Magnetic nozzles

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EPIC Lecture series 2017, Madrid:
Watch the lecture at
www.youtube.com/watch?v=IEpd1ME2P30

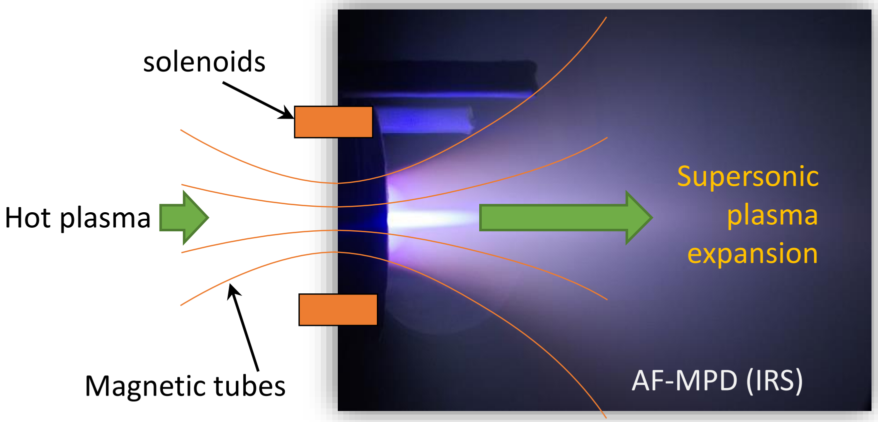
Lecture notes:
M. Merino, E. Ahedo, "*Magnetic Nozzles for Space Plasma Thrusters*"
Encyclopedia of Plasma Technology, 2016

All EP2 open source codes are available on GitHub:
https://github.com/ep2lab

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)

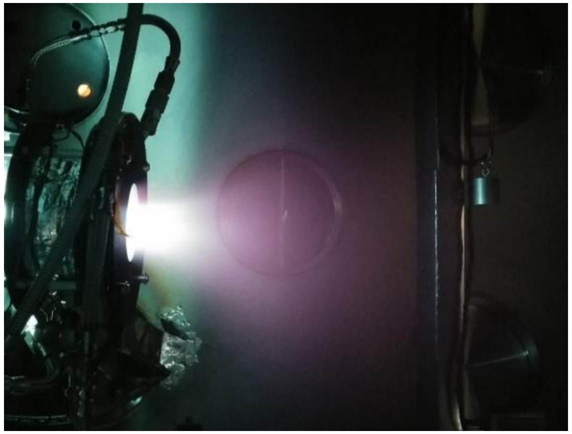
RL-10 rocket "de Laval" nozzle



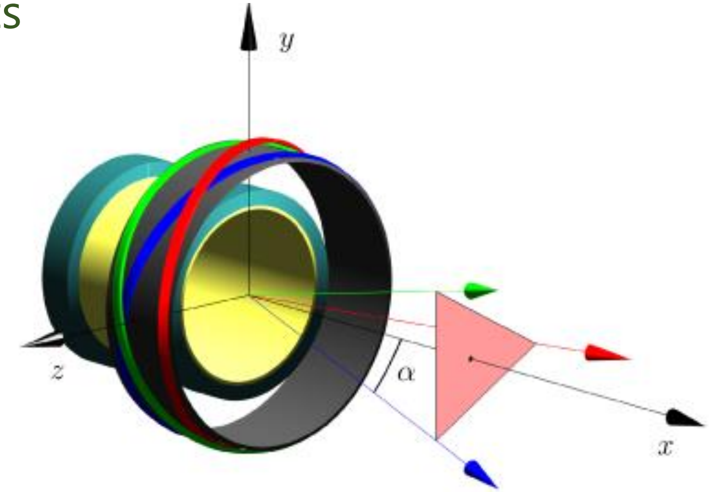
A magnetic nozzle in operation

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

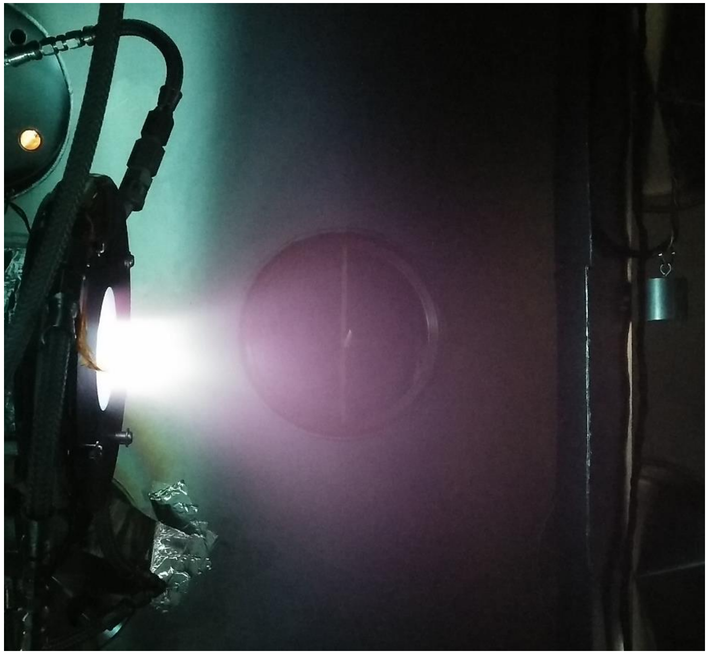


MN of SENER-EP2 Helicon plasma thruster HPT05 running on Xe (EP2 lab)

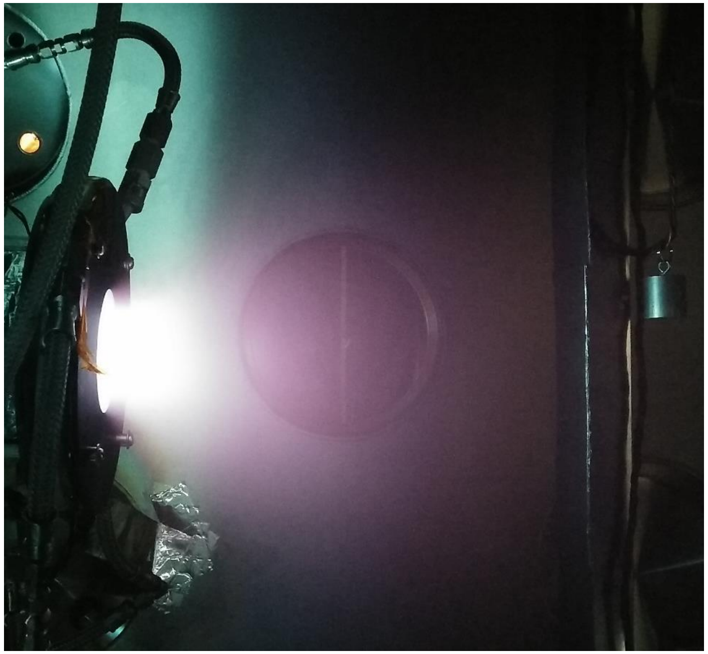


3D MN configuration for thrust vector control

Magnetic nozzle on / off



HPT05 thruster, MN coil on

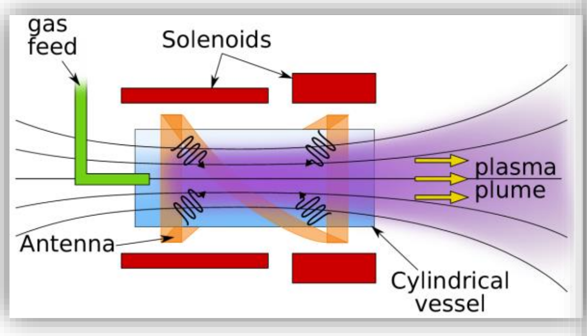


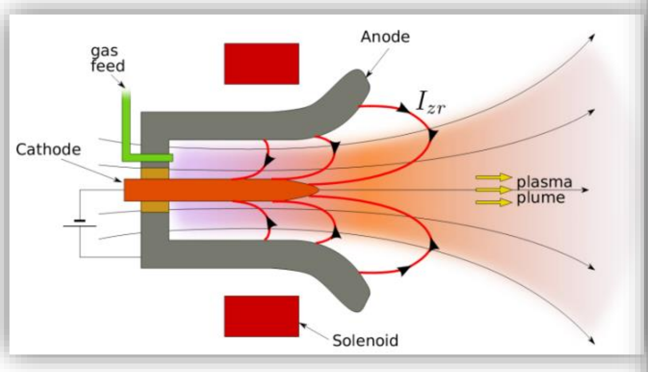
HPT05 thruster, MN coil off

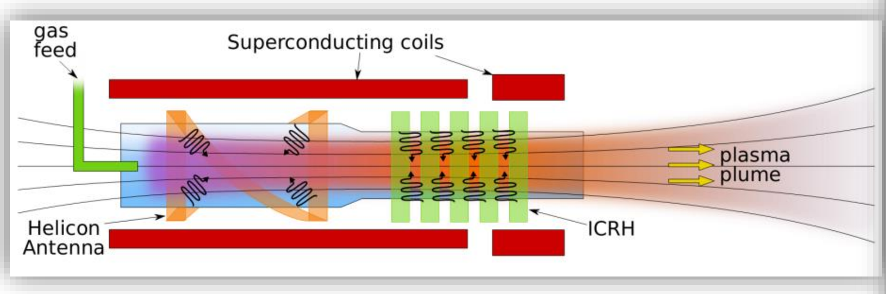
- Different MN plasma thrusters have different physics. This must be taken into account when studying MN plasma flows

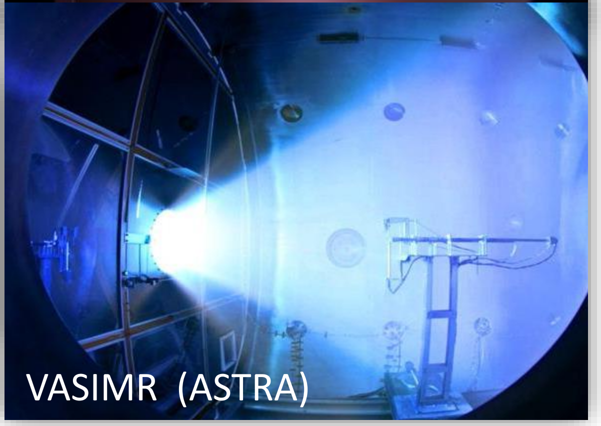
Plasma thrusters with MNs

- Helicon Plasma Thruster (HPT)
  - High plasma density ($10^{18} - 10^{20}$ 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 $\boldsymbol{B}$
  - $\eta_T < 0.72$



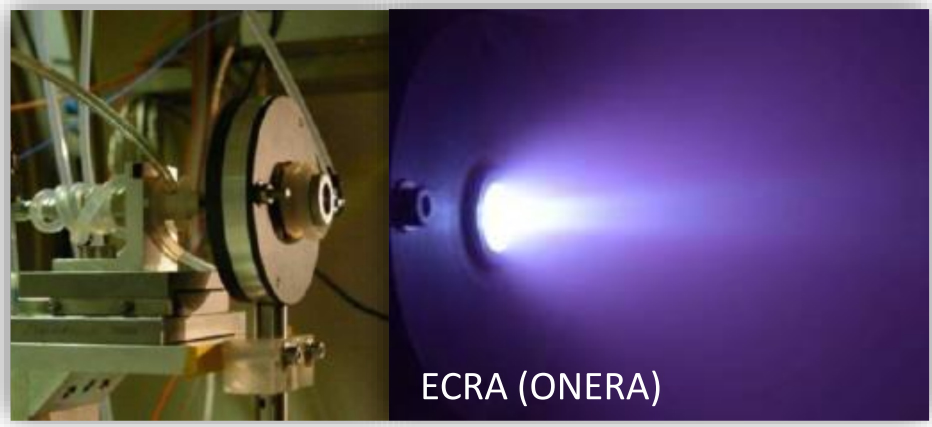


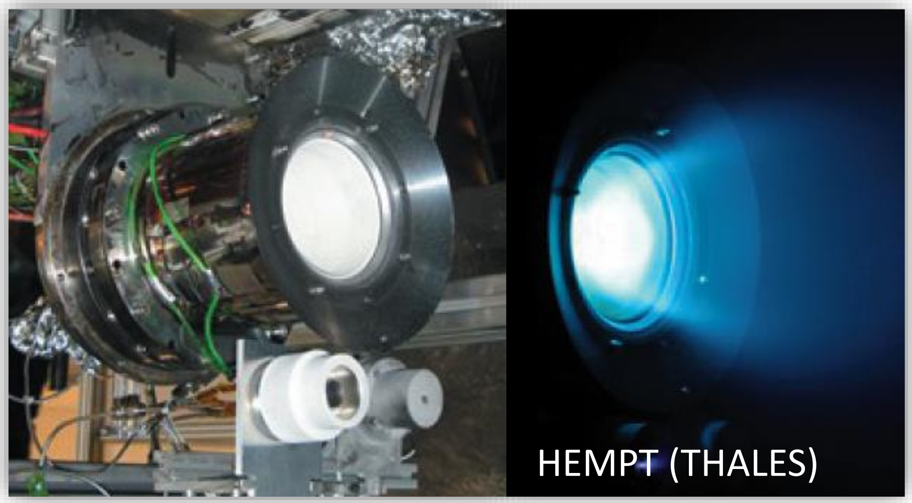


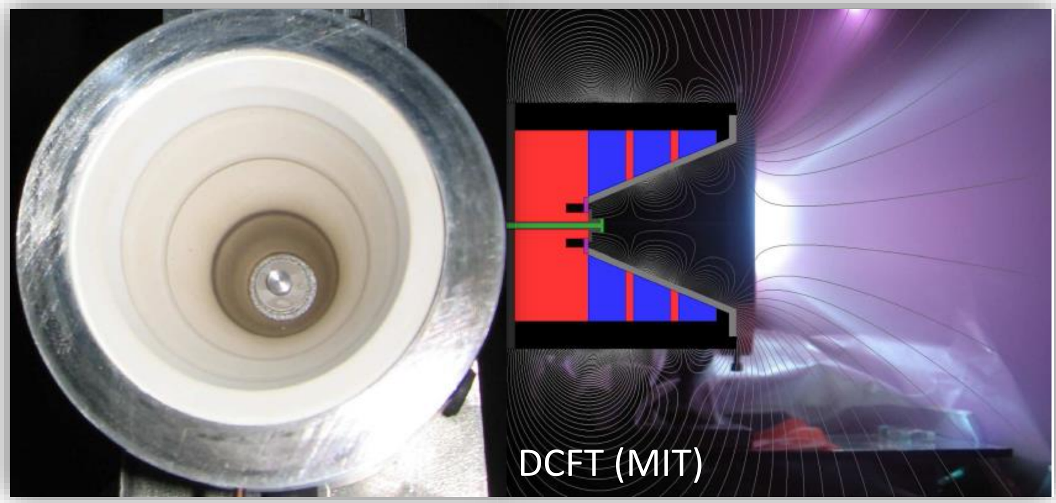


Plasma thrusters with MNs

- 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







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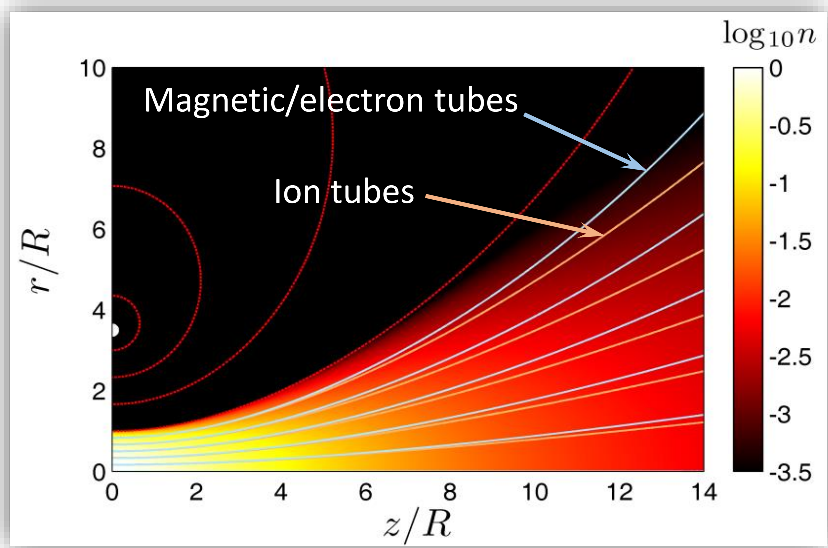
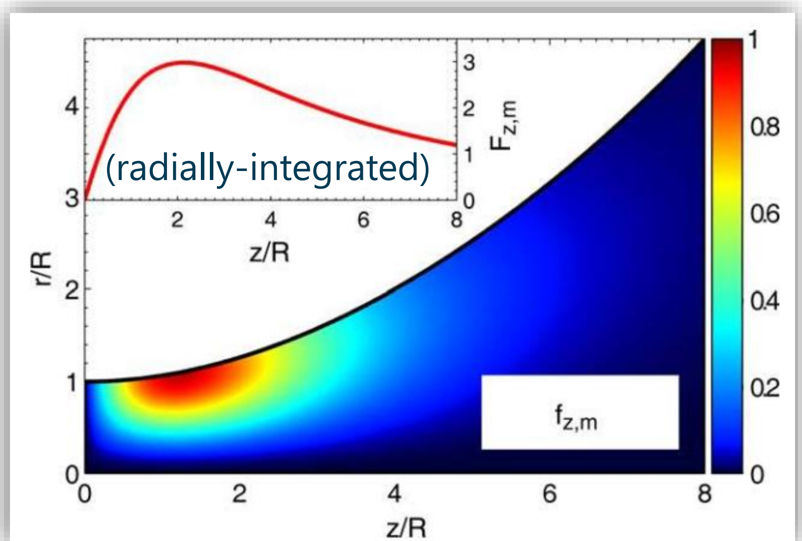
DIMAGNO code for Magnetic nozzles

- Fundamental 2D code for magnetic nozzles. Has enabled research conducting to more than 12 journal publications
- 2D Two-fluid ion-electron plasma model of a diverging MN
  - Fully magnetized electrons; arbitrary ion magnetization degree
  - Accurate integration with the method of characteristics
  - Yields plasma density, potential, velocity, temperature maps; thrust density, nozzle efficiency
  - Has been used to solve thrust generation mechanisms, plasma detachment, plasma-induced magnetic field effects, electric double layers, etc



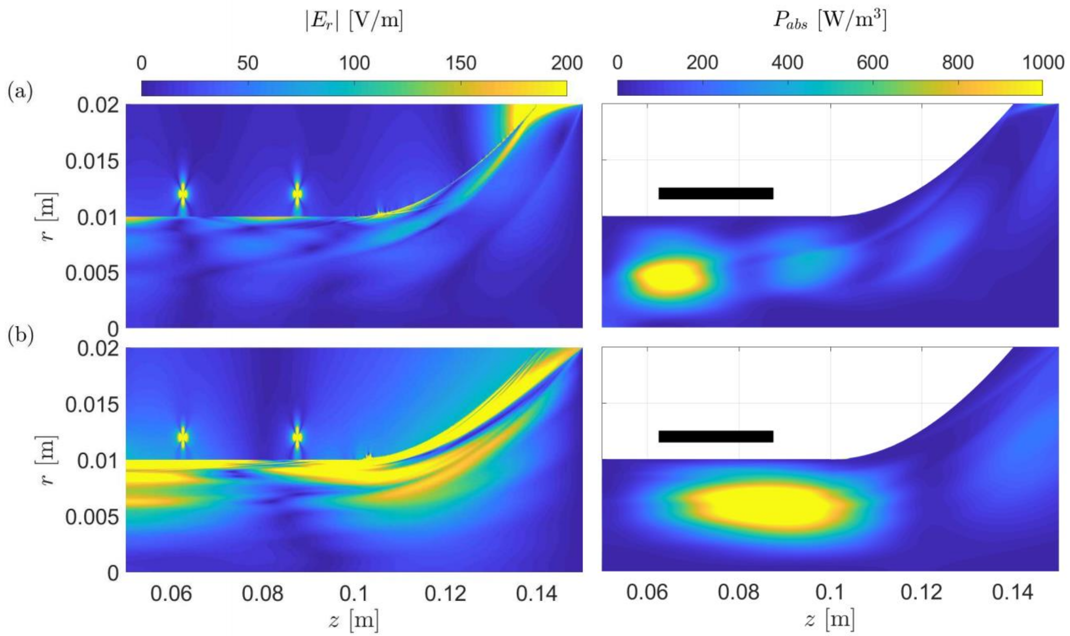
Plasma density map and detachment

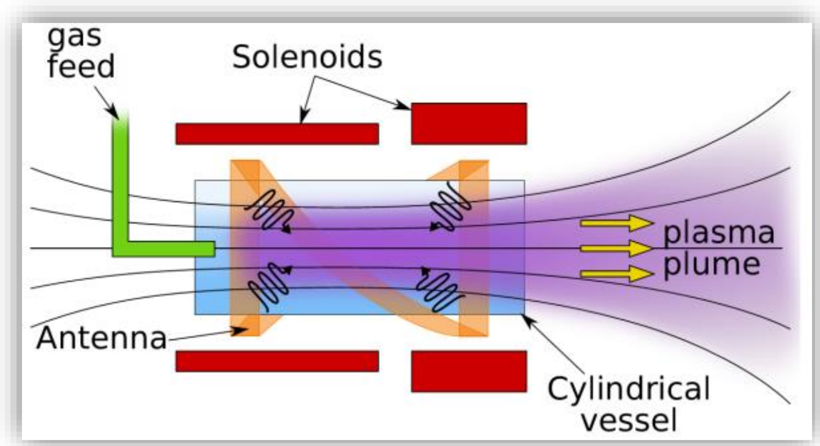


Axial magnetic force density in the plasma

DIMAGNO code for Magnetic nozzles

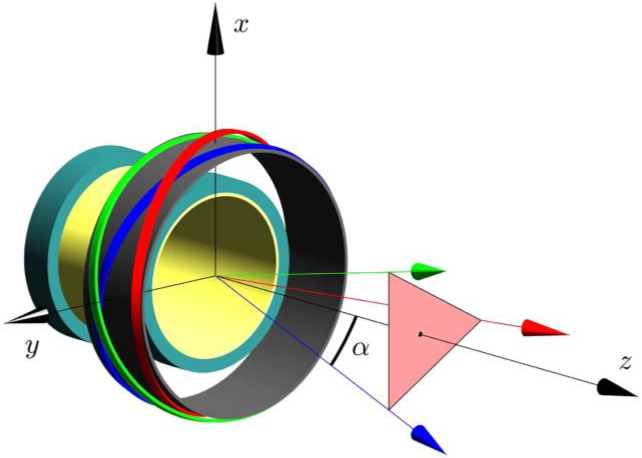
- In the framework of the H2020 MINOTOR project, DIMAGNO is a module of the SURFET code for the simulation of ECRT
- DIMAGNO is currently being extended in several directions:
  - Anisotropic electron populations (relevant in ECRT)
  - Coupling with plasma source + wave-plasma interaction codes
  - Kinetic electron cooling models (from EP2 kinetic codes)

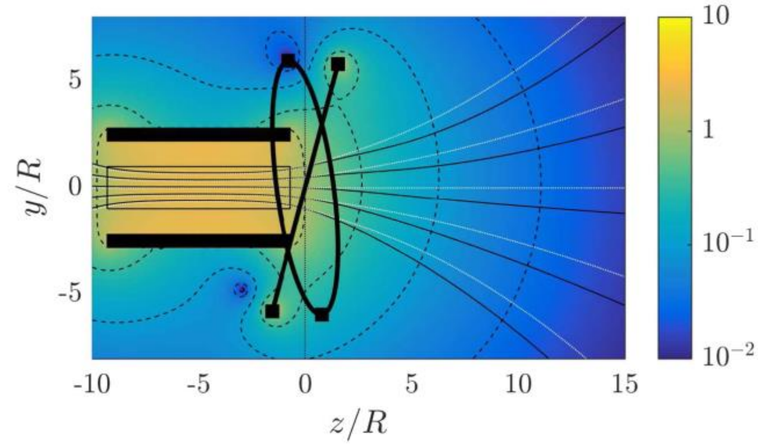


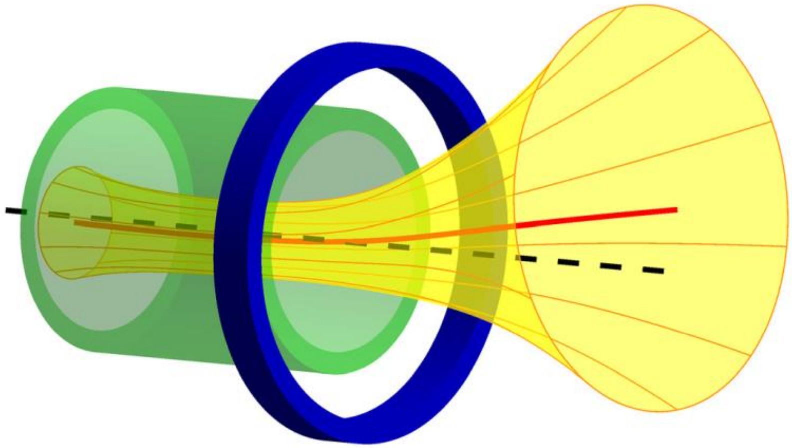


FUMAGNO (fully-magnetized limit)

- Fully-magnetized limit of DIMAGNO
  - Electrons AND Ions are treated as fully magnetized species
  - Allows quick estimation of plasma properties in converging-diverging
  - Enables study of 3D magnetic topologies and thrust vectoring







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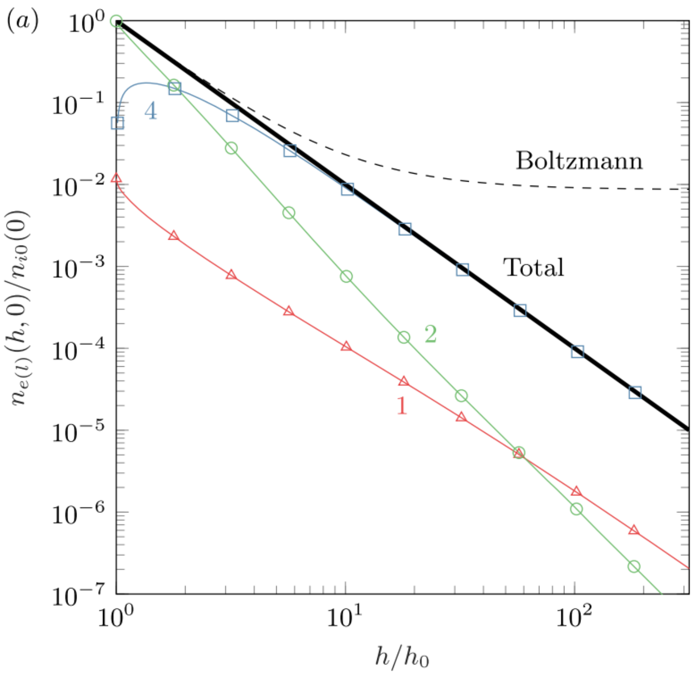
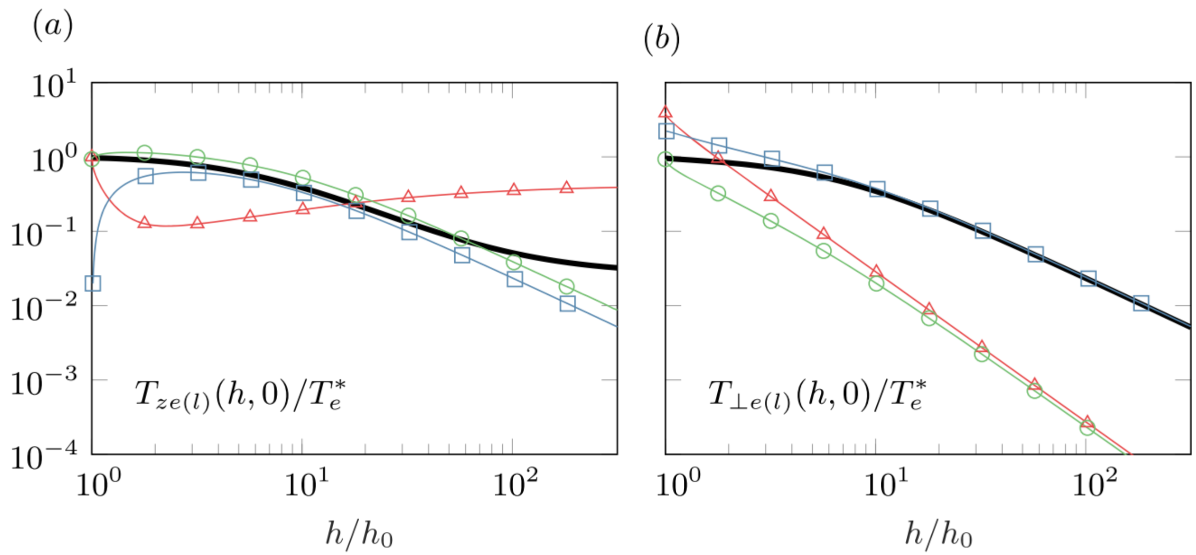
AKILES (kinetic electron model)

- Quasi-1D, steady-state, collisionless, quasineutral Vlasov plasma plume model (magnetized/unmagnetized)
  - Recovers electron distribution function in the expanding plasma using the conservation of adiabatic invariants
  - AKILES recovers the collisionless cooling of the electrons, their anisotropization, and the self-consistent electric potential
- Ambipolar electric field and magnetic mirror effect divide electrons into (1) free, (2) reflected, and (4) trapped populations:

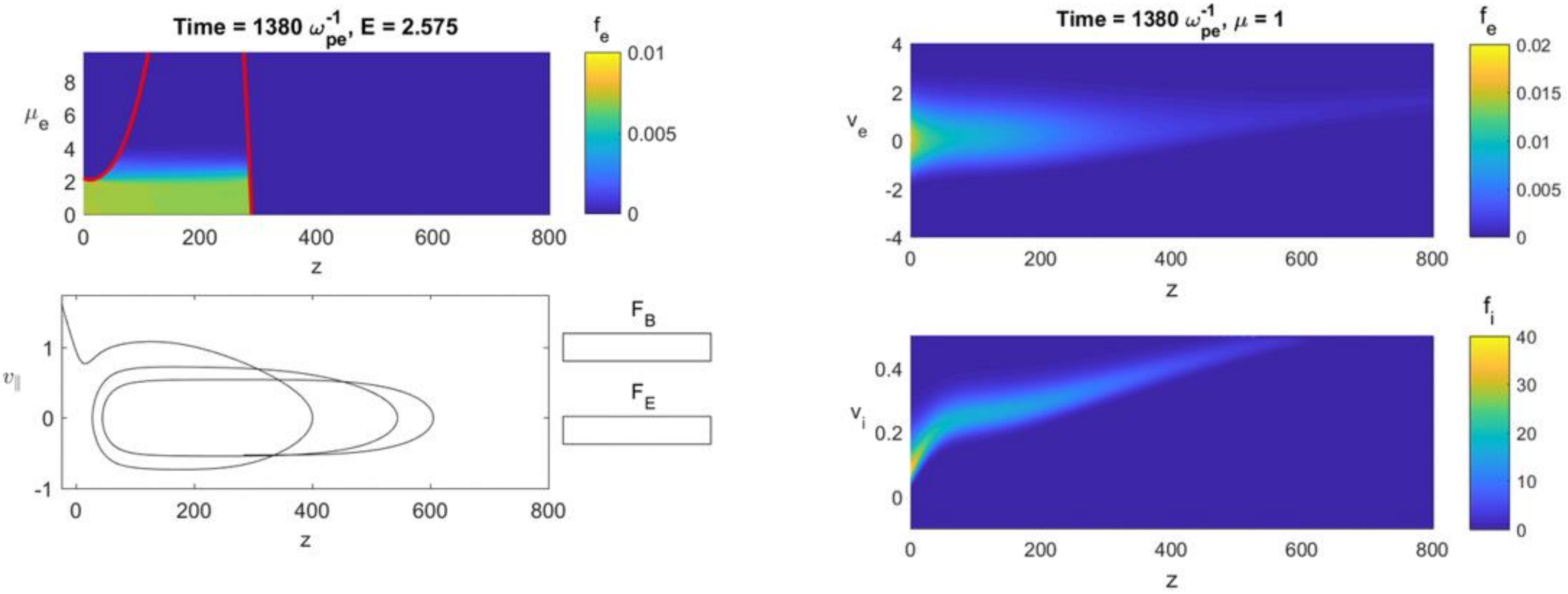




* Results shown are for an unmagnetized plume

VLASMAN Simulator for Magnetic Nozzle

- Non-stationary Boltzmann-Poisson solver.
  - Parallelized Eulerian algorithm: physical and velocity space mesh.
  - Trapped particles are computed self-consistently
  - Unlike PIC codes, the algorithm has no statistical noise.
- Currently implemented for 1D paraxial expansion. The extension to a 2D configuration is in progress.



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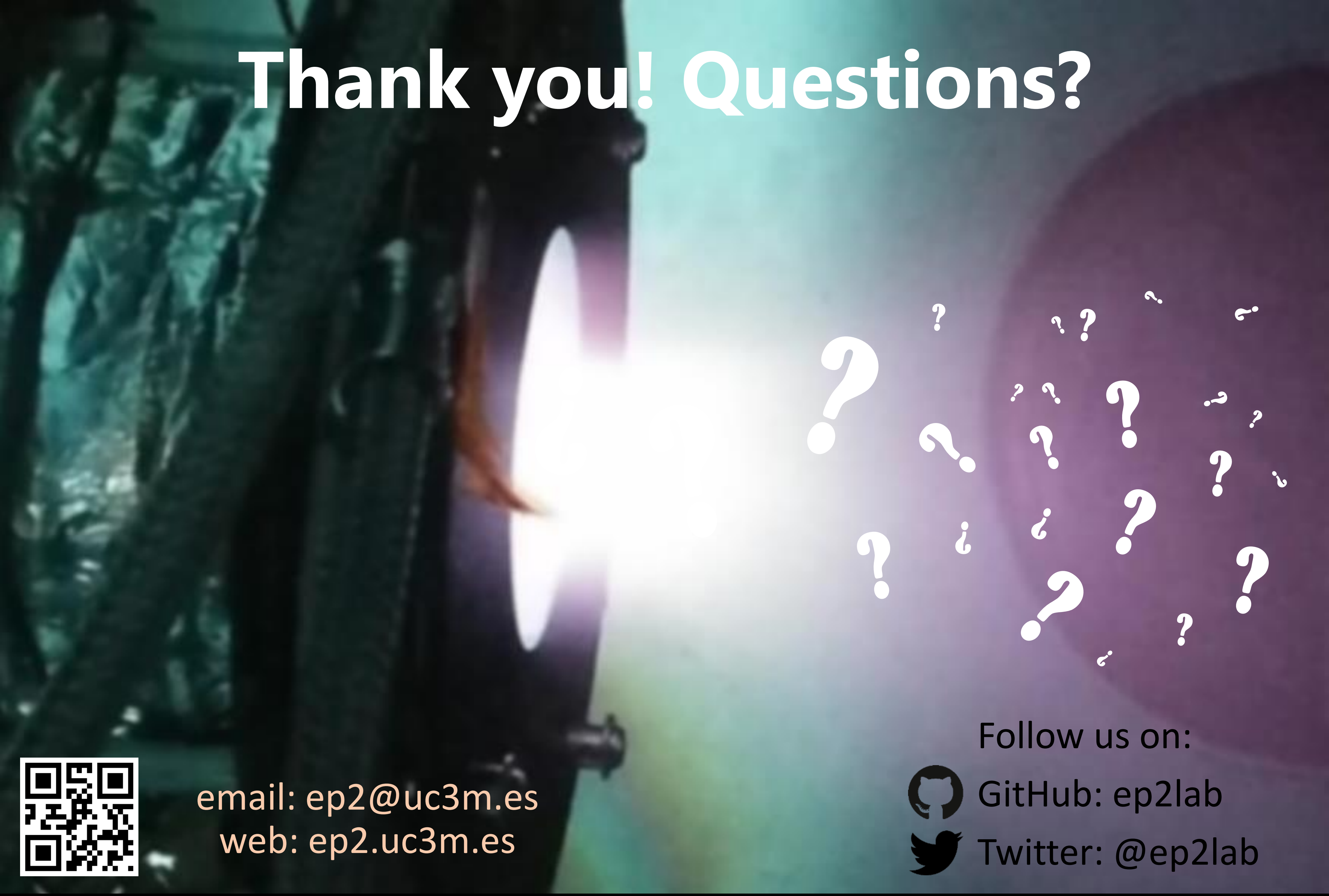
Summary

- Magnetic nozzles are a transversal technology used in many next-gen plasma thrusters as acceleration stage
  - Contactless operation
  - In-flight geometry modification (including 3d vectoring)
- EP2 has modeled and studied magnetic nozzles for 10 years
  - Thrust generation mechanisms and energy conversion
  - Plasma detachment far downstream
  - Advanced phenomena: induced magnetic field effects, collisional and electron-inertial effects, collisionless cooling and anisotropization of electrons
- Codes are available to study magnetic nozzle flows:
  - quasi-1D, 2D and 3D
  - two-fluid, kinetic



Thank you! Questions?

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