Sputtering of EUROFER and Fe-W layers by D⁺ in PISCES A

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Motivation:

- Explore the possibility to use bare EUROFER 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 EUROFER at energies close to the threshold energy for W sputtering
- Study low energy, high fluence erosion of EUROFER in PISCES A
- 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

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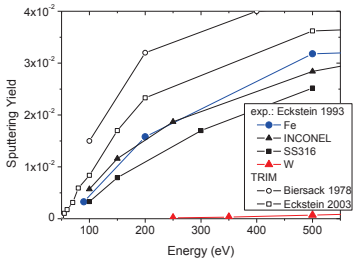
Sputtering Yield of Fe and W in the threshold regime

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

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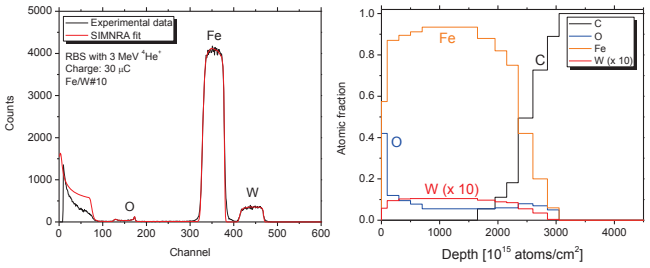
Preparation of Fe/W mixtures as test system for study of mechanisms

Magnetron sputter deposition on highly polished graphite about 350nm, W concentration between 0.5 and 1.2 at%



Sample preparation (C.Falsini, F.Koch, G.Matern), RBS sample analysis (H.Maier, K.Sugiyama)

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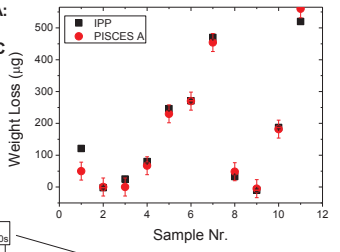
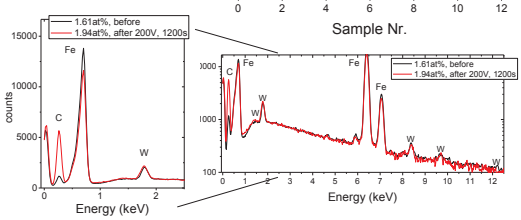
Exposures of Fe-W layers in PISCES A

- **Typical exposure conditions at PISCES A:**
  ion flux about 4x10²¹ /m²s
  temperatures between 100 and 500°C
  bias 100 to 200 V
- **Diagnostics at UCSD**

  micro balance for weight loss
  EDX



EDX in SEM



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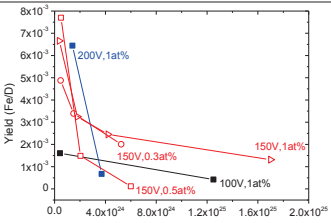
Erosion of the Fe/W layers determined RBS

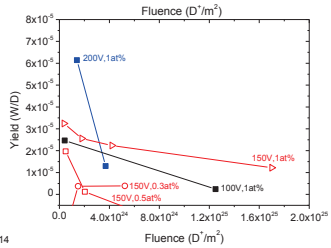
Fluence dependence of Fe erosion for different initial W concentrations:

- **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.**



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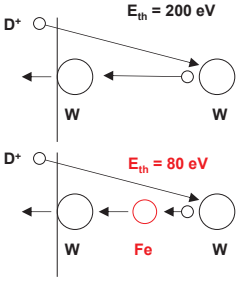
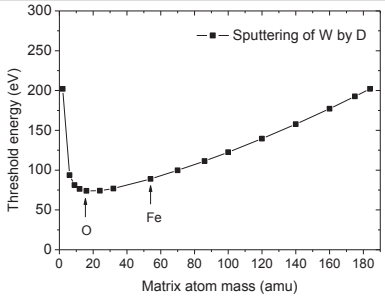
Threshold energy of W sputtering by D⁺ as function of matrix atom mass

Analytic calculation:
Threshold energy for the simplest sputtering process:





$$E_{max} = \frac{4\,M_1 M_2}{(M_1 + M_2)^2}\,E_{in}$$

D (200 eV) on W: E_{max} ~ 8 eV
D (80 eV) on Fe: E_{max} ~ 11 eV
Fe (11 eV) on W: E_{max} ~ 8 eV

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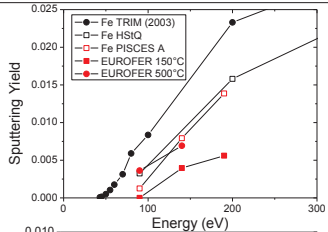
Erosion Yield of EUROFER compared to pure Fe and TRIDYN

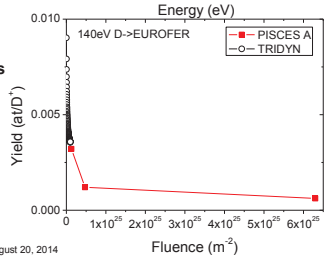
Dependence on Energy:

- **Literature values for pure Fe can be reproduced**
- **EUROFER values are much lower, threshold at 100eV**
- **At 500°C same values as for pure Fe**



Dependence on Fluence:

- **Erosion yield measurements of EUROFER agree with the low fluence dependence predicted by TRIDYN**



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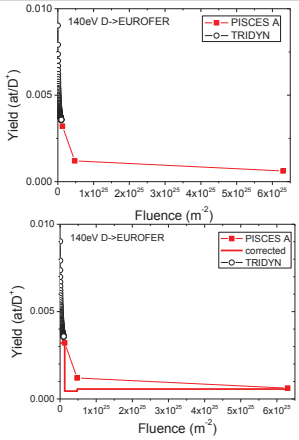
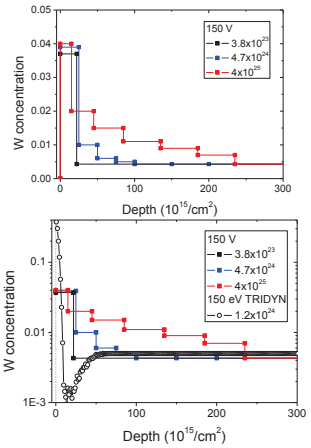
Fluence dependence of sputtering yield compared to experiments



- **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}.**

Comparison to TRIDYN simulation: W. Eckstein 2013

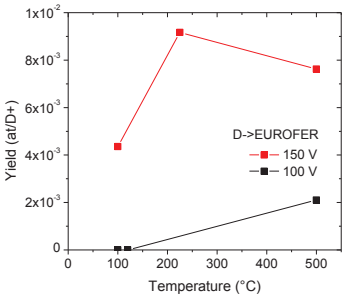


- **W surface peak is narrower than the achievable depth resolution of 22x10^{15}/cm^2. It is compatible with full W coverage at a layer thickness of 0.5 nm.**
- **W layer broadens slowly with increasing fluence (development of surface topography)**
- **TRIDYN shows a much higher W enrichment, but restricted to much less than 1 nm**

Erosion Yield of EUROFER as function of temperature

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**



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 disappears at about 225°C. The reason for this transition is thought to be due to Fe diffusion through the layer of W enrichment.**

Fe-W layers:

- **350 nm Fe-W layers were exposed to similar plasma conditions as EUROFER. The layers allow the distinction of Fe from W erosion by ion beam analysis.**
- **Depth resolved analysis of the W concentration was performed in ion beam analysis at IPP.**
- **The results are used for validation of TRIDYN code simulation**

Outstanding Issues

- Determine temperature threshold for yield reduction
  - Useful temperature for energy conversion will be relatively high
- Expose EUROFER (or similar steel) to mixed D/He plasma
  - Connect to, or take advantage of, work on structural materials and He bubble nucleation
- 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
- 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