained yet): higher ion energy at low pressure

Comparison: PPA vs gridded Faraday



- Agreement on energy peak position
- Vion/Vthruster ~1,4: « usual » value

Thrust measurement



- Data more scattered: one important parameter not yet controled
- Thrust at ONERA smaller: to be confirmed; electrostatic effect possible

More data to be analyzed (comparison of faraday currents)

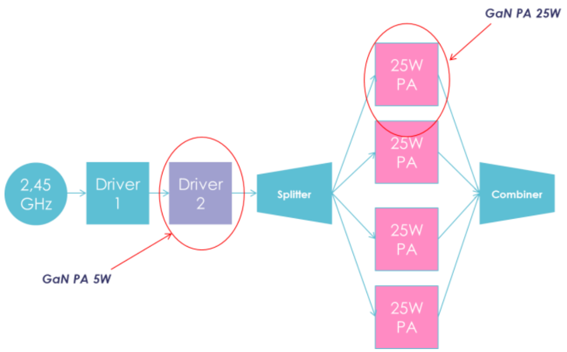
WP7: high efficiency microwave generator

WP7: MW generator

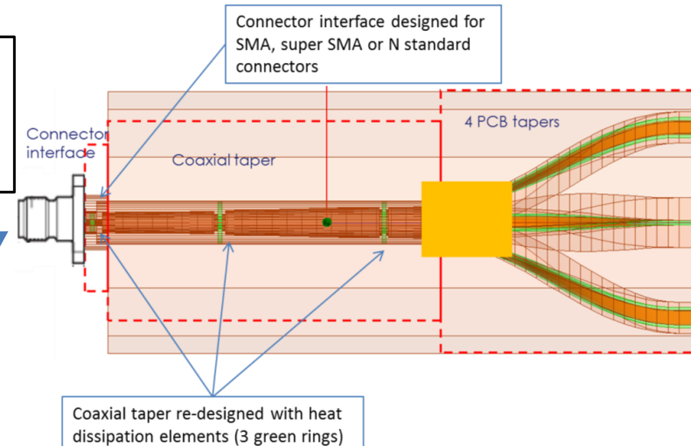
PPU efficiency is a major factor in the thruster system efficiency. No off-the-shelf MW generator with higher than 60-70% eff.

BUT new technology + Thales patent can reach high power 85-90% efficiency.

Strategy of technology demonstration:
- 5W single chip → 25 W single chip → 100 W multi-chip (combiner)
- In parralel, simulation with an EU chip (non-dependance)



Structure of the microwave generator planned for MINOTOR.



Achievement: 5W @ 85% simulated, hardware demonstration ongoing

WP8: system impact

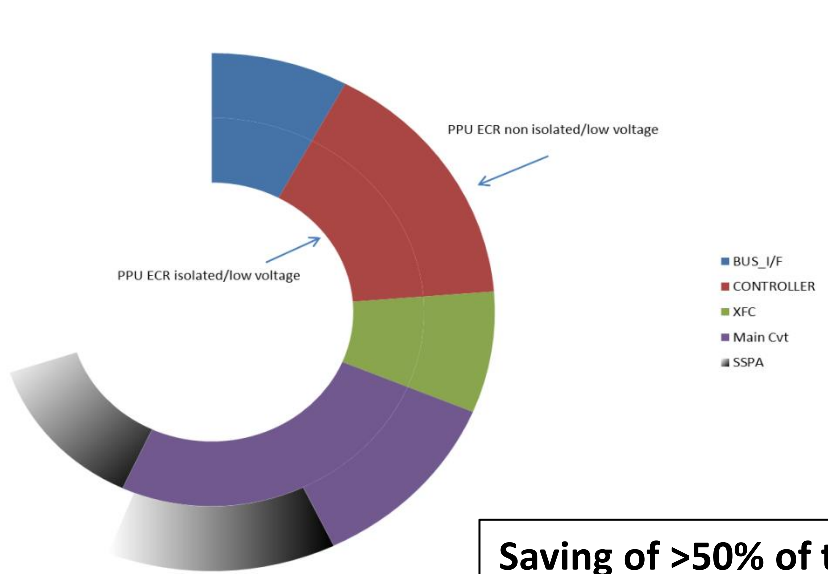
WP8: System Impact

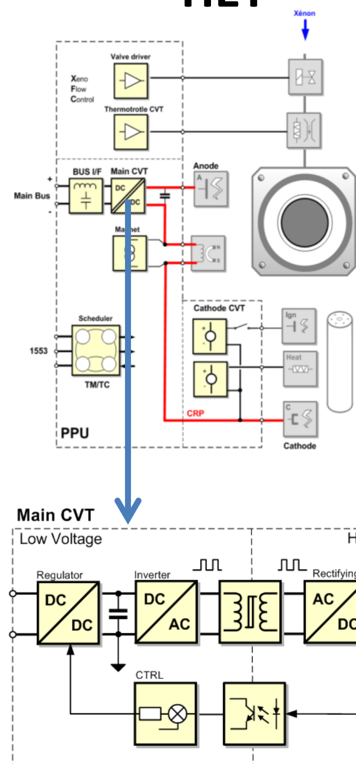
Focus on the simplification of the PPU:

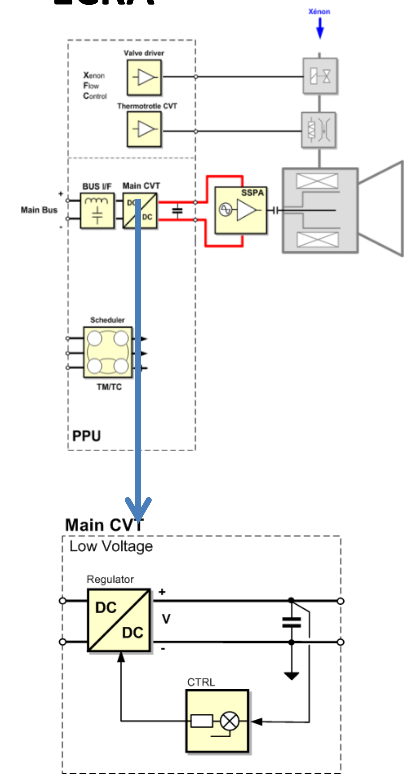
ECRA requires:

- No cathode
- No coil
- No galvanic isolator (thruster floating)

Achievement:



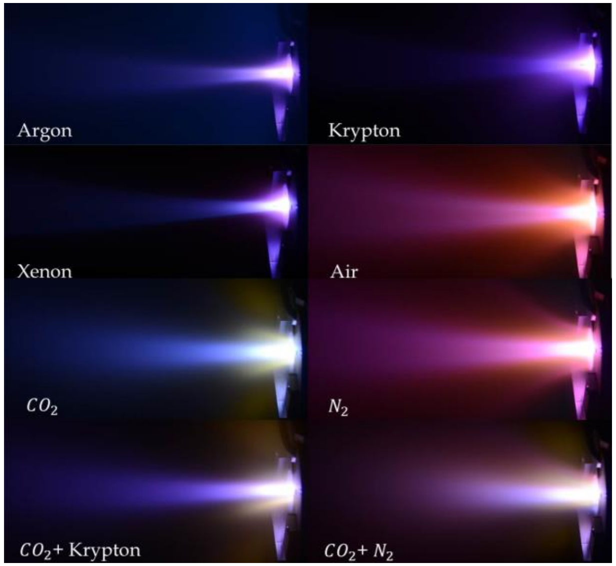




Saving of >50% of the PPU Cost. But need to add MW amplifier Cost (SSPA).

Conclusion

- MINOTOR has made good progress, several achievements in the different work packages.
- journal publications, two in preparation.
- 8 papers presented at IEPC-2017, including a best student paper award on the joint ONERA-UC3M work (S. Correyero).
- Way forward: further tests, and the availability of modelling codes, in the next few months should help have a better view of the scalability, and performance envelopes of the technology.



MINOTOR

ECRA at startup


MINOTOR
Magnetic nozzle thruster with
electron cyclotron resonance