

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

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Recent advances in the space sector have led to new improvements in propulsion capabilities for the next generation space missions. Foreseen interplanetary missions such as the Cislunar space stations, cargo missions to Mars, and possibly human exploration of Mars call for novel, more advanced propulsion systems, with Electric Propulsion (EP) systems playing a significant role in this scenario [1], given their high efficiency combined with lower propellant consumption.

Mission energy demands (ΔV) are increasing, requiring propulsion systems with high exhaust velocities to minimize propellant consumption. Specific impulse (I_{sp}), defined as thrust-to-propellant weight flow ratio, is a key performance metric, with higher I_{sp} indicating greater exhaust velocity. Additionally, high thrust levels are essential for reducing maneuver time and propellant usage. EP has been considered for high ΔV missions since the mid-20th century. The most common systems include electrostatic accelerators like ion and Hall thrusters, with I_{sp} between 2000-4000s limited by the electric field strength.

In light of what has been said, it is evident that next-generation space missions would require low-weight thrusters with higher thrust and specific impulse to obtain the required ΔV .

The current strategy to develop a thruster with higher levels of thrust and specific impulse involves the scaling up process of notable conventional electric propulsion. However, this strategy poses a serious problem: the scaling laws towards high power and high thrust engines depend mostly on increasing the thruster footprint. Therefore, developing a thruster for very high-power applications will impact the spacecraft overall dimensions and weight.

The advanced studies in the field of electric propulsion then have mostly focused on innovative and possibly groundbreaking concepts capable of overcoming the current limits of the state-of-art.

In recent years, there has been an increased interest in developing an innovative thruster based on magnetic reconnection (MR) as main acceleration mechanism [2]. MR is a common phenomenon in space and laboratory plasmas [3]. It occurs in solar flares, planetary magnetospheres, jets from active galactic nuclei, neutron stars, laser-plasma interactions, astrophysical dynamos, and toroidal plasmas in fusion experiments. It releases magnetic energy, converting it into kinetic and thermal energy, accelerating particles to non-thermal velocities and generating waves and turbulence. Harnessing this mechanism, observed in natural phenomena like solar flares and coronal mass ejections, offers a way to produce high-power plasma jets for spacecraft propulsion. Magnetic reconnection, involving the breaking and reconnecting of antiparallel magnetic field lines, has potential as a main acceleration mechanism, although prior attempts to use it for space thrusters have been limited.

In this contribution, we present the work performed at University of Pisa and Jet Propulsion Laboratory in the field of magnetic reconnection thruster [4], showing the different approaches undertaken to conceptualize the thruster, and the methodology adopted to verify its functionality.

In particular, we have been investigating the plasma generated by multiple flux ropes, and the MR phenomena obtained by the flux ropes collision when affected by the kink instability. The MR event within this setup accelerates the ions primarily in the radial and axial direction, from which we can obtain a net thrust at the exit of the thruster. Preliminary estimations highlight how the effective specific impulse from this concept can be as high as 10000s.

Reference:

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