# Investigation of sputtering of RAFM steel in PISCES


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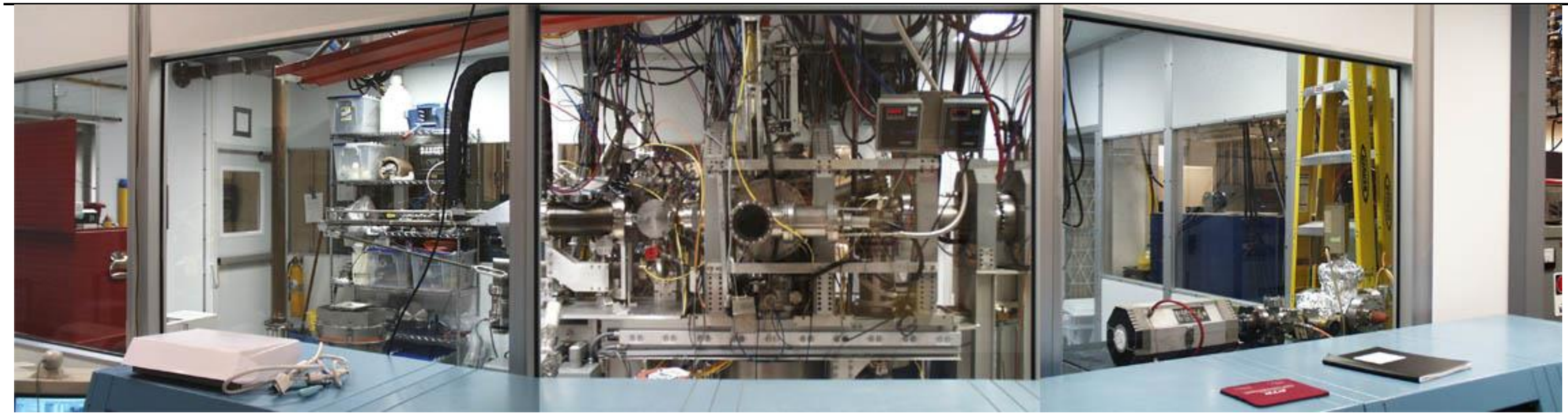
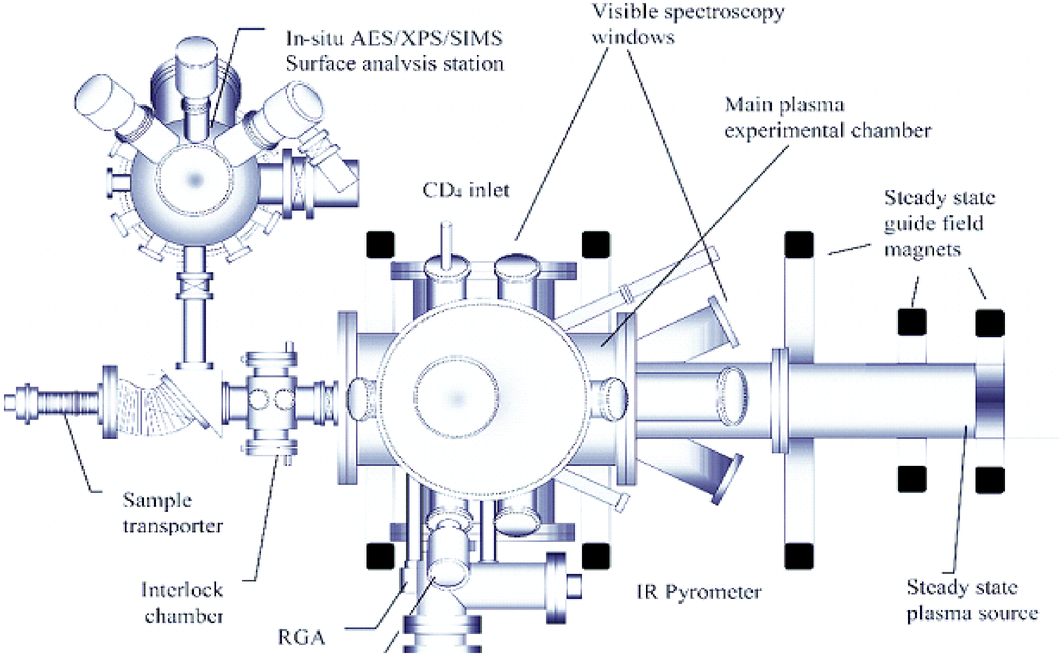
# The PISCES-B facility at UCSD



| | PISCES-B |
|---|---|
| **Ion flux (cm$^2$s$^{-1}$)** | **$10^{17}$–$10^{19}$** |
| **Ion energy (eV)** | **20–300 (bias)** |
| $T_e$ (eV) | 3–40 |
| **$n_e$ (cm$^{-3}$)** | **$10^{12}$–$10^{13}$** |
| **Be Imp. fraction (%)** | **Up to a few %** |
| **Pulse length (s)** | **Steady state** |
| PSI materials | C, W, Be |
| Plasma species | H, D, He |



# Motivation:

- Explore the possibility to use bare RAFM steel as plasma facing material on the main vessel wall of DEMO
- The limiting factor is the erosion life time of bare steel. Rough erosion estimate (ITER) yields ~5 cm/year at the first wall. Needs reduction by factor 10
- Nuclear steels contain typically 0.5-1 at% W (EUROFER, RUSFER, F82H(Japan))
- Investigate the influence of W on the erosion yield of RAFM steel at energies close to the threshold energy for W sputtering
- Study low energy, high fluence erosion of RAFM steel in PISCES
- Study fundamental aspects of preferential sputtering in the simple Fe-W system on deposited layers on C
- Modelling of tungsten enrichment in EUROFER due to plasma erosion

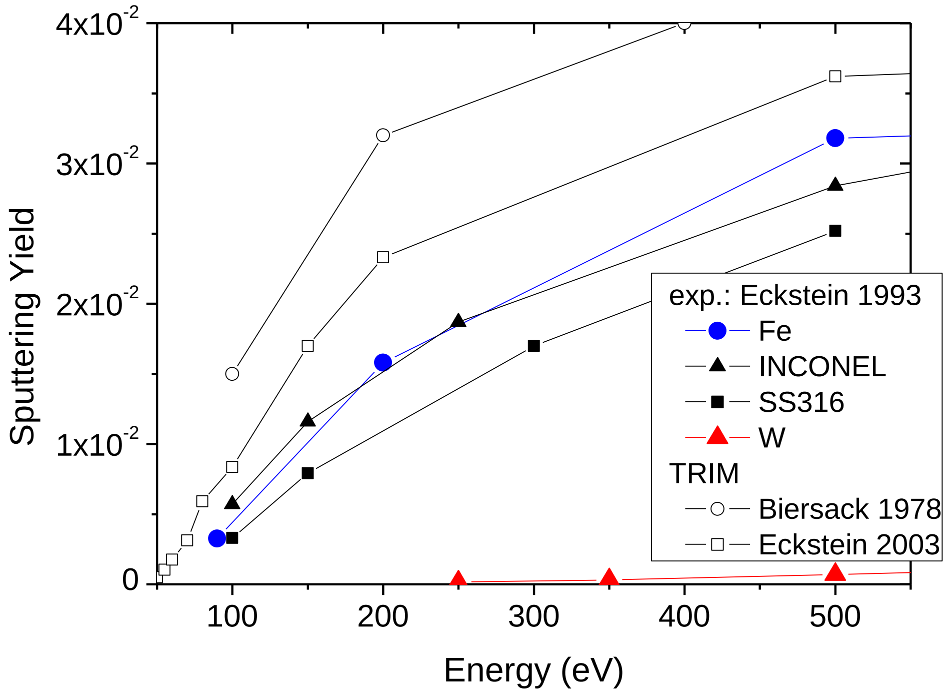
## Sputtering Yield of Fe and W in the threshold regime

**D threshold energies: Fe ~45 eV**

**W ~200 eV**

**The large difference in erosion yield close to the threshold energies may lead to strong modifications of the composition for Fe-W alloys:**

- **Enrichment of W**
- **Reduction of erosion yield**




**Composition of RAFM steels (in wt.%) (Fe is base material)**

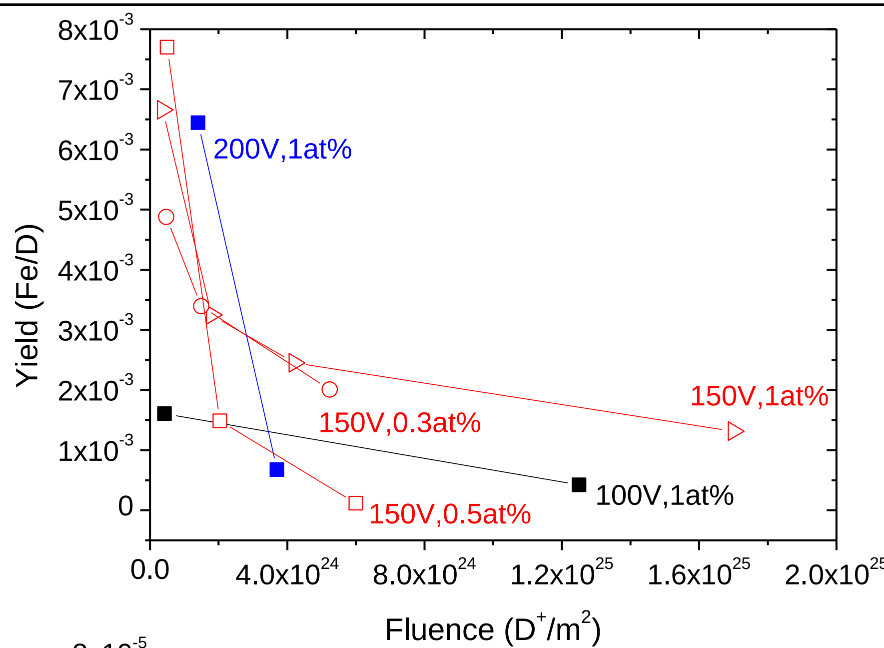
| | C | Cr | W | Mn | V | Ta | $N_2$ | P | S | $O_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Eurofer 97 | 0.09-0.12 | 8.5-9.5 | 1.0-1.2 | 0.2-0.6 | 0.15-0.25 | 0.10-0.14 | 0.015-0.045 | 0.004-0.005 | 0.003-0.004 | 0.0013-0.0018 |
| F82H (Japan) | 0.09 | 7.7 | 1.94 | 0.16 | 0.16 | 0.02 | 0.006 | 0.002 | 0.002 | 0.01 |

# Erosion of the Fe/W layers determined by RBS

**Fluence dependence of Fe erosion for different initial W concentrations:**

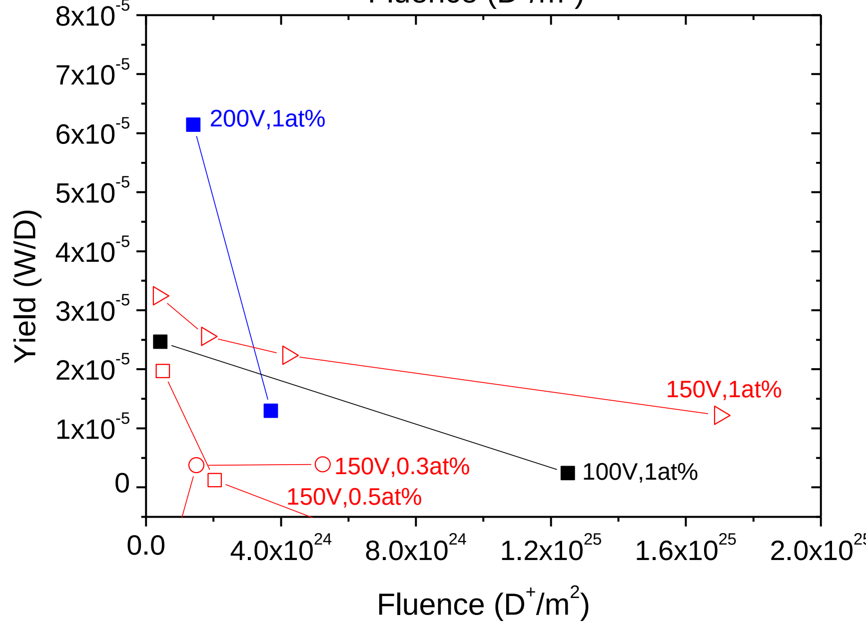
- **Already at the lowest fluences, Fe/W layers show lower erosion than pure Fe (8e-3).**
  (J. Roth et al. Report IPP 9/26 (1979))

- **Strong yield reduction with increasing fluence, more than one order of magnitude**

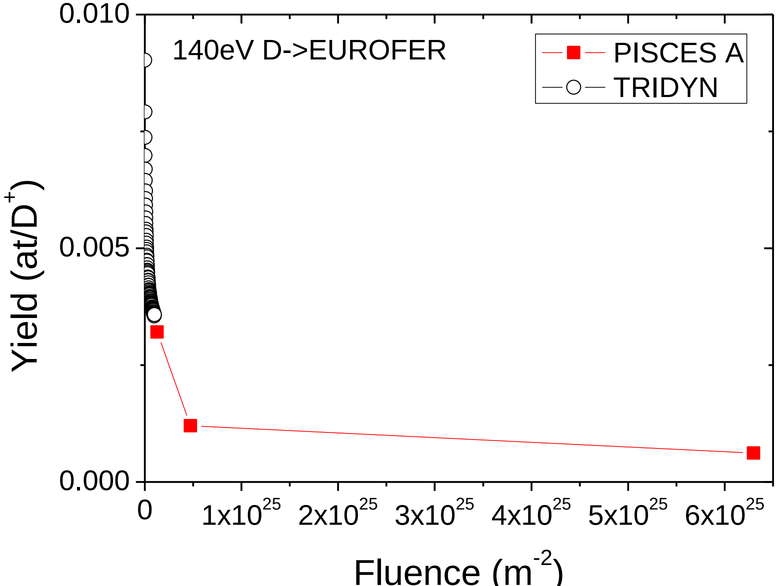


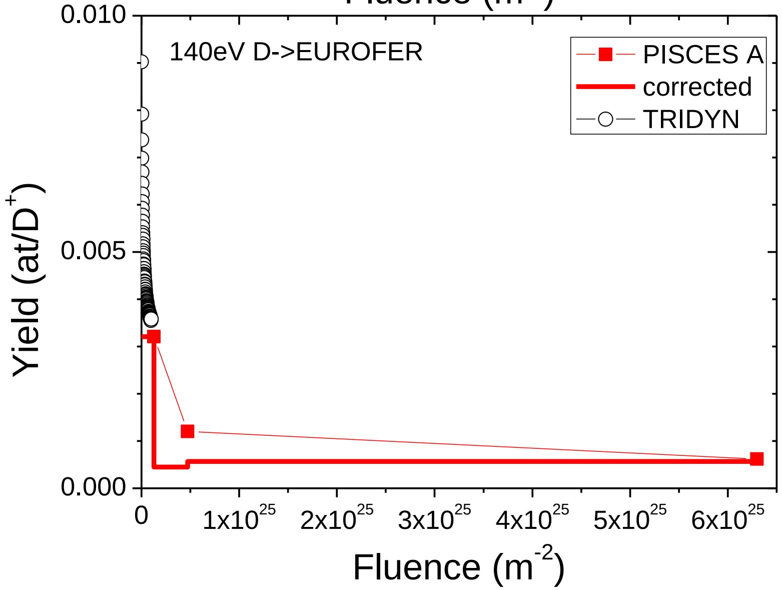

**Fluence dependence of W erosion for different initial W concentrations:**

- **W erosion about two orders of magnitude smaller than Fe. However, some erosion even at energies below 200V.**



# Fluence dependence of sputtering yield compared to experiments



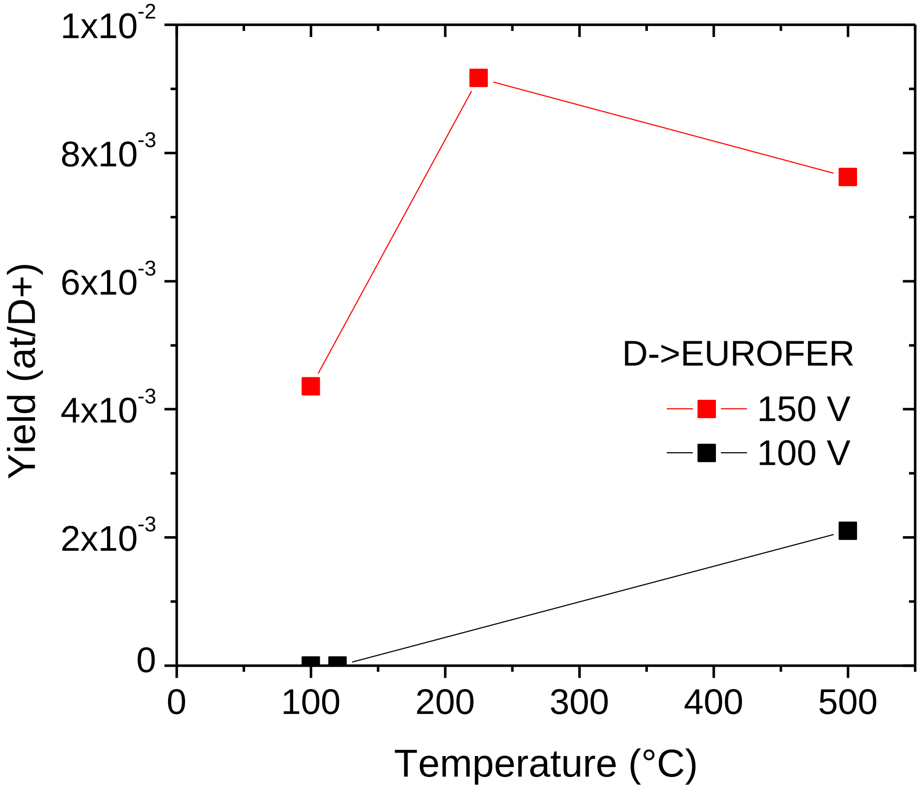

- **Experimental data from PISCES-A follow the trend indicated by TRIDYN**
- **Experimental values represent an average over the total fluence. For comparison with TRIDYN the values need to be recalculated into yield values for each fluence interval.**
- **“Corrected” values show steady state erosion with a yield $5x10^{-4}$.**

# Erosion Yield of EUROFER as function of temperature

Preliminary data presented at Steel TM was in error. EUROFER samples were not outgassed prior to exposure in PISCES-A.

**Dependence on Temperature:**

- **At 225°C the erosion yield increases to values for pure Fe**
- **At 500°C measurable sputtering even for 100V**
- **More data needed to determine transition temperature**

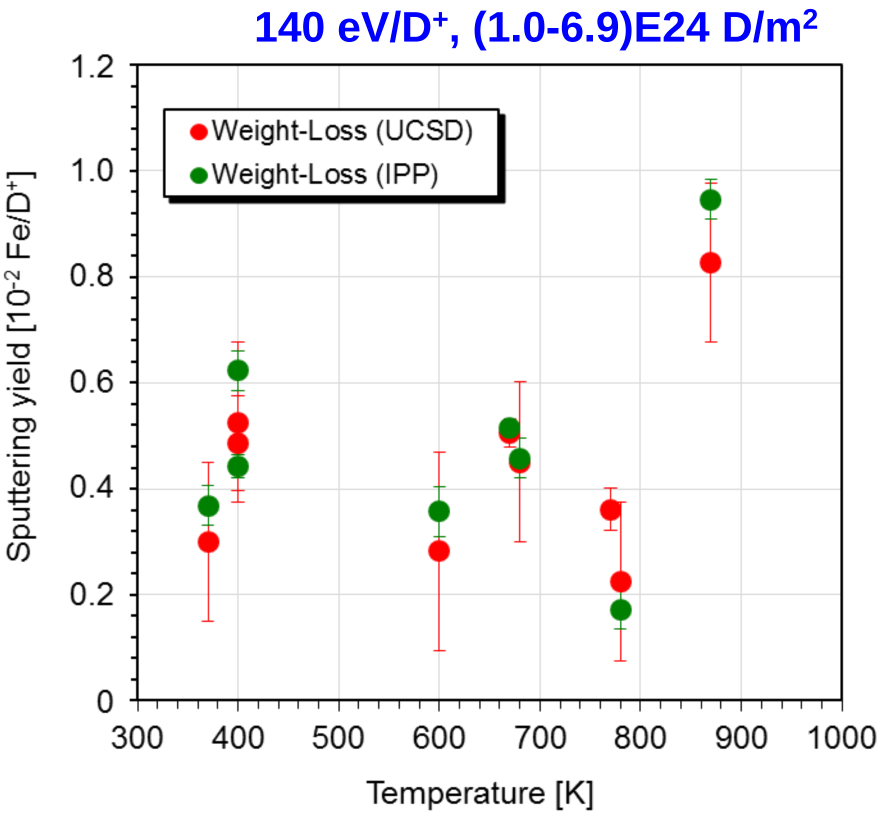


# Temperature Dependent Erosion Yield of EUROFER in PISCES-A

- Exposure of EUROFER to low-energy (140 eV/$D^+$) / high-flux (~$10^{21}$ $D^+/m^2s$) plasma at various temperatures (370 - 870 K).

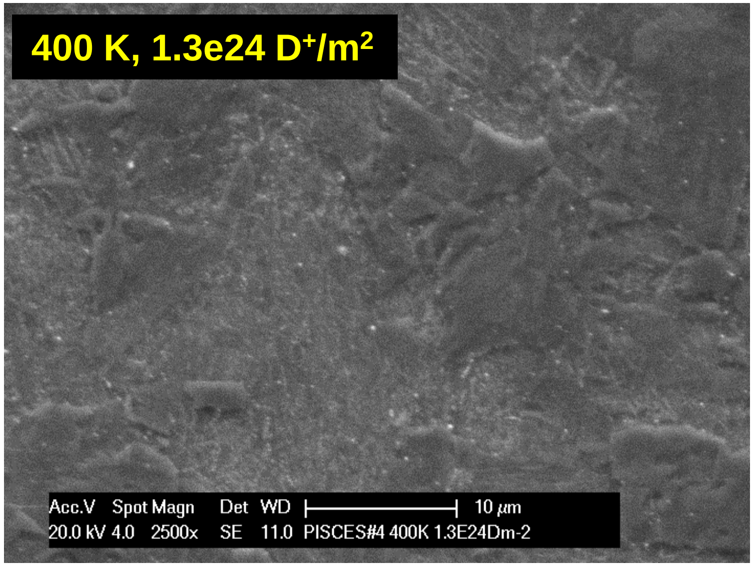
- Sputtering yield varies within a limited range at < ~800 K, while it clearly increases at 870 K.

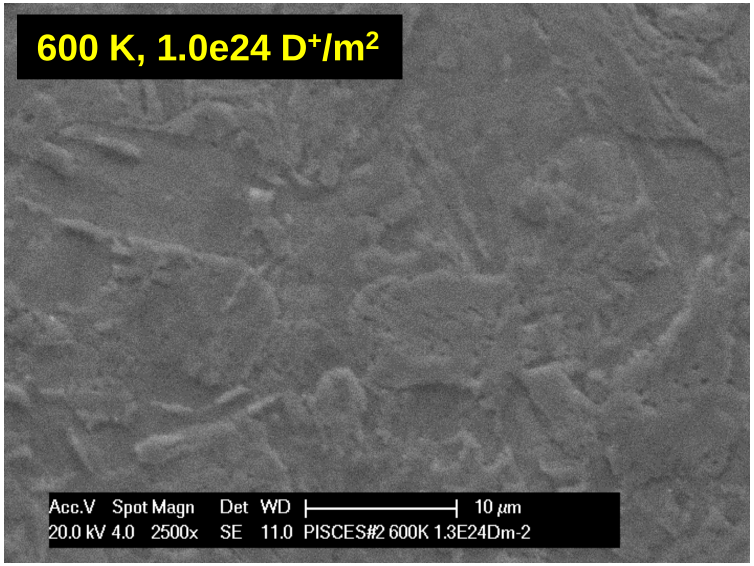
- No clear temperature dependence of sputtering in the DEMO FW working temperature range (< 800 K)
  - to be carefully compared with low-flux irradiation data (exposure duration may influence the elemental diffusion and the sputtering behaviour).

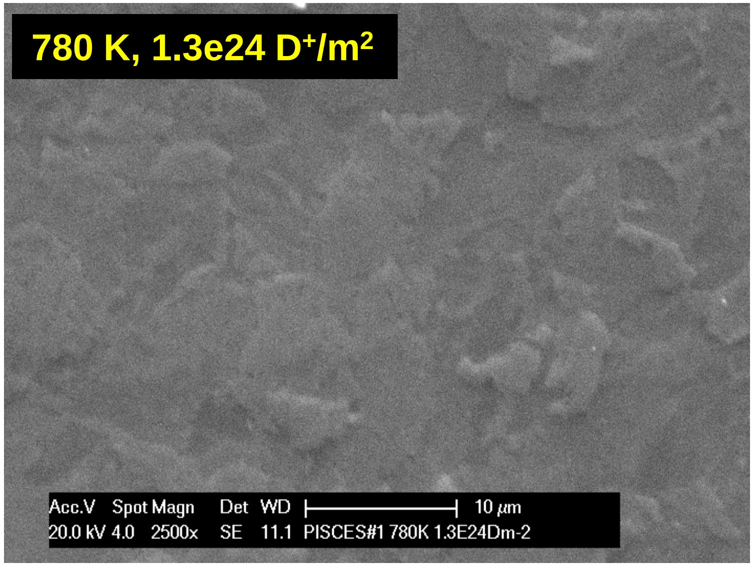


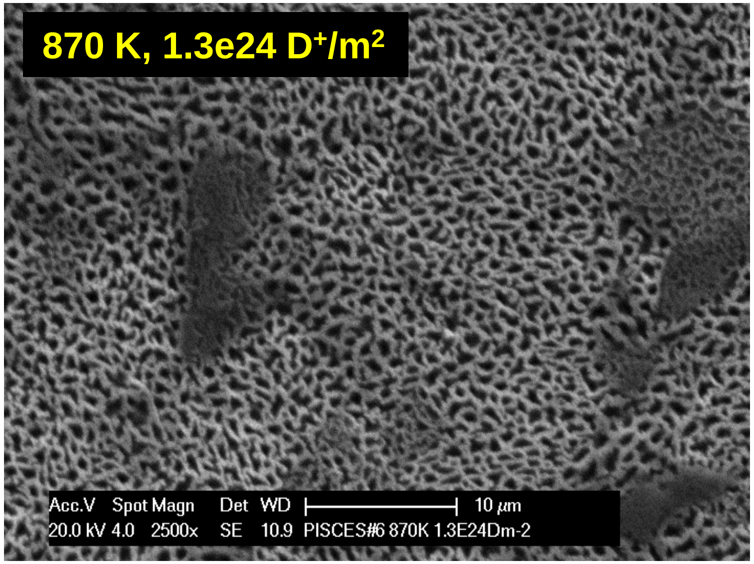

*Sputtering yield of EUROFER steel by 140 eV/$D^+$ exposure as a function of exposure temperature*

# Surface Morphology: PISCES-A D Exposure



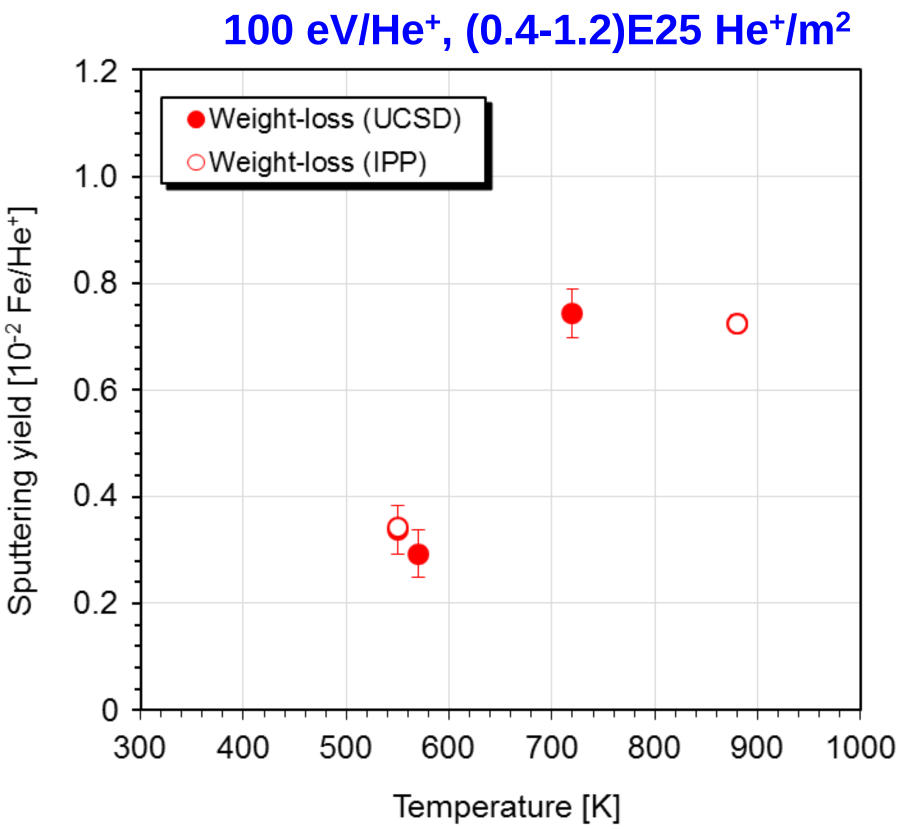



# Erosion study of EUROFER at PISCES-A in He plasma

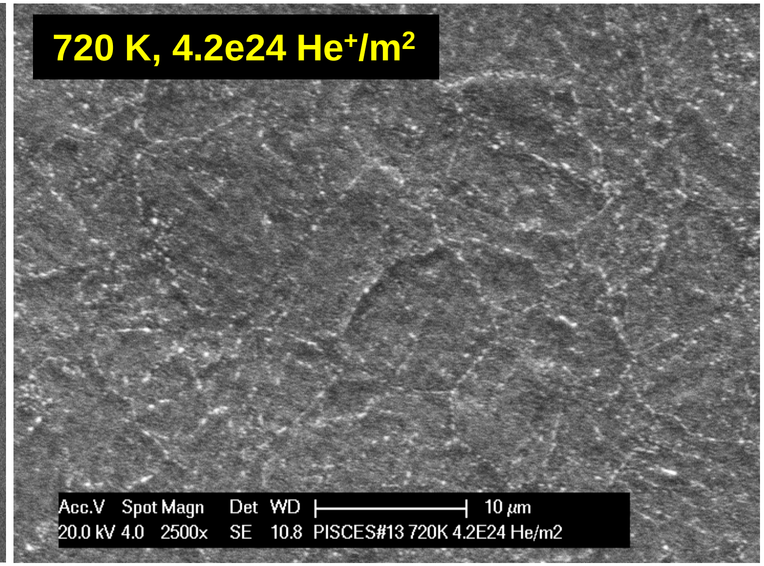
- Exposure of EUROFER to low-energy (100 eV/$He^+$) / high-flux (~$10^{21}$ $He^+/m^2s$) plasma at various temperatures (370 - 870 K).

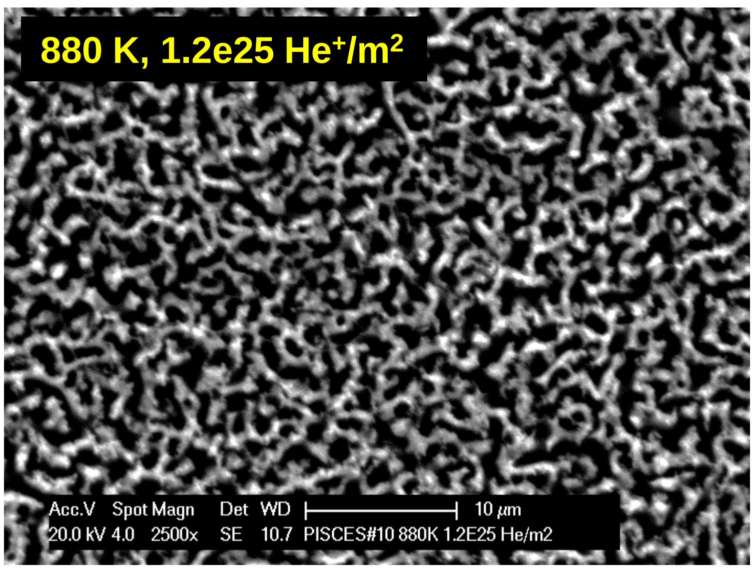
- Lower sputtering yield at < ~ 600 K, while it already increases > 700 K. ($Y_{He \rightarrow Fe}$ (100eV/He) ~ 4.6 x $10^{-2}$)




*Sputtering yield of EUROFER steel by 100 eV/$He^+$ exposure as a function of exposure temperature*

# Surface Morphology: PISCES-A He Exposure


- Exposed surface turns black after He plasma exposure (under all exposure conditions).

## Preliminary findings

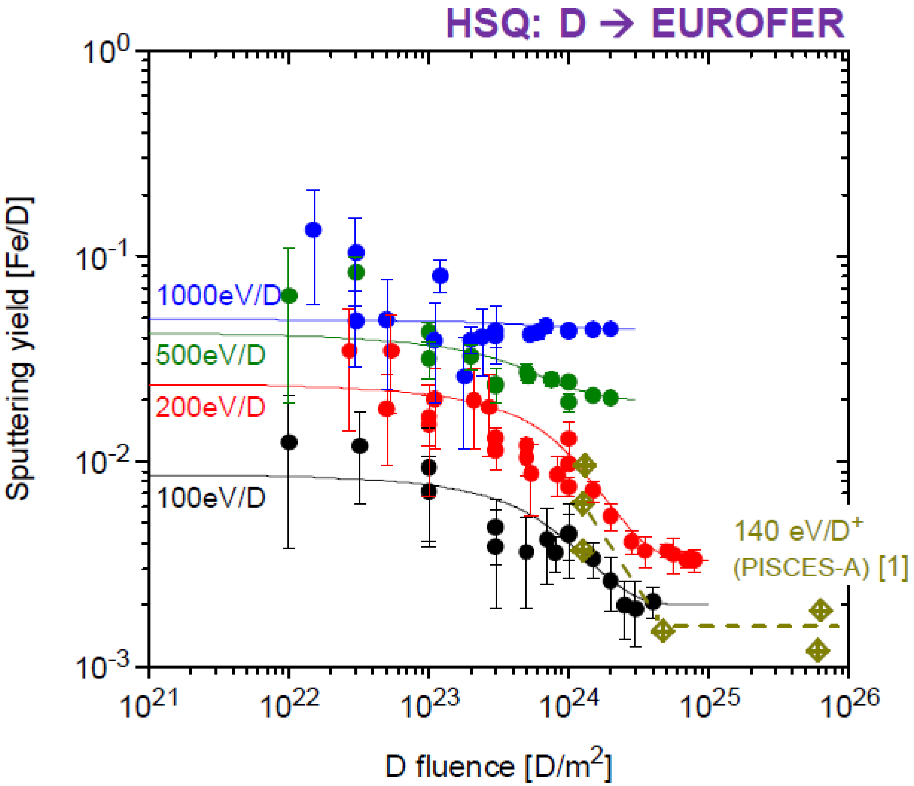
**EUROFER:**

- **Sputtering yield of EUROFER is strongly reduced compared to pure iron. The reason for this reduction is thought to be W enrichment at the surface.**
- **The reduction continues up to ~ 550C. The reason for this transition is thought to be due to Fe diffusion through the layer of W enrichment, but could also be due to surface morphology.**
- **Strong surface morphology changes are observed with temperature and plasma species.**

## Outstanding Issues

- Identify readily available material for study
  - Recall in the early days of W investigations, the variety of materials and fabrication techniques made systematic investigations difficult
- Determine temperature threshold for yield reduction/surface enrichment
  - Useful temperature for energy conversion will be relatively high
  - Possible flux dependence
- Expose EUROFER (or similar steel) to mixed D/He plasma
  - Connect to, or take advantage of, work on structural materials and He bubble nucleation
  - Examine the role of He in altering surface morphology
- Influence of other trace materials in steels (i.e. Cr)
- Changing surface morphology will be an issue and how do we deal with that in a database
  - Will morphology be different in a confinement device?

## PISCES Steel Work Plan



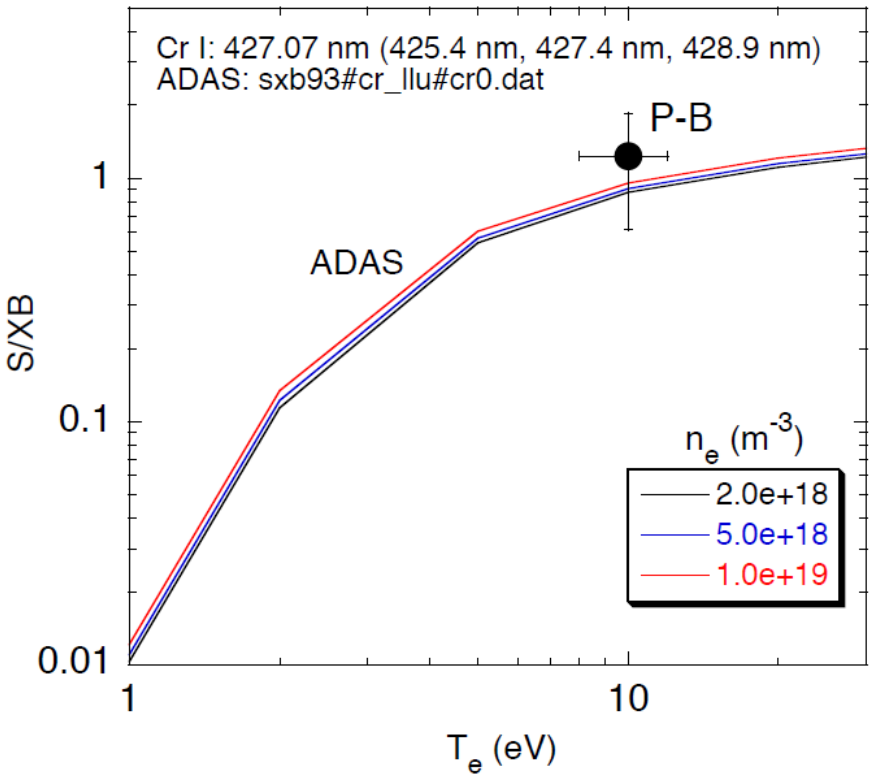

*Sputtering yield of EUROFER steel by D ion irradiation with different D energies as a function of D fluence (320 K)*

From W. Jacob et al, ICFRM 2015 presentation.

- Fe sputtering can result in W surface enrichment
- Temperature limit for Fe diffusion to surface
- Role of Cr is uncertain
- PISCES-B will provide basic S/XB data for Fe and Cr
- Examine fluence dependence of F82H surface sputtering at various sample temperatures
- Expose samples to mixed D/He plasma

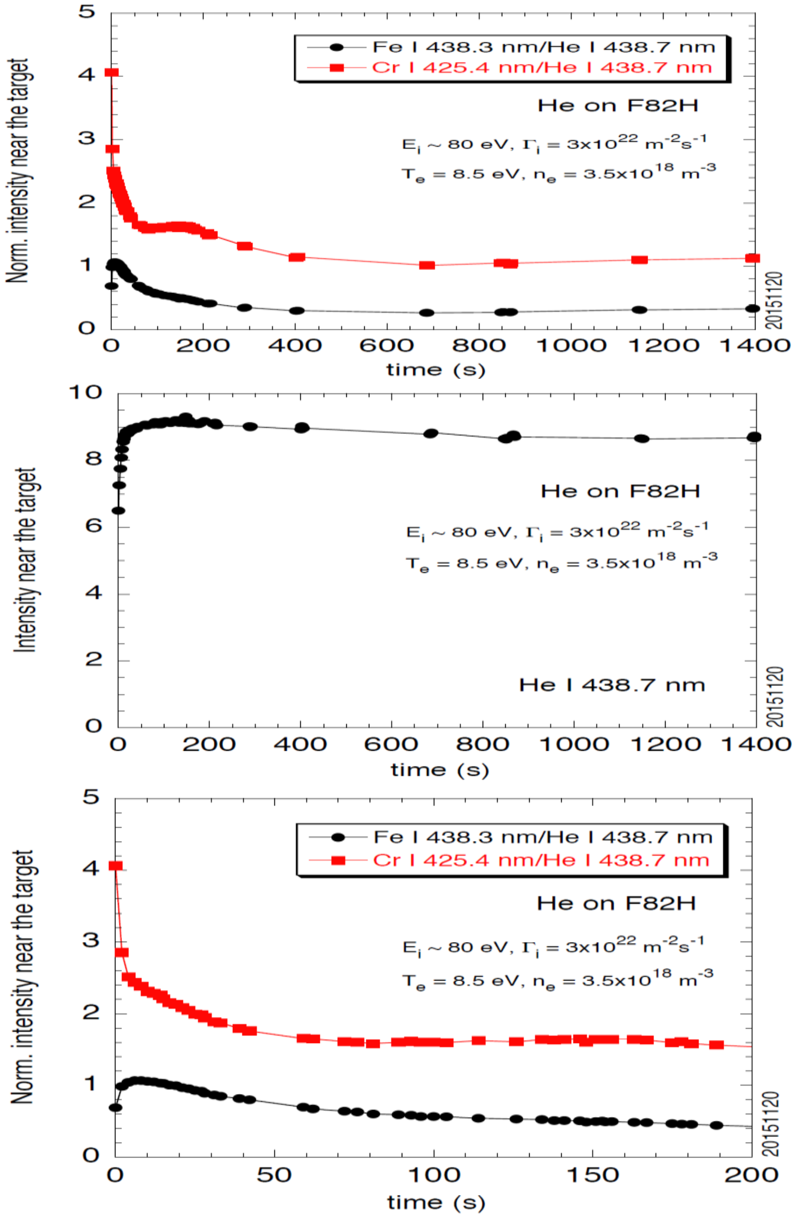
# Preliminary S/XB Measurements From PISCES

- Pure Fe and Pure Cr samples have been prepared
- F82H samples have been obtained from Japan
- Fe I, Cr I and W I emission lines identified (ADAS calculations exist for Cr I and W I)
- S/XB (ionizations per photon) for both Cr and Fe samples will be measured for a variety of plasma conditions
- Data will be compared to ADAS calculations for Cr (no ADAS calculations for Fe available)



# Preliminary Fluence Dependence Results From PISCES

- Fluence dependence of erosion from F82H has been measured at 300°C
- Both Fe and Cr sputtering is reduced in He plasma until a fluence of ~ $3x10^{24}$ $m^{-2}$ is reached then erosion is constant
- S/XB will quantify sputtering rate from measured intensity
- Post-exposure surface analysis (AES) will quantify change in surface composition
- Try to separate surface composition from morphology effects on erosion



# Summary – PISCES Work Plan

- **Year 1:**
  - Under controlled plasma conditions, measure the S/XB for Fe I, vary ne & Te
  - Under controlled plasma conditions, measure the S/XB for Cr I, vary ne & Te
  - Investigate the temperature dependence of W surface segregation

- **Year 2:**
  - Investigate the surface loss rates of each of the components of steel in real time using visible spectroscopy (quantify these losses with the S/XB data mentioned above), vary ion energy
  - Investigate the impact of mixed D/He plasma on steel and surface segregation, vary plasma composition, surface temperature

- **Year 3:**
  - Use LIBS (under development in PISCES) to investigate real-time surface composition as a function of plasma fluence
  - Investigate changes to the surface composition after exposure to transients heat pulses using existing laser systems and the aforementioned real-time diagnostic techniques