



Australian
National
University

SP₃

<http://sp3.anu.edu.au>
Space Plasma, Power & Propulsion

Lab to Launch

C. Charles and R. Boswell

1- Space Plasma, Power and Propulsion laboratory (SP3)

Centre for Plasmas and Fluids, RSPE, The Australian National University, Australia

W. Liang, L. Raymond and J. Rivas Davila

2- Department of Electrical Engineering, Stanford University, USA

J. Cater and N. Rattenbury

3- The University of Auckland, New Zealand



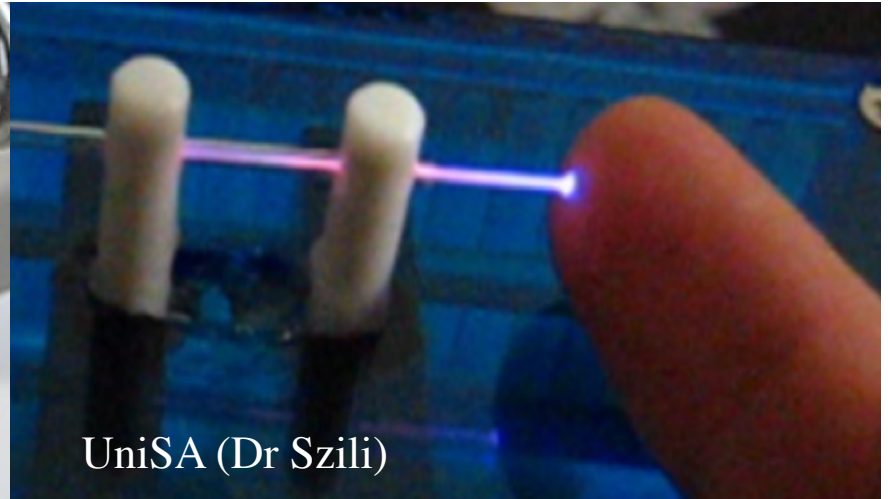
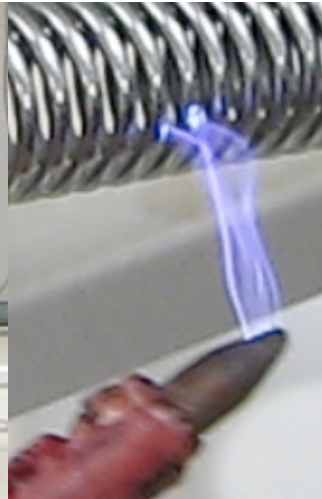
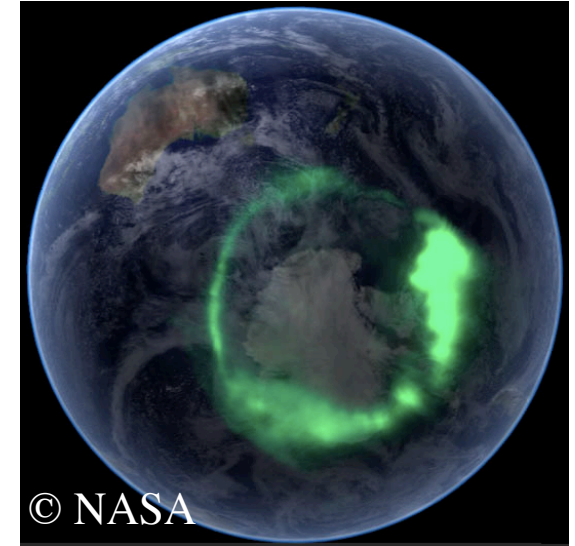
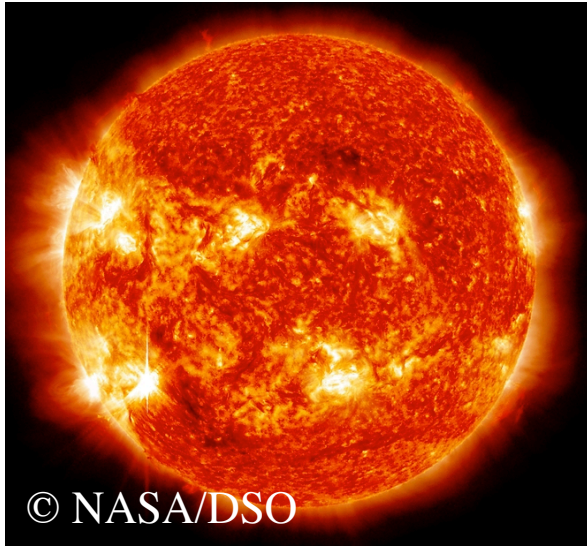
Stanford
University



THE UNIVERSITY OF
AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

VASSCAA-9, 2018, Sydney, August 12-16, Australia

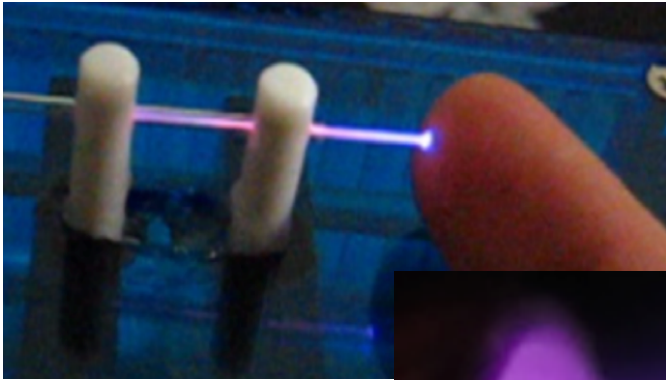
Space and laboratory plasmas:



Except for scaling, parameter ranges of both coronal plasma and plasma arcs/jets can be achieved in the laboratory and tailored to suit many applications

Scaling and expansion of the plasma

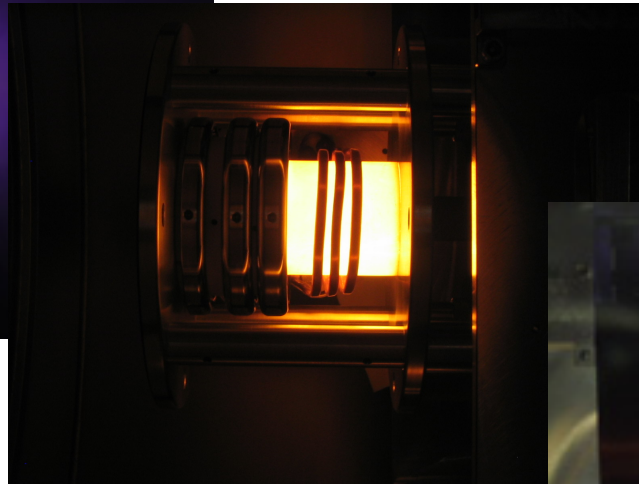
<1mm



decreasing
pressure

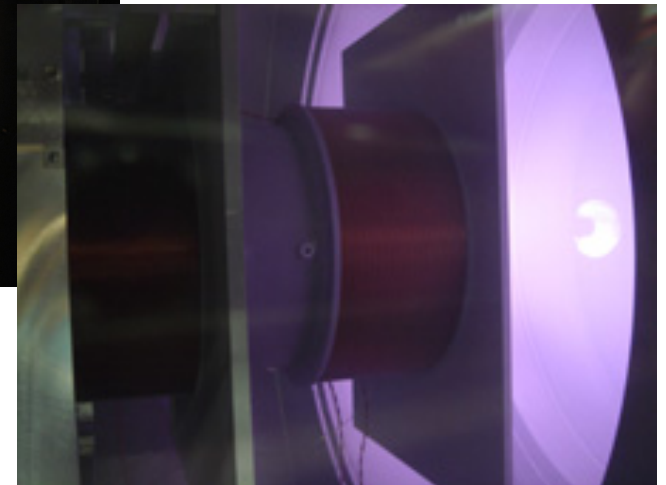


1-6 mm



1-10 cm

>10 cm

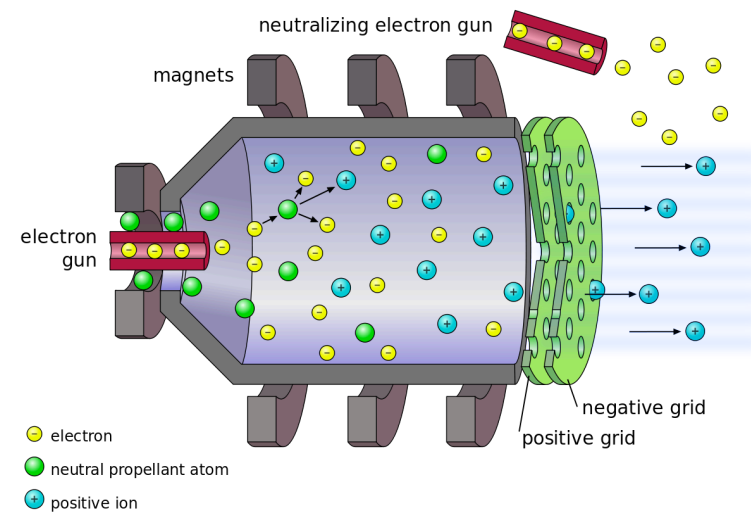
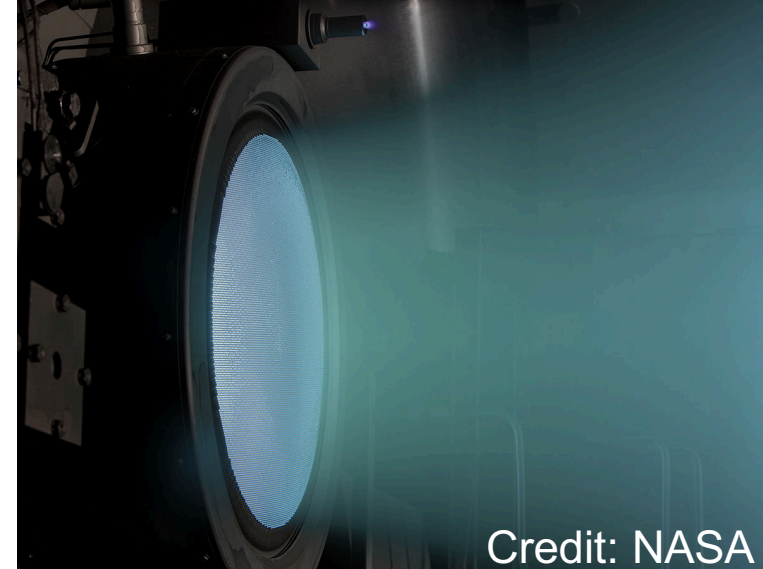


From capillary to very large

Pressure regime and coupling modes will be derived from given size: atm, high, medium, low pressure, pressure gradient

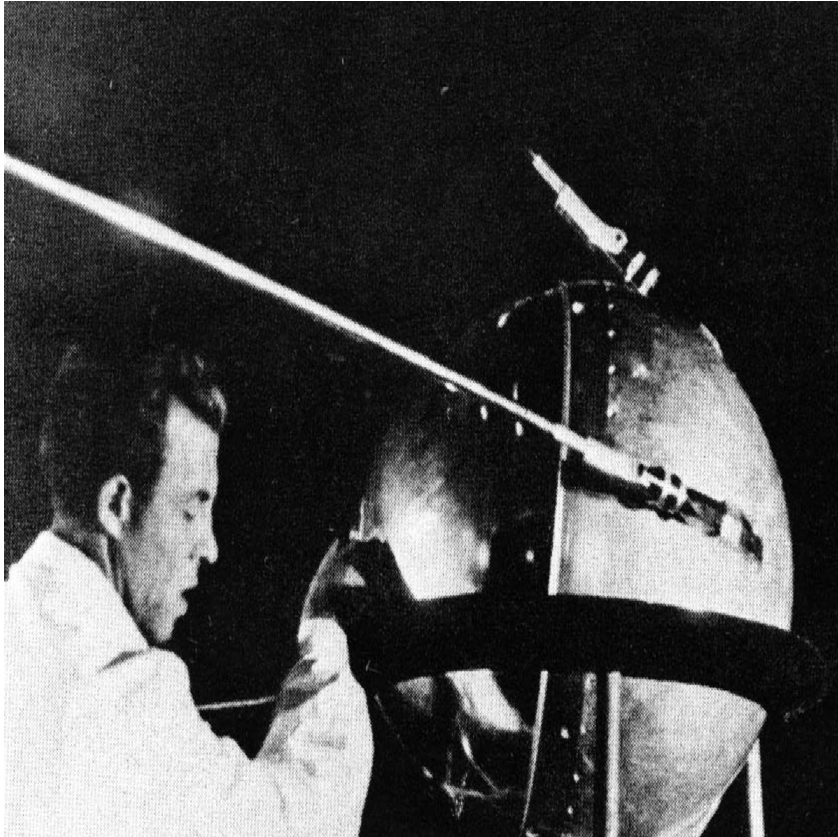
Crucial to the microelectronics industry

Chemical and electric propulsion



Source: Wikipedia

From Sputnik to the ISS



1957: Sputnik, 1st satellite, 83kg

1960: Titos, 1st Meteorology Sat.

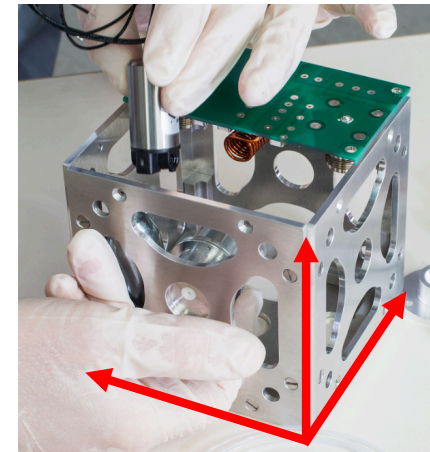
1962: Telstart 1, 1st Telecom Sat.

1998: International Space Station (ISS),
400 tons, >\$100 billions

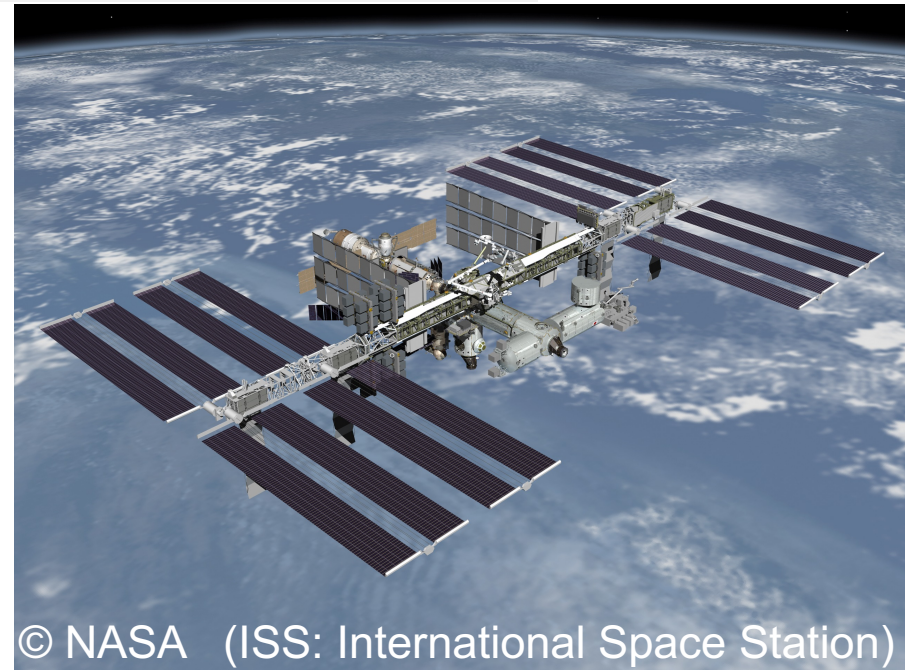
1999: Nano-satellites (CubeSat),
1-10 kg, \$100 000

$$T = \frac{d(mv_{ex})}{dt}$$

$$I_{sp} = \frac{T}{\left(\frac{dW}{dt}\right)} = \frac{v_{ex}\left(\frac{dm}{dt}\right)}{g \frac{dm}{dt}} = \frac{v_{ex}}{g}$$



CubeSat: 10x10x10 cm³



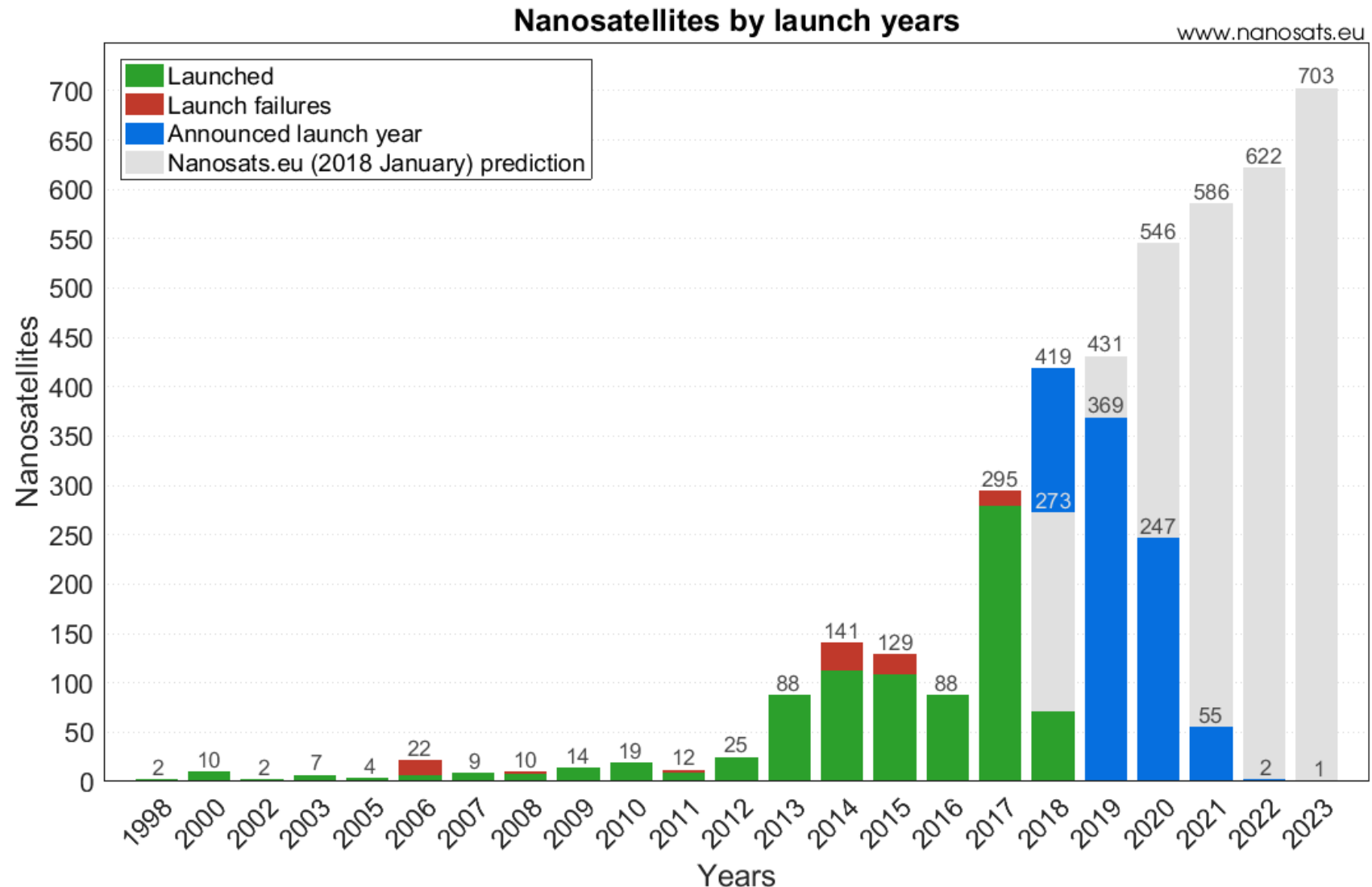
© NASA (ISS: International Space Station)

60 years of space use = space junk

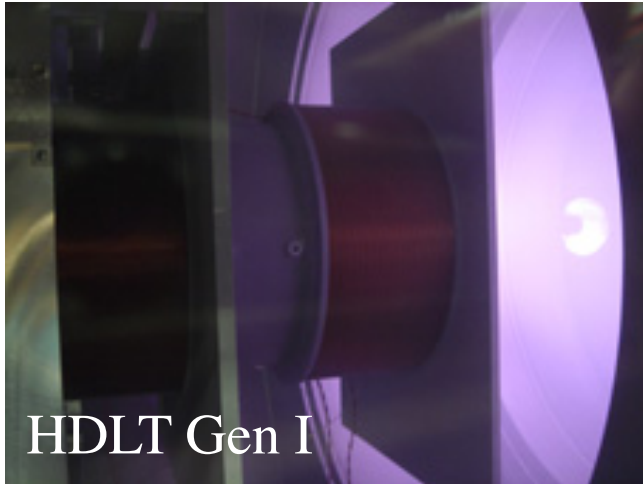


Placement of large telecom satellites on graveyard orbit, Hydrazine (new regulations)
Low-power low-cost 'green' thruster for small satellites, Long-term interplanetary travel

CubeSats: from ISS or secondary payload



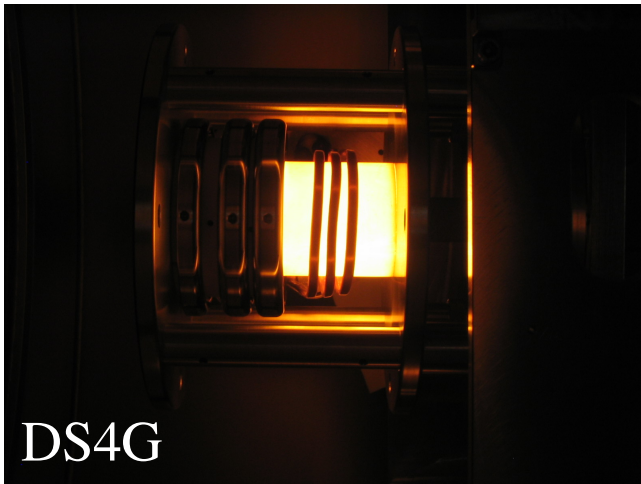
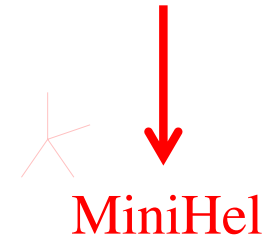
SP3_ANU rf thrusters



HDLT Gen I

HDLT (Helicon Double Layer Thruster)
– 2002, electrodeless radiofrequency (rf)
plasma thruster
Astrium (AIRBUS) 2006-2013

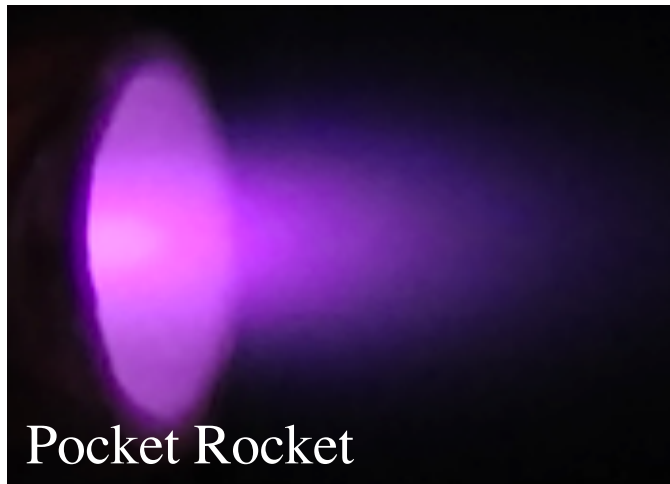
Miniaturisation



DS4G

DS4G (Dual Stage Four Grid thruster) –
2005-2006, ion gridded rf thruster
European Space Agency (ESA)

BBthruster

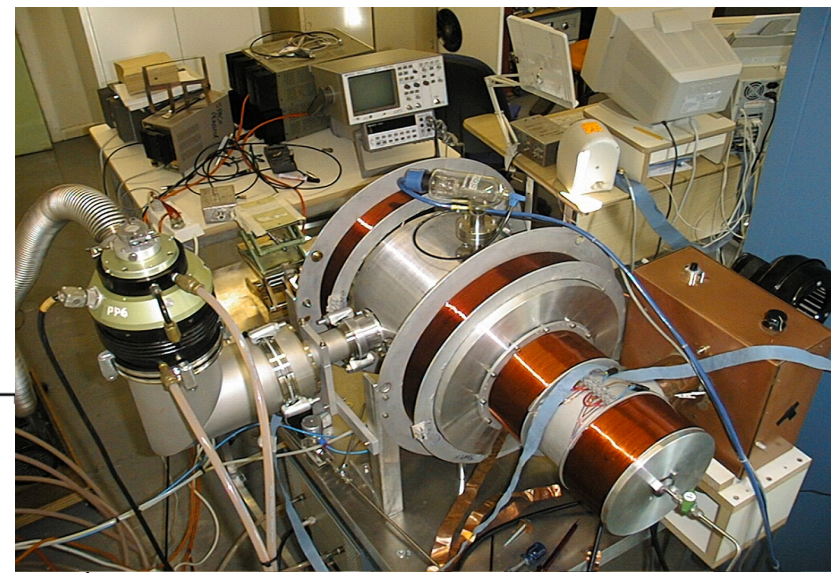


Pocket Rocket

PR (Pocket Rocket Thruster) –
2010, electrothermal rf plasma micro-
thruster
Lockheed Martin US 2013-2015

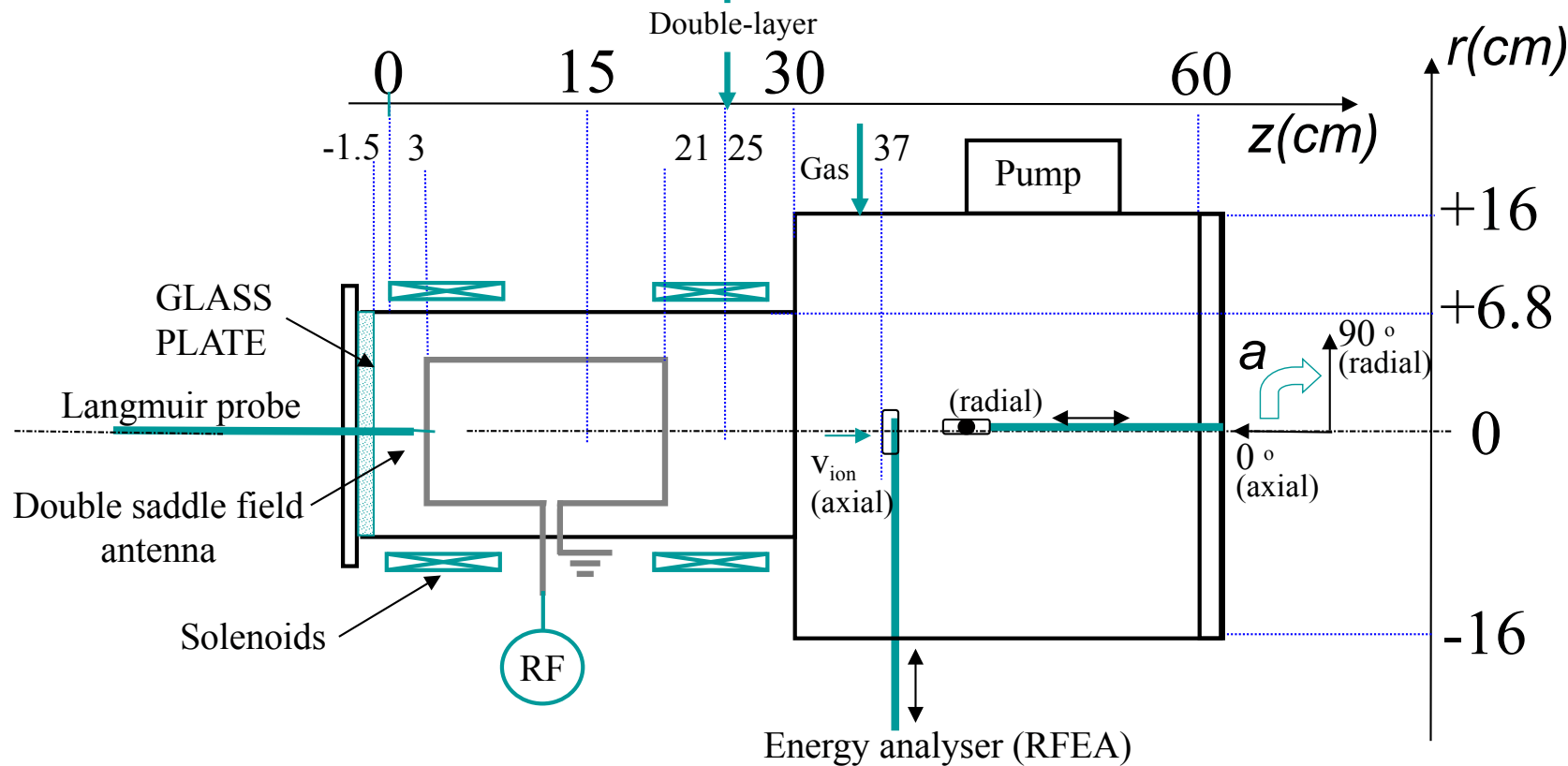
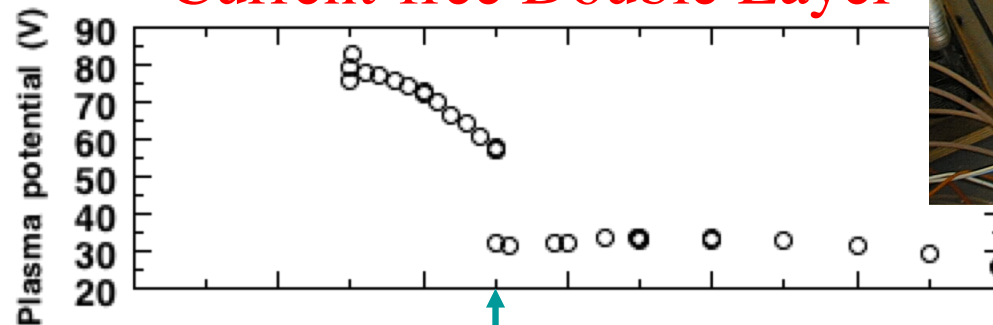
MiniPR

Helicon source: low pressure expanding magnetized plasma



March 1999

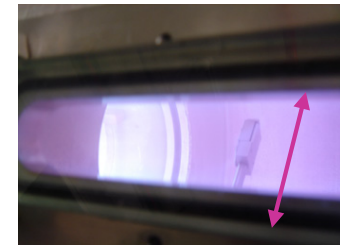
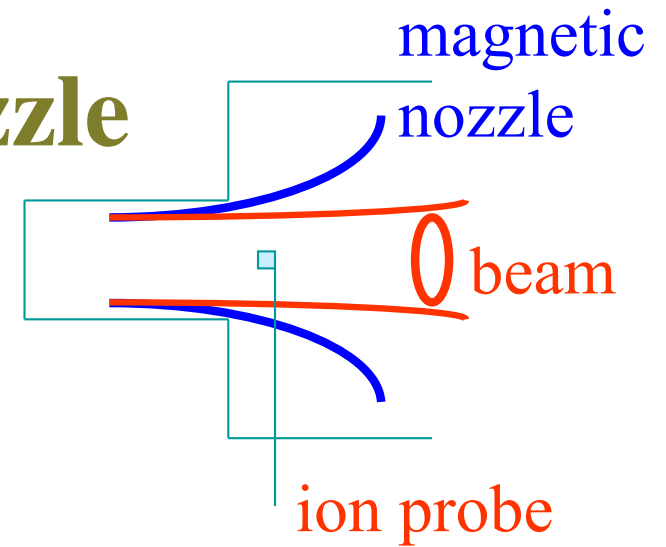
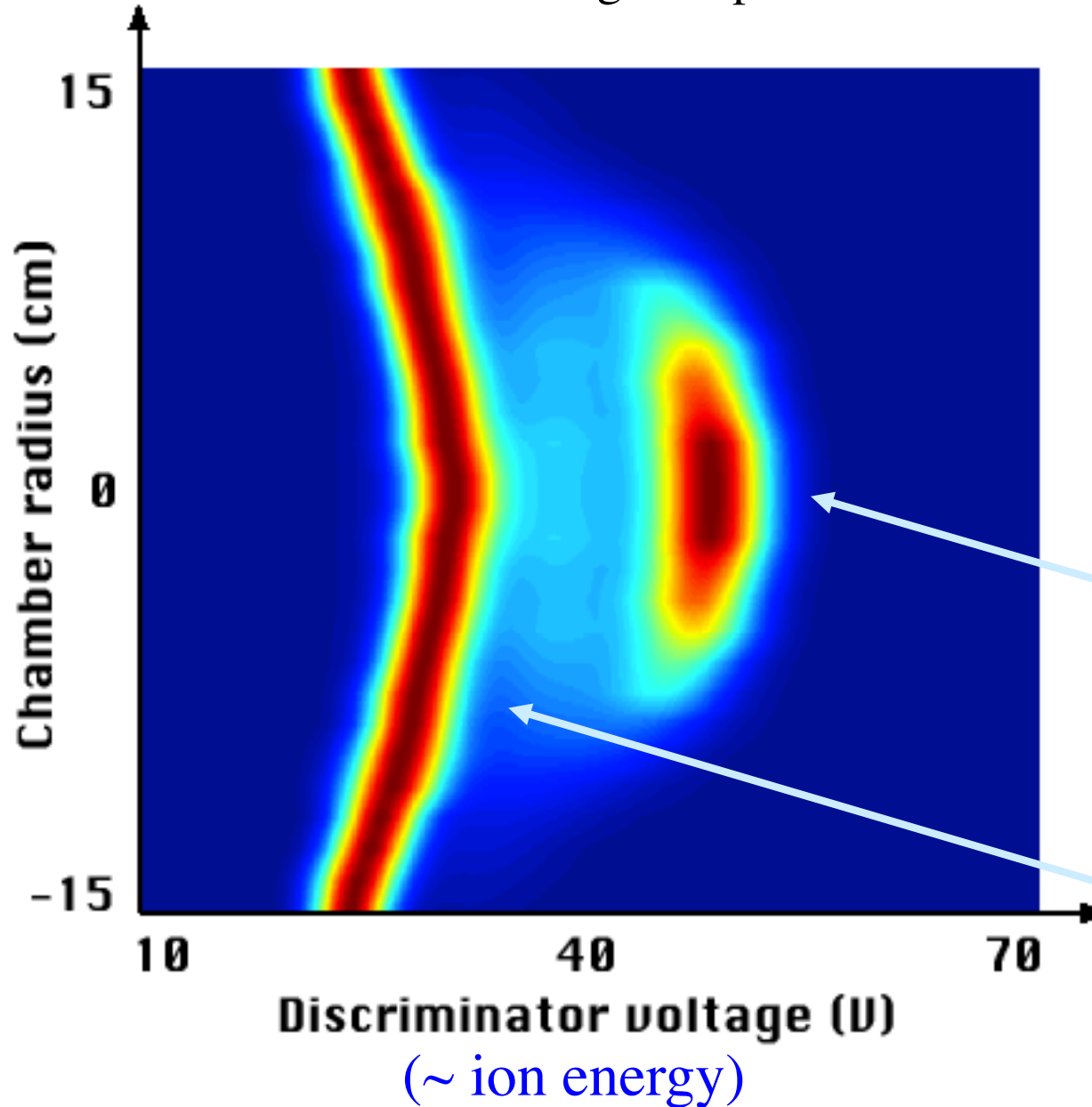
Current-free Double Layer



13.56 MHz
~ 1 mTorr
~ 120 G
diverging

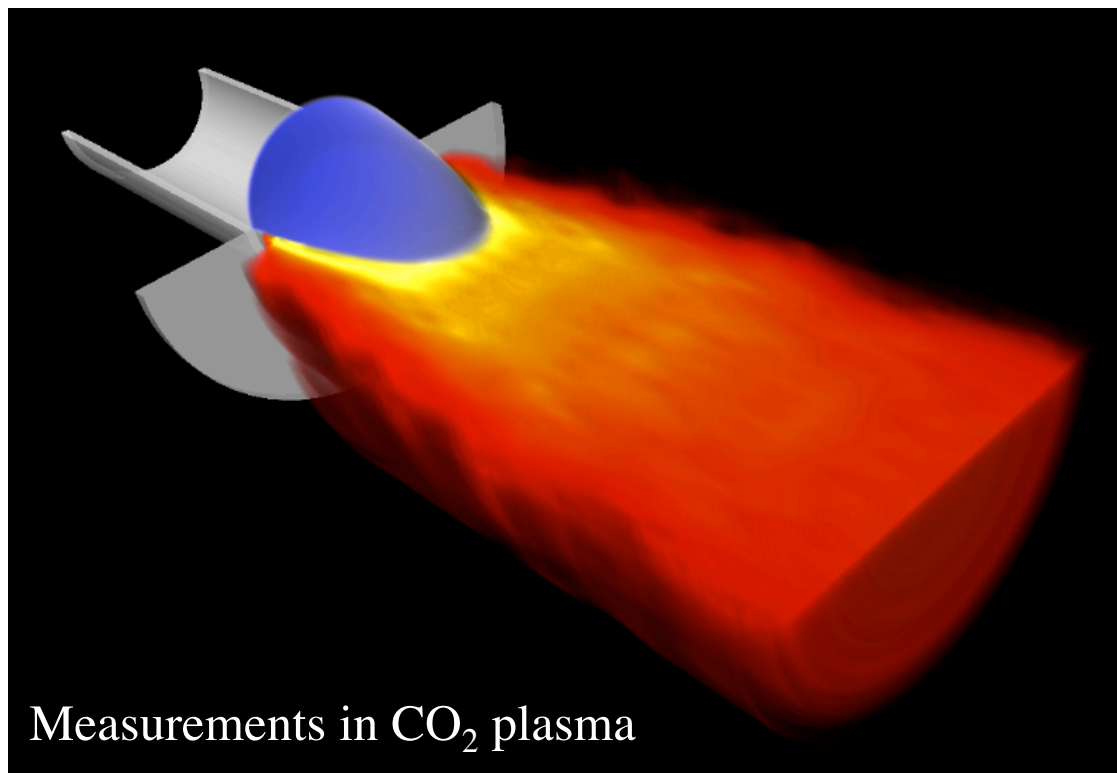
Ion beam accelerated by double layer in a magnetic nozzle

Electrostatic and Electromagnetic plasma acceleration



50 eV ion beam:
supersonic ($\geq 10 \text{ km.s}^{-1}$)
Low beam divergence
 $A_{\text{beam}} \sim 150 \text{ cm}^2$

Local downstream
plasma potential



Measurements in CO₂ plasma

The Australian Plasma Thruster (~10 cm diam)

Helicon Double Layer Thruster: HDLT

Inductive/wave heated radiofrequency plasma source

No neutraliser needed --> simple and low cost

No electrodes --> no erosion, extended lifetime

No moving parts --> safe and reliable

Choice of propellants (Xe, Ar, O₂, H₂, CH₄, NH₃, CO₂, N₂...)

Scalable in power (10 W-100 kW) and in geometry



The gutted Mount Stromlo observatory. Photo: AFP/Torsten Blackwood



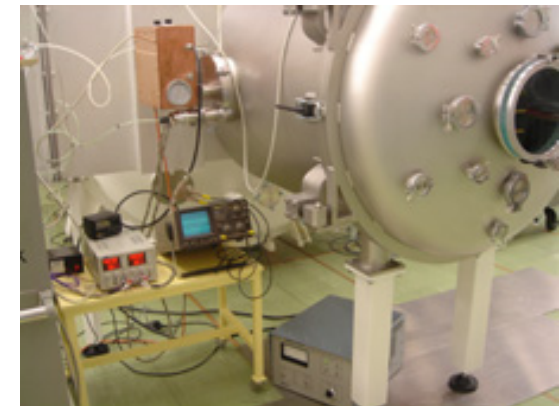
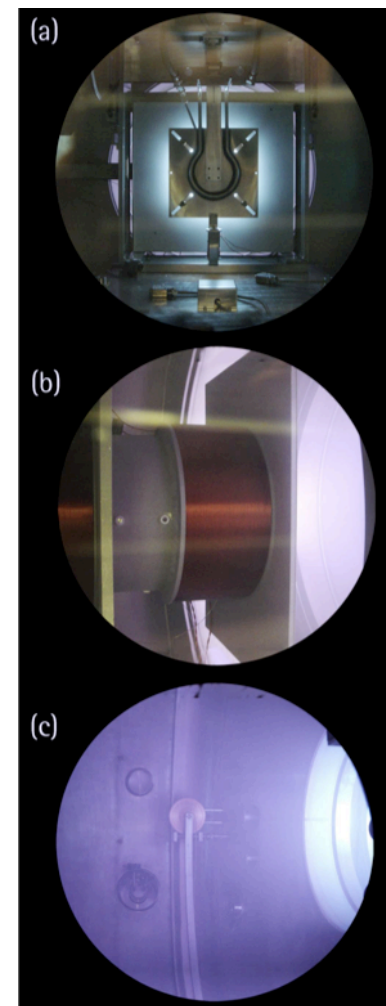
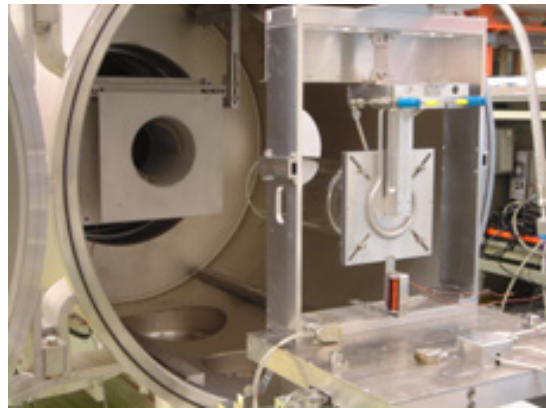
2003



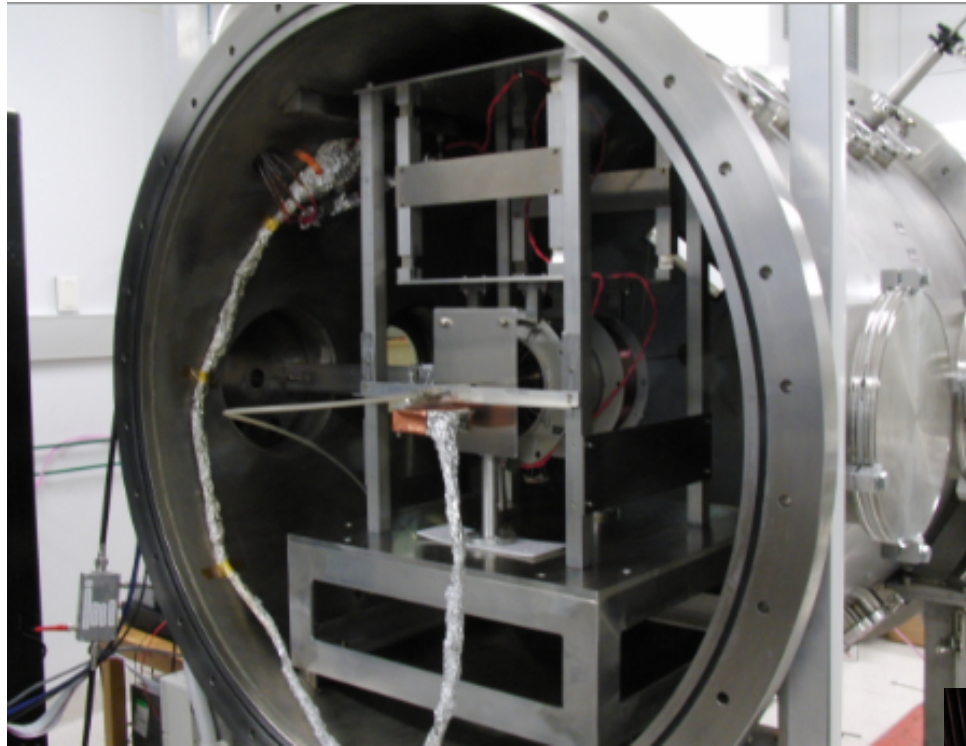
HDLT Gen I Testing Campaign at European Space Agency

April - May 2005

Xenon
1 kW
0-500 G
80 sccm



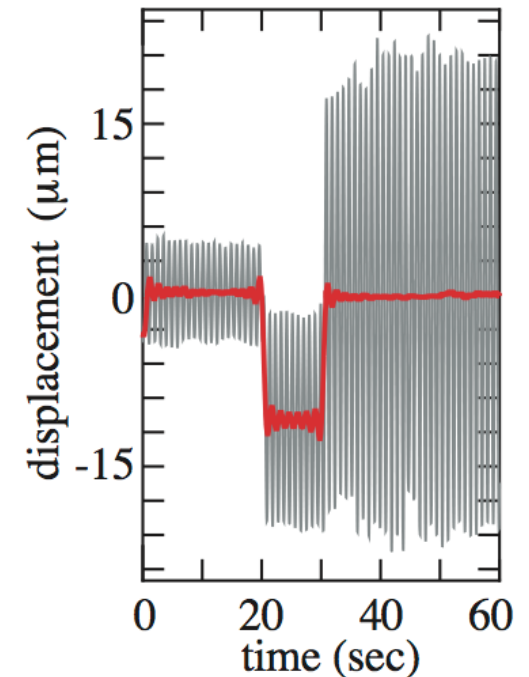
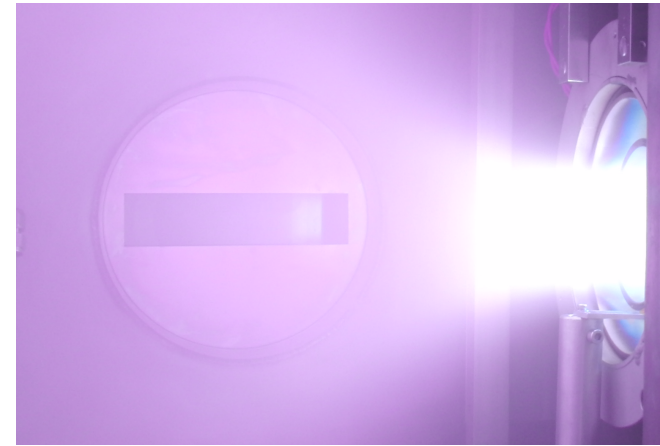
HDLT Gen II: direct thrust measurements



IRUKANDJI, Diam 1m, Length 1.4 m

Diagnostics:
Thrust balance
Langmuir Probe
Energy analyser

Consortium: Astrium (Airbus) Paris (2006)
Surrey Space Centre UK, VIPAC, ANU (2009)
Collaboration: Iwate Uni (2011), Japan
Tohoku University Sendai (2013), Japan



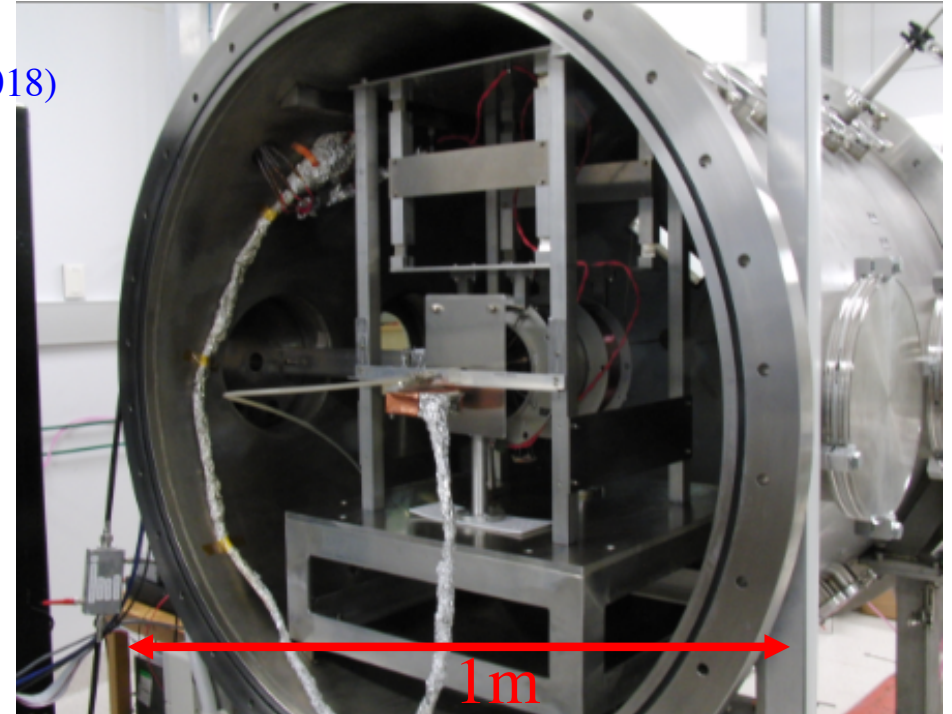
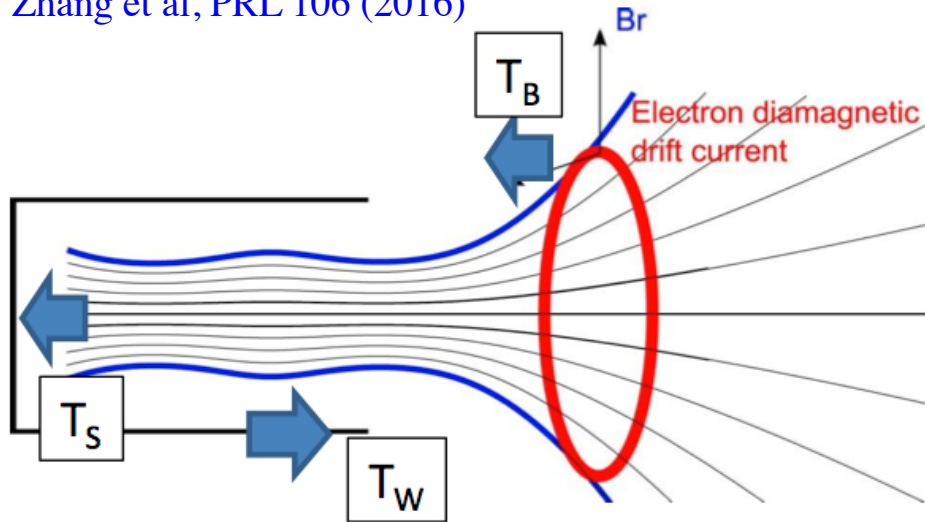
Pottinger et al, J. Phys. D, 2011
Takahashi et al, APL 2011
Lafleur et al, APL 2011
Charles et al, APL 2012

Plasma thrust components for HDLT

Worldwide collaborations (Japan, Israel, UK, France...)

Takahashi et al, Phys. Rev. Letts 107 (2011a,b), 110 (2013), 120 (2018)

Zhang et al, PRL 106 (2016)



Momentum equation in expanding magnetised plasma

$$T_{total}(z) = 2\pi \int_0^{r_s} r p_e(r, z_0) dr$$

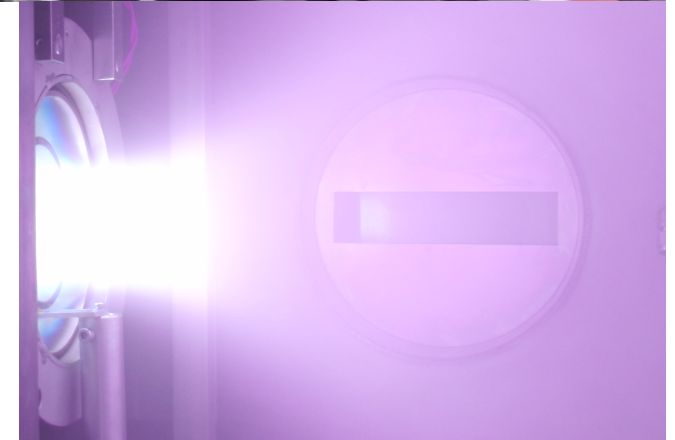
T_S

$$- 2\pi \int_{z_0}^z \int_0^{r_p(z)} r \frac{B_r}{B_z} \frac{\partial p_e}{\partial r} dr dz$$

T_B

$$- 2\pi \int_{z_0}^z \int_0^{r_p(z)} \frac{\partial}{\partial r} (r m n u_r u_z) dr dz,$$

T_W

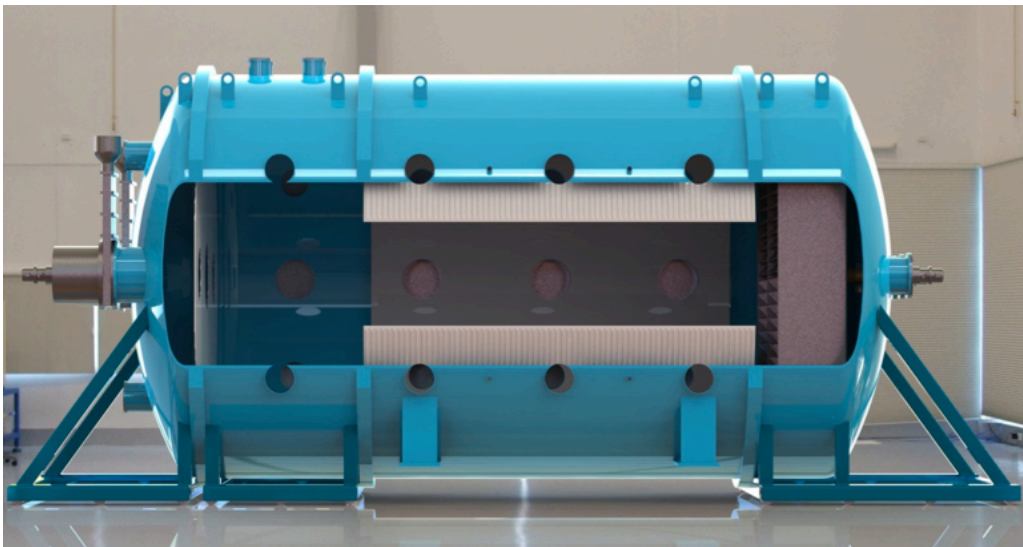


100 W ~ 1mN

AITC: Advanced Instrumentation Technology Centre

Mount Stromlo, Canberra, Australia

<http://www.mso.anu.edu.au/technology/>



APT project funded by the
Australian Space Research Program

Space (e.g. thruster qualification) & Astronomy center (e.g. Giant Magellan Telescope)
Small satellites & space payloads & astronomical instrumentation Testing



Sept 4, 2013: WOMBAT XL arrives at Stromlo

WOMBAT XL

Diameter 3 m, Length 5 m

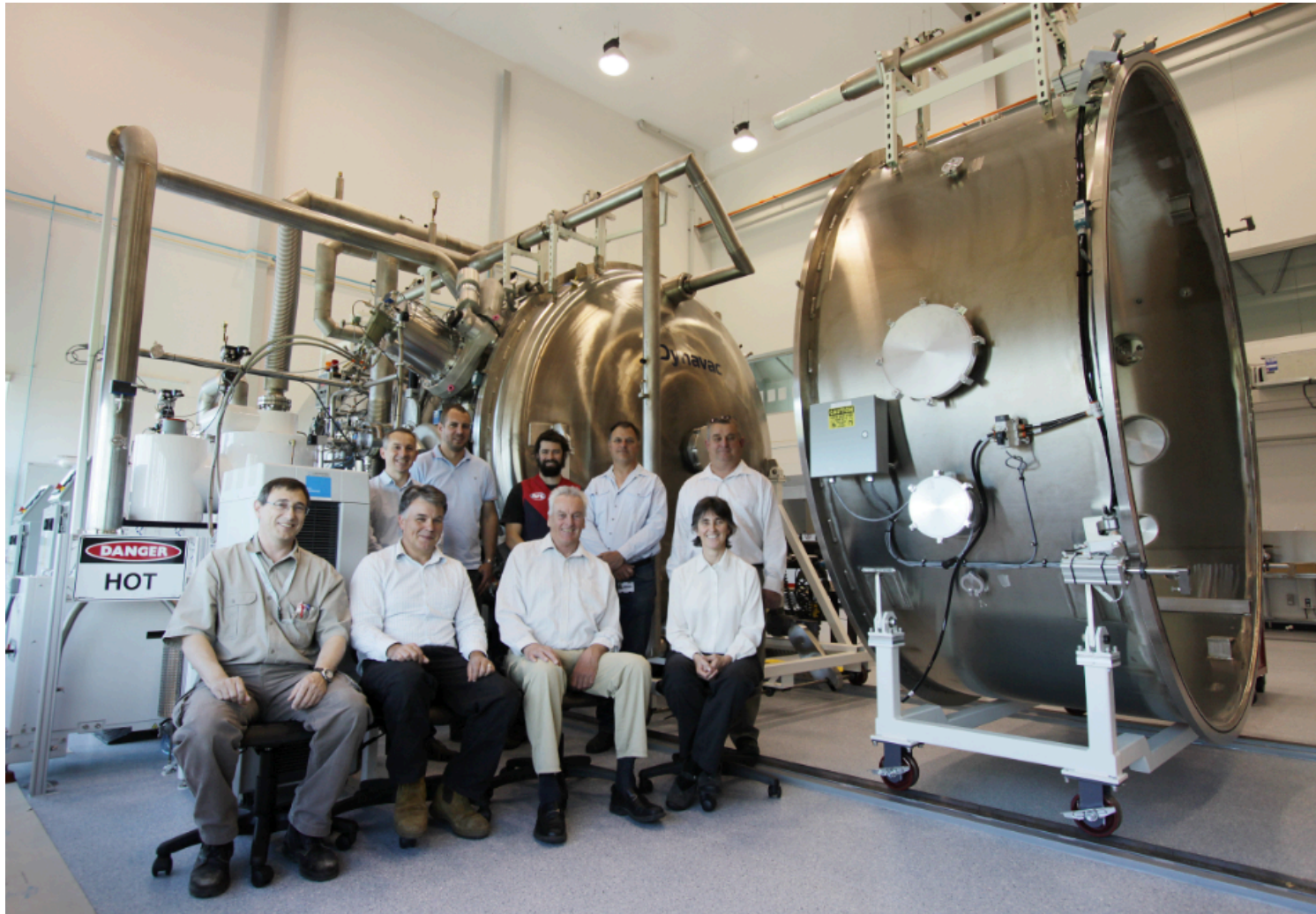
Pumping speed $\sim 140\,000\text{ ls}^{-1}$

-190 to +150 °C

Large Thermal Vacuum Chamber



The largest space simulation facility in the Southern hemisphere



Dual purpose national facility:
Thermal test configuration and Thruster test configuration

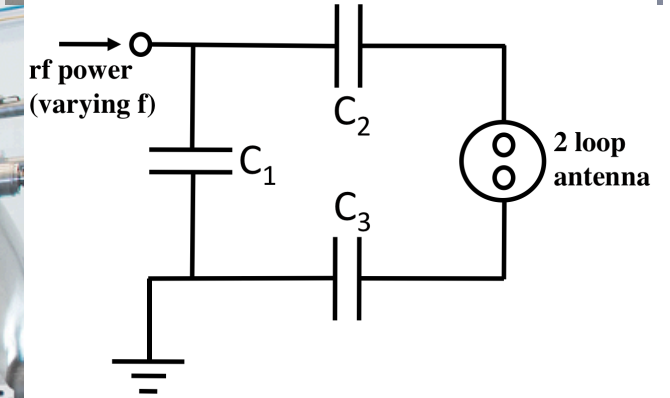
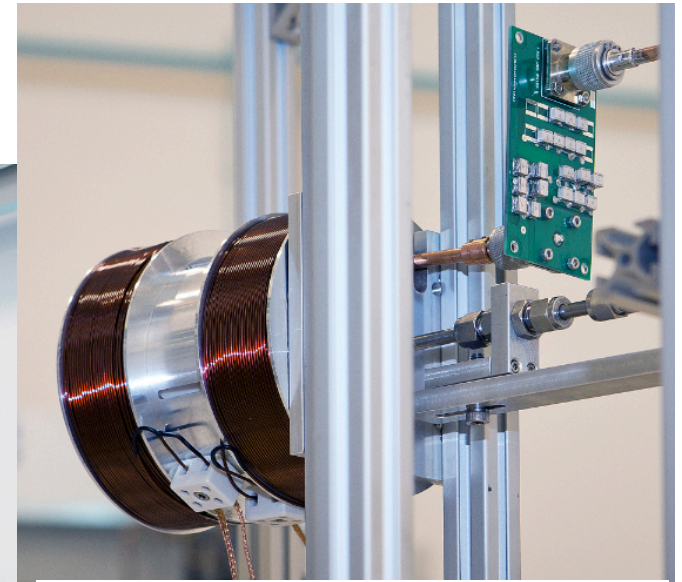
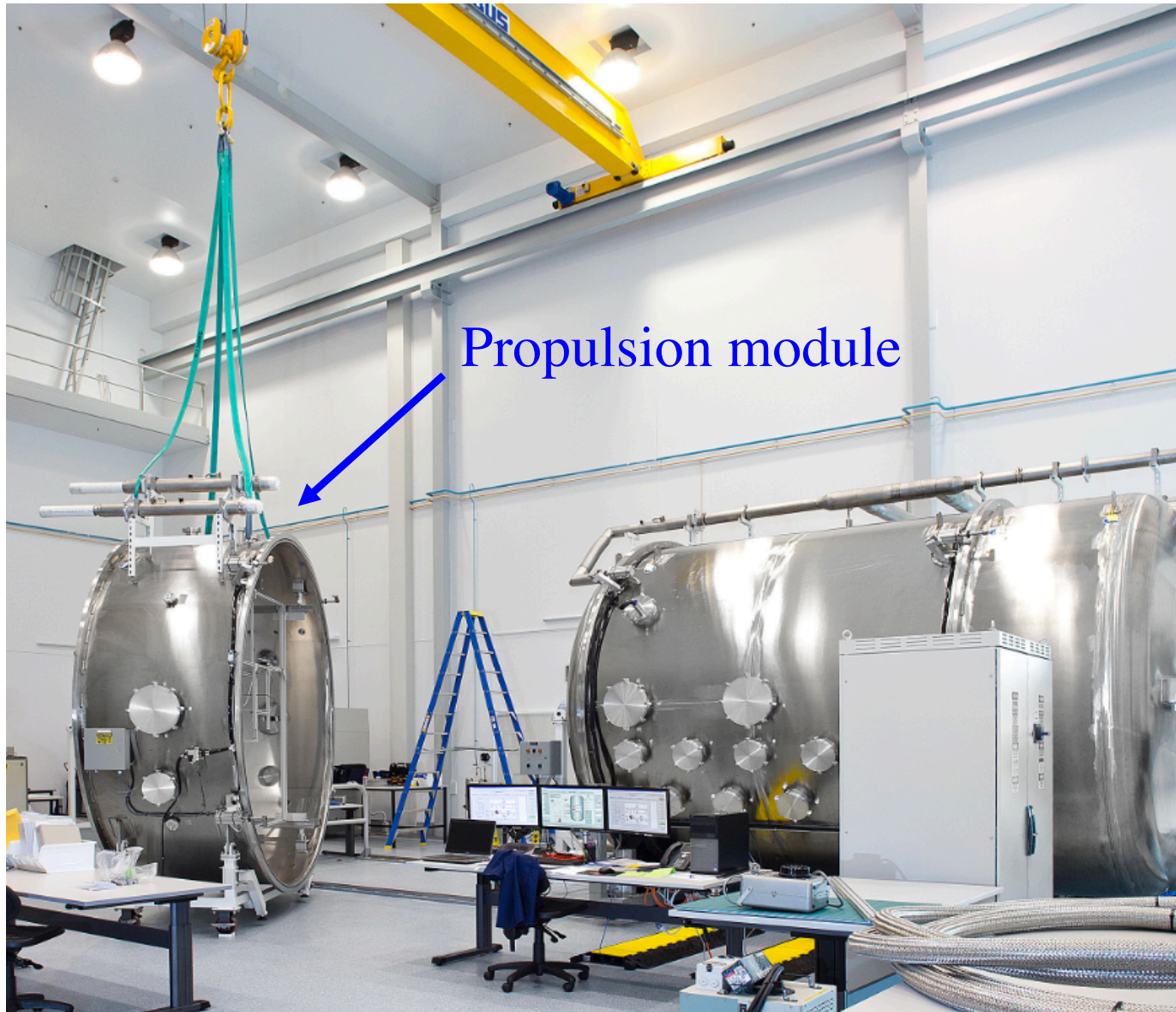
Australian thermal-vac chamber: Wombat XL

develop expertise using HDLT

key technological challenges:

thrust balance for radiofrequency thrusters with B_{field}

HDLT Gen II++



From space qualification to flight heritage

'Premium' access to space:

Expensive, Largely government funded, Fierce competition

Collaboration with major partners outside Australia

'Cheaper' access to space:

Piggy back method for cheaper access: CubeSats or arrays of CubeSats

Alternate form of funding (e.g. Kickstarter, groups of universities)

SP3 status:

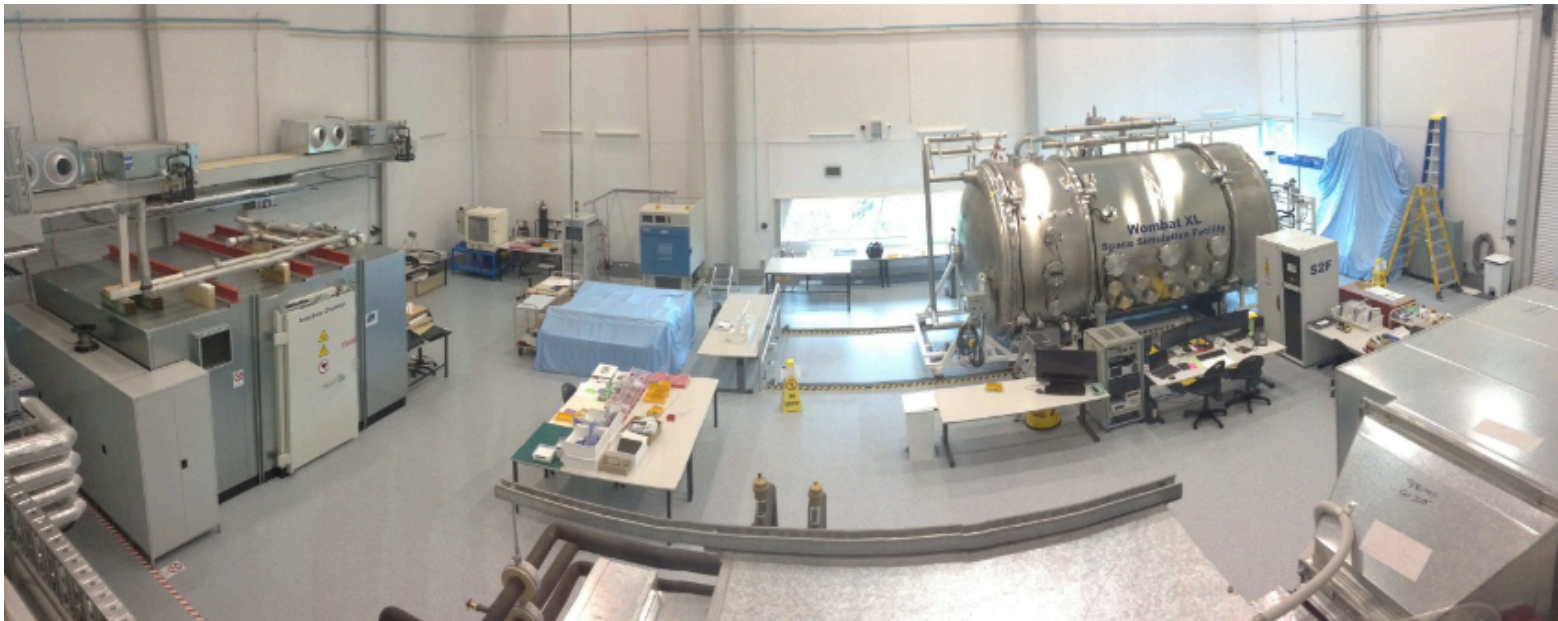
Plasma physics expertise (momentum imparted by a plasma)

Engineering expertise (rf in vacuum, thrust balance), Industry portfolio

AITC status:

Open to national and international users (officially opened on July 15, 2014)

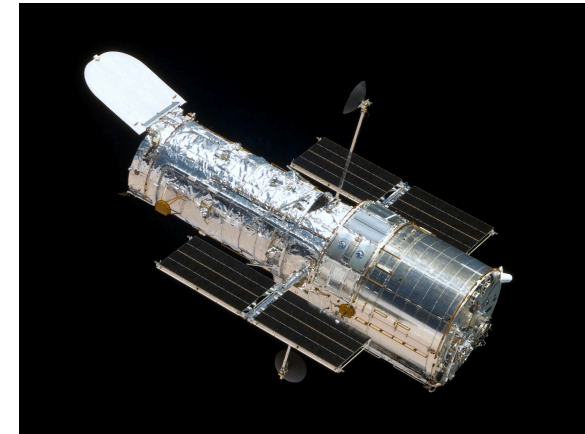
Large TV chamber, satellite shaker, clean room, anechoic chamber, labs and workshops



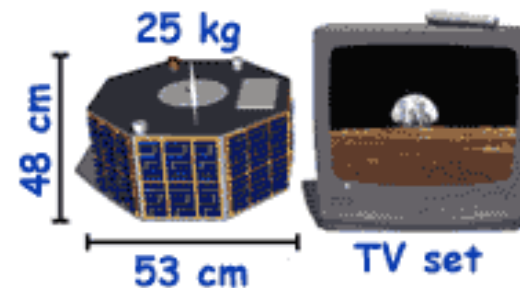
Emergence of small satellites

- Cheaper access to space
 - Less heavy
 - Launch in multiples
 - Piggyback on other missions
- Doing what larger satellites can't
 - Constellations for low data rate communications
 - Multi-point measurements
 - In-orbit inspection of larger satellites
 - Education
 - Test/qualification of space hardware
- Growing commercial space

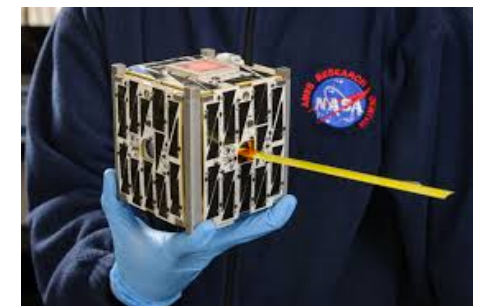
“Large satellites” >1000kg
(Hubble ~ 11 tons)



Small satellites
(broadly) <500 kg

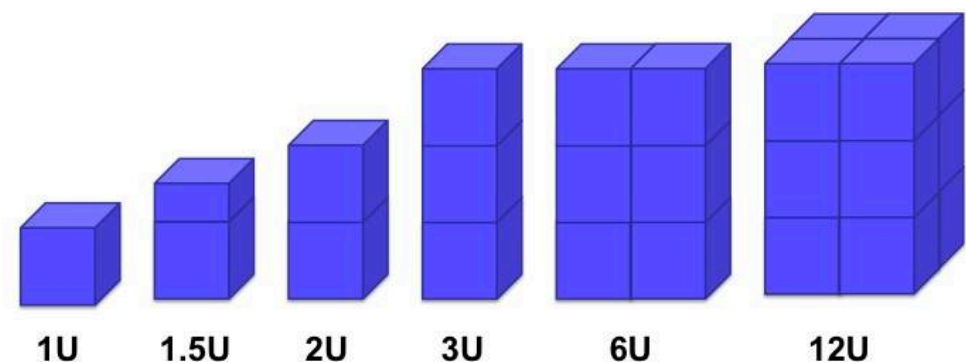
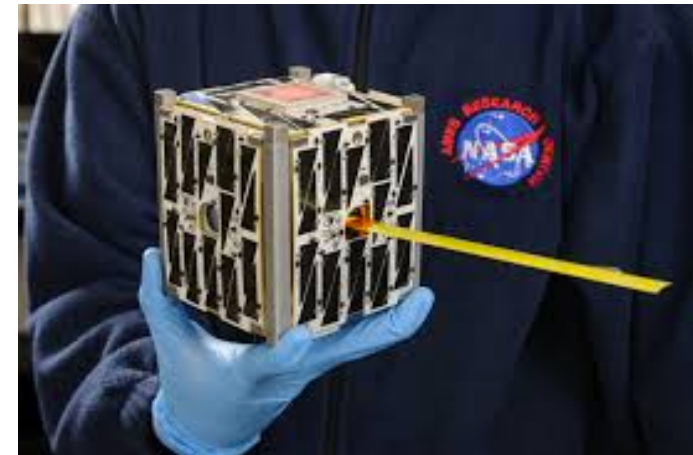


NASA
ST5



CubeSat

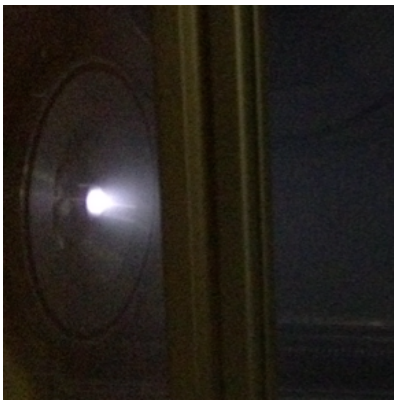
- Multiples of 10x10x10cm (1U) configurations
- Standardised format developed in late 90s at Cal Poly and Stanford
- Allows for multiples launched, deployment from ISS etc.
- Missions involving Earth observation, communications and science payloads
- MarCO CubeSats the first to leave Earth orbit on their way to Mars (May 2018)
- Over 800 launched as of April 2018
- Systems miniaturisation critical



Micro-satellite propulsion systems

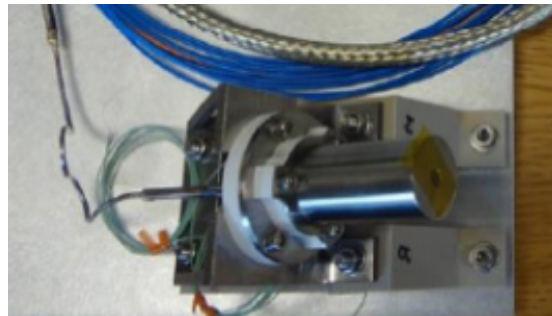
- Chemical thrusters, Small gridded thrusters, Hall effect thrusters
- Cold Gas Thruster: No heating, low I_{sp}
- Arcjet: Arc heating, erosion issues, kW, part chemical
- Resistojet: Wall heating, $10^2 - 10^3$ W
- Hollow Cathode Thruster (HCT_SSTL)
- Pulsed Plasma Thruster (STRaND-1_SSTL)
- Electrospray thruster

$$T = \frac{d(mv)}{dt}$$

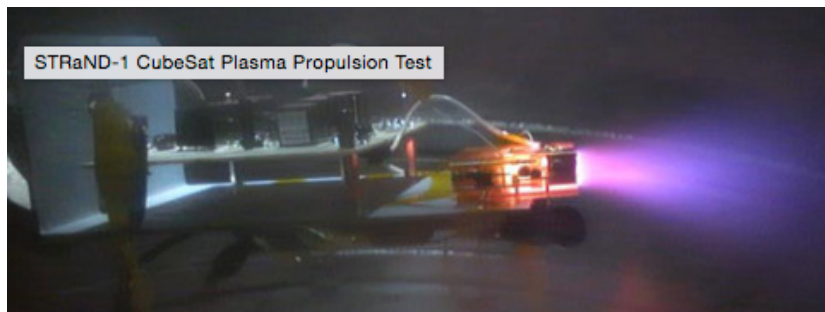


Pocket Rocket rf
plasma thruster

SSTL Hollow Cathode Thruster

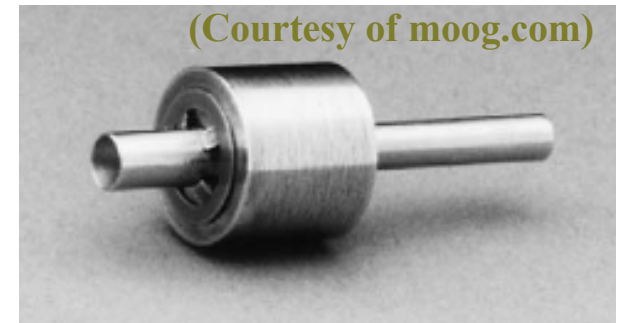


SSTL Pulsed Plasma Thruster



STRaND-1 CubeSat Plasma Propulsion Test

Cold Gas Thruster
(Courtesy of moog.com)



Busek BIT-3 RF thruster



BIT-3

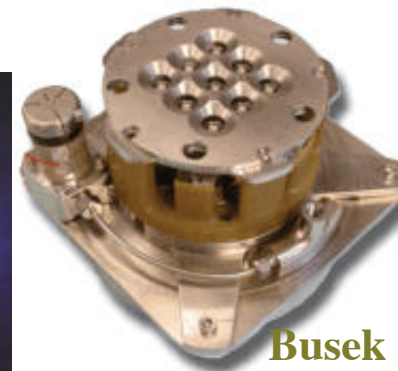
60 W

21 mA

0.4 sccm

1.4 mN

3500 sec



Busek 1mN

Electrospray: S-iEPS MIT 8 MEMS ($0.1 \mu\text{N}$)



Astrium's
hydrazine system

Pocket Rocket rf micro-thruster: PR

Low-power (**0.5-50 W**) capacitive radiofrequency plasma source at **~ a few Torr**

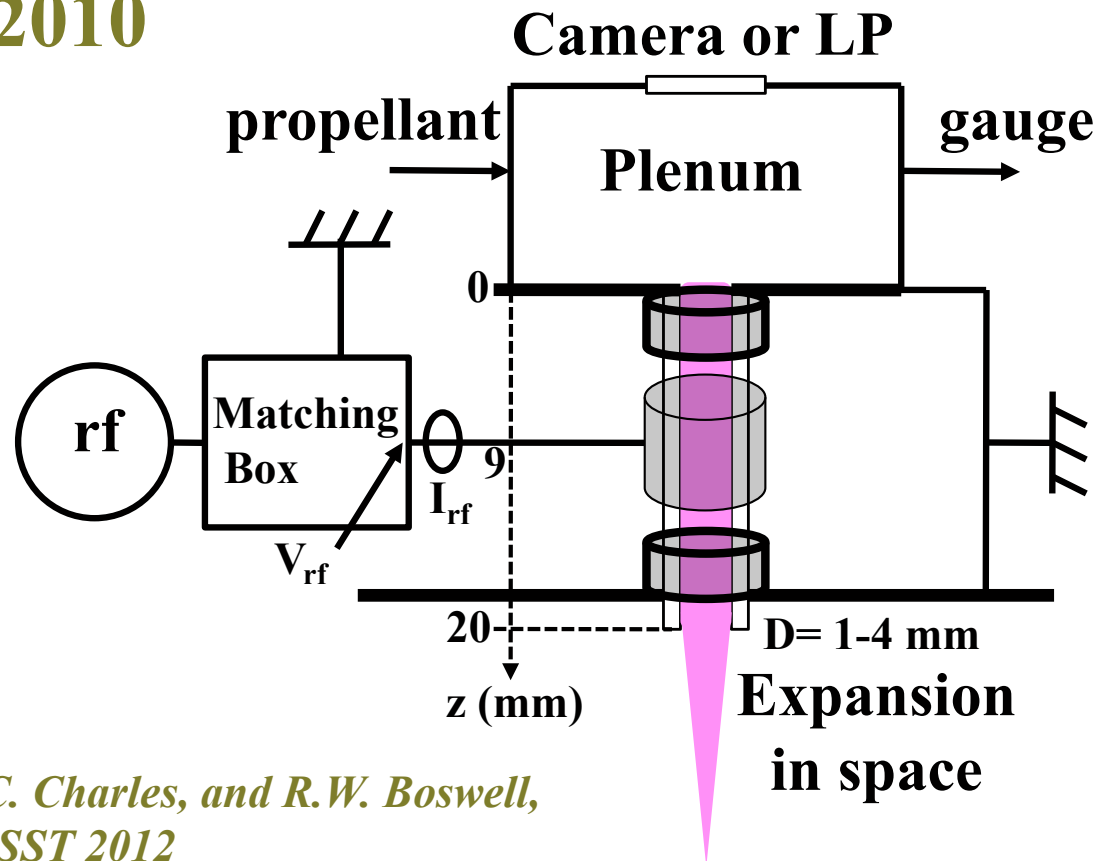
Electrothermal micro-thruster (1.5 mm diameter, 2 cm long)

Thrust from hot neutrals (ion-neutral charge exchange collisions) **~ 0.1-1 mN**

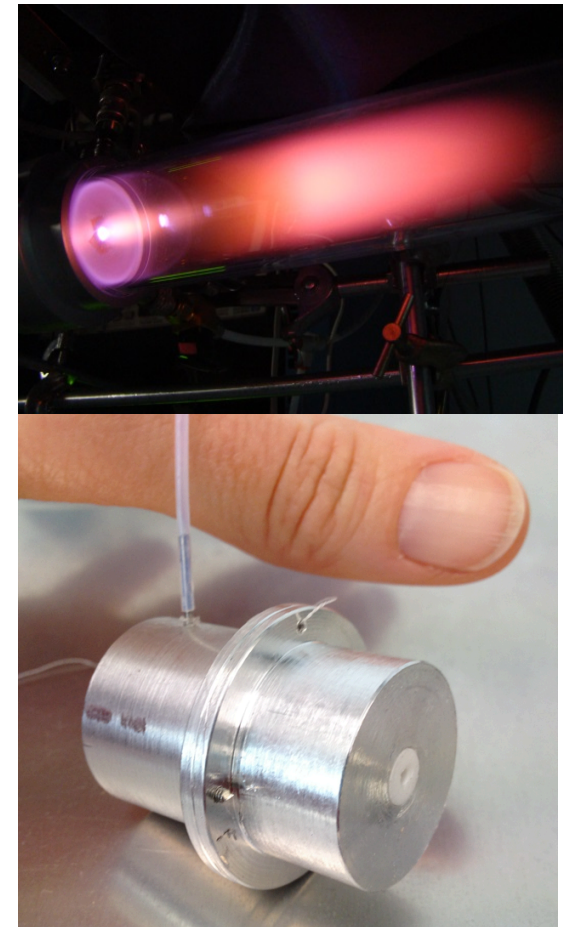
Safe, low-cost 'green' propellants (Ar, Xe), best with atomic gases

rf power subsystem and gas propellant subsystem not commercially available

2010



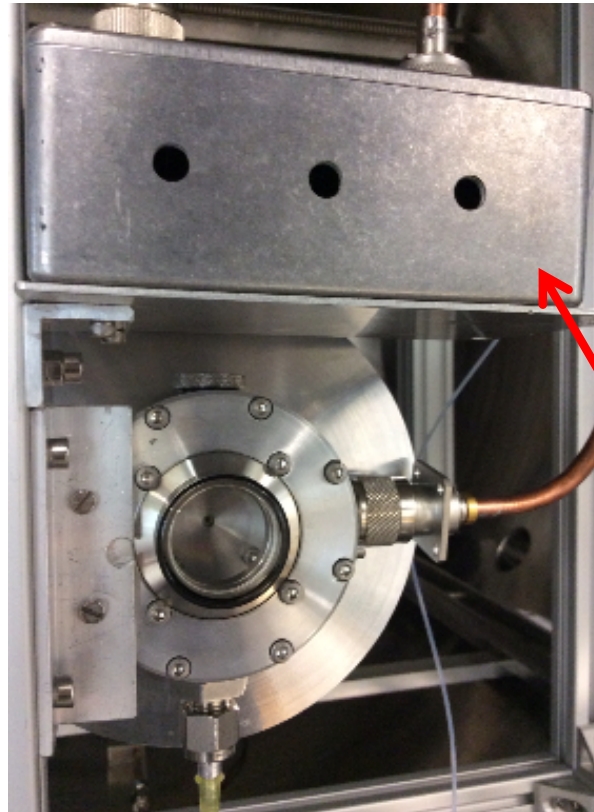
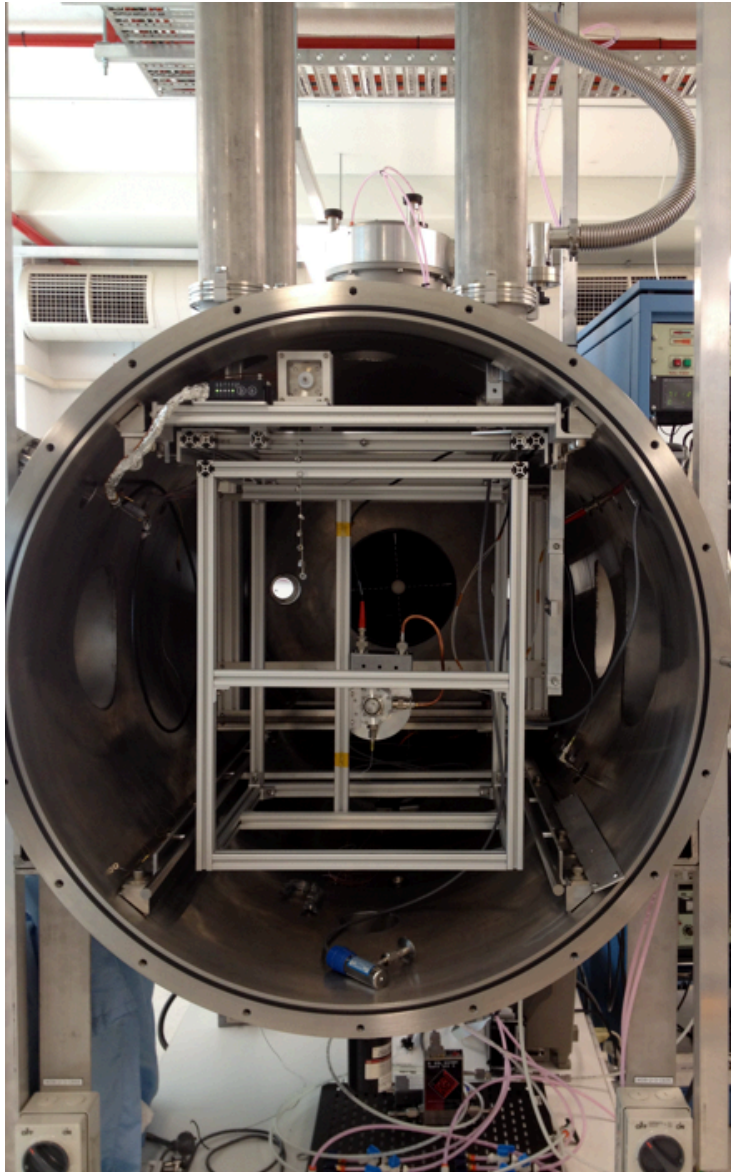
*C. Charles, and R.W. Boswell,
PSST 2012*



Pocket Rocket thrust in Wombat vacuum

C. Charles et al, JPP 30 (2014)

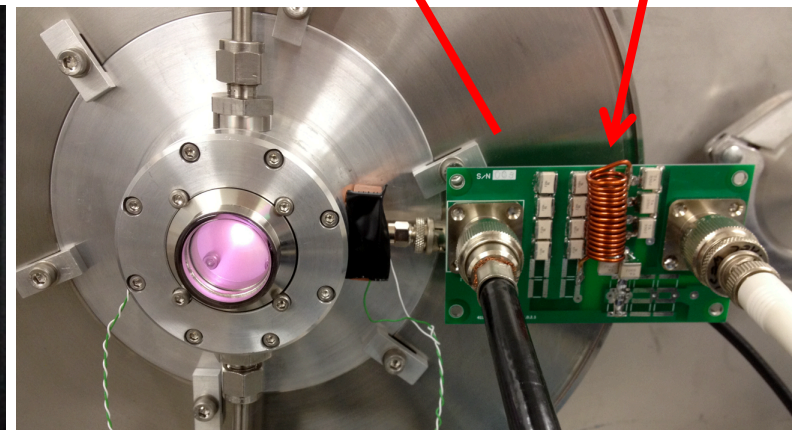
C. Charles et al, Front Phys (2016)



Mounted on thrust balance
Immersed in vacuum
Gas and rf line connected
0.1-2 mN

Partner: Lockheed Martin

Source of
Power loss



Cold gas and plasma thrust component (Xe)

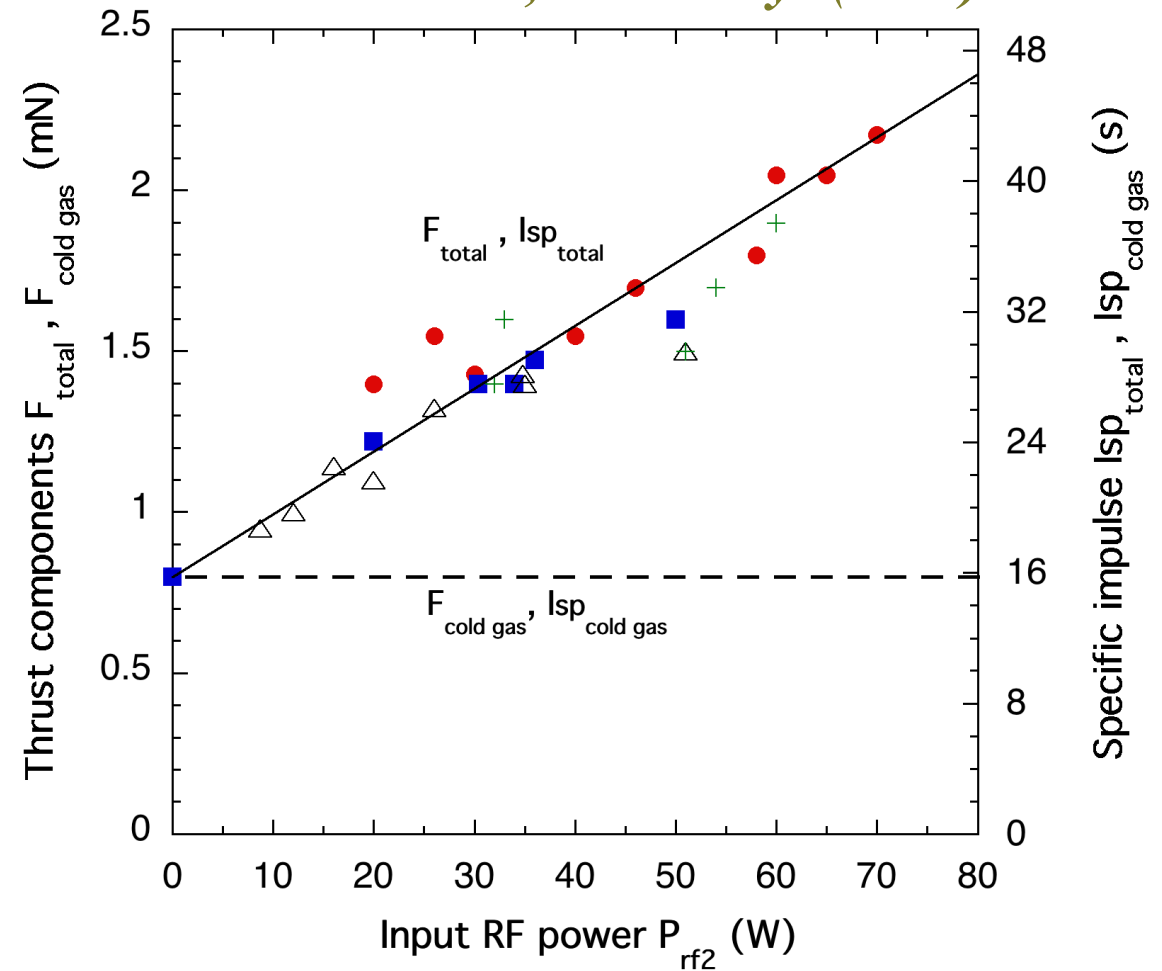
$$F_{total} = F_{plasma} + F_{cold\ gas}$$

$$F_{cold\ gas} = \dot{m}c_s$$

$$I_{sp\ cold\ gas} = \frac{c_s}{g_0}$$

$$G = \frac{F_{plasma}}{F_{cold\ gas}}$$

C. Charles et al, Front Phys (2016)



Use Xe to facilitate measurement, Large loss in PCB match

Plasma thrust gain about a factor of two

(increases for decreasing flowrate)

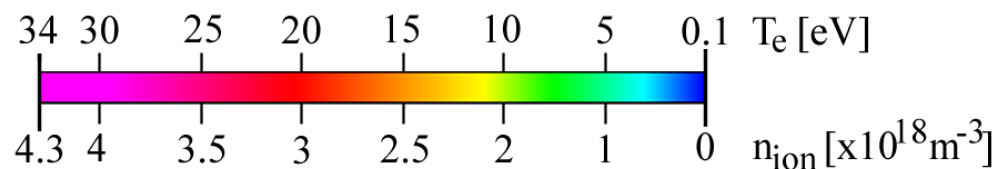
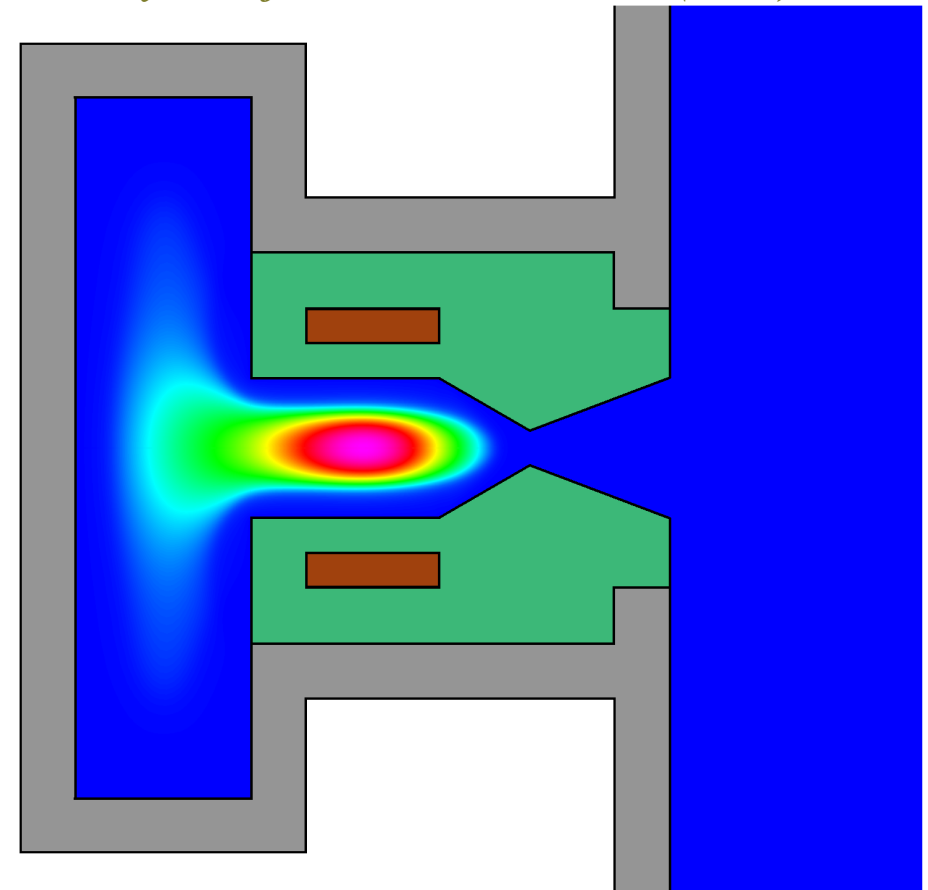
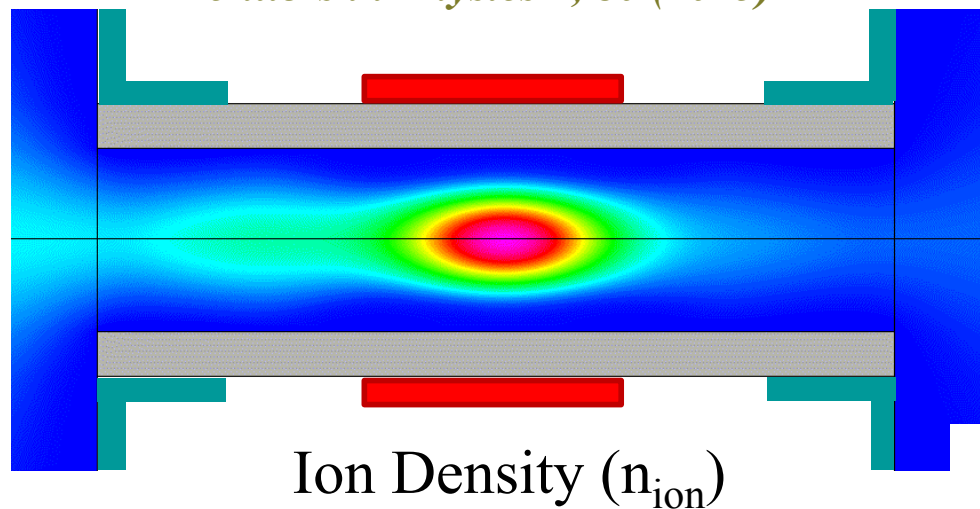
Prototype and subsystems need optimising

CFD-Ace+: Asymmetric Plasma simulation

Plasma simulation: propellant heating modelling and optimisation

*T.S. Ho, C. Charles, and R.W. Boswell,
Physics of Plasmas 24, 084501 (2017)*

*A. Greig, C. Charles, and R.W. Boswell,
Frontiers in Physics 2, 80 (2015)*



European Union QB50 CubeSat project

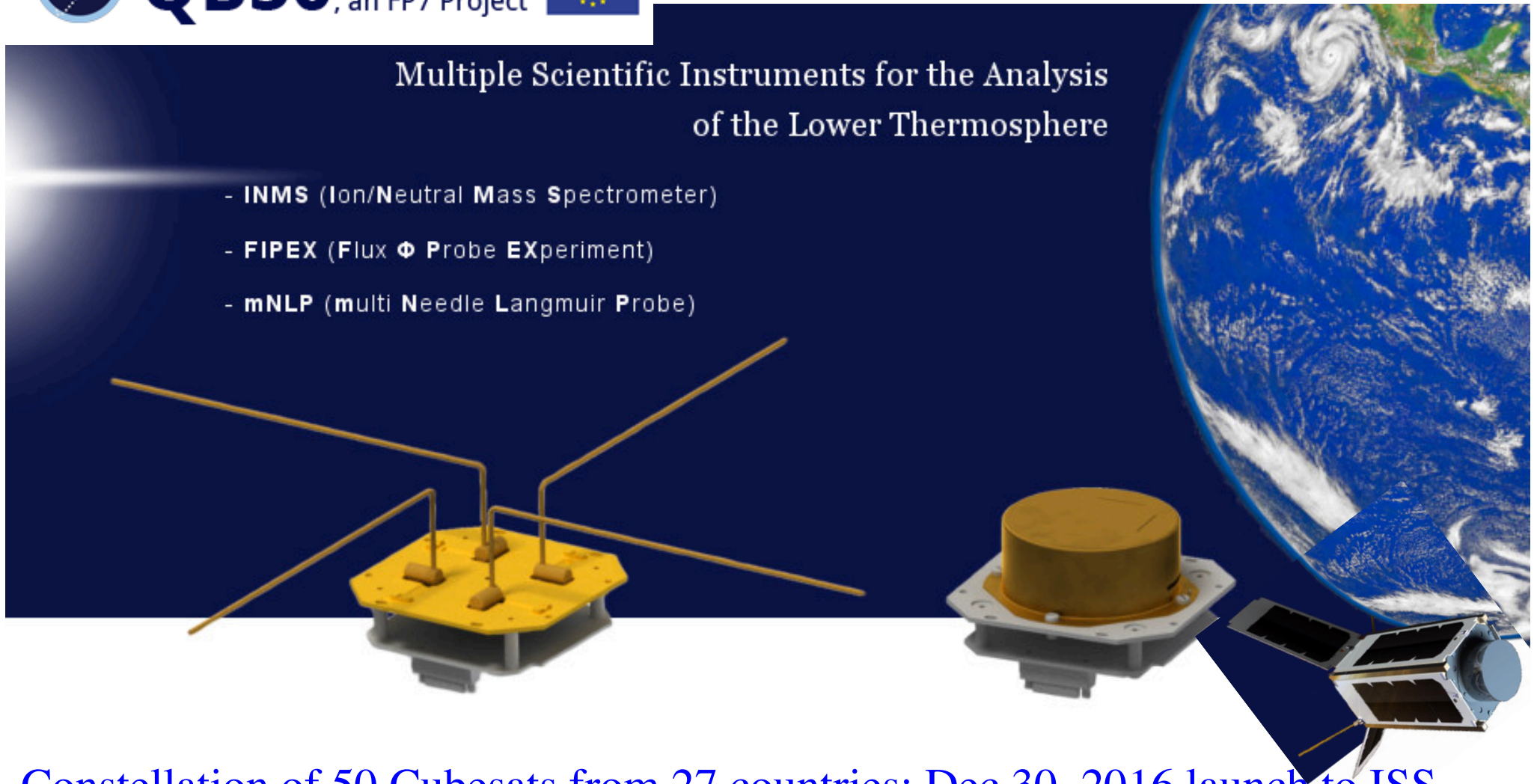


QB50, an FP7 Project



Multiple Scientific Instruments for the Analysis
of the Lower Thermosphere

- **INMS** (Ion/Neutral Mass Spectrometer)
- **FIPEX** (Flux Φ Probe EXperiment)
- **mNLP** (multi Needle Langmuir Probe)

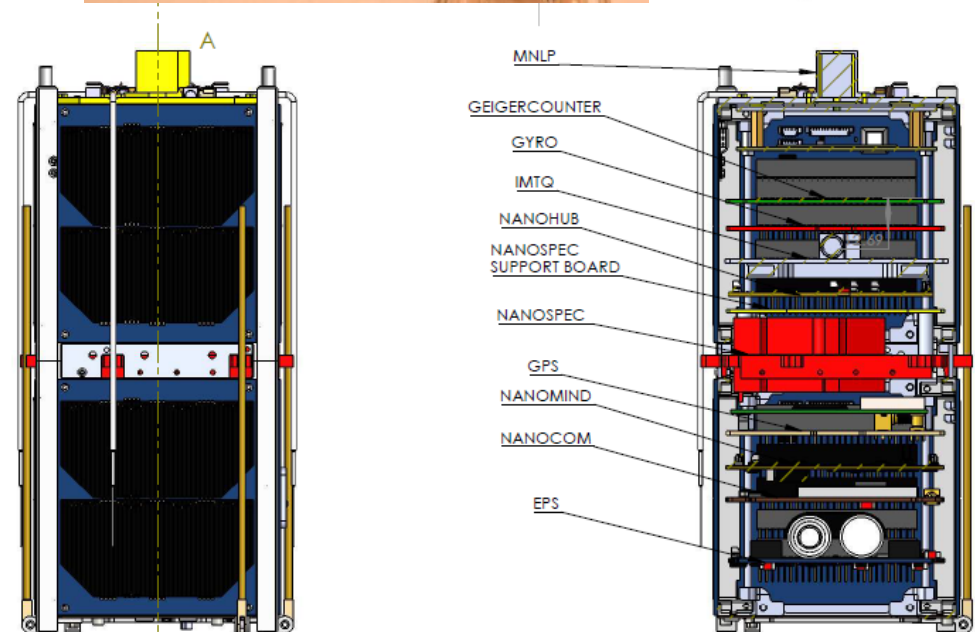
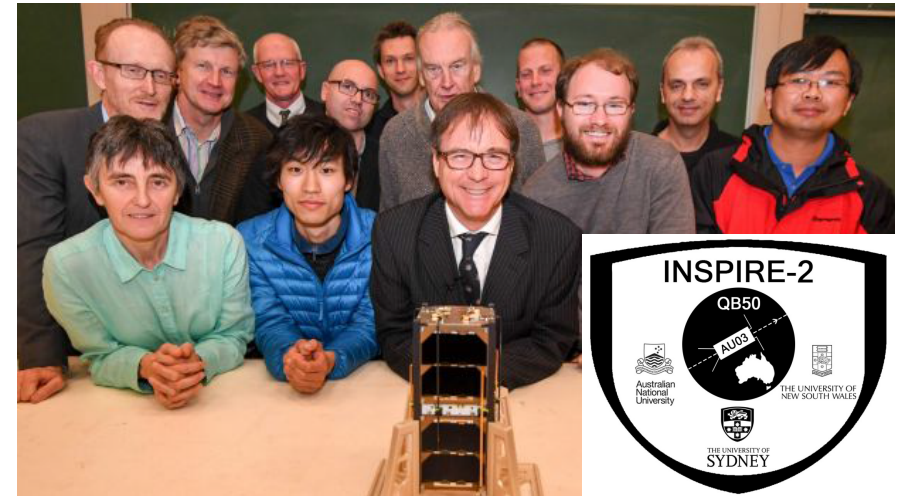


Constellation of 50 Cubesats from 27 countries: Dec 30, 2016 launch to ISS
Jan 2017 release from ISS, 1-2 year orbit, 'open source' www.qb50.eu

1- Lower thermosphere, ionosphere of the Earth

2- 'plasma & gas' sensors INMS (MSSL), mNLP (Oslo), FIPEX (Dresden)

- Originally assigned to University of Sydney
- Became a collaboration between ANU, UNSW and USyd
- Multi-Needle Langmuir Probe
- Built in Sydney based off the design of AU02 (UNSW-ECO)
- Tested in thermal vacuum chamber and vibration table (Stromlo)



Nano-satellites: a path towards flight heritage

University project: from TRL 6 to 9 ?

TRL 9

- Actual system “flight proven” through successful mission operations

TRL 8

- Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 7

- System prototype demonstration in a space environment

TRL 6

- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5

- Component and/or breadboard validation in relevant environment

TRL 4

- Component and/or breadboard validation in laboratory environment

TRL 3

- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2

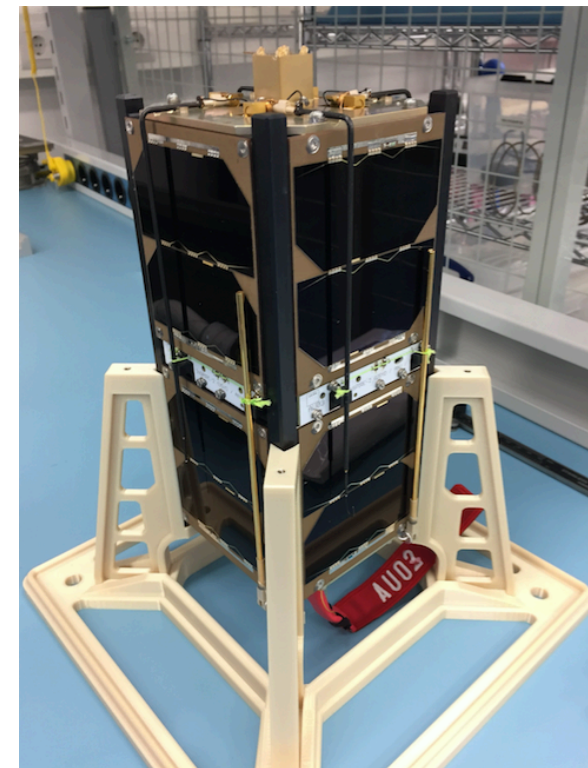
- Technology concept and/or application formulated

TRL 1

- Basic principles observed and reported

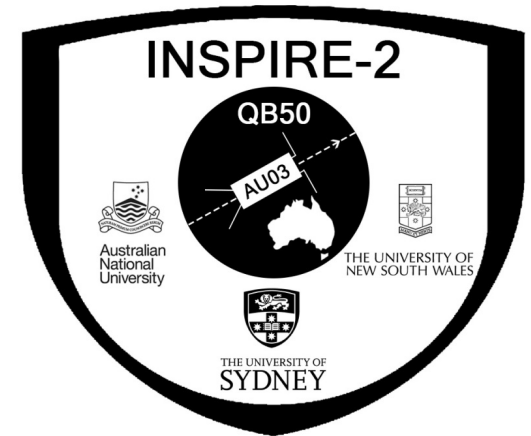
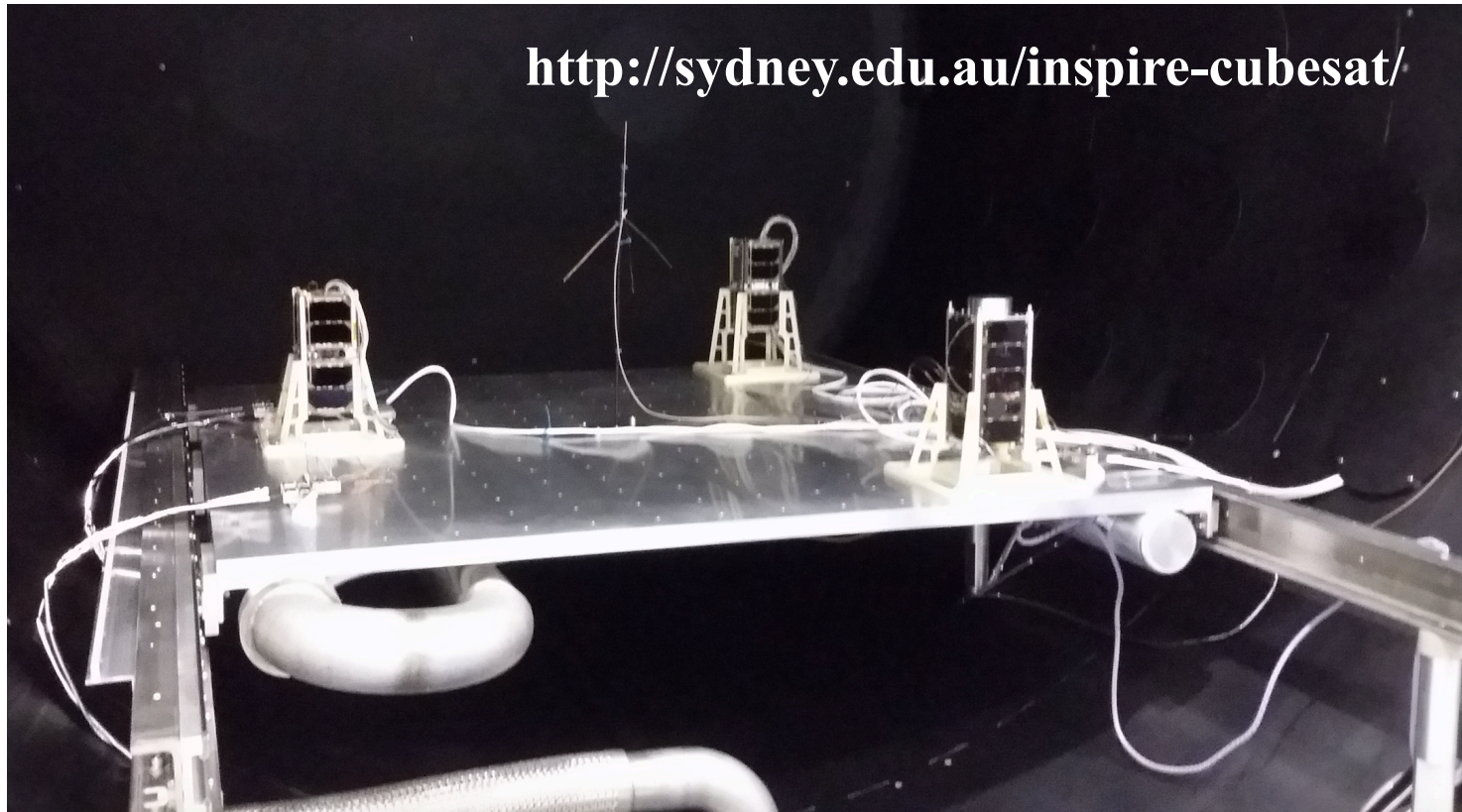
Miniaturisation
Low cost
Innovation

Baseline



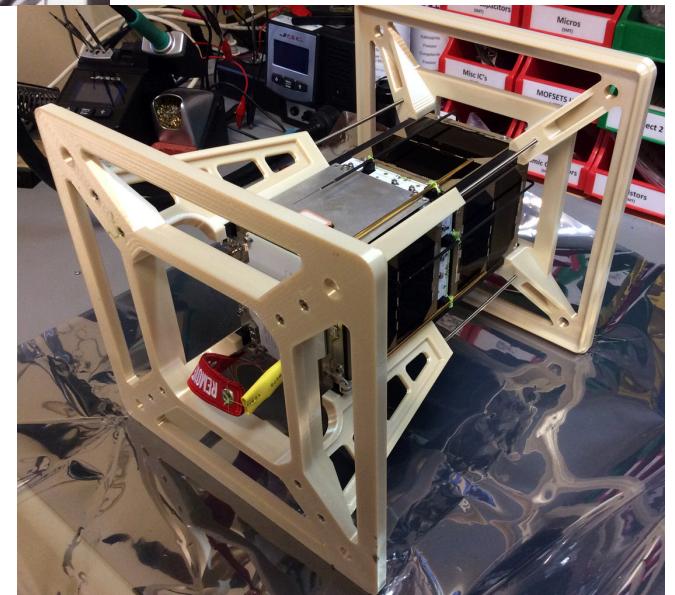
INSPIRE-2: a 2 U qb50 CubeSat
<http://sydney.edu.au/inspire-cubesat/>

QB50 Australian final Testing in Wombat XL



INSPIRE-2: 30th september 2015,
Wrapped and shipped to Europe
Flight-ready on 19th august 2016
6 months wait, launched May 2017

Disruptive technology & Need of propulsion unit

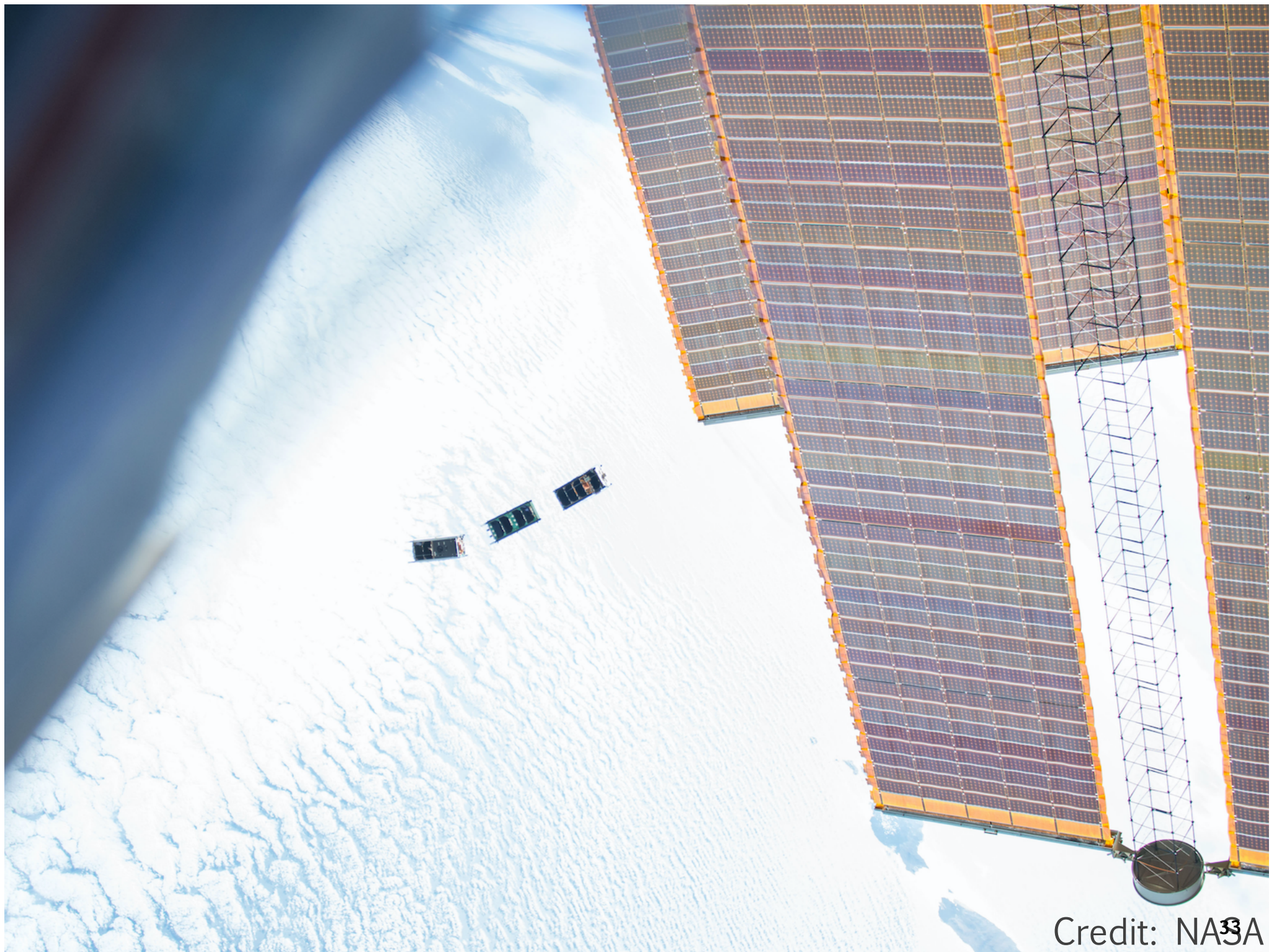


**Launch to the ISS: 19 April 2017
(rescheduled from ... 30 December 2016 ...
9, 22, 24, 27 March 2017, ... 18 April 2017...)**



**ROCKET LAUNCH: UNITED LAUNCH
ALLIANCE ATLAS V CYGNUS OA-7/CRS-7**

With AU01, AU02, AU03, Biarri-Point → 4 Australian CubeSats
Wait some more before deployment in to orbit by Nanoracks



Credit: NASA

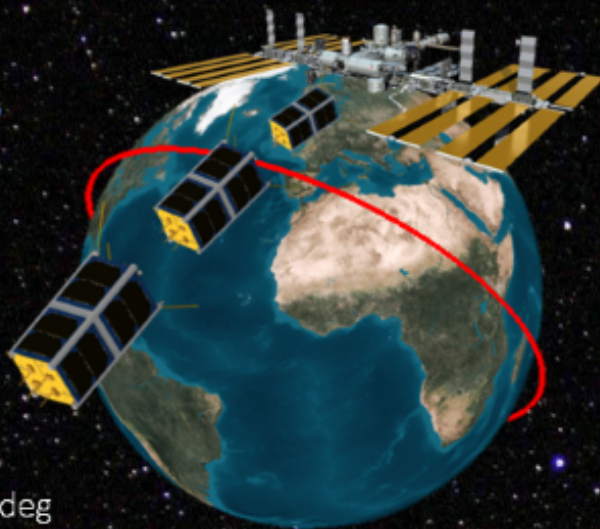
QB50: two space launches

28 CUBESATS LAUNCHED FROM THE INTERNATIONAL SPACE STATION



QB50-ISS

- 28 CubeSats
- Altitude 415km
- Inclination 51.6deg
- Launched on 18th April 2017
- Atlas-V Rocket from Cape Canaveral (USA)
- Deployed from the ISS in May 2017



ISS

8 CUBESATS LAUNCHED ON THE PSLV INDIAN ROCKET



QB50-PL

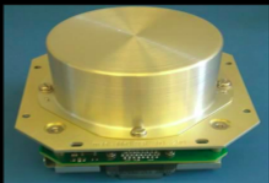
- 8 CubeSats
- Altitude 500km
- Sun Synchronous Orbit 97.1deg
- Part of the Science Campaign
- Launched on 23rd June 2017
- PSLV Rocket from Satish Dhawan Space Centre



PSLV

- Access: Give opportunities for space access to small companies and universities
- Education: Help facilitate student involvement in space systems engineering
- Science: In-situ measurement of the thermosphere using m-NLP and INMS

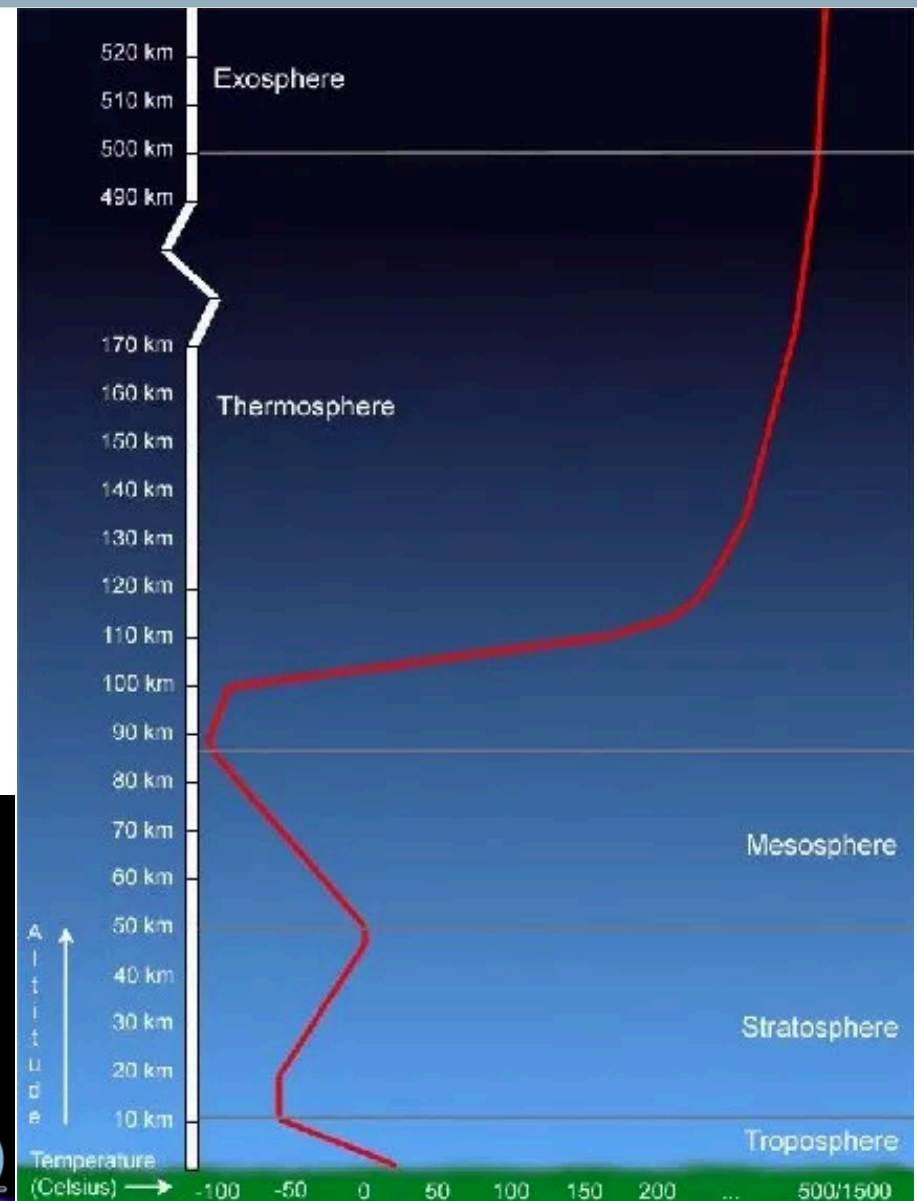
10 INMS – Ion/Neutral
Mass Spectrometer



14 FiPEX – Flux Probe
EXperiment

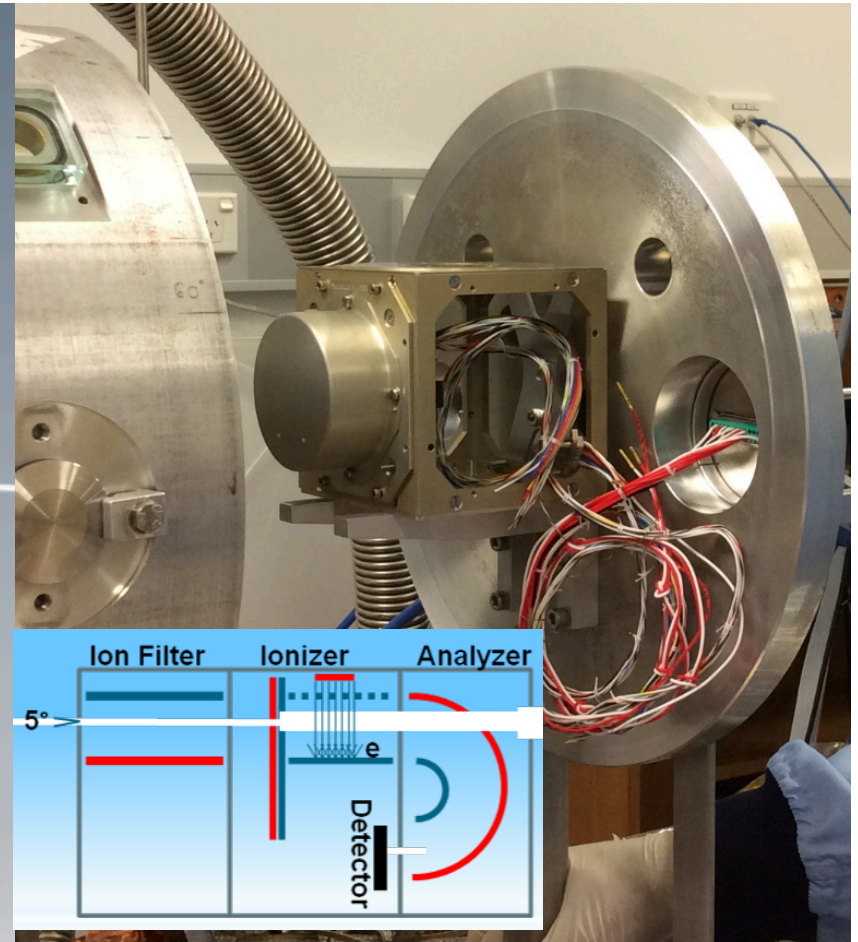
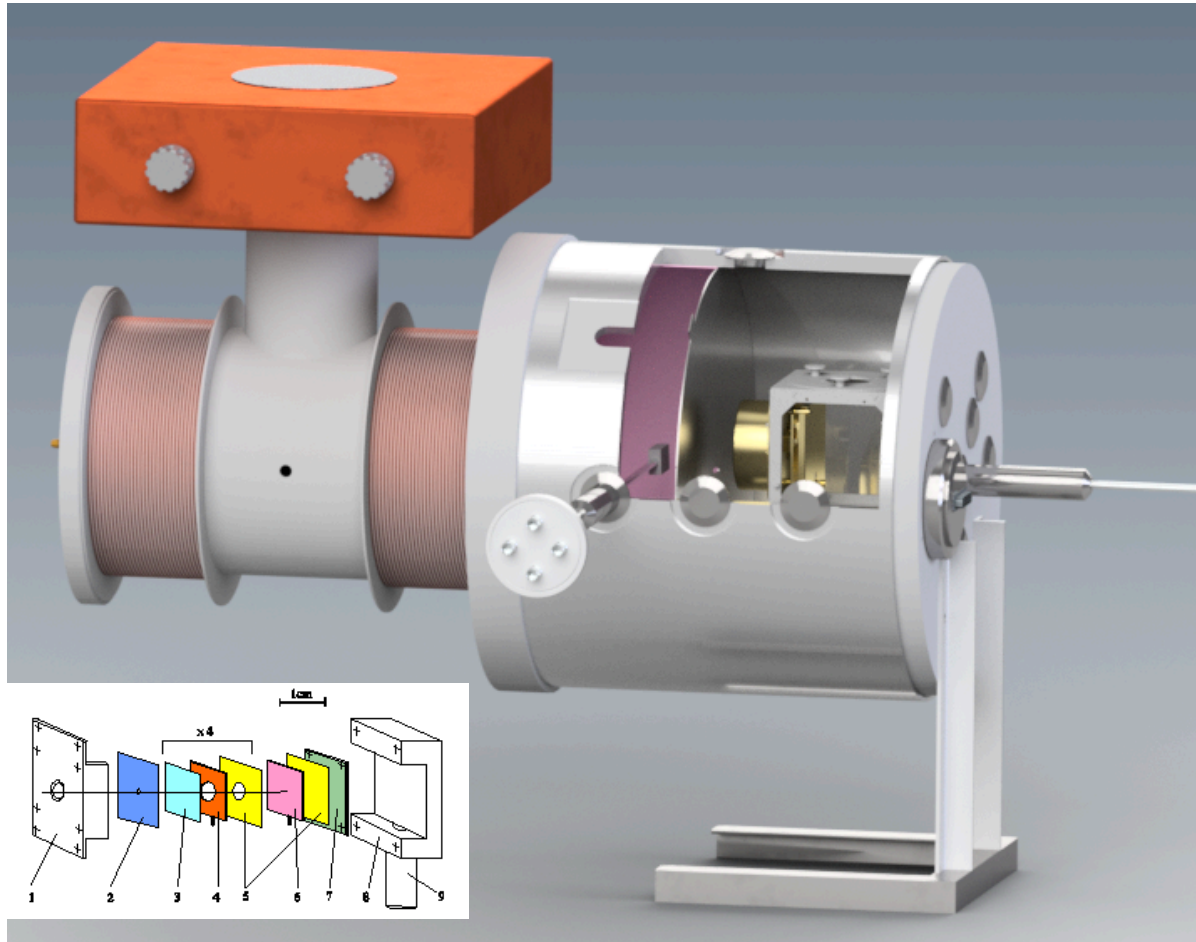


10 mNLP – multi Needle
Langmuir Probe



QB50 INMS testing in ANU ChiKung plasma wind tunnel experiment

Collab with Dhiren Kataria



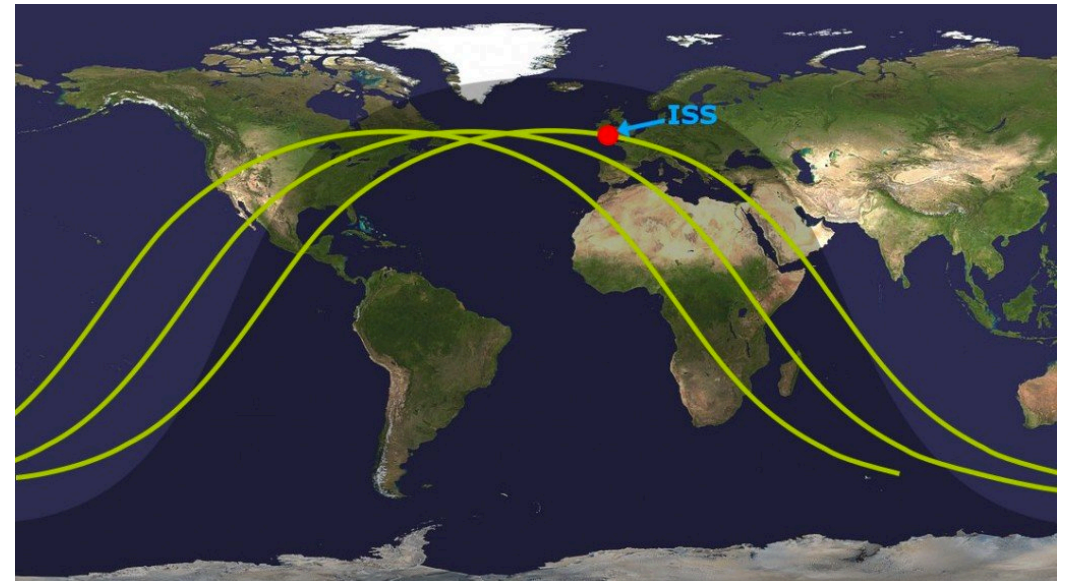
Ion analyser (RFEA) & baffle:
fast ions & neutrals (~ 10 km/s) & immobile
satellite

UCL INMS sensor (12QB50s)
QB50 Flight prototype (UK)
immobile ions & satellite at
 ~ 8 km/s

Ground-based low ion beam energy calibration < 100 eV / physics (PHOENIX)

The need for ground stations

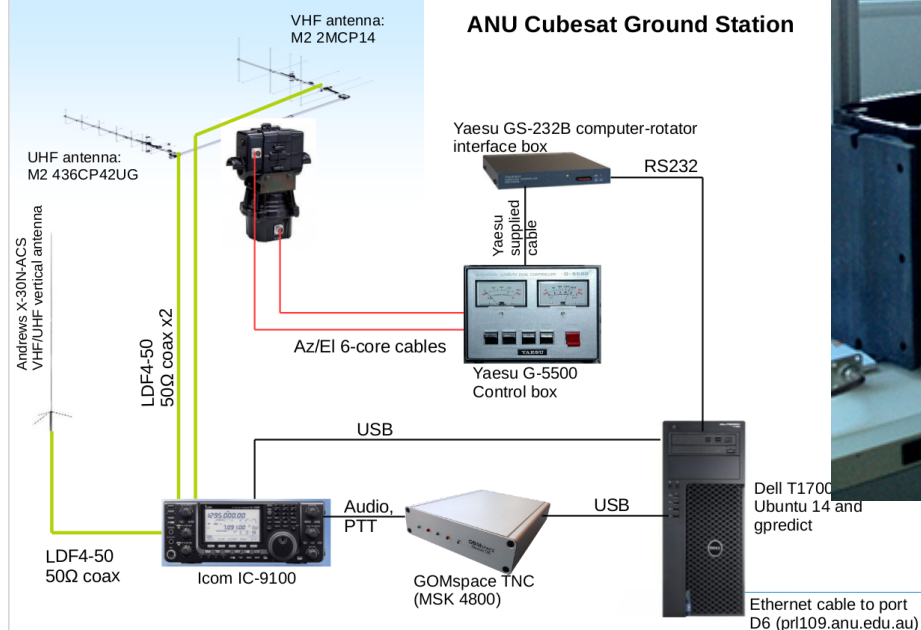
- Typical orbit altitudes for LEO are ~410-500km
- Expected lifetime of 1-1.5 yrs if starting at 400km (no onboard propulsion)
- Orbital velocity ~8km/s
- Results in two or three ~10 min passes per day for a given location (inclination dependent)
- Need many ground stations around the world to make the most of your CubeSat





Australian
National
University

“Blue Wren” ground station (ANU)



Azimuth and
elevation
control

GOMspace
TNC

Dimitris

Radio

PC

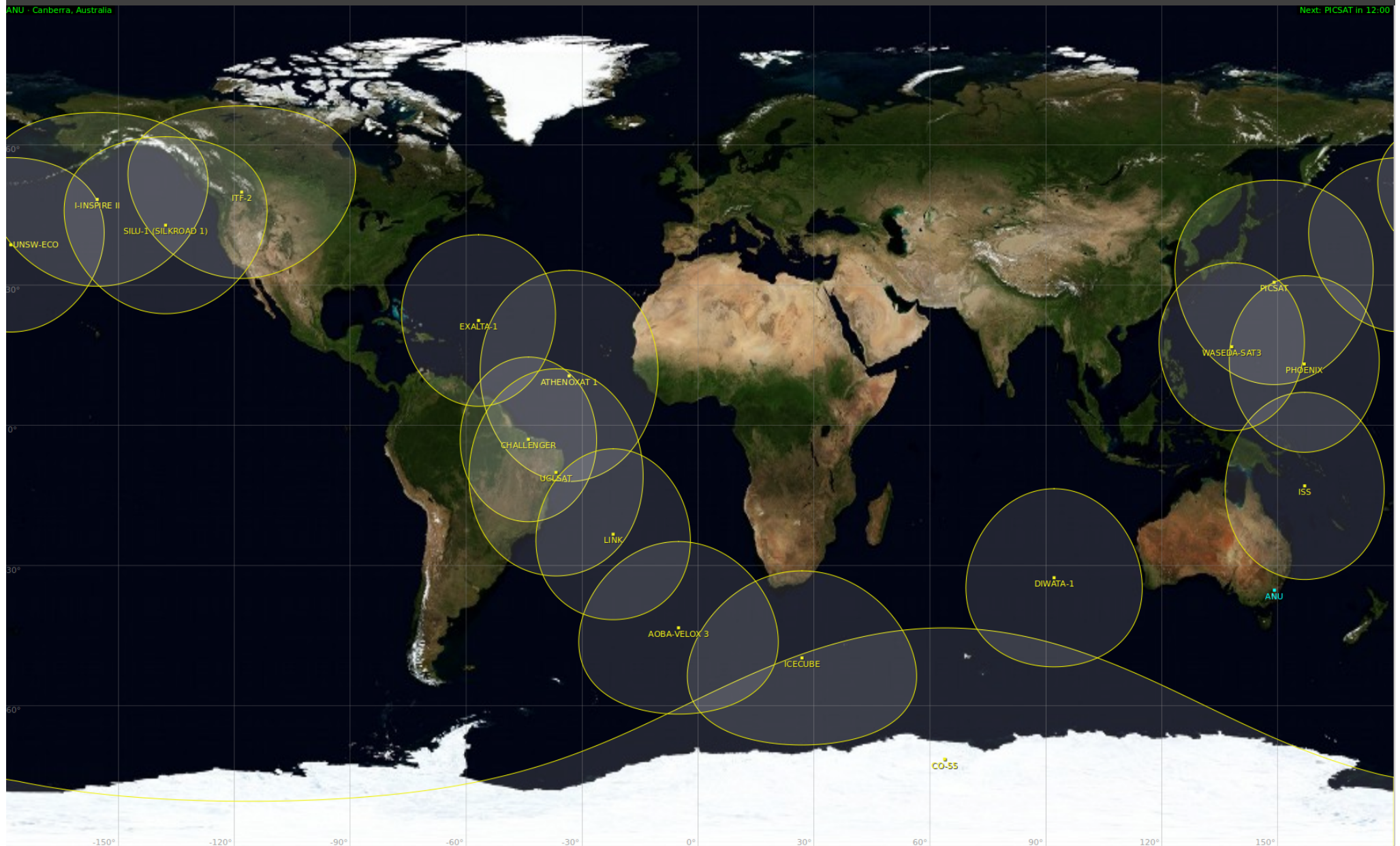


Australian
National
University

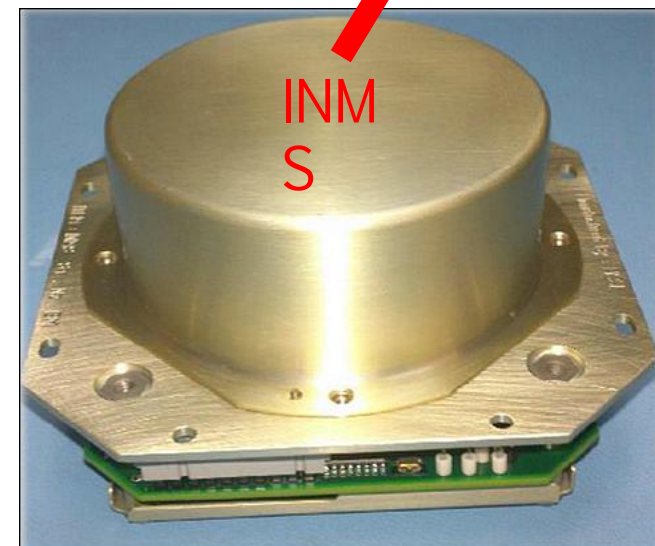
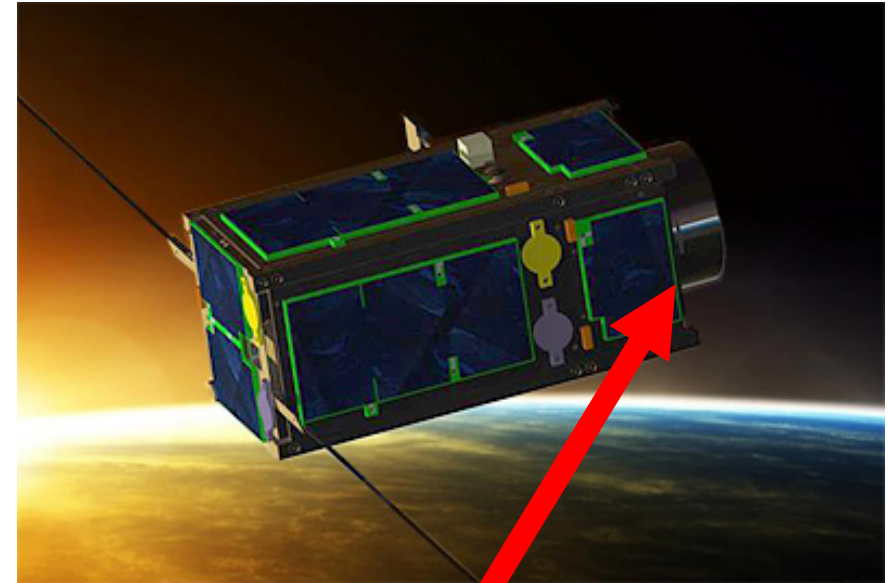
QB50 satellites

ANU - Canberra, Australia

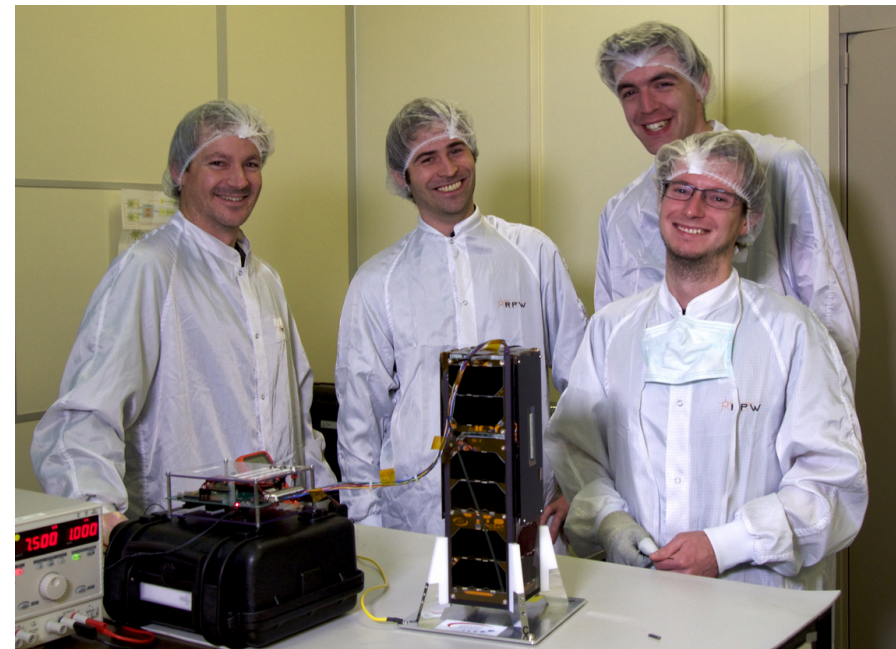
Next: PICSAT in 12:00



- One of the only QB50 CubeSats still functional
- Built by a team of students from Cheng Kung University (Taiwan)
- Instruments:
 - INMS
 - Thermistors
 - Solar EUV sensors
- Ongoing communications with ANU ground station
 - Schedule data broadcast
 - Automated ground station



- Non QB50 CubeSat from LESIA Laboratory (Paris Observatory)
- Point camera at known location of young exoplanet of young star Beta Pictoris
- Excellent engagement with amateur radio community
- Radio amateurs contribute to data download
- Silence from 20 March 2018 ☹️



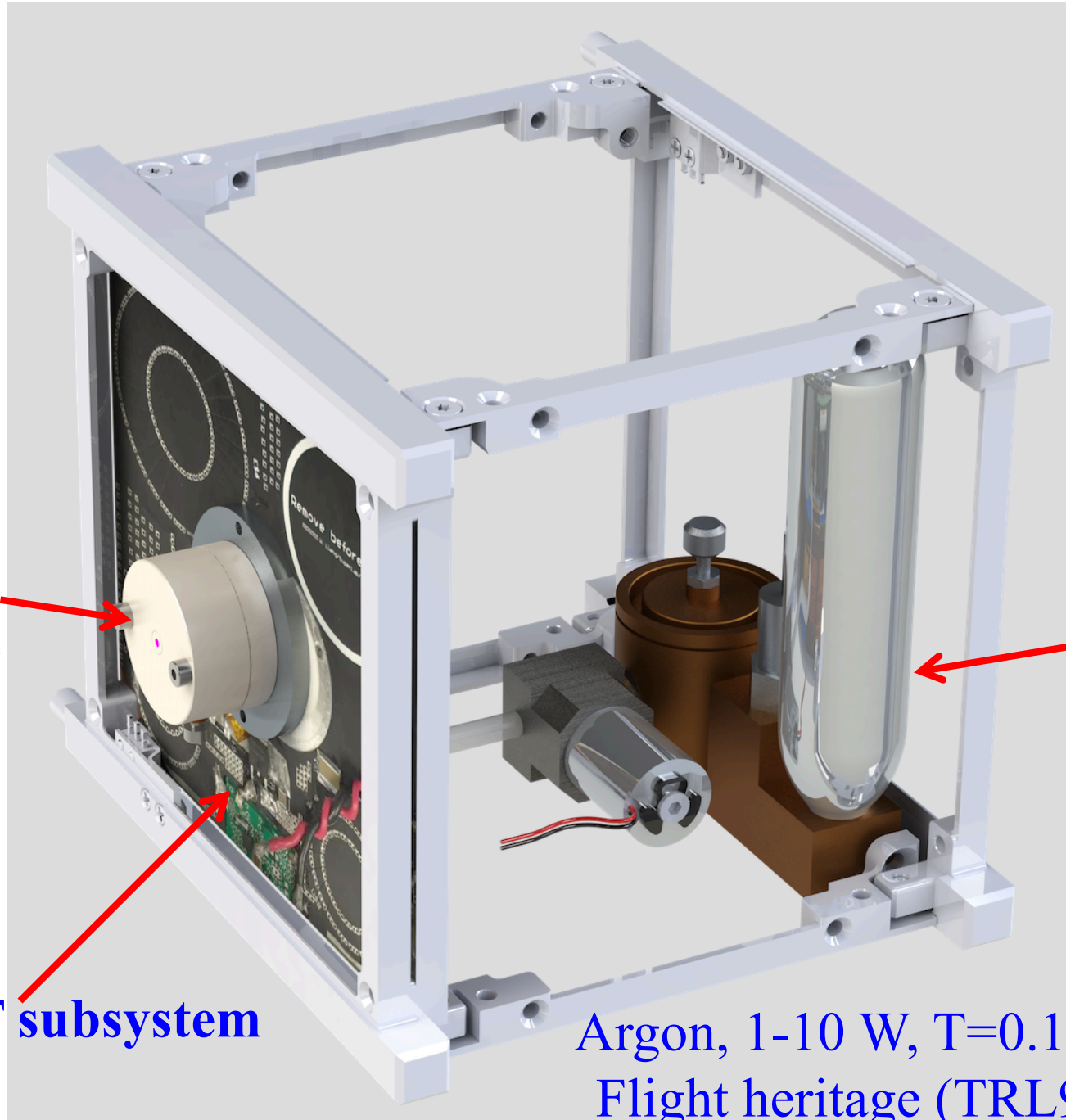
Pocket Rocket ½ U propulsion for `CubeSat`

MiniPR
thruster

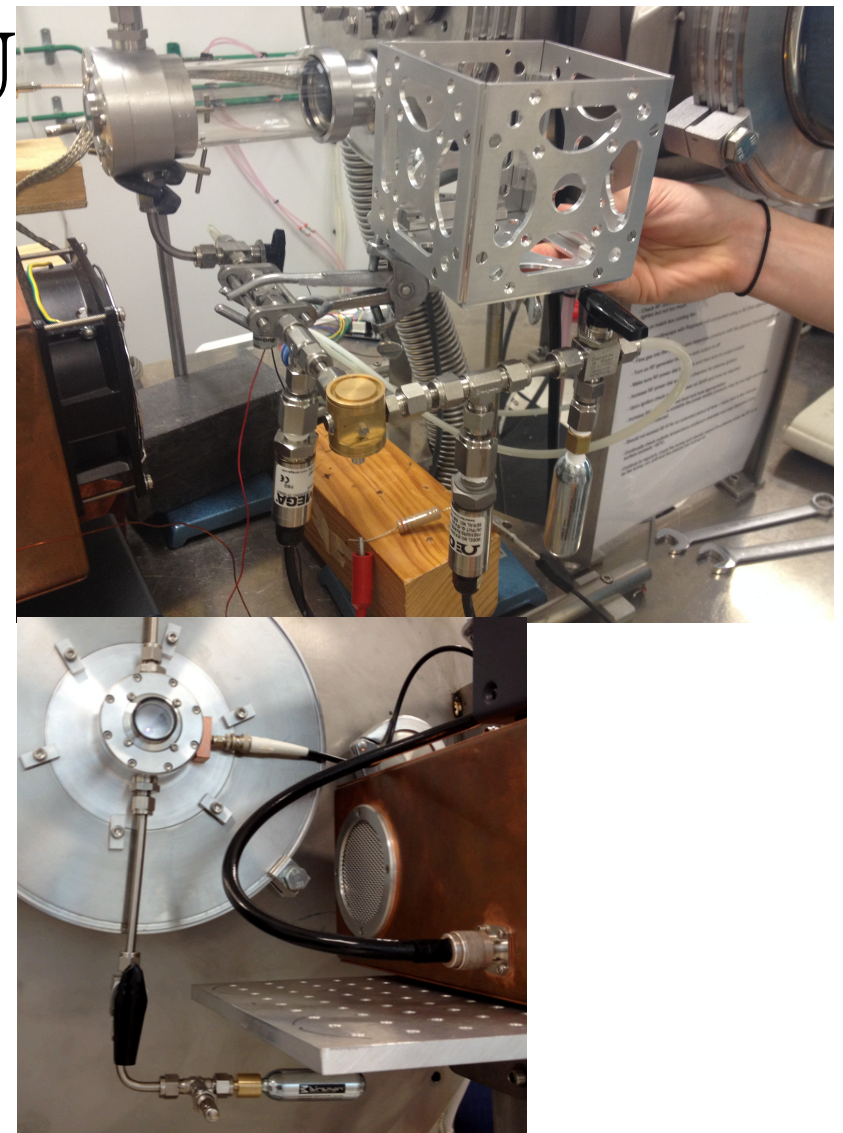
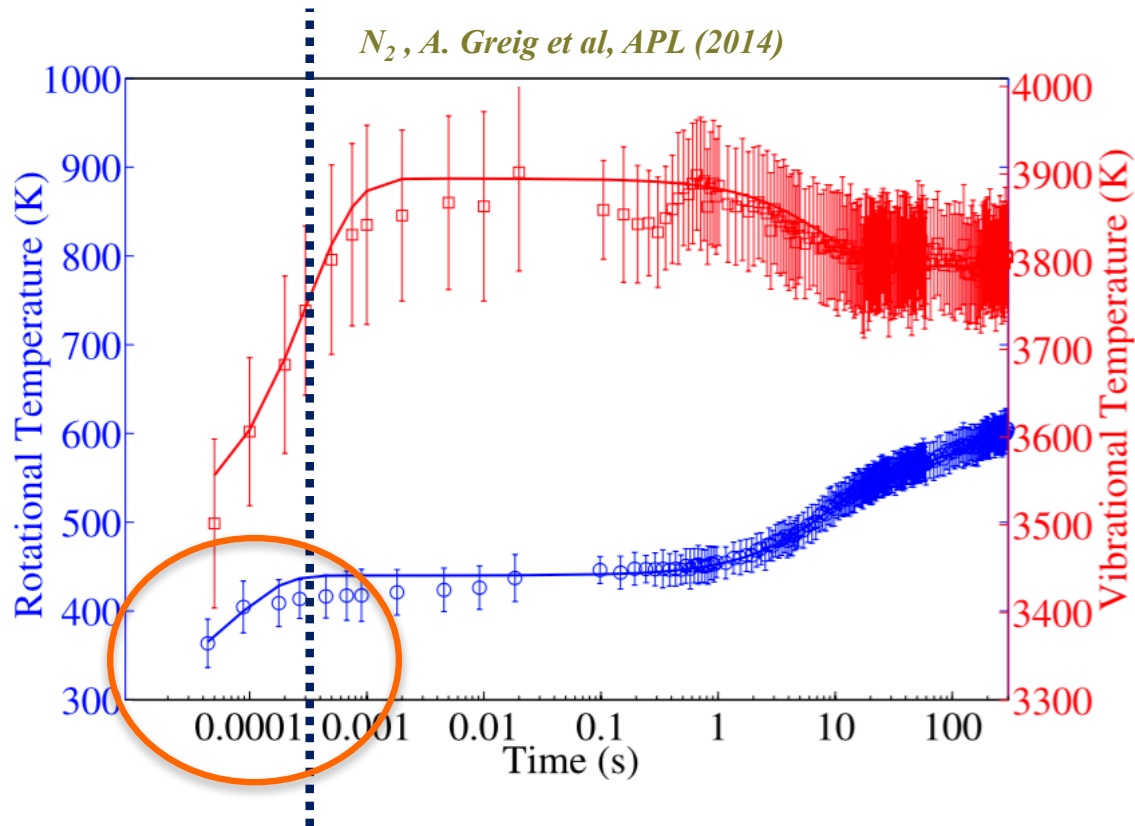
RF subsystem

Argon gas
subsystem
-cold gas
-plasma

Argon, 1-10 W, T=0.1-1 mN, $I_{sp} < 100$ s,
Flight heritage (TRL9 is the objective)



Propellant sub-system:1/3U



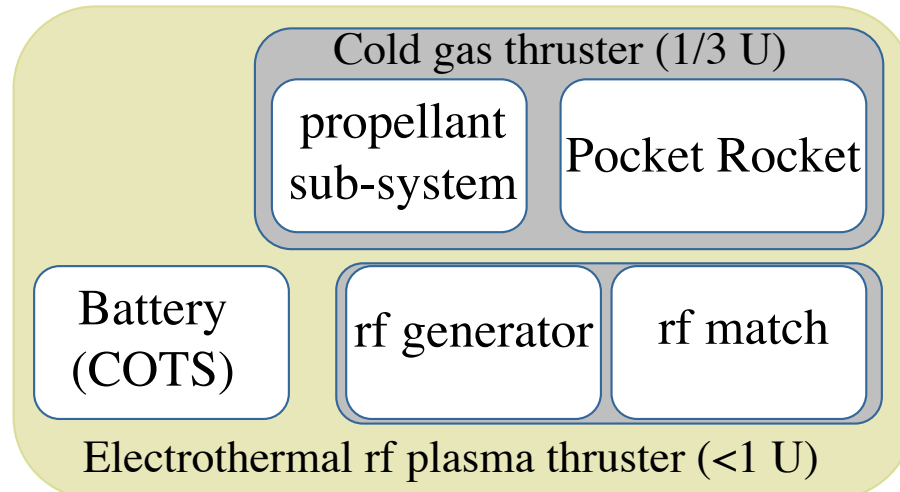
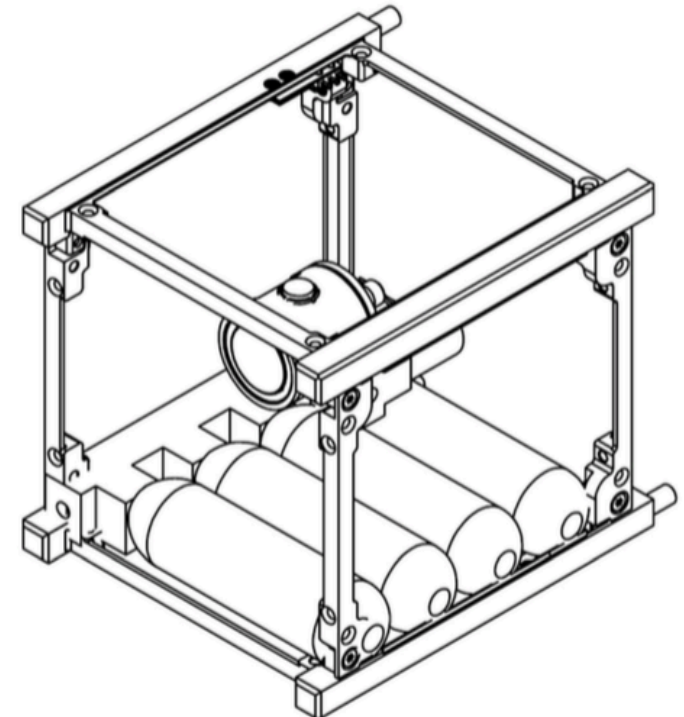
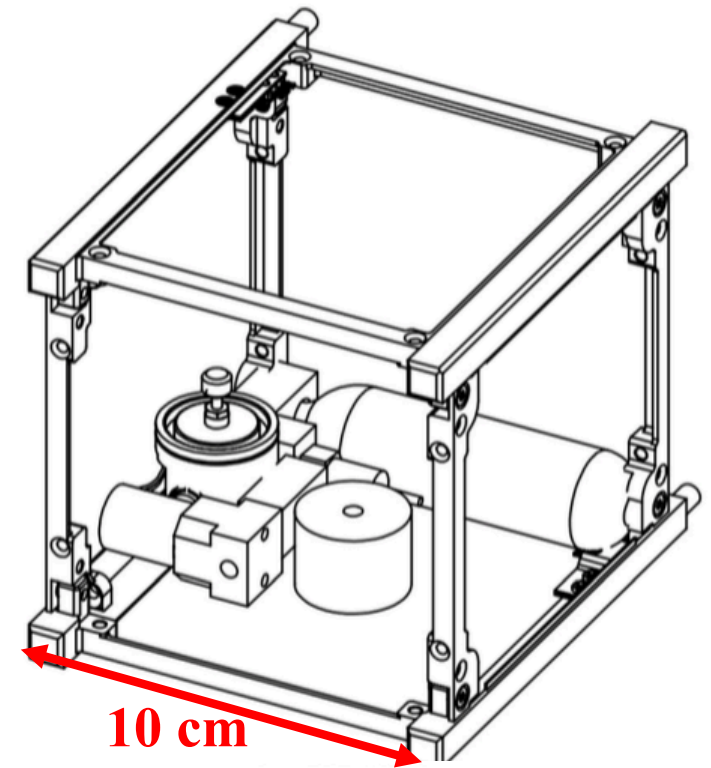
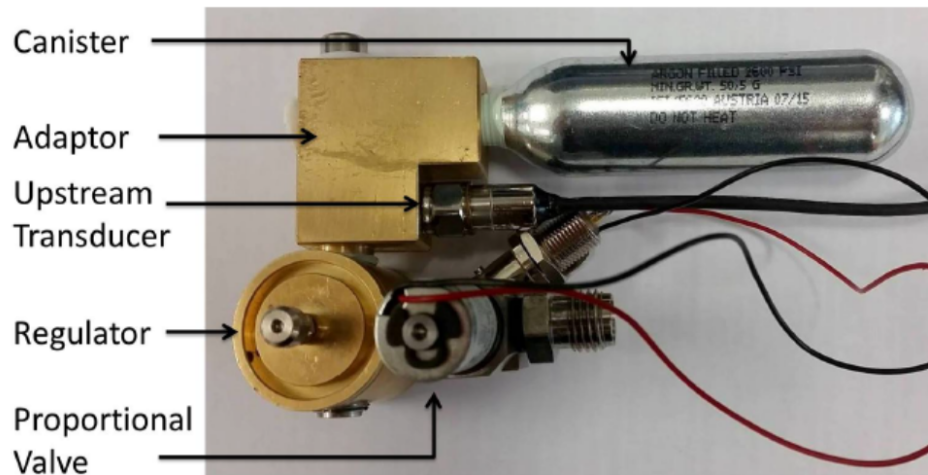
Ar propellant (not N₂ due to vibrational states at low power)
Bulk plasma heating (μ s) by pulsing
COTS parts for propellant sub-system (gas canisters, 3D printed tubing)

Propellant sub-system:<1/2U

Ashley Ellis, Honours Thesis (2016)

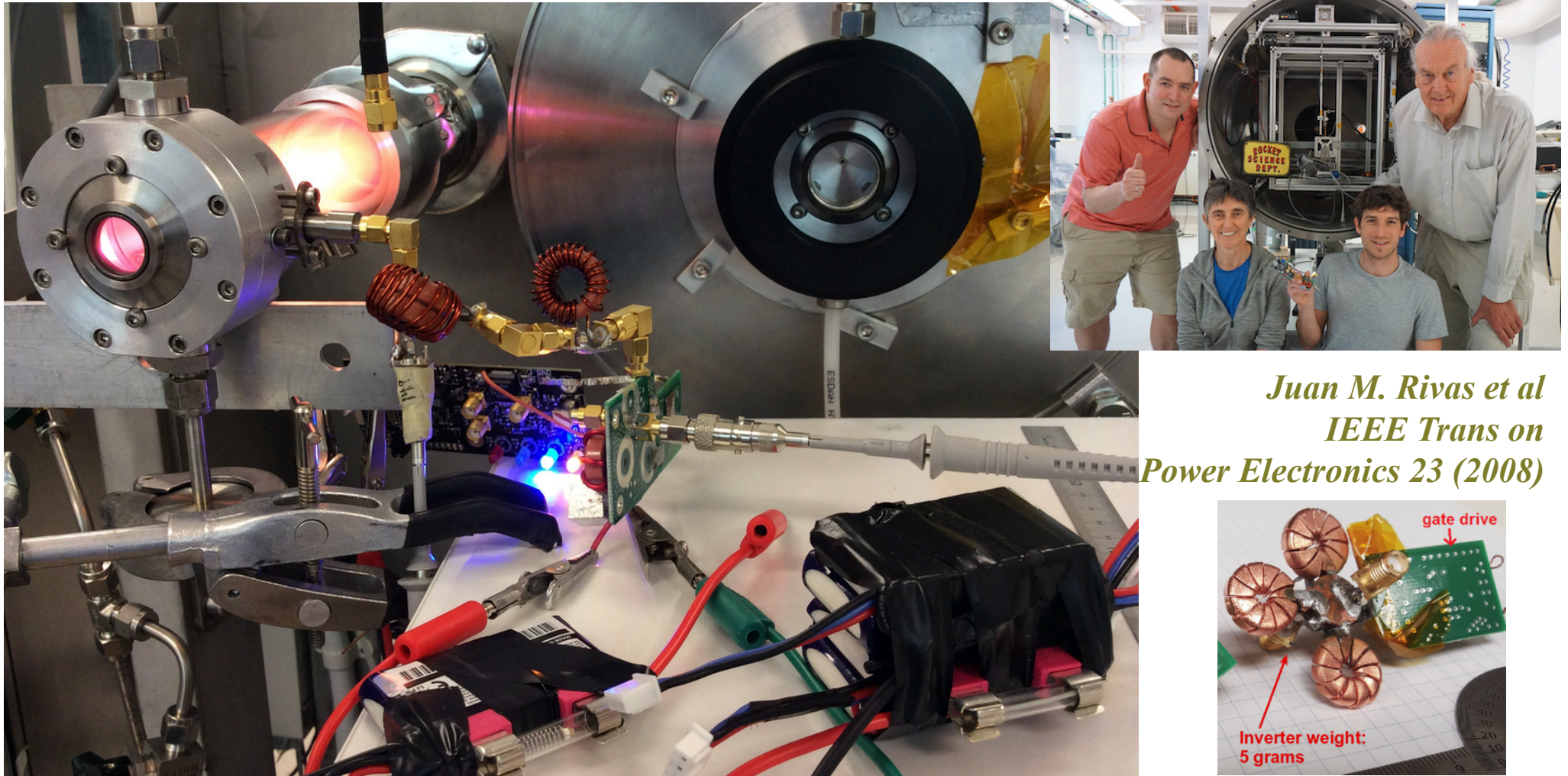
Thomas Charoy, 6 months visit (2016)

Alex Stuchbery, Honours Thesis (2017)



Stanford-ANU test campaign March 2016:

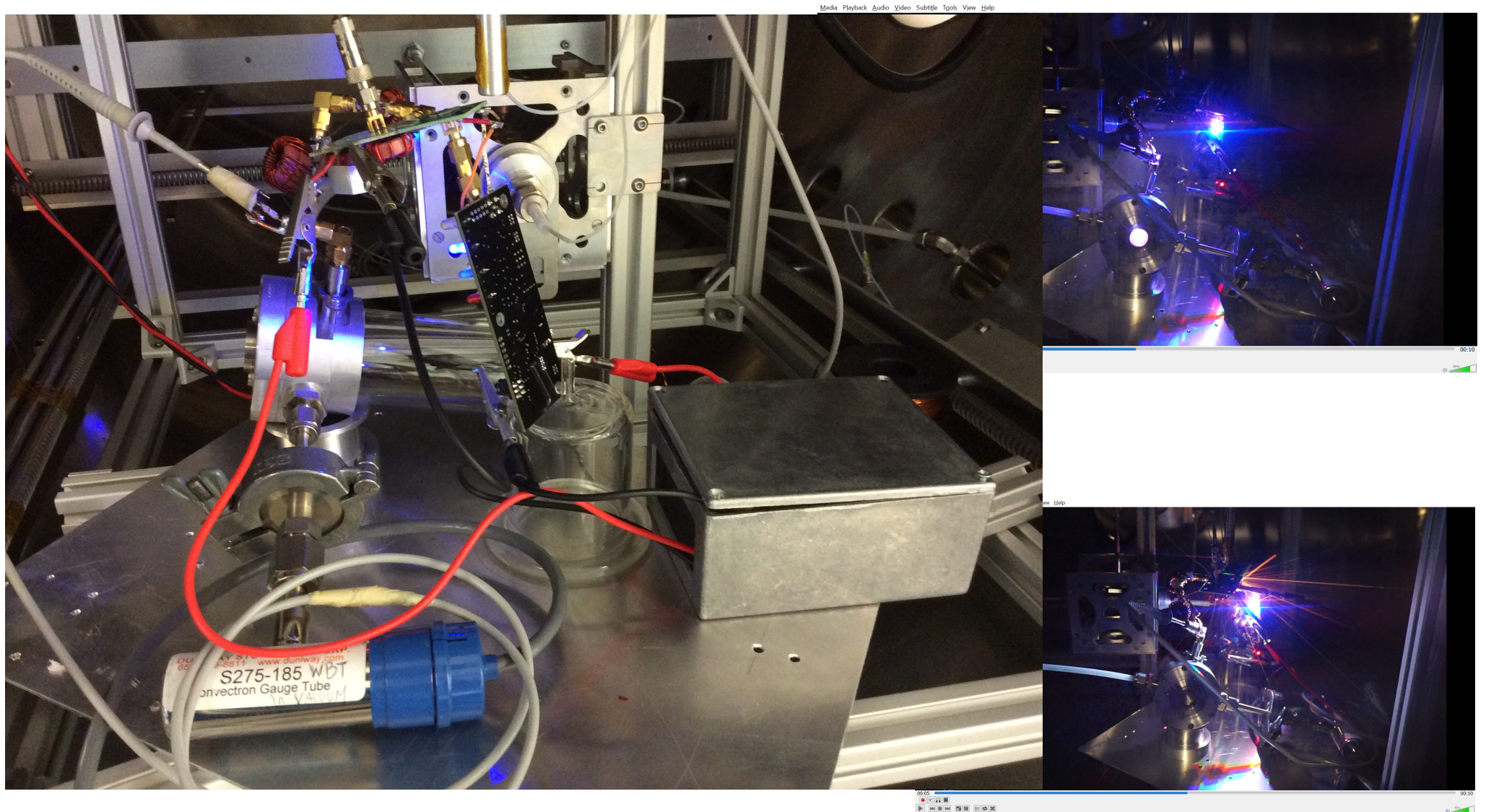
RF sub-system prototype developed by Luke Raymond, Juan Rivas, Max Praglin & Wei Liang



Class $\Phi 2$ inverter: allows the use of lower voltage FETs by introducing a component of second harmonic into the amplifier and thereby reducing the peak height. Low weight, small, robust and efficient system power supply.

Stanford-ANU test campaign March 2016:

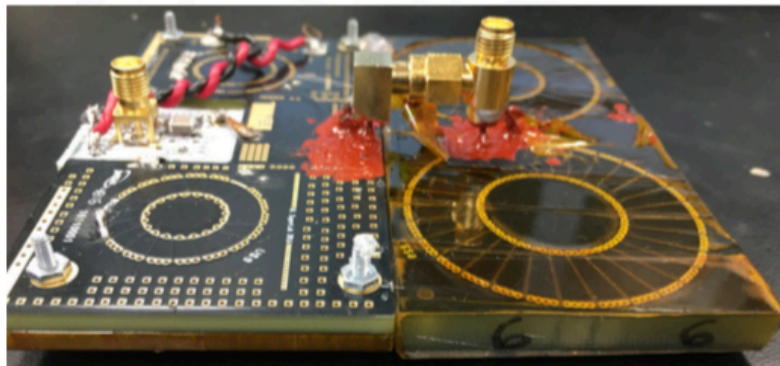
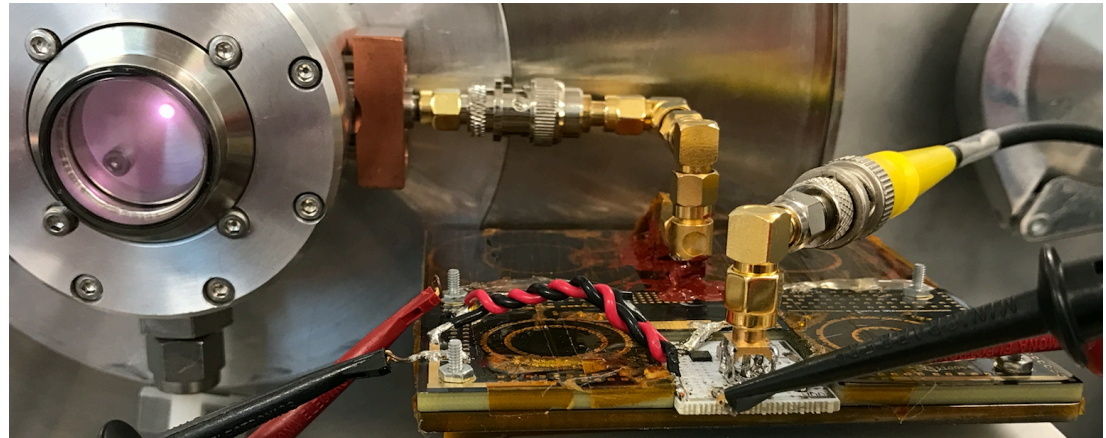
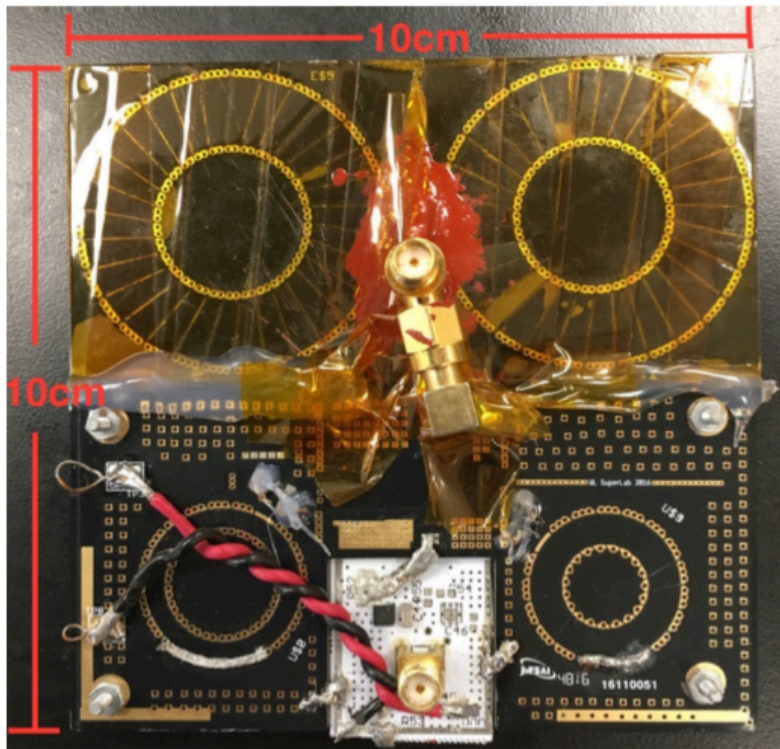
RF sub-system prototype initial testing in vacuum



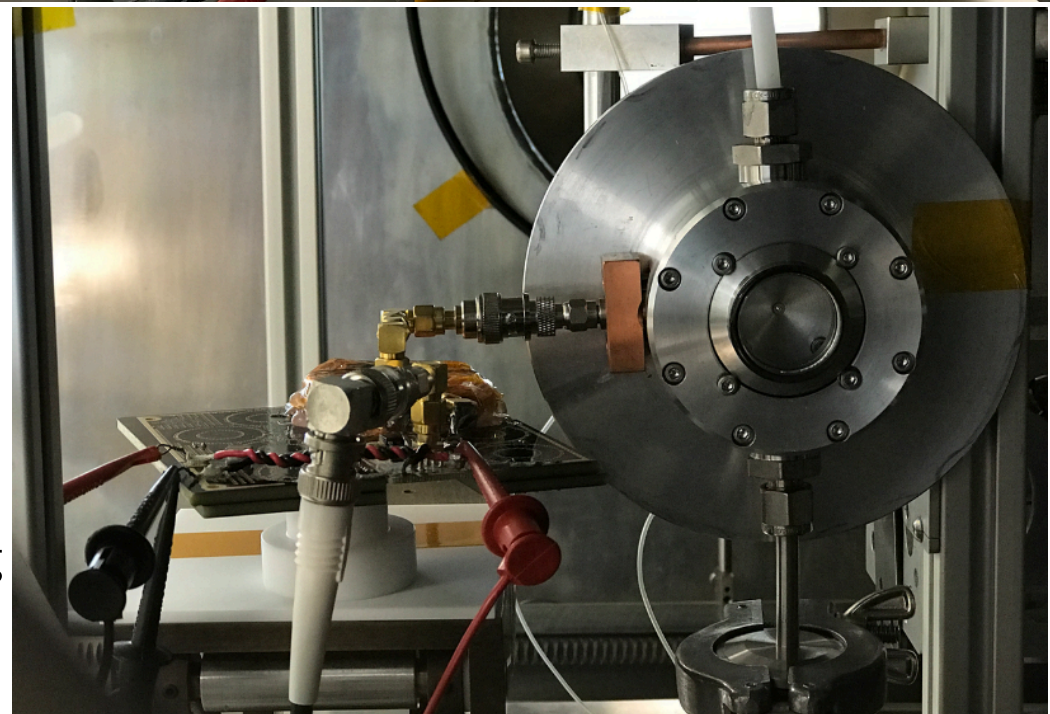
Complete system in WOMBAT showing (from right) battery box, DDS, rf amplifier and 2 stage match connected to Pocket Rocket (~10 shots).

Power sub-system: current prototype status

Provisional Patent Application (23-3-2017, S17-109/PROV): W. Liang, L.C. Raymond, J.M. Rivas Davila, R. Boswell and C. Charles, “*Structurally supportive micro plasma thruster and its power processing unit for cubesat applications.*”



150 g



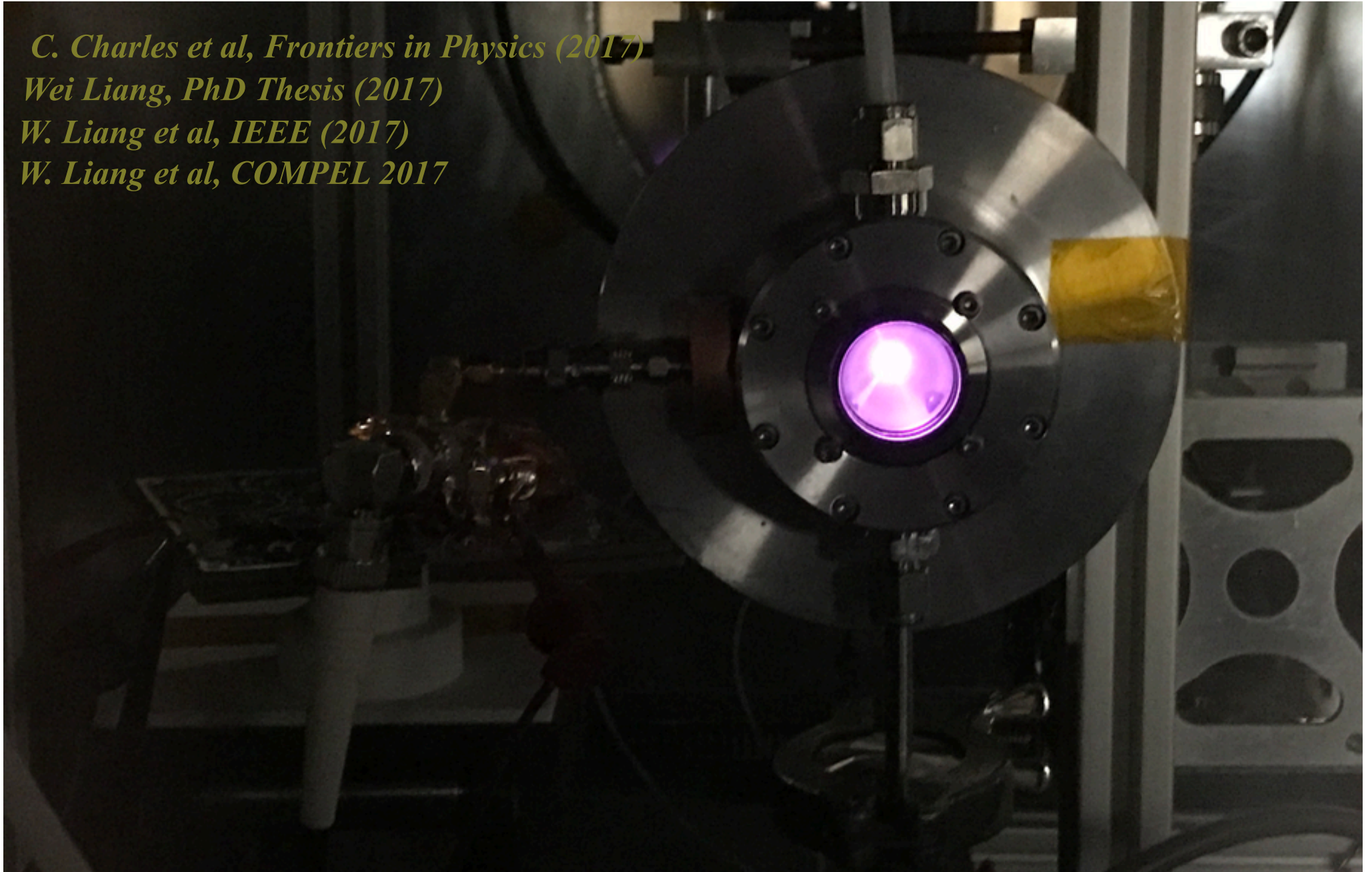
Stanford-ANU test campaign March 2017:

C. Charles et al, Frontiers in Physics (2017)

Wei Liang, PhD Thesis (2017)

W. Liang et al, IEEE (2017)

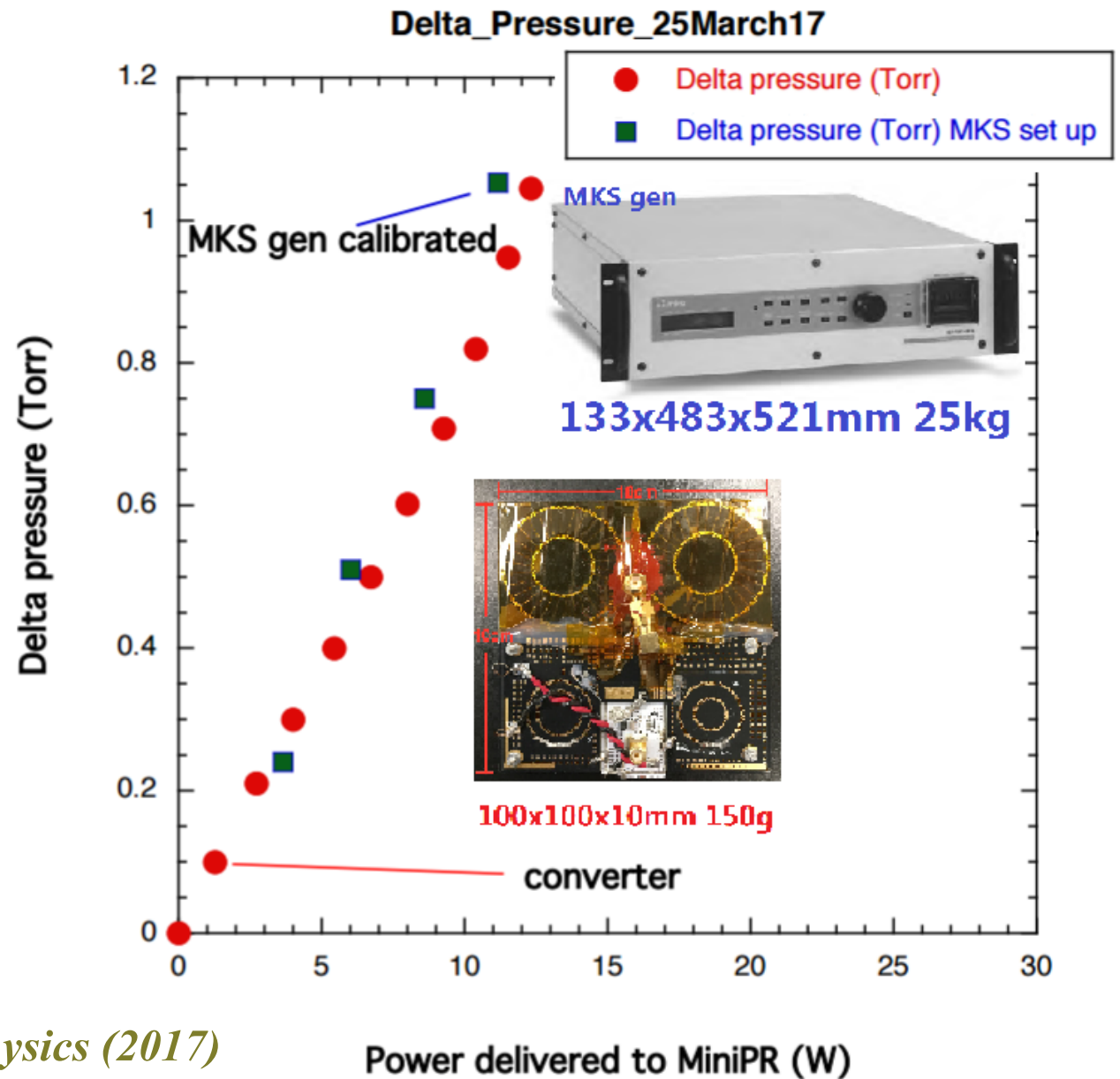
W. Liang et al, COMPEL 2017



>100 plasma tests (~2.4 W nominal) in vacuum with no parasitic discharges

Stanford-ANU test campaign March 2017:

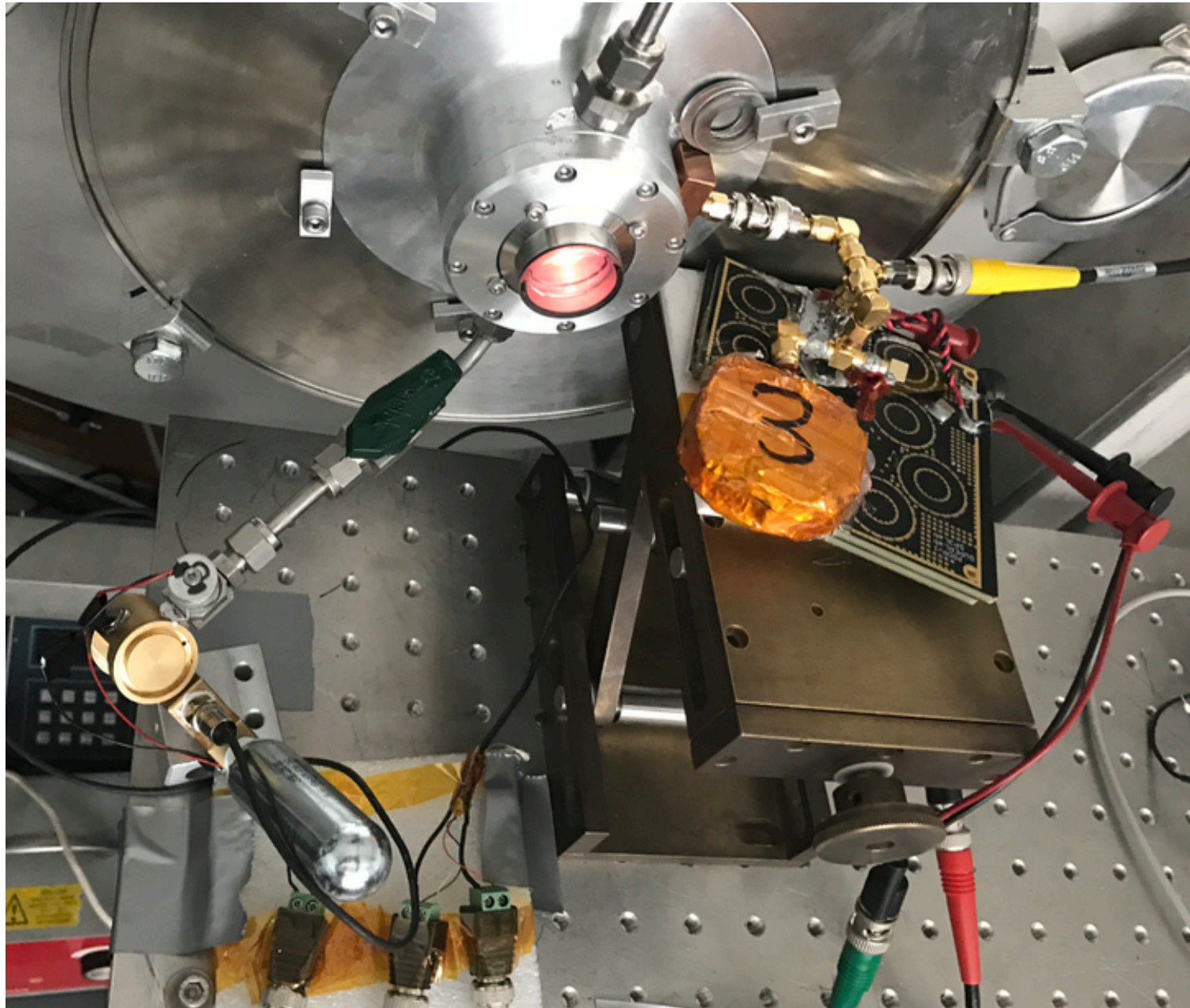
Footprint
suitable for
CubeSats



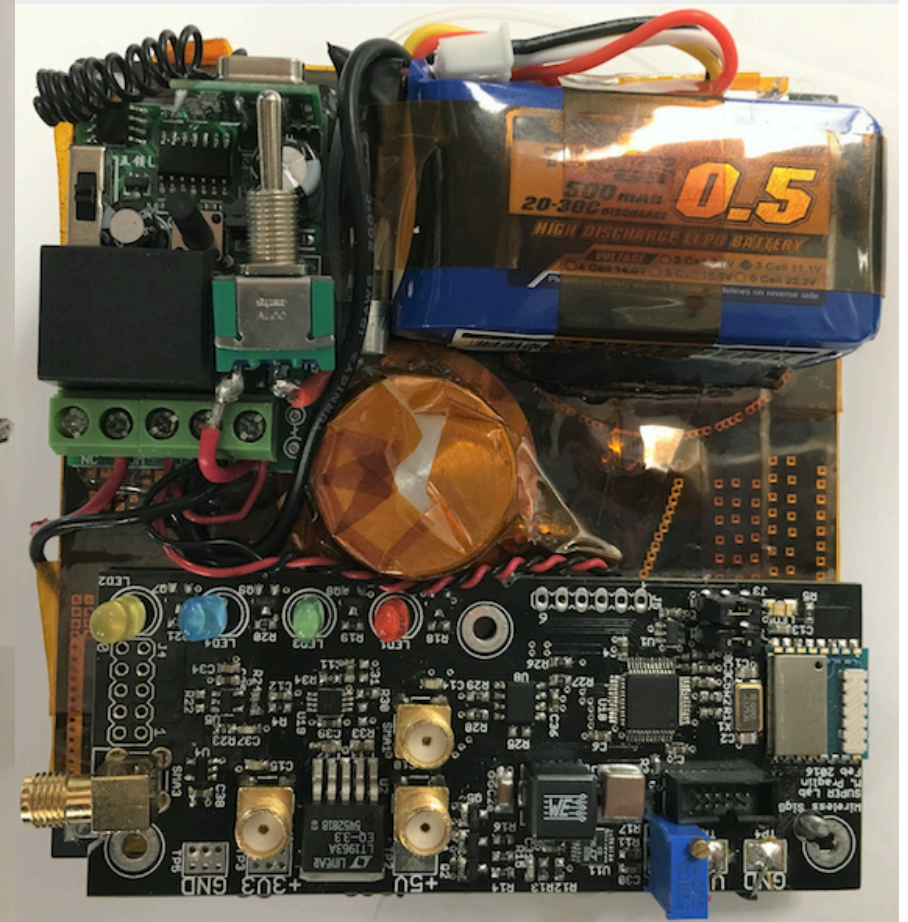
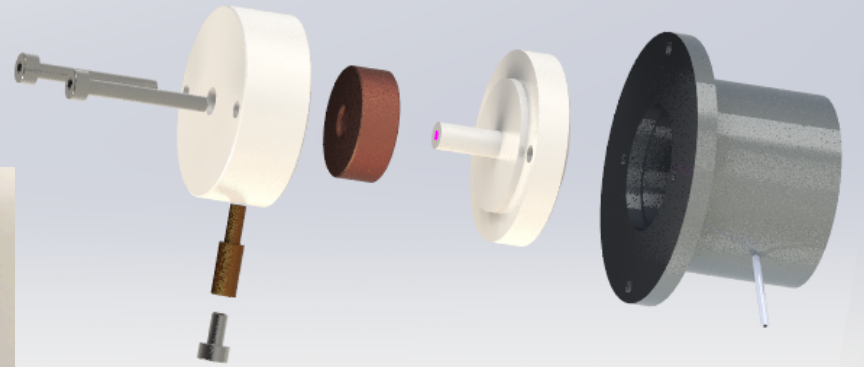
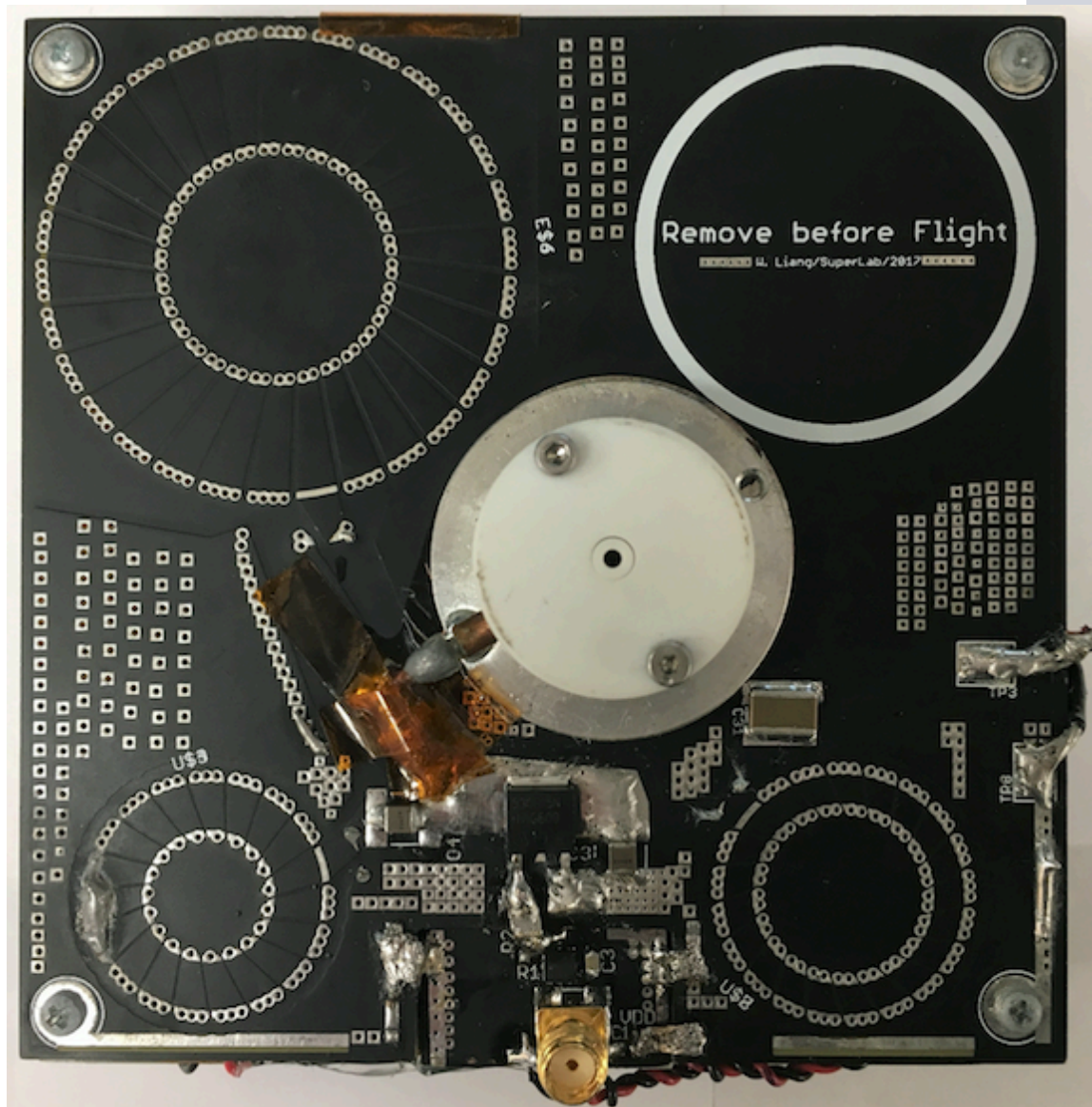
C. Charles et al, Frontiers in Physics (2017)

Wei Liang, PhD Thesis (2017)

Combined subsystems testing (not in vacuum)

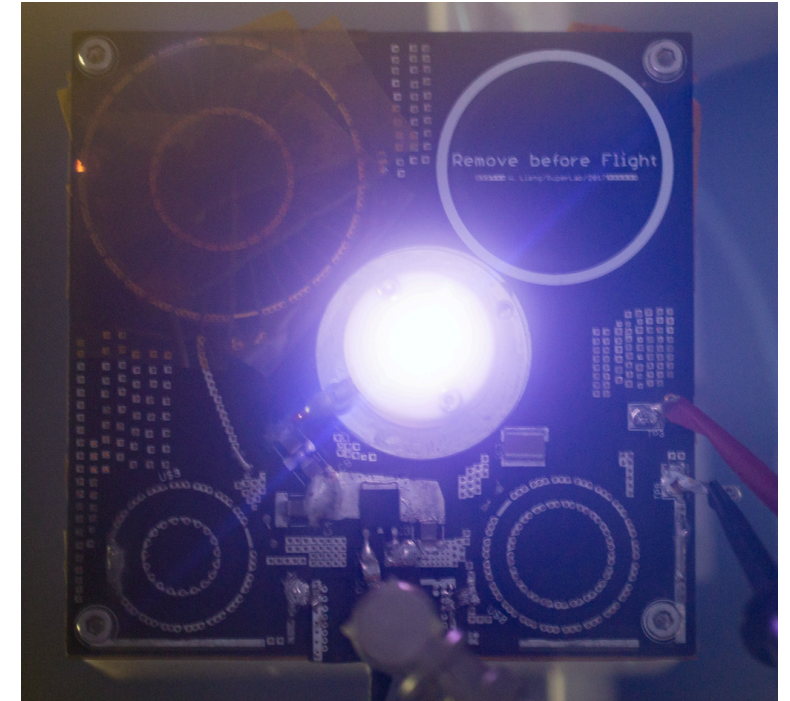
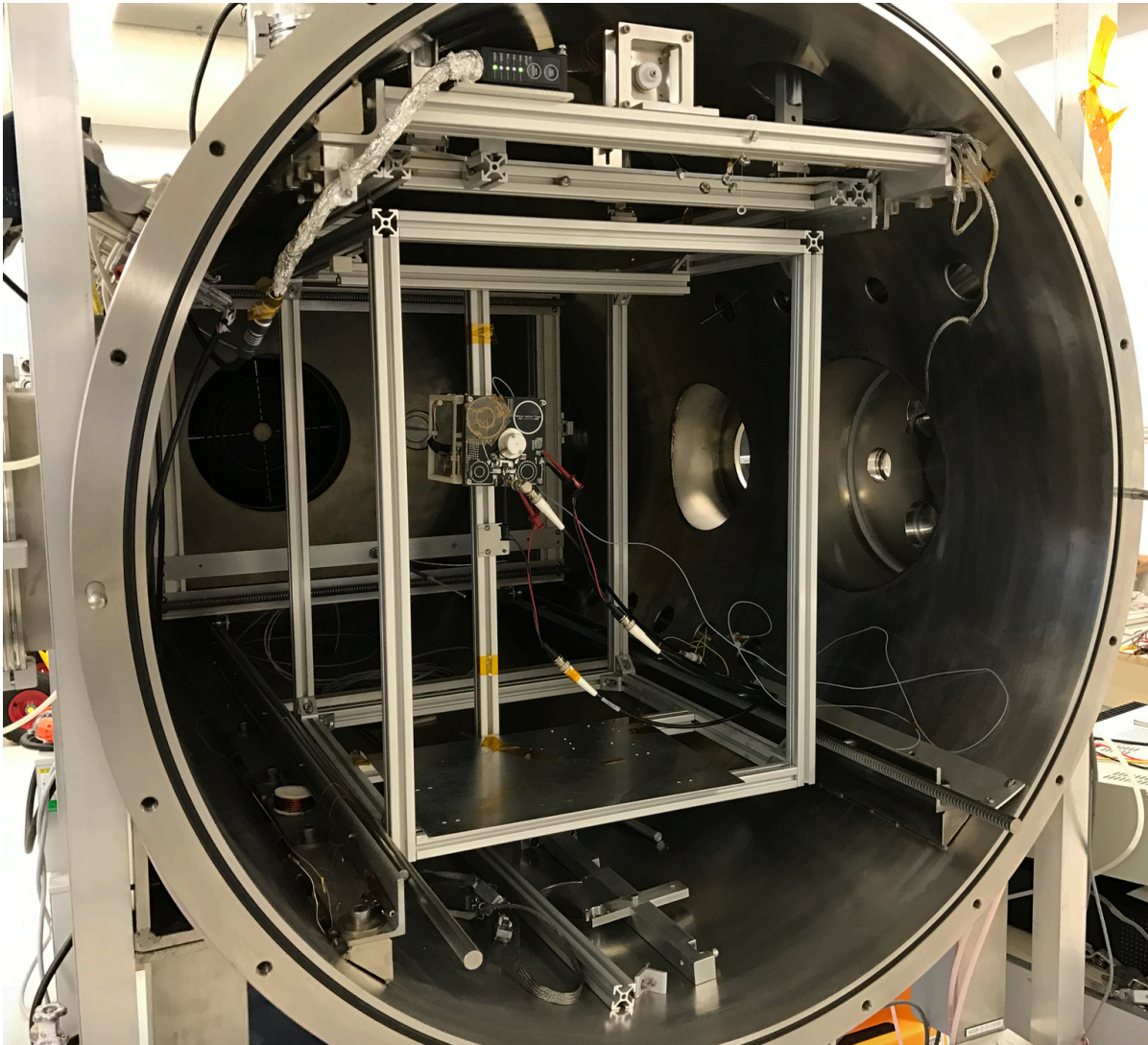


1U CubeSat integration



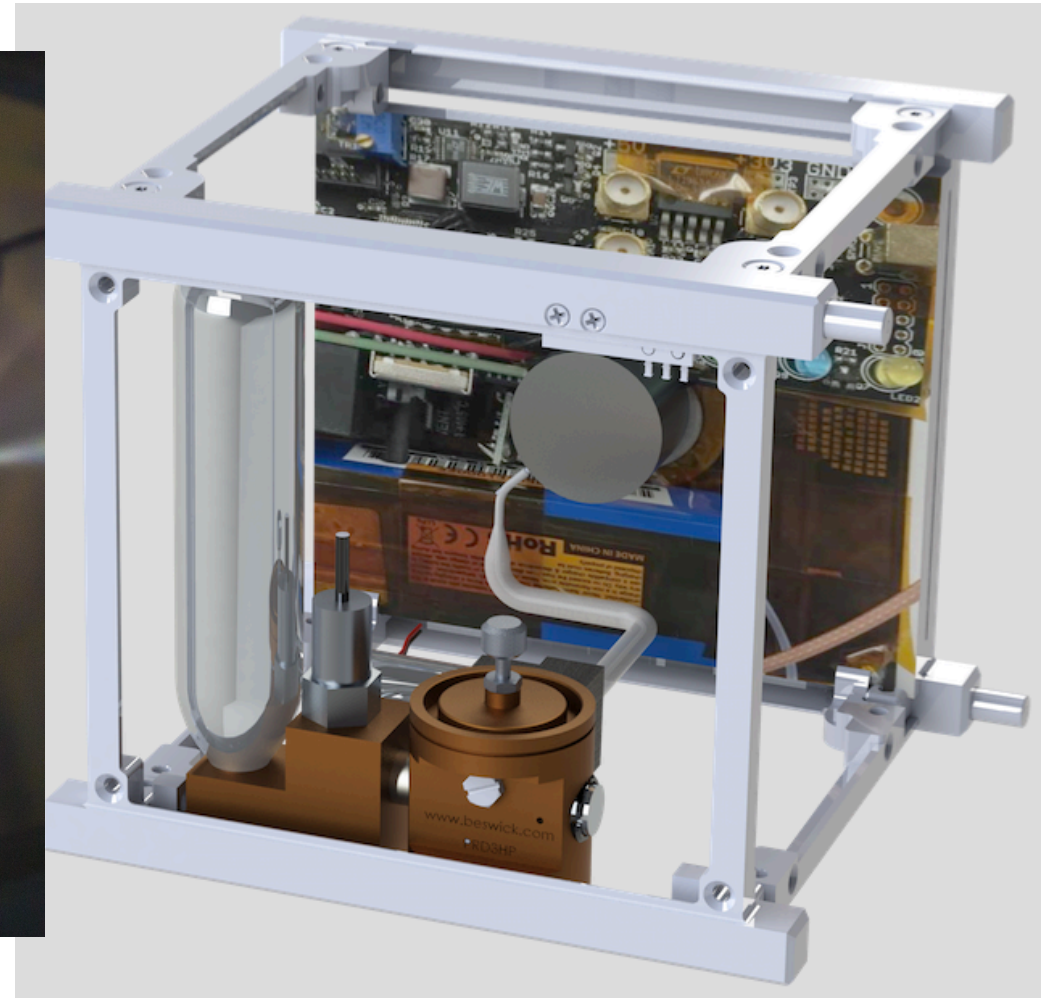
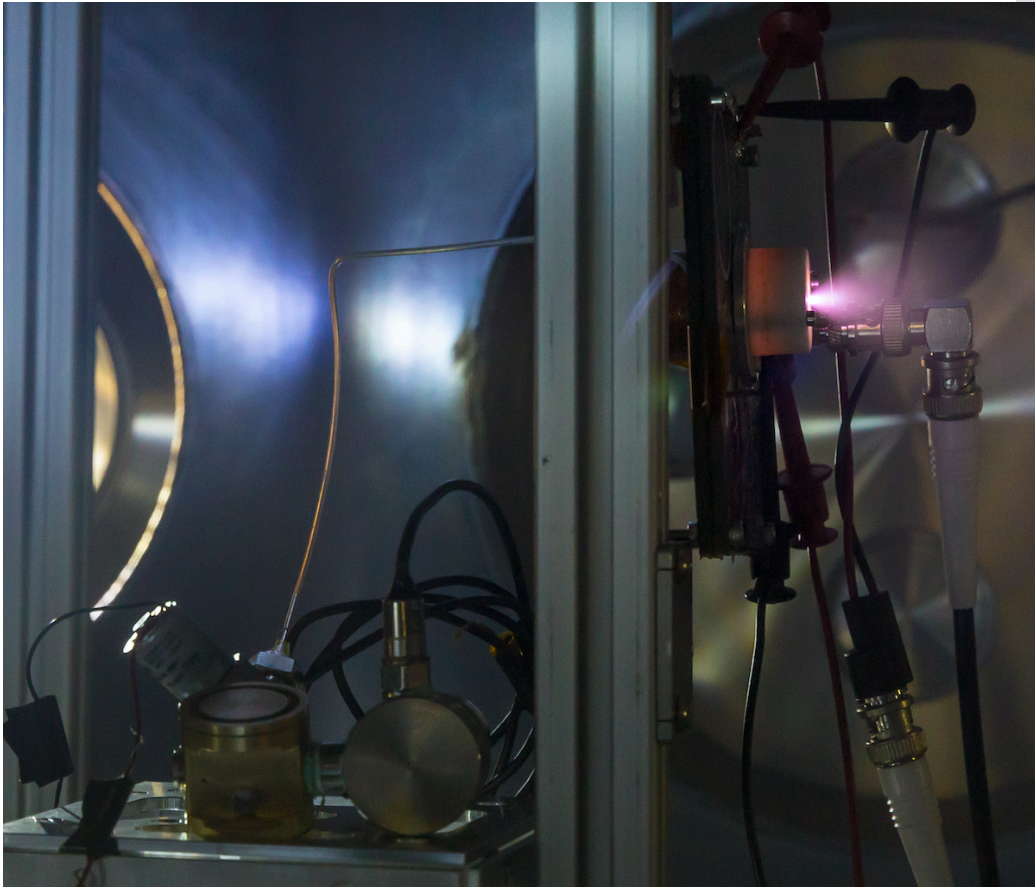
Latest prototype: battery-powered with wireless remote control

Vacuum testing of in Wombat (Sept 2017)



- 1- Demonstration of ignition and tuning with no parasitic discharge
- 2- Option of wireless control for future thrust balance measurements

Vacuum testing of all subsystems in Wombat

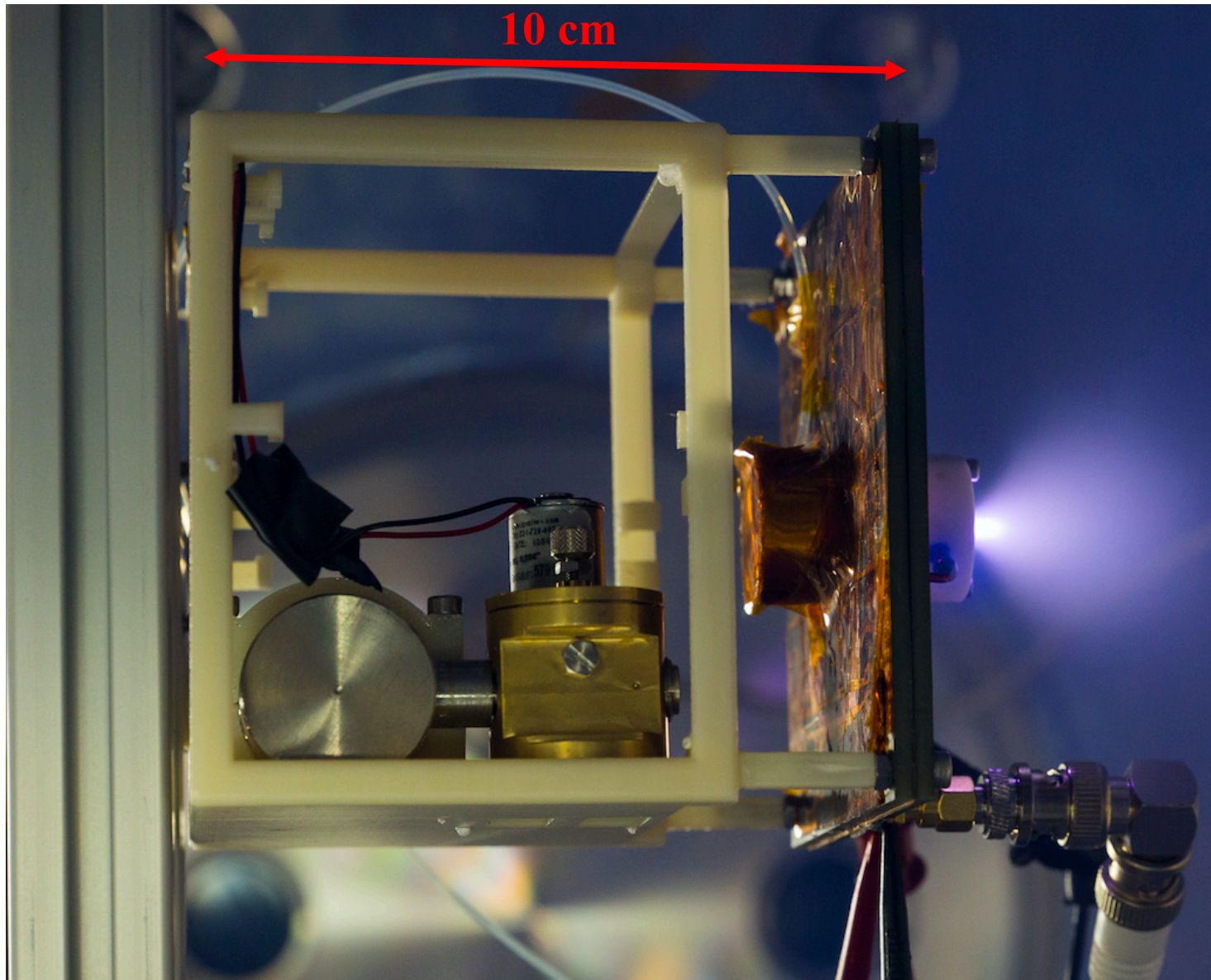


1- Demonstration of Pocket Rocket propulsion system for nano-satellites

2- Future possible options:

- nozzle optimisation
- 3 axis Pocket Rocket
- satellite docking

Vacuum testing of Pocket Rocket in Wombat

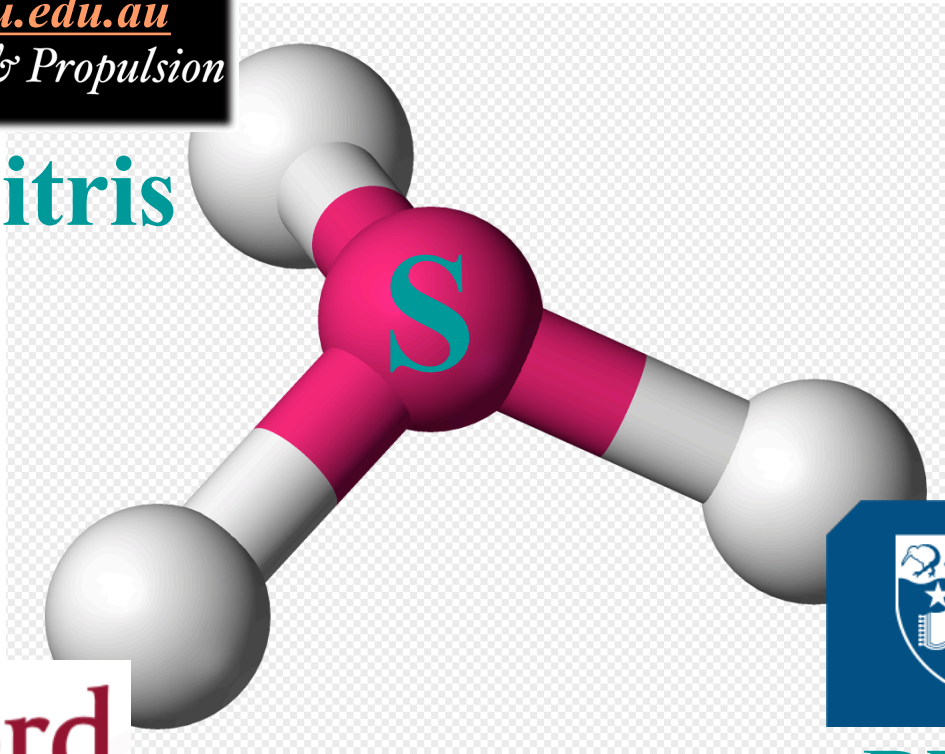


- 1-Argon 1-60sccm (nominal 20 sccm), 1-100 W (nominal 5 W)
- 2-TRL 7 demonstration for $<1/2$ U CubeSat assembly ($\sim 500\text{g}$)

Lab to Launch



PhD: Dimitris



Stanford
University

PhD: Weston



THE UNIVERSITY OF
AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

PhD: Félicien

New Zealand Space Agency since 2016

The Auckland Programme for Space Systems



Open to all undergraduate students from across the University

Competition to choose best CubeSat mission each year

First mission, APSS-1 will be Q1 2019 with Rocket Lab USA

Ionosphere electron density measurements

Peter Beck and Rocketlab (New Zealand)



SUPPLIE

The Electron rocket skipped its third test launch to go straight into commercial operations.



ROCKET LAB/SUPPLIED

The first Rocket Lab test flight failed 100 metres from orbit, but the second was a success, delivering four spacecraft to orbit.

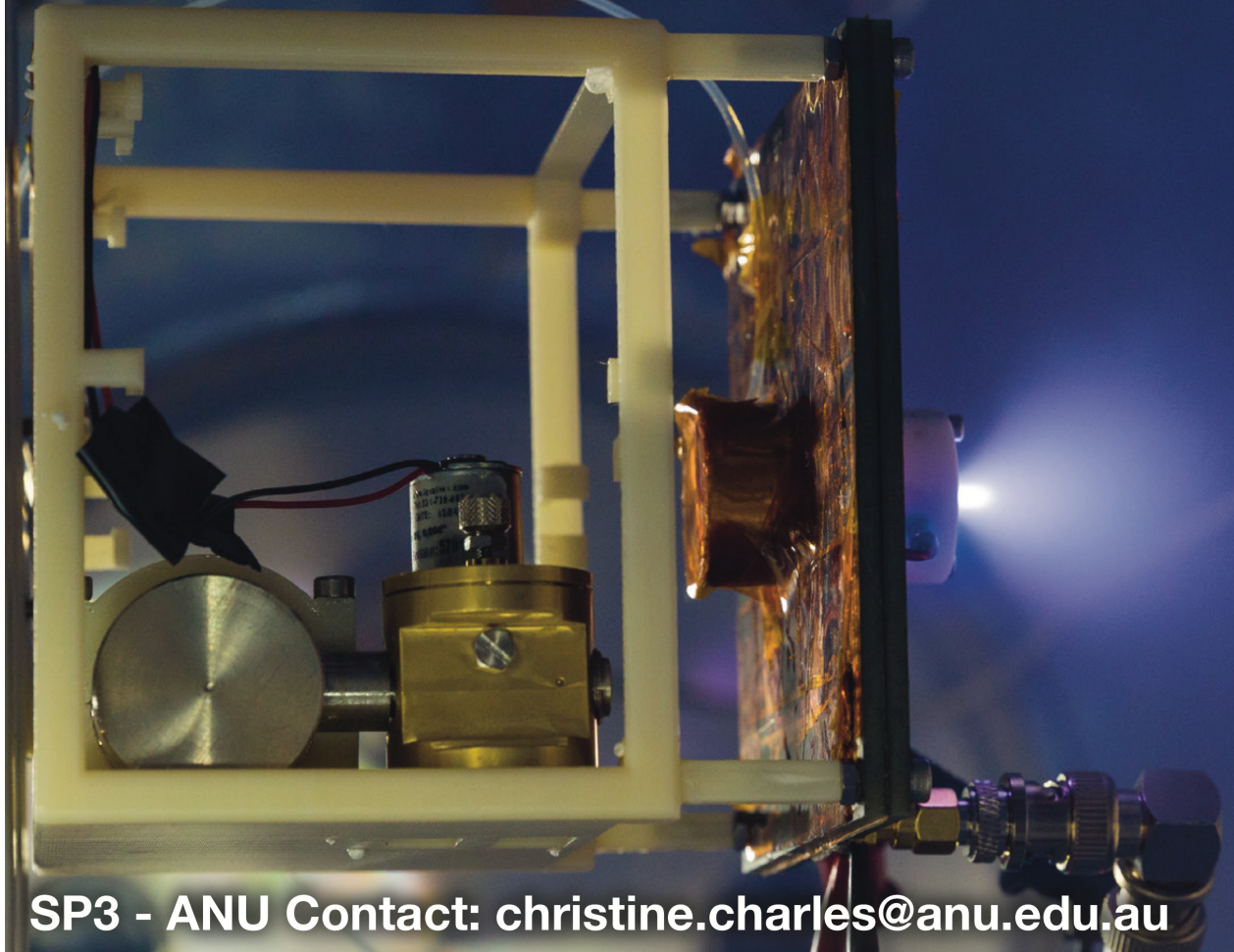
- 1- Launch site from Mahia Peninsula in New Zealand
- 2- Second flight delivered 4 spacecrafts into orbit



Credit: Rocket Lab

Pocket Rocket

Australian National University
Stanford University



SP3 - ANU Contact: christine.charles@anu.edu.au

Find partner or \$\$ for

- getting 2U Engineering Model to work on interfacing Pocket Rocket with COTS
- thrust testing of complete satellite (TRL 8), mission opportunities to reach TRL 9



Australian
National
University

Lab to Launch: 2 steps to space

TRL 7 → TRL 8 → TRL 9



Australian Space Agency?

