From plasma physics to electric propulsion: magnetic reconnection for future space thrusters

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Università di Pisa

Jet Propulsion Laboratory
California Institute of Technology

Presentation Outline

- Introduction: space electric propulsion
- Introduction: Magnetic reconnection thruster
- Review of existing concepts for MR thrusters
- Concept based on multi flux-ropes collisions
- Expected performance parameters
- Experimental campaign preliminary results
- Next steps toward validation
- Conclusions

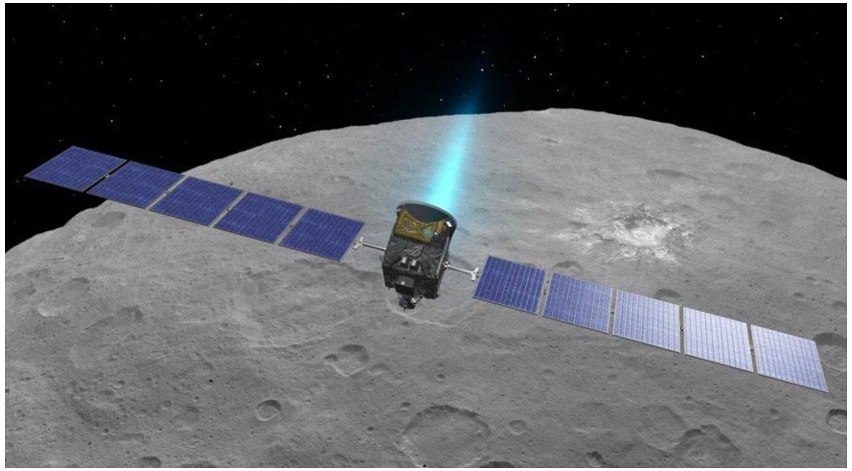
Introduction

Plasma Propulsion

- High values of **efficiency** and **exhaust velocities** an order of magnitude higher than typical chemical systems
- **Significant reduction of the propellant** needed to perform a given mission.
- Current applications of EP
  - attitude control, station keeping, de-orbiting of satellites
  - orbit raising of platforms to GEO, mission to Moon/Mars
  - **deep space exploration missions** (e.g. DEEP SPACE 1, DAWN, SMART1, Bepi Colombo, Psyche …)

Credit: ESA Smart

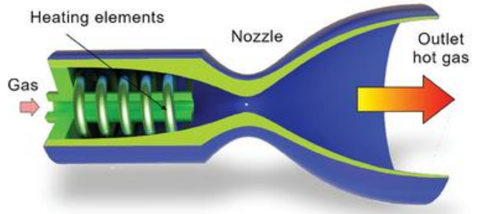
Credit: NASA DAWN



Introduction

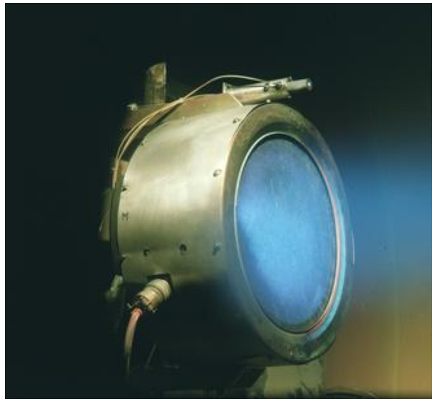
Electric thrusters classification

Accelerating Process			Electric		
Gasdyn.	$v_e \sim \sqrt{\frac{T}{\mathcal{M}}}$		Electro thermal		Resistojets Arcjets
Electrostatic	$v_e \sim \sqrt{\frac{2qV}{M}}$		Electro static	Ion Thrusters	Gridded Ion Thrusters FEEP, Colloid Thrusters
				Plasma Thrusters	Hall Thrusters
Electromag.	$v_e \sim \frac{I^2}{\dot{m}}$		Electro magnetic		MPD Thrusters

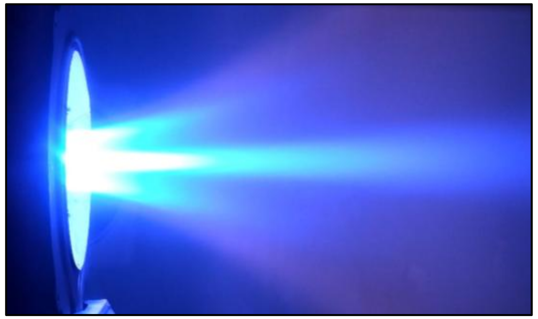


Resistojet

Ion thruster



Hall thruster



AF-MPDT

INTRODUCTION

- **Tsiolkovsky equation** of rockets

$$\Delta v = v_f - v_0 = v_e \, ln\left(\frac{m_0}{m_f}\right) = v_e \, ln\left(1 + \frac{m_p}{m_f}\right)$$

- To achieve **large $\boldsymbol{\Delta v}$**: either burn a substantial amount of propellant ($m_p \approx m_0$) or use a thruster able to generate a high v_e.

	LEO-GEO	Nearby planets	Far-off planets
Delta-V required	4.8 km/s	5-8 km/s	10-15 km/s

- This second option leads to **high $\boldsymbol{I_{sp}}$** thrusters, where

$$I_{sp} = \frac{T}{\dot{w}} = \frac{\dot{m} v_e}{\dot{m} g_0} = \frac{v_e}{g_0}$$

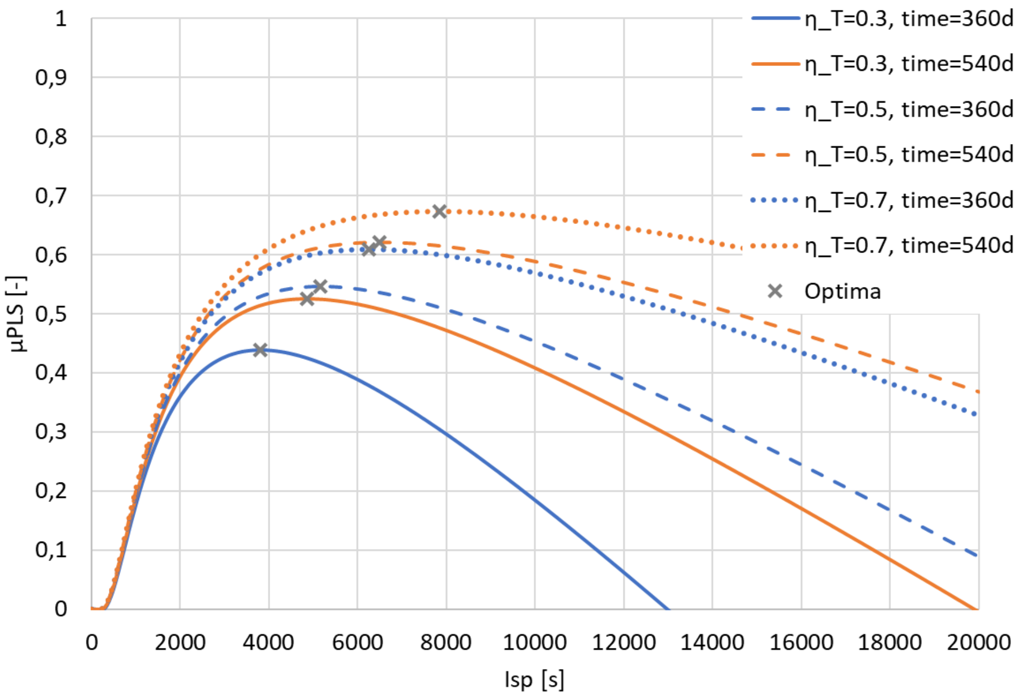
	Resistojet	Arcjet	Ion thruster	Hall thruster	MPDT
Specific Impulse (s)*	300	500-2000	Up to 10000	Up to 3000	Up to 4500

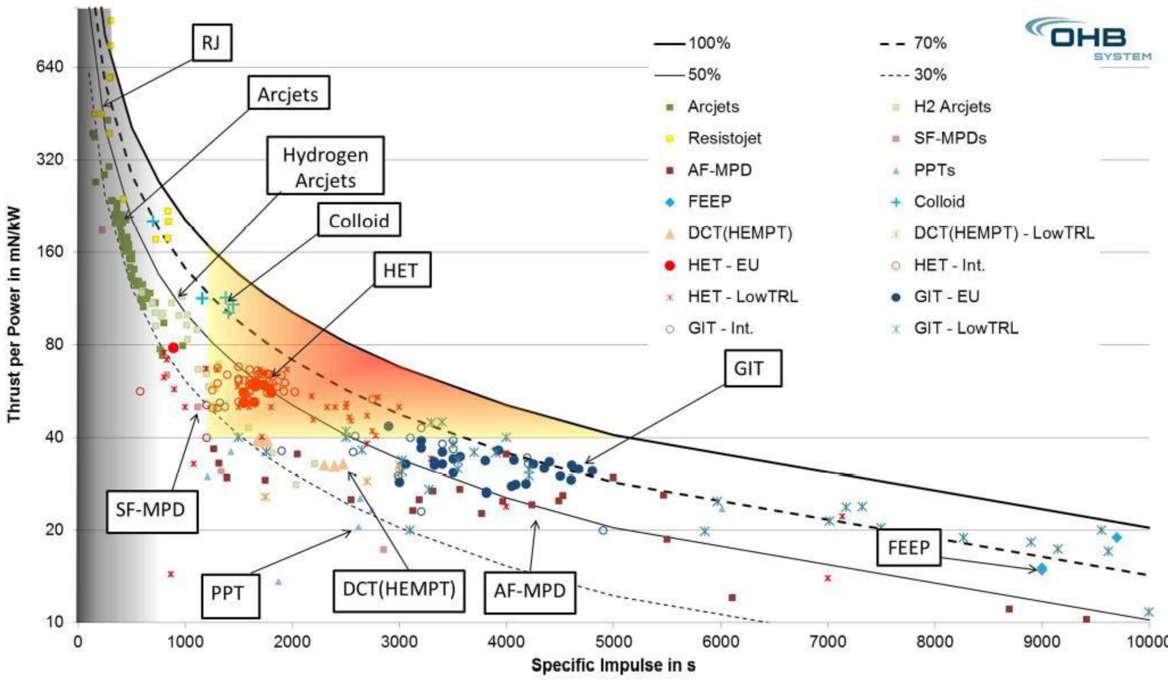
** Depending on propellant used and applied mass flow*

INTRODUCTION

- By simply looking at the Rocket equation, one might be tempted to say that the highest I_{sp} the better it is…
- Considering however the non-dimensional Rocket Equation we can find an optimal Isp for a given mission

Payload mass fraction





Peukert & Wollenhaupt EPIC 2014

Example: mission LEO to Ceres Orbit (between Mars and Jupiter)

Introduction

- For **electrostatic thrusters** (Hall, ion): the I_{sp} achievable is linked to the conversion to kinetic energy of the electric energy stored in the electric fields.
- In **MPDT** the obtainable I_{sp} is linked to the power level at which the thruster can operate at.
- Can there be an **energy alternative source** to have higher I_{sp}?

Stored energy in a magnetic field: $u_m = \frac{1}{2}\frac{B^2}{\mu}$ Stored energy in an electric field: $u_e = \frac{1}{2}\epsilon_0 E^2$

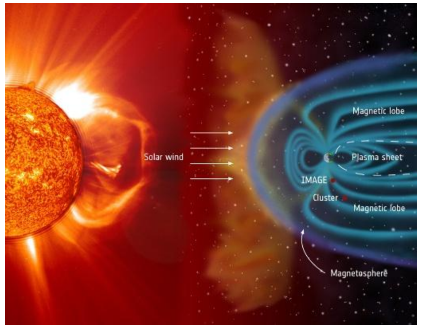
$$\frac{u_m}{u_e} = c^2 \frac{B^2}{E^2}$$

Due to the factor of c^2, the magnetic field energy is far greater than that found in electric fields

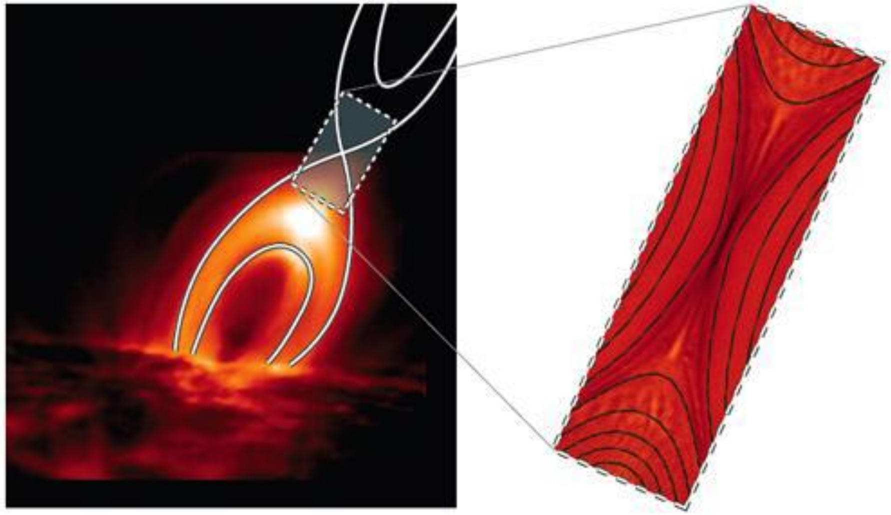
How to we extract this energy?

Introduction

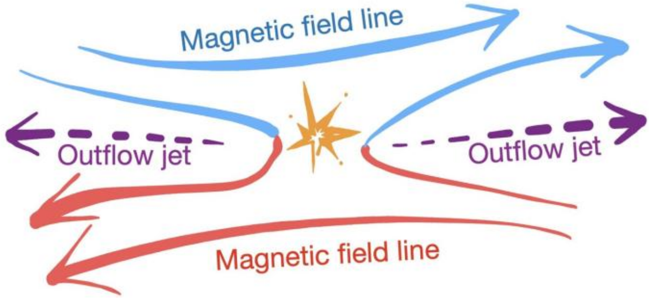
The “easy” way comes from observing **natural phenomena** that continuously accelerate particles and plasma throughout release of the magnetic energy contained in the magnetic fields (**Solar Flares, Coronal Mass Ejection)**



Magnetic reconnection



- Rearrangement of magnetic field topology of plasmas, in which **magnet energy is converted to kinetic energy and heat**. Magnetic reconnection occurs when antiparallel magnetic field lines break and reconnect, converting the magnetic energy into kinetic and thermal energy and producing an outflowing plasma.



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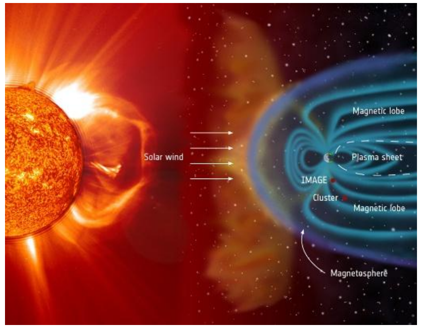

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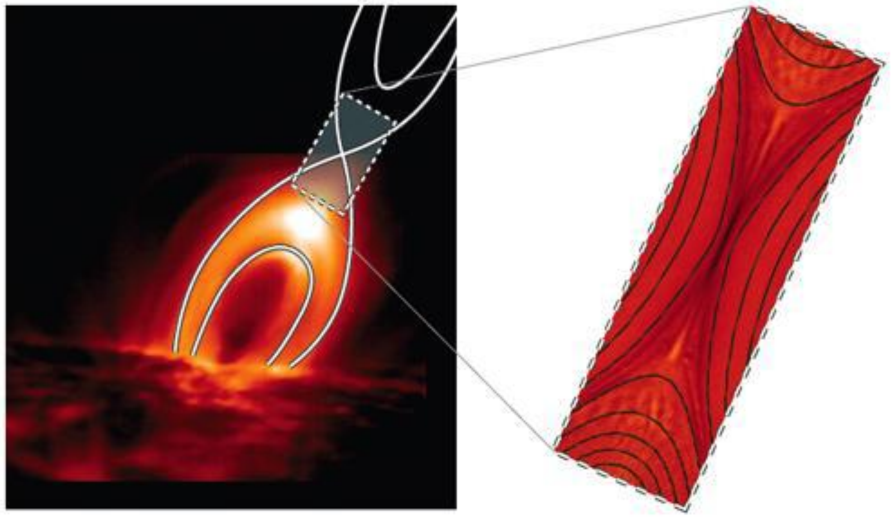
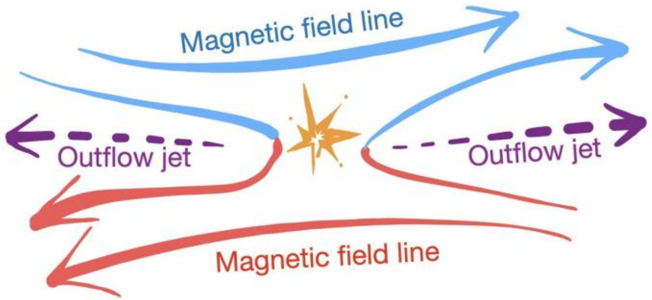


- Plasma accelerated up to the **Alfvén velocity** (~ 10^5-10^6 m/s in our case as we will see later) means that the $\mathbf{I_{sp}}$ **can be up to 10^4-10^5 s**
- Using magnetic reconnection as **main acceleration mechanism** would lead to an innovative thruster capable of delivering a very high specific impulse and high level of thrust



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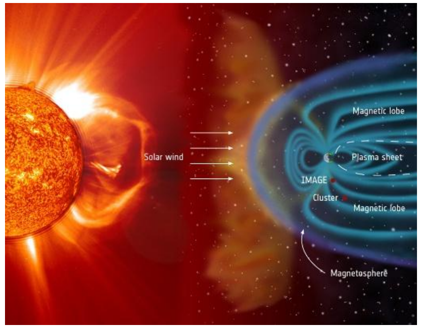
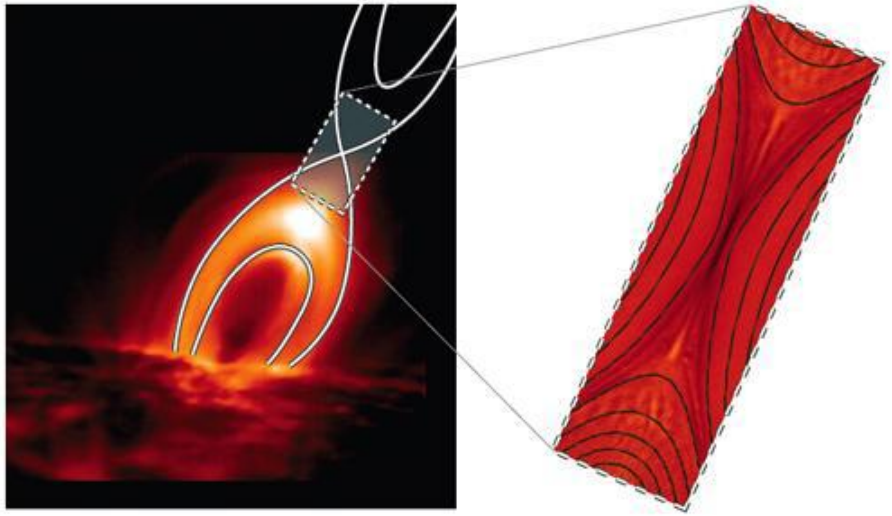
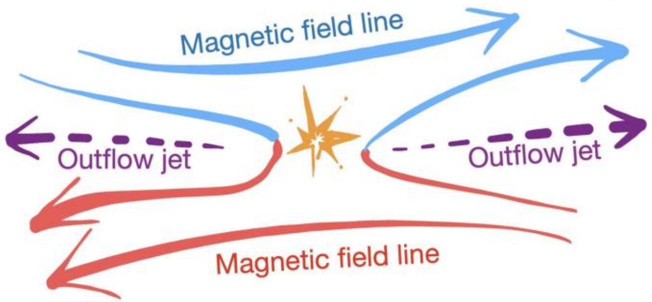


Magnetic reconnection



- Plasma accelerated up to the **Alfvén velocity** (~ 10^5-10^6 m/s in our case as we will see later) means that the $\mathbf{I_{sp}}$ **can be up to $\mathbf{10^4}$-$\mathbf{10^5}$ s**
- Using magnetic reconnection as **main acceleration mechanism** would lead to an in impulse and

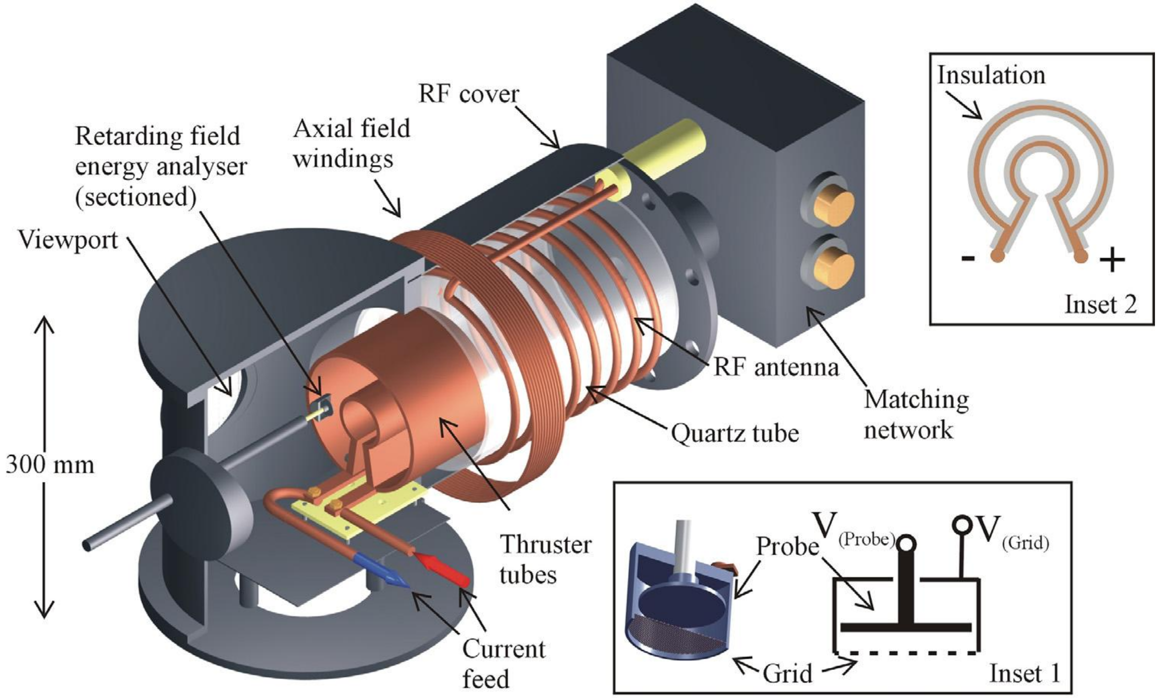
Problem: in 2D MR the outflow plasma is accelerated in both direction (no net thrust!) → we need ways to break this simmetry



Existing concepts

Bathgate, S. N., et al, University of Sydney, NSW 2006, Australia

- **Pair of coaxial coils** to generate an axial magnetic field with oppositely directed field lines, and therefore a **null surface**, off-axis of the thruster, in a configuration similar to a theta-pitch accelerator
- Plasma discharge is generated externally via **Radio Frequency** (RF) coils and accelerated through both theta-pitch effect and reconnection
- A **magnetic mirror** is placed behind the RF coils to reduce plasma backflow from the reconnection region



Bathgate, S. N., et al., "A thruster using magnetic reconnection to create a high-speed plasma jet," European Physical Journal Applied Physics, Vol. 84, No. 2, 2018, 20801.

Existing concepts

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Experimental test with:

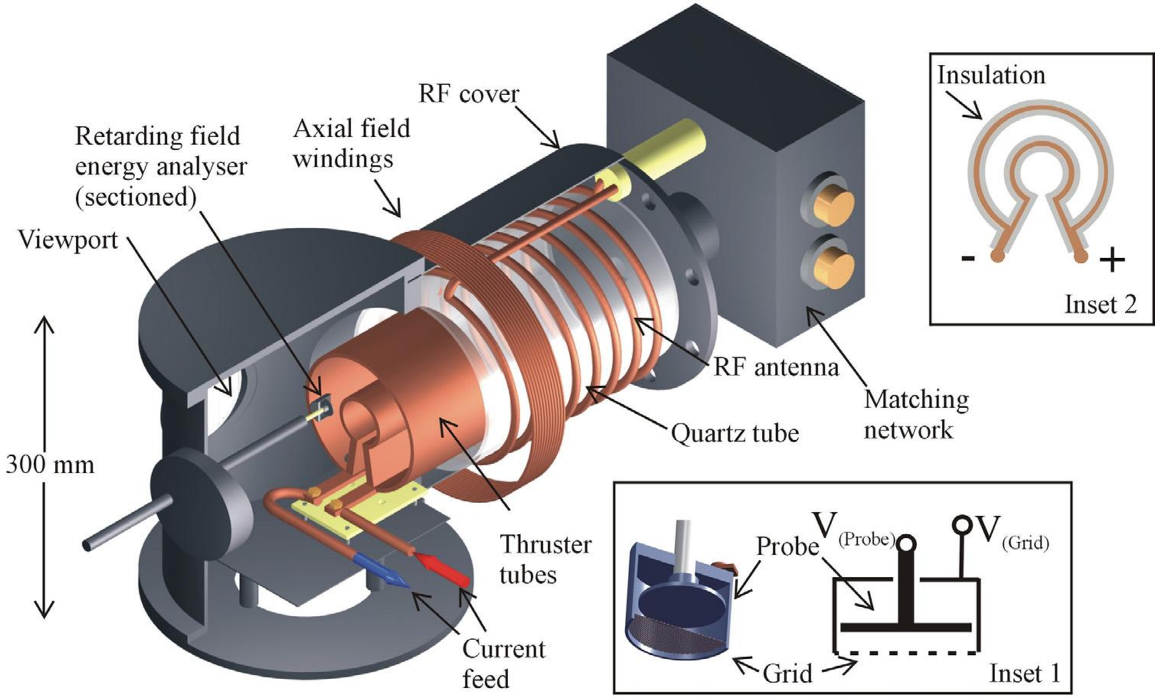
- argon plasma, $n \approx 4 \cdot 10^{18}\, m^{-3}$, $B = 0.0049\, T$

Experimental results:

- $I_{sp} = 860\, s$, thrust of $4.3 \cdot 10^{-8}\, N$, thrust efficiency of $5.6 \cdot 10^{-4}\, \%$.

Important notes:

- They effectively measured accelerated electrons, sign of magnetic reconnection
- The concept uses a magnetic topology made from external coils.



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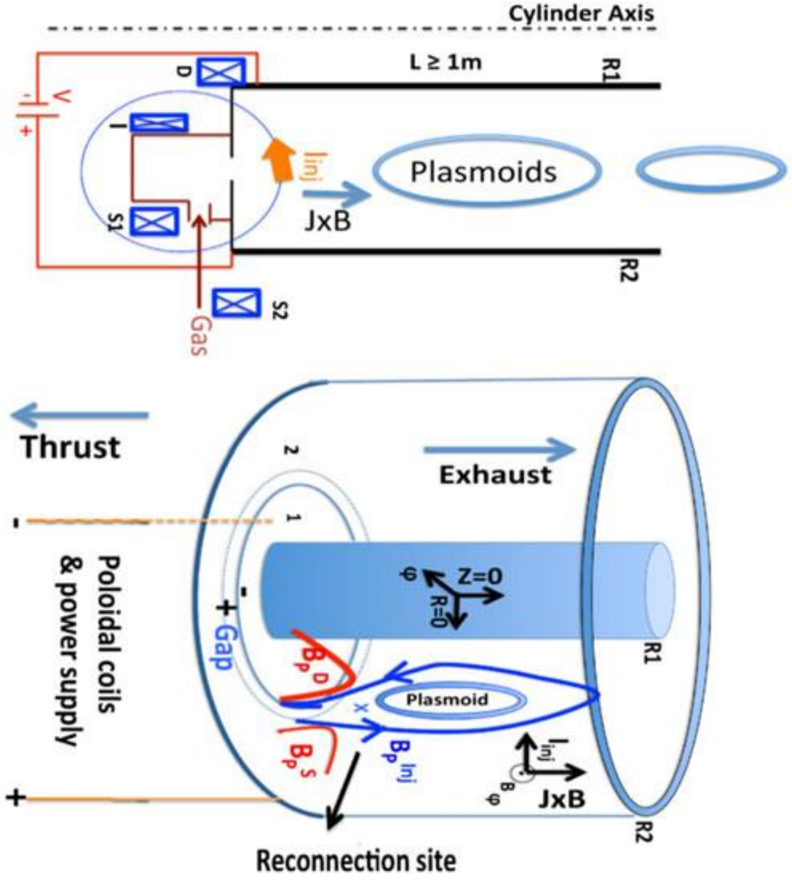
Existing concepts

Ebrahimi, F., Princeton University, US

- **Current is injected** across two annular electrodes which flows along the open magnetic field lines between them.
- This induces an **azimuthal magnetic field**, stretching the open field lines upwards via a Lorentz force on the plasma (frozen flow).
- The central field loop is then compressed laterally by the external shaping fields. Due to the compression an **axially elongated current sheet** is formed, allowing reconnection to occur and **eject a plasmoid** from the thruster at the Alfvén speed.
- At high Lundquist number ($S > 10^4$): **plasmoid (tearing) instability**, continually forming and ejecting plasmoid loops.



Ebrahimi, F., "An Alfvenic reconnecting plasmoid thruster," Journal of Plasma Physics, Vol. 86, No. 6, 2020, p. 905860614.

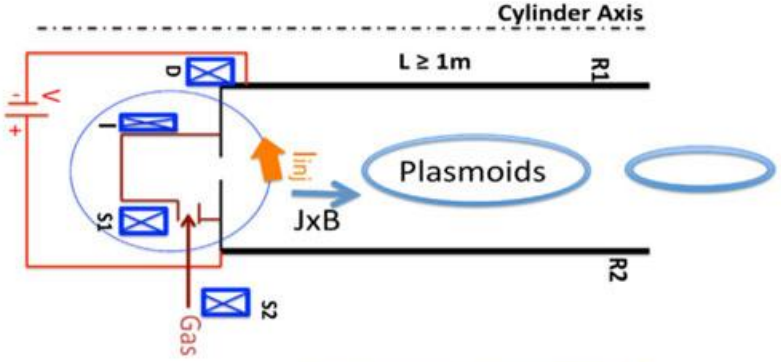
Existing concepts

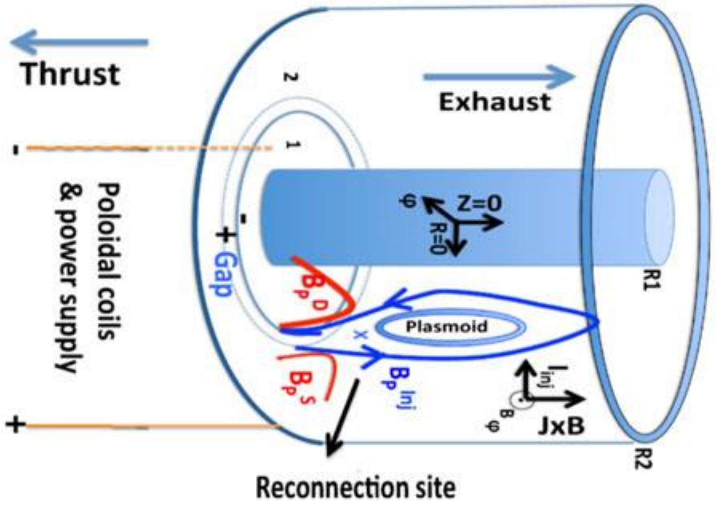
Ebrahimi, F., Princeton University, US

- Performances verified with a series of **MHD simulations**
- Exhaust velocity of the order of **5×10^5 ms^{-1}** at a field strength of 0.05 T to 0.06 T

Important notes:

- Exhaust plasma is only ejected in **one direction** rather than symmetrically.
- The discrete ejection of plasmoids rather than a continual flow does not generate **any wall erosion**
- Magnetic configuration design does not include a reconnection point obtained from static externally applied magnetic fields. However, **very large currents** (1kA-100kA) are required to overcome the magnetic field line tension.





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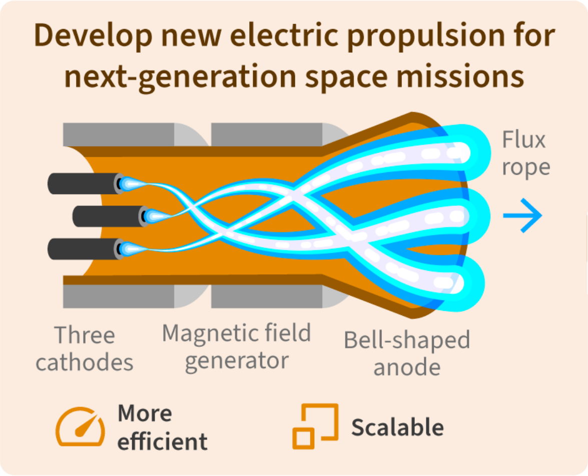
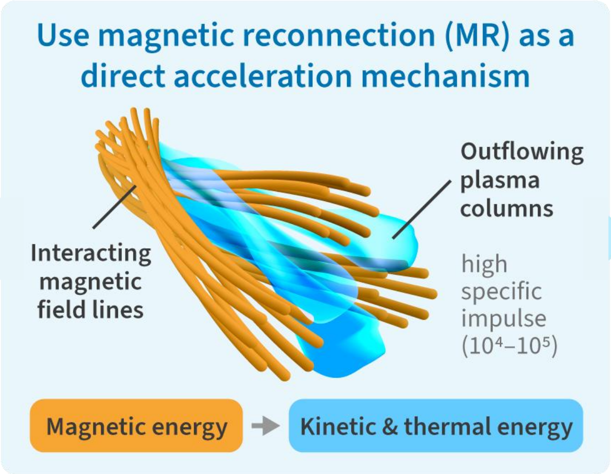
A MULTI FLUX ROPES THRUSTER





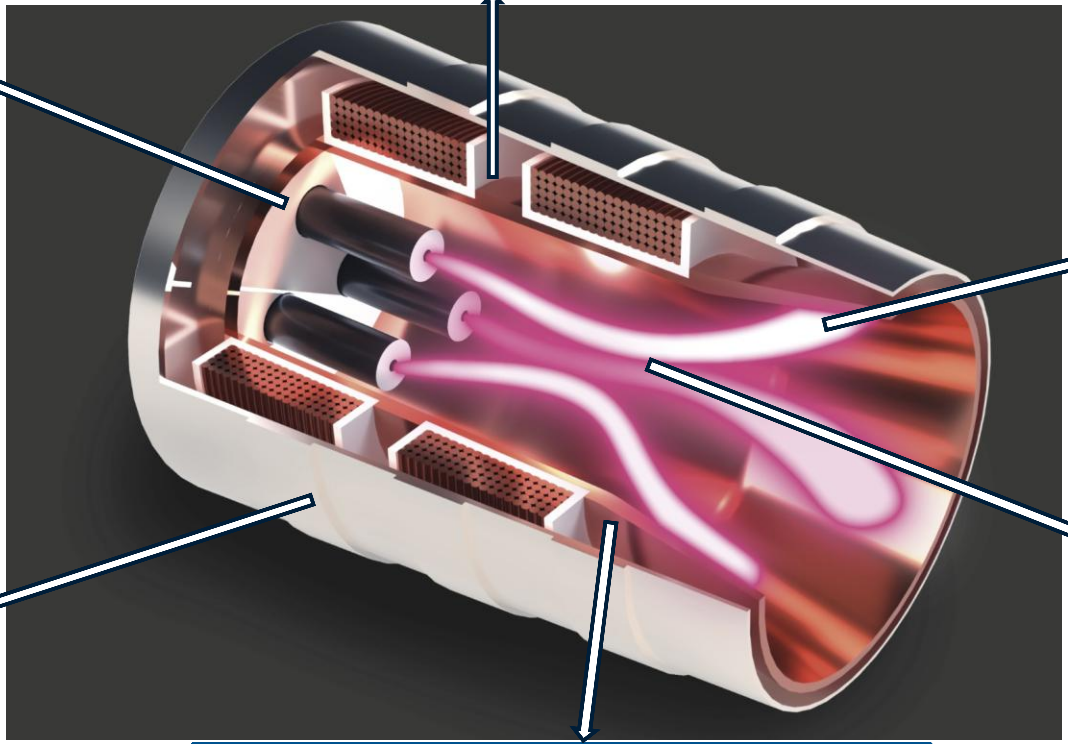
- Generation of **multi flux ropes** by means of hollow cathodes
- Flux ropes (or plasma channels) are magnetically confined by an **axial external applied magnetic field**
- **Bell-shaped** anode close the circuit, and a **magnetic nozzle** is at the exit to further enhance the acceleration

- At sufficiently high current the flux ropes become **kink-unstable**, interacts and collide on each other which leads directly to the **reconnection of magnetic field lines**.

A multi flux ropes thruster

Coils
Generate the axial magnetic guide field

LaB6 Hollow cathodes
Plasma source and negative electrode for the discharge



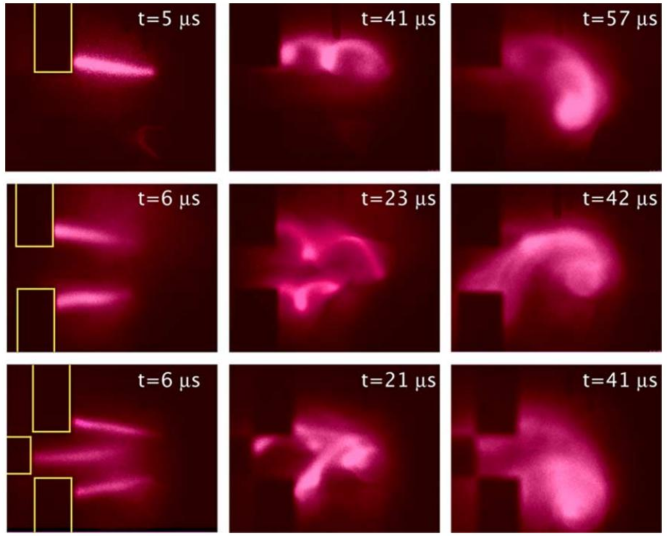
Flux ropes
Kink unstable at current > I_{KS} twist and collide with each other favouring magnetic reconnection

Case
Shielding and protection of sensitive components

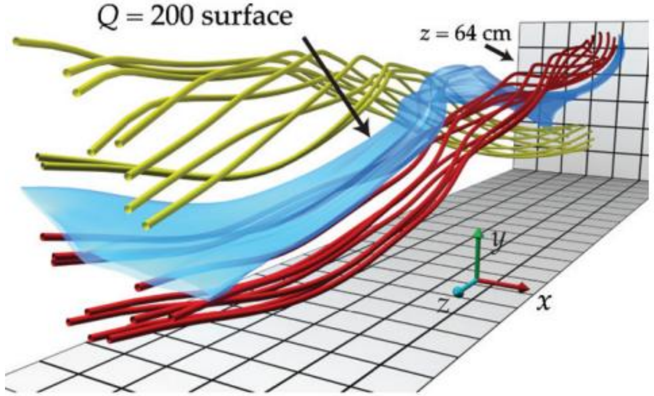
Magnetic reconnection site
Flux ropes collisions generate multiple reconnection sites

Anode
Positive electrode for the discharge
Aligns with magnetic nozzle

Relevant background

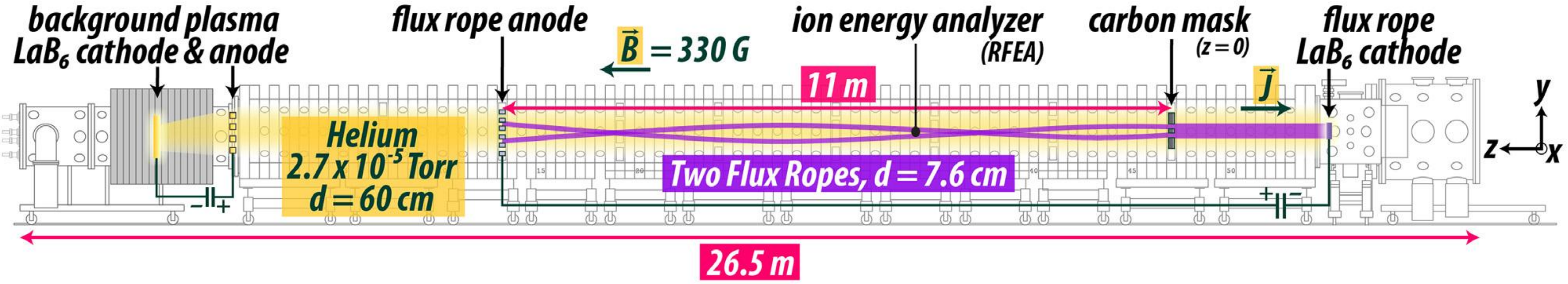


Hemsing, E. W., Furno, I., & Intrator, T. P. (2005). Fast camera images of flux ropes during plasma relaxation. IEEE Transactions on Plasma Science, 33(2), 448-449.



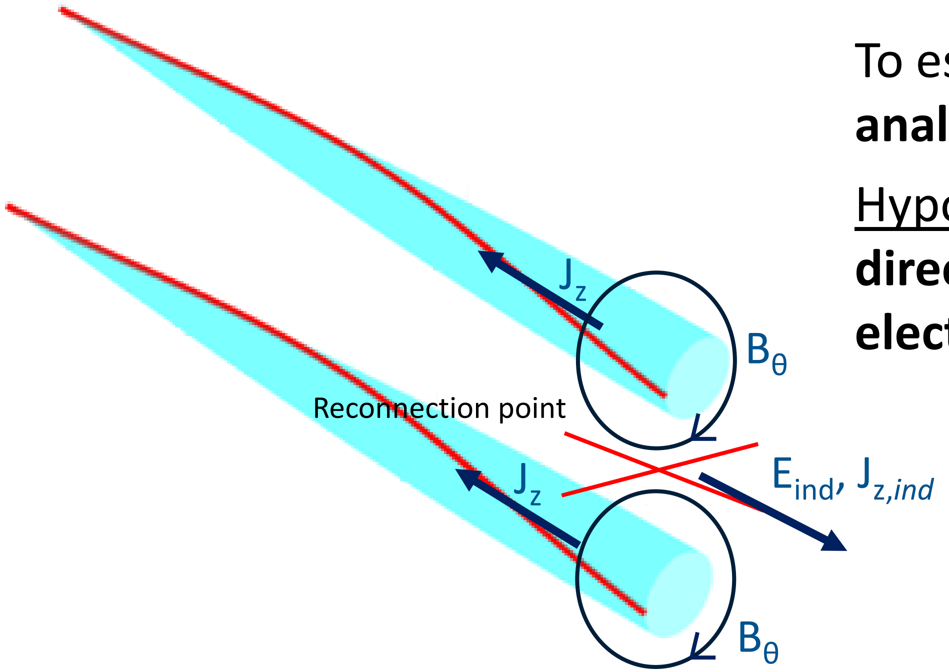
**Gekelman, W., Lawrence, E., & Van Compernolle, B. (2012). Three-dimensional reconnection involving magnetic flux ropes. The Astrophysical Journal, 753(2), 131.*

- Flux ropes are **current carrying columns of plasma** that are abundant in space and play a major role in the study of astrophysical plasmas, such as those found in the solar photosphere and corona.
- They can become **kink-unstable** by carrying a sufficiently large current ($I > I_{KS}$), which then causes the ropes to writhe, twist, and collide with each other, **triggering magnetic reconnection**.
- Evidence of **ion heating and acceleration** can be observed during the reconnection events of solar flares and coronal mass ejections, and from ion flows within the Earth's magnetotail.
- In the LAPD experiment*, they studied the reconnection of two and three flux ropes and observed **a field-aligned ion beam at sub-Alfvenic ion velocity**.



**Tang, S. W., Gekelman, W., & Sydora, R. D. (2023). Experimental observation of a field-aligned ion beam produced by magnetic reconnection of two flux ropes. Physics of Plasmas, 30(8).*

Expected performance



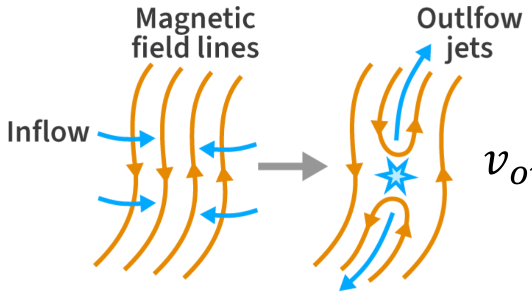
To estimate the performance of our thruster, we do an **order of magnitude analysis** from Maxwell's equations

<u>Hypothesis:</u> the main acceleration mechanism for the ions in the **axial direction** (perpendicular to the poloidal plane) comes from the **induced electric field** from the reconnection point

$$\nabla \times E = -\frac{\partial B}{\partial t} \rightarrow E_z = -\frac{\partial A_z}{\partial t} \quad \text{where} \quad \nabla \times A_z = \mathrm{B}$$

$$\rightarrow E_z \sim -\frac{A_z(\bar{r})}{\tau_{rec}}$$

In 2D (Sweet-Parker model) we would have on the poloidal plane:

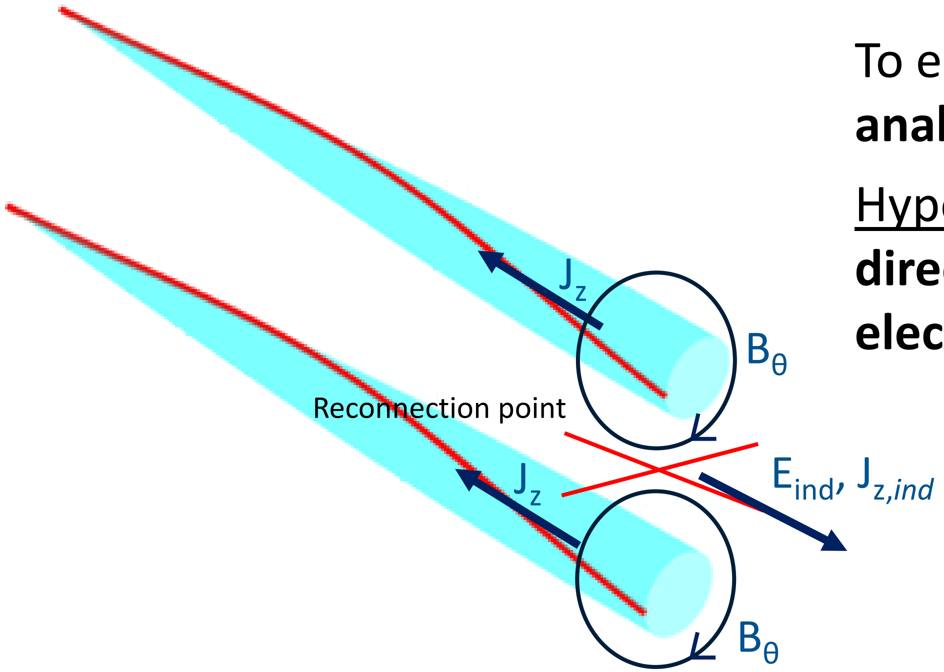


$$v_{out} = \frac{B_{in}}{\sqrt{\mu_0 \rho}} \equiv v_a$$

In first approx. we consider the magnetic field as generated by a current carrying long wire, therefore the magnetic potential is:

$$A_z = -\frac{\mu_0 I}{2\pi} \ln r$$

Expected performance



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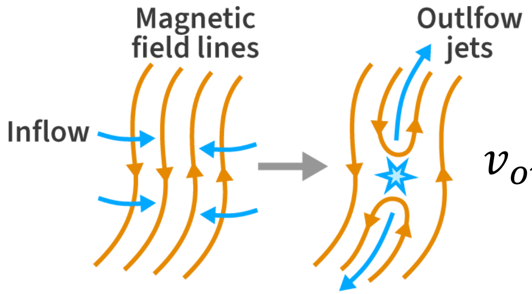


$$v_{out} = \frac{B_{in}}{\sqrt{\mu_0 \rho}} \equiv v_a$$

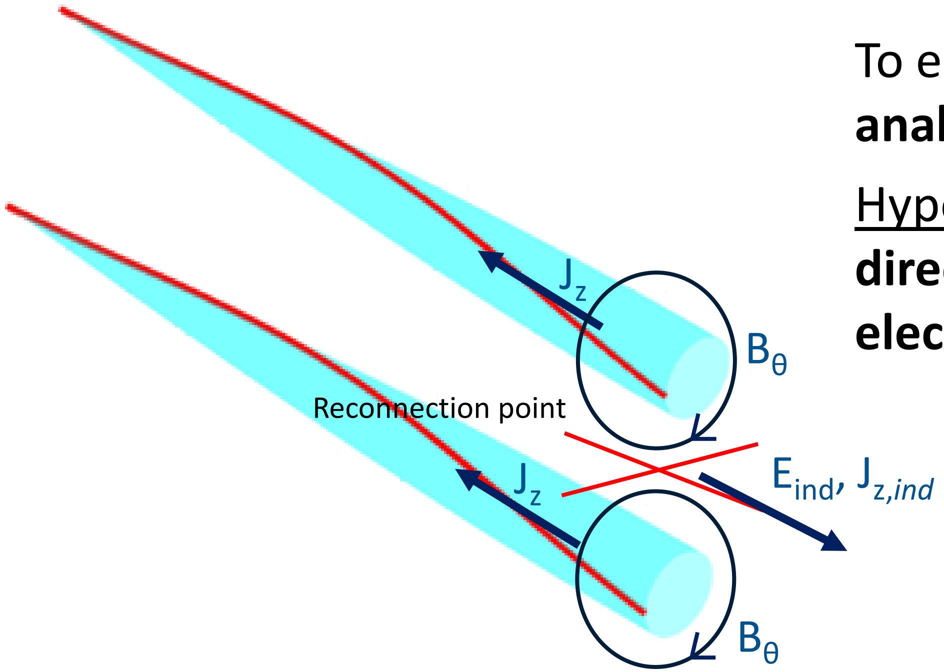
The reconnection time is modeled as (Sweet-Parker):

$$\tau_{rec} = \tau_a{}^{1/2} \tau_{res}{}^{1/2}$$

where $\tau_a = \frac{L}{v_a}$ is the Alfvén time, and

$\tau_{res} = \frac{\mu_0 L^2}{\eta}$ is resistive time

Expected performance



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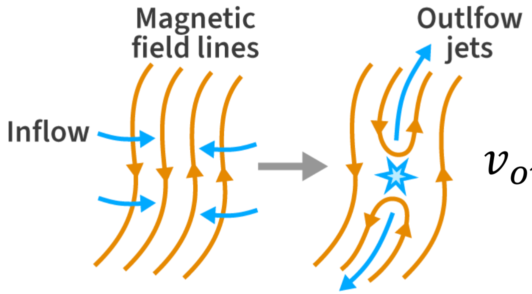
With the plasma parameters shown before we get:

$$\tau_A \sim 10^{-7} s \qquad \tau_{res} \sim 10^{-3} s \quad \rightarrow \quad \tau_{rec} \sim 10^{-5} s$$

and at $r = r_{column} \rightarrow A_z \sim 10^{-5}\, Wb\, m^{-1}$

$$\rightarrow \boldsymbol{E_z \sim 1\, V/m}$$

In 2D (Sweet-Parker model) we would have on the poloidal plane:



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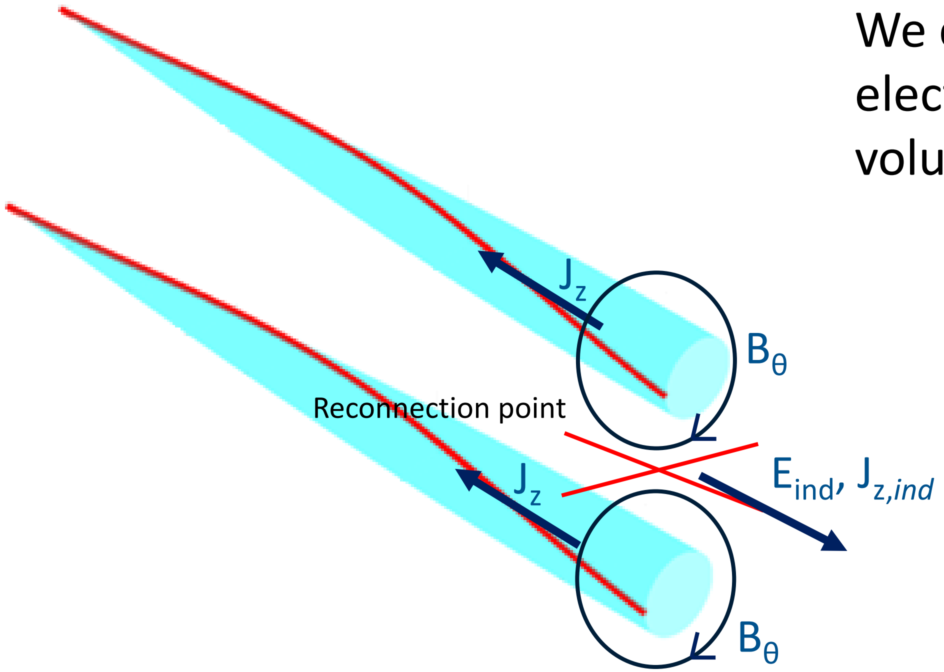
Expected performance



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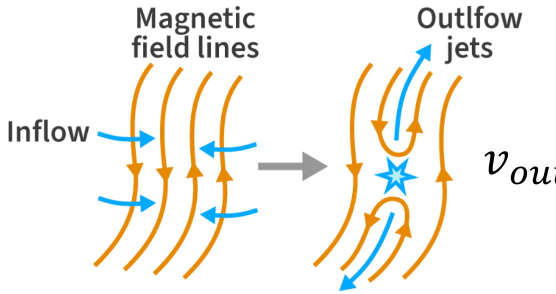


$$v_{out} = \frac{B_{in}}{\sqrt{\mu_0 \rho}} \equiv v_a$$

We can now approximate the energy (per unit volume) from the induced electric field (i.e. the work done by the induced electric field per unit volume)

$$\varepsilon_{rec} \sim J_z \cdot E_z \, \tau_{rec}$$

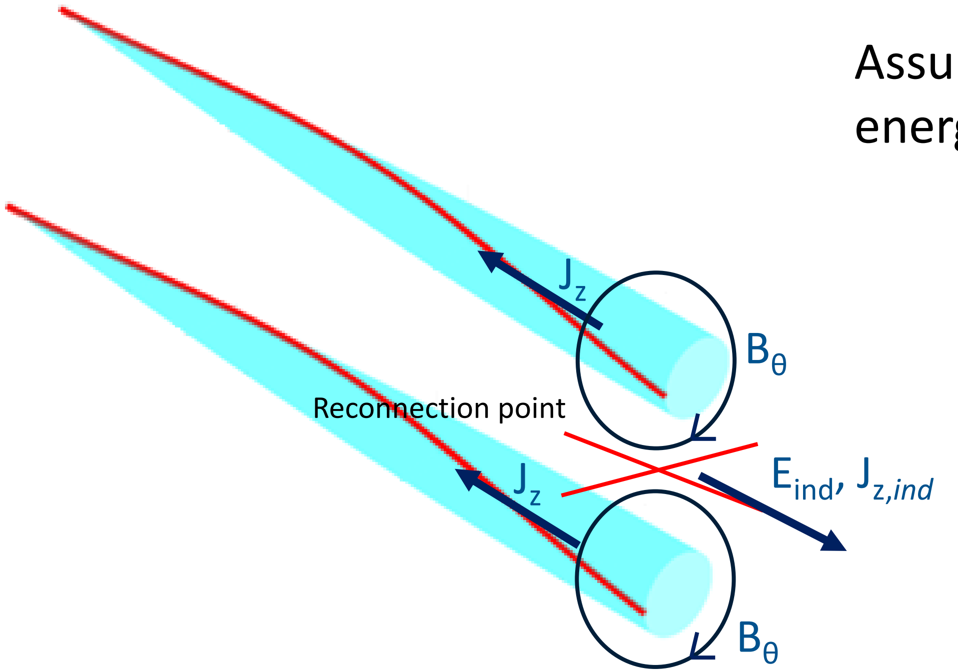
where J_z is the induced current density in the axial direction from the reconnection point calculated from:

$$\nabla \times B = \mu_0 J$$

$$\rightarrow J_z = \frac{B_\theta}{\mu_0 r} \sim 10^6 A/m^2$$

$$\rightarrow \boldsymbol{\varepsilon_{rec} \sim 10 \, J/m^3}$$

Expected performance



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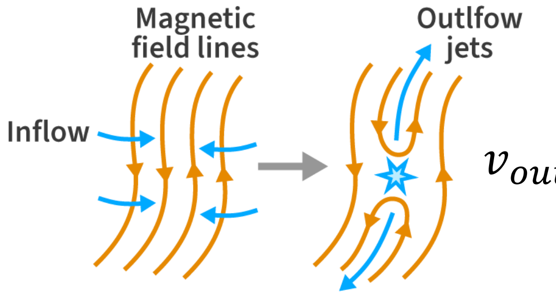


$$v_{out} = \frac{B_{in}}{\sqrt{\mu_0 \rho}} \equiv v_a$$

Assuming that about half of the computed energy is transformed into kinetic energy,

$$\varepsilon_{kin} = \frac{1}{2} m {v_i}^2 n \cong 0.5 \varepsilon_{rec}$$

we can estimate the velocity of the ions

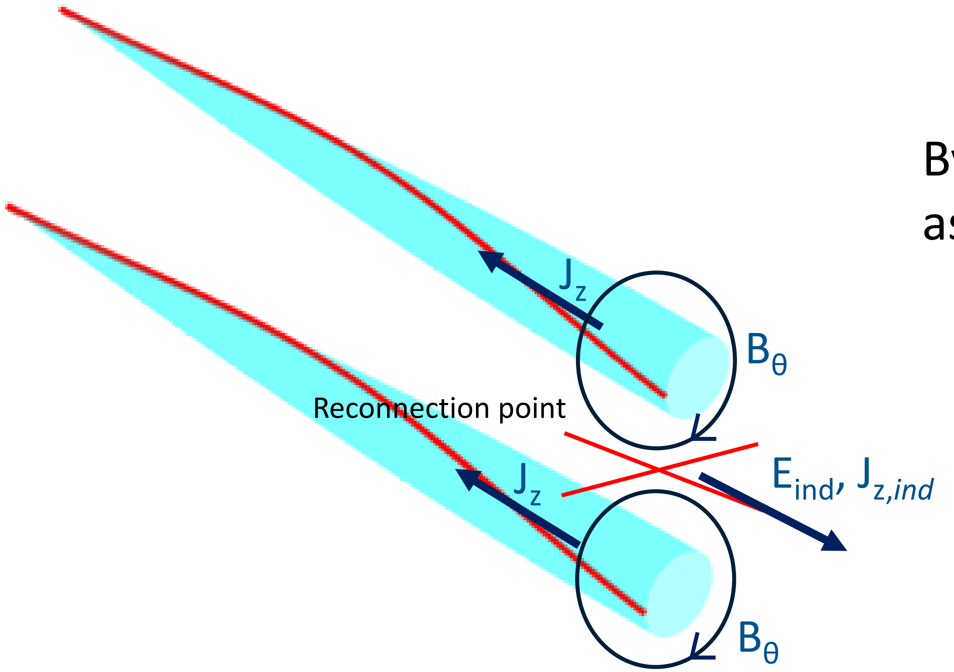
$$\boldsymbol{v_i \sim 10^5\ m/s}$$

and the I_{sp}

$$\boldsymbol{I_{sp} \sim 10^4\ s}$$

assuming $n = 10^{18} m^{-3}$ particles accelerated in the reconnection volume

Expected performance



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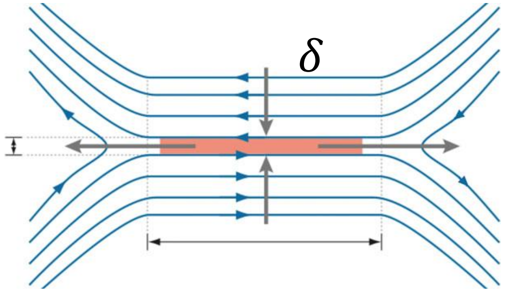


What about Thrust?

By definition, the thrust can be computed as $T = mnv_{out}{}^2 A \approx mnv_i{}^2 A$

Where A is the cross section of plasma effectively accelerated, meaning the effective reconnection cross section

Considering a 2D reconnection process in the poloidal plane, $A = \delta\Delta$ where δ is the current sheet thickness and Δ is the half length of the current sheet

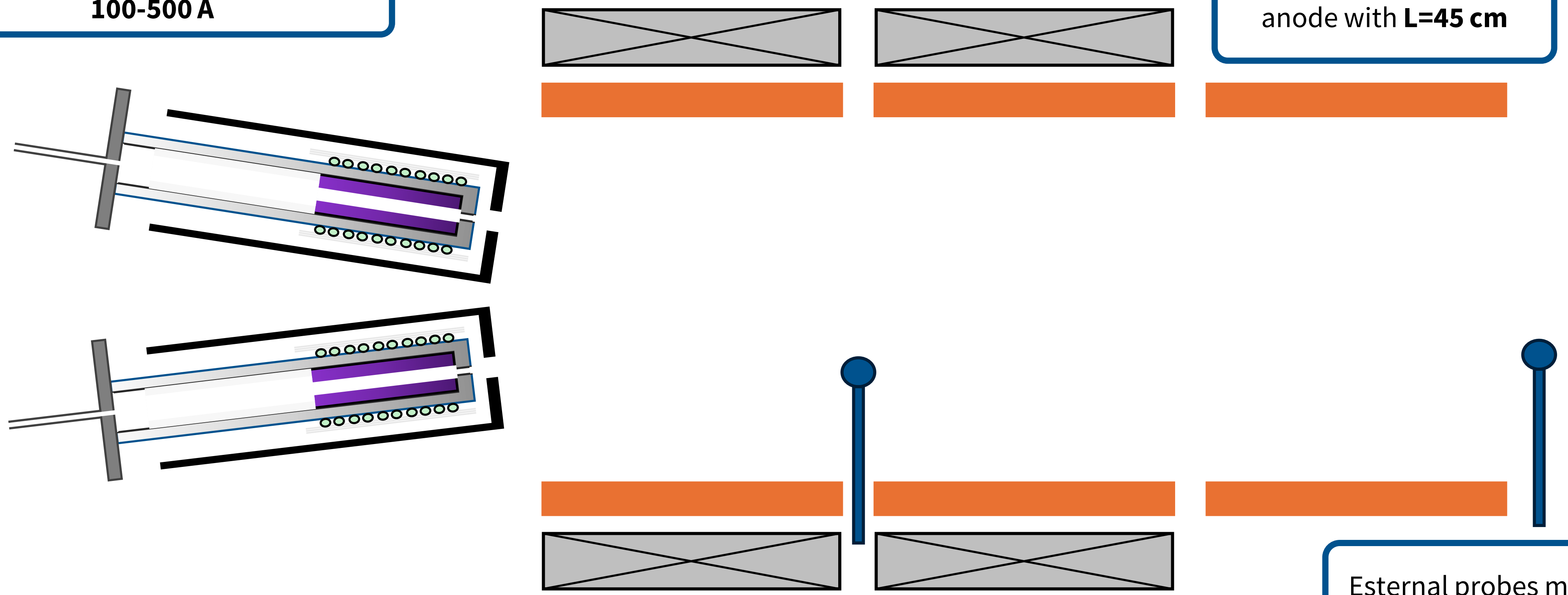
However, we found difficult to estimate these parameters with the simple model used. Therefore, we will try to measure the thrust from the experiments.

Ongoing experimental campaign

Plasma generated by two Hollow Cathodes. Discharge current range **100-500 A**

Axial external magnetic field generated by solenoids. **B field peak = 500 G**

Cylindrical segmented anode with **L=45 cm**



Esternal probes mounted: **RPA, Langmuir probes**.

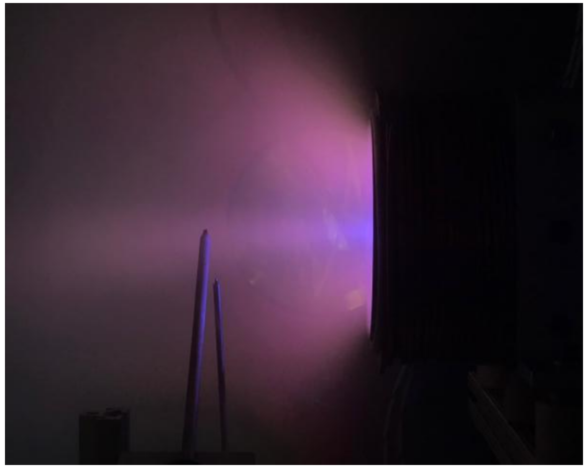
Access points for intrusive and non intrusive diagnostics.
In preparation: RPA, $\dot{B}$ probes, Langmuir, etc.

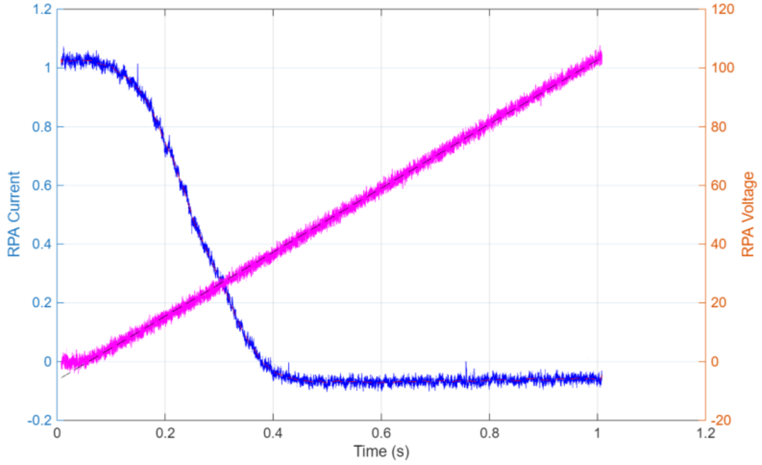
Ongoing experimental campaign

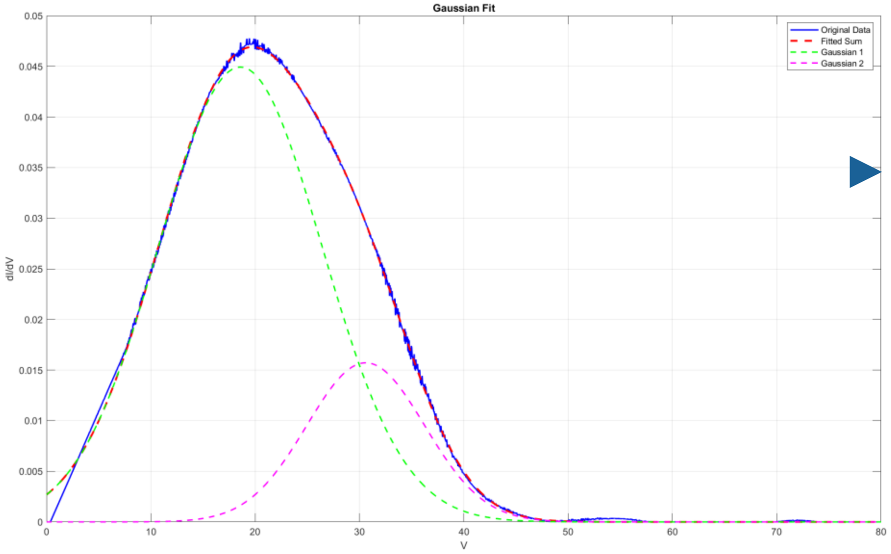
- Working fluid: **argon**
- External applied guide field: **100 – 500 G**
- Max applied current per column: **100 A**
- Ions partially magnetized --> ion Larmor radius **approx. 2 cm** at 250 G
- Kink threshold at 250 G per plasma column: **~70 A**
- Column length (max): **45 cm**
- Plasma density 10^{12} cm^{-3}, electron temperature 5 eV

Ongoing experimental campaign

200A total, 250 G







Preliminary results:

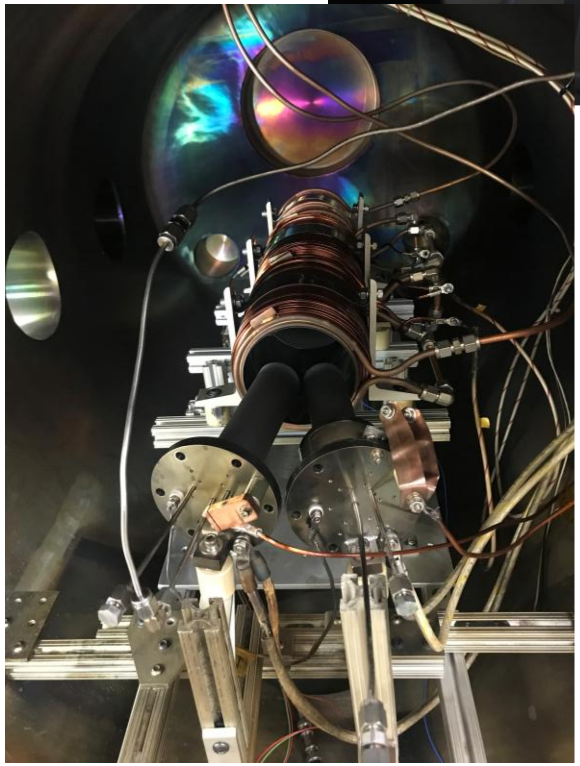
- Setup fully functional with 2 HC operated simultaneously
- Miniaturized RPA placed at the end of the thruster capable of collecting ions energy data.
- At 250 G and 200 A, we detect **two ions populations** at the exit of the thruster, with a distinct higher energy part.
- We see different regimes at the various magnetic fields tested. The columns visually merge at low value of B field (100 G), with no sign of magnetic reconnection. At higher B field (250 G) the ropes are visually more separated and higher energetic ions are detected.

Next Steps toward Validation

Università di Pisa

Jet Propulsion Laboratory
California Institute of Technology

Project currently funded with internal fundings and active collaboration with JPL



Experimental Campaign

- Hydrogen will be employed instead of argon to favor full magnetization
- Discharge current increased to 250 A per column
- Diagnostics: RPA and magnetic probes on a 3 axis movable apparatus

Simulations

- 3D MHD simulations with g-PLUTO
- Kinetic simulations in collaboration with Princeton University are investigated

Conclusions

- **Magnetic reconnection** has the capability to accelerate particles at up to the Alfvén velocity of the plasma => it can be employed in innovative type of plasma propulsions for **very high Δv missions**.
- Different thrusters concepts based on MR as acceleration mechanisms have been proposed worldwide
- We propose an innovative concept based on **multi flux ropes**. When the ropes are kink unstable they collide with each other triggering magnetic reconnection
- The induced electric field and current can accelerate ions at velocities up to **10^5 m/s**
- The **experimental campaign** is on-going. The setup is fully functional and tested with Argon.
- Next steps include the test with **hydrogen** and the detection of magnetic reconnection.
- **3D simulations** are under investigation.

Thanks for your attention

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