Hall thruster discharge characterization with HYPHEN in CHEOPS-LP

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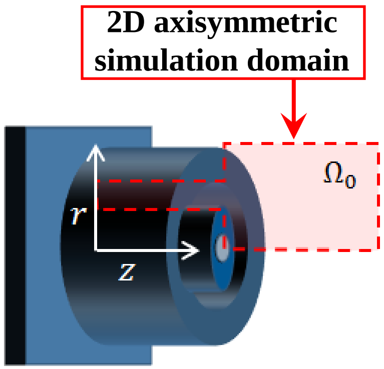
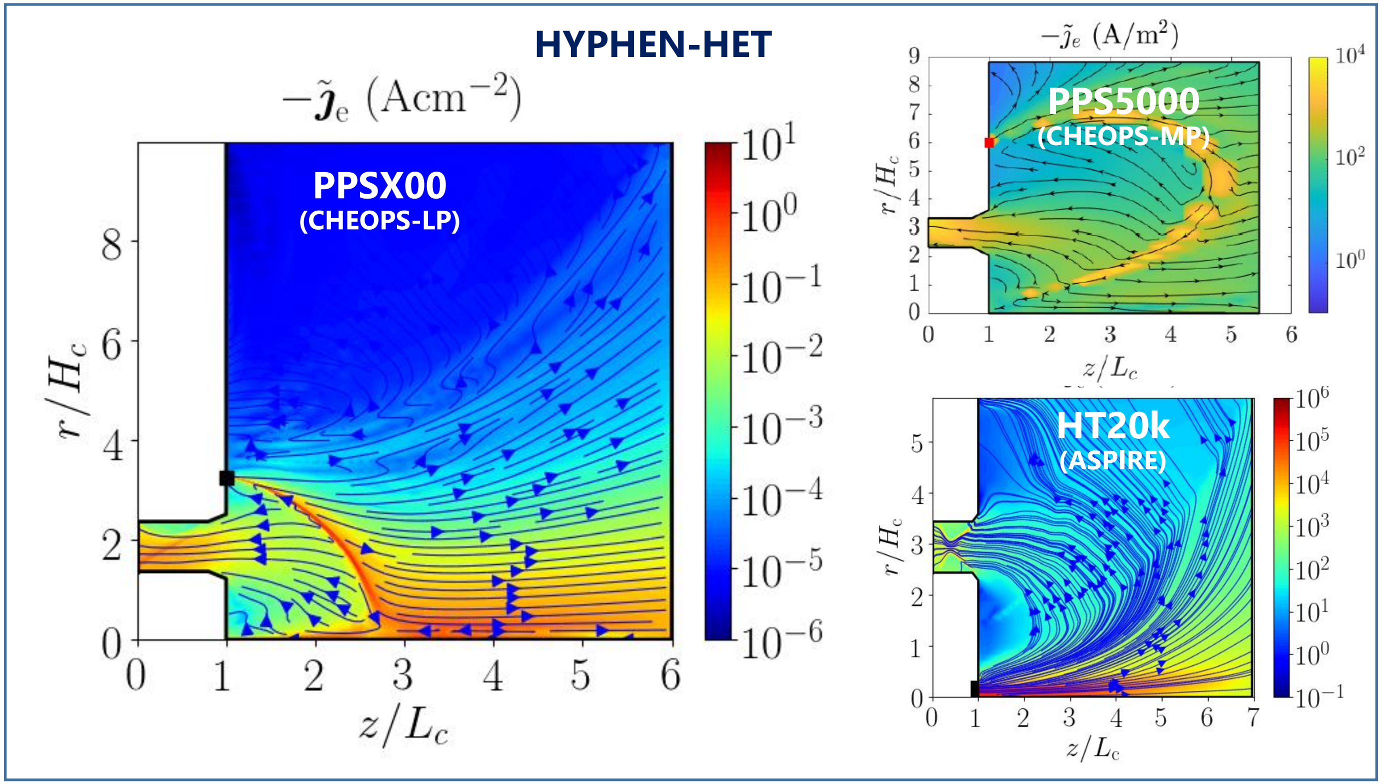
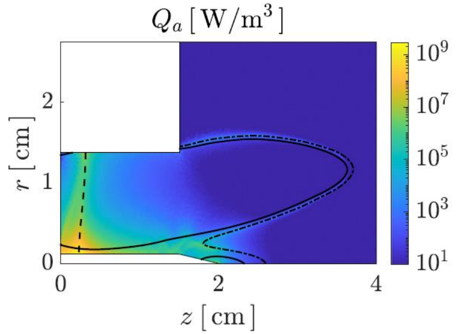
HYPHEN code (I)



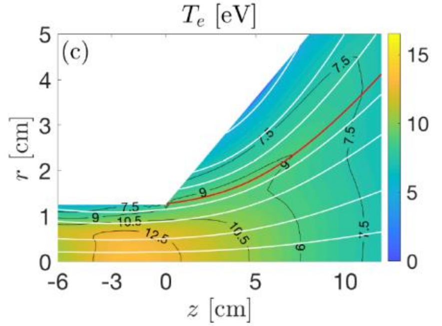
- **HYPHEN: HY**brid **P**lasma thruster **H**olistic simulation **EN**vironment
  - 2D (axial-radial) multi-thruster simulation platform for electromagnetic thrusters (EMT) operating with weakly-collisional plasmas
  - Developed under H2020 CHEOPS, MINOTOR, HIPATIA, EDDA, CHEOPS-LP
  - Application to HETs, EPTs (HPT, ECRT)
  - Current application to PPS5000 (CHEOPS-MP), PPSX00 (CHEOPS-LP), HT20k (ASPIRE)

HYPHEN-HET





HYPHEN-ECRT (MINOTOR)

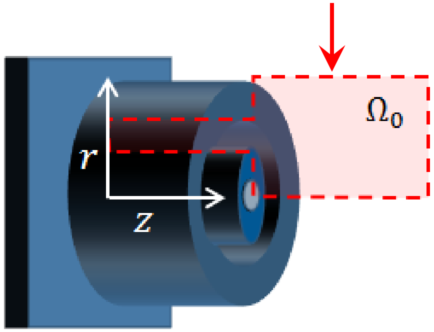


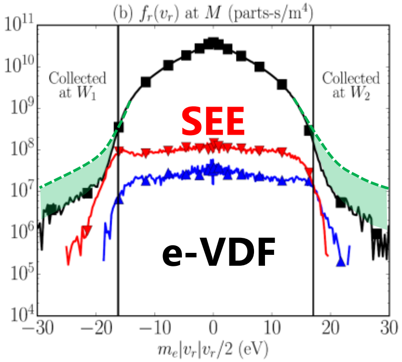
HYPHEN-HPT (HIPATIA)

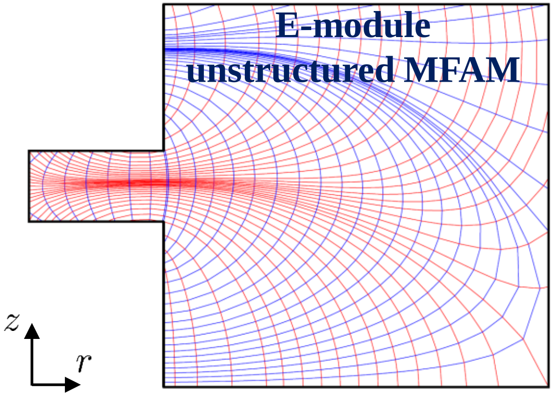
HYPHEN code (II)

- **Ion-module:** PIC formulation for multiple ions+neutrals
  - Xe, Xe+, Xe++, CEX, alternative propellants (Kr, N2, O2,…)
  - Optimized structured mesh for computational efficiency
- **Electron-module:** magnetized, diffusive fluid model
  - Applies quasineutrality
  - Works on an unstructured magnetic field aligned mesh (MFAM)
- **Sheath-module:** coupling between quasineutral plasma and walls
  - Different wall types (dielectric, metallic,…), SEE, sheath saturation
  - Coupled to kinetic code for non-Maxwellian electron VDF
- **Wave-module:** only for EPTs, Maxwell equations in frequency domain
  - Plasma-wave coupling and energy deposition

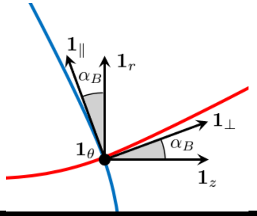
2D axisymmetric simulation domain







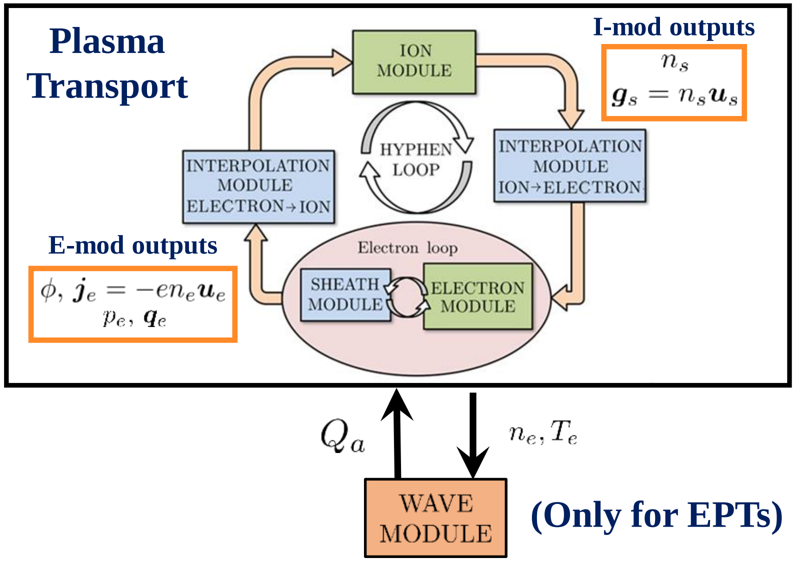
Local magnetic frame



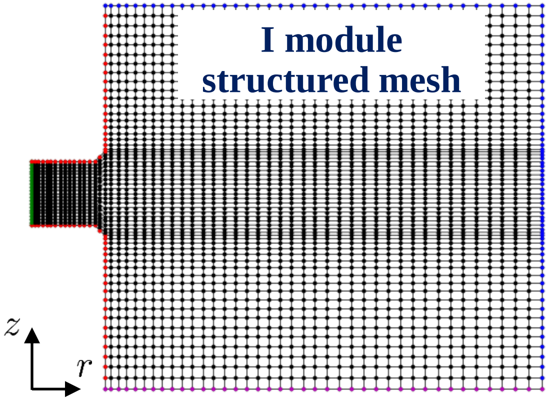
$$\{\mathbf{1}_\perp,\ \mathbf{1}_\parallel,\ \mathbf{1}_\theta\}$$

$$\mathbf{1}_\parallel = \boldsymbol{B}/B$$

$$\mathbf{1}_\perp = \mathbf{1}_\parallel \times \mathbf{1}_\theta$$



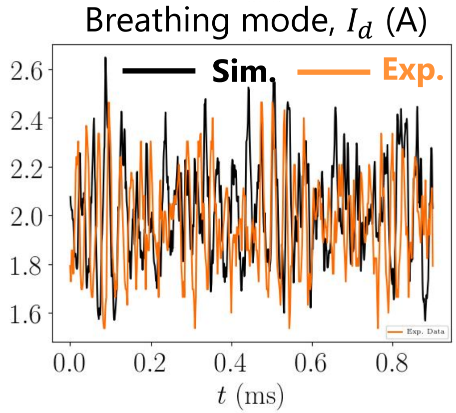
(Only for EPTs)



Performance and breathing mode

- HYPHEN offers many capabilities at low computational cost:
  - ❑ Parametric analyses of performances
  - ❑ Breathing mode characterization

1ms sim. takes ~10h in parallel run with10 cores



PPSX00 results at V_d=300 V, $\dot{m}_A$ =2.5 mg/s, $\dot{m}_C$ = 0.3 mg/s

Prop.	I_d (A)	F (mN)	f_d (kHz)	$\Delta I_d/I_d$ (%)
Xe	2.04 (0.13%)	35.64 (0.11%)	28.53 (15.75%)	± 18.5 (13.5%)
Kr	1.87 (N/A)	29.53 (N/A)	21.94 (N/A)	± 23.6 (N/A)

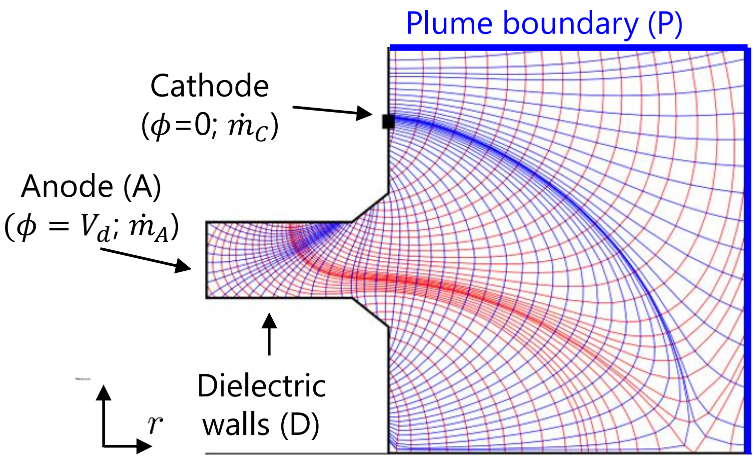
- ❑ Plasma current and power balances
- ❑ Detailed analyses of inefficiency sources
- ❑ Dissection of thrust efficiency

$$I_{prod} = I_{i\infty} + I_{iA} + I_{iD}$$

$$P_d = P_\infty + P_A + P_D$$

$$\eta = \frac{F^2}{2\,\dot{m}P_d} = \eta_{ene}\eta_{div}\eta_{disp},$$

$$\eta_{disp} \propto \eta_u, \qquad \eta_{ene} = \eta_{vol}\eta_{cur}$$



Prop.	V_d (V)	$\dot{m}_A$ (mg/s)	$\dot{m}_C$ (mg/s)	I_{prod} (A)	$I_{i\infty}/I_{prod}$	I_{iD}/I_{prod}	I_{iA}/I_{prod}	η_u	η_{cur}	η_{ch}
Xe	300	2.50	0.30	2.36	0.70	0.25	0.05	0.75	0.81	0.93
Kr	300	2.50	0.30	2.30	0.74	0.22	0.04	0.50	0.90	0.96

Prop.	V_d (V)	$\dot{m}_A$ (mg/s)	$\dot{m}_C$ (mg/s)	P (kW)	η	P_{inel}/P	P_D/P	P_A/P	P_∞/P ($=\eta_{ene}$)	η_{div}	η_{disp}
Xe	300	2.50	0.30	0.62	0.37	0.07	0.25	0.05	0.64	0.84	0.67
Kr	300	2.50	0.30	0.57	0.27	0.07	0.27	0.07	0.67	0.88	0.47

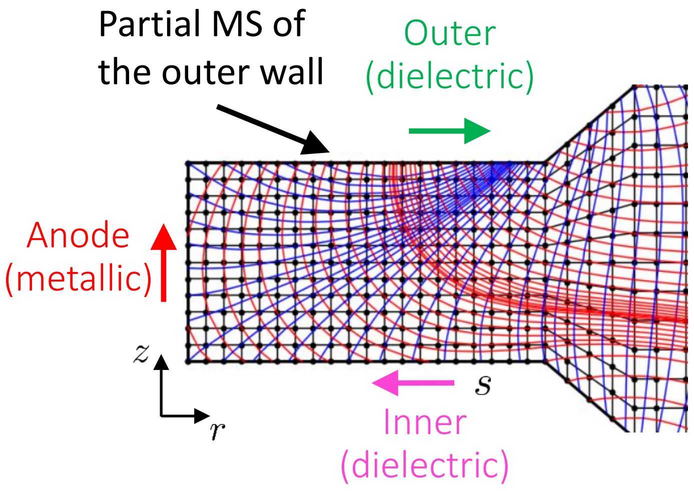
- ❑ Xe: Ionization is not very efficient. Power losses to lateral walls admit improvement. Remaining figures are reasonable.
- ❑ Kr: Ionization is inefficient. Rest as with Xe

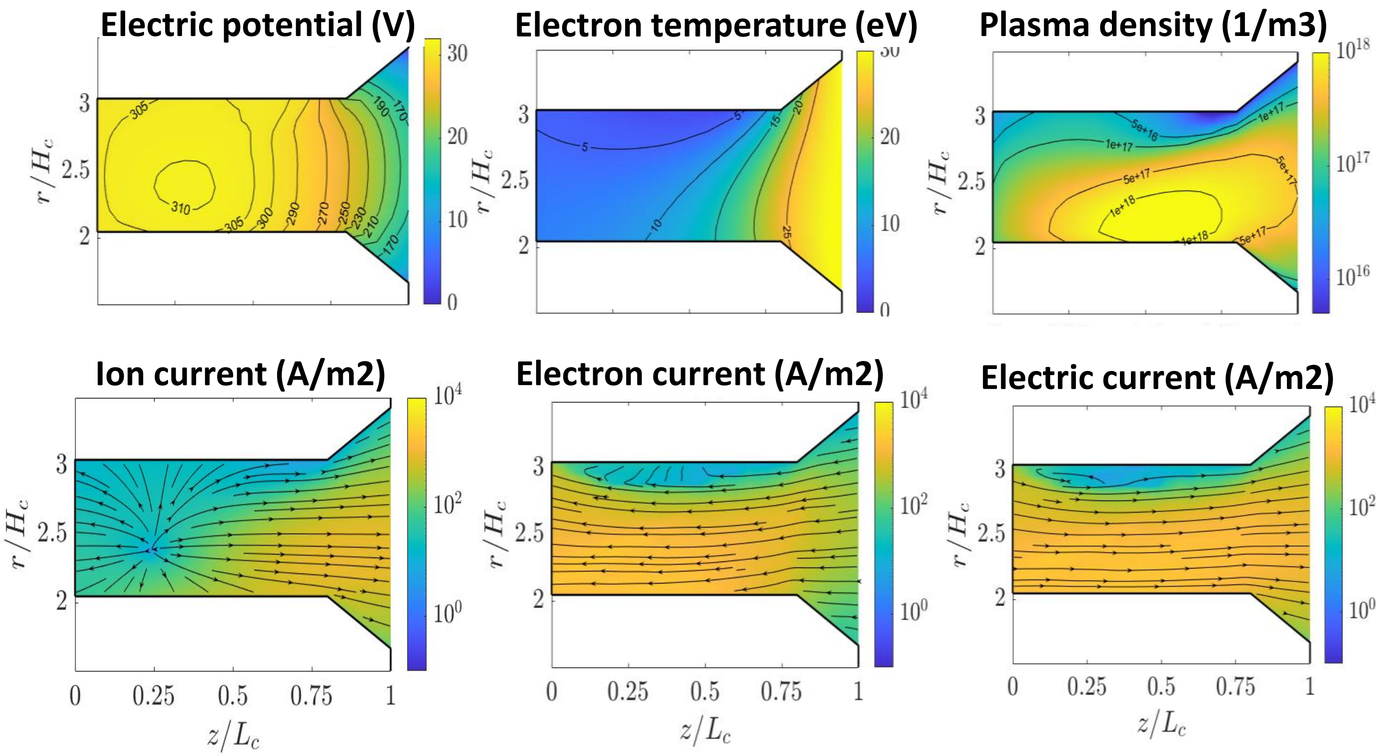
Magnetic confinement

- Simulation of realistic thruster geometry and magnetic topology
  - Magnetic shielding (MS) of channel walls
  - Singular points

- PPSX00 magnetic topology is: ‘shielded’ at outer wall, 'conventional’ at inner wall, and ‘normal’ at the anode
- This generates large asymmetries in the plasma discharge and between inner and outer walls fluxes

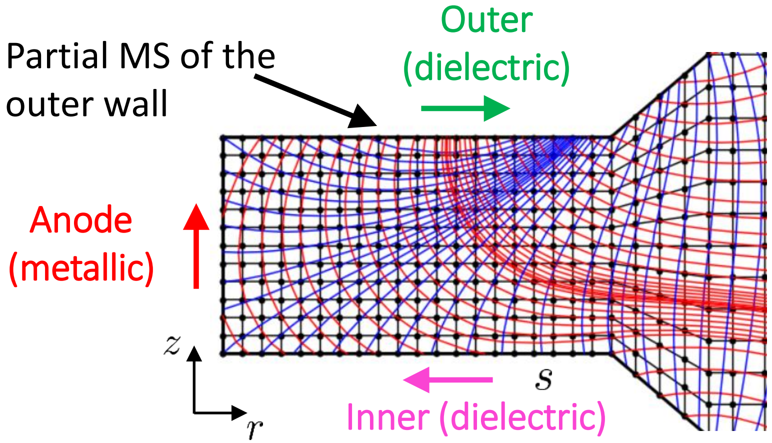
PPSX00 results at V_d=300 V; $\dot{m}_A$ =2.5 mg/s; $\dot{m}_C$ = 0.3 mg/s





Power losses to channel walls

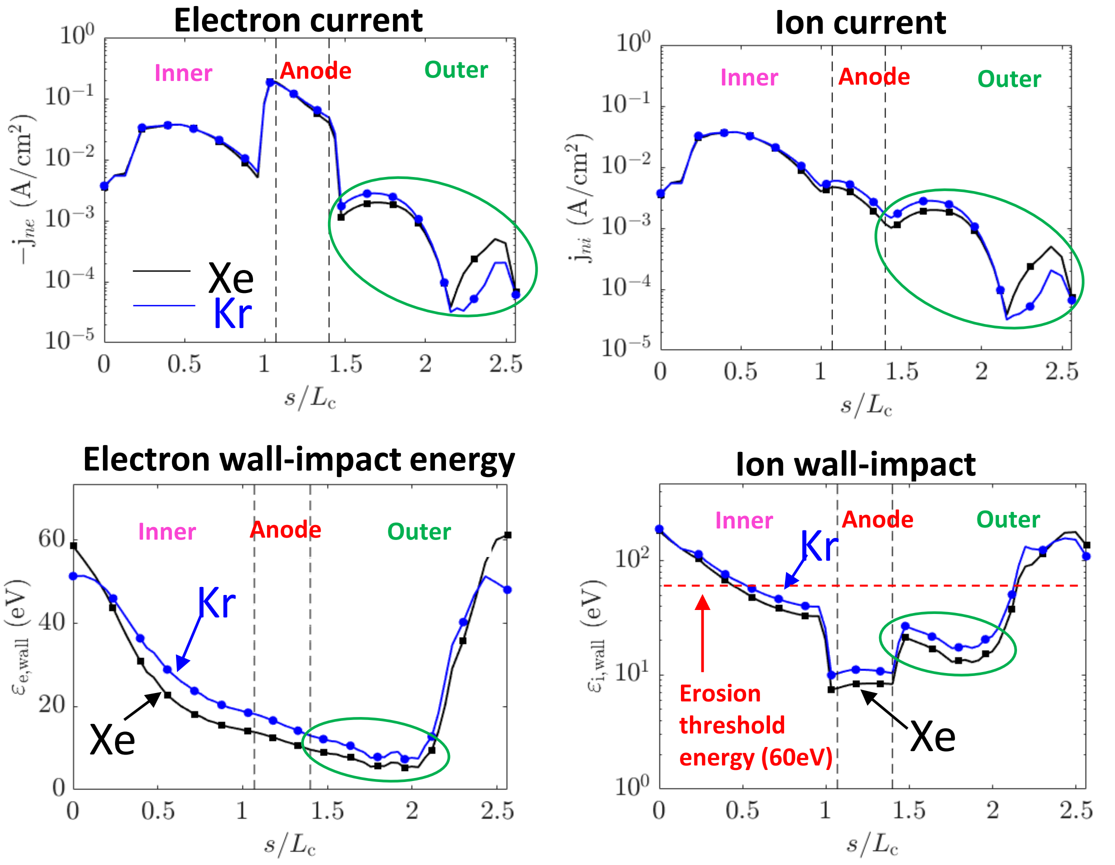
- Accurate estimation of current and power losses along thruster walls
  - Different wall types (dielectric, metallic,…)



PPSX00 results at V_d=300 V, $\dot{m}_A$ =2.5 mg/s, $\dot{m}_C$ = 0.3 mg/s

- Partial MS of outer wall:
  - Lower currents and wall-impact energies
  - >90% of power lost in inner wall
- Similar behavior for Xe and Kr, but:
  - Higher ion wall-impact energies with Kr
  - Higher erosion with Kr

- Power fluxes deposited to walls:
- $P''_{wall}\left[\frac{W}{cm^2}\right] = P''_{i,wall} + P''_{e,wall}$;
- Ions $\rightarrow P''_{i,wall} = \frac{|j_{i,wall}|}{e} \cdot E_{i,wall}$
- Electrons $\rightarrow P''_{e,wall} = \frac{|j_{e,wall}|}{e} \cdot E_{e,wall}$

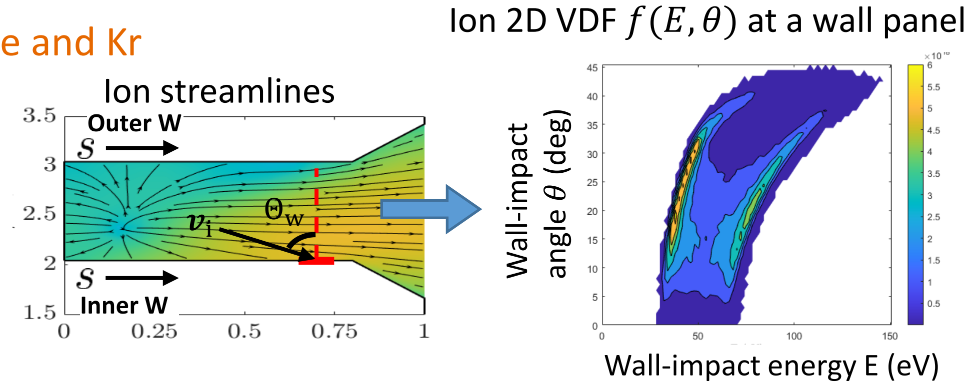


Erosion of channel walls

- VHET at V_d=300 V; $\dot{m}_A$ =2.5 mg/s; $\dot{m}_C$ = 0.3 mg/s for Xe and Kr
- Erosion rate:

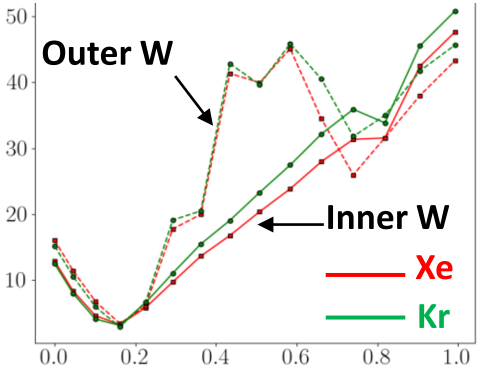
$$\frac{dh}{dt} = \sum_{s} \int\int \underbrace{\boxed{f_{\rm ws}(E_{\rm ws},\theta_{\rm ws})}}_{\text{2D VDF}} \underbrace{\boxed{eY_{\rm v}(E_{\rm ws},\theta_{\rm ws})}}_{\text{sputtering yield}} dE_{\rm ws} d\theta_{\rm ws}$$

- Several options for the sputtering model (e.g. Ahedo et al. IEPC 2007-067)
- Ion VDF computed at all wall panels
  - Accurate erosion computations
- MS of outer wall ⟹ reduced erosion
- Kr vs Xe:
  - Larger ion currents and impact energies
  - Larger erosion
  - In line with Andreussi et al. (IEPC 2017-380)
- Further investigation is ongoing

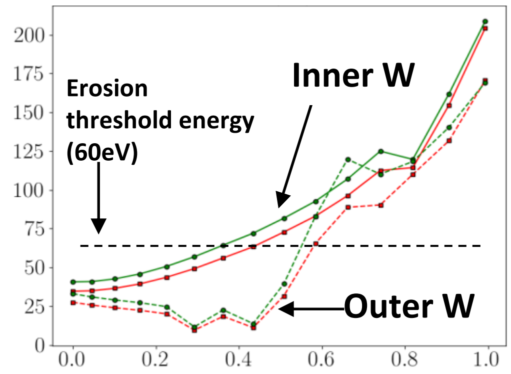

Ion streamlines

Ion 2D VDF $f(E,\theta)$ at a wall panel

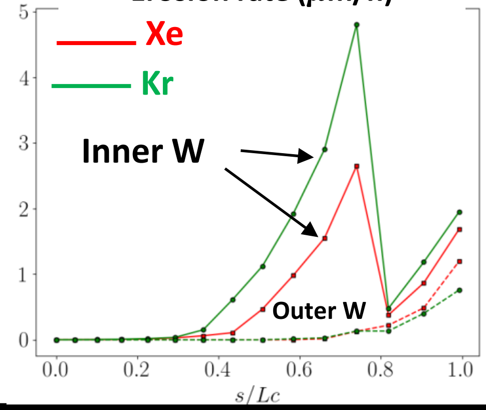
Ion wall-impact angle (deg)



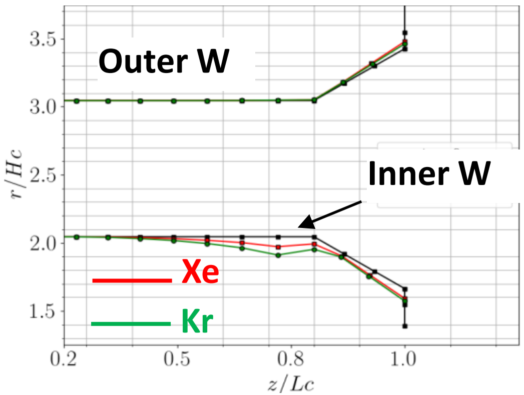
Ion wall-impact energy (eV)



Erosion rate (μm/h)



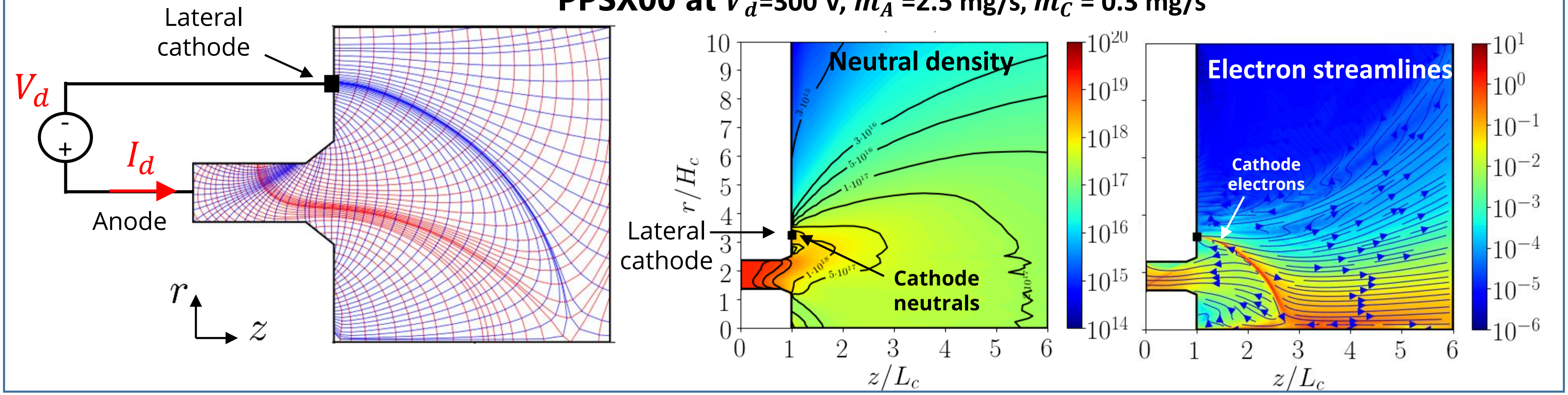
Erosion after 300h of operation



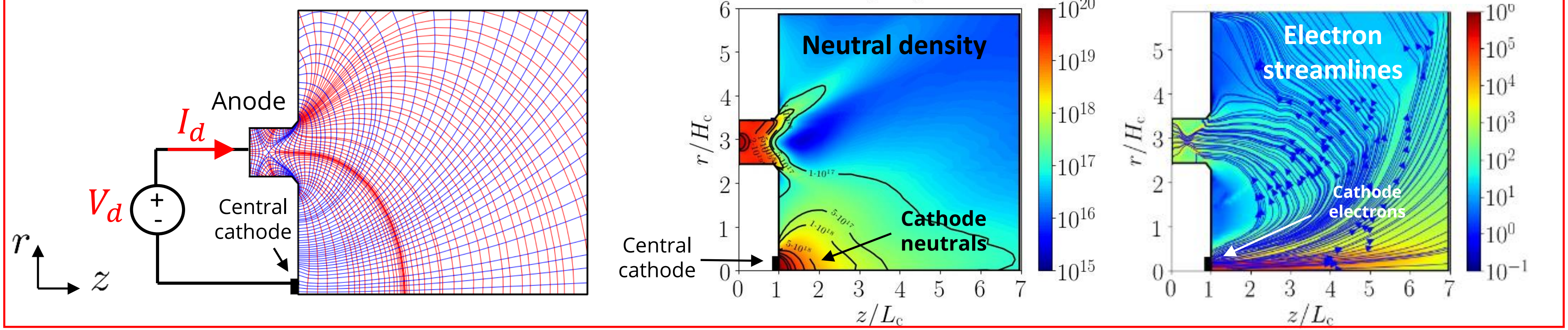
Cathode-beam coupling

- Simulation of central and lateral cathode
  - Cathode/main plume coupling
  - Neutral injection through the cathode facilitates coupling of electrons with ion beam

PPSX00 at V_d=300 V, $\dot{m}_A$ =2.5 mg/s, $\dot{m}_C$ = 0.3 mg/s

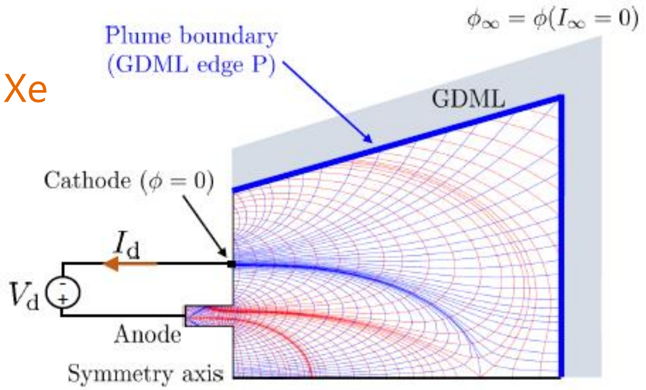


HT20k at V_d=500 V, $\dot{m}_A$ =25 mg/s, $\dot{m}_C$ = 2 mg/s

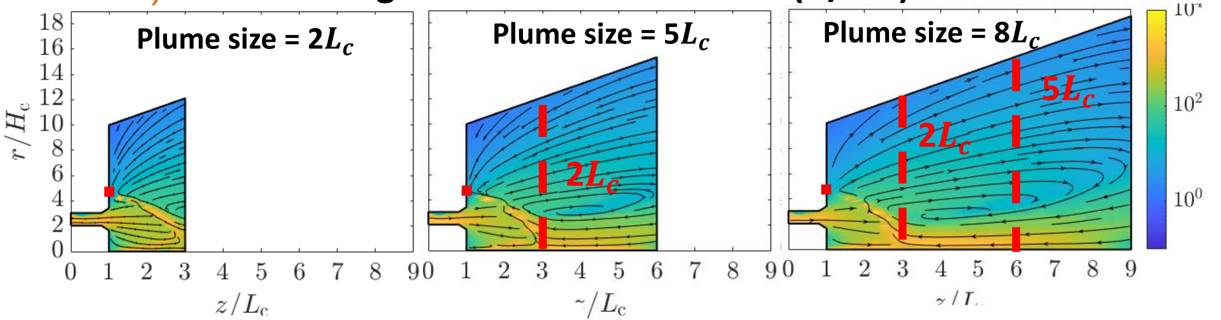


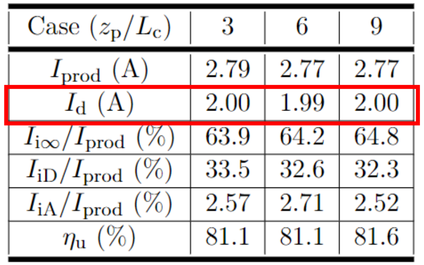
Plume size and boundary conditions

- Precise characterization of plasma solution in plume
  - Important for diagnostics in plume
- Plume size studies on VHET at V_d=300 V; $\dot{m}_A$ =2.5 mg/s; $\dot{m}_C$ = 0.3 mg/s for Xe
- Improved BC at plume: GDML imposes I_∞=0 and estimates ϕ_∞
  - Robust to plume size → Size $5L_c$ optimizes accuracy vs. computational cost
- Plume size affects mainly ϕ, T_e, $\mathbf{j}_e$ and only outside the chamber
- Changes in performances are mild but not negligible
- Similar conclusions for 5kW VHET (IEPC-2022-338)

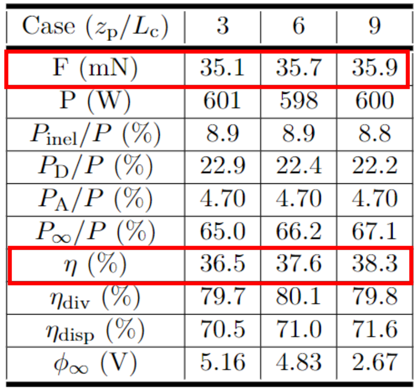


Longitudinal electric current (A/m2)

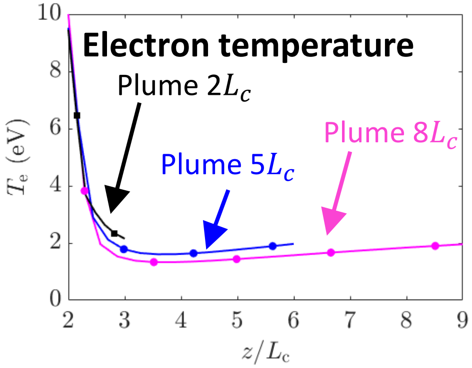


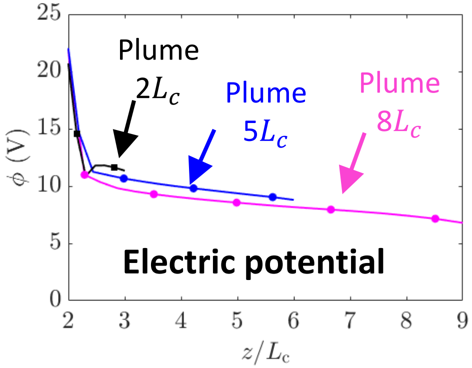


Case (z_p/L_c)	3	6	9
I_prod (A)	2.79	2.77	2.77
I_d (A)	2.00	1.99	2.00
$I_{\mathrm{i}\infty}/I_\mathrm{prod}$ (%)	63.9	64.2	64.8
$I_\mathrm{iD}/I_\mathrm{prod}$ (%)	33.5	32.6	32.3
$I_\mathrm{iA}/I_\mathrm{prod}$ (%)	2.57	2.71	2.52
η_u (%)	81.1	81.1	81.6



Case (z_p/L_c)	3	6	9
F (mN)	35.1	35.7	35.9
P (W)	601	598	600
P_inel/P (%)	8.9	8.9	8.8
P_D/P (%)	22.9	22.4	22.2
P_A/P (%)	4.70	4.70	4.70
P_∞/P (%)	65.0	66.2	67.1
η (%)	36.5	37.6	38.3
η_div (%)	79.7	80.1	79.8
η_disp (%)	70.5	71.0	71.6
ϕ_∞ (V)	5.16	4.83	2.67

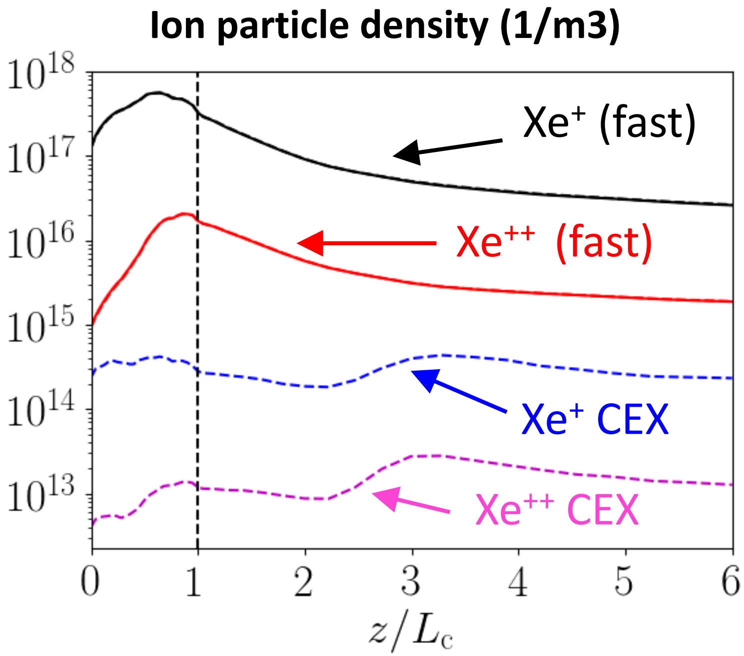


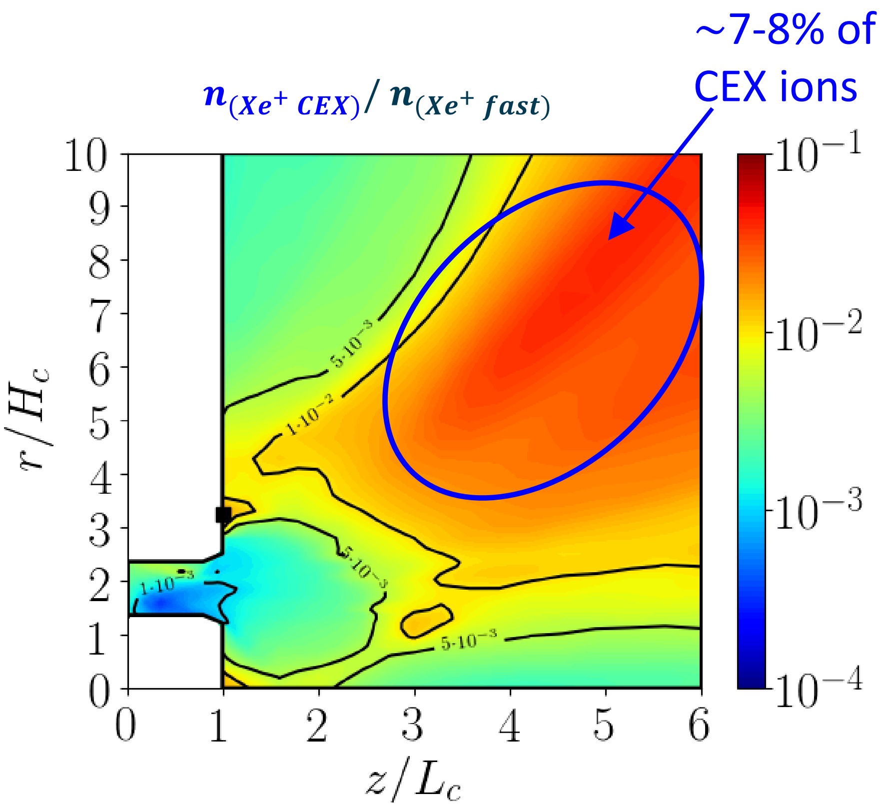


Effect of CEX

- No significant effect on performance
- CEX ions contribute to plasma density mainly in the near plume region

PPSX00 at V_d=300 V, $\dot{m}_A$ =2.5 mg/s, $\dot{m}_C$ = 0.3 mg/s


Ion particle density (1/m3)

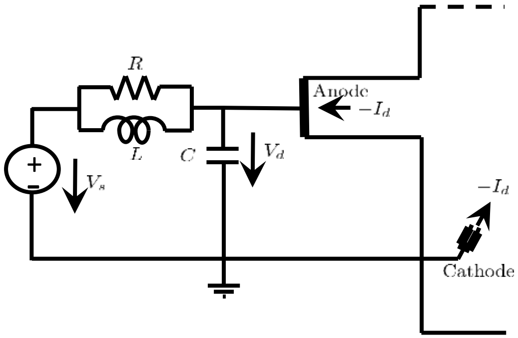

~7-8% of CEX ions

$n_{(Xe^+\ CEX)}/\ n_{(Xe^+\ fast)}$

- Ongoing:
  Effect on currents collected at plume boundaries

TU coupling with other subsystems

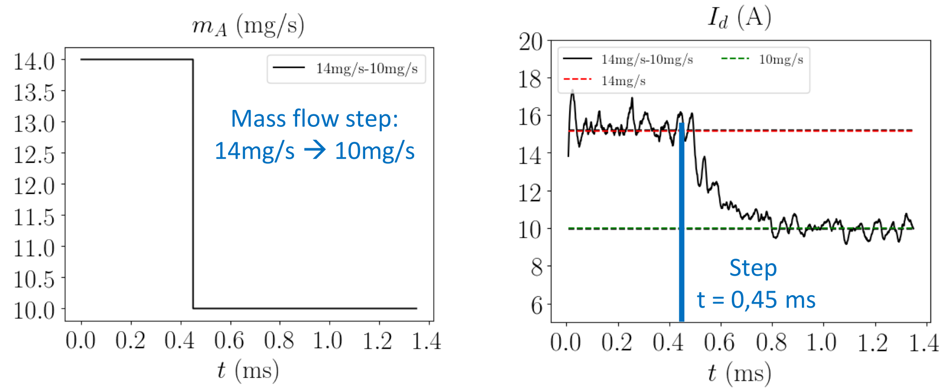
- RLC filters can be simulated in the anode-cathode electric circuit
  - ☐ Time response of V_d and I_d depends on filter parameters
  - ☐ Time-average performance not significantly affected



- Time-varying V_d and $\dot{m}_A$

Mass flow rate step response

HT5k at V_d=300 V; $\dot{m}_A$ =14 → 10 mg/s; I_d= 14.6 → 10.3 A



- ☐ Characterization of response time (~0,35ms, depending on neutral res. time in chamber)
- ☐ Application to operation in direct-drive mode
- ☐ M. Reza et al, Acta Astronautica 178, 392-405 (2021)

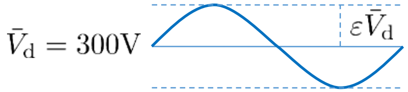
Anode voltage modulation

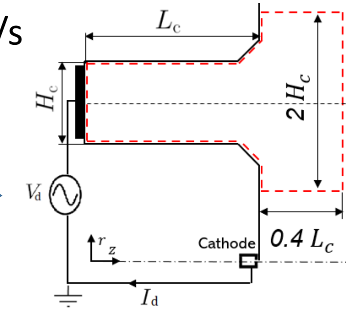
Thursday 11/05, 12:00-12:20h Poster, Meeting room 2

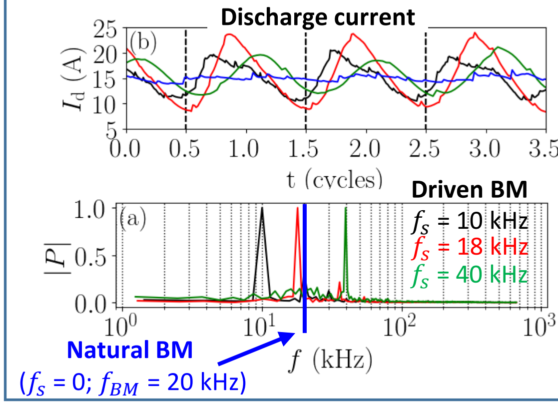
HT5k at $\bar{V}_d$=300 V; $\dot{m}_A$ =14 mg/s

Sinusoidal modulation of anode voltage

$$V_d(t) = \bar{V}_d\left[1 + \varepsilon \sin\left(2\pi f_s t\right)\right]$$







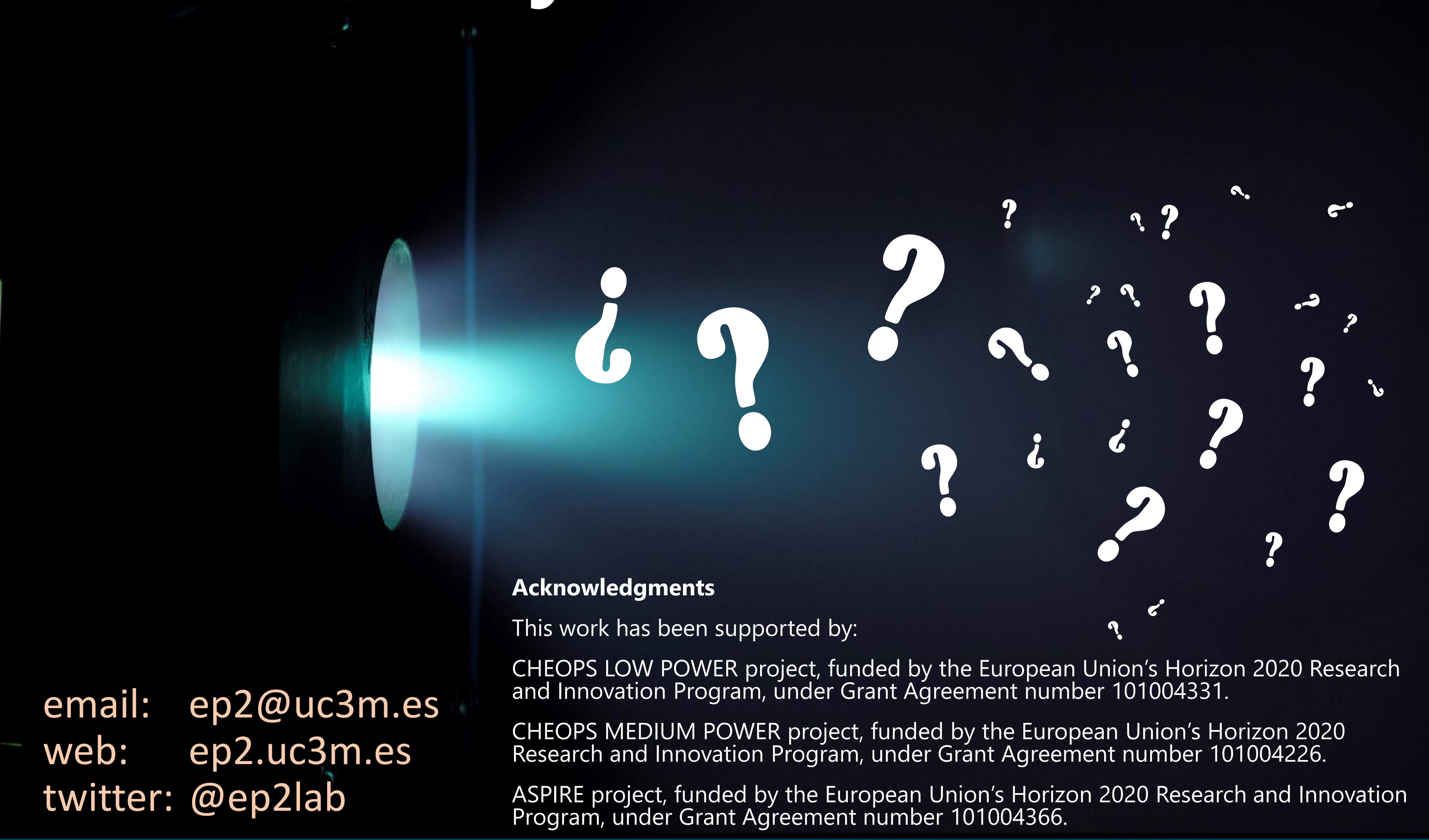
- Response similar to 1kW HETs (Romadanov et al. PSST, 27(9):094006, 2018)
- Externally driven BM at f_s
- Application to EMC and diagnostics

Conclusions

- HYPHEN is advanced 2D(z-r) multi-thurster simulation platform for HETs and EPTs
- Hybrid formulation is suitable for R&D on the full thurster:
  - Characterization and optimization of prototypes in low, medium and high power ranges
    - Performance, lifetime and erosion, heat loads
    - Cathode/beam coupling in near plume
    - Alternative propellants
  - Coupling between the TU and other electrical/fluidic subsystems
    - Plasma oscillations, dynamic response of the TU, I-V curve, direct-drive operation
- HYPHEN is at the vanguard on modeling
  - Axial-radial electron dynamics, plasma-wall interaction
  - Plasma-wave coupling (for EPTs)
- Still, there is margin of improvement in both physics & algorithmics
  - Turbulent transport relies on empirically-fitted model $\nu_t(\boldsymbol{r}, \alpha_{t1}, \alpha_{t2}, \dots)$ →
    - Uncertainty quantification strategies are ongoing
    - Model for ν_t through matching with 2D axial-azimuthal kinetic codes under development

Main challenge for a predictive HET code

Thank you! Questions?



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