Analysis of the plasma discharge in a radiofrequency ion thruster

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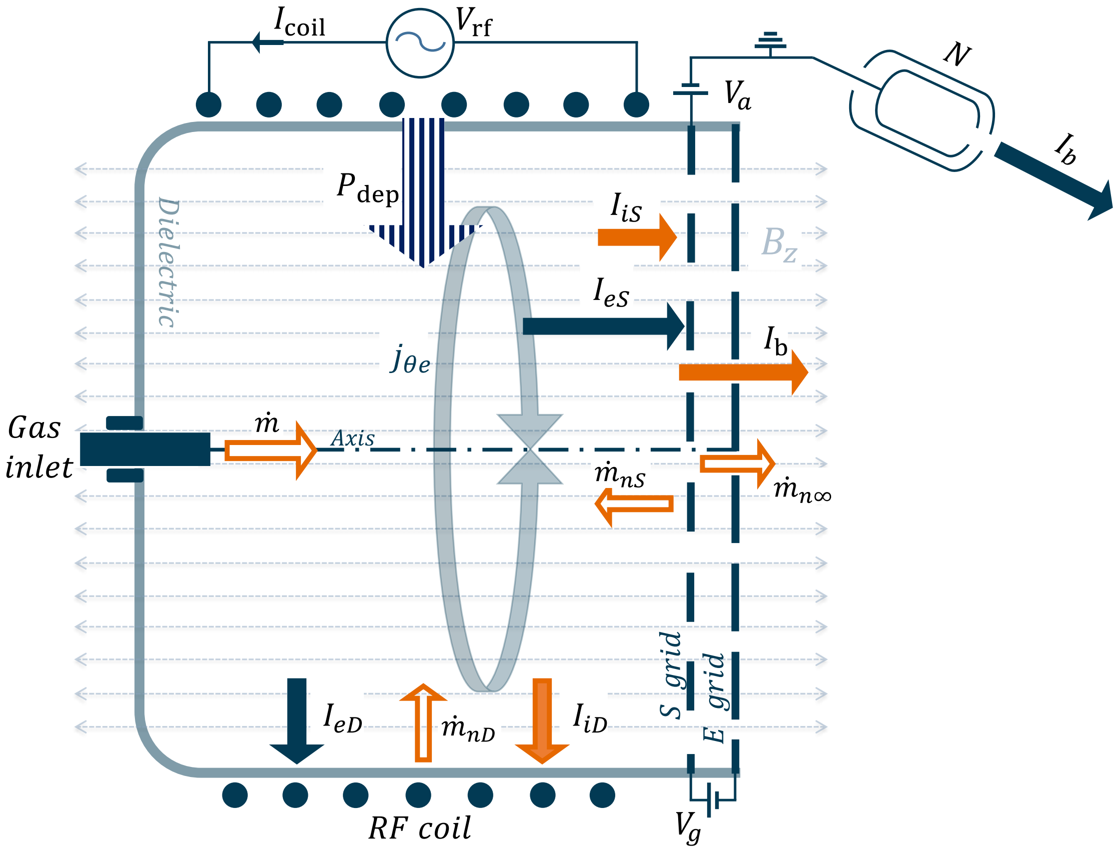
What is a Radiofrequency Ion Thruster (RIT)?

- **Radiofrequency**:
  - Time-varying EM (MHz) fields generated by an external RF antenna
  - RF power is transferred to electrons via azimuthal electric fields
  - Electron bombardment
- **Ion Thruster**:
  - Electrostatic grids



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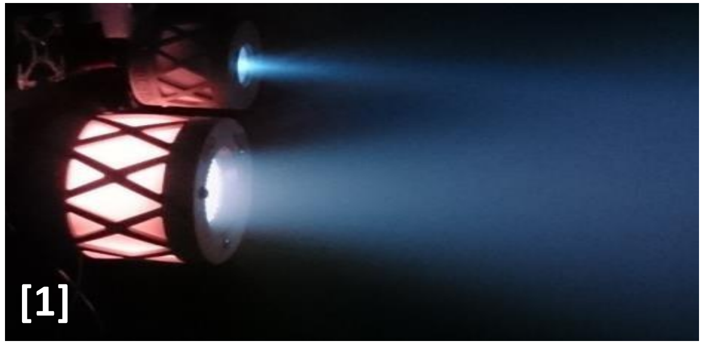
- **Ion Thruster**:
  - Electrostatic grids
- One of the **most mature technologies** for EP
  - Successfully flew on several missions like EURECA and ARTEMIS
  - Commercialized by several companies (Ariane, Busek, ThustMe, ecc…)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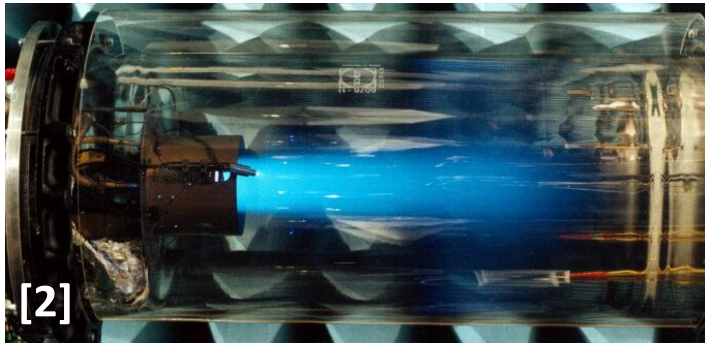
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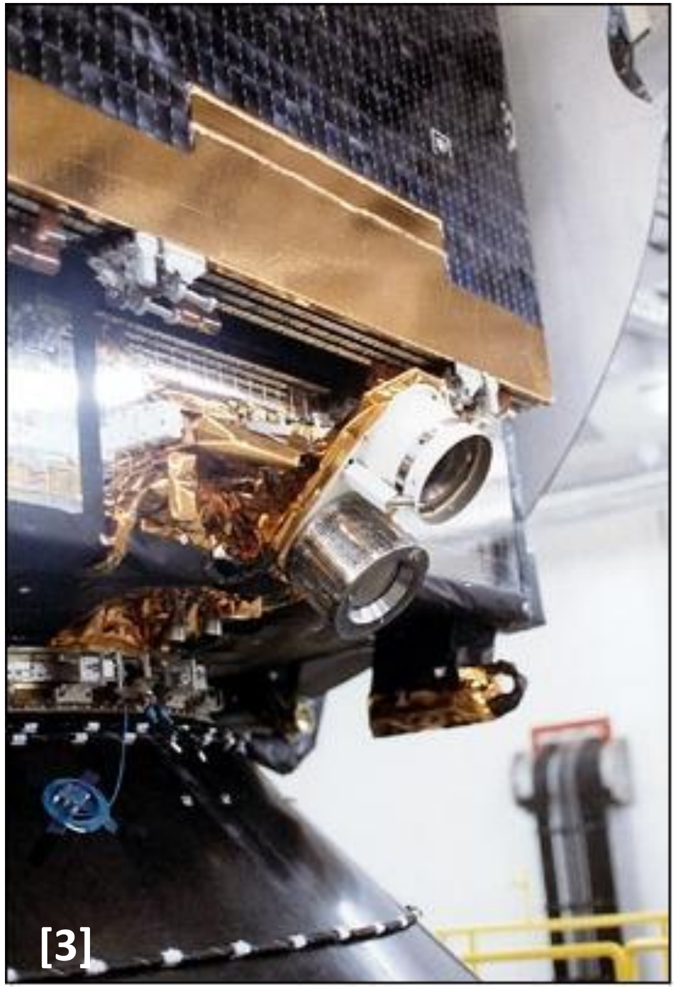

[3]

[1] M. Tsay et al. "Integrated Testing of Iodine BIT-3 RF Ion Propulsion System for 6U CubeSat Applications". *35th International Electric Propulsion Conference, Atlanta, GA, USA,* 2017
[2] Picture of a RIT commercialized by APCON"https://apcon.aero/various-rfg-and-ep-activities/ ''
[3] Picture of the RIT 10 installed in ARTEMIS, Astrium. ''https://www.eoportal.org''

Why is it important to study RITs?

- **Ion Thrusters:**
  - Advantages with respect to HET:
    - **Higher specific impulse I_{sp}**
    - Higher thrust efficiency η

    Best options for **scientific missions**
  - Disadvantages:
    - **Lower Thrust to Power ratio**
    - More complex electrical circuit
- **Radiofrequency:**
  - Advantages:
    - Simpler configuration
    - **Higher lifetime**
    - **Easy to scale**
    - **Alternative propellants**

Objective:

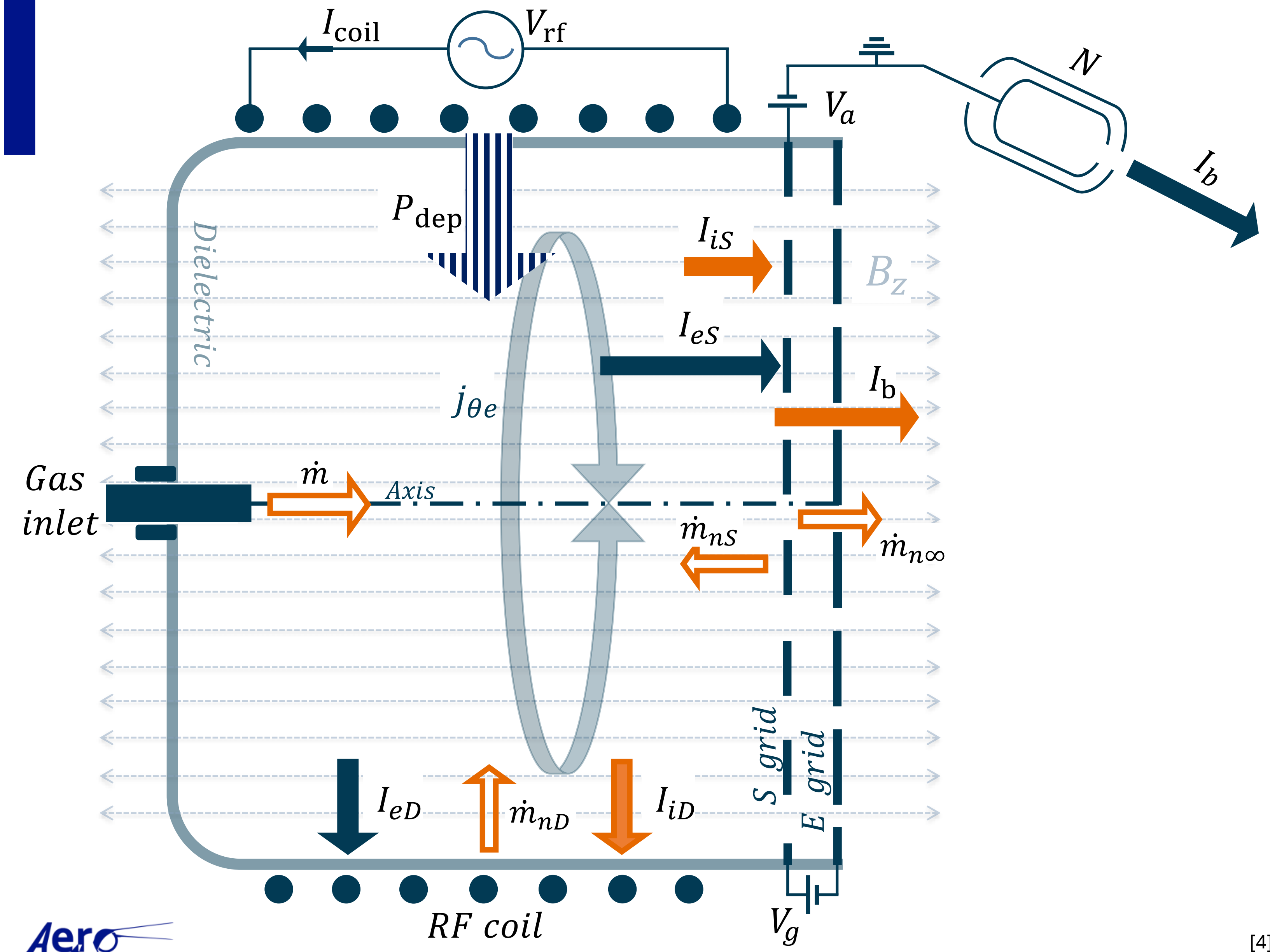
model and understand the **physics of RITs** to improve their performances

How:

Numerical modelling with hybrid codes (HYPHEN and EP2PLUS)

- 2D axisymmetric and 3D Cartesian
- Compromise accuracy – comp. time

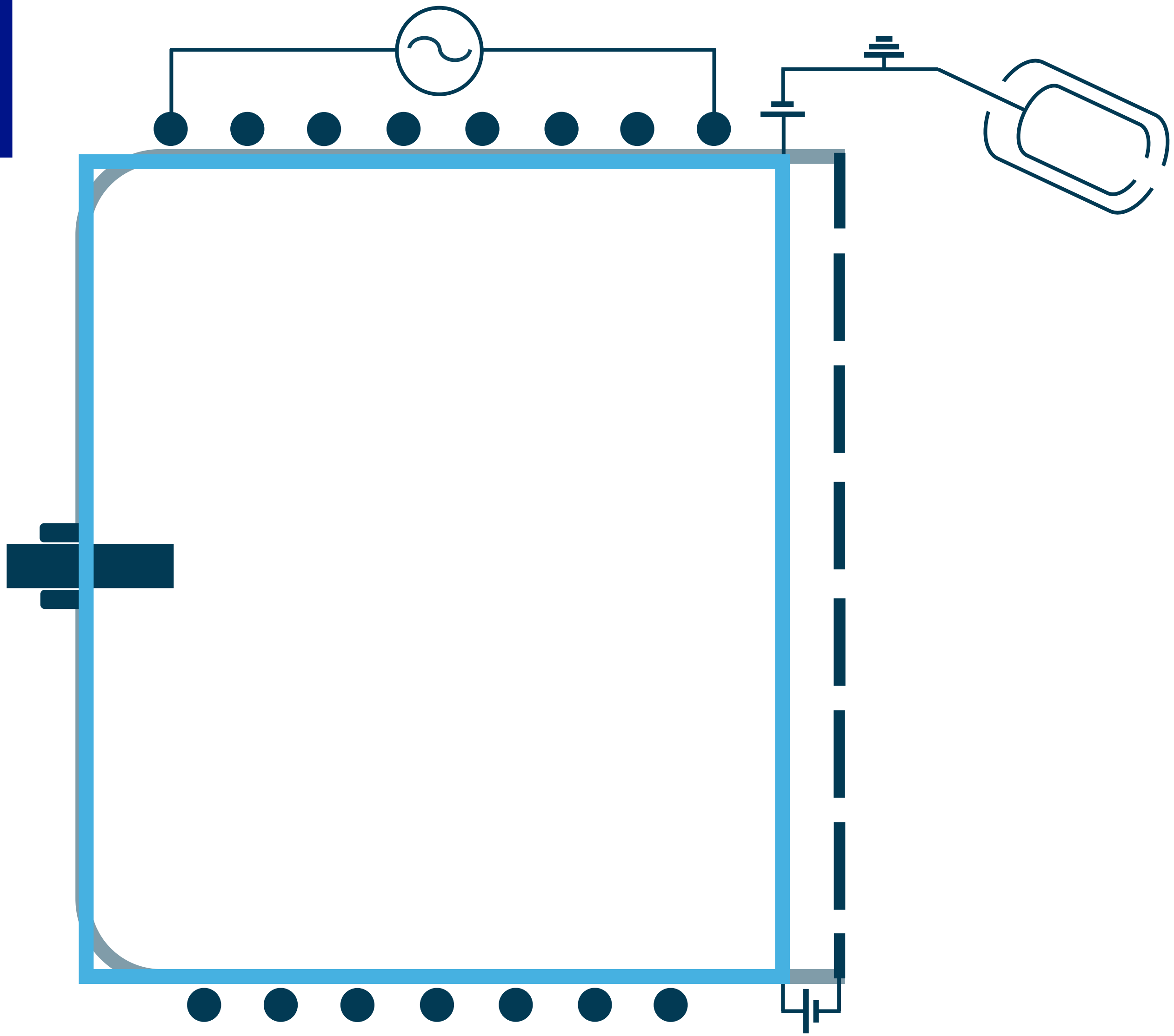
Methodology



[4]

[4] Picture of the RIT 10 Evo, Ariane Group. ''https://www.space-propulsion.com''

Methodology




[4]

- 4 different regions:
  - **Discharge chamber**

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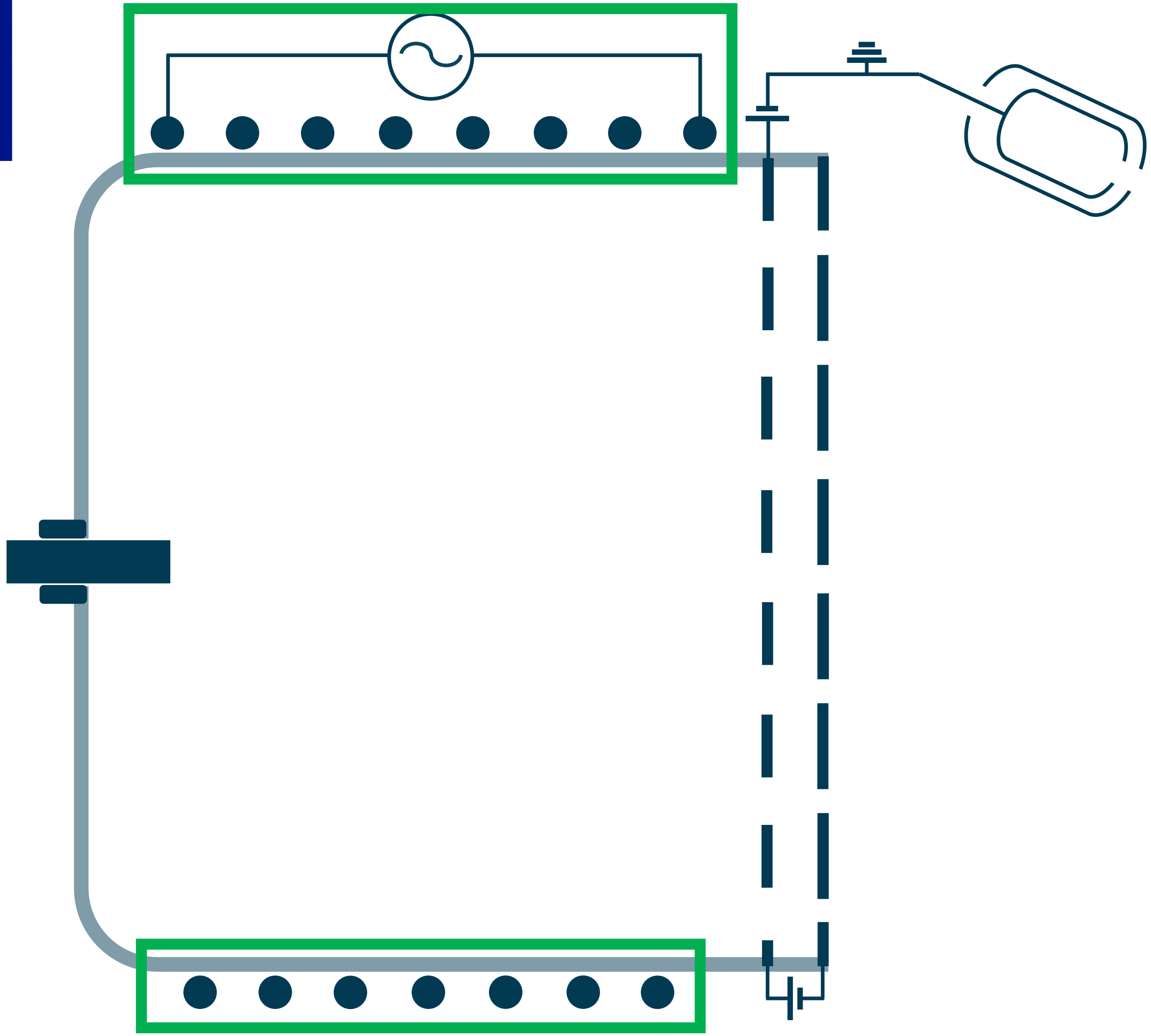

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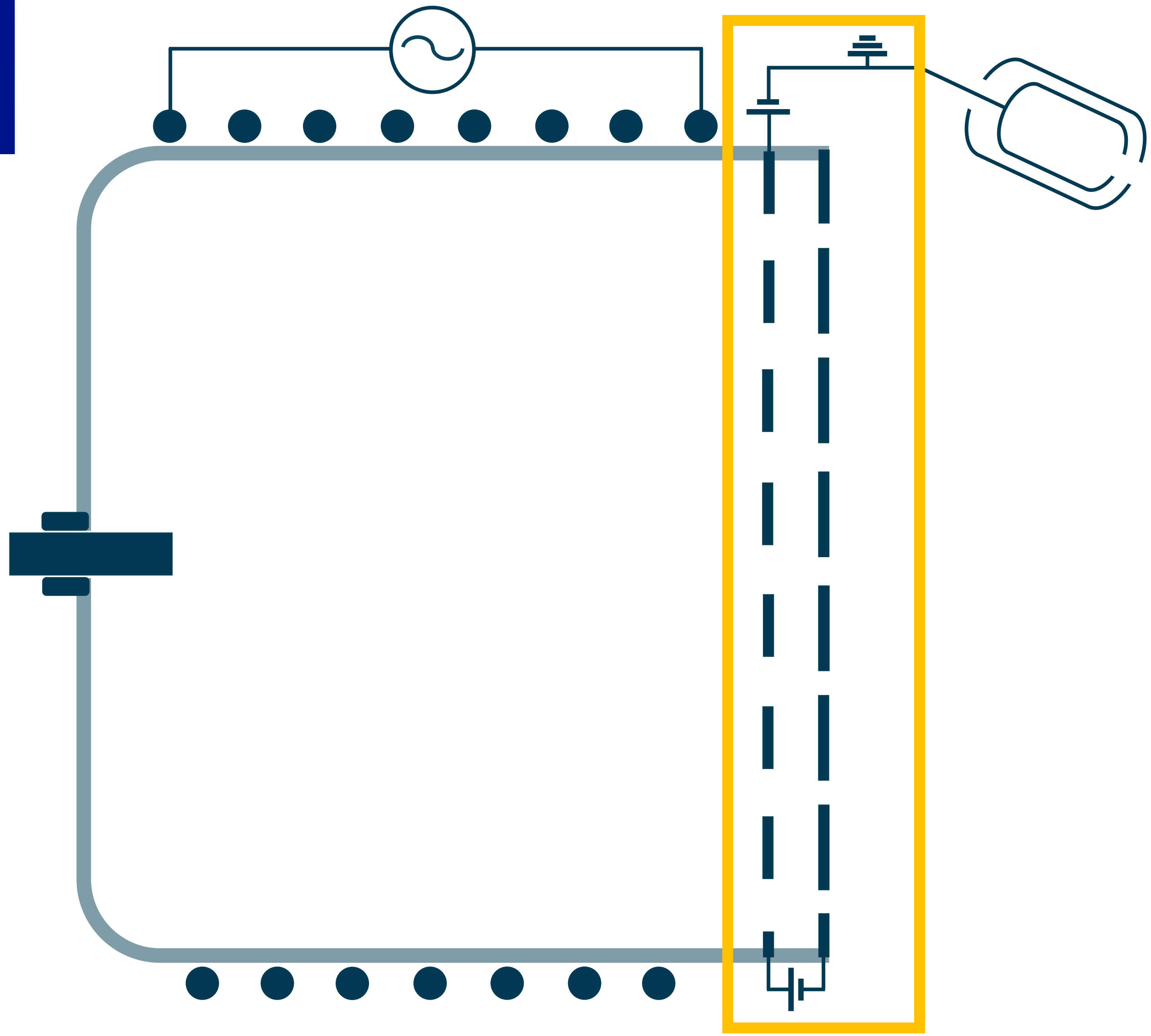

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- 4 different regions:
  - Discharge chamber
  - Radiofrequency generator
  - Grids system

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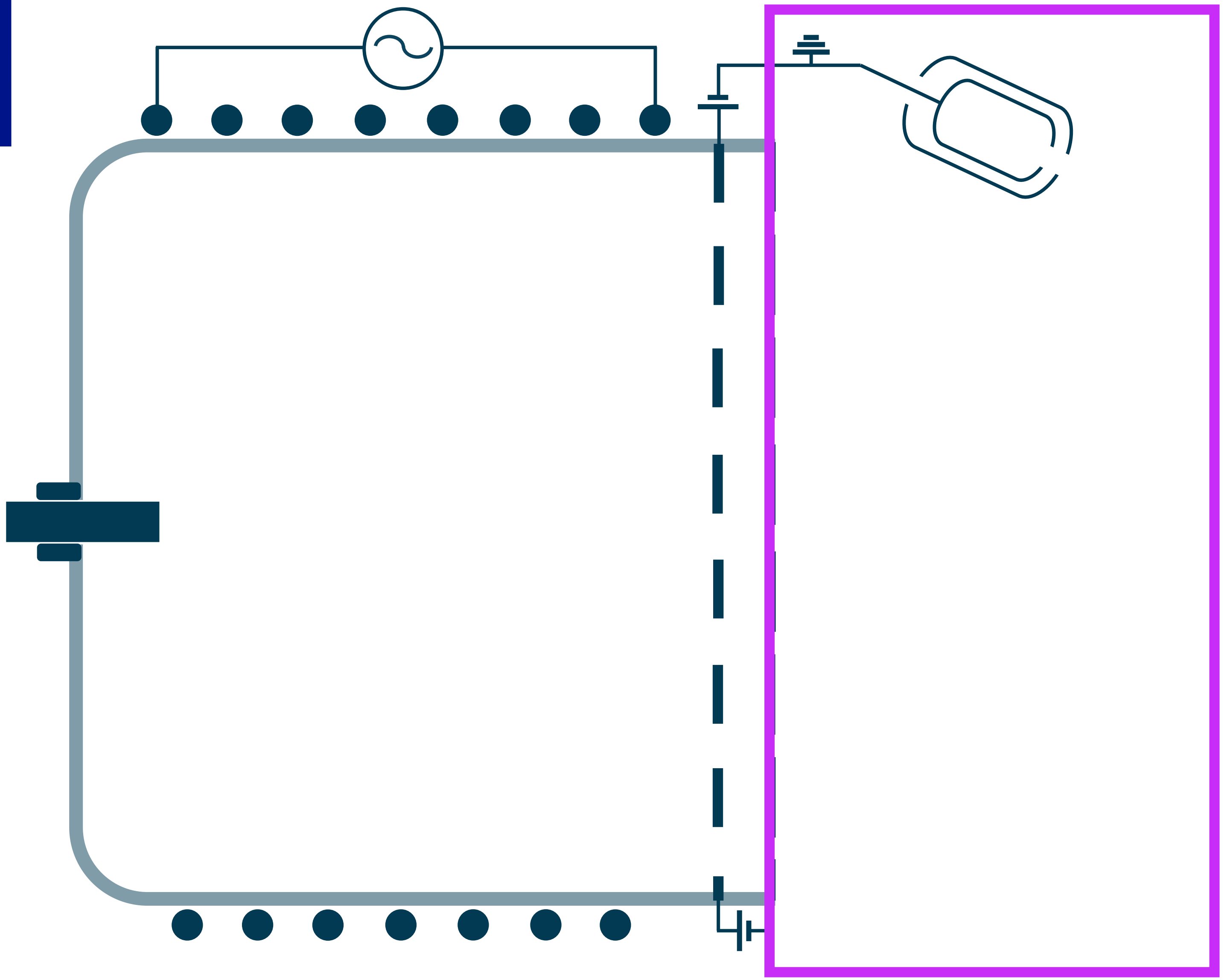

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  - **Plume**

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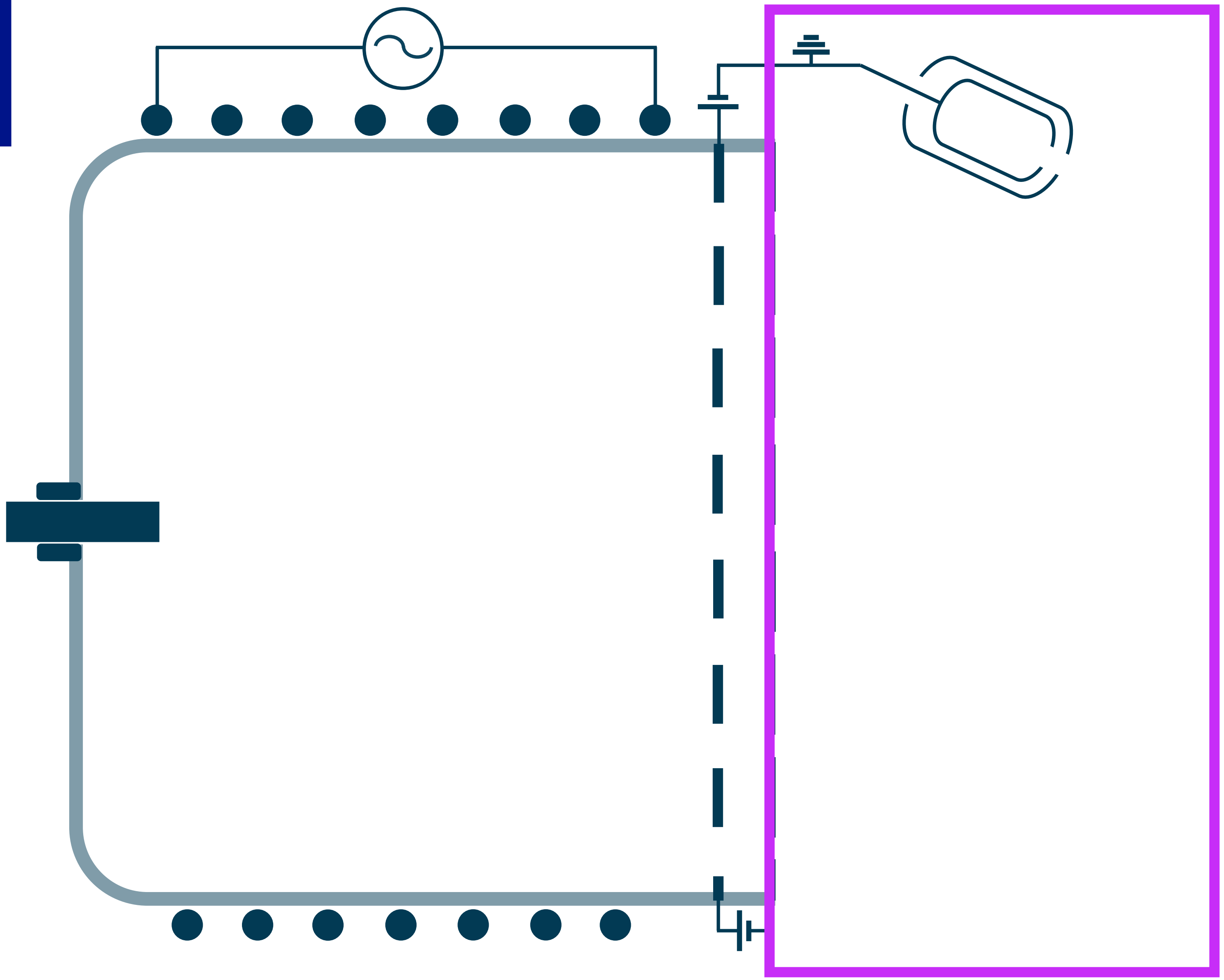

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- 4 different regions:
  - **Discharge chamber**
  - **Radiofrequency generator**
  - **Grids system**
  - **Plume (out of my thesis)**

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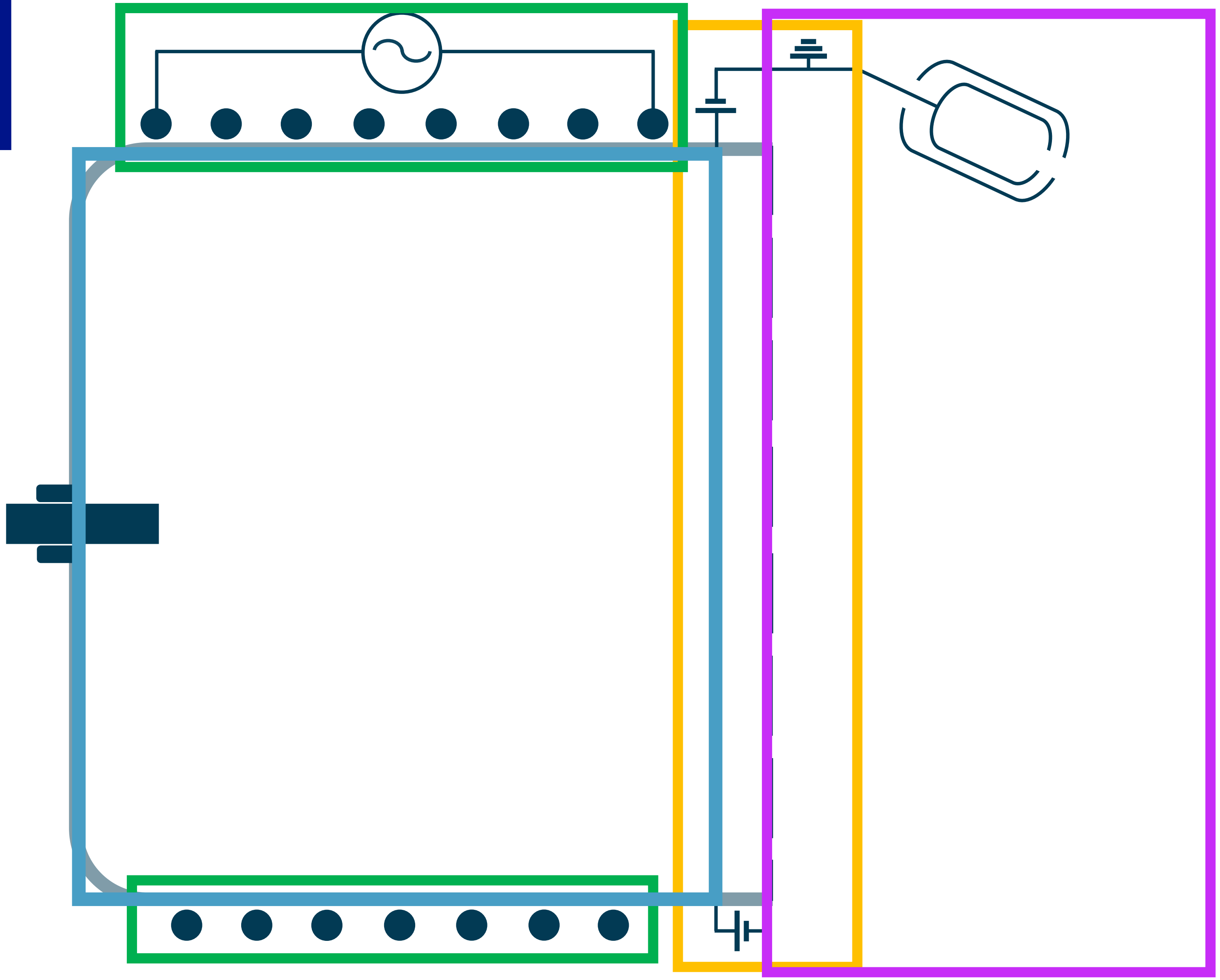
Methodology

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- 4 different regions:
  - **Discharge chamber**
  - **Radiofrequency generator**
  - **Grids system**
  - **Plume**
- Difficult to consider all aspects of a RIT at once
  - **We need to further simplify the problem**

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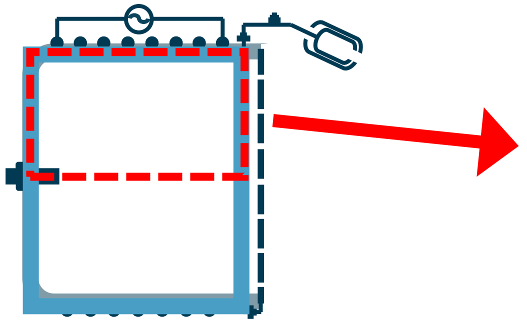
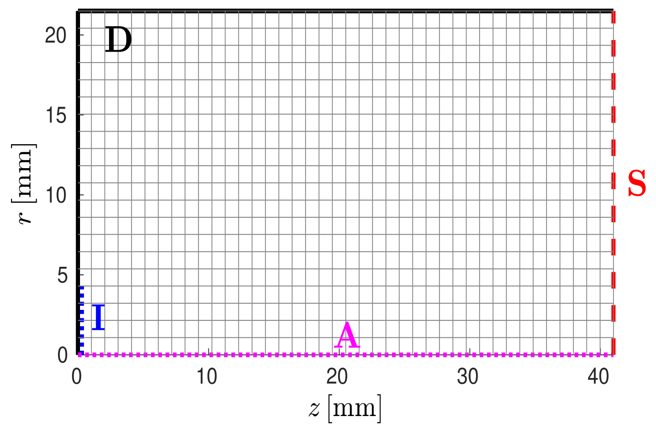
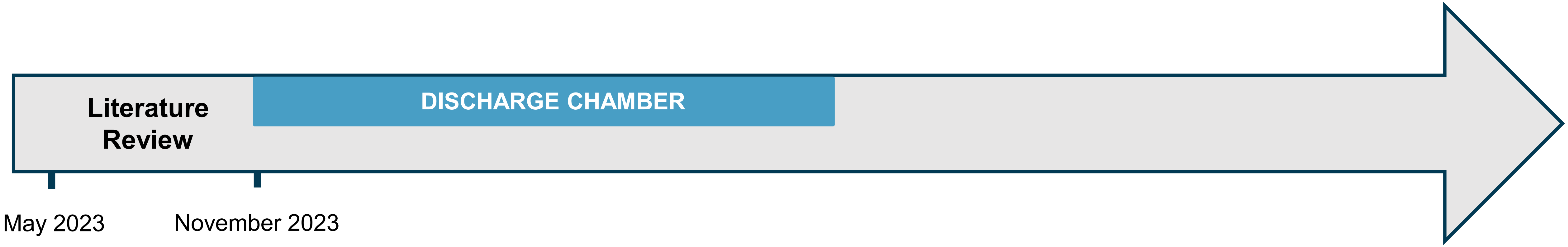
Discharge chamber analysis



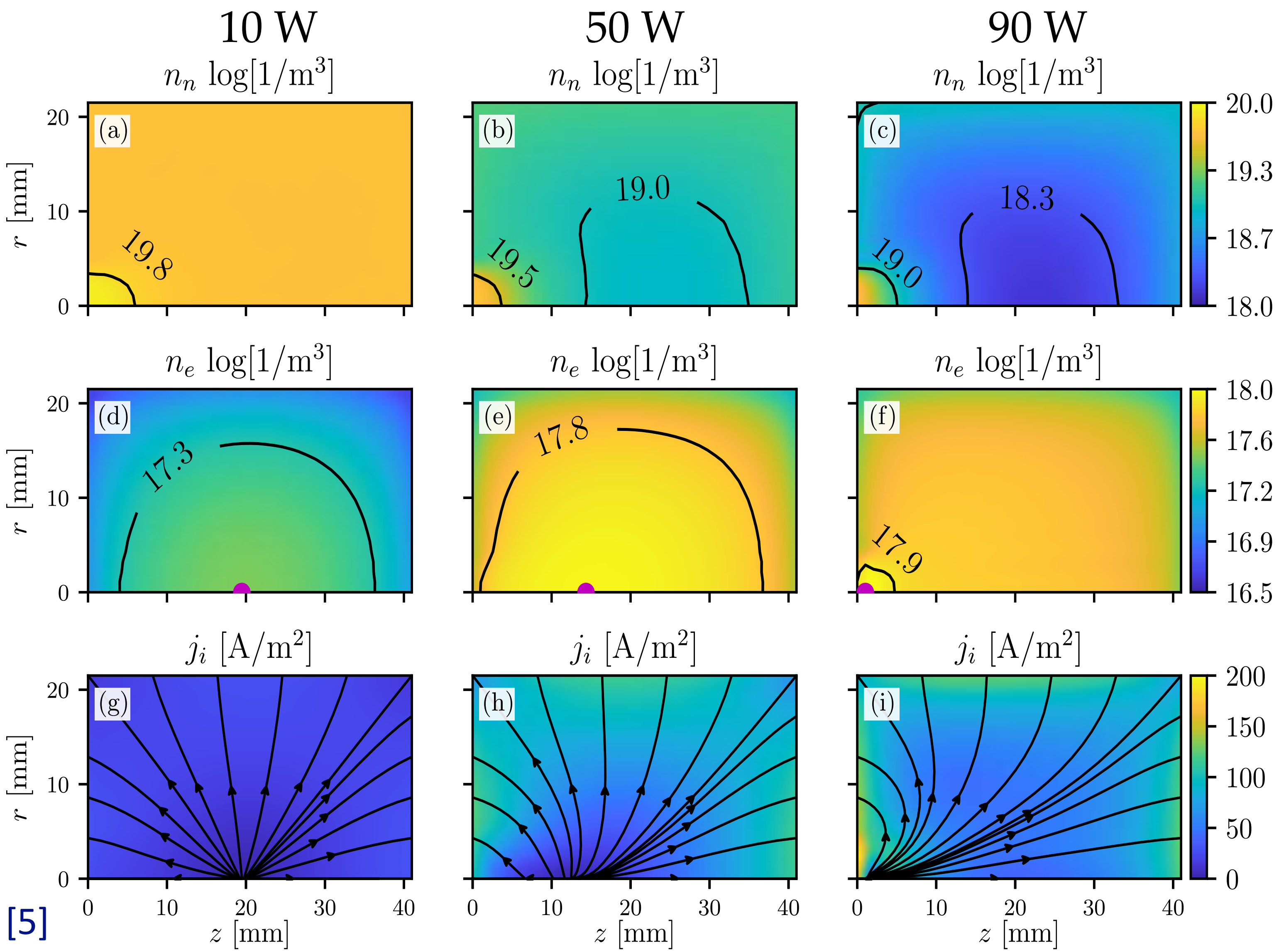


- Simplification of the problem
  - No RFG → **uniform and constant power deposition**
  - No acceleration system: **semi-transparent surface**
- Objective:
  - Influence of operative and design parameters on total performance



Discharge chamber analysis

- We studied:
  - 2D axisymmetric profiles
    - Displacement of plasma bulk
    - Ions accelerated towards walls → **high wall losses**



[5]

[5] S. Dalle Fabbriche, J. Zhou and E. Ahedo. " An axisymmetric hybrid model of the plasma in a radio-frequency ion thruster chamber". PSST 2025

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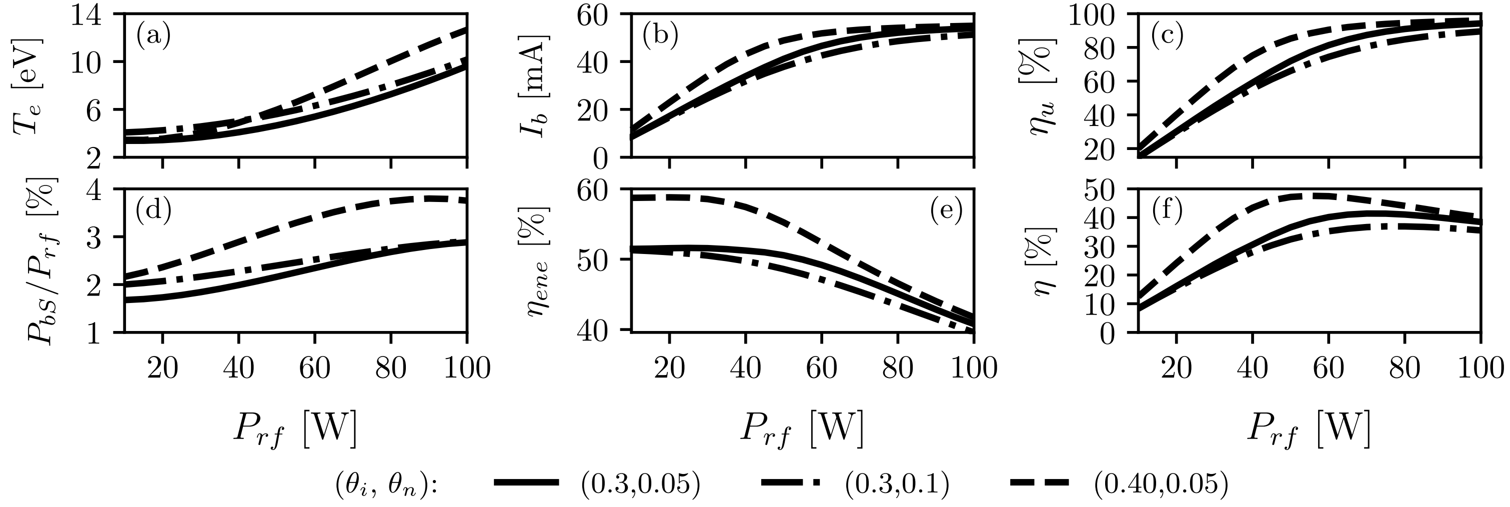
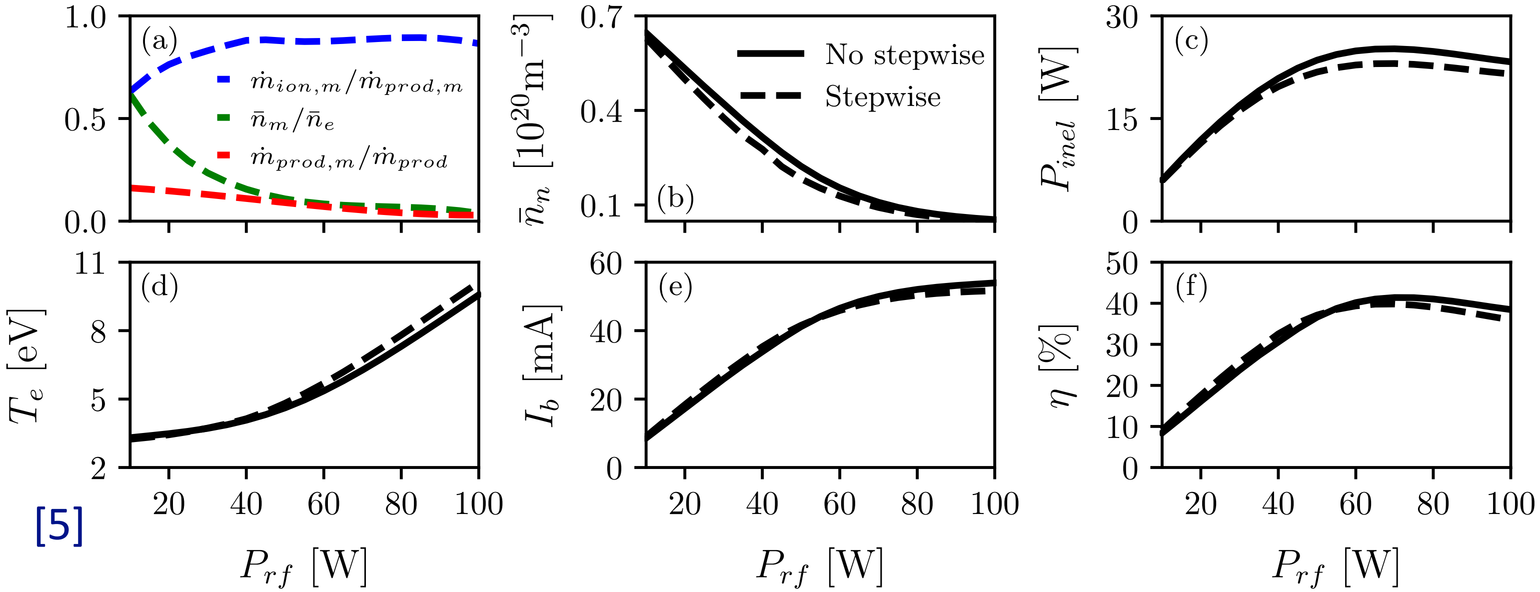


  - Parametric analysis
    - Operative conditions (massflow and power)
    - Numerical parameters (Grids' transparencies and wall accommodation
    - Chemistry (Stepwise ionization)



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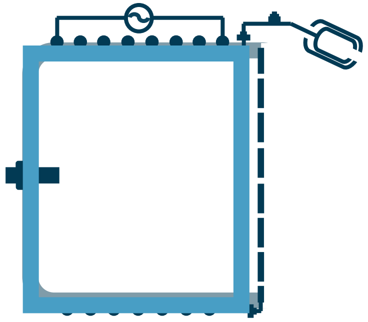
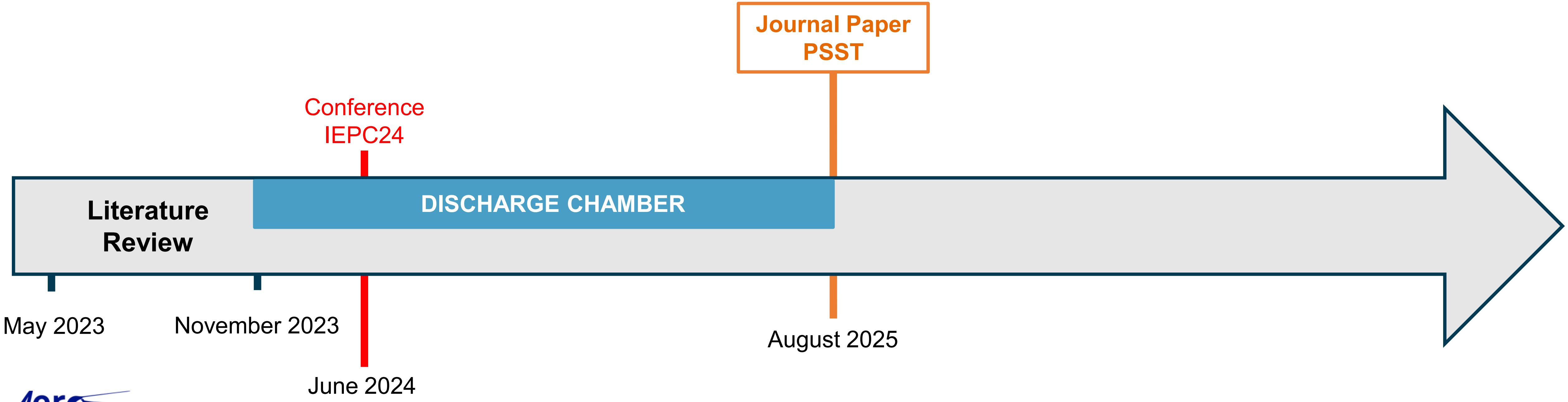
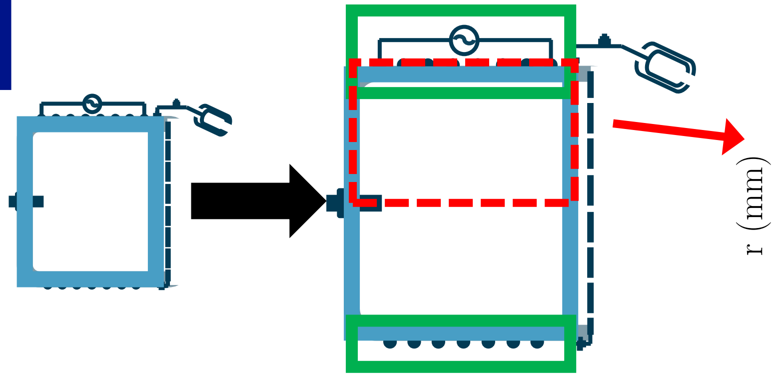
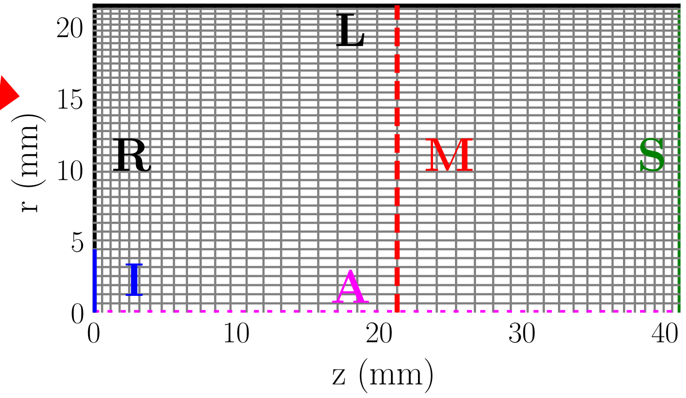


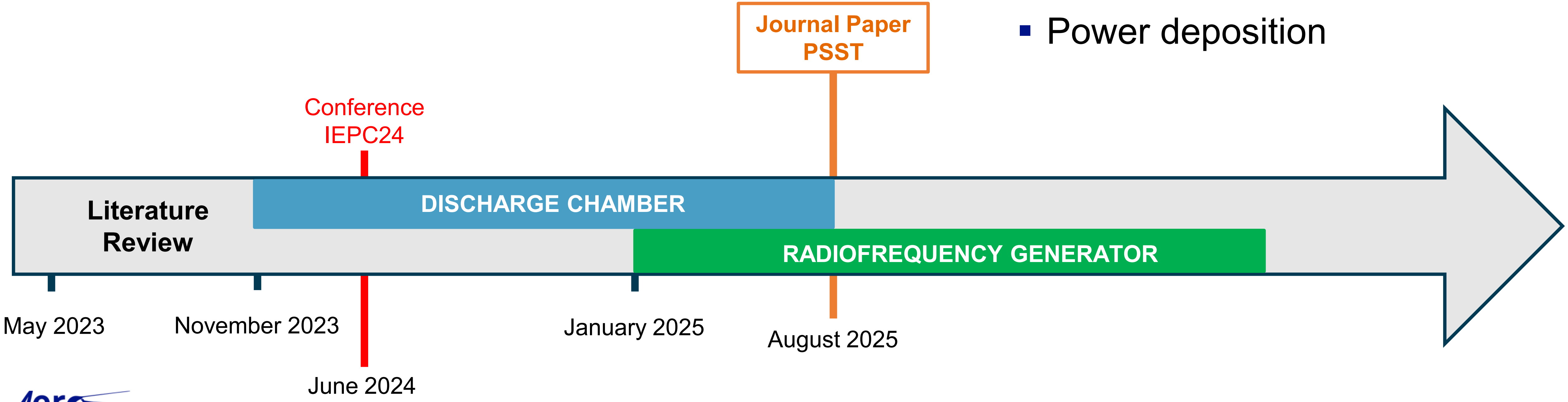


Radiofrequency generator





- Introduced the RF wave-plasma interactions
  - **Purely axial magnetic field**
  - **Maxwell 1D** (at M)
- Objectives:
  - Power deposition

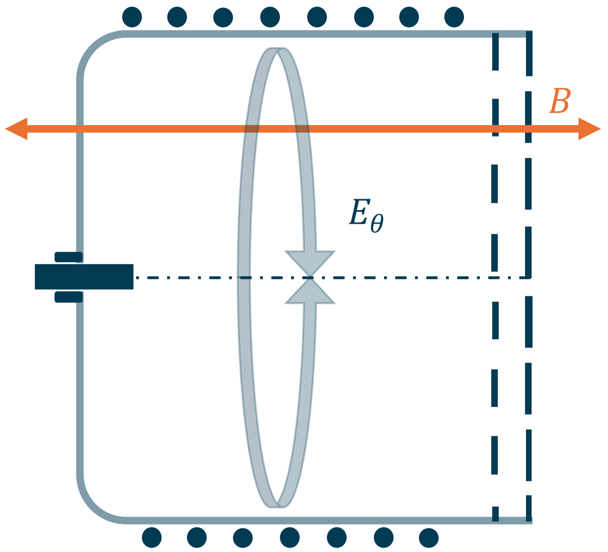


Radiofrequency generator

- Assumptions:
  - **Infinite coil**
    - Purely axial magnetic field B
  - **Magneto quasistatic**
    - No displacement current
  - **1D approximation**
    - Computed in the axial mid-section

$$\boldsymbol{B} = B(r,t)\boldsymbol{i_z}$$

$$\boldsymbol{E} = E_\theta(r,t)\boldsymbol{i_\theta} - \nabla\phi(z,r,t)$$



- We now solve:
  - Simplified **1D Maxwell's** equations
    - Governed by BC $B(R,t)$
    - Driving frequency f_0

$$\frac{1}{r}\frac{\partial(rE_\theta)}{\partial r} = -\frac{\partial B}{\partial t}, \qquad \frac{\partial B}{\partial r} = -\mu_0 j_{\theta e \mathrm{M}}$$

$$B(R,t) = B_0 \cos(2\pi f_0 t), \qquad E_\theta(0,t) = 0$$

  - Consistent **power source term**

$$\boldsymbol{j_e} \cdot \boldsymbol{E} = \boxed{j_{\theta e} E_\theta} - \boldsymbol{j_e} \cdot \nabla\phi$$

$$j_{\theta e} E_\theta \equiv P'''_{\mathrm{dep}}$$

The momentum equations

- Previous model ($B = 0$):
  - No magnetic field
  - No electron inertia
  - No radial-azimuthal coupling

$$j_{er} = \mu \nabla_r p_e + \sigma E_r$$

$$j_{e\theta} \approx 0$$

$$j_{ez} = \mu \nabla_z p_e + \sigma E_z$$

- New model (RF):
  - Time-varying **magnetic field**
    - **Radial-azimuthal coupling**
    - **Azimuthal electric field**
  - **Electron inertia** (explicit form)

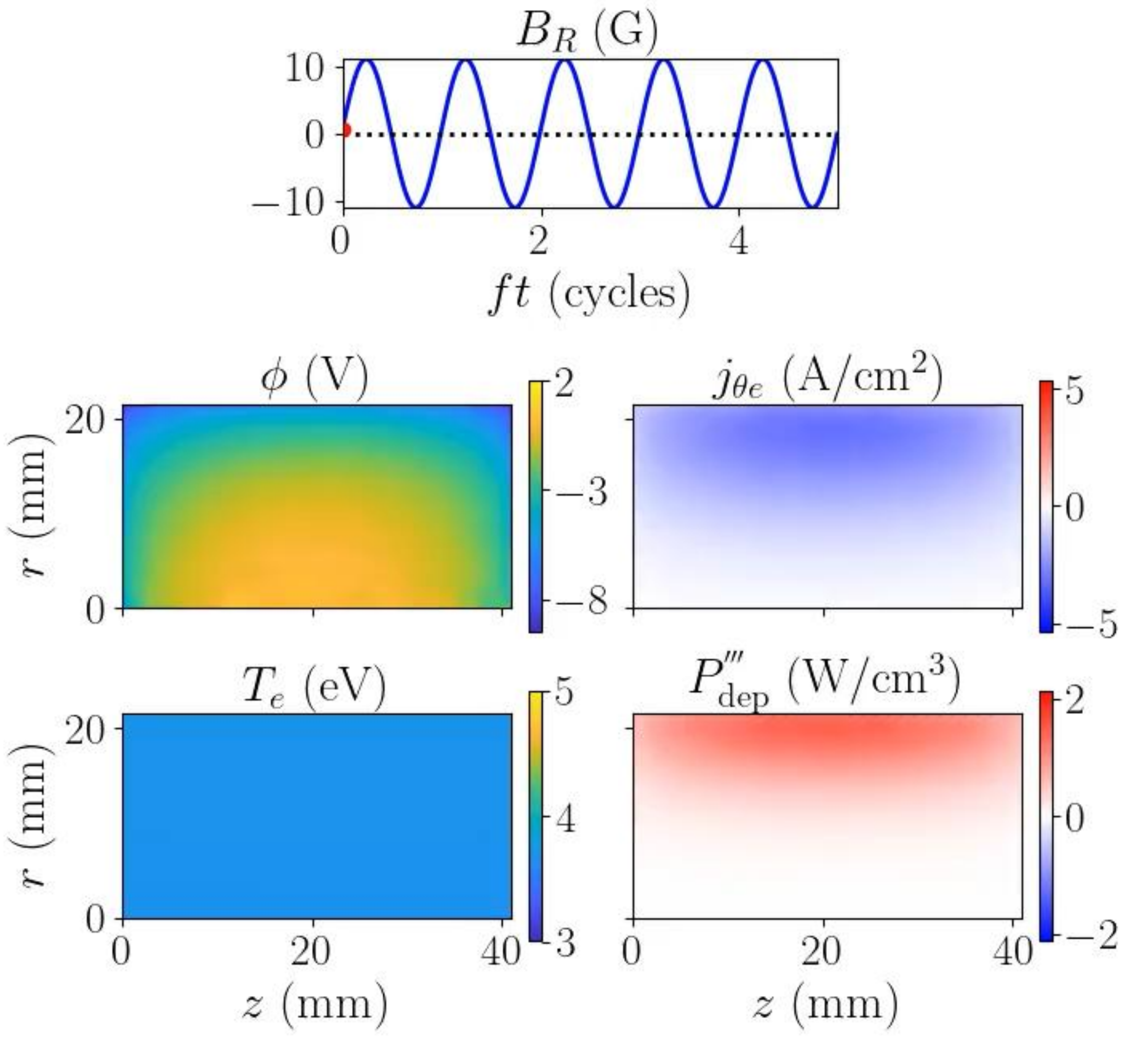
$$j_{er} = \mu \nabla_r p_e + \sigma E_r - \mu B j_{e\theta} + \mu K_r$$

$$j_{e\theta} = \mu B j_{er} + \sigma E_\theta + \mu K_\theta$$

$$j_{ez} = \mu \nabla_z p_e + \sigma E_z + \mu K_z$$

Radiofrequency generator

- We studied:
  - Time-varying profiles
    - Periodic oscillations
    - Phase shifts
    - RFG external circuit



Radiofrequency generator

- We studied:
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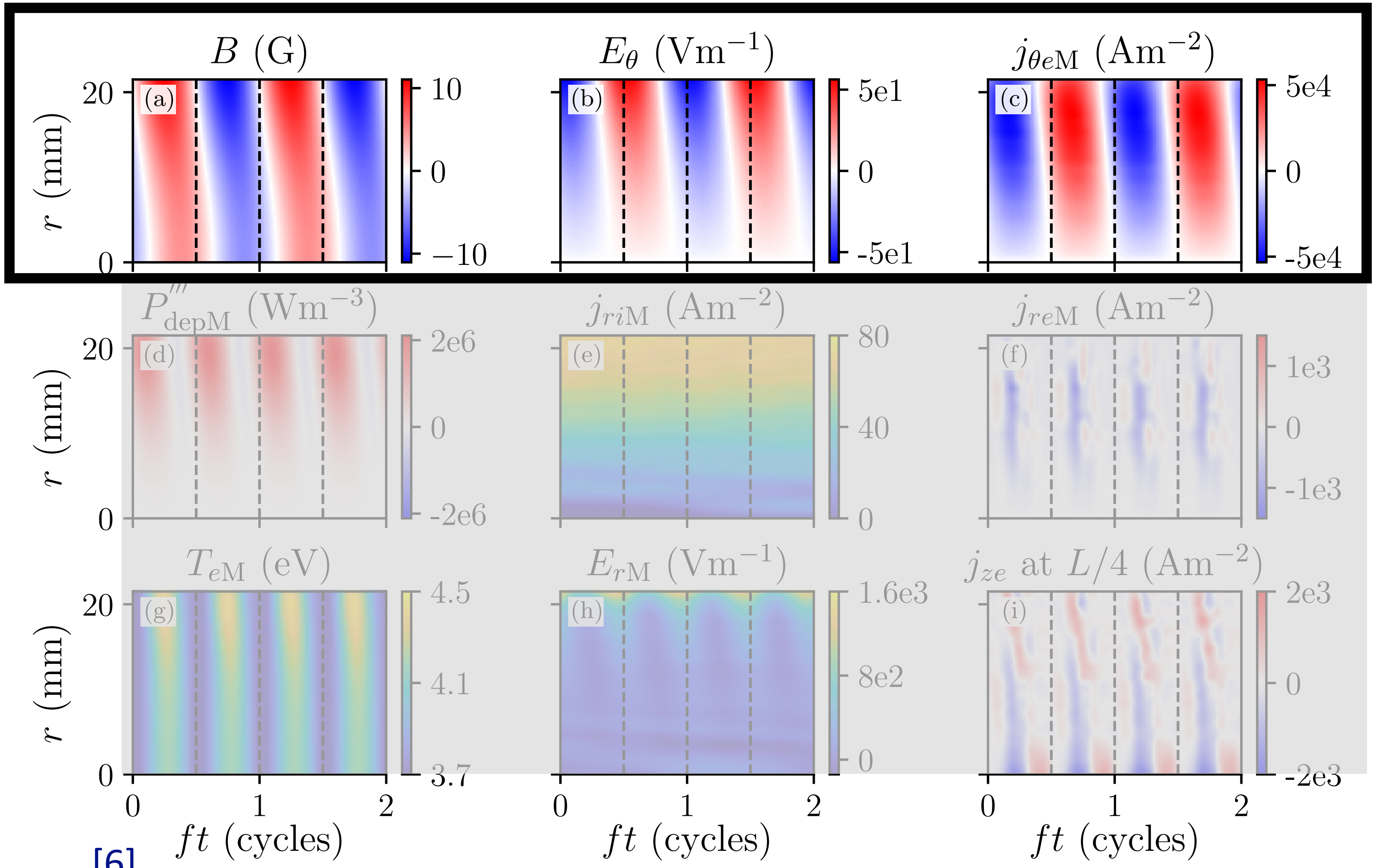
  - Radial-time maps
    - B, E_θ and $j_{\theta e}$ sinusoidal behavior at f_0



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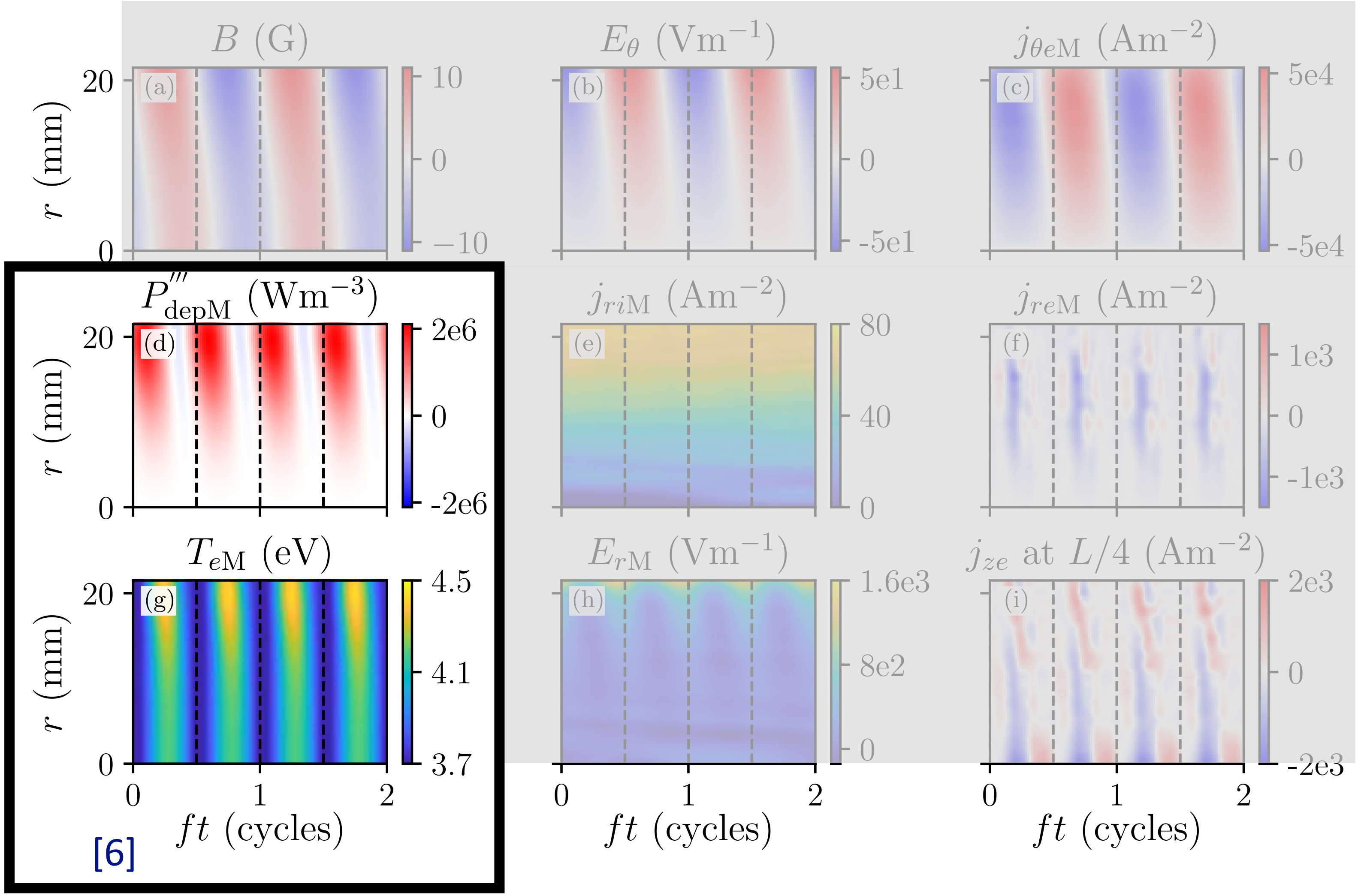
    - P'''_{depM} and T_e at $2f_0$



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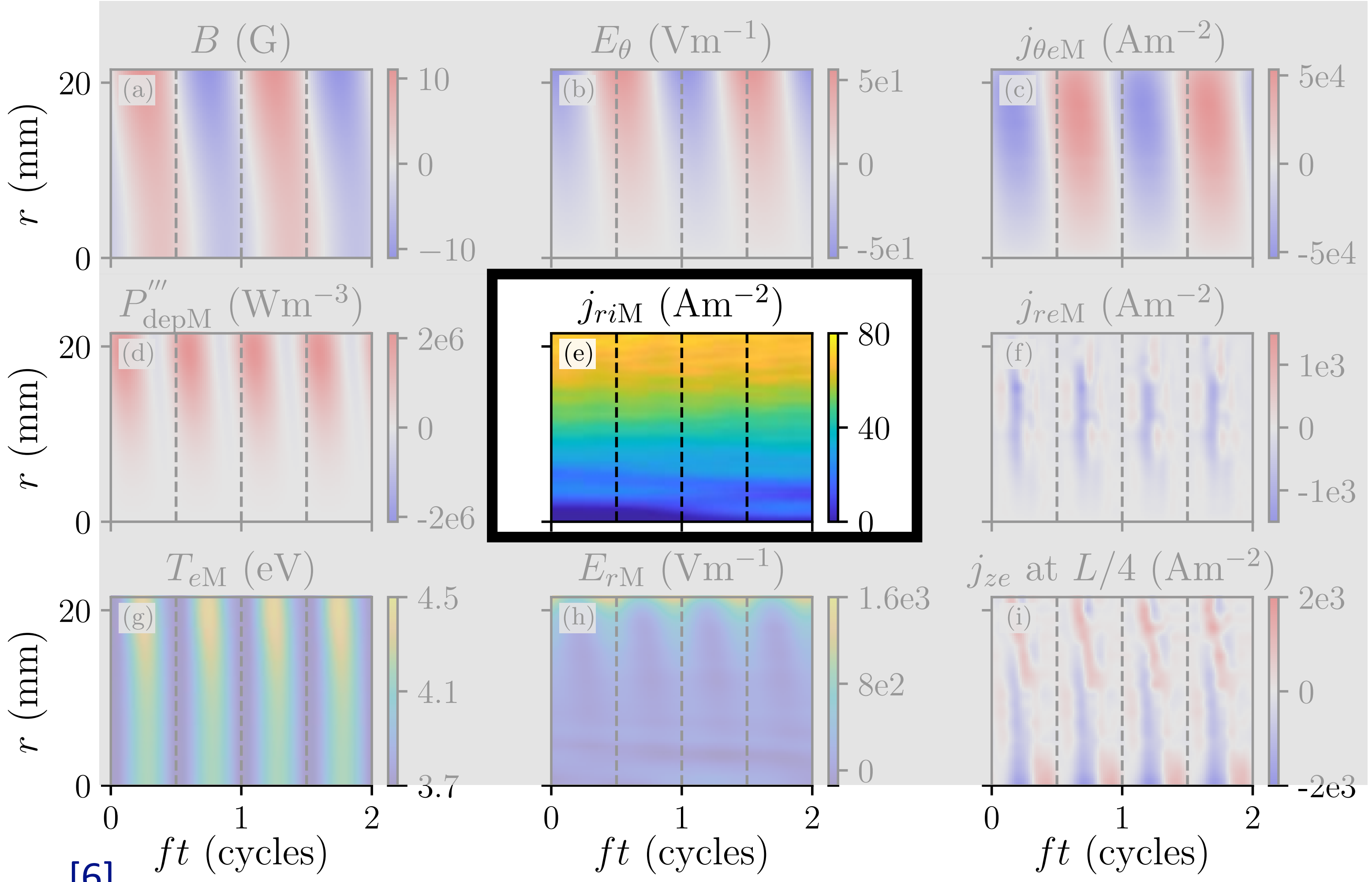
    - RFG external circuit
  - Radial-time maps
    - B, E_θ and $j_{\theta e}$ sinusoidal behavior at f_0
    - P'''_{depM} and T_e at $2f_0$
    - Ion's magnitudes do not oscillate



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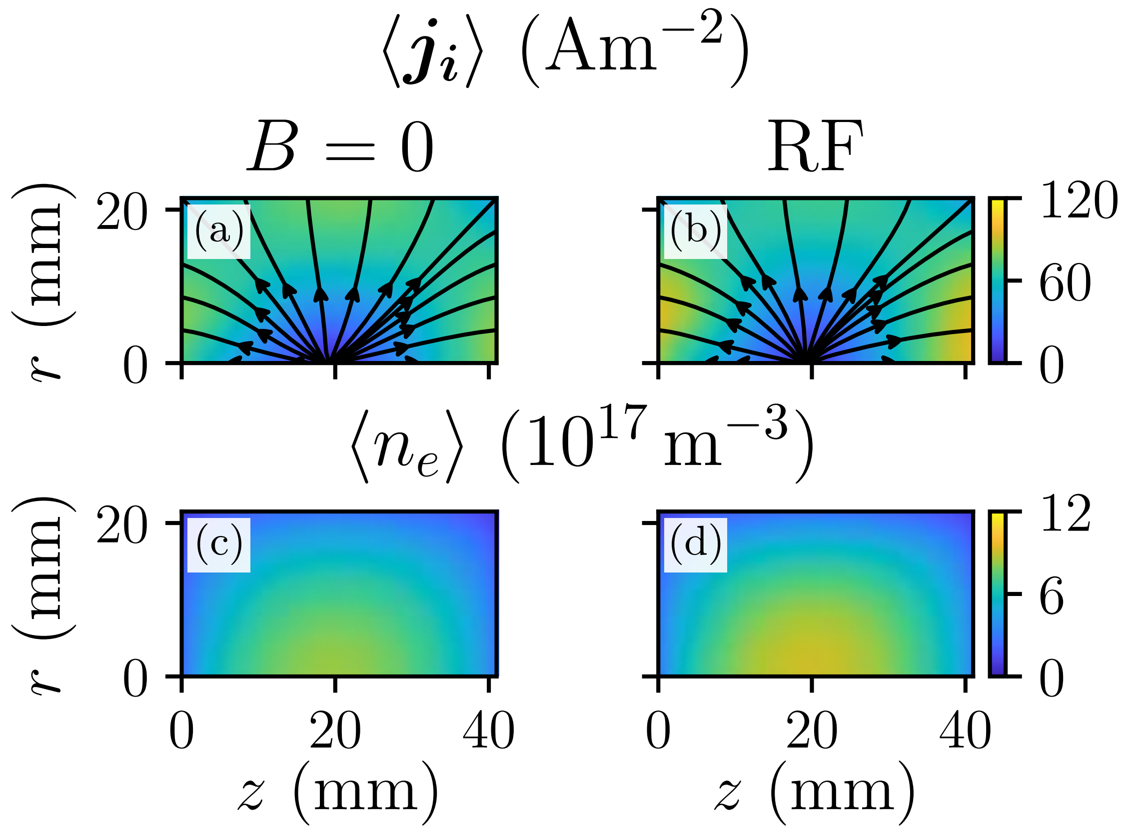
Radiofrequency generator

- We studied:
    - **Electron confinement**
        - **no permanent magnetic** field in a RIT
        - Self-induced magnetic field **confines the plasma**
        - **Improvements** on thruster performance



	$B = 0$	RF
$\langle I_{\text{prod}} \rangle$ (mA)	517	503
$\langle I_{\text{b}} \rangle$ (mA)	25.2	28.8
$\langle \eta_{\text{u}} \rangle$ (%)	42.9	49.0

Radiofrequency generator

- We studied:
  - **Electron confinement**
    - **no permanent magnetic** field in a RIT
    - Self-induced magnetic field **confines the plasma**
    - **Improvements** on thruster performance
    - Compressing term 25% higher with RF

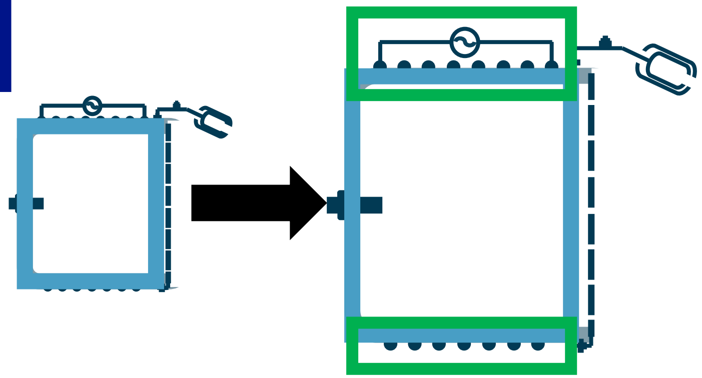
Time-averaged electron radial momentum balance

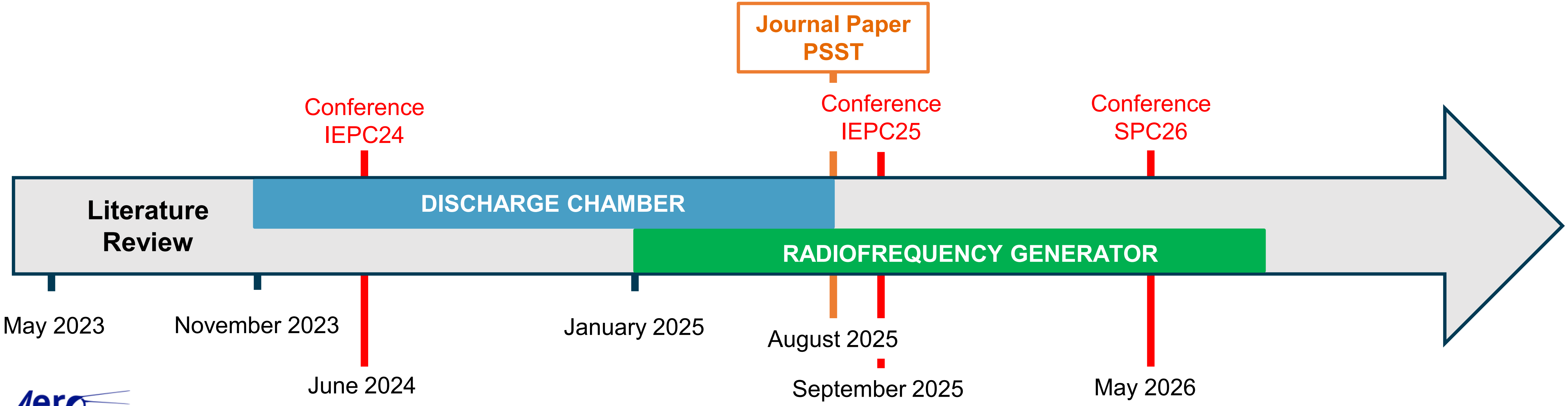
$$\langle j_{re}\rangle = \langle \mu\nabla_r p_e\rangle + \langle e n_e \mu E_r\rangle - \langle \mu B j_{\theta e}\rangle + \langle \mu K_r\rangle$$

$\mathrm{A/cm^2}$	$B = 0$	RF
$\langle j_{re}\rangle$	$-7.8 \cdot 10^{-3}$	$-6.9 \cdot 10^{-3}$
$\langle \mu\nabla_r p_e\rangle$	-98.1	-119.0
$\langle e n_e \mu E_r\rangle$	98.1	96.1
$-\langle \mu B j_{\theta e}\rangle$	-	32.1
$\langle \mu K_r\rangle$	-	-9.2

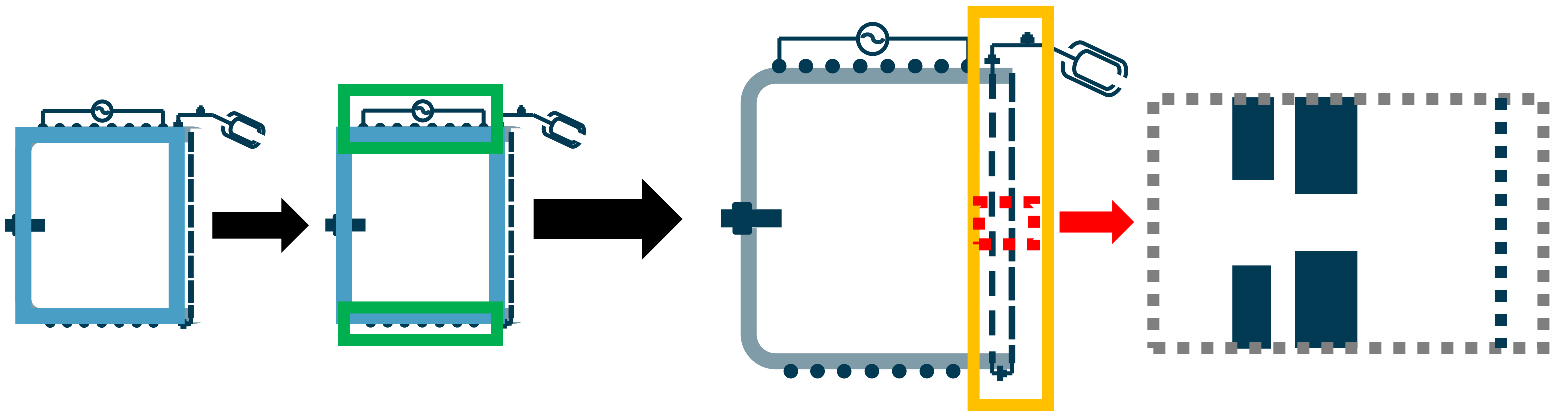
*Values computed at $(\mathrm{z}, \mathrm{r}) = \left(\frac{L}{2}, R\right)$

Radiofrequency generator

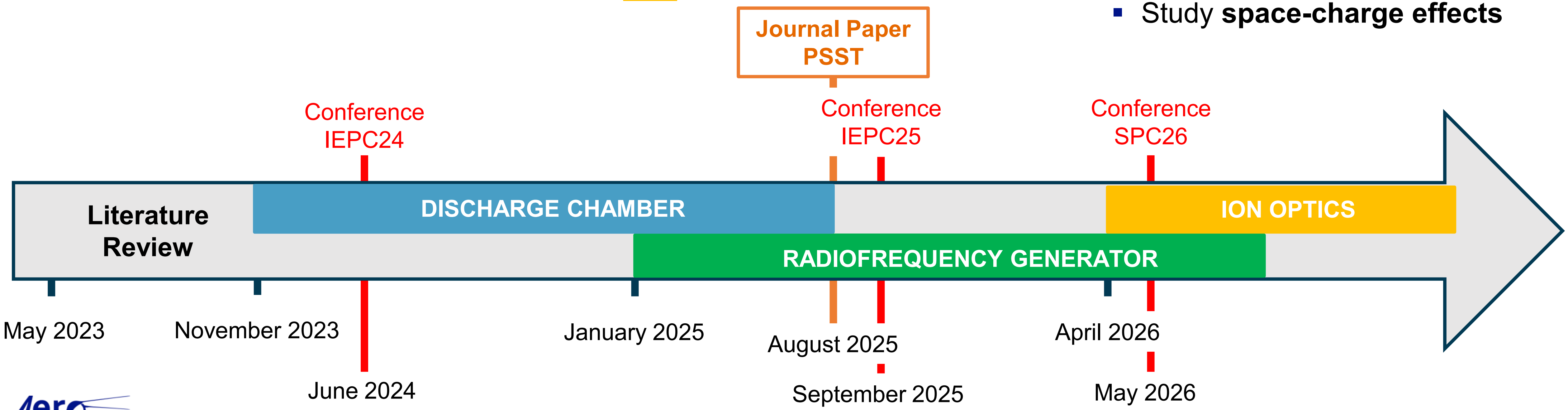




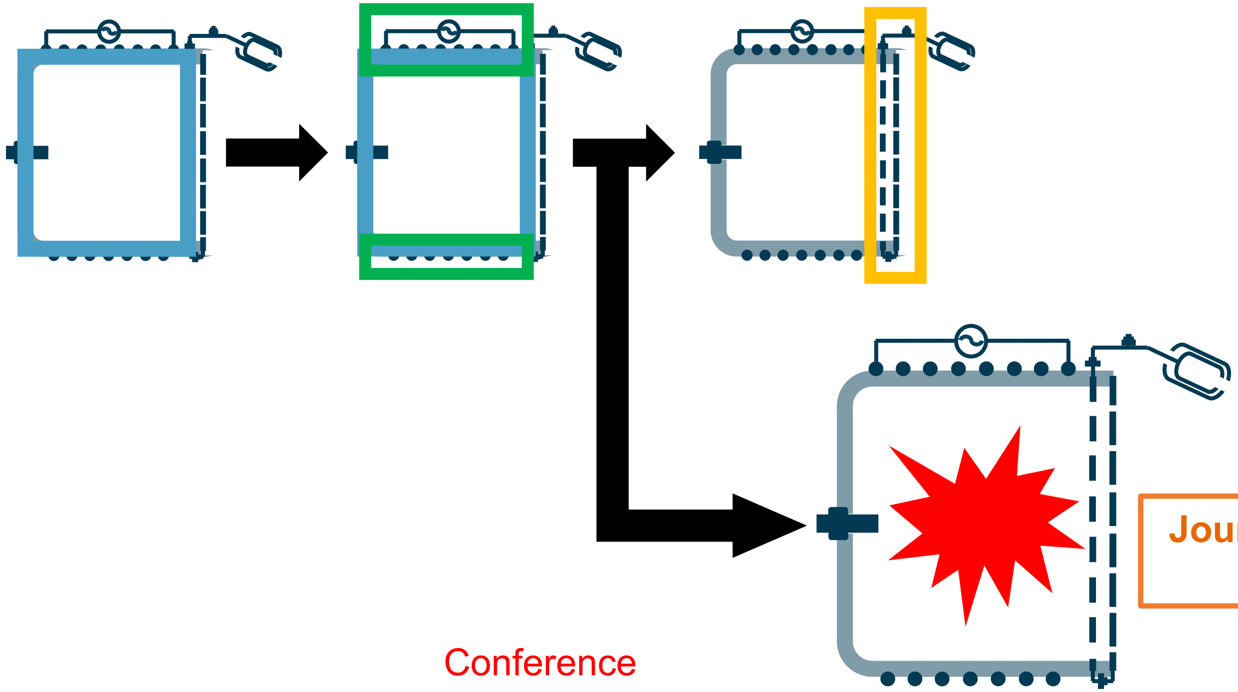
What's next? Ion optics



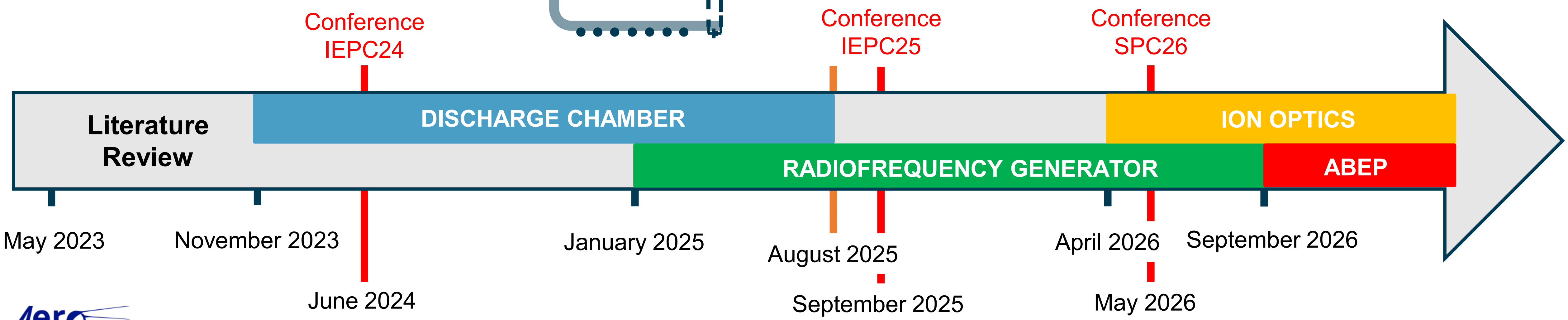
- Simulation characteristics
  - Non-neutral region (EP2PLUS)
  - Consistent injection (from HYPHEN)
- Objectives:
  - Characterize **maximum beam current**
  - Study **space-charge effects**



What's next? Air Breathing Electric Propulsion (ABEP)



- Research stay at CNR-ISTP Bari:
  - Improve **air chemistry** in HYPHEN
  - **ABEP RIT**
- Objectives:
  - Multispecies discharge
  - Influence of nitric oxide (NO)



Achievements

- Journal papers
  - **S. Dalle Fabbriche**, J. Zhou and E. Ahedo. “ An axisymmetric hybrid model of the plasma in a radio-frequency ion thruster chamber”. Published in PSST, August 2025
  - **S. Dalle Fabbriche**, J. Zhou and E. Ahedo. “A coupled model of the wave emission and the 2D plasma discharge in a radiofrequency ion thruster”. Ongoing
- Conference papers
  - **S. Dalle Fabbriche**, J. Zhou, J. Perales-Dìaz, E. Ahedo and K. Holste. “Analysis of the plasma discharge in a radio-frequency ion thruster chamber”. Presented at the International Electric Propulsion Conference, Toulouse, France. June 23-28, 2024
  - **S. Dalle Fabbriche**, J. Zhou and E. Ahedo. “2D model coupling the radio-frequency generator to the plasma discharge in a RIT”. Presented at the International Electric Propulsion Conference, London, United Kingdom. September 14-19, 2025
  - **S. Dalle Fabbriche**, J. Zhou and E. Ahedo. “2D PIC–Fluid Modeling of Inductive Coupling in a Radiofrequency Ion Thruster”. Presented at the Space Propulsion Conference, Bari, Italy. May 18-21, 2026
- Courses
  - Attended the Electric Propulsion Summer School. Noordwijk, Netherlands, October 10-12, 2023
- Scientific Outreach
  - Semana de la ciencia
    - “Pintura Acústica: Convertir Imágenes en Música”, 12/11/2024
    - “Sobre las ondas y la naturaleza ondulatoria de la luz”, 7/11/2025
  - Noche Europea de los Investigadores y de las Investigadoras
    - "¿Puede la luz realmente empujar satélites?“. 26/09/2025

Thank you! Questions?

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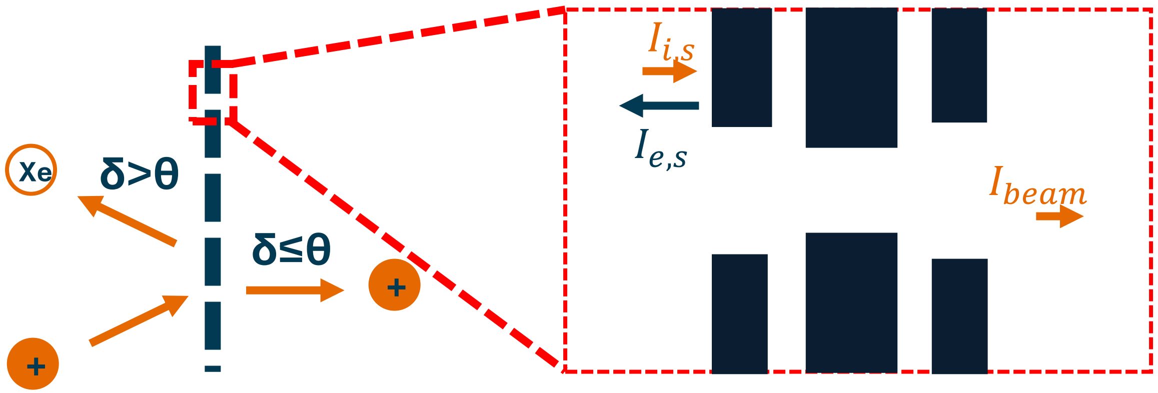
The semi-transparent surface

- Grids require different setup
  - Problems come from non-neutrality and cell size in Debye scale
  - Self-consistent simulations with discharge chamber and grid systems are computationally heavy

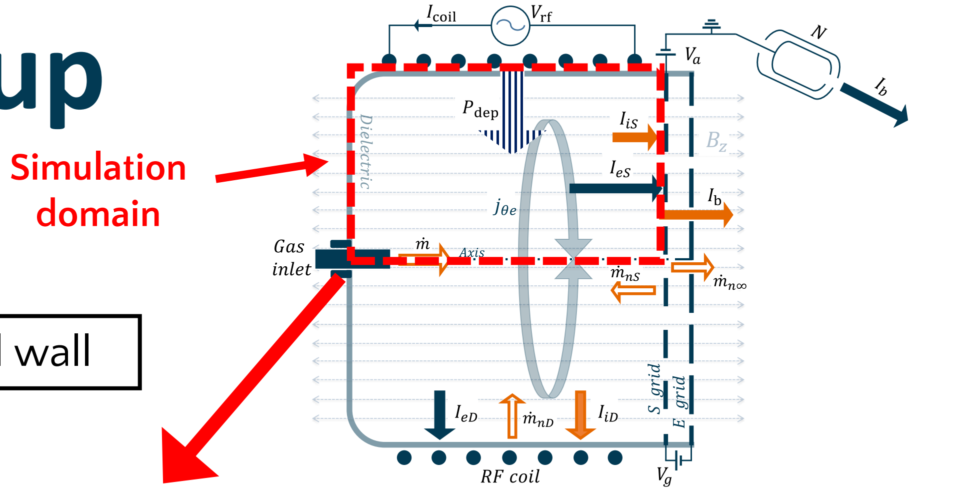
- Semi-transparent surface
  - Acts as both material or free loss surface
  - The behavior of k-th species is governed by a set of transparency coefficients θ_k
  - Every time a macro-particle approaches the surface, a random number δ ϵ $[0,1]$ is generated.
  - If δ≤ θ_k, the surface acts as a free loss

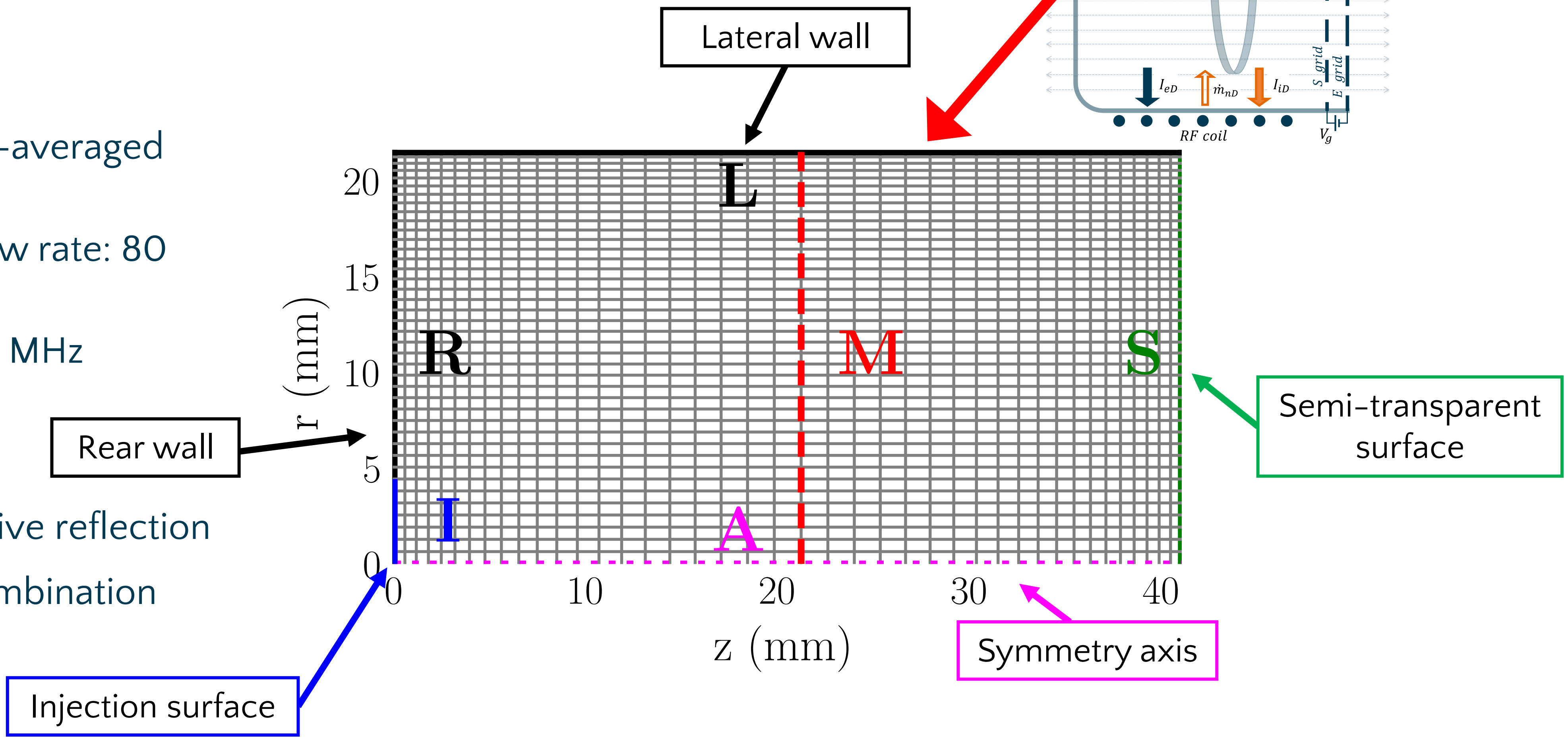
- Characteristics for simulations
  - θ_k constant all over the surface
  - Two values:
    - $\theta_i = 30\ \%$ for singly charged ions
    - $\theta_n = 5\ \%$ for neutrals
  - Global zero net current, thus potential on grid surface ϕ_s adjusted to fulfill the current balance: $I_{e,s} = -(I_{i,s} + I_{beam})$



Simulation setup

- RIT-4 geometry:
  - Axial length: 41mm
  - Radial length: 21.5mm
- Operational point:
  - Steady state time-averaged power: 29 W
  - Injection mass flow rate: 80 µg/s (Xe)
  - RF frequency f_0: 1 MHz
- Wall interaction:
  - Neutrals → Diffusive reflection
  - Ions → Recombination

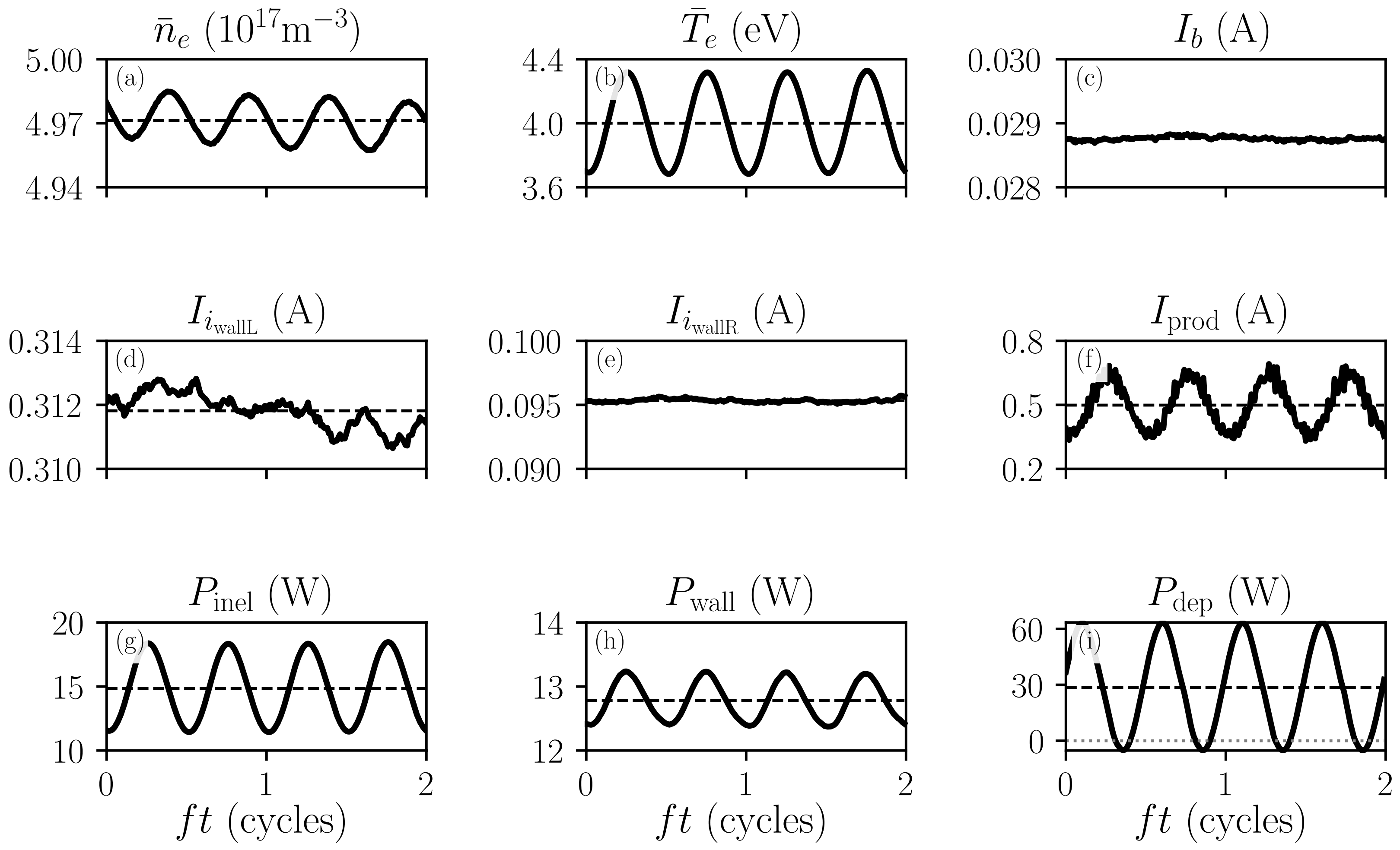




Time averaged performance variables

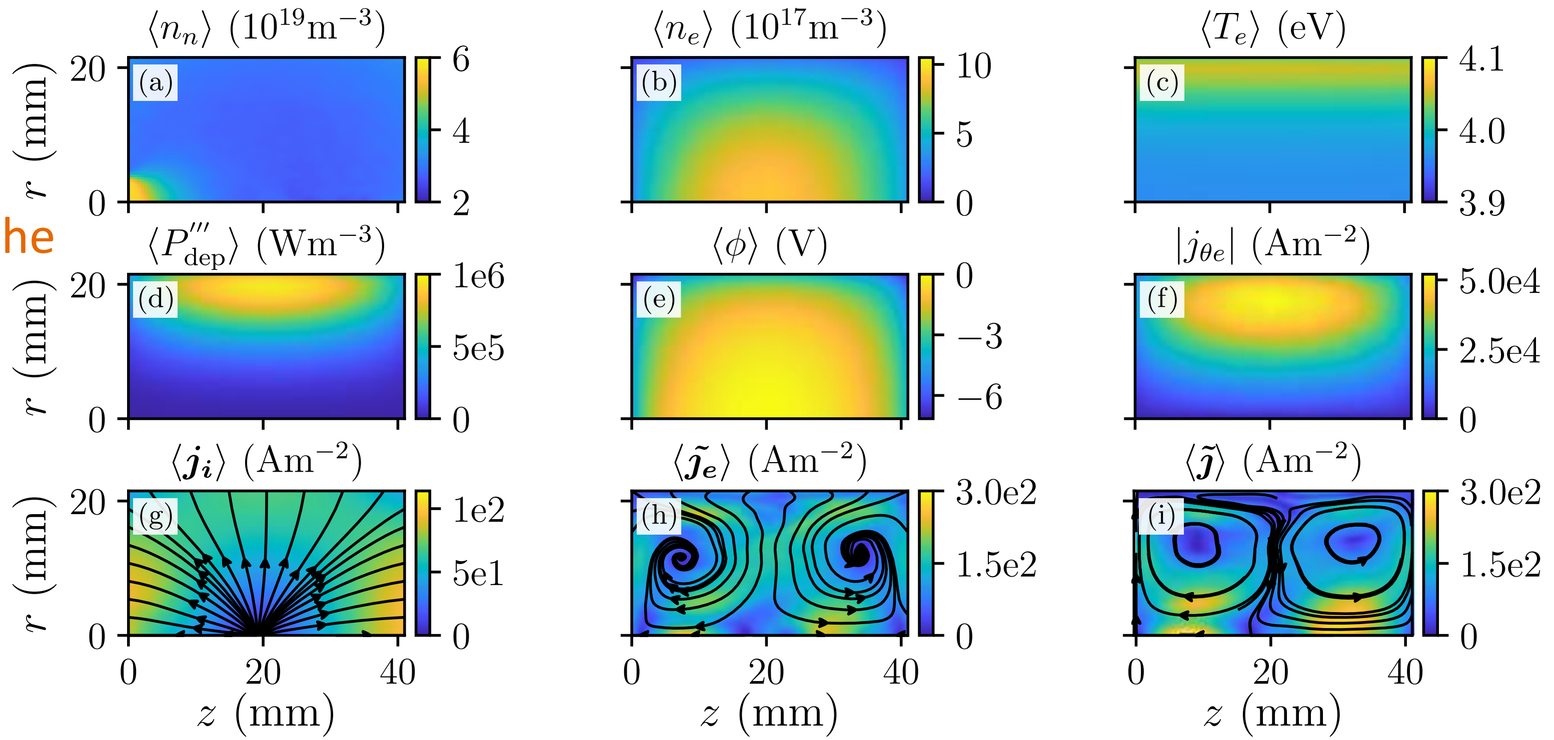
Magnitude	Time averaged value	RSD (%)
$\bar{n}_n$ (10^{19}m^{-3})	2.92	0.01
$\bar{n}_e$ (10^{17}m^{-3})	4.97	0.17
$\bar{T}_e$ (eV)	4.00	5.63
$\bar{\mu}$ (G^{-1})	1.90	0.31
I_{b} (A)	0.03	0.11
$I_{i\mathrm{L}}$ (A)	0.31	0.17
$I_{i,\mathrm{R+S}}$ (A)	0.16	0.10
I_{prod} (A)	0.50	20.70
P_{bS} (W)	0.67	0.23
P_{inel} (W)	15.0	16.60
P_{L} (W)	8.54	3.93
$P_{\mathrm{R+S}}$ (W)	4.87	3.12
P_{dep} (W)	29.00	83.80
η_{prod} (%)	5.7	-
η_{ene} (%)	55.4	-
η_{u} (%)	49.0	-
η (%)	27.2	-

Instantaneous balances



Simulation results: time-averaged 2D maps

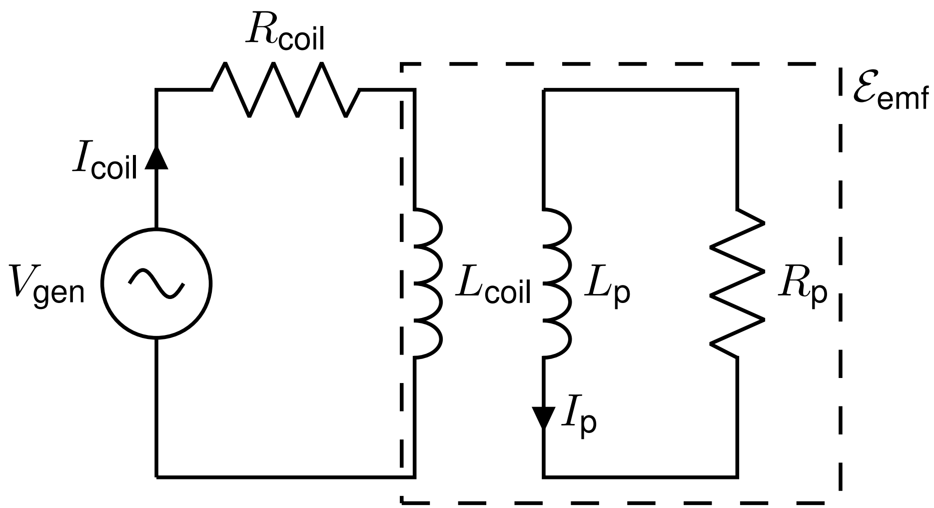
- $\langle n_n \rangle$, $\langle n_e \rangle$ and following typical profiles [2]
  - $\langle n_n \rangle$ peak next to the injection
- $\langle T_e \rangle$, $|j_{\theta e}|$ and $\langle P'''_{\text{dep}} \rangle$ higher at R
- Ions are accelerated from the center to the walls
- $\langle \tilde{j}_e \rangle = \langle \boldsymbol{j}_e \rangle - \langle j_{\theta e} \rangle i_\theta$ presents two symmetric loops
  - Quasi-neutrality + dielectric walls
- $\langle \tilde{j} \rangle$ follows the electron current
  - $\langle \tilde{j}_e \rangle > \langle j_i \rangle$



[2] S. Dalle-Fabbriche, et al., "An axisymmetric hybrid model of the plasma in a radio-frequency ion thruster chamber," PSST. 2025

External circuit

- An external Radiofrequency generator (RFG) provides the current $I_{coil} \propto B_0$
- The entire thruster can be seen as an electromotive force acting on the circuit
- R_{coil} is neglected
- In the model, tune B_0 to obtained a specific averaged T_e
  - From B_0, we can compute circuital values
- The total power introduced in the circuit is divided into deposited and reactive power

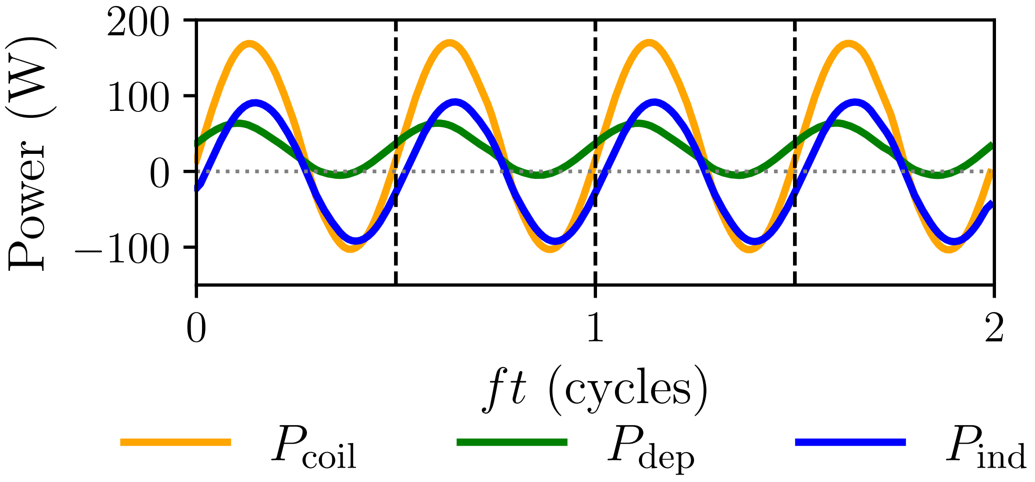


$$P_{dep} = \int_{\Omega} E_\theta j_{\theta e} d\Omega = P_{coil} - P_{ind}$$

$$P_{coil} = -2\pi R N E_{\theta R} I_{coil}$$

$$P_{ind} = \frac{2\pi L}{\mu_0} \frac{\partial}{\partial t} \int_0^R \frac{r B^2}{2} dr$$

Circuit results and performance



- P_{coil} has an amplitude 3 times larger than P_{dep}
- P_{ind} collects most of the power, but $\langle P_{\text{ind}} \rangle \approx 0$
- $\langle P_{\text{coil}} \rangle \approx \langle P_{\text{dep}} \rangle$
  - Differences due to 2D distribution of $j_{\theta e}$ vs 1D approximation

$$P_{\text{dep}} = \int_\Omega E_\theta j_{\theta e} d\Omega = P_{\text{coil}} - P_{\text{ind}}$$

$$P_{\text{coil}} = -2\pi R N E_{\theta R} I_{\text{coil}}$$

$$P_{\text{ind}} = \frac{2\pi L}{\mu_0} \frac{\partial}{\partial t} \int_0^R \frac{rB^2}{2} dr$$

Results: influences on $\langle j_{re} \rangle$

- **Without magnetic field:**
  - Electric and pressure forces compensate each other
- **Introducing the RF effects:**
  - The magnetic term enhances the confinement ($\approx 25\%$ of total contribution)
  - Inertial effects instead act in opposite way ($\approx 7\%$)
    - Mostly governed by centrifugal terms
    - **Not negligible** with respect to $\langle j_{re} \rangle$
- $\langle j_{re} \rangle$ **expresses the effects of the confinement**
  - When $B = 0$, $\langle j_{re} \rangle$ is larger in absolute value
    - $j_{re} = j_{ri}$ at the wall → higher wall losses

$$\langle j_{re} \rangle = \langle \mu \nabla_r p_e \rangle + \langle e n_e \mu E_r \rangle + \langle \mu K_r \rangle - \langle \mu B j_{\theta e} \rangle$$

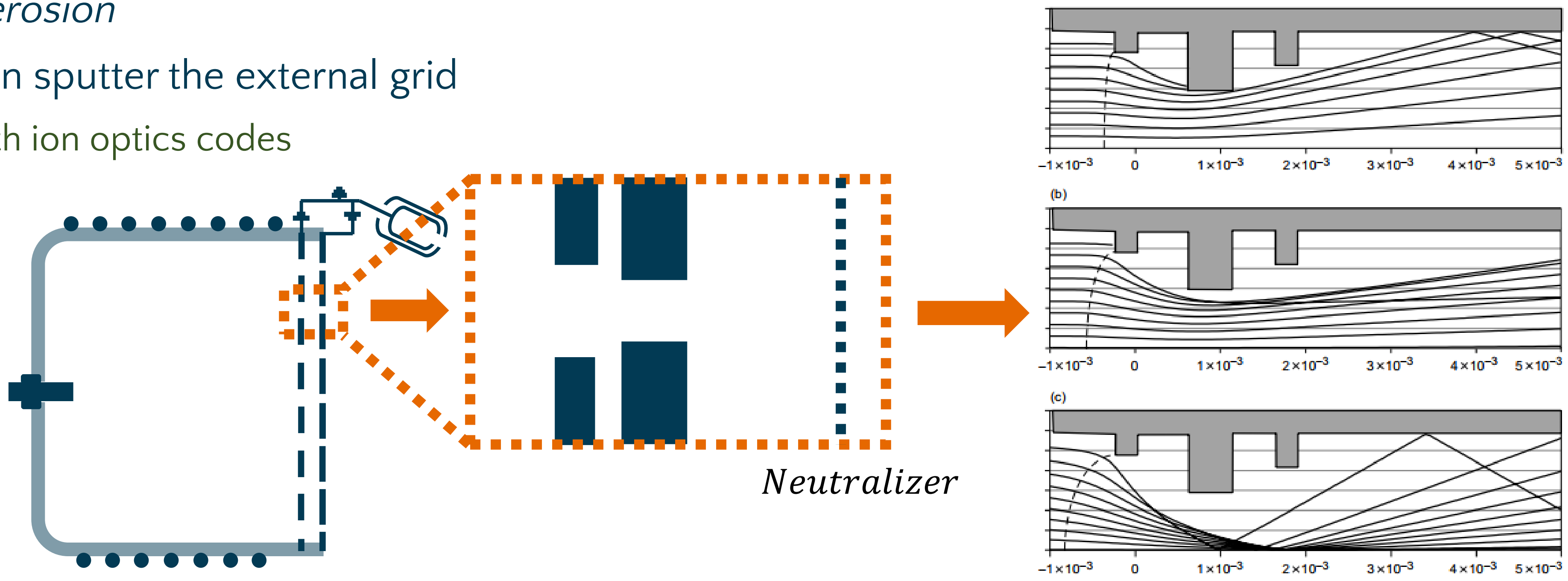
$\mathrm{A/cm^2}$	$B = 0$	RF
$\langle j_{re} \rangle$	$-7.8 \cdot 10^{-3}$	$-6.9 \cdot 10^{-3}$
$\langle \mu \nabla_r p_e \rangle$	-98.1	-119.0
$\langle e n_e \mu E_r \rangle$	98.1	96.1
$\langle \mu K_r \rangle$	-	-9.2
$-\langle \mu B j_{\theta e} \rangle$	-	32.1

Values computed at $(\mathrm{z,r}) = \left(\frac{L}{2}, R\right)$

Ion optics

- **Acceleration system:**
  - Constituted by 2 or 3 grids
  - Vital and critical component
  - Correct ion focusing → decrease beam divergence and *erosion*
  - CEX collisions can sputter the external grid
    - Simulated with ion optics codes

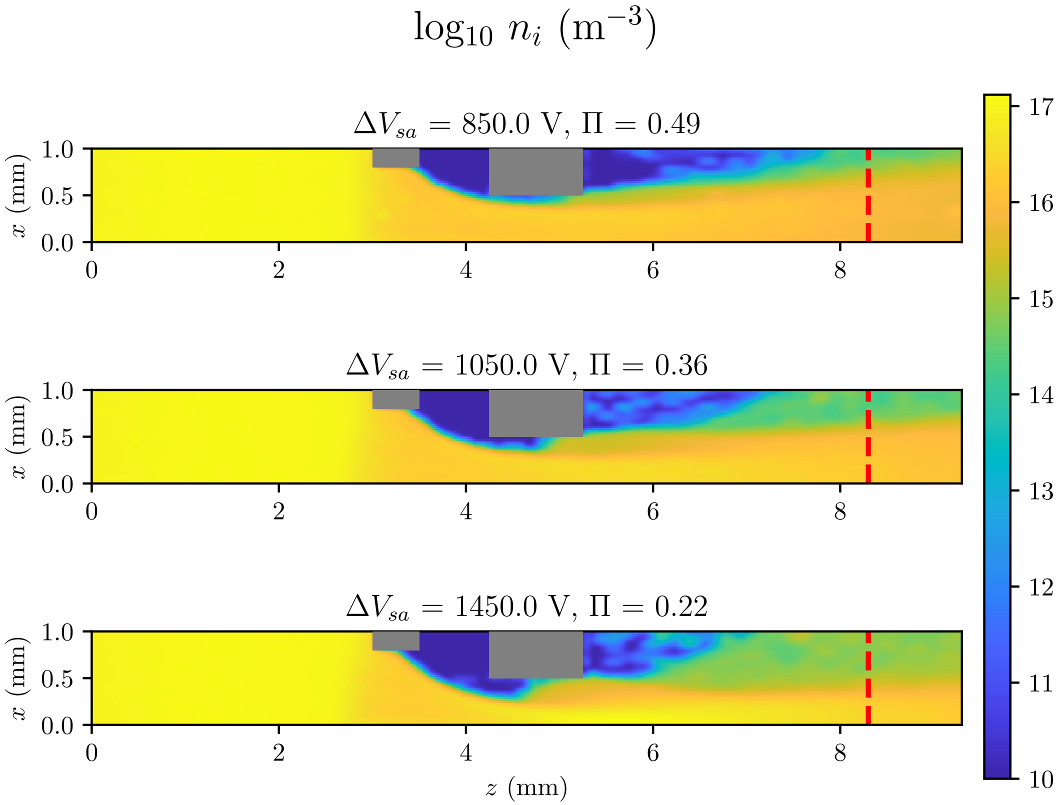
- **Open questions:**
  - Influence of ionization in ion optics
  - Behaviour of penetrating electrons
  - Alternative propellants

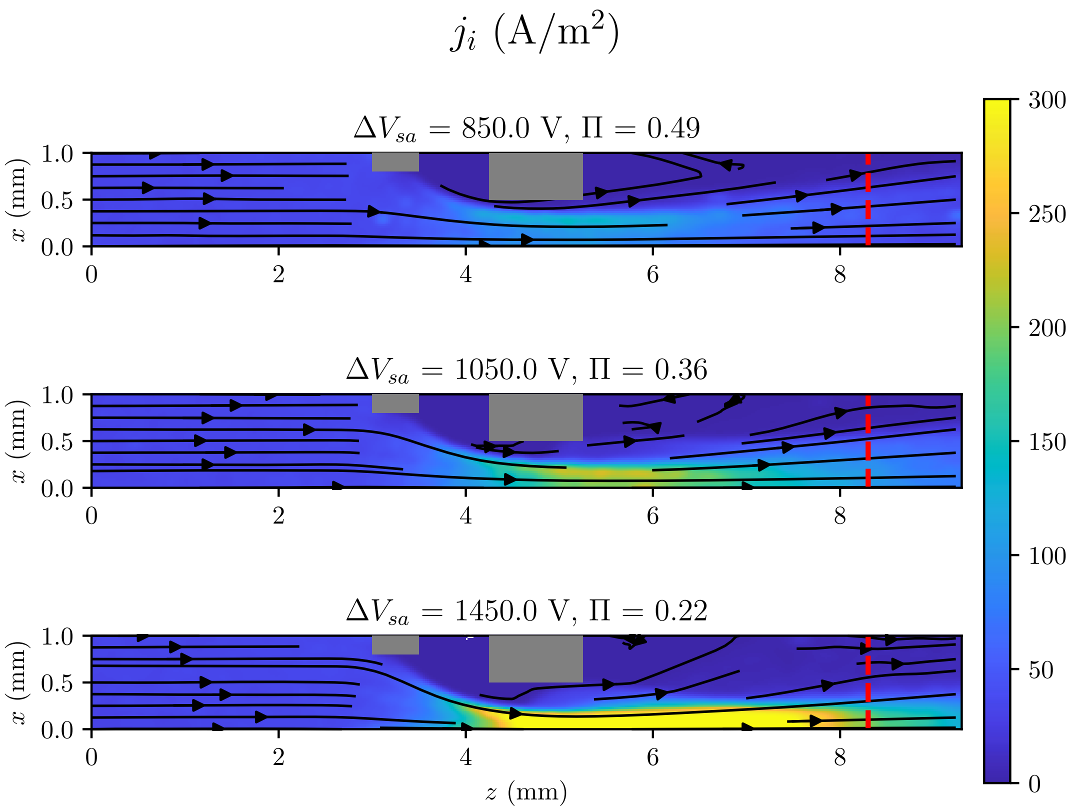


[7]

[7] Dan Goebel, Ira Katz and Ioannis Mikellides. “Fundamentals of Electric Propulsion”. 2nd ed. Wiley, 2023

Acceleration system





Acceleration system

➢ Ion optics preliminary results

- ❑ Perveance test
- ❑ Influence of ionization collisions

	Collsions	No collisions
I_b	38 [μA]	35 [μA]
I_{is}	34 [μA]	28 [μA]
I_{iA}	0.7[μA]	0.5 [μA]