Utilisation des codes PIC pour l'étude des interactions plasma-paroi à l'IJL

Atelier Gaines Plasmas

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04/11/2024

Outline

- A) Temperature of a tungsten surface under high heat flux plasma

  Thesis C. Djerroud (initiation of unipolar arcs started 2019)

- B) Erosion & redeposition of a liquid metal PFCs

  Thesis R. Avril / Renaissance Fusion (started 2023)

- C) Radio-frequency sheath and sputtering mitigation (ICRF antennas)

  Thesis L. Tsowemoo / IPP Garching – V. Bobkov (started 2024)

A) Temperature of a tungsten surface under high heat flux plasma

→ J. Moritz et al, Nuclear Materials and Energy 41, 101753 (2024)

→ J. Moritz et al, Phys. Plasmas 30, 083514 (2023)

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Experimental context of bifurcation

Ye et al. / J Nucl. Mat. 241, 1243 (1997)

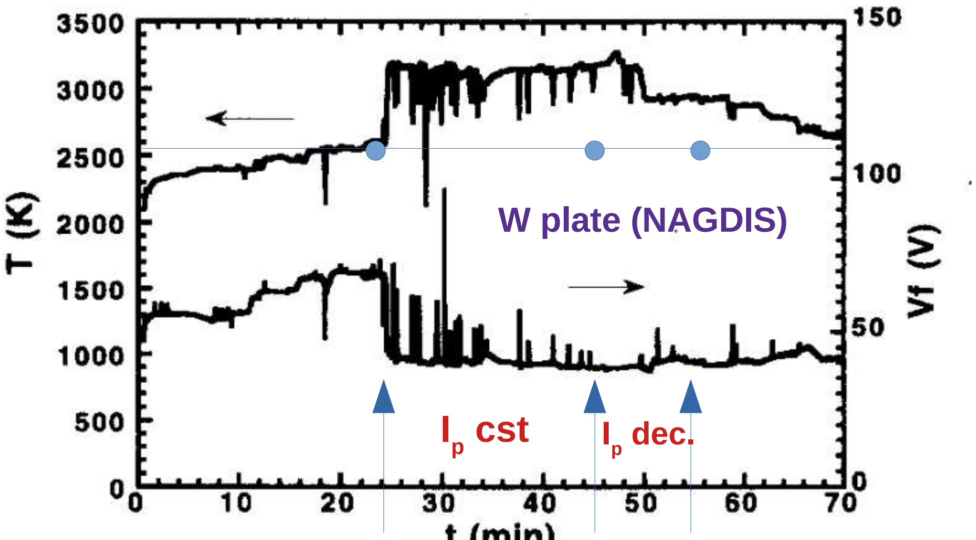
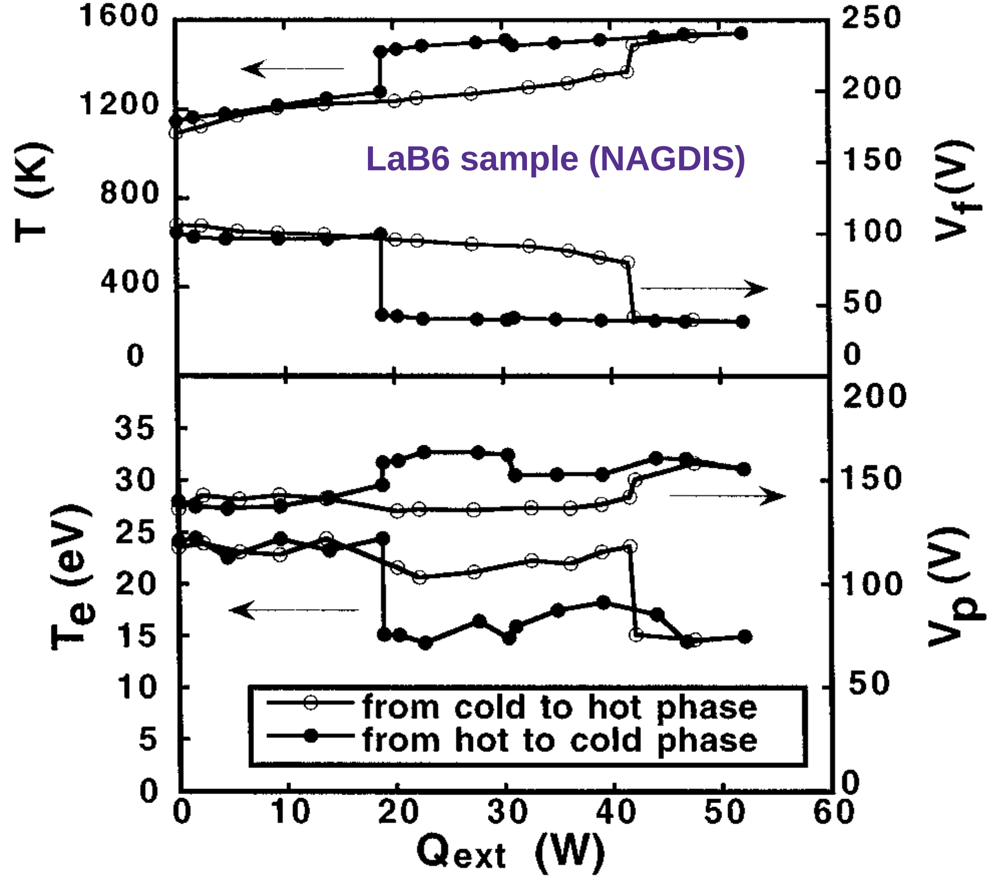


Fig. 2. The experimental results for tungsten plate in helium plasma. At $t = 24$ min, corresponding to $I_p = 98$ A, $V_p = 190$ V, $n_e \approx 4.0 \times 10^{18}$ m^{-3}

Physics of Plasmas 3, 281 (1996)



- Floating conditions
- Cooling of the plasma due to cold thermoelectrons
- Hysteresis

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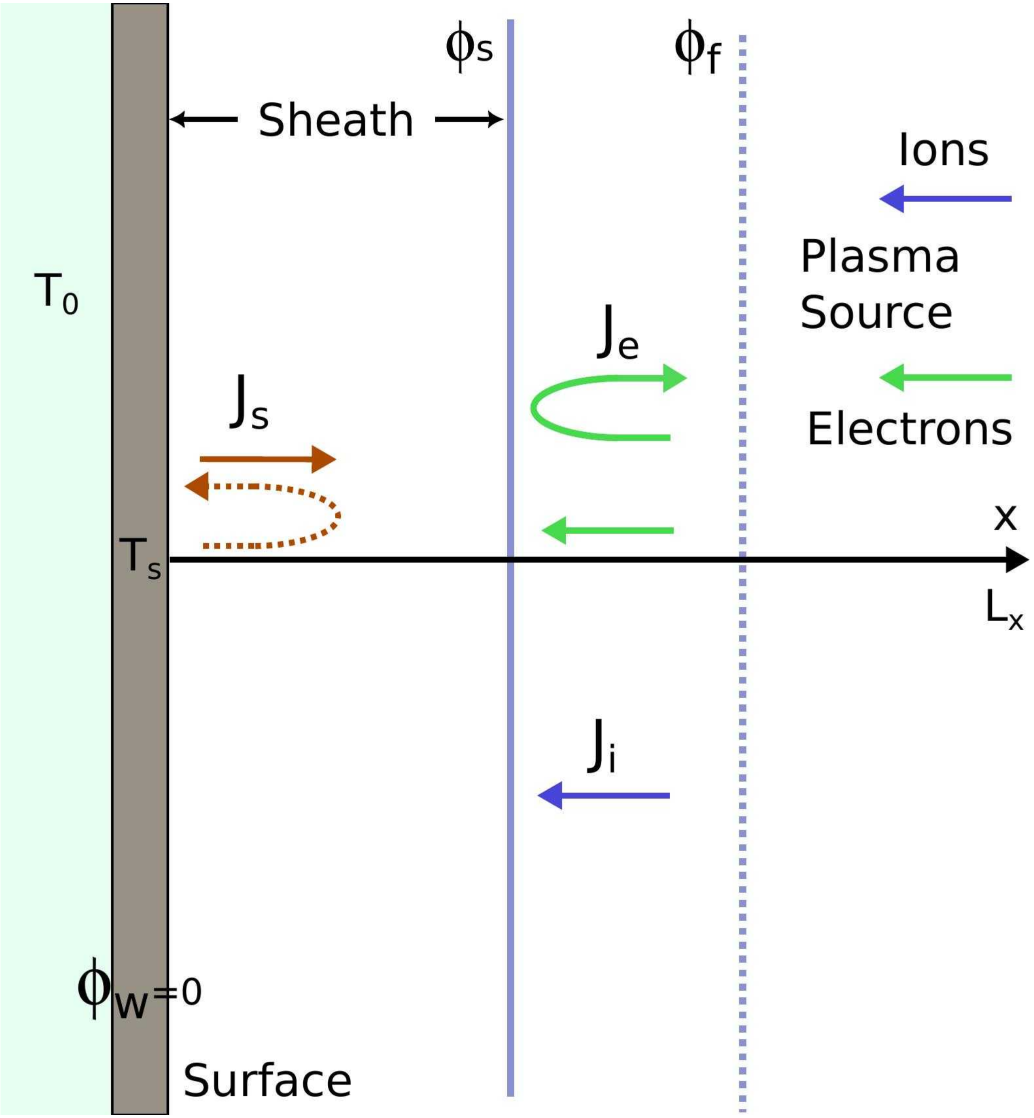
Spot & Surface Model



- Tungsten surface with κ in the range 15-160 $Wm^{-1}K^{-1}$ (altered surface)
- Fluid modeling and PIC simulations
- $L_x=100\lambda_d$
- Different plasma conditions, plasma source **(no electron cooling)**, **B=0**

→ Determine self-consistently T_s

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Heat Flux & Fluid Approach of bifurcation

Heat flux at the surface:

Conduction

$$Q_c = J_s / e \left(2 k_b T_s + B_w \right) + \epsilon \sigma T_s^4 + \frac{\kappa}{t} \left(T_s - T_0 \right)$$

Thermionic current surface cooling

$$Q_p = J_i / e \left(2 k_b T_i + E_i - B_w + e \phi_s \right) + J_e / e \left(2 k_b T_e + B_w \right)$$

Ion heating — Electron heating

The constants of W are
$A = 0.6 \times 10^6 \ Am^{-2}K^{-2}$,
$B_w = 4.55$eV and $\varepsilon = 0.25$

Tokar, Nedospasov, and Yarochkin, Nuclear Fusion 32, 15 (1992)

Currents:

$$J_s = A T_s^2 \exp - \frac{B_w}{k_b T_s}$$ → Richardson Formula

$$J_e = \frac{e n_s c_e}{4} \exp - \frac{e \phi_s}{k_b T_e}$$ → Maxwellian flux

$$J_i = e n_s c_s$$ → Bohm flux

Sheath potential:

$$e \phi_s = e \phi_f - k_b T_e \log \left(1 + \frac{J_S}{e n_s c_s} \right)$$

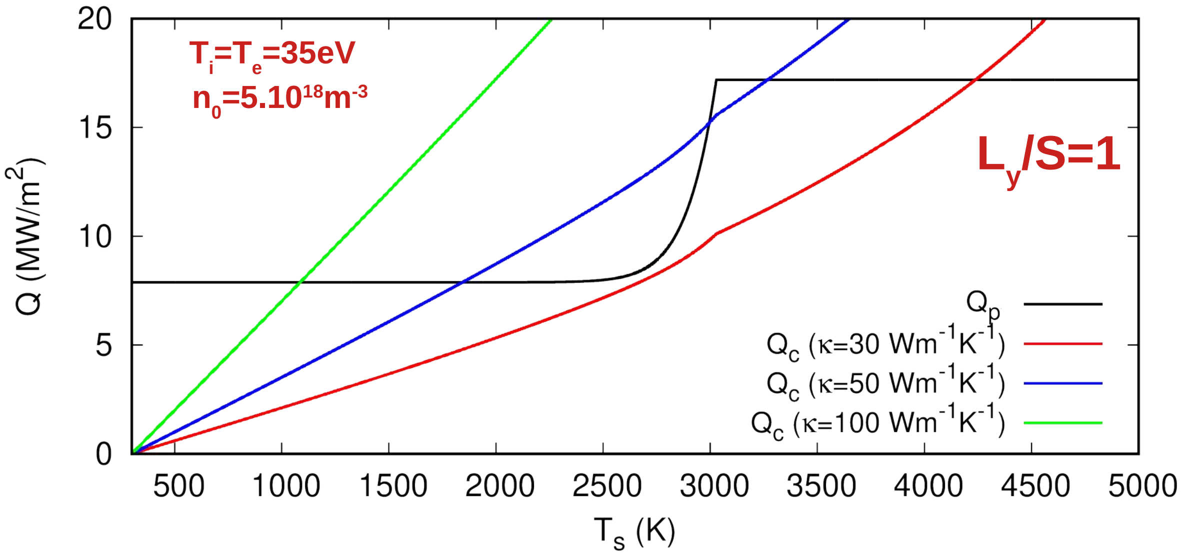
→ 1d Approx. ambipolarity $J_i + J_s \simeq J_e$

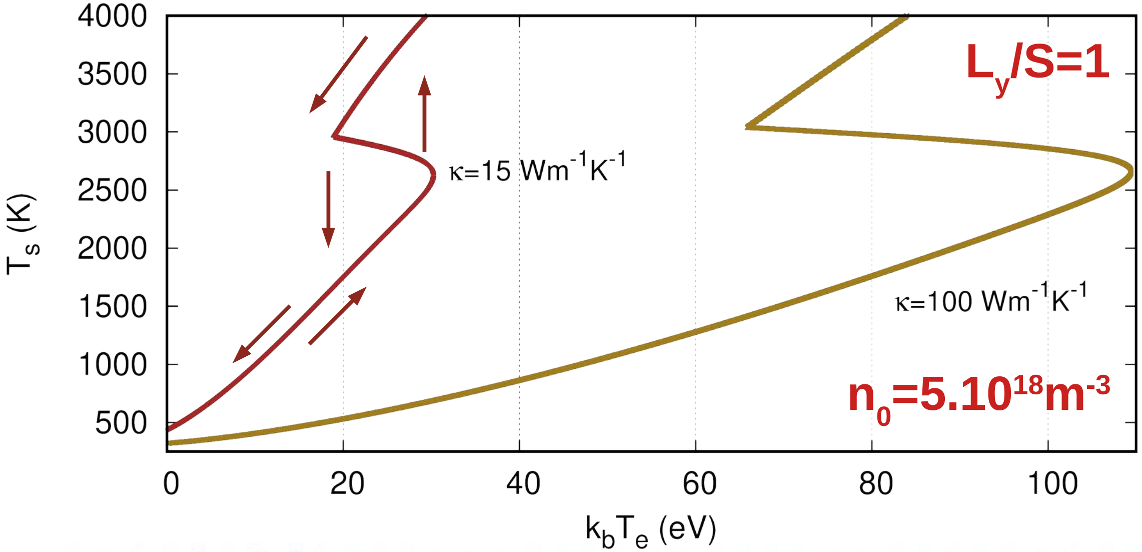
Surface Electric field:

$$E_s = f \left(\phi_s , J_s \right)$$ → Until E_s=0 then SCL regime

Hobbs and Wesson, Plasma Physics 9, 85 (1967)

Heat Flux & Fluid Approach of bifurcation





- Using fluid formula calculation of $Q_p(t)$ and $Q_c(t)$ → T_s
- "S" curves of $T_s = f(T_e, κ, n_0...)$
- Hysteresis arises from such characteristics → bifurcation from a cold to a hot cathode surface and reciprocally

Plasma Space potential vs. thermal cond.

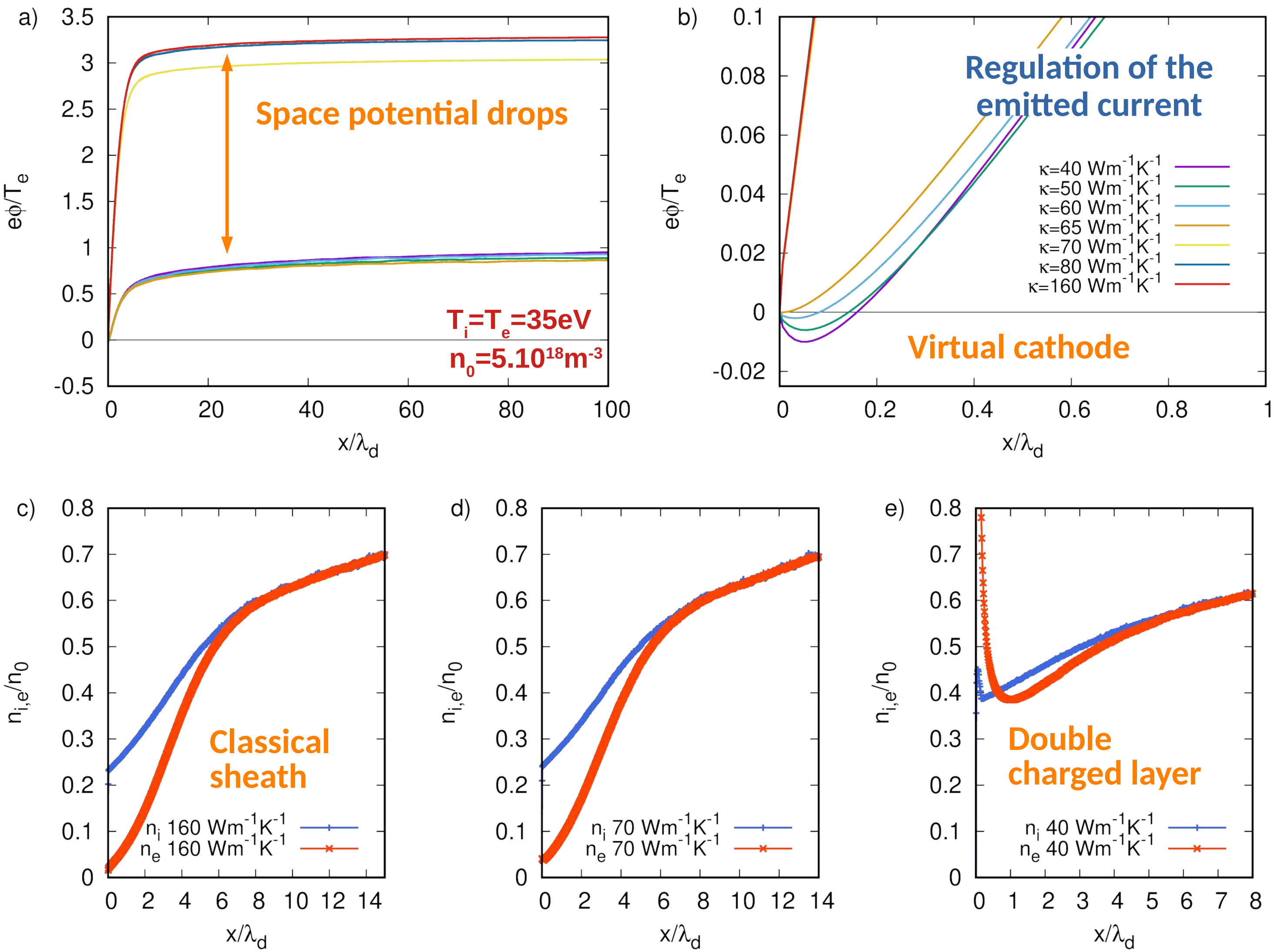
w/ PIC simulations:

❈ At each t, $Q_p = Q_c \rightarrow T_s$ until the steady state

❈ One parameter change (T_e, κ, n_0) = one simulation = one T_s, space potential…

❈ Averaging for several dozen of pl. periods for determining T_s

❈ **Hysteresis ?**



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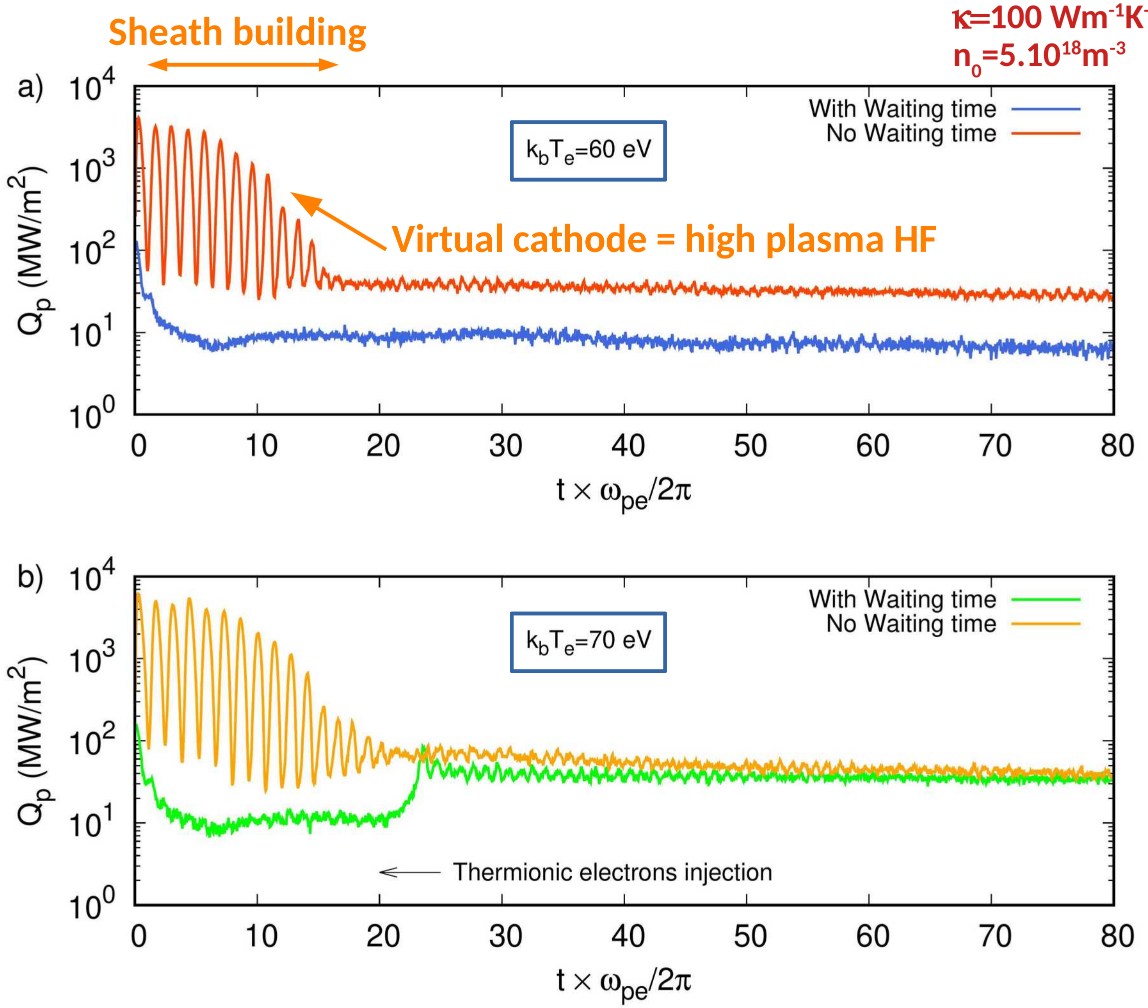
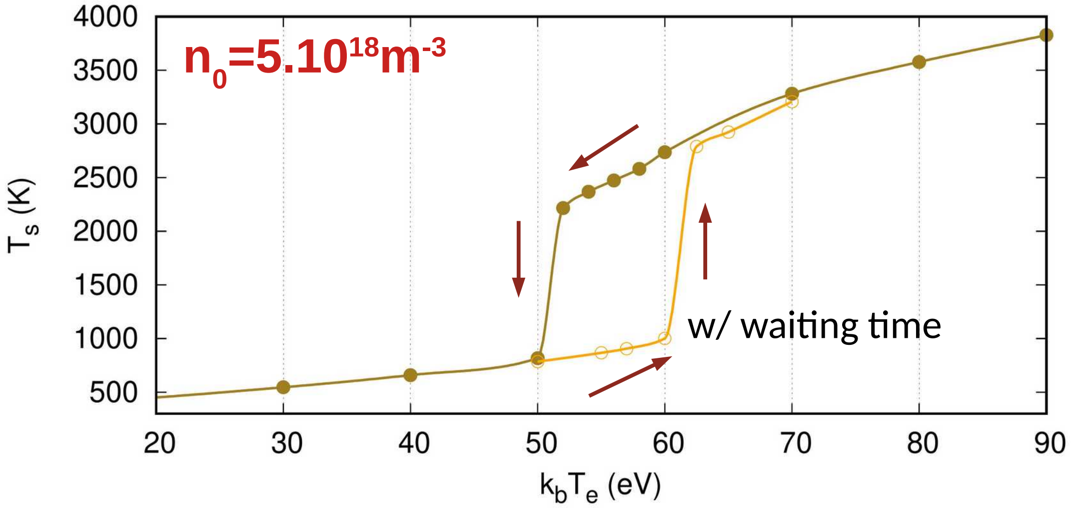
PIC : Sheath building

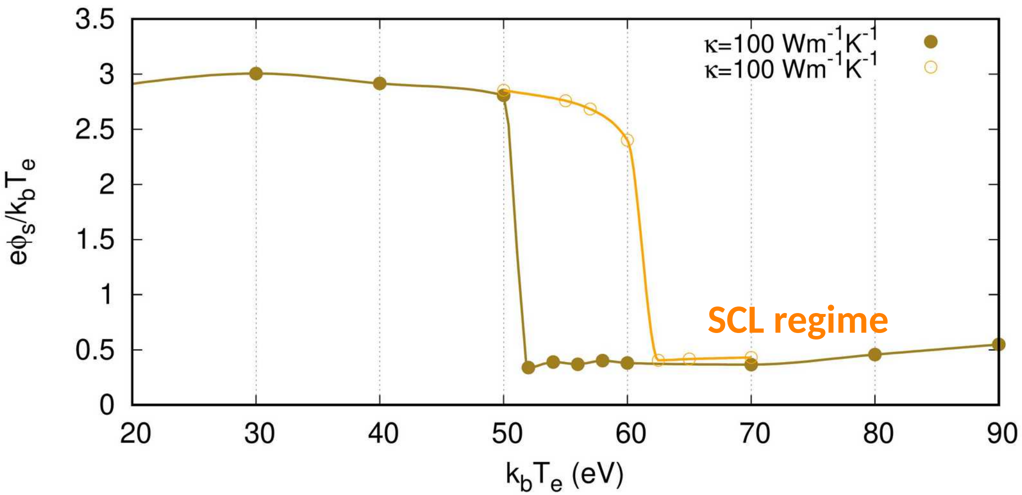
- At each t, $Q_p = Q_c$
- First plasma periods = sheath building and high heat loads
- Introduction of a waiting time in the simulations before injecting TE electrons
- For intermediate plasma heat loads can result in 2 different final states = hysteresis

κ=100 $Wm^{-1}K^{-1}$
$n_0=5.10^{18}m^{-3}$



PIC & Hysteresis

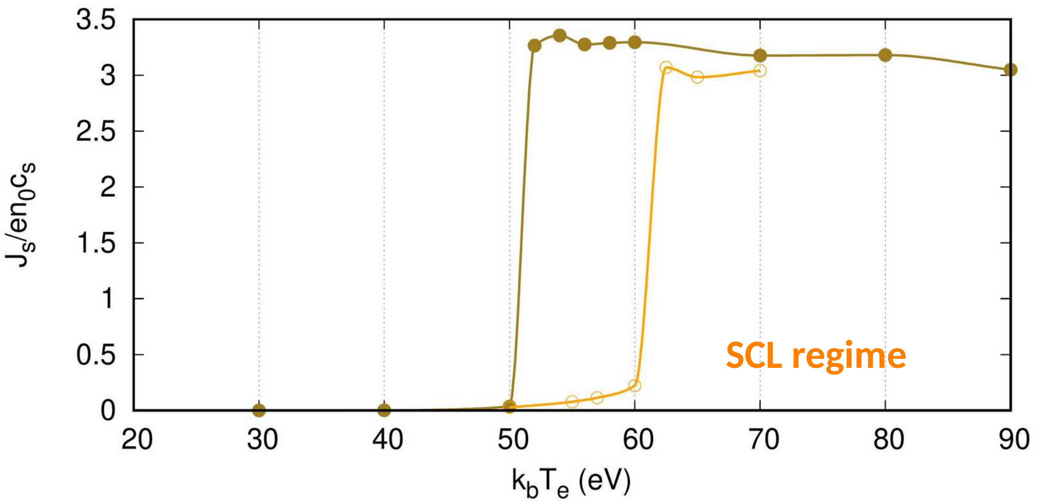




❋ High V_f, low T_s and low current / low V_f, high T_s and max current

❋ Hysteresis evidenced by changing initial conditions in the PIC simulations.

❋ J_s saturates around $3n_0c_s$ = when emitted current → Bohm current = bifurcation



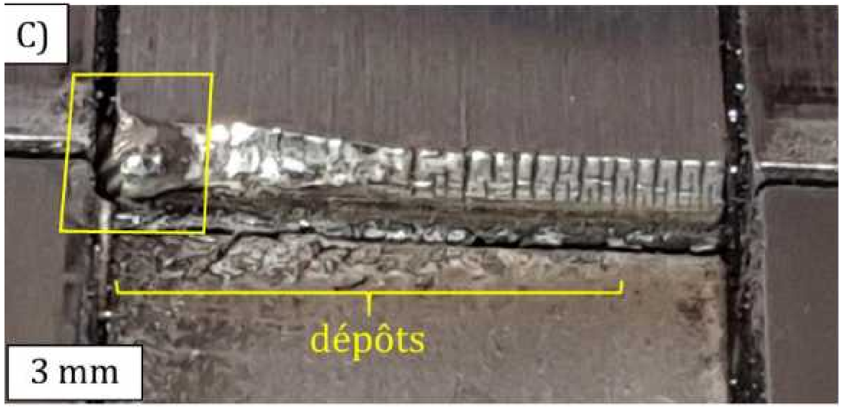
B) Erosion & redeposition of a liquid metal plasma-facing components

Romain Avril, PhD

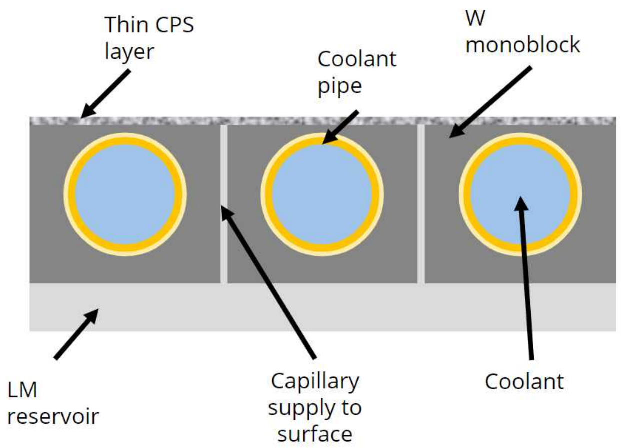
→ “Erosion and transport of lithium from a liquid metal wall facing a fusion plasma” - Romain Avril, Oral presentation at the *“Journée de la Matière Condensée* 2024”, 28-31 Oct. 2024, Marseille

Liquid metal plasma-facing components

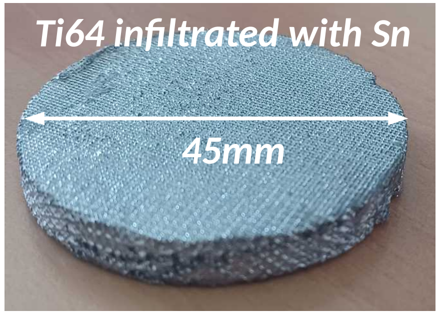
- Liquid metals might be an interesting option for economically competitive fusion reactors, especially for compact machines, due to **'self-healing'** properties
- Several designs classified as function of the dominating heat transfer mechanism and flow characteristics (velocity, thickness, etc)

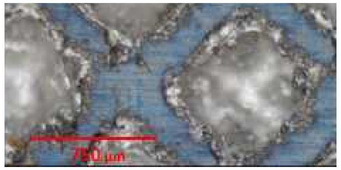


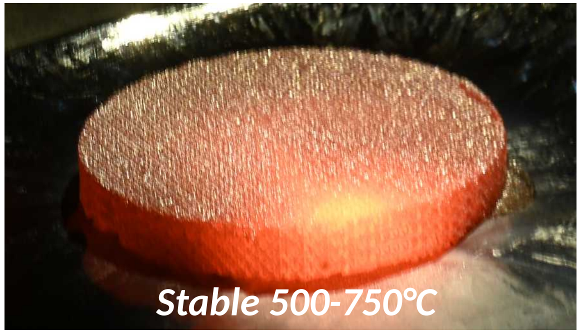
W Solid PFC = cracking / melting
(Q. Tichit / IRFM thesis 2024)



CPS working principle
(Courtesy to T. Morgan 2023)

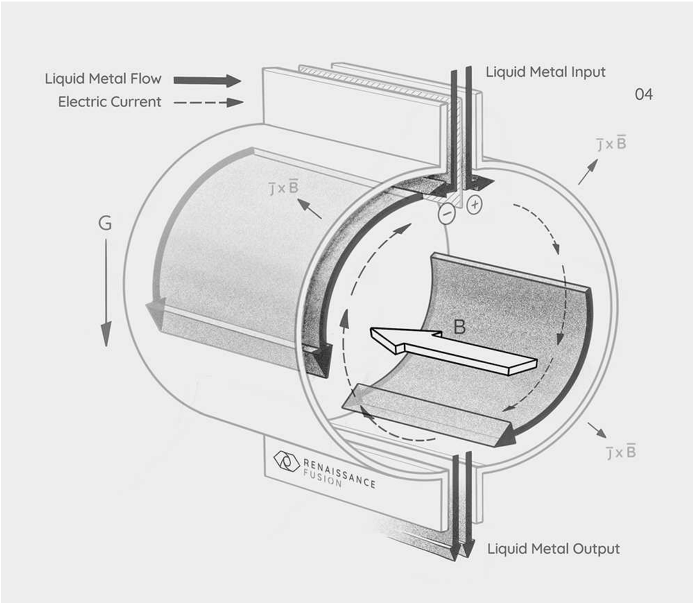


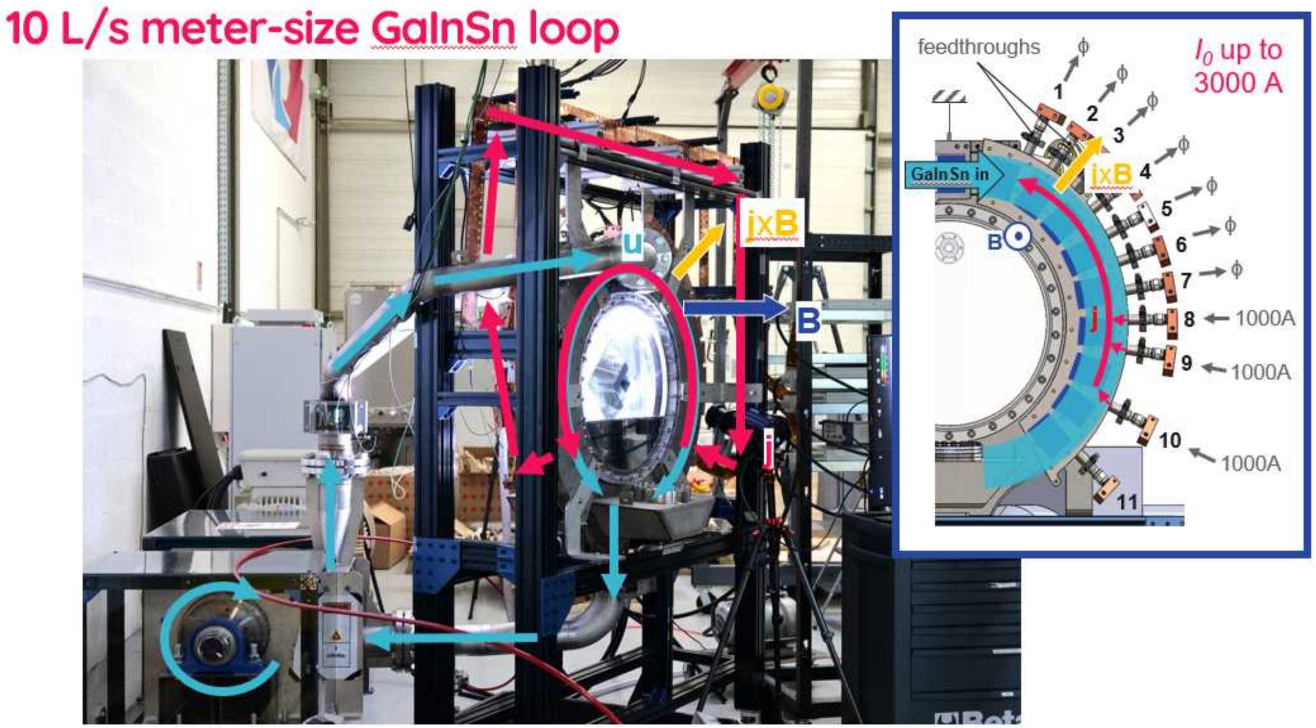




Renaissance Fusion's concept of LMW

- 30cm thick fast flowing Li-LiH mixture with Pb cerramic pebbles between 700°C and 900°C
- Poloidal electric current (few kA) injected in the liquid metal layer + axial magnetic field (10T) = Radial force



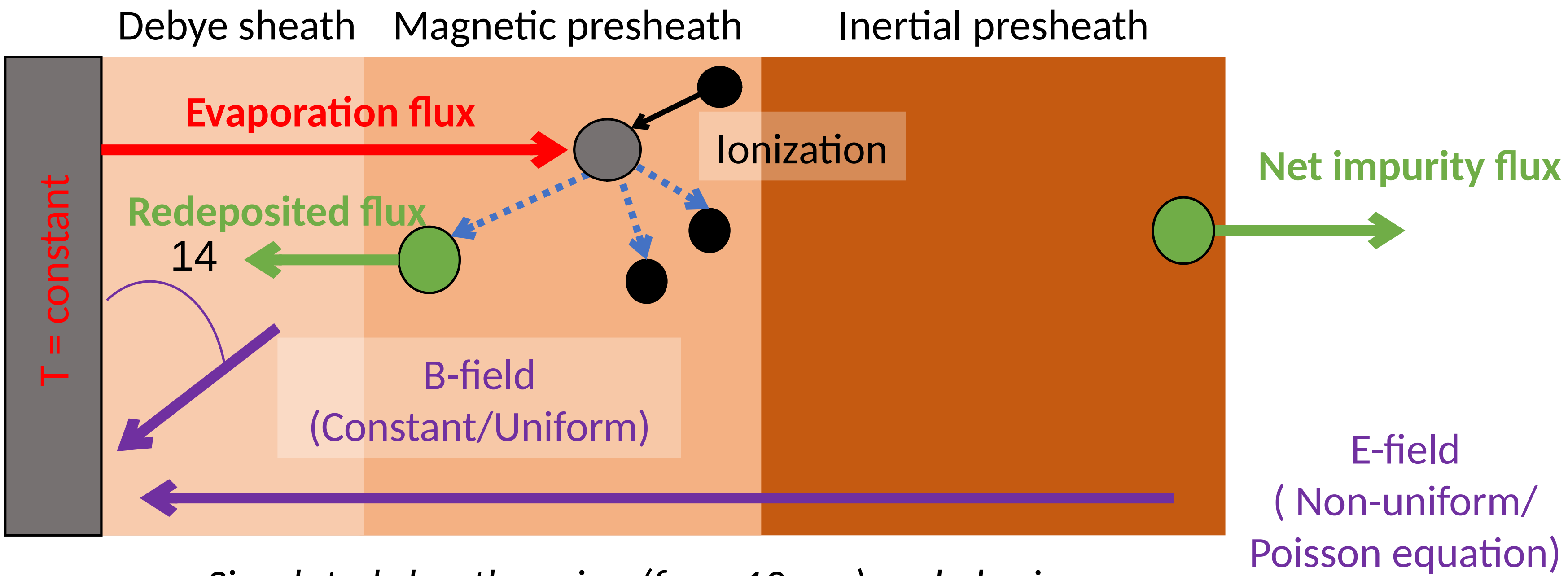


Skyfall liquid metal (galinstan) loop (taken from N. Baker-Wolff - 13th PAMIR conference)

PIC model for ionization

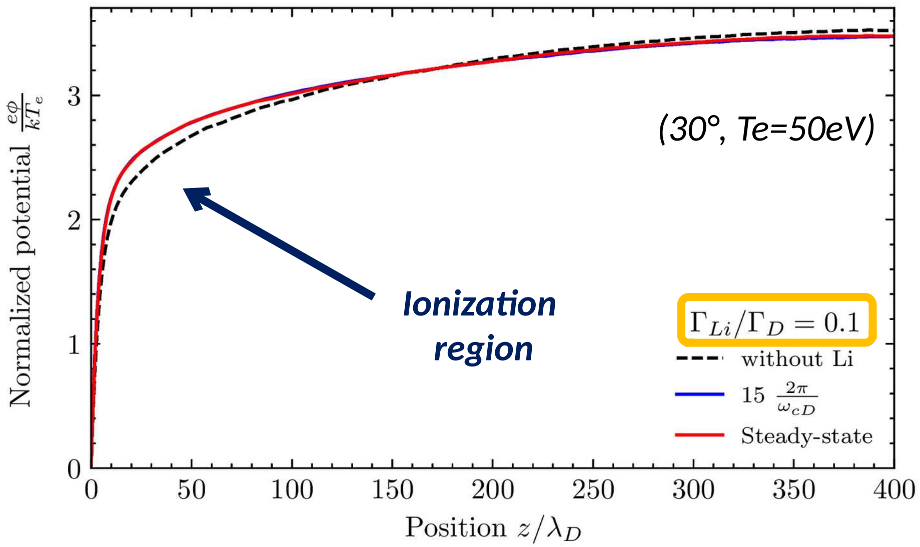
- Investigation with a 1D3V Particle-in-Cell (PIC) code
- Electron-induced ionization is the only simulated atomic process
- Only evaporation is considered in the relevant temperature range where it is dominant (500°C-700°C)
- Surface temperature is constant (Renaissance Fusion's configuration)

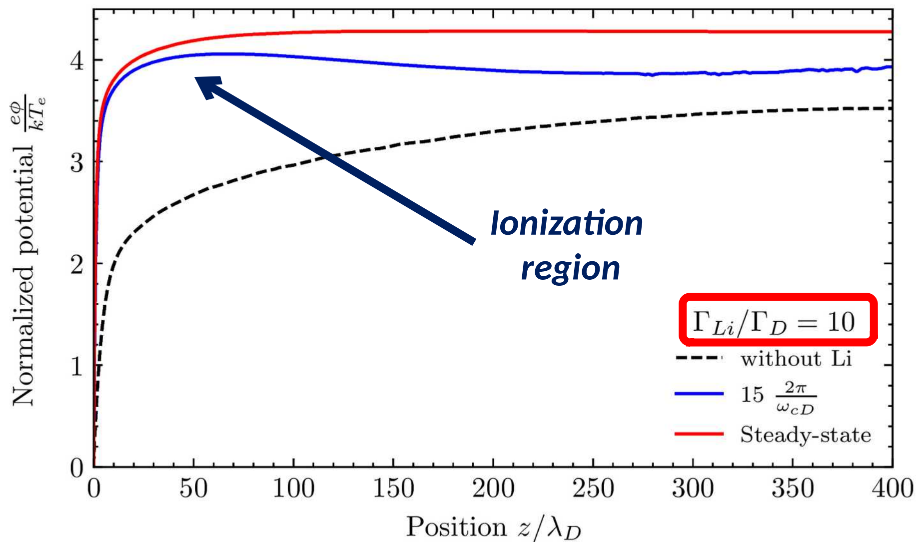
- **Objective** : Make first redeposition estimations and investigate the impact of Li on sheath/presheath



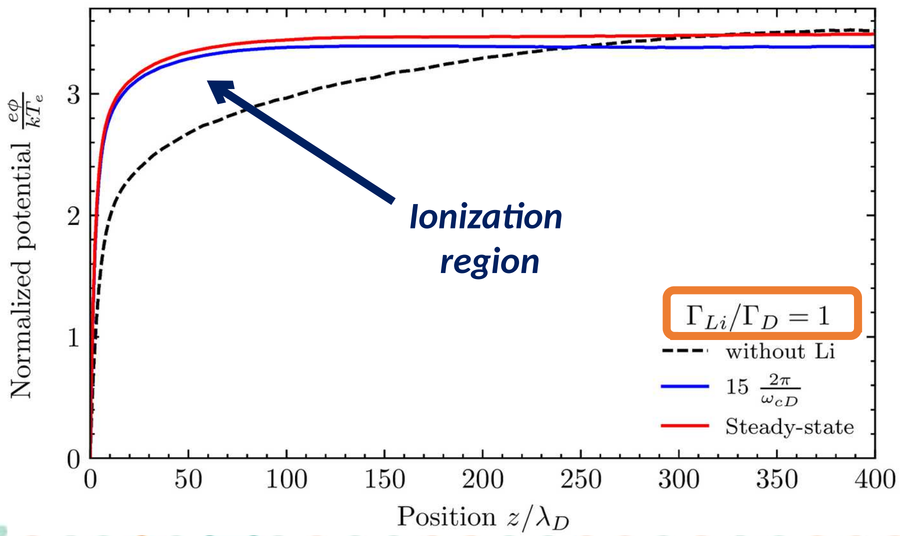
Simulated sheath region (fews 10mm) and physics

Space Potential profiles with Li





Evolution of the potential profile for several flux ratios



- Ionization in the presheath
- Potential profile flattenning in the ionization region due to Li injection
- Decrease of the redeposition
- Transient potential hump

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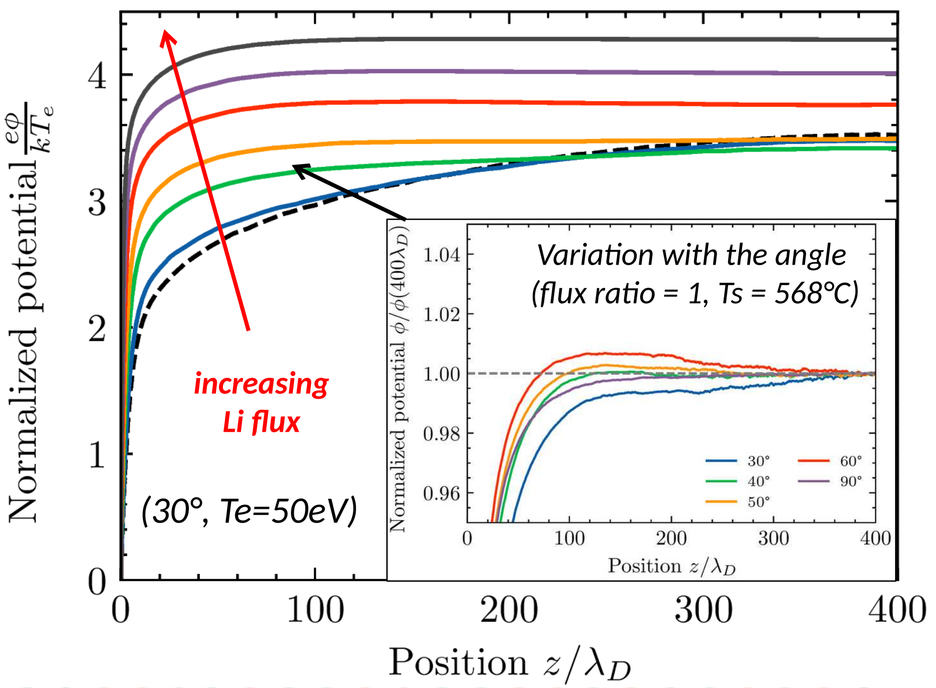
Redeposition trends

- **4 keys parameters :** Γ_{Li}/Γ_D, λ_{iz}/λ_D, θ and B
- High redeposition of evaporated Li atoms (>95%)
- Results in accordance with the work of *Brooks and Naujoks (2000)* made with BPHI-3D
- Prediction of a potential hump that accelerates Li ions towards the plasma (depends on the Li source and the magnetic inclination) => Reduces the redeposited fraction

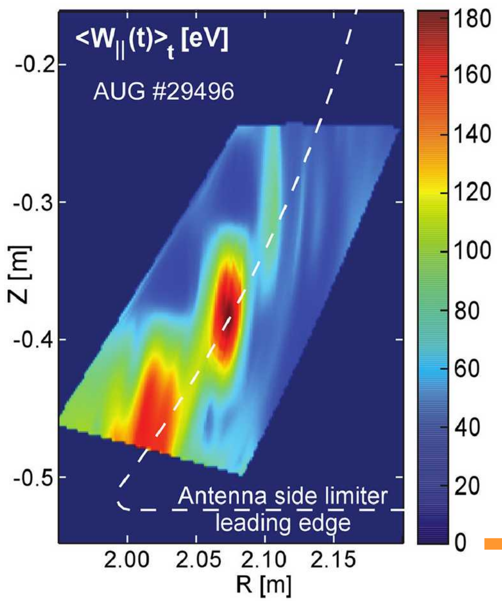
Increased parameter	Γ_{Li}/Γ_D	λ_{iz}/λ_D	*Redeposited fraction*
(°C)	increases	increases	decreases
n_0 (m^{-3})	decreases	decreases	increases
$T_e=T_D$(eV)	decreases	decreases	increases
B (T)	unchanged	unchanged	decreases
θ (deg)	unchanged	unchanged	**depends**



C) Radio-frequency sheath and sputtering mitigation (ICRF antennas)

Léonel Tsowemoo, PhD

Objectives & context (collab. IPP Garching + Uni. Basel)



180eV w/ ICRH vs. 30eV Ohmic case (Bobkov NME 18,131)

- ICRF antenna source of strong RF fields → oscillating sheaths
- Sheath rectification leads to ion acceleration → Sputtering
- Major concern for the application of ICRF power in a high-Z environment

Objectives:

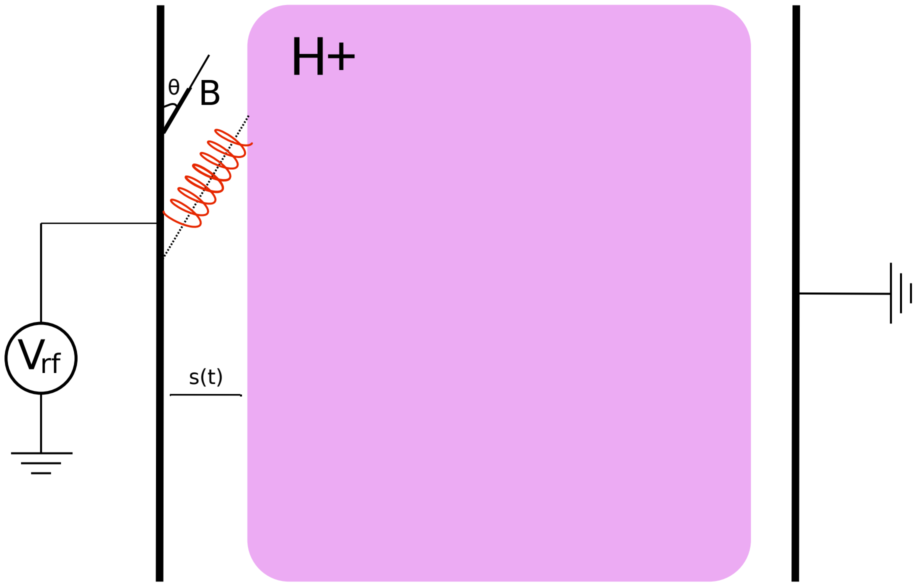
- Characterization of RF sheath properties for H/D/T species vs RF frequency, B amplitude and incidence (focus on grazing ones), sheath impedance + measurements @ Basel

- W sputtering due to C,O, B + self sputt. + redep. vs edge plasma properties + measurements @ Basel

Model / some results

- 1D/3V symmetric RF plasma discharge

- Electrons magnetized ($\rho<\lambda_d$) (not ions)



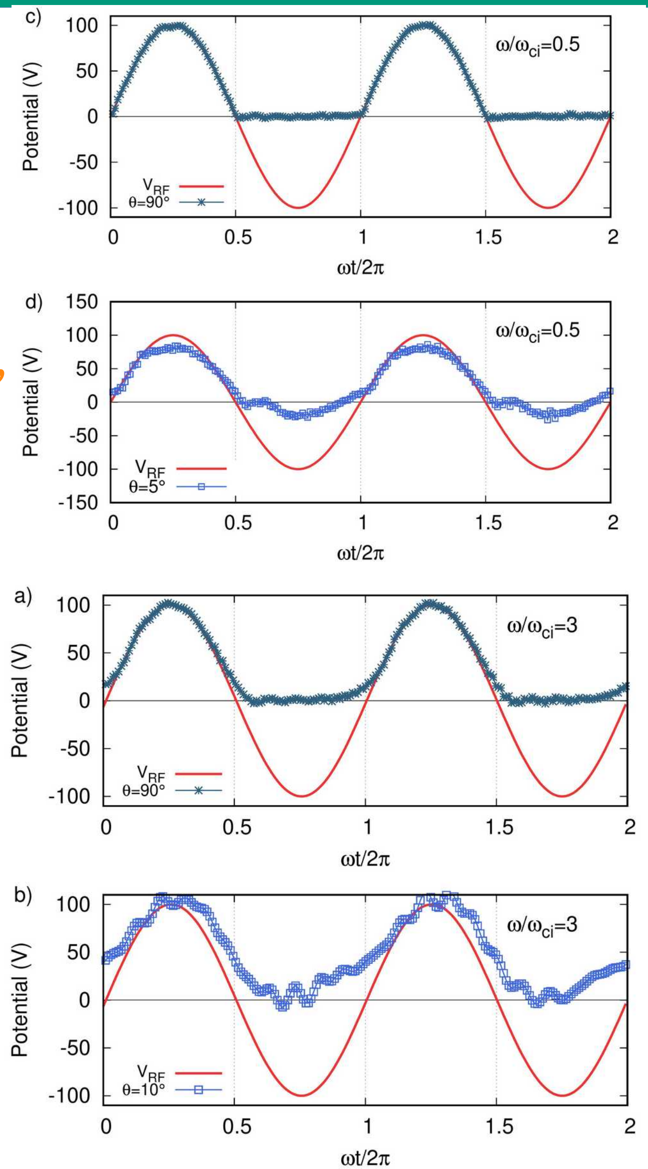
⋆ n_0 ranges 10^{17}-$10^{19}m^{-3}$ / T=2eV / V_{rf}=100V
⋆ ω_{rf} scales with ω_{ci}

Low ω & large θ, resistive sheath

Low ω & grazing θ, inverted sheath

Higher ω & large θ, less resistive sheath

Higher ω & small θ, capacitive sheath



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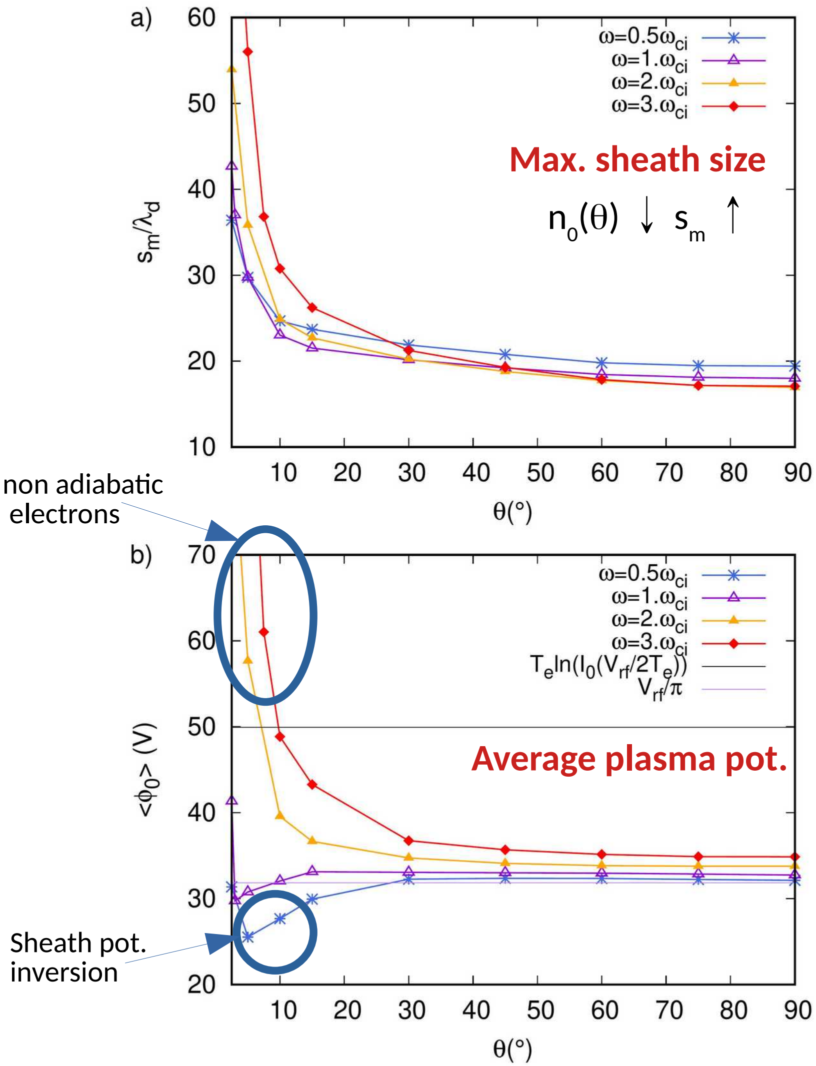
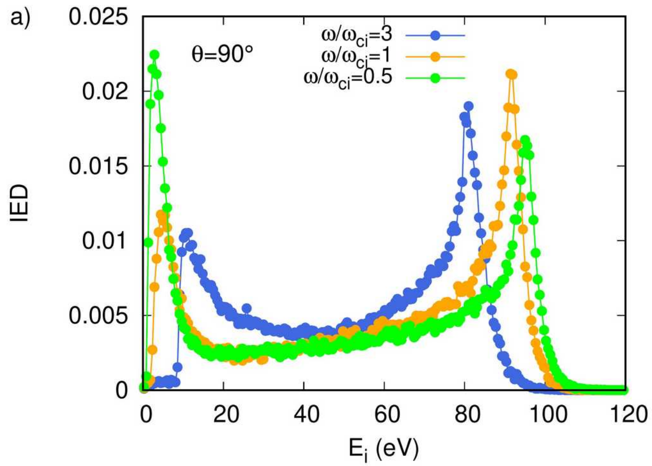
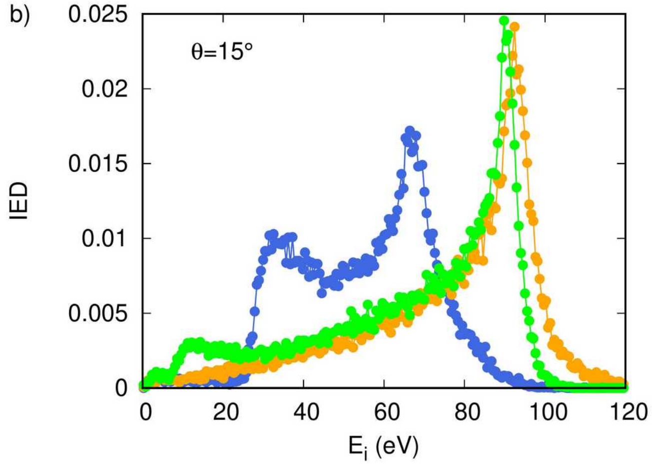
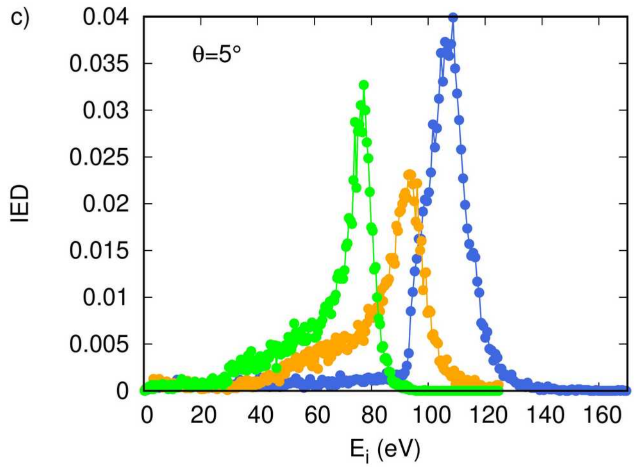
Model / some results









- ω_{pi}/ω_{rf} ↓ with θ → ion dynamics

- IED&IAD influence the sputtering rate → depends on both ω and θ

- Adiabatic elec. approx. for rectified potential may fail at grazing incidence

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