Radiofrequency plasma heating for electrodeless space thruster applications

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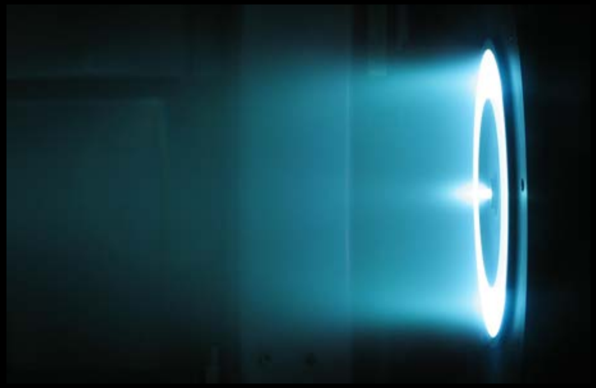
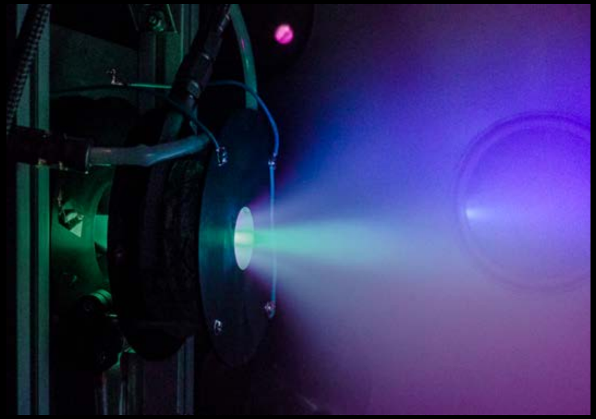
Contents

Overview of EPTs and wave plasma heating

- Hall thrusters, gridded ion engines employ electrodes to create a discharge and accelerate the plasma.
  - However, electrodes limit thruster lifetime and restrict applicable propellant gases
- Electrodeless plasma thrusters (EPTs) attempt to overcome these limitations using:
  1. Electromagnetic waves (in the MHz-GHz range) to energize the the electrons in the plasma
  2. A stationary magnetic field to expand and accelerate the resulting plasma to high velocities (Magnetic Nozzle)
- EPT performance is still poor.
  - Physics are still not well understood
    - Plasma-wave interaction and effects of the EM fields on plasma transport
    - Mechanisms that explain the high losses to the walls still unknown
    - External expansion in the diverging magnetic nozzle: kinetic behavior of the near-collisionless electrons
  - Intrinsic limitations: Challenging magnetic field generation, generator and transmission line losses …



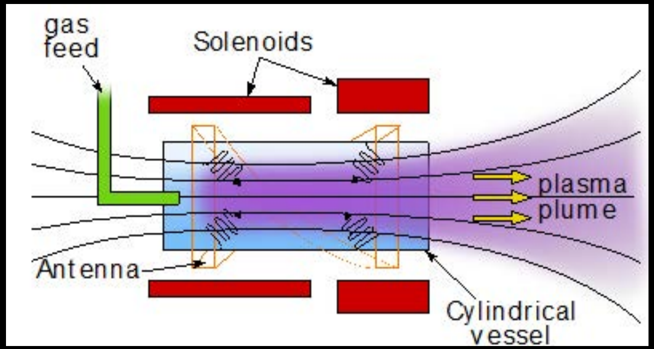
Hall effect thruster

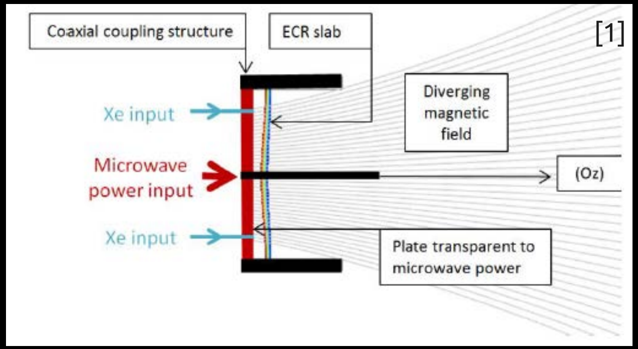


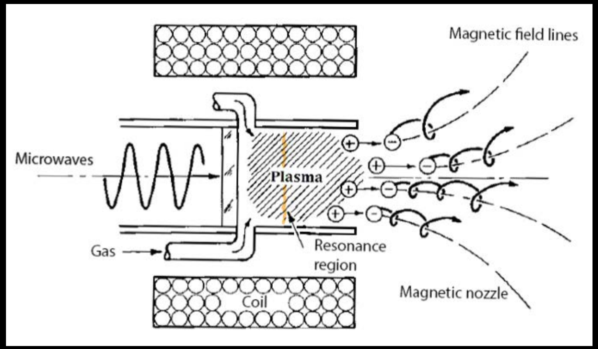
Helicon plasma thruster

POWER COUPLING STRATEGIES

- Two major power-coupling mechanisms have been explored in EPTs:
  - Ohmic heating: helical antenna around the cylindrical chamber of HPTs, to induce the azimuthal m =1 mode with large fields, in the MHz range. Electron collisions would then lead to the absorption of the EM power by the plasma
  - Electron cyclotron resonance: matching the wave frequency and the applied magnetic field we can use the ECR to cause localized power absorption. Same concept (and also other particle resonances) used in plasma fusion successfully







[1] Peterschmitt, S., & Packan, D. (2019, September). *IEPC 2019*.

- What are the design drivers?
  - Couple large power (100s, 1000s of W) to the plasma with little circuit losses
  - Localize the power in the center of the plasma, i.e. away from walls, to prevent further losses
  - Enable operation in a wide range of conditions without affecting coupling performance: wave accessibility issues, impedance matching issues…

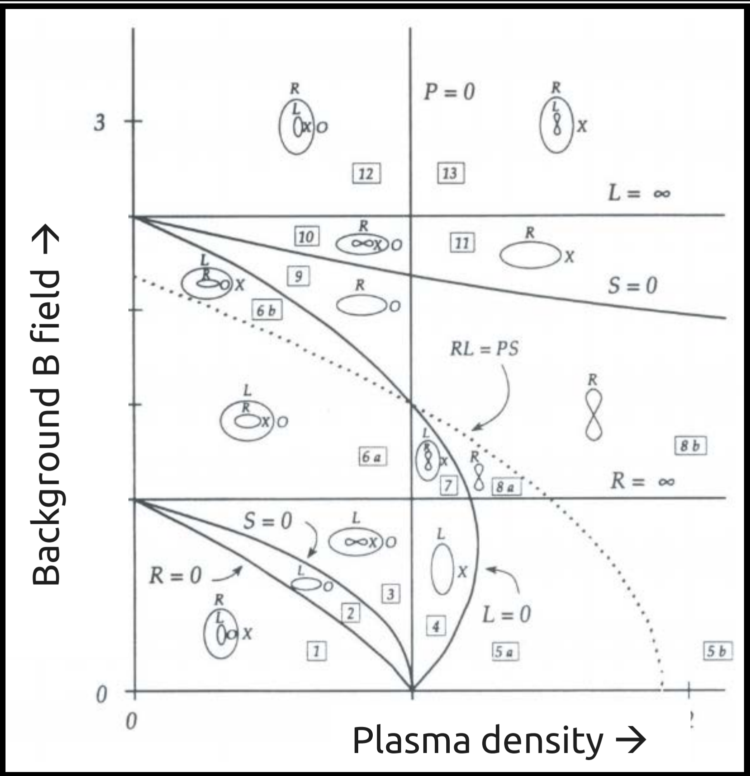
Cold plasma model

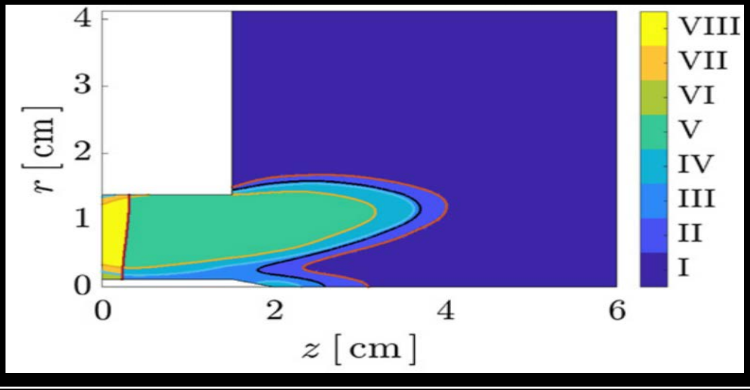
- Basic framework from which to understand plasma-wave interaction
  - The magnetoplasma is an anisotropic, gyrotropic, lossy dielectric medium described by the tensor

$$\kappa = \kappa(\omega, n, B, \nu) \quad \rightarrow \quad \begin{bmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$

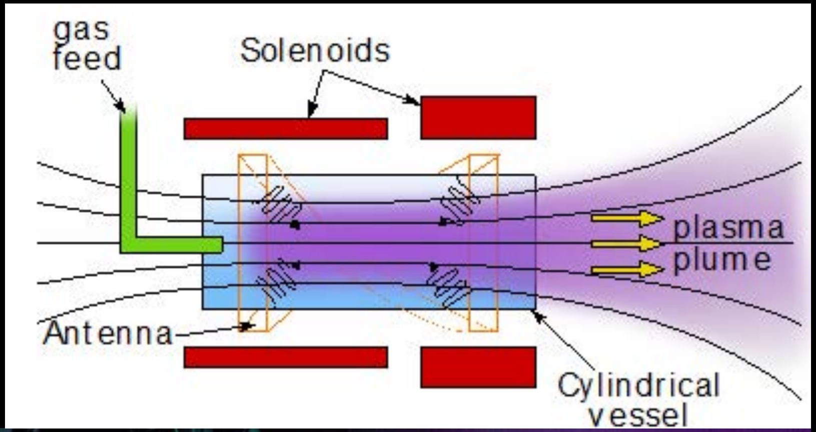
- As the <u>plasma density</u> and <u>applied magnetic field</u> strength vary spatially, so does the wave propagation regime. In general, the R- and L- hand side polarizations may or may not propagate. Rich parametric map!
  - Separating each parametric region, there is a resonance or a cutoff transition, where wavelength goes to zero or infinity

- In an EPT…
  - Several of these regions are present simultaneously in a short distance
  - Characteristic wavelengths vary widely, from $\lambda \gg L$ to $\lambda \ll L$
    - Raytracing simulation is generally not possible, and only full-wave schemes can be used
  - Some transitions are mathematically ill-posed in certain limits (e.g. collisionless limit)

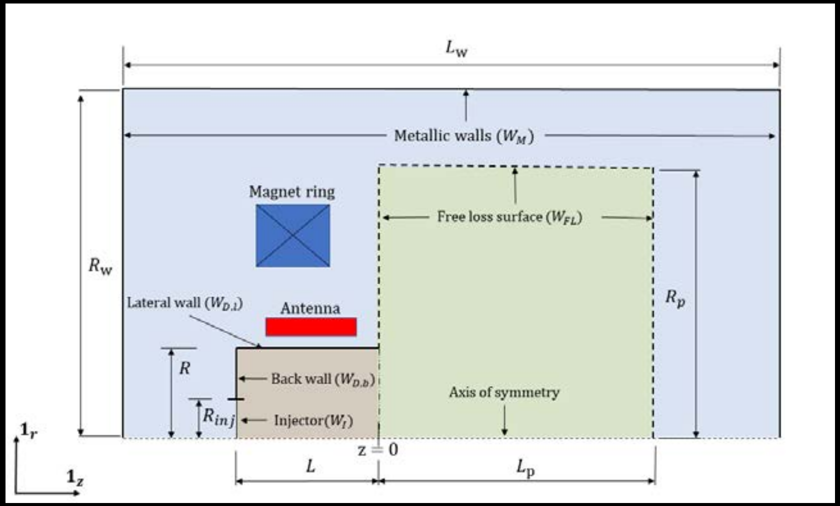




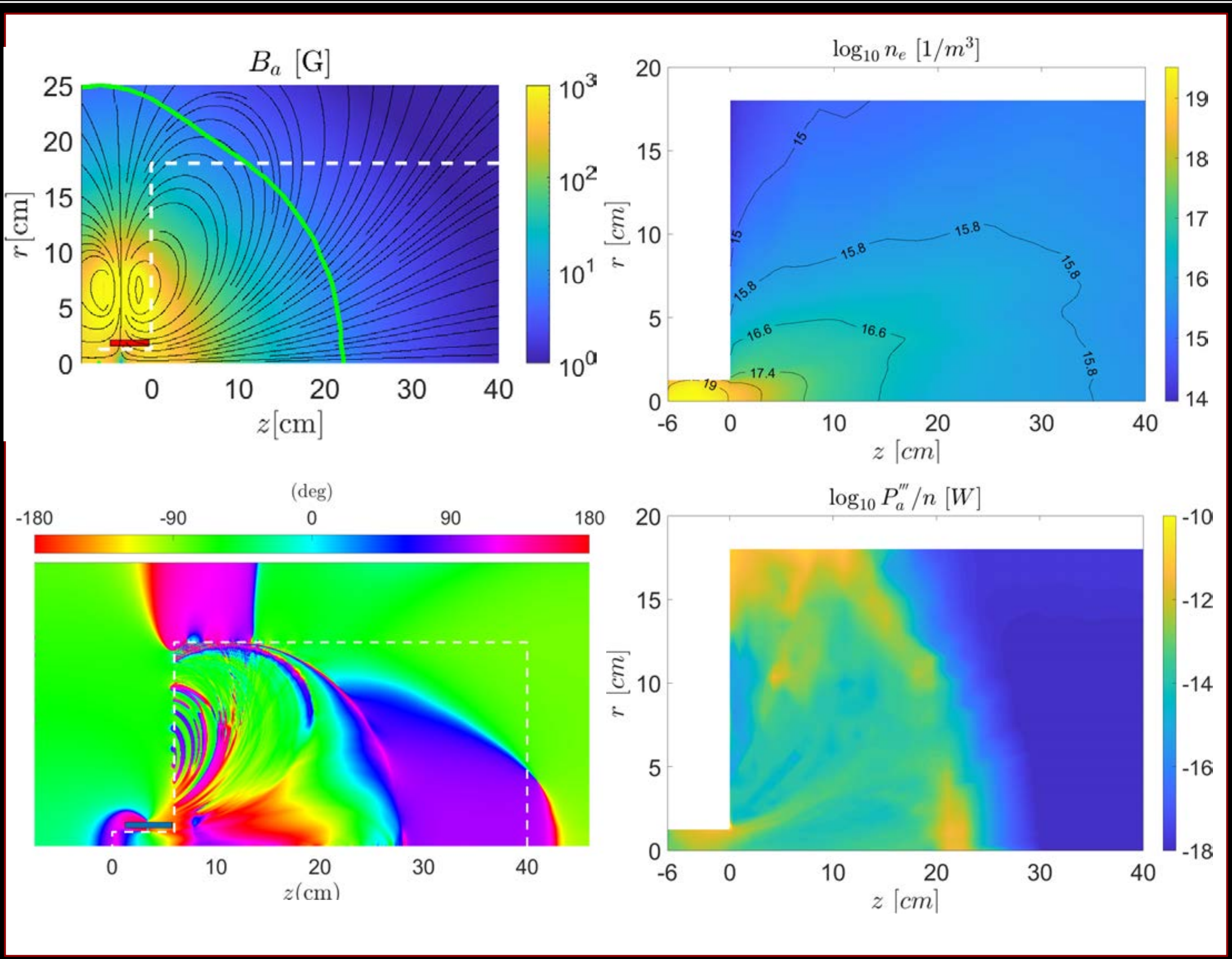
HELICON PLASMA THRUSTER



- Principle of operation:
  - Neutral gas ionization and plasma heating by electromagnetic wave radiation from an antenna or RF coupling with an inductor
  - Helicon and Trivelpiece-Gould (TG) waves
  - Acceleration of the quasi-neutral plasma in a magnetic nozzle
- HPT05 and HPT03 (Helicon prototypes tested at our lab)
  - Compact cylindrical devices Ø = 20-25mm and L = 6 -14 cm
  - Low power 300-450 W and thrust 3-6 mN
  - Helical antennas (inductors) placed outside the tube
  - Magnetic topology created by permanent magnets (HPT03) or solenoids (HPT05)

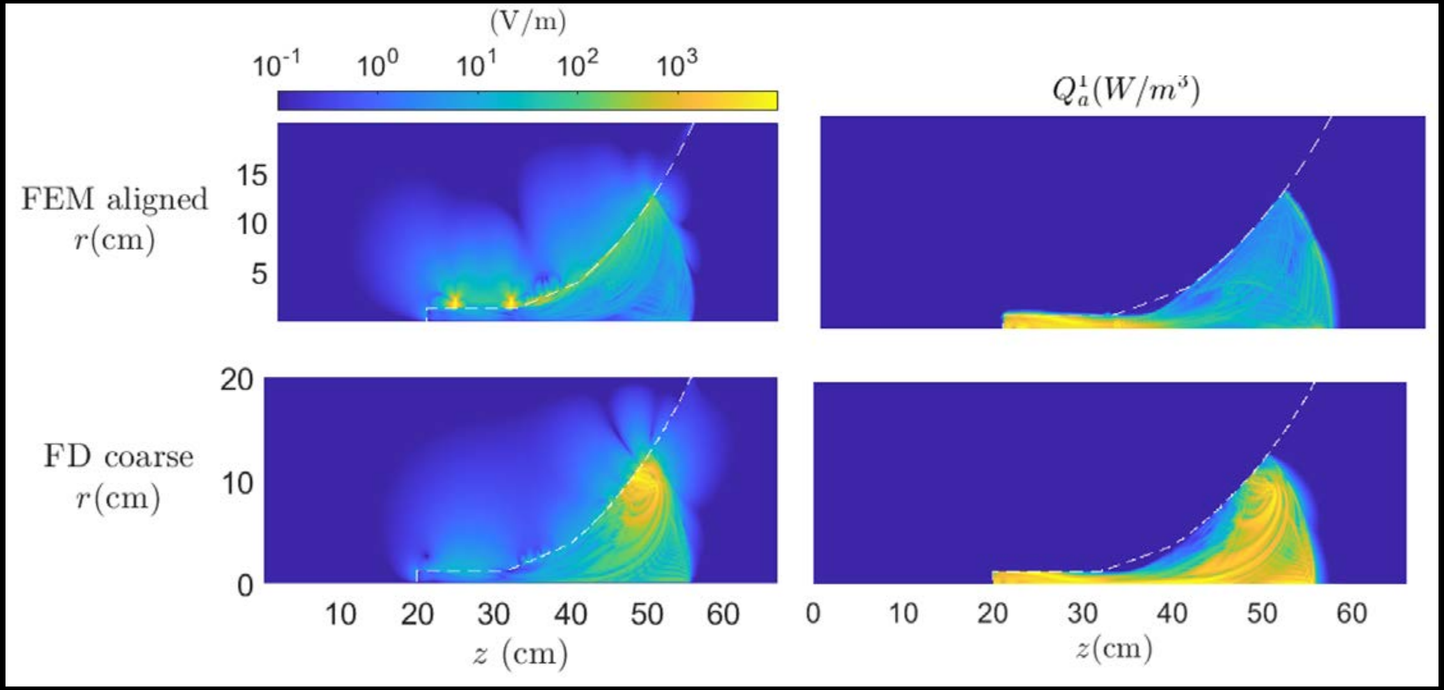


- Transport module:
  - Particle-In-Cell Monte Carlo for heavy species. Electron fluid FVM solver.
  - Provides the plasma density and collision frequency maps for the wave module
  - The wave heating is captured as a source term into the electron energy equation.
- Full-Wave module:
  - Frequency-domain Full-Maxwell
  - The antenna is modeled as a current density loop



NUMERICAL PROBLEMS

- Underdense-to-Overdense transition (P=0 CMA diagram)
  - Double limit, resonance + cutoff
  - One of the terms of the dielectric tensor becomes 0 (or approaches 0 if collisions are included)
  - The problem is locally ill-conditioned. Numerical noise appears and propagates to the rest of the domain
  - Very critical in the Helicon Thruster. There is an interface between vacuum (antenna region) and over-dense plasma (tube). Collisionallity is usually low at this transition.



- What we know:
  - FEM (with conforming vector elements) behaves better than FD (Yee grid + interpolation)
  - Mesh-magnetic field orientation is important
    - Avoid staircase conditions
  - Mitigation strategies like including background plasma pressure or including artificial collisions band

ELECTRON CYCLOTRON RESONANCE THRUSTER (ECRT)

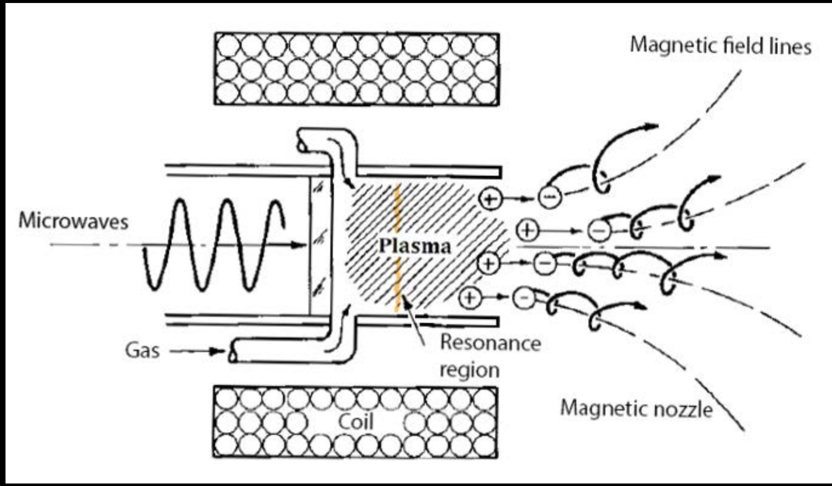
WORKING PRINCIPLE

- ECR + Magnetic nozzle
- Axial diverging magnetic field
- Microwaves are injected into the plasma chamber
- Ionization and electron heating happens at the resonance region
- The plasma is accelerated in the magnetic nozzle to obtain thrust

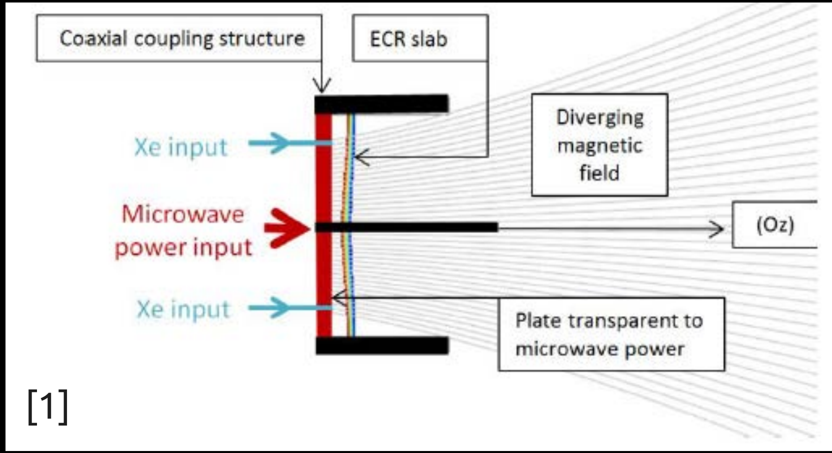
Two designs :

- Waveguide-based ECRT
- Coaxial ECRT

Waveguide Design



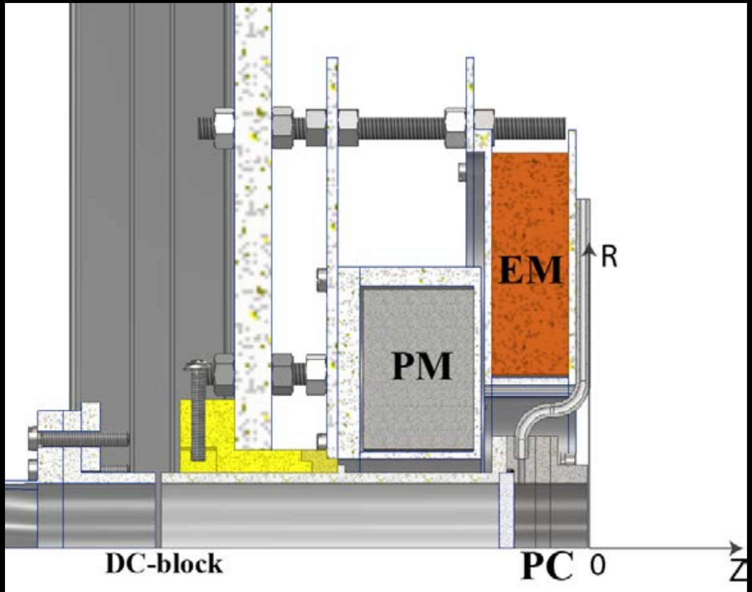
Coaxial Design



[1] Peterschmitt, S., & Packan, D. (2019, September). *IEPC 2019*.

WAVEGUIDE ECRT DESIGN (EP2)

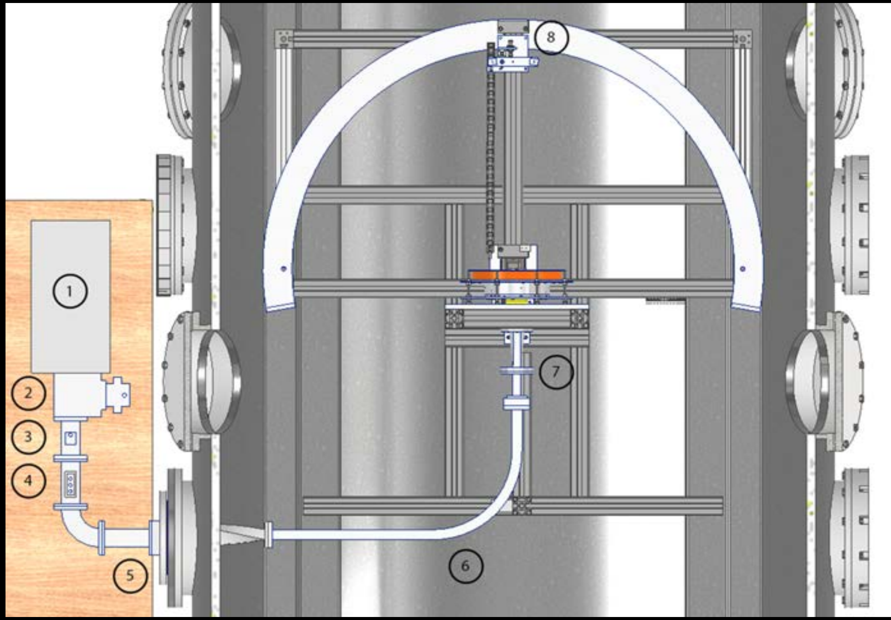
- Modular approach for easy design iterations.
- 5.8GHz microwaves for smaller plasma chamber and lower power and mass flow rate requirements.
- Stainless steel plasma chamber (PC) separated from the waveguide.
- Magnetic field generator: permanent magnet (PM) + electromagnet (EM) for resonance position tuning and nozzle divergence control.
- Thruster left floating by using a waveguide “vacuum-gap” DC-Block.
- Radial propellant injection.

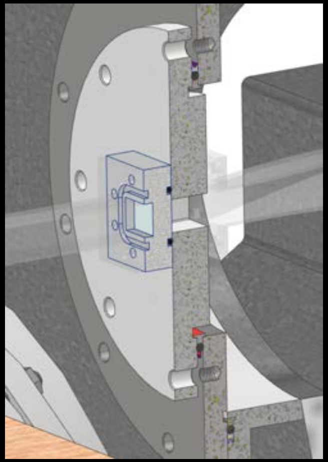


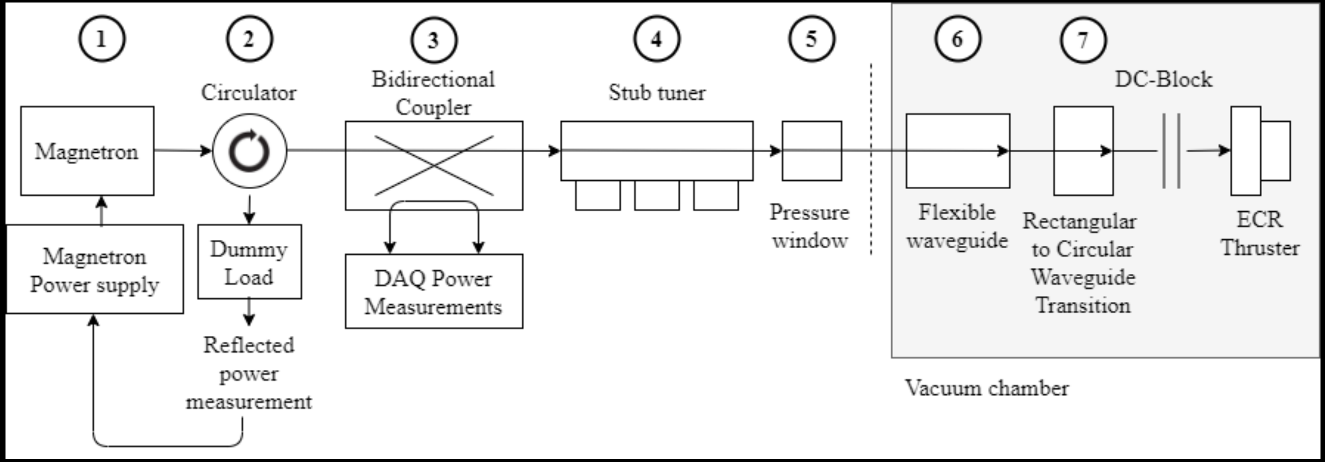
Plasma Chamber Dimensions: Radius, Length	18mm, 20mm
Microwave Power	50-300 W
Mass flow rate (Xe)	1-40sccm
MW frequency	5.8 GHz
B resonance	2070 G
Magnet type	Sm-Co YXG-32
Max electromagnet power	500 W
Electromagnet max B field	900G

MICROWAVE TRANSMISSION LINE

- 5.8 GHz Tuneable Power Magnetron microwave generator.
- Waveguide WR159 standard for the whole transmission line.
- Forward and reflected power measured through a Bidirectional coupler equipped with power meters.
- Stub Tuner for matching to the thruster impedance.
- Pressure window + custom vacuum chamber waveguide feedthrough.
- Flexible waveguide components for easy alignment of the setup.
- Rectangular to circular waveguide transition.

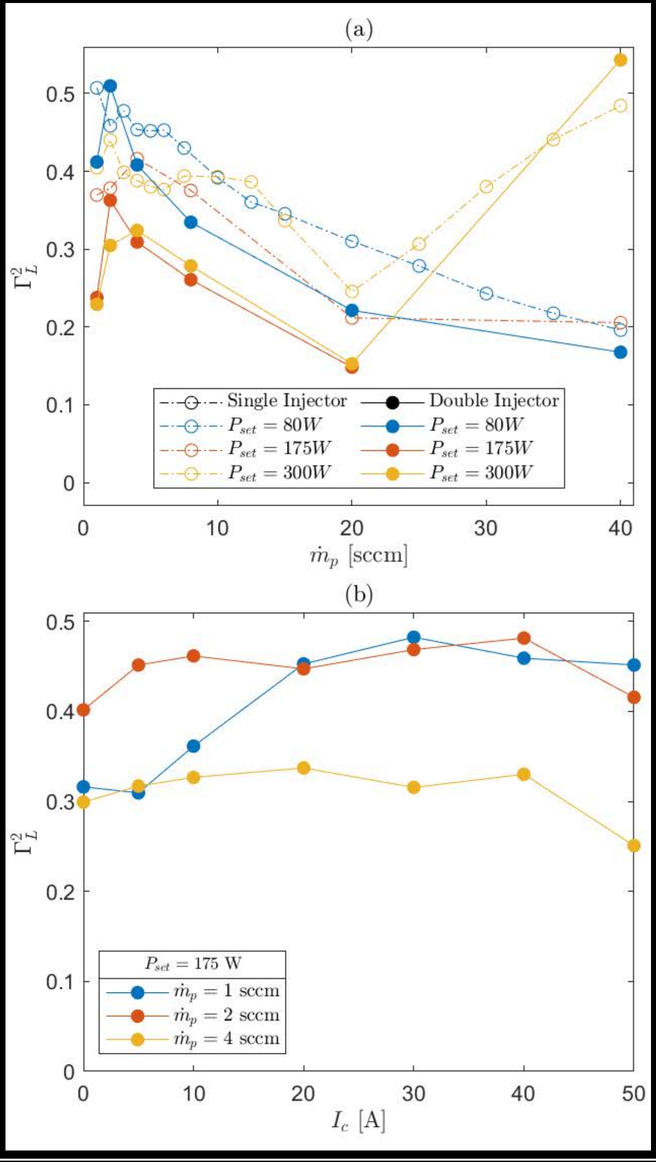


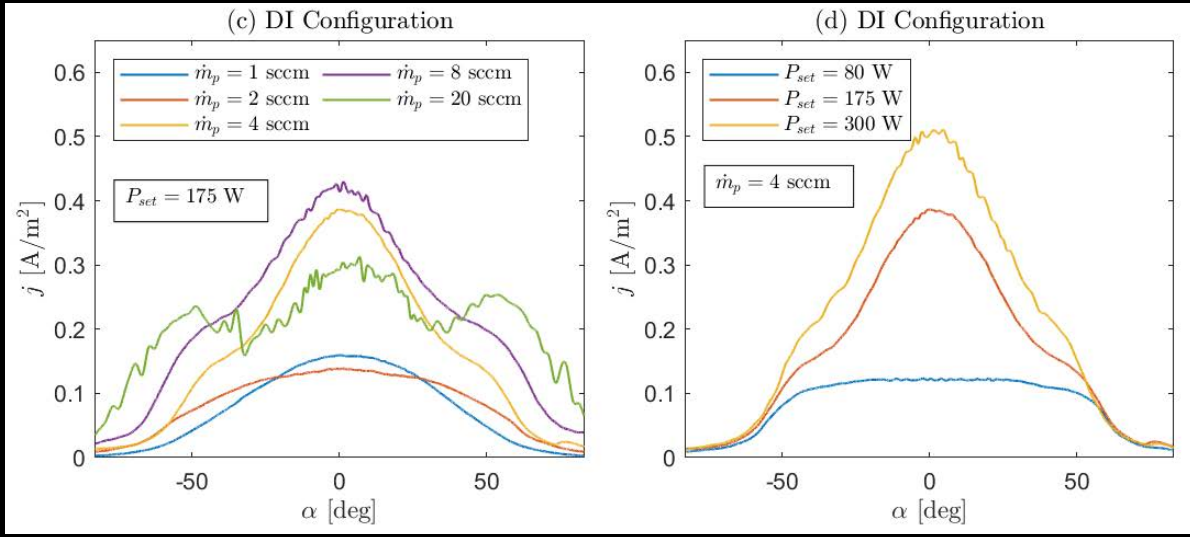




SOME RESULTS

- High level of reflected power experienced for most of the explored ranges.
  - The reflection coefficient was observed to vary considerably depending on the working point when the stub tuner was not used.
  - This confirms the expectation that the thruster input impedance is being affected by the plasma conditions.
- Plume topology and thruster performances are strongly affected by the free parameters: input power, mass flow rate and coil current.
- Further research is required to investigate the relation between power coupling and input impedance and how these affect the discharge physics.



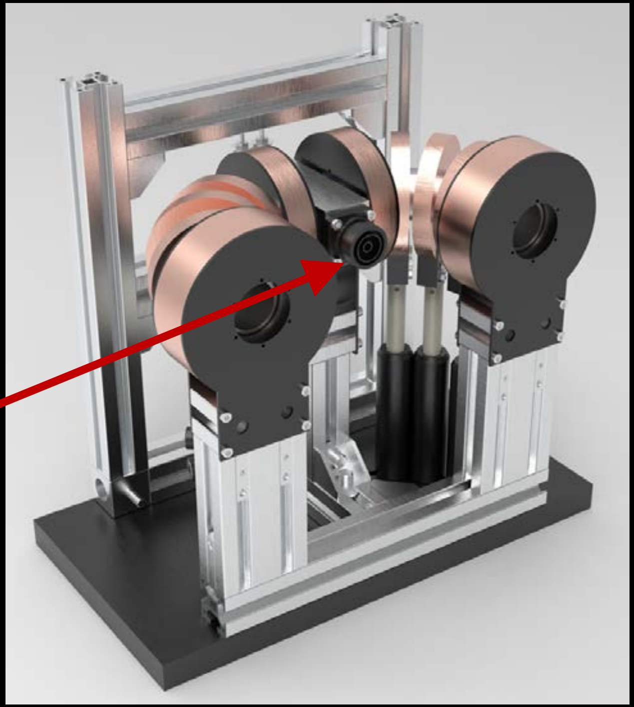


Magnetic Arch Prototype Configuration

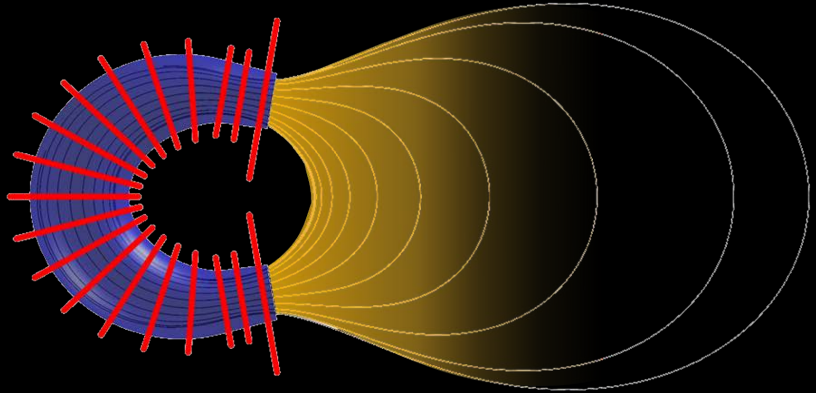
- Novel design of EPT:
  - Rationale: curved chamber avoids rear wall (plasma losses); magnetic field is everywhere parallel to the thruster wall; two-exits allow thrust vector control
  - Power injection: 7-16 DIN coaxial at the center part of the device

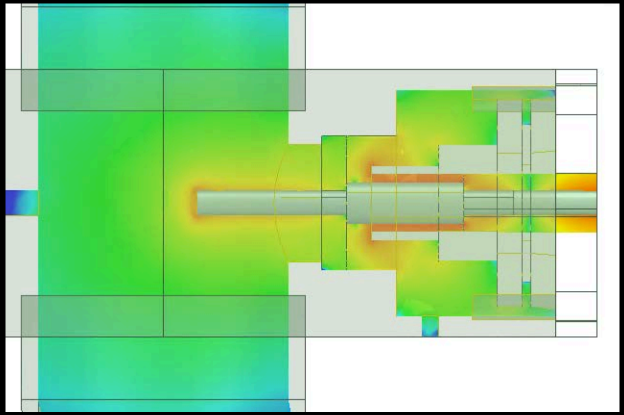
- Alternatives to power coupling will be explored:
  - Injecting power closer to the nozzles
  - Inductive helical antenna

Power injection



Plasma chamber length	364 mm
Plasma chamber radius	29.7 mm
Microwave Power	10 – 1000 W
Estimated mass flow rate (Xe)	[1 ; 50] sccm
MW frequency	2.45 GHz
B Resonance	875 G
Max electromagnet power	1500 W





Conclusion and Open Questions

- Power coupling via EM waves is an essential part of EPTs, still to be fully understood.
- Modeling is full of challenges (multitude of wavelengths, regimes, resonances, cutoffs). Understanding propagation and absorption is needed to improve EPT design and operation.
- FDFD and FEM approaches have both been used with success.
- Cold plasma model is but a first idealization of the complex plasma-wave and particle-wave interactions that take place
  - Multiple time scales exist in the problem: fast EM time, electron gyration time, electron transport time, ion transport time...
  - Kinetic effects: EM fields affect EVDF in nontrivial ways: e.g. non-Maxwellian populations, which may in turn affect propagation & absorption
  - Nonlinear effects exist and may complicate the self-consistent solution: enhanced transport, instabilities...

- Experiments are needed to validate the model predictions, but accurate measurements are hard:
  - Difficulty in measuring wavefields directly, or the local power absorption
  - Difficulty measuring inside the plasma source

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Thank you!

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