Progress toward predictive modeling and in-situ monitoring of tungsten net erosion in tokamak divertor

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28th IAEA Fusion Energy Conference

May 10-15, 2021

DIII-D
NATIONAL FUSION FACILITY

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

GENERAL ATOMICS

Highlights

- Tungsten(W) prompt redeposition in tokamak divertor is mainly governed by the ratio of the ionization mean-free path of sputtered neutral W particles over the sheath width:
  - *New scaling law for W prompt redeposition with analytical formulation*
- The governing parameter of W prompt redeposition scales linearly with the magnetic field strength:
  - *W net erosion in the divertor region might significantly increase in fusion devices operating with high magnetic field*
- In-situ monitoring of net erosion of W impurities in divertors requires *monitoring photon emissions associated with the ionization of W impurities in charge states Z > 2+, typically W-III, W-IV and W-V for ITER*
- Parameter governing W prompt redeposition has similar values for divertor plasma conditions in DIII-D experiments and in ITER far-SOL:
  - *Experiments conducted at DIII-D to validate predictive modeling of W net erosion in ITER divertor and beyond*
    - Measurement of sheath width from erosion of carbon micro-spheres
    - Measurement of W net erosion through small/large dots experiments

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III. Scaling and dependency of W prompt redeposition with sheath and divertor plasma parameters

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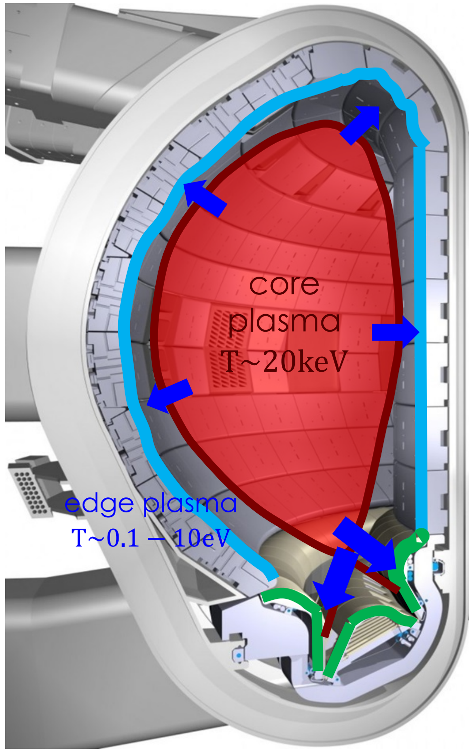
Exposure of W plasma facing components to extreme plasma conditions in divertors may limit performance and sustainability of fusion reactors



Divertor (W)

- **Divertors in ITER and future fusion reactors must handle large particle and heat fluxes during long plasma pulses, for instance in ITER[1]:**
  - High heat flux $\sim 10\ \mathrm{MWm^{-2}}$
  - High particle flux $\sim 10^{23} - 10^{24}\mathrm{m^{-2}s^{-1}}$
- Most of power dissipated through radiations in detached divertor plasma …
- … but ITER and future fusion reactors will likely operate with partially detached divertor plasma and maybe with small ELMs
- **Erosion of W plasma facing components caused by attached plasma conditions and transient plasma events may limit**
  - ***lifetime of W divertor***
  - ***core plasma performances*** (due to contamination by W impurities)

<u>Predicting and monitoring</u> erosion of tungsten plasma-facing components in divertor is critical to design and operate future fusion reactors!

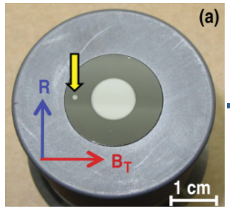
W net erosion from divertor PFCs largely determined by W prompt redeposition but no direct measurement available in tokamak divertors

W net erosion in divertor ≈ gross erosion x (1- prompt redeposition) x (1 – non-prompt local redeposition)

- gross erosion: Impurity fluxes + sputtering physics
  - **In-situ exp. measurements of W gross erosion (WI 400.9 nm +SXB)** [1,2]
    - BCA models (TRIM,SRIM,…)
- prompt redeposition: ionization physics + sheath physics
- non-prompt local redeposition: parallel impurity transport physics + cross-field impurity transport physics
- **No in-situ measurements of W deposition/transport**
  - Post-mortem analysis of W deposition on PFCs
  - Kinetic models (ERO,GITR,…)

Predictive model benchmarking ↔ DIII-D experiments

small/large dots experiment [1]



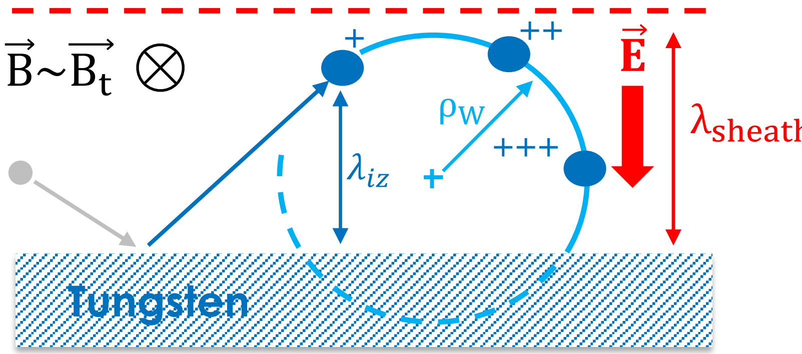
Metal ring experiment [2]

- **W prompt redeposition is usually large in attached plasma conditions and determines the overall W net erosion (prompt redeposition~1)**
- **No in-situ measurements available to monitor W prompt redeposition and net erosion**
- **Developing predictive models for W prompt redeposition in divertors is thus critical and requires to:**
  - → **understand physics processes governing W prompt redeposition**
  - → **validate predictive models of W prompt redeposition against experiments**

[1] D. Rudakov *Physica Scripta* 2014
[2] J. Guterl *Nuclear Fusion* 2019

Modeling of W prompt redeposition in presence of grazing magnetic field must include sheath effects and multiple ionizations of W

- Sputtered particle emitted from the material surface with Thompson energy distribution, cosine polar distribution and uniform azimuthal distribution
- Ionization of sputtered W near divertor surface due to collisions with electrons

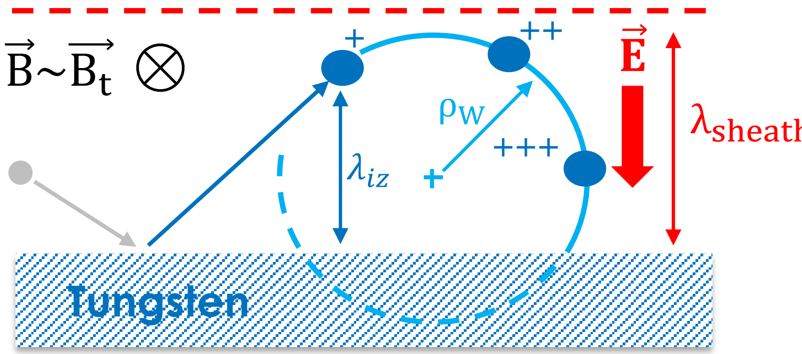


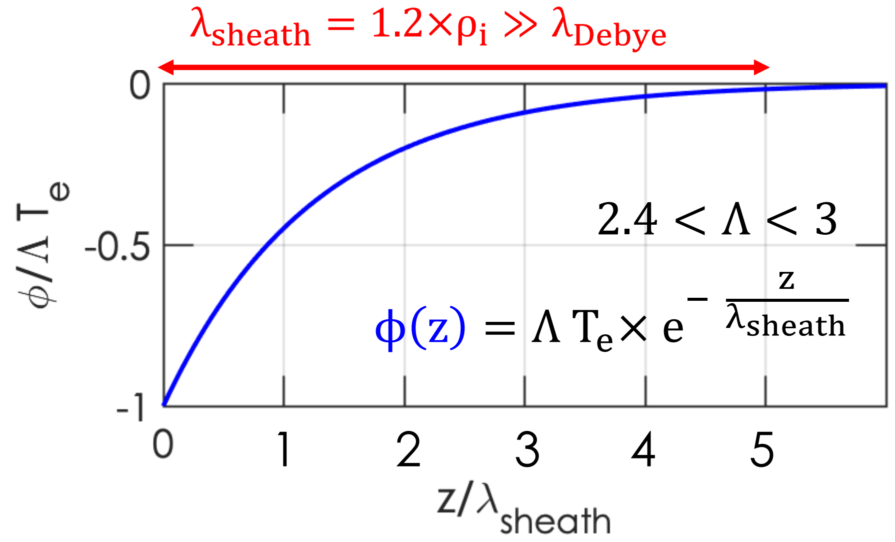
- **W prompt redeposition = redeposition of charged W impurities during their first gyration**
- **W prompt redeposition affected by multiple ionizations of W impurities & electric sheath**
- 3D trajectory of W impurities modeled by Monte-Carlo particle pusher with E and B fields embedded in ERO-D3D (HPC version of ERO[1])
  - Collisions of W impurities with plasma ion and neutral species negligible for W prompt redeposition in attached plasma conditions ($\tau_{collision}\omega_c \gg 1$)
- **Effects of electric sheath and multiple W ionizations on W prompt redeposition qualitatively described by Brooks[2] and Fussmann[3] in 90's …**
- **…but quantitative modeling of W prompt redeposition now required for ITER W divertor and beyond!**

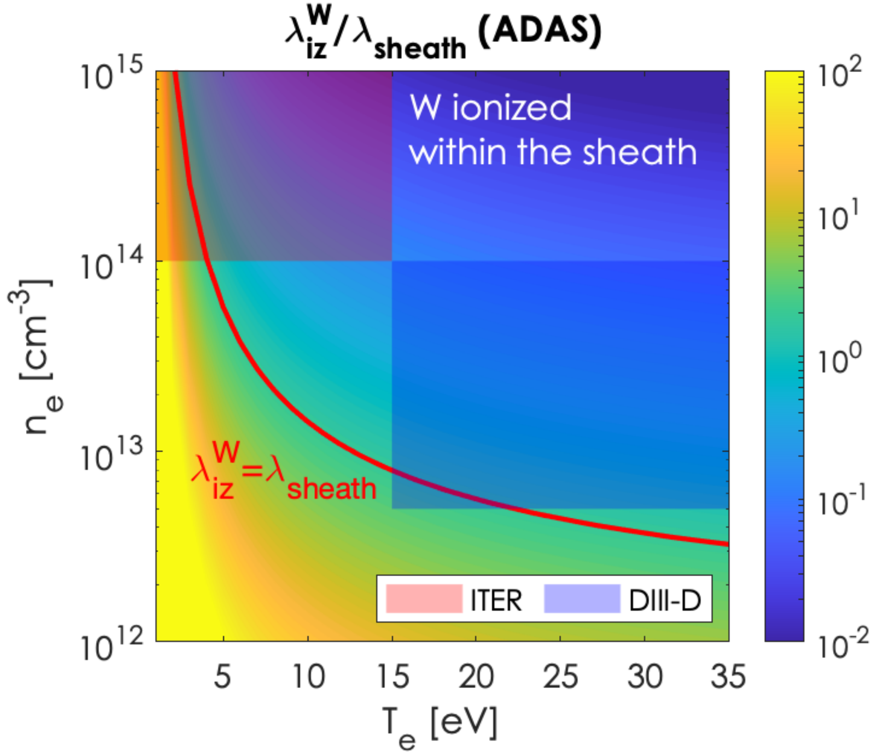
[1] A. Kirschner CPP 2016 [2] J.N. Brooks *Physics of Fluid* 1990 [3] G. Fussmann *Proc. 15th Int. Conf. IAEA* 1995

W impurities ionized within the sheath because of the large sheath width due to magnetic field lines intersecting divertor targets at grazing incidence

- **Wide electric sheath (Chodura sheath) due to grazing magnetic field (< 5°) in divertor[1]:** $\lambda_{sheath} \sim \rho_i$
- T_e constant in the sheath region
- Sheath electric potential profile provided by kinetic simulations [2,3]







- **In ITER and DIII-D:**

  → Sputtered neutral W ionized within the sheath :

$$\lambda_{iz} \lesssim \lambda_{sheath} \lesssim \rho_W$$

[1] D. Ryutov CPP 1996 [2] D. Coulette *PPCF* 2016 [3] D. Tskhakaya *JNM* 2015

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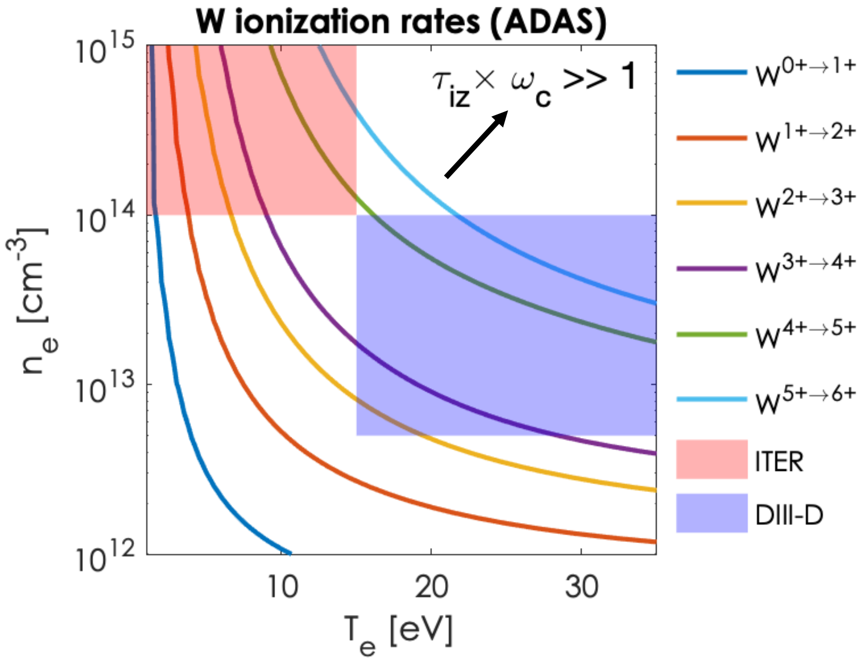
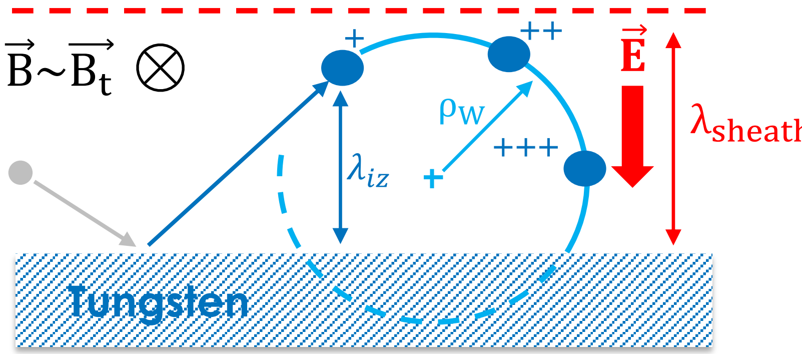
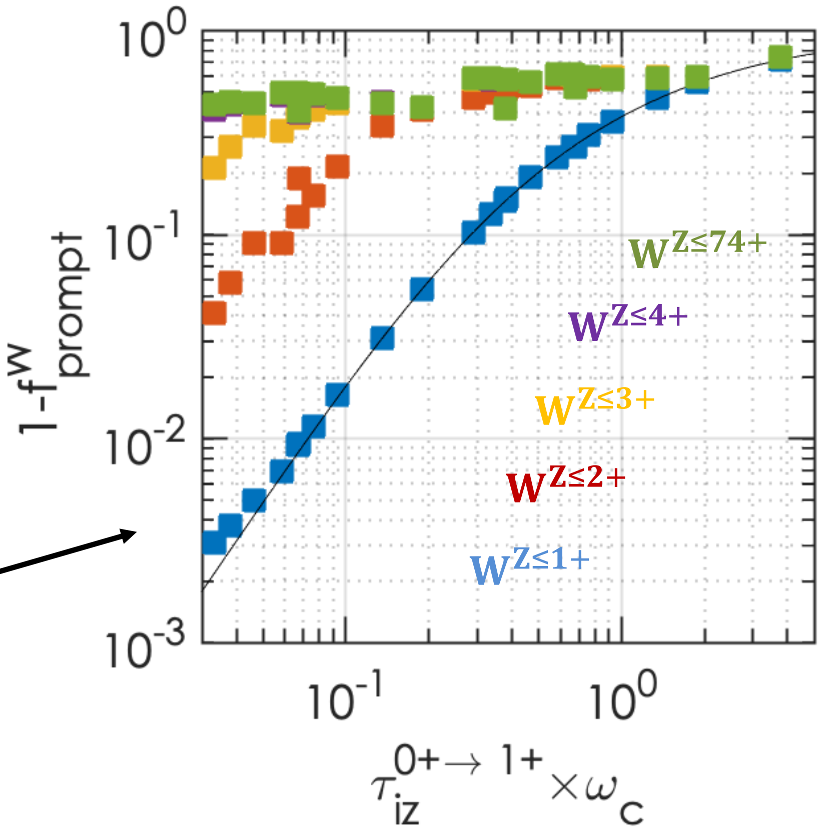
Strong reduction of W prompt redeposition due to multiple ionizations of sputtered W impurities near material surface

- **Multiple ionization of sputtered W near divertor surface** without the electric sheath







- **Multiple ionizations of W impurity are very effective to reduce W prompt redeposition**
- **Note that amount of promptly redeposited W significantly differs from prompt redeposition of impurity singly ionized during first gyration (e.g. prompt redeposition of C or Be impurity)**

W prompt redeposition strongly enhanced by the sheath electric field because of the large inertia of W impurity

- **When W ionized within the sheath ($\lambda_{iz} \lesssim \lambda_{sheath}$), W prompt redeposition affected by Chodura sheath due to:**
  - increase of λ_{iz} due to the decay of n_e in the sheath

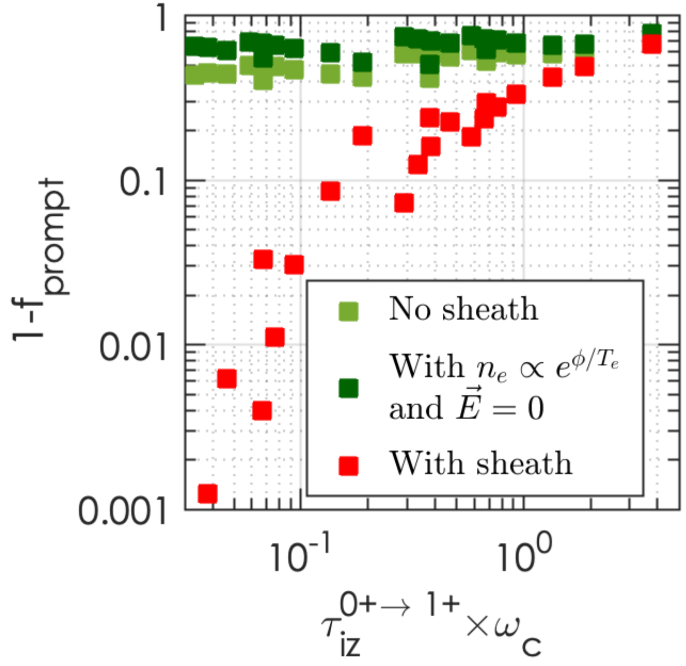
$$n_e(z) = n_{e,0} e^{\phi(z)/T_e}$$

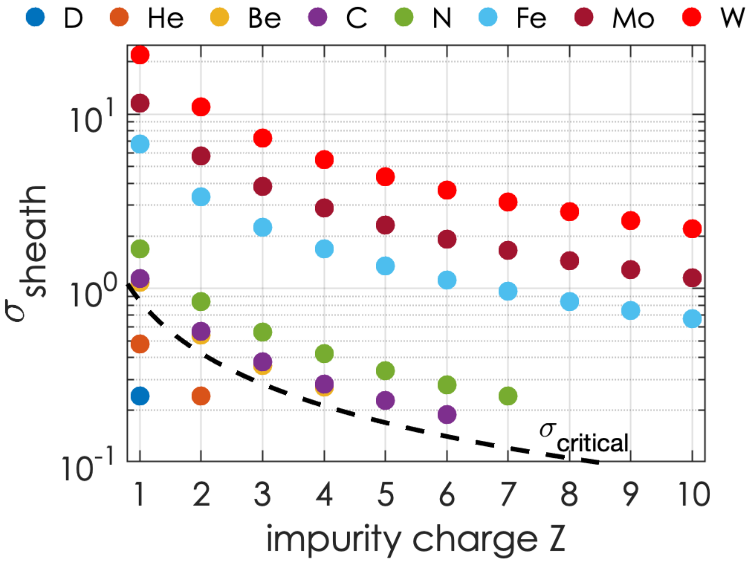
  - acceleration of impurity toward material surface by the sheath electric field

- **Sheath electric field strongly enhances W prompt redeposition and has stronger effects than multiple W ionizations and decay of n_e in the sheath**

- **Electric field remains much stronger than Lorentz force despite high W charge state due to large W mass**

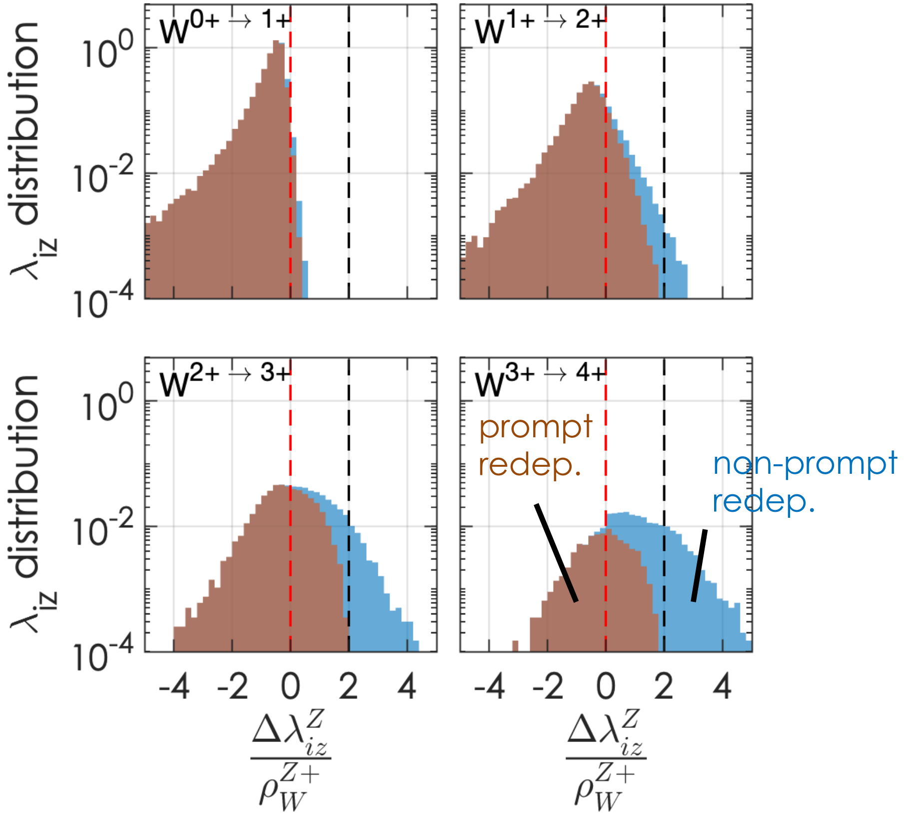
$$\sigma^{W}_{sheath} = \frac{Z\Lambda Te}{\frac{1}{2} m_W \omega_c^2 \lambda_{sheath}^2} > \sigma_{critical} = \left(\frac{E_{cutoff}}{E_{binding}}\right)/\Lambda Z$$

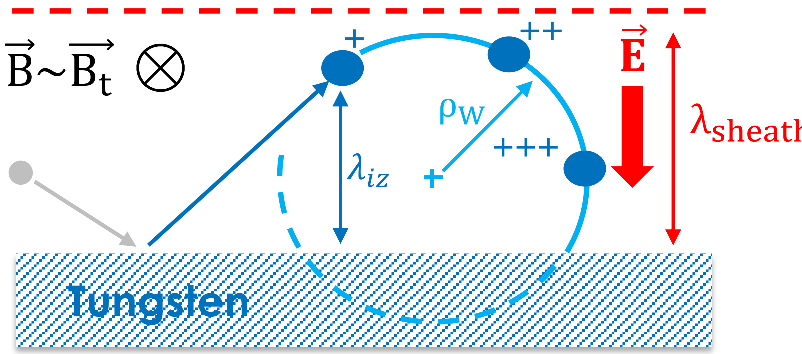


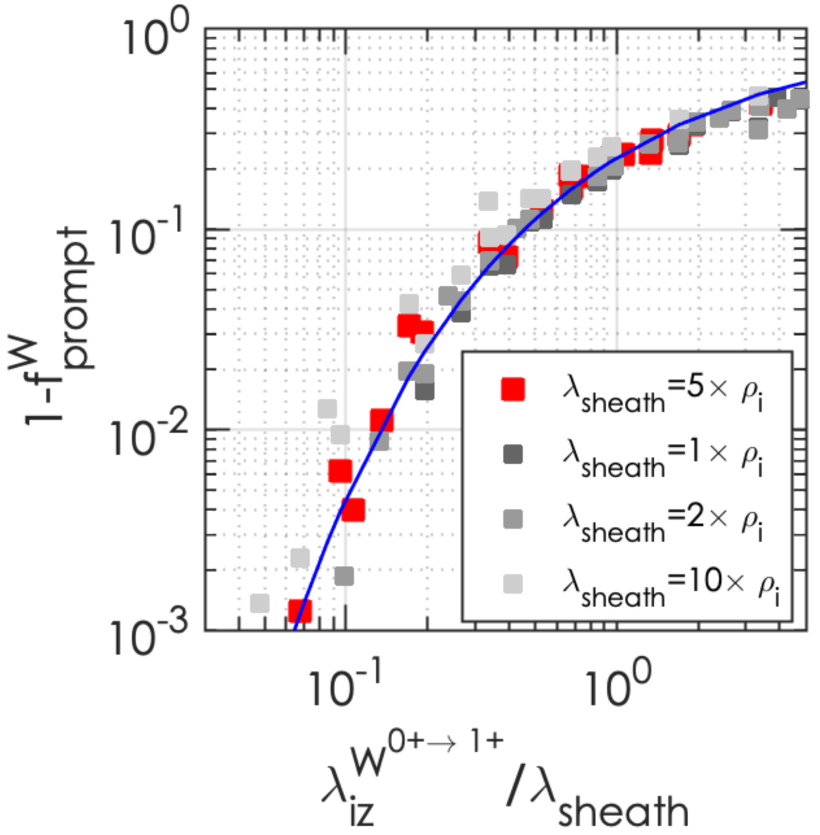


W prompt redeposition scales with the ratio of the neutral W ionization mean-free path over the sheath width

- **Only W impurity ionizing out of the sheath do not promptly redeposit because of the strong sheath electric field**







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

$$\frac{\lambda_{iz}^{0+\rightarrow 1+}}{\lambda_{sheath}} = \frac{<v_W> \tau_{iz}^{0+\rightarrow 1+}}{\lambda_{sheath}}$$

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New scaling law for W prompt redeposition with analytical formulation

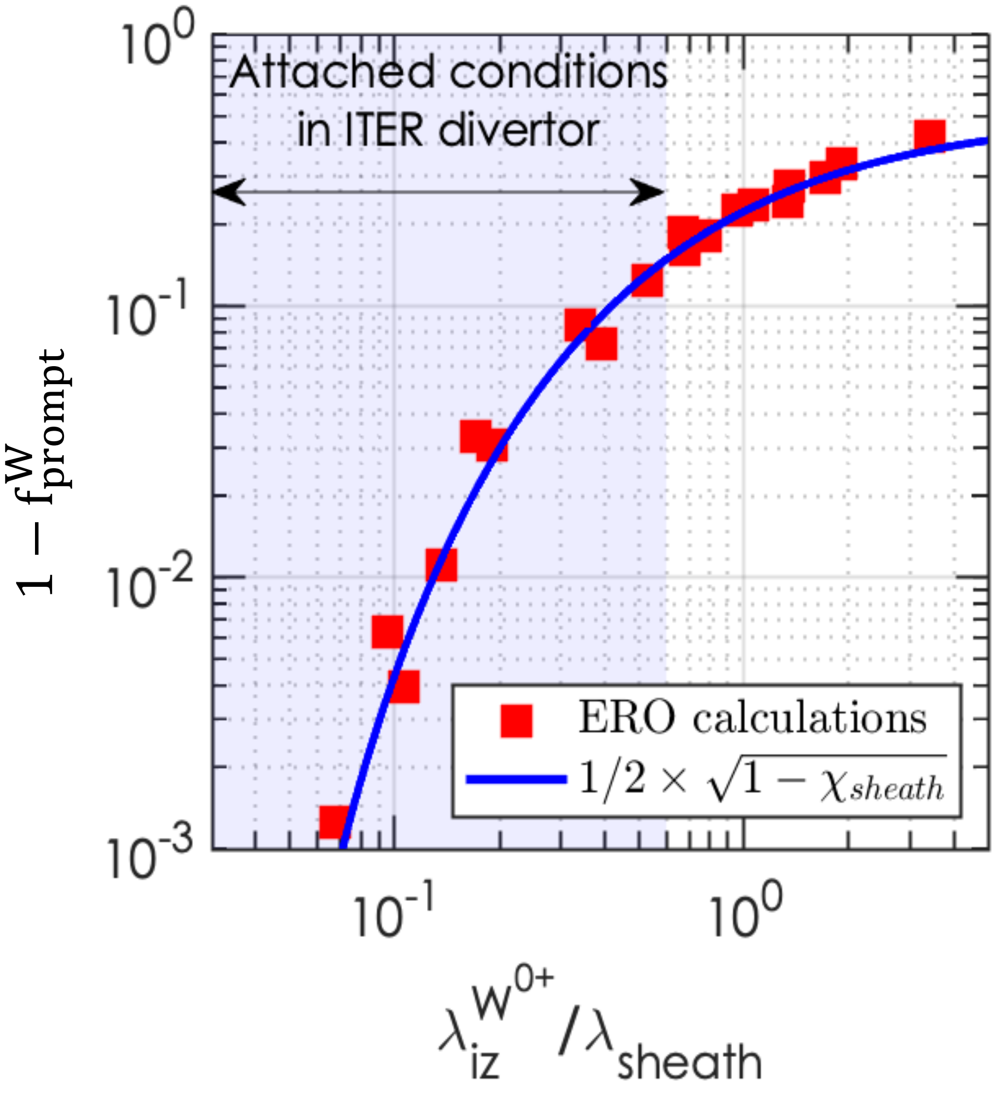
- **Consequently, the fraction $1-f^{W}_{prompt}$ of W impurities non-promptly redeposited is correlated to the fraction f^{W}_{sheath} of W impurities ionized within the sheath:**

$$1 - f^{W}_{prompt} \approx \tfrac{1}{2}\sqrt{1 - f^{W}_{sheath}}$$

- **f^{W}_{sheath} can be analytically expressed[1]:**

$$f^{W}_{sheath} = \int_0^{\left(\frac{\lambda_{iz}^{W^{0+\to1+}}}{\lambda_{sheath}}\right)^{-1}} \Upsilon_{\xi_c}(\eta_b)\, d\eta_b \text{ where } \xi_c = \frac{E_c}{E_b}$$

- **New robust analytical scaling law for W prompt redeposition[2]**
- **Tungsten prompt redeposition governed by:**
  - $\lambda_{iz}^{W^{0+\to1+}}$: tungsten ionization rates
  - λ_{sheath}: width of the sheath
  - E_c: tail of the energy distribution of sputtered W particles, determined by energy of particles impinging on W PFCs



[1] J. Guterl CPP 2020 [2] J. Guterl NME 2021

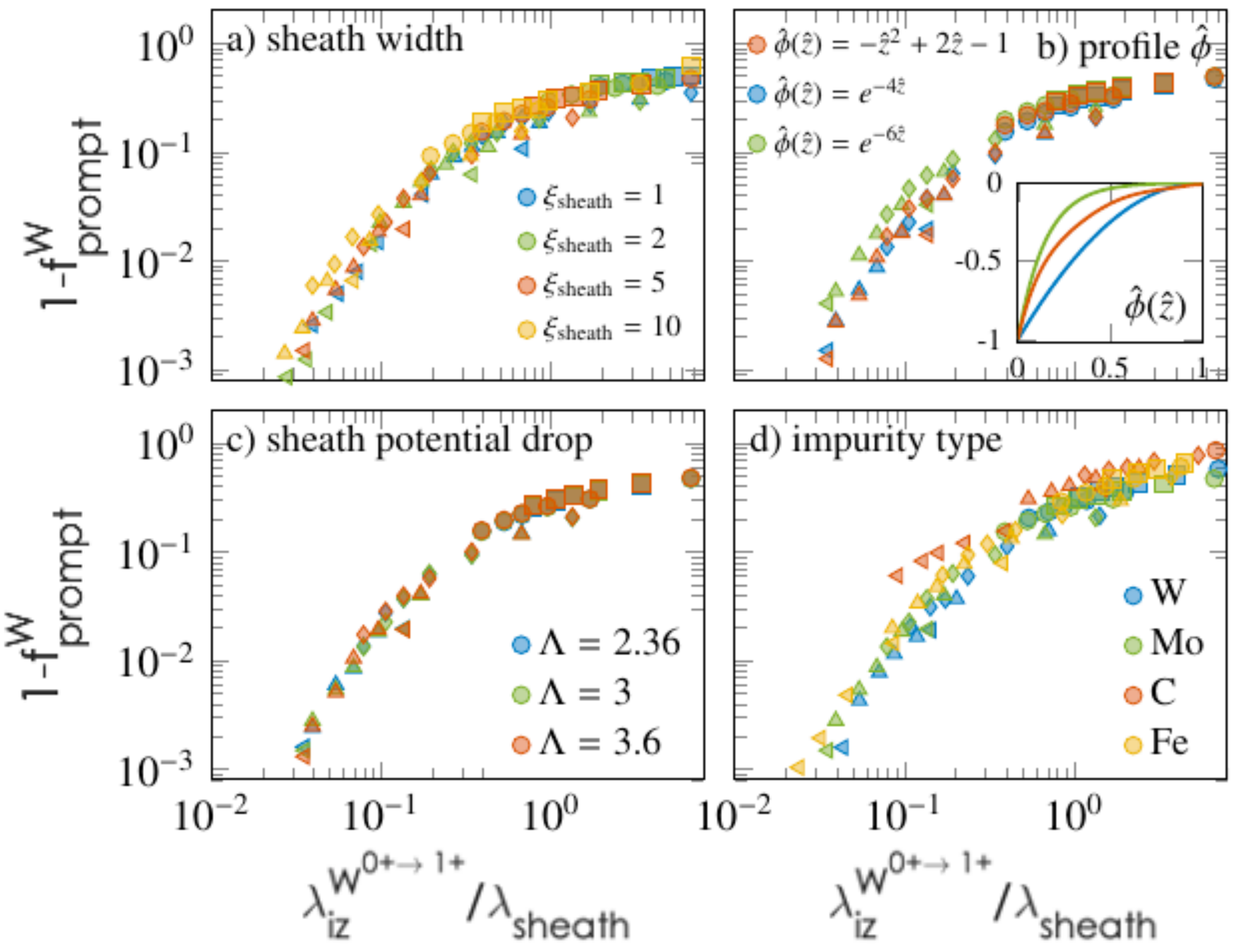
Scaling law for W prompt redeposition robust against uncertainties of the sheath model

- **Robust scaling law for W prompt redeposition against uncertainties in sheath model:**
  - **sheath width**
  - **electric potential profile**
  - **electric potential drop**

- **Robust scaling law for prompt redeposition of heavy impurities in the regime**

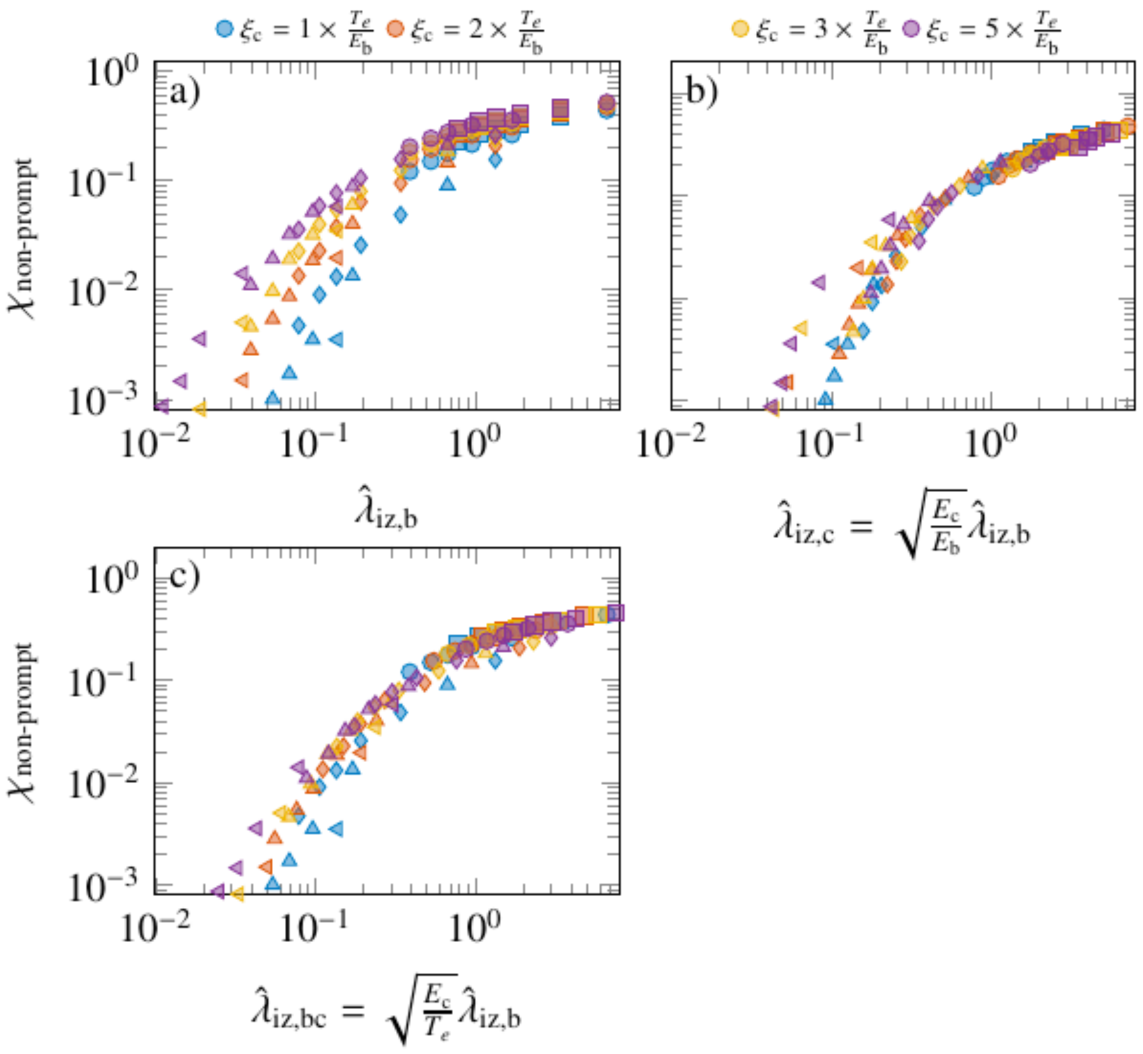
$$\sigma_{sheath} \gg \sigma_{critical}$$

- **Departure of prompt redeposition from scaling law for low-Z impurities for which $\sigma_{sheath} \sim \sigma_{critical}$**



W prompt redeposition strongly depends on the tail of the energy distribution of sputtered W particles

- **Sputtered tungsten impurities emitted with a Thompson energy distribution**
- **W prompt redeposition strongly influenced by the cutoff energy E_c of the Thompson energy distribution**
- **W prompt redeposition strongly affected by the tail of the energy distribution of sputtered W particles, which itself depend on the energy distribution of particles impinging on W PFCs**



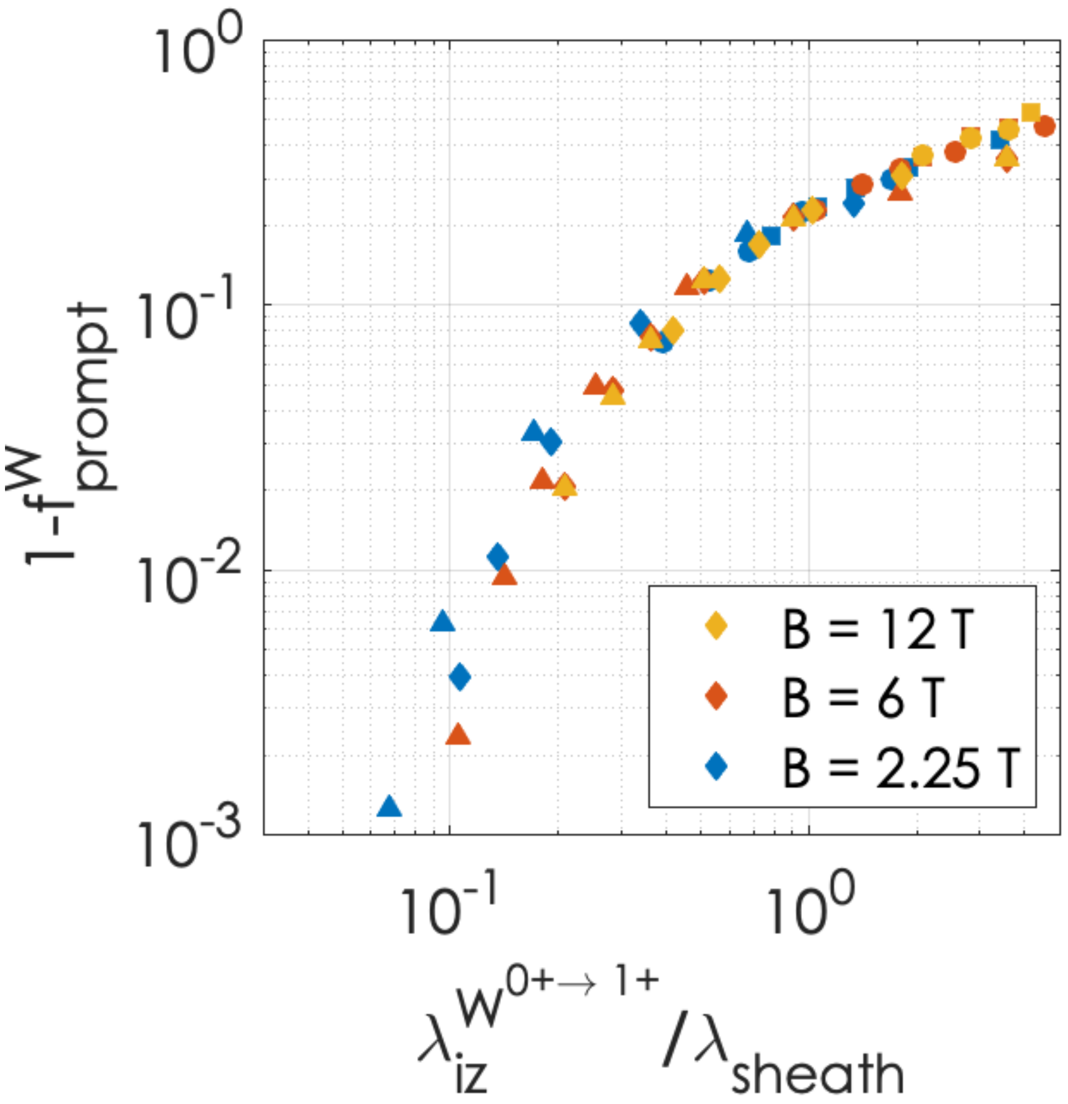
W net erosion may be significantly higher in fusion devices operating at high magnetic field

- **Ionization mean-free path over sheath width scales linearly with the magnetic field strength B:**

$$\frac{\lambda_{iz}^{W^{0+\rightarrow 1+}}}{\lambda_{sheath}} \sim \mathbf{B}$$

→ **W prompt reduction reduced as B increases**

- **W net erosion expected to be significantly higher in fusion devices operating with high magnetic field (e.g. SPARC) than in fusion devices with low magnetic field (ITER) for similar attached divertor conditions**



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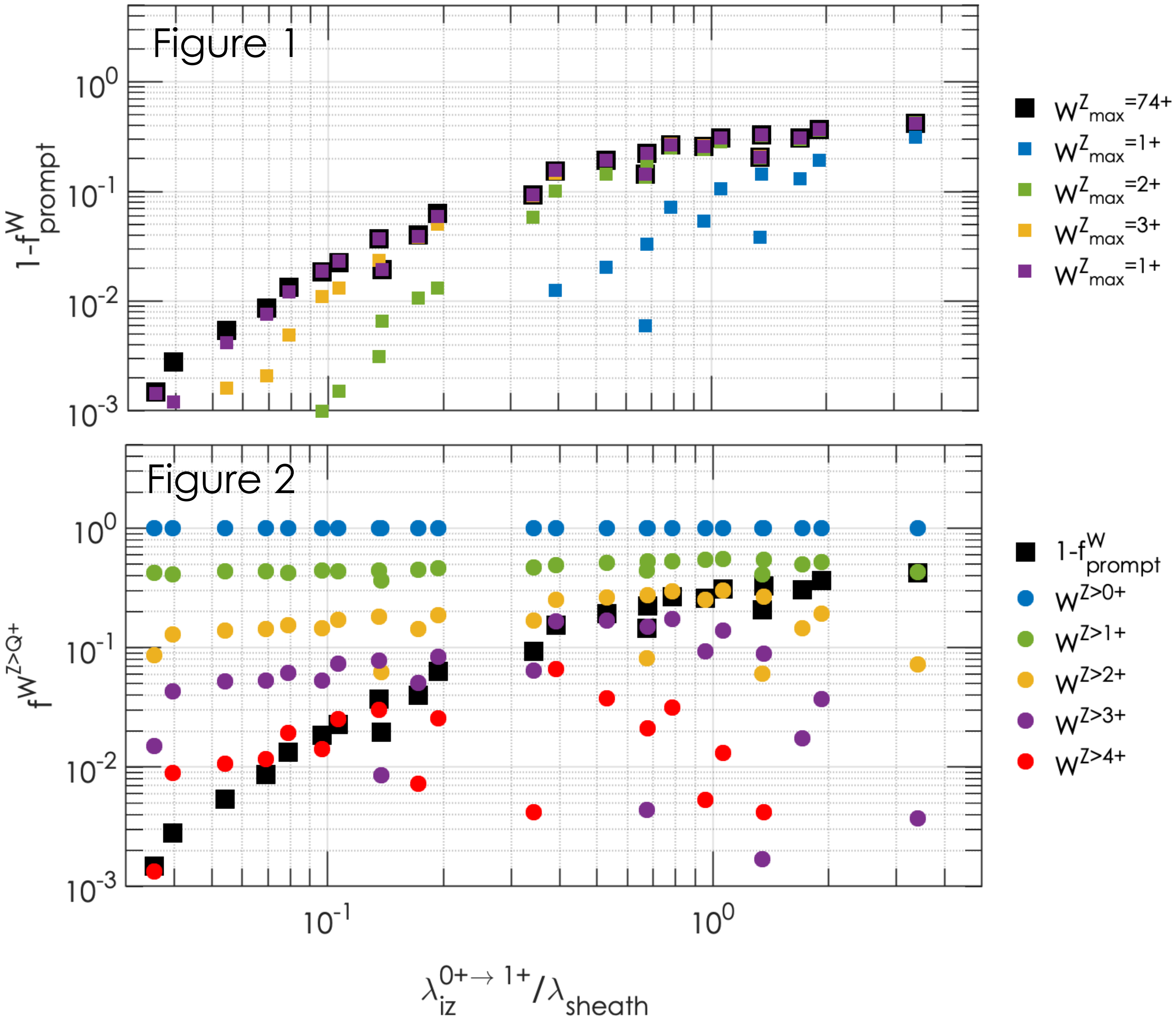
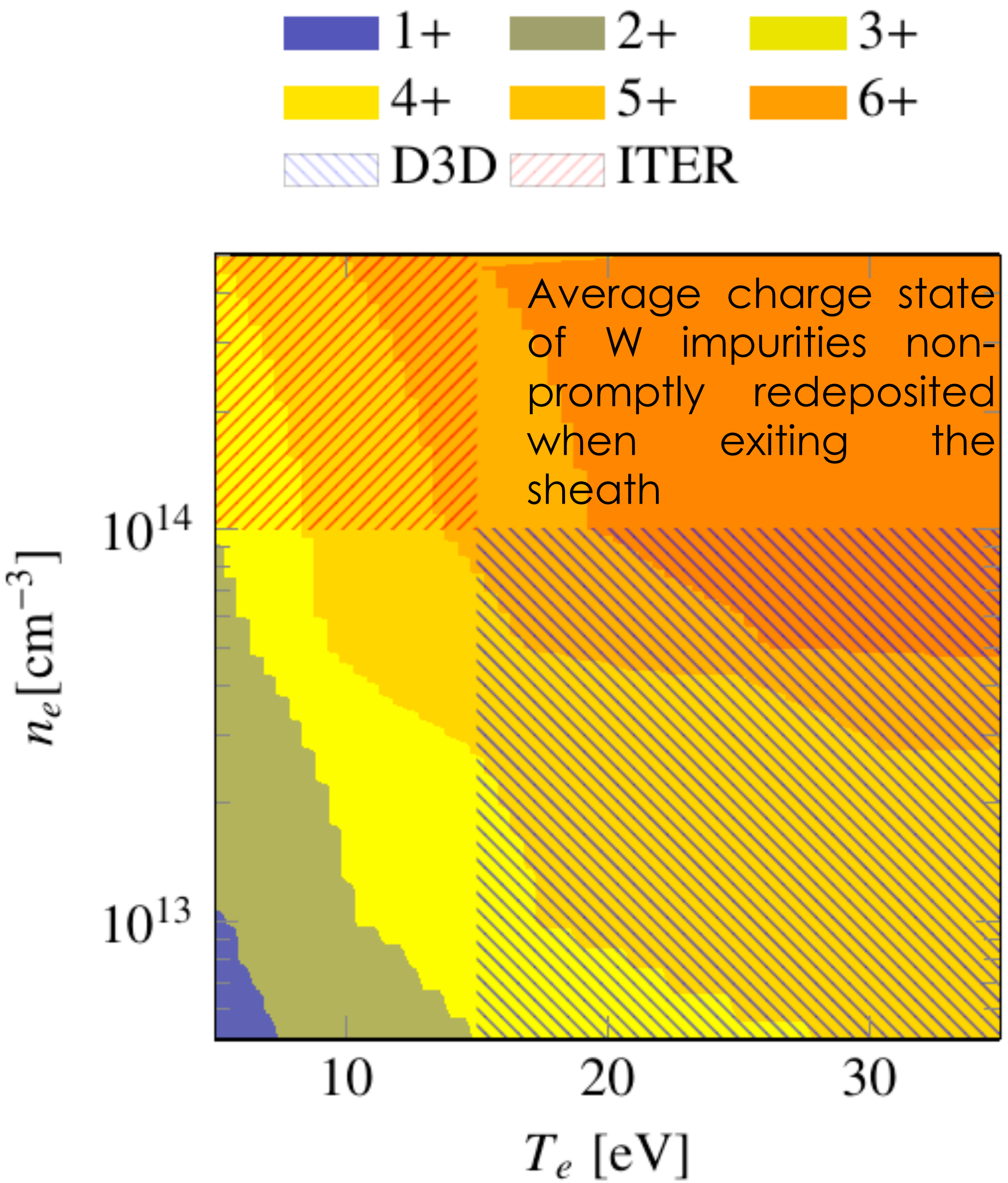
W prompt redeposition not directly correlated to the multiple ionizations of W impurities during their first gyro-orbit

- **In-situ monitoring of tungsten net erosion not possible through the sole monitoring of W gross erosion in divertors because of the large prompt redeposition of W**
- **Multiple ionizations of W impurities during their first gyro-orbit critical to allow W impurities to escape the sheath region and avoid prompt redeposition (fig. 1)**
- **No global correlation between tungsten prompt redeposition and W ionization events across divertor conditions (fig. 2) !**



In-situ monitoring of W net erosion in ITER divertor requires spectroscopic measurements of emissions from W-III, W-IV and W-V lines

- **In absence of global correlation between ionizations and prompt redeposition of W impurities, spectroscopic measurement of multiple emission lines required to monitor W net erosion**
- **In-situ monitoring of W net erosion only possible through spectroscopic measurements of W-III, W-IV and W-V emission lines**
- **Dominant charge-states for non-promptly redeposited W impurities expected to be similar in current tokamaks, e.g. DIII-D, and in future fusion devices (ITER) operating at higher divertor plasma density**



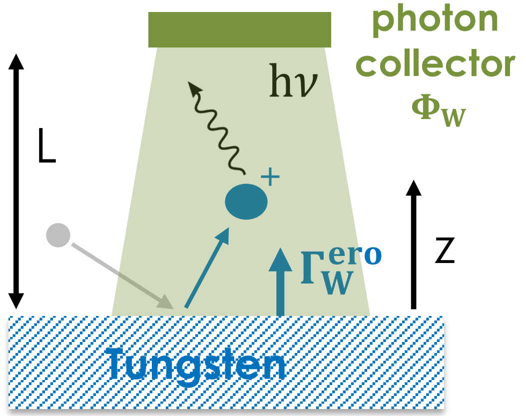
In-situ monitoring of W erosion through S/XB coefficients strongly affected by the ionization and emission of sputtered W impurities within the sheath region

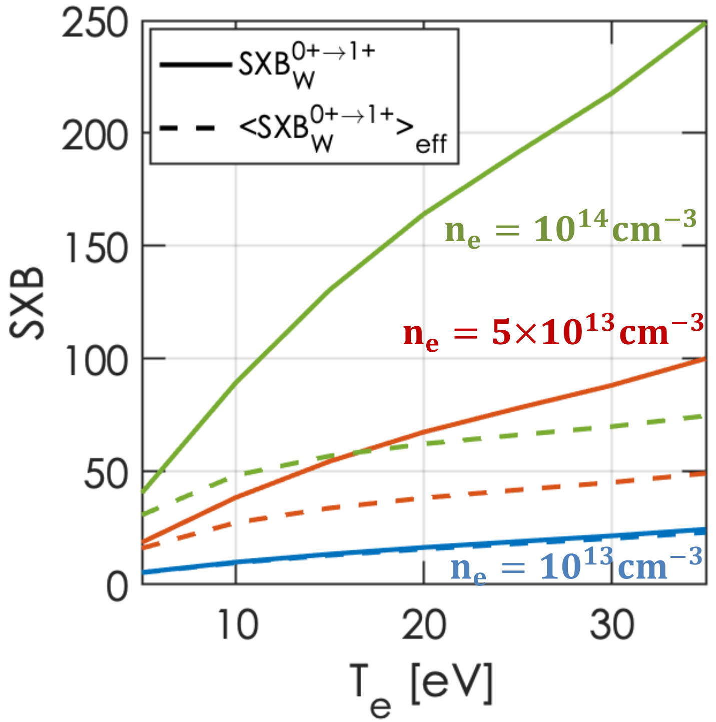
- **W gross erosion flux given by** $\Gamma_W^{ero} = \int_0^L S_{iz}^{W^{0+}\to W^{1+}}(T_e, n_e)\, n_{W^{0+}}\, n_e\, dz$
- Introducing the photon emissivity coefficient $\sigma_{photon}^{W^{0+\to1+}}$, W gross erosion flux can be inferred using the S/XB coefficient[1]

$$\Gamma_W^{ero} = \int_0^L \underbrace{\frac{S_{iz}^{W^{0+\to1+}}(T_e,n_e)}{\sigma_{photon}^{W^{0+\to1+}}(T_e,n_e)}}_{S/XB^{W^{0+\to1+}}} \times \underbrace{\sigma_{photon}^{W^{0+\to1+}}(T_e,n_e)\, n_{W^{0+}} n_e dz}_{\Phi_W}$$

- It is usually assumed $\lambda_{sheath} < \lambda_{iz}^{W^{0+\to1+}}$, such that $\Gamma_W^{ero} = S/XB^{W^{0+\to1+}} \times \Phi_W$
- **But when** $\lambda_{iz}^{W^{0+\to1+}} < \lambda_{sheath}$, $\Gamma_W^{ero} = \underbrace{\frac{\int_0^L S_{iz}^{W^{0+\to1+}}(T_e,n_e(z))\, n_{W^{0+}}(z) n_e(z)\, dz}{\int_0^L \sigma_{photon}^{W^{0+\to1+}}(T_e,n_e(z))\, n_{W^{0+}}(z) n_e(z) dz}}_{<S/XB^{W^{0+\to1+}}>_{eff}} \times \Phi_W$

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

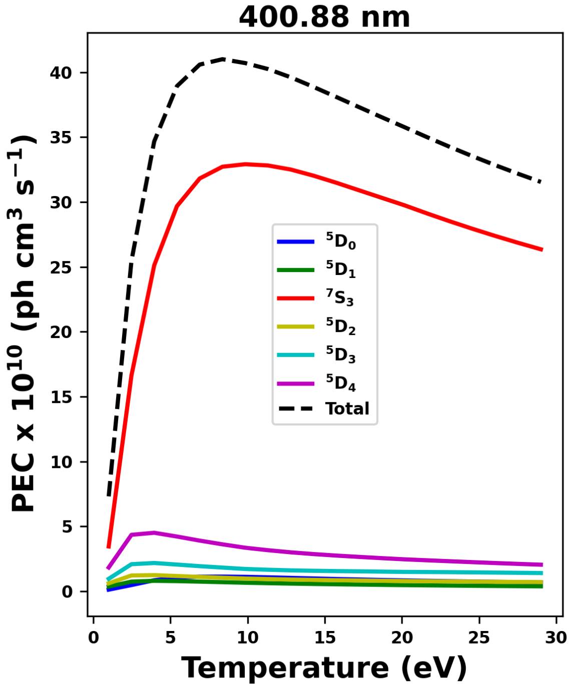


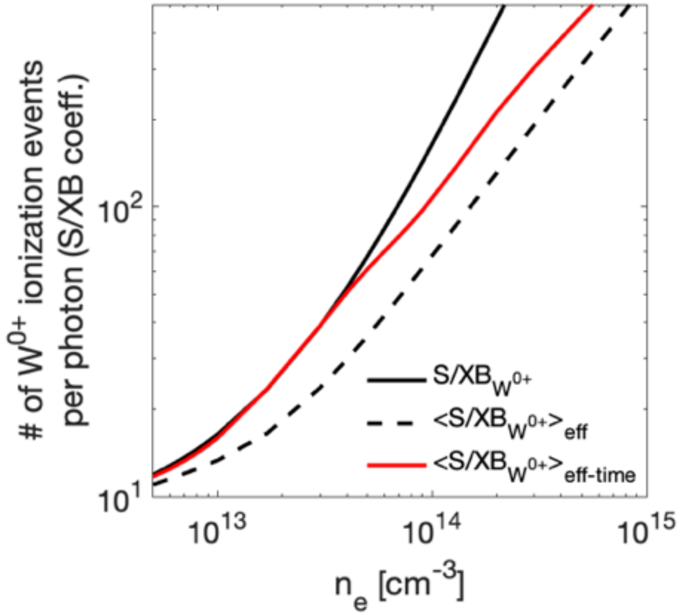


[1] K. Behringer PPCF 1989
[2] J. Guterl CPP 2020

Transient W metastable states also shown to impact S/XB coefficients

- Using excitation rates from a new non-perturbative Dirac R-matrix electron-impact calculation for WI[1] , it can be shown[3]:
  - **W I PECs for intense spectra lines are dominated by a single metastable level*,****
  - **Total value of the ionization coefficient for neutral tungsten is relativel insensitive to changes in the metastable fraction**





- Using the new collision-radiative solver ColRadpy[3] :
  - **Time dependent effective S/XBs can deviate significantly from steady-state due to non-equilibrium population of metastable state**

[1] Smyth *et al.* Phys. Rev. A 2018 [2]Johnson *et al. PPCF* 2020 [3] C. Johnson *et al. NME 2019* NME

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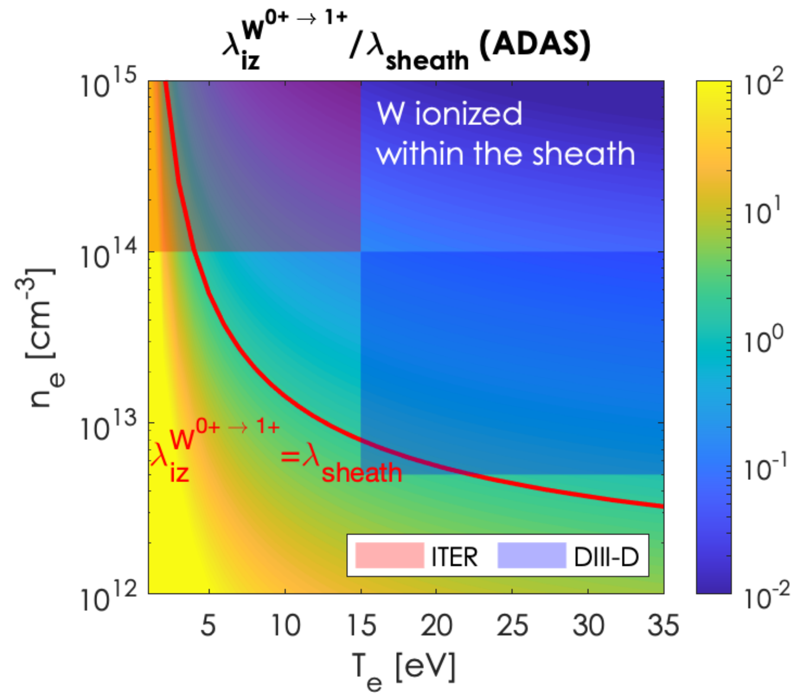
Predictive modeling for W net erosion in divertors can be validated with innovative experiments in DIII-D

- W prompt redeposition governed by the ratio of W neutral ionization mean-free path over the sheath width:

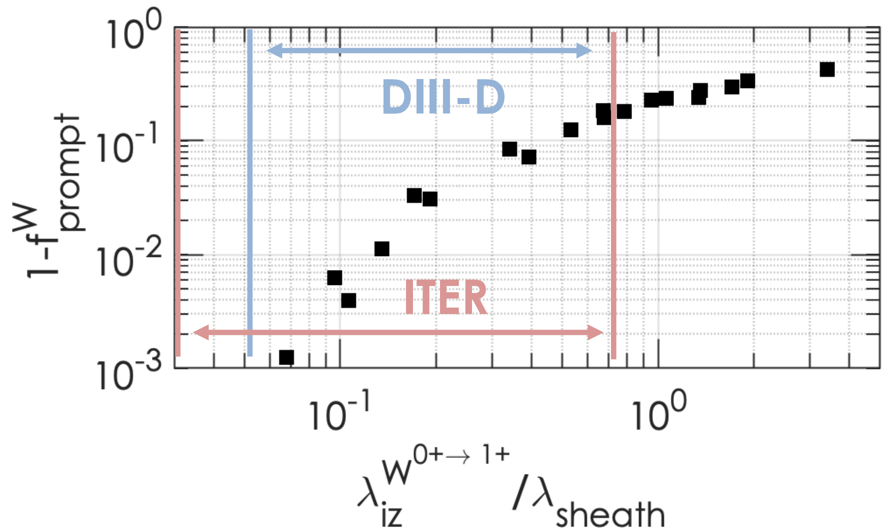
$$\lambda_{iz}^{W^{0+\rightarrow 1+}} / \lambda_{sheath}$$

- **Divertor plasma density in DIII-D lower than in ITER but values of $\lambda_{iz}^{W^{0+\rightarrow 1+}} / \lambda_{sheath}$ are similar:**
  - **Regime of W prompt redeposition similar for DIII-D and ITER divertor conditions**



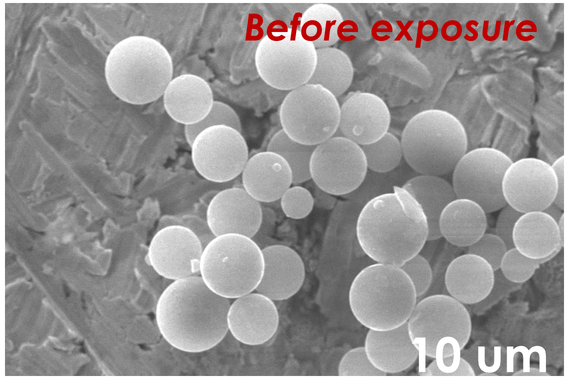
Innovative experiments conducted at DIII-D to validate predictive modeling of W net erosion and assess physics parameters governing W net erosion:

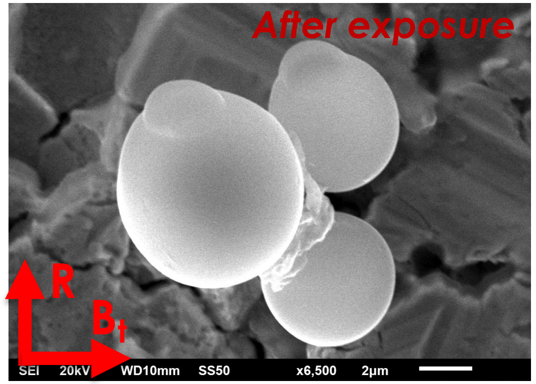
- Experimental estimations of the sheath width
- Direct measurement of W net erosion
- Spectroscopic measurements of W lines

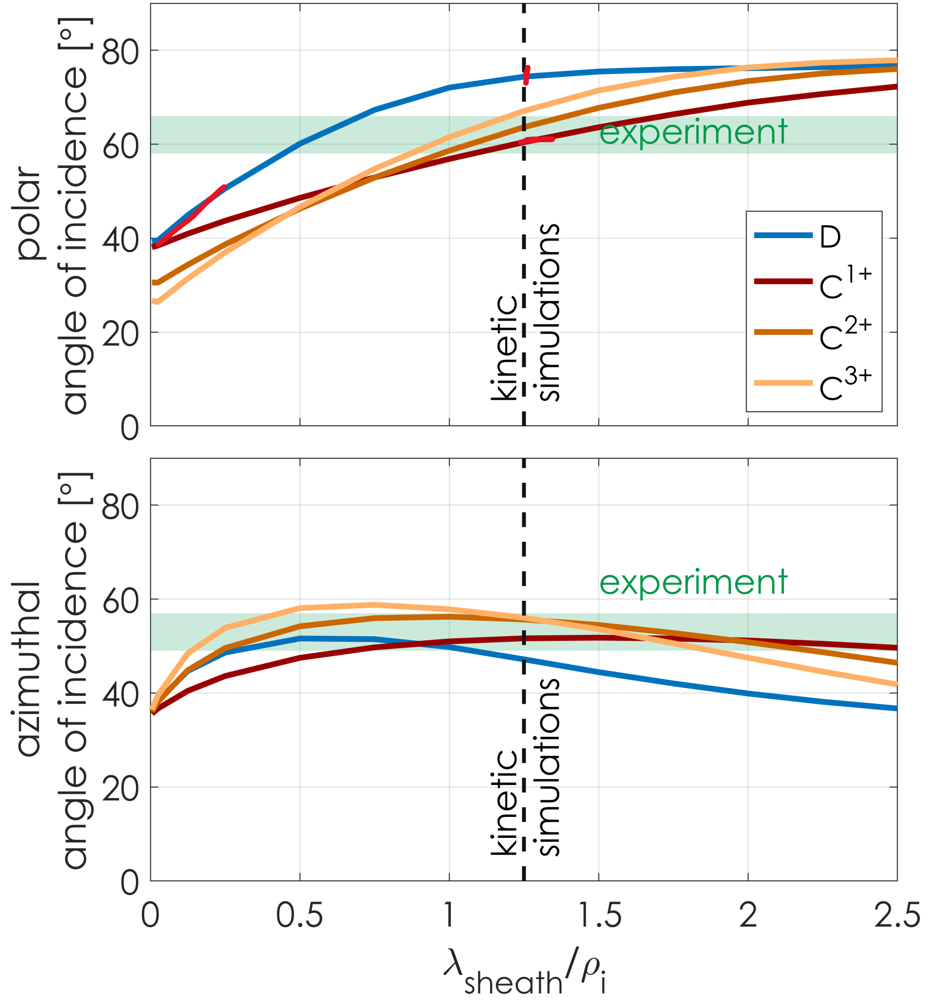


Experimental estimation of the sheath width in the DIII-D divertor from the erosion of carbon micro-spheres

- Sheath width λ_{sheath} at divertor targets numerically estimated with PIC and kinetic simulations[1]: $\boldsymbol{\lambda_{sheath} = 1.2 \times \rho_i}$
- **Innovative experiments conducted in DIII-D to assess the sheath width :**
  - Angles of incidence of C impurities on divertor target inferred from small C deposition caps observed on C micro-spheres after exposure
  - ERO simulations show that angle of incidence of carbon impurities mainly determined by sheath width







- **λ_{sheath} inferred from the measurement of the angle of incidence of C ions impinging on divertor target in excellent agreement with kinetic simulation[1] of the sheath on divertor targets!**
- **Similar experiments conducted with micro-trenches**

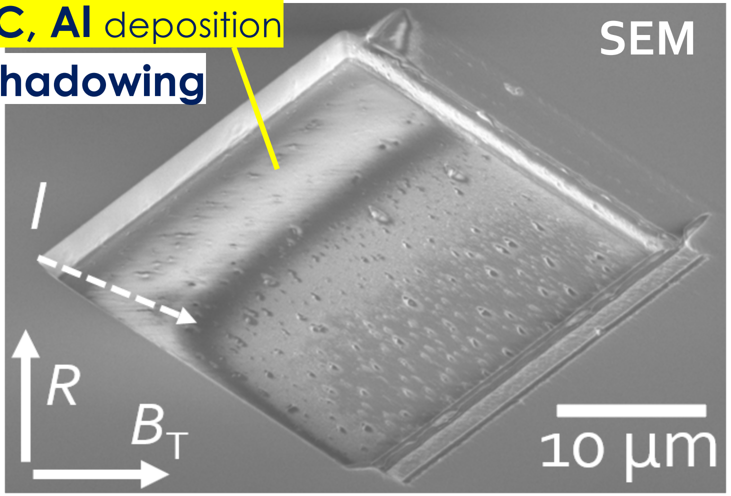
[1]D. Coulette *PPCF* 2016

Experimental Verification of Ion Impact Angle Distributions (IADs) using Micro-trench samples [Princeton U.]

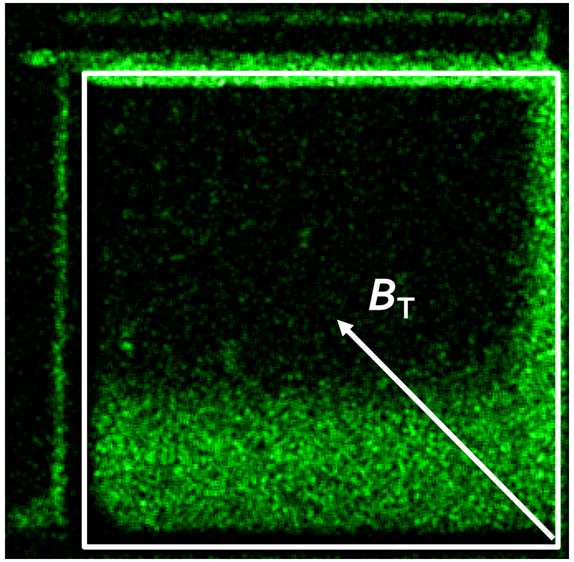
D plasma (L-mode): $T_e \sim 30$ eV, $n_e \sim 10^{13}$ cm^{-3}

Polar peak ~ 79-86° (*B*=88.5°)
Azimuthal peak ~ -35° (B_t=0°)

Micro-trenches (Si)
30x30x2-4 μm deep

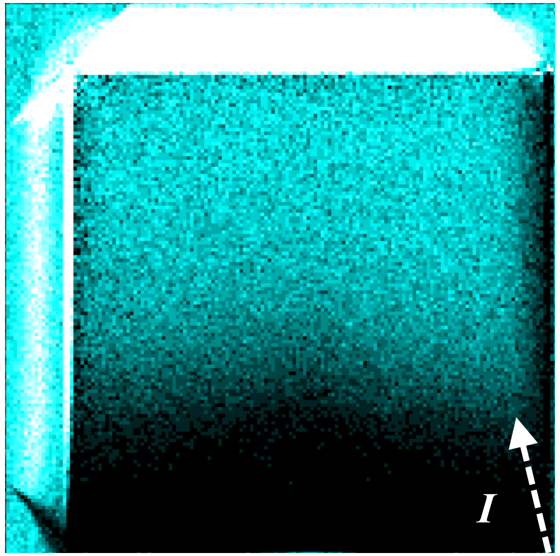


Deposition profile (EDS)



COMPARISON

Net erosion profile
by **MPR**† (calculation)



INPUT

Calculated IADs*

†A. Lasa and J. Coburn
https://github.com/ORNL-Fusion/MPR
*Chrobak et al., NF 2018

IAD verification by comparing C and Al deposition profiles with calculated net erosion profiles

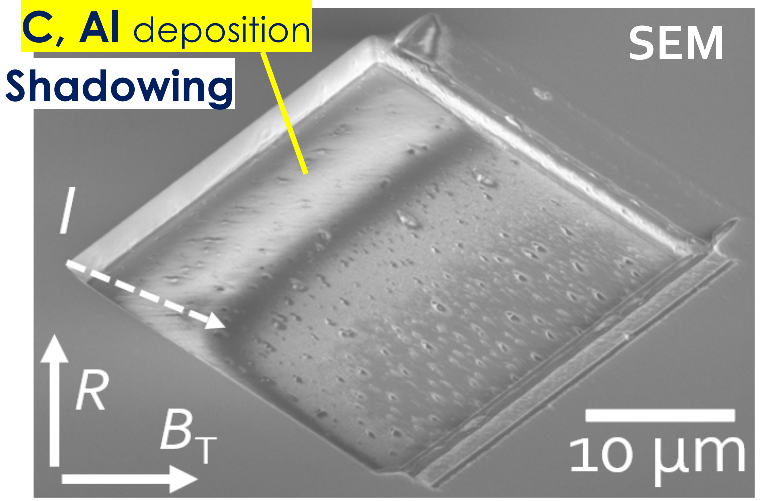
Experimental Verification of Ion Impact Angle Distributions (IADs) using Micro-trench samples [Princeton U.]

[S. Abe, C.H. Skinner et al., Nucl. Mater. Energy, (2021) submitted]

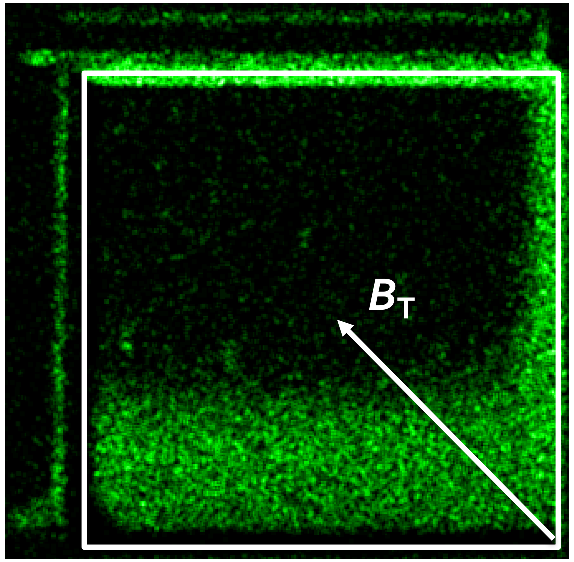
D plasma (L-mode): T_e ~ 30 eV, n_e ~ 10^{13} cm^{-3}

Polar peak ~ 79-86° (*B*=88.5°)
Azimuthal peak ~ -35° (B_t=0°)

Micro-trenches (Si)
30x30x2-4 μm deep

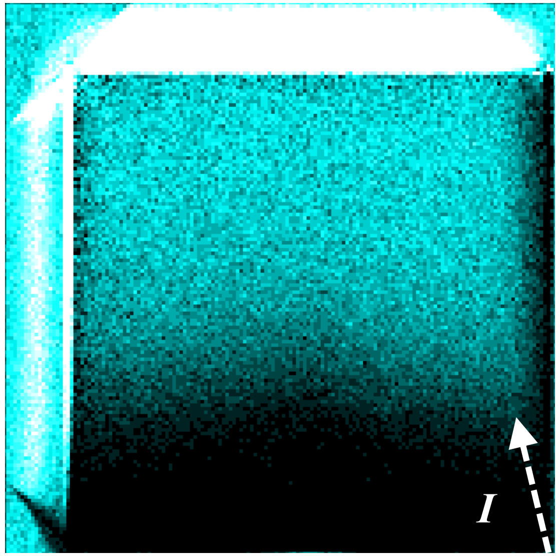


Deposition profile (EDS)



COMPARISON

Net erosion profile
by **MPR**†(calculation)



INPUT

Calculated IADs*

IAD verification by comparing C and Al deposition profiles with calculated net erosion profiles

†A. Lasa and J. Coburn
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*Chrobak et al., NF 2018

Experimental validation of model for W prompt redeposition and net erosion in DIII-D divertor with DiMES

- The Divertor Material Evaluation System (DiMES) allows for exposure of material samples in the lower divertor of DIII-D under well-diagnosed plasma conditions

- Experimental estimations of W net erosion through small/large dots DiMES experiments in DIII-D[1,2]:

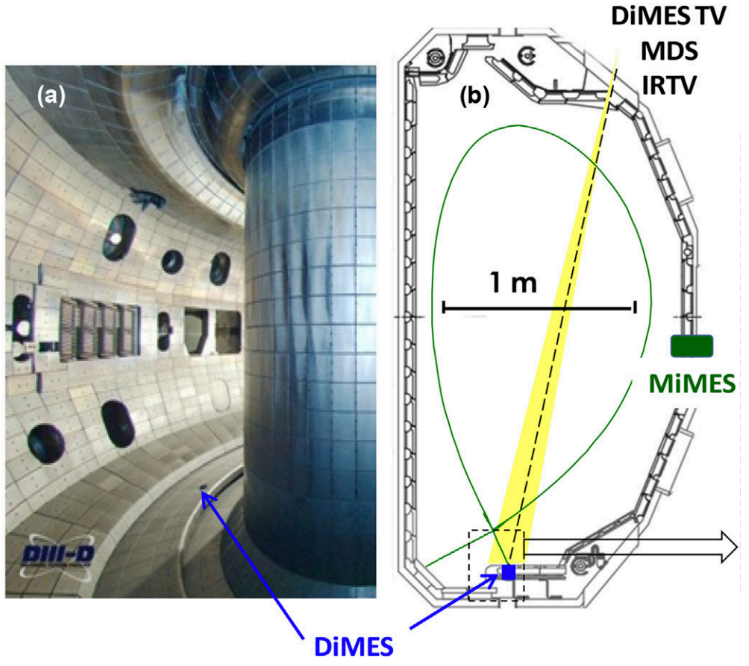
$$< \Gamma_W^{net} >_{R_{disk}} = \Gamma_W^{gross} \left(1 - \xi_{redep}(R_{disk})\right)$$

ξ_{redep}: Fraction of W redeposited on W sample

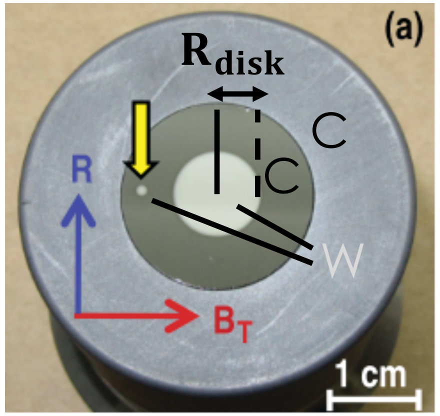
- Strong dependency of ξ_{redep} on R_{disk} when $R_{disk} \sim \lambda_{redep} \sim 1mm$

- **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**

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



DiMES with small and large W dots[1]



[1] D.Rudakov *Physica Scripta* 2014 [2] R. Ding *Nuclear Fusion* 2016

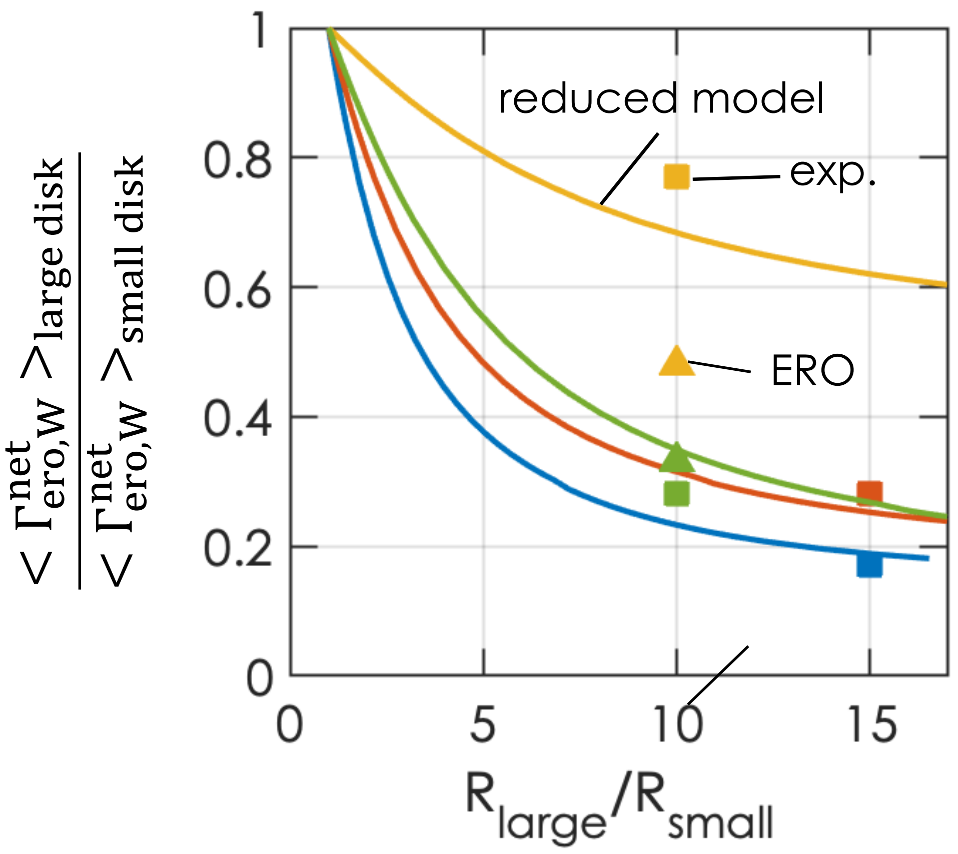
Reduced model of W prompt redeposition and net erosion in agreement with experimental measurements of W net erosion in DIII-D

- **Reduced model with few characteristic parameters $(\beta_{redep}, \lambda_{redep})$ developed to analyze small/large dots DiMES experiments**

W ionization rates, energy distribution, n_e, T_e, sheath, B field

$\beta_{redep}, \lambda_{redep}$

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



- **Reduced model in good agreement with experimental measurements in various plasma conditions and with comprehensive ERO model[1]**
- **Experimental framework available in DIII-D for quantitative assessment of critical parameters controlling W prompt redeposition and net erosion (W ionization rates, PEC)**

[1] J .Guterl PPCF 2019

Summary

- **Tungsten(W) prompt redeposition in tokamak divertors is mainly governed by the ratio of the ionization mean-free path of sputtered neutral W particles over the sheath width:**
  - ***New scaling law for W prompt redeposition with analytical formulation***
- **The governing parameter of W prompt redeposition scales linearly with the magnetic field strength:**
  - ***W net erosion from divertor PFCs might significantly increase in fusion devices operating with high magnetic field***
- **In-situ monitoring of W net erosion in divertors requires *monitoring photon emissions associated with the ionization of W impurities in charge states Z > 2+, typically W-III, W-IV and W-V lines for ITER***
- **Parameter governing W prompt redeposition has similar values for divertor plasma conditions in DIII-D experiments and in ITER far-SOL:**
  - ***Experiments conducted at DIII-D to validate predictive modeling of W net erosion in ITER divertor and beyond***
    - **Measurement of sheath width from erosion of carbon micro-spheres**
    - **Measurement of W net erosion through small/large dots experiments**