THE AUSTRALIAN NATIONAL UNIVERSITY

Ion beam formation in expanding plasmas and its application to plasma thrusters

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SP3

http://sp3.anu.edu.au

Space Plasma, Power & Propulsion

Space Plasma, Power and Propulsion Laboratory

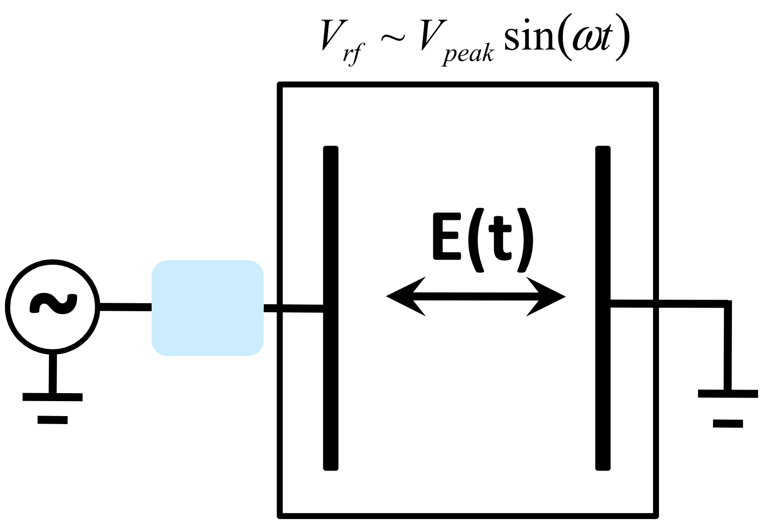
Research School of Physics and Engineering

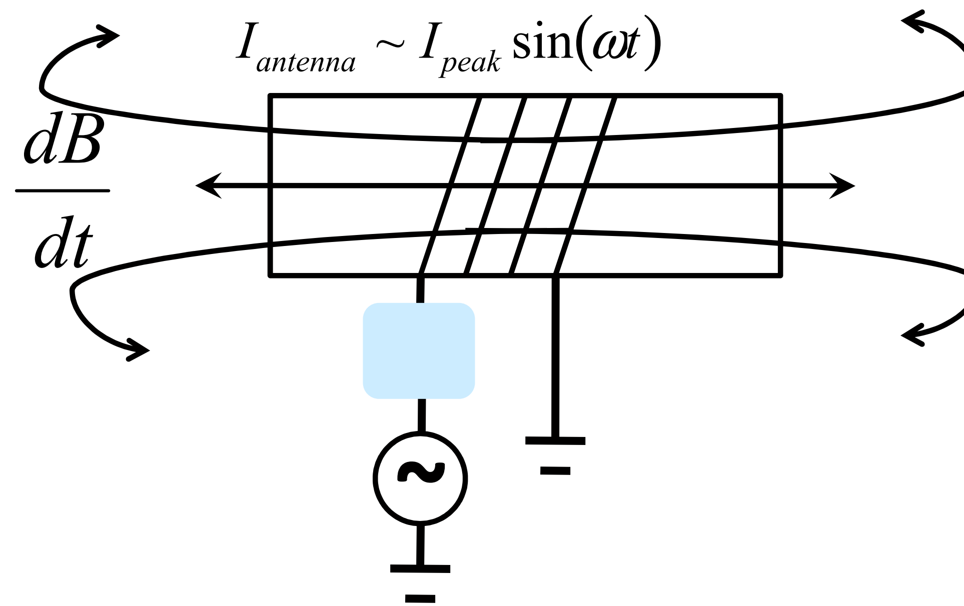
The Australian National University

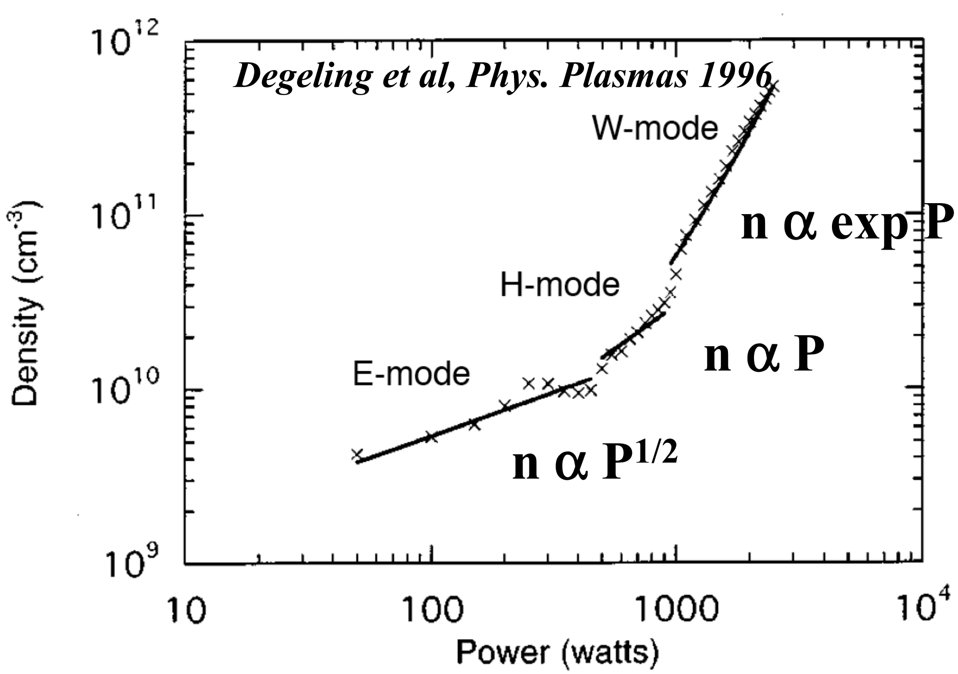
Australia

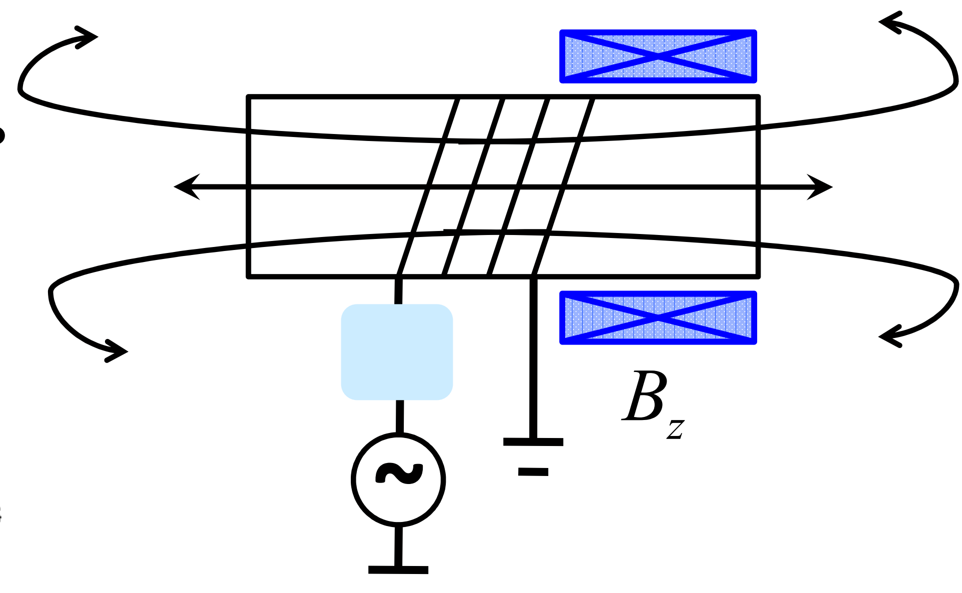
ECRIS 2012, Sydney Sept 24-28, Australia

Creating a plasma: DC, RF, µwave



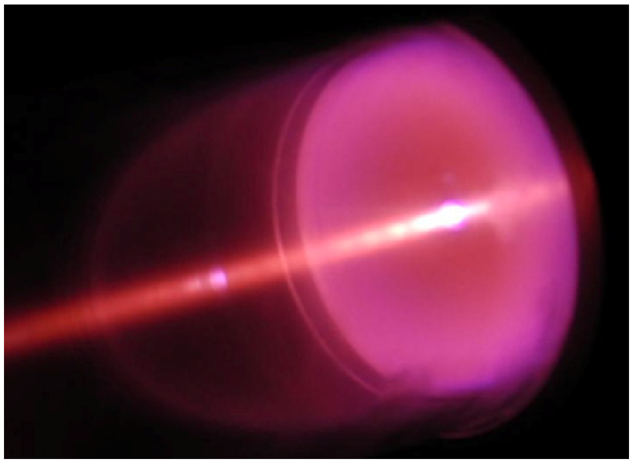




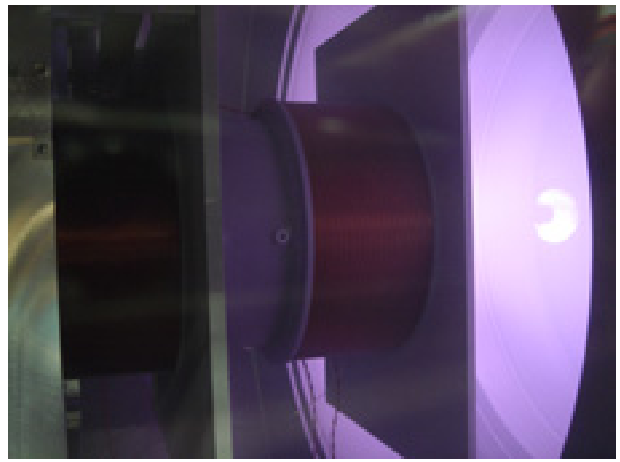


Radiofrequency thrusters study in SP3

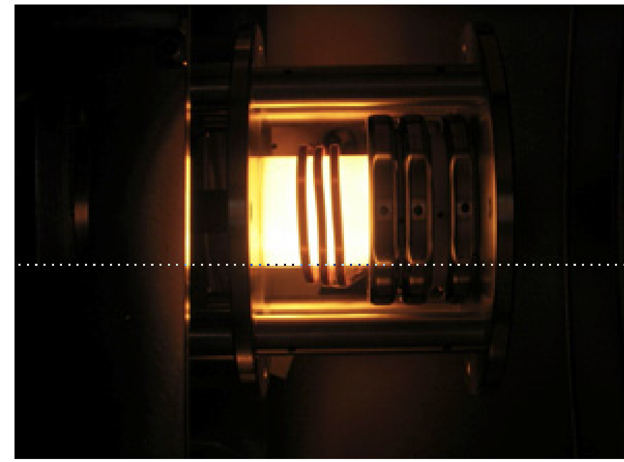
Micro thruster
Pocket Rocket (~1 Torr)



Plasma thruster
HDLT (~1 mTorr)



Ion thruster
DS4G



$$T = \frac{d(m\mathrm{v})}{dt}$$

$$I_{sp} = \frac{T}{(dW/dt)} = \frac{\mathrm{v}_e(dm/dt)}{g(dm/dt)} = \frac{\mathrm{v}_e}{g}$$

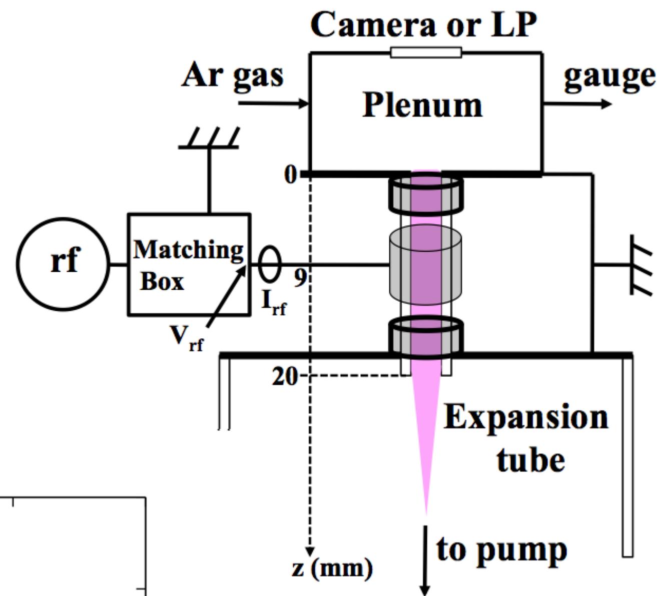
High flux of massive particles at high speed (cold gas, heated gas, accelerated ions…)

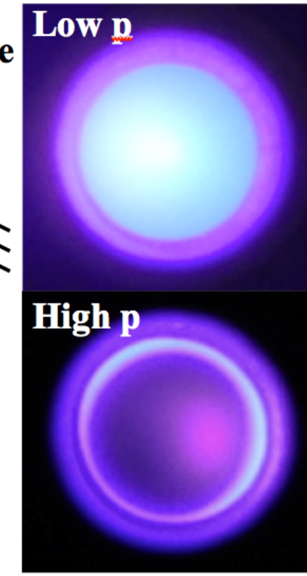
Thrust, Specific impulse, Power efficiency, Mass efficiency

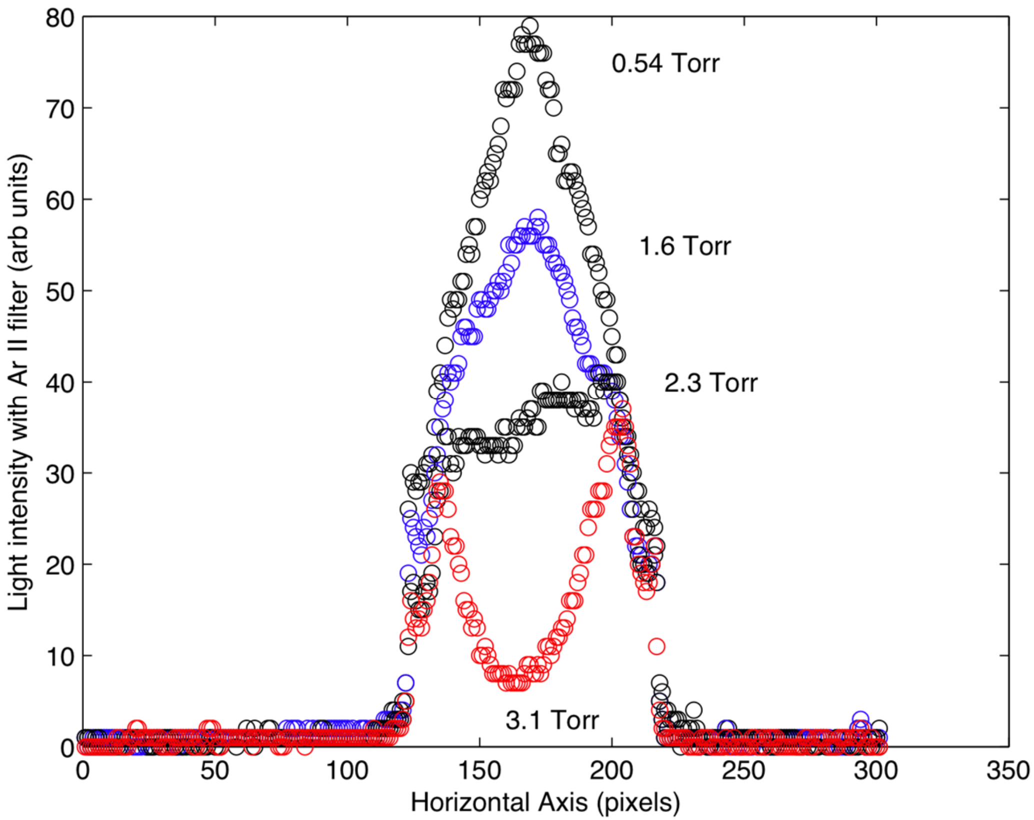
All of these systems used for materials processing or analysis

Pocket Rocket micro-thruster

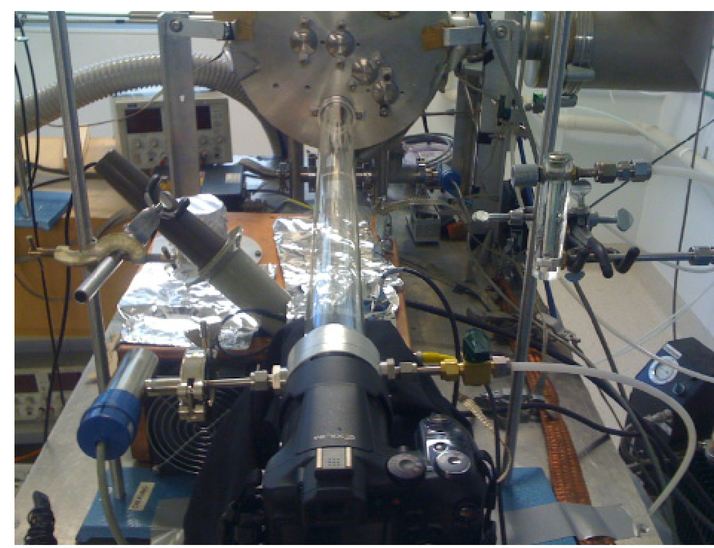
- intermediate pressure (1 Torr)
- heated neutrals / large dissociation







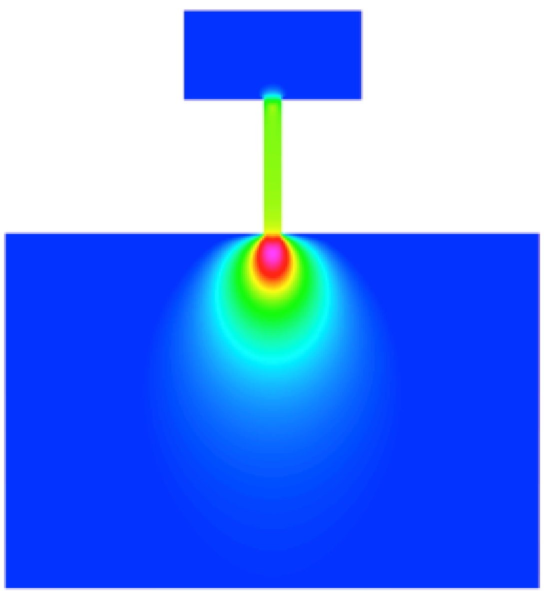
Electrodes: L_{stack} 1.8 cm, $A_{rf}=A_{earth}$~1 cm^2
Ceramic: D_{int} 4.2 mm, D_{ext} 5.3 mm, L_{cer} 2 cm, d~0.55 mm



Intermediate pressure: mTorr to Torr

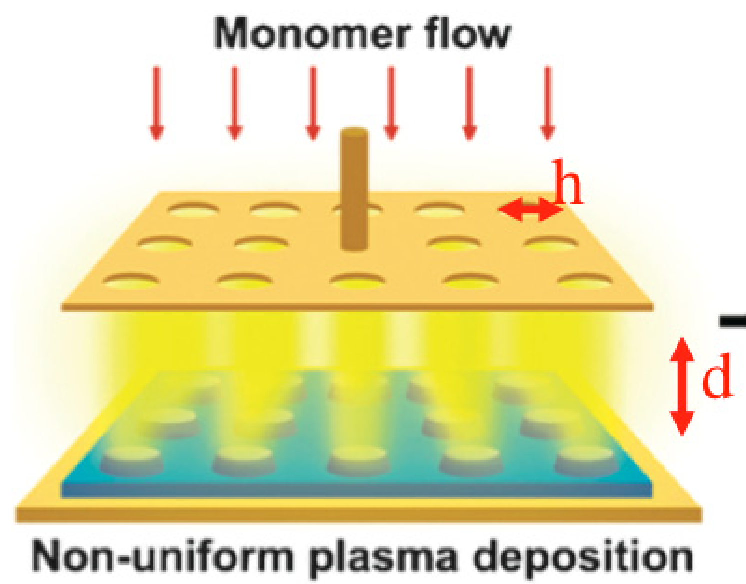
1- Pocket Rocket (space propulsion)
2- LAMWICH, an array of discharges (microelectronics)
3- Global models for CSIRO polymer dep device (plasma medicine)

1



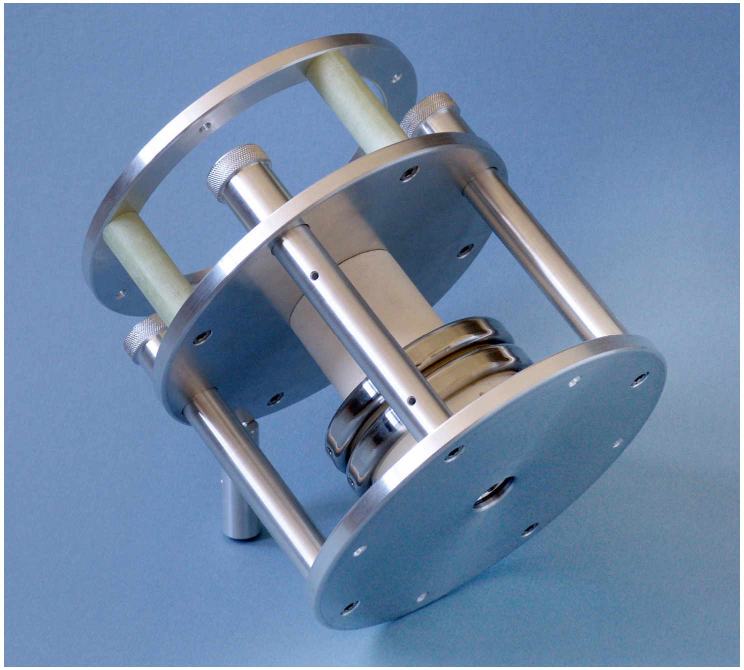
2

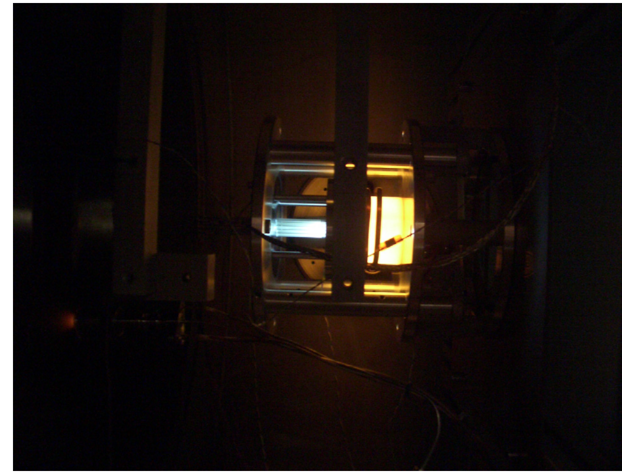
3

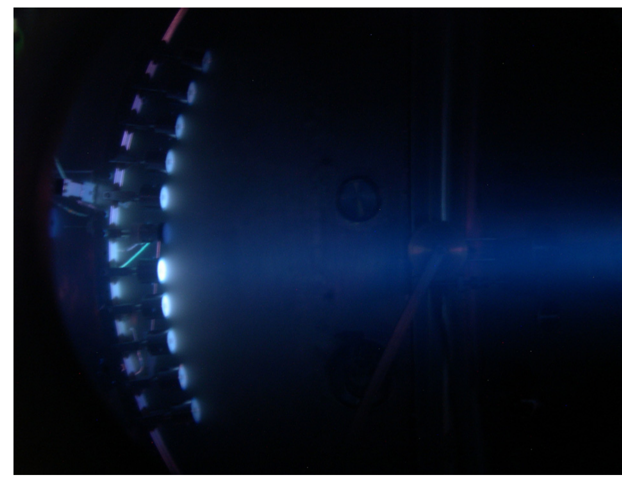


Frequency range: 100 kHz to 30 MHz

The Dual Stage Four Grid Thruster (DS4G)







- low pressure (~ mTorr)
- plasma and first electrode floating at 10-30 kV

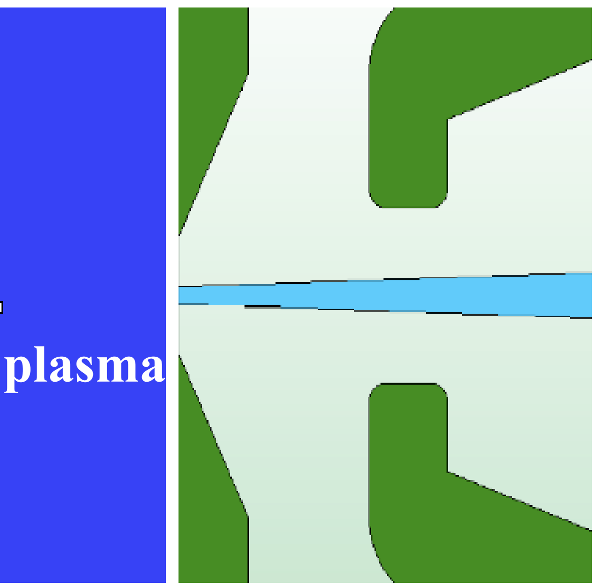
- 2005, 2006 test campaigns at ESA
- RF, HV and systems successful.
- 30 kV beam energy
- 60% Total Efficiency
- Beam divergence less than 5 degrees

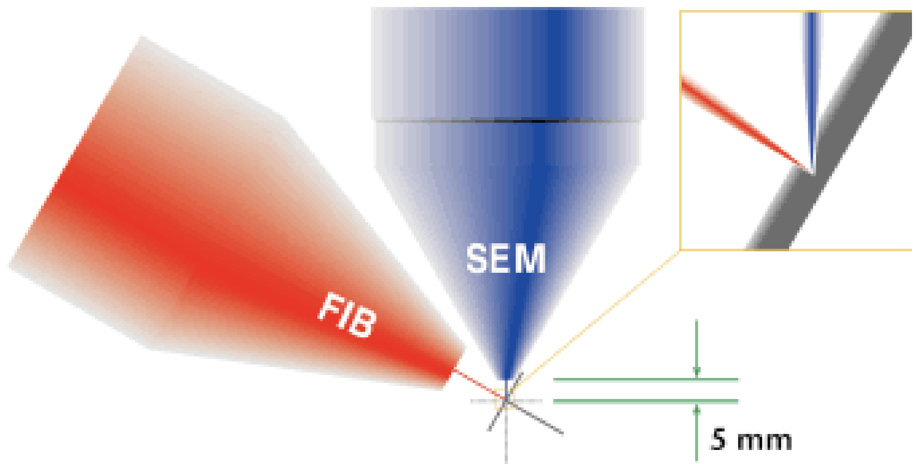
- From FEI to ARC to ESA to Oregon Physics

Oregon Physics: from idea to start up

Oregon Physics is a privately owned company situated in Portland.

Products:***Hyperion***^{TM} ***FIB*** Plasma ion source for inert FIB (Focused Ion Beam) and fast milling (xenon, helium, oxygen)





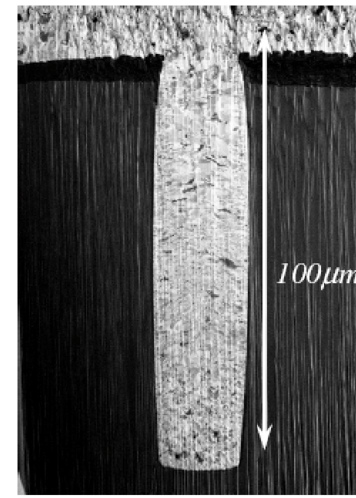


Fig. 4. Xe^+ FIB image.

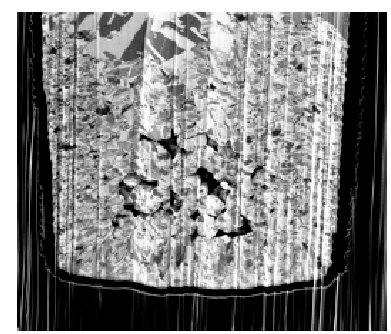


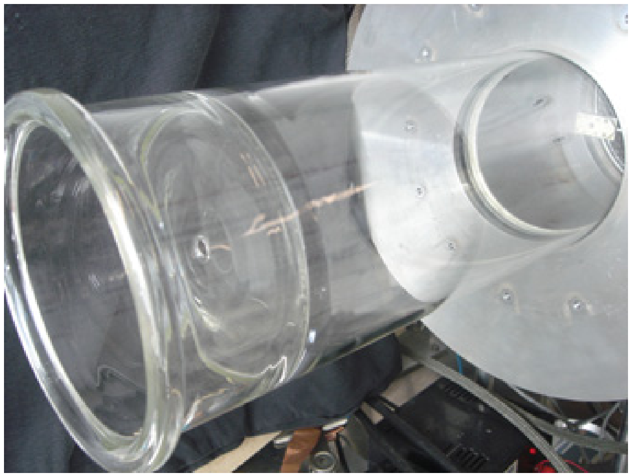
Fig. 5. FIB induced SE image.

Dual beam plasma for milling and high resolution liquid metal ion source for imaging

Typical Helicon source at ANU

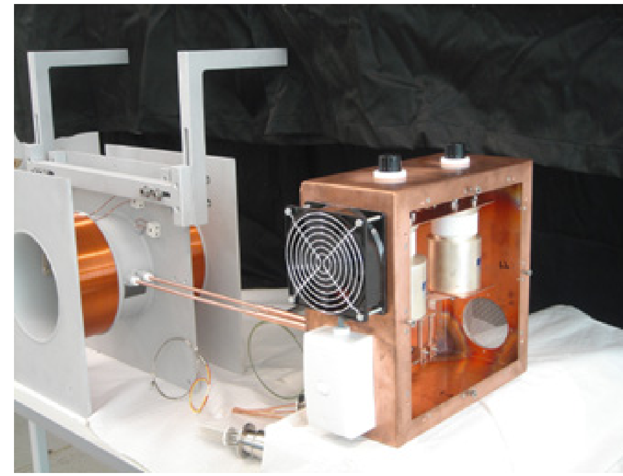
Use of magnetic field to access to various plasma modes and parameter ranges

Glass tube

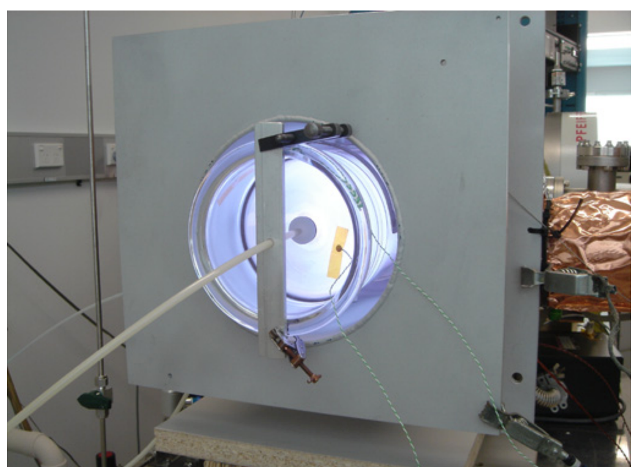


'Helicon' antenna

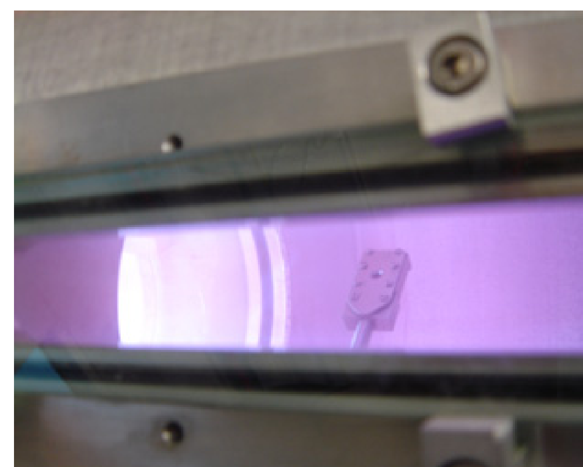
Solenoids



Vacuum chamber



Plasma



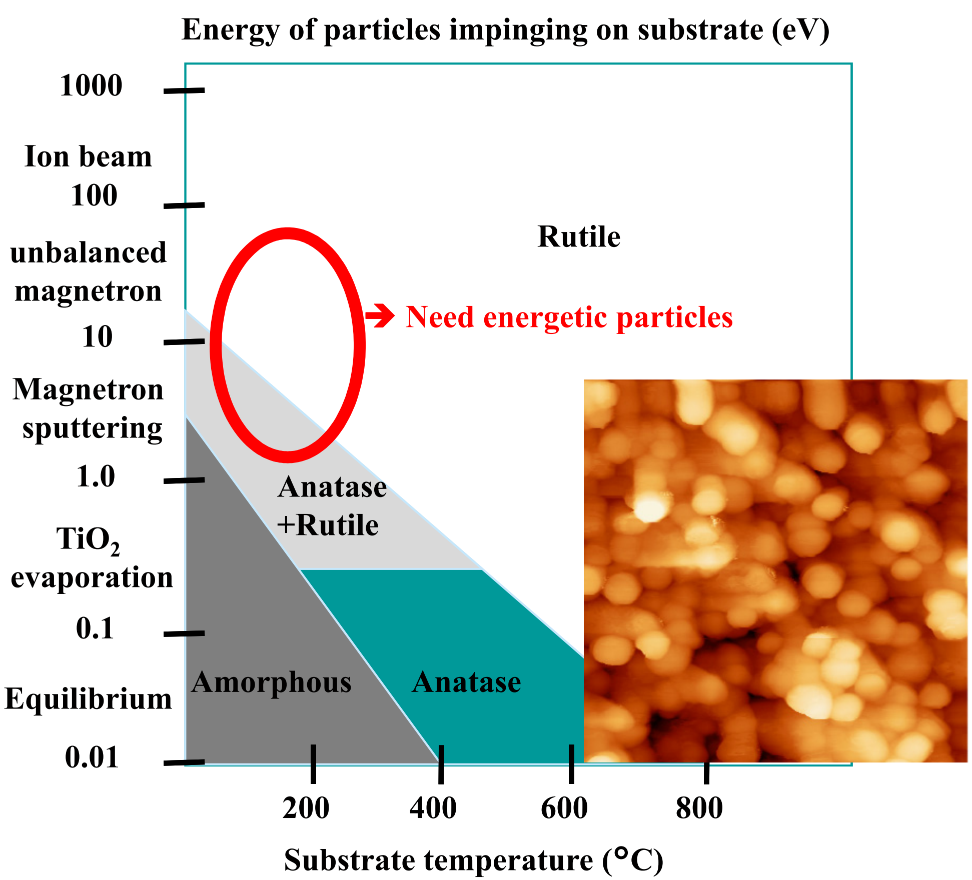
Plasma probe

Material science: low T, ion flux

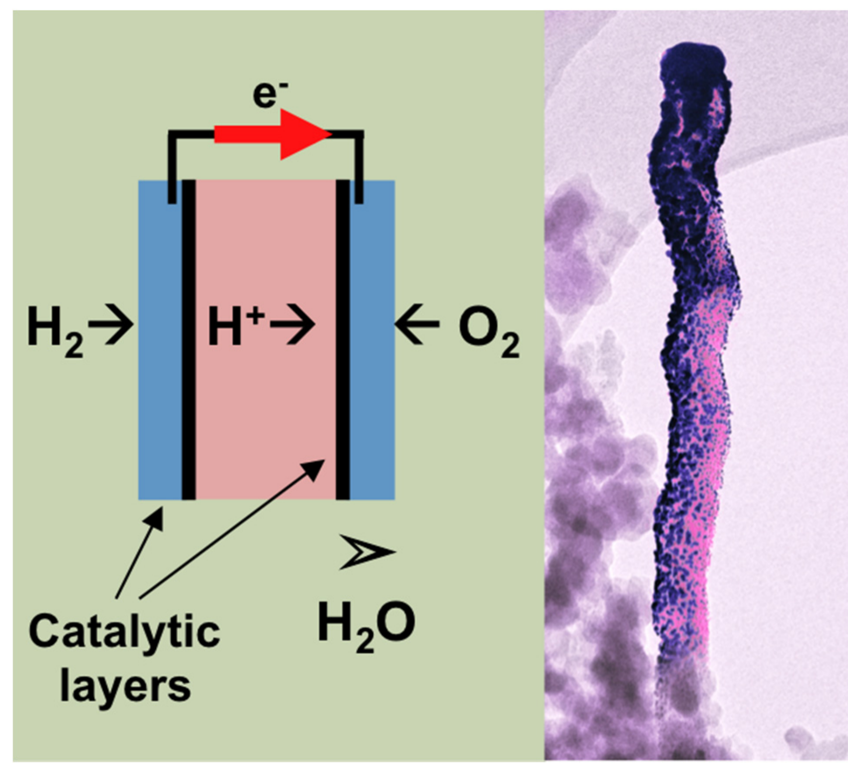
Effect of high ion flux and low substrate temperature on various growth mechanisms

1- HARE: Crystalline N doped TiO_2 at low temperature for photocatalysis (antibacterial applications, water treatment etc…)
2- SOUTHERN CROSS: CNFs coated with Pt at low temperature for efficient catalytic reactions (hydrogen fuel cells)

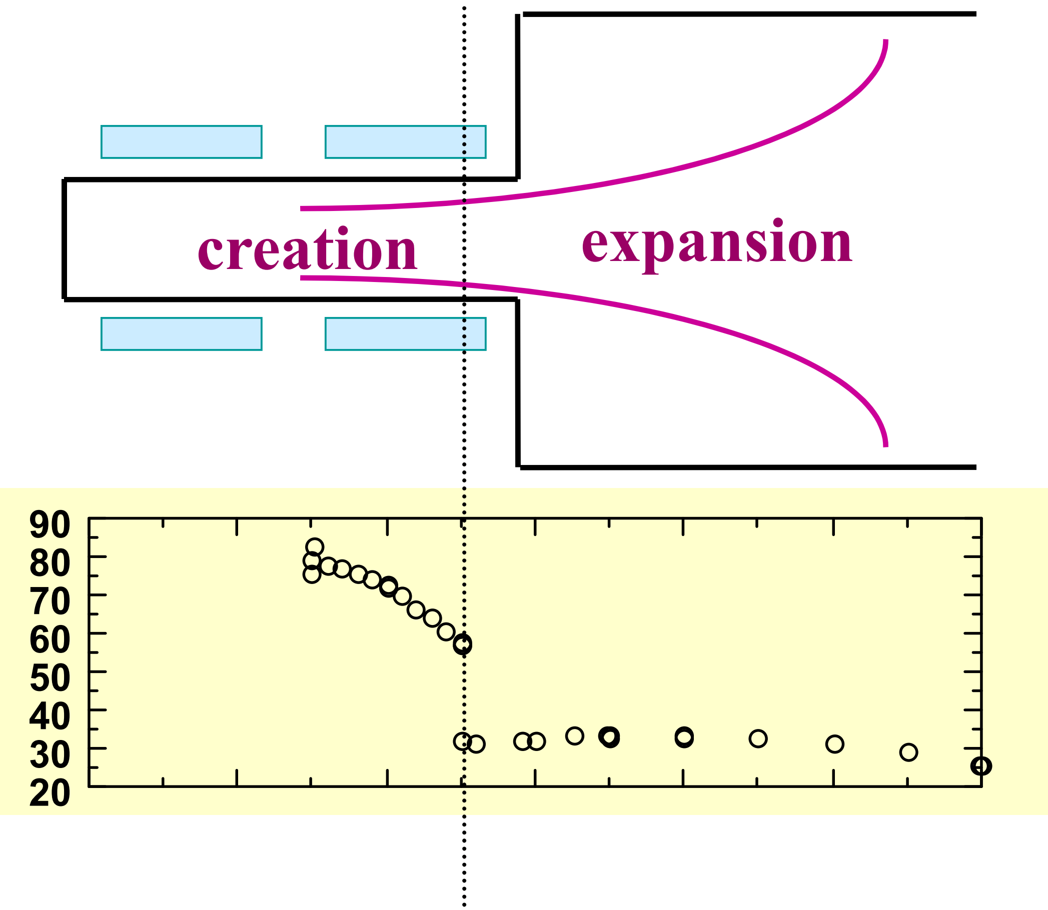
1



2



Low pressure expanding plasmas



Boltzmann relation for e⁻:

$$\nabla p = \nabla(n_e T_e) = -e n_e E$$

Isothermal e⁻:

$$n(z) = n_0 \exp\frac{e\phi(z)}{kT_e}$$

E **is created to retard the e⁻**

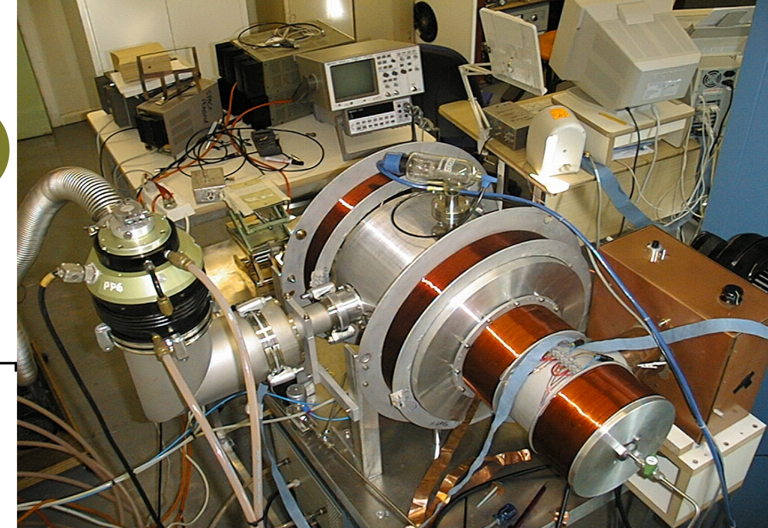
Ions are accelerated

Can add divergent B field in area of expansion

Spontaneous formation of an electric Double Layer

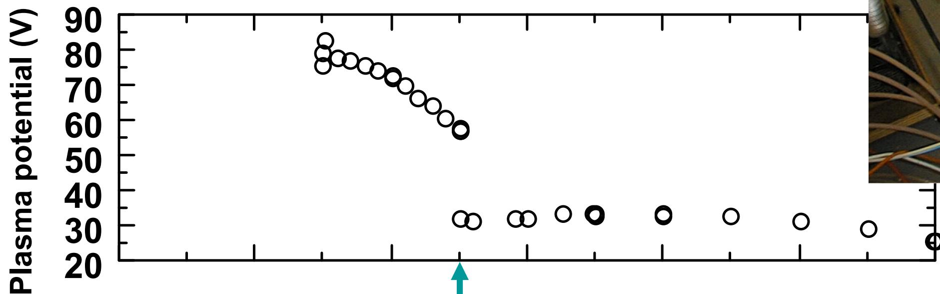
D14cm

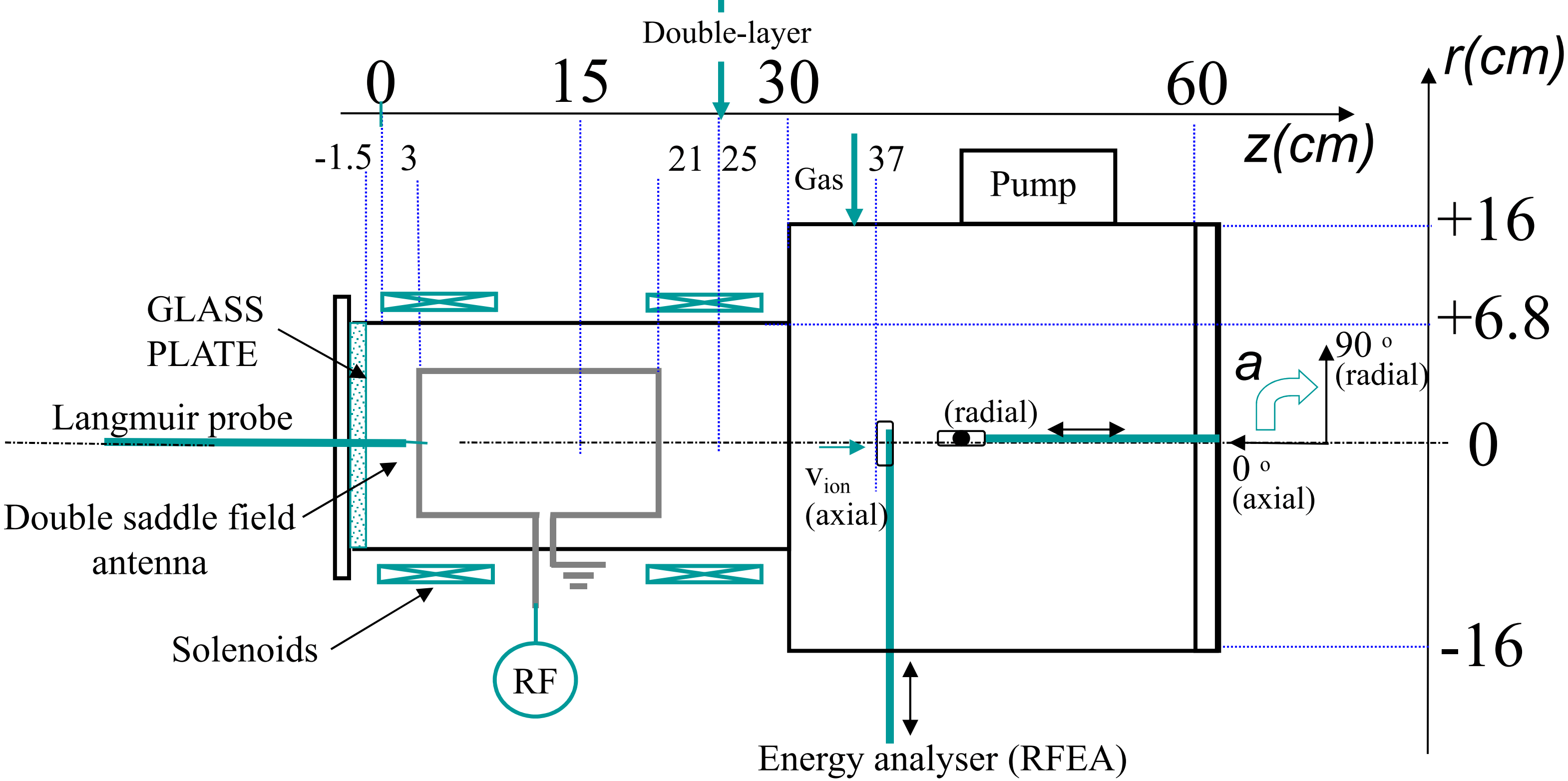
CHI KUNG:
Helicon Double-Layer (DL)



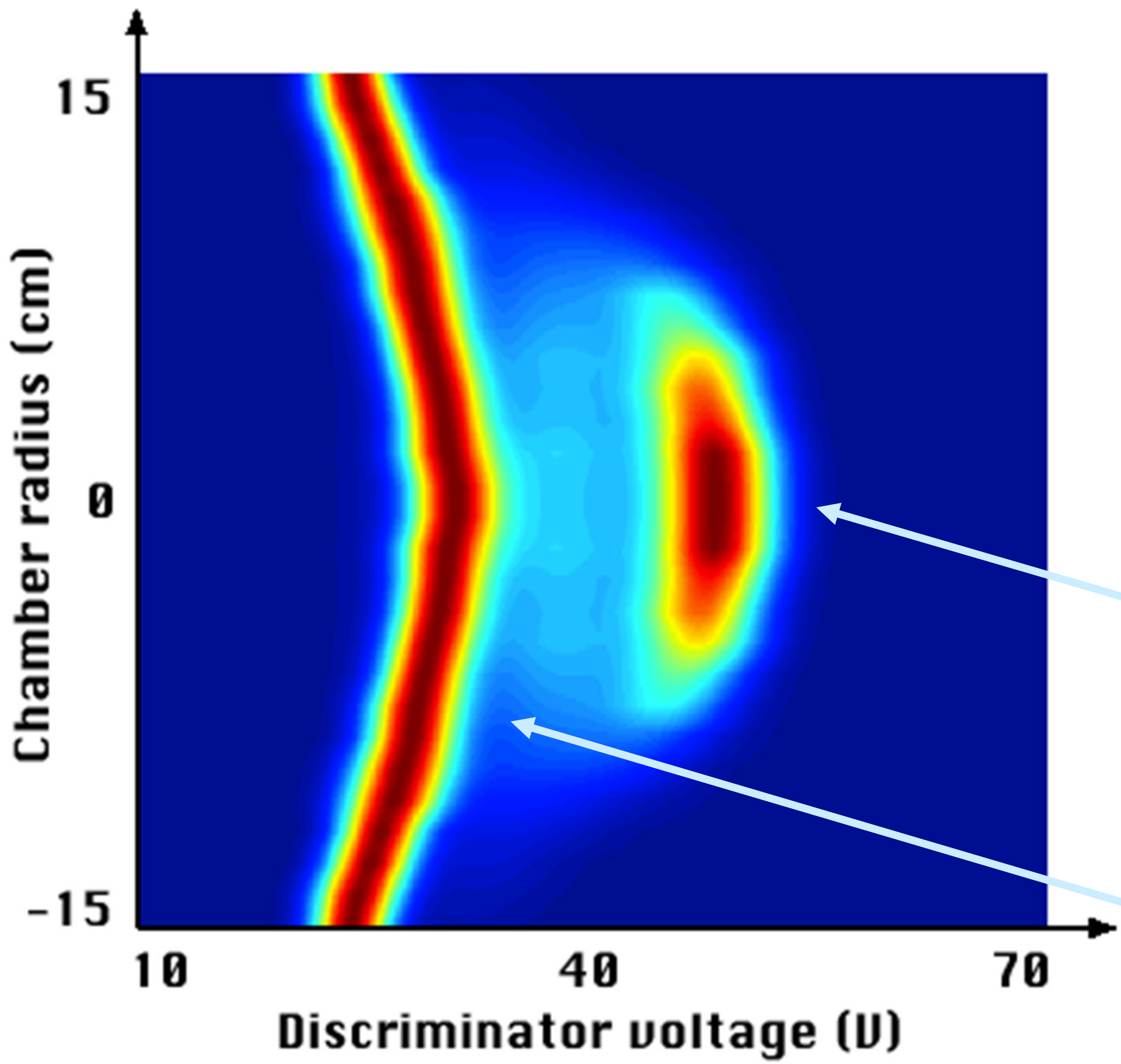
March 1999

Current-free DL

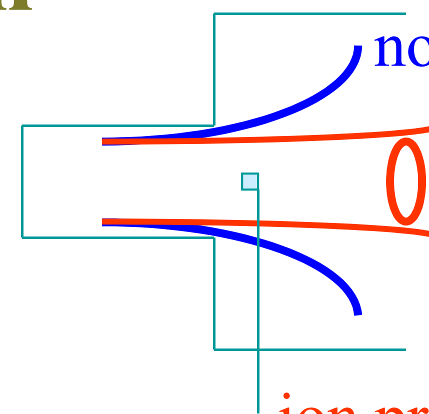


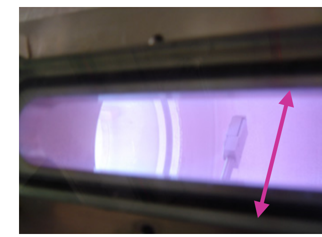


Double Layer mode: ion beam



(~ ion energy)





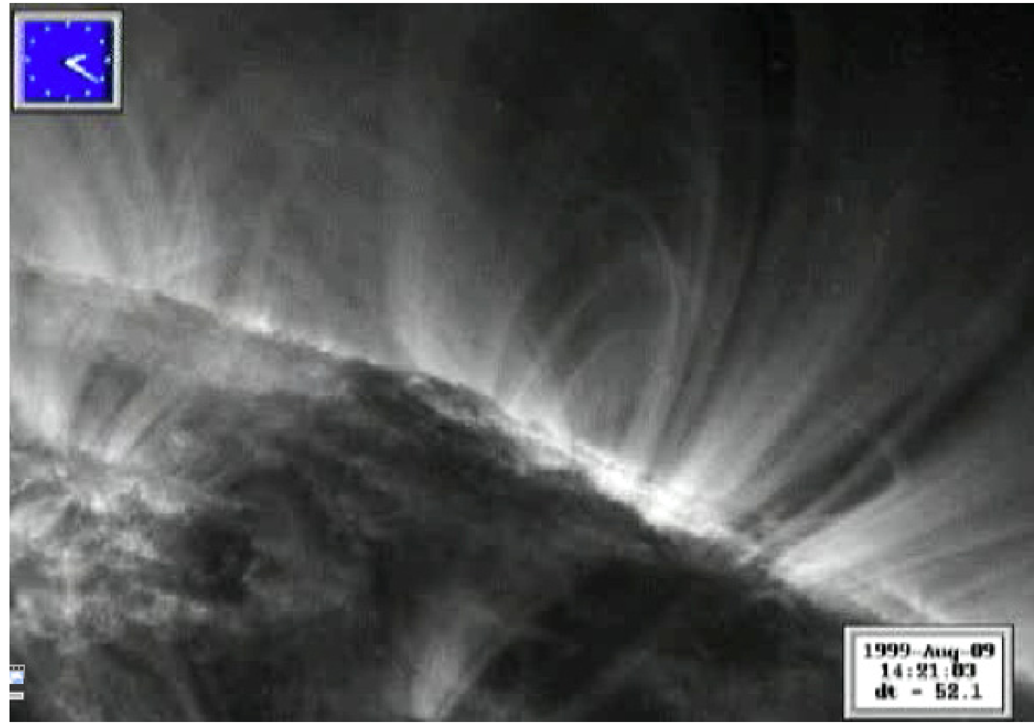
50 eV ion beam:
supersonic (≥10km.s^{-1})
Low beam divergence
A_{beam}~150 cm^2

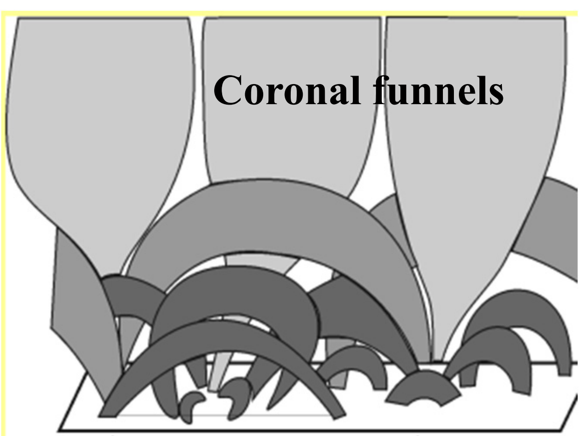
Local downstream
plasma potential

Solar wind: Double Layer scaling?

An expanding magnetised plasma

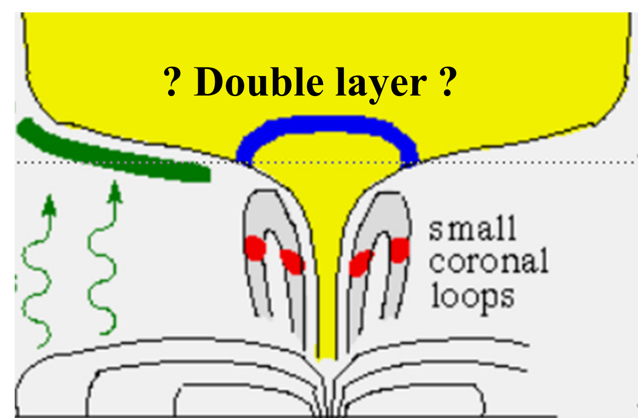
Protons: H^+
α particles: ${}^4_2He^{++}$
Electrons: e^-
...





Dowdy et al., *Solar Phys.*, 105, 35, 1986

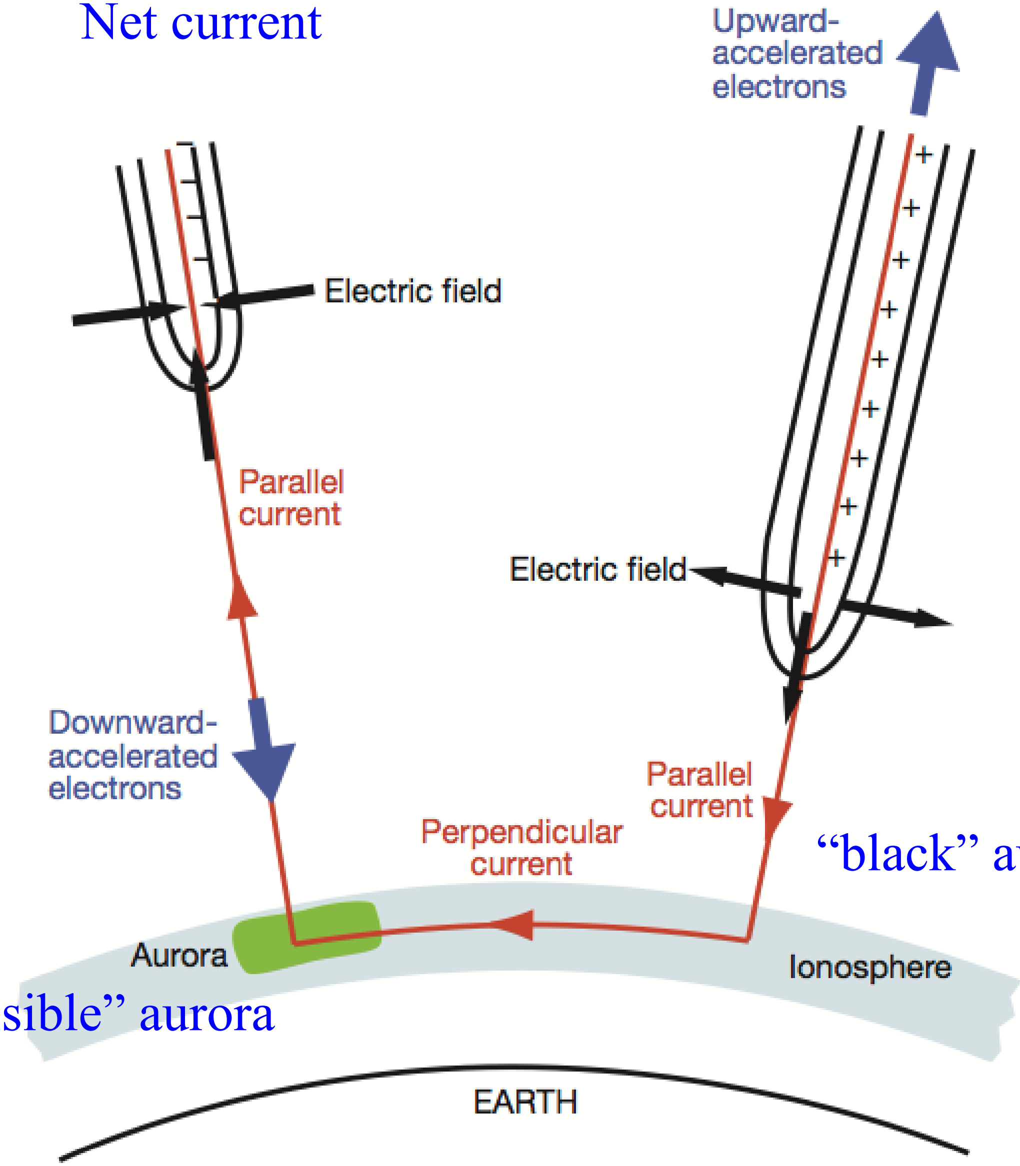
Initial plasma heating in small coronal loops
Unexplained acceleration of solar wind
at 20 Mm, Ne^{7+} at 10km/s
at 5 Mm, C^{3+} at 0km/s



Marsch et al., private communication 2005

Auroral current circuit (field-aligned)

Inwards or Outwards pointing Electric field
Net current

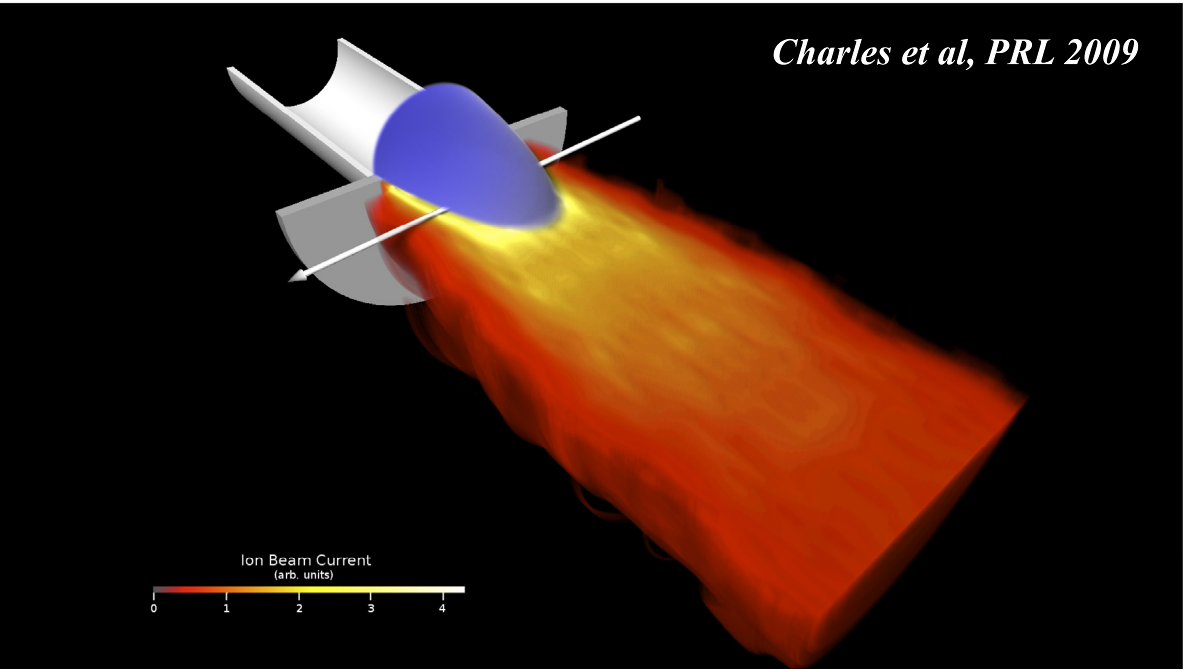


"black" aurora

"visible" aurora

Marklund et al 2001, 2004
Nature 414

Double Layer shape



Complex electron dynamics

From
Helicon plasmas
to
Helicon thrusters

Helicon Double Layer Thruster: HDLT

- Magneto-plasma thruster --> no neutraliser
- No electrodes --> no erosion, infinite lifetime
- No moving parts --> safe and reliable
- Choice of propellants (Xe, Ar, O_2, H_2, CH_4, NH_3, CO_2, N_2…)
- Low divergence
- Scalable in power and Scalable in geometry
- Works in continuous or pulsed modes

Electric versus chemical propulsion

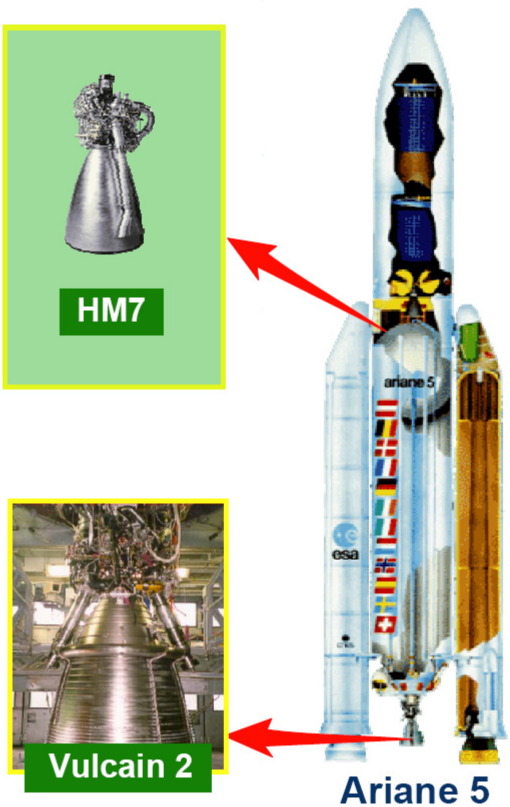
Chemical

Propellant is burnt to create thrust.

Thrust: N - MN

Specific Impulse: < 350 s

Take off (e.g. Earth) and in space



Ariane 5

Electric

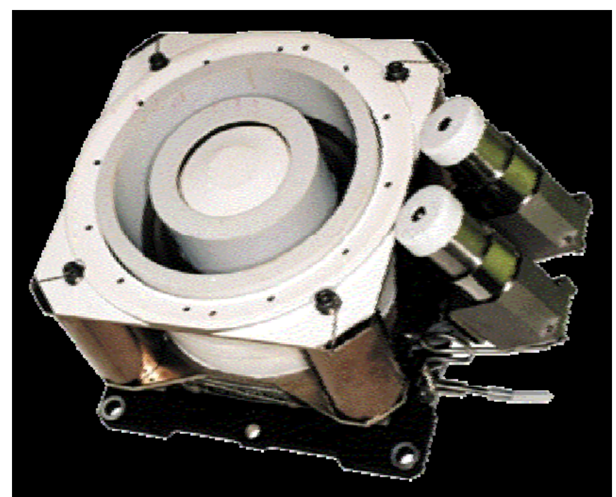
Uses electric and/or magnetic fields to accelerate propellant mass and create thrust.

Thrust: mN - N

Specific Impulse: > 600s

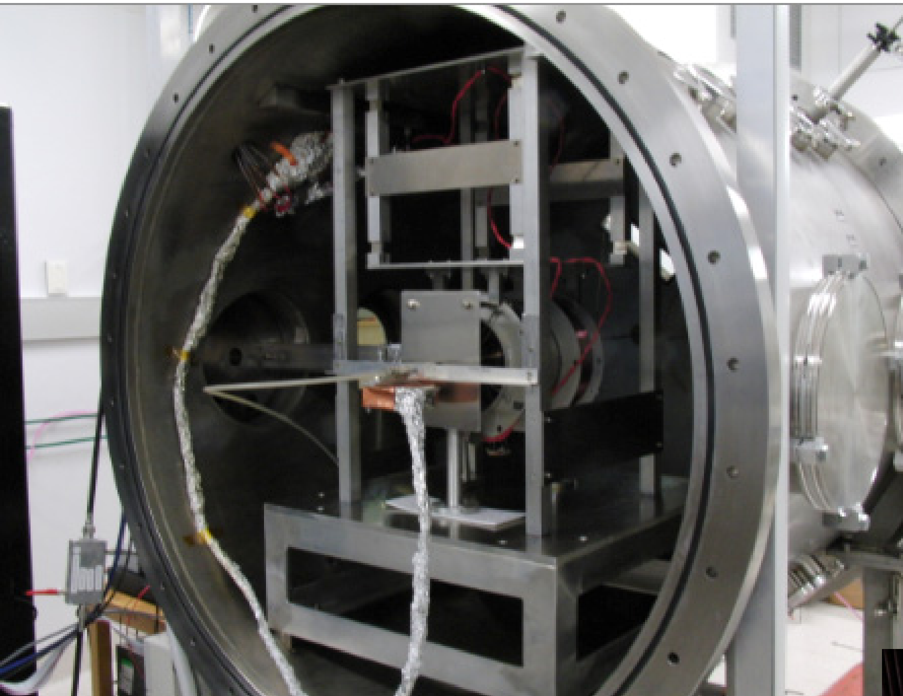
Deployed in space only (vacuum required)

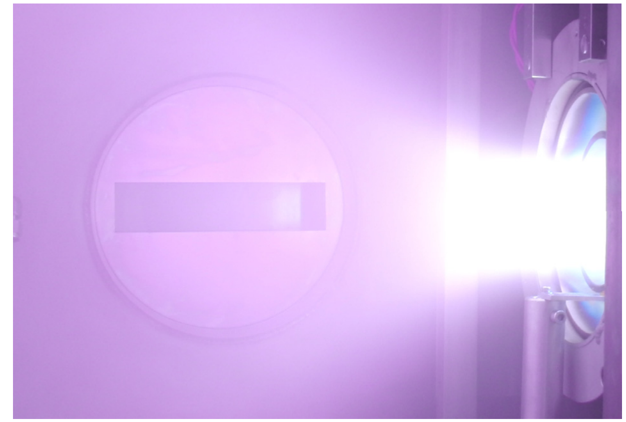
Continuous very low thrust allows a geodesic (shortest time) rather than a ballistic trajectory hence saving time



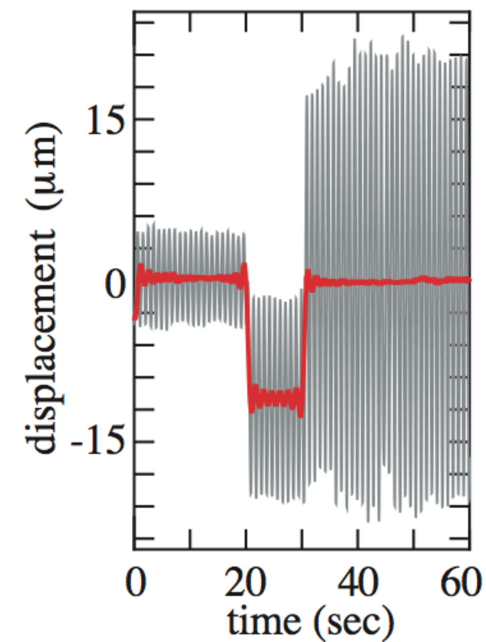
PPS®1350 Hall effect thruster

IRUKANDJI, Diam 1m, Length 1.4 m





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



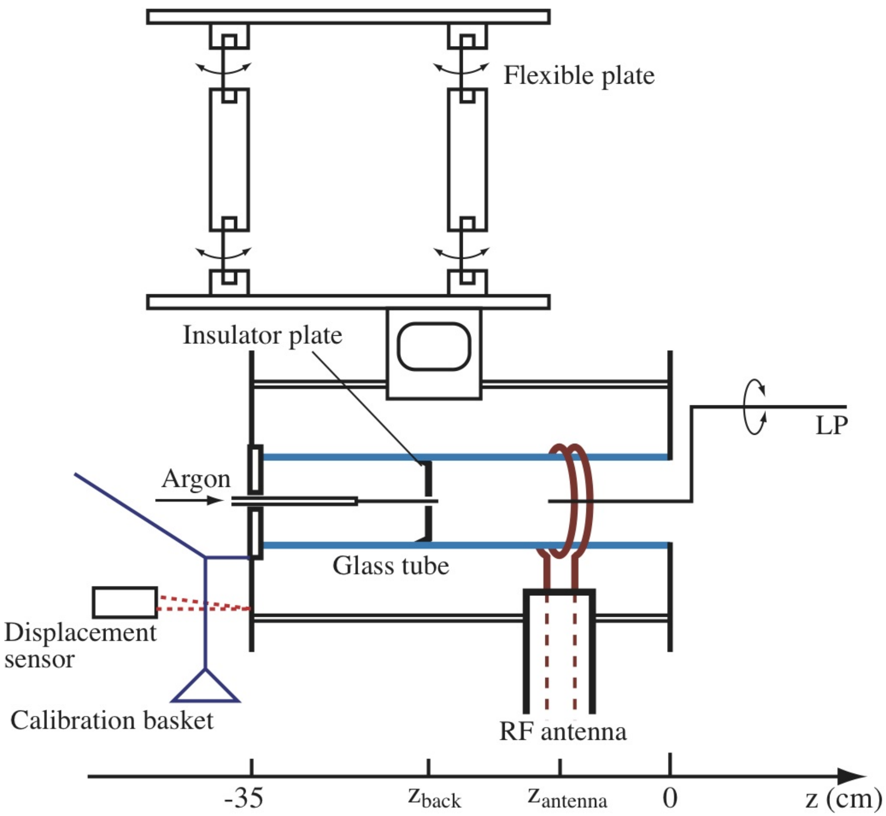
Diagnostics:
Thrust balance
Langmuir Probe
Energy analyser

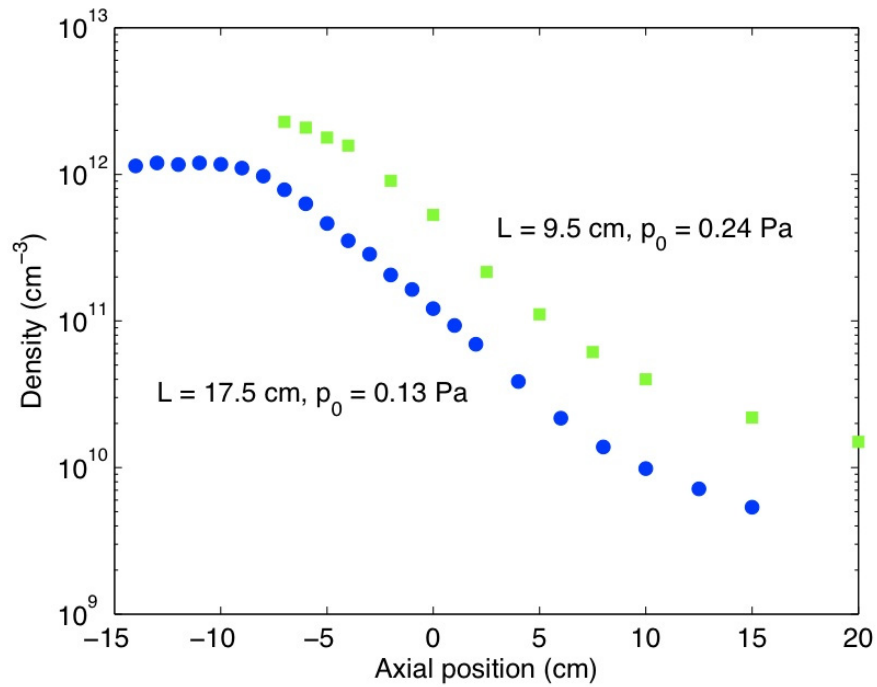
No magnetic field: electron pressure only

$$T = M\langle nv_z^2\rangle A_e + q\langle nT_e\rangle A_e = \text{constant}$$

$$T = q\langle n\rangle_{max} A_e T_e$$

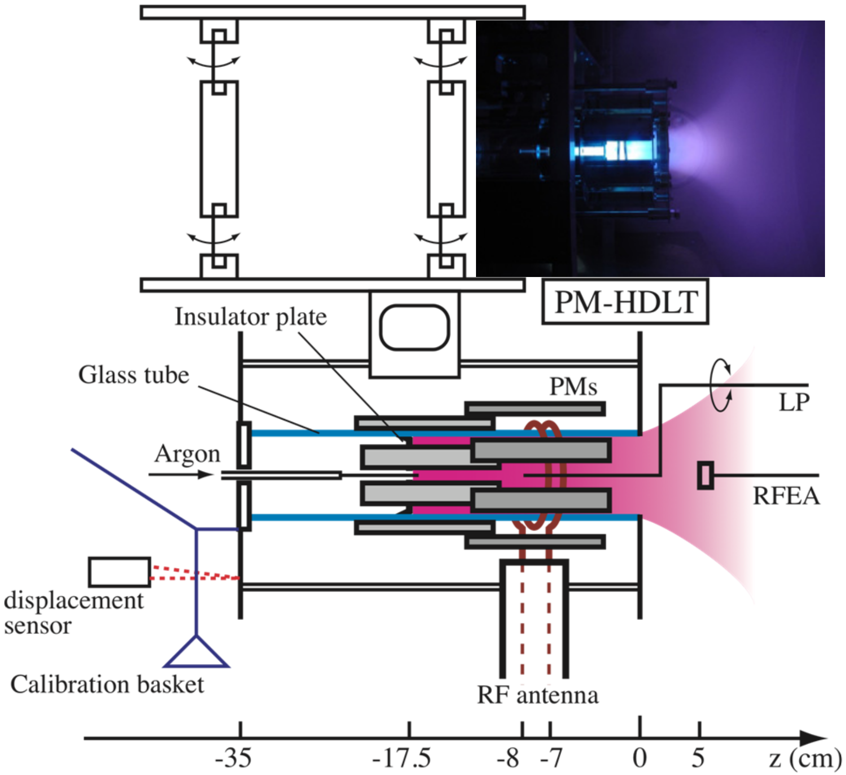
Assume no radial loss on tube
Ion term + electron term = constant along z
All is radially averaged
Use maximum axial value of n where $v_{z\ ion}=0$





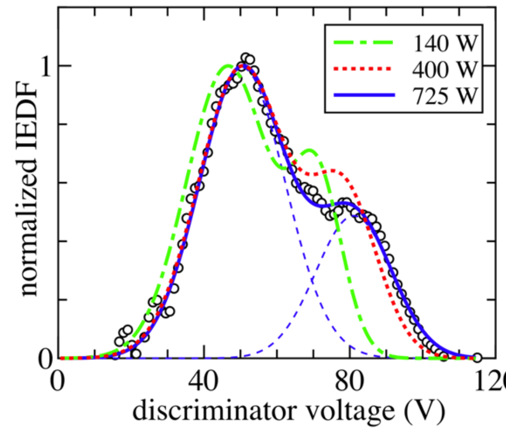
Lafleur et al, PoP 2011

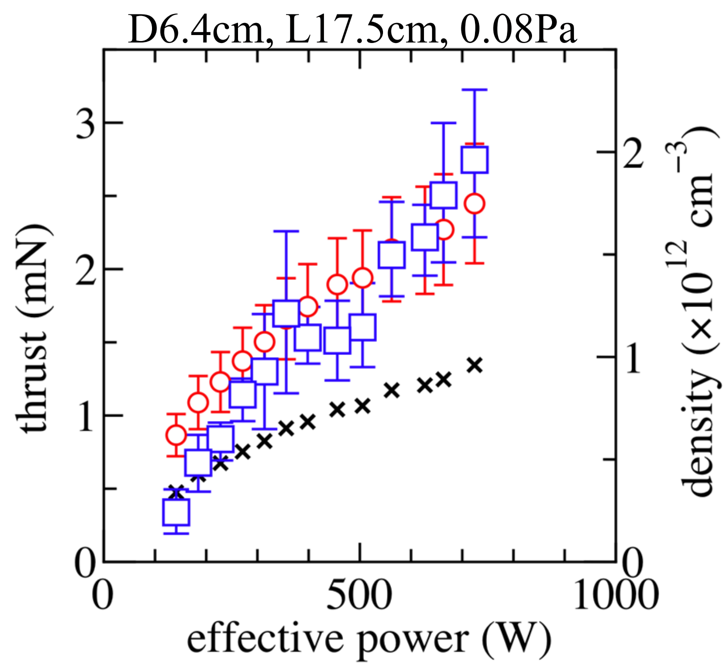
HDLT: B_{field} from Permanent Magnets



$$T = q\langle n\rangle_{max} A_e T_e$$

Takahashi et al, APL 2011



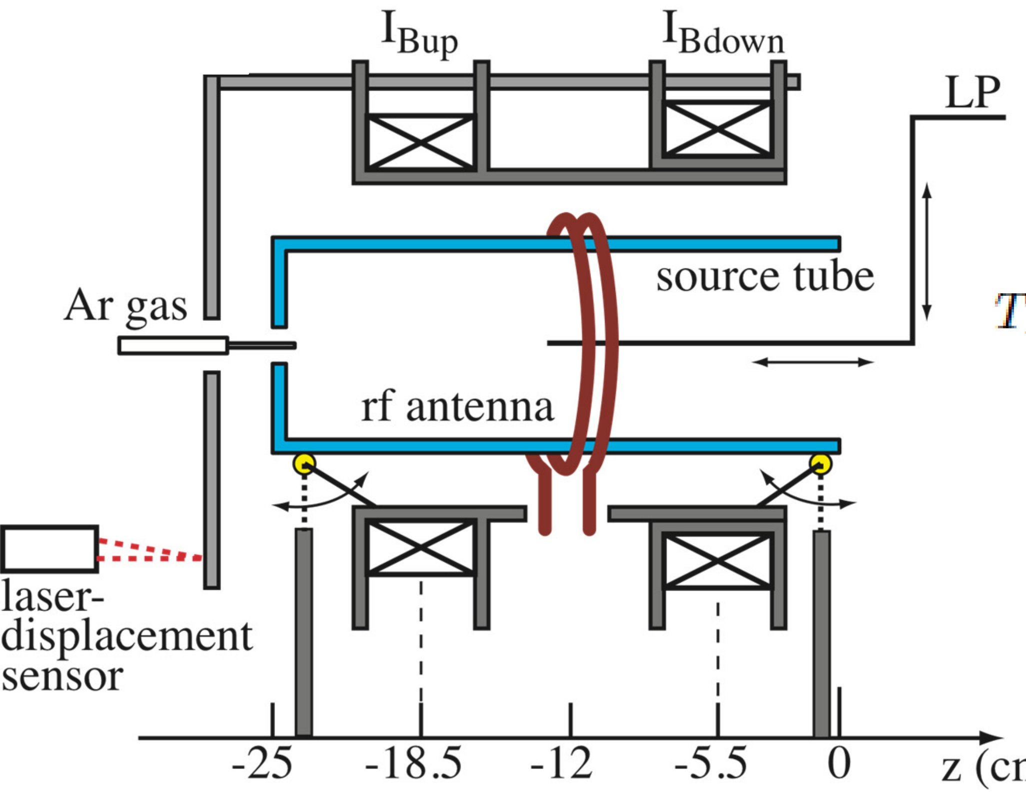


The maximum upstream electron pressure determines the thrust

No major effect from B_{field} in this configuration (tube length is too long)

HDLT: B_{field} from axial solenoids

Takahashi et al, PRL 2011



T_s from electron pressure **T_B from magnetic field pressure**

$$T_z(z) = T_s - 2\pi \int_{z_0}^{z} \int_0^{r_p(z)} r \frac{B_r}{B_z} \frac{\partial p_{e\perp}}{\partial r} dr dz$$

$T_z(z)$ is given by the volume integration of $\partial\tau/\partial z$

$\partial\tau/\partial z$ corresponds to the gain of axial momentum flux at unit cross section in the r - θ plane.

2D mapping of Bfield and electron pressure needed

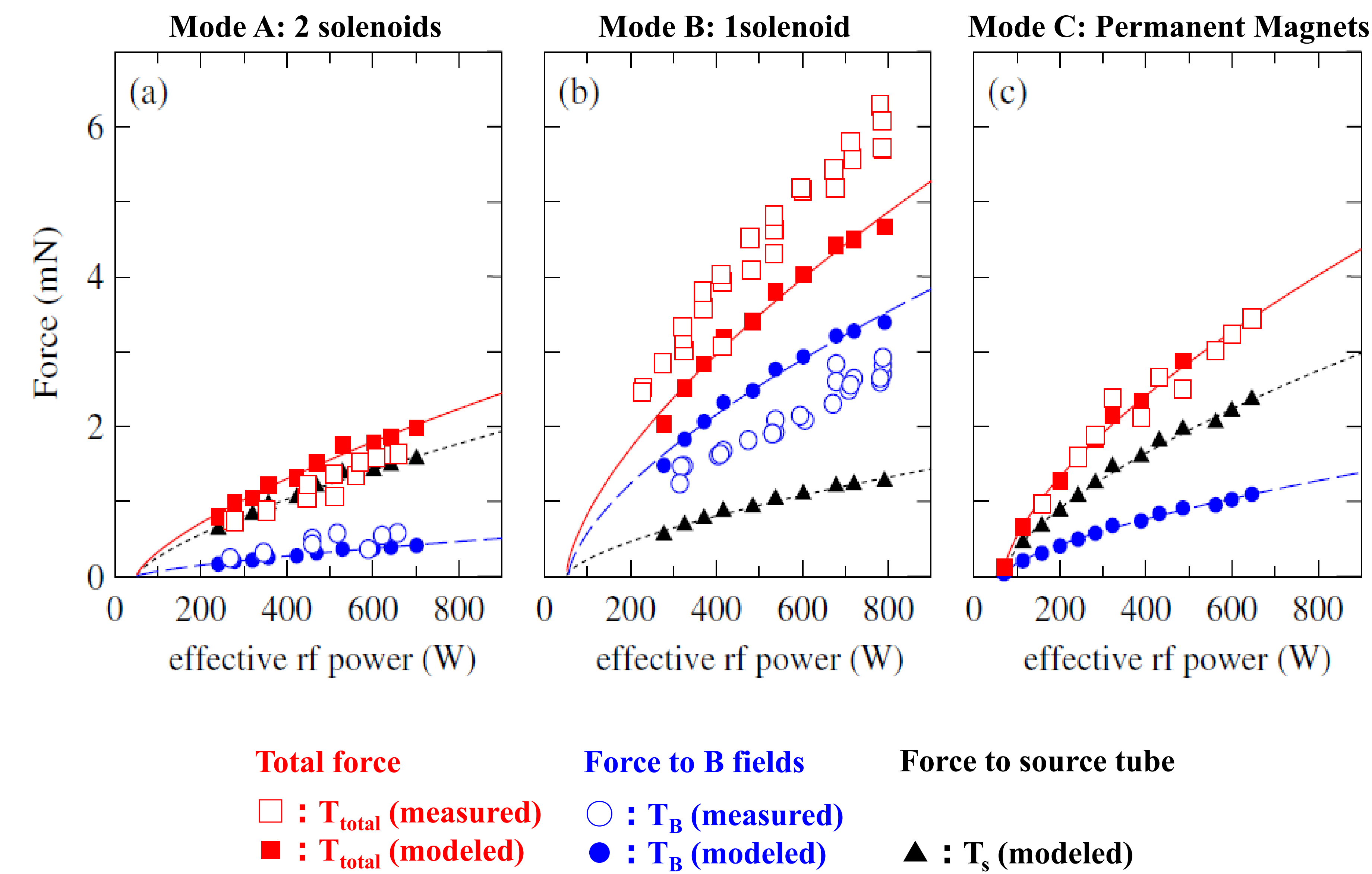
Thrust from electron pressure (backwall) & from magnetic field pressure

Measurement of total thrust: cavity+solenoids attached to balance

Measurement of thrust from B_{field}: only solenoids attached to balance

Check permanent magnet configuration for shorter cavity length

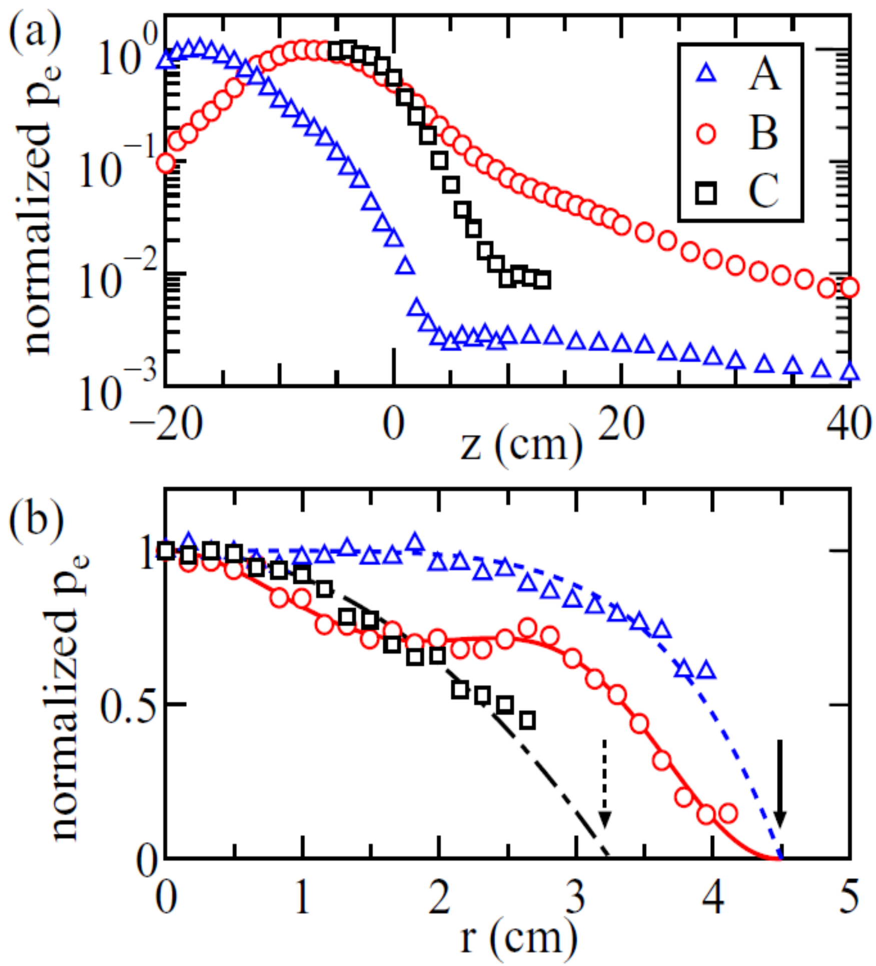
Axial force measurement on cavity and B_{field}

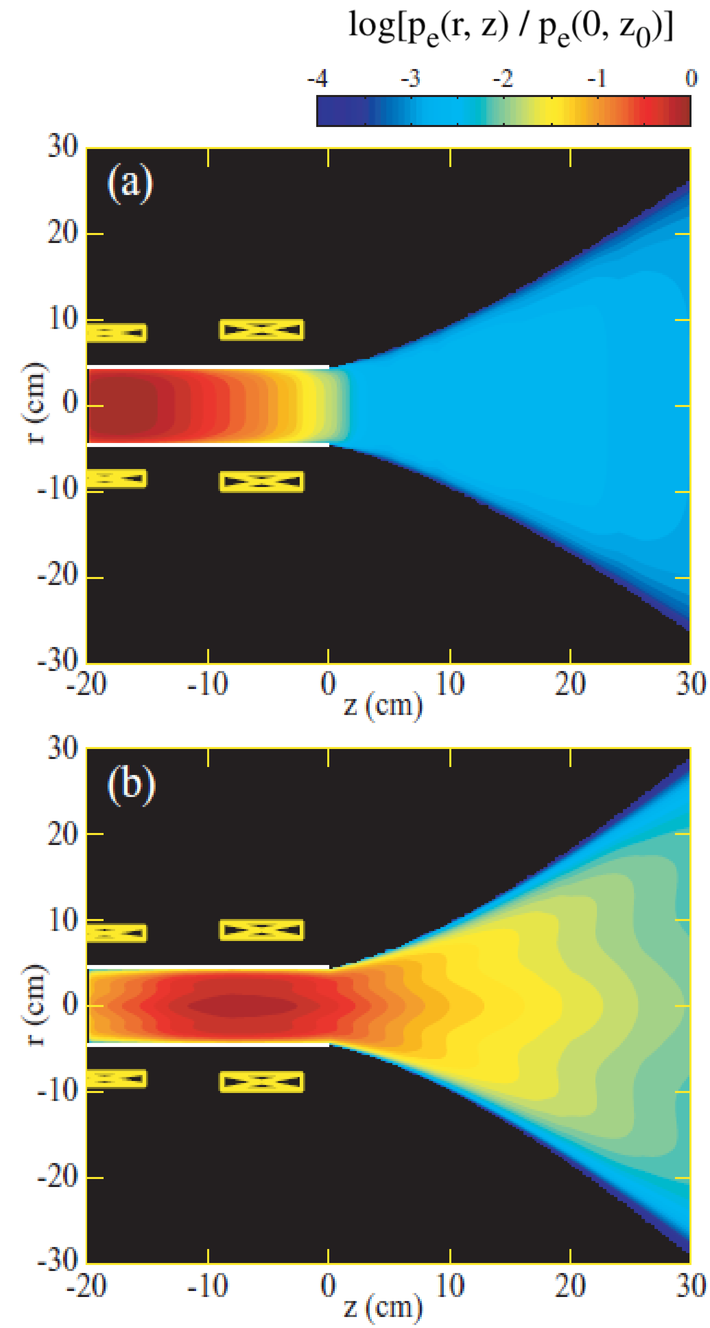


Takahashi et al, PRL 2011

Electron pressure measurements and model

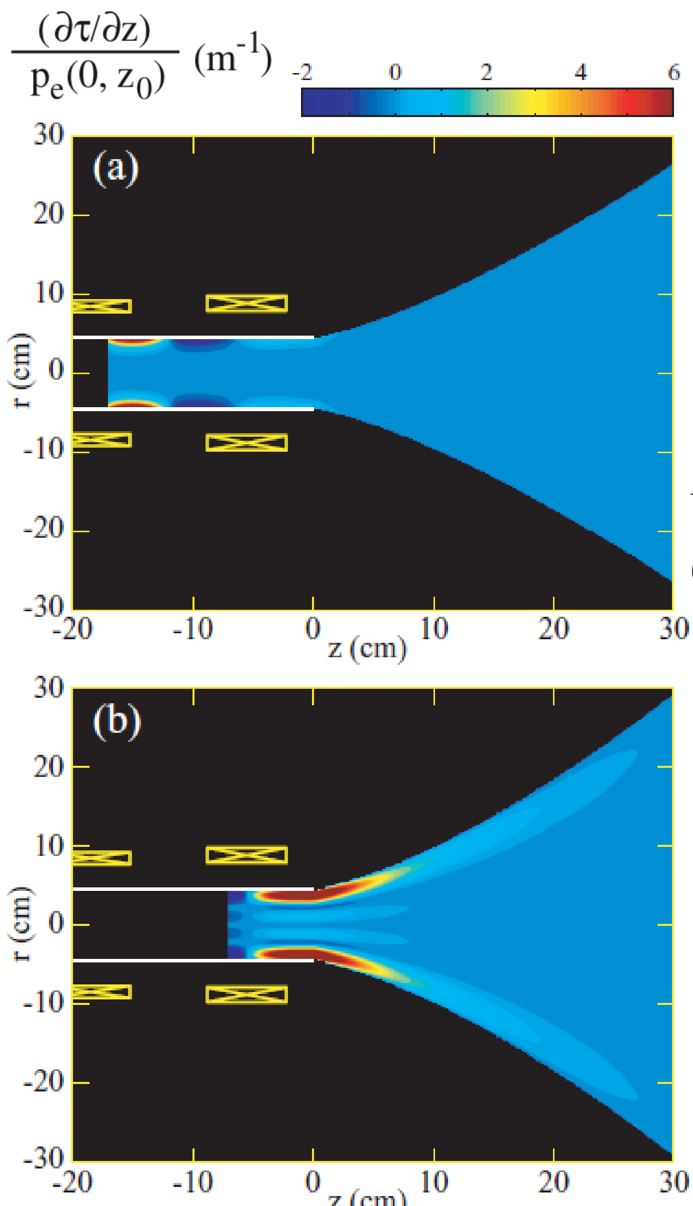
Takahashi et al, PRL 2011, PoP submitted





Plasma radius expands along B fields.
Radial profile is conserved.
Pressure outside the plasma radius is zero.

Magnetic field pressure measurements and model



Thrust gain profile

$$T_{\mathrm{total}}(z) = T_s - 2\pi \int_{z_0}^{z} \int_0^{r_p(z)} r \boxed{\frac{B_r}{B_z} \frac{\partial p_{e\perp}}{\partial r}} drdz$$

Upstream electron pressure

(= total momentum of ions and electrons for no Bfield case)

Momentum gain due to JxB force

J : electron diamagnetic current

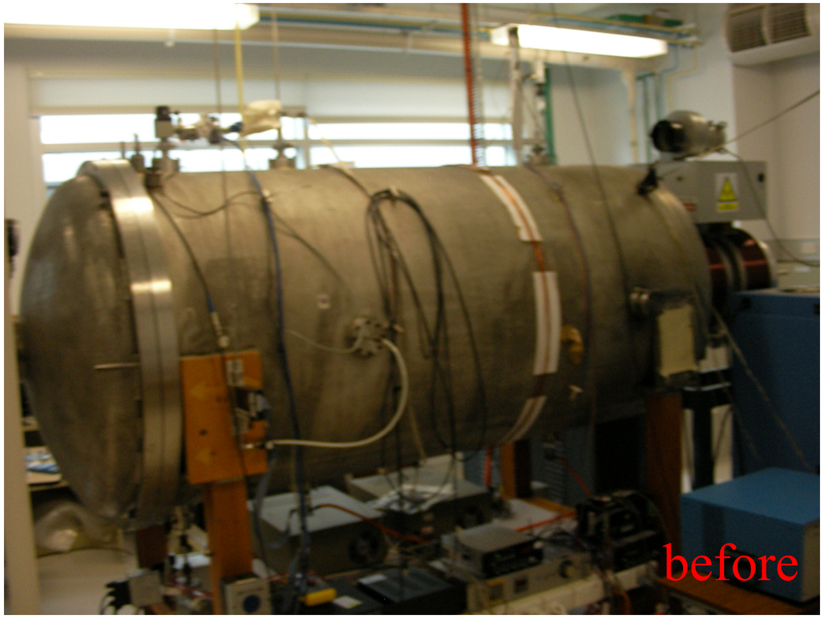
B_r: applied radial magnetic field

***T* is conserved for no magnetic field case**

***T* increases due to the Lorentz (JxB) force resulting from electron diamagnetic current and radial component of the expanding B field.**

Takahashi et al, PRL 2011, PoP in press 2012

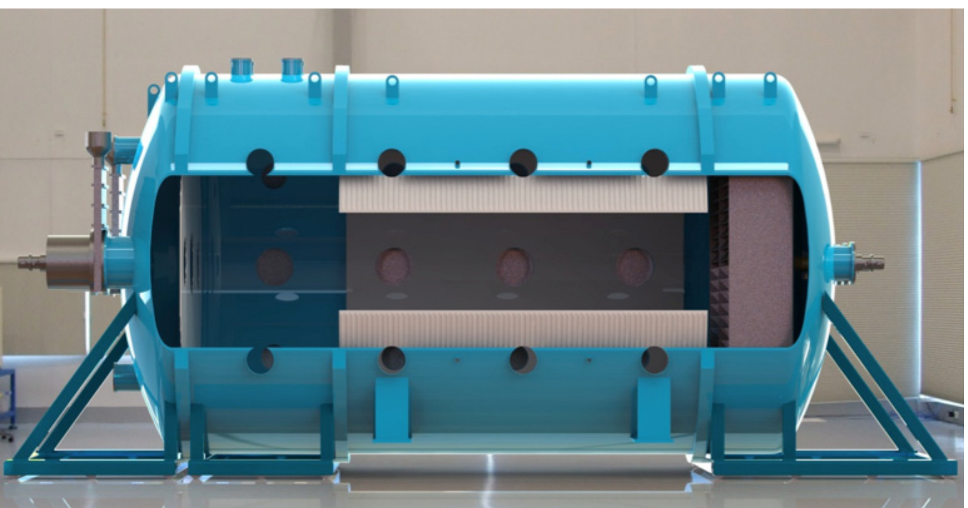
WOMBAT, Diam 1m, Length 2 m



WOMBAT upgrade at RSPE
Cryogenic pumping
Automated plume diagnostics
Extended balance
Optimise **HDLT Gen II+** in preparation for space qualification
Space qualification in WOMBAT XL (Diam 3m, Length 4m)

2013: Advanced Instrumentation Technology Center

Mount Stromlo, Canberra, Australia http://www.mso.anu.edu.au/technology/



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