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Polytechnic University of Valencia (Spain)

IRRADIATION EFFECTS ON RPV STEELS: MICROSTRUCTURE & MECHANICAL PROPERTIES

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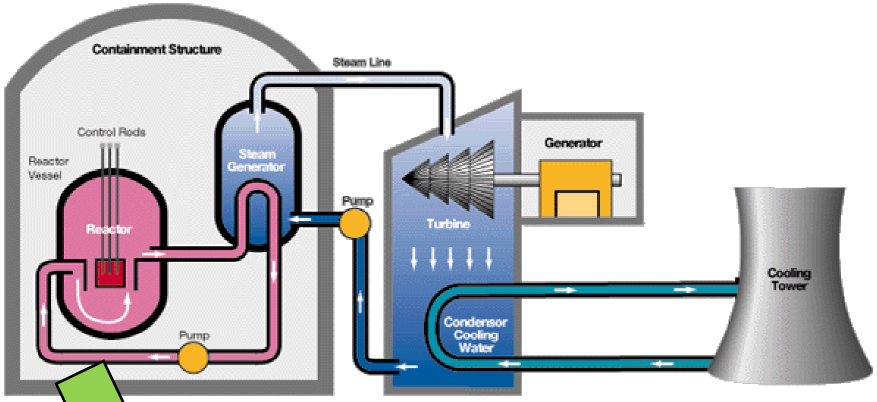
Outline

- Introduction to RPV steel embrittlement
- Main microstructural and microchemical changes under irradiation
  - Damage production in cascades
  - Point-defect driven microstructural changes (cavities, loops, …)
  - Solute redistribution
- Origin of radiation hardening
  - Dislocation pinning
- Radiation hardening and embrittlement
  - Origin of the correlation between hardening and embrittlement
  - Embrittlement without hardening
- Origin of radiation embrittlement in RPV steels
  - Handbook mechanisms and three feature models (trend curves)
  - Current understanding in SOTERIA: paradigm shift

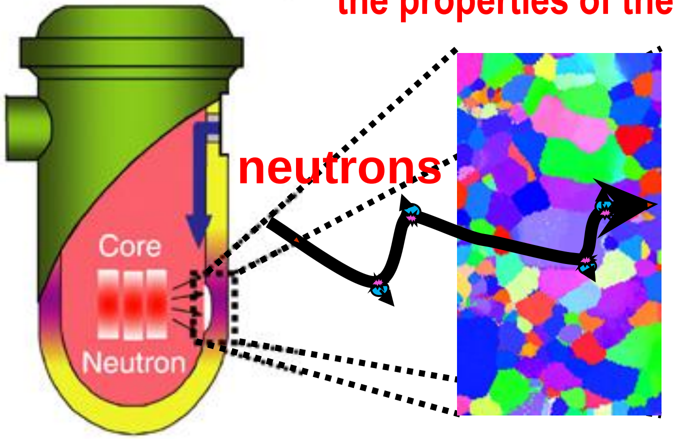
INTRODUCTION TO RPV STEEL EMBRITTLEMENT

Irradiation embrittlement of reactor pressure vessel steels

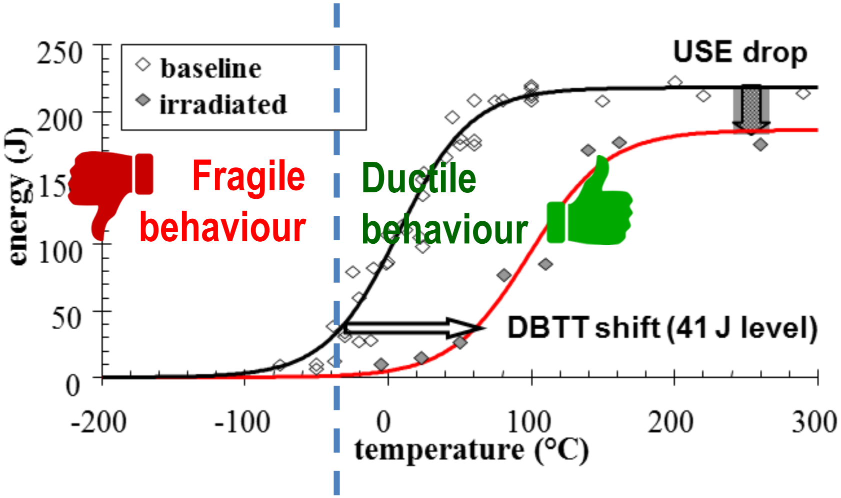


Irreplaceable component
Contains the radioactive core
Key safety function!

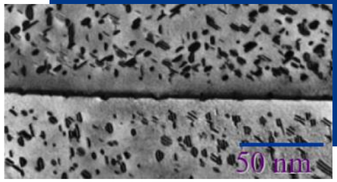
Reactor pressure vessel

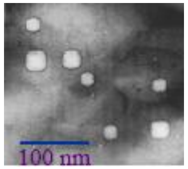


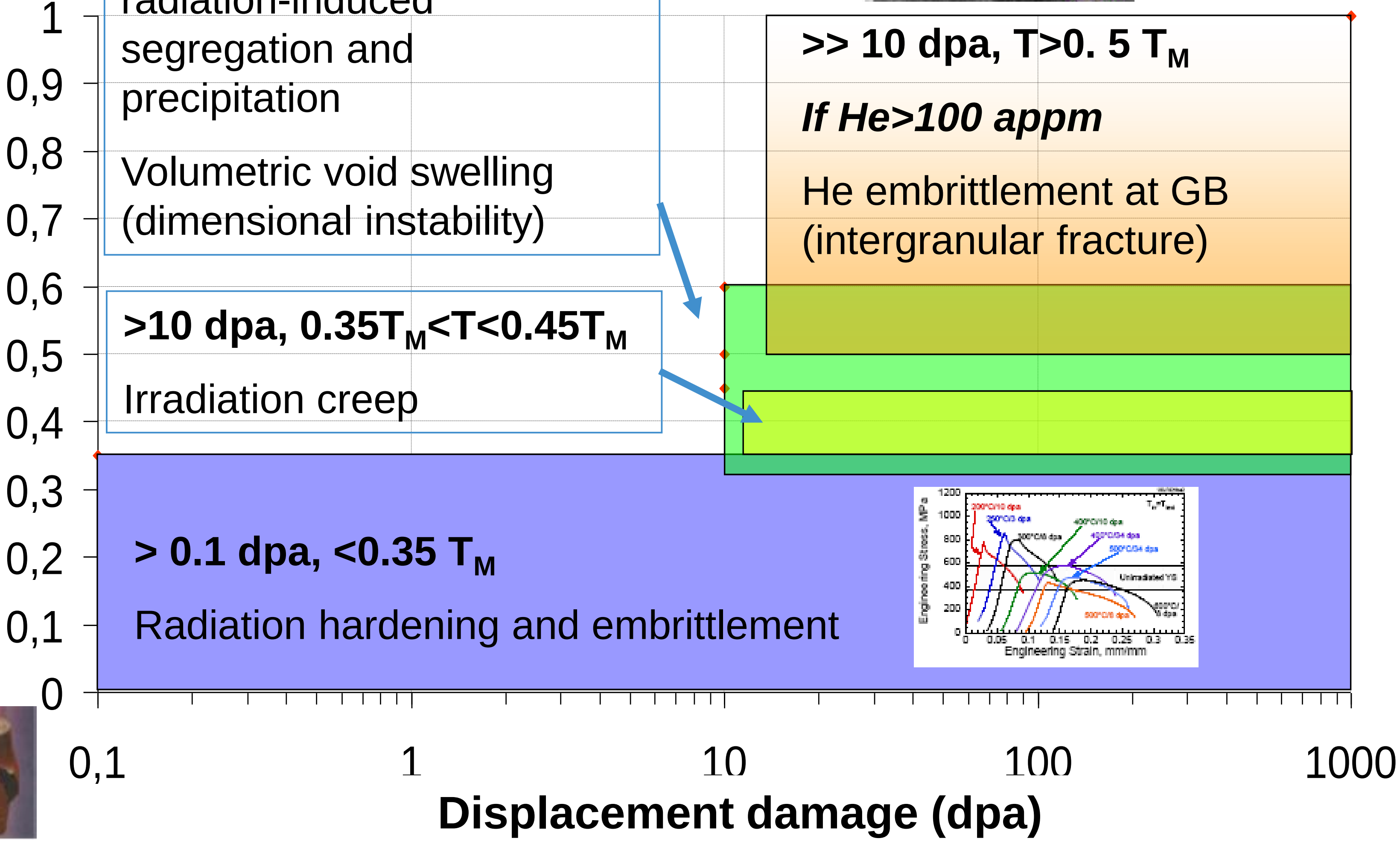
Neutron irradiation changes the properties of the material



Irradiation produces plenty of (bad) effects in materials







>10 dpa, $0.3T_M<T<0.6T_M$

Phase instabilities from radiation-induced segregation and precipitation

Volumetric void swelling (dimensional instability)

>> 10 dpa, $T>0.5 T_M$

If He>100 appm

He embrittlement at GB (intergranular fracture)

>10 dpa, $0.35T_M<T<0.45T_M$

Irradiation creep

> 0.1 dpa, $<0.35 T_M$

Radiation hardening and embrittlement

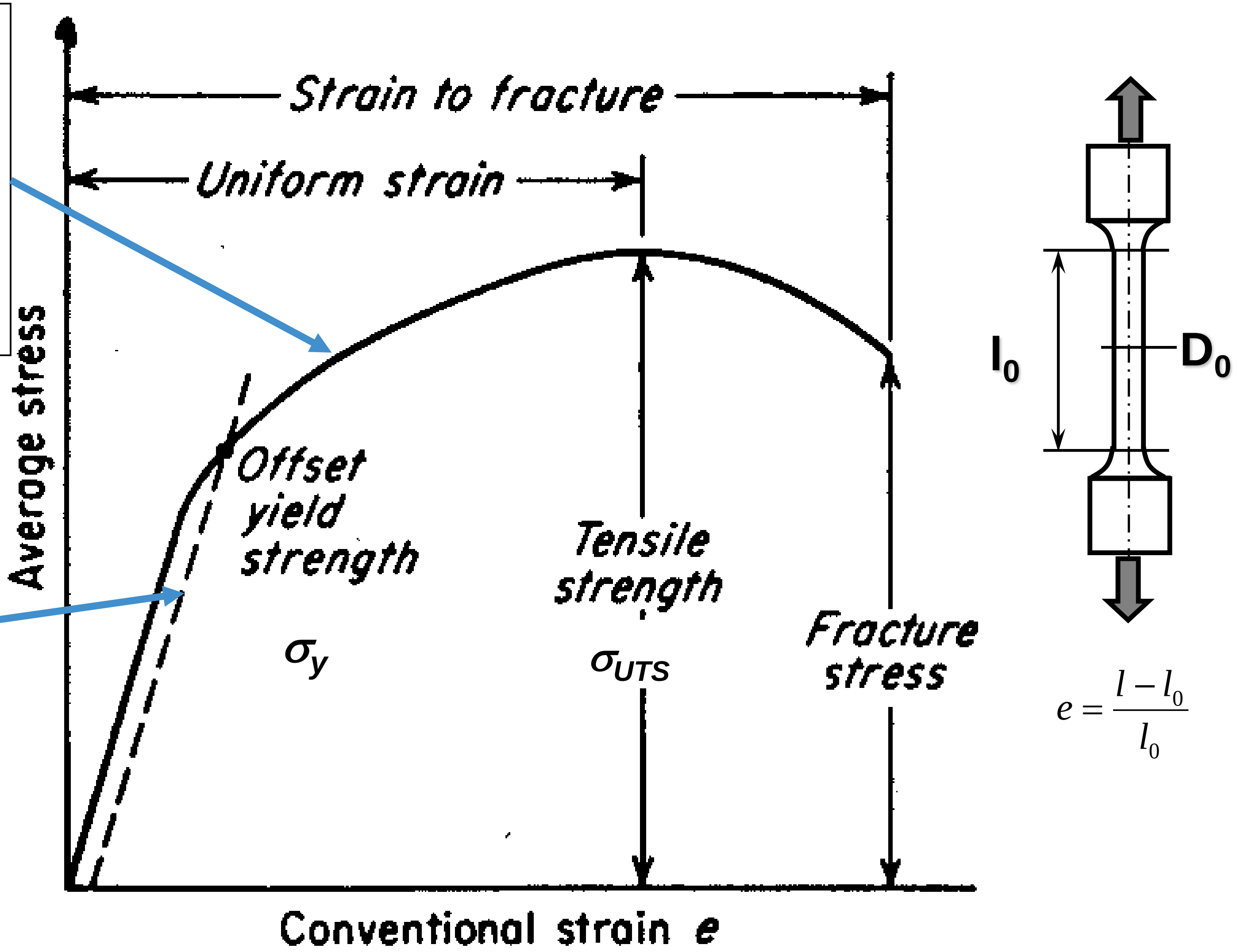
What is radiation hardening?

Tensile test on non-irradiated steel : stress-strain curve

Plastic behaviour: irreversible deformation

(dislocations in motion)

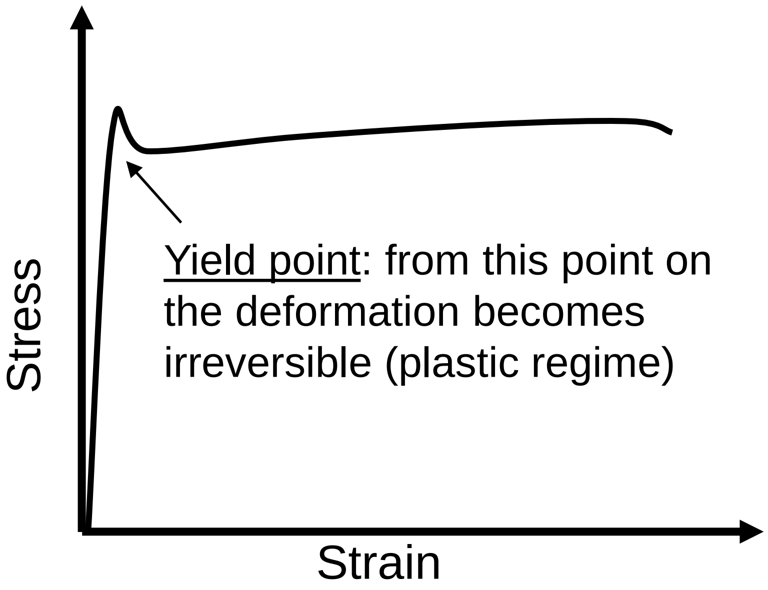
Elastic behaviour: reversible deformation



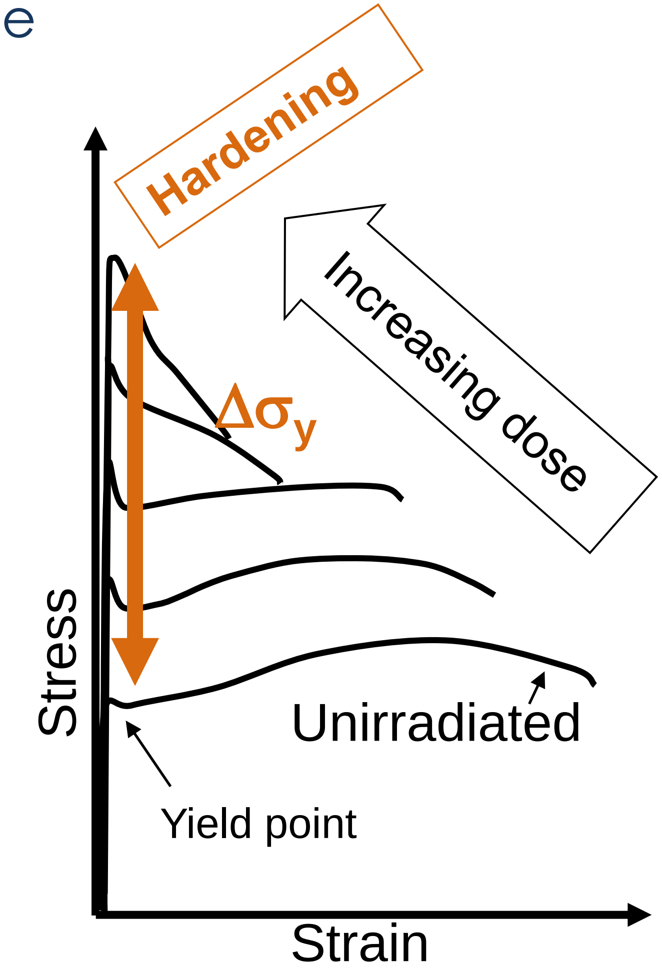
$$e = \frac{l - l_0}{l_0}$$

What is radiation hardening?

Hardening = Yield strength increase



Yield point: from this point on the deformation becomes irreversible (plastic regime)

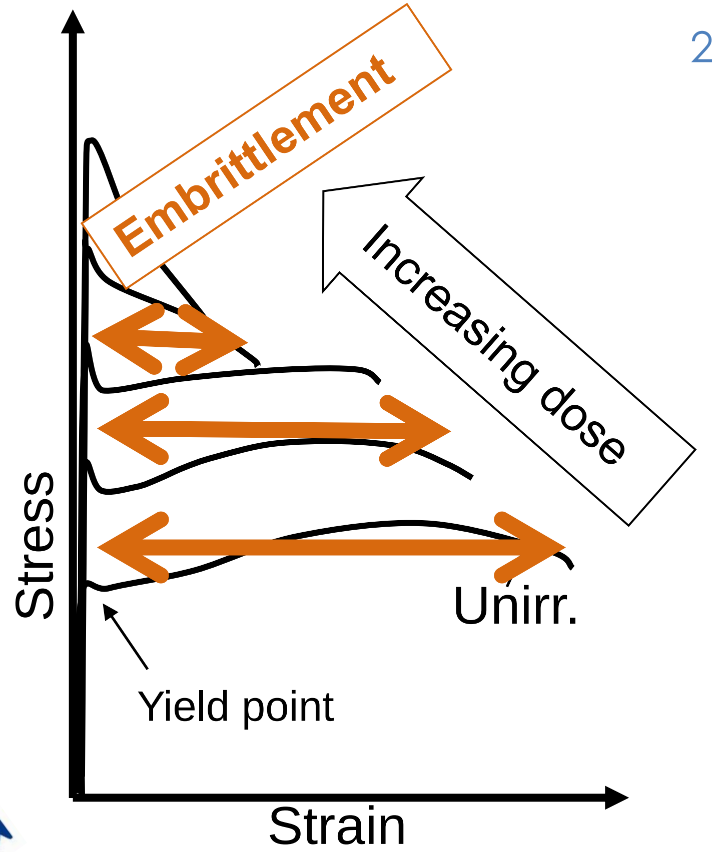


What is radiation embrittlement?

Brittle material = breaks without prior deformation

Embrittlement =

1. **reduction of elongation (deformation) before fracture**
2. increase of temperature below which material is brittle



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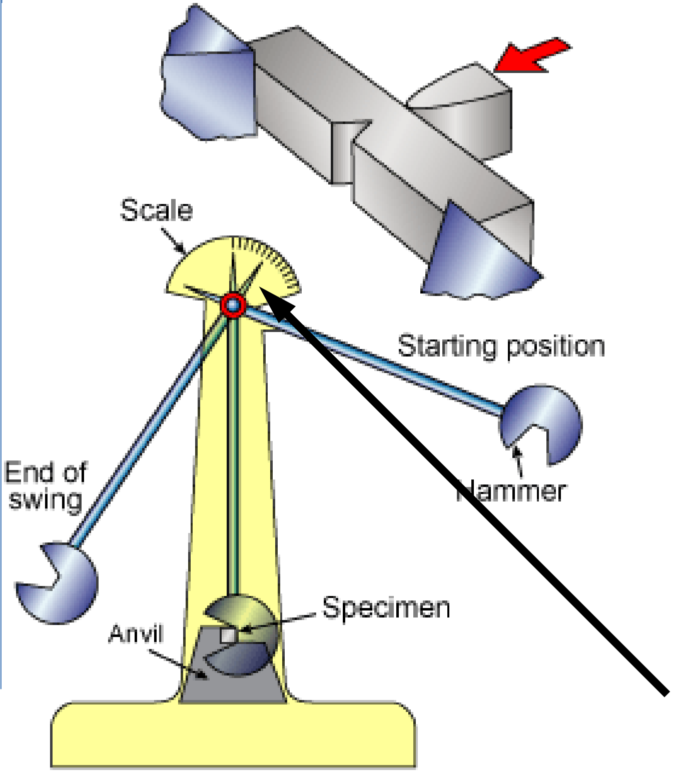
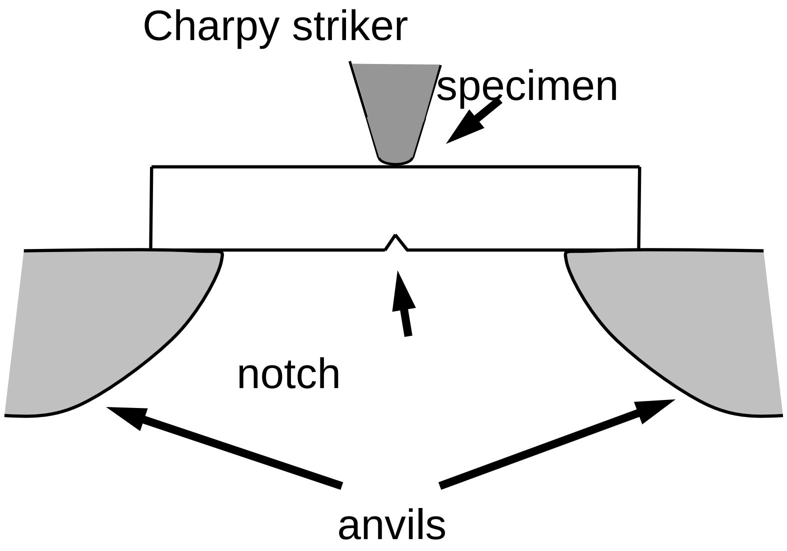
Charpy impact test





Scale provides energy absorbed by specimen when breaking: the higher, the more ductile the material

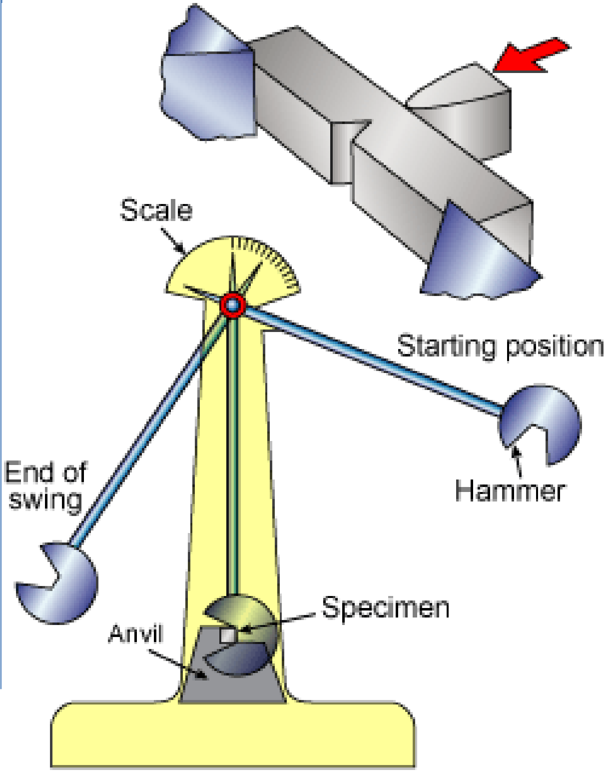
What is radiation embrittlement?

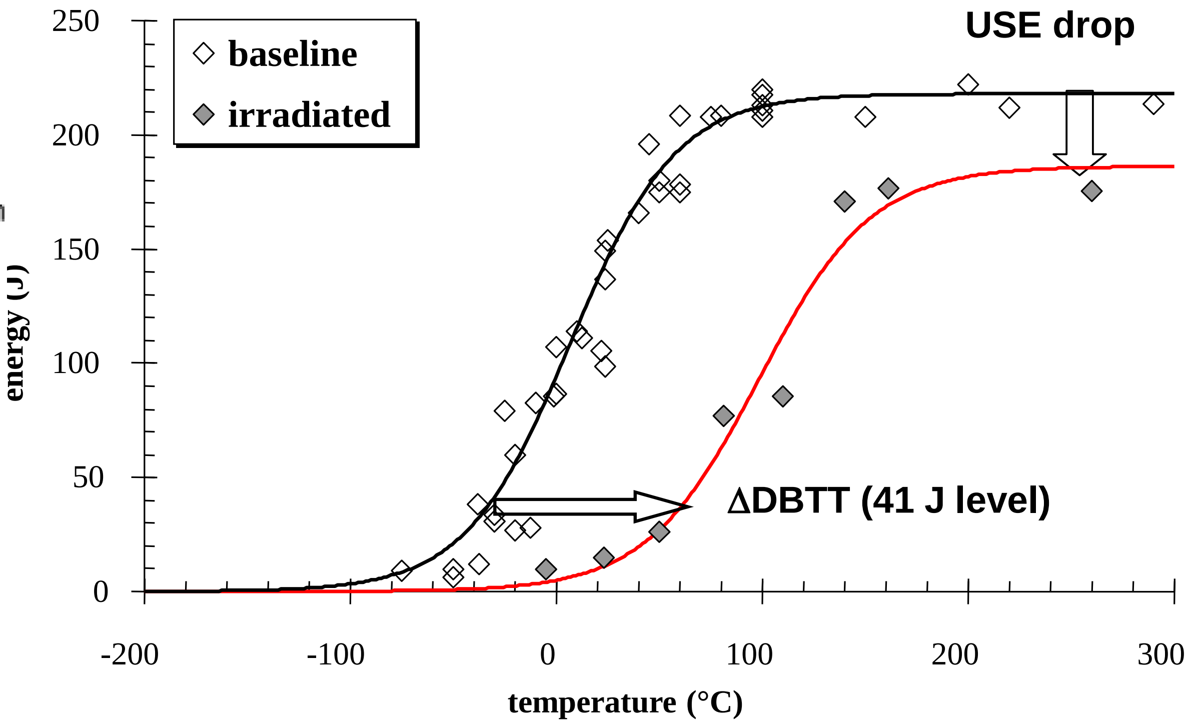
Brittle material = breaks without prior deformation

Embrittlement =

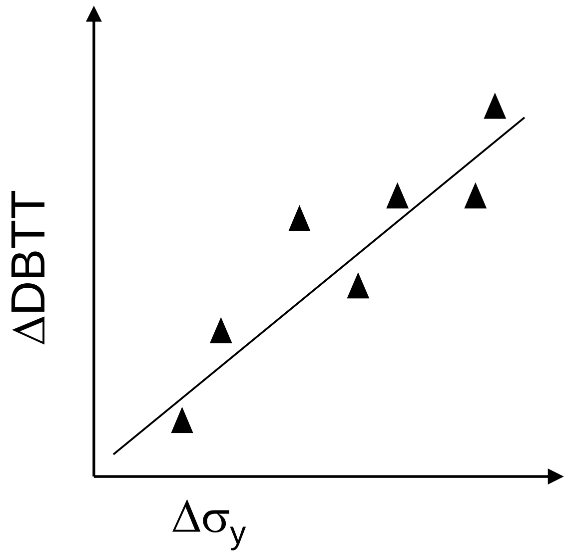
1. reduction of elongation (deformation) before fracture
2. **increase of temperature below which material is brittle**

Charpy impact test





ΔDBTT and $\Delta\sigma_y$ are (generally) linearly correlated …



Example from: Böhmert et al. JNM 334 (2004) 71

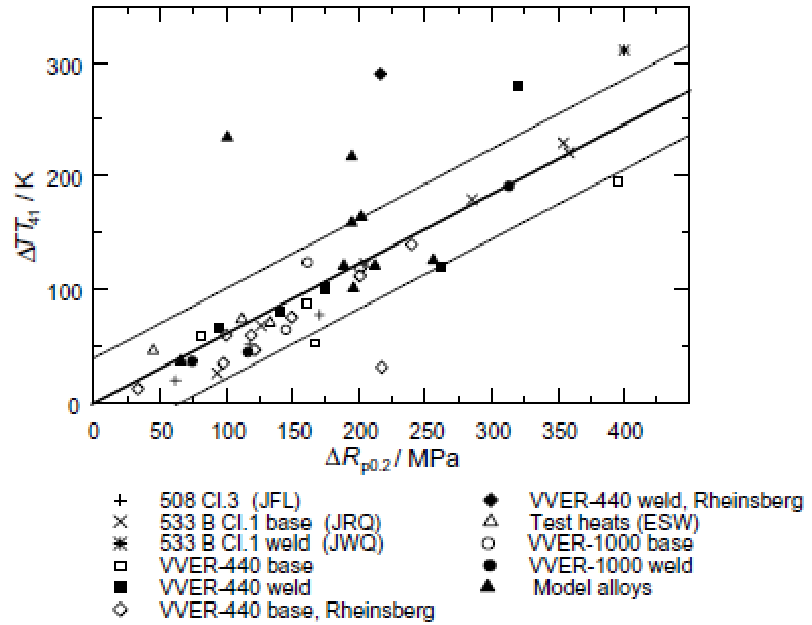


Fig. 8. Correlation between the shift of transition temperature ΔTT_{48} and the yield stress increase $\Delta R_{p0.2}$.

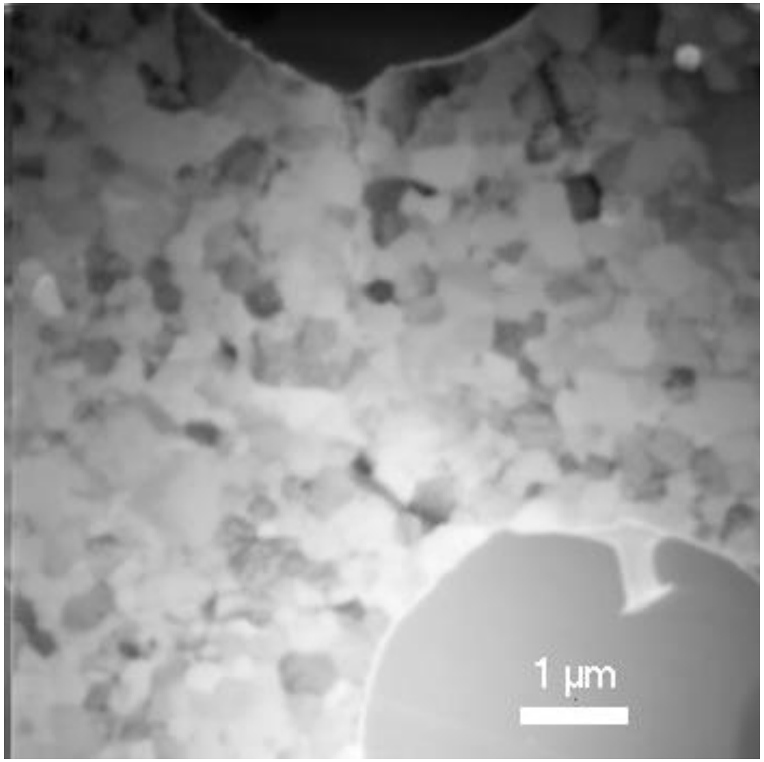
Radiation embrittlement with hardening disappears above ~400°C.

Embrittlement without hardening exists as well, e.g. in presence of He (He-embrittlement), or due to segregation of elements like P at GBs: this may occur at all temperatures

MAIN MICROSTRUCTURAL & MICROCHEMICAL CHANGES UNDER IRRADIATION

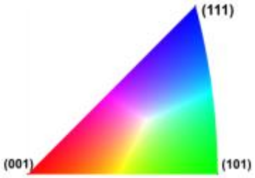
Under a microscope steels are aggregates of grains

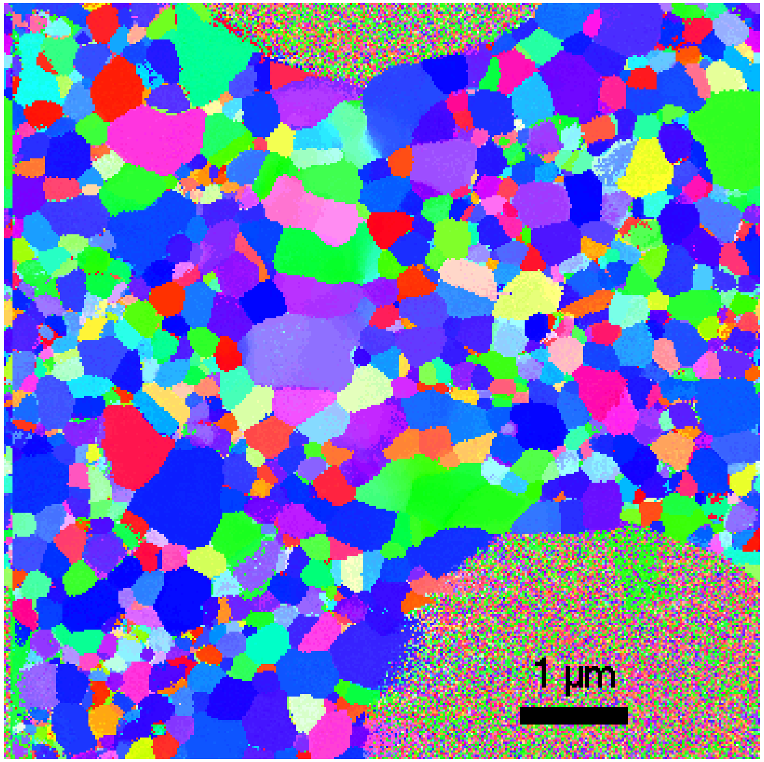
Brightfield image (TEM)



Metallographic examination of deformed specimen – grains are clearly visible

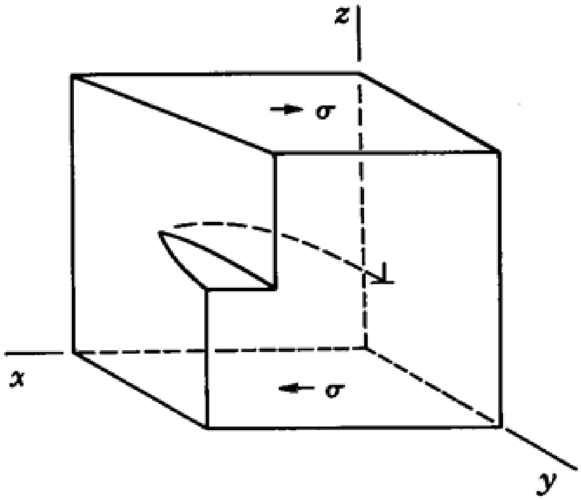
Orientation map



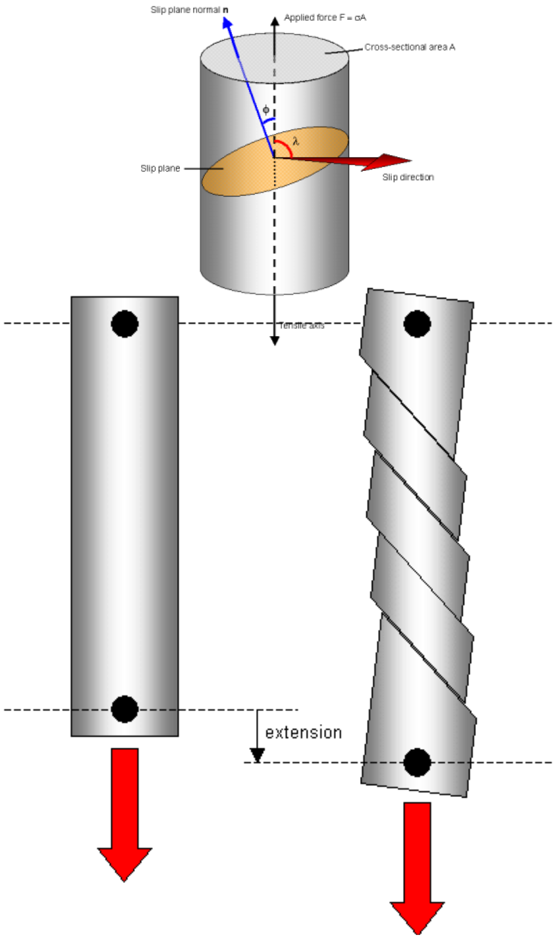


Electron back-scatter diffraction (EBSD) – each colour corresponds to a grain with different orientation

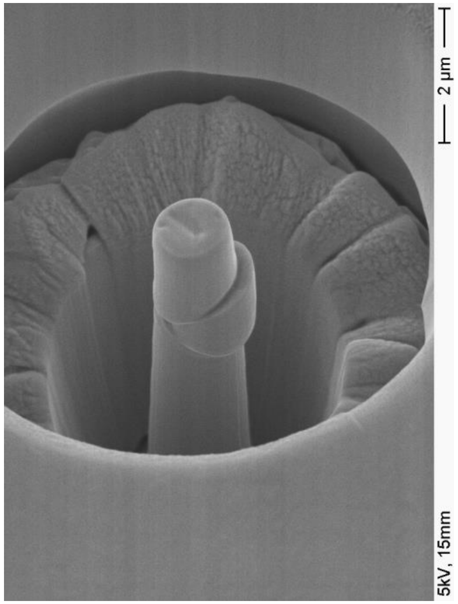
Inside grains, dislocations allow plastic deformation



Mixed dislocation line inside a grain gliding on a slip plane

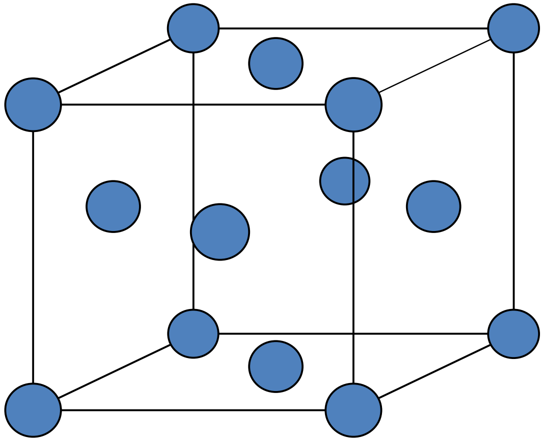


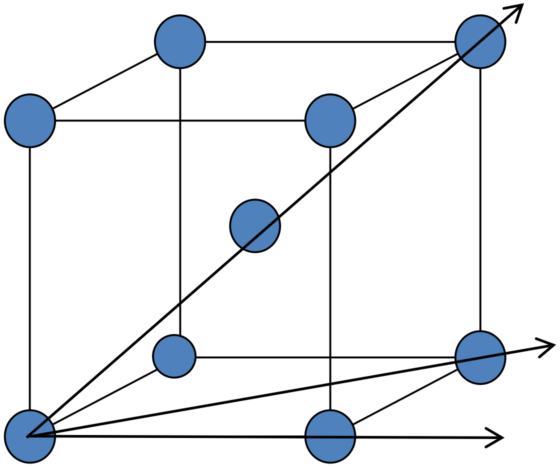
Deformation under tension of single crystal along slip planes



Compression test on nano-pillar in single grain

At the atomic scale a metal is a crystal lattice





Face centered cubic, fcc

↓

Austenitic steels

Body centered cubic, bcc

↓

Fe, RPV steels

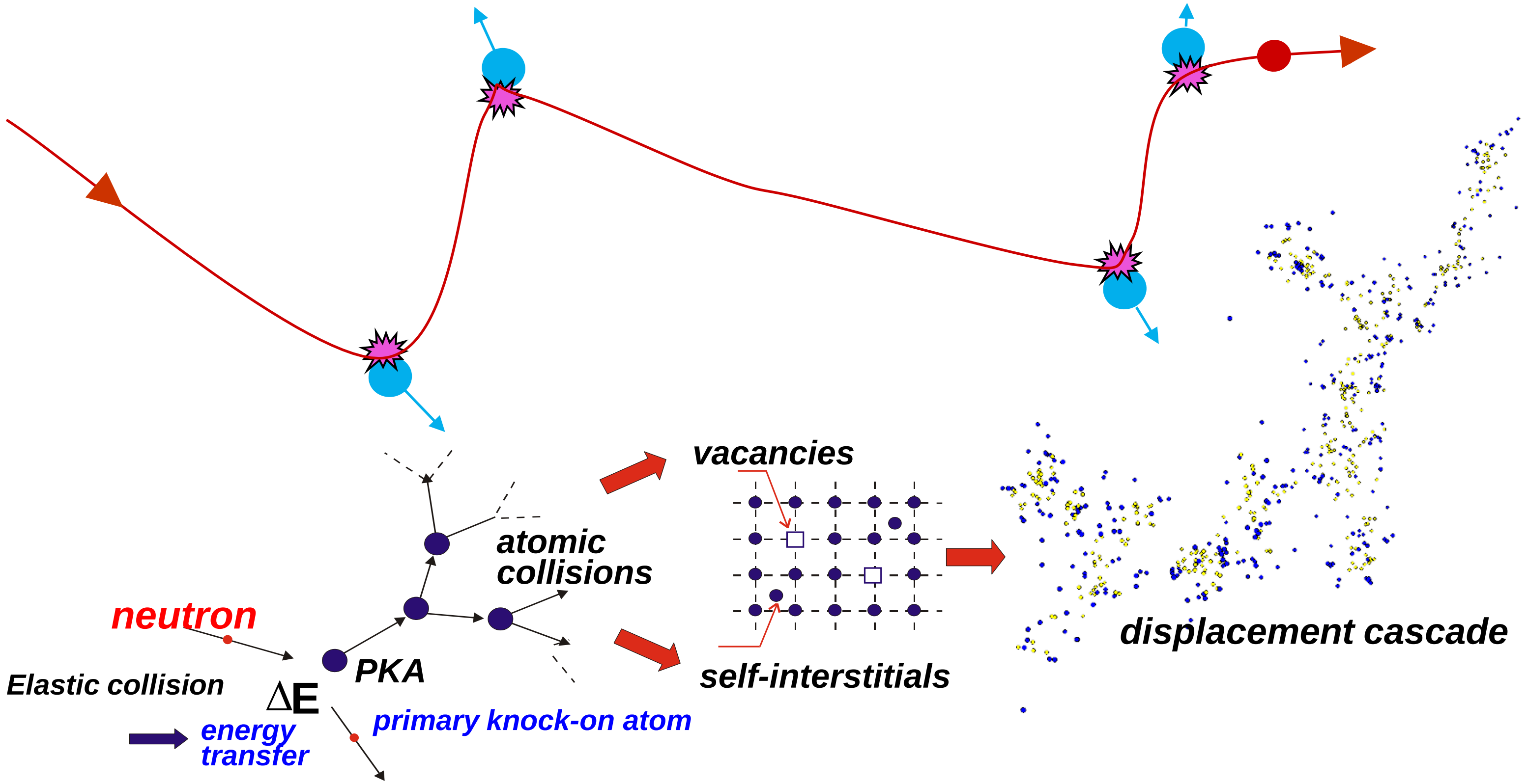
[100] [110] [111]

Radiation damage: It all starts with a neutron hitting an atom …

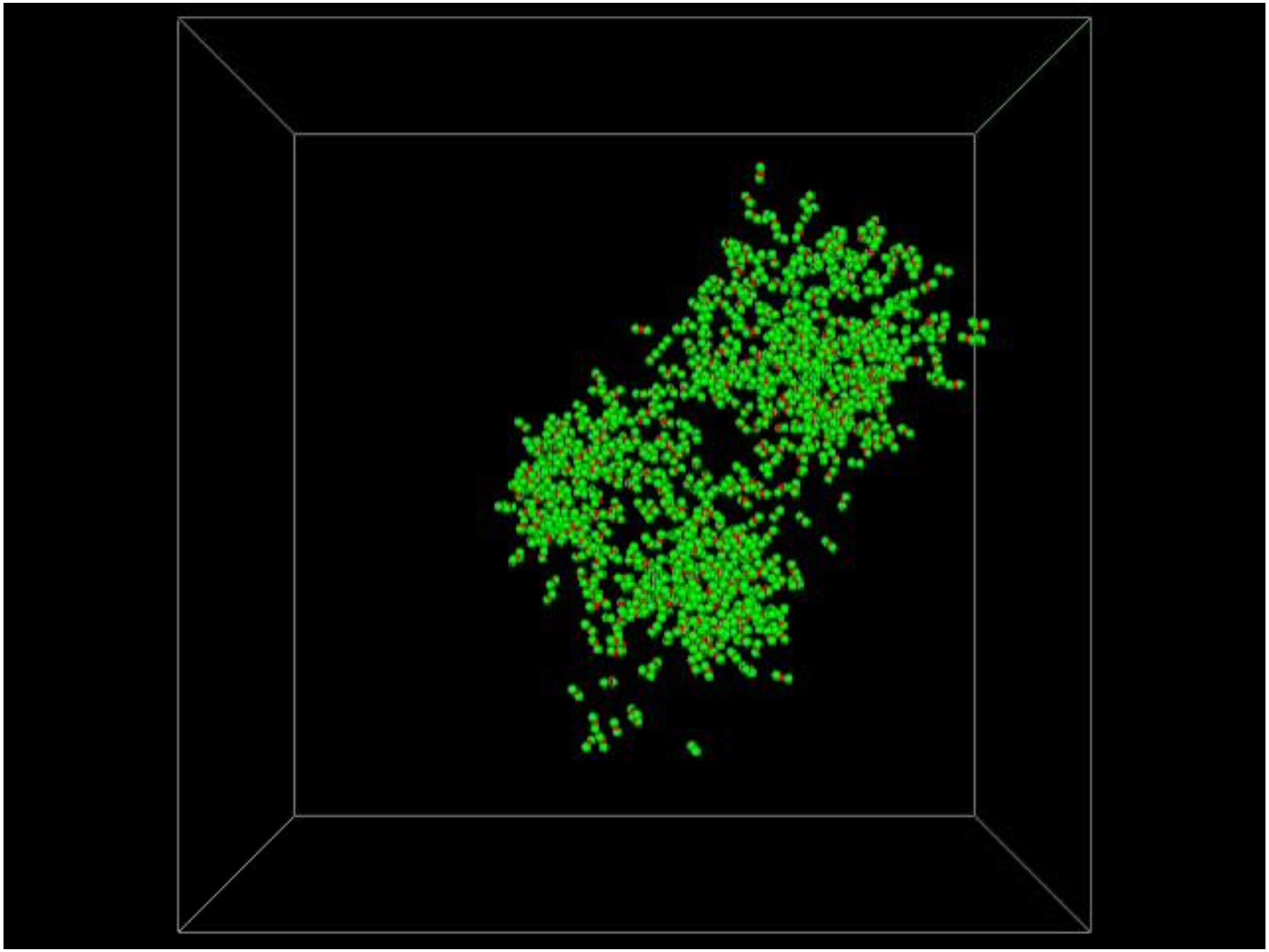
Neutrons = uncharged particles ⇒ can travel long distances in matter

When reacting with nuclei of atoms they can produce

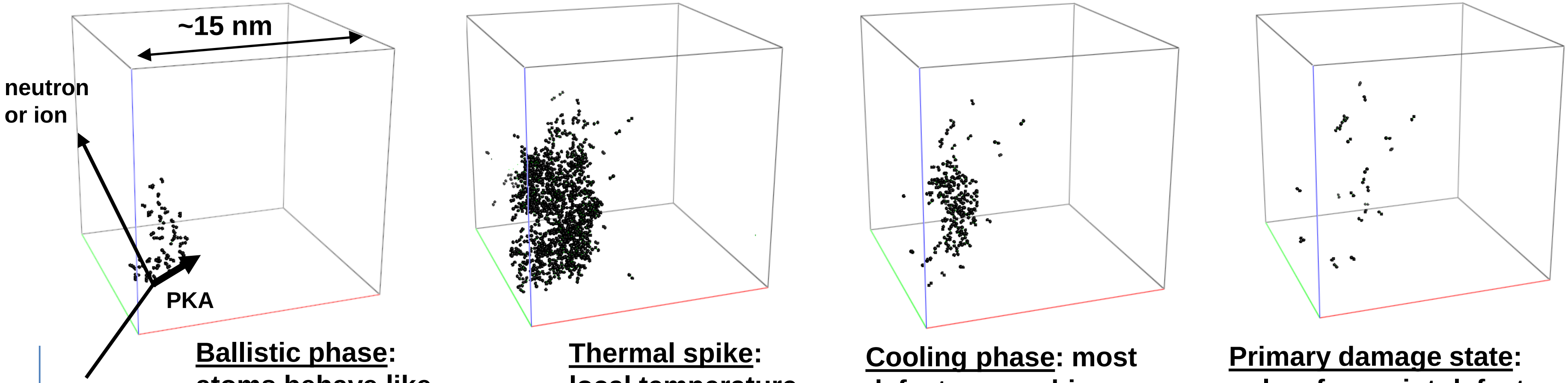
- Activation
- Transmutation (He, H)
- Displacement damage (elastic collisions)



Displacement cascade: the mother of all evils …



A closer look at the cascade phases

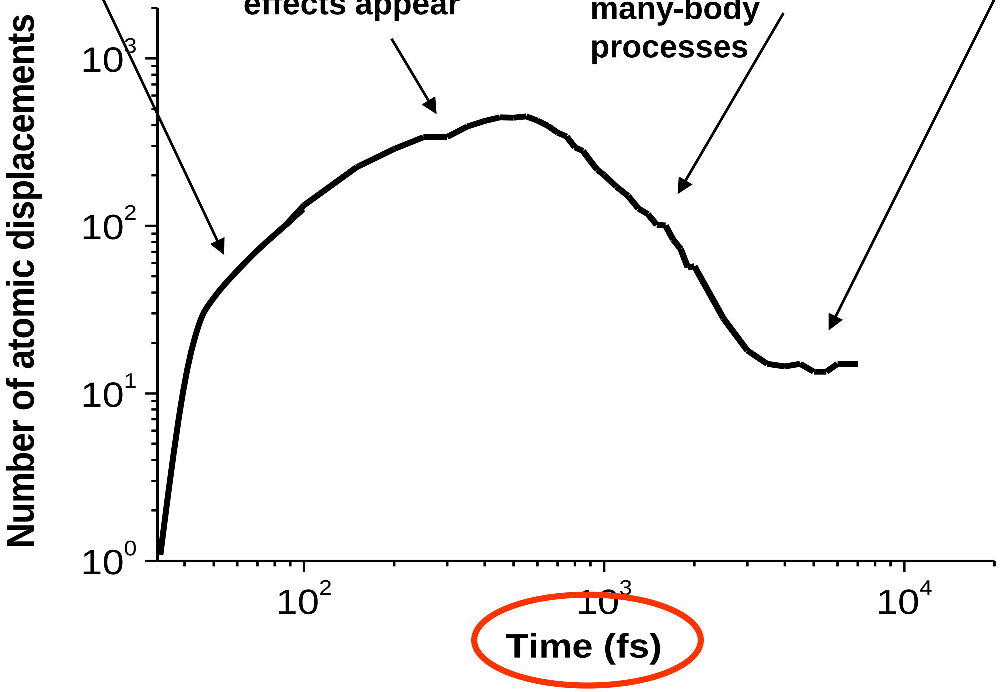


Ballistic phase: atoms behave like colliding hard spheres

Thermal spike: local temperature rises, collective effects appear

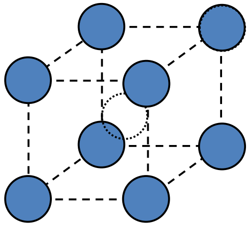
Cooling phase: most defects recombine, following complex many-body processes

Primary damage state: only a few point defects and clusters survive (cascade debris)



Clustering of vacancies

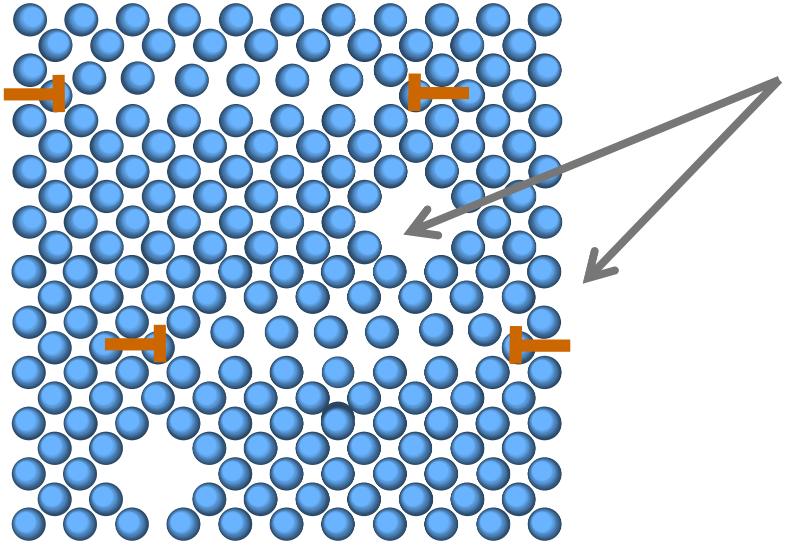
What's a vacancy and how does it migrate?



Vacancy and its migration mechanism in the bcc structure

When vacancies meet during migration they form stable clusters

How does a vacancy cluster look like?



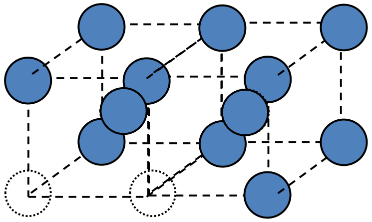
nano-cavity
vacancy dislocation loop

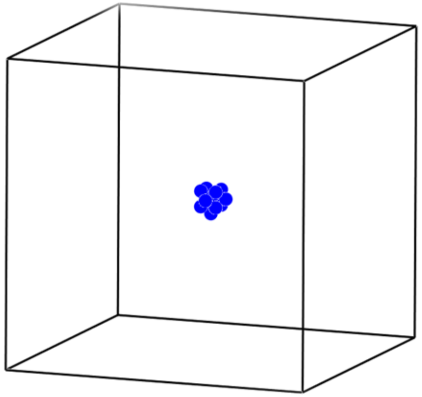
- nano-cavities growing to voids are typical of Fe alloys
- vacancy dislocation loops are rarely observed in Fe alloys (only under heavy ion irradiation: dense cascades)

Vacancy cluster migration

Can nano-cavities and voids migrate?

Di-vacancy

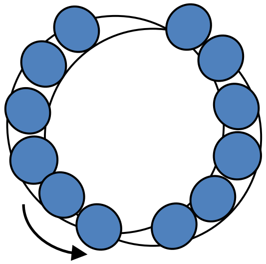




Small vacancy clusters can migrate (slowly) in 3D

Voids may grow by coalescence

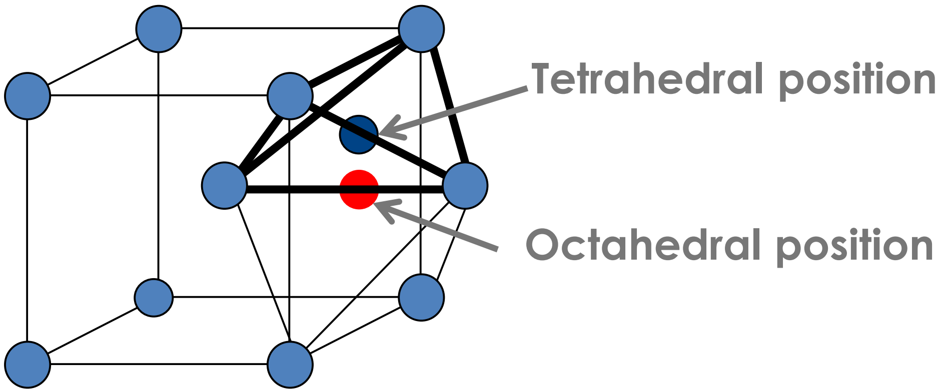
Void

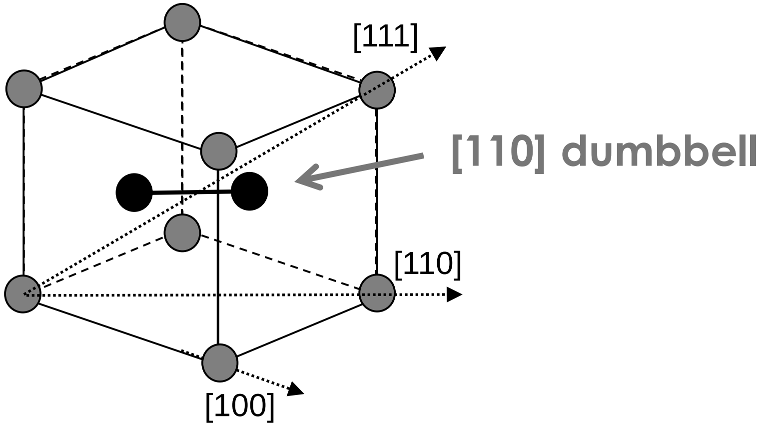


Even voids may migrate via surface vacancy rearrangement

Self-interstitial atoms (SIA) in Fe alloys

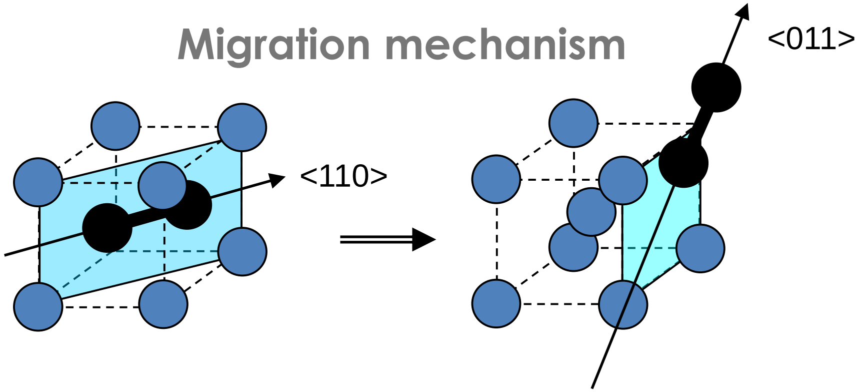
How does an SIA in Fe look like? How does it migrate?

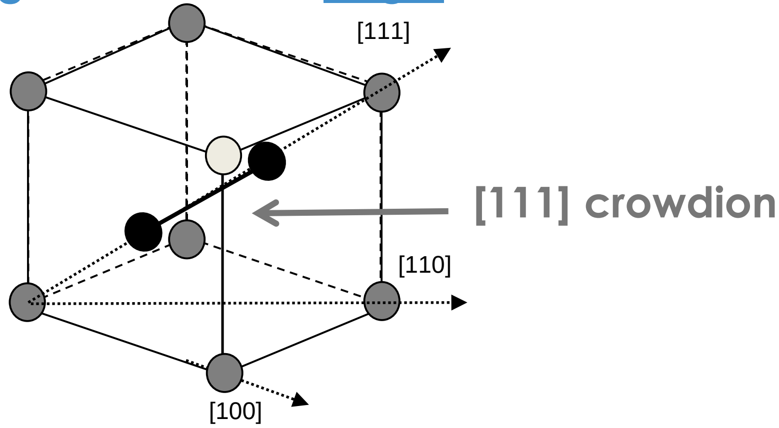




The [110] dumbbell is the most stable configuration for the <u>single</u> SIA in Fe

Migration mechanism



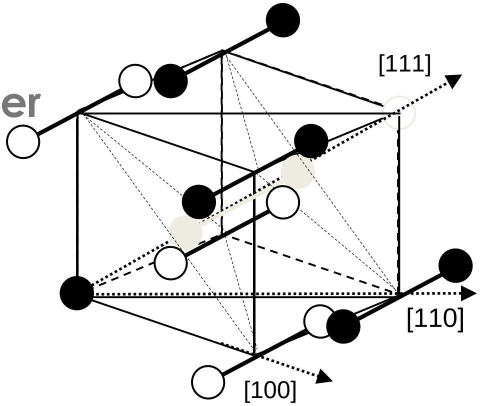


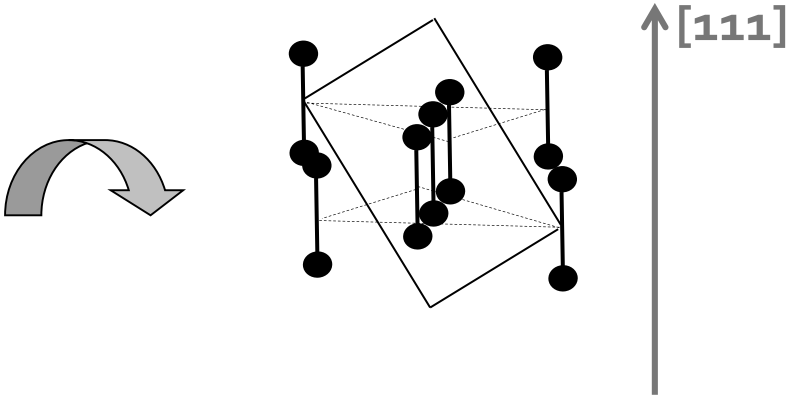
The [111] crowdion is stable in other bcc metals and is the unit for SIA clusters in Fe

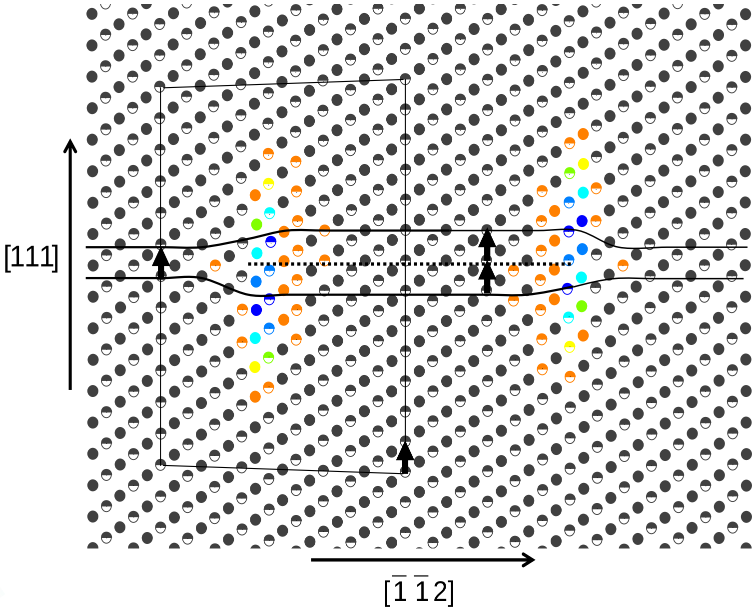
SIA clusters in Fe alloys: prismatic dislocation loops

7 crowdion cluster

Smallest perfect dislocation loop

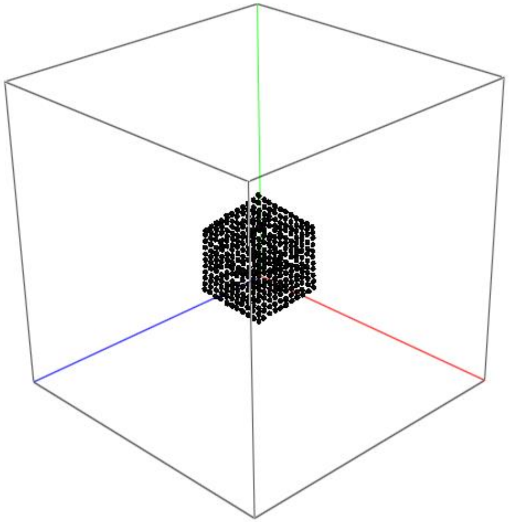






Dislocation loop with Burgers vector ½<111>

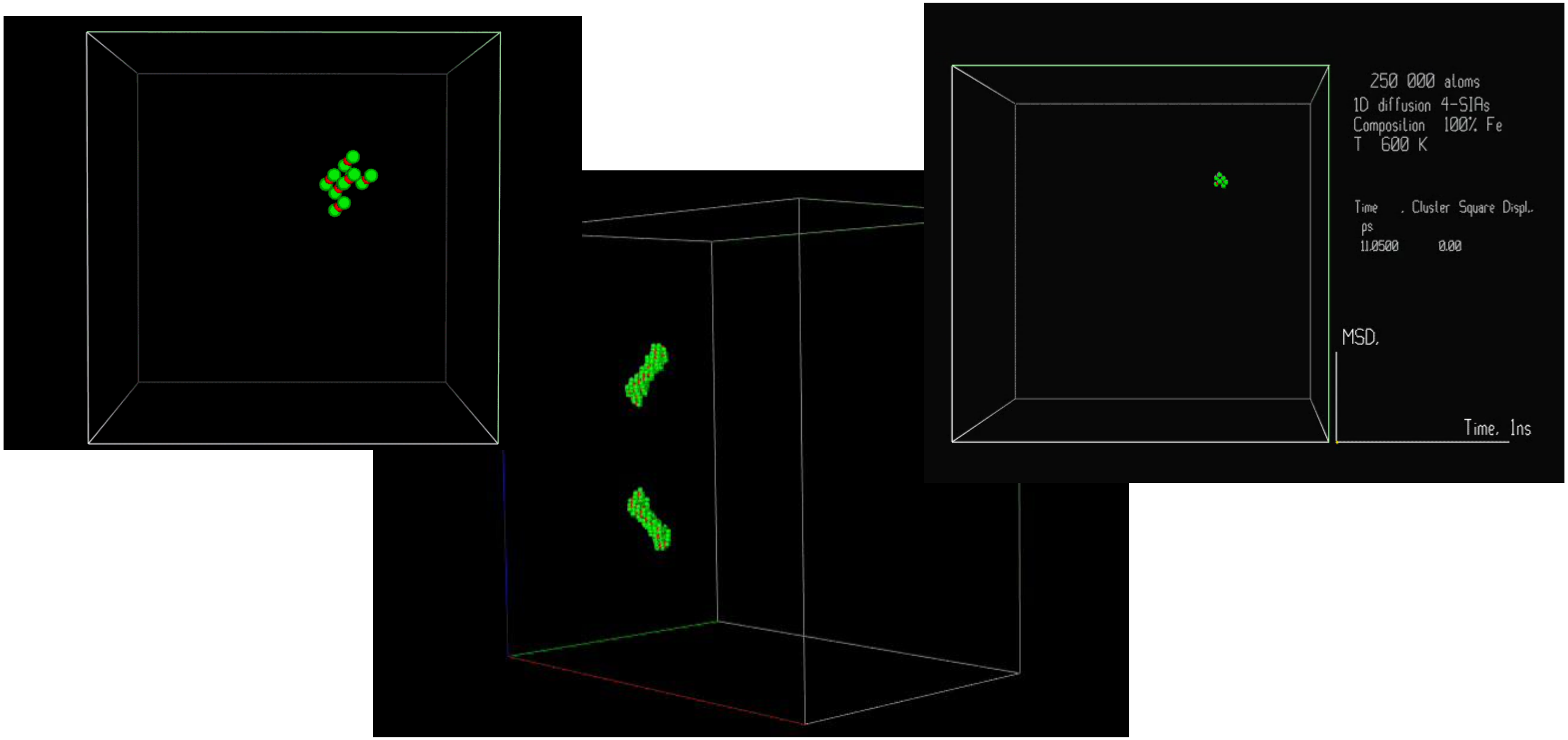
View normal to [111]



Migration of SIA loops = bunches of parallel crowdions

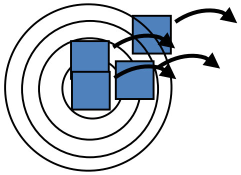
SIA clusters migrate fast in one-dimension

(at least in pure metals)



Cluster dissolution

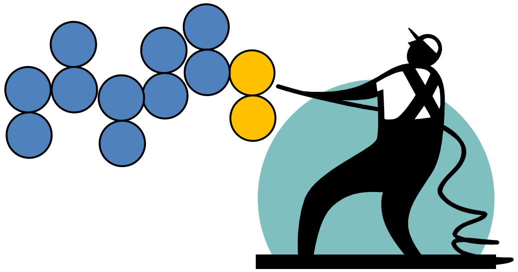
Emission of vacancies from small clusters and voids



At ~300°C small vacancy clusters dissolve easily unless stabilised by something else (eg He or solute atoms): the smaller, the easier the emission

Large voids, however, are stable up to ~500°C or higher and may grow at the expenses of small clusters that dissolve

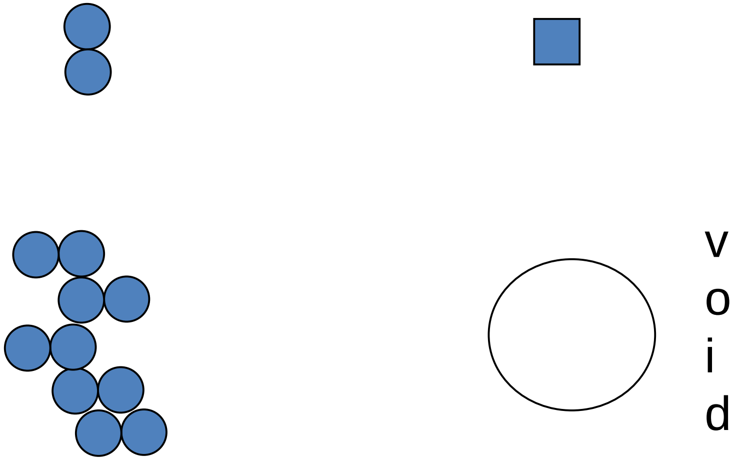
Emission of SIA from loops



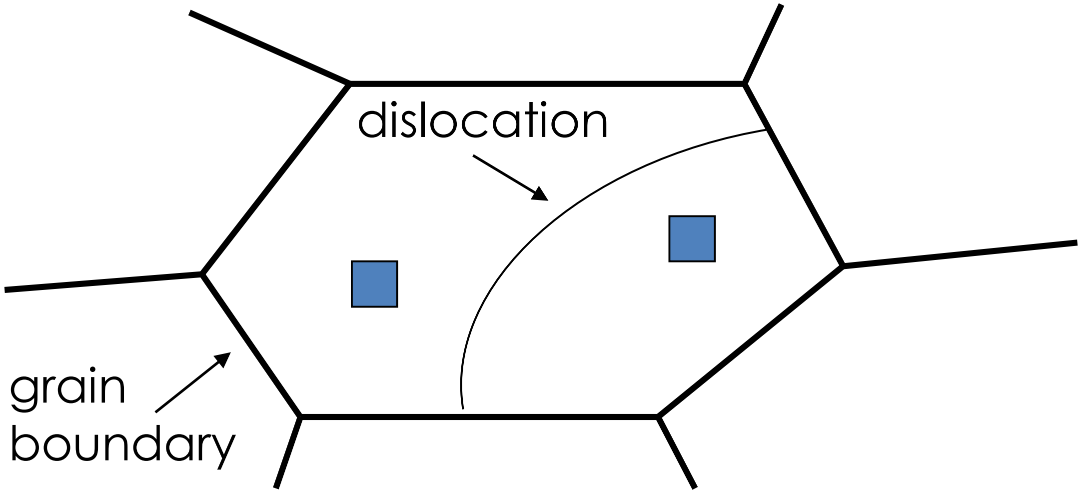
SIA clusters are highly stable and generally do not easily emit single SIAs spontaneously

Defect recombination and disappearance at sinks

Recombination of SIA with Vacs

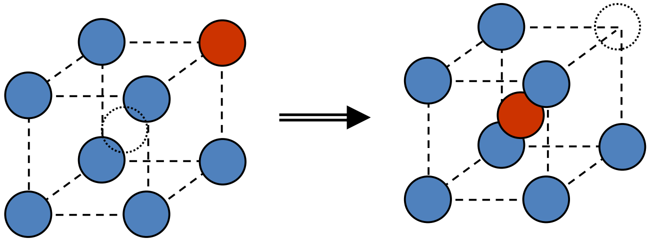


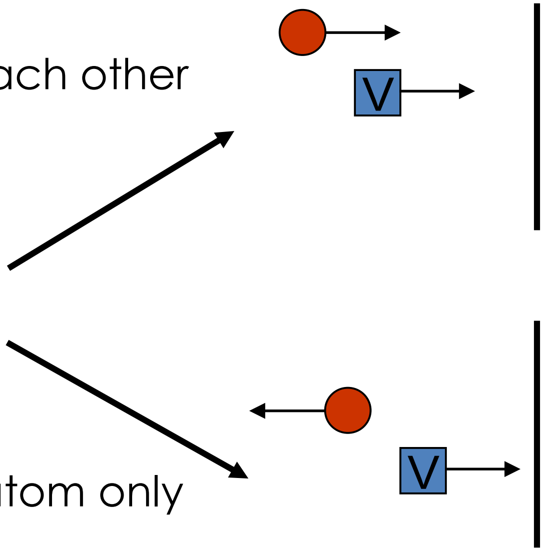
Disappearance at sinks



Transport of chemical species

Vacancy & solute atom attract each other

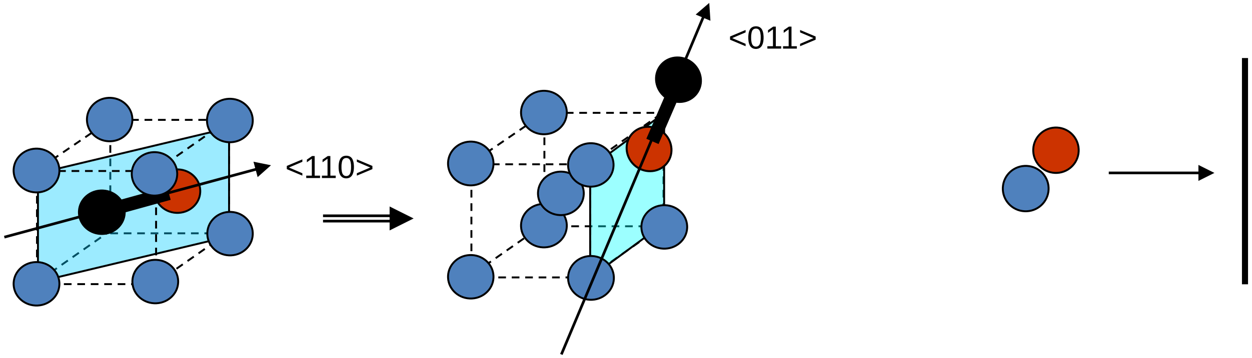




No attraction: vacancy & solute atom only exchange position

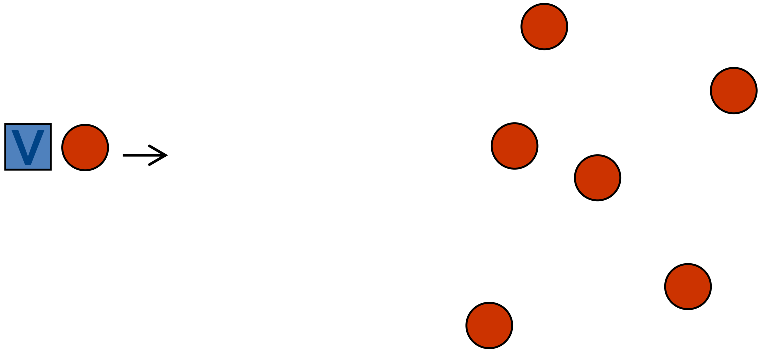
Sink for Vacs

Sink for SIAs

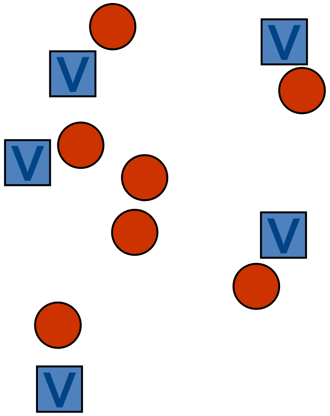


If stable, mixed dumbbell transports solutes to sinks

Formation of aggregates of solutes = **radiation enhanced precipitation** (if stable thermodynamic phase)



If solutes “like each other” (free energy decreases when they cluster → **formation of new phase**), precipitation occurs



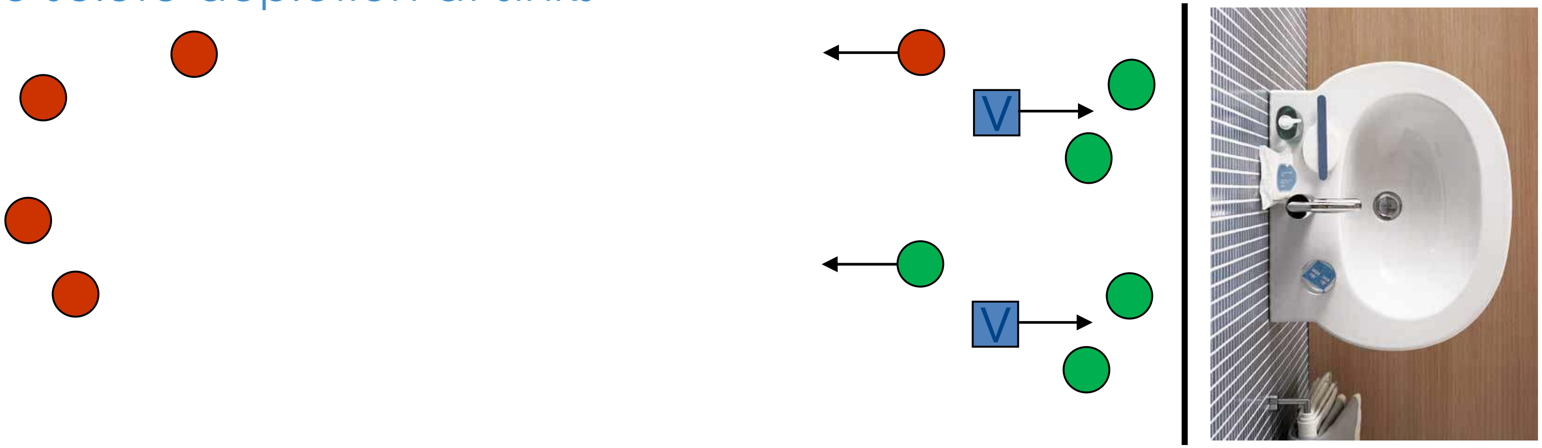
Under **irradiation** the presence of many point-defects **enhances precipitation**

If vacancies “like” the solutes, then complexes containing both may form (same can happen with SIAs)

Segregation at sinks = accumulation/depletion of solutes = **radiation induced segregation (RIS)**

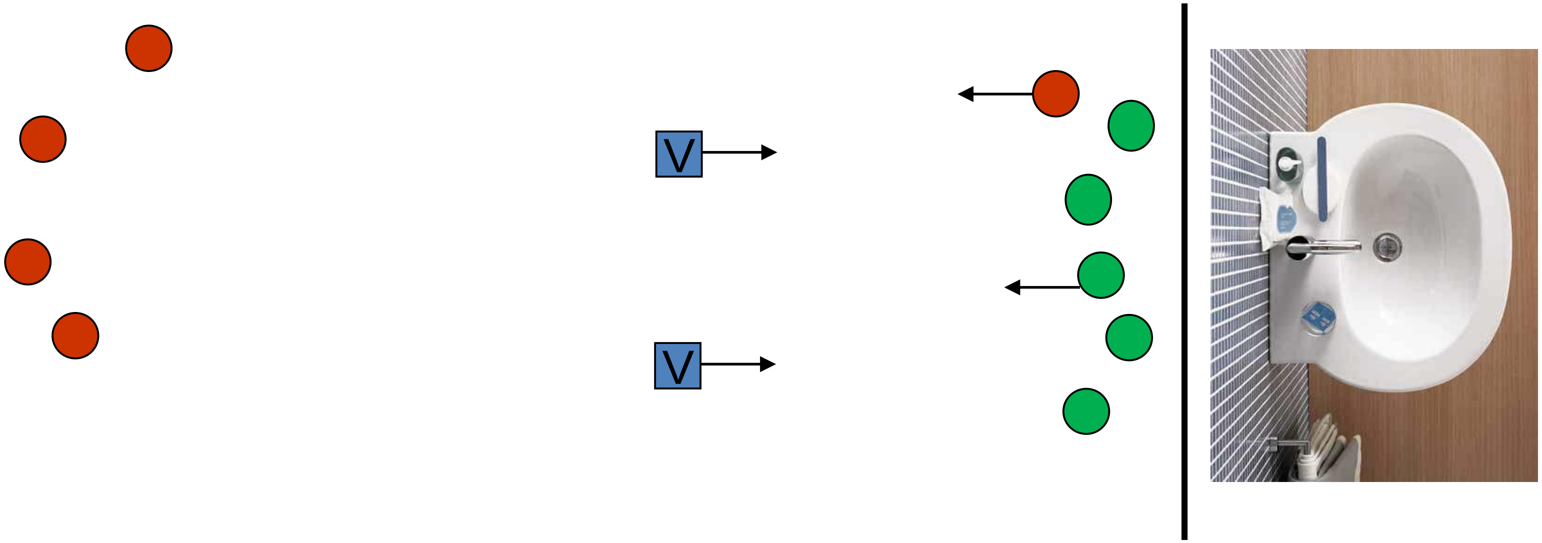
Under irradiation, massive solute transport by SIAs induces accumulation of solutes at sinks

Different diffusivity via non attracted vacancies may lead to solute depletion at sinks



NB Sinks are not only dislocations & GB, but also immobile point-defect clusters

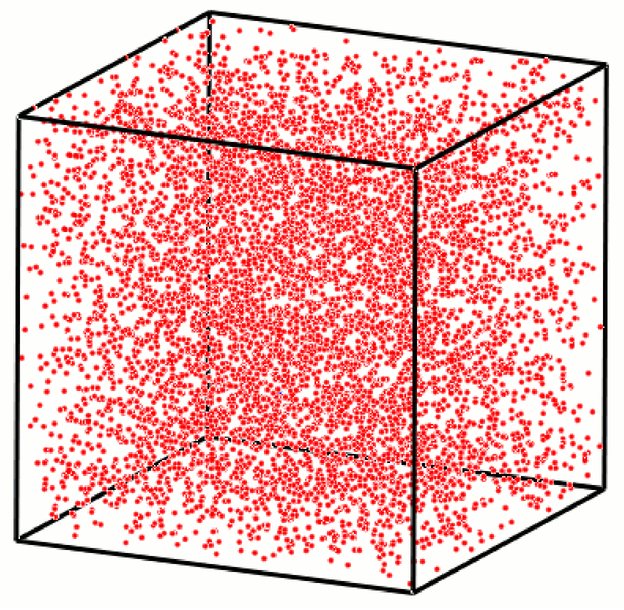
Competition between chemical species can produce solute separation



All these mechanisms lead to solute redistribution under irradiation

Radiation enhanced and radiation induced

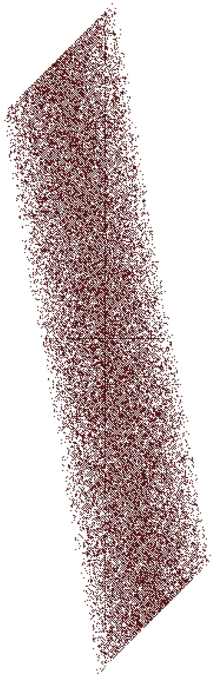
Enhanced



Precipitates form because higher number of point defects under irradiation enhances transport and accelerates their formation

They would form also under high T annealing

Induced



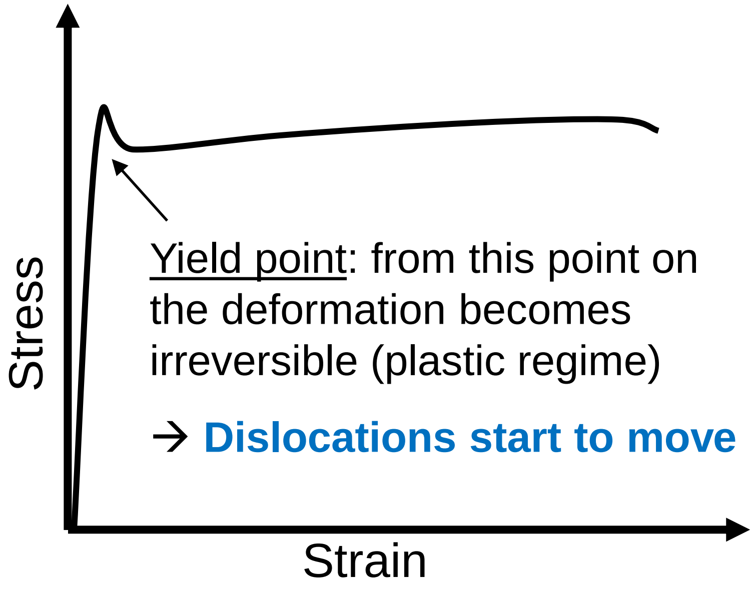
Courtesy F. Soisson

Precipitates form because continuous flux of point defects to sink increases local solute concentration, until solubility limit is locally exceeded

This would **NOT** happen without irradiation

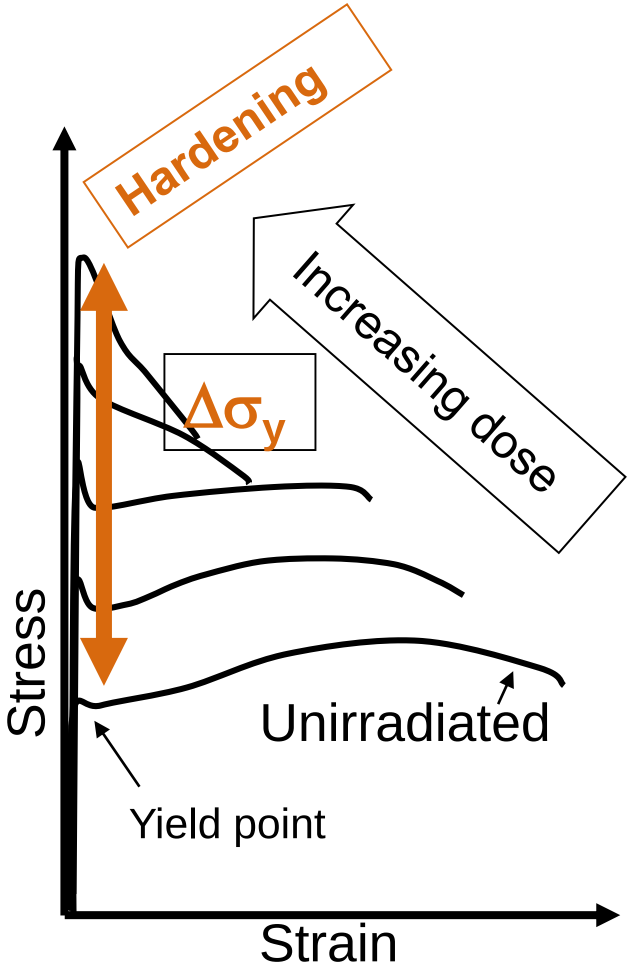
ORIGIN OF RADIATION HARDENING

Hardening = Yield strength increase



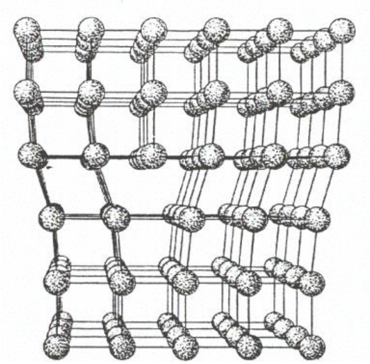
Yield point: from this point on the deformation becomes irreversible (plastic regime)

→ **Dislocations start to move**

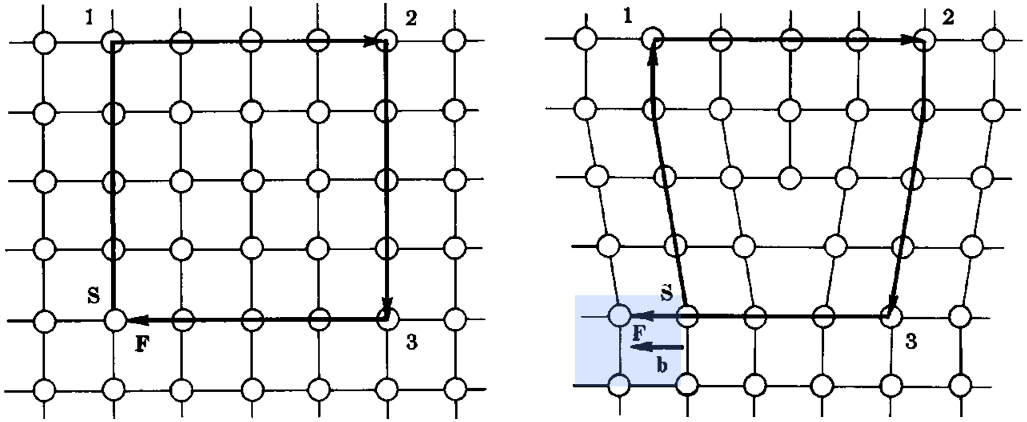


Dislocations

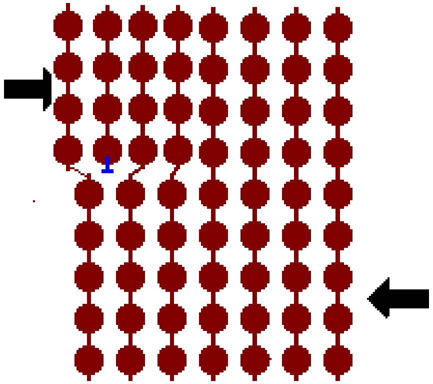
Edge type



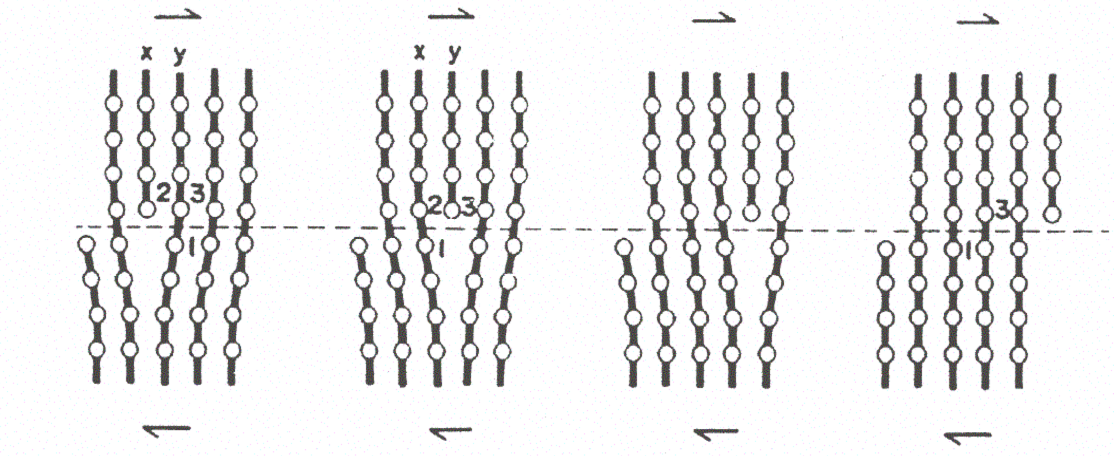
$\hat{\xi}$ Edge dislocation:
line normal to slide



Burgers circuit & vector



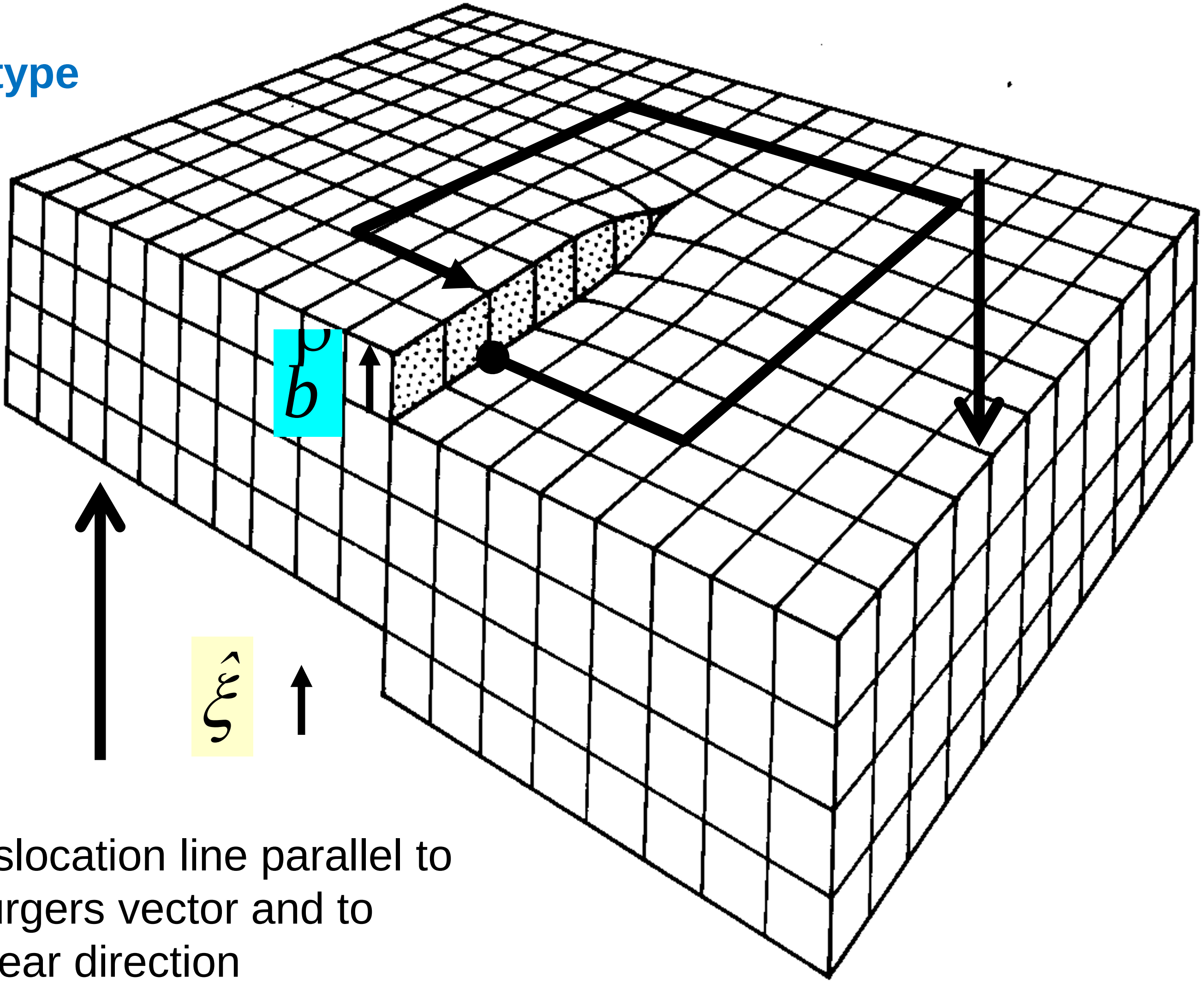
Shear along Burgers vector



Dislocation glide under shear is the most frequent mechanism whereby metals are irreversibly deformed (plastic deformation)

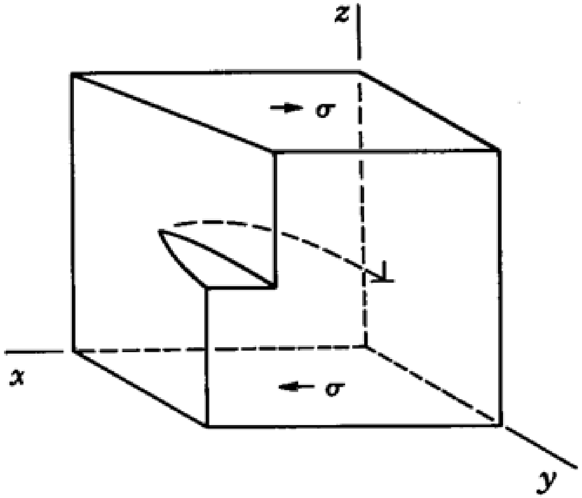
Dislocations

Screw type

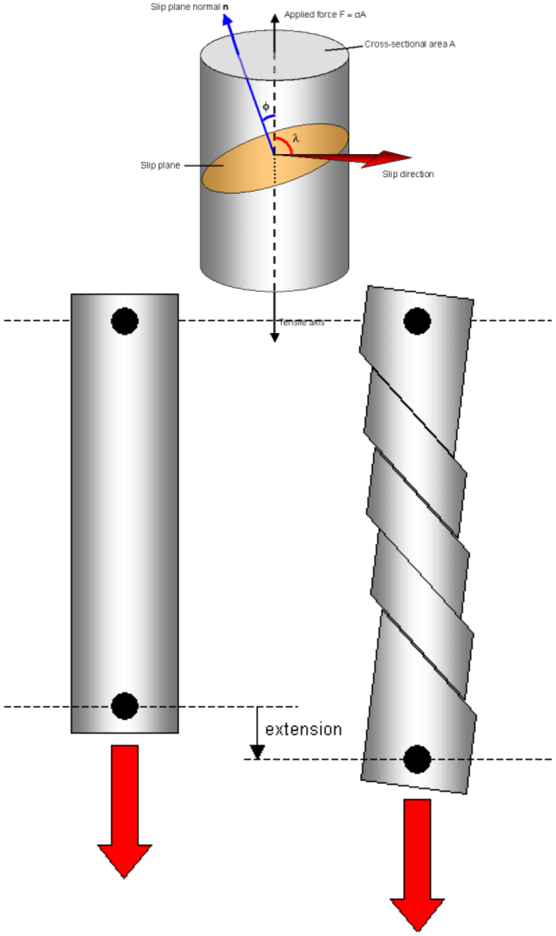


Dislocation line parallel to Burgers vector and to shear direction

Metals deform plastically via dislocation motion



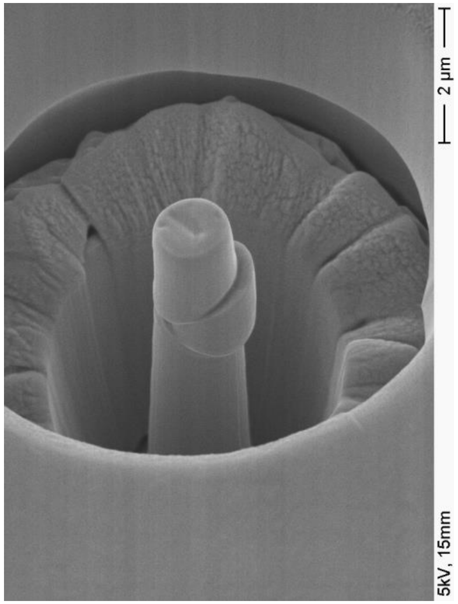
Mixed dislocation line inside a grain gliding on a slip plane



Unslipped single crystal fixed at top end.

Single crystal after plastic deformation by tensile stress

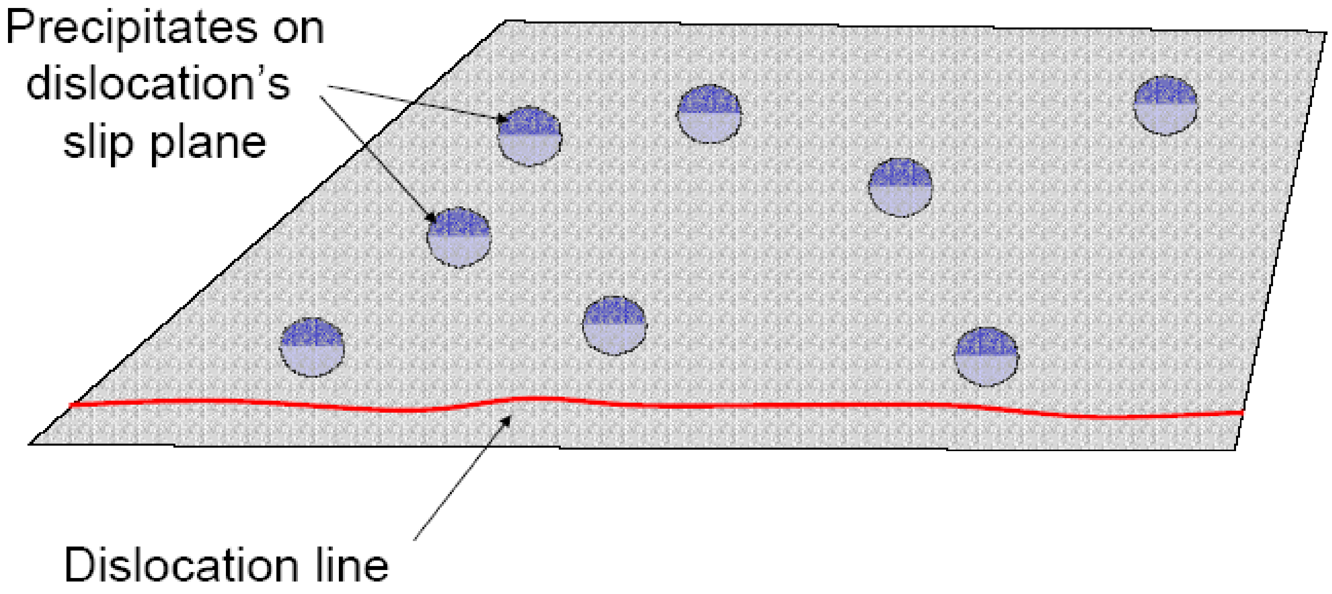
Deformation under tension of single crystal along slip planes



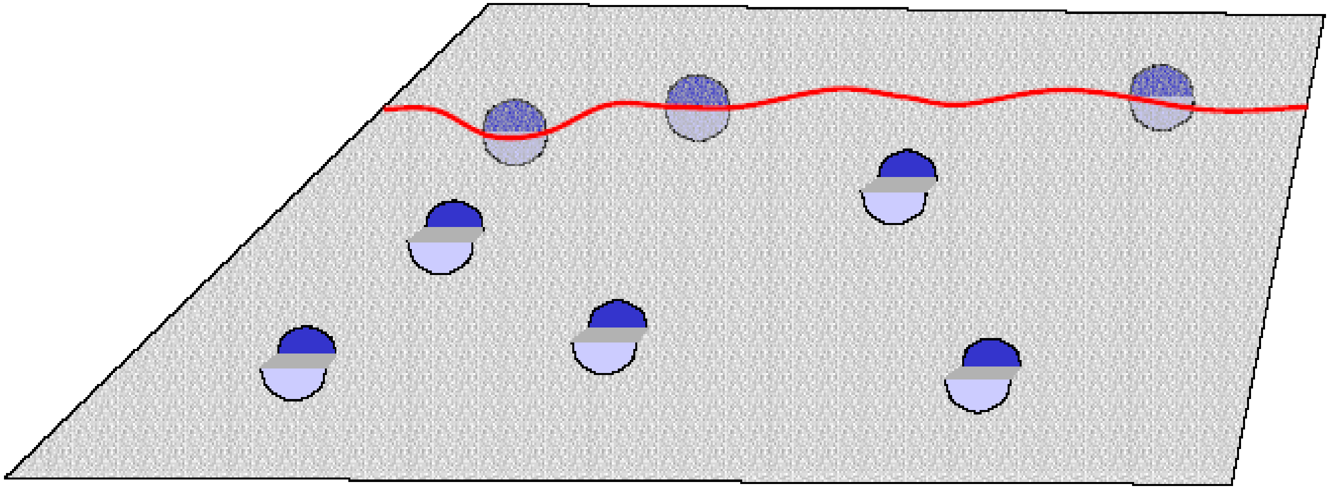
Compression test on nano-pillar in single grain

But what if something impedes dislocation motion?

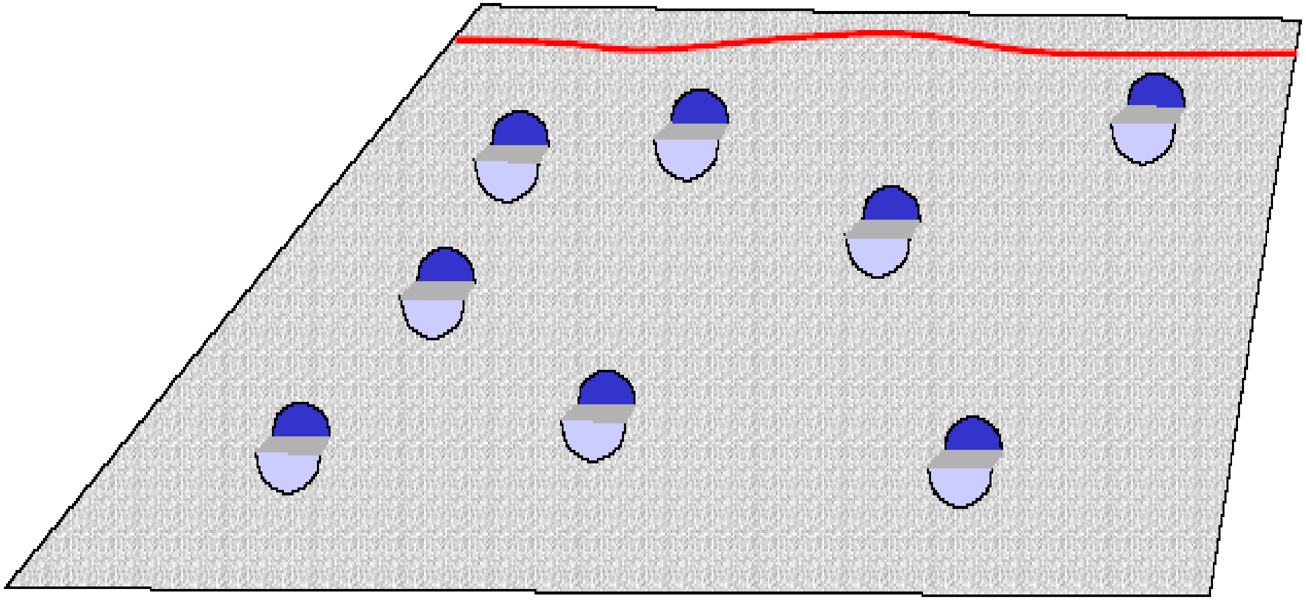
Shearable obstacles



Shearable obstacles

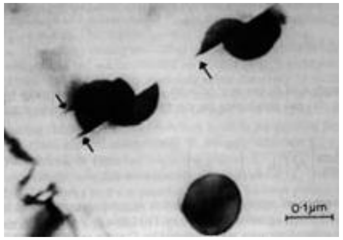


Shearable (weak) obstacles



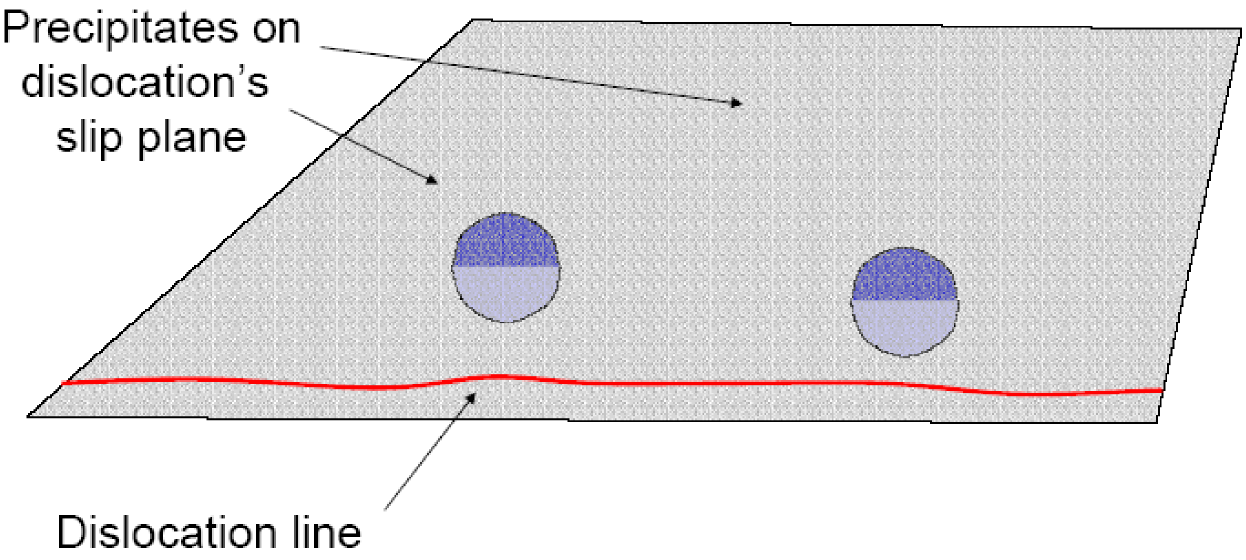
Dislocations can cut through the obstacle: the bigger, the more difficult to cut it through

Elastic, chemical, and phase stability effects also determine obstacle strength

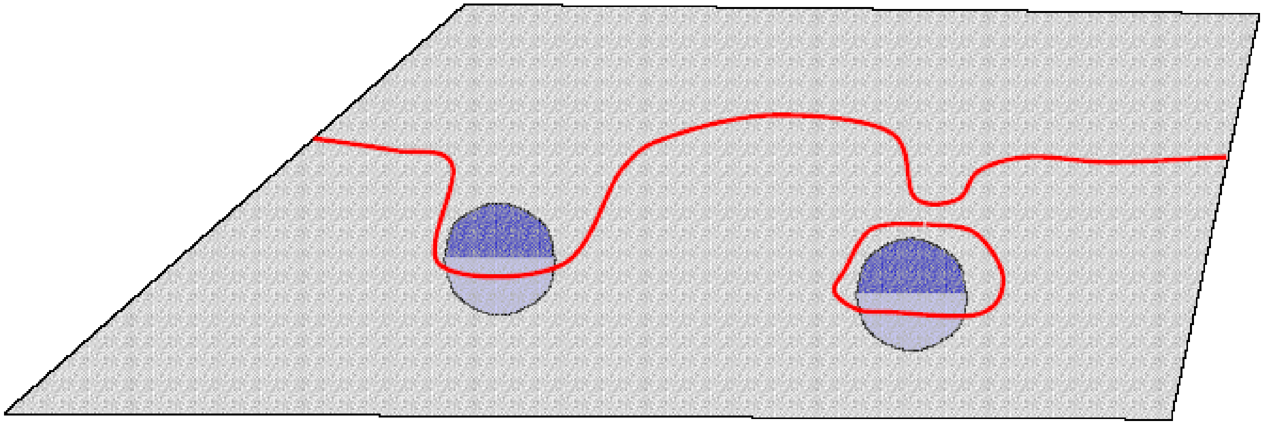


Increasing strain ‘chops up’ sheareable obstacles

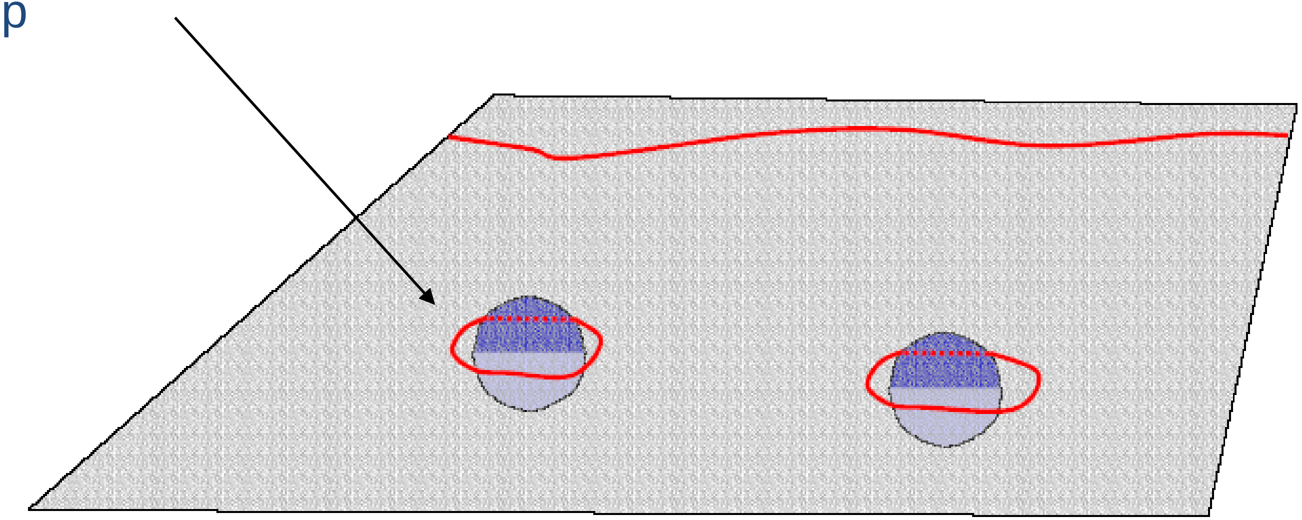
Impenetrable obstacles



Impenetrable obstacles



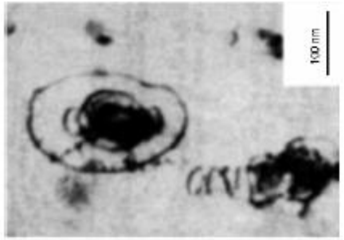
Impenetrable obstacles



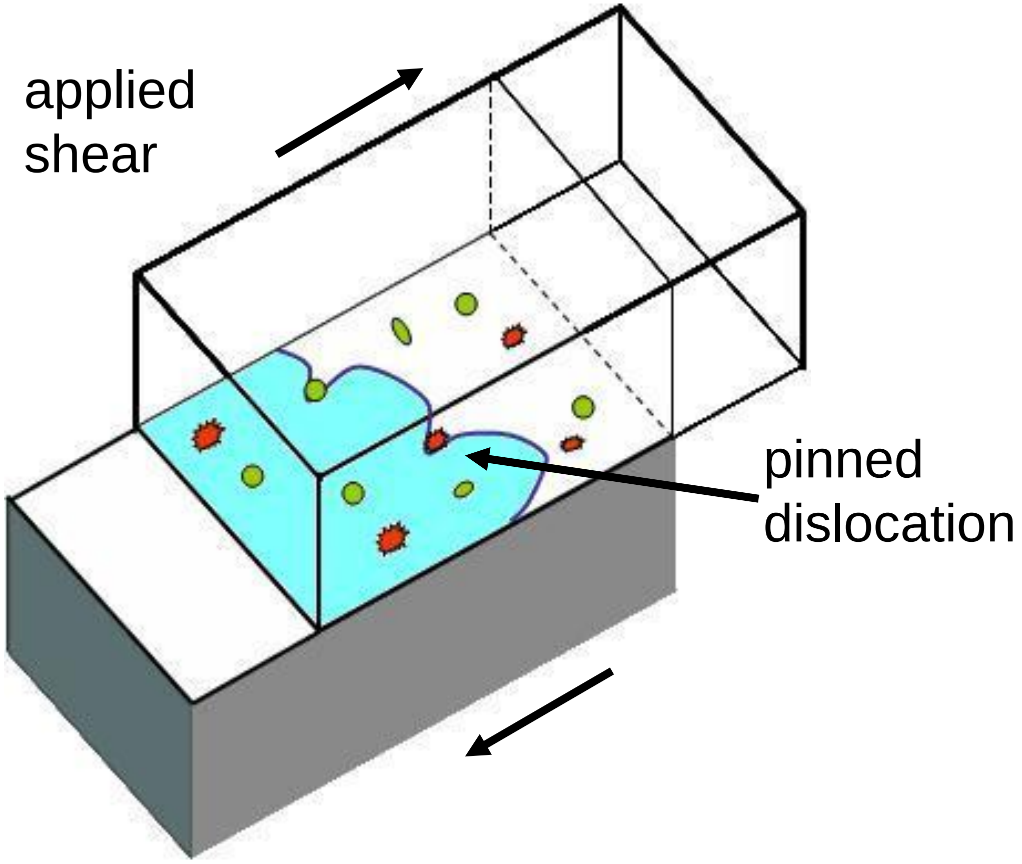
Orowan loop

The bigger the spacing between obstacles, the easier for the dislocation to squeeze through the gaps.

Each ‘bypass’ event leaves a dislocation loop behind, narrowing the gaps and increasing hardening.

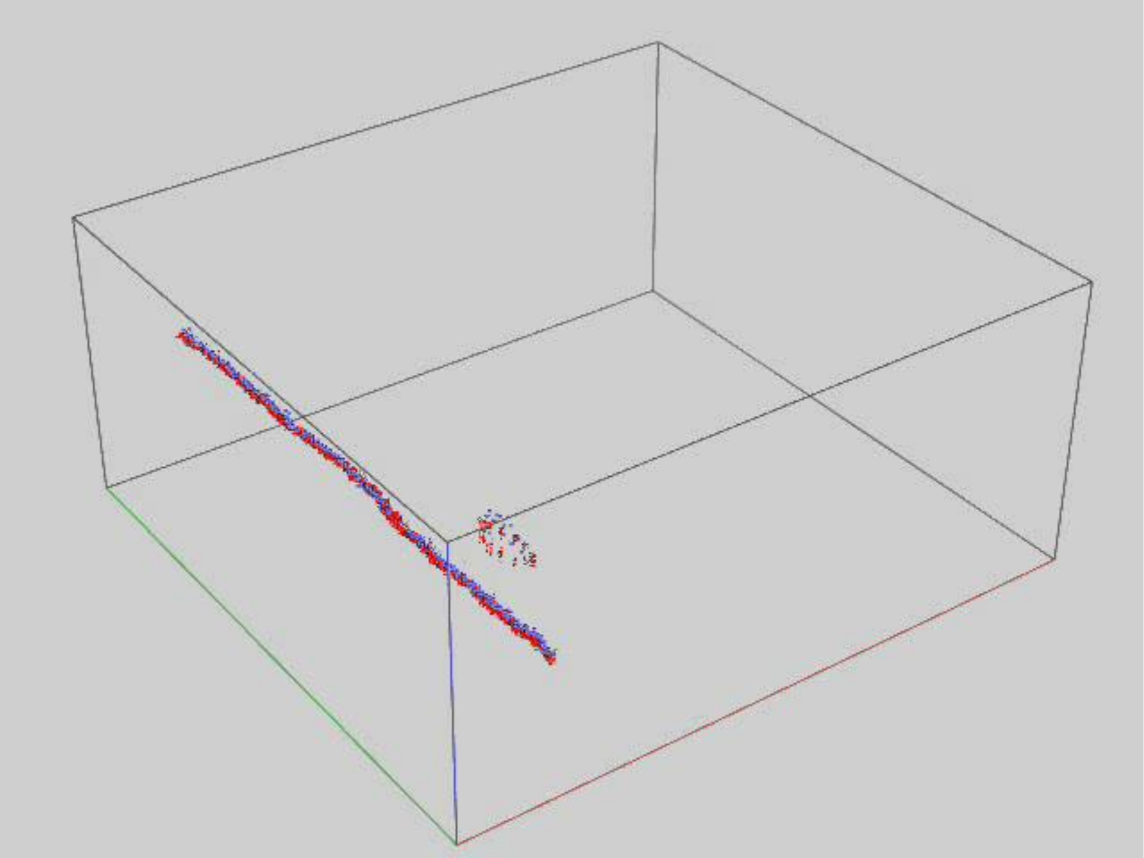


So, why does the yield strength increase after irradiation?



Radiation defect populations act as obstacles to dislocation motion

For example, what happens when a dislocation line meets a dislocation loop



Edge dislocation interacting with SIA loop at 600 K

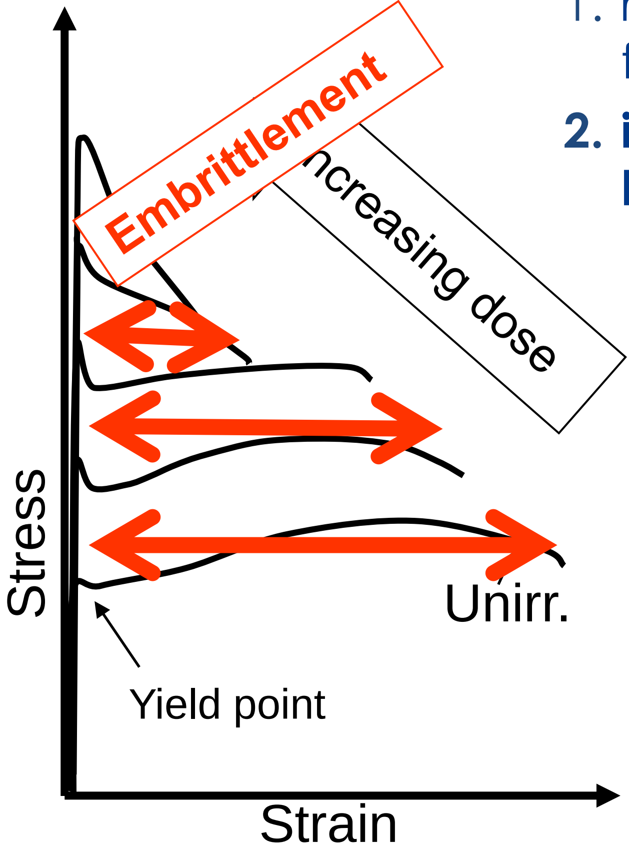
RADIATION HARDENING & EMBRITTLEMENT

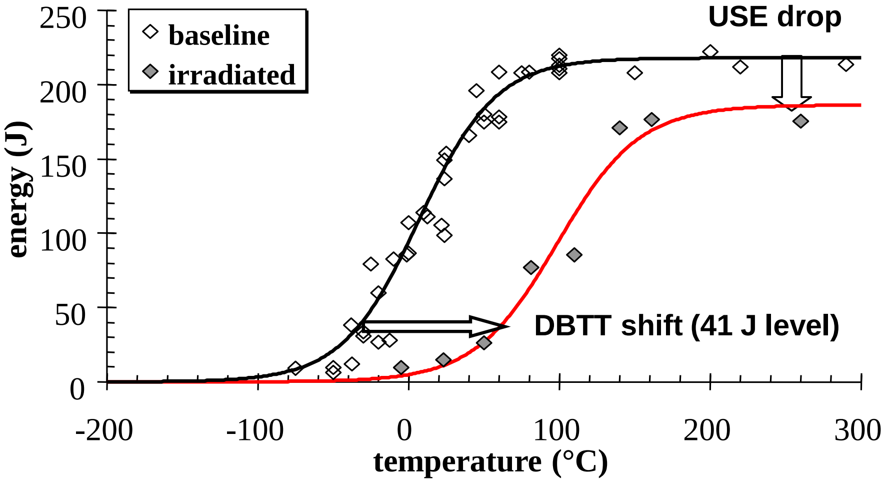
Embrittlement = ?

Brittle material = breaks without prior deformation

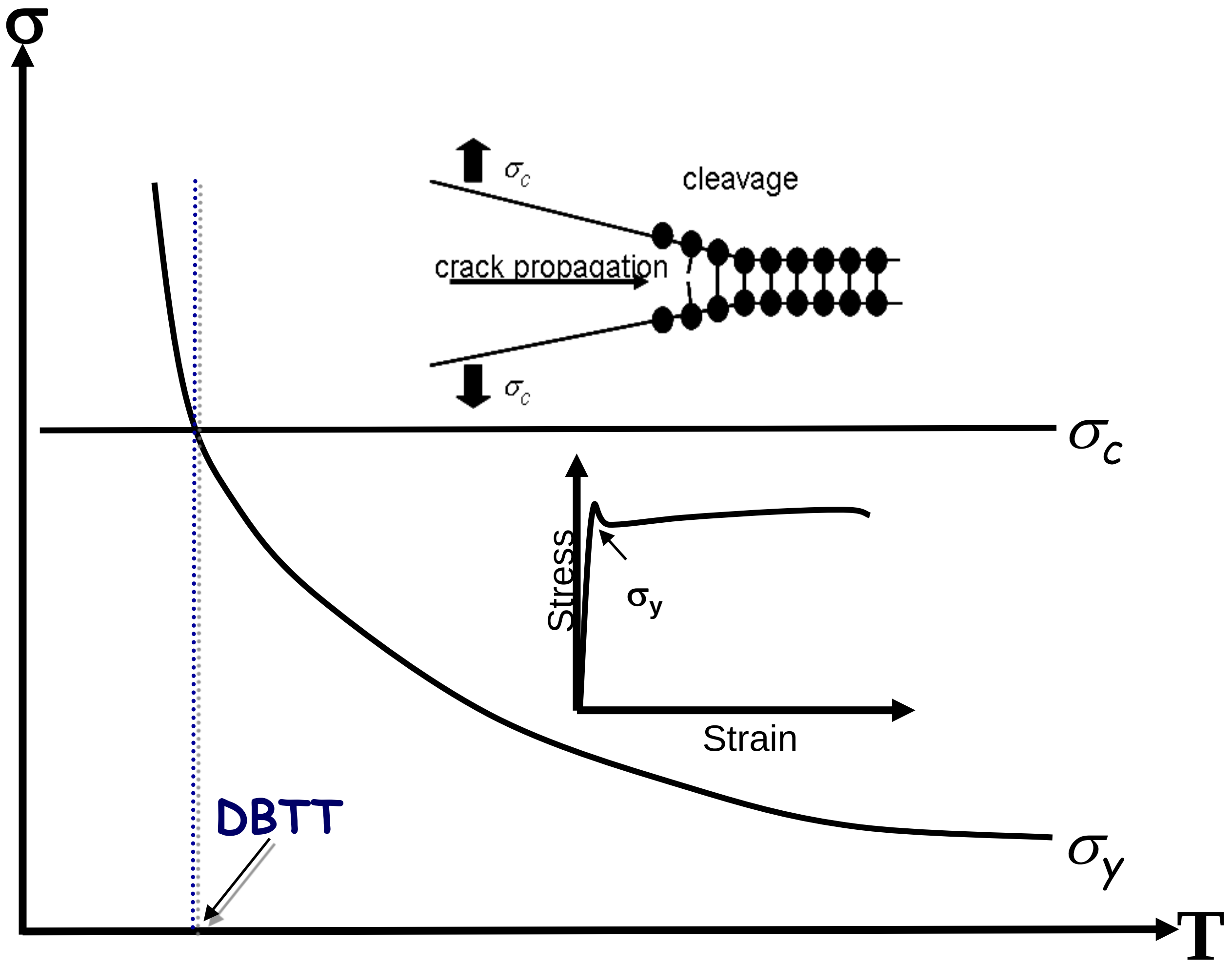
Embrittlement =

1. reduction of elongation (deformation) before fracture
2. **increase of temperature below which material is brittle**





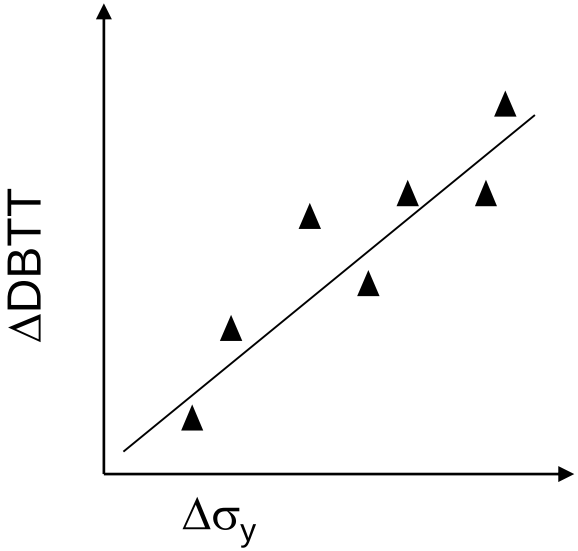
What is the DBTT? The classical explanation



Ductile-brittle transition temperature (DBTT, or T_c) = temperature at which cleavage stress equals yield strength

However, the DBTT is <u>not</u> a material property: it depends also how the test is done

ΔDBTT and $\Delta\sigma_y$ are (generally) linearly correlated: **why?**



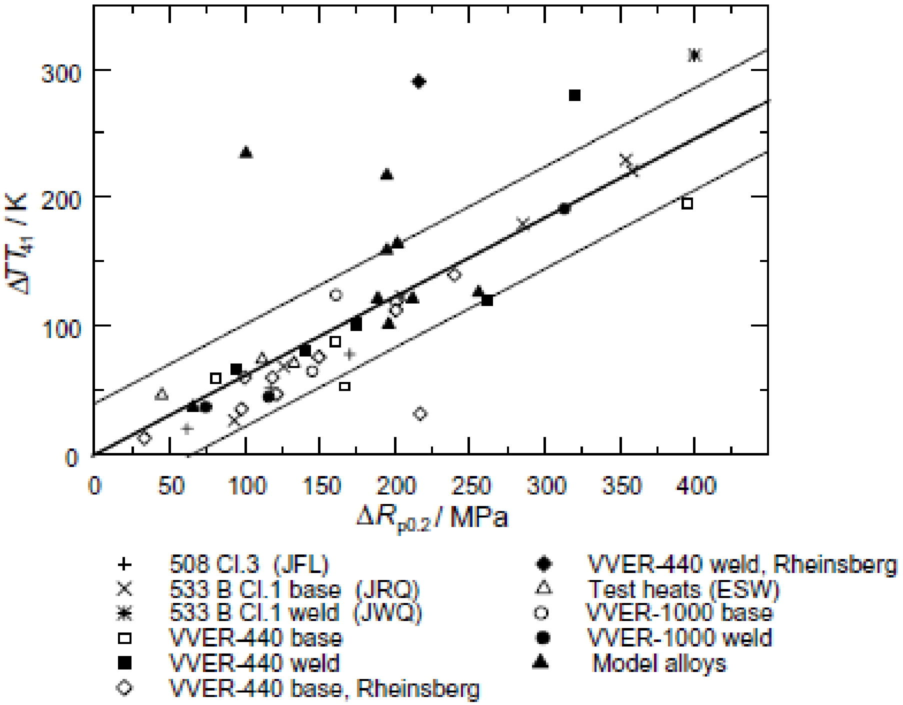
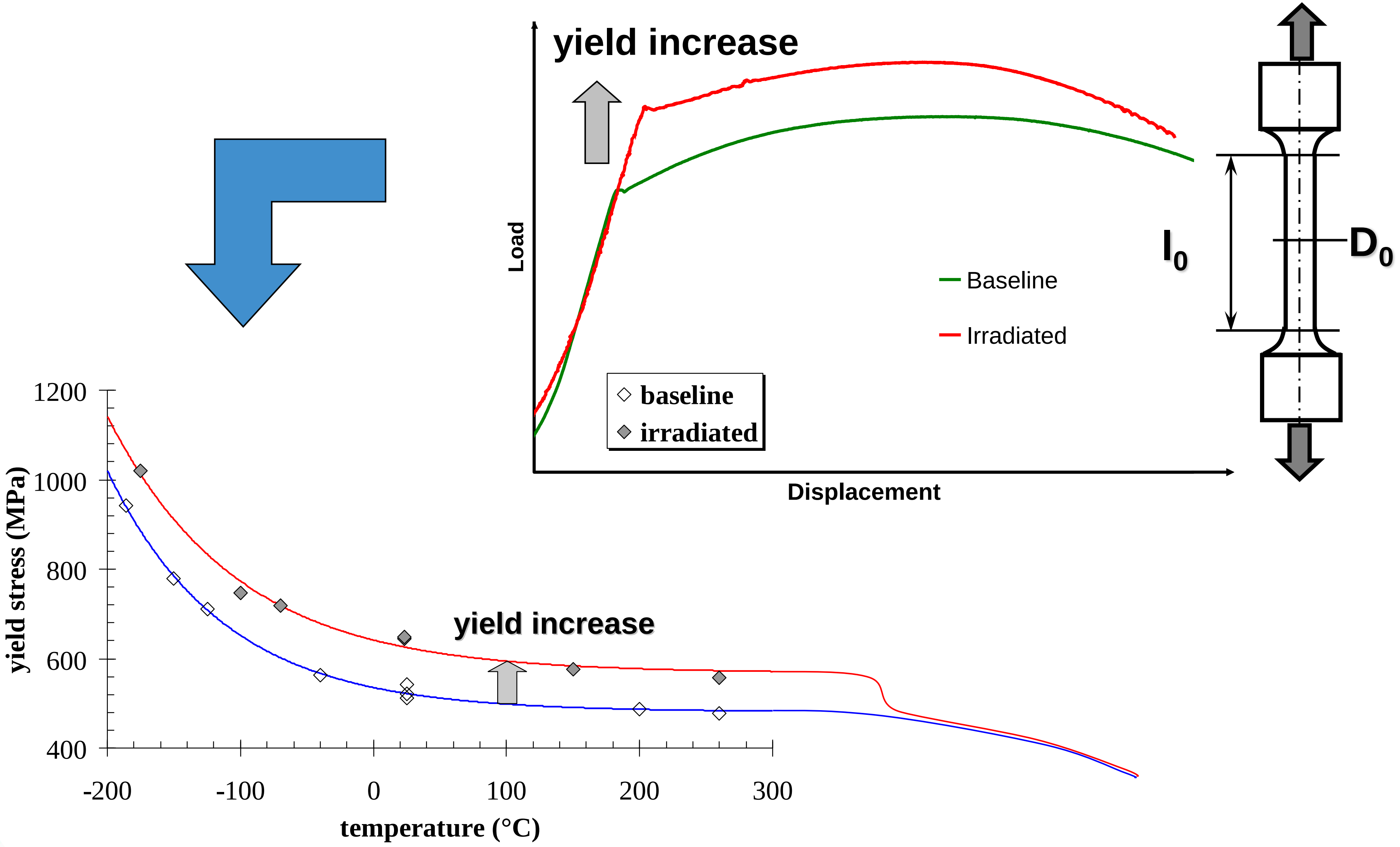


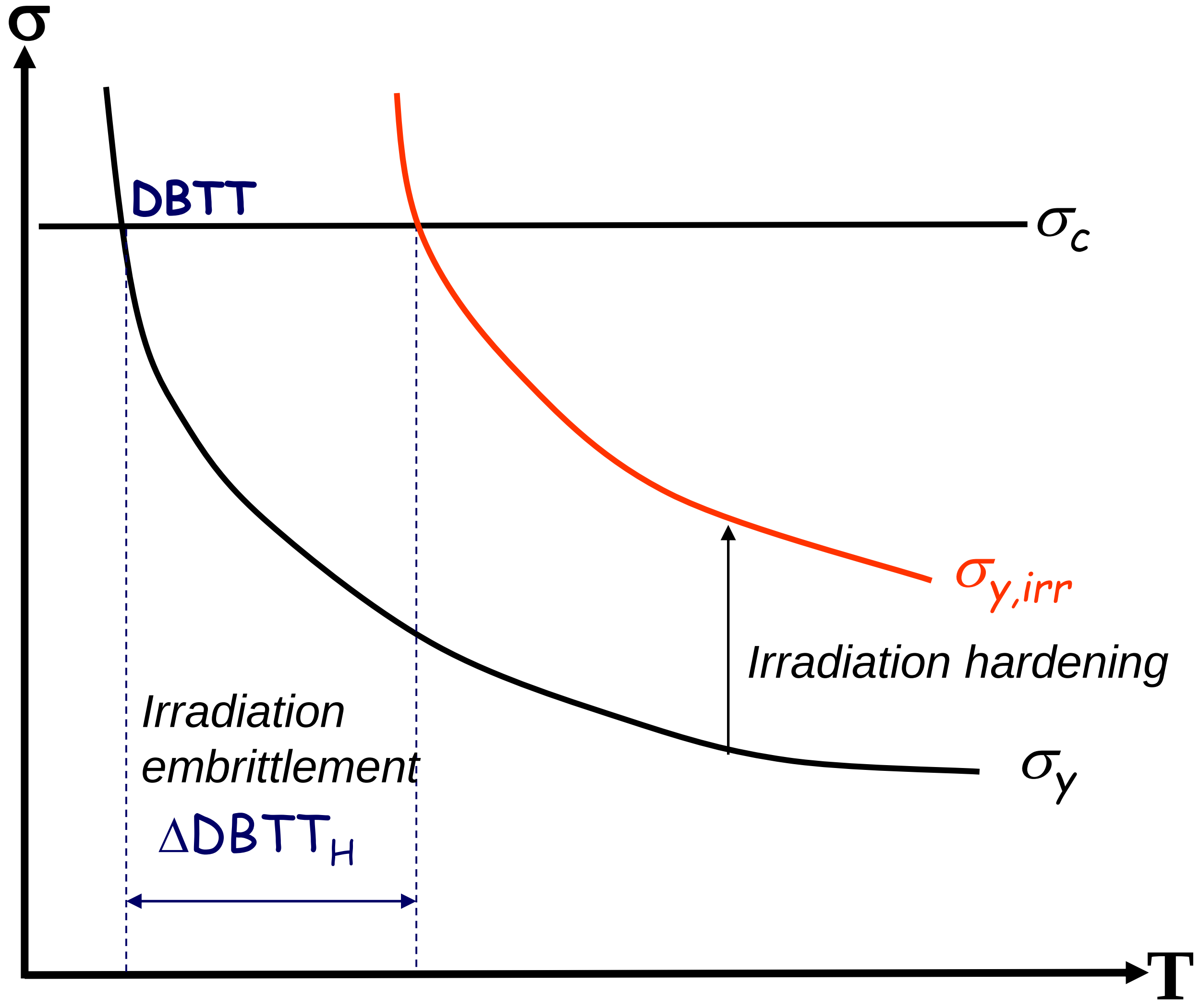
Fig. 8. Correlation between the shift of transition temperature ΔTT_{48} and the yield stress increase $\Delta R_{p0.2}$.

Example from: Böhmert et al. JNM 334 (2004) 71

Radiation hardening versus temperature



Effect of irradiation on σ_y and DBTT: The classical explanation:



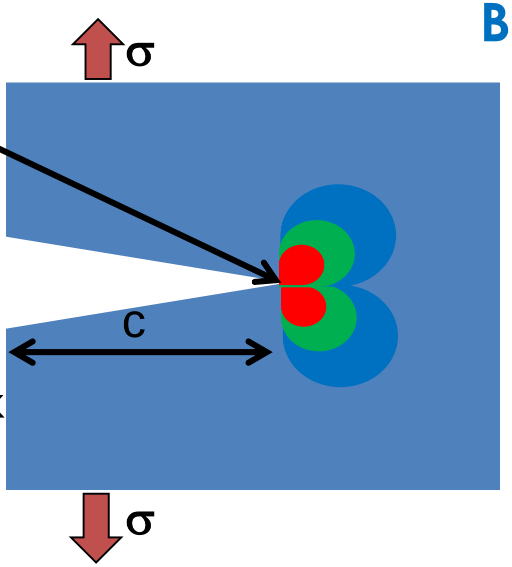
The linear relationship is valid so long as the curve $s_y(T)$ is rigidly shifted upward by irradiation for all temperatures

A closer look

Crack tip – stress concentrator

Stress intensity factor
$K = a\sigma\sqrt{\pi c}$

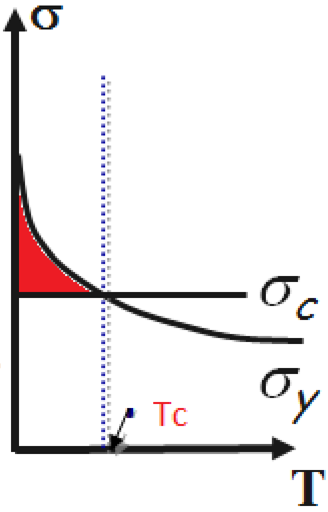
$K \geq K_{Ic}$ ($\sigma \geq \sigma_c$) ⇒ crack propagates



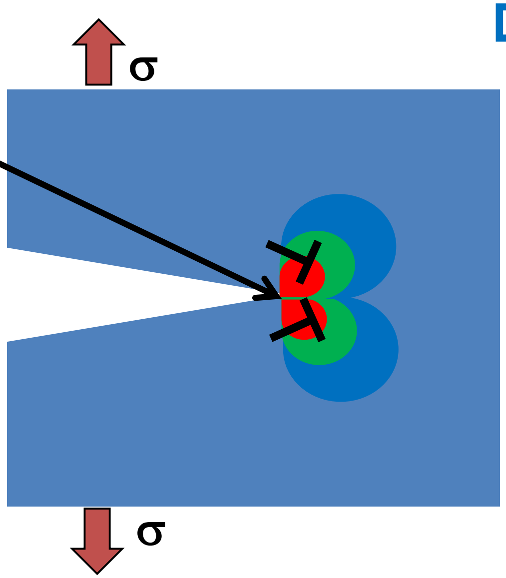
Brittle behaviour

$T < T_c$

$\sigma_c < \sigma < \sigma_y$ ⇒ when crack propagates dislocations cannot move ⇒ cleavage occurs



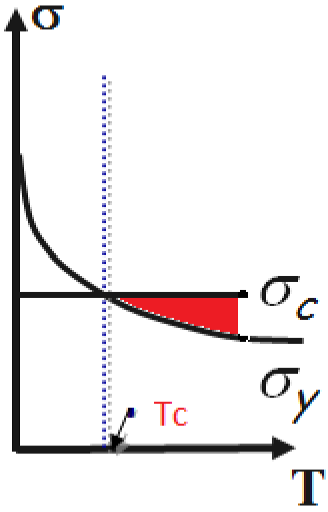
Crack tip – dislocation source



Ductile behaviour

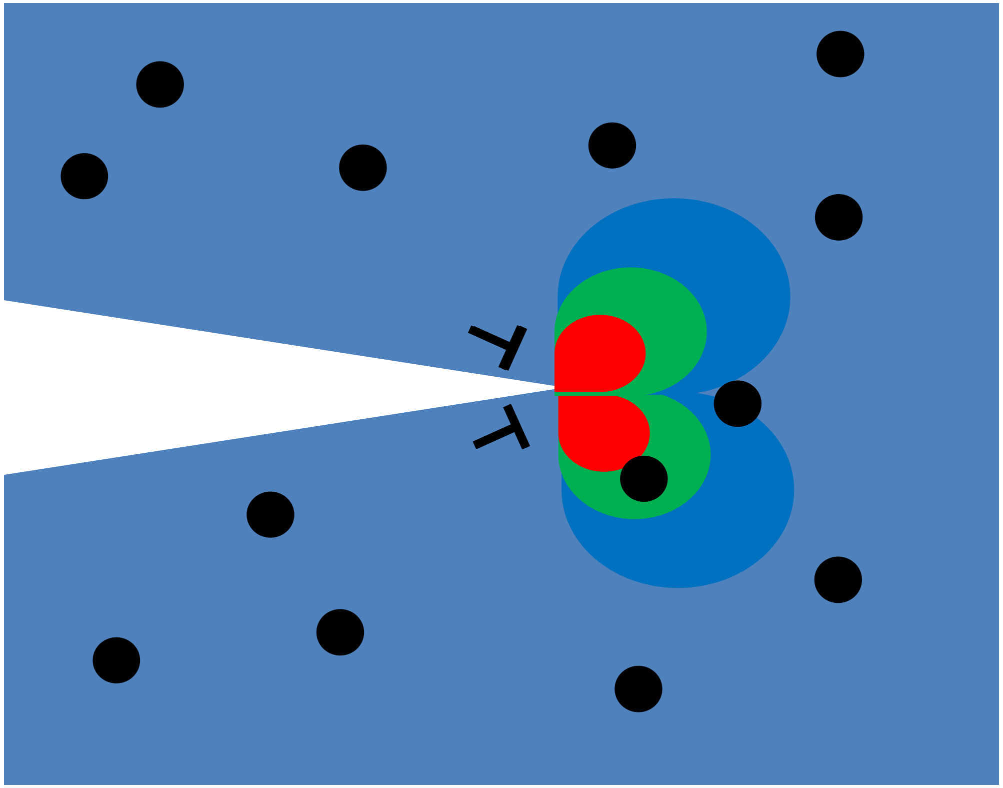
$T > T_c$

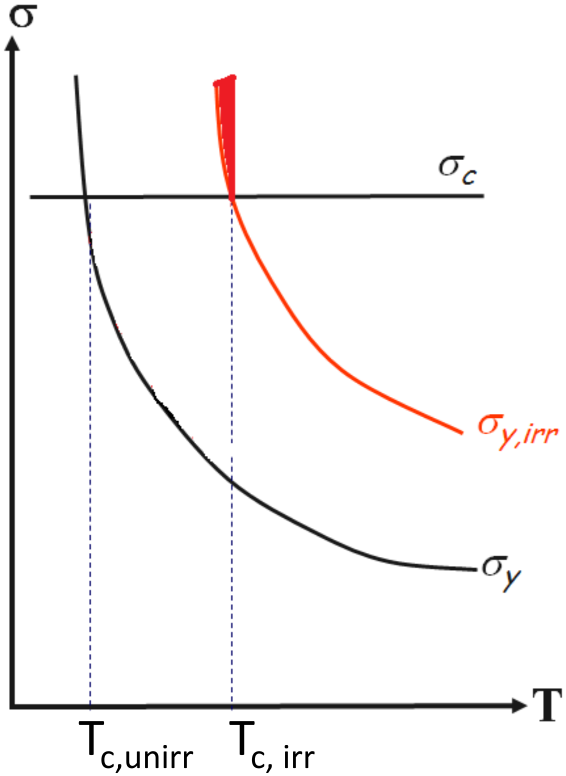
$\sigma_y < \sigma < \sigma_c$ → dislocations start to move before crack can propagate ⇒ deformation occurs before fracture



A closer look in presence of radiation defects

$T > T_{c\text{-unirr}}$: Dislocation motion hampered by obstacles ⇒ even if dislocation are emitted, no (or little) deformation occurs

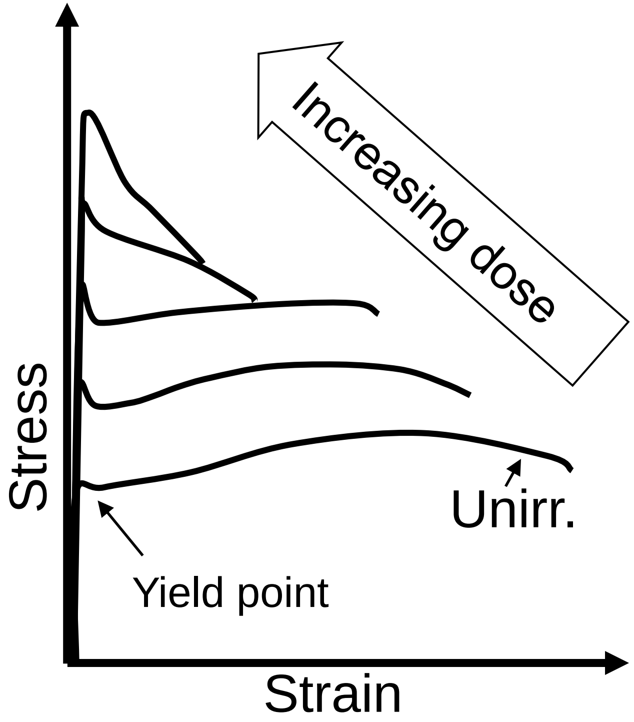




σ_c is exceeded before dislocations set free ⇒ brittle behaviour

Only if $\sigma_{y,irr}$ is exceeded dislocations become free and there is deformation, but cleavage already started ⇒ T_c effectively increased

Why is hardening accompanied by loss of elongation and does it correlate with embrittlement?



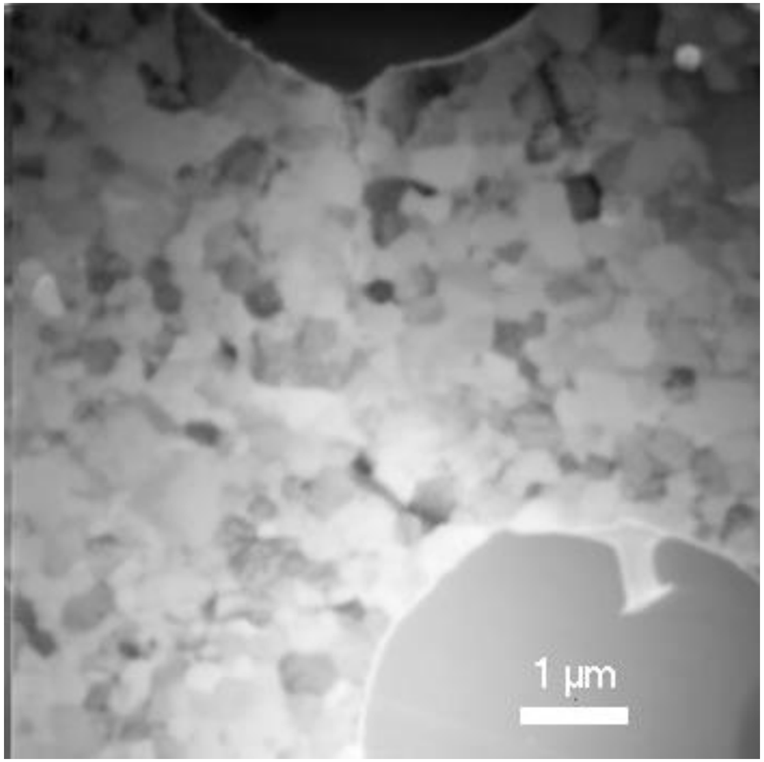
Because *in general* the origin of both hardening and embrittlement is the presence of obstacles to dislocation motion

Key question to predict radiation hardening: which obstacles are responsible for dislocation pinning?

Moreover, embrittlement may have also other origins…

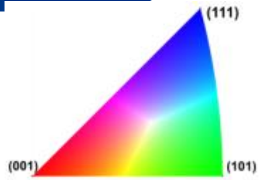
Grains and grain boundaries

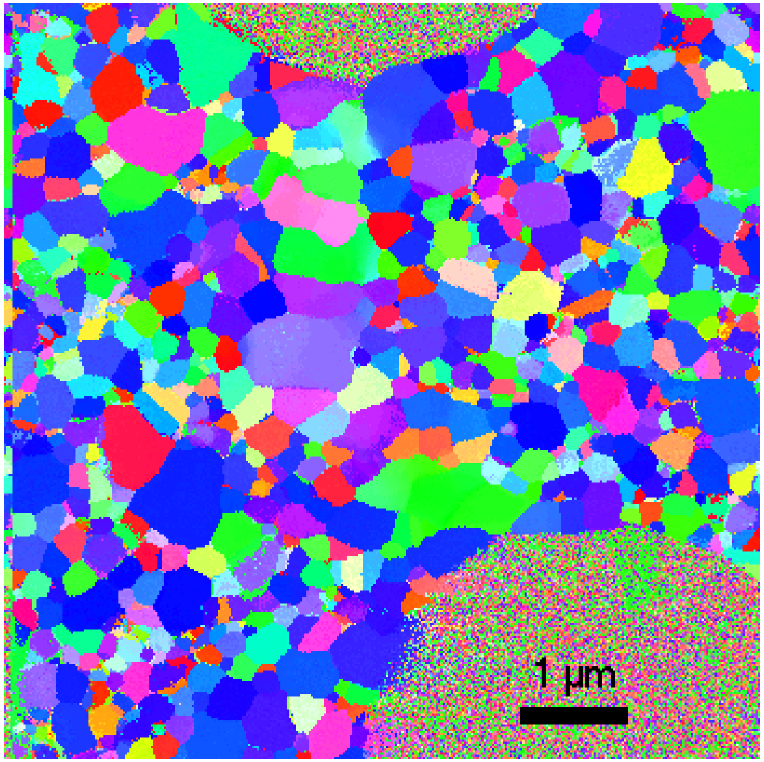
Brightfield image (TEM)



Metallographic examination of deformed specimen – grains are clearly visible

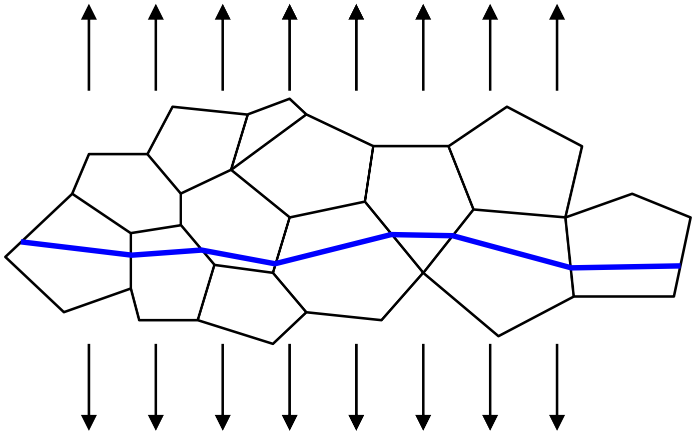
Orientation map





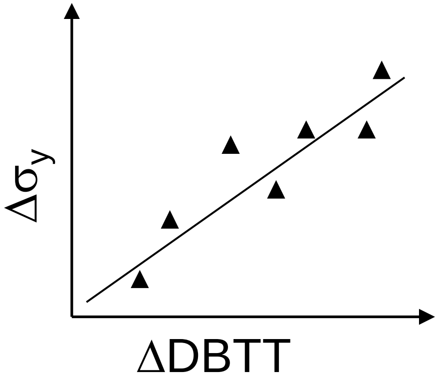
Electron back-scatter diffraction (EBSD) – each colour corresponds to a different crystallographic orientation

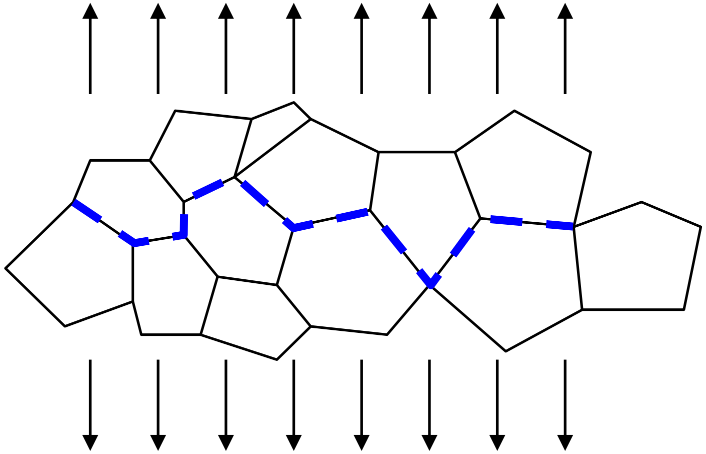
Transgranular and intergranular fracture



Cleavage fracture is transgranular

Embrittlement characterised by transgranular fracture is most often related to hardening (same fundamental mechanism)





Intergranular fracture may happen as a consequence of grain decohesion

Here fracture mechanism is *unrelated to dislocations*

→ no correlation with hardening

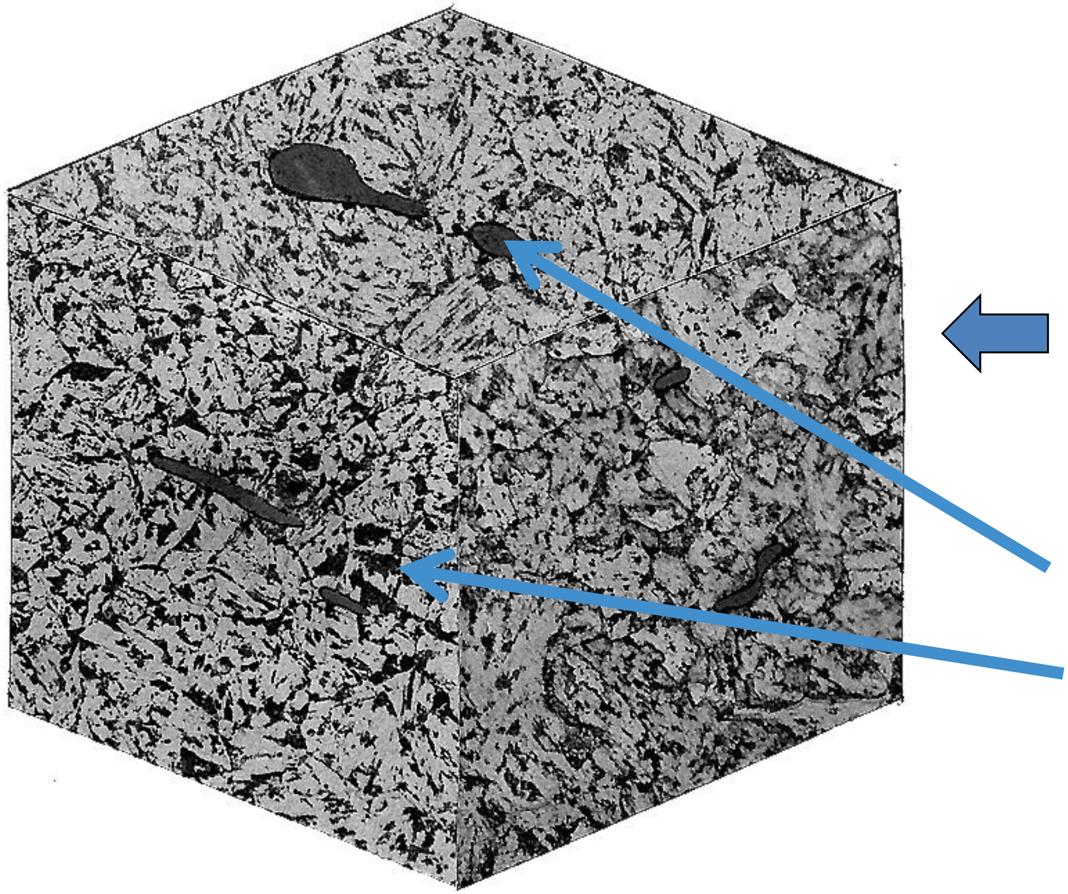
→ no previous deformation

ORIGIN OF RADIATION EMBRITTLEMENT IN RPV STEELS

RPV Steels are Low Alloy Steels with Mn, Ni and Mo (Cr) addition

A typical composition in a European PWR could be: **0.1% C - 1.4% Mn - 0.2% Si - 0.7% Ni - 0.5% Mo - 0.02% Al – 0.1% Cu – 0.01% P – (*… Cr, Co, S)* + Fe (balance)**

US RPV steels contain up to 0.3%Cu, some steels have high Ni&Mn content ~1.5%, VVER steels may have high Ni content (or none) and contain ~2%Cr, …

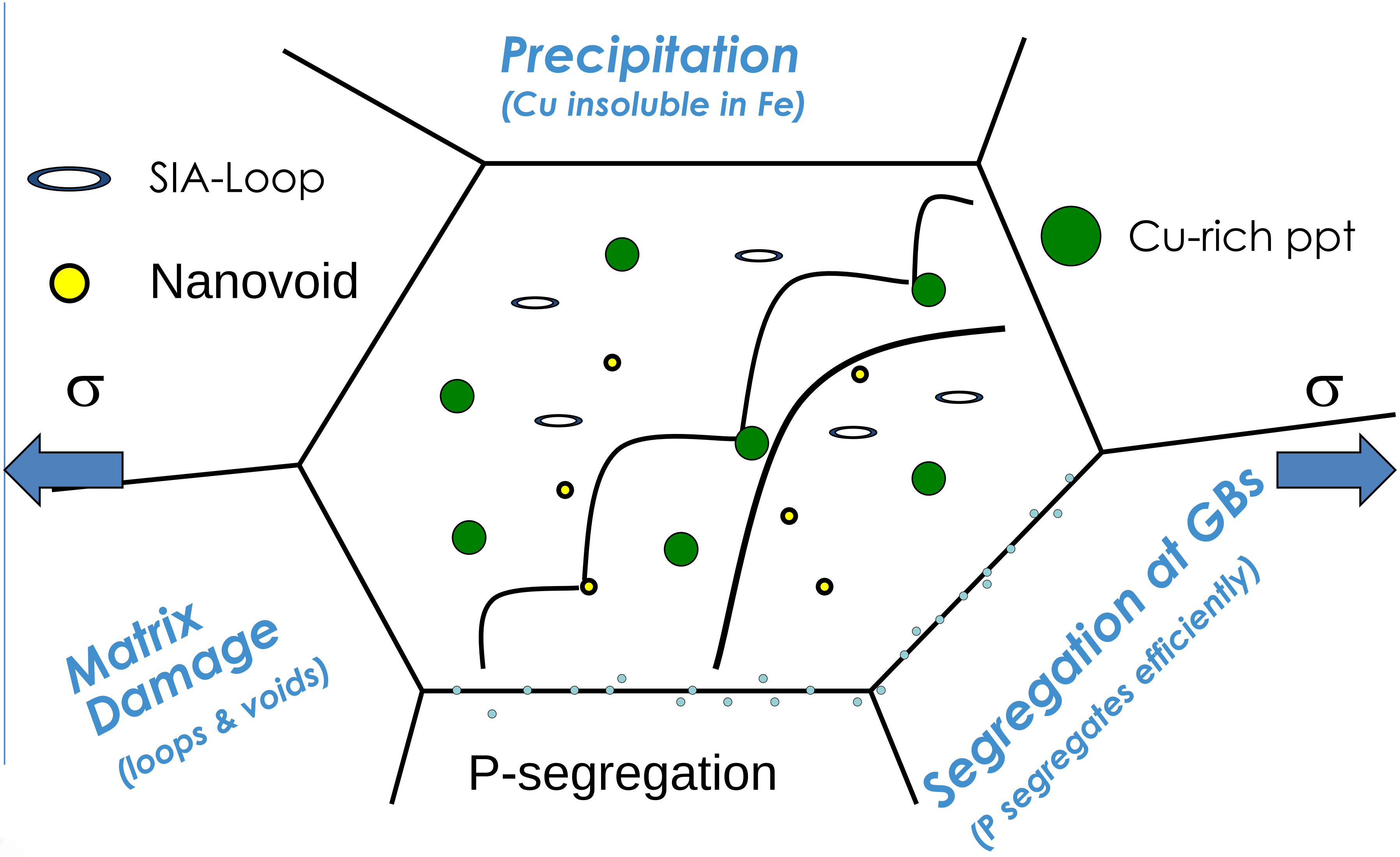


Bainitic microstructure (peculiar distribution of ferrite)

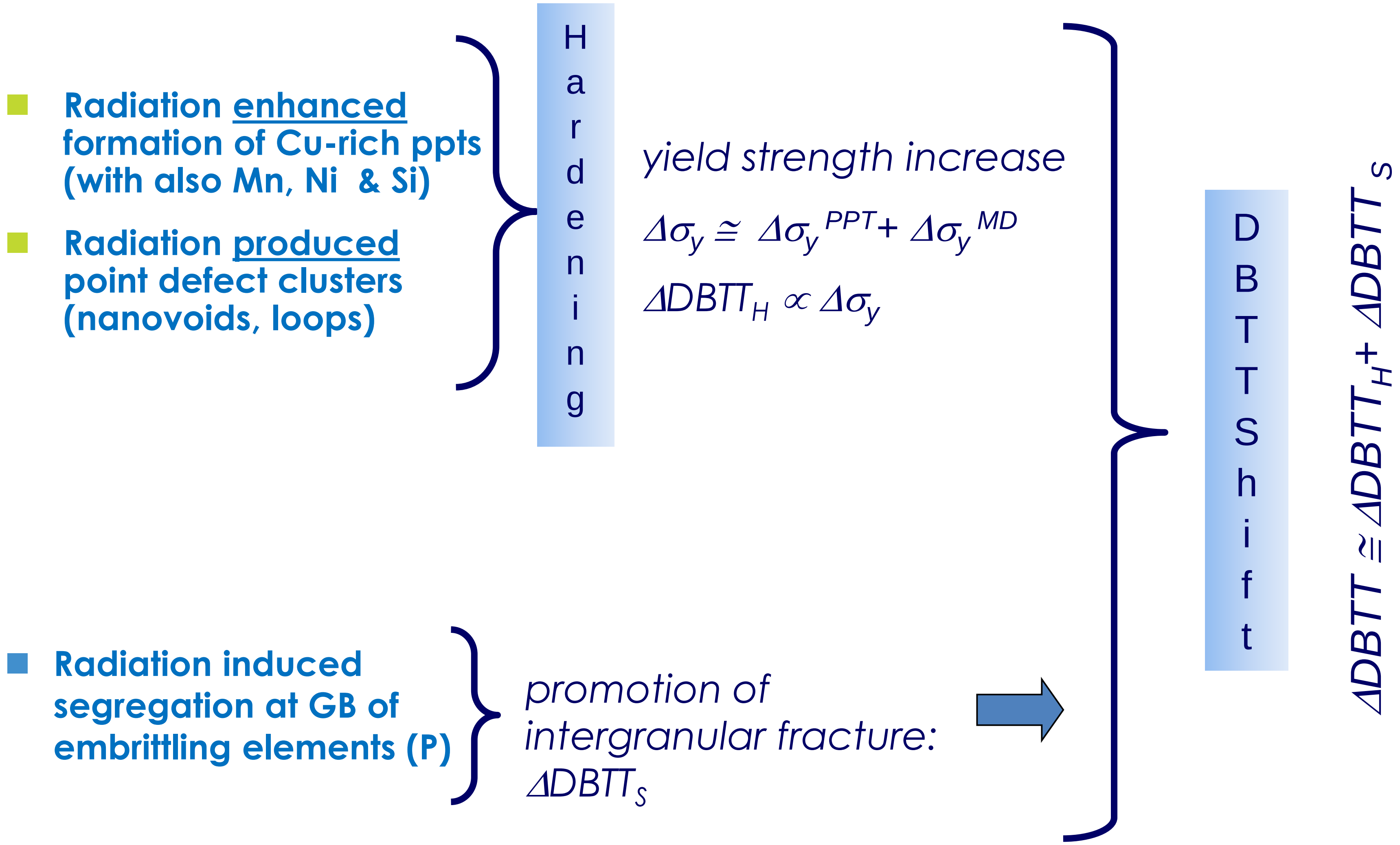
Carbides

Inclusions

Handbook mechanisms of RPV steel embrittlement under irradiation



Traditional mechanistic approach in the RPV steel world



- **Radiation enhanced formation of Cu-rich ppts (with also Mn, Ni & Si)**
- **Radiation produced point defect clusters (nanovoids, loops)**

Hardening

yield strength increase

$\Delta\sigma_y \cong \Delta\sigma_y^{PPT} + \Delta\sigma_y^{MD}$

$\Delta DBTT_H \propto \Delta\sigma_y$

- **Radiation induced segregation at GB of embrittling elements (P)**

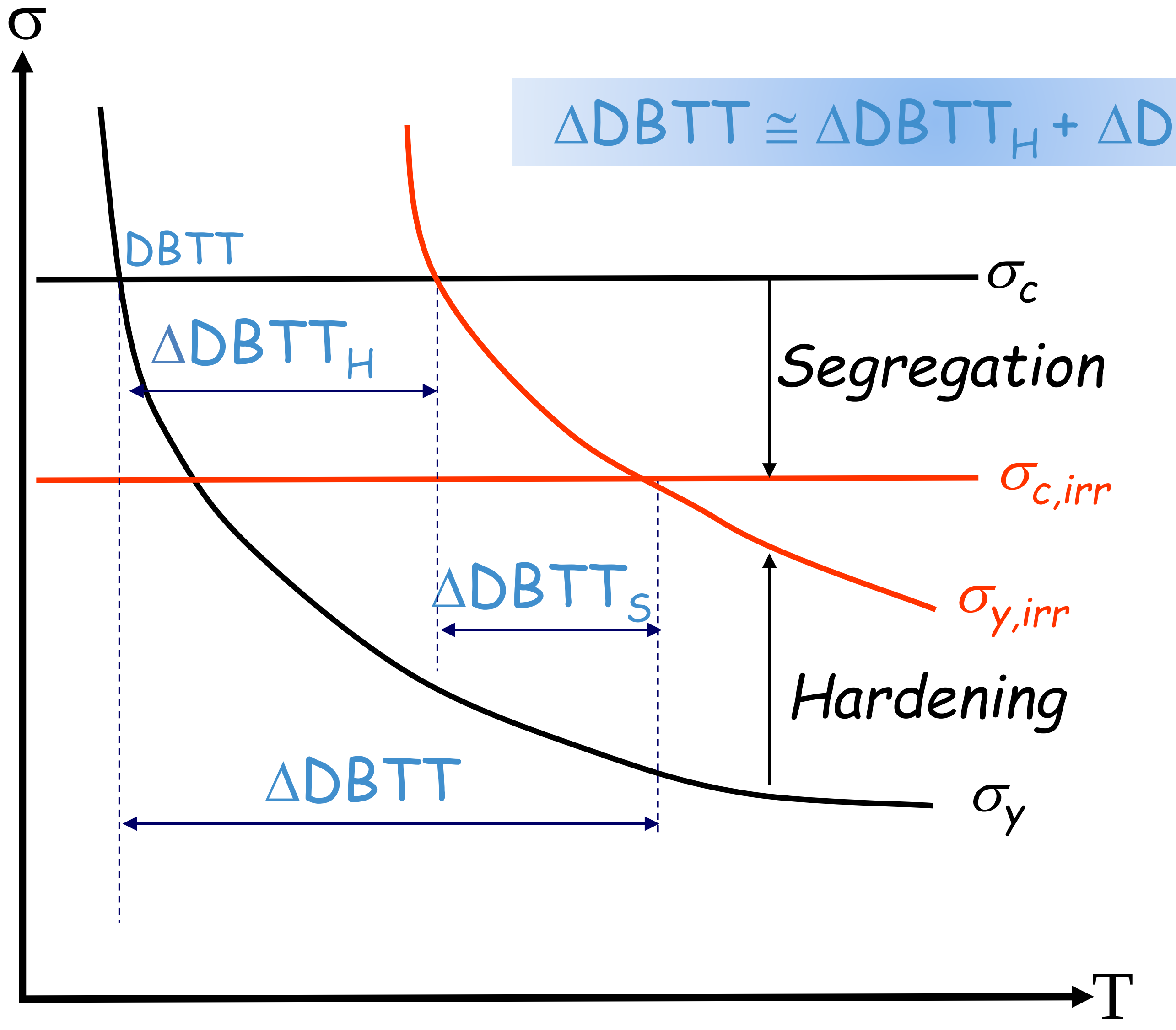
promotion of intergranular fracture: $\Delta DBTT_S$

DBTT Shift

$\Delta DBTT \cong \Delta DBTT_H + \Delta DBTT_S$

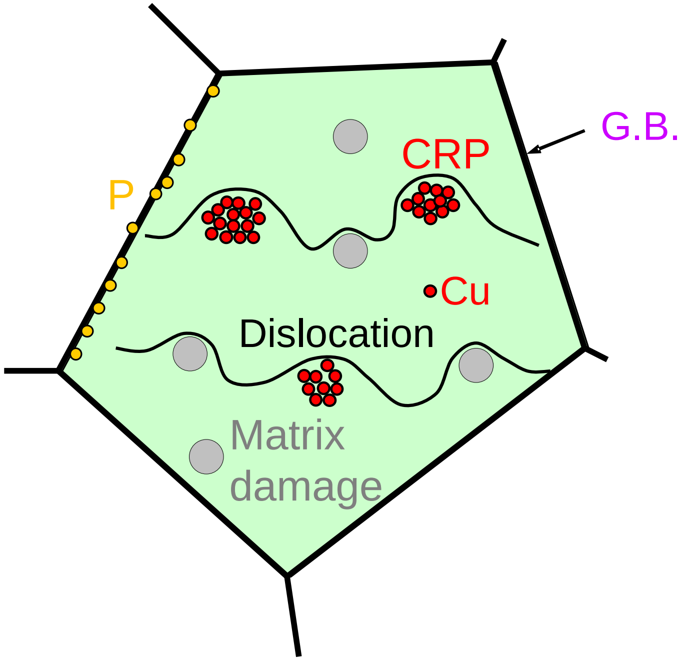
Graphical representation

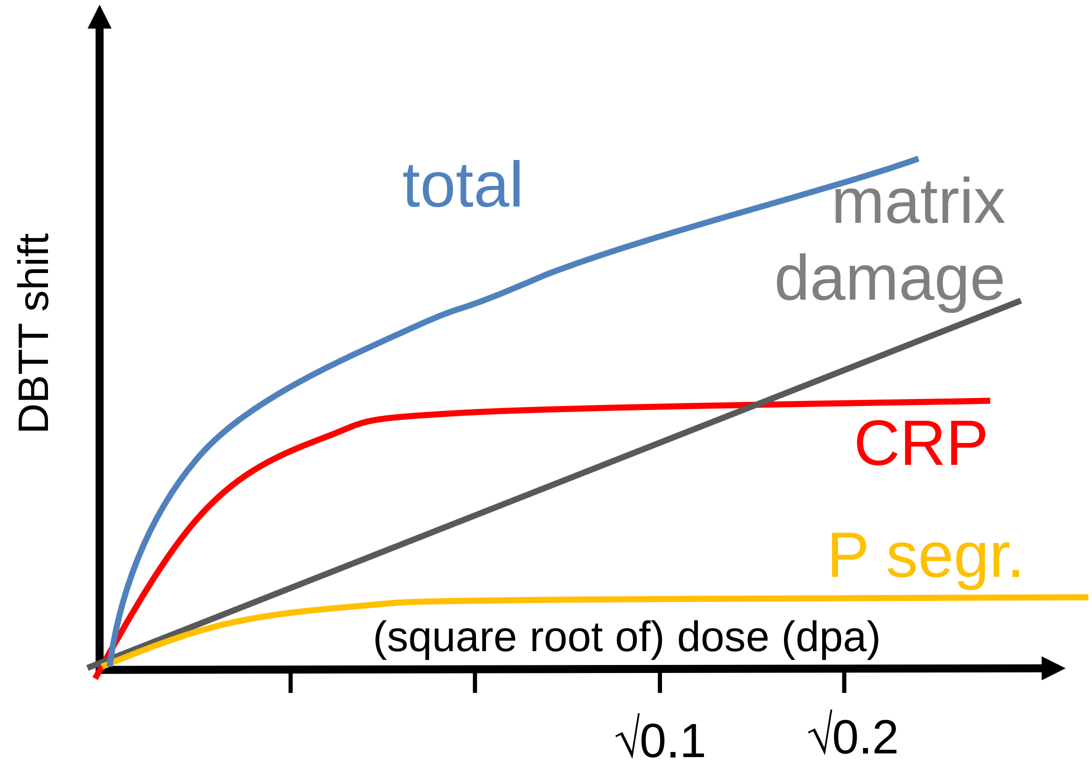
$$\Delta DBTT \cong \Delta DBTT_H + \Delta DBTT_S$$



The relative weight of the different contributions depends on composition and other factors

So, existing advanced mechanistic trend curves include up to three components





Three-feature model:

- Matrix damage = microvoids, dislocation loops, small solute/point-defect clusters
- CRP = Cu-rich precipitates (Cu is virtually insoluble in Fe)
- P = radiation-induced segregation at grain boundaries GB

Examples of Mechanistic Correlations (trend curves)

- Reg. Guide 1.99 – Rev. 2 (May 1988)*

$$\Delta T = CF \cdot f^{(0.28-0.10\cdot\log(f))}$$

CF, chemistry factor is a function of **Cu** and **Ni** content and is given in tables for base and weld metals

f is the fast fluence (E > 1 MeV, 10^{19} n/cm²)

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*E.D. Eason, J.E. Wright and G.R. Odette, *Improved Embrittlement Correlations for Reactor Pressure Vessel Steels*, NUREG/CR-6551, MCS 970501, November 1998

Examples of Mechanistic Correlations (trend curves)

- ASTM E900-02*

$$\Delta T = SMD + CRP$$

SMD, stable matrix damage term, is given by:

$$SMD = A \cdot e^{\frac{20730}{T_c + 460}} \cdot \phi_t^{0.5076}$$

A = 6.70 × 10^{-18}, T_C = irradiation temperature (°F),
ϕ_t = fast fluence in n/cm² (E > 1 MeV)

CRP, copper-rich precipitation term (again Cu and Ni), is given by:

$$CRP = B \cdot \left(1 + 2.106 \cdot Ni^{1.173}\right) \cdot F(Cu) \cdot \left[\frac{1}{2} + \frac{1}{2} \cdot \tanh\left(\frac{\log(\phi) - 18.24}{1.052}\right)\right]$$

B = 234 for welds
B = 128 for forgings
B = 208 for Combusition Engineering plates
B = 156 for other plates
f(Cu) = 0 if Cu ≤ 0.072%
f(Cu) = $(Cu-0.072)^{0.577}$ if Cu > 0.072%

*Current version of ASTM E900 (E900-02, *Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials*)

Examples of Mechanistic Correlations (trend curves)

- NRC model*

$$\Delta TT = SMD + CRP + bias$$

SMD, stable matrix damage term, is biased with P content (segregation):

$$SMD = A \cdot e^{\frac{19310}{T_c+460}} \cdot \left(1+110\cdot P\right) \cdot \phi_t^{0.4601}$$

A = 8.86 × 10^{-17} for welds
A = 9.30 × 10^{-17} for forgings
A = 12.7 × 10^{-17} for plates
P = phosphorus content

CRP, copper-rich precipitation term, again depends on Cu and Ni content:

$$CRP = B \cdot \left(1+2.40\cdot Ni^{1.250}\right) \cdot F(Cu) \cdot \left[\frac{1}{2}+\frac{1}{2}\cdot \tanh\left(\frac{\log(\phi+4.579\times10^{12}\,t_f)-18.265}{0.713}\right)\right]$$

B = 230 for welds
B = 132 for forgings
B = 206 for Combusition Engineering plates
B = 156 for other plates
f(Cu) = 0 if Cu ≤ 0.072%
f(Cu) = $(Cu-0.072)^{0.659}$ if Cu > 0.072%

Subject to Cu_{max} = 0.25 (for welds with Linde 80 or Linde 0091 flux) or 0.305 (other welds), and t_f = irradiation time, in hours
Bias term is equal to 0 if t_f < 97,000 h or 9.4 °F if $t_f \geq$ 97,000 h

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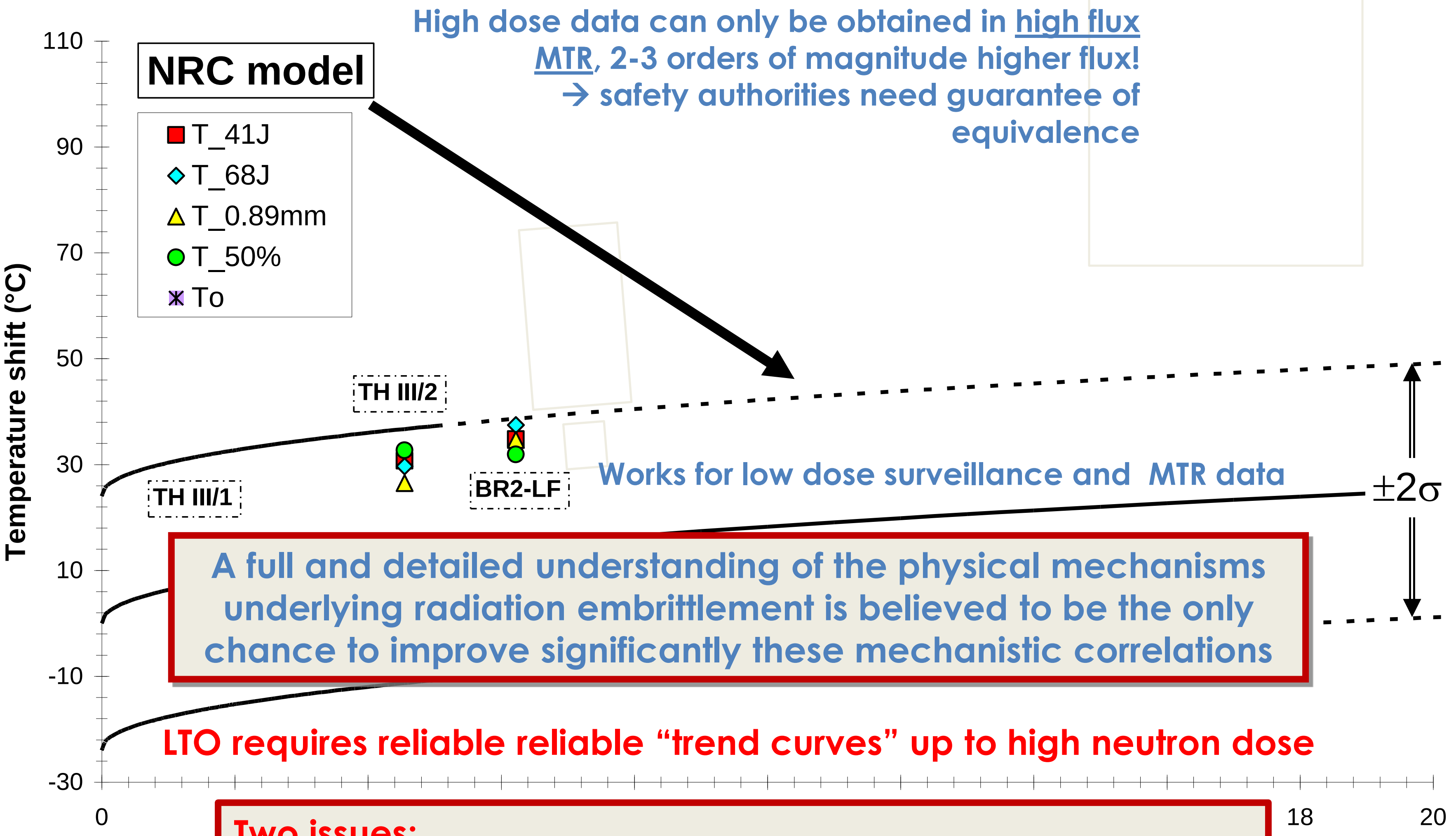
*_Charpy Embrittlement Correlations – Status of Combined Mechanistic and Statistical Bases for U.S. RPV Steels (MRP-45): PWR Materials Reliability Program (PWRMRP)_, EPRI, Palo Alto, CA: 2001, 1000705

… but do they really work?



High dose data can only be obtained in <u>high flux MTR</u>, 2-3 orders of magnitude higher flux!
→ safety authorities need guarantee of equivalence

Works for low dose surveillance and MTR data

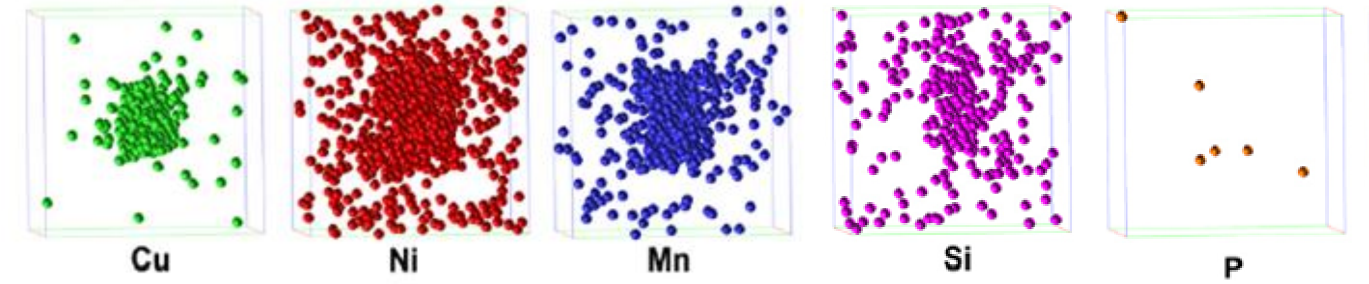
A full and detailed understanding of the physical mechanisms underlying radiation embrittlement is believed to be the only chance to improve significantly these mechanistic correlations

LTO requires reliable reliable "trend curves" up to high neutron dose

Two issues:

- Predict correctly the DBTT shift at high (for RPV) dose
- Account for flux effect

Search for mechanisms made the RPV jargon more and more complicated



Miller & Russel, JNM 371 (2007) 145

- **Plenty of atom probe studies show that CRP contain also Ni, Mn, Si & P**
- **In low or no Cu steels "precipitates" that contain only Ni, Mn & Si are observed** ***(even if none of these elements is above the solubility limit of the corresponding binary …)***

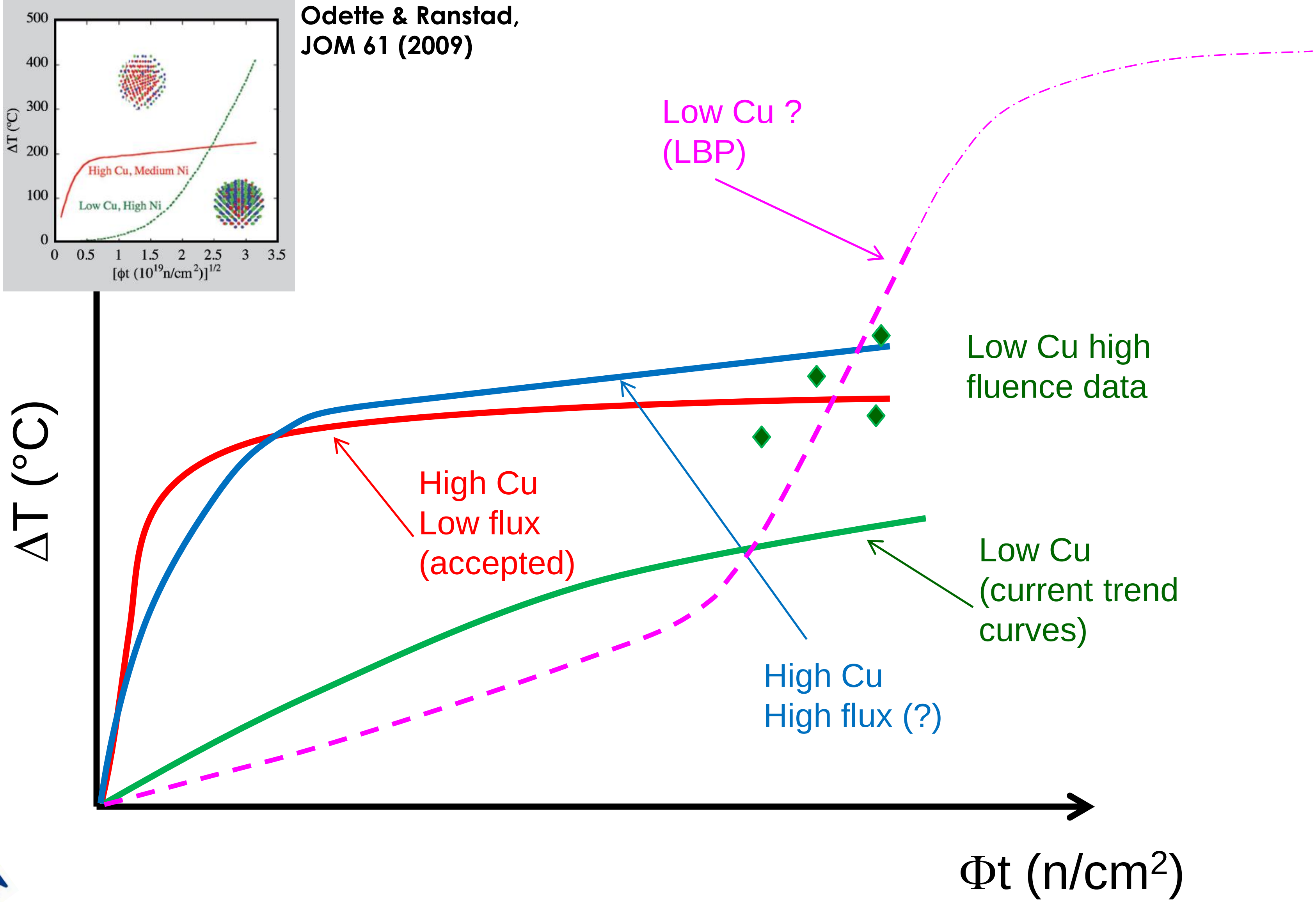
MD = matrix damage

- SMD = Stable matrix damage (*loops, voids*)
  - Recently evolved into SMF=stable matrix features (*defect-solute clusters*)
- UMD = Unstable matrix damage (*would exist only if flux = dose-rate is high*)

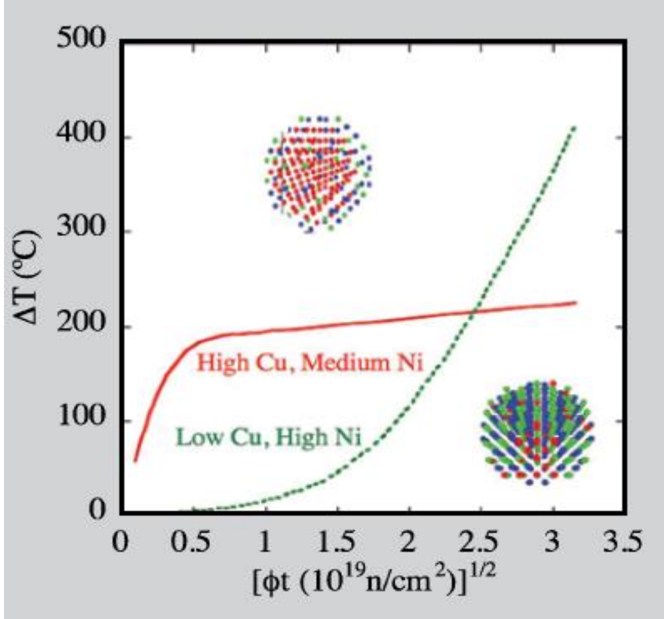
P = precipitates/phases

- CRP = copper-rich precipitates (*more Cu than other solutes: Mn, Ni, P, Si*)
- MNP = manganese-nickel-rich precipitates (*more Mn-Ni than Cu*)
- **LBPs = "late blooming" phases**
  - Phases that give rise to sudden (and unexpected) increase in embrittlement, because they
    - I. have a long incubation period
    - II. have rapid growth thereafter
    - III. will be present in large volume fractions at equilibrium

Late blooming phases: *The great fear*

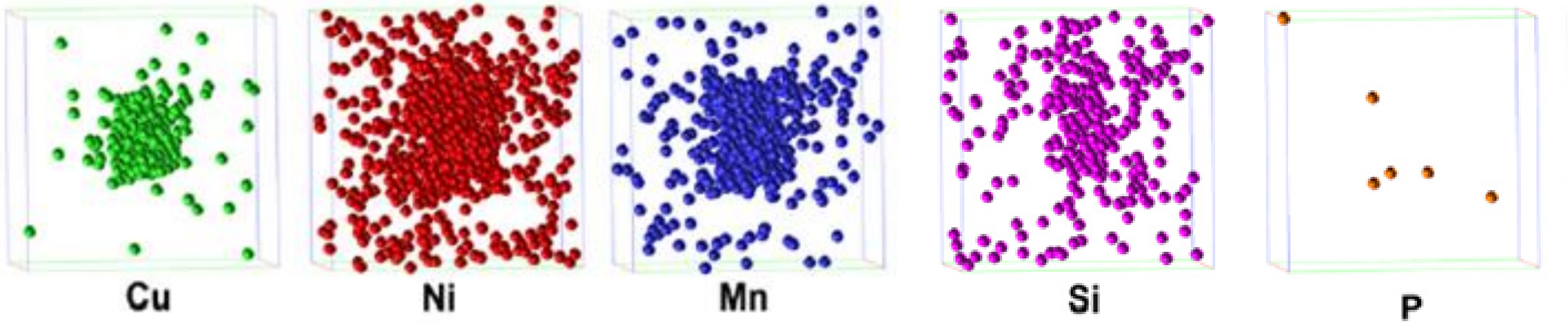


Odette & Ranstad, JOM 61 (2009)

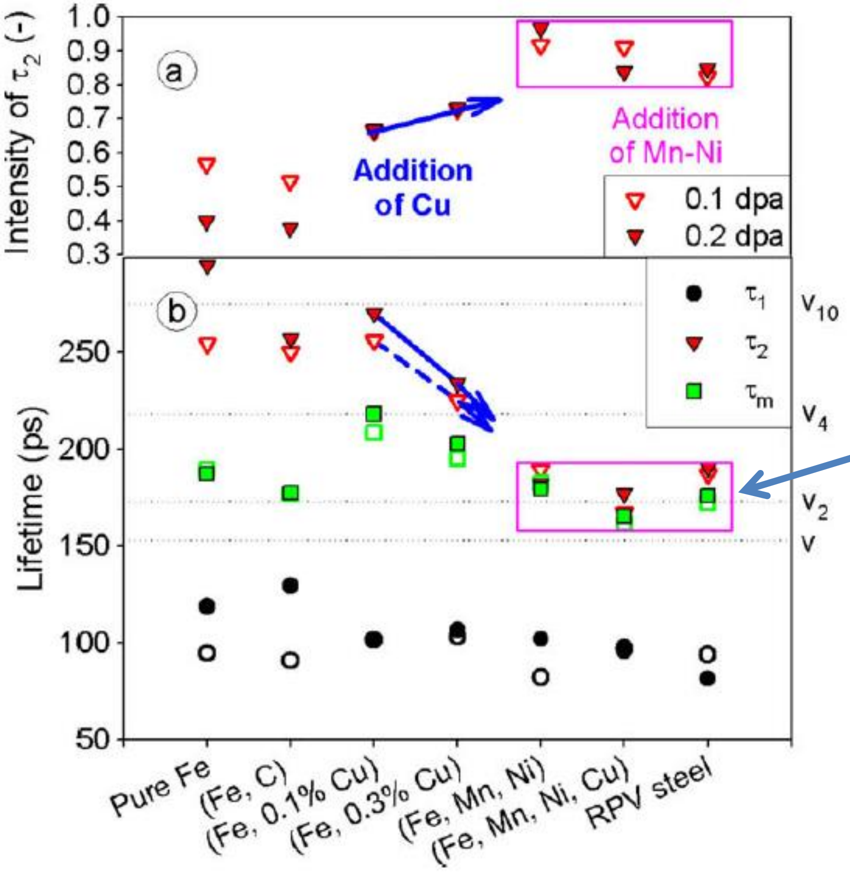


Is this prediction real?

Attention needs to be focused on the physics of the USUAL SUSPECTS:



Voids are not observed in RPV steels irradiated to doses of relevance for extended lifetime of NPP



M. Lambrecht, A. Almazouzi, Journal of Nuclear Materials 385 (2009) 334

Positron Annihilation Spectroscopy (PAS) reveals that only single- & di-vacancies form in alloys containing Mn&Ni, including RPV steels

⇒ If anything, Matrix Damage = loops only

What is special about Cu, Ni, Mn, Si, P, …?

PHYSICAL REVIEW B 81, 054102 (2010)

Ab initio study of solute transition-metal interactions with point defects in bcc Fe

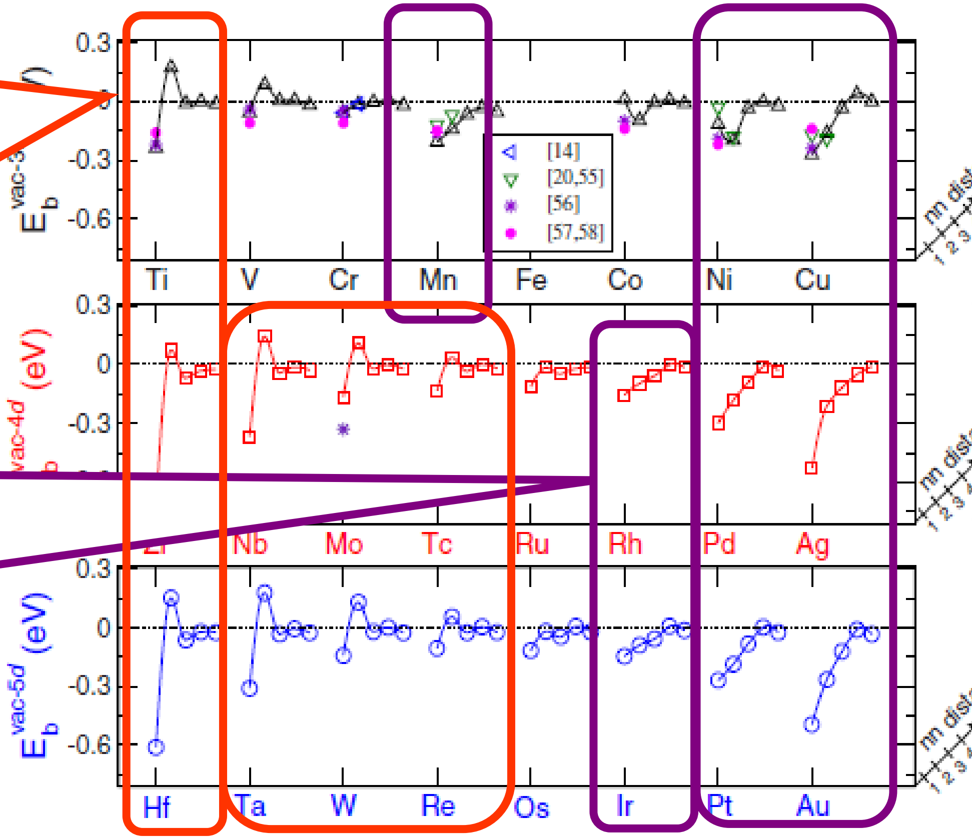
P. Olsson,[1] T. P. C. Klaver,[2] and C. Domain[1]

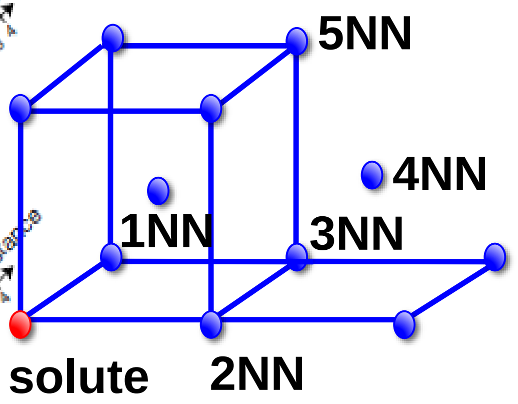
These elements may trap single vacancies

A

These elements can be dragged by single vacancies

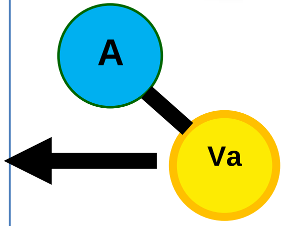
B



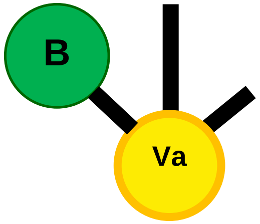


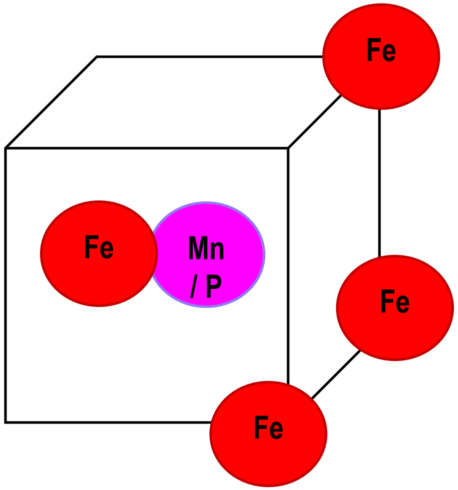
Key atomistic mechanism: solute dragging by point defects

Most solute atoms, for example Mo and Cr, will move via vacancy in the opposite direction to the vacancy



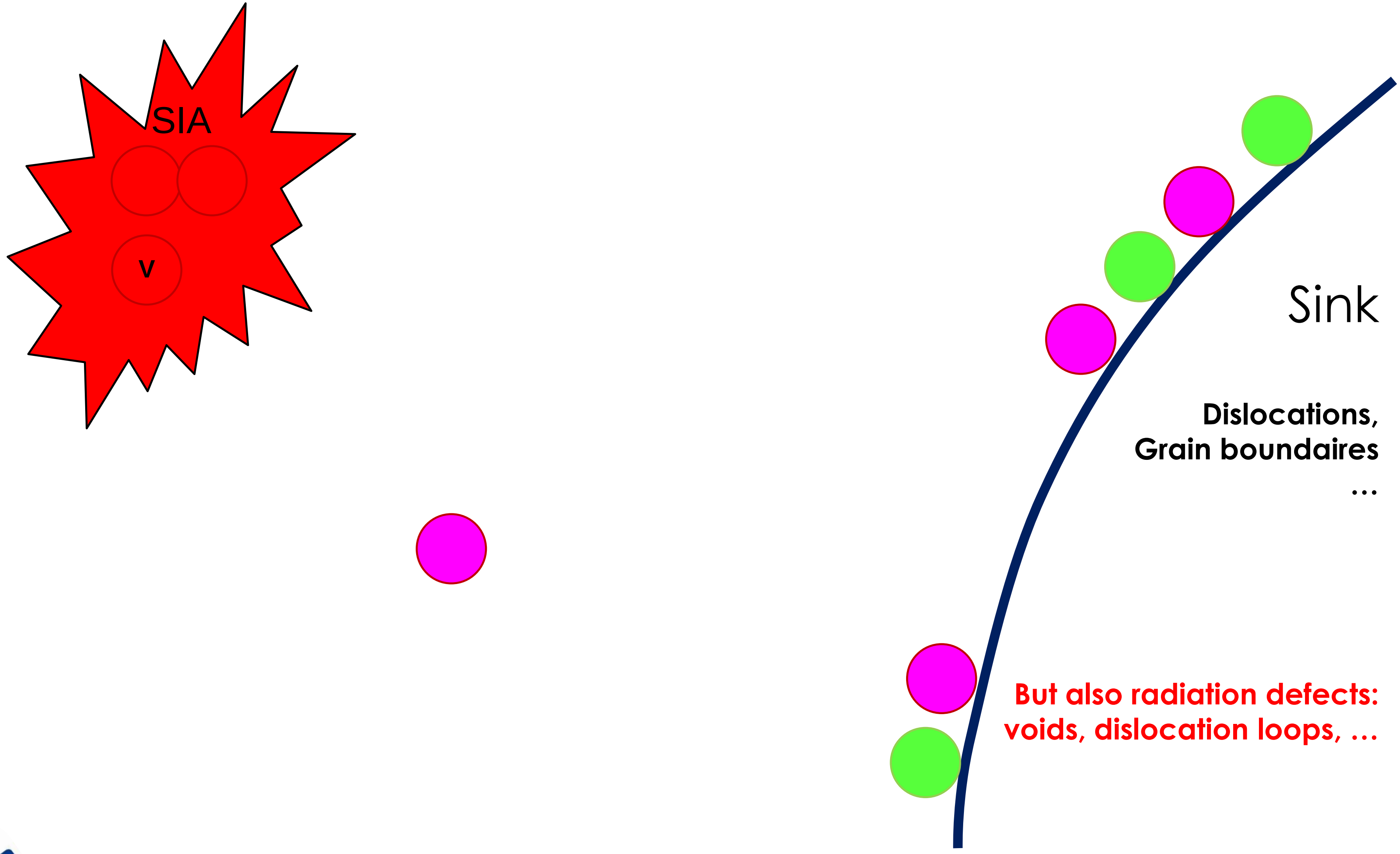
Instead, Mn and Ni, but also Cu, Si, and P, follow the vacancy during its migration





Moreover, Mn & P form stable a mixed dumbbell and so wil be dragged by it

Consequence: all "usual suspects" in Fe will segregate at sinks!



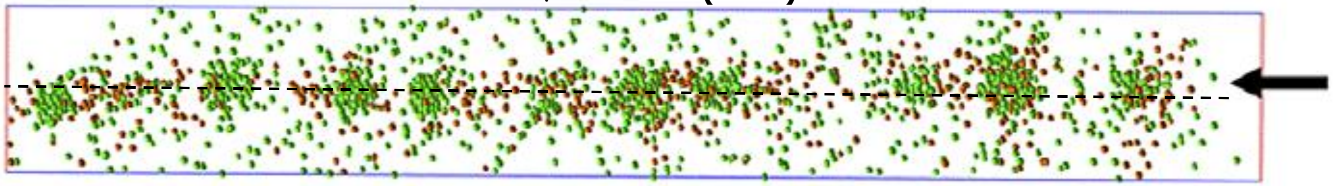
Sink

Dislocations,
Grain boundaires
…

But also radiation defects:
voids, dislocation loops, …

And atom probe shows that indeed they do!

Miller & Russel, JNM 371 (2007) 145

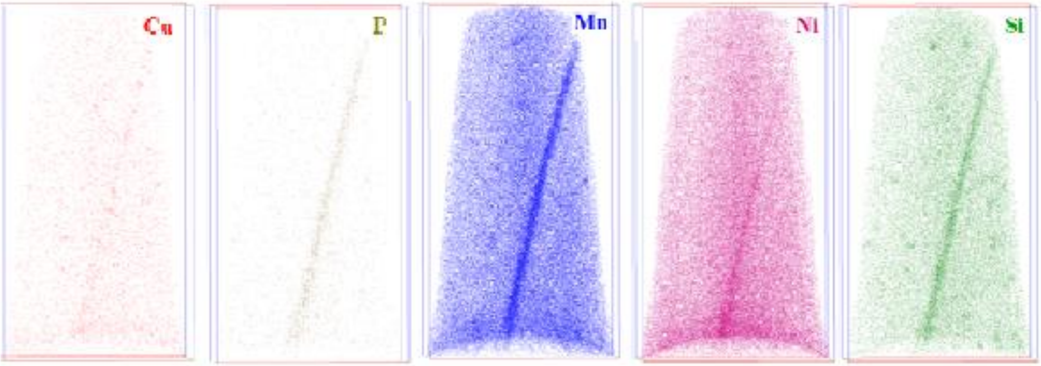


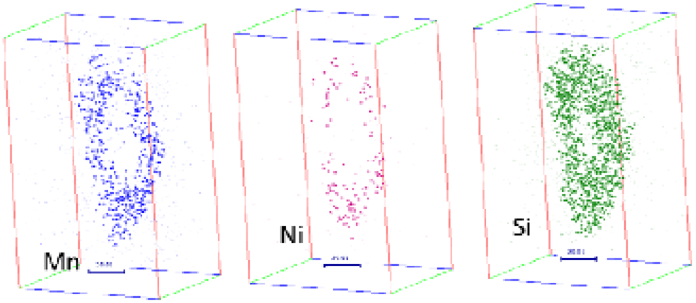
Dislocation line

APT on RPV steels

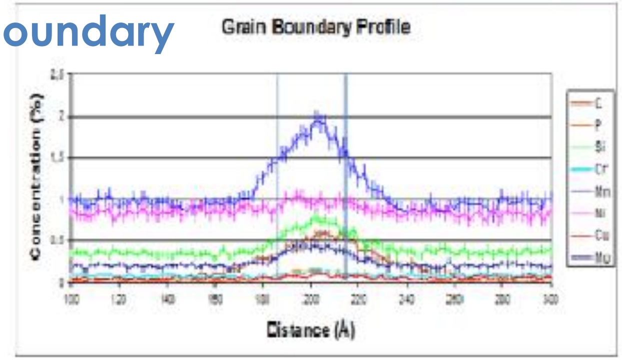
Dislocation loop

Radiguet , Huang, Cammelli & Pareige, GPM – FP7/Longlife





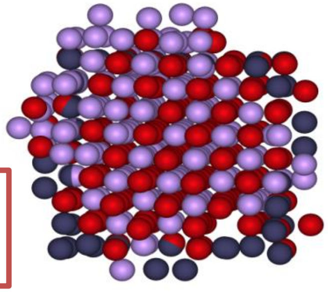
Grain boundary



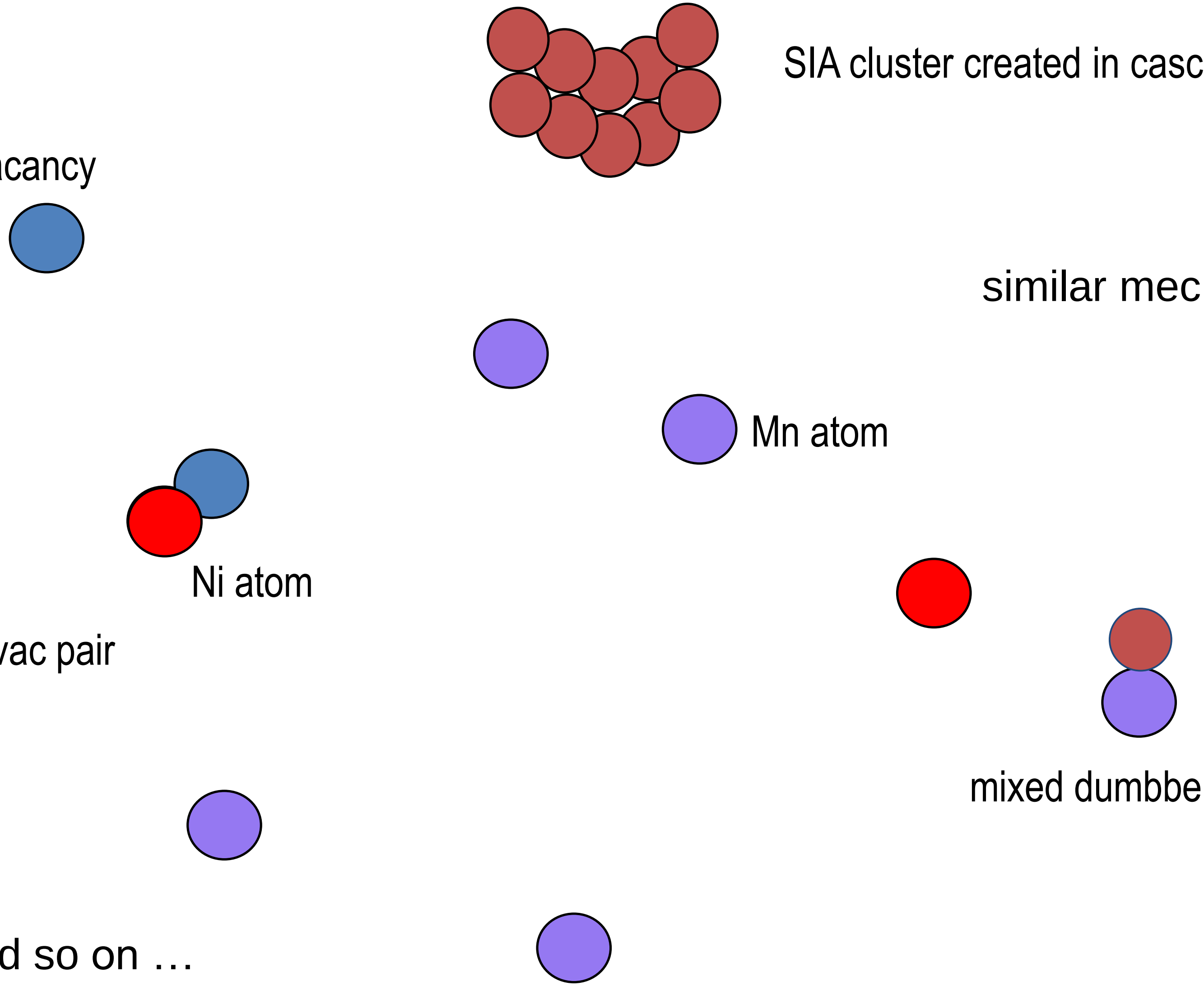
G. Bonny et al., J. Nucl. Mater. 452 (2014) 486

Atomistic simulations tell that loops make Mn-Ni ppts stable even outside thermodynamic field of stability:

Point-defect clusters catalyse the formation of precipitates!



So, how could solute-rich clusters be formed?



SIA cluster created in cascade

vacancy

similar mechanisms …

Mn atom

Ni atom

Ni-vac pair

mixed dumbbell

… and so on …

Based on this idea microstructure evolution models have been developed within SOTERIA

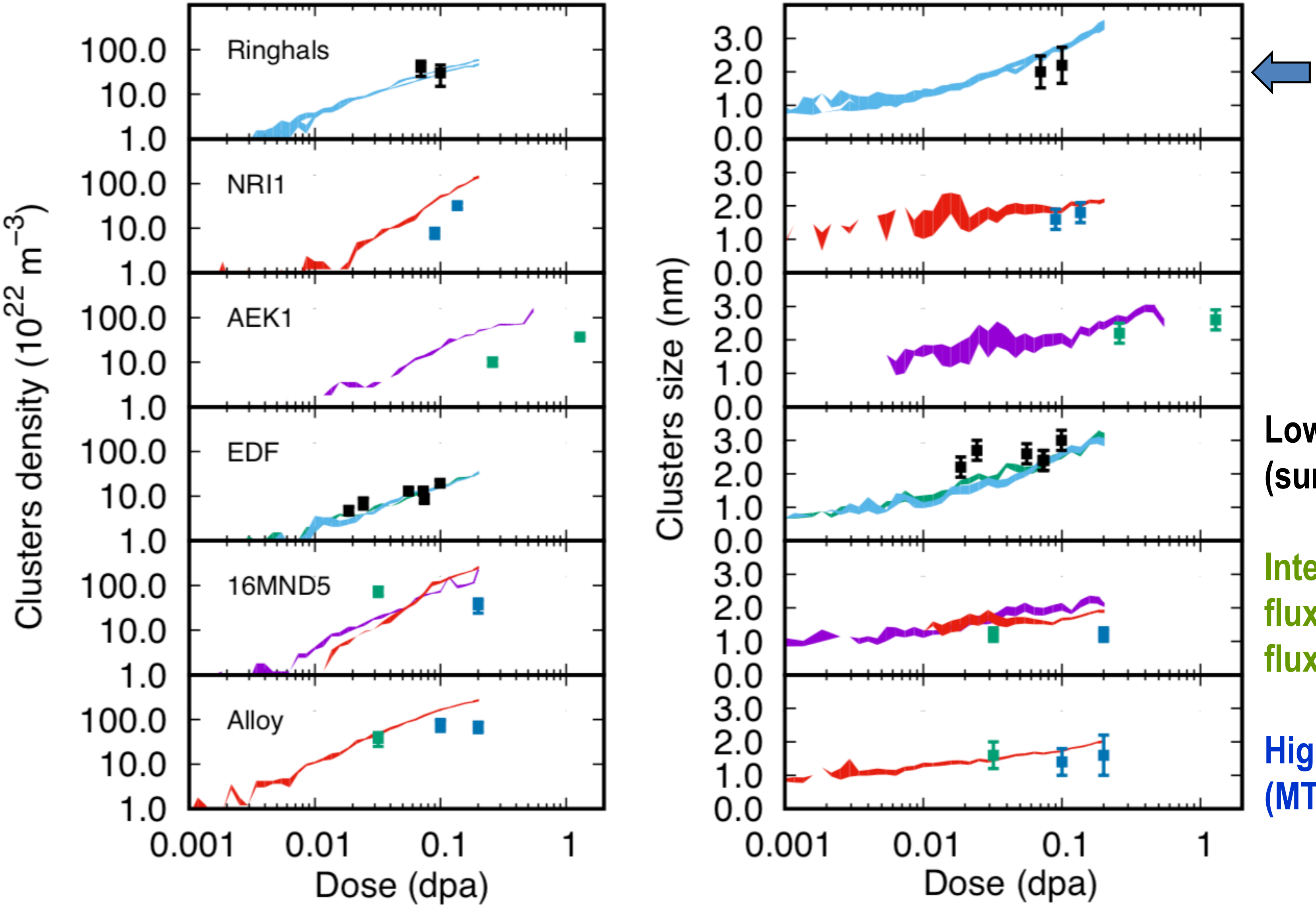
Composition of steels & irradiation conditions that have been simulated

	C	**P**	**Si**	**Mn**	**Ni**	**Cu**	**Cr**	**Mo**	**V**
Ringhals	0.24	0.016	0.42	**1.48**	**1.50**	0.07	0.07	0.31	0.002
NRI 1	0.32	0.011	0.73	0.75	1.59	0.035	**1.99**	0.40	-
AEK 1	0.74	0.032	0.57	0.54	0.066	0.078	**2.82**	0.39	0.30
EDF 1	0.78	0.018	0.61	**1.28**	**0.61**	0.078	0.16	0.23	0.022
EDF 3	0.25	0.016	0.69	**1.43**	**0.61**	0.029	0.021	0.33	0.004
16MND5	0.65	0.013	0.39	**1.32**	**0.71**	<0.005	0.21	0.33	-
Alloy	<0.01	0.009	<0.01	**1.11**	**0.71**	0.056	-	-	-

at% - Fe balance

- All of them low Cu steels
- Ringhals: very high Ni+Mn
- NRI1 & AEK1: VVER type (2-3% Cr), one high Ni, one no Ni
- EDF1, EDF3, 16MND5: typical French RPV steels
- Alloy: FeMnNi model alloy
- Irradiation conditions: surveillance, MTR (different fluxes), T~300°C

Preliminary predictions for several RPV steels irradiated under different conditions: **size & density**

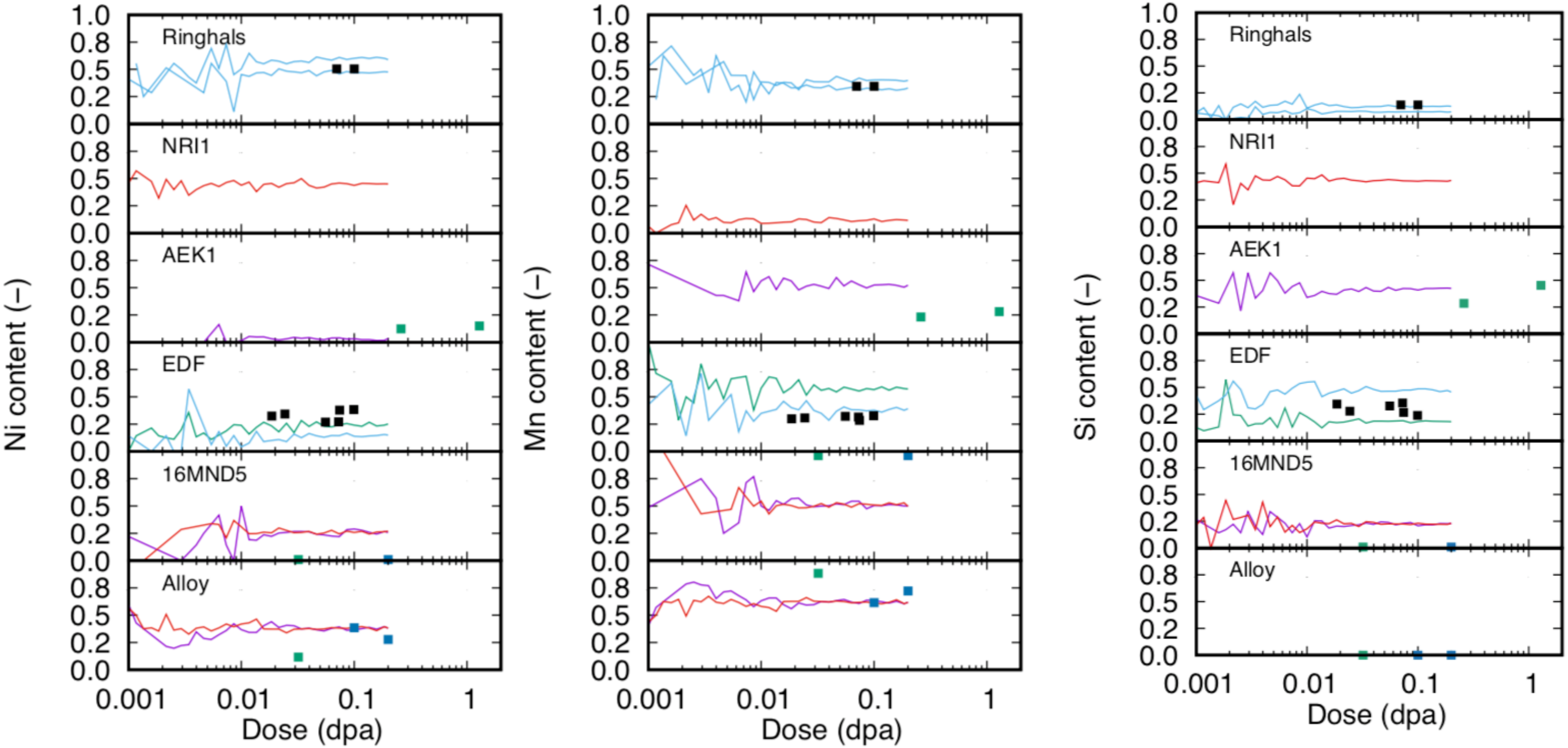


Low flux (surveillance)

Intermediate flux (low MTR flux)

High flux (MTR)

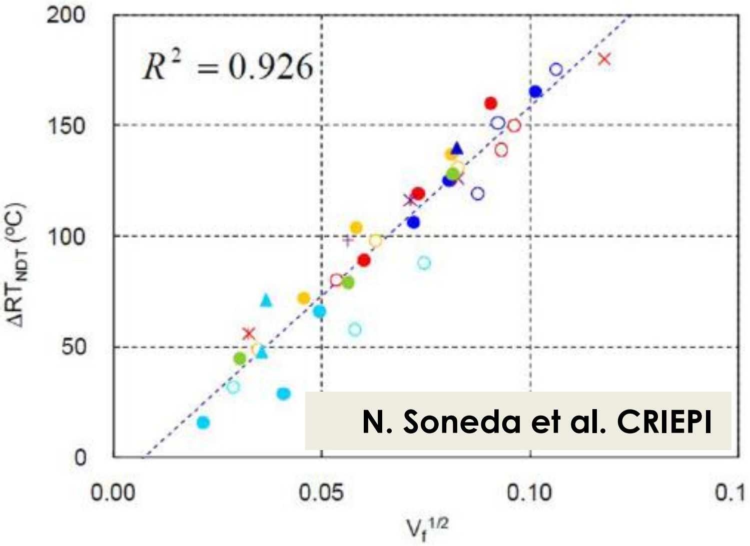
Predictions for several RPV steels irradiated under different conditions: **composition**



This model suggests that the distinction between matrix damage and precipitation is not real

- ☐ **Solutes segregate at point-defect clusters**, thereby creating complexes that contain both
- ☐ These complexes are the **main cause** of **dislocation motion obstruction**
- ☐ This is indirectly confirmed by the empirical **linear correlation between** (square root of) **solute cluster volume fraction and DBTT** (T_{NDT}) **shift**

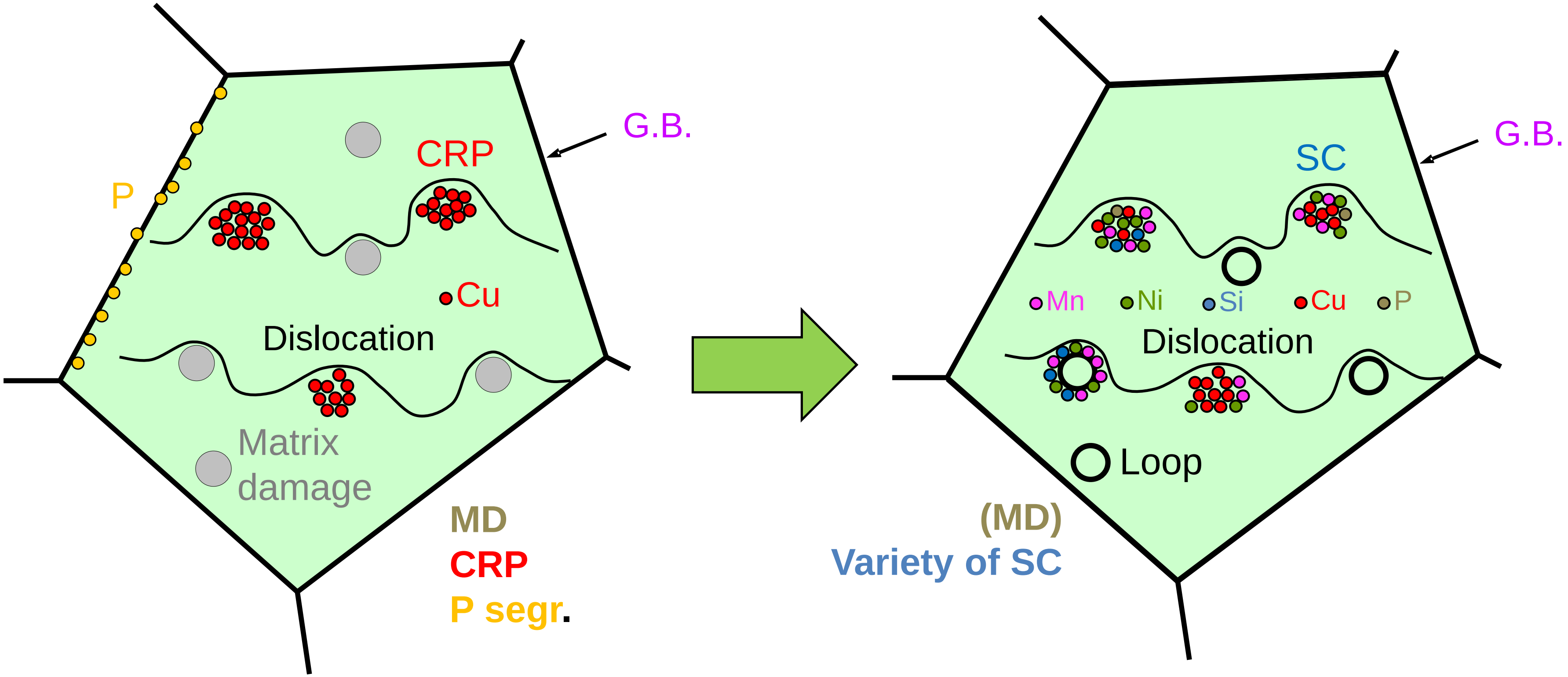
$$\Delta RT_{NDT} = 1709 \times \sqrt{V_f} - 12.5$$



N. Soneda et al. CRIEPI

- ☐ This mechanism will determine the **kinetics of formation** of obstacles under irradiation
- ☐ The **solute clusters** that form **may eventually evolve into** defined **phases**, either stabilized by point-defects or thermodynamically foreseen, or both (**catalysis**)
- ☐ The formation of phases, however, is not governed by a classical nucleation and growth process, so **most likely there will be no "late blooming"** because phases are forming in a continuous way, since the beginning, while the irradiation proceeds

Conclusion: paradigm change for RPV embrittlement origin is in course



Combining microstructural examination with advanced atomistic modelling changed the understanding of the origin of RPV embrittlement from matrix damage & precipitates **to solute/point-defect nanoclusters**, potentially leading to improved engineering correlations and physics-based multiscale models applicable to steels

Acknowledgments

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- *Part of the research leading to these results was funded by the European Atomic Energy Community's (**Euratom**) Seventh Framework Programme FP7/2007-2013 under grant agreement Ni. 604862 (**MatISSE Project**) and contributes to the Joint Programme on Nuclear Materials of the European Energy Research Alliance (**EERA-JPNM**)*