avs

EN 9100

ISO 9001

BOOSTING SCIENTIFIC KNOWLEDGE

Early test results for AQUAJET and XMET

UK SPACE AGENCY

SURREY SPACE CENTRE

SURREY SATELLITE TECHNOLOGY

UNIVERSITY OF Southampton

EPIC Workshop 2018

16th OCTOBER

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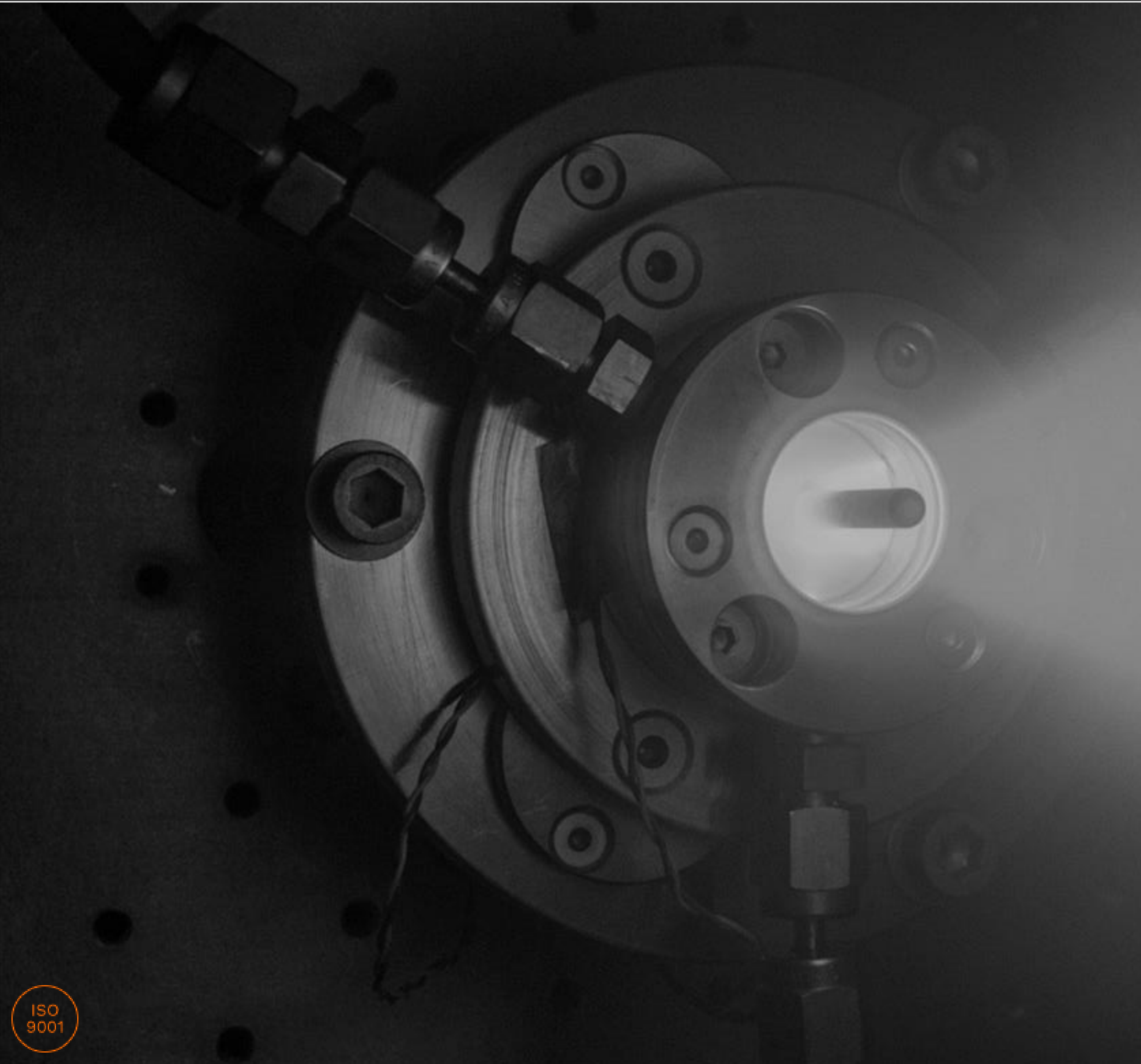

1. AVS | SPACE PROPULSION OVERVIEW
2. AQUAJET
3. XMET

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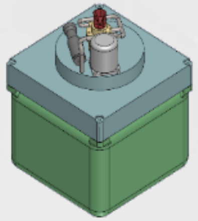
SMALL SATELLITES



Mini-MET

Microwave Electrothermal Thruster
Ammonia
- dimensions: 1U + tuna
- Mass: 50 g (thruster), 1.4 kg (system, wet)

AQUAJET

Cathodeless ECR thruster
Water, xenon or argon.
- Dimensions: 0.8cm radius, 5cm length
- Mass: 600 g
- Alternative propellants

ICE CUBE

Water electrolysis chemical (hybrid)
Continous mode
High density energy storage
Dimensions: 1U
Mass: ~1.2kg

ELECTROSPRAY

Ionic liquid propellant, highly modular.
High Efficiency / Higher thrust / Higher total impulse alternative to FEEP (Enpulsion).

scalable

TELECOM/GEO SATELLITES

ECR GIE

ECR Gridded ion engine
Xenon
- Dimensions: 10cm radius, 8cm length
- Mass: 2kg
- 1kW

XMET

Microwave Electrothermal Thruster
Xenon
- Dimensions: 5cm radius, 10cm length
- Mass: 500g
- 1kW

IMPULSE

Integrated Microwave PropULsion Architecture for satEllites:
For fully all-electric missions, performing orbit raising, station keeping and reaction control

XJET (AQUAJET)

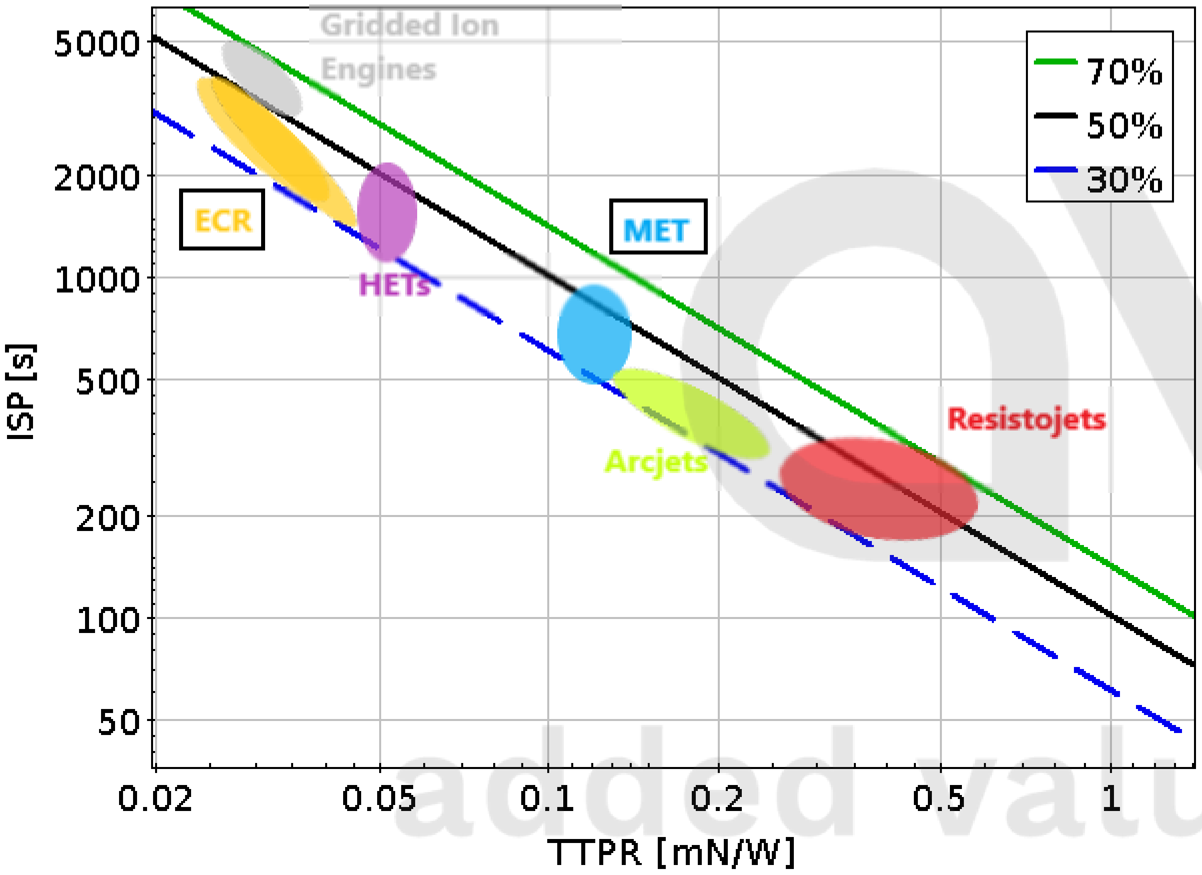
Scalable to: ~10mN, ISP=1500s @200W
~30mN, ISP~4000s @1kW

ICE CUBE

Scalable up to ~300 mN @1.5kW (continuous mode)

	ISP [s]	Thrust [mN]	Power [W]	Efficiency [%]	Propellant
AQUAJET	1000	1	30	16	Water, **Xenon**, Argon, any…
ECR GIE	3000 - 5500	20 - 170	Up to 1000	50	Xenon
XMET*	90 - 120	Up to 500	Up to 1000	50	Xenon
Mini-MET	300 - 550	1 - 4	25	20	Ammonia
Electrospray	4500	0.5	17	60	Ionic liquid
ICE CUBE	310	2	20	20	Water

Propulsion system comparison



Specific impulse against thrust-to-power ratio as occupied by current EP systems and as achievable by ECR and MET

Development enabled by NSTP Fast Track

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ECR-type (AQUAJET):

- At high power levels, performance expected to be competitive with GIE, HET
- Low thrust, high ISP solution
- Lower-cost & more suited to alternative propellants than GIE, HET

MET-type (XMET):

- With alternative propellants (H_2O, NH_3), reach higher ISP than arcjet/resistojet
- Medium thrust & ISP solution
- Fills gap between high-power & low performance EP families

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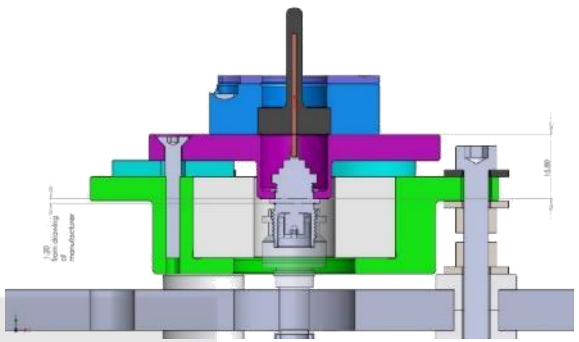
AQUAJET

Electrodeless ECR thruster w. magnetic nozzle:
@ 2.45 GHz

- Efficient ionization, outperforming helicon-type
- Simple & low-cost design
- No grid erosion

- HIGHLY FLEXIBLE PROPELLANT CHOICE: Kr, Ar, Ne, Xe, CO_2, N_2 , O_2, air

- Xe, H_2O & NH_3 of particular interest to us
  -> simply adjust chamber length & radius to optimise
  -> designed, assembled & tested highly flexible prototype



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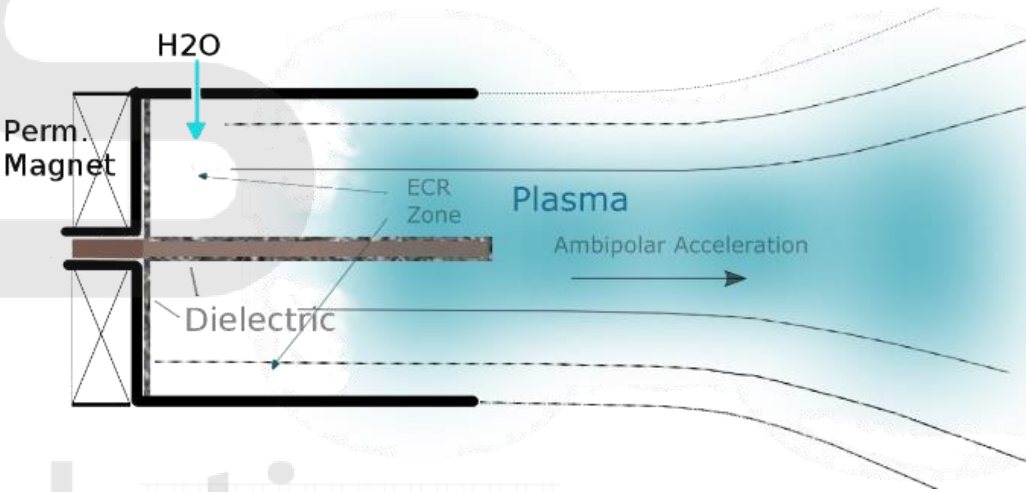
NSTP



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SURREY SATELLITE TECHNOLOGY

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AQUAJET

- **Plasma source**

  ECR condition 0.0875 Tesla at 2.45 GHz

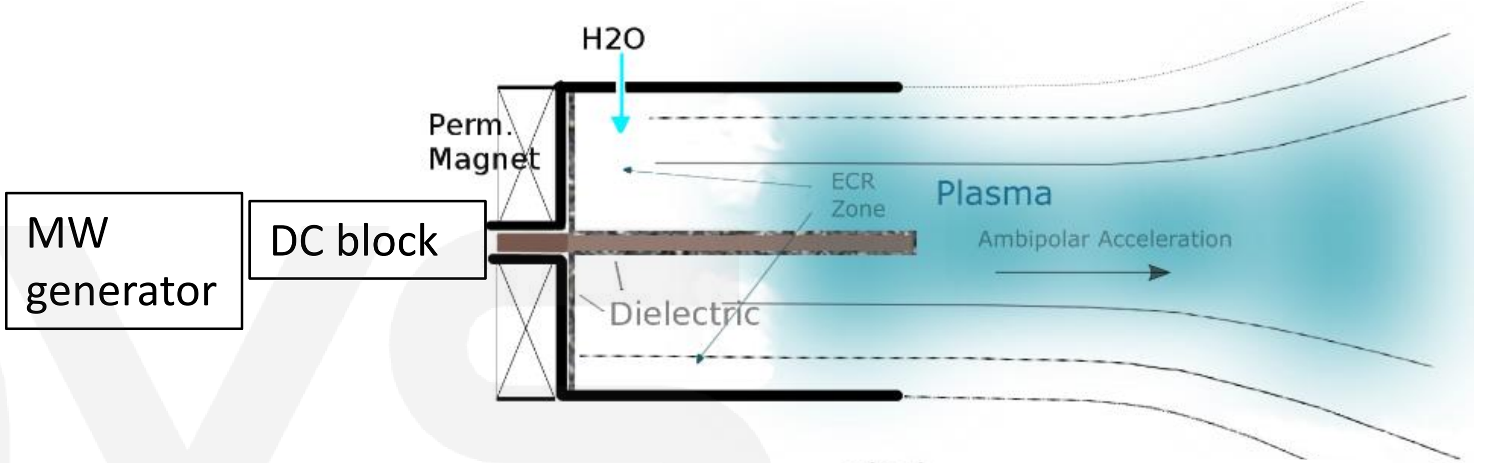
- **Radial & axial plasma confinement**

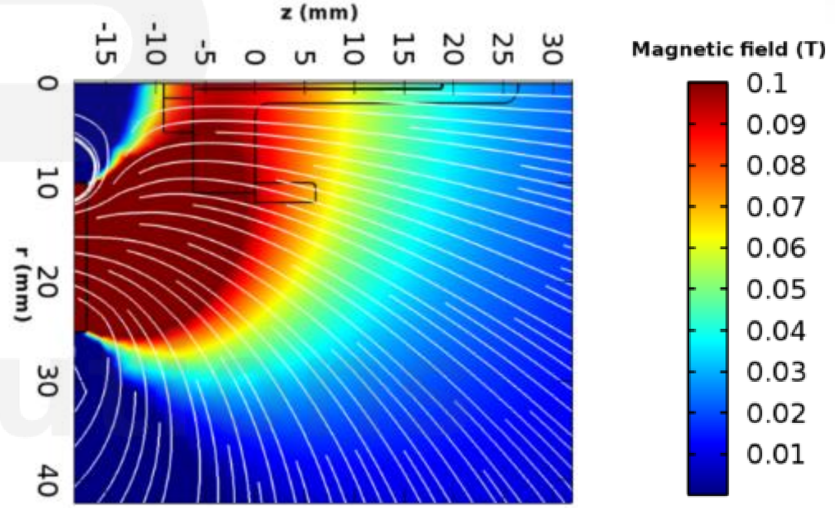
- **Magnetic nozzle**

- **Coaxial antenna – chamber**

  Break-through developed by ONERA lab* :
  $\eta_T \sim 13\%$ **at 1 mN thrust, ISP ~ 1300 s (Xenon), ~ 50 Watts**
  -> MINOTOR

- **Dielectric sleeve: H_2O plasma erosion**

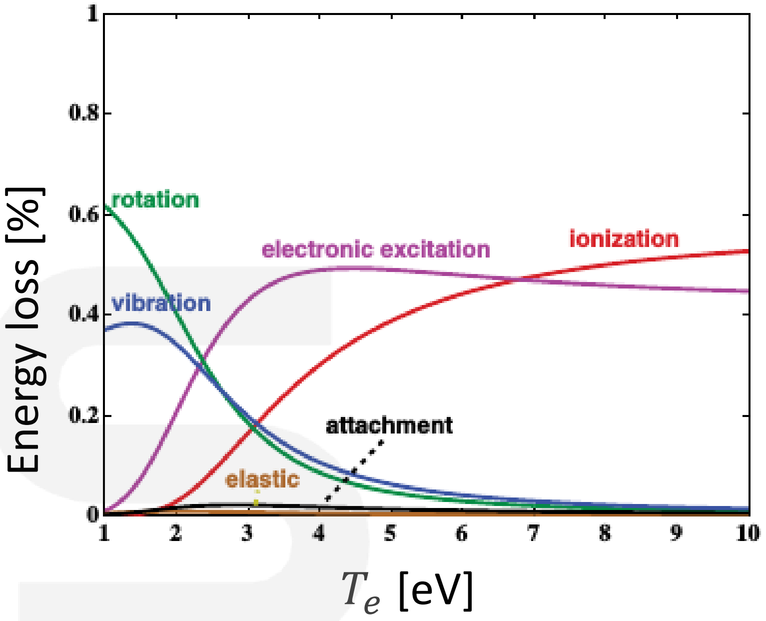




*Cannat, F., Lafleur, T., Jarrige, J., et.al. (2015), *Physics of Plasmas*, 22, 053503
Vialis, T., Jarrige, J., Packan, D. (2017), IEPC-2017-378 + references therein

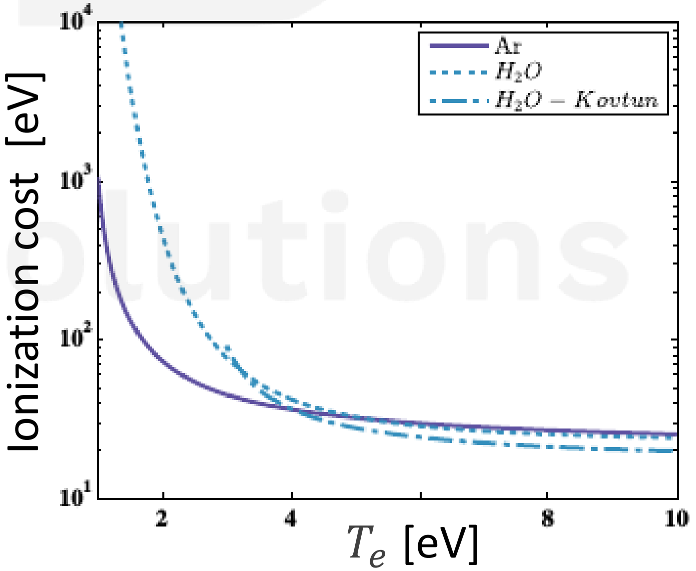
Why H_2O?

- "ultimate green propellant", storage, cost, ISRU ? (see COMET, HYDROS products in US)
- Predicted performance promising:
  ionization cost & η_T v. similar to argon ($T_e > 5$ eV)



Approach

- Simple analytical model & flexible geometry prototype
- Direct performance measurements
- First tests of H_2O propellant, benchmark against Argon



Petro, E. M. & Sedwick, R. J. (2017) Journal of Prop. and Power. 33:6

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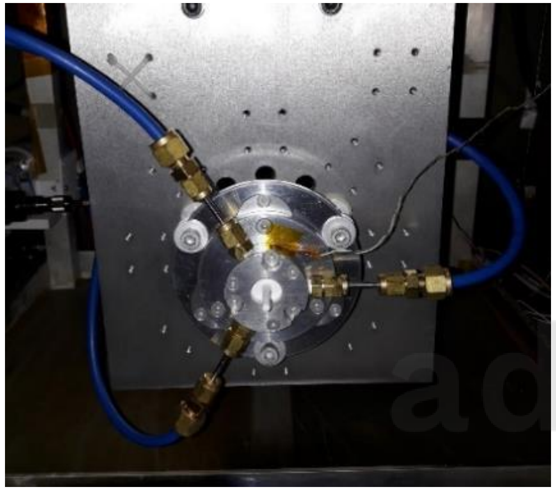
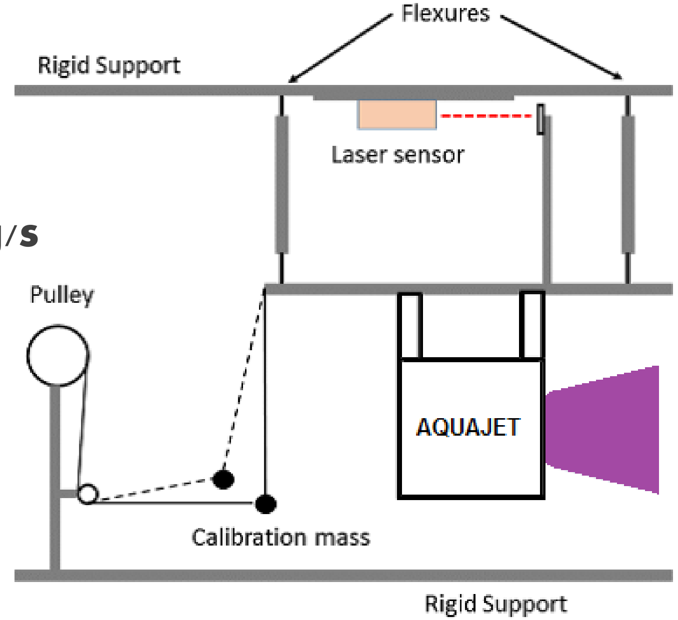
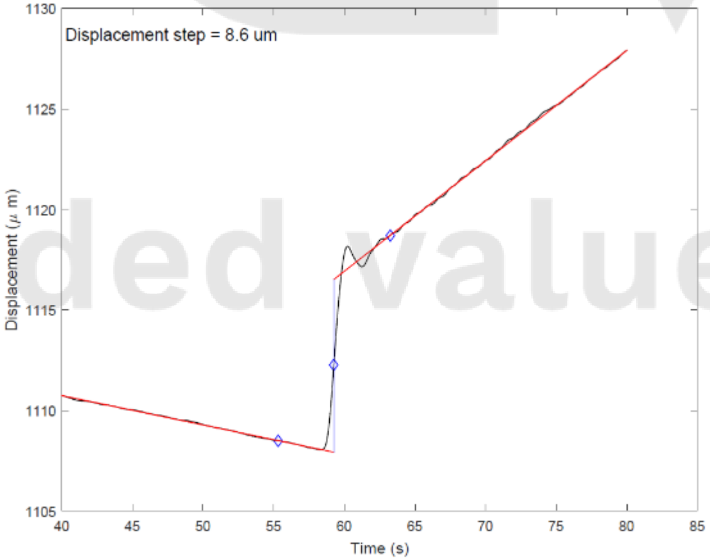
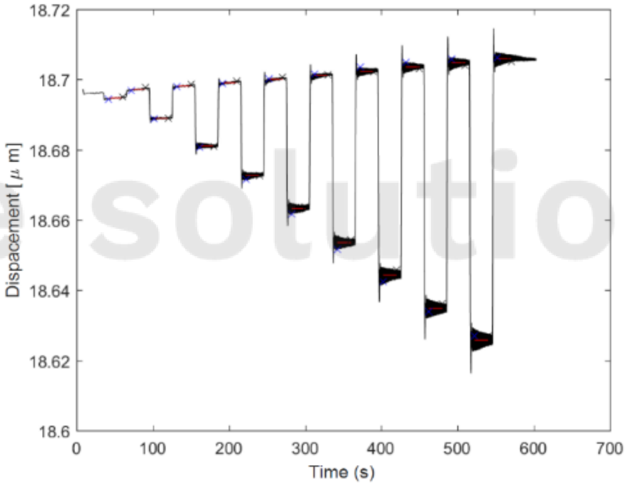


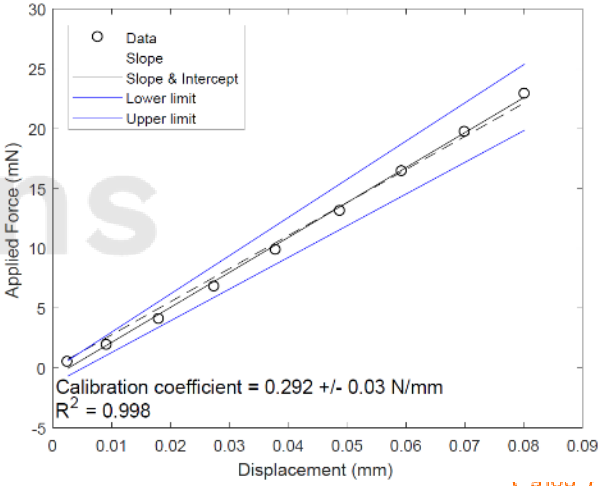
Test campaign

- **"Daedalus" chamber 1.5 x 2.5 m**
  - **-> cryogenic + turbomolecular pumping: 12000 l/s (air)**
  - **-> pressure during firing ~ 2 - 6 x 10^{-5} mbar @ 0.1-0.3 mg/s**
- **Thrust balance calibration:**
  - **-> account for stiffness including feed lines**
  - **-> rotational stage + pulley system moves cal. mass**
- **Thermal drift compensation: displacement at switch-off**









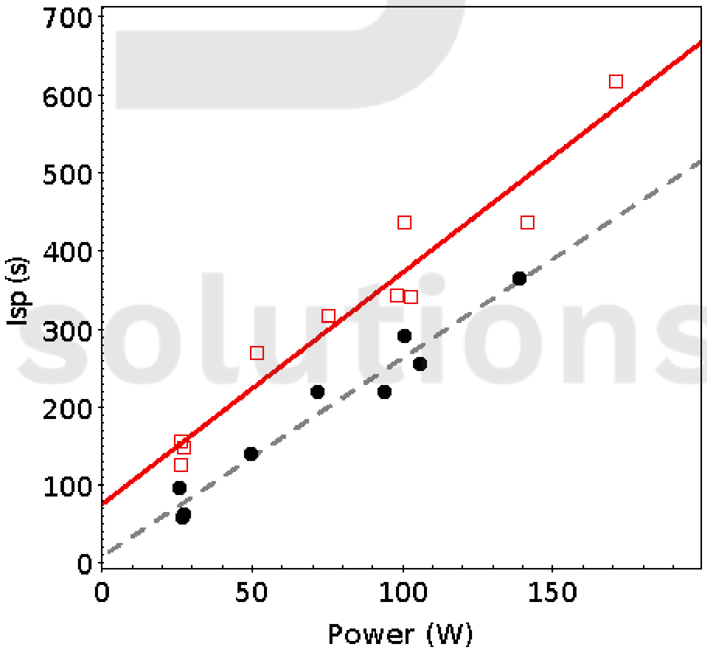
AQUAJET

Milestones to date

we have demonstrated for the first time:

- **Use of H_2O propellant: reliable ignition & stable operations across 210 firings**
- **Power up to ~180 Watts (previous record in literature = 50 Watts)**
- **Linear performance scaling with power (Ar, Xe)**

Performance measurements to date focussed on Ar & Xe benchmarks:
~ 100 test firings w. direct thrust data @ 0.1 – 0.7 mN



2 prototype configurations with Argon, and corresponding linear fits. We measured 10 such series to date.

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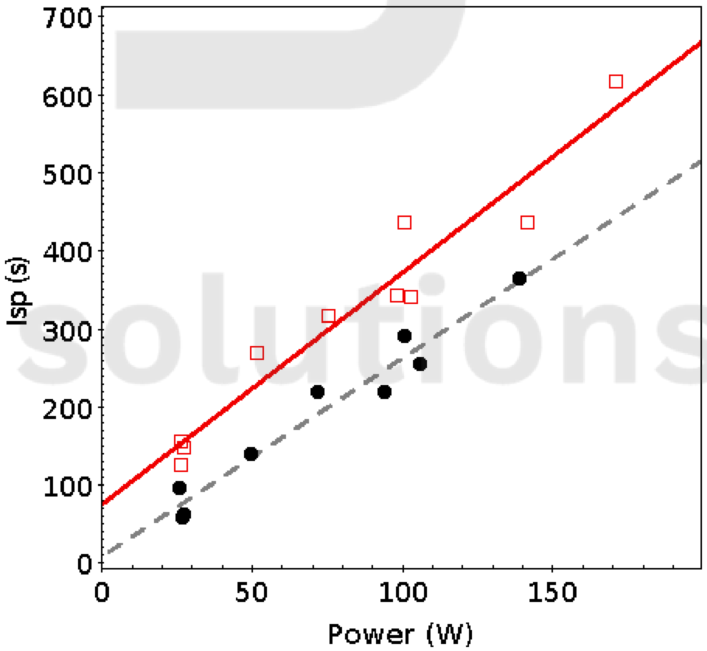
AQUAJET

Next steps

- Complete Xe, H_2O performance tests at lower background pressure
- Demonstrate Ammonia propellant
- Breadboard model re-design from lessons learnt
- Antenna erosion study



2 prototype configurations with Argon, and corresponding linear fits. We measured 10 such series to date.

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3. **XMET**

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INTEGRATED MICROWAVE PROPULSION ARCHITECTURE (IMPULSE)

XMET

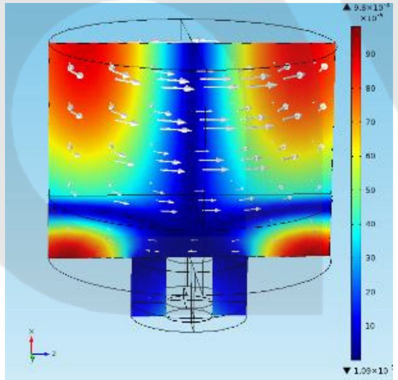
0.5-1 KW first fully all-electric EU platform

ECR-GIE

avs added value solutions

University of Southampton

Microwave electrothermal RCS thrusters



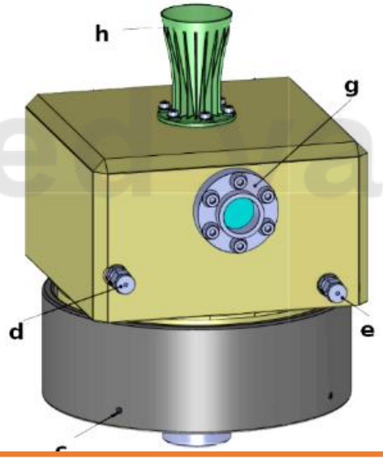
Thrust: 200-500 mN

ISP: ~100s

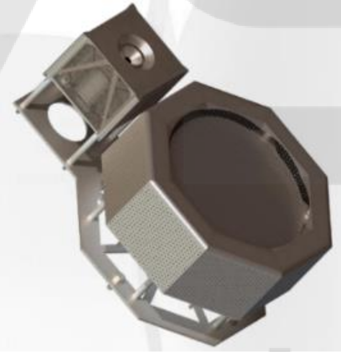
Cylindrical resonant cavity

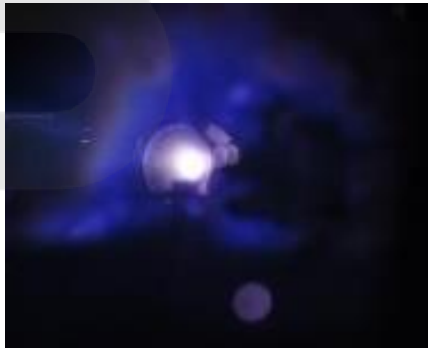
Xenon propellant

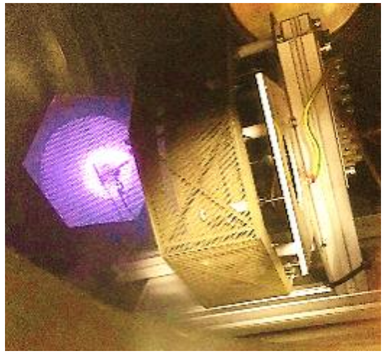
2.45 GHz solid state MW generator



22cm Xenon ECR gridded ion engine (XEPT-22) with ECR neutraliser

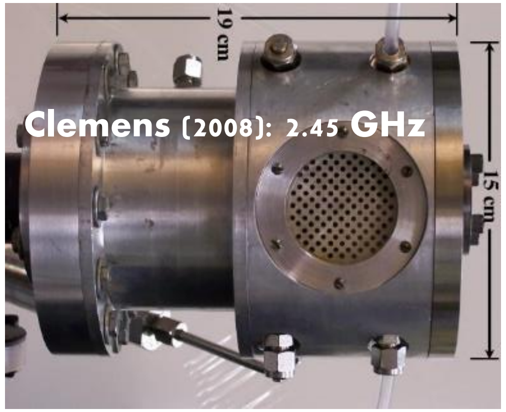


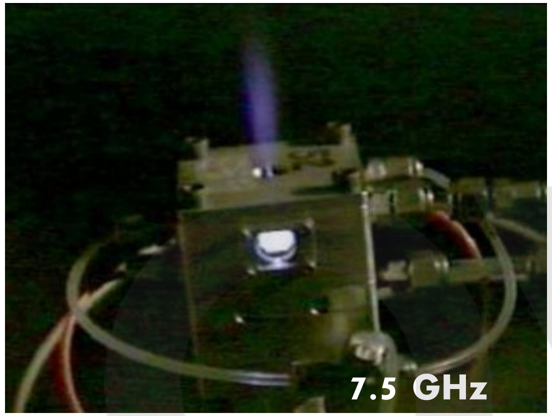


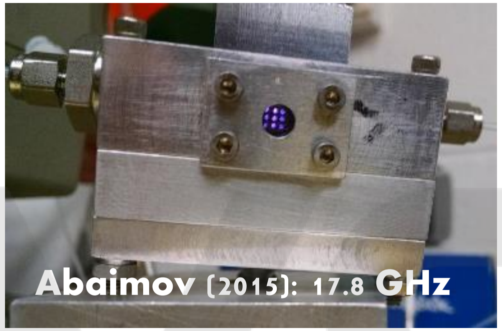


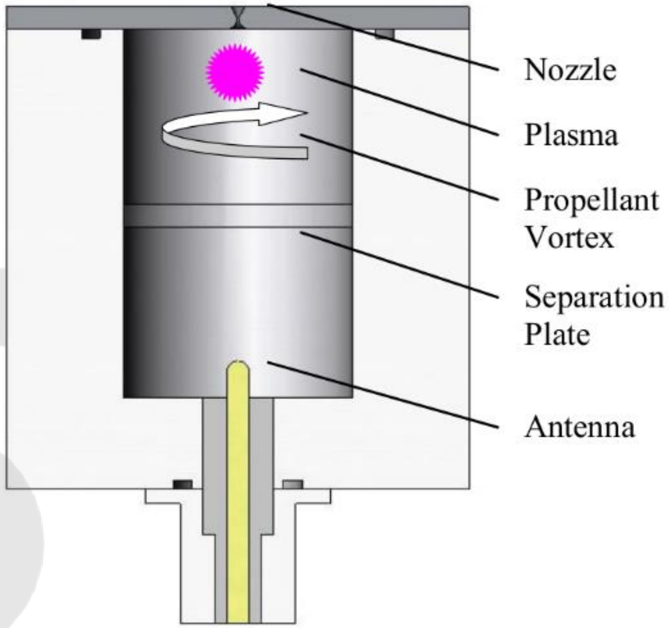
-> Angelo Grubisic presentation

MET background









Developed at Penn State university

- cavity radii: 50-7 mm @ 2.45-17.8 GHz
- power ~ 2000-20 W
- thrust ~ 300-1 mN

- Highly flexible propellant choice demonstrated: N_2, O_2, NH_3, H_2O, He, …

- Promising performance for NH_3 and H_2O:

propellant	ISP [s]	Thrust [mN]	Power [W]
NH3	550	84	350
H2O	800	120	1000

- Resonant cavity free-floating plasma discharge & conventional nozzle
- Simple, rugged, cheap, highly scalable
- Outperform arcjet, resistojet

XMET at AVS

XMET as part of IMPULSE architecture: Ar, Xe propellant test campaign

- Direct & indirect thrust measurements
- Optimal nozzle size & operating pressure
- Determine power required for ignition & firing at desired performance (up to 1 kW)

- First European MET thruster
- Optimised cavity design compared to Penn State
- Breadboard model hot-fire tests at Southampton
- Flexible design w. exchangeable nozzle insets, tuneable cavity height

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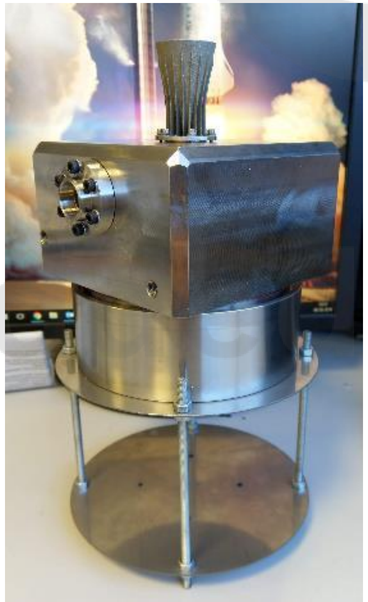
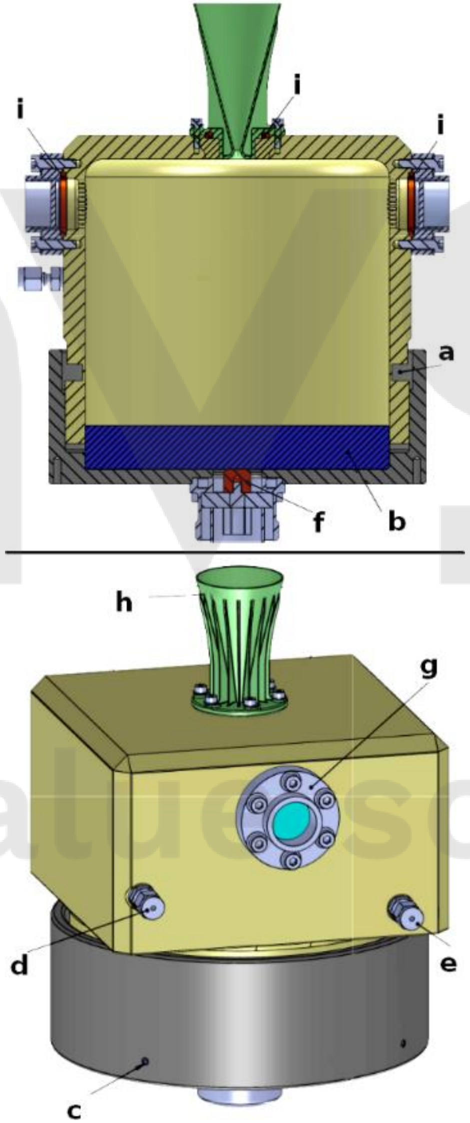
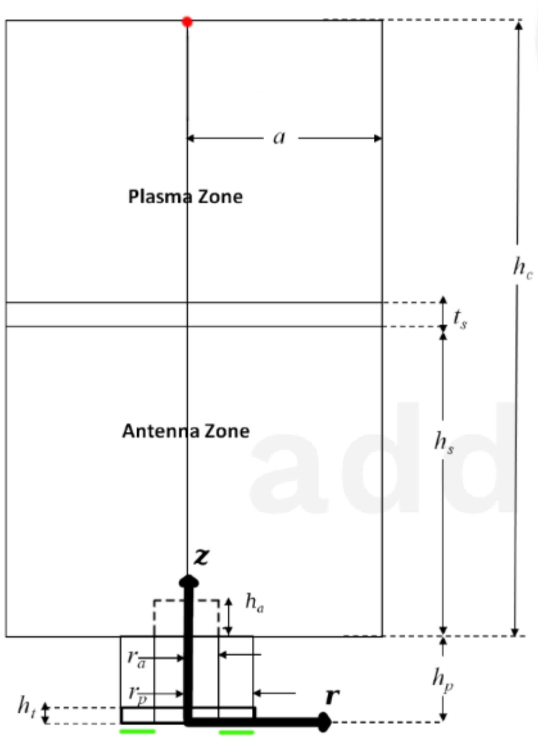


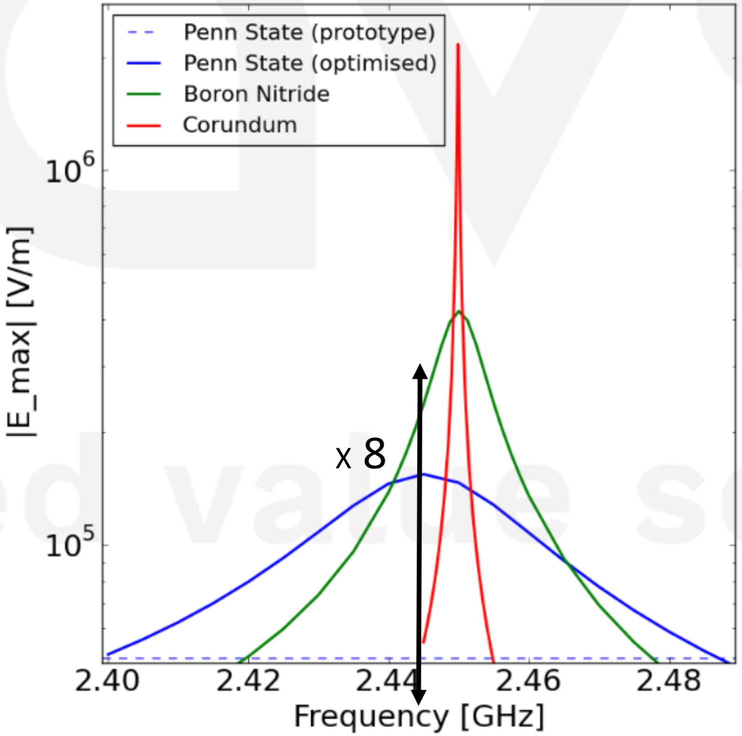


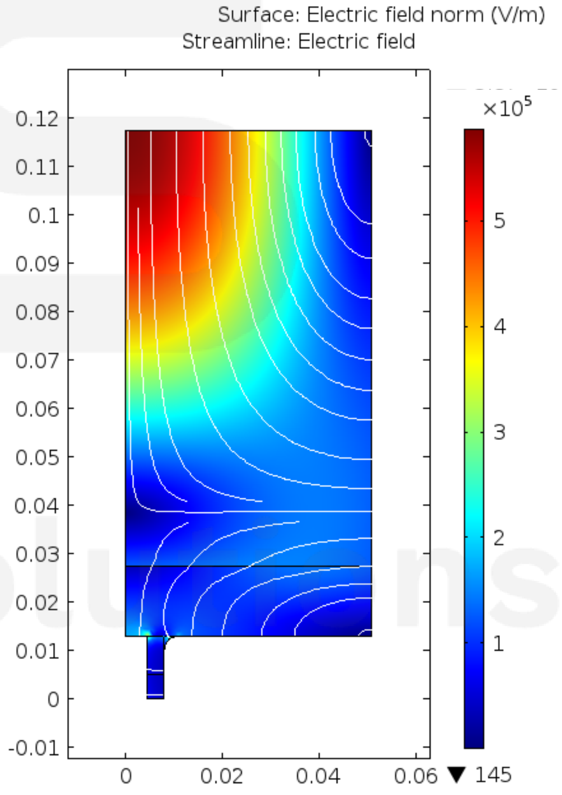
Cavity Model

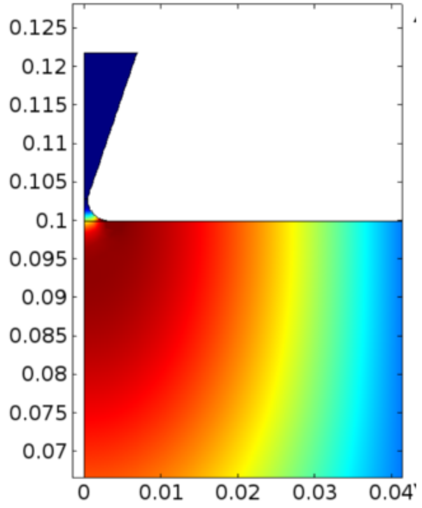
- **EM model via multiphysics software**
- **Cylindrical symmetry**

- **Key metrics: f_{res}, FWHM , |E_max|**
- **Material & geometry optimisation**





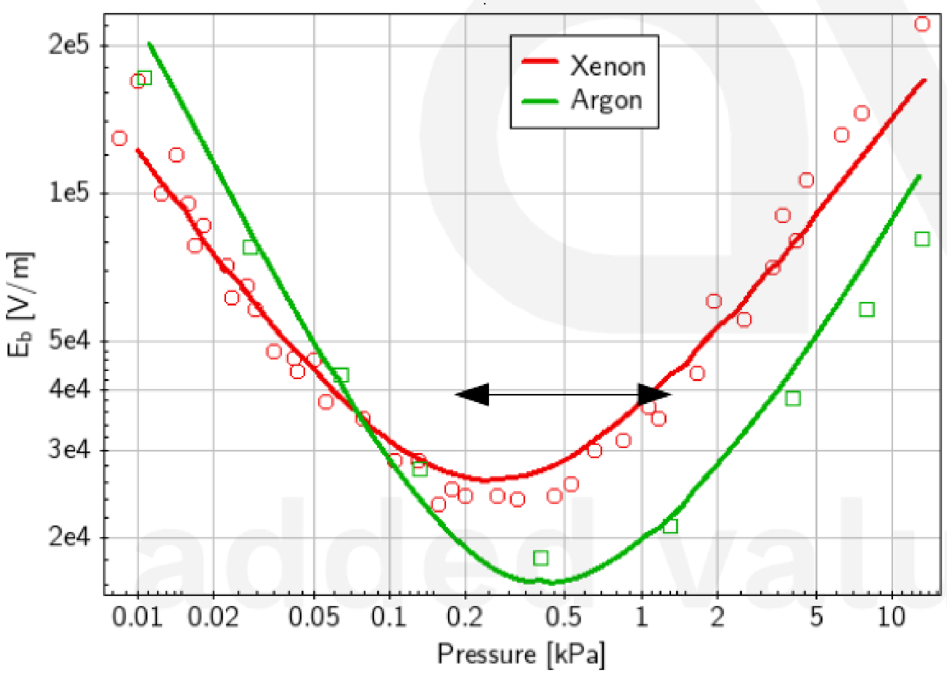




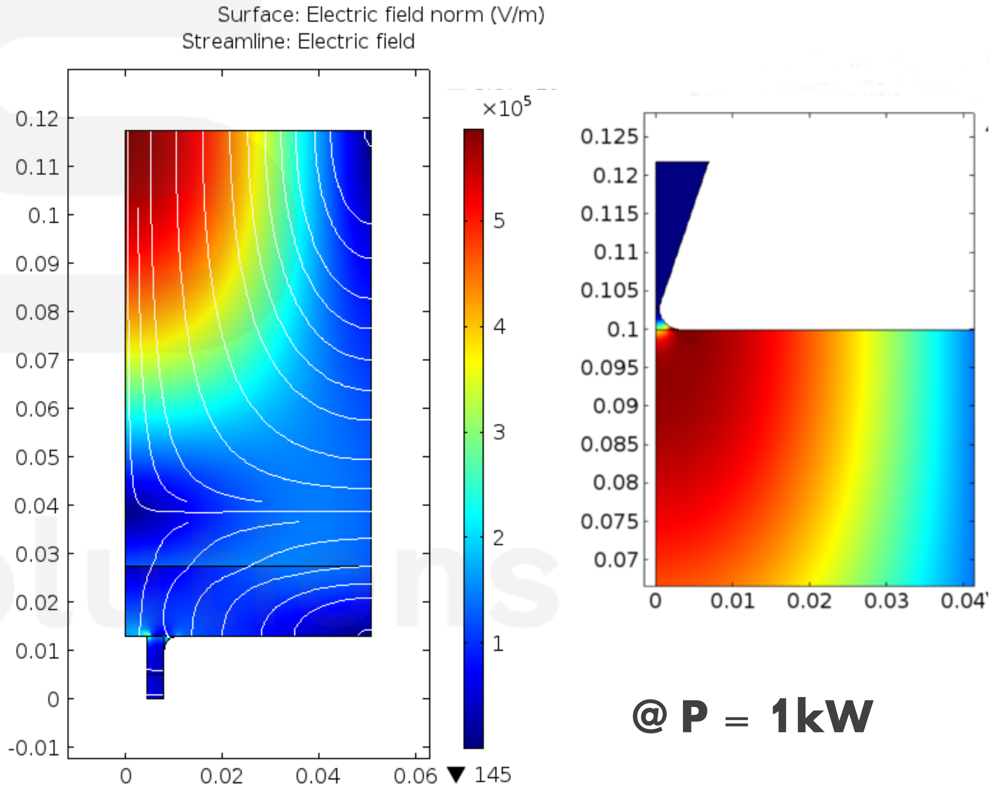
@ P = 1kW

Cavity Model

- **Ignition at low flow rate**
- **Predicted breakdown field strength: < 10 Watts**



MW breakdown voltage (2.8 GHz):
data from Liskovskiy (1999) & Cook et al (2010)



@ P = 1kW

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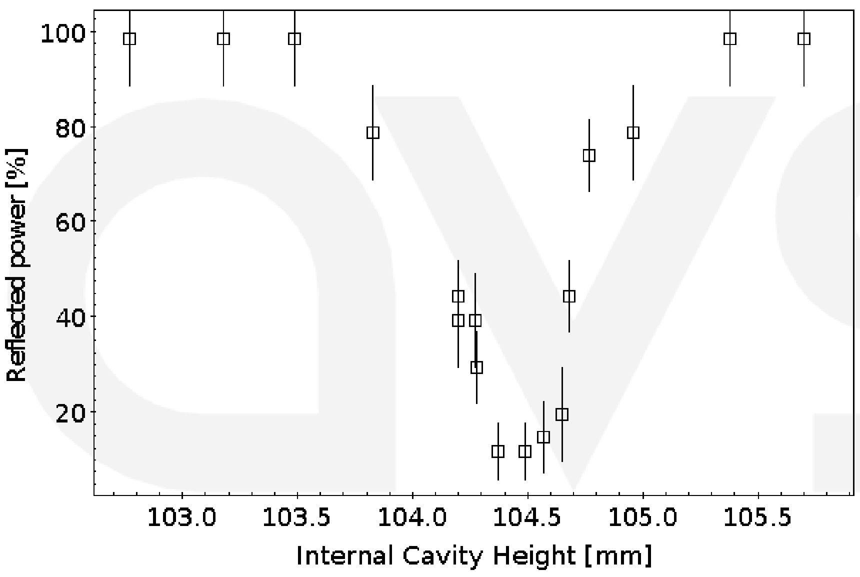
Early Testing: Argon

Cavity Tuning

- sharp resonance confirmed:

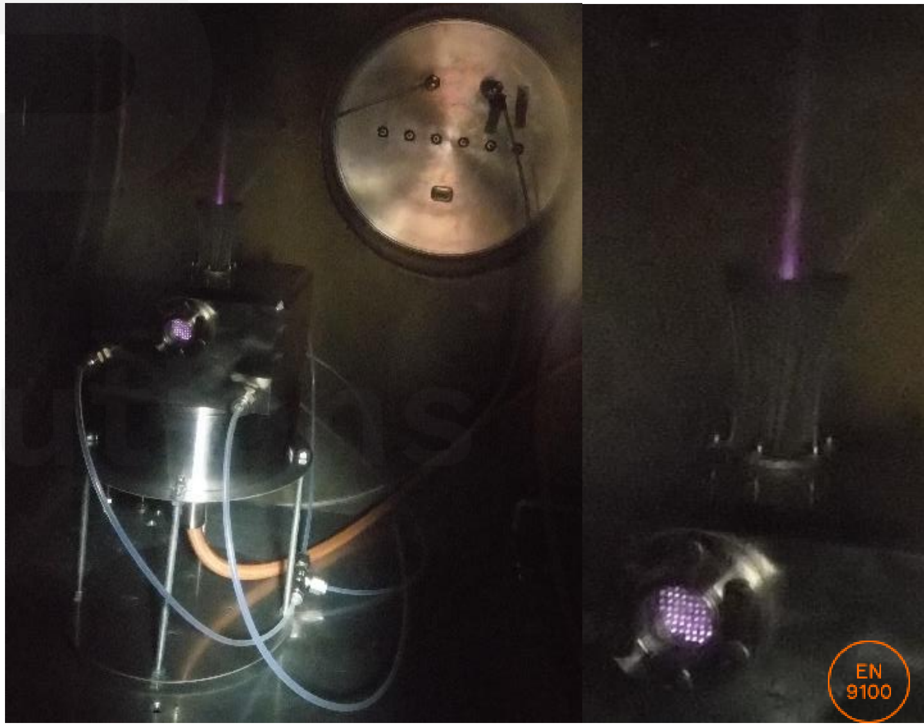


Ignition

- achieved at ~4 Watts

Stable operation

- up to 220 Watts (60 mg/s)
  100 Watts (140 mg/s)



Next steps

- Complete Argon performance tests: higher power, flow rates
- Demonstrate Xenon propellant
- Direct thrust measurements
- Breadboard model re-design from lessons learnt

Thank you for your attention