Magnetic nozzles for electric propulsion

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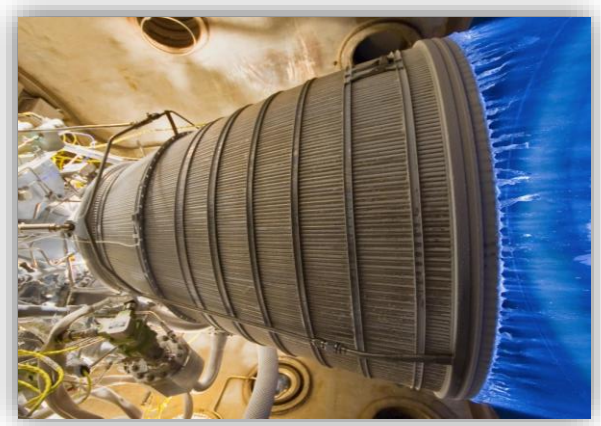
EP2 uc3m

Contents

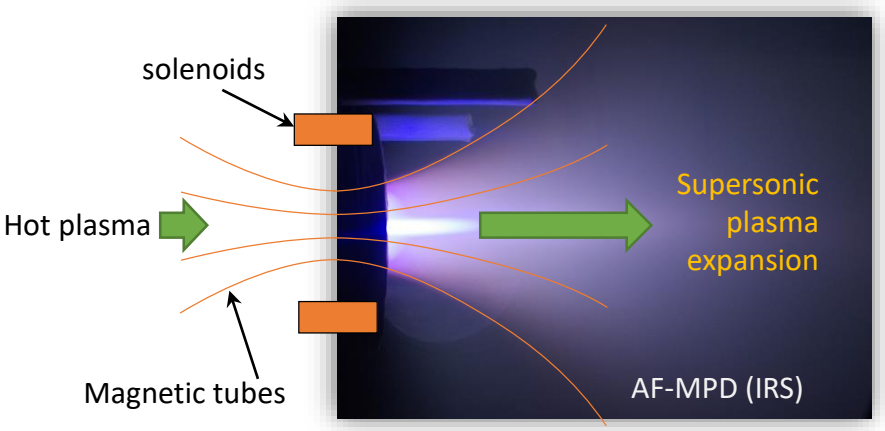
Lecture notes:
M. Merino, E. Ahedo, "*Magnetic Nozzles for Space Plasma Thrusters*"
Encyclopedia of Plasma Technology, 2016.
Downloadable at: http://mariomerino.uc3m.es

What is a magnetic nozzle?

- A magnetic nozzle (MN) is a convergent-divergent magnetic field created by coils or permanent magnets to guide the expansion of a hot plasma, accelerating it supersonically and generating thrust
- The MN works in a similar way to a traditional "de Laval" nozzle with a neutral gas, except that:
  - The nozzle walls (and its reaction force on the expanding gas) are substituted by magnetic lines (and a magnetic force on the charged particles that compose the plasma)



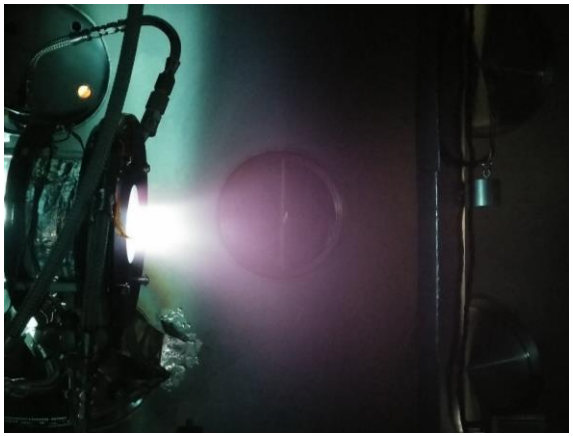
RL-10 rocket "de Laval" nozzle



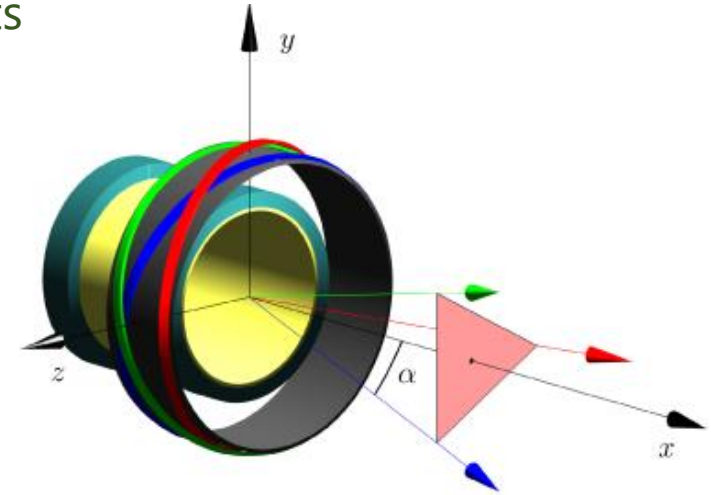
A magnetic nozzle in operation

What is a magnetic nozzle?

- The MN has the following advantages:
  - It operates contactlessly: we avoid touching the hot plasma
    - No erosion of the walls, no heat load, no plasma losses
  - MN shape can be modified in-flight, by changing the coil currents
    - We can throttle thrust F and specific impulse I_{sp} to adapt to varying mission requirements
  - With more than one coil, we can create 3D magnetic configurations to deflect the plasma jet laterally
    - Thrust vector control without moving parts



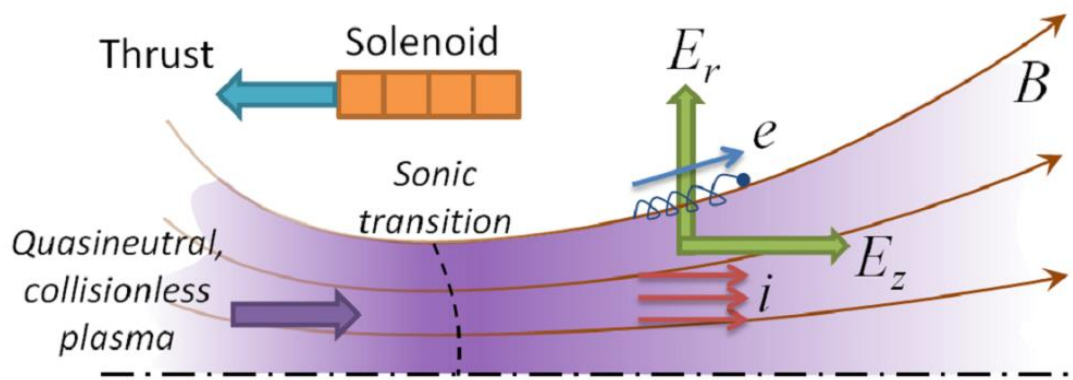
MN of SENER-EP2 Helicon plasma thruster HPT05 running on Xe (EP2 lab)



3D MN configuration for thrust vector control

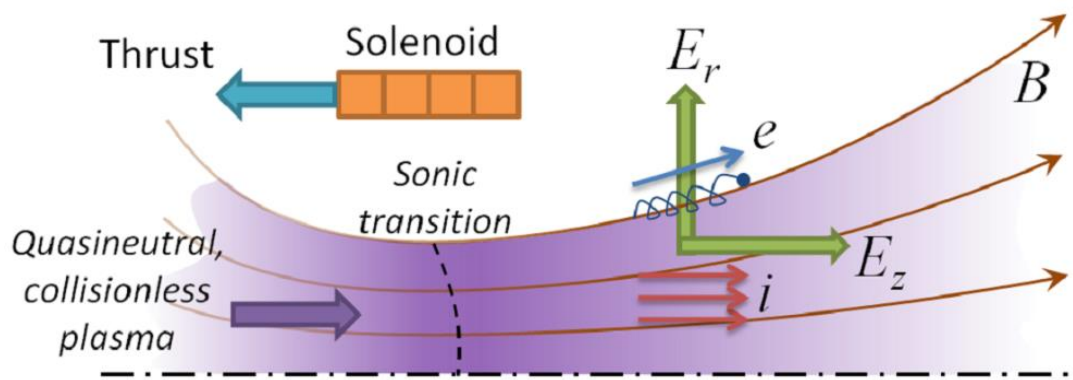
Principles of operation

- The plasma is composed of electrons (–) and ions (+), but remains *quasineutral*: if charges try to separate from each other an electric field appears to prevent it
- Charged particles spiral about the magnetic field lines
  - Electrons, which are very light, perform tight orbits and are easily guided by the magnetic field $\boldsymbol{B}$. The electron species as a whole feels a *magnetic force* that confines them radially and pushes them downstream
  - Ions, which are heavy, are almost unaffected by $\boldsymbol{B}$ (unless it is large)
  - As a result, electrons try to follow the MN geometry, while ions tend to continue straight.



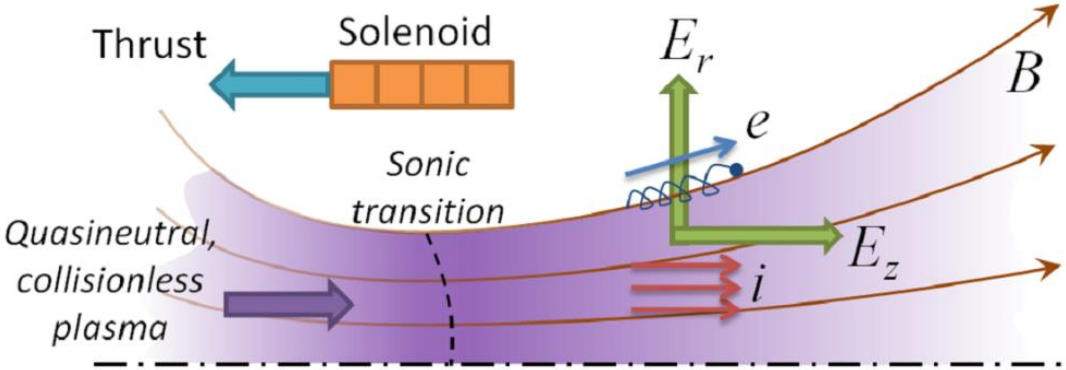
Principles of operation

- Electrons have a large thermal energy (ions usually don't)
  - Electrons try to expand into vacuum ahead of the ions because their thermal velocity is much higher (they are light and hot)
  - As they expand downstream, they cool down
- The different behavior of ions and electrons would give rise to charge separation, but an *ambipolar electric field* $\boldsymbol{E}$ builds up to prevent it
  - This $\boldsymbol{E}$ field expands ions radially and accelerates them axially. Ions undergo a sonic transition at the magnetic throat and become supersonic in the divergent part of the nozzle, creating the high-velocity plasma jet
  - At the same time, the $\boldsymbol{E}$ field confines the electrons and prevents them from escaping downstream, except for the most energetic ones



Principles of operation

- Each gyrating electron generates its own magnetic field, which opposes the applied one. Together with the (small) ion contribution, this is the *plasma-induced magnetic field*
  - Macroscopically, the sum of all electron gyrations is seen as an *azimuthal electric current* in the plasma
- The applied and induced magnetic fields repel each other:
  - This pushes the electrons downstream
  - By reaction, the solenoids that generate the applied field are pushed back: this is the *magnetic thrust* felt by the thruster



Principles of operation

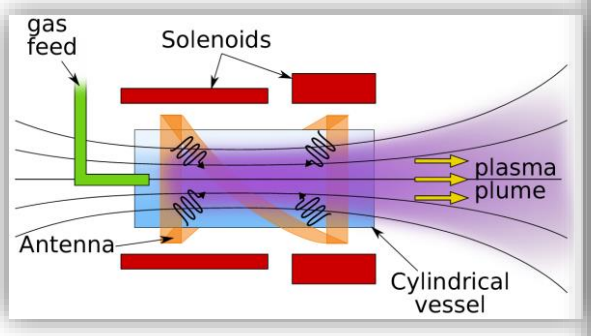
- In summary:
  - The hot electrons try to expand radially and axially
    - The magnetic force confines them radially and pushes them axially.
    - The electric field that appears confines them axially (also radially). At the same time, it accelerates ions axially (also radially)
  - The magnetic reaction force on the solenoids (created mostly by the electrons) is called *magnetic thrust*.
    - From the viewpoint of forces, this is an electromagnetic device
  - The energy that feeds the ion acceleration is the electron thermal energy. The ambipolar electric field acts as the middleman in this energy transaction.
    - From the viewpoint of energy, this is an electrothermal device
  - From momentum conservation, the thrust force felt on the thruster is equal to the momentum flux of the plasma jet downstream
    - Since electrons are very light and cool down downstream, the plasma momentum is essentially equal to the ion momentum:

$$\boxed{F \simeq \frac{m_i}{q_i} I_i u_i}$$

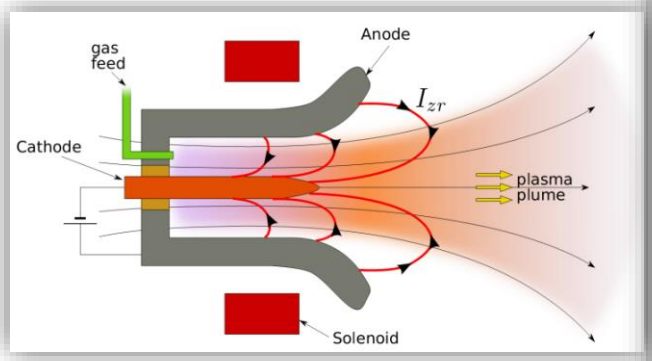
m_i, q_i: ion mass and charge
I_i: ion current
u_i: ion velocity

Plasma thrusters with MNs

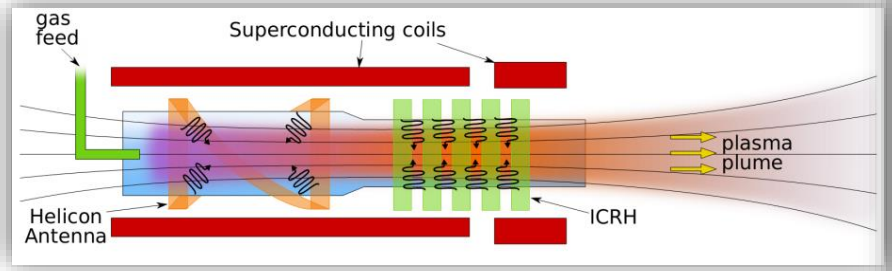
- Helicon Plasma Thruster (HPT)
  - High plasma density ($10^{18} - 10^{20}\ \mathrm{m}^{-3}$)
  - Prototypes in the 50 W – 50 kW range, but still low efficiency: $\eta_T \ll 0.5$

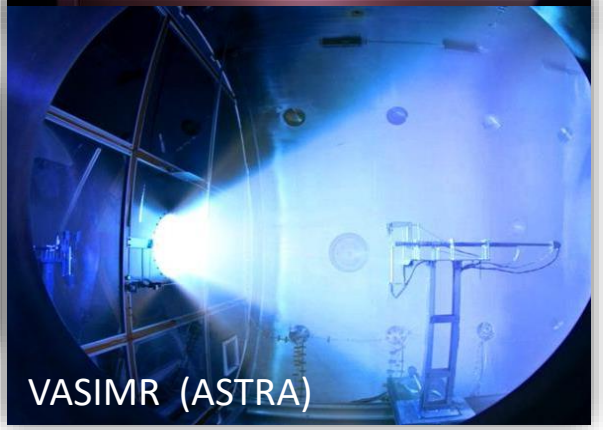


- AF-MPD
  - DC discharge, high power (10 kW – 200 kW)
  - $\eta_T < 0.5$



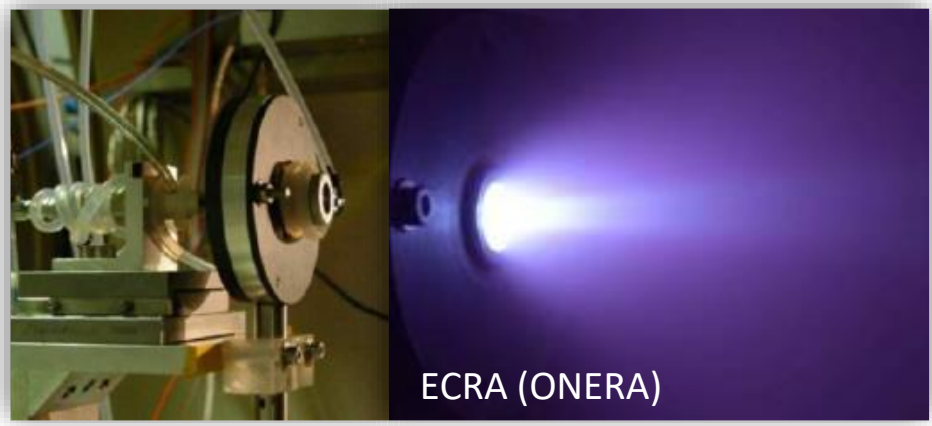
- VASIMR
  - A HPT enhanced with an ICRH stage
  - High power (200 kW)
  - Requires much higher $\boldsymbol{B}$
  - $\eta_T < 0.72$

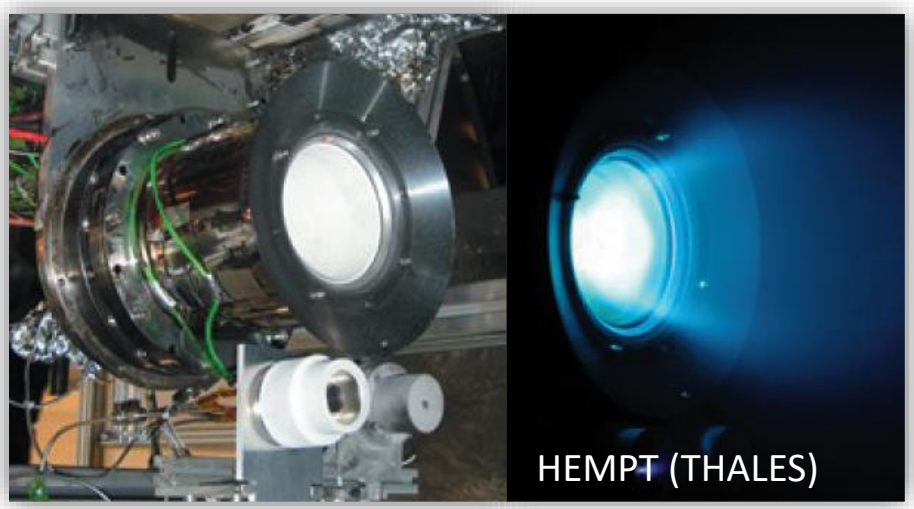


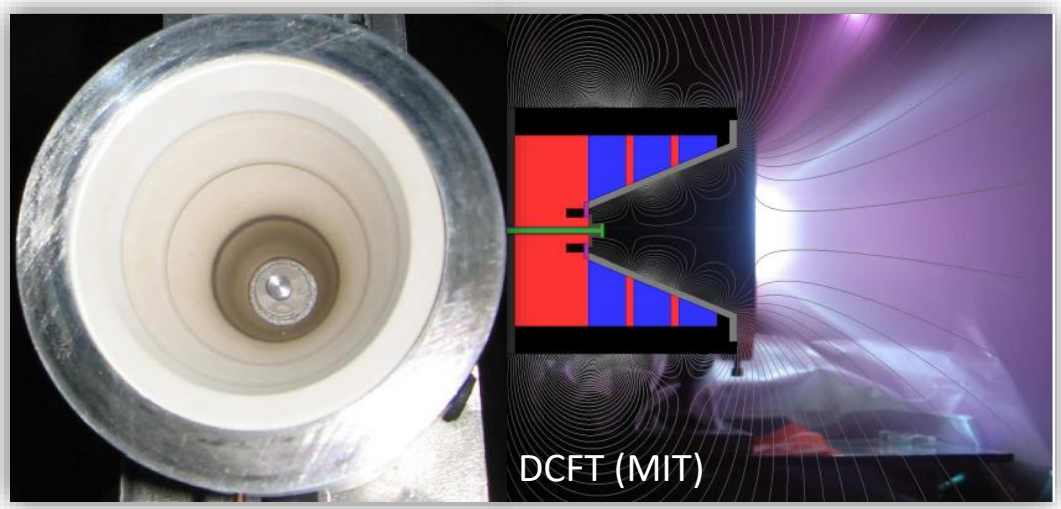


Plasma thrusters with MNs

- Electron Cyclotron Resonance Thruster
  - Similar to HPT but different plasma-wave heating system
- All these thrusters have no external neutralizer
  - Less complex, more lifetime
- All, except AFMPDT, have no electrodes
- Other thrusters with MN-like configurations: HEMPT and DCFT







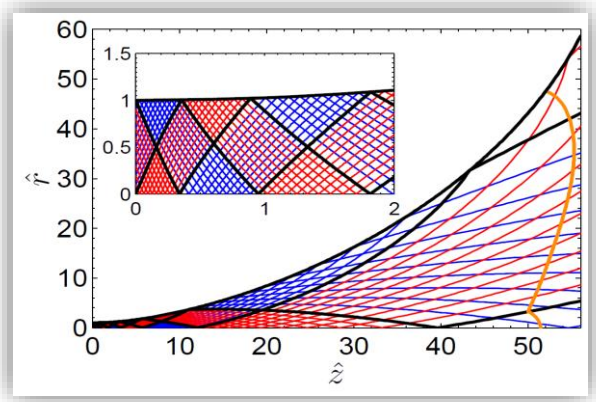
Contents

Acceleration and magnetic thrust

- We consider the steady-state plasma flow in the MN and assume:
  - Quasineutral and collisionless plasma
  - Electrons are fully magnetized and have negligible inertia
  - Ions are cold, compared to electrons, and partially magnetized
  - Plasma-induced magnetic field is much smaller than applied one
- The plasma expansion in the MN can be modeled with the fluid equations for ions and electrons:

$$\left.\begin{aligned} \nabla \cdot (n\mathbf{u}_i) &= 0 \\ \nabla \cdot (n\mathbf{u}_e) &= 0 \end{aligned}\right\} \text{Continuity equations for } i, e$$

$$\left.\begin{aligned} m_i(\mathbf{u}_i \cdot \nabla)\mathbf{u}_i &= -e\nabla\phi + e\mathbf{u}_i \times \mathbf{B} \\ 0 &= -\nabla \cdot P_e + en\nabla\phi - enu_{\theta e}B\mathbf{1}_\perp \end{aligned}\right\} \text{Momentum equations for } i, e$$

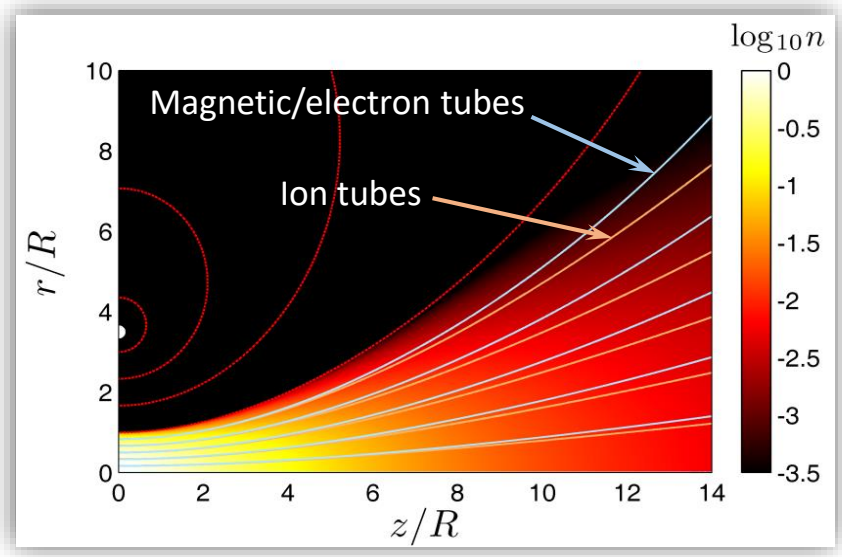


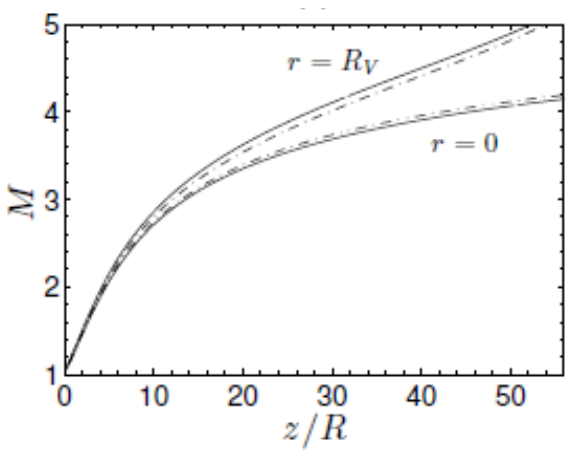
Solving with the MoC

  - After some algebra, electron equations are fully algebraic. Ion equations are hyperbolic for the supersonic expansion
  - The model is integrated numerically with the *method of characteristics*

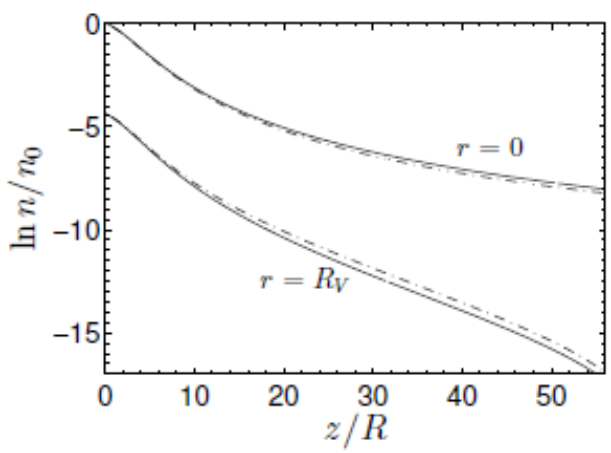
Acceleration and magnetic thrust

- Plasma density decreases axially and radially as the plasma expands in the MN
- Ion Mach number (ion velocity) increases downstream (quickly first, then slower)
- Electric potential decreases (the ambipolar electric field points downstream)
- Fully-magnetized electron tubes and magnetic tubes coincide; this is not true for ion tubes (only partially magnetized)

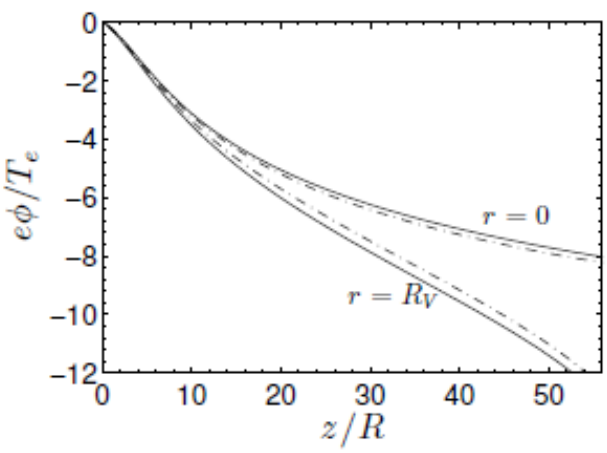




Ion Mach number



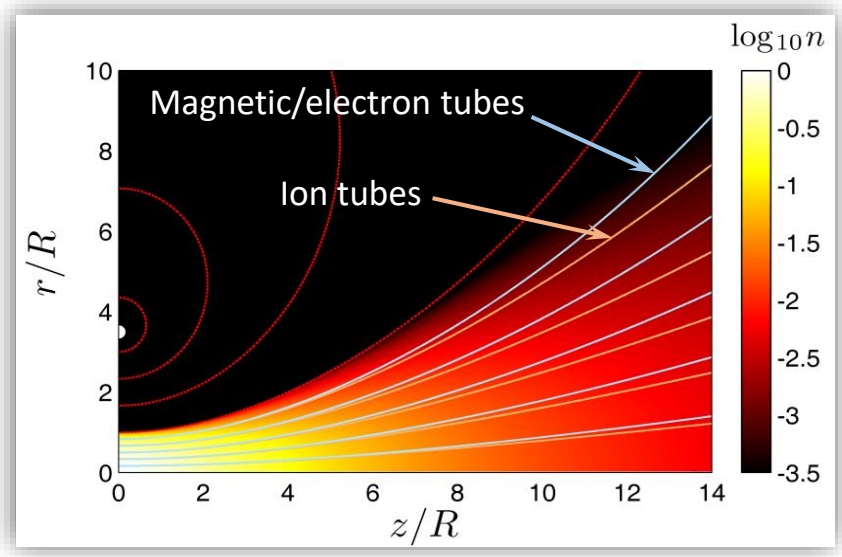
Plasma density

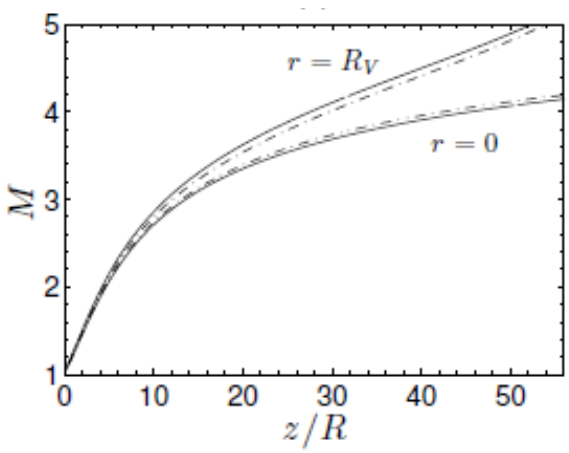


Electric potential

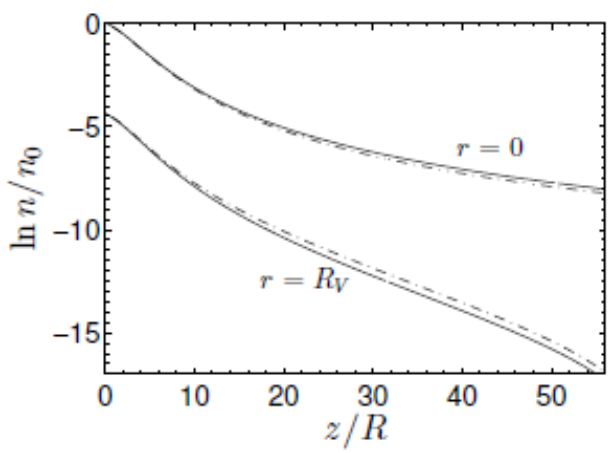
Acceleration and magnetic thrust

- Electric potential fall is proportional to T_e
  - The hotter the electrons, the larger the electric field, and the larger the ion acceleration
- Ion velocity scales as $\sqrt{T_e}$.
  - Therefore, the specific impulse too: $I_{sp} \propto \sqrt{T_e}$

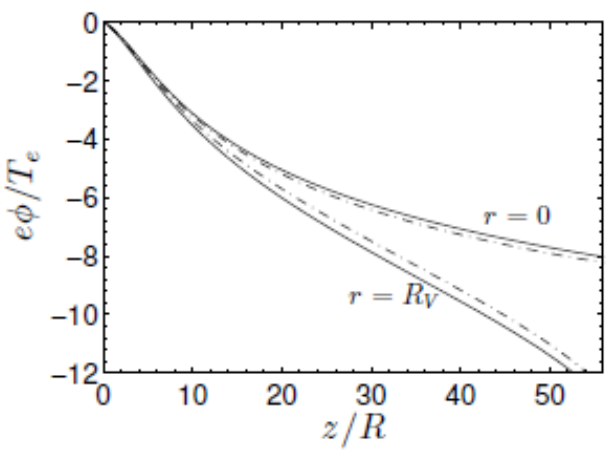




Ion Mach number



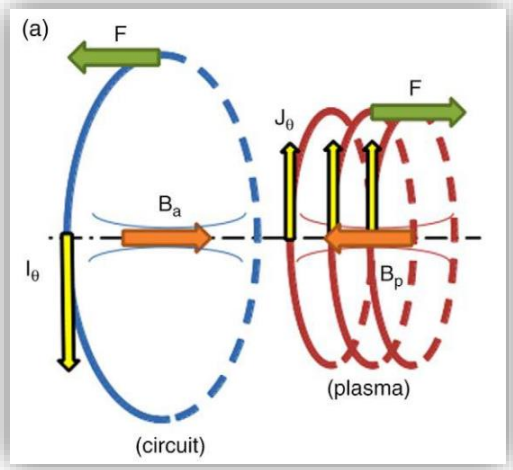
Plasma density

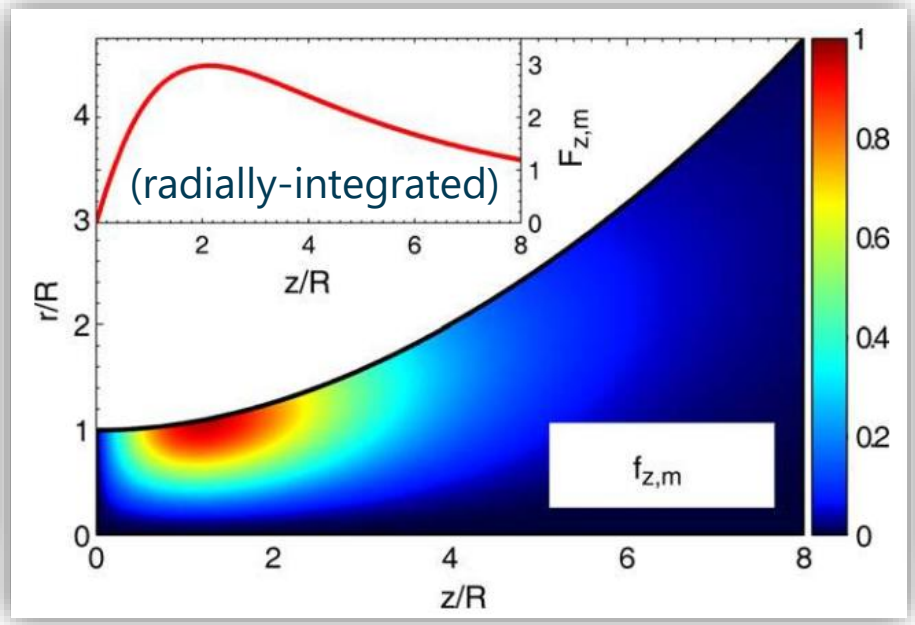


Electric potential

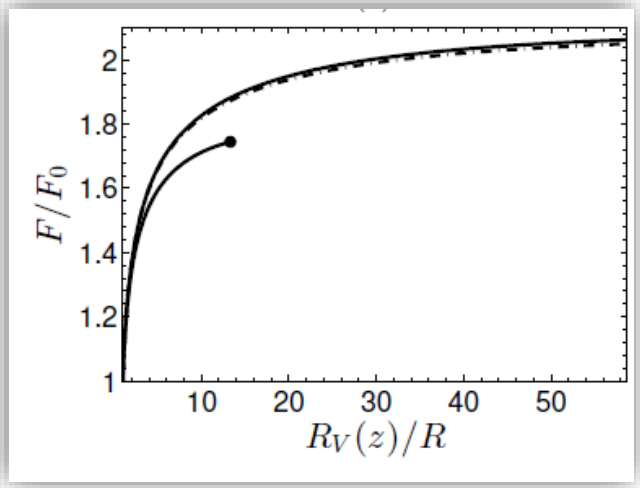
Acceleration and magnetic thrust

- The azimuthal plasma electric current density j_θ is responsible for the generation of the plasma-induced magnetic field, which opposes the applied one.
  - Plasma currents run in the opposite direction to the solenoid currents. Azimuthal currents scale as $j_\theta \propto nT_e/(BR)$
- The magnetic thrust force density is $j_\theta B_r$
  - Thust scales as $F \propto nT_e R^2$: the hotter the electrons, the denser the plasma, and the wider the nozzle, the higher F is





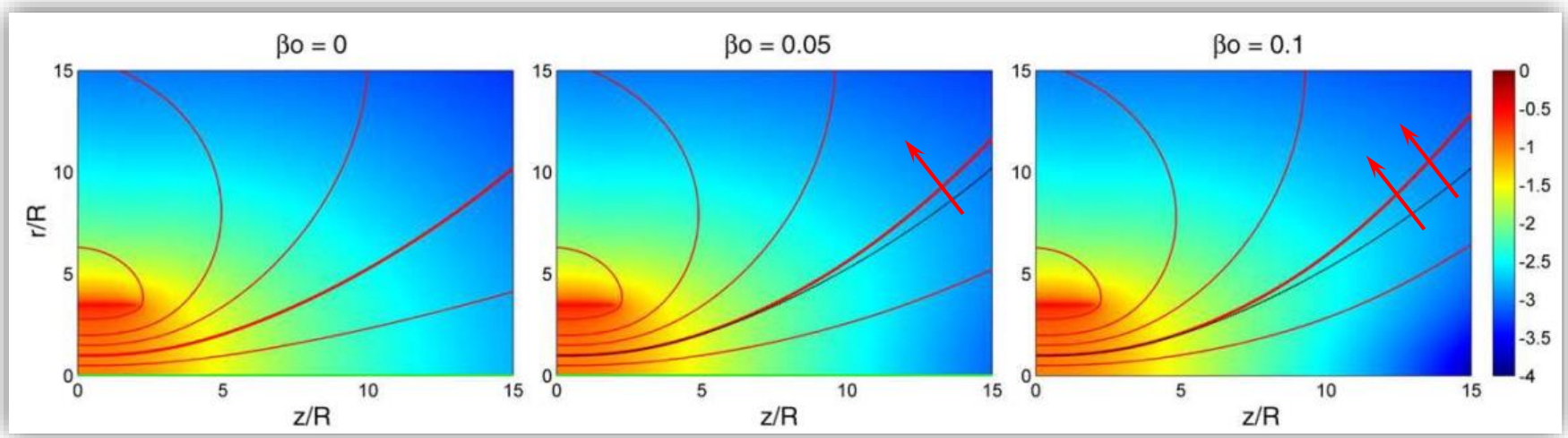
Axial magnetic force density in the plasma



Thrust gain

Acceleration and magnetic thrust

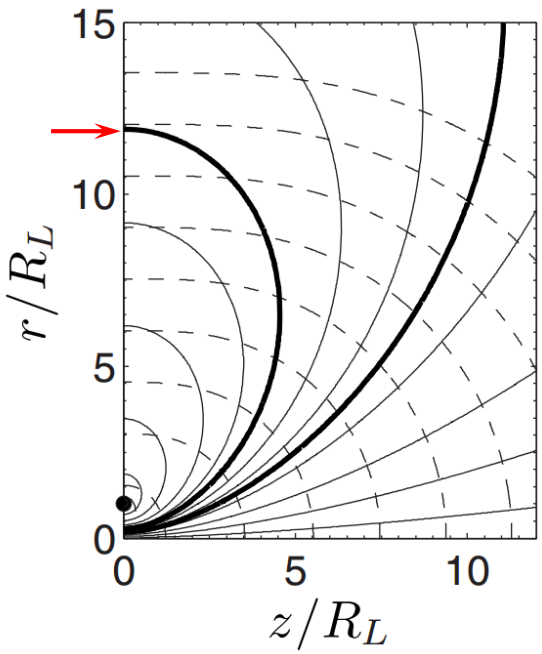
- The plasma-induced magnetic field is the key to generate magnetic thrust. But it can also have a detrimental effect:
  - If the induced field is too large, it will be comparable to the applied one, and decrease the magnitude of the field felt by the plasma, affecting also the topology of the magnetic nozzle (undesired effect)
  - The ratio induced-field-to-applied-field scales with $\beta = \mu_0 n T_e / B^2$. Thus, if we want to have a large nT_e (for large thrust), we need to provide a large applied field
- The magnetic field in the MN has to remain large enough to ensure that at least the electrons are initially magnetized; otherwise, the MN effect disappears. If the plasma is collisional, more magnetic field is required too



Contents

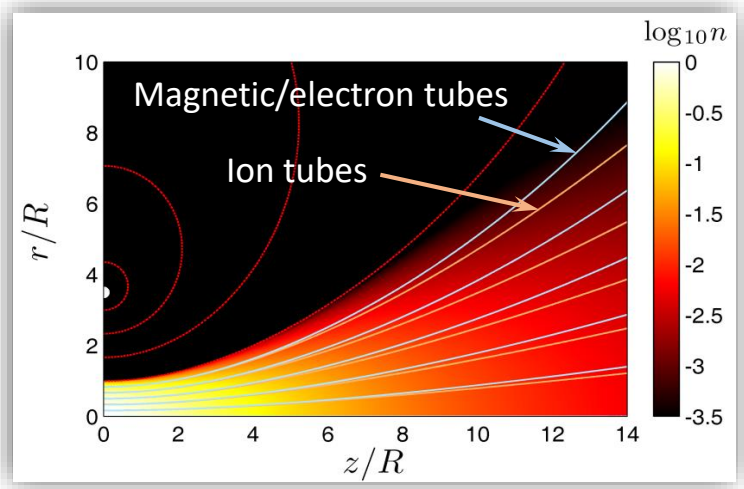
Plasma detachment

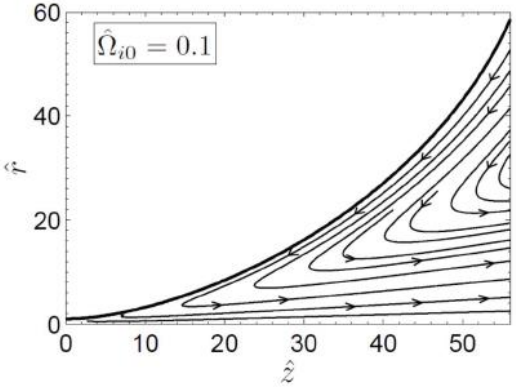
- Magnetic lines are closed. If the plasma remained always attached to the lines, it would return back to the thruster, cancelling thrust and damaging the spacecraft



Magnetic lines for a current loop of radius R_L

- The plasma must separate from $\boldsymbol{B}$ lines before they start to turn back
- The ions, which are the particles carrying mass and momentum, separate already in the near plume region as soon as they demagnetize completely
- The different behavior of ions and electrons gives rise to longitudinal electric currents



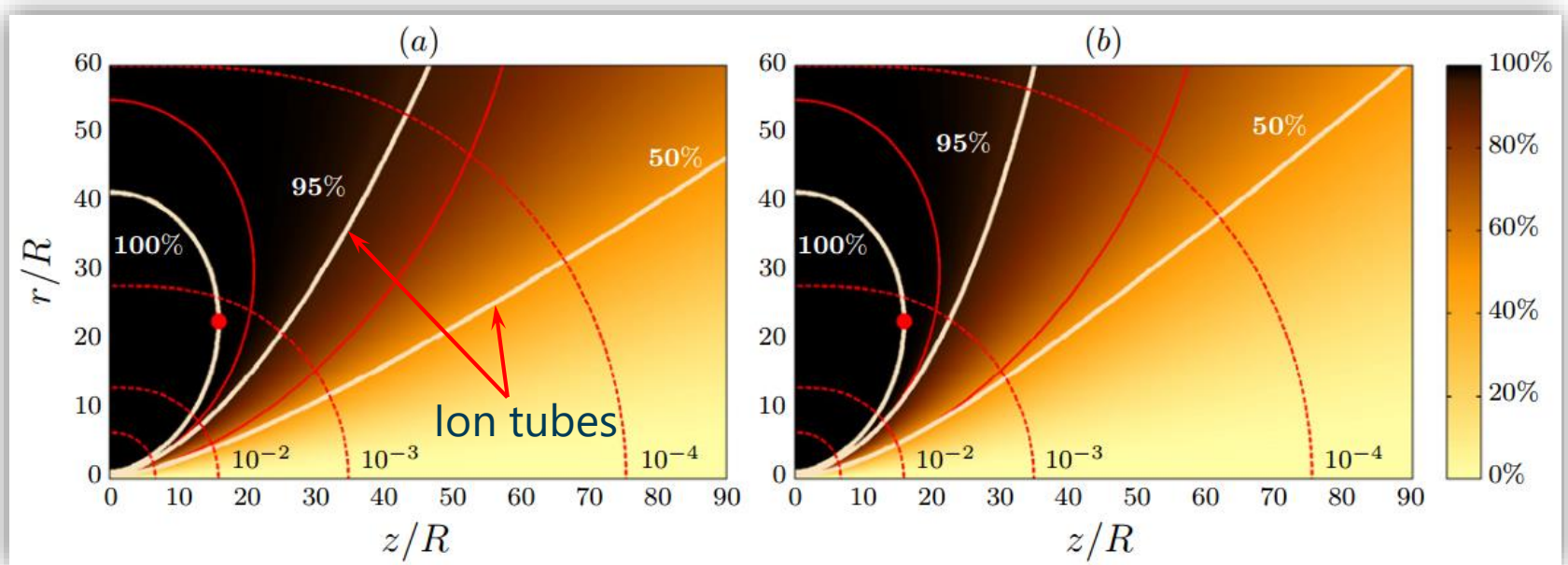


Longitudinal electric currents in the plasma

Plasma detachment

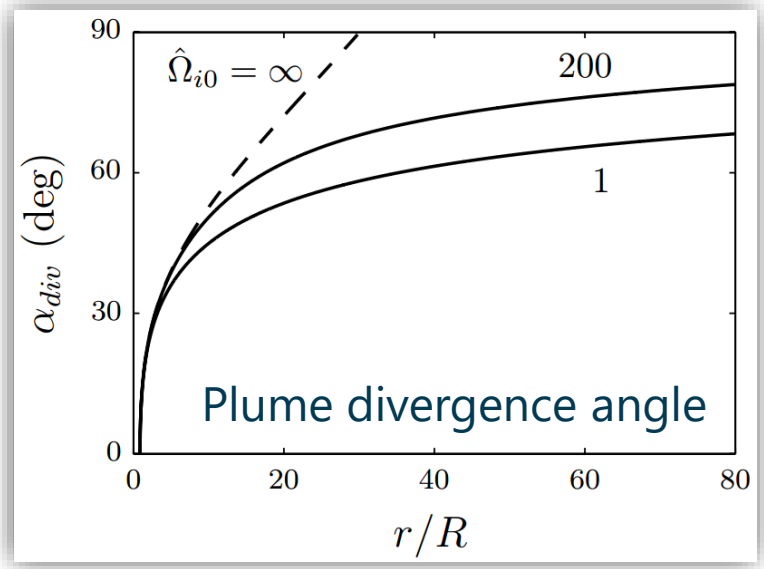
- If we take a look at the *far plume region* we see that most of the plasma mass and momentum does not turn back: it detaches naturally thanks to the demagnetization of the ions
  - The initial ion magnetization defines where the ions detach. It is measured by the parameter $\widehat{\Omega}_{i0} = eBR/\sqrt{m_i T_e}$
  - Electron demagnatization takes place much further downstream due to the large mass difference, $m_e \ll m_i$

Low $\widehat{\Omega}_{i0}$ High $\widehat{\Omega}_{i0}$

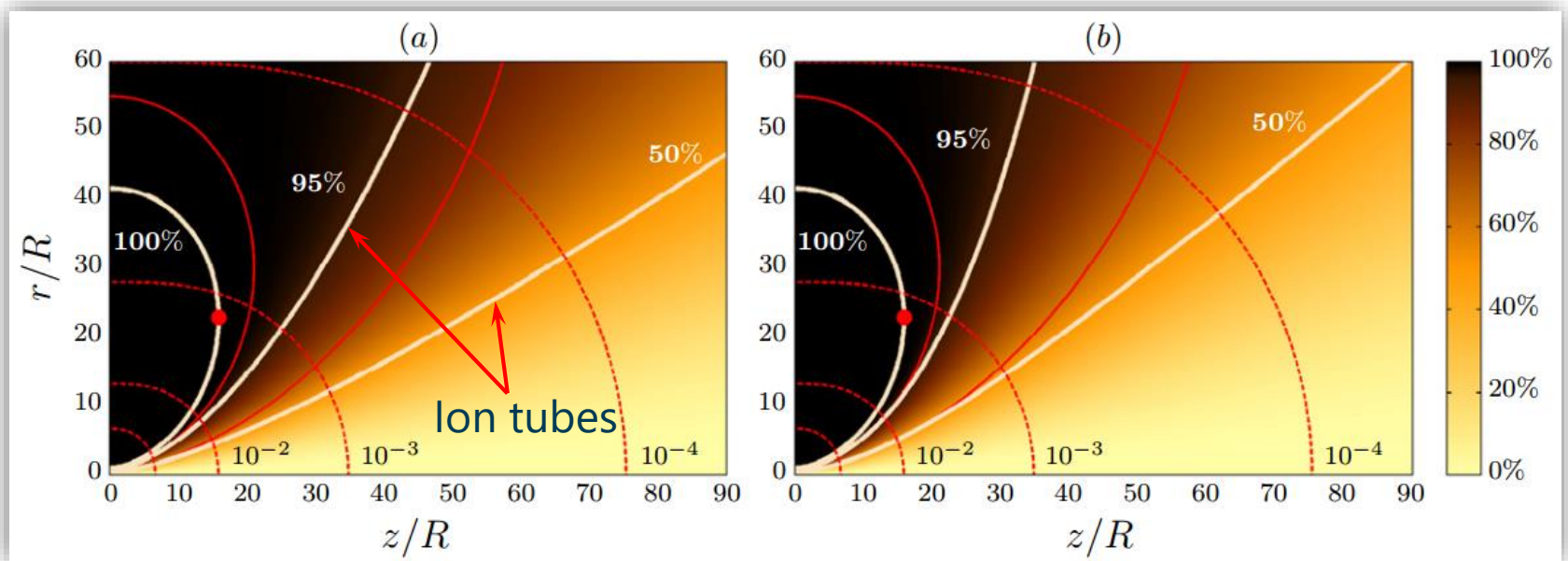


Plasma detachment

- To ensure that the plasma detaches early and to obtain a low *plume divergence angle*, it is desirable to keep $\boldsymbol{B}$ as low as possible, without violating the previous conditions on $\boldsymbol{B}$
  - A large α_{div} is problematic for S/C integration, since the peripheral plasma can hit solar arrays, etc



Low $\widehat{\Omega}_{i0}$ High $\widehat{\Omega}_{i0}$

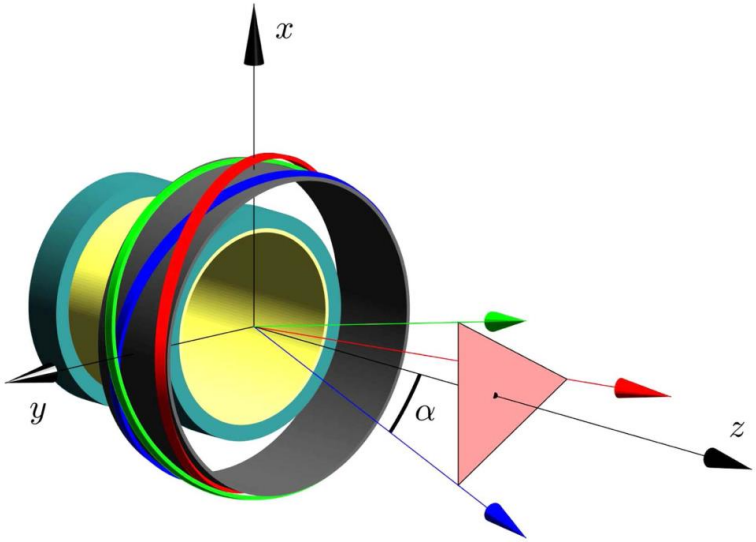


Conclusions

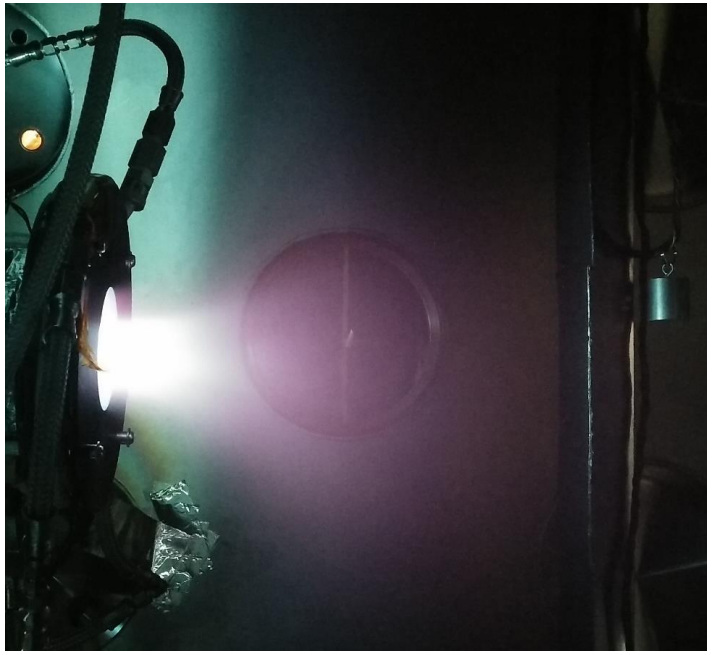
- Magnetic nozzles are a promising plasma acceleration device which is a fundamental part of many new-generation plasma thrusters. Advantages:
  - Contactless operation
  - In-flight MN geometry and strength modification
- Explaining the operation of MNs requires understanding the interplay between magnetic forces, plasma-induced magnetic field, ambipolar electric field, and the different behavior of light electrons and heavy ions
  - Hot electrons (large T_e) are necessary to obtain large exhaust velocities and large specific impulse I_{sp}
  - Thrust scales with plasma pressure (nT_e)
  - Most of the plasma mass and momentum detaches downstream thanks to ion demagnetization
- The magnetic field strength should be:
  - Enough to keep electrons magnetized in the acceleration region
  - Enough to prevent the induced magnetic field from distorting the MN
  - As low as possible to facilitate ion detachment and keep α_{div} low

Conclusions

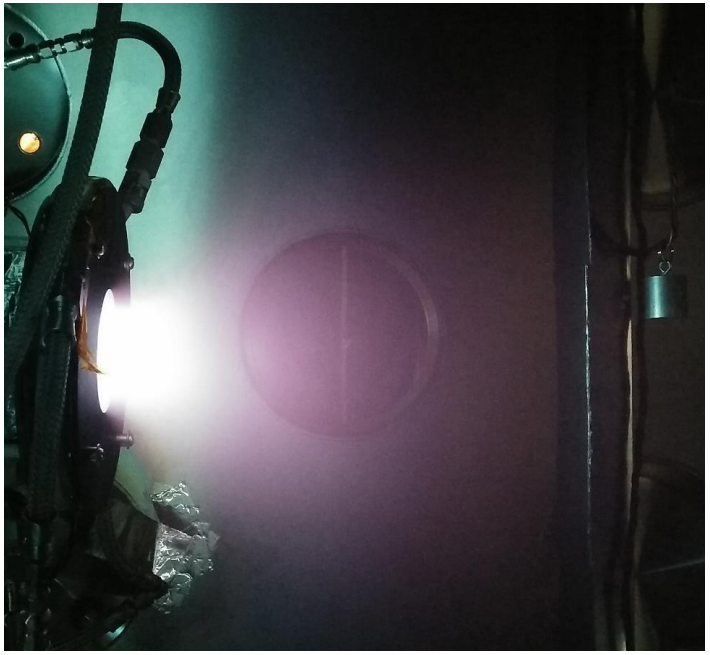
- A two-fluid model, like DIMAGNO code, is a useful tool to understand many of these aspects
  - A 3D version of DIMAGNO with fully-magnetized ions, named FUMAGNO (Matlab code), has been open-sourced
- There are many aspects of MNs that remain unkown are actively researched:
  - How do collisions affect confinement and the expansion? This requires a model with collisions, not included in DIMAGNO yet
  - How does a 3D magnetic nozzle work? can it really be used for thrust vector control? 3D code FUMAGNO used already to start exploring this
    - An experimental prototype will soon be built and tested at EP2
  - How do the collisionless electrons cool down? This study requires a kinetic code. First results have been obtained already
  - What is the effect of pressure anisotropy in the expansion? some thrusters, like the ECRT, are expected to produce an anisotropic plasma



Magnetic nozzle on / off

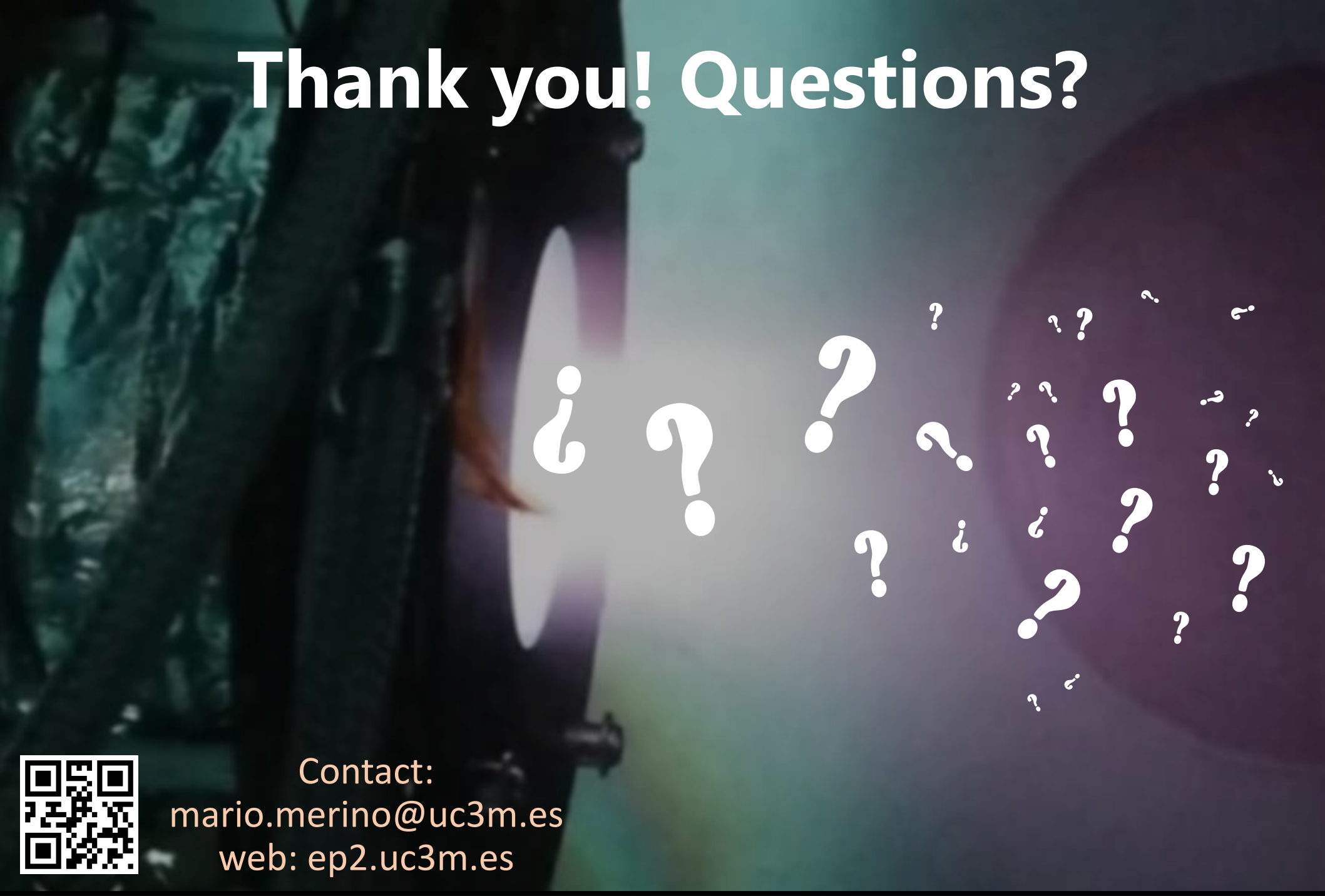


HPT05 thruster, MN coil on



HPT05 thruster, MN coil off

Thank you! Questions?



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