On the Erosion and Redeposition of Tungsten in Tokamak Divertor

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Presented at the

**61st Annual Meeting of the American Physical Society, Division of Plasma Physics
Fort Lauderdale, Florida**

October 21 – 25, 2019

Divertor Physics and Plasma-Material Interactions

DIII-D
NATIONAL FUSION FACILITY

Work supported by U.S. DOE under DE-SC0018423

GENERAL ATOMICS

019-19/JG/jy

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  - **Reduction of SXB coefficients for W at high plasma density**

- **Experiments available in DIII-D to validate model of W prompt redeposition and net erosion in divertor**

Quantitative Modeling of W Prompt Redeposition Including Chodura Sheath and Multiple W Ionizations Required for ITER and Beyond

W erosion in divertor $\approx$ **gross erosion x (1- prompt redeposition) x (1 – non-prompt local redeposition)**

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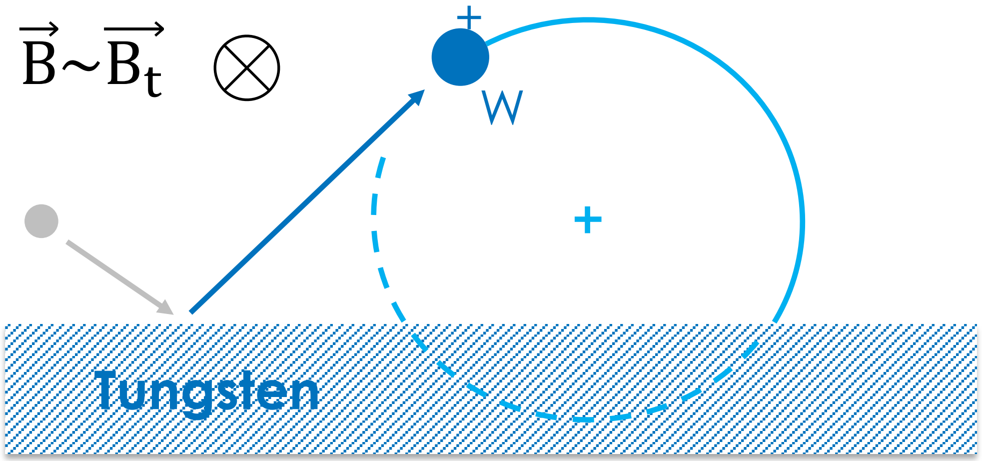

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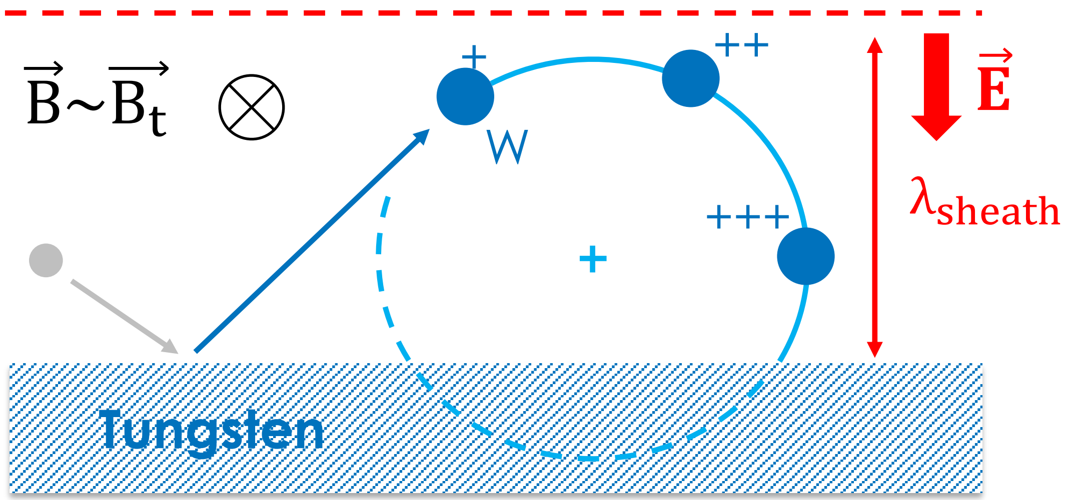

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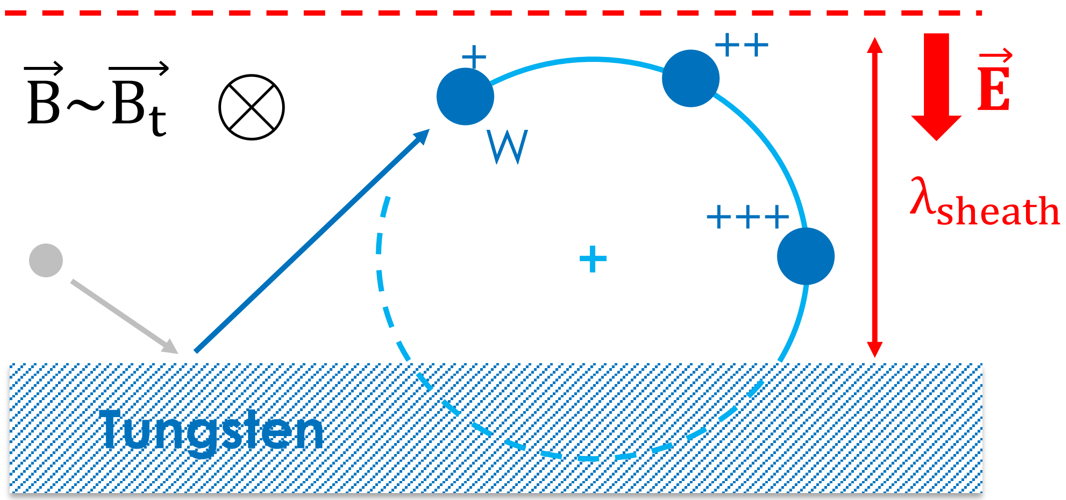

- …but ITER W divertor and beyond now requires:

  i) Quantitative modeling of W prompt redeposition:

  → Quantify effects of sheath and multiple W ionizations on W prompt redeposition

  ii) Validation of predictive model of W prompt redeposition against experiments:

  → Dedicated experiments in DIII-D divertor[3]

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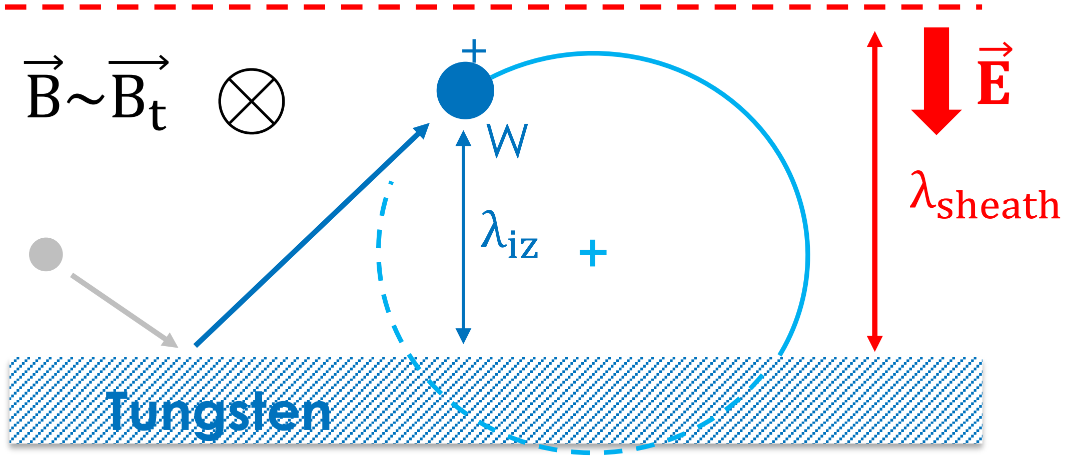
W Ionized within the Sheath Due to Large Width of Electric Sheath in Presence of Magnetic Field Line at Grazing Incidence

- **Wide electric sheath (Chodura sheath) due to grazing magnetic field ($< 5°$) in divertor[1]:**

$$\lambda_{sheath} \sim \rho_i$$



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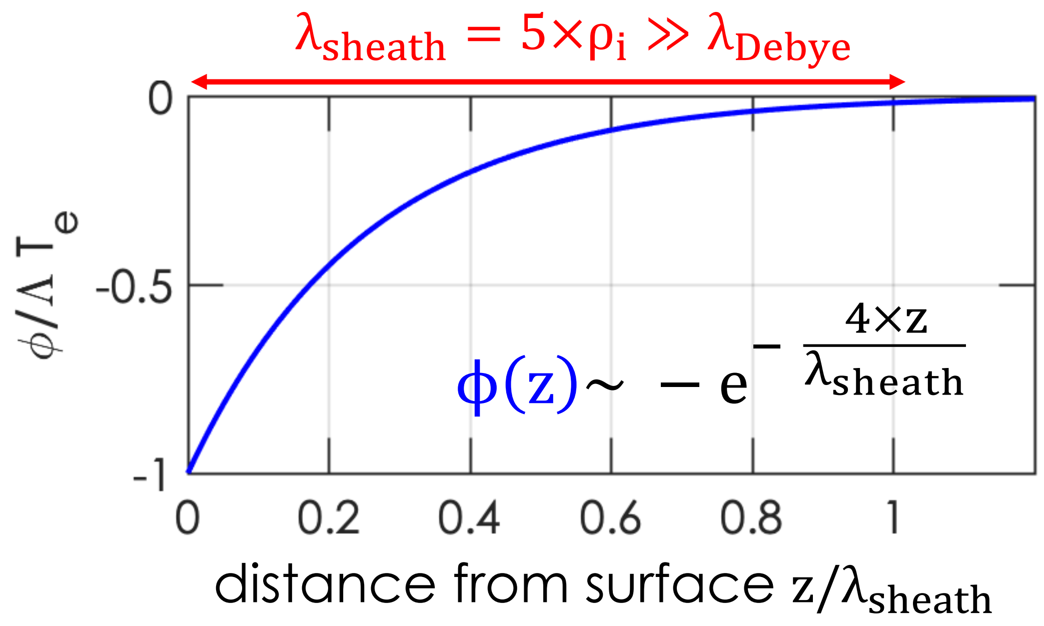

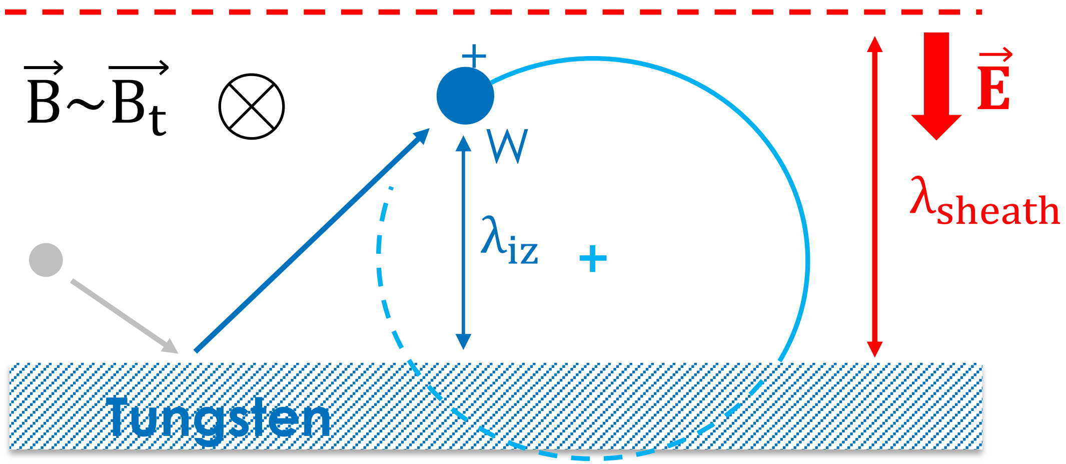

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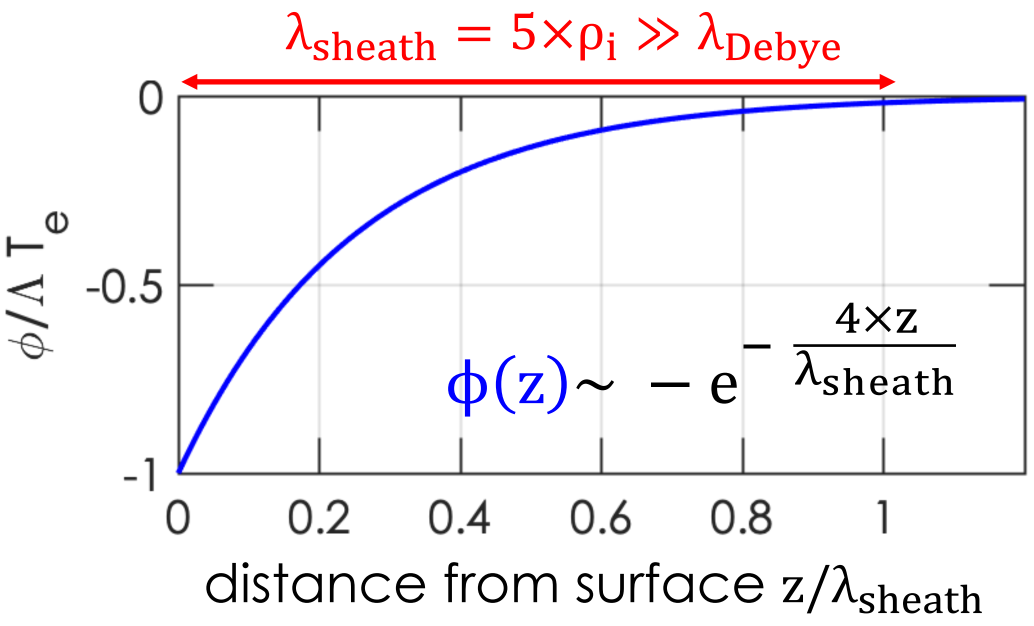

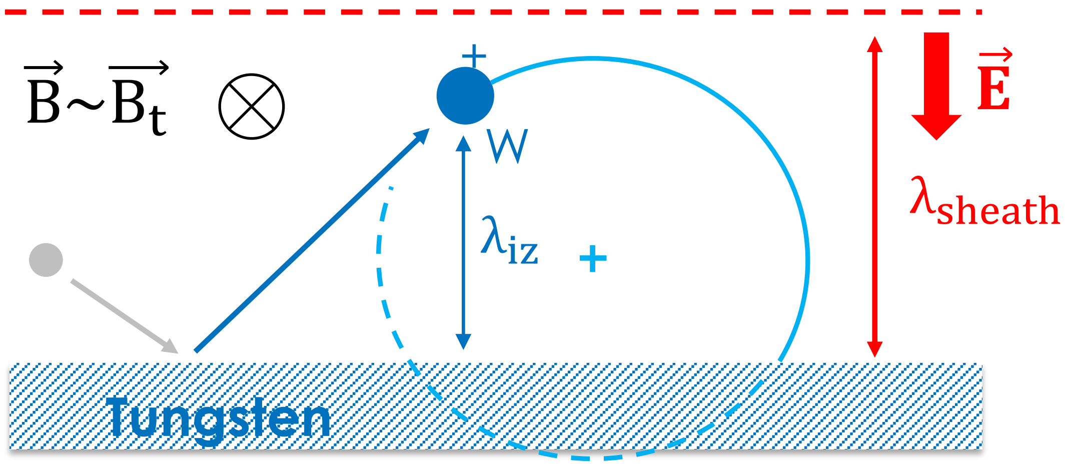

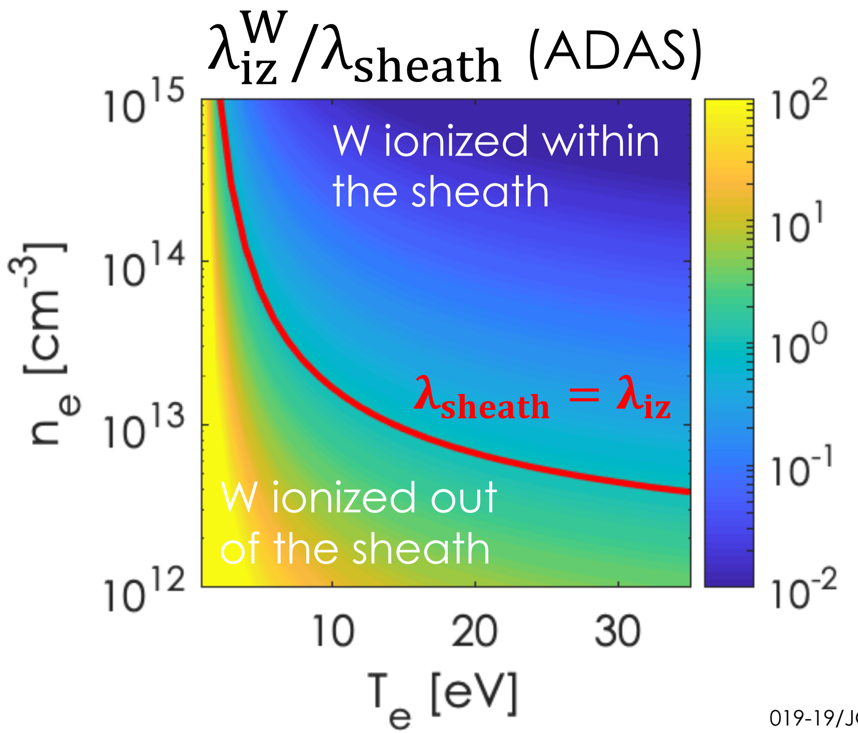

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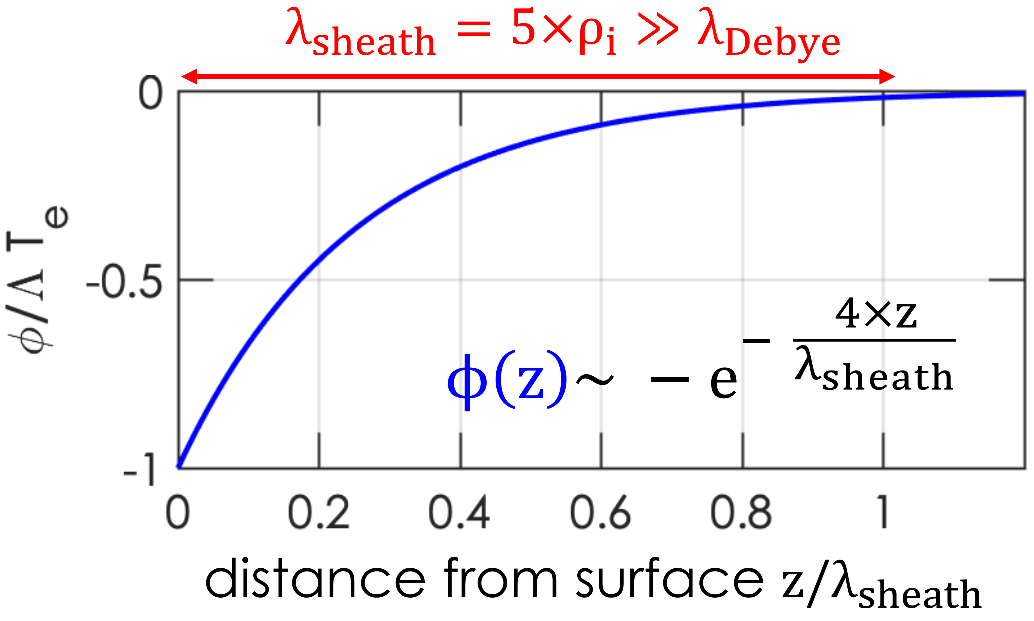

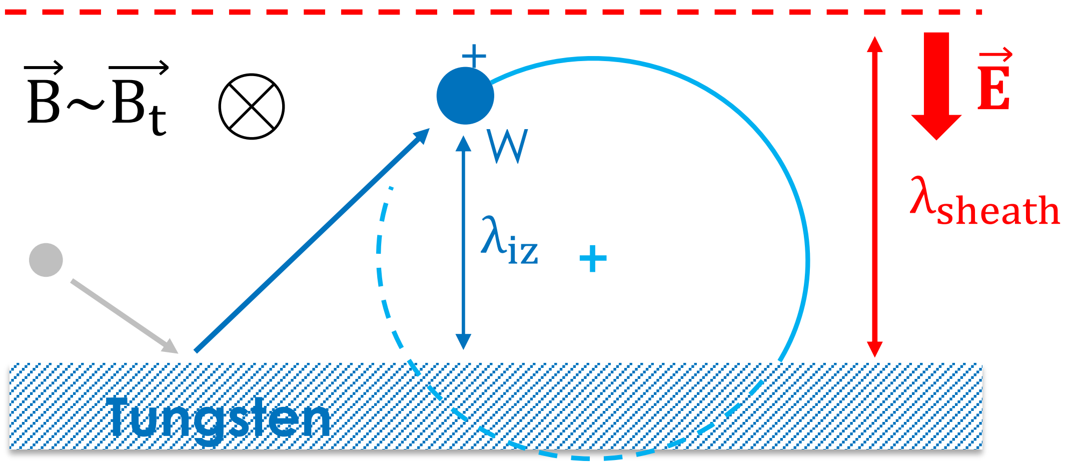

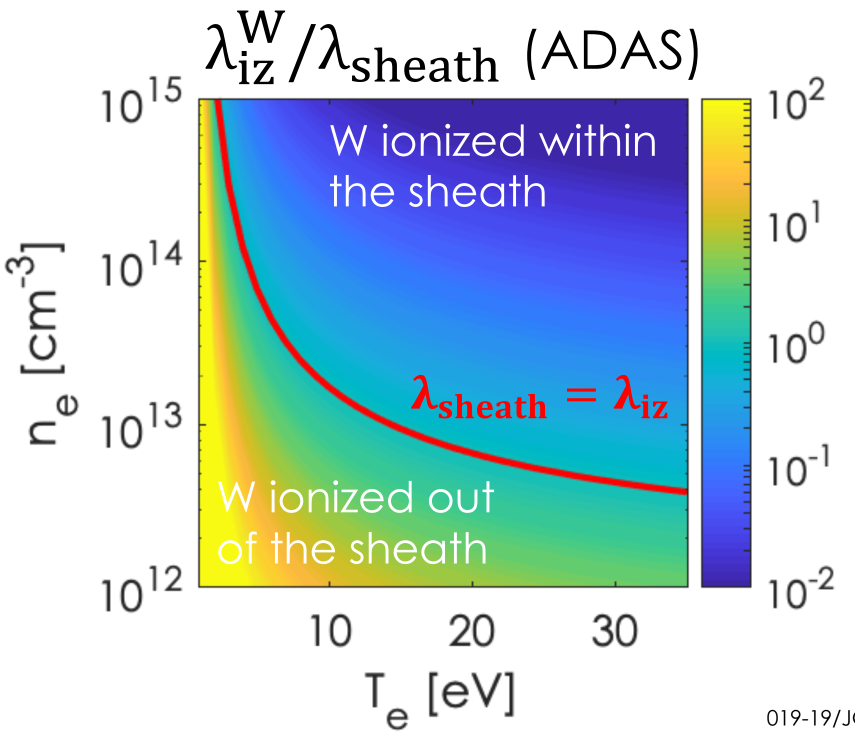

→ **Neutral W ionized in the sheath: $\lambda_{iz} \lesssim \lambda_{sheath}$**

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W Prompt Redeposition Strongly Enhanced by the Sheath Electric Field Because of The Large Inertia of W Impurity

- **When W ionized within the sheath ($\lambda_{iz} < \lambda_{sheath}$), W prompt redeposition affected by Chodura sheath due to:**
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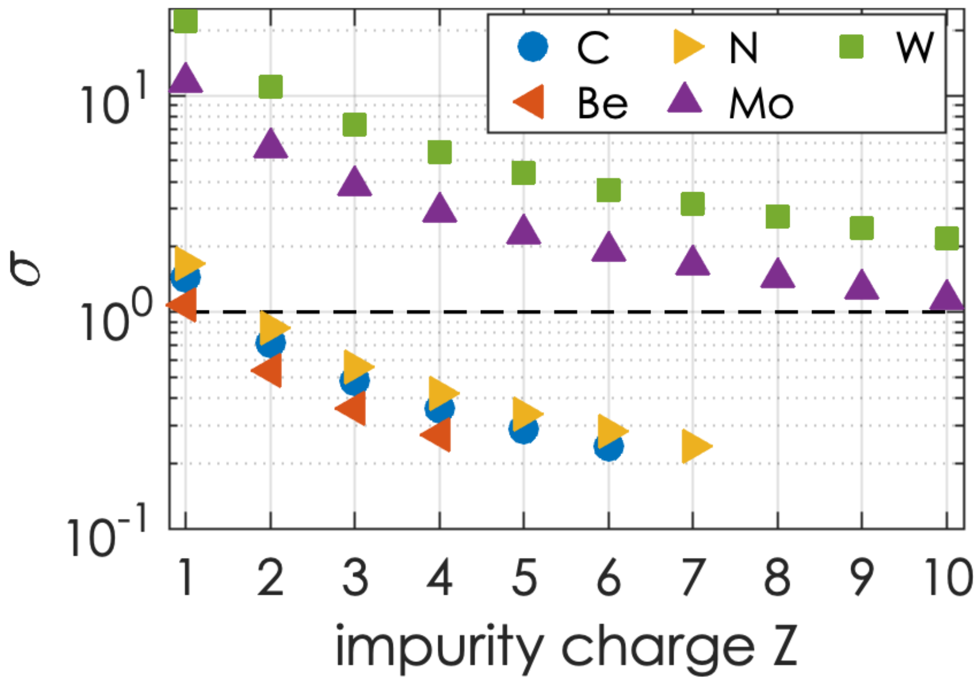
- **Electric field remains much stronger than Lorentz force despite high W charge state due to large W mass**

$$\sigma = \frac{Z\Lambda Te}{\frac{1}{2} m_W \omega_c^2 \lambda_{sheath}^2} \Rightarrow \sigma_W \sim \frac{1}{4}\frac{1}{Z}\frac{m_W}{m_i} > 1$$



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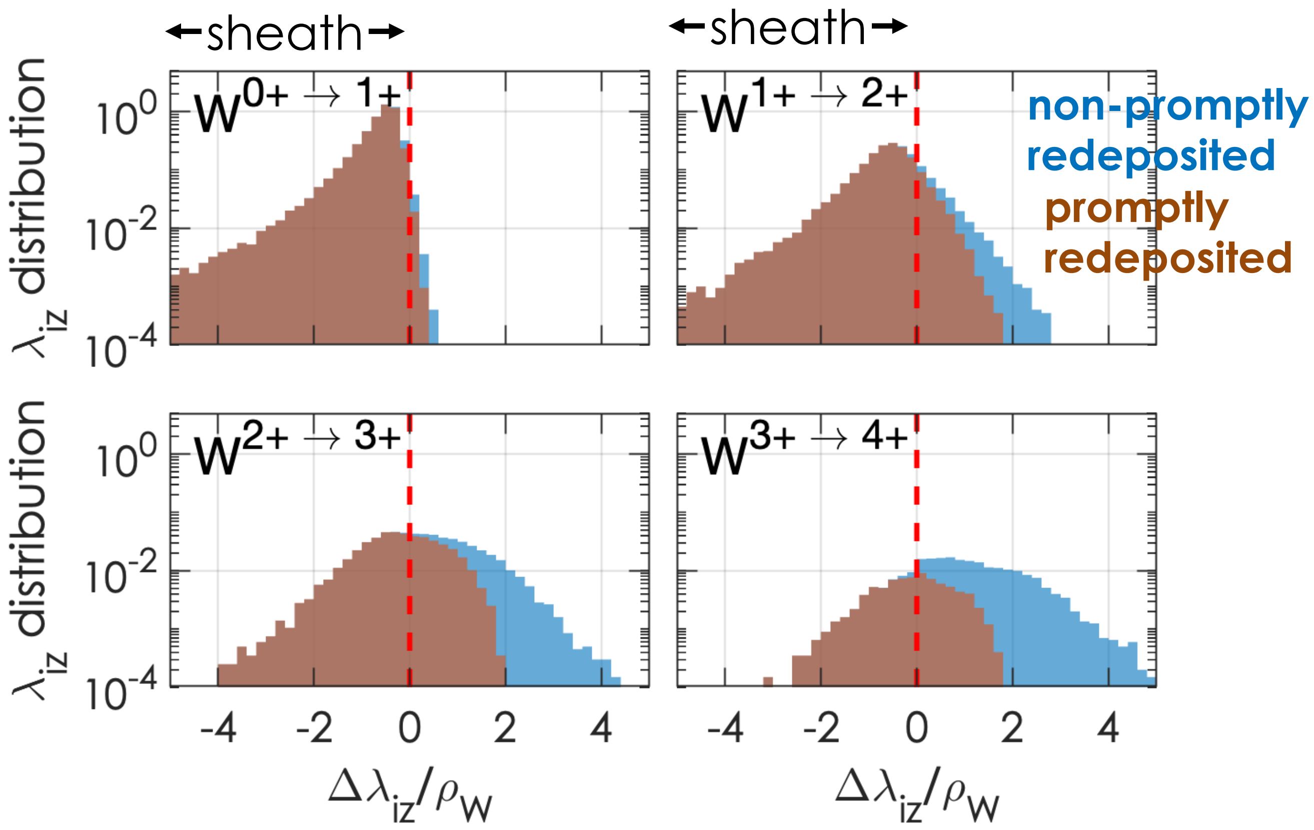
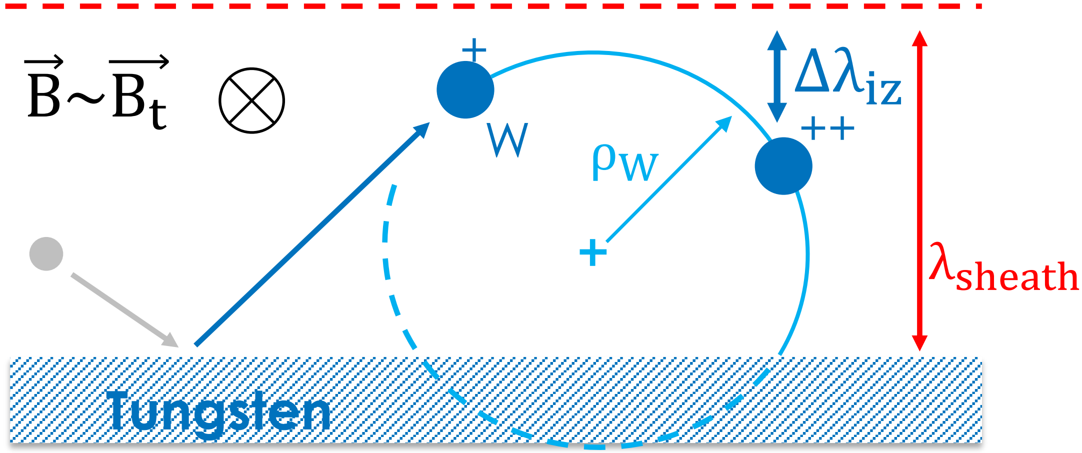
W Prompt Redeposition Scales With the Ratio of the Neutral W Ionization Mean-free Path Over the Sheath Scale Length

- **Only W impurities ionizing out of the sheath do not promptly redeposit because of the strong sheath electric field (ERO simulation)**





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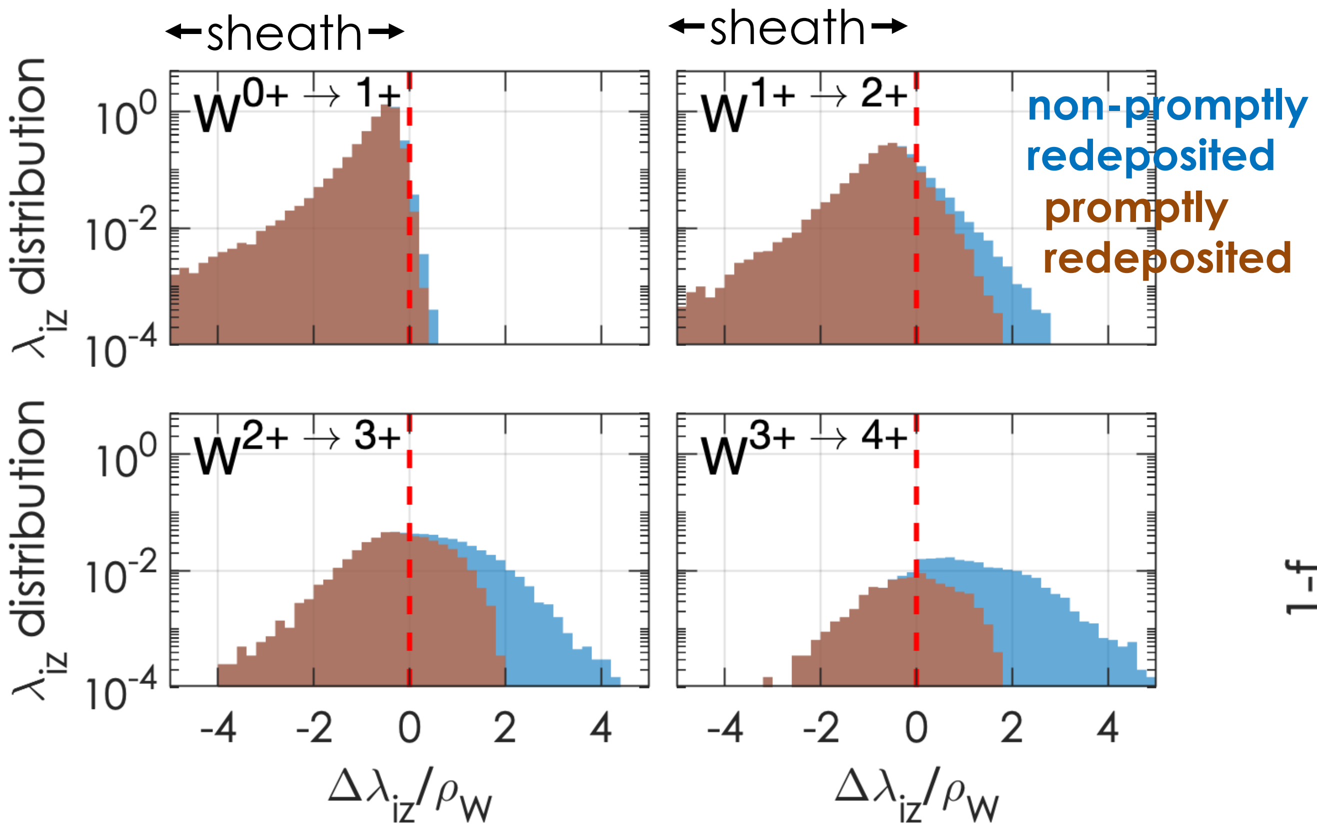

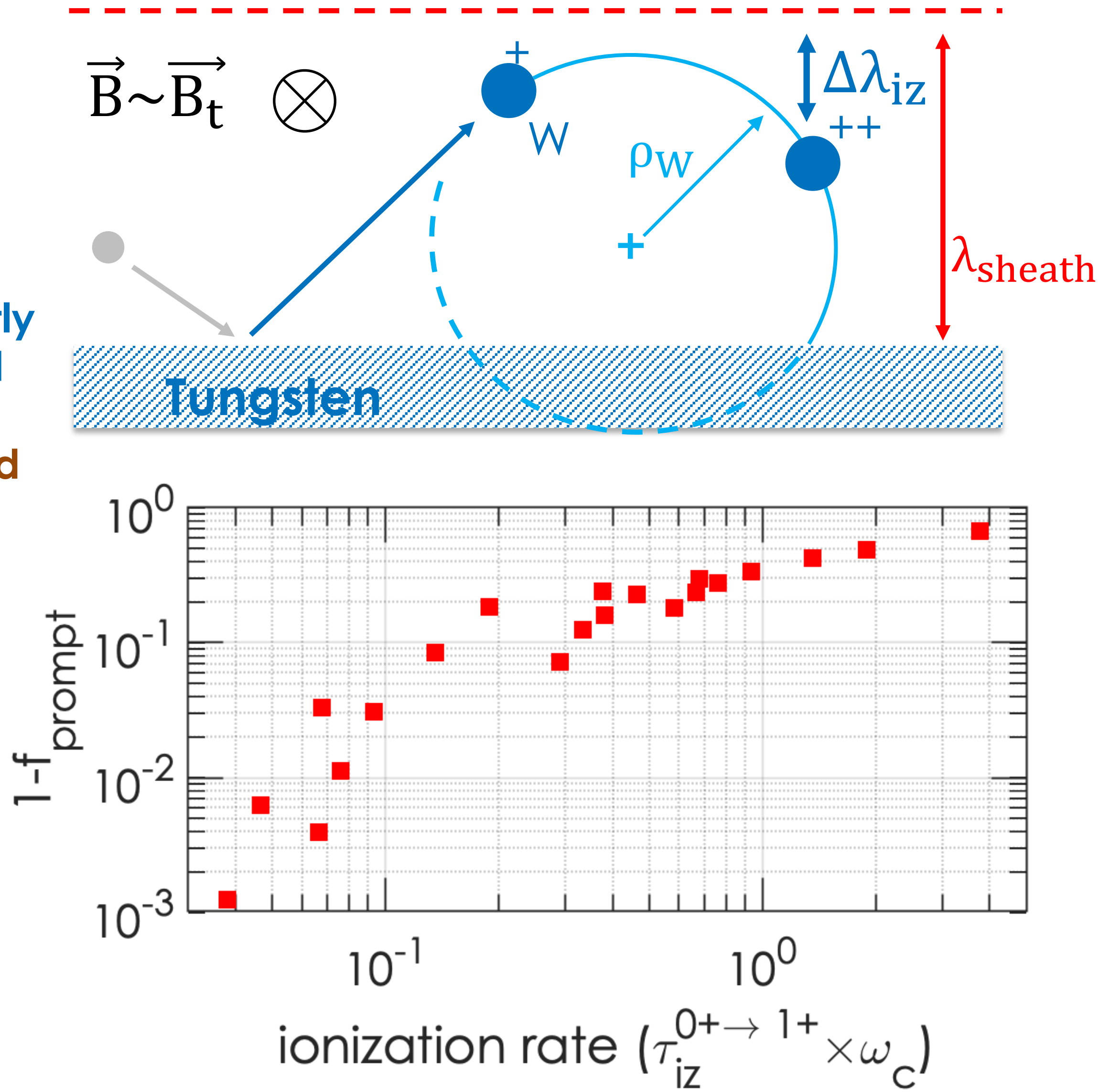

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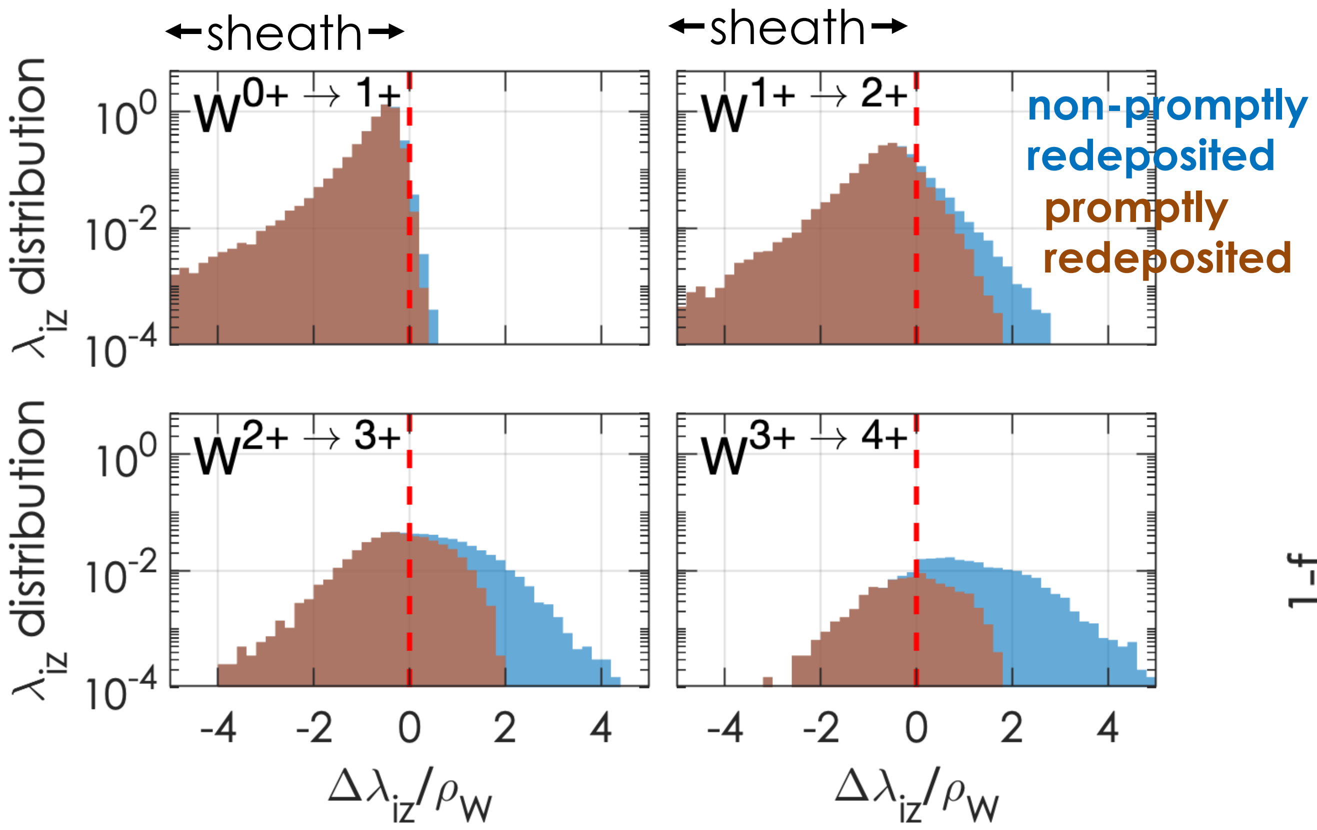
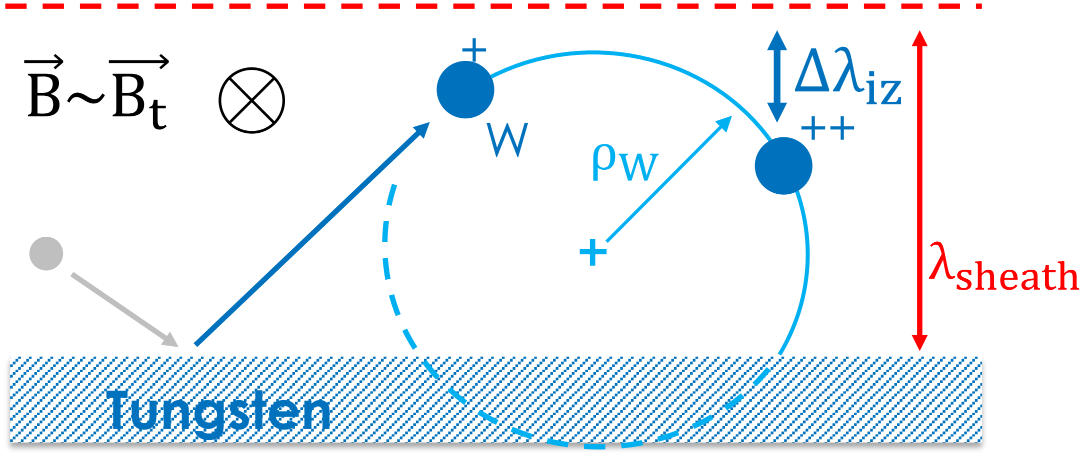
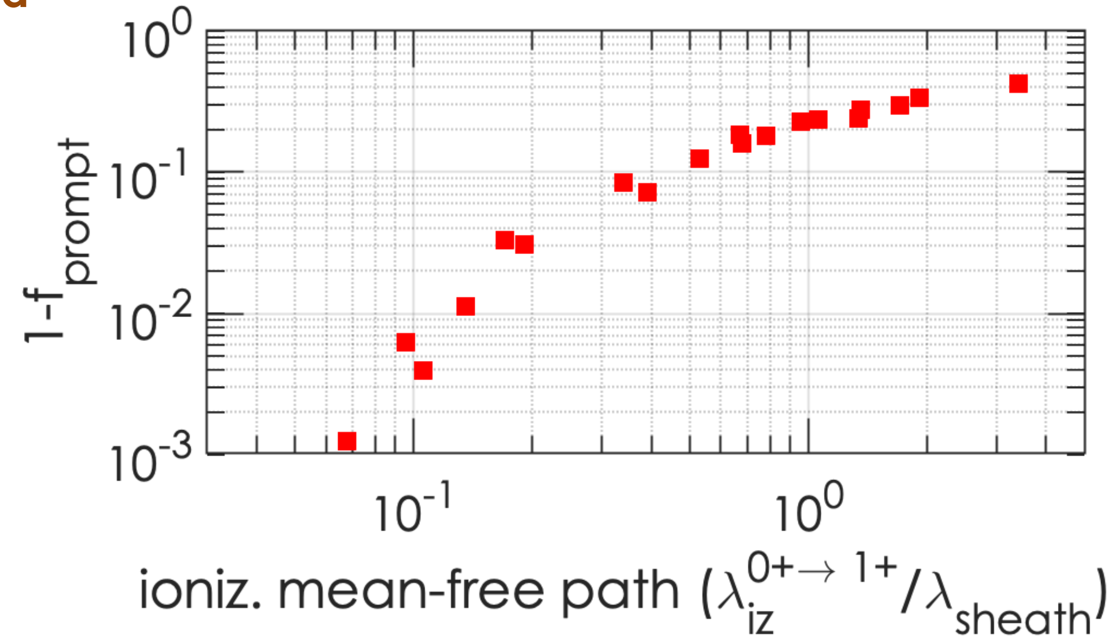
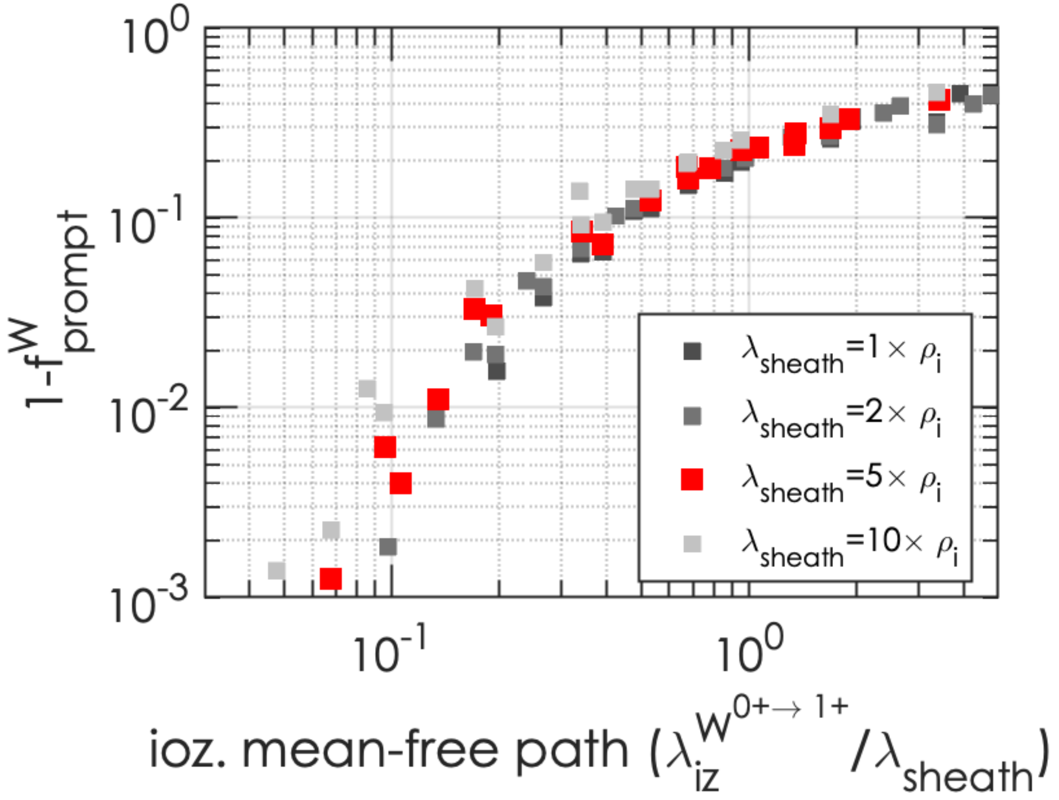






- **W prompt redeposition scales as the W neutral ionization mean-free path over the sheath width**

W Prompt Redeposition Governed by W Ionization Rates, Sheath Width and Energy Distribution of Sputtered Neutral W



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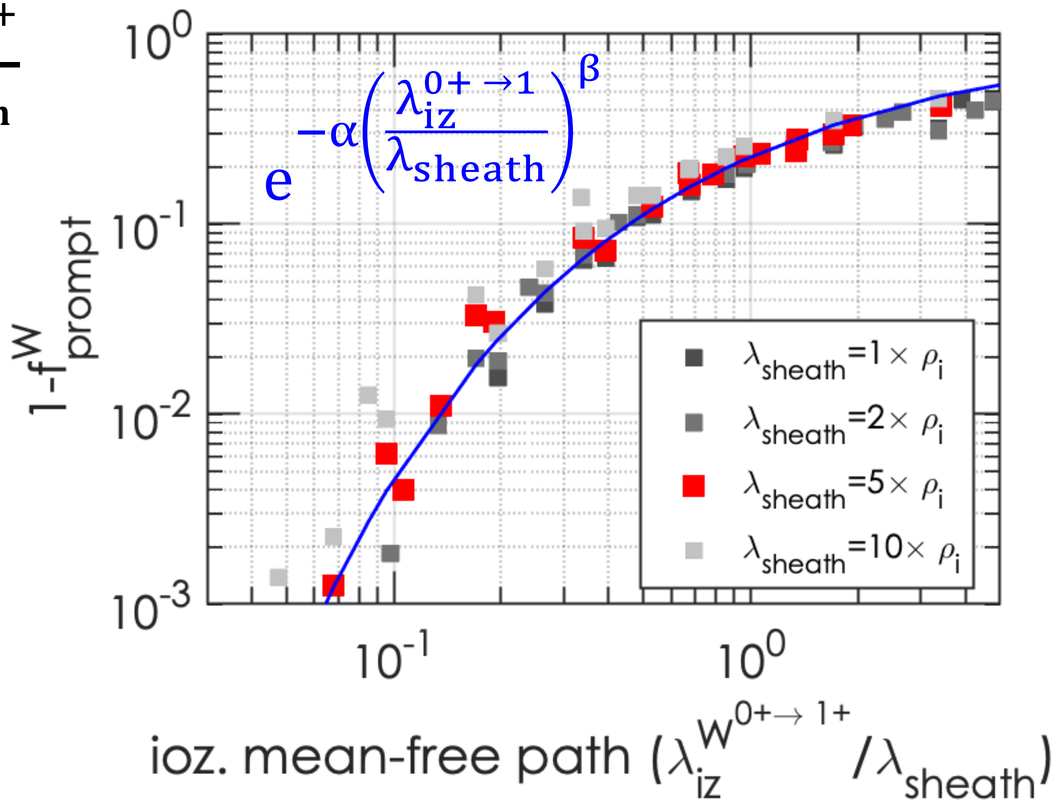

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low-Z impurity (Be,C)	high-Z impurity (W)
prompt redep. scales with	prompt redep. scales with
$p = \tau_{iz}^{0+\to 1+} \times \omega_c$	$q = \lambda_{iz}^{0+\to 1+}/\lambda_{sheath}$
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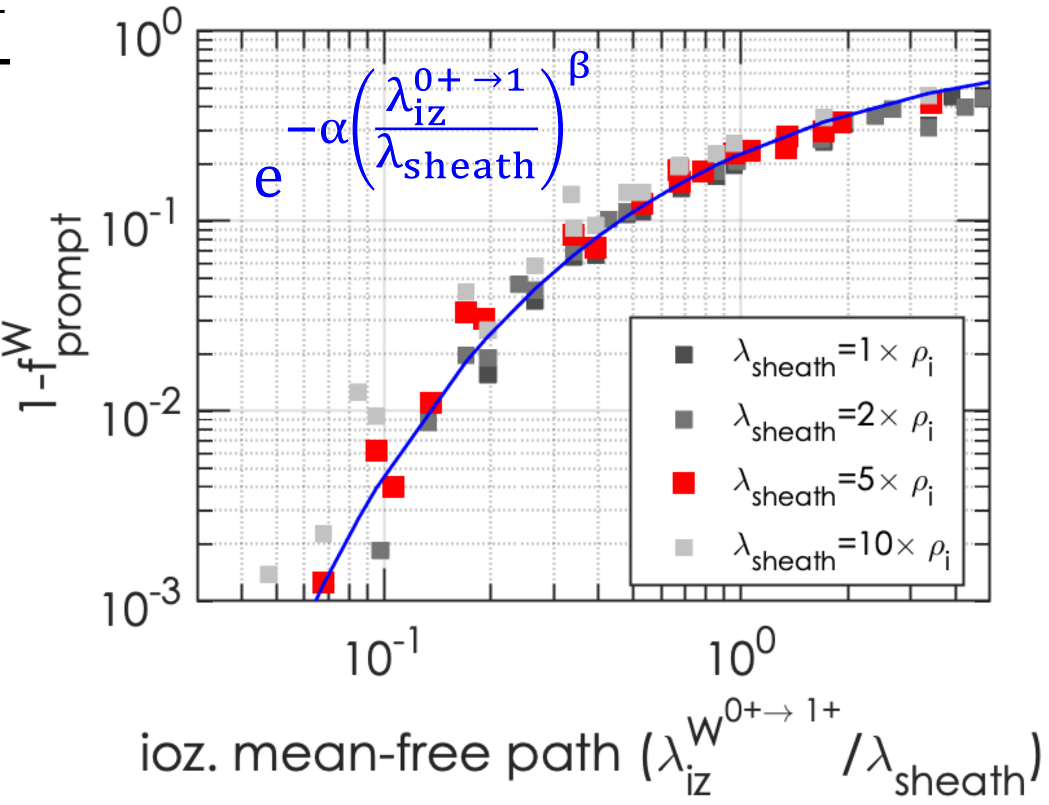

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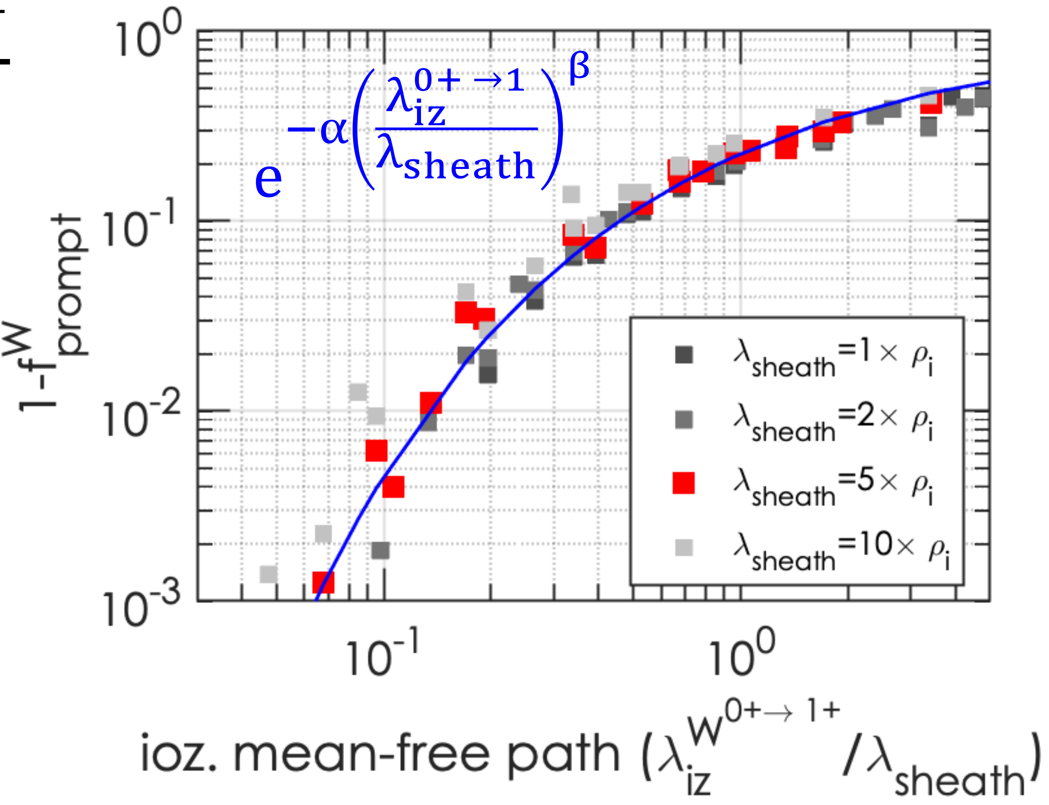

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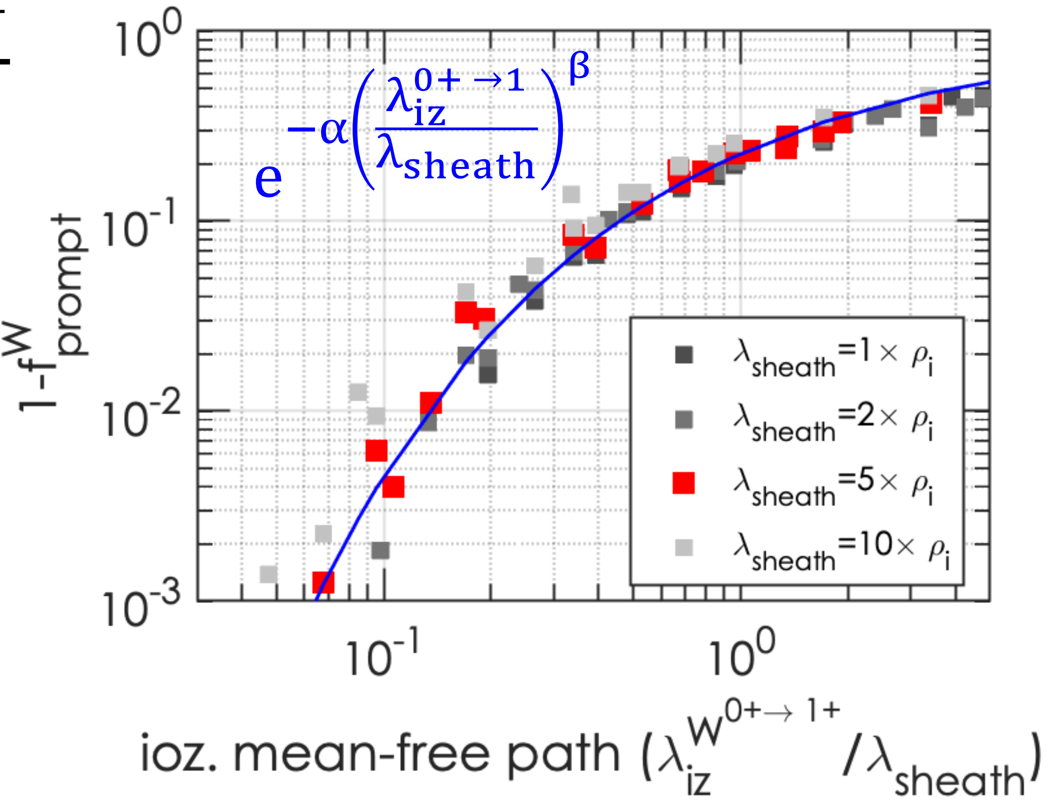
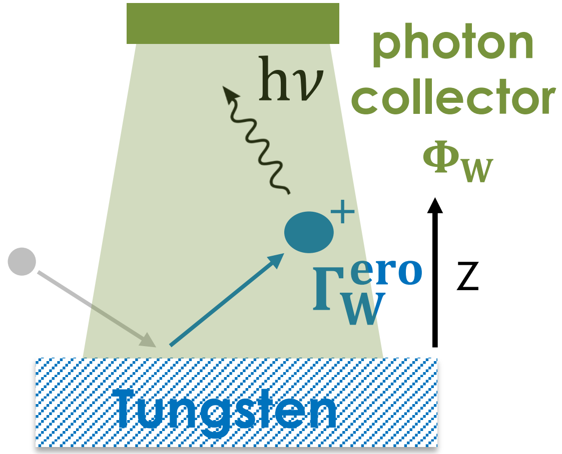


- **W prompt redeposition governed by W ionization rates, sheath width and energy distribution of sputtered neutral W**
- **W prompt redeposition weakly depends on shape of sheath electric potential, potential drop in the sheath (in the regime $\sigma_W > 1$) and incidence of magnetic field on divertor target**

Reduction of the Effective SXB Coefficients at High Divertor Plasma Density Due to W Ionization Within the Electric Sheath

- **W gross erosion flux given by** $\Gamma_W^{ero} = \int_0^L S_{iz}^{W^{0+} \to W^{1+}}(T_e, n_e)\, n_{W^{0+}}\, n_e\, dz$ **but only photon flux measured in experiments…**



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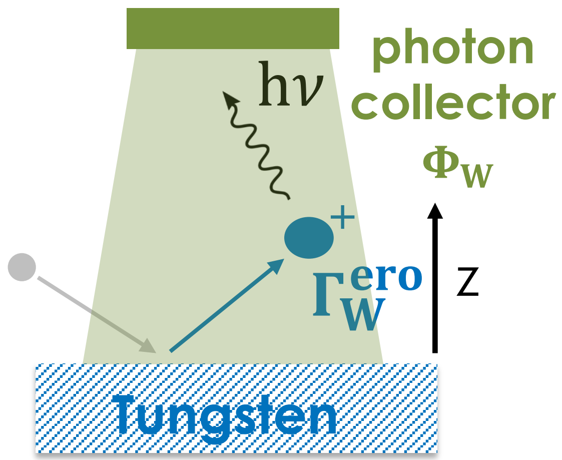

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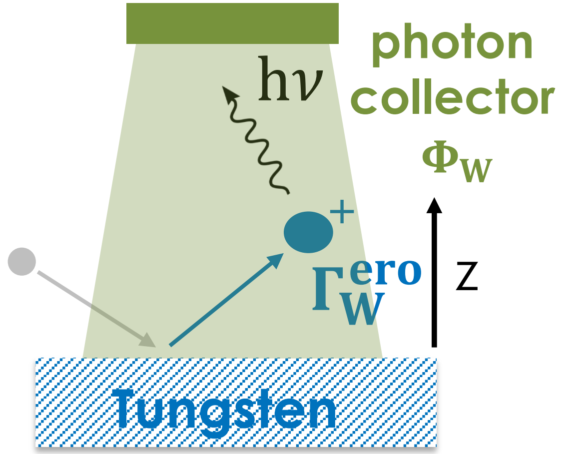

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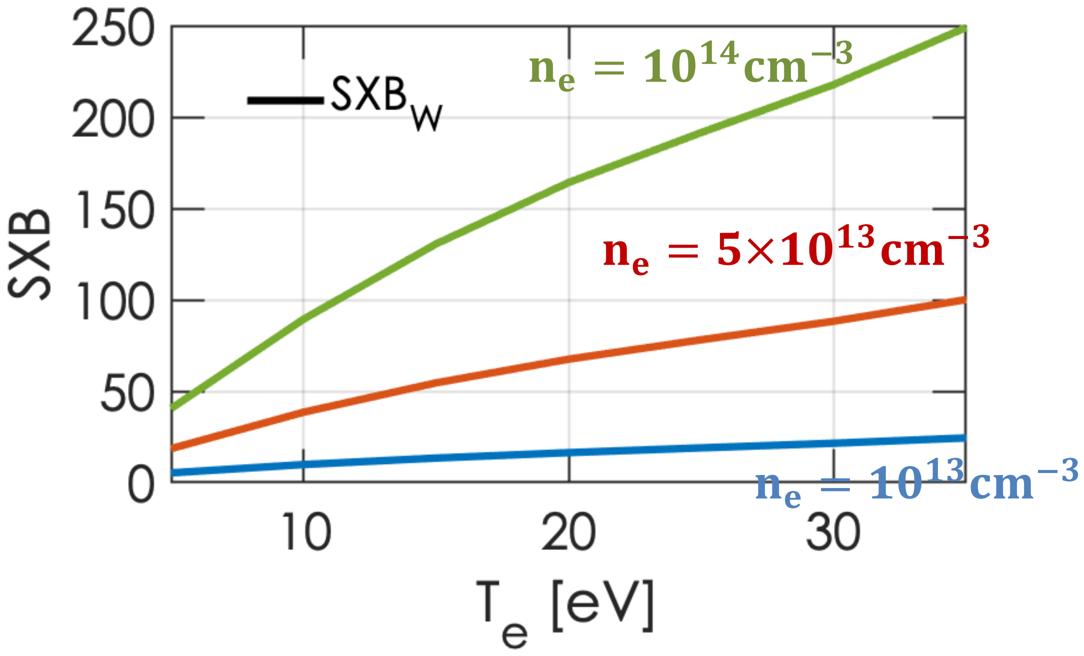

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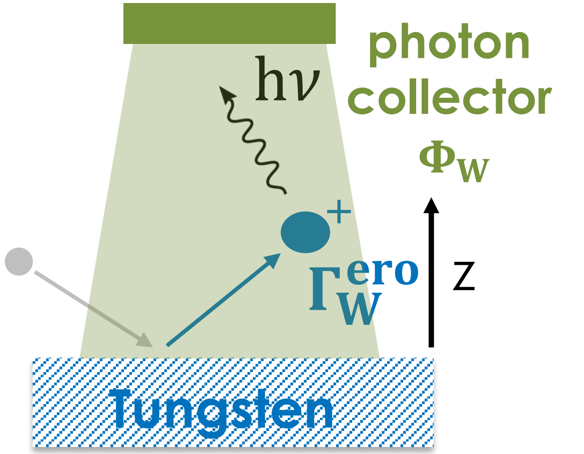
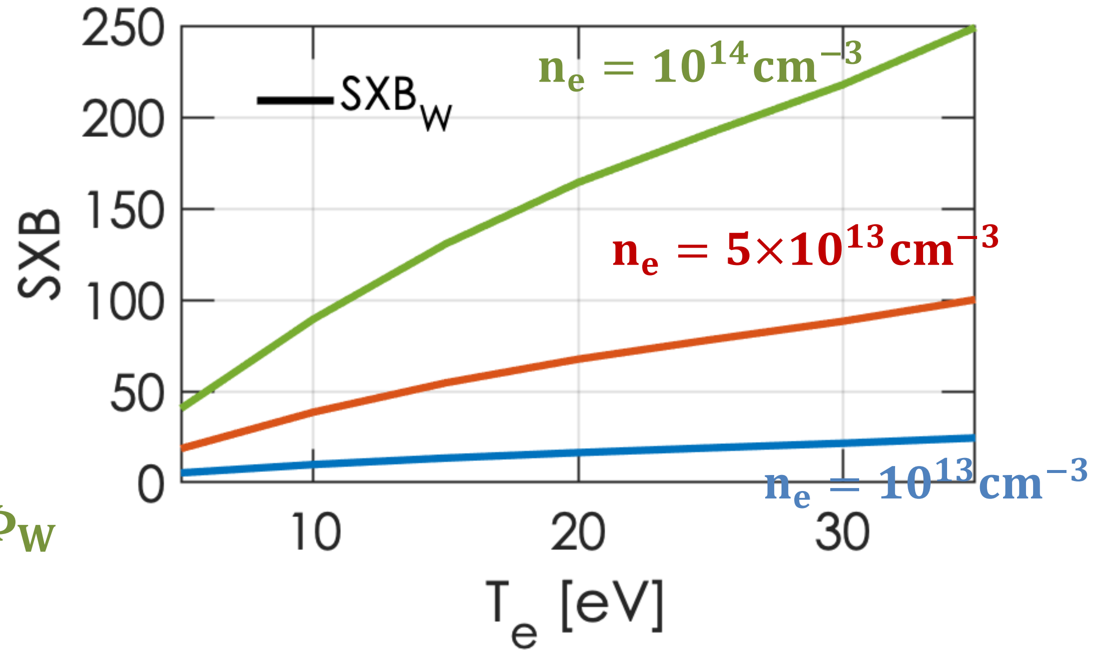
- **But when** $\lambda_{iz}^{W^{0+\rightarrow 1+}} < \lambda_{sheath}$

$$\Gamma_W^{ero} = \frac{\int_0^L S_{iz}^{W^{0+\rightarrow 1+}}(T_e, n_e(z))\, n_{W^{0+}}(z)\, n_e(z)\, dz}{\int_0^L S_{photon}^{W^{0+\rightarrow 1+}}(T_e, n_e(z))\, n_{W^{0+}}(z)\, n_e(z) dz} \times \Phi_W$$

$$< SXB^{W^{0+\rightarrow 1+}} >_{eff}$$





[1] Behringer *PPCF* 1989

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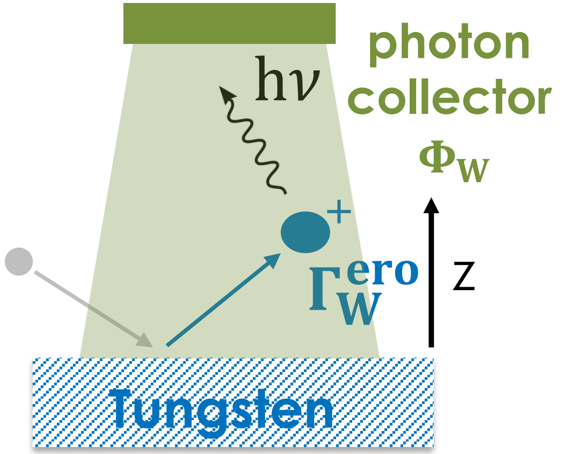

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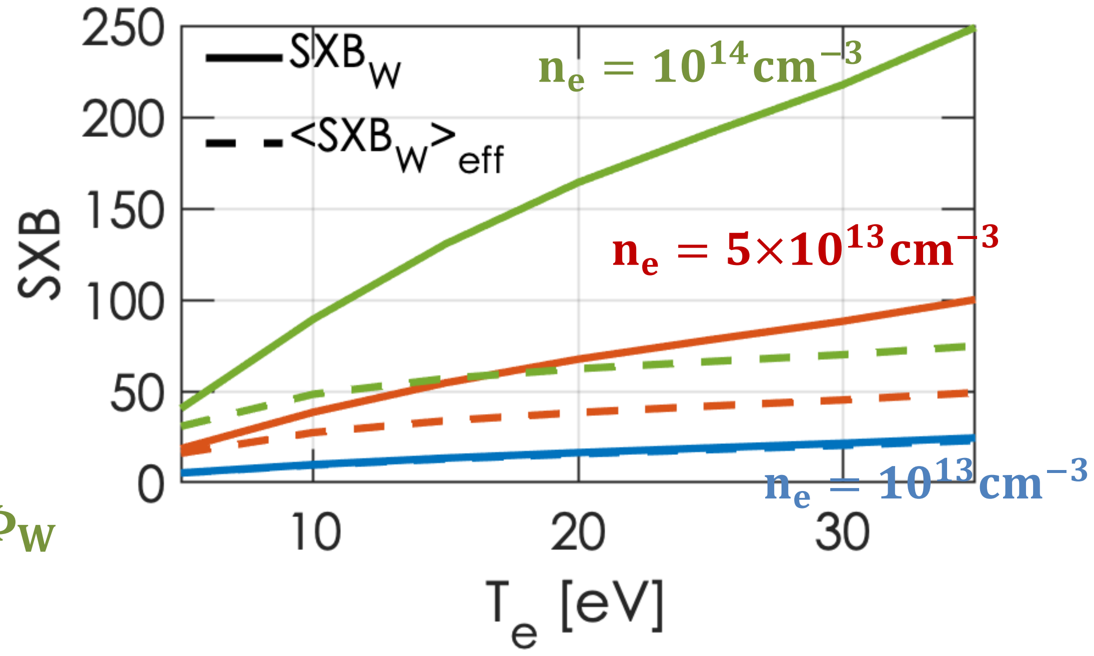
$$\Gamma_W^{ero} = \underbrace{\frac{\int_0^L S_{iz}^{W^{0+\rightarrow 1+}}(T_e, n_e(z))\, n_{W^{0+}}(z)\, n_e(z)\, dz}{\int_0^L S_{photon}^{W^{0+\rightarrow 1+}}(T_e, n_e(z))\, n_{W^{0+}}(z)\, n_e(z) dz}}_{< SXB^{W^{0+\rightarrow 1+}} >_{eff}} \times \Phi_W$$



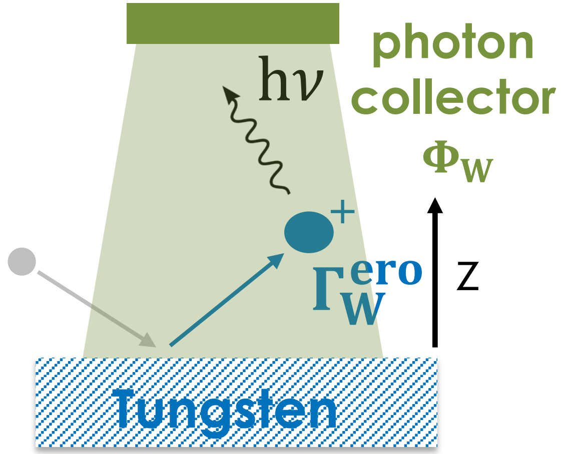
[1] Behringer *PPCF* 1989

019-19/JG/jy

Reduction of the Effective SXB Coefficients at High Divertor Plasma Density Due to W Ionization Within the Electric Sheath

- **W gross erosion flux given by** $\Gamma_W^{ero} = \int_0^L S_{iz}^{W^{0+}\rightarrow W^{1+}}(T_e, n_e)\, n_{W^{0+}}\ n_e\, dz$

  but only photon flux measured in experiments…



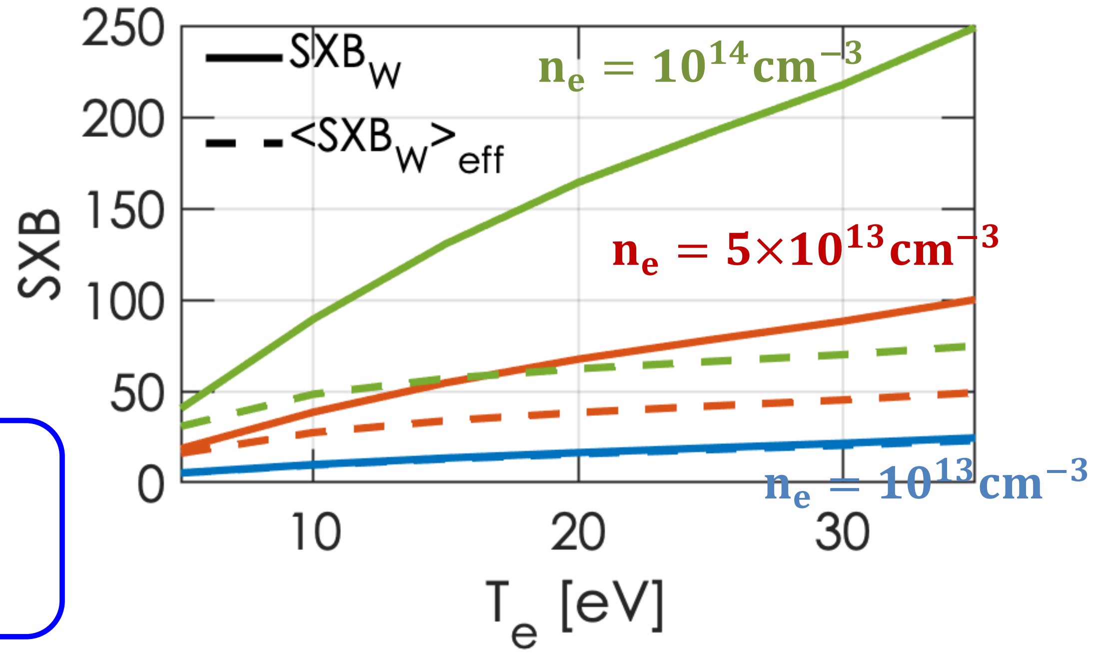
- Introducing the photon emissivity coefficient[1] $S_{photon}^{W^{0+\rightarrow 1+}}$

$$\Gamma_W^{ero} = \underbrace{\int_0^L \frac{S_{iz}^{W^{0+\rightarrow 1+}}(T_e,n_e)}{S_{photon}^{W^{0+\rightarrow 1+}}(T_e,n_e)}}_{SXB^{W^{0+\rightarrow 1+}}} \times \underbrace{S_{photon}^{W^{0+\rightarrow 1+}}(T_e, n_e)\, n_{W^{0+}} n_e dz}_{\Phi_W}$$

- **Usually it is assumed that** $\lambda_{sheath} < \lambda_{iz}^{W^{0+\rightarrow 1+}} \ll \lambda_{n_e}, \lambda_{T_e}$

$$\Gamma_W^{ero} = SXB^{W^{0+\rightarrow 1+}}(T_e, n_e) \times \Phi_W$$

- **But when** $\lambda_{iz}^{W^{0+\rightarrow 1+}} < \lambda_{sheath}$



Reduction of the effective SXB coefficients at high n_e due to W ionization within the electric sheath[2]

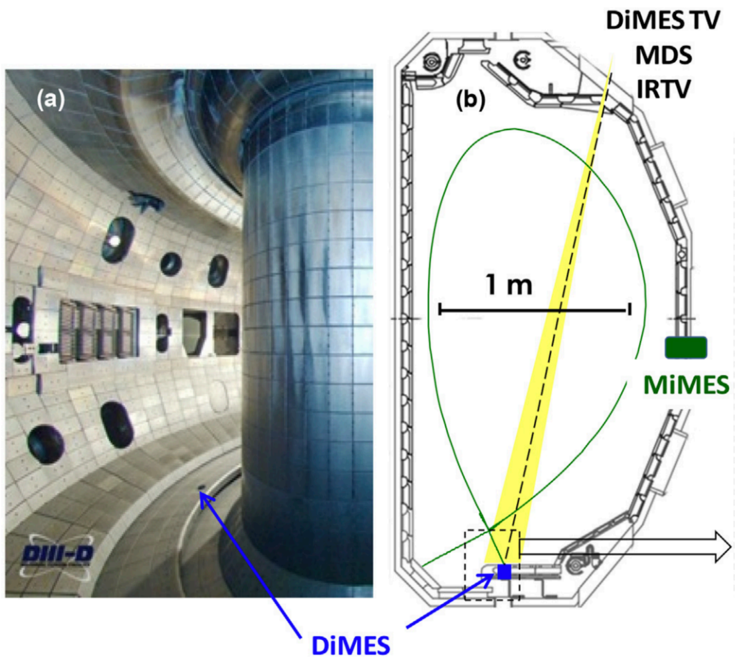
[1] Behringer *PPCF* 1989 [2] Guterl CPP 2019

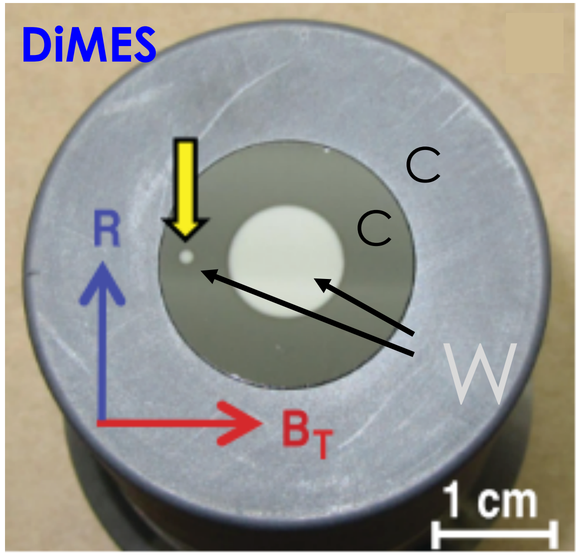
019-19/JG/jy

Experiments Available in DIII-D Divertor to Validate Model of W Prompt Redeposition and Net Erosion In Divertor

- **Experimental validation of model for W prompt redeposition and net erosion through comparison of net erosion from small and large W dots exposed in DIII-D divertor with DiMES[1]**

$$\frac{<\Gamma_{\mathrm{W}}^{\mathrm{net}}>_{\text{large disk}}}{<\Gamma_{\mathrm{W}}^{\mathrm{net}}>_{\text{small disk}}} = \frac{\cancel{\boldsymbol{\Gamma}_{\mathbf{W}}^{\mathbf{gross}}}\left(\mathbf{1}-\boldsymbol{\xi}_{\mathbf{redep}}^{\boldsymbol{large}}\right)}{\cancel{\boldsymbol{\Gamma}_{\mathbf{W}}^{\mathbf{gross}}}\left(\mathbf{1}-\boldsymbol{\xi}_{\mathbf{redep}}^{\boldsymbol{small}}\right)}$$





[1] D. Rudakov *PS* 2014 [2] J.Guterl *PPCF* 2019 [3] R. Ding *NF* 2015

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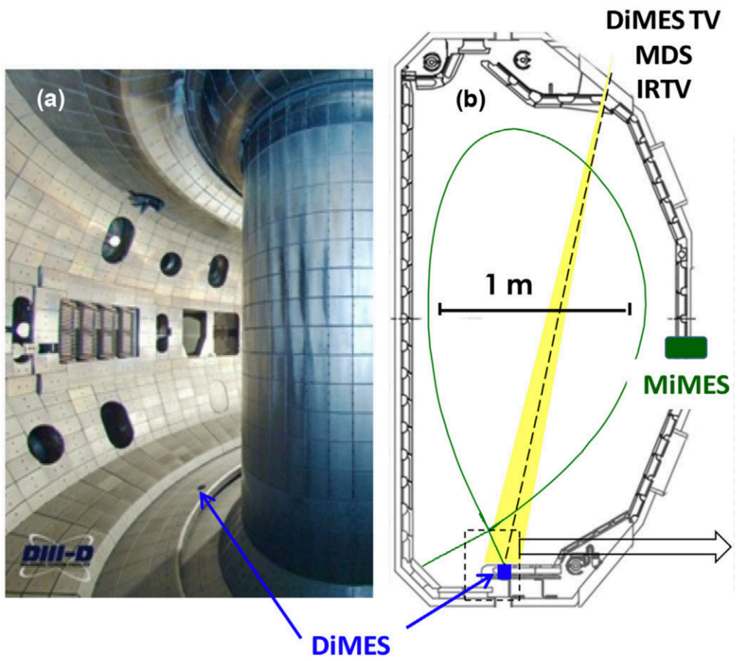
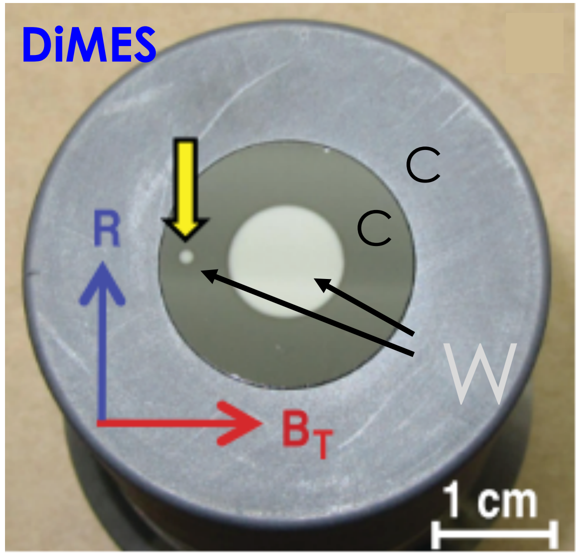
- Strong dependence of fraction of redeposited W ξ_{redep} on $\mathrm{R_{disk}}$ when $\mathrm{R_{disk}} \sim \lambda_{\mathrm{redep}} \sim 1\mathrm{mm}$





[1] D. Rudakov *PS* 2014

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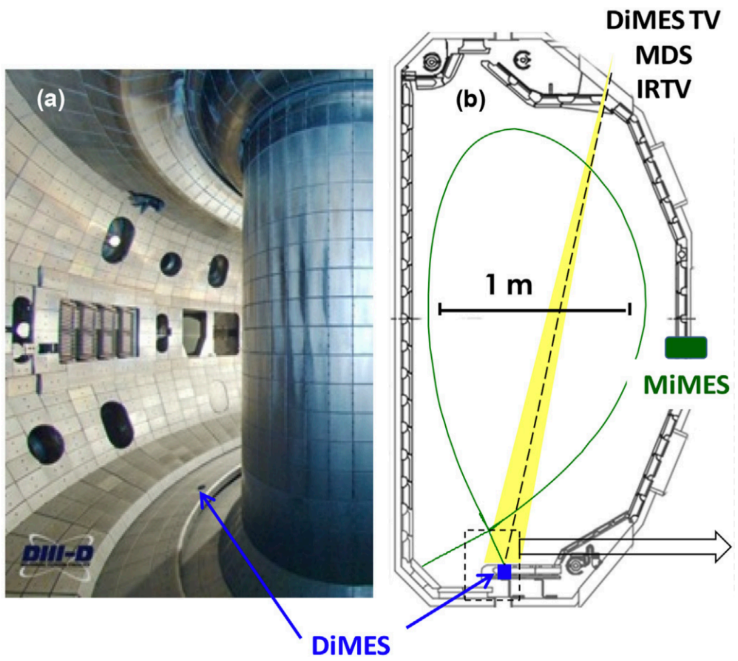
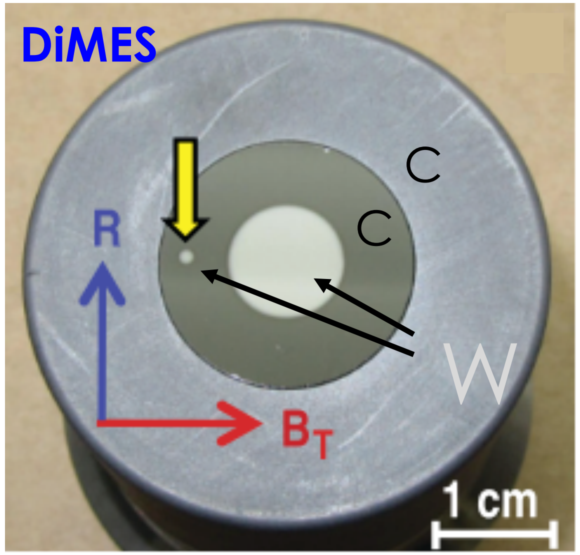
  - Strong dependence of fraction of redeposited W ξ_{redep} on R_{disk} when $R_{disk} \sim \lambda_{redep} \sim 1mm$
  - **Reduced model for ξ_{redep} in good agreement with experimental measurements in various plasma conditions [2] and with comprehensive ERO model [3]…**

- **… but additional experiments required to provide <u>quantitative</u> assessment of critical parameters controlling W prompt redeposition and net erosion (W ionization rates and sheath width)**





[1] D. Rudakov *PS* 2014 [2] J.Guterl *PPCF* 2019 [3] R. Ding *NF* 2015

Conclusions

- **Sputtered neutral W are ionized within the electric sheath in divertor (Chodura sheath)**
  - W prompt redeposition scales with the ionization mean-free path over the sheath width
    - **New scaling law for W prompt redeposition**
    - **Reduction of W SXB coefficients at high plasma density**

- **W prompt redeposition mainly determined by W ionization rates, sheath width, and energy of sputtered W**
  - First-principle models available for the sheath width in divertor
  - But robust first-principle estimations of W ionization rates remain to be completed [1,2]

- **Experiments available in DIII-D divertor to analyze and assess validity of W ionization rates, sheath width, …**

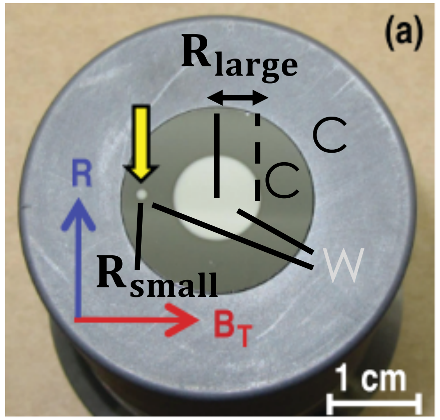
Thank you for your attention!

[1] R. T. Smyth *Phys. Rev. A* 2018
[2] C.A. Johnson *PPCF* 2019

GENERAL ATOMICS

Reduced Model of W Prompt Redeposition and Net Erosion in Agreement with Experimental Measurements of W Net Erosion in DIII-D

- **Experimental validation of model for W prompt redeposition and net erosion through comparison of net erosion from small and large W dots exposed in DIII-D divertor with DiMES[1]**



$$\frac{<\Gamma_W^{net}>_{\text{large disk}}}{<\Gamma_W^{net}>_{\text{small disk}}} = \frac{\cancel{\Gamma_W^{gross}}\left(1-\xi_{redep}\left(R_{large}\right)\right)}{\cancel{\Gamma_W^{gross}}\left(1-\xi_{redep}\left(R_{small}\right)\right)}$$

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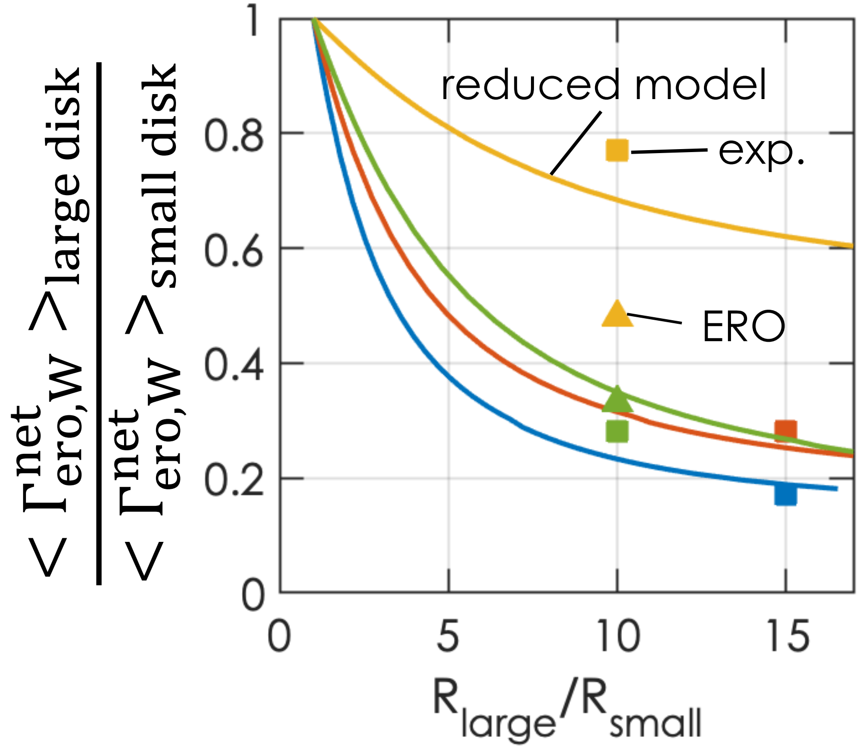

[1] D. Rudakov *PS* 2014 [2] J.Guterl *PPCF* 2019 [3] R. Ding *NF* 2015