# Existing irradiation data and its validation, extension and assessment of neutron spectrum effects

***M. Rieth***

# Overview

- What are the relevant materials? Which applications?
- Why do we need irradiation data?
- What irradiation data do we have? What are the available irradiation facilities?
- How does irradiation damage depend on the irradiation source?
- Which irradiation data do we need?
- Which data cannot or should not be generated by IFMIF/DONES?

# What are the relevant materials?
# What are the applications?

- Baseline
  - **EUROFER97**: blanket (first wall, caps, etc.), divertor cassettes
  - **CuCrZr**: pipes for water cooled plasma-facing units (divertor)
  - **W**: armor material (monoblocks for divertor, layer for first wall)
  - **Li ceramics**: breeder materials
  - **Be and Be alloys**: neutron multiplyer materials
  - **Functional materials** (diamond, alumina, …): Heating&CD, diagnostics, …
  - **various specific materials** (see ITER, …, e.g. bolts, springs, …)
- Advanced materials
  - **ODS steels**: blanket first wall (and maybe parts of blanket)
  - **ODS copper**, **W fiber reinforced copper alloy** (pipes for water cooled divertor)
  - **self passivating W alloys**: layer for first wall
- Materials Technology
  - **welds**: EUROFER97 (diffusion, e-beam, laser, TIG, …), CuCrZr pipes
  - **dissimilar joints**: EUROFER97-W graded coating (plasma sprayed), alumina-coatings
  - **brazings**: W-CuCrZr (divertor), diamond-Cu (H&CD)
  - **production, fabrication, machining related material issues** … (AM, large scale, …)

**structure materials**

**R&D**

very few data

# Why do we need irradiation data?

- A DEMO reactor is a nuclear facility and, therefore, its **design, construction, and commissioning has to undergo a specific licensing procedure**.
  - For fission reactors, nuclear power plant design and analysis codes were established in the past. But for fusion reactors, such design codes are not available yet.
  - To **develop design codes and design rules**, high-quality material data for operation relevant conditions are required.
  - The raw material data is collected in **databases**. After processing, the data is published in **material property handbooks**.
- R&D work on advanced materials for DEMO and future power reactors is ongoing. The **candidate materials have to be assessed** w.r.t. possible advantages compared to the baseline materials.

# What irradiation data do we have? What are the available irradiation facilities?

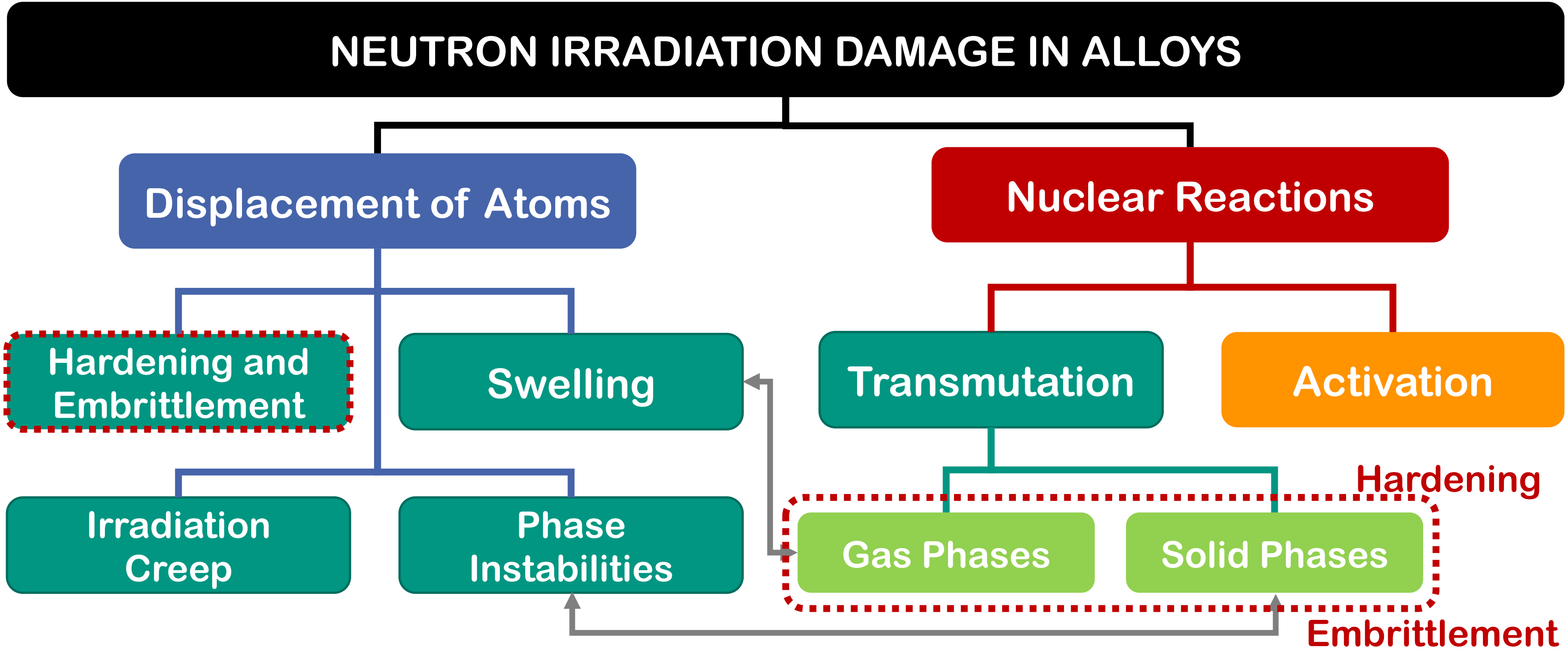
- **Material test reactors** (MTRs) **now**: BR2 (Mol), LVR-15 (Rez), HFIR (ORNL), ATR (INL), MITR (MIT), *BOR-60 and 3 others (RIAR), HFR (Petten), …* PROBLEM: low neutron energies (<<14 MeV)
- **Material test reactors** in **2030**: BR2?, LVR-15, US reactors?, ???
PROBLEM: reduced number of available MTRs in the near future
- **Proton irradiation facilities**: not many data yet, possible applications are currently under investigation (→ presentation of R. Rayaprolu)
- **Neutron Spallation sources**: most data available from SINQ (PSI), PROBLEM: high energies (>> 14 MeV) → very high transmutation rates of He and H, but also of “alloying elements and impurities”
- ***Ion irradiation facilities:*** less relevant due to shallow penetration depth (μm scale) and high damage rates

# Mechanical Properties after MTR Irradiation

| | |
|---|---|
| EUROFER97 | • basic mechanical properties (hardness, tensile, Charpy, fracture mechanics, low cycle fatigue) very well characterized up to 5 dpa (also due to ITER/TBM studies) – 250-450°C<br>• good data sets are available up to 15-20 dpa / 250-450°C<br>• reduced data up to 70 dpa / 320-330°C |
| CuCrZr | • basic mechanical properties (hardness, tensile, Charpy, low cycle fatigue) up to 5 dpa / 150-350°C very well characterized (due to ITER studies → ITER MPH) |
| Advanced Steels and Cu materials | • Hardness, tensile, low cycle fatigue studies on ODS-EUROFER<br>• Tensile & fracture mechanics study for steels in HFIR (300°C, 3dpa)<br>• Tensile & fracture mechanics study for steels in BR2 (300°C, 3 dpa) in preparation<br>• Tensile study for Cu alloys and composites (150, 350, 450°C, 2.5 dpa) |
| Materials Technology | • Very few investigations (e.g. powder metallurgy)<br>→ Systematic weld studies (and other issues) are missing |

Impact of differences in Material Test Reactor (MTR) and fusion neutrons → next 10 slides

# How does irradiation damage depend on the irradiation source and what is relevant for nuclear fusion?



NEUTRON IRRADIATION DAMAGE IN ALLOYS

Displacement of Atoms

Nuclear Reactions

Hardening and Embrittlement

Swelling

Transmutation

Activation

Irradiation Creep

Phase Instabilities

Hardening

Gas Phases

Solid Phases

Embrittlement

# Displacement Damage Evaluation

| | MTR | | DEMO (peak) |
|---|---|---|---|
| **Neutron energy E** | **1 MeV** | **2 MeV** | **14.1 MeV** |
| Transferred energy (max.) | 69 keV | 138 keV | 972 keV |
| Damage energy (max.) | 48 keV | 96 keV | 530 keV |
| Transferred energy (average) T | 35 keV | 70 keV | 485 keV |
| **Damage energy (average) $T_{dam}$** | **24 keV** | **48 keV** | **265 keV** |
| **Displacements (by 1 neutron)** | **240** | **480** | **2650** |

## Norgett-Robinson-Torrens (NRT) dpa calculation:

**If $T_{dam} > E_d$ then the number of displacements $N_d$ (frenkel pairs) is**

$$N_d = \frac{0.8\,T_{dam}}{2E_d}$$

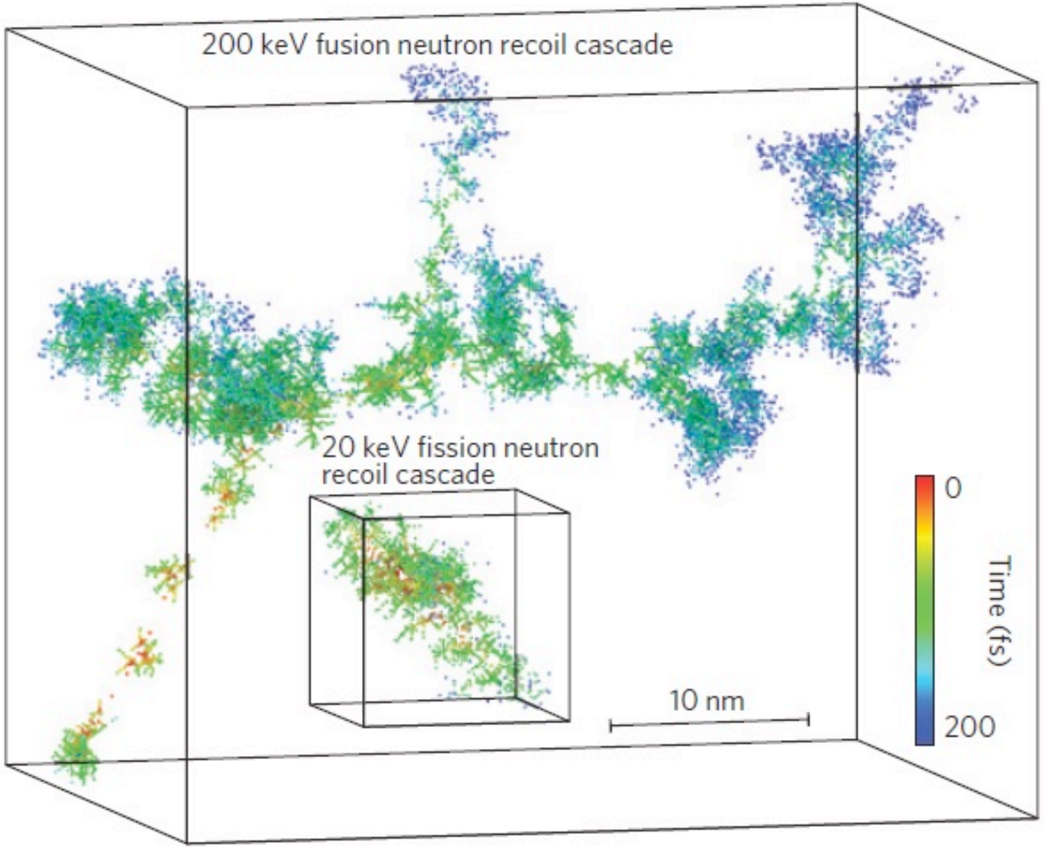
**for iron $E_d$ = 40 eV, thus**

$$N_d = \frac{10}{keV} T_{dam}$$

**According to the NRT dpa calculation scheme, for the same displacement damage, 5-10 times more MRT neutrons are required or the irradiation time has to be extended by a factor of 5-10 compared to a DEMO first wall scenario.**

# Displacement Damage

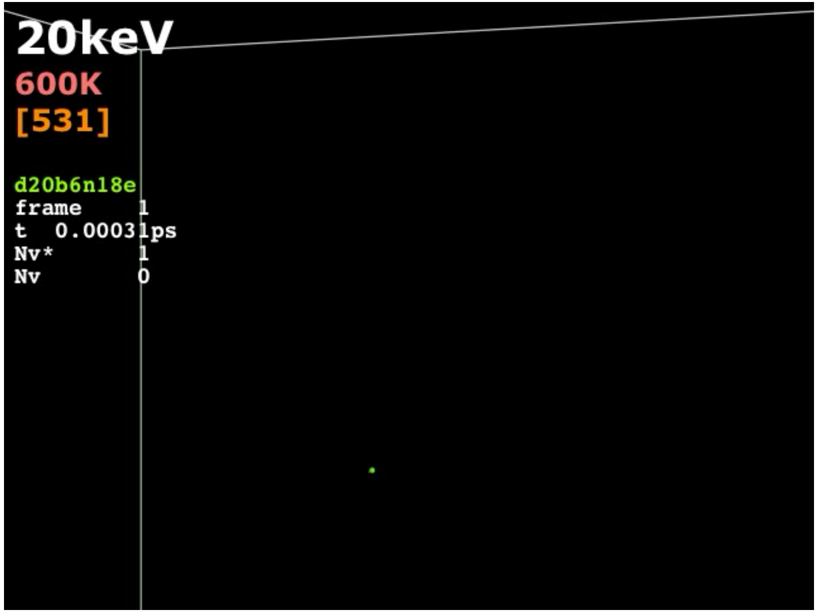
Recoil Cascades



*A. Sand and K. Nordlund in:*
*J. Knaster, A. Möslang and T. Muroga, Nature Physics (2016)*

# Molecular Dynamics Simulation

| | MTR | | DEMO peak |
|---|---|---|---|
| **PKA damage energy $T_{dam}$** | **20 keV** | 50 keV | 250 keV |
| **Displacements $N_d$ (in video: $N_v$)** | **200** | 500 | 2500 |



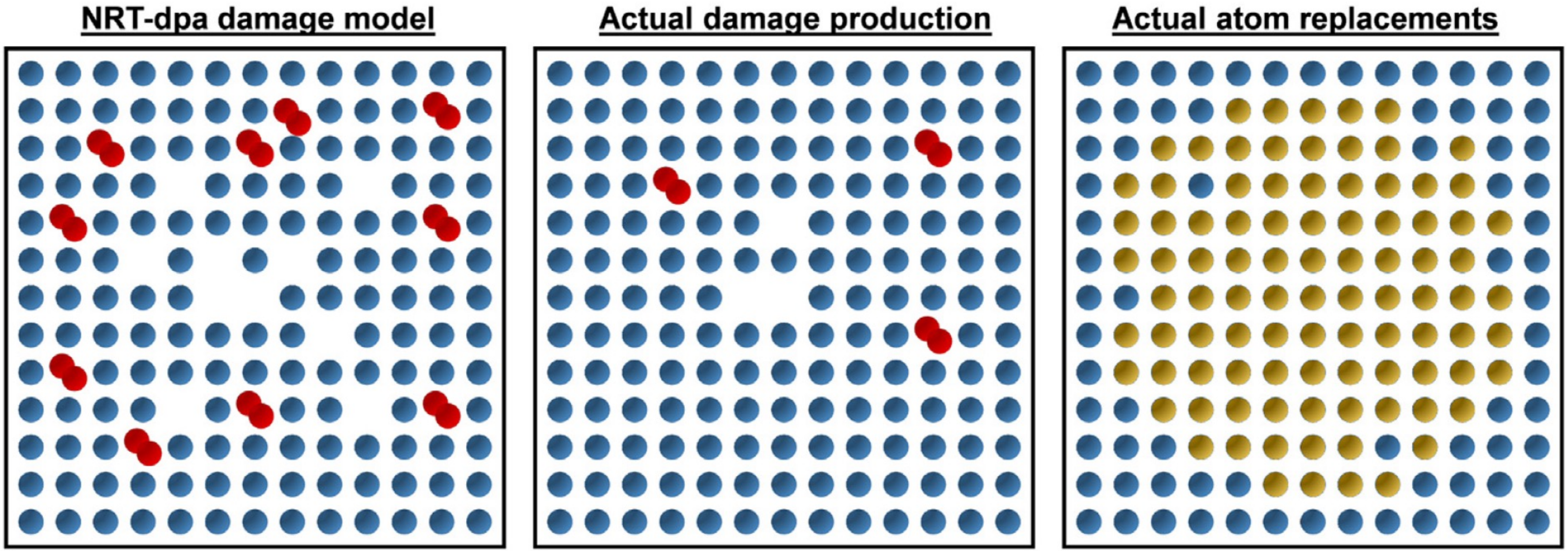
- **(Sub-)Cascades develop**
- **Much more damage as calculated during thermal spike**
- **Much less defects after collapse**
- **Not only Frenkel pairs but clusters survive**

***University of Liverpool***

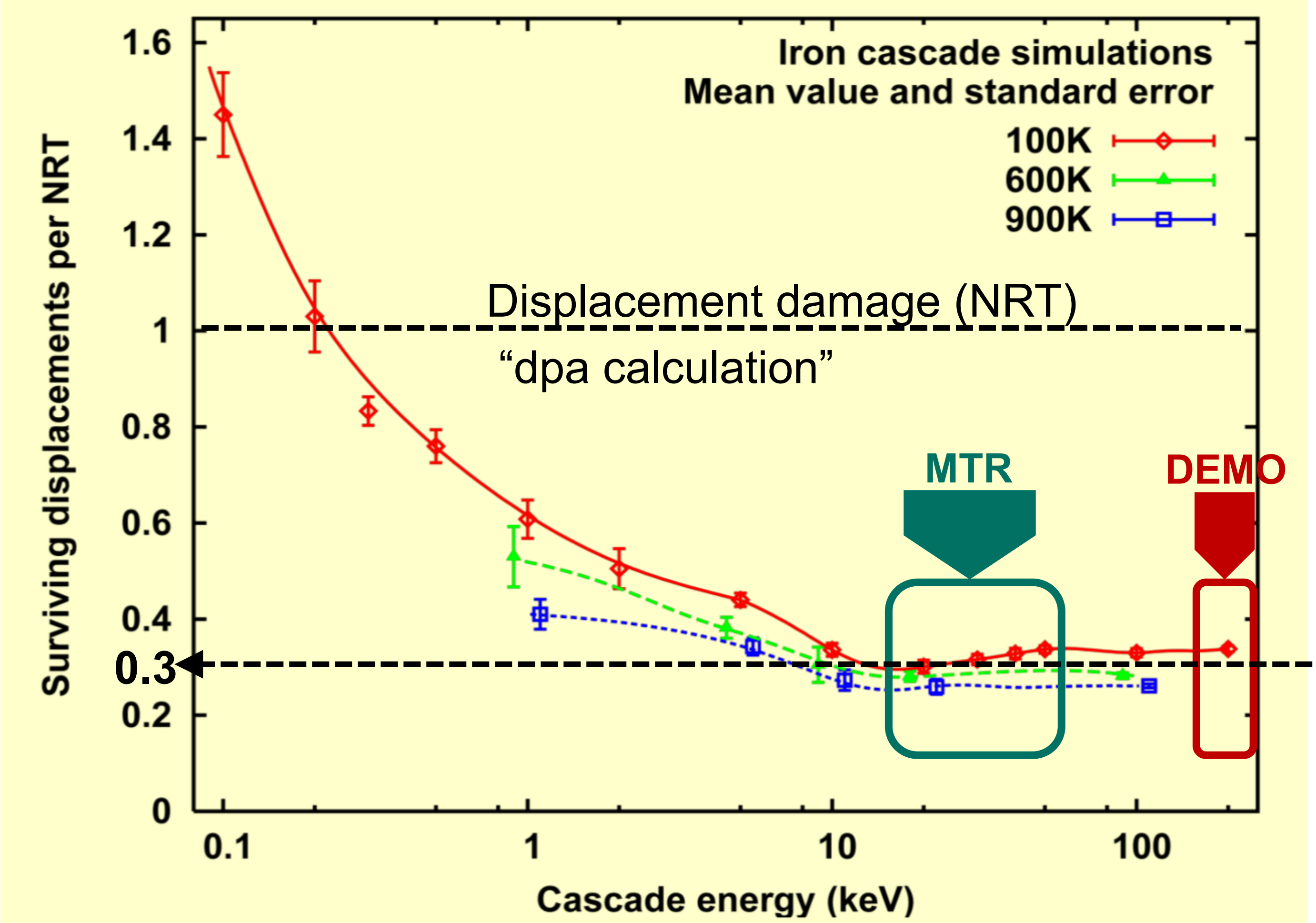
***MD Simulation for Fe at 600 K***

# Comparison: NRT-dpa model vs. simulation

*K. Nordlund et al., Journal of Nuclear Materials 512 (2018) 450-479*



20 keV example: **200** **65** **3900**



Displacement damage (NRT)

“dpa calculation”

0.3

**MTR**

**DEMO**

*R. Stoller et al.*

# Displacement Damage Evaluation

**How do MRT and DEMO neutrons cause damage?**

**Answer: The basic damage mechanism is sub-cascade development and collapse.**

**Do the neutrons (via PKAs) really produce 200-500 and 2000 Frenkel pairs?**

**Answer: No! The NRT displacement damage calculation scheme is not fully realistic. But it is equally wrong for both MRT and DEMO neutrons (PKAs).**

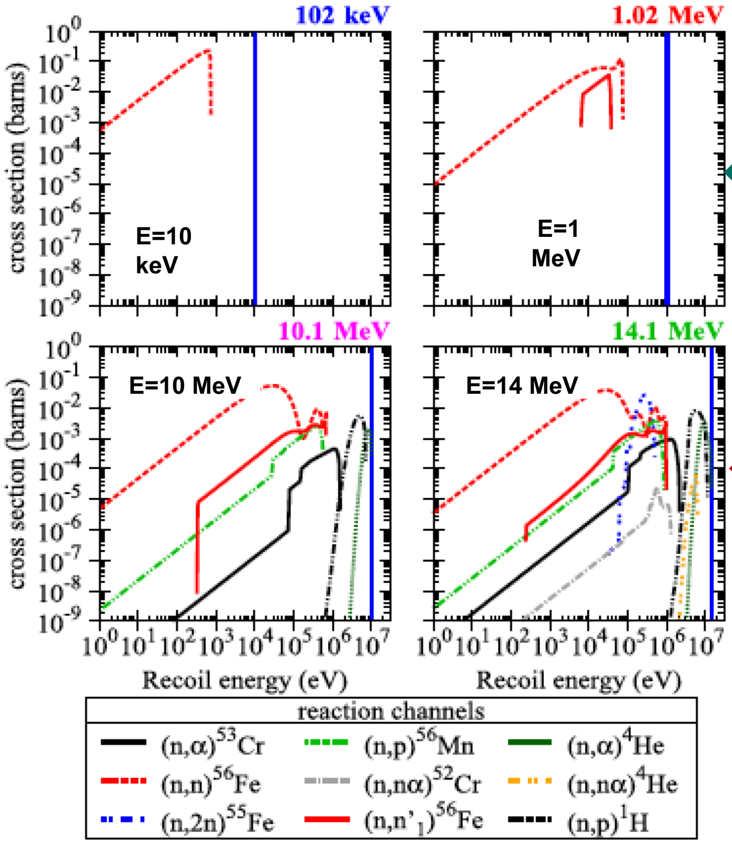
**Is it realistic to simulate "DEMO neutrons" by experiments in material test reactors (MTRs)? Which differences are to expect?**

**Answer: *<u>In terms of "displacement damage"</u>*, there are no major differences to expect! That is, the dpa approach (even if it doesn't mirror reality) is still applicable to the MTR simulation of DEMO neutrons.**

# He Transmutation in Steel

- Anelastic n – $^{56}$Fe scattering mainly at high neutron energies
- DEMO neutrons produce much more He and H compared to MTR neutrons (transmutation)
- The amount of produced He per displacement damage depends strongly on neutron spectrum and chemical composition, but not on temperature.
- ratio R: produced He per damage

**MTR → R≈<1 appm He/dpa**
**DEMO → R≈10-15 appm He/dpa**

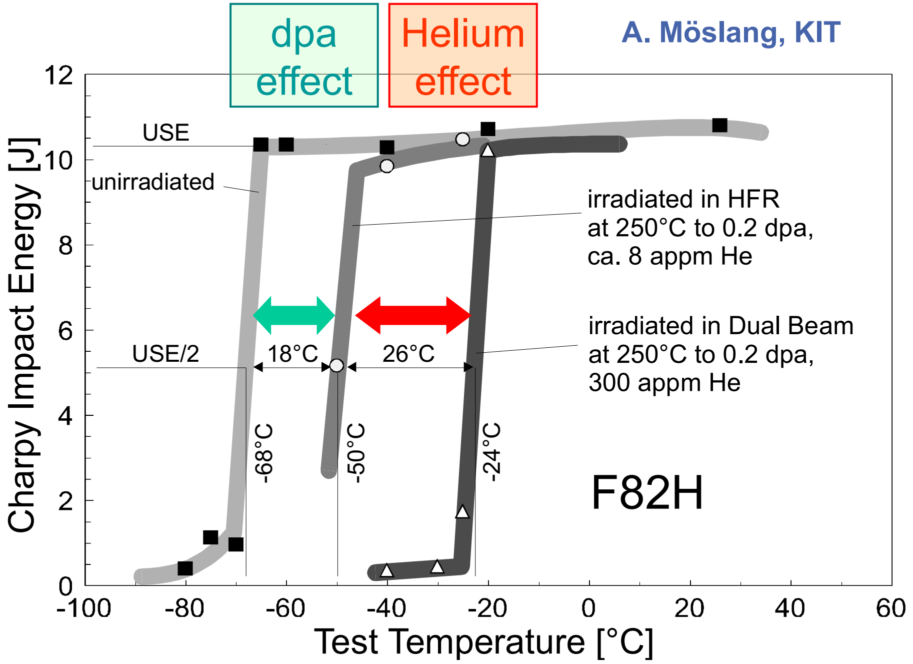


MTR
E=1-3 MeV

DEMO
E=14.1 MeV

*M. Gilbert et al.*

# Helium Embrittlement (transmutation)



**Helium leads to an additional shift in DBTT**

## Simulation in MTRs by isotopic tailoring

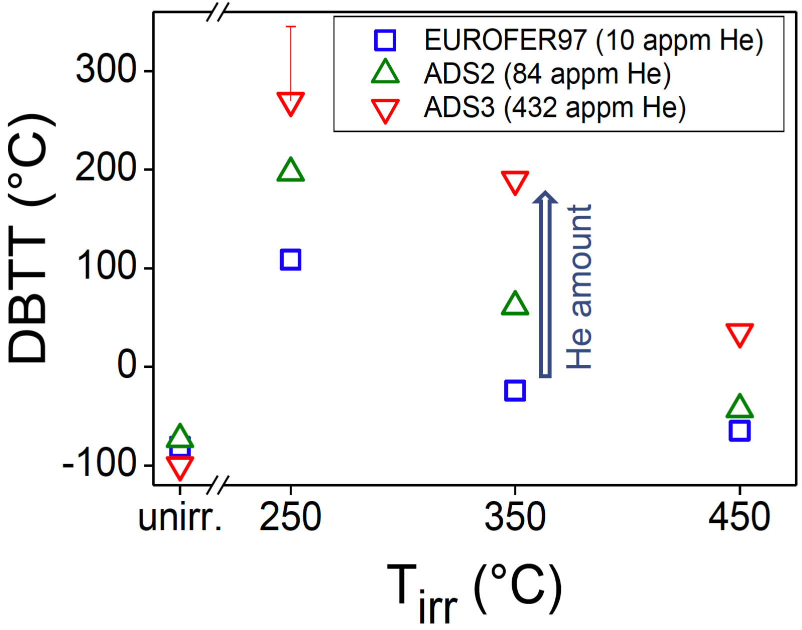
- **Boron: overestimation due to grain boundary sgregation**
- **Nickel-58: side effects due to Fe/Ni solid solution have to be cross checked**
- **Iron-54: R < 3, very expensive**
- **In all cases, constant R=10-15 requires production of many specific isotopic tailored materials**

# Helium embrittlement

## What do we know?

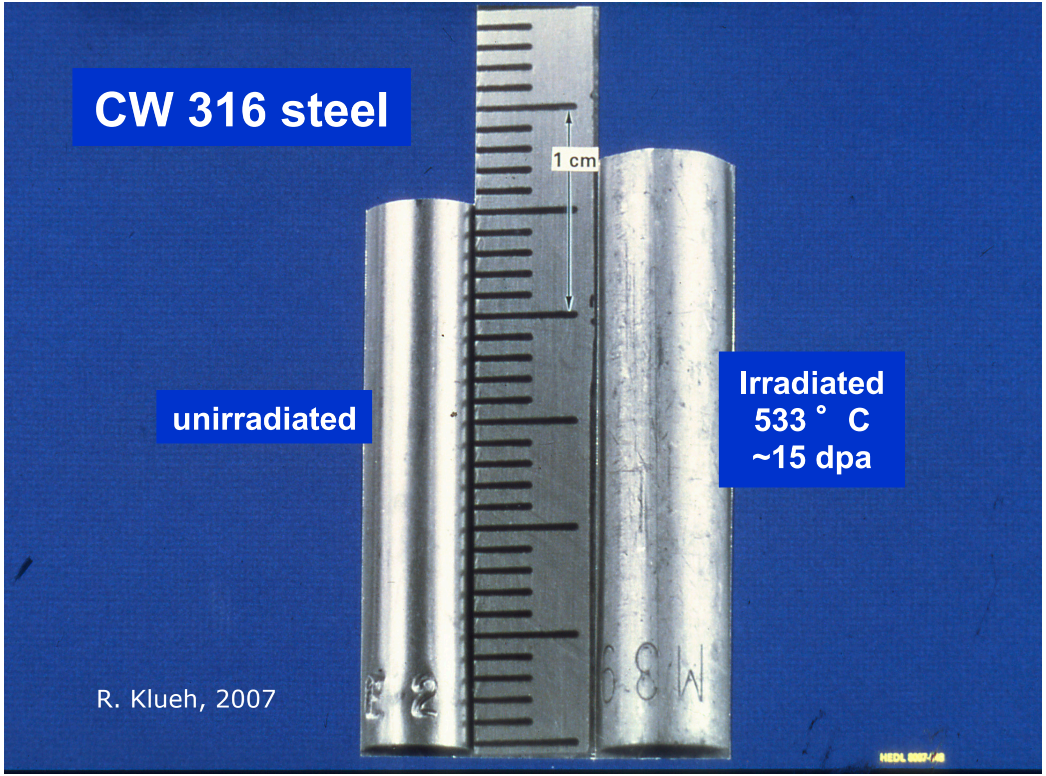
- At temperatures >0.5 $T_m$, stress and transmutation lead to He migration to grain boundaries.
- At grain boundaries, the formation of large intergranular bubbles significantly degrade strength and toughness.
- **The critical helium amount is estimated to be 200-500 appm, corresponding to 20-50 dpa for a DEMO first wall**

*Gaganidze, et al., Fus. Eng. Des. 2008*

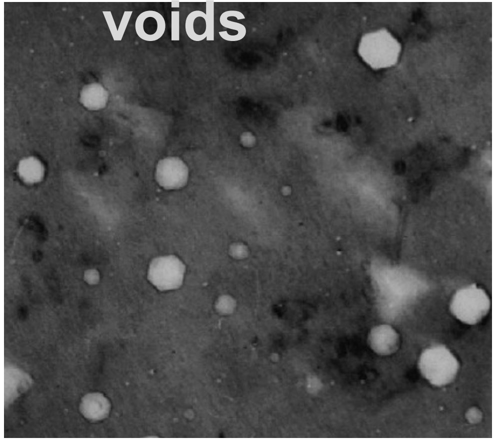


**Neutron irradiation experiments with boron-doped EUROFER**

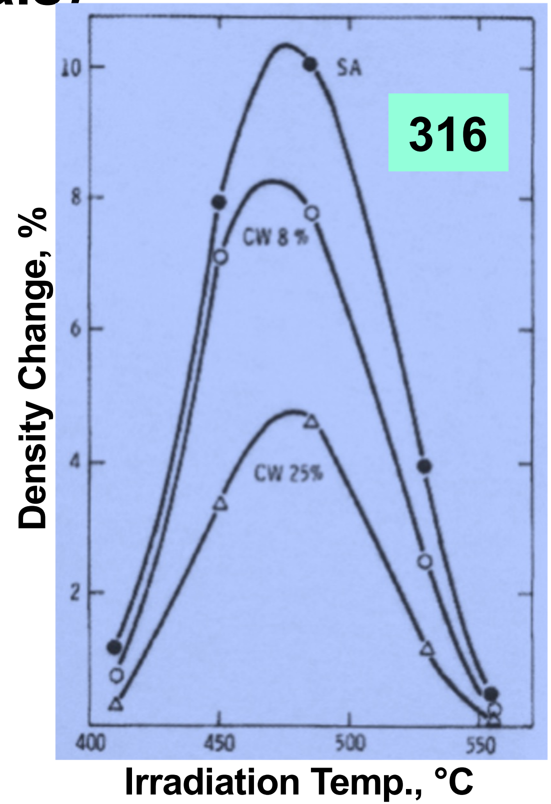
# Void Swelling (effect of vacancy clustering)

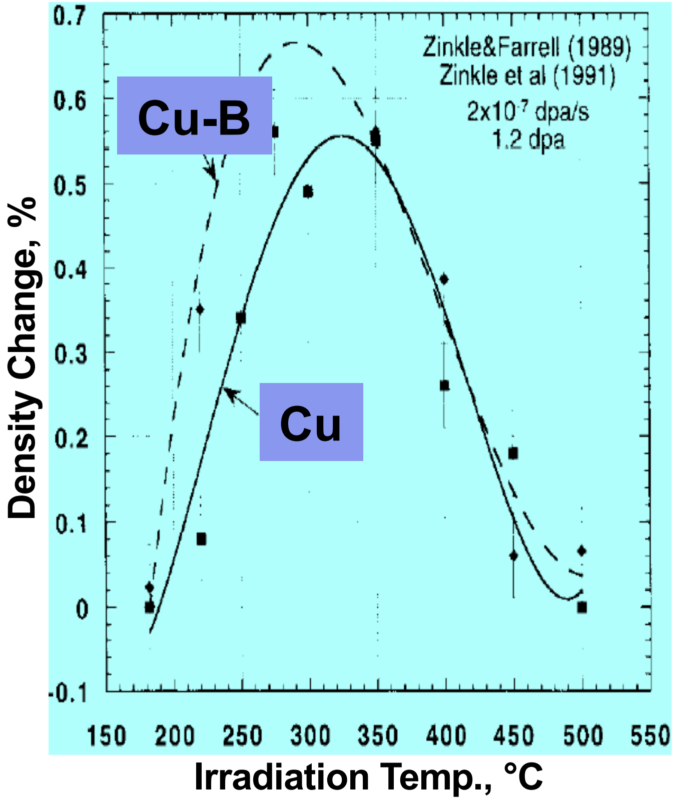


R. Klueh, 2007

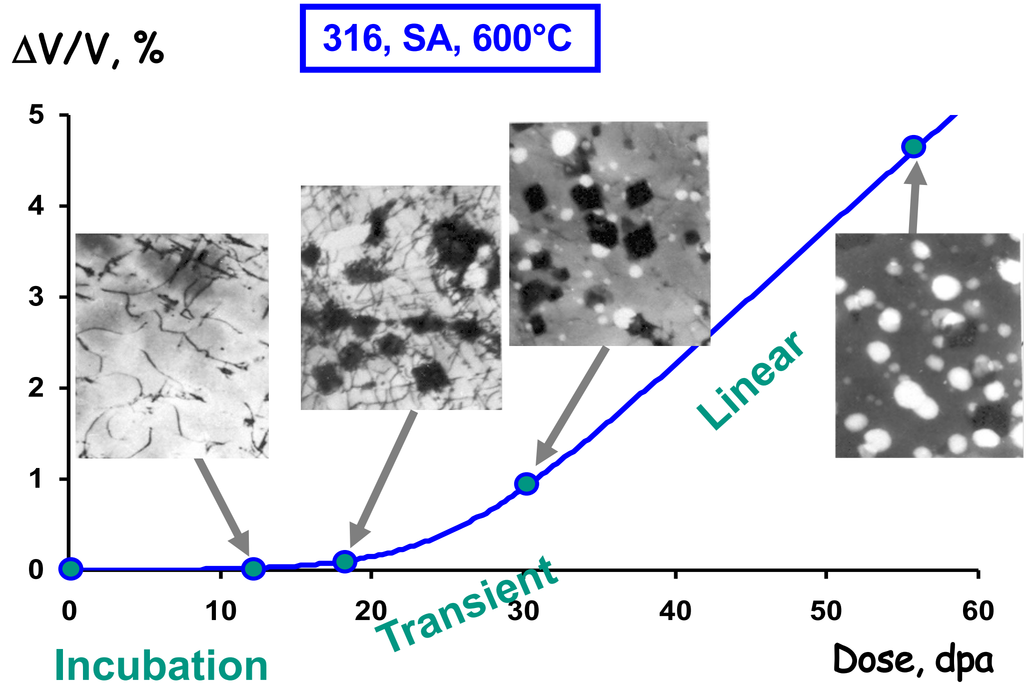


# Swelling (pronounced in fcc steels and Cu materials)

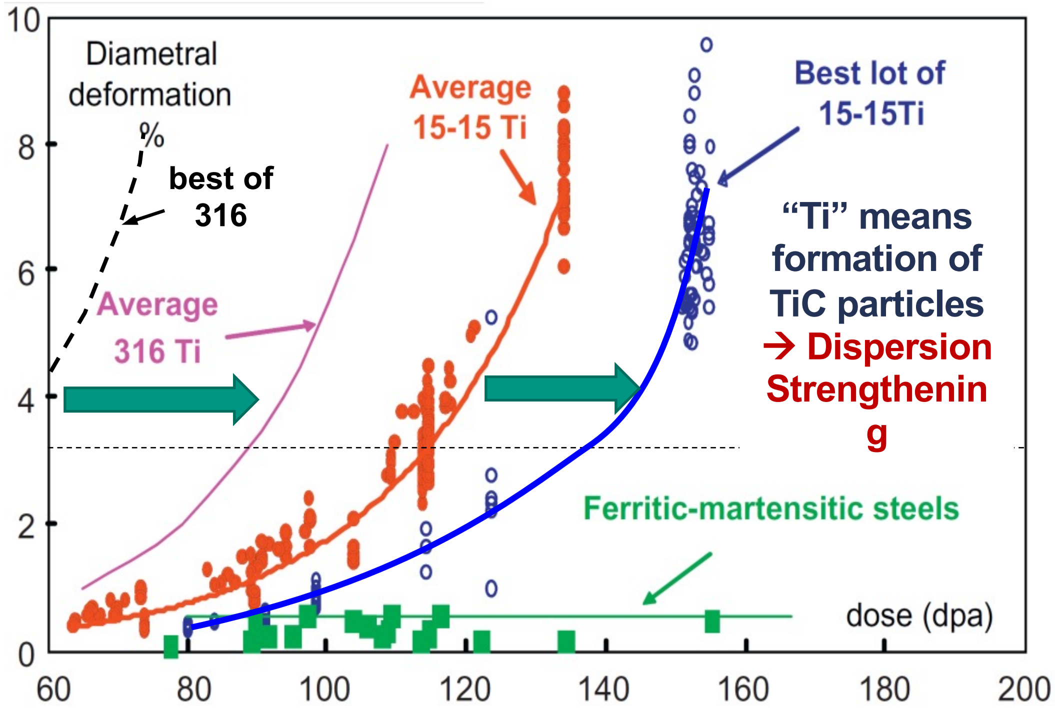




# Swelling (316 steel, dose effect)



# Swelling (effect of lattice and sink density)



"Ti" means formation of TiC particles

→ Dispersion Strengthening

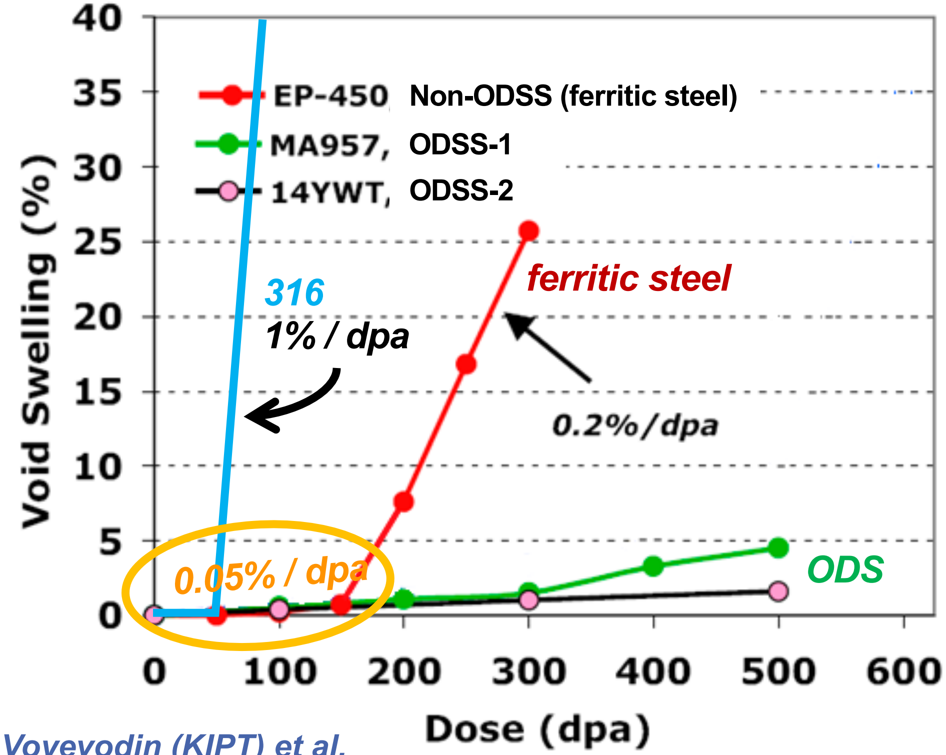
**fcc**

**bcc**

Séran et al., CEA

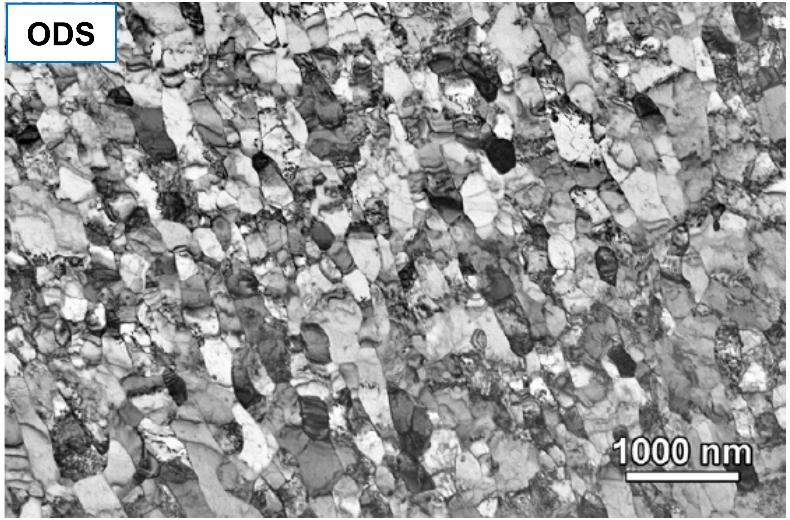
# Void Swelling

presented by A. Kimura
at FJOH 2016



*Voyevodin (KIPT) et al.*

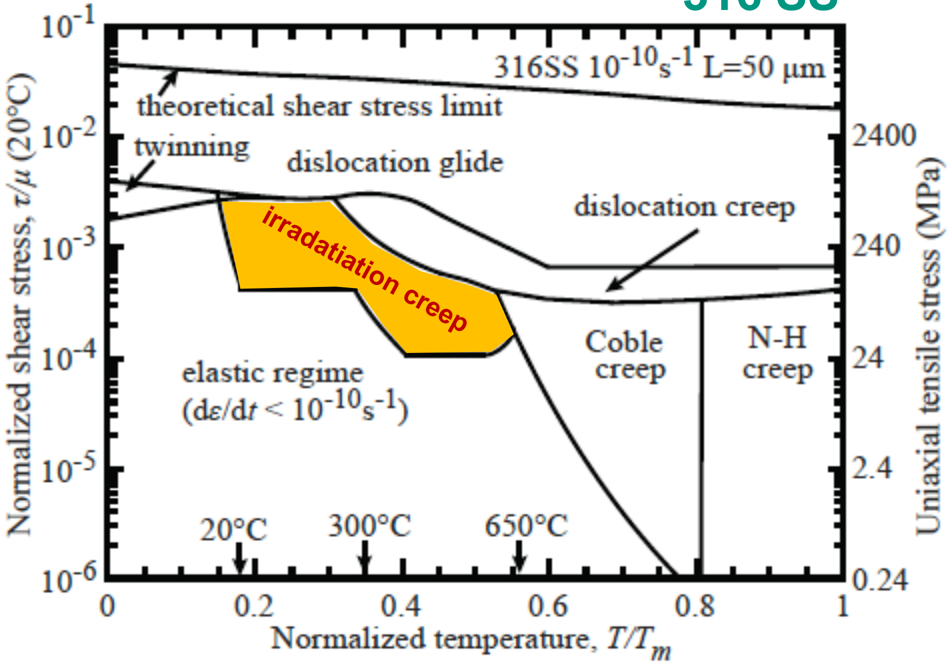
*F.A. Garner et al., J. Nucl. Mater. 329-333 (2005) 1008*



Oxide particles suppress grain growth and supply a number of grain boundaries that absorb vacancies.

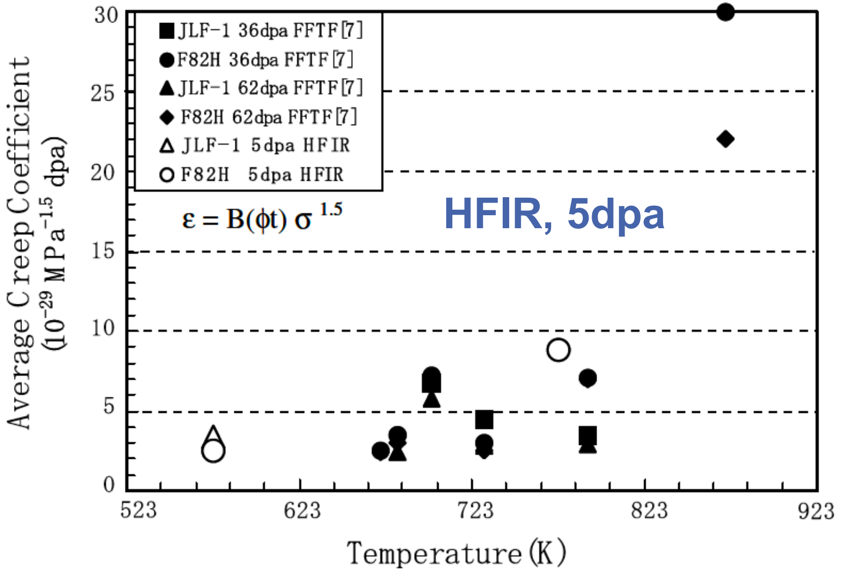
# Irradiation Creep

**316 SS**



*S. Zinkle and G. E. Lucas, Deformation and Fracture Mechanisms in Irradiated FCC and BCC Metals, U. S. Department of Energy, Semi-annual report, DOE-ER-0313/34 (2003).*

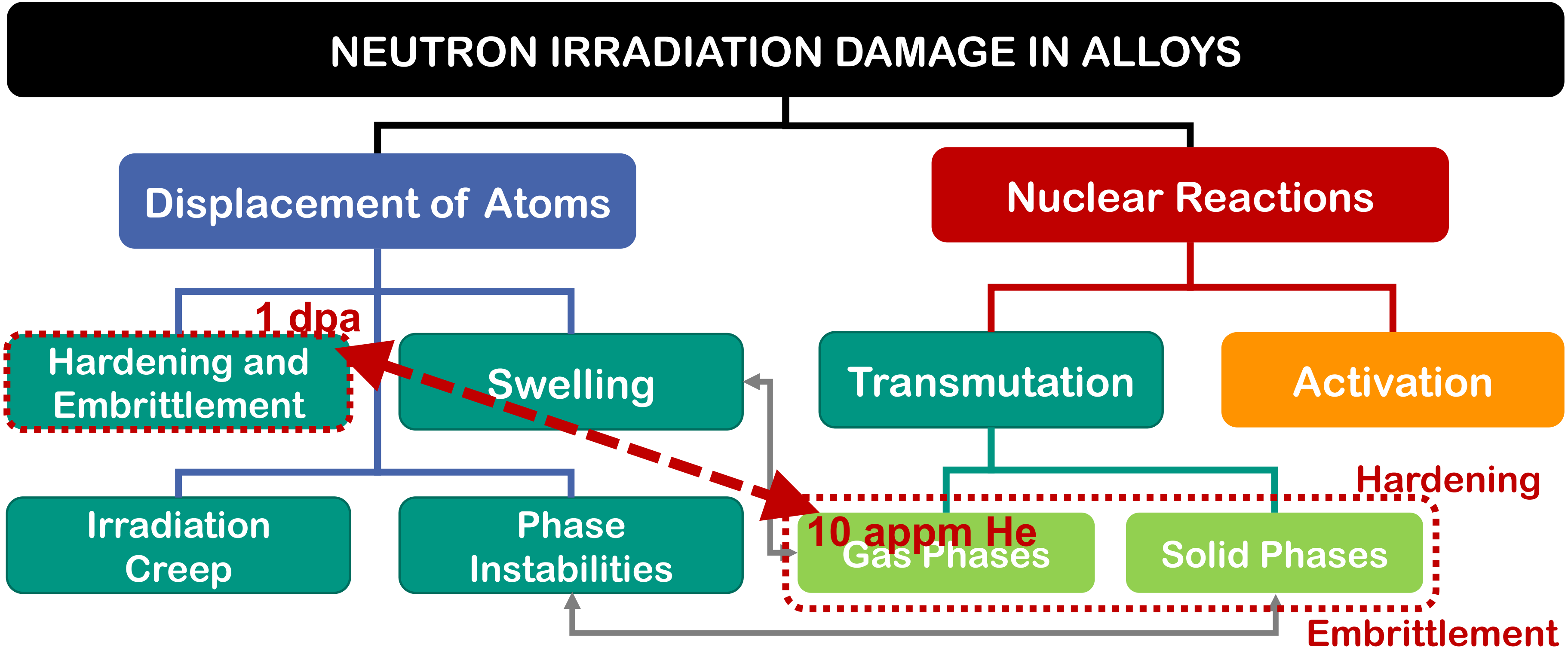
**B-doped RAFM steels**



**HFIR, 5dpa**

**EUROFER97 data missing**

# Overview



NEUTRON IRRADIATION DAMAGE IN ALLOYS

Displacement of Atoms

Nuclear Reactions

1 dpa

Hardening and Embrittlement

Swelling

Transmutation

Activation

Hardening

10 appm He

Gas Phases

Solid Phases

Irradiation Creep

Phase Instabilities

Embrittlement

# Which irradiation data do we need?

| | |
|---|---|
| EUROFER97 | • Impact of He transmutation on ALL basic mechanical properties (tensile, fracture toughness, DBTT and/or $T_0$, low cycle fatigue) at 20 dpa, 50 dpa, and higher doses for irradiation temperature of 300°C and 550°C → design limits → verification of phase instabilities (softening) and swelling<br>• Basic studies on irradiation creep >10 dpa and below 550°C → verification |
| CuCrZr | • Clarification of the impact of He transmutation on mechanical properties → If there is no impact, then MTR studies are representative<br>• Basic mechanical properties (tensile, fracture toughness, low cycle fatigue) 5 dpa, 10 dpa, 20 dpa / 150-350°C → design limits<br>• Creep/fatigue interaction … |
| Advanced Steels and Cu materials | • Verification of improved resistance against He embrittlement for ODS alloys (after identification of EUROFER97 limits)<br>• Verification of higher resistance against phase instabilities (softening) for ODS Cu and composites (>350°C, 2.5 dpa) |

# Conclusions

- Due to the large amount of required data, a massive use of MTRs is unavoidable. In the near future there will be only one high-flux MTR available: JHR. Start of operation: probably in 2030 → involvement of the fusion community is highly recommended !!!
- IFMIF/DONES should be primarily used to benefit from its unique features
  - Neutron spectrum → impact of He/H transmutation on properties
  - Possibility for unique experimental setups → in-pile creep, creep-fatigue interaction, …  → this is important for licensing, is potentially life-time limiting and current data has still a high uncertainty !
  - High flux, as long as suitable MTRs are not available
- Drawback: DONES/IFMIF requires Small Specimen Test Technology (SSTT), which excludes or restricts specific investigations (→ presentation of M. Serano)

# Which Data cannot or should not be generated by IFMIF/DONES?

- Material properties, which requires standardized test geometries that exceed the available space in IFMIF/DONES (this strongly depends on the licensing procedure).
  - Fracture toughness of ductile materials (EUROFER97, CuCrZr) and maybe other properties, if SSTT specimens become too small.
  - A number of joints (e.g. TIG welds) and joint geometries are not suitable for SSTT! In any case, a significant survey and possibly down-selection of welds should be performed by use of MTRs prior to investigations in IFMIF/DONES.

***Thank you very much*** ☺