Max-Planck-Institut für Plasmaphysik

Laboratory measurements of RAFM steel erosion and H retention in RAFM steel

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Content:

- Introduction: Sputtering of mixed materials
- Erosion of EUROFER and model samples
- What do we need?

EUROfusion

This work has partially been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Work performed under EUROfusion WP PFC.

What do we need to answer the question:

Can we use RAFM steels at some areas of the first wall of a future fusion power plant?

Certainly, steel is not an option for areas receiving a high power load and high particle flux.

And probably also not for areas receiving a non-negligible ion (plasma) flux.

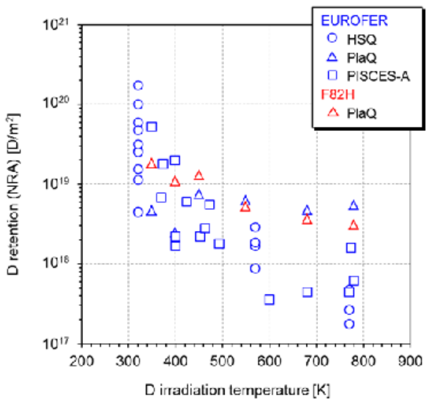
Introduction

Why should we use RAFM (reduced activation ferritic-martensitic) steel at all?

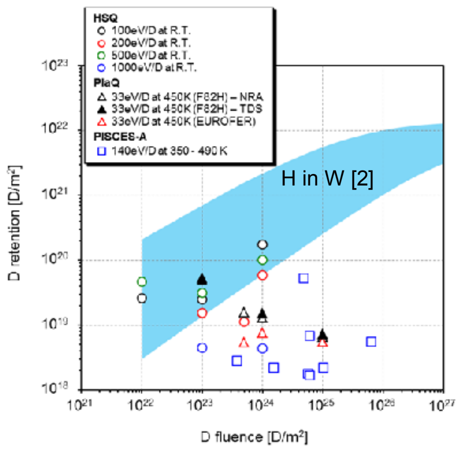
- Blanket modules for the first wall blankets are made of RAFM steel
- Technologically it would be much easier and less expensive
- H retention in RAFM steels is low, even lower than in W

Hydrogen retention

H isotope retention in steels even lower than in W



Temperature dependence of D retention in EUROFER and F82H [1] irradiated by D ion / exposed to D plasma under various conditions in HSQ, PlaQ and PISCES-A devices.



Comparison of fluence dependence of D retention between W [2] and RAFM steels (EUROFER and F82H).

[1] F82 H data: N. Ashikawa et al., Poster P2-020, ISFNT-12,2015

[2] ITPA SOL/Div topical group / B. Lipschultz et al., MIT report PSFC/RR-10-4

Introduction

Why should we use RAFM steel at all?

- Blanket modules for the first wall blankets are made of RAFM steel
- Technologically it would be much easier and less expensive
- H retention in RAFM steels is low, even lower than in W

So what is the problem in using steel?

EUROfusion

Introduction: Sputter Yields of Fe and W

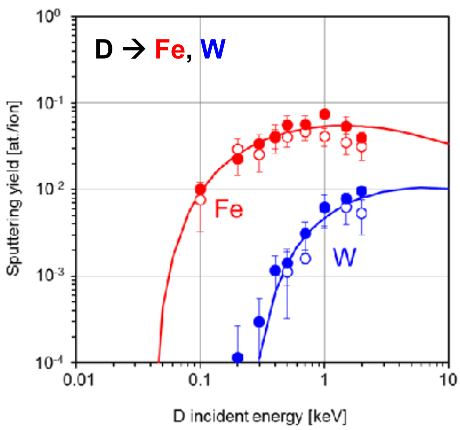
- ❑ Energy dependence of sputtering yield of Fe and W measured by weight loss & RBS
  (perpendicular ion incidence)
- ❑ Data fitted with Bohdansky formula

$$Y(E) = QSn^{KrC}(\varepsilon)\left[1-\left(\frac{E_{th}}{E}\right)^{2/3}\right]\left(1-\frac{E_{th}}{E}\right)^2$$

$$Q(D \rightarrow Fe) = 0.154\ [at./ion]$$
$$Q(D \rightarrow W) = 0.034\ [at./ion]$$
$$E_{th}(D \rightarrow Fe) = 37.5\ [eV]$$
$$E_{th}(D \rightarrow W) = 216\ [eV]$$

- ❑ Fe has lower sputter threshold and higher yield
- ❑ In relevant E region (50 to 1000 eV) $Y_{Fe} > 10 * Y_W$

→ Fe (steel) not useable as PFM



Sputtering yields of Fe and W due to D bombardment as a function of D energy.
- Open circle: determined by weight-loss measurement,
- Closed circle: determined by RBS (Rutherford Backscattering Spectrometry).
- The curve is derived from the fitting by Bohdansky formula.

Introduction

Sputtering of pure Fe (the main component of steel) **is too high!**

But: steel is not pure Fe

RAFM steels (EUROFER, RUSFER, F82H)
contain small amounts (0.4 to 1.0 at.%) of W

Sputter yield of W, Y_W, is much lower than Y_{Fe}
→ W enrichment / Fe depletion at the surface

This phenomenon is called "*preferential sputtering*"

Preferential sputtering will lead to a continuous change of the sputtering behavior

Introduction: SDTrimSP

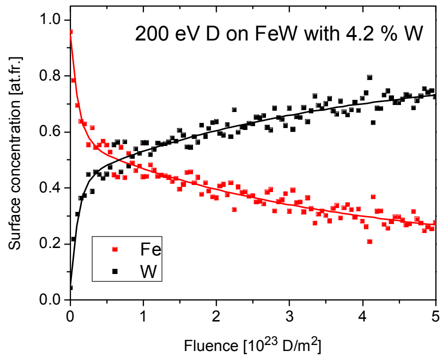
The dynamic surface evolution due to preferential sputtering can be simulated by SDTrimSP

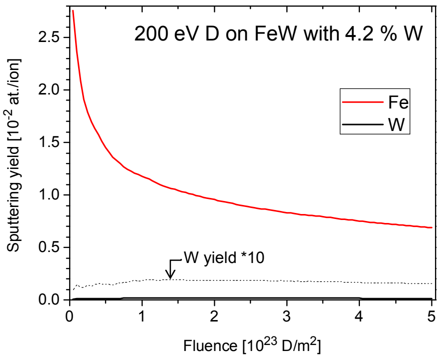
- SDTrimSP: dynamic version of TRIM.SP [1] (an earlier version was called TRIDYN [2])
- TRIM.SP describes the sputtering of surfaces due to impact of energetic species in the binary collision approximation
- TRIM.SP is well established and benchmarked with numerous experimental results
- SDTrimSP takes into account dynamic changes at the surface during sputtering, for example those due to preferential sputtering [3]
- Important for extrapolation to conditions not (easily) accessible to experiments (e.g. sputtering by tritium)

[1] W. Eckstein, Springer Series in Materials Science, Springer, Berlin, 1991
[2] W. Möller, W. Eckstein, J. P. Biersack, Comput. Phys. Comm. 51 (1988) 355
[3] Mutzke et al., IPP Report #12/8 "SDTrimSP, Version 5.00", 2011

SDTrimSP results: Dynamic Behaviour

- RAFM steels contain **W** which has a much lower sputter yield than Fe etc.
  - Preferential sputtering leads to W enrichment due to the difference of sputtering yields.
  - Erosion yield is reduced.





Dynamic surface evolution due to preferential sputtering

Preferential Sputtering

The two most important factors for preferential sputtering:

- Max transferable energy for a given projectile/target combination
- Surface binding energy

Energy transfer in binary collisions: $$T_{max} = 4 \cdot \frac{M_1 M_2}{(M_1 + M_2)^2}$$

	M_1	M_2	T_{max}	E_{Trans} at 200 eV (in eV)
D on W	2	184	0.043	8.6
D on Fe	2	56	0.133	26.6

Surface binding energy of W (in W!) = 8.7 eV
Fe (in Fe!) = 4.4 eV

Preferential sputtering

- Leads to enrichment of one component (transient phase until steady state)
- Reduces total sputter yield
- Effect increases with difference of sputter yield of the 2 components
- Occurs for all energies, but is strongest in the region between the 2 threshold energies

SDTrimSP can simulate the dynamic surface evolution due to preferential sputtering

Preparation of EUROFER samples (W conc. = 0.42 at%)

- Specimens cut out from a EUROFER sheet (EUROFER 97-2 [heat 993 393])
- Surface polished to mirror-finish and pre-annealed at 800 K.

Preparation of Fe/W binary system layers as "model" of RAFM steel

- Deposition by magnetron-sputtering from Fe and W targets
- Composition variable: Prepared W concentrations: 0.7, 1.5 and 4.2 at%.

Fe/W model layers are used for benchmarking of SDTrimSP simulations.

Experiment: D Irradiation

D ion irradiation & plasma exposure

"High current ion source (HSQ)" ion-beam set-up (IPP-Garching)

- Conditions well-defined: mass-separated mono-energetic D_3^+ ion beam
- But relatively low D flux ≤ 10^{19} $m^{-2}s^{-1}$

"PISCES-A" linear plasma device (UCSD) and Linear plasma device "PSI-2" (FZJ)

- High flux (D^+, D_2^+, D_3^+) plasma ~ 10^{21} D^+/m^2s
- But possible influences of plasma impurities (e.g. O) and redeposition

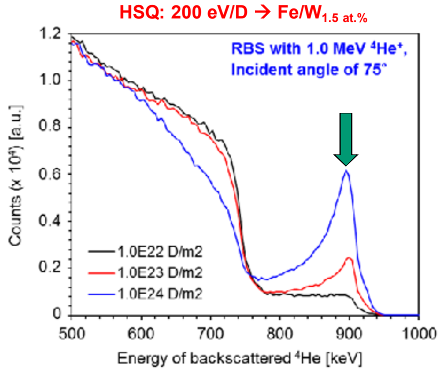
Experiment: Post-irradiation Analysis

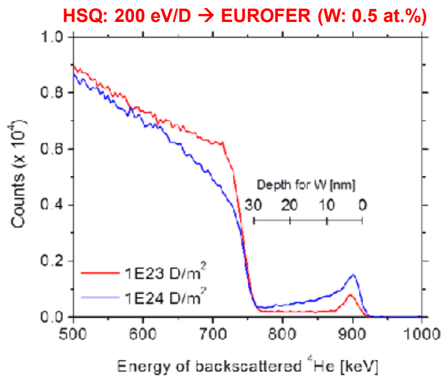
Post-irradiation analysis

- **Weight-loss measurement**
  - the only applicable technique to determine the sputtering yield of bulk materials, e.g., EUROFER steel
- **Rutherford Backscattering Spectroscopy (RBS)**
  - with 1 MeV $^4He^+$: determination of surface composition and measurement of sputtered amount
- **Scanning Electron Microscopy (SEM)**
  - Surface morphology examination

Experiment: Post-irradiation Analysis

- Surface composition changes with D irradiation fluence (HSQ exposure).
- W concentration at the top surface increases with fluence (for all D impinging energies).





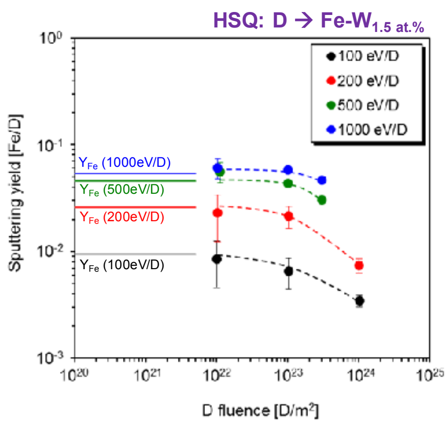
RBS spectra obtained from $Fe/W_{1.5\ at.\%}$ and EUROFER steel irradiated by 200 eV/D with different fluences: 1.0e22, 1.0e23 and 1.0e24 D/m^2.

→ Predicted effect of surface enrichment experimentally proven

Erosion of Fe/W Model Layers

Decrease of sputter yield with increasing fluence

- Initial level similar to that for pure Fe (Y_{Fe}) (solid lines)
- Clear decrease with fluence (in range of ≥ 10^{23} D/m^2)
- Yield reduction by 30 to 50% compared with that of pure Fe at 10^{24} D/m^2

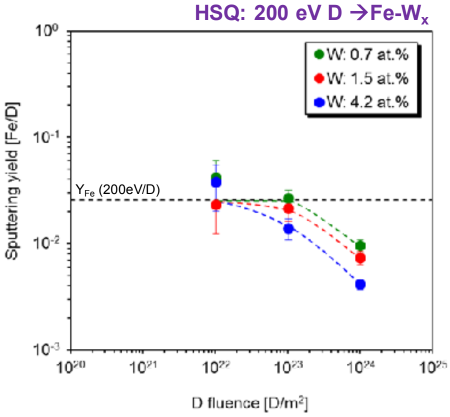


Sputtering yield of Fe/W (W ~1.5 at.%) layer by D ion irradiation with different D energies as a function of D fluence (320 K)

Erosion of Fe/W Model Layers

Decrease of sputter yield with increasing fluence

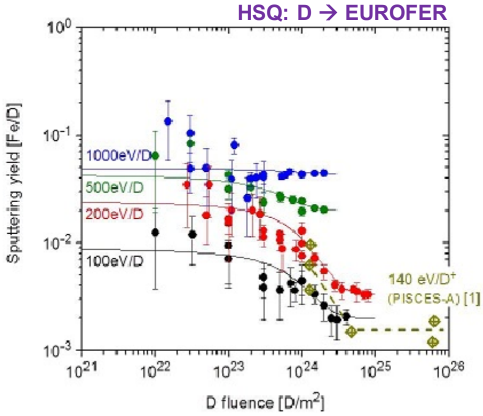
- Initial level similar to that for pure Fe (Y_{Fe}) (solid lines)
- Clear decrease with fluence (in range of ≥ 10^{23} D/m^2)
- Yield reduction by 30 to 50% compared with that of pure Fe at 10^{24} D/m^2
- Yield reduction depends also on the initial W content in the Fe-W binary layer.



Sputtering yield of Fe/W layers with different W content by 200 eV/D ion irradiation as a function of D fluence (320 K)

Erosion of EUROFER

- Yield reduction in the higher fluence range (≥ 10^{23} D/m^2), as well as for Fe/W layer.
- For 200 eV/D steady state seems to be reached for fluence > ~ 5 x 10^{24} D/m^2.
- PISCES-A data[1] at very high fluence and 140 eV/D also indicate steady state for fluence > ~ 5 x 10^{24} D/m^2.

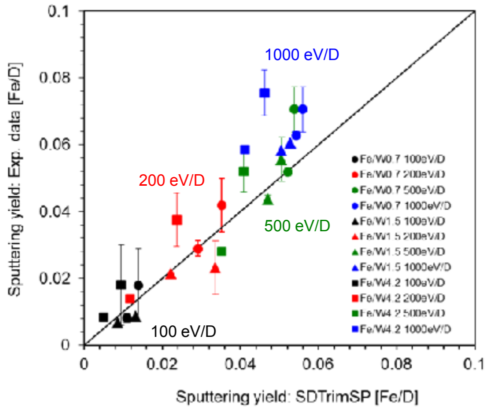


Sputtering yield of EUROFER steel by D ion irradiation with different D energies as a function of D fluence (320 K)

[1] J. Roth et al., J. Nucl. Mater. **454** (2014) 1

Comparison SDTrimSP – Experiment

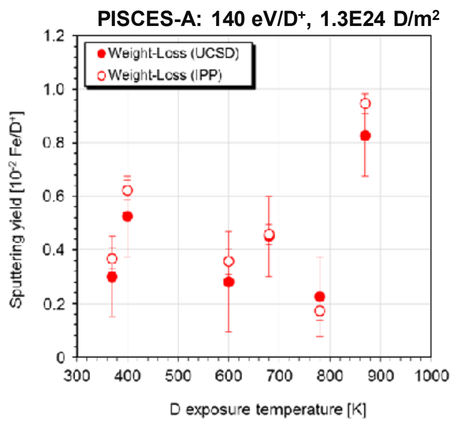
- Fe/W binary layers: Experimental data and SDTrimSP result agree within ~ 30 %



Comparison of sputtering yields between SDTrimSP calculation result and experimental data obtained for Fe/W binary layers with different W content.

Temperature Dependence

- 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.
  - consistent trend with the numerical prediction.
  - No clear temperature dependence of sputtering in the DEMO FW working temperature range (< 800 K)



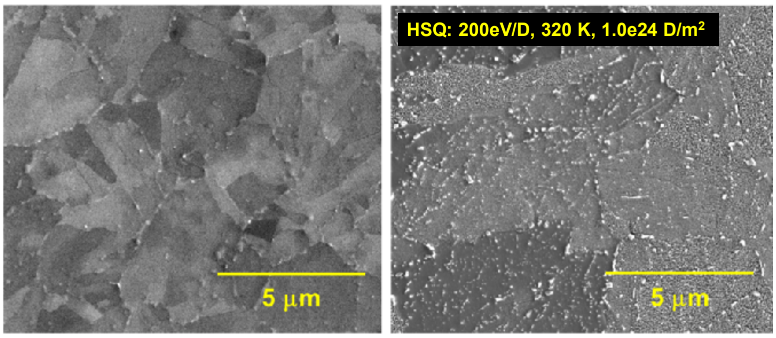
Sputtering yield of EUROFER steel by 140 eV/D$^+$ exposure as a function of exposure temperature (measured at PISCES-A)

[1] J. Roth et al., J. Nucl. Mater. **454** (2014) 1

Surface Morphology

Surface morphology change of EUROFER

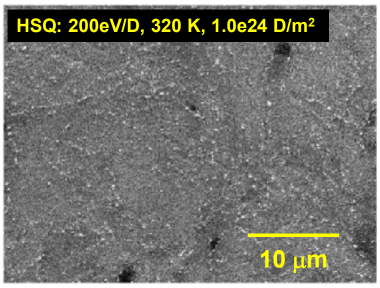
- EUROFER surface sputtering is not homogeneous…:
  - grain-dependent erosion.
  - high-Z precipitates.
  - nano-scale roughness.

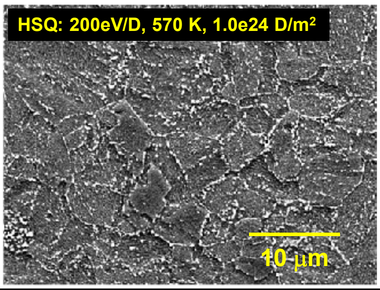


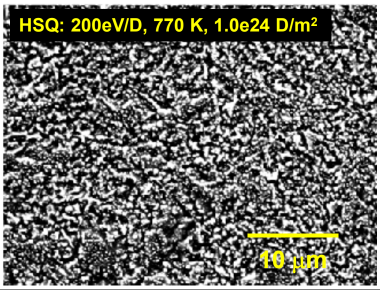
SEM images of EUROFER steels: as-deposited and after D irradiation with 200 eV/D, 1.0e24 D/m^2.

Surface Morphology

- Irradiation of EUROFER by low-flux (~10^{19} D/m^{2}s) D ion beam in **HSQ** at several temperatures (320 - 770 K).
  - Development of surface topography is strongly affected by the exposure temperature.

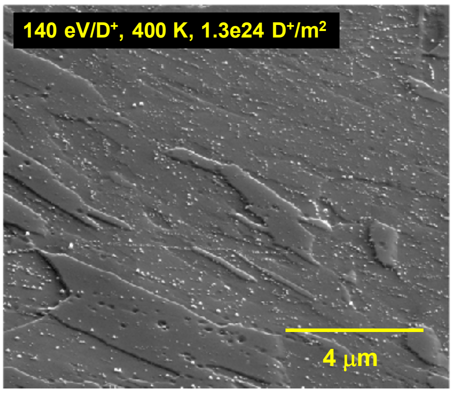


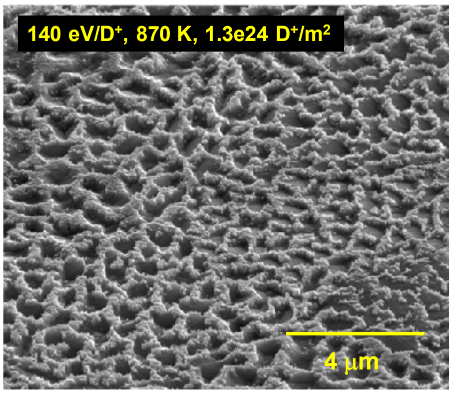




Surface Morphology

❑ EUROFER exposed to PISCES-A plasma: Development of surface topography is strongly affected by the exposure temperature as well.





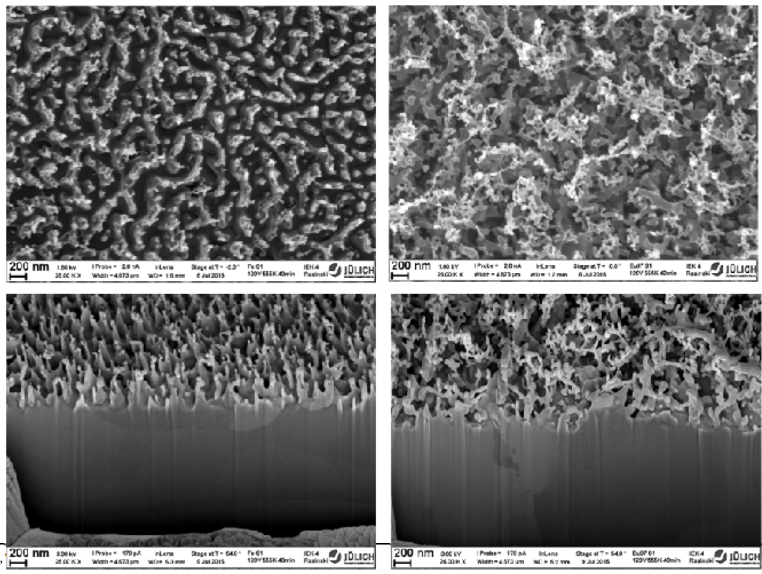
Surface Morphology

PSI-2: 555 K, 90 eV, 2.6×10^{25} D m^{-2}

Fe 1.5 at% W Eurofer-97

surface

cross section



Open questions

Temperature Dependence

- T dependence of sputter yield
- Onset of diffusion (counteracting enrichment?)
- T dependence of surface morphology

Impurity sputtering

- Higher mass → higher sputtering of W
- Ions: higher energy due to sheath acceleration

Summary

- Erosion of RAFM steel and model systems was investigated in ion beam experiment and in linear plasma devices
- Surface enrichment of W and reduction of sputter yield were experimentally proven
- For the model layers reasonable agreement with theoretical predictions (SDTrimSP)
- Reduction of EUROFER sputter yield by factor up to 8 (at 200 eV)
- Reduction possibly strongly influenced by surface morphology development
- H retention in steel is low (even lower than in W)

EUROfusion

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Summary

Where could RAFM steel be used?

- First wall in areas without plasma contact
- Impinging flux “only” CX neutrals
- CX neutrals have a very wide E distribution, but dominantly low-E (< 200 eV) hydrogen isotopes
- Under such conditions W enrichment (and the corresponding reduction of the sputter yield) might be effective

Why “no plasma contact”?

- Impurity ions (higher mass and higher energy)
- Higher mass → better E transfer → higher sputtering of W
- Ions, sheath acceleration → higher E → higher sputtering
- Under such conditions W enrichment probably not effective

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What is still needed?

What do we need to answer the question:

Can we use RAFM steels at some areas of the first wall of a future fusion power plant?

What is still needed?

- From lab results: better understanding of T dependence and surface morphology effects
- Improved surface diagnostics
- Influence of impurities
- From the fusion plasma side: mass and energy distribution of impinging particle fluxes

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