This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them

SMART materials for DEMO: towards industrial production

September 2023 I **Andrey Litnovsky**

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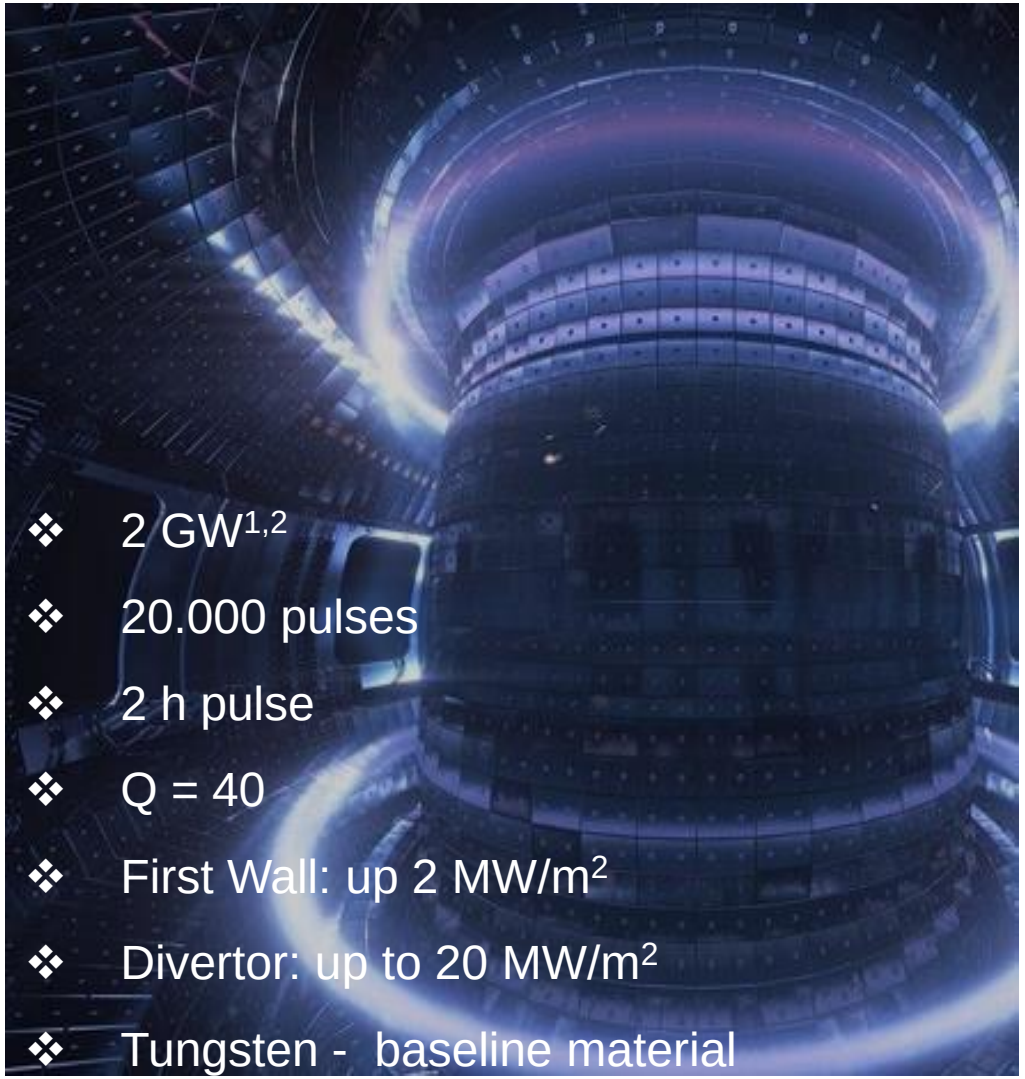
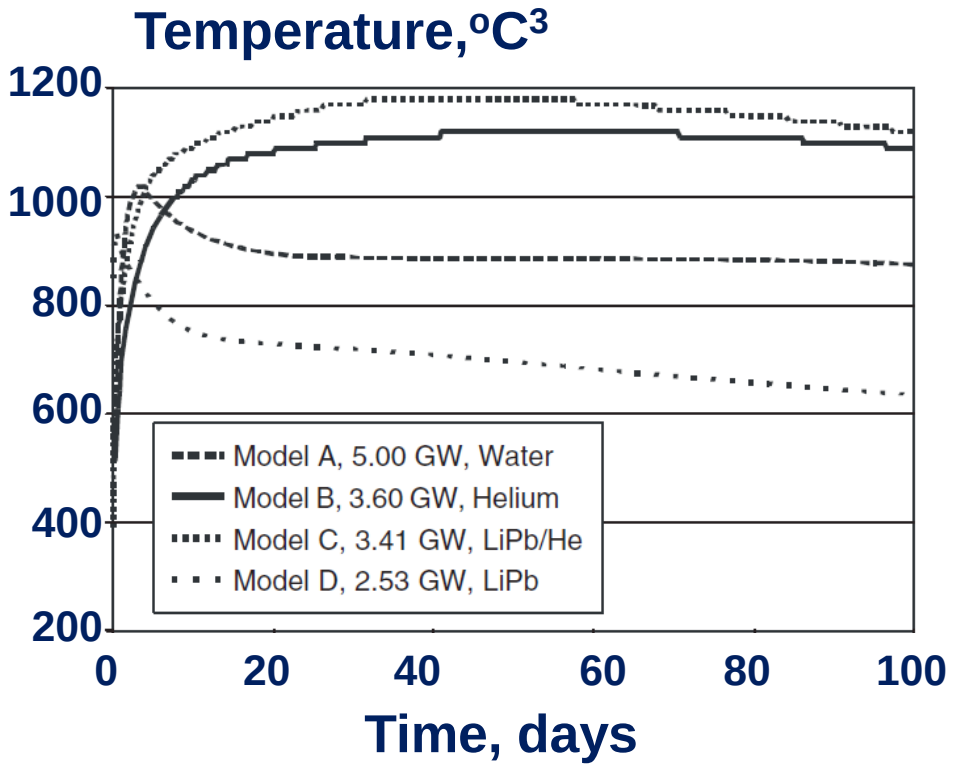
Jan Willem Coenen, Christian Linsmeier and collaborators

Fusion power plant - a challenge for materials



- 2 GW[1,2]
- 20.000 pulses
- 2 h pulse
- Q = 40
- First Wall: up 2 MW/m^2
- Divertor: up to 20 MW/m^2
- Tungsten - baseline material

Severe accident



- Loss of coolant: temperatures of first wall >1000°C
- Additional air ingress: formation of volatile WO_3 (Re, Os)
- For 1000 m^2 surface, Sublimation rate: 10 -100 kg/h

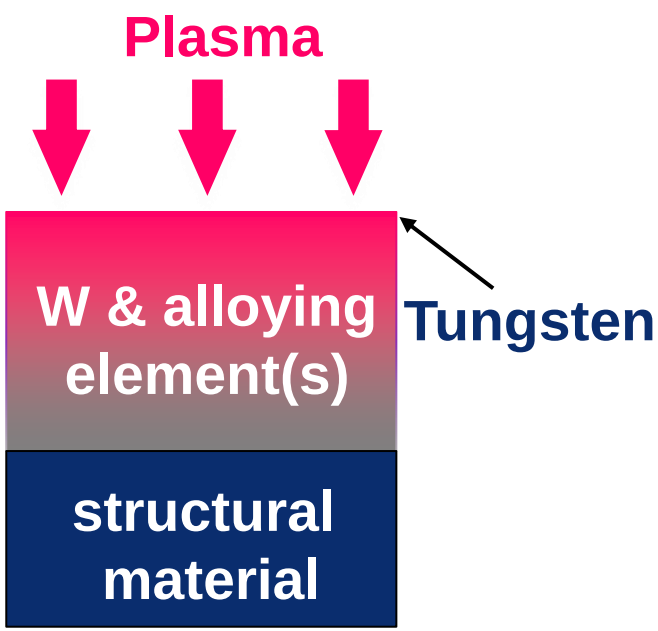
W represents a safety issue

[1] C. Bachmann et al., FED 98-99 (2015) 1423
[2] G. Federici et al., FED 89, 7-8 (2014) 882
[3] Final Report EFDA RP-RE 5.0, 2005

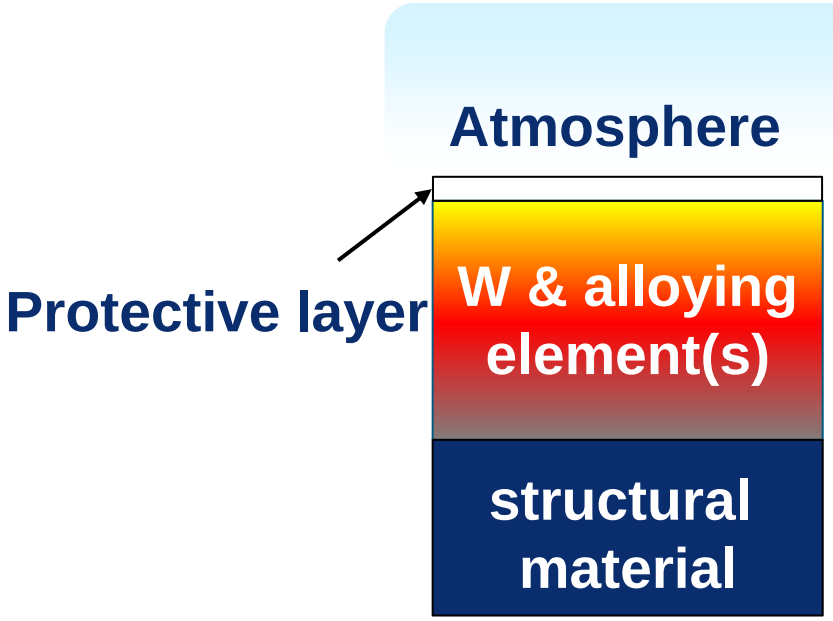
SMART materials: a “chameleon”

Self-passivating **M**etal **A**lloys with **R**educed **T**hermo-oxidation

Regular operation[2] (730°C->550°C):
Tungsten surface via sputtering of alloying element(s) by plasma



Accident conditions:
(air ingress, up to 1200°C)
Formation of protective layer

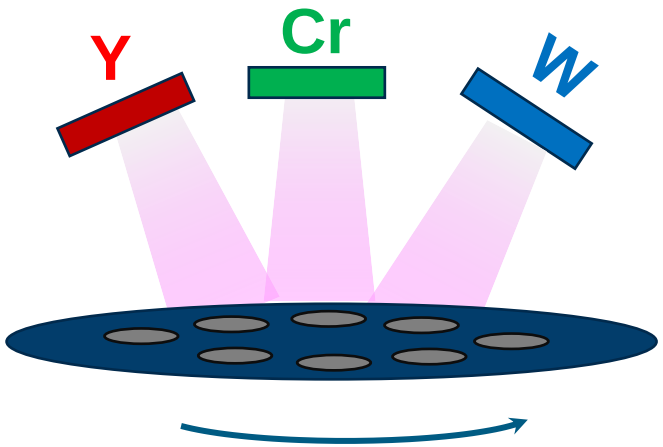


Behave like tungsten during plasma operation ← **SMART materials** → **Suppress oxidation during accident[1]**

[1]F. Koch and H. Bolt, Phys. Scr. 128(2007)100
[2]Yu. Igitkhanov et al., Report-Nr. KIT-SR 7637.

SMART: a production route

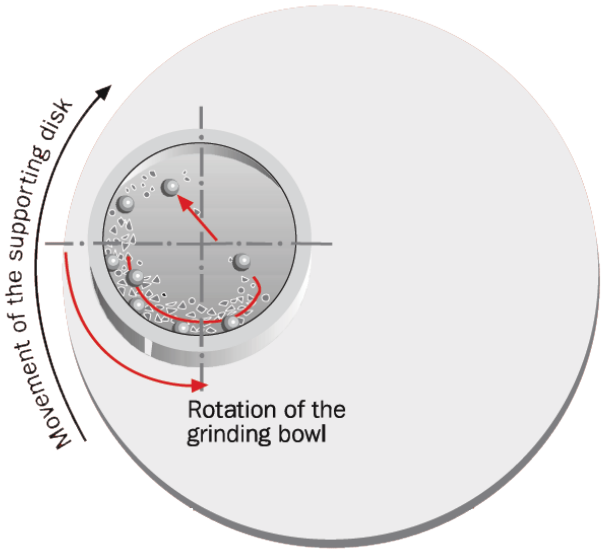
Thin films



Magnetron deposition – proof of a concept

- SMART coatings 2-5 μm thick

Bulk materials

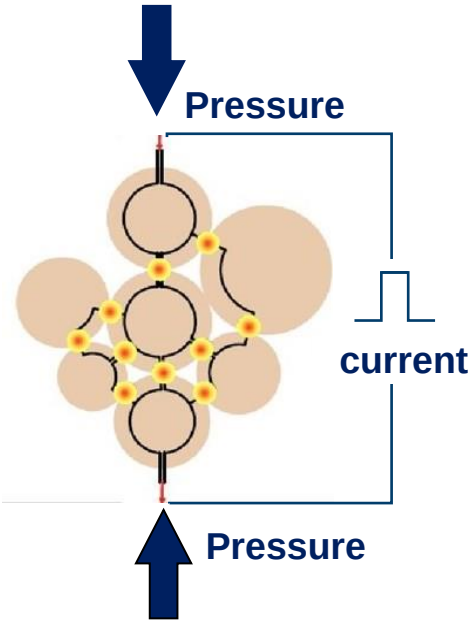


Mechanical alloying

- Up to 60 hours in the lab

Field-Assisted Sintering Technology (FAST)

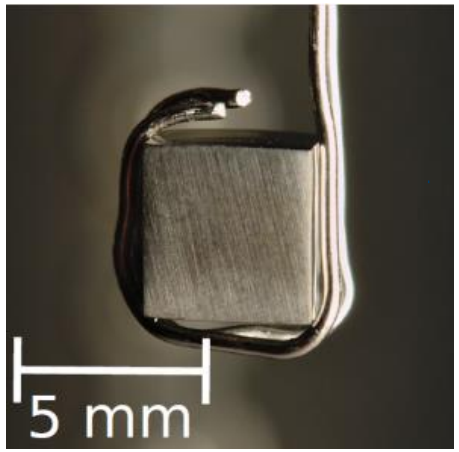
- Takes minutes



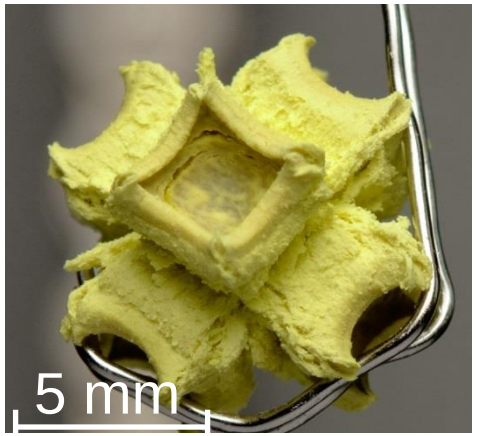
SMART oxidation resistance: taking a look

1000°C, 1 bar, 80 vol.% Ar+20 vol.% O_2, 10 hours

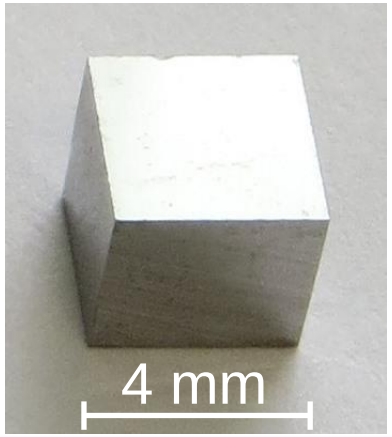
Before oxidation



After oxidation

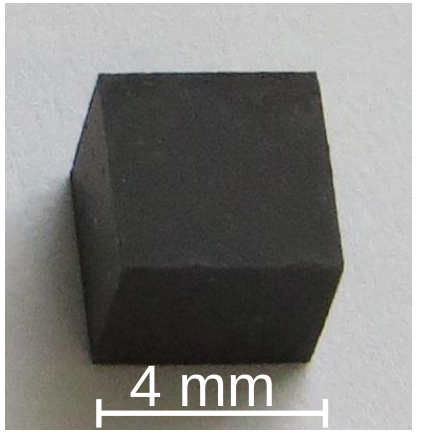


Pure W

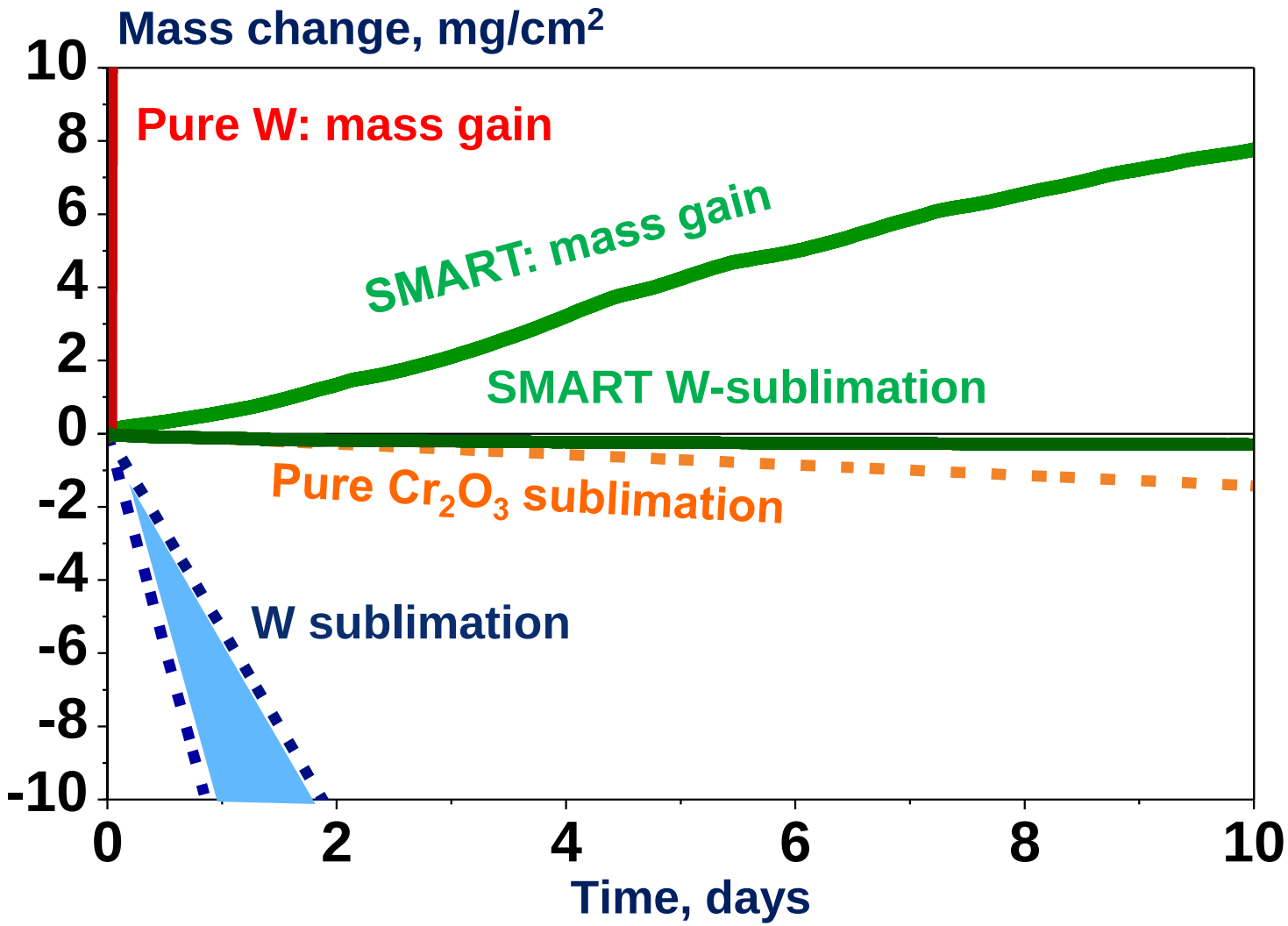


SMART:

W-11.4 wt.%Cr-0.6 wt.%Y



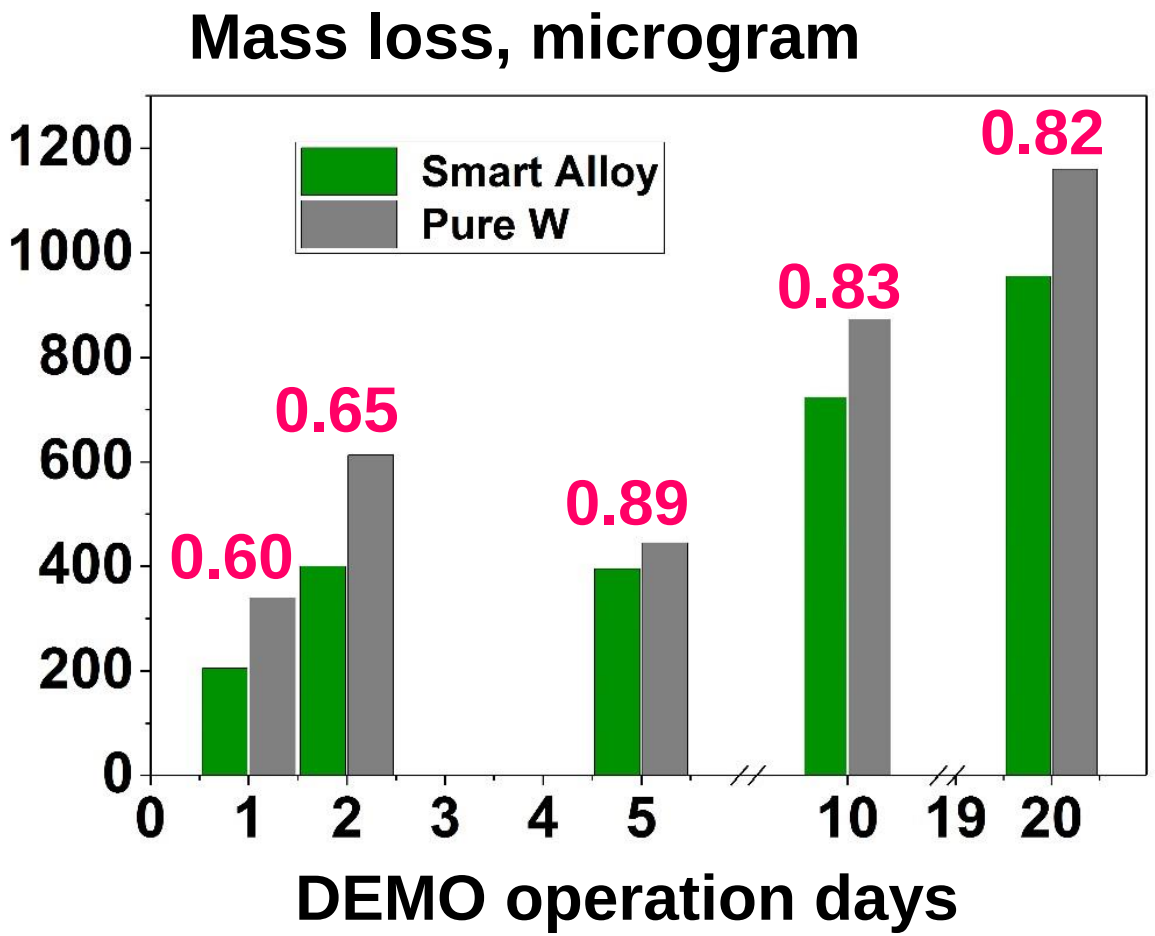
SMART oxidation resistance: now in numbers[1,2]



- > 10^4-fold suppression of oxidation
- > 40-fold suppression of W sublimation

[1]A. Litnovsky et al., Phys. Scr T170 (2017) 014012
[2]F. Klein et al., Fus. Eng. and Design 146 (2019) 1198

Plasma performance: sputtering resistance[1,2]



Surface recession
W vs. SMART
210 nm : 220 nm
260 nm : 260 nm

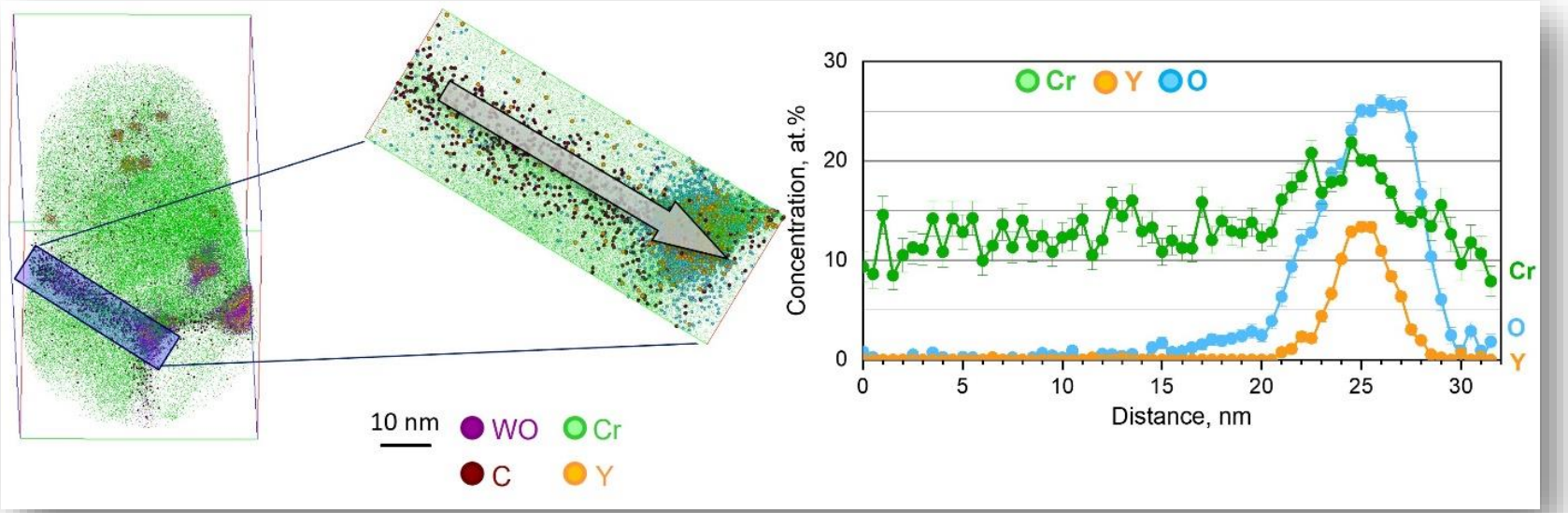
$R=m_{SA}/m_W$
$R\sim0.82$

Higher mass loss for pure W

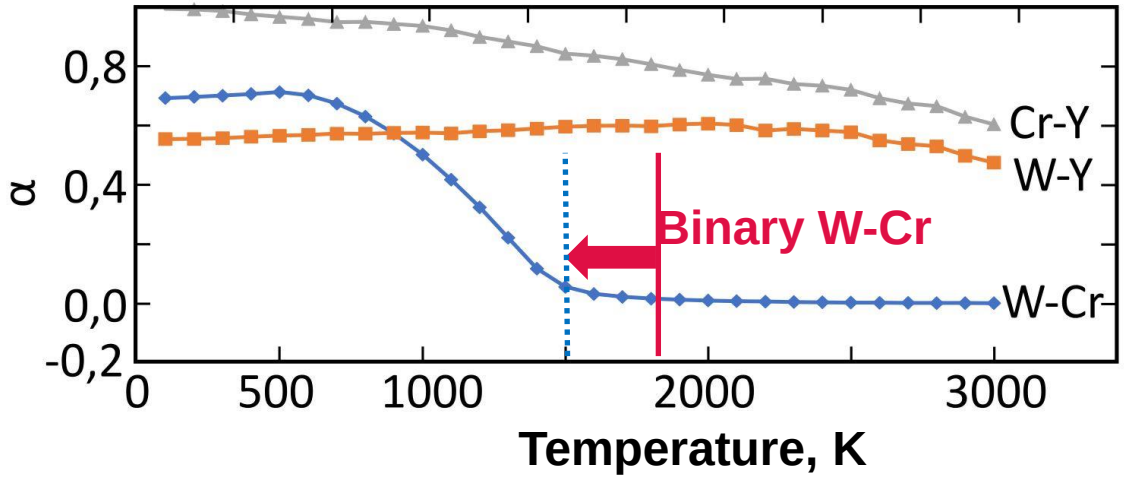
No additional loss of Cr and Y

[1]J. Schmitz Ph.D. Thesis, FZJ, Univ. of Bochum and Univ. of Gent, 2020
[2]A. Litnovsky et al., Metals 11 (2021) 1255

Exploring SMART: from nanometer…



Yttrium "cleans" grain boundaries from oxygen (atom probe tomography)



$$\alpha_n^{IJ}(c_J) = 1 - \frac{P_n^{I-J}}{c_J}$$

P_n^{I-J} - conditional probability of finding an atom *J* in the *n*-th neighbourhood of an atom *I*.

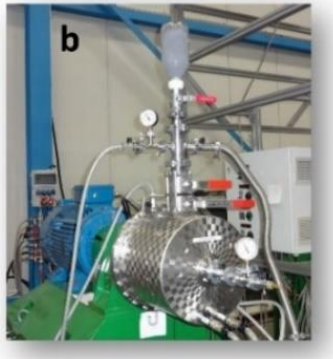
[1]A.Fernandez-Caballero, J. S. Wrobel, P. M. Mummery and D. Nguyen-Manh J. Phase Equilib. Diffus. 38 (2017) 391

Yttrium stabilizes W-Cr solid solution at lower temperature[1]

…up to tens of centimeter: industrial scale-up of mechanical alloying

Simoloyer ™ mills at Zoz GmbH

Zoz GmbH



Details of the mechanical alloying : a) bottles with elemental W, Cr and Y powders and the mixing bottle, b) mixing bottle attached to the Simoloyer ™ CM 20 industrial mill, c) an interior of the Simoloyer™ CM 20 mill before the milling and d) after 90 minutes of the milling e) sample powders taken under argon atmosphere from the mill.

Milling at industrial scale

- **Elementary powders: 4 kg procured – minimum value**
- **Milled with (yttria stabilized) zirconia balls for 25-45 hours**
- **Sampling powders for analyses after 0.5, 1.5, 6.5, 9.5, 12.5, 15.5, 18.5 and 21.5 hours**

- **Full alloying can be attained after 21.5 hours**

Industrial scale-up: Sintering

DR. FRITSCH

Sintering of SMART W-Cr-Y at Dr. Fritsch using industrial DSP 615 FAST facility

May 2022 Stuttgart-Fellbach

- Large SMART alloy “made in Stuttgart”
- From powder alloyed at Zoz
- Density about 90%
- Rectangular

Outcome:

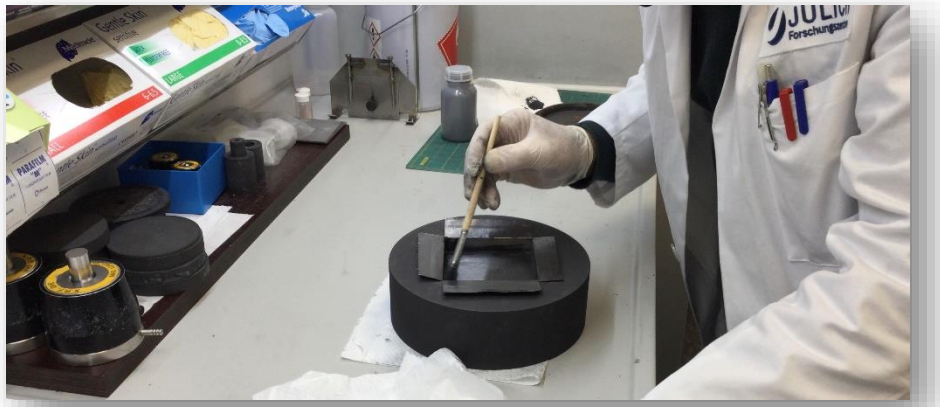
- New material of dyes
- New tools for powder preparation
- Numerous tips and tricks ☺

A. Litnovsky et al, SMART materials for DEMO: towards industrial production
International Symposium on Fusion Nuclear Technology (ISFNT-2023), Las Palmas de Gran Canaria, September 2023

Fine tuning industrial scale-up sintering at FZJ

DR.FRITSCH

Sintering of SMART W-Cr-Y-Zr using industrial DSP 515 FAST facility at FZJ



News from the School of fine Arts at FZJ ;)

Highlights:

- Novel 4-segment sintering tool from Dr. Fritsch
- Powder leveling tool from Dr. Fritsch
- New program from us ☺
- Sintering at 1500C holding at 1500C for 10 minutes
- No powder loss (3g out of 791 g)
- Fully automatic sintering program

Introducing FAST 170L

- 10×10 cm
- 788 g
- 5.1 mm thickness
- Apr. density >97%

A big step toward 100%

A. Litnovsky et al, SMART materials for DEMO: towards industrial production
International Symposium on Fusion Nuclear Technology (ISFNT-2023), Las Palmas de Gran Canaria, September 2023

JÜLICH Forschungszentrum

One more thing…

© Apple

One more thing… some back-of-envelope calculations

Supposing ITER-like first wall for DEMO
1000 m² á 3 mm thick armor
3 m³ material

2021

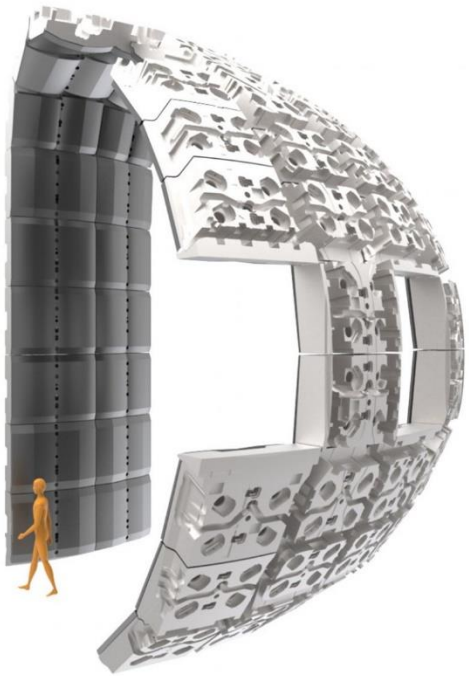
We would need to pay for about 60 tons of W:
60.000 x 60 Euro **= 3.6 Mio. Euro (in 2021 Euros)**

For the same volume of SMART alloys W-11.4Cr-0.6Y we would need about 47 tons of material:
47.000x0.88x60 Euro+47.000x0.114x56Euro+47.000x0.006x10000 Euro = **5.6 Mio Euro, from which 2.8 Mio. Euro is Y**

W (industry)= 60 Euro/kg
Cr (industry)= 56 Euro/kg
Y (farmac…lab research)=10.000 Euro/kg…

Construction costs for Gen IV fission reactor vary from 0.8 Billion to 3.8 Billion Euro (report G. Rothwell NEA/OECD)

One more thing… some back-of-envelope calculations



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47.000x0.88x60 Euro+47.000x0.114x56Euro+47.000x0.006x1860 Euro =

3.3 Mio Euro, which is cheaper than the pure W

W (industry)= 60 Euro/kg
Cr (industry)= 56 Euro/kg
Y (industry)= 1860 Euro/kg

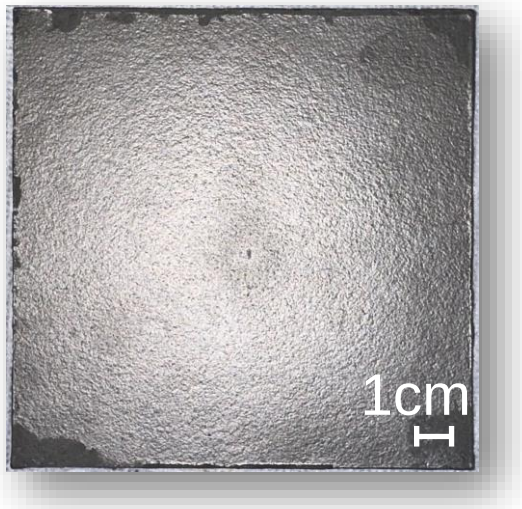
Construction costs for Gen IV fission reactor vary from 0.8 Billion to 3.8 Billion Euro (report G. Rothwell NEA/OECD)

- **First wall material is very affordable**
- **Getting industry-grade yttrium: done**
- **Full industrial cycle for SMART introduced for the first time**

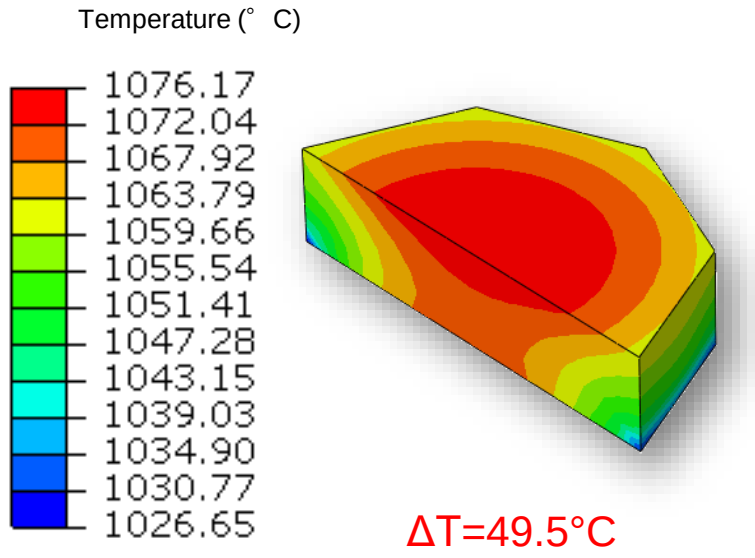
Summary

- Tungsten-based SMART materials are under development for a fusion power plant
- Bulk SMART materials produced via mechanical alloying and field-assisted sintering
- Alloys feature more than 40-fold suppression of sublimation as compared to W
- Acceptable plasma performance for 20 days of continuous DEMO operation in deuterium plasma
- Fundamental understanding of physics processes through modeling and experiments
- Industrial scale-up of SMART technology has started: alloying and sintering at industrial partners
- Procurement of industrial feedstock has completed the industrial production cycle for SMART

Outlook



- Industrial scale-up: “finding a perfect shape” and the best sintering recipe in a collaboration with IWM RWTH Aachen
- Producing the first wall mockup for a fusion power plant



Introducing solar SMART:

Compositions and oxidation constant	k_p * 10^{-7} [$mg^2/(cm^4 s)$]
Solar SMART W-17.8Cr-6.4Al (dry air)	7
Solar SMART W-17.8Cr-6.4Al (humid air)	**0.84**
SMART W-11.4Cr-0.6 Y (humid air)	48

More information on SMART:

Thank you