Karlsruhe Institute of Technology

Monaco iter
International Fusion Energy Days 2013

ODS Steels and their behavior under neutron irradiation

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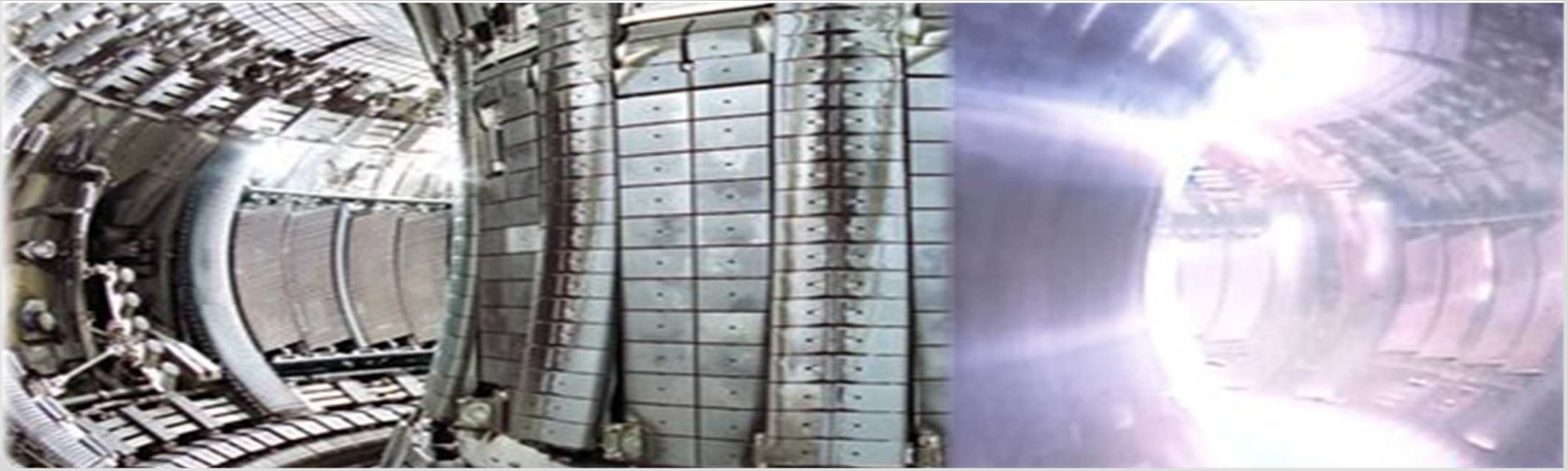
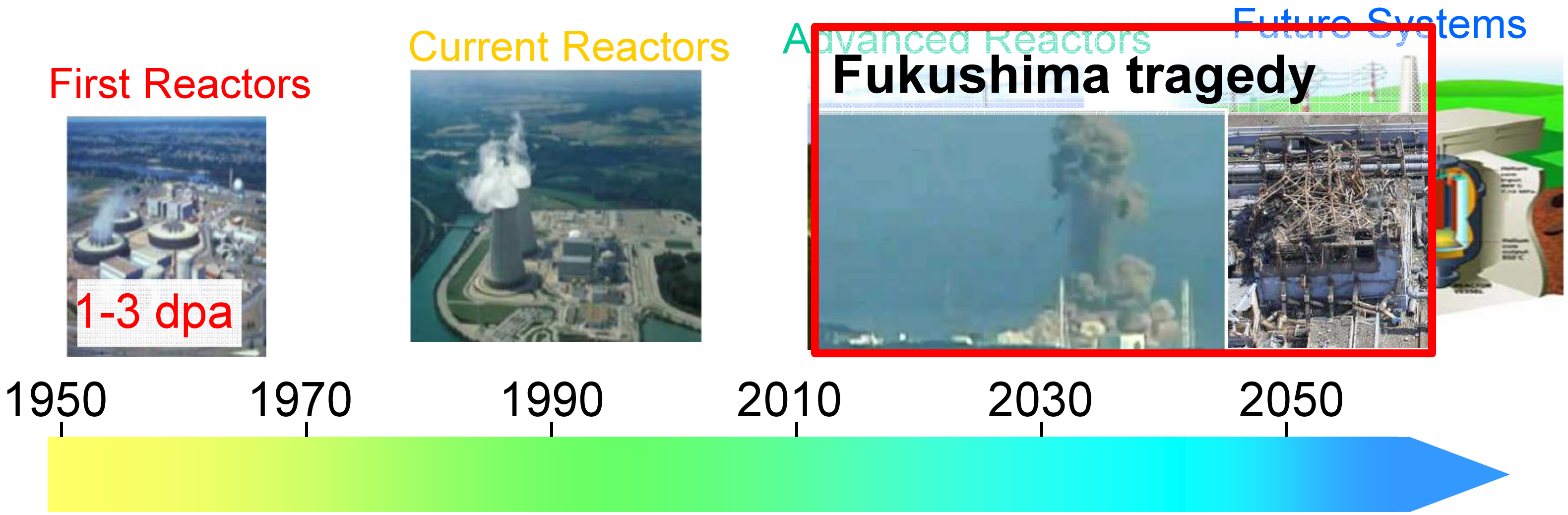
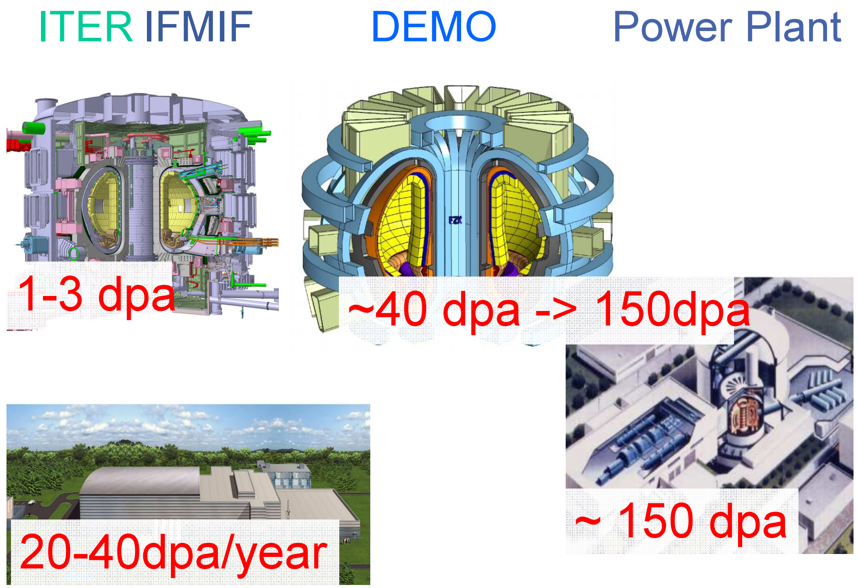
INSTITUT FÜR ANGEWANDTE MATERIALIEN - ANGEWANDTE WERKSTOFFPHYSIK (IAM – AWP)



High Performance Materials for Energy





Strategic Missions:
- Electricity, Heat, Hydrogen
- Environmental compatibility
- Cost effectiveness, sustainability

Safety first

Specific challenges for fusion:
- Short development path
- Loading more demanding (e.g H/He)

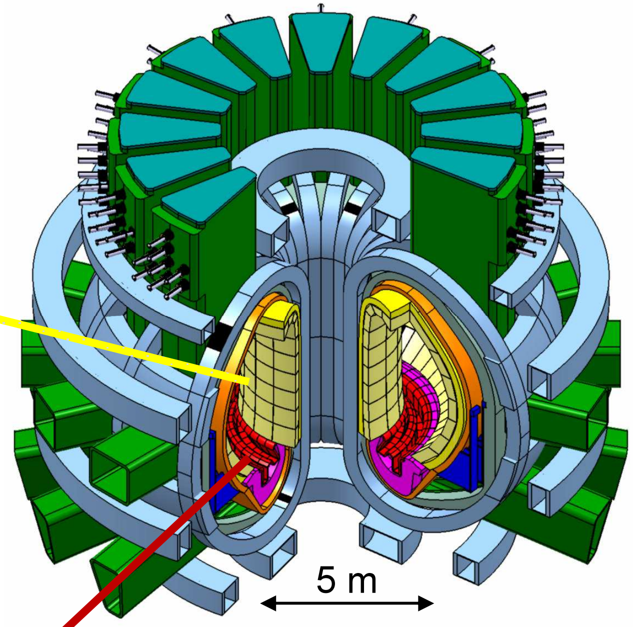
Outline

- In-vessel materials: short overview and loading conditions
- - Ferritic-martensitic ODS steels (9Cr-YO)
  - Ferritic ODS steels (>13Cr-TiYO)
- Mechanical and microstructural properties
- Properties under neutron and ion irradiation
- Microstructure – property correlations
- Summary and Conclusions

Fusion Power Plants: Material Challenges beyond ITER

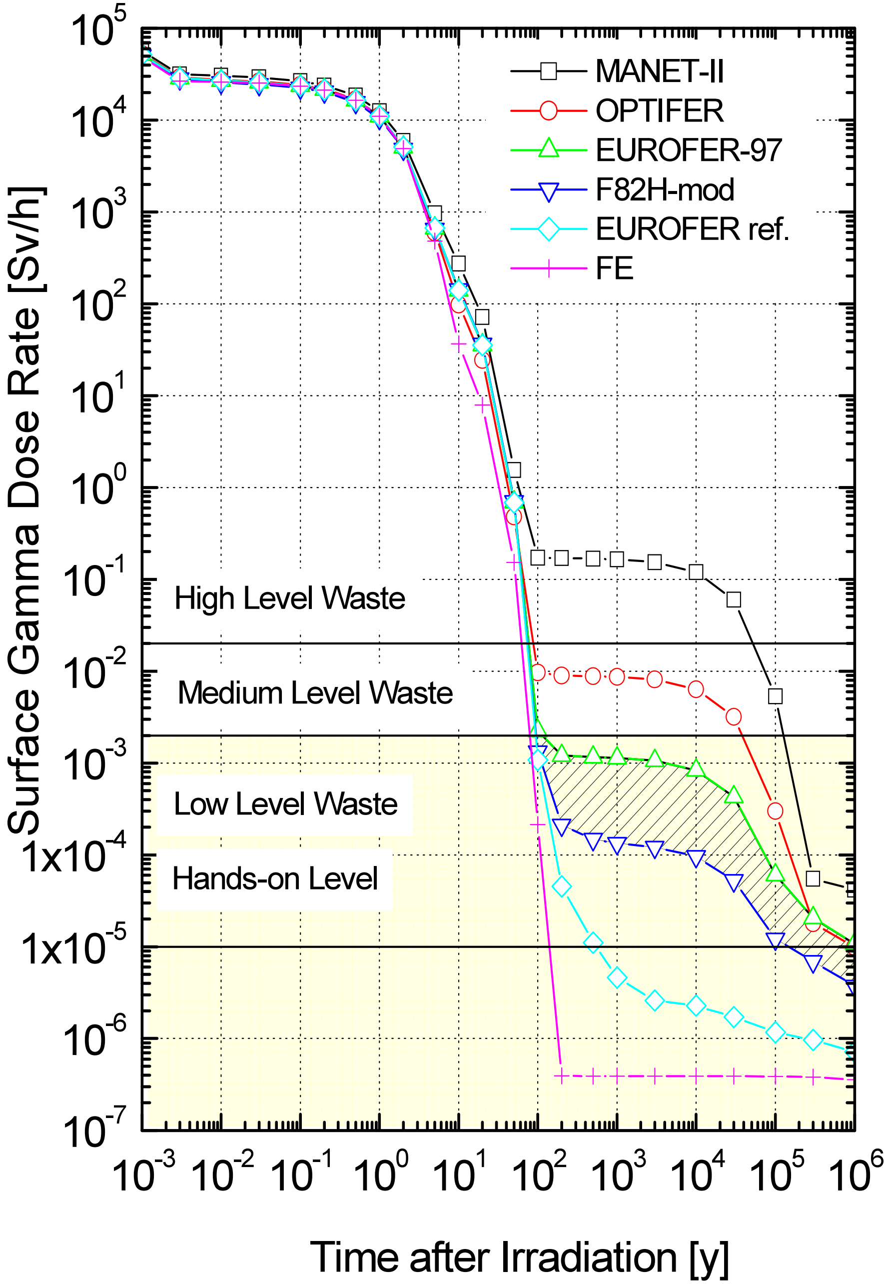
Blanket: ≤30 dpa/yr, ≤ 2.5MW/m²

- Plasma Facing Materials
- Reduced Activation Structural Materials:
  - RAFM Steels (EUROFER, F82H) 350-550 °C
  - RAFM ODS Steels 300-650 °C
- Functional Materials
  - Neutron Multipliers (Be), Li ceramics
  - Diagnostics, Windows and Insulators



Divertor: ≤10 dpa/yr, 10-15 MW/m²

- Refractories (e.g. W-materials), others?
  850-1100 °C → ~600 - 1300 °C
- Nano-scaled RAF(M)-ODS Steels, others?
  350-650 °C → ~300 - 800 °C



FUSION Priority:
Low activation capability

RAFM 8-10%CrWTaV steels

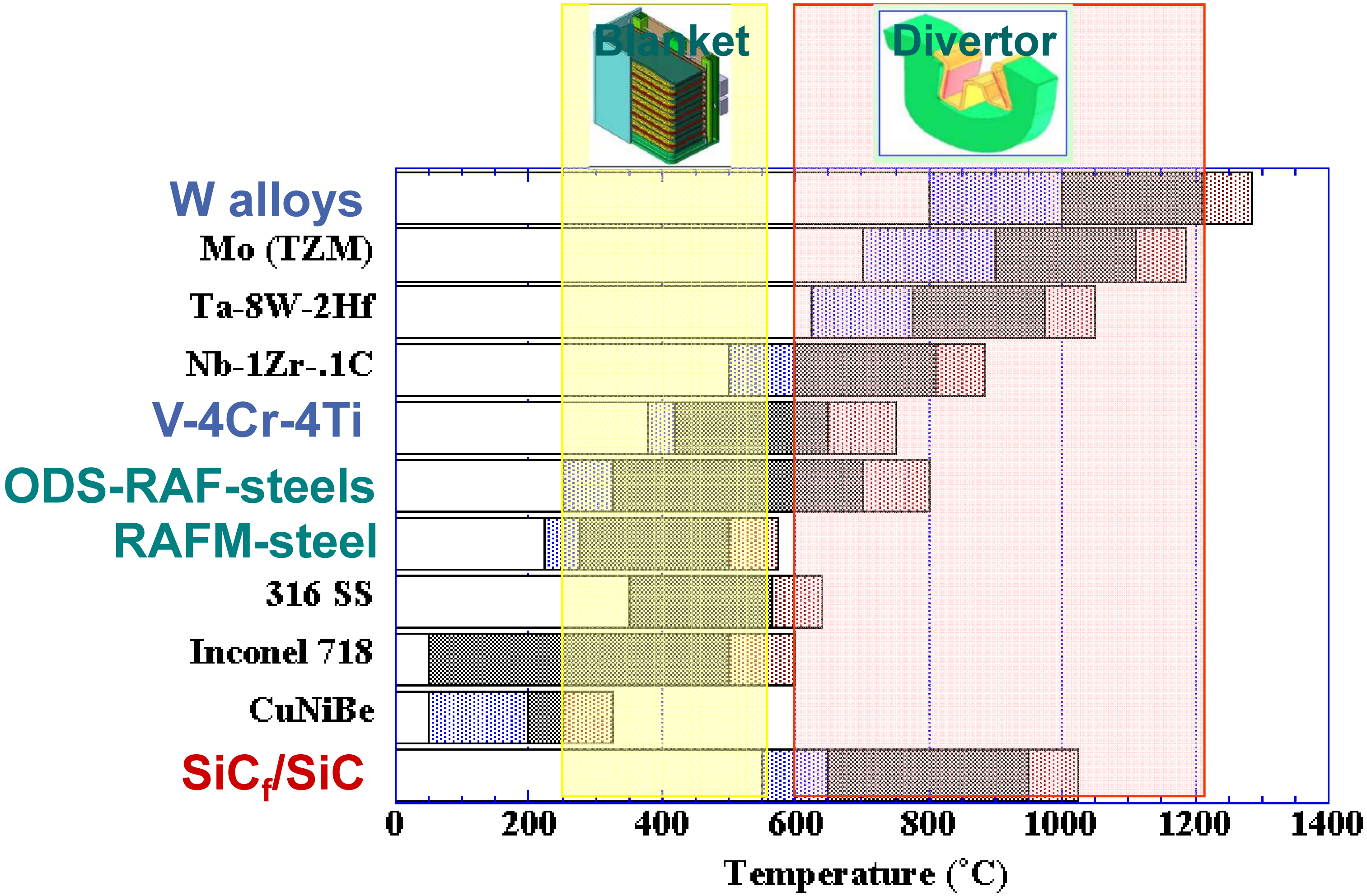
- Substantial progress since the early 90-ies
- „Low level waste" already after 80-100 years
- No "high level" waste disposal
- More than 60 tons produced in JA (F82H mod) and EU (EUROFER)

The European reference steel EUROFER is presently characterized and code qualified (RCC-Mx)

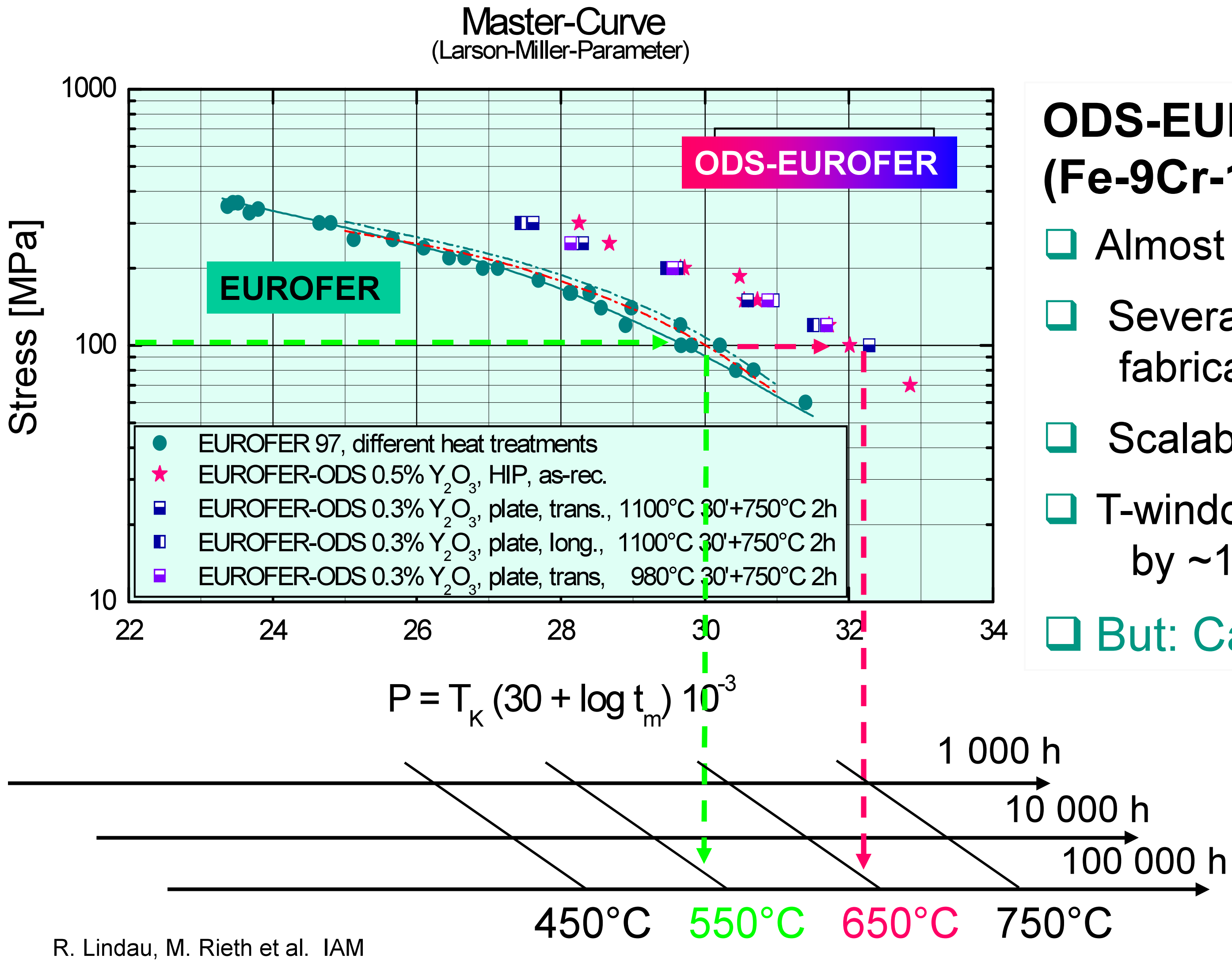
Long term irradiation (12.5 MWa/m^2) of a DEMO reactor first wall
Source: IMF I, FZK

Application window of today's materials (~10 dpa)

S.J. Zinkle, N. Ghoniem



Long-term Creep Behavior: 100 MPa for ≥50 000 h

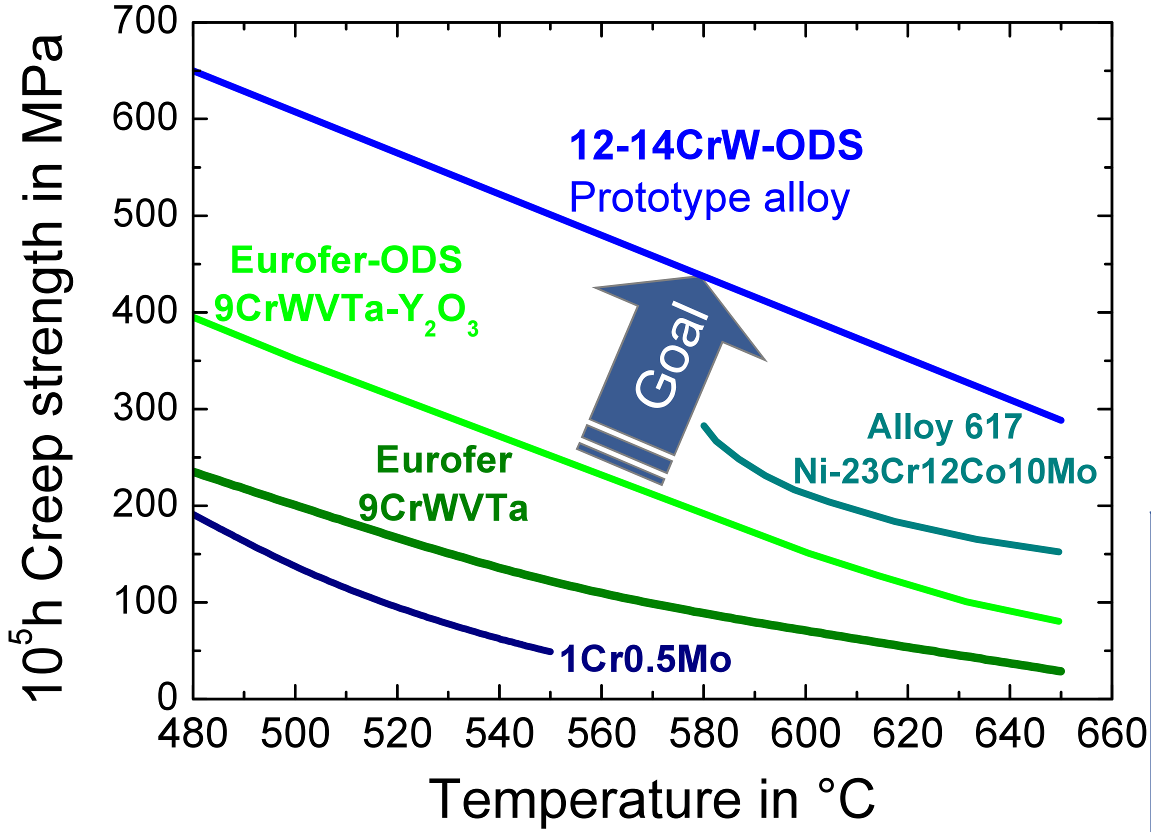


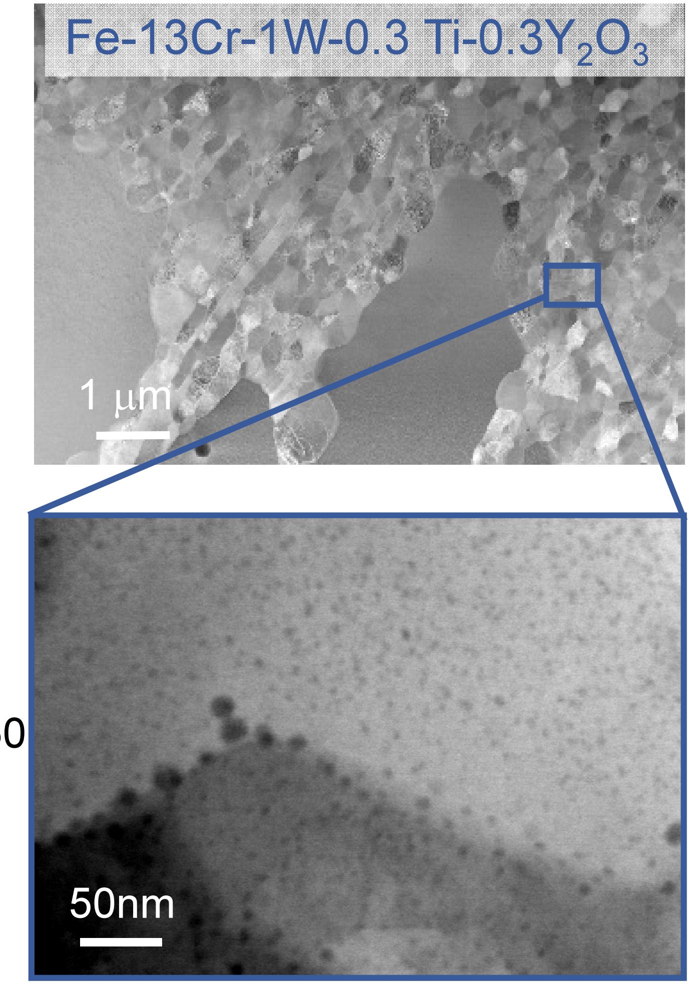
ODS-EUROFER (Fe-9Cr-1WVTa-0.3Y2O3):

- ❑ Almost isotropic properties
- ❑ Several 50 kg batches fabricated with Industry
- ❑ Scalable technology
- ❑ T-window increased by ~100 °C to 650 °C
- ❑ But: Can we do it better?

R. Lindau, M. Rieth et al. IAM

International challenge: Development of nanoscaled iron based "super alloys" (nanoscaled ODS steels)





E. Eiselt, M. Klimenkov, R. Lindau, A. Möslang
J. Nucl. Mater 2010

Fabrication process

KIT
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Mechanical alloying of powders

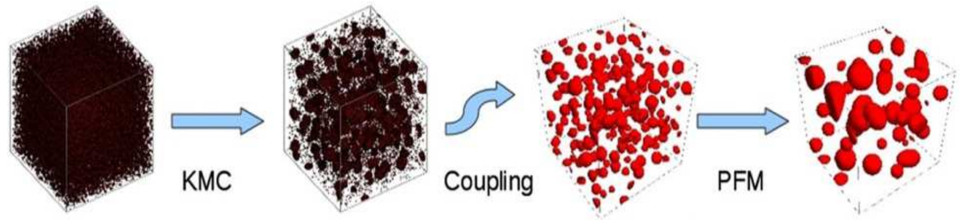
Capsules after HIP

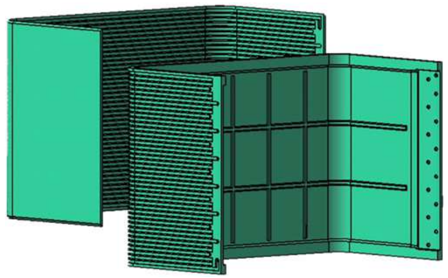
Hot Extrusion

Annealing + Hot rolling

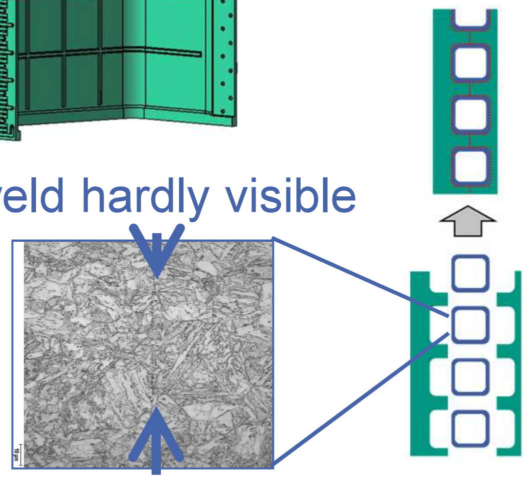
Joining technology for ODS steels

TIG, EB and Laser welding not suitable:
ODS particle coarsening above ~1250°C



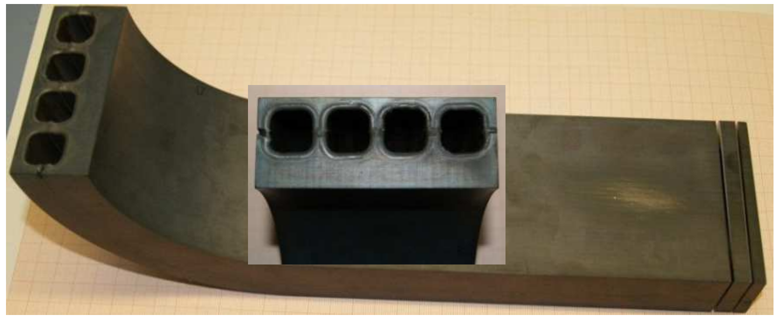


Diffusion weld hardly visible



Diffusion welding successfully qualified

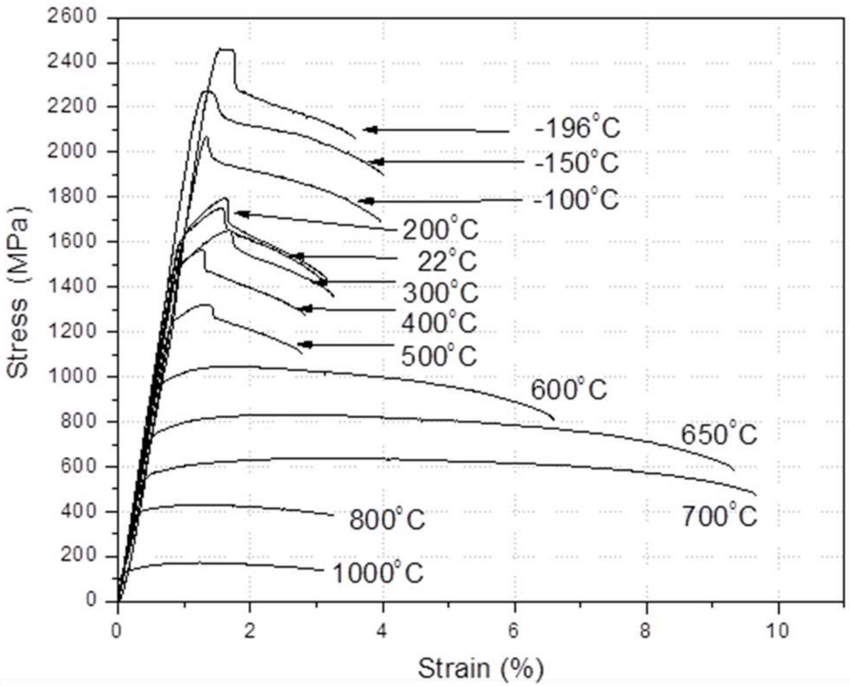
- E.g. as large scale FW fabrication method
- cost effective, robust and fail-safe fabrication route
- Compatible with industrial environment
- Tolerant against scattering of process parameters

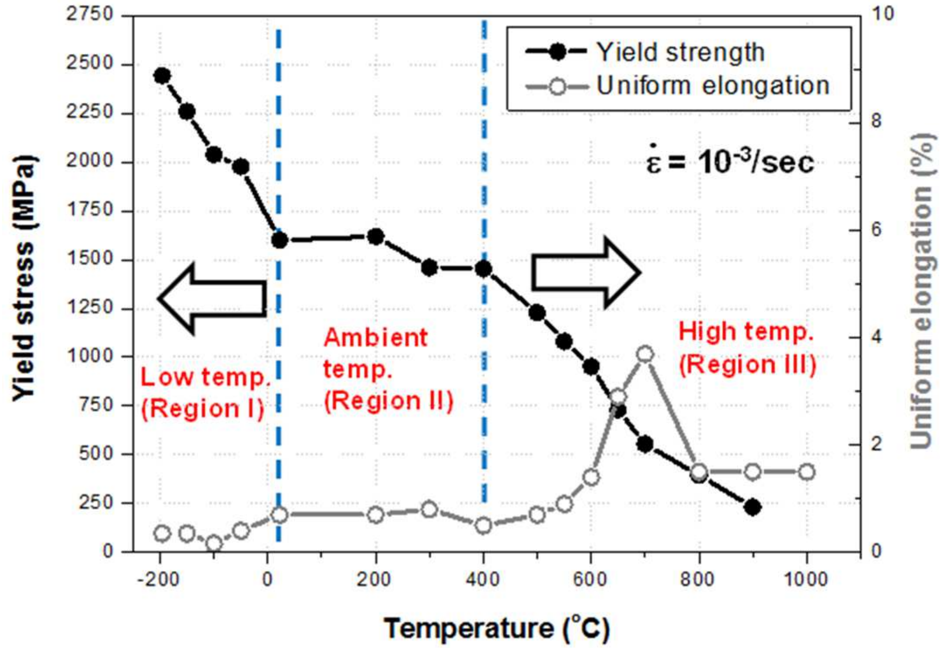


M. Rieth et al, KIT

Tensile properties of nanoscaled ODS steel
14YWT (Fe-14Cr-3W-0.4Ti-0.3Y_2O_3)

Courtesy of D. Hoelzer, ORNL



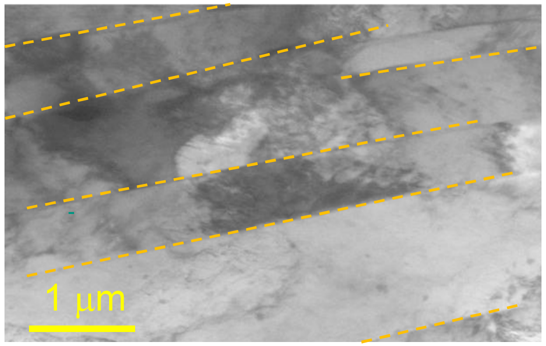


- ❑ Low uniform elongation, but extensive plastic deformation occurs after plastic instability until failure
- ❑ Ductile Brittle Transition well below room tepmerature (not shown here)

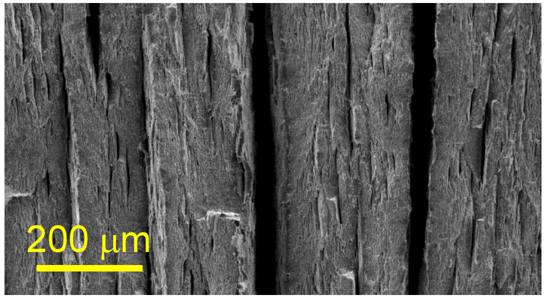
Deformed ODS Steels: highly non-isotropic

ODS steels: Influence of hot rolling (~80% reduction) on properties

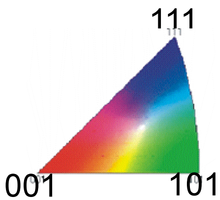
- Transmission Electron Microscopy (TEM): Rolling texture on microstructure

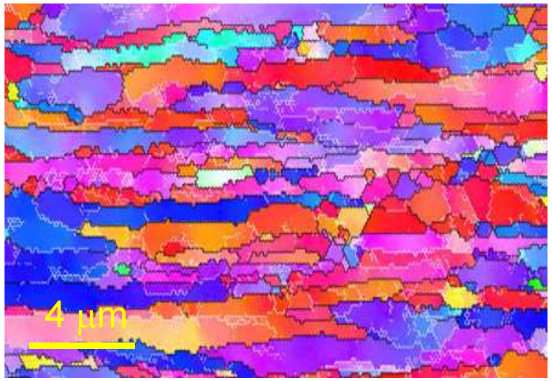


- Scanning Electron Microscopy (SEM): Fracture surface of Charpy tested samples shows clear fracture along texture, similar to Tungsten alloys
  J. Hoffmann et al., 2012



- Electron Backscatter Diffraction (EBSD):
  - Pronounced elongated grains
  - typical for textured microstructures
    ND: (001)<110> and (111)<110>



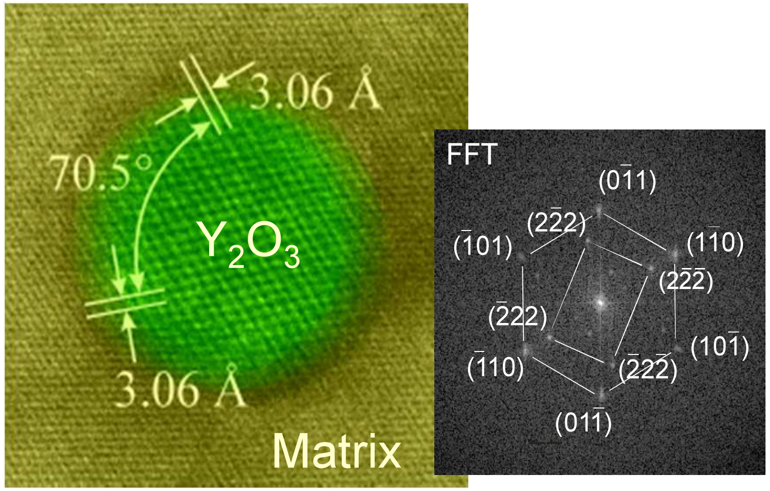


Nanoscaled ODS Steels: High resolution TEM

Y_2O_3 particles (~4-15 nm):

- (111)Y_2O_3 || (110)FeCr - orientation of atomic planes; contradiction to classical text books
- Coherence despite of the high melting temperature (~2500 °C) of Y_2O_3

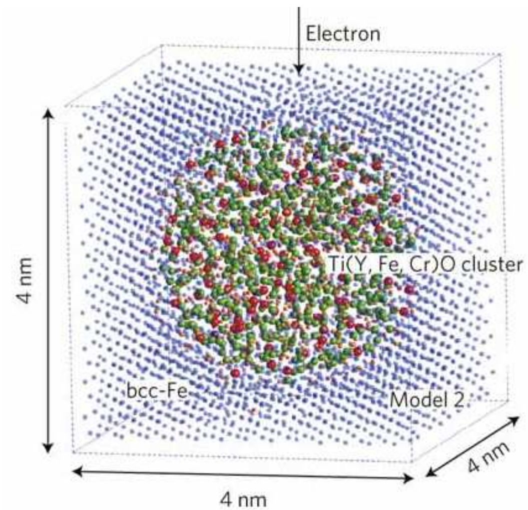
M.Klimenkov et al ., J. Cryst. Growth 249 (2003) 381–387



Ti-Y-O particles (≤4nm):

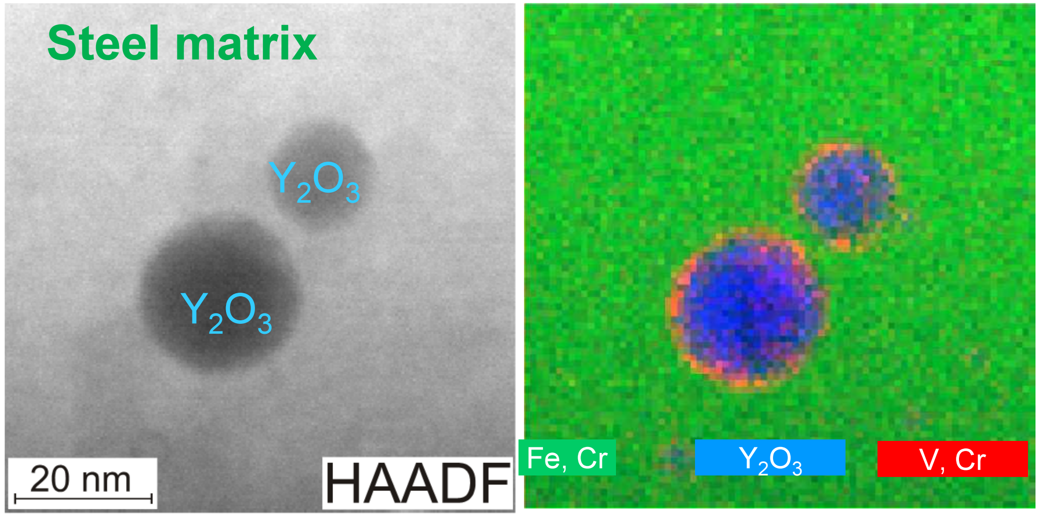
- Also bcc structure and still coherent
- But varying composition: Ti-(Y,Fe,Cr)-O

A.Hirata et al., NATURE MATERIALS 10 (2011) 922-926



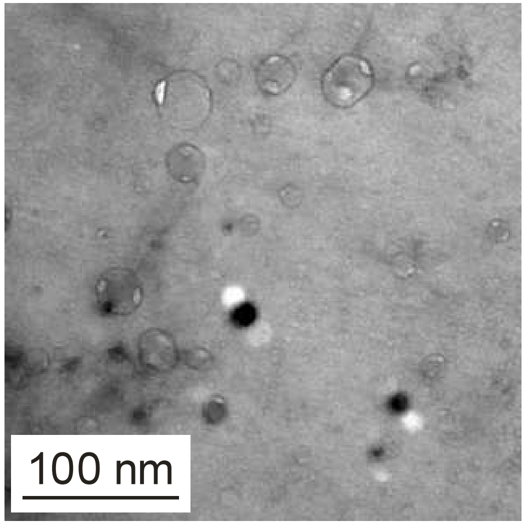
Why nanoscaled iron based ODS-alloys have the potential for outstanding aging and irradiation resistance?

Core shell structure



P. He, M. Klimenkov et al. J. Nucl. Mater. 428 (2012)131-138

Trapping of Ar bubbles

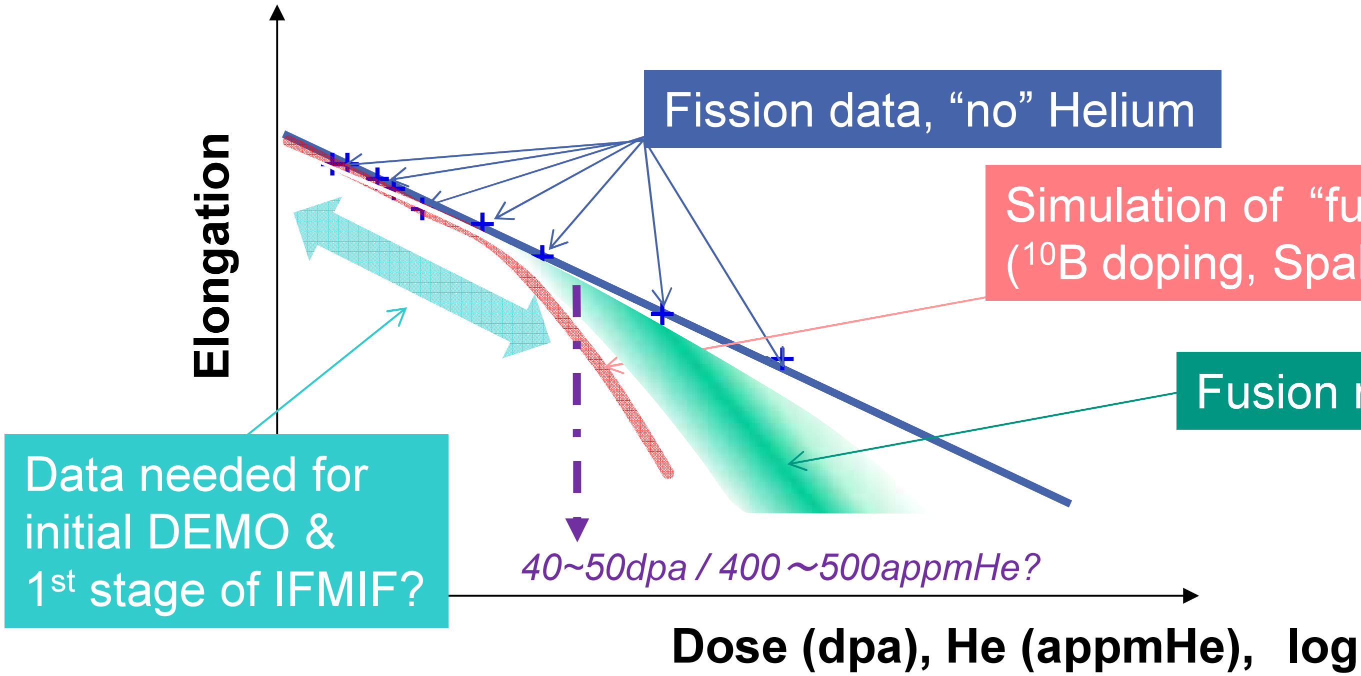


M. Klimenkov J. Nucl. Mater. 411 (2011) 160

- Interface Engineering"
  Nano-scaled ODS particles like Y_2O_3 or $Y_2Ti_2O_7$ are efficient trapping centers for diffusing alloying elements (Cr, V) and Ar.
- Outstanding perspectives, if also true for irradiation induced defects (vacancies, He)

Possible steps towards a fusion design code: Tensile properties as example

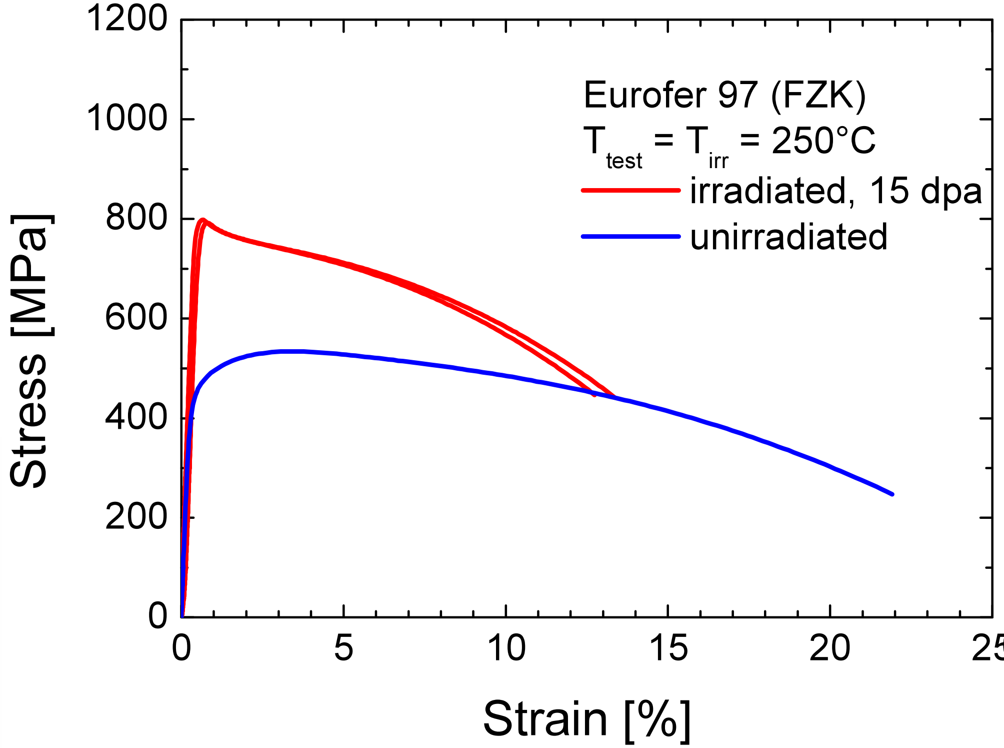
According to H. Tanigawa, E.Wakai



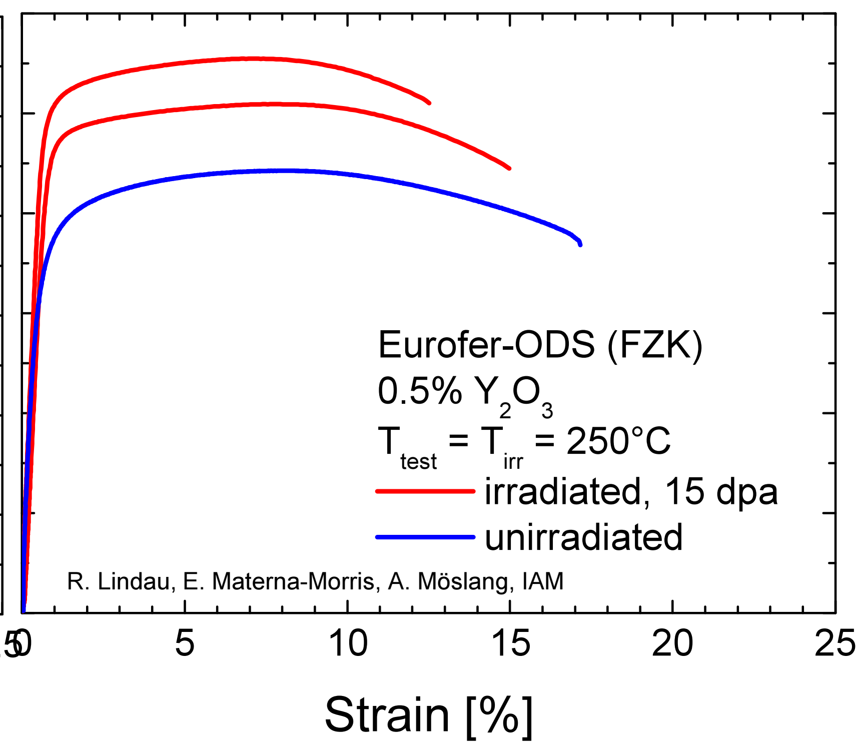
- Critical condition around 40~50 dpa / 400~500 appm He?
- This might be also the parameter window for initial DEMO and 1st stage of IFMIF and related design code development

ODS EUROFER after Neutron irradiation:
Substantial Improvement of tensile properties

RAFM Steel



RAFM-ODS Steel

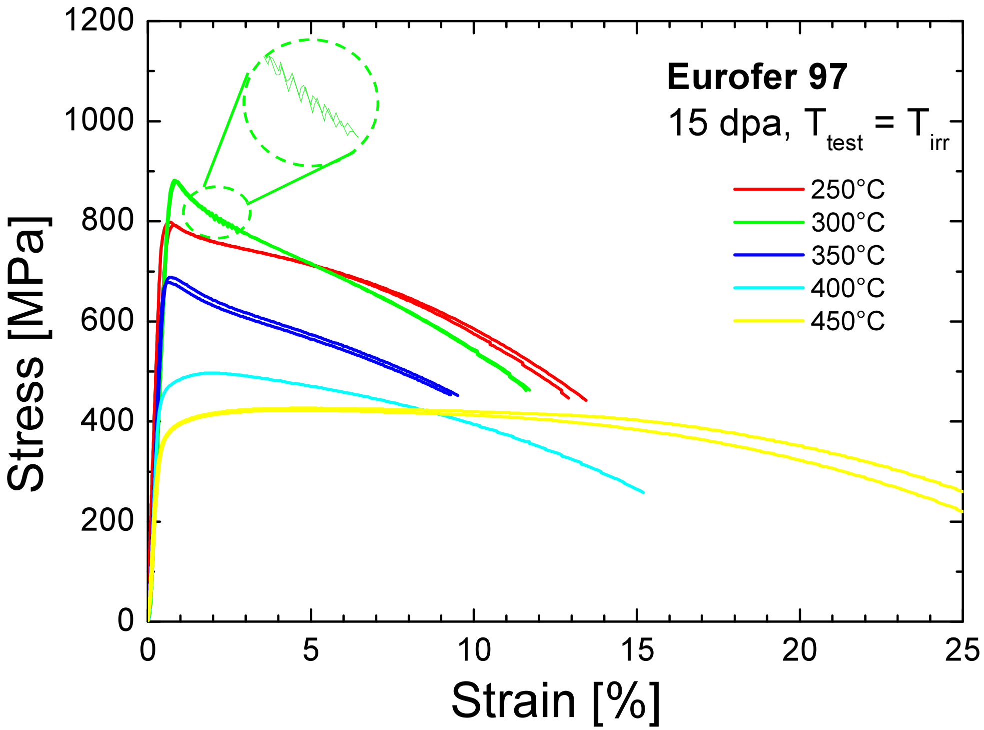


- ☹ Substantial irradiation hardening
- ☹ Early strain localization due to dislocation channeling → A_u ~0.3%

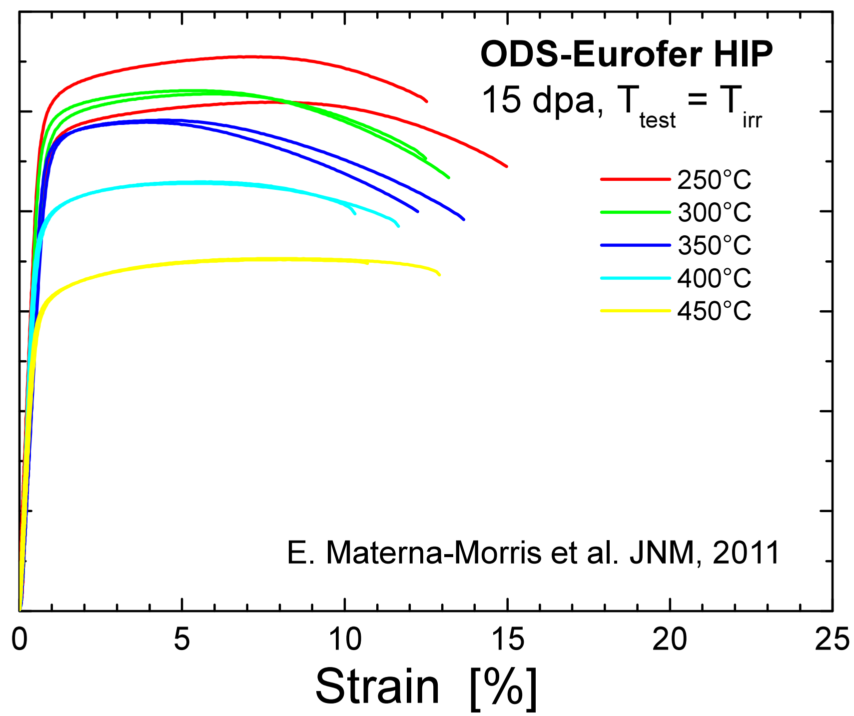
- ☺ Somewhat less irrad. hardening
- ☺ Still work hardening → almost no loss of uniform elongation (A_u ~7%)

ODS EUROFER after Neutron irradiation:
Substantial improvement at all irradiation temperatures

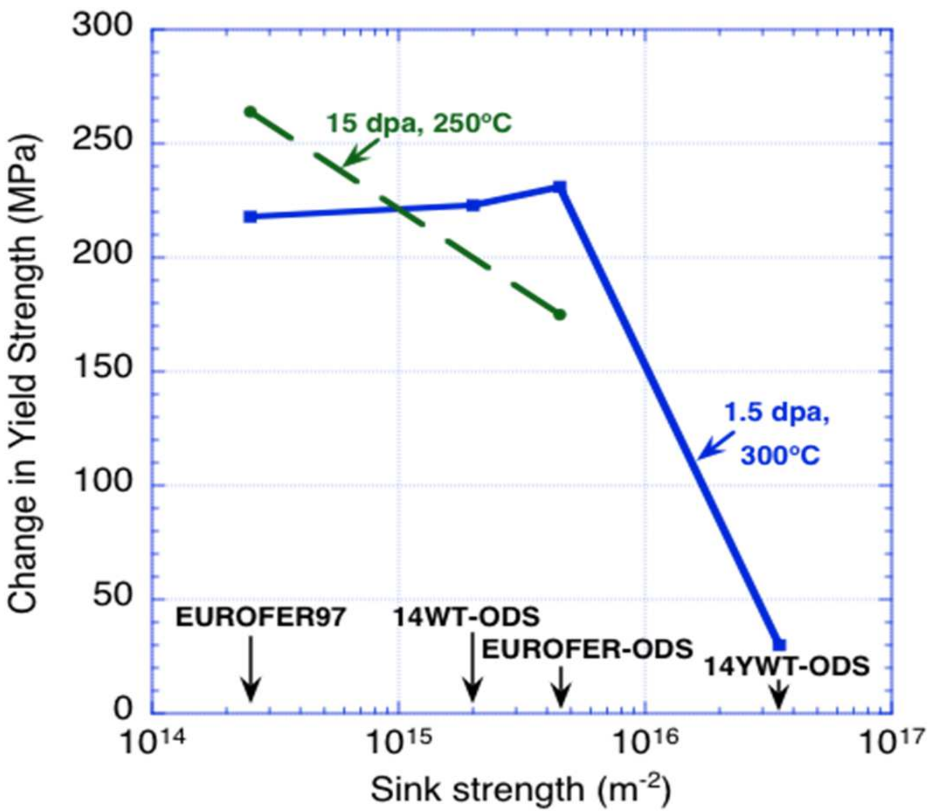
RAFM Steel



RAFM-ODS Steel



Neutron irradiation of ODS steels:
Tensile strength vs. sink strength (density of ODS particles)



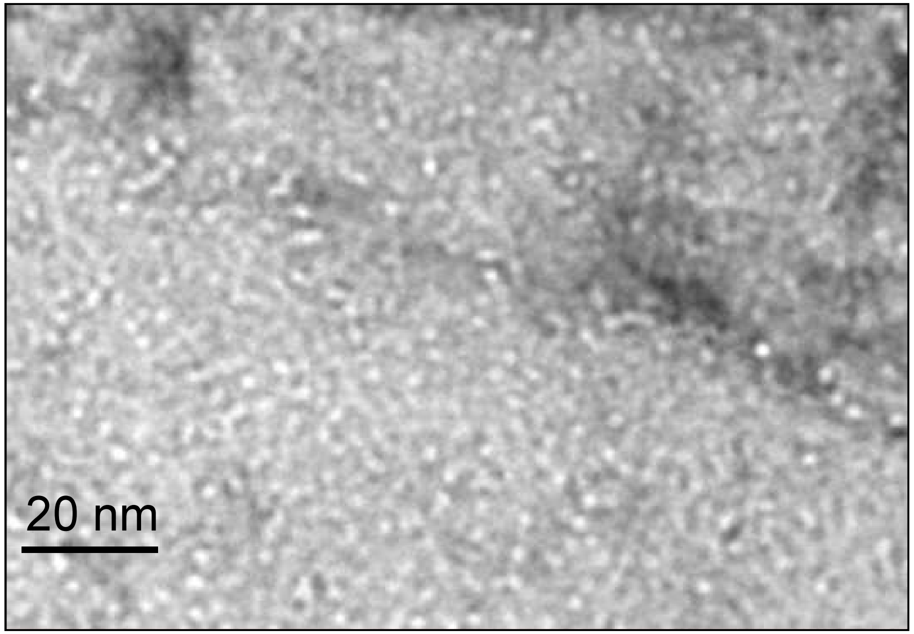
S.J. Zinkle, A. Möslang, T. Muroga, H. Tanigawa; Nucl. Fusion **53** (2013) 104024 -104037

The irradiation tolerance increases substantially with ODS particle density
→ defects are trapped at particle matrix interface and recombine

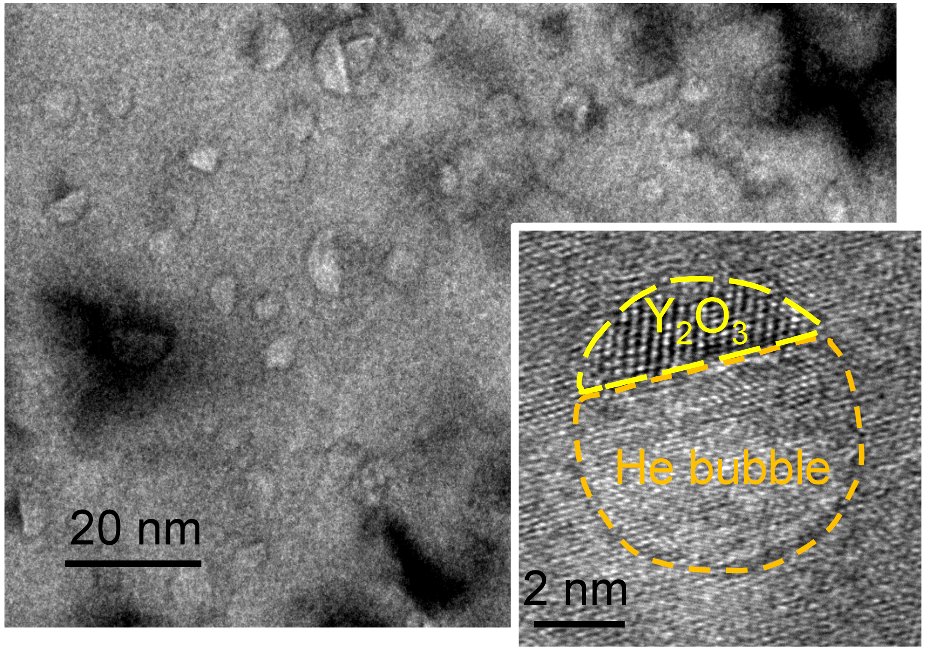
ODS steels: He trapping at particle-matrix interface

Karlsruhe Institute of Technology

14YWT (14Cr-3W-TiYO)	EUROFER-ODS (9CrWVTa-YO)
❑ irrad. Fe^{3+} (6.4 MeV), He^{++} (1 MeV), ❑ 2200 appm He, 650°C	❑ He^{++} (30 MeV), ❑ 1000 appm He, 550°C



Courtesy of D. Hoelzer, ORNL



A. Ryazanov et al., J. Nucl. Matter 442 (2013)153-157

Effective He trapping indicates: ODS steels may be extremely irradiation tolerant

Summary and Conclusions

- Significant progress has been made in the fabrication of ferritic nanoscaled ODS Steels
  - The powder metallurgy based production route is practically established
  - near term step are medium sized heats (10-50 Kg range)
- The mechanisms responsible for high-temperature strength and creep behavior are emerging
- Scientific understanding of structure-property relationships advanced
- Nanoscaled ODS steels have the potential for extremely high aging and irradiation resistance at high service temperatures and fit perfectly into an energy efficient landscape