The Development and Qualification of the STAR Resistojet System for Telecommunications Applications

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and

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UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- National Space Technology Programme (NSTP) Flagship project: 2-years TRL innovation (KO in April)
- Consortium:
  - Developed High-Temperature Resistojet (HTR) AM design
  - Proved first AM resistojet prototype in 316L†
  - ➢ Goal: design and testing of STAR EM model in high-temperature materials

†**Manufacturing of a high-temperature resistojet heat exchanger by selective laser melting** F Romei, AN Grubišić, D Gibbon – Acta Astronautica, 2017

UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - Global supplier of refractory metal powders for AM
  - Developer of advanced refractory metal alloys
  - Custom SLM powder including Ta/W alloys

UK Space Agency Flagship

UK SPACE AGENCY

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:

UNIVERSITY OF Southampton

H.C.Starck HiETA technologies CATAPULT Satellite Applications SURREY SATELLITE TECHNOLOGY LTD

  - Market leader in additive manufacturing
  - Produced parts in nickel alloys and pure Ta. Next will produce parts in Ta/W alloys

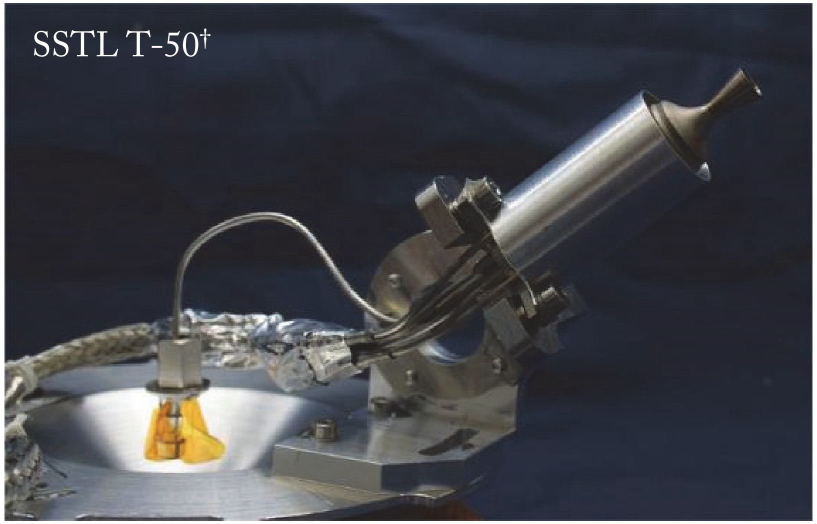
UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - Independent innovation and technology company
  - Develop standardization processes and secure supply chain strategy for the STAR thruster

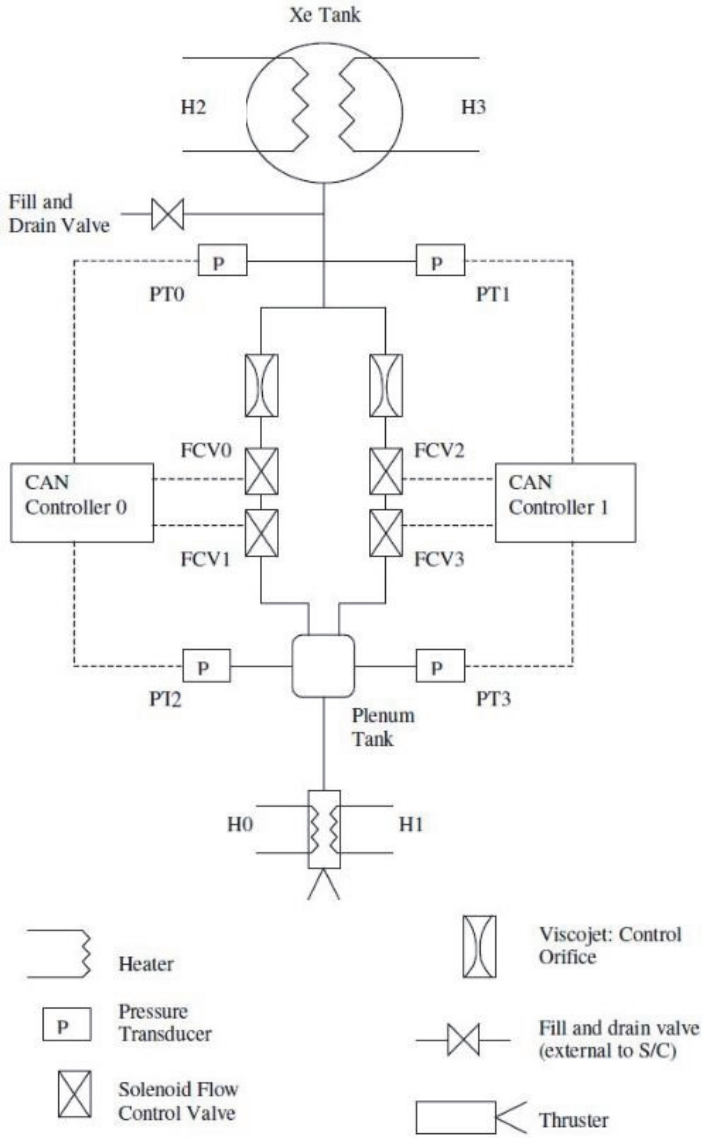
UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - World's leading small satellite manufacturer
  - Extensive heritage with Xe and butane resistojets
  - End user requirements and guidelines for the STAR

State of the Art Xenon Resistojets (SSTL)



- Small satellite orbit correction and station keeping
- Heater 28V DC bus voltage at 15W and 30W



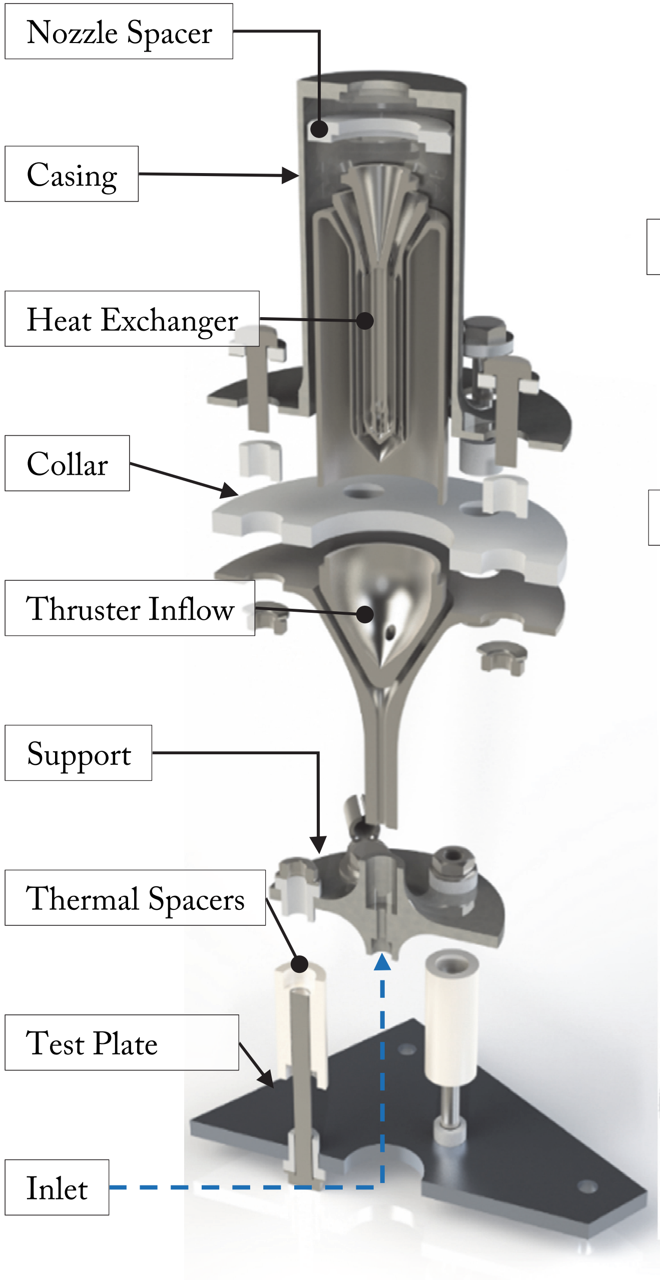
Vari ant	Redundant heater power	Propel lant	Thrusters	Typical operation temperature	I_{sp}
T30	30 W	Xe	10 launched on 10 S/Cs, 2 waiting launch	530°C	48 s
T15	15 W	C_4H_{10}	19 launched on 10 S/Cs, 4 waiting launch	250-350°C	> 100

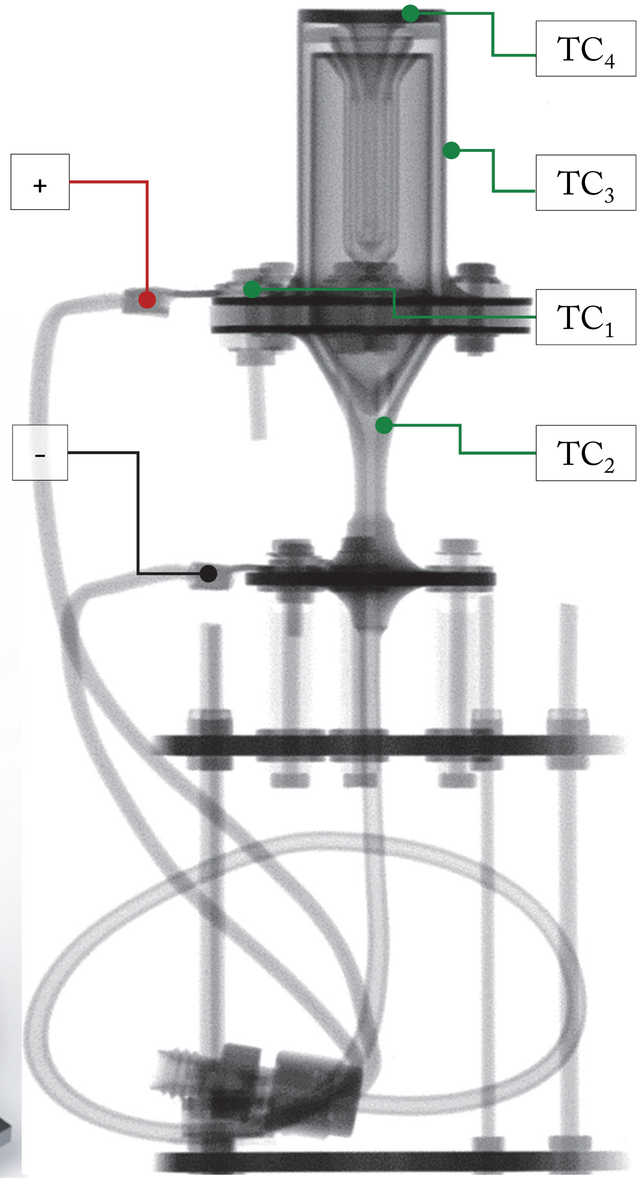
Concept of the STAR Thruster

- Maximise specific impulse, hence stagnation temperature

$$I_{sp} \approx \frac{1}{g_0}\sqrt{\frac{2c_{p,m}T_0}{M}}$$

- 3D printed monolithic regenerative heat exchanger
- 316L prototype (T_0 = 1,000 K) demonstrated†
- Refractory metals (T_0 > 2,500 K) to reach I_{sp} > 80 s with Xe





†**Validation of an Additively Manufactured Resistojet through Experimental and Computational Analysis** F. Romei, A. Grubišić – Acta Astronautica, 2019

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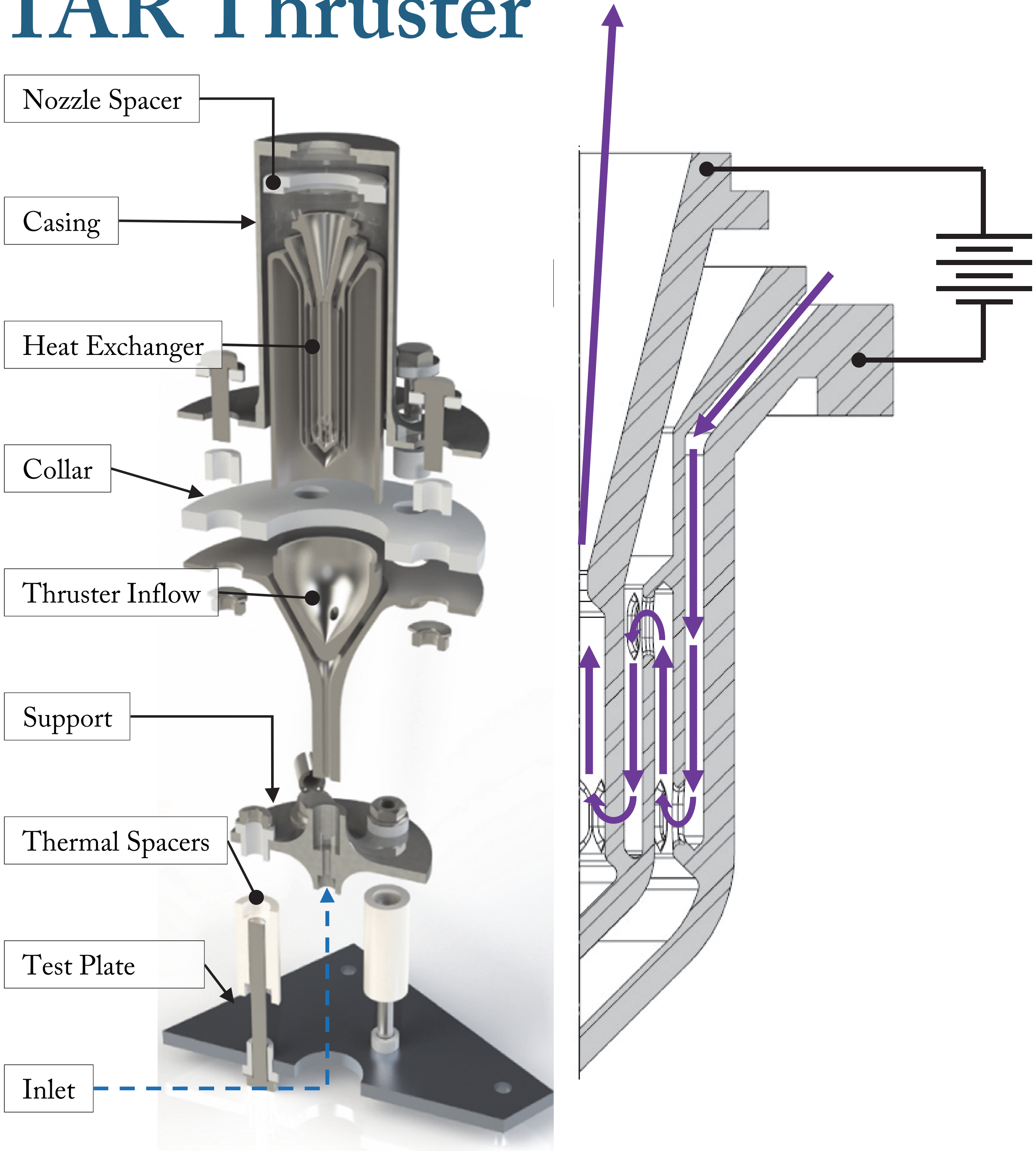

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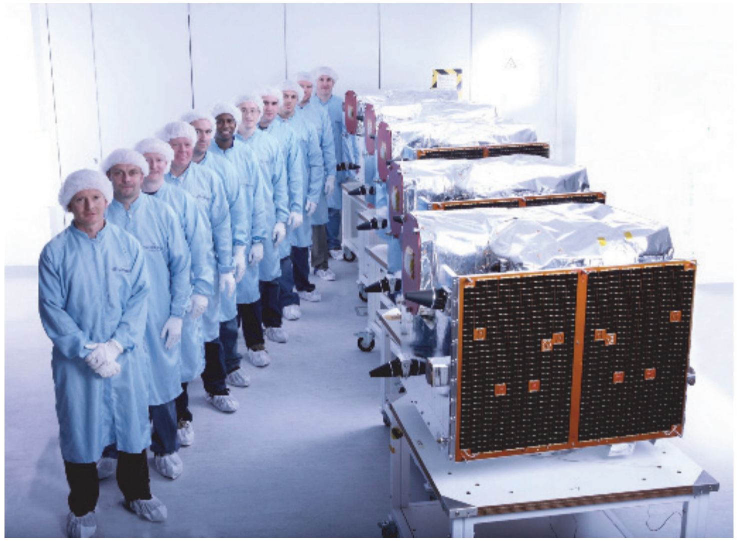
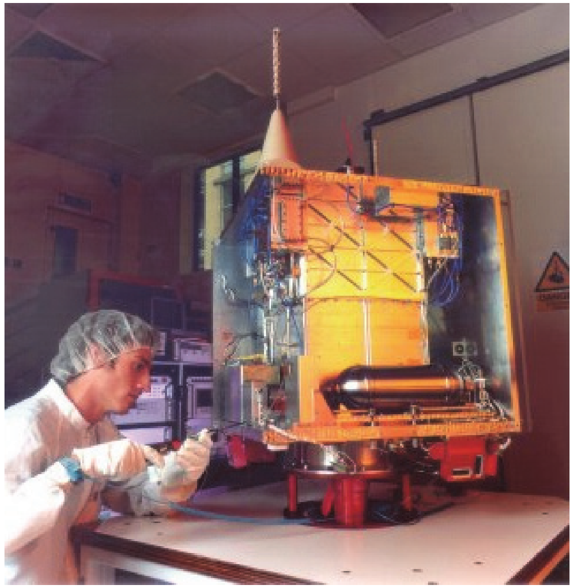
Application 1: Stand-Alone Propulsion



RapidEye constellation, SSTL (Xe resistojet)



Disaster monitoring constellation
AlSAT-1, SSTL (Butane resistojet)

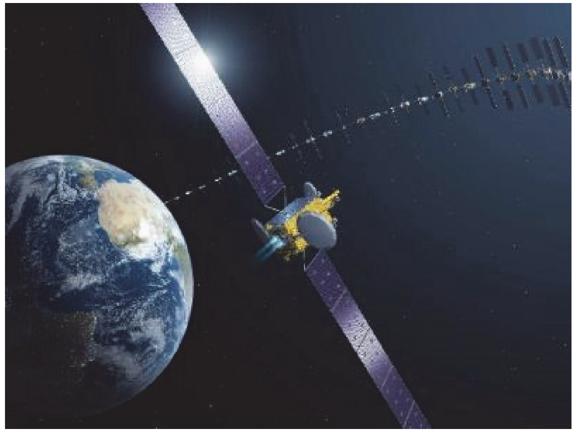
- Small Satellites:
  - Limited resources
    - Volume (0.75 m^3)
    - Mass (200 kg)
    - Power (100 W)
  - Dependence on:
    - High storage density – I_{SP} product
    - Inert propellants
    - Lower cost of AIT

➢ Resulting system:
- Low I_{SP}
- Low total impulse/ low Δv
- Limited on-orbit/deorbit capability
- +70% Δv from STAR thruster = game changer

Application 2: All-Electric Spacecraft

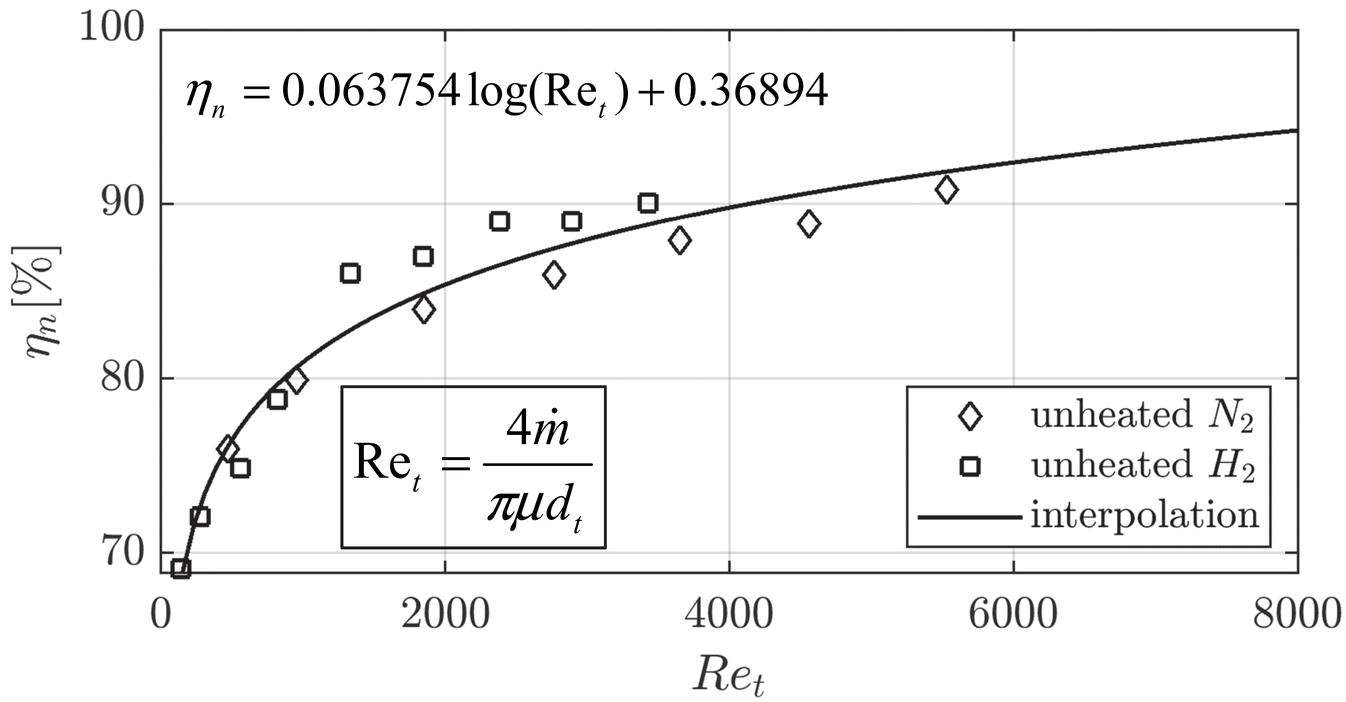
- Advantages of A-E spacecraft:
  - Common Xenon Propellant Management System
    - System mass saving (1 vs 2 PMS)
    - Complexity reduction and reuse of architecture
    - PPS & RCS mass fraction optimisation (Deep Space 1, SMART 1, Hayabusa)
  - Absence of hydrazine
    - Lower cost of AIT
    - Lower risk of regulation changes
  - Safe mode operations
    - Xe resistojets can operate in cold redundancy for safe mode/de-spin

Boeing – 702SP (ABS-3A and Eutelsat 115 West B, 2015)



OHB System – Electra, SmallGEO Flex platform (http://www.esa.int/)

Nozzle Considerations

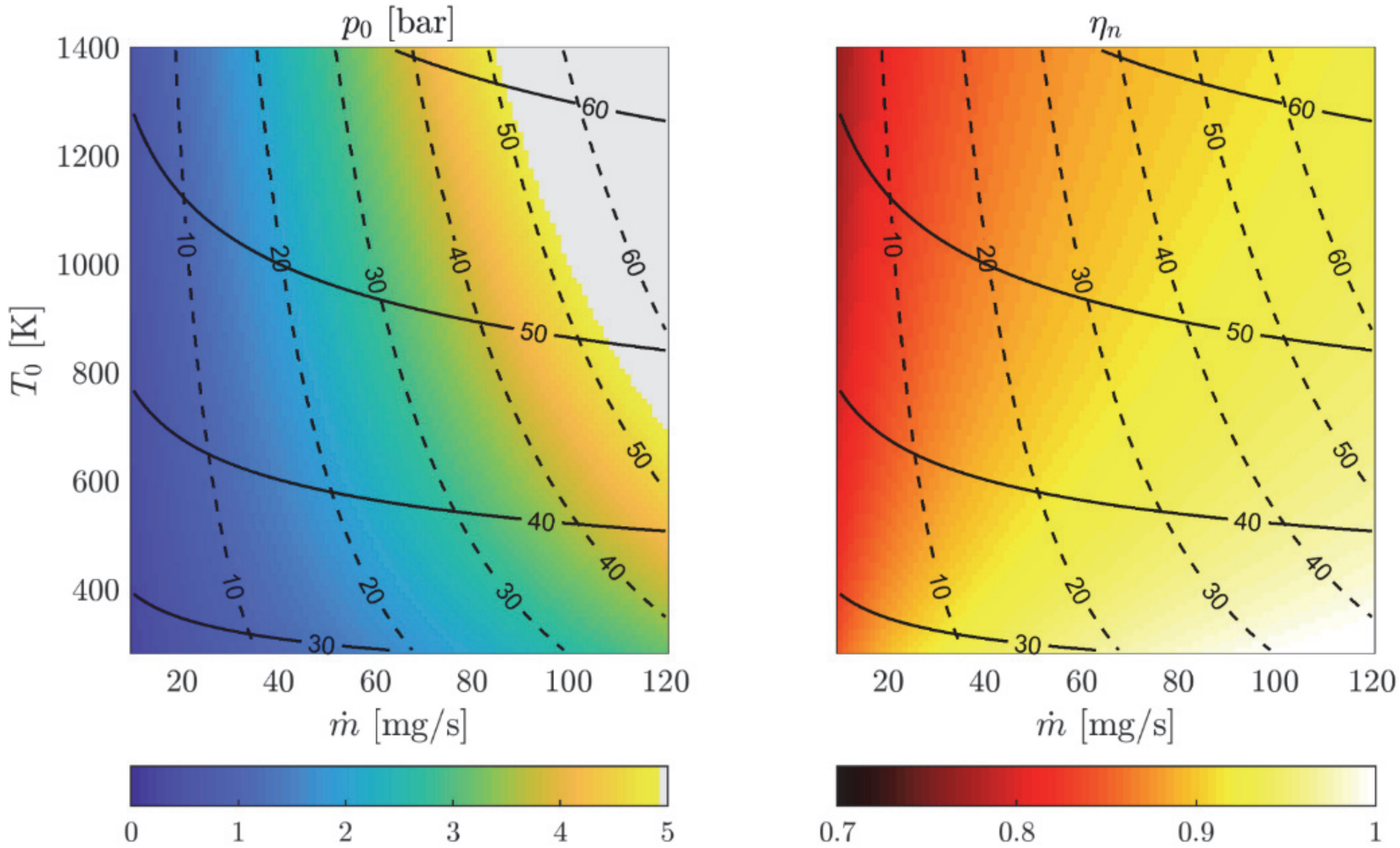


Efficiency curve of a conical nozzle with 15° half-conical angle (solid line) and experimental data gathered from .

- Low Reynolds number nozzles at high temperature
- Need of high nozzle efficiency (>90%), i.e. $\mathrm{Re}_t > 4000$
- To size the nozzle based on mission requirements

Nozzle Considerations

- LEO application: primary propulsion for Δv manoeuvres (no pulse)
- Material: nickel alloys, temperature range: 1,100 K – 1,400 K



Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of **thrust** (- - - -) and **specific impulse** (——) iso-contours as function of the mass flow rate and propellant stagnation temperature T_0. Calculations are made for d_t = 0.3 mm.

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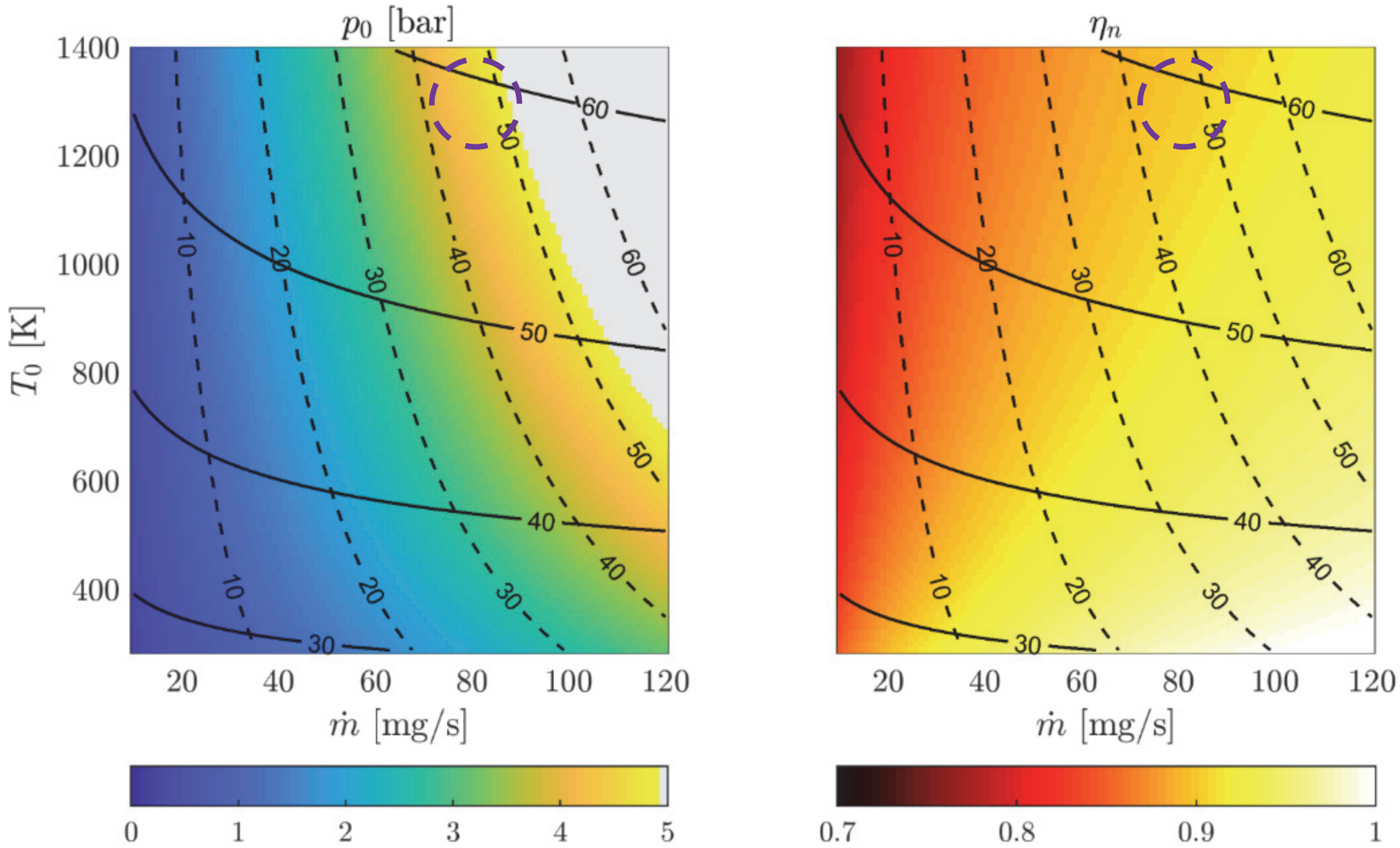


Design point:

$F = 50\,\mathrm{mN}$

$I_{sp} = 60\,\mathrm{s}$

$p_0 = 5$ bar

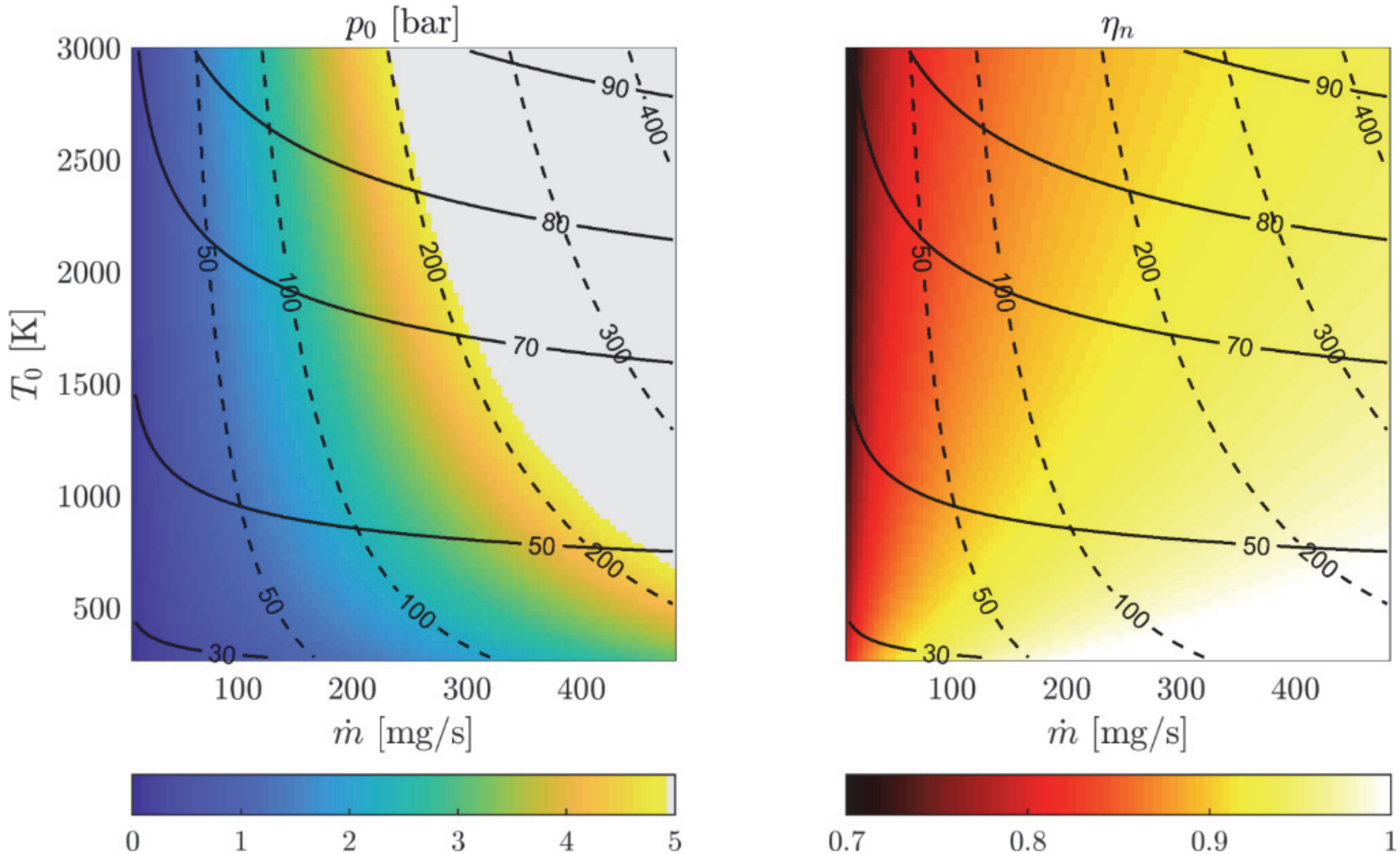
$P_e < 50$ W

$\eta_{ts} > 60\%$

Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of **thrust** (- - - -) and **specific impulse** (———) iso-contours as function of the mass flow rate and propellant stagnation temperature T_0. Calculations are made for $d_t = 0.3$ mm.

Nozzle Considerations

- GEO A-E application: RCS, de-spin and momentum damping
- Material: Ta/W alloys, temperature range: 2,100 K – 2,600 K



Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of **thrust** (- - - -) and **specific impulse** (——) iso-contours as function of the mass flow rate and propellant stagnation temperature T_0. Calculations are made for $d_t = 0.6$ mm.

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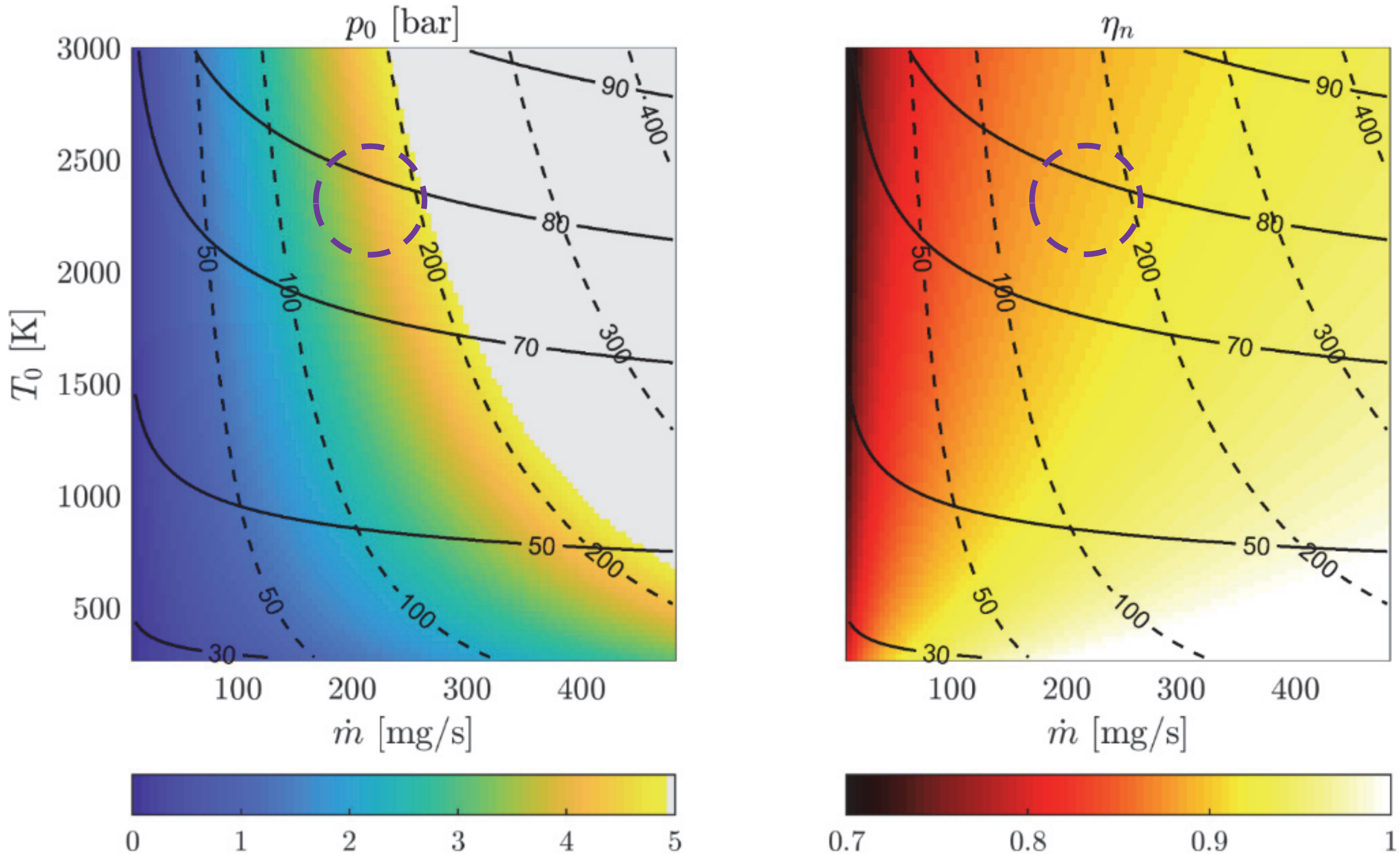


Design point:

$F = 200\,\text{mN}$

$I_{sp} > 80\,\text{s}$

$p_0 = 5$ bar

$P_e < 150$ W

$\eta_{ts} > 60\%$

Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of **thrust** (- - - -) and **specific impulse** (———) iso-contours as function of the mass flow rate and propellant stagnation temperature T_0. Calculations are made for $d_t = 0.6$ mm.

Iterative Heater Design

Low resistance (low risk – high priority)

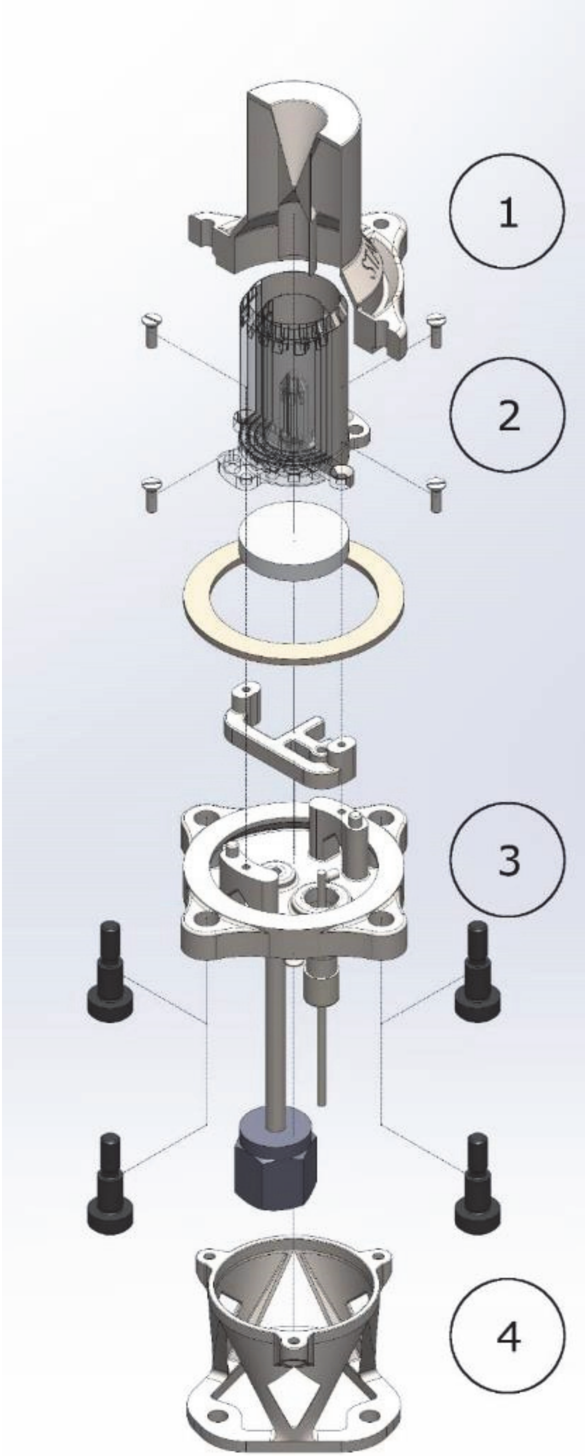
- Straight cylinders

Medium resistance (medium risk – medium priority)

- Heater with inner helix
- Heater with meshed cylinders

High resistance (high risk – low priority)

- Single track helix



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Low resistance (low risk – high priority)

- Straight cylinders

Medium resistance (medium risk – medium priority)

- Heater with inner helix
- Heater with meshed cylinders

High resistance (high risk – low priority)

- Single track helix

- Heater resistance ~ 10 mΩ

Straight cylinders: first design in 316L (left) and current design in Nickel alloy (right)

Iterative Heater Design

Low resistance (low risk – high priority)

- Straight cylinders

Medium resistance (medium risk – medium priority)

- Heater with inner helix
- Heater with meshed cylinders

High resistance (high risk – low priority)

- Single track helix

- Heater resistance ~ 100 mΩ

Meshed cylinders design

Iterative Heater Design

Low resistance (low risk – high priority)

- Straight cylinders

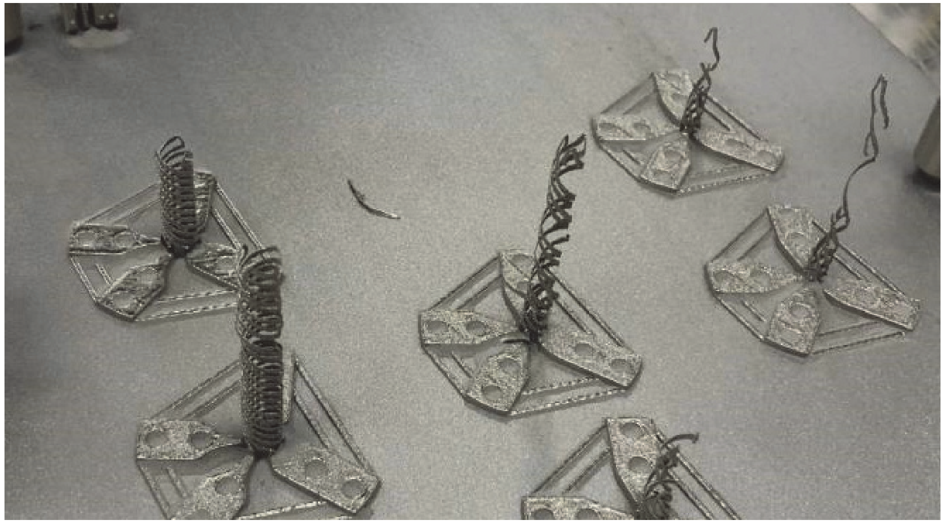
Medium resistance (medium risk – medium priority)

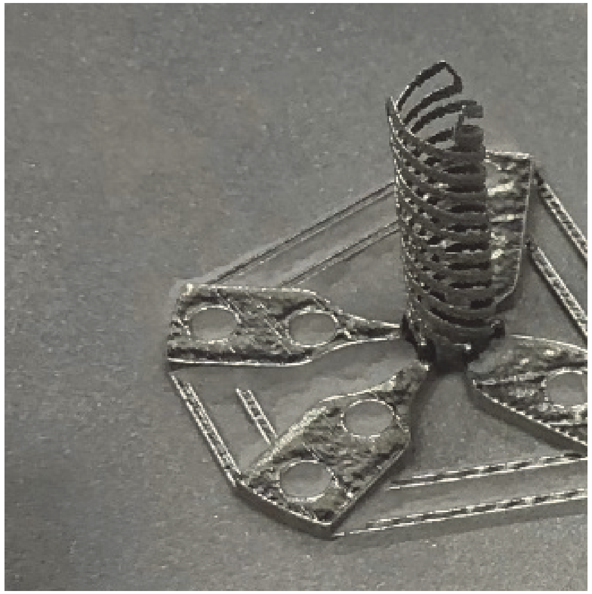
- Heater with inner helix
- Heater with meshed cylinders

High resistance (high risk – low priority)

- Single track helix

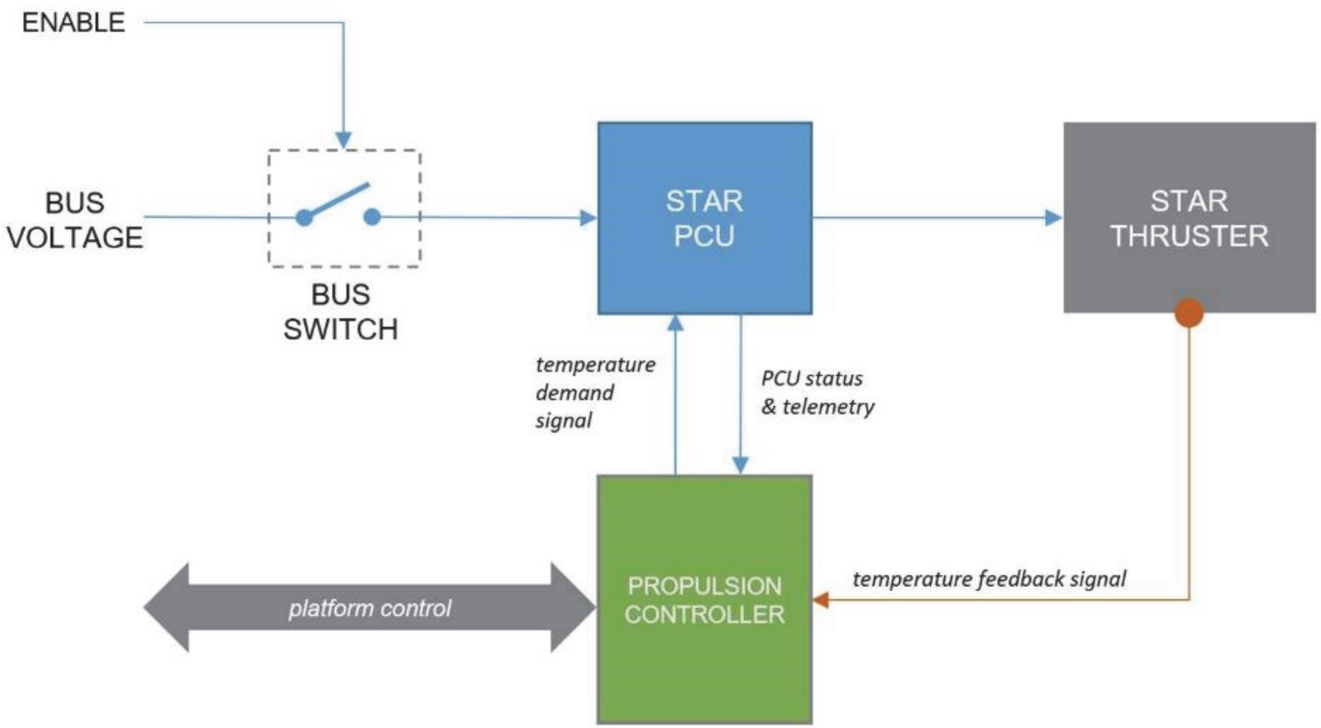
- Heater resistance ~ 1 Ω





STAR PCU development

- LEO application:
  - EM model for full STAR system tests
  - low cost, current controlled output
- A-E GEO application: BOM and schematics only



Test Campaign

- Sub-component:
  - Heater cycling tests of several designs -> selection of heater

    M. Robinson (A393): Ta - low resistance design: ~ 340 cycles performed, 120 at 80% of T_{max}
  - Selective Laser Melting high temperature properties

    C. Ogunlesi (A403): surface emissivity and electrical conductivity at high-temperature
  - PCU design + environmental testing

- Full system (STAR thruster + PCU) tests:
  - Thermal cycling + vibration + shock tests
  - Leak + performance tests + thruster cleanliness verification
  - Life test + NDT inspection

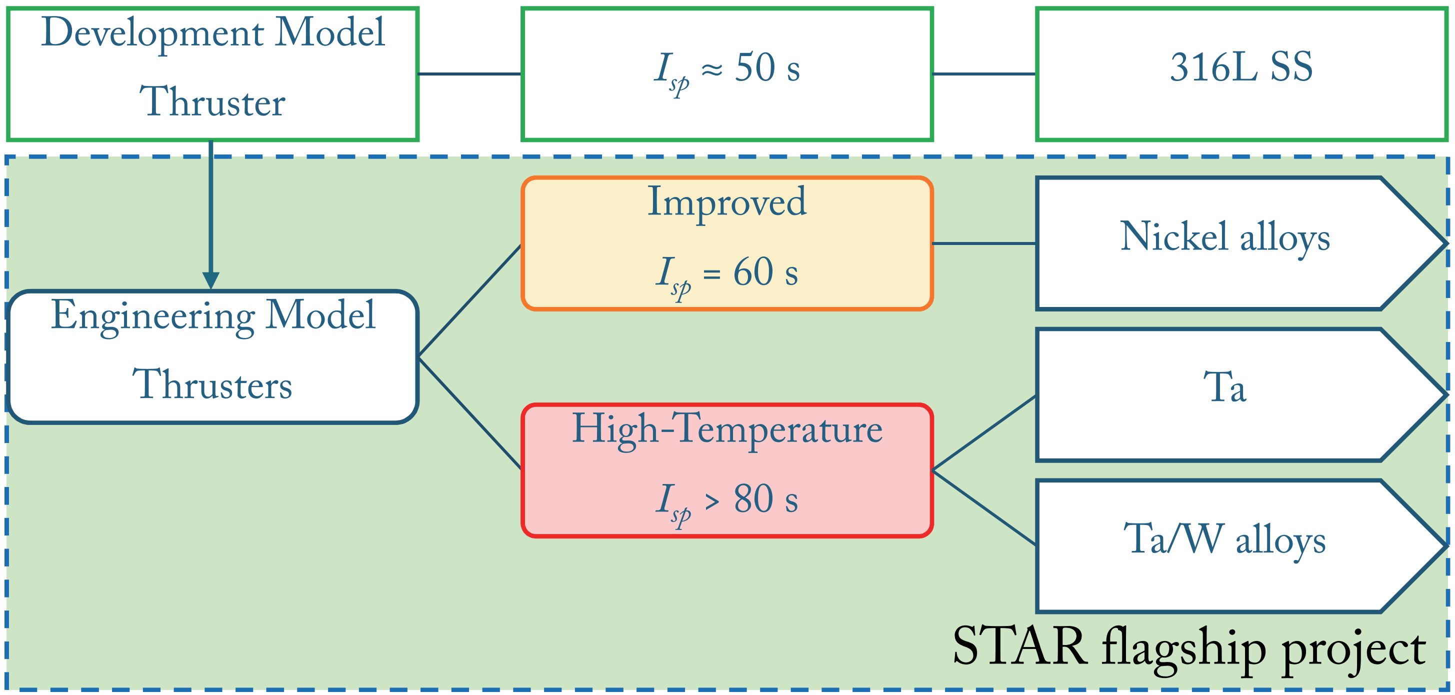
Summary of STAR project

Phase 1:

- Investigate on resistivity and surface emissivity of SLM custom material
- Iteration of heater design to maximise lifetime/electrical resistance

Phase 2:

- Testing of PCU
- Testing of STAR thrusters in Ta/W and nickel alloys
- STAR system EM model test



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Thank you for your attention

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