New electric propulsion technologies investigation by simulation

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- The EP2 group and their activities
- Modeling plasma plumes
  - An application: IBS space debris removal
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The EP2 Group

- Main activities: model & simulation of plasma thrusters and plasma processes:
  - Hall effect thruster
  - Helicon thruster
  - Magnetic nozzles
  - Surface-plasma erosion
  - Ion beam space debris removal
- Long experience with fluid and PIC codes (HP-Hall2, DIMAGNO 2D, HALLMA, HELFLU, HELPIC, IBIS)
- Current members:
  - One Professor
  - Two Teaching assistants
  - Three PhD students
  - Two MSc students
- International collaborations and research projects (ESA, FP7, EOARD...)

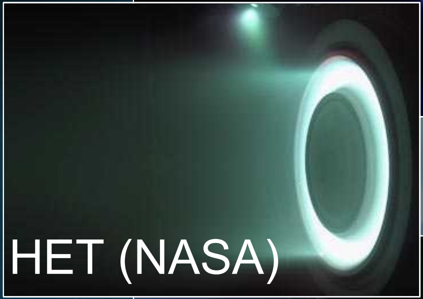
More info & publications:
http://web.fmetsia.upm.es/ep2

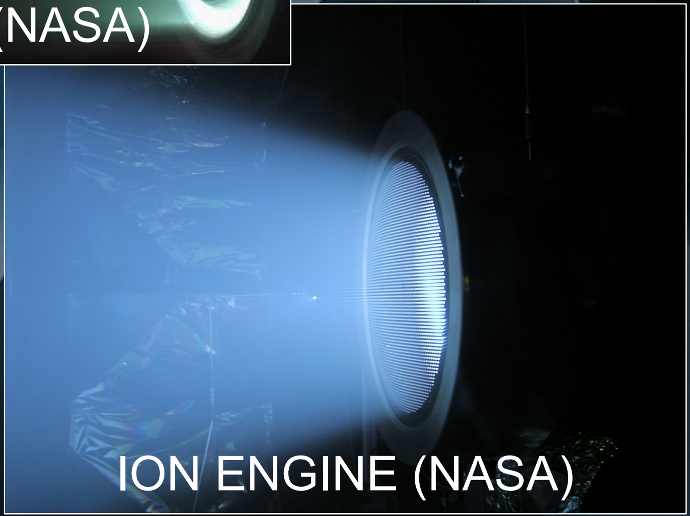
EP2

Free EP plumes:
Ion Beam Shepherd

EP plasma plumes in space

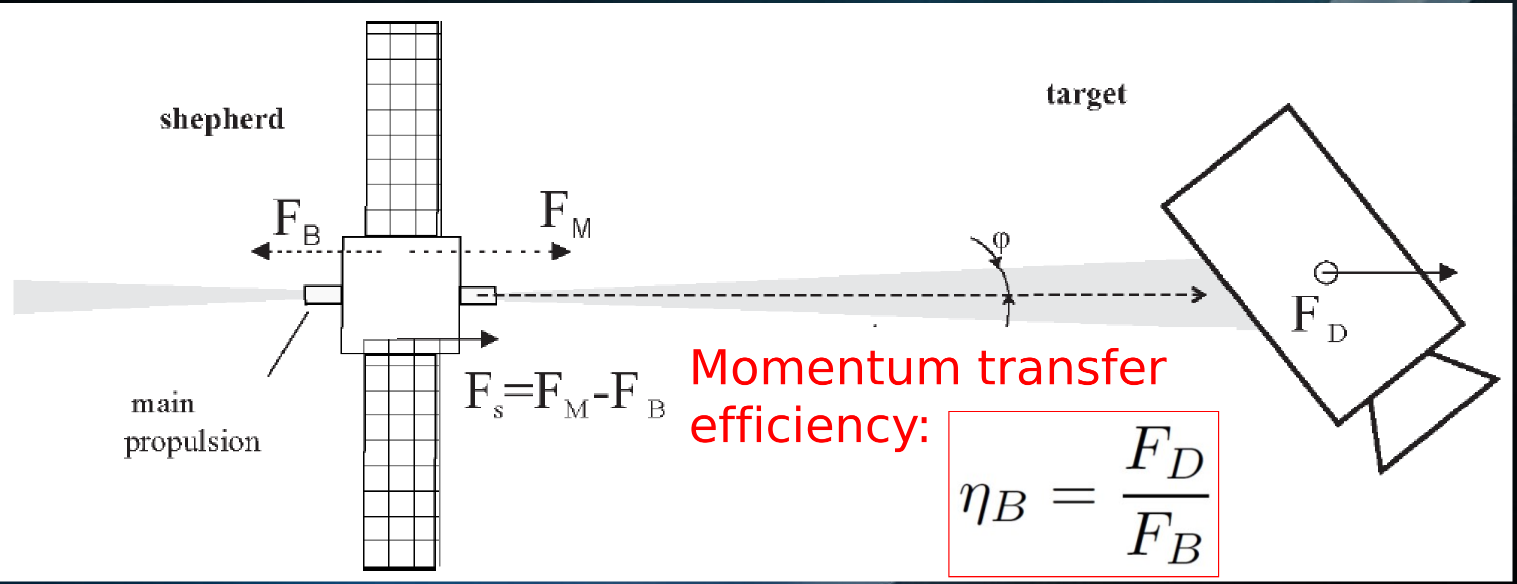
- Plasma plumes are ubiquitous in Electric Propulsion
- Characteristics strongly dependent on thruster type and operation, but typically: moderate-highly collimated, quasineutral, ~ 1 keV beams
- Understanding and modeling plasma plumes paramount for many applications:
  - Study divergence losses in EP
  - To predict solar panel degradation
  - Understand EM-plasma interaction
  - Also: material processing, ion deposition, etc.





Ion Beam Shepherd Space debris removal

- Space Debris removal is complex and costly, as it typically involves docking with a non-cooperative, tumbling body
- Docking is avoided using an efficient ion beam to transmit the deorbiting force from a safe distance
- While maintaining this contactless link in close formation-flying, the main propulsion deorbits the two-body system to a target orbit for debris disposal
- Once deorbited, IBS can proceed with next debris (multi-mission capability)



[JGCD34-916]

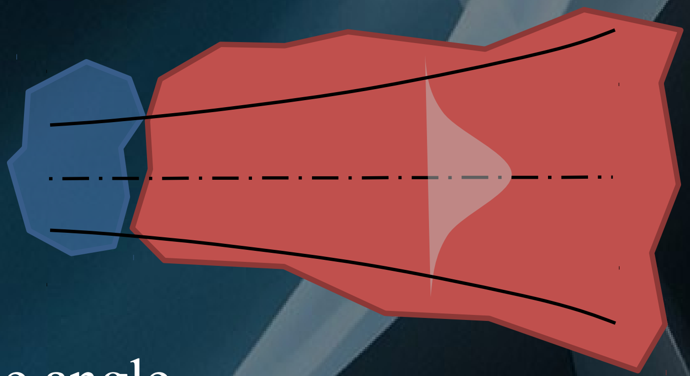
Plasma plume modeling

- We need to model and understand plume dynamics for IBS
- The EP exhaust has a near-field and a far-field plume:
  - ✔ In the near field (few thruster radii), many effects and processes are present:
    - Plasma inhomogeneities
    - Thruster's electromagnetic fields
    - Most CEX and other effects

    → These determine the initial divergence angle

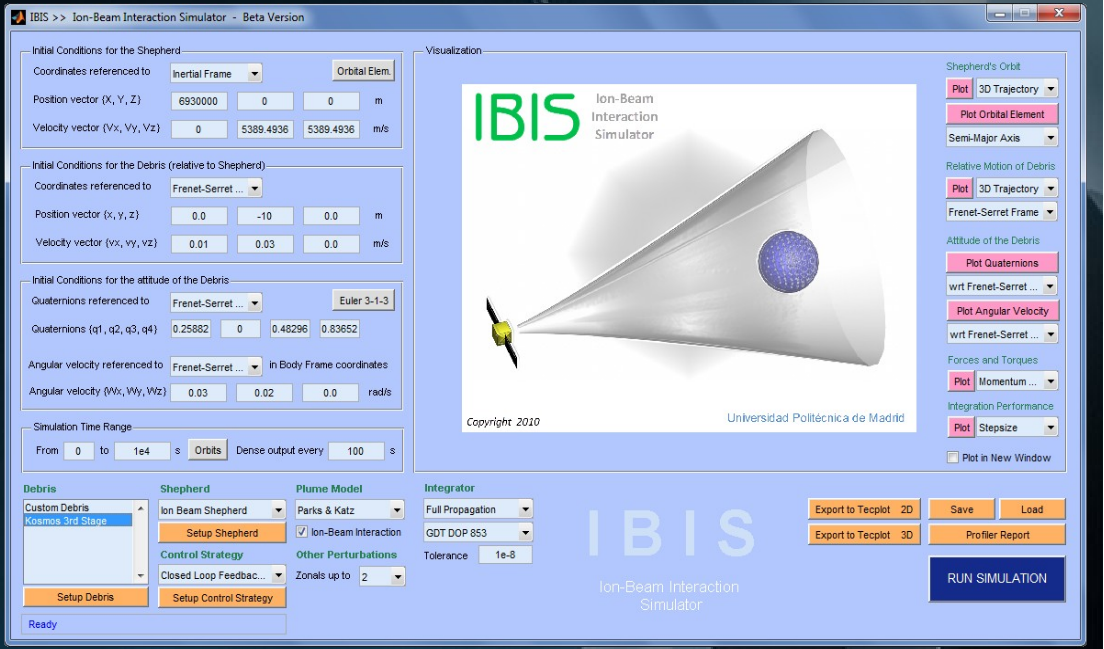
  - ✔ Downstream, a smooth, bell-shaped profile forms (in HET, profile is single-peaked 2 diam away). Residual pressure and the ambipolar electric field dictate the evolution of the plasma

    → Quasi-self-similar models [IEPC-2011-086]

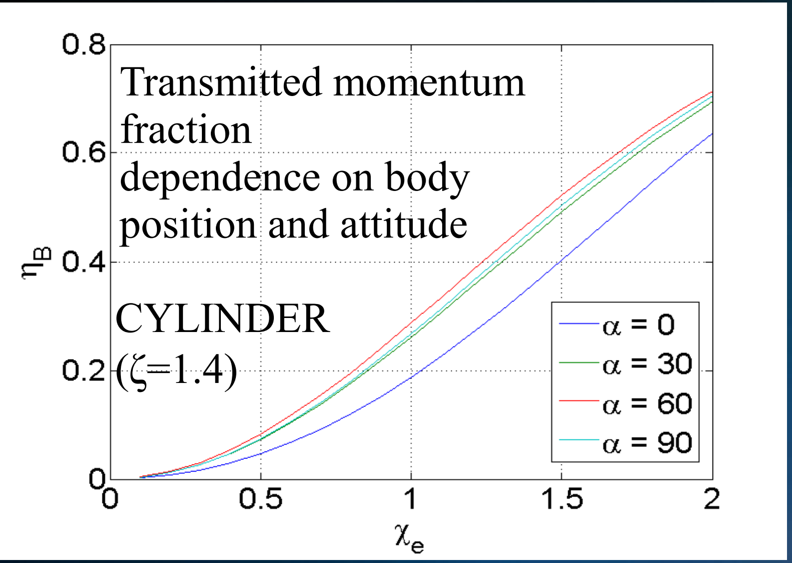


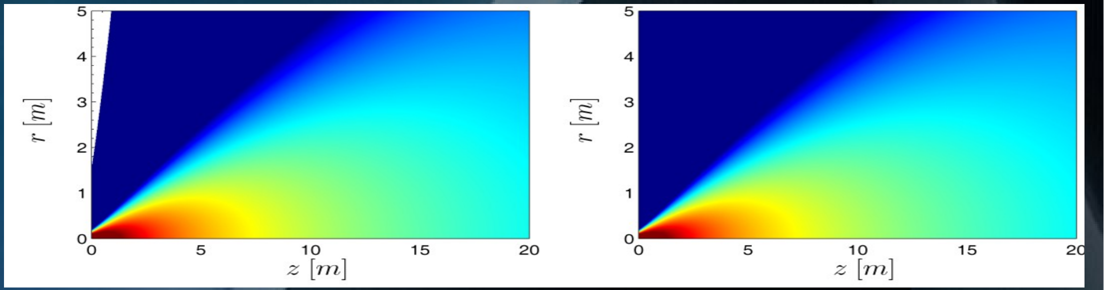
IBIS code and results

IBIS Ion - Beam Interaction Simulator



- In-house developed tool
- Matlab + Fortran/C
- Plume interaction, forces & torques, orbital motion, control

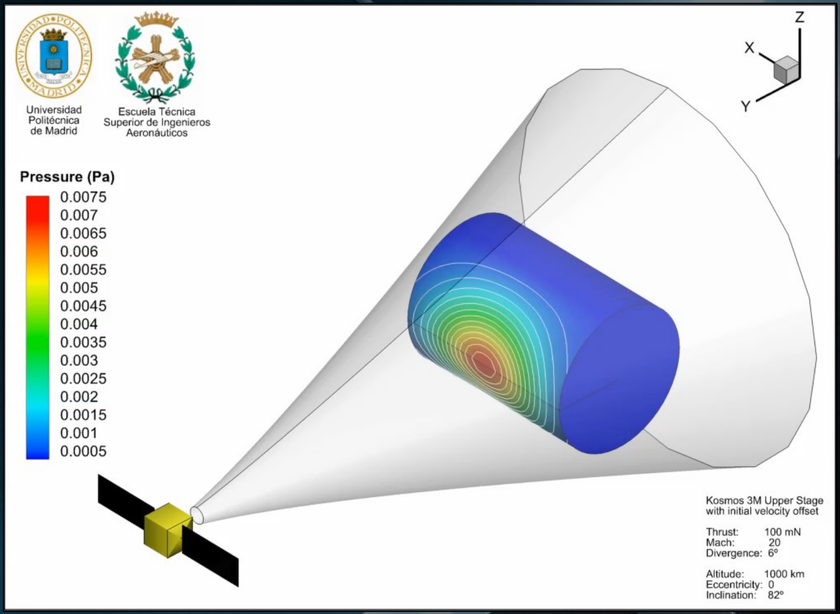


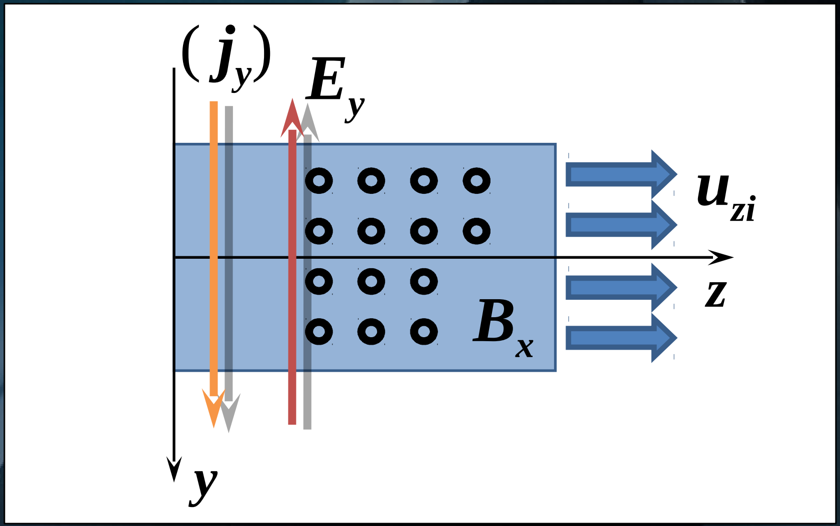


Self-similar plume profiles: log nu_{zi}

Present and future work

- So far, we have proved the concept and characterized:
  - Momentum transmission for simple geometries
  - Stability of formation flying and control
  - Deorbiting strategies
- Ongoing efforts dedicated to study:
  - Interaction of beam with *B* field (deflection? SPIS?)
  - Charging, sputtering and heating of debris (SPIS?)
  - Backscattered particles and CEX (contamination?)
- SPIS could be an interesting tool for us

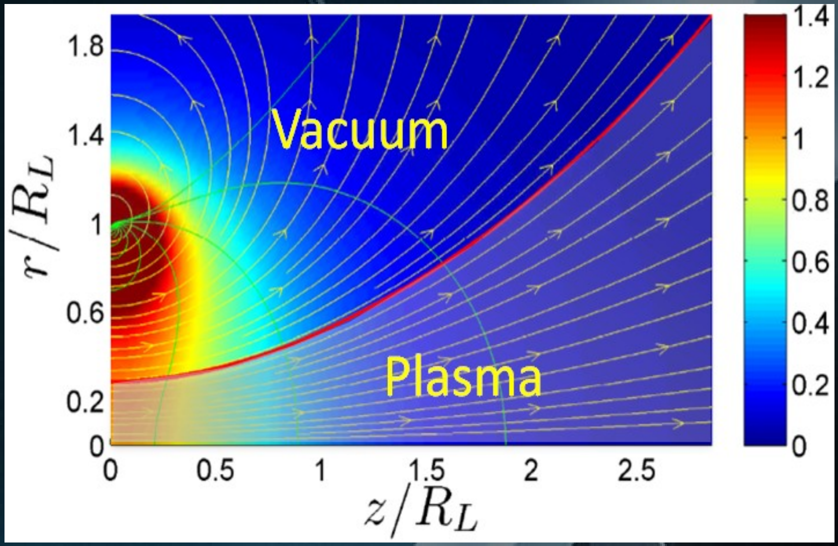


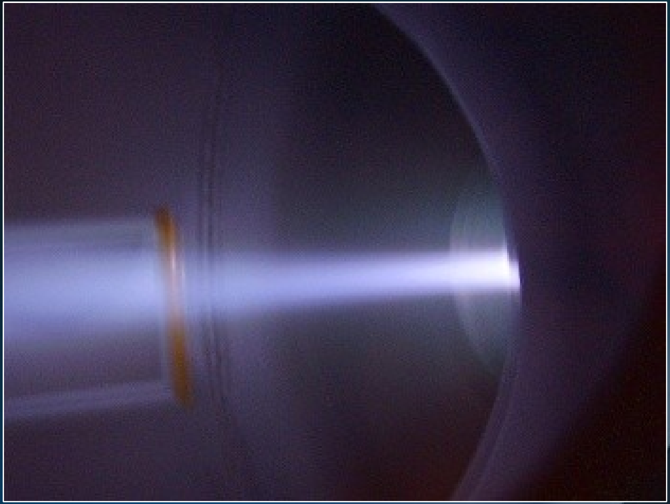


Magnetized plumes: Magnetic nozzles

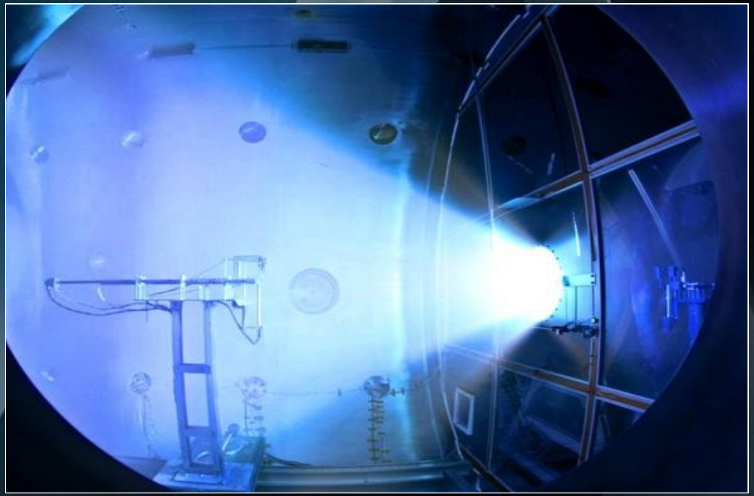
Plasma expansion in a Magnetic Nozzle

- Resembles a free plume, but an external longitudinal B field is applied to confine, control and accelerate the plasma
- VASIMR, Helicon thruster (e.g. HPH.com), AFMPD thruster all use MN → Relevant Propulsion Mechanism
- Wall-plasma contact is avoided
- Isp and thrust control





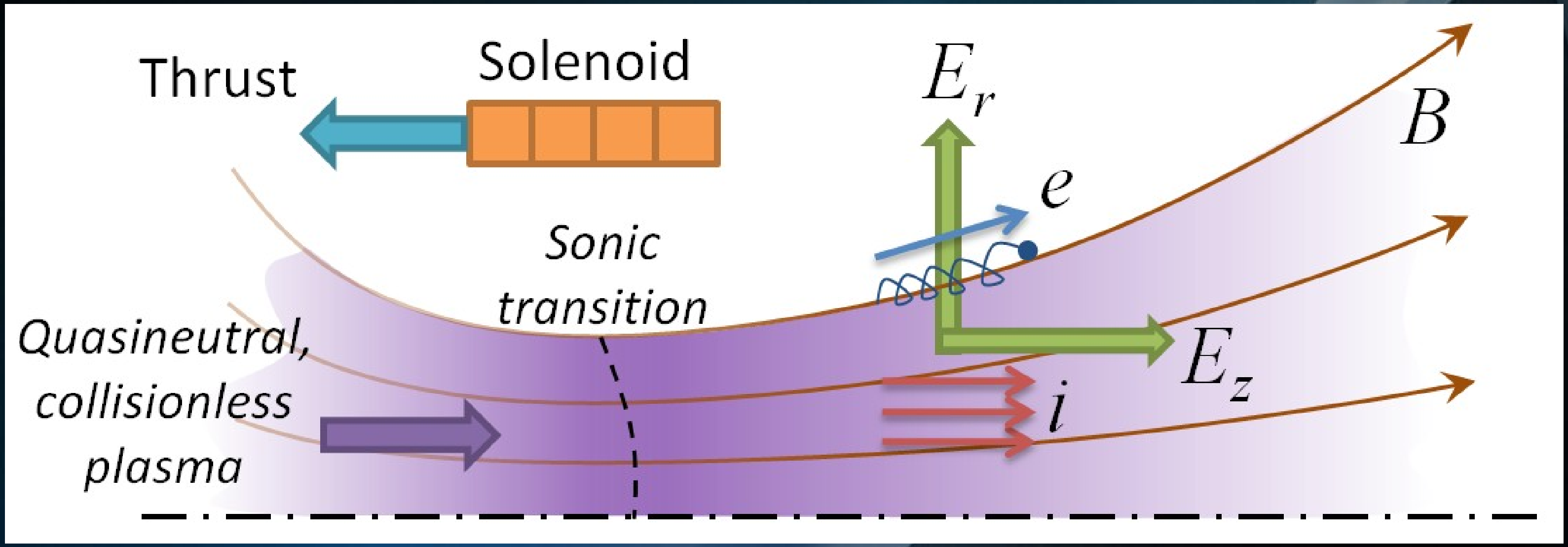
Magnetic Nozzle test of a prototype of the European HPH.com thruster.



Magnetic Nozzle of VASIMR undergoing test (AARC)

Principles of a Magnetic Nozzle

1. An external magnetic field is established; plasma is injected at the throat
2. Electrons are totally magnetized and describe the field geometry.
3. Cold Ions are pulled and forced to expand (collisionlessly) by the ambipolar electric field that arises to maintain the plasma quasineutrality.
4. Internal pressure causes electron azimuthal currents which confine and accelerate the plasma, and transmit thrust back to thruster
5. After acceleration, plasma needs to detach from the imposed field



Confinement and detachment

- Plasma needs to be well-confined during initial expansion, to avoid wall erosion and sensible surface damage → strong B fields
- After acceleration, plasma has to be detached from the field: otherwise, it will run back along closed B lines and attack the spacecraft → mild B fields

  → Correct operation is a delicate balance between confinement and detachment.

  → Both losses cause plasma to reach surfaces.

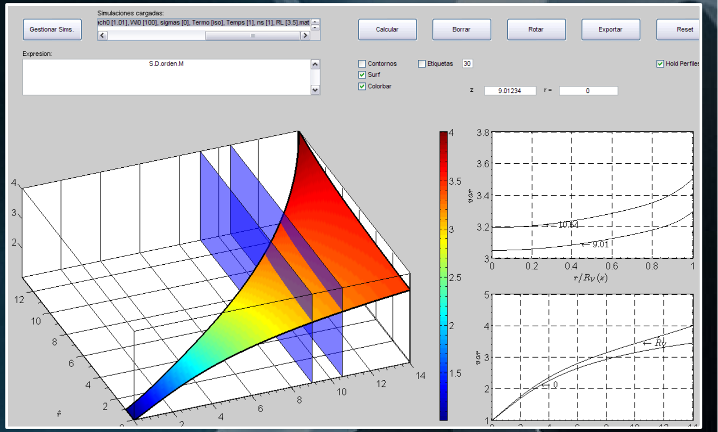
- Also: CEX with remaining neutrals will spoil efficiency and contaminate surfaces

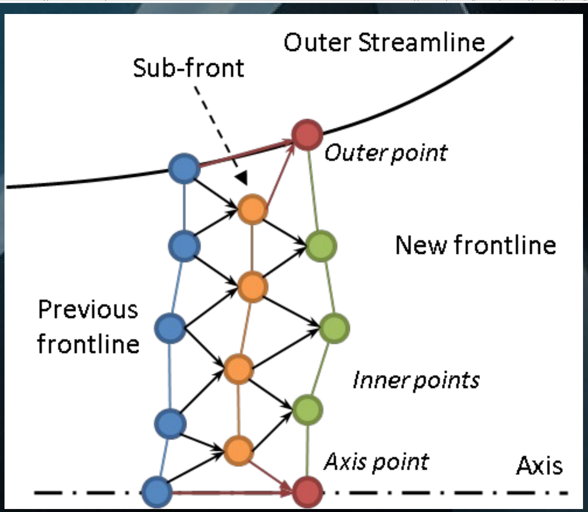
DIMAGNO 2D and fluid model

- Assuming totally-ionized, collisionless plasma, and magnetized electrons
- DIMAGNO 2D is an axisymmetric fluid code developed in-house for studying MN with:
  - Ions and multiple species of electrons
  - Different electron thermodynamics
  - Plasma-induced magnetic field
  - First-order electron inertia effects
- DIMAGNO 2D used OO programming in Matlab, and a highly-optimized Method of Characteristics algorithm for integrating the supersonic ion flow (→ fast + accurate)

$$\lambda_D \ll \ell_e \ll R_V \ll \lambda_{ie}$$

$$\ell_i \sim R_V \quad \beta \ll 1$$

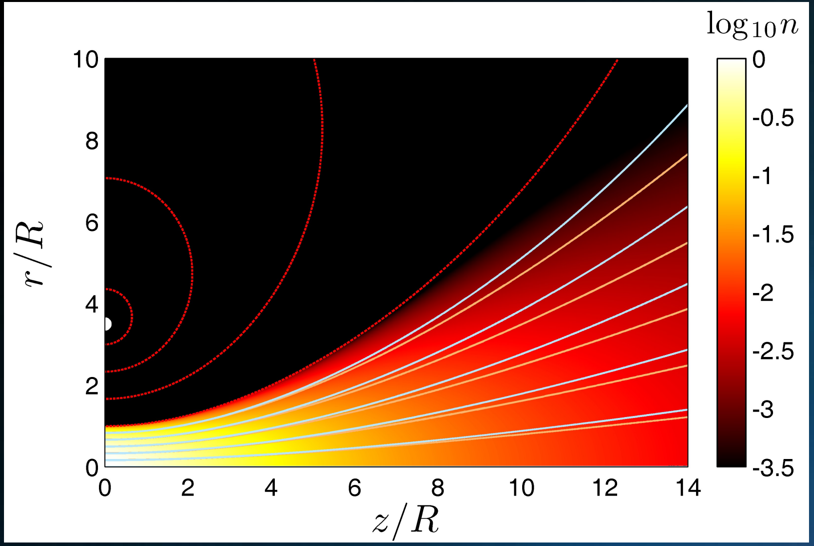




Solution advancement scheme of DiMagNo 2D

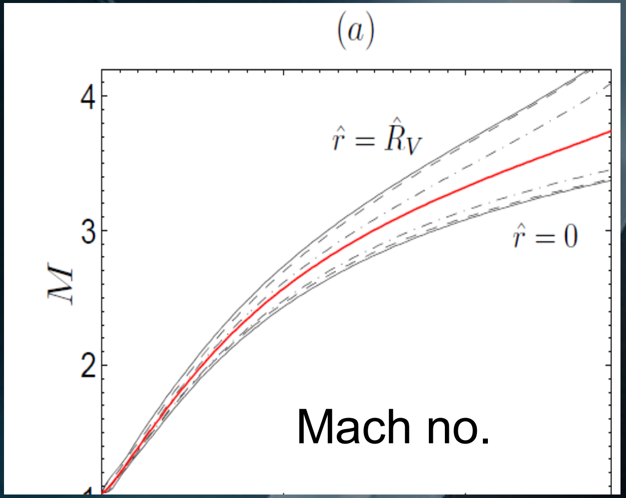
Main results

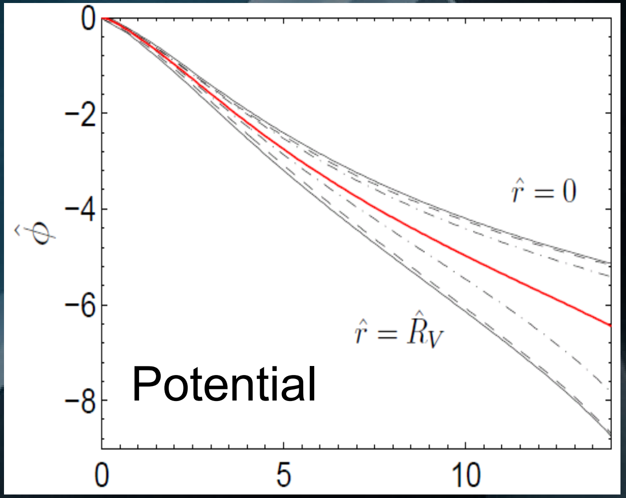
- So far we have studied:
  - Plasma expansion and acceleration, plasma currents, and acceleration mechanisms
  - Plume performance, parametric investigation
  - Basic detachment (existing theories fail)
  - Effect of electron thermodynamics
  - Induced field and electron inertia effects



Density, ion (orange) and electron (blue) streamlines. Magnetic lines in red.

[Phys. Plasmas 17 073501]
[Phys. Plasmas 18 053504]

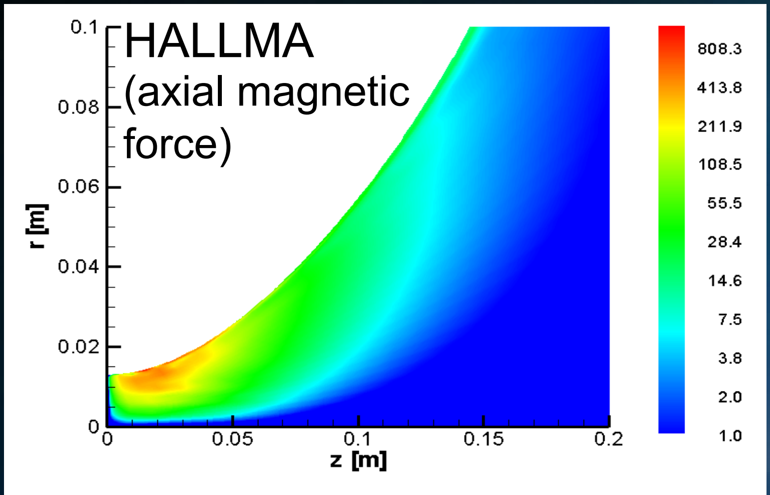


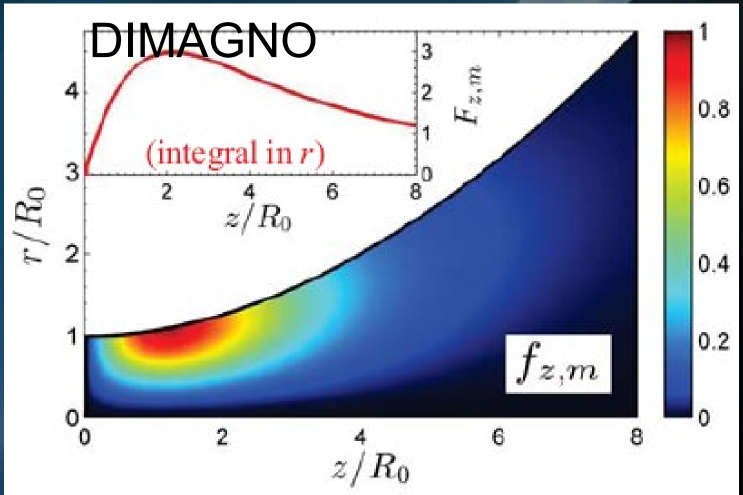


Evolution of Mach number and electric potential. Red line depicts a 1D model. Different simulations.

Current efforts and future work

- ✗ Fluid model lacks insight on collisional processes, IEDF effects, difficult to study demagnetization (SPIS?)
- ✗ Code requires hyperbolic Eqs. → No study of the plasma source
- Hybrid PIC/fluid development started to overcome such difficulties. Based upon HP-Hall-2 code know-how
- We also aim to obtain a complete code for the source + MN (HELIFLU, HELIPIC)
- First results show great agreement with DIMAGNO data:





[IEPC-2011-048]

Conclusions

- EP2 is an active group whose main activity is modeling and simulation of plasma thrusters (fluid, PIC: long experience)
- Magnetized and non-magnetized plasma plumes are a central topic in EP and satellite integration
- Continued study is necessary to understand and improve thrusters and plasma interaction with SC
- SPIS could prove a valuable tool for us, specially for the IBS plume interaction with a far body
- Our know-how on thruster simulation could potentially contribute to the SPIS community

Thank you!

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