# Radiation Induced Segregation (RIS) + Defects

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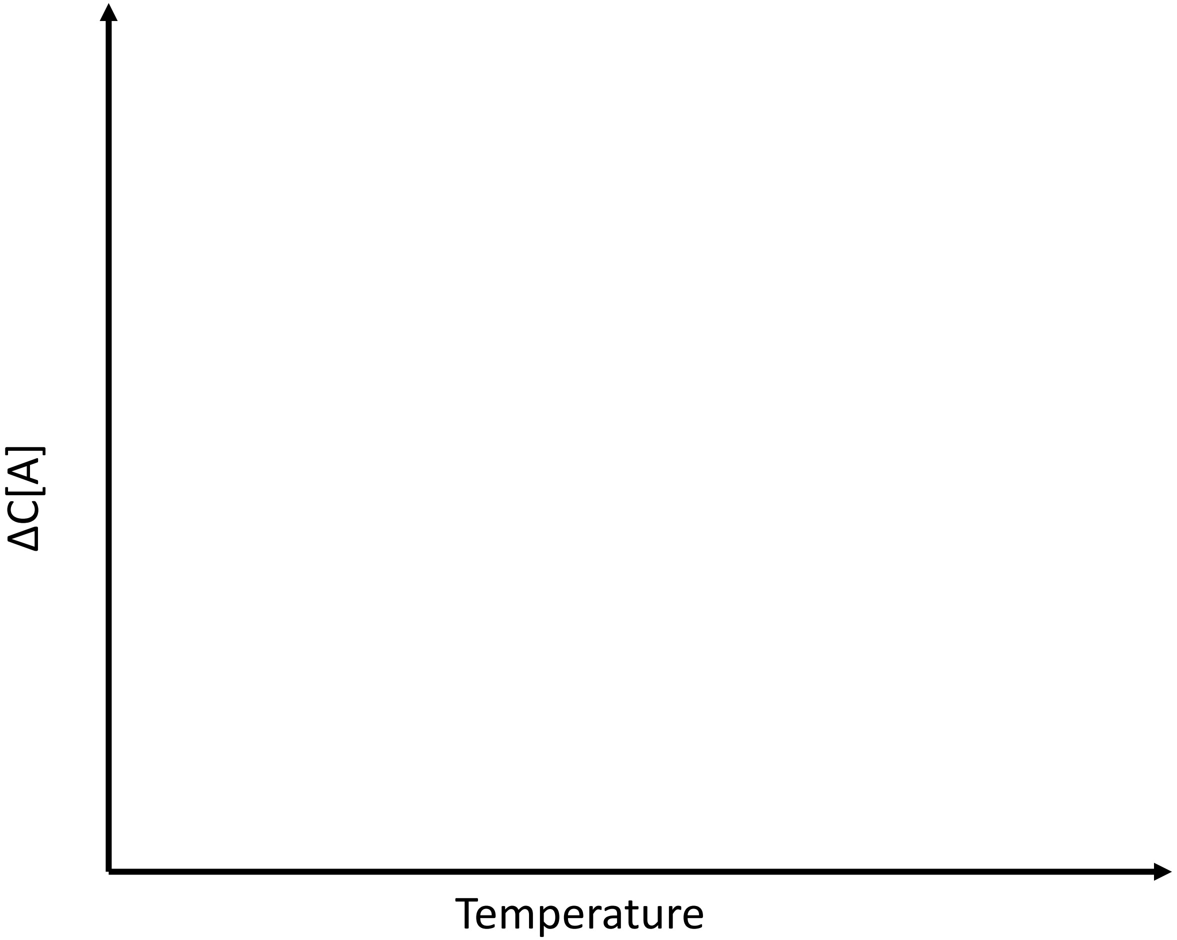
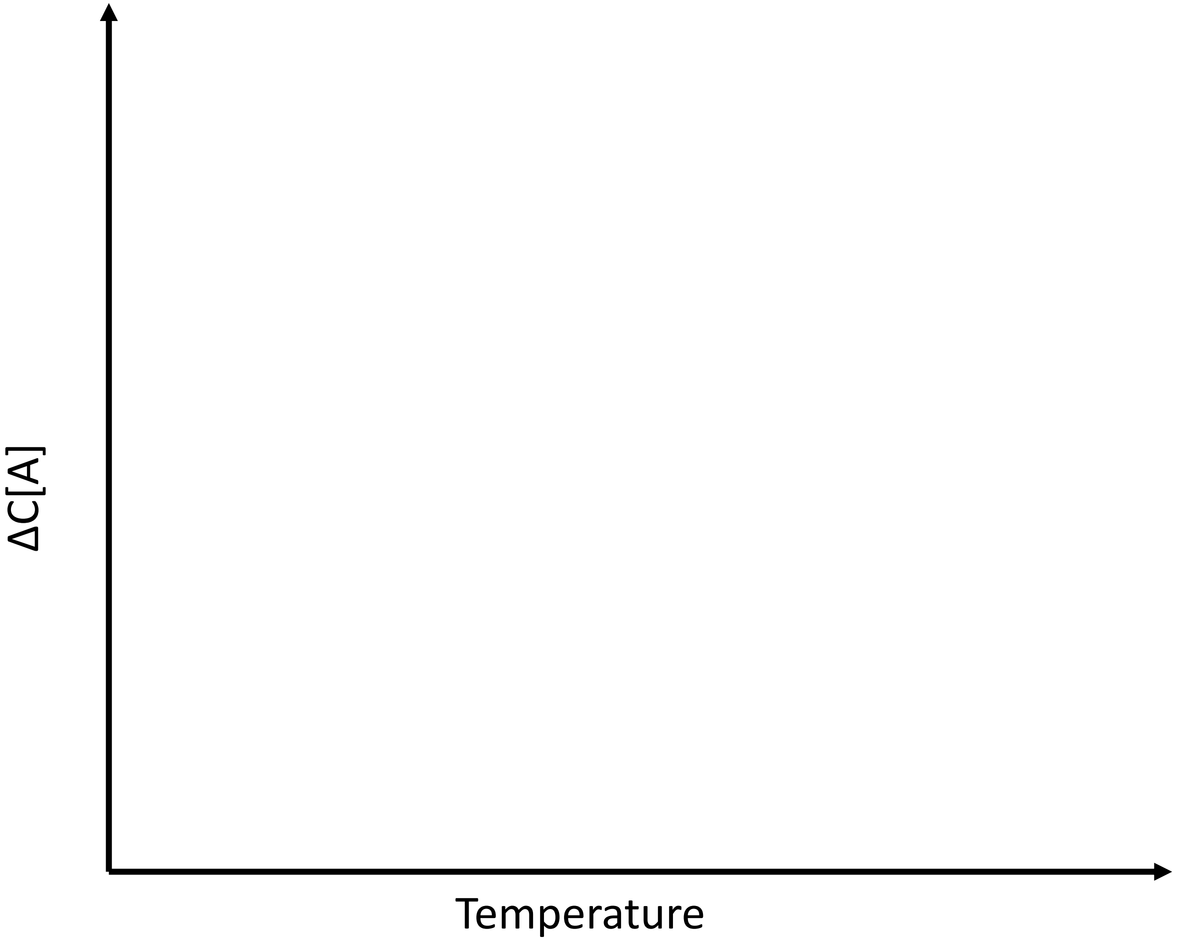
# Last lecture we talked about RIS

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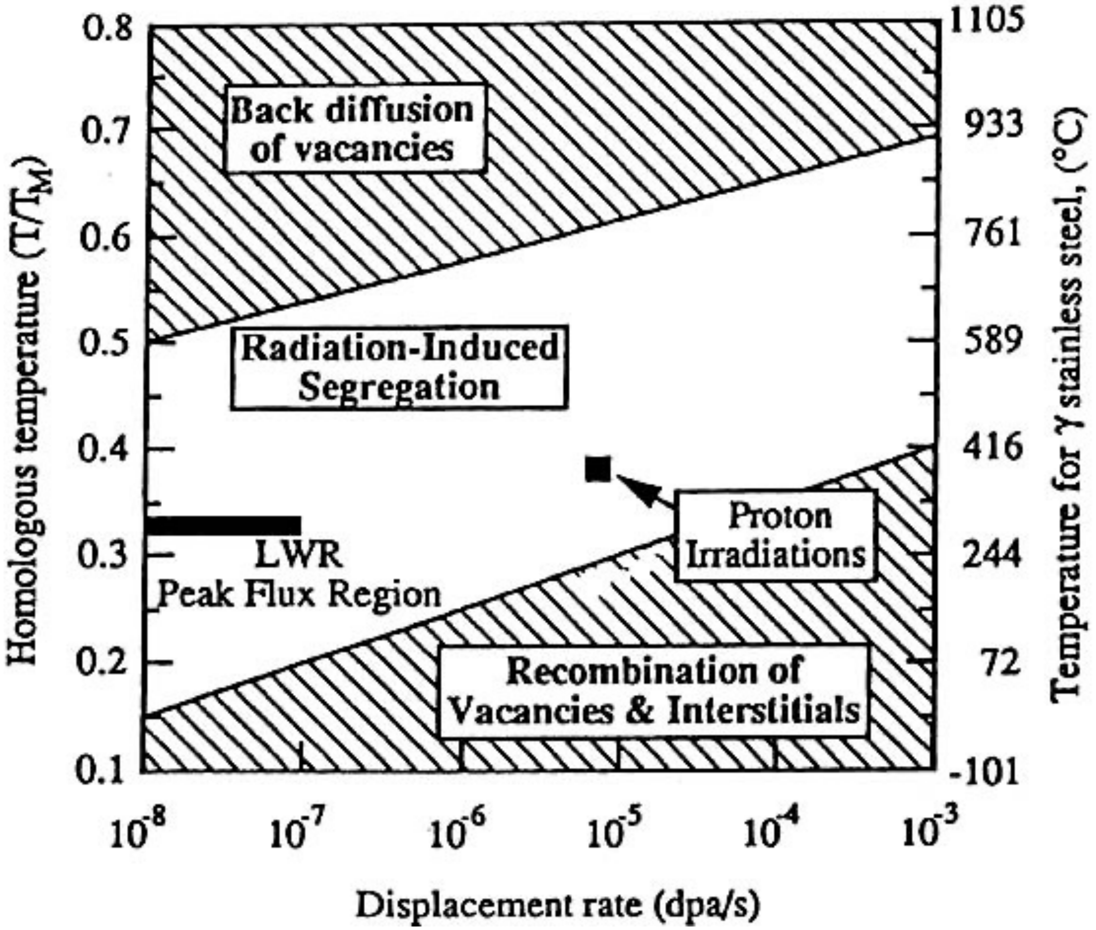


$$\nabla C_A = \frac{N_A N_B d_{Bi} d_{Ai}}{\alpha(d_{Bi} N_B D_A + d_{Ai} N_A D_B)} \times \left(\frac{d_{Av}}{d_{Bv}} - \frac{d_{Ai}}{d_{Bi}}\right) \nabla C_v$$

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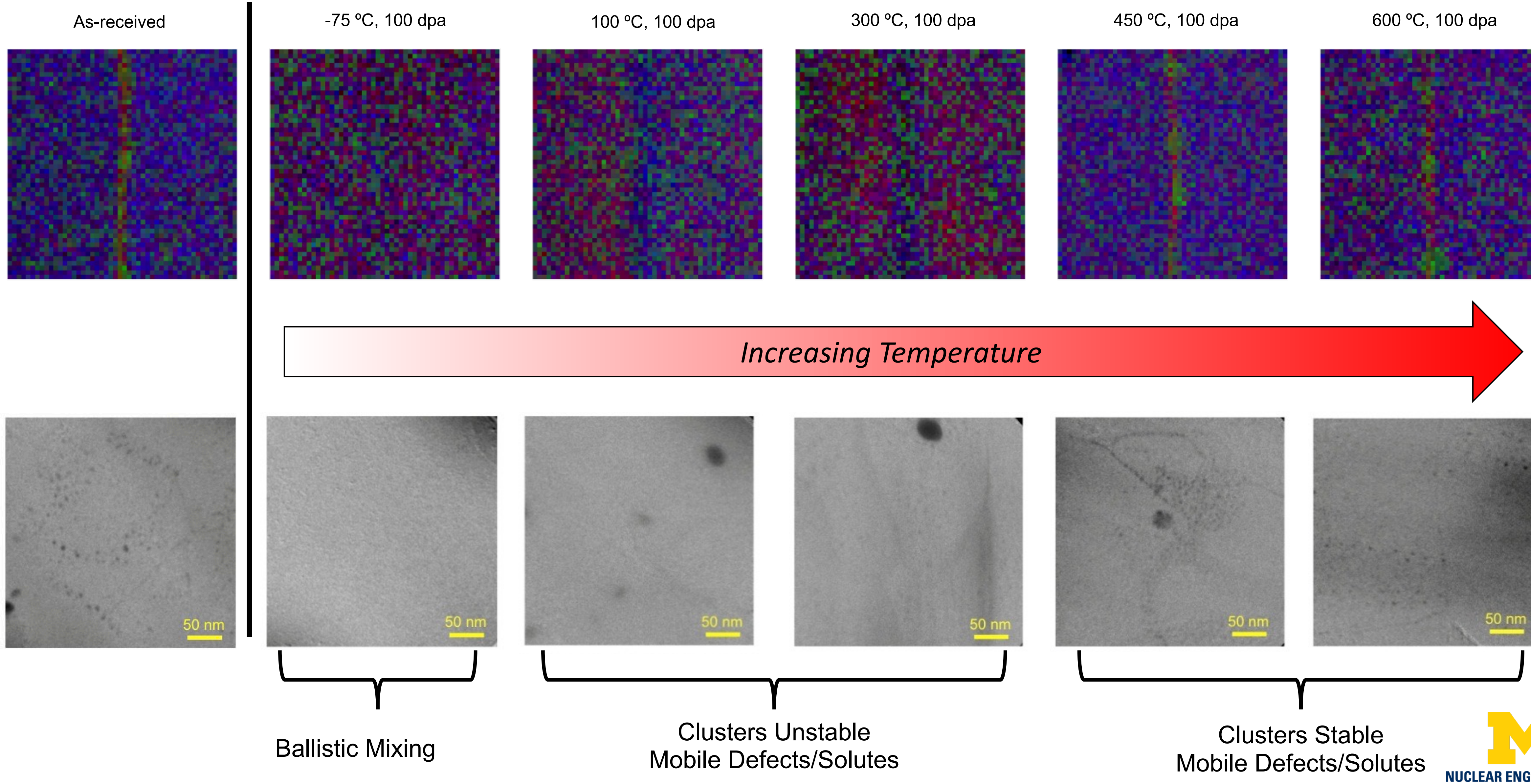
# RIS is a "finger print" for defect mobility and loss

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# Outline

**Defect Energetics:**

- Role of loops on material response
- Interstitial loop formation and energetics
- Vacancy loop vs. void formation

**Goal:**

1. Understand the energetics associated with the formation of extended defects and the corresponding responses as a function of temperature and dose/dose rate.

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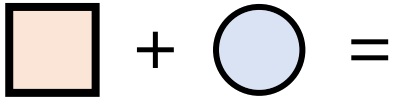
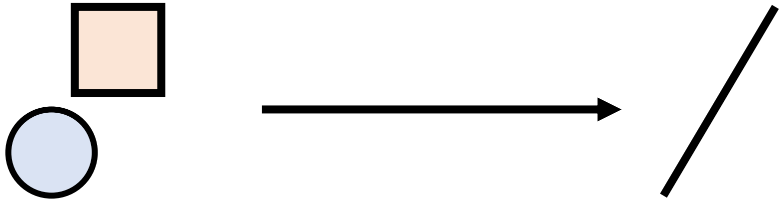
# Options of vacancies and interstitials

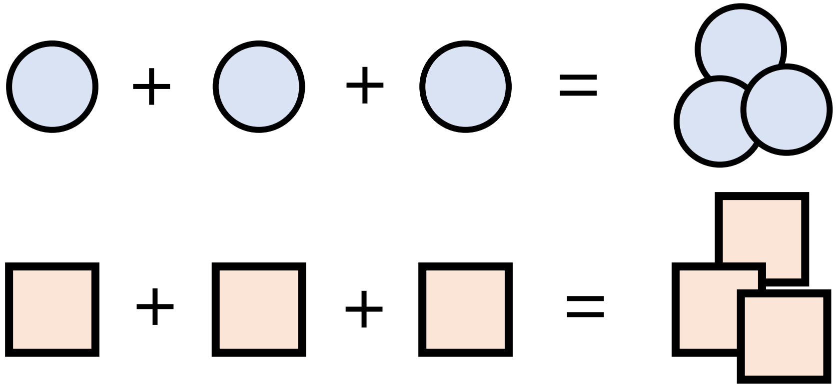
- Vacancies and interstitials can react with each other (recombination)



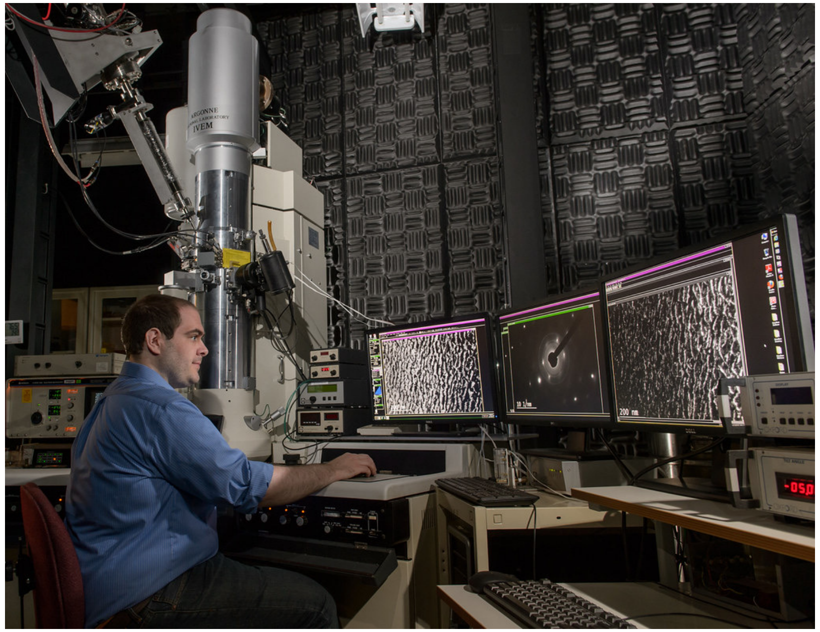
- They can react with defect sinks

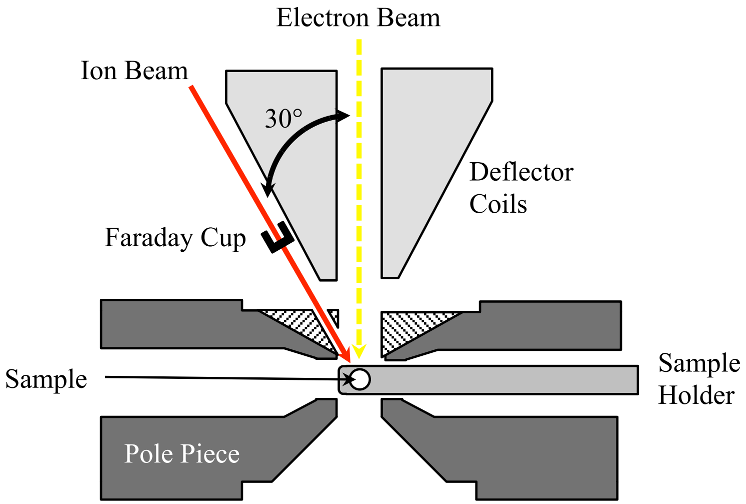


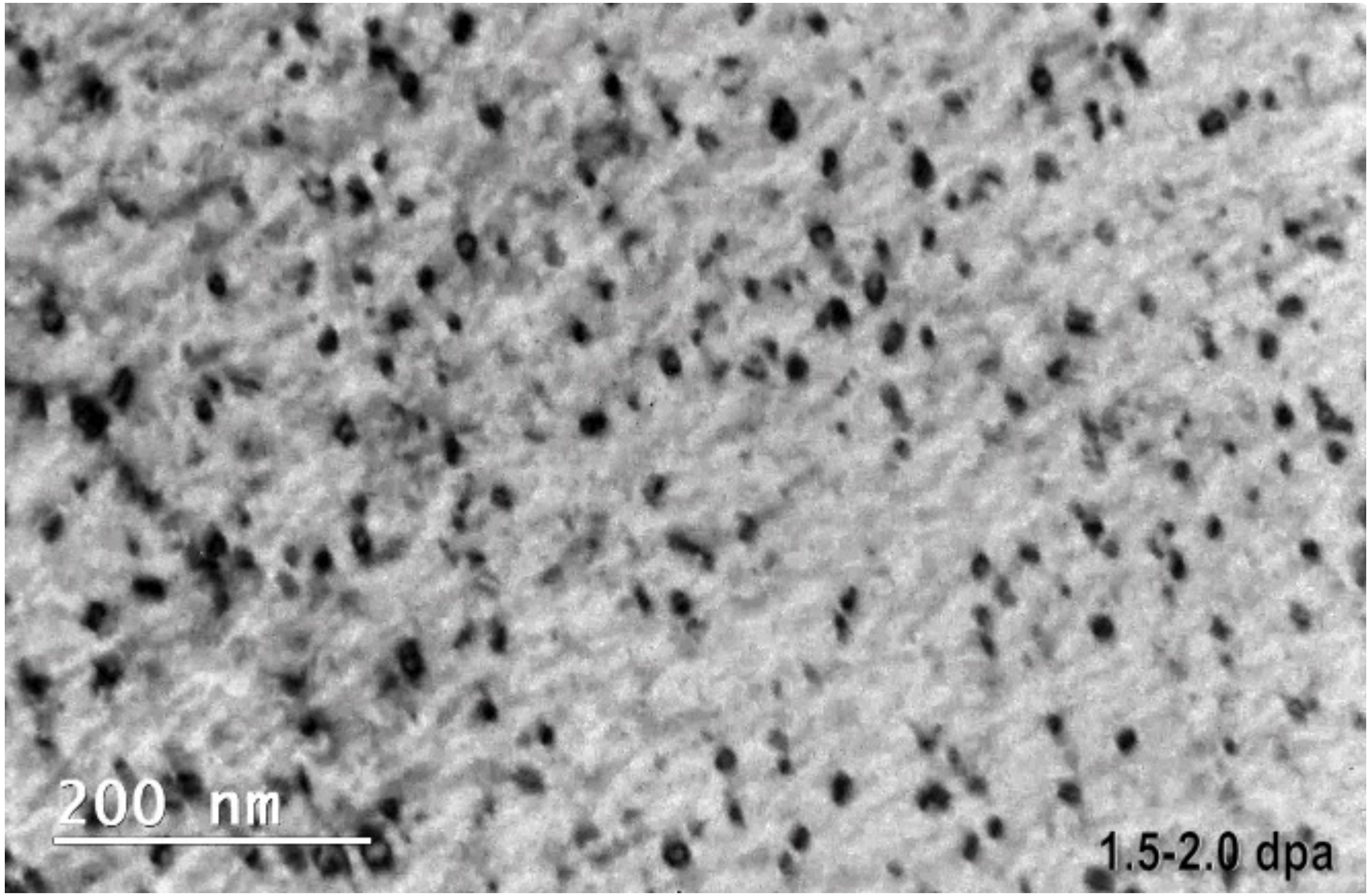
- They can react with themselves



# Dislocation Loop Formation






Video of in-situ ion irradiation of Fe-10Cr-4.8Al Gen I alloy irradiated at 320°C

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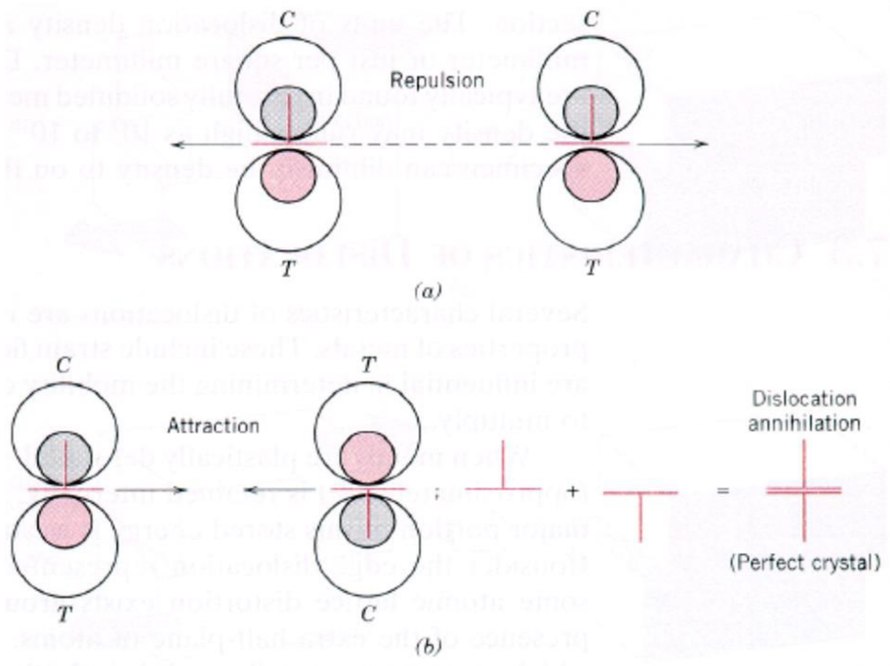
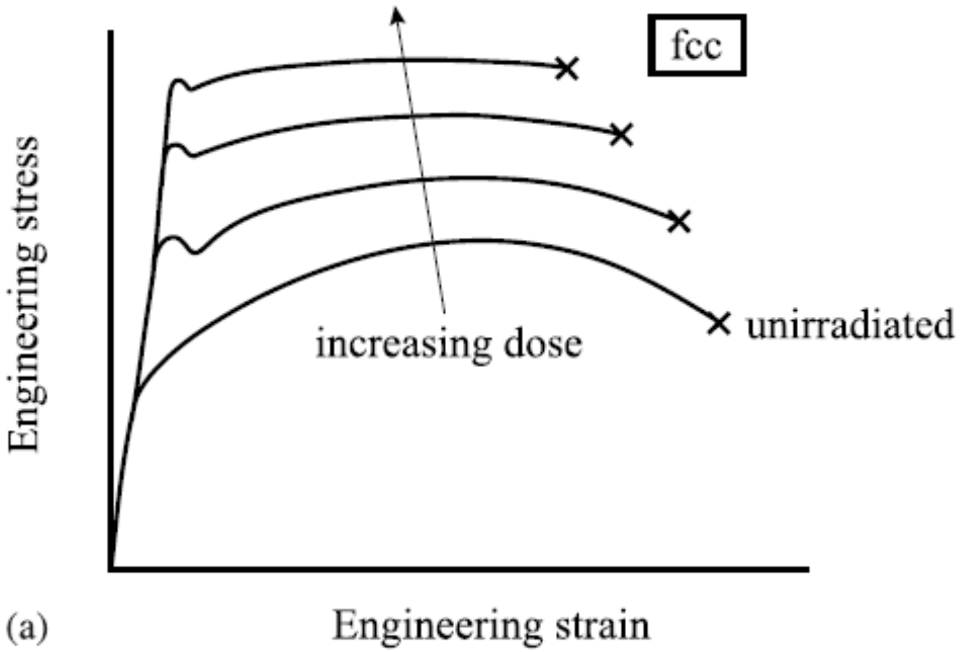
# Effects of dislocation loops on mechanical properties




- Slowing down or impeding dislocation motion in metals results in hardening but can also lead to embrittlement
- Dislocation loop formation by irradiation will cause this hardening and embrittlement response

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# Dislocation Loop Formation

- In any crystal lattice there are close packed planes (e.g. most densely packed)
  - Normal to the closed pack plane is lattice plans that are widely separated
- Loops can be considered as a condensation of radiation-produced vacancies or interstitials

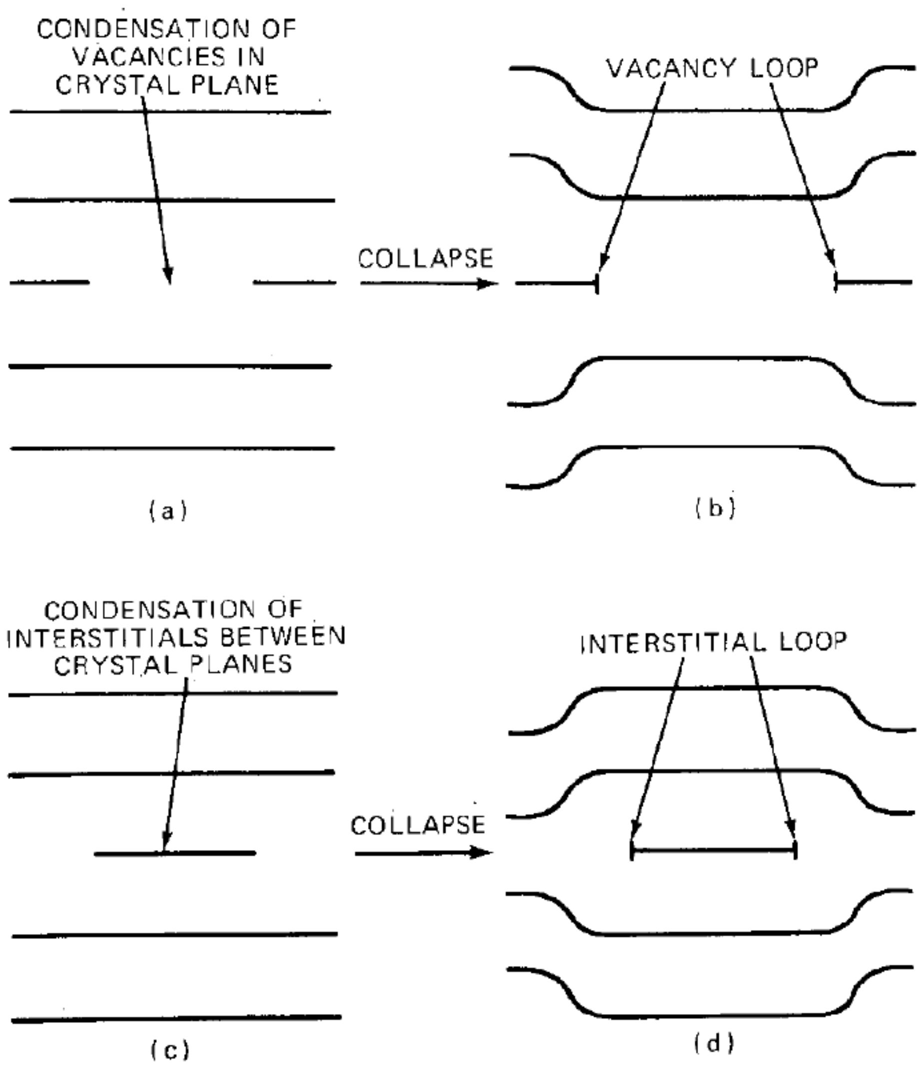


Fig. 18.4 Formation of vacancy loops and interstitial loops.

# A simple though experiment

If we placed a sphere and a disc into a finite volume of material, what aspects of those features would help define the change in energy for the total system?

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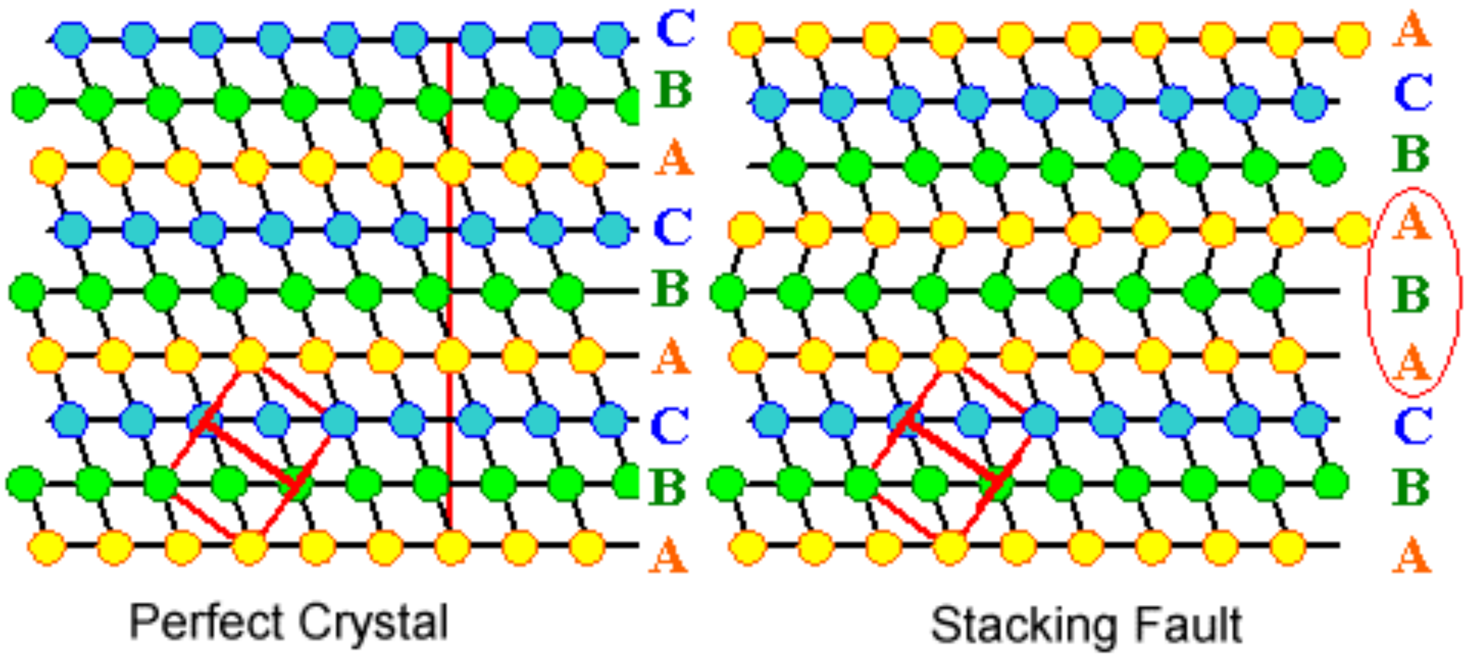
# Dislocation Loop Formation

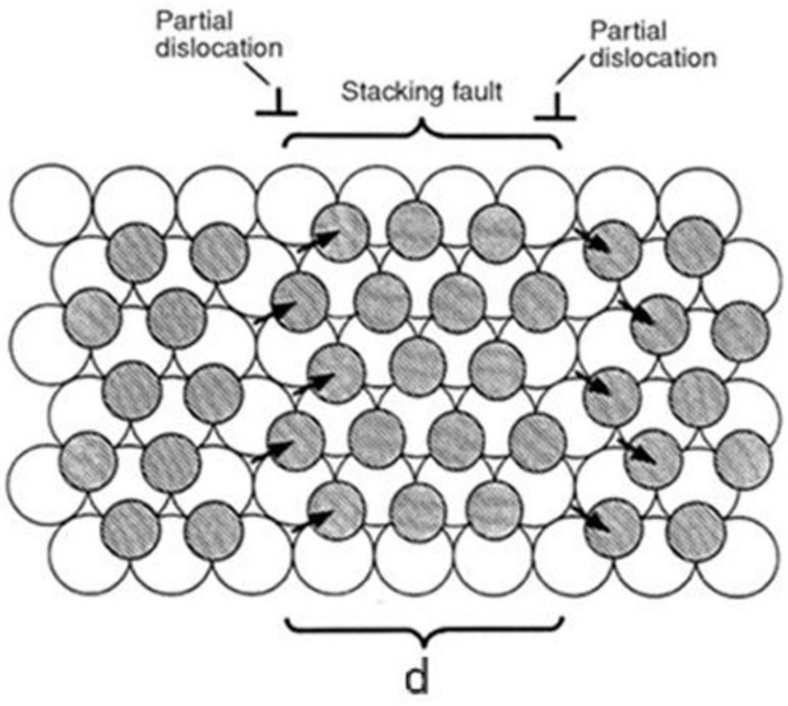
- Loops formed from interstitial atoms or vacancies can be distinguished in three ways:
  1. The **Burgers vector** (magnitude and direction)
  2. The **stacking fault** (if any) contained by the loop
  3. The **nature** (e.g. vacancy or interstitial loops)

# What is a stacking fault?

Side View

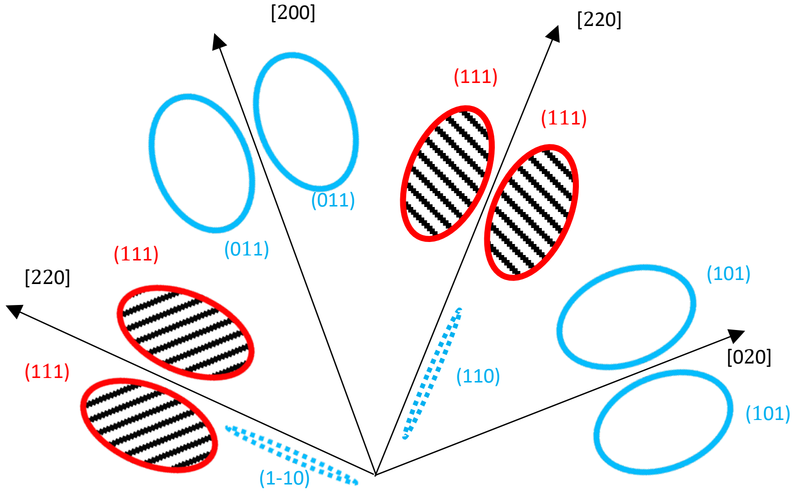


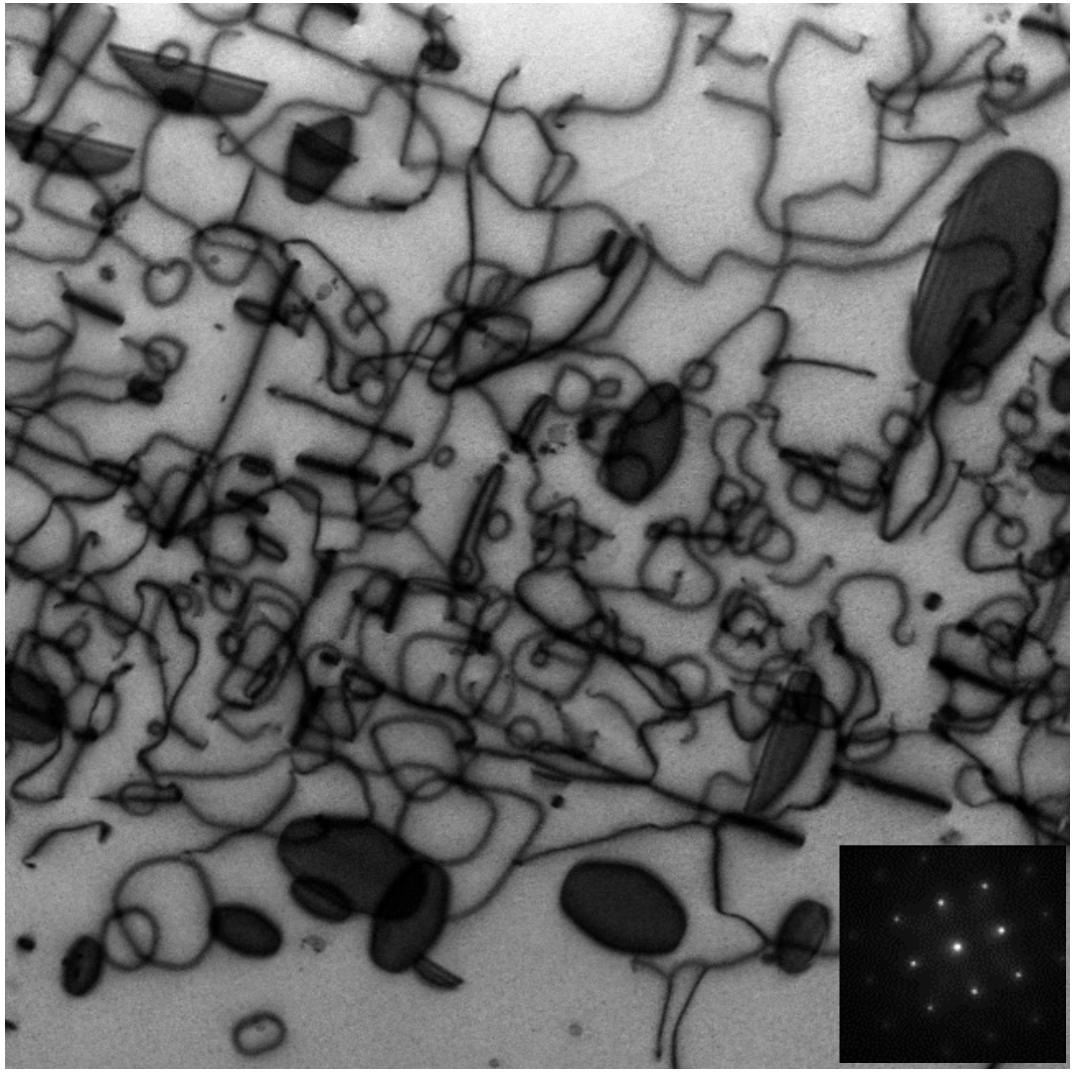

Top View




- The shifted portion of the partial dislocation location is a "stacking fault" – more simply it is a "mistake" in the layering of atoms
- Found in closed-packed face centered cubic and hcp crystals because only the second-nearest neighbors are different at the fault

# Dislocation loop energy in FCC alloys



What year was the last time that a British constructor didn't have a 1st place win in the F1 championship season?

# Interstitial Loops Formation

- Let's first consider interstitial loop formation:

- Formation of extended defects occurs between closed packed planes
- In FCC materials, this can cause a break in the stacking sequence leading to stacking faults (also known as Frank loops)
- Disc/platelet of defects it the minimum energy configuration for defect clusters when the number of defects is small

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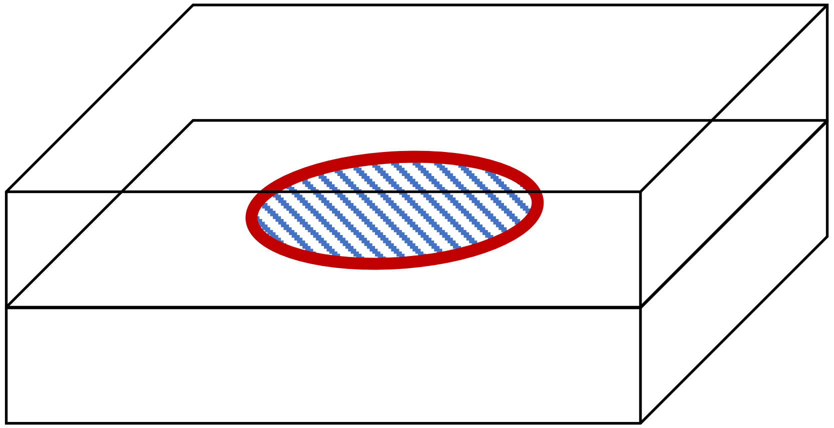
# Dislocation loop energy in FCC alloys

- For FCC, we must consider both the energy created because of the loop and of the possible stacking fault:



# Dislocation loop energy in FCC alloys

- For an FCC crystal we can typically see two loop types:
  - Faulted:

$$E_L^f = 2\pi r_L \Gamma + \pi r_L^2 \gamma_{SFE}$$

Writing in terms of materials constants we get:

$$E_L^f = \frac{2}{3}\frac{1}{(1-\upsilon)}\mu b^2 r_L \left[ln\frac{4r_L}{r_0} - 2\right] + \pi r_L^2 \gamma_{SFE}$$

  - Perfect:

$$E_L^p = \left[\frac{2}{3}\frac{1}{(1-\upsilon)} + \frac{1}{3}\left(\frac{2-\upsilon}{2(1-\upsilon)}\right)\right]\mu b^2 r_L \left[ln\frac{4r_L}{r_0} - 2\right]$$

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# Dislocation loop energy in FCC alloys

$$\gamma_{SFE} > \frac{\mu b^2}{3\pi r_L}\left(\frac{2-\upsilon}{2(1-\upsilon)}\right) ln\left[\frac{4r_L}{r_0} - 2\right]$$

| Metal/Alloy | $\gamma\ (mJm^{-2})$ | Reference |
|---|---|---|
| SS-304 | 21 | Murr 1975, Hadji & Badji 2002 |
| SS-316 | 42 | Hadji & Badji 2002 |
| Ni | 128 | Murr 1975 |
| Ti | 15 | Conrad 1981 |
| Al | 166 | Murr 1975 |
| Zr | 240 | Murr 1975 |

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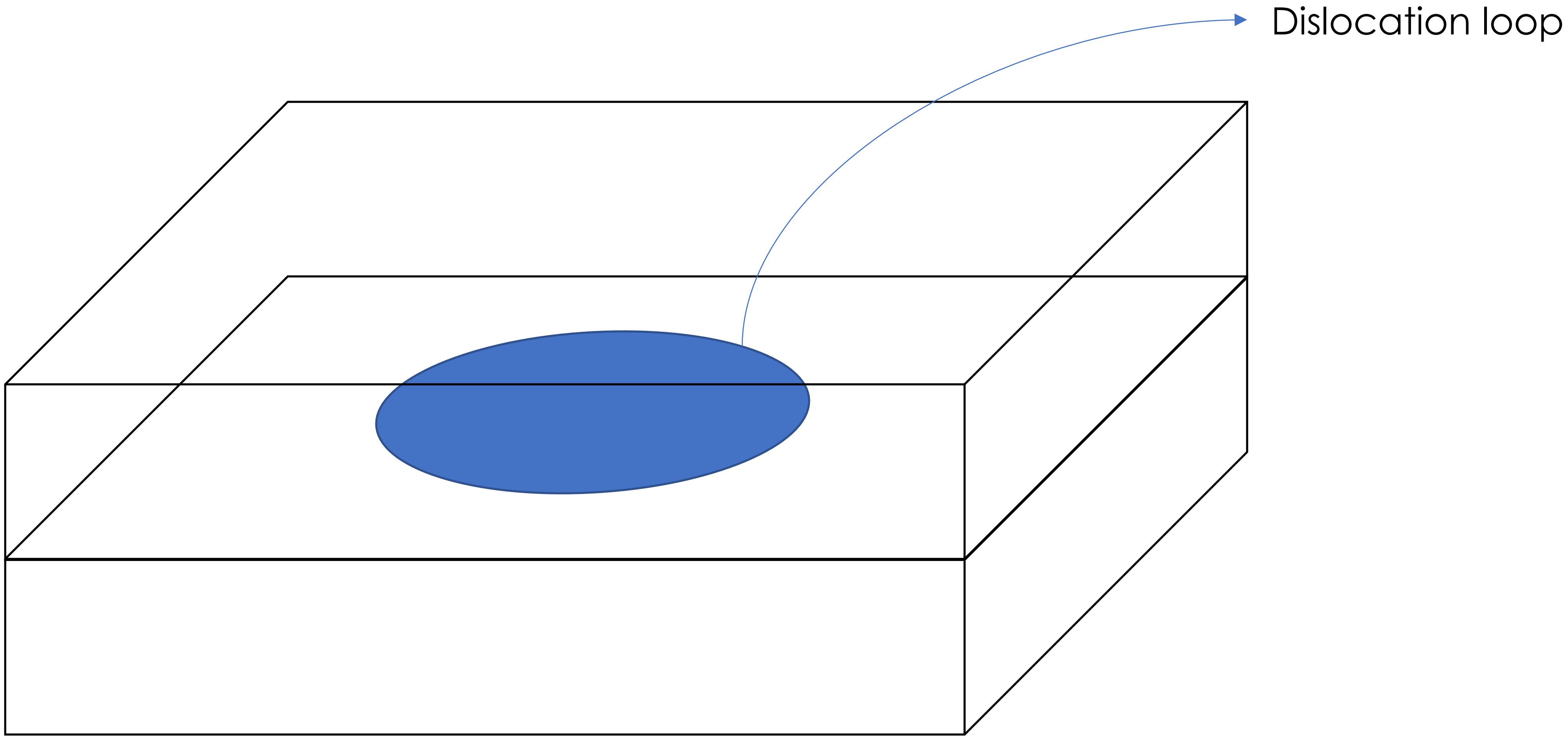
# A simple loop growth model

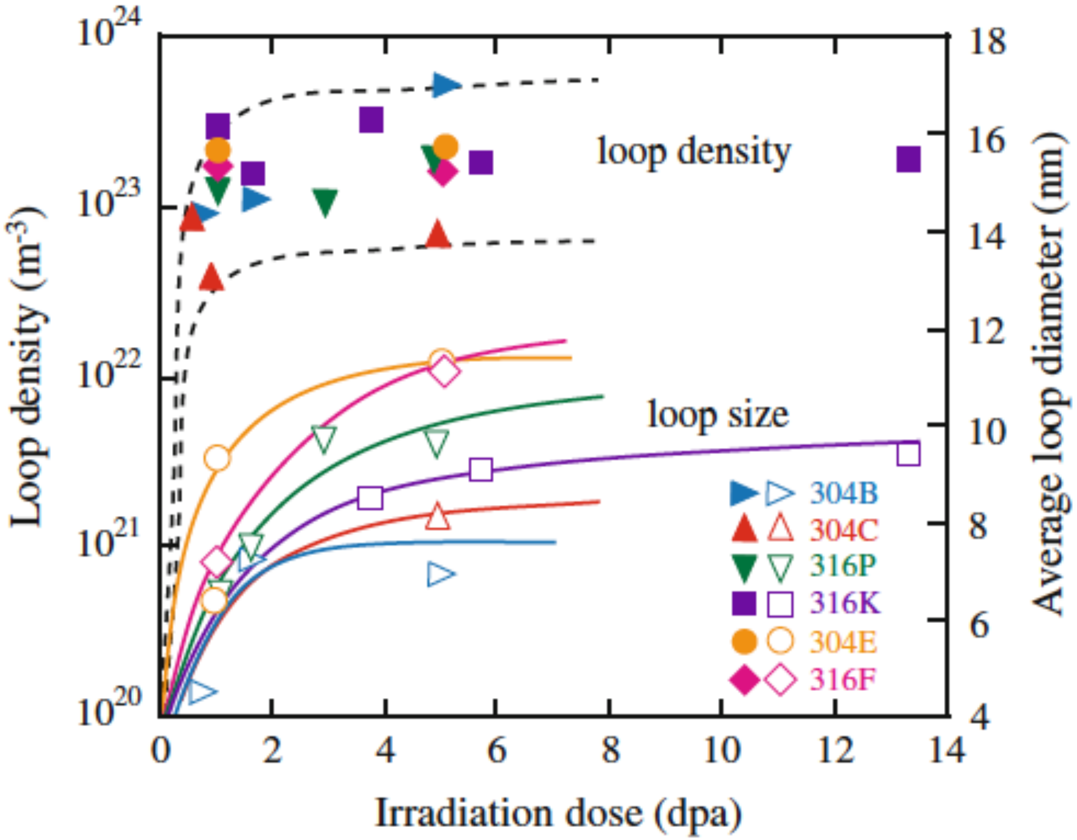


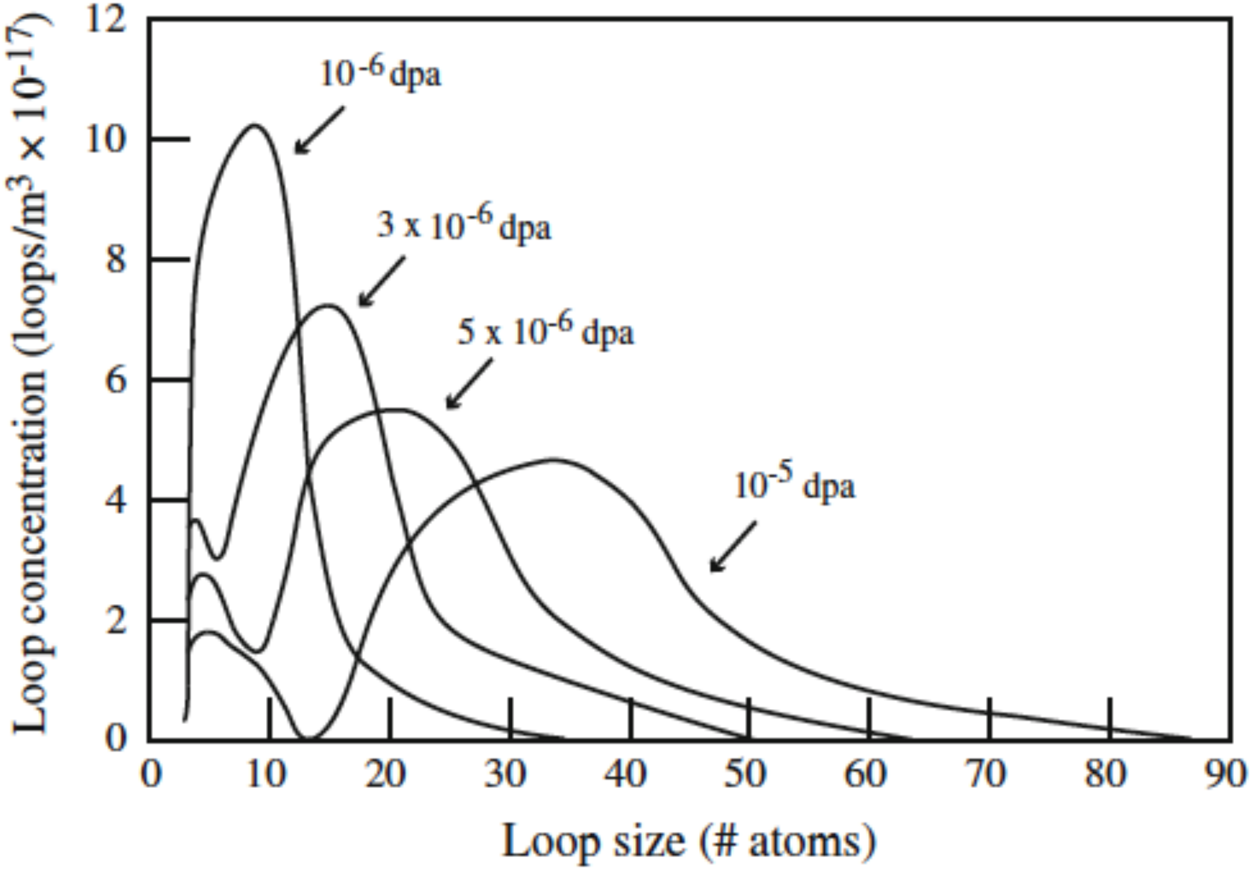
# A simple loop growth model

$$\left(\frac{dr_L}{dt}\right)_v = \frac{1}{b}\left[D_v C_v - Z_i D_i C_i - D_s^v \exp\left(\frac{\tau b^2}{r_L k_b T}\right) + D_s^i exp\left(-\frac{\tau b^2}{r_L k_b T}\right)\right]$$

$$\left(\frac{dr_L}{dt}\right)_i = \frac{1}{b}\left[Z_i D_i C_i - D_v C_v - D_s^i \exp\left(\frac{\tau b^2}{r_L k_b T}\right) + D_s^v exp\left(-\frac{\tau b^2}{r_L k_b T}\right)\right]$$

# Dose dependence

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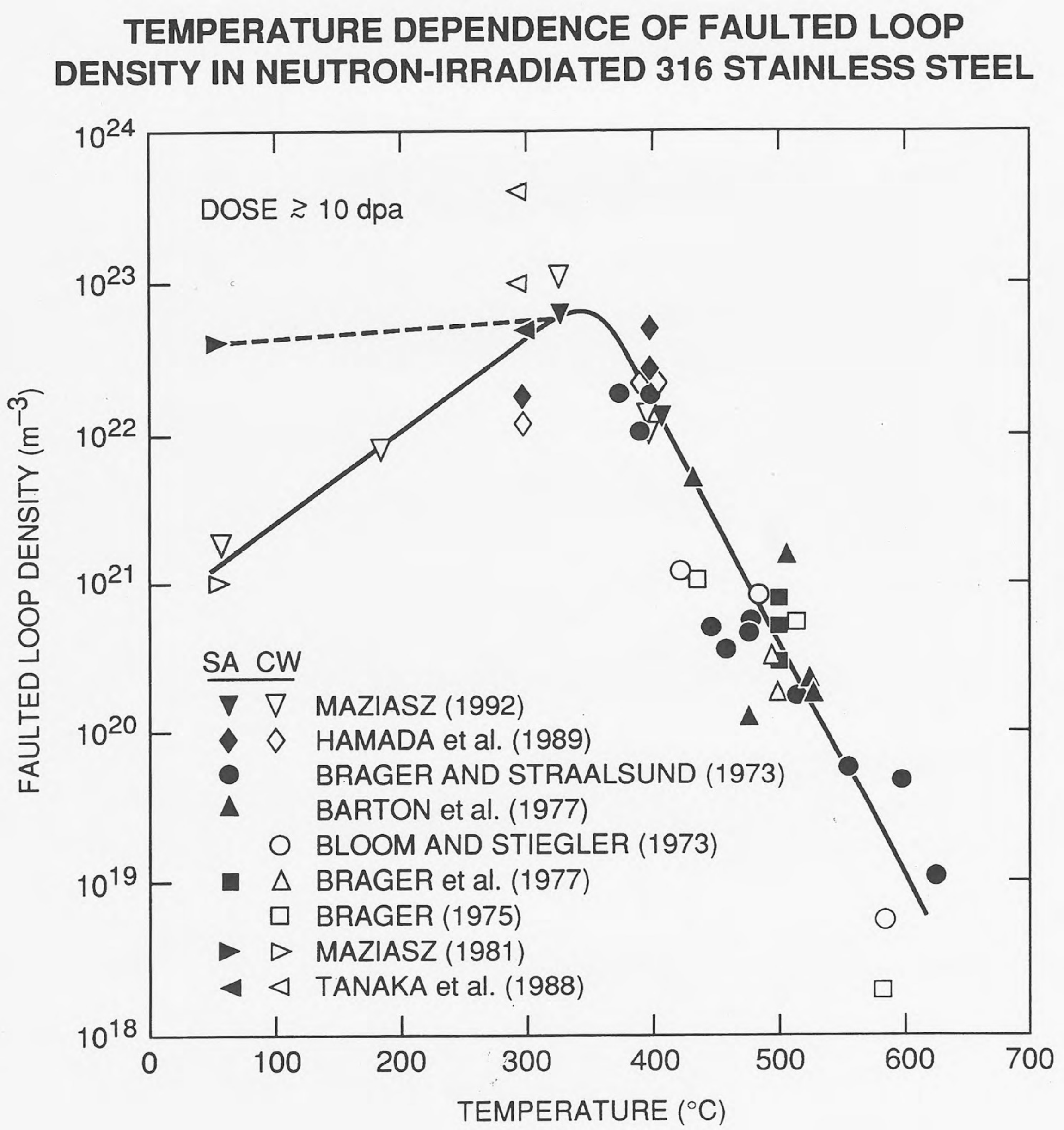
# Temperature dependence




Zinkle, Maziasz & Stoller, JNM 206 (1993) 266

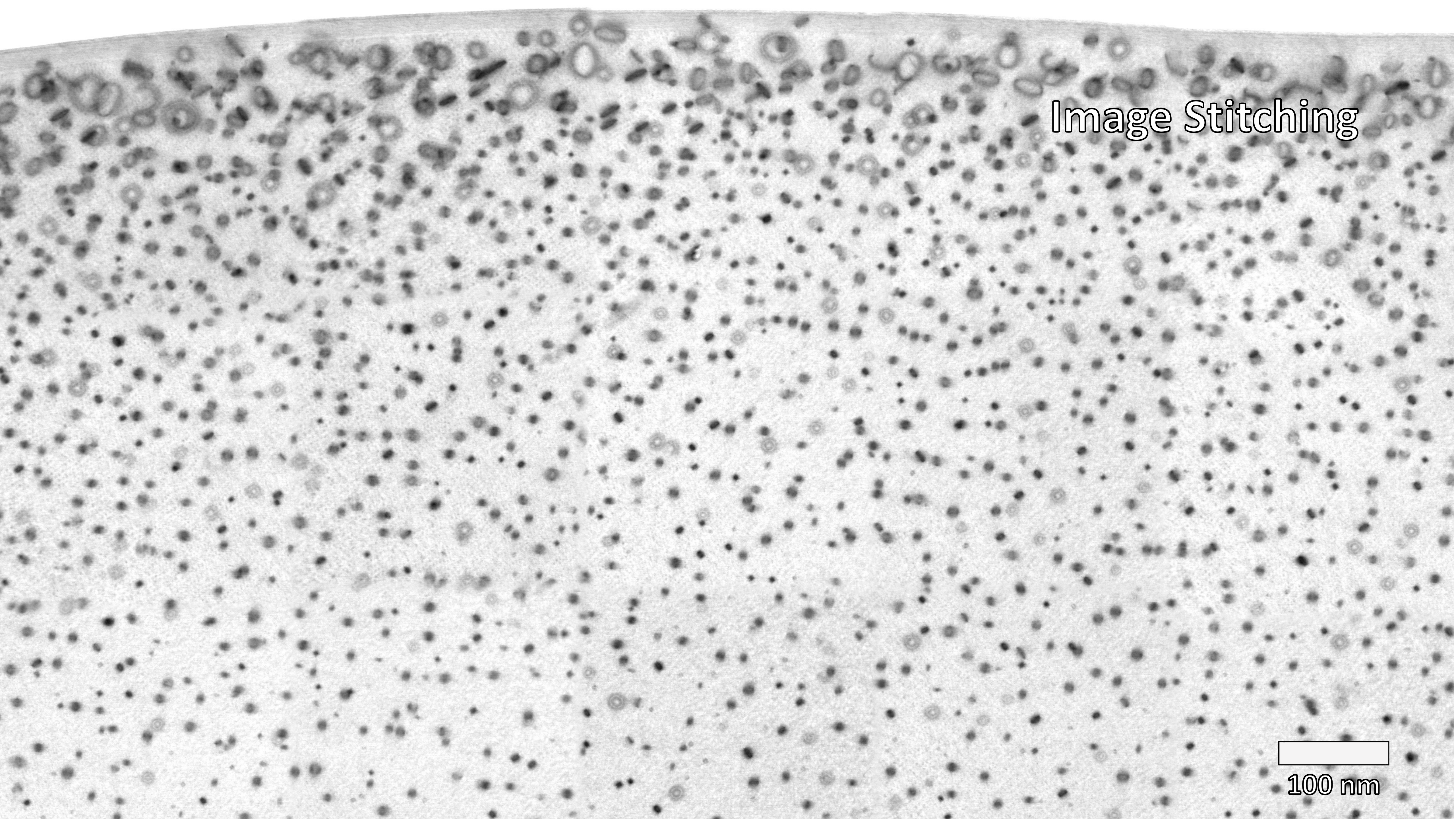


Image Stitching
100 nm

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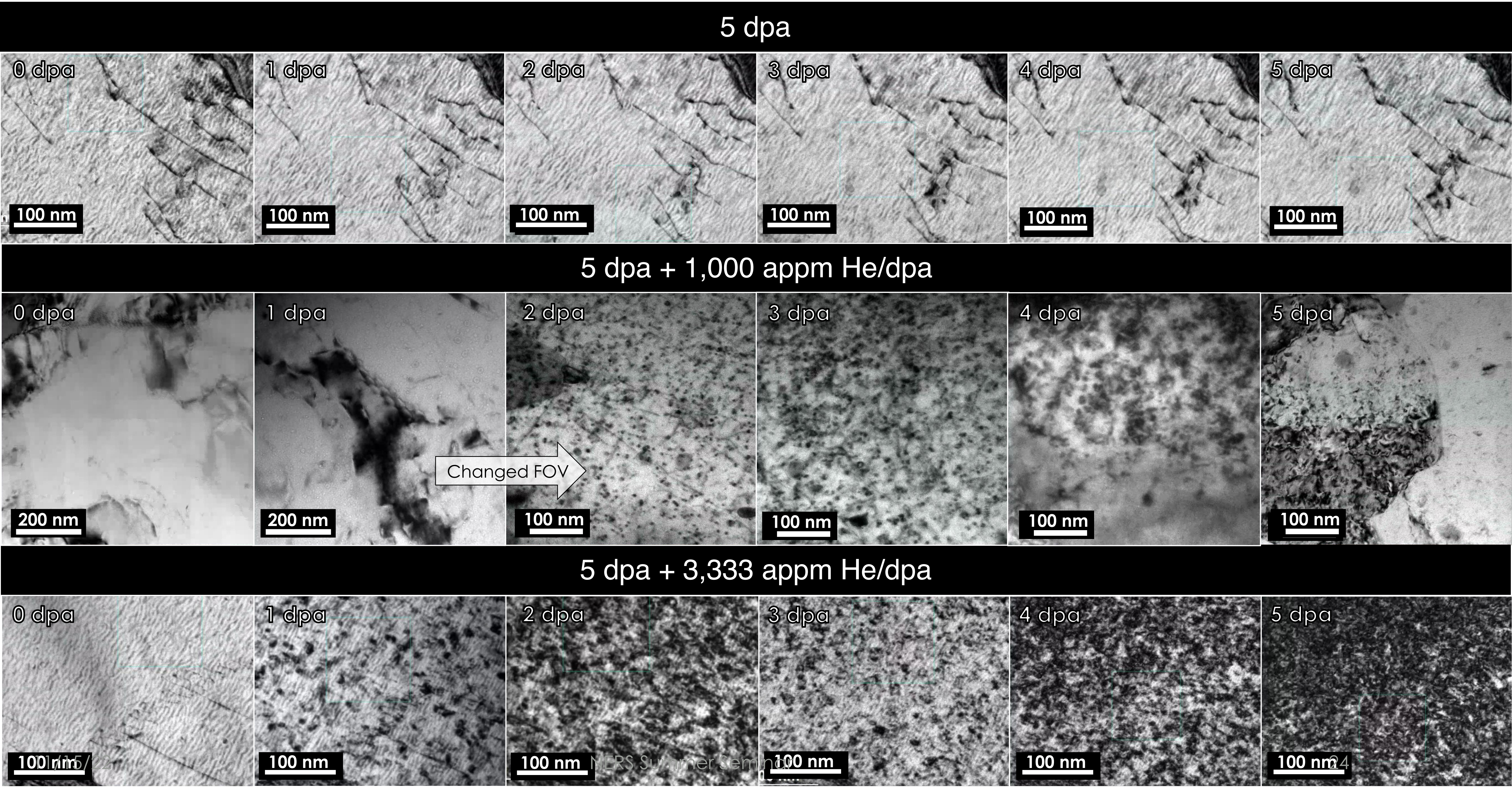
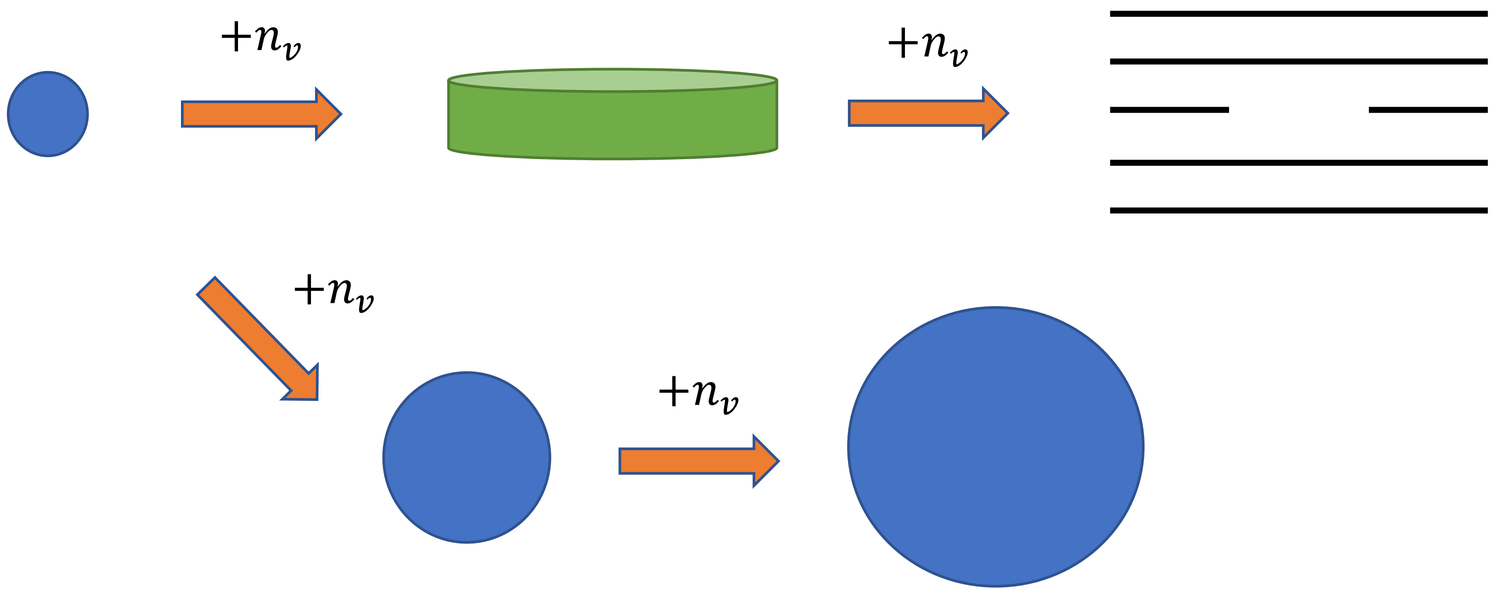


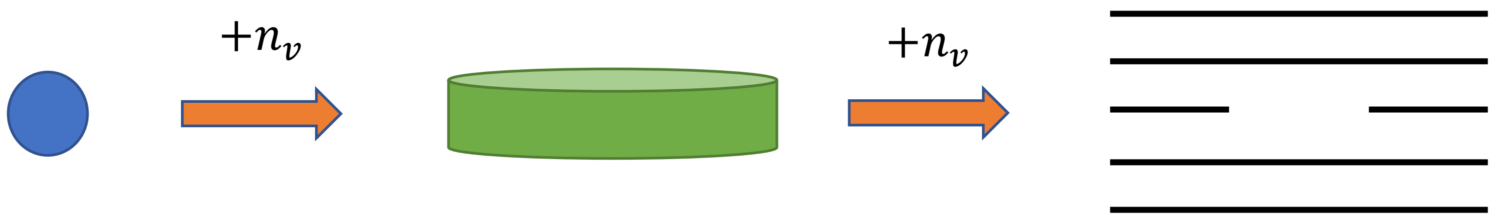
# Now let's consider vacancy condensation




$$E_s = 4\pi r^2\sigma \rightarrow E_c = 2\pi r^2\sigma$$

- For the same $n_v$, $E_C > E_s$ meaning an activation energy is required to generate large spherical voids

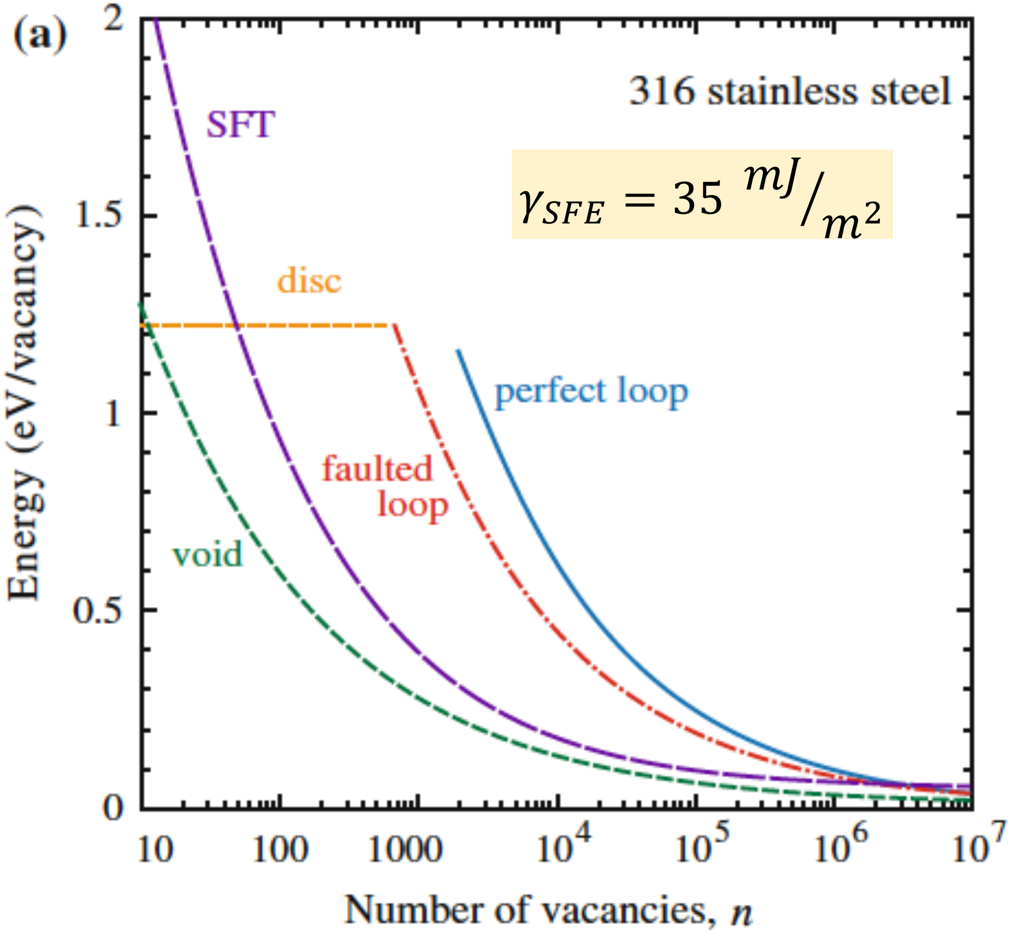
# Now let's consider vacancy condensation

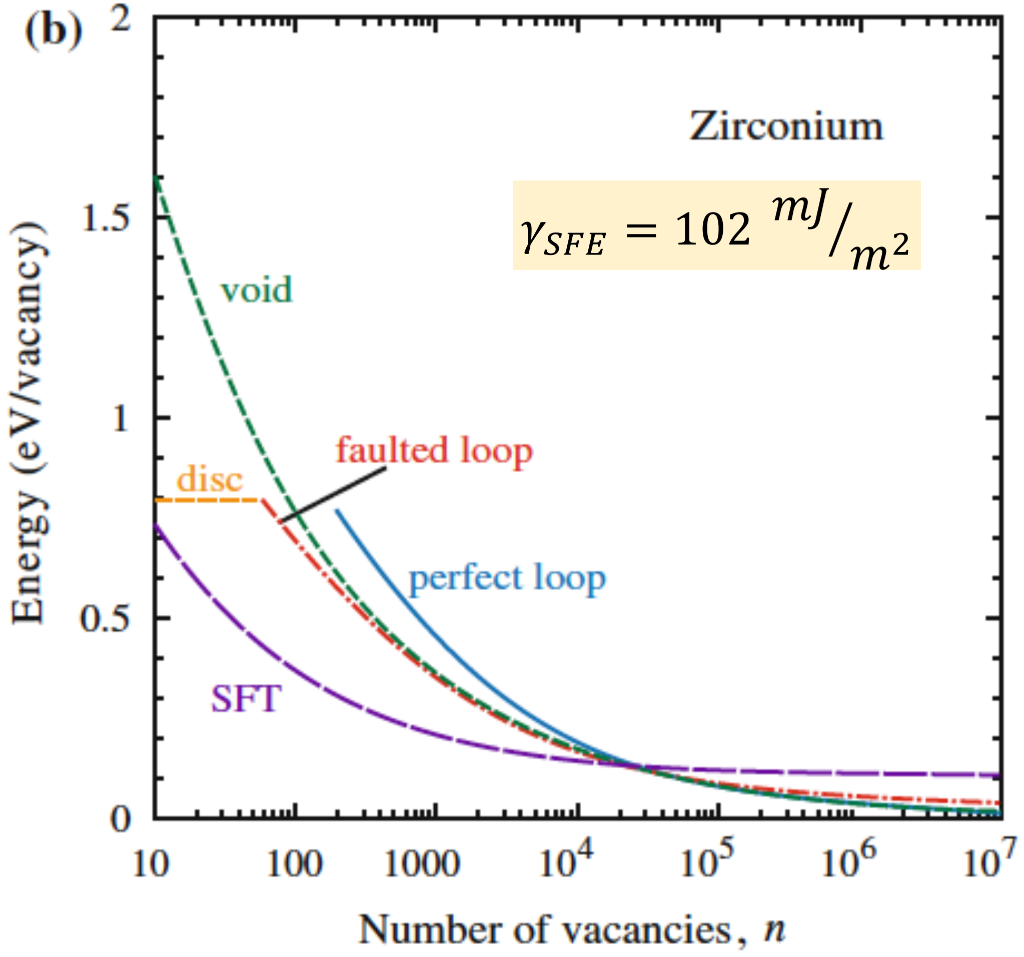



$$\therefore \quad E_s = 4\pi r^2\sigma \;\rightarrow\; E_c = 2\pi r^2\sigma$$

- For the same nv, $E_C > E_s$ meaning an activation energy is required to generate loops

# Visualizing the energetics

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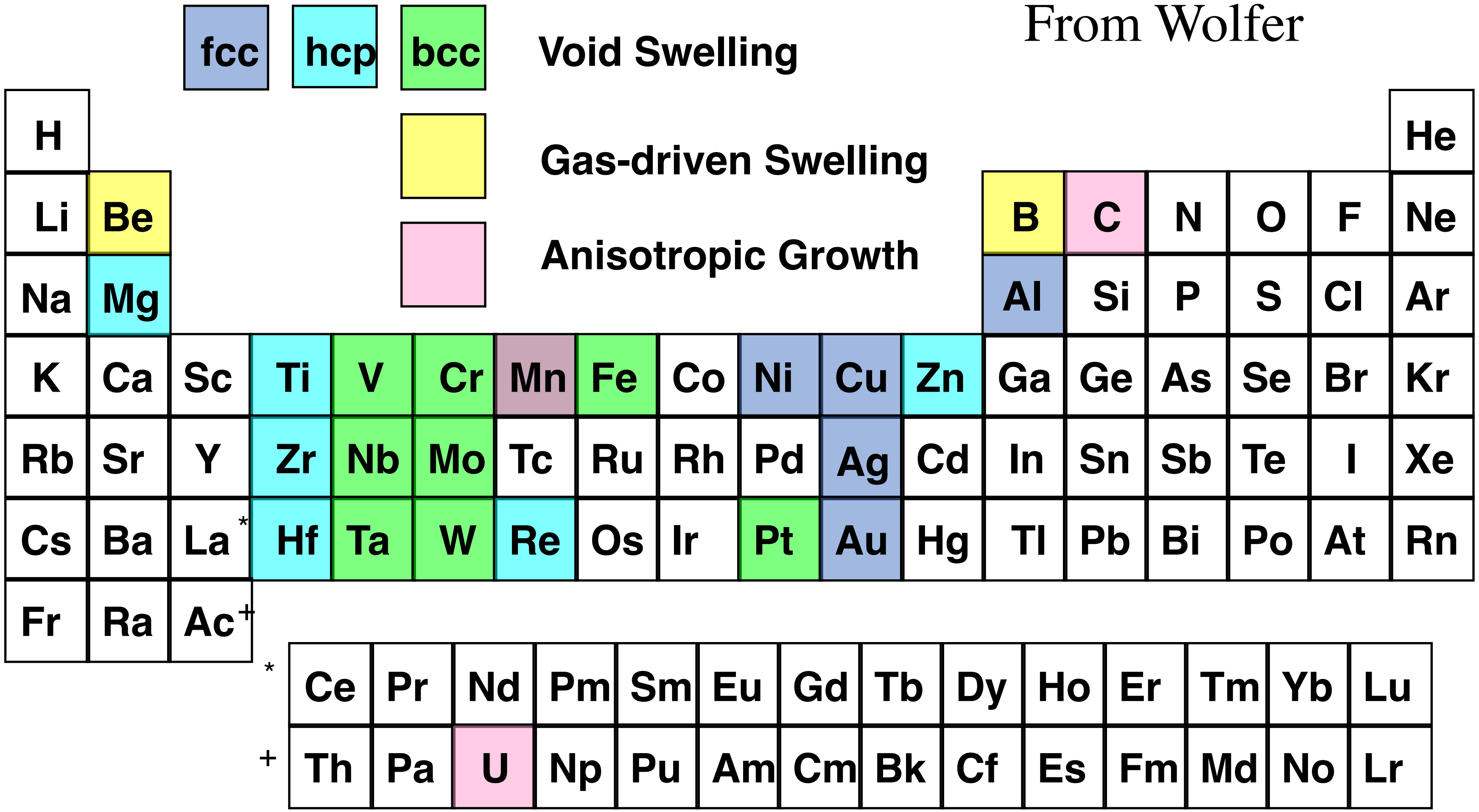
# Voids formed in metals

- Voids form by vacancy condensation. Vacancies are supersaturated in irradiated metals.
- Void formation requires "bias" or preferential absorption of self-interstitials at dislocations or other sinks, relative to vacancies
  - V - I recombination is an "unbiased" process since it removes vacancies and interstitials at the same rate
  - Cavities are unbiased sinks for point defects
  - Because of dislocation bias, slightly more interstitials (~20%) are absorbed by dislocations, leaving a slight excess of vacancies to first *nucleate* and then *grow* voids.
- These processes are very sensitive to gas pressure in the cavity
  - A void has no gas (in practice, could have very low levels of gas atoms)
  - Impurity atoms within the metal (e.g., O, N) and He produced by (n,a) reactions or by direct implantation are the principal radiation-produced gases that can be trapped by cavities.

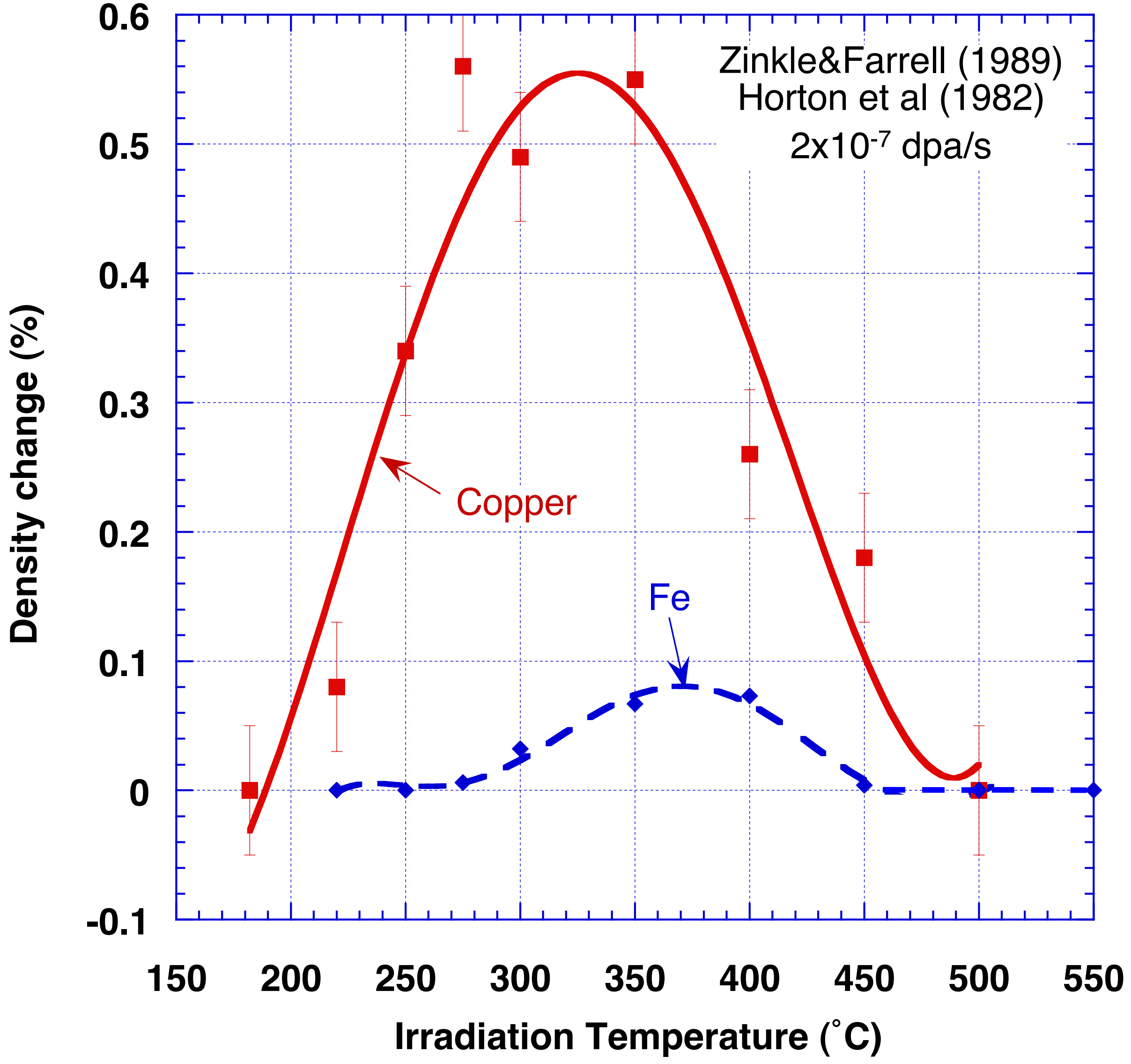
# Effect of materials variables on void growth

From Wolfer



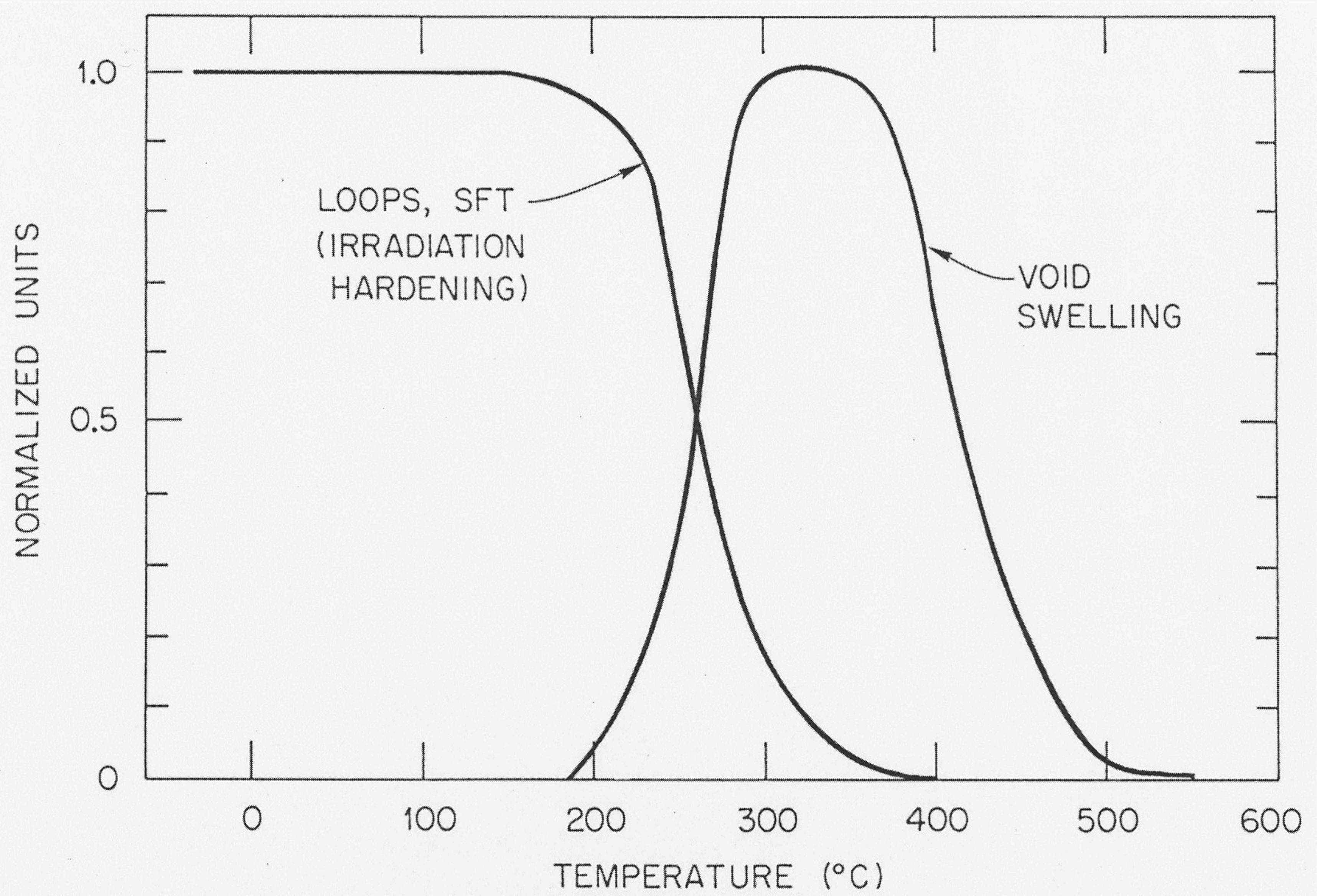

***No Element Tested Has Ever Failed to Swell***

# Comparison of Temperature-Dependent Void Swelling in Neutron Irradiated Cu and Fe at 1 dpa




Void swelling is typically of concern for irradiation temperatures between ~0.3 and ~0.6 $T_M$

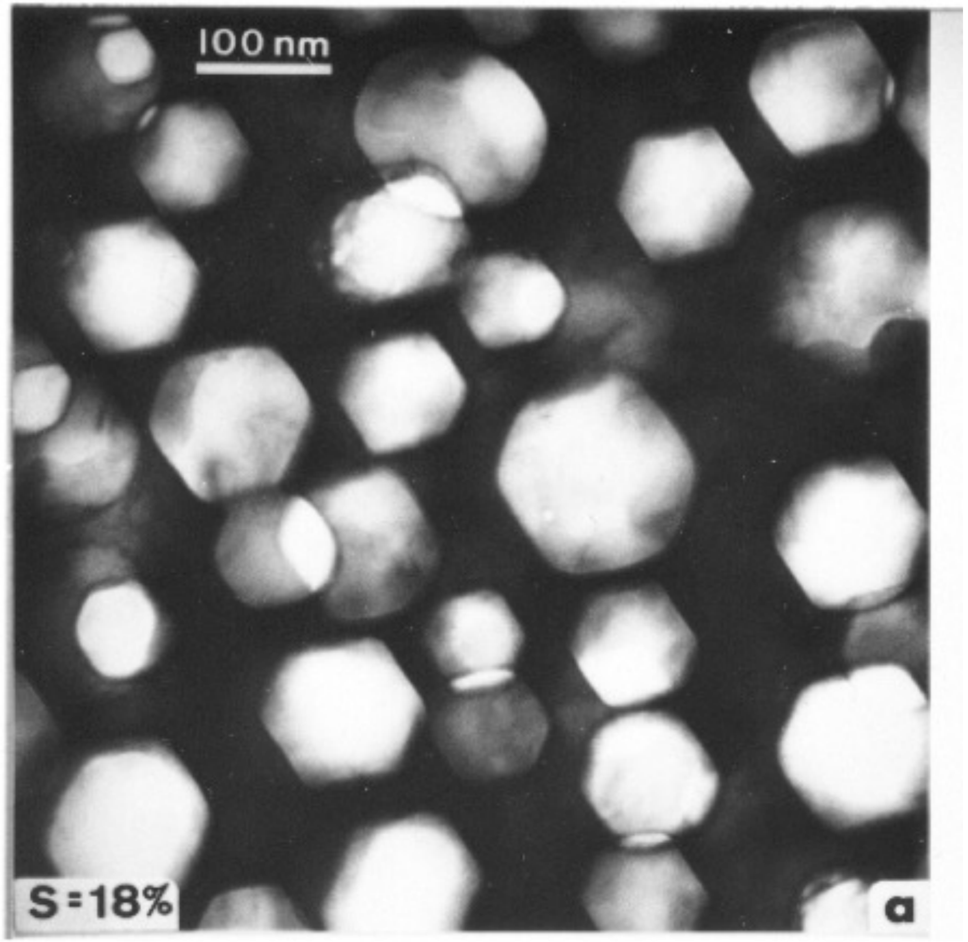
# Temperature dependence for void swelling involves balance between recombination and vacancy emission




*Zinkle, ASTM STP 1125 (1992) p. 813*

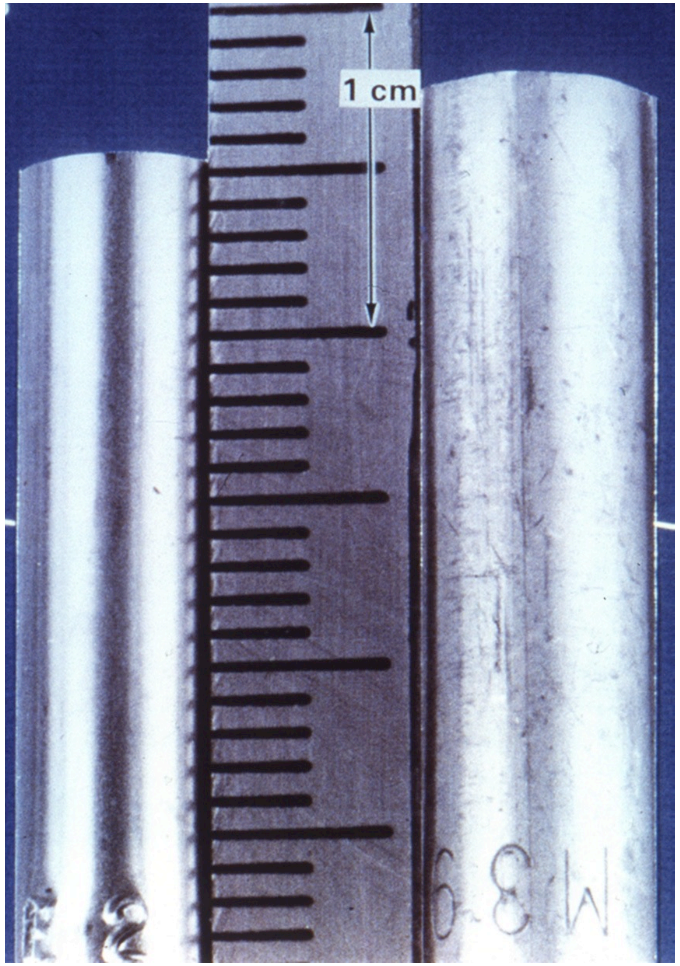
# Physical effect of void formation in a material

ion-irradiated austenitic stainless steel (625˚C, 70 dpa)




N. Packan & K. Farrell, *J. Nucl. Mater.* 85&86 (1979) 677

neutron irradiated 20%CW 316 steel at $T=523^{0}C$, $1.5x10^{23} n/cm^{2}$




*J.L. Straalsund et al., J. Nucl. Mater.* 108&109 *(1982) 299*

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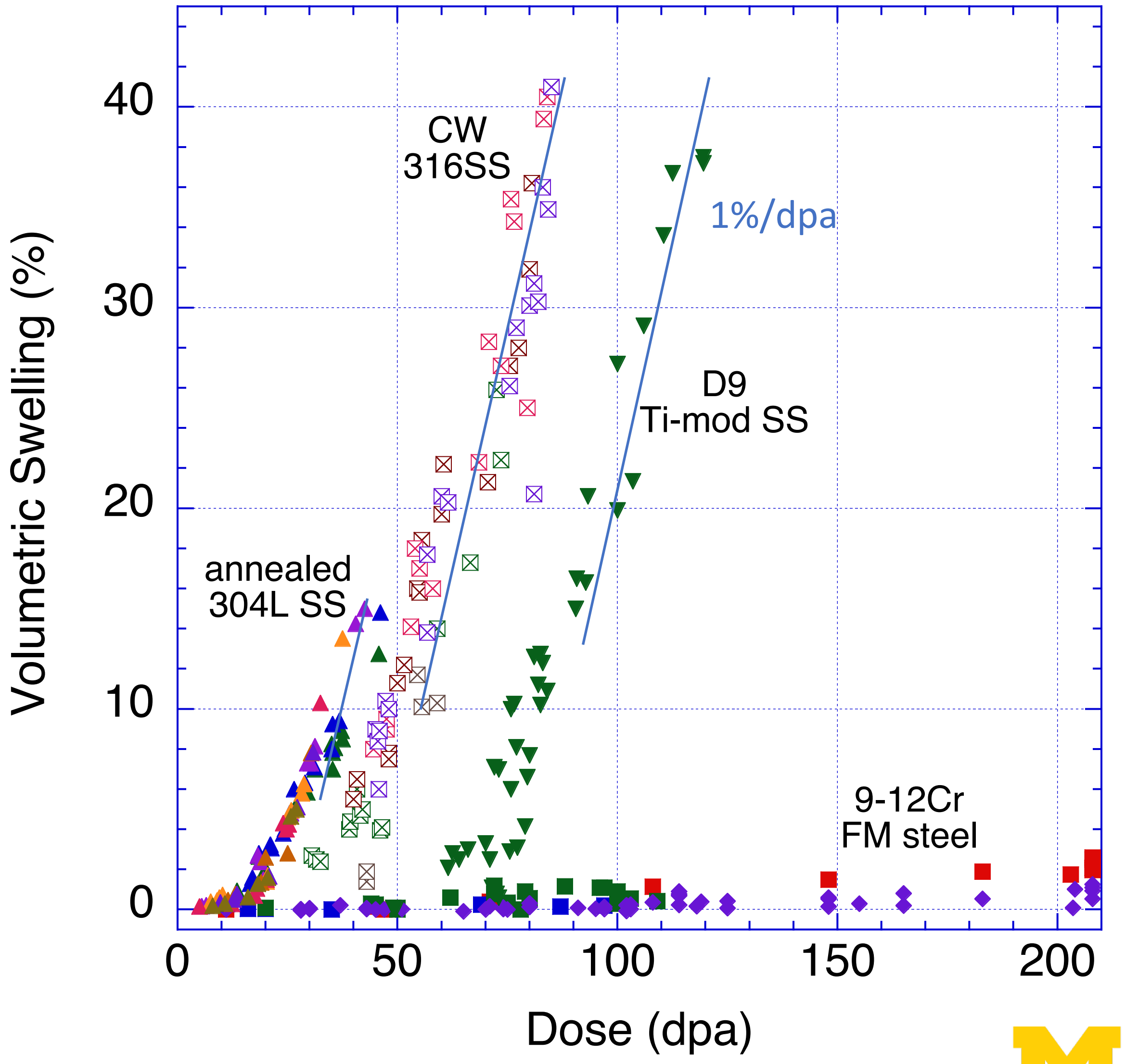
# Physical effect of void formation in a material

Dimensional changes >5-10 vol.% are unacceptable for typical engineering designs

E.g., linear dimensional change due thermal expansion in 316SS between room temperature and 500°C is:

$$Dl=a\Delta T=18\mathrm{x}10^{6}/^{\circ}C*480^{\circ}C=0.86\%$$




Zinkle & Was, Acta Mater. 61 (2013)

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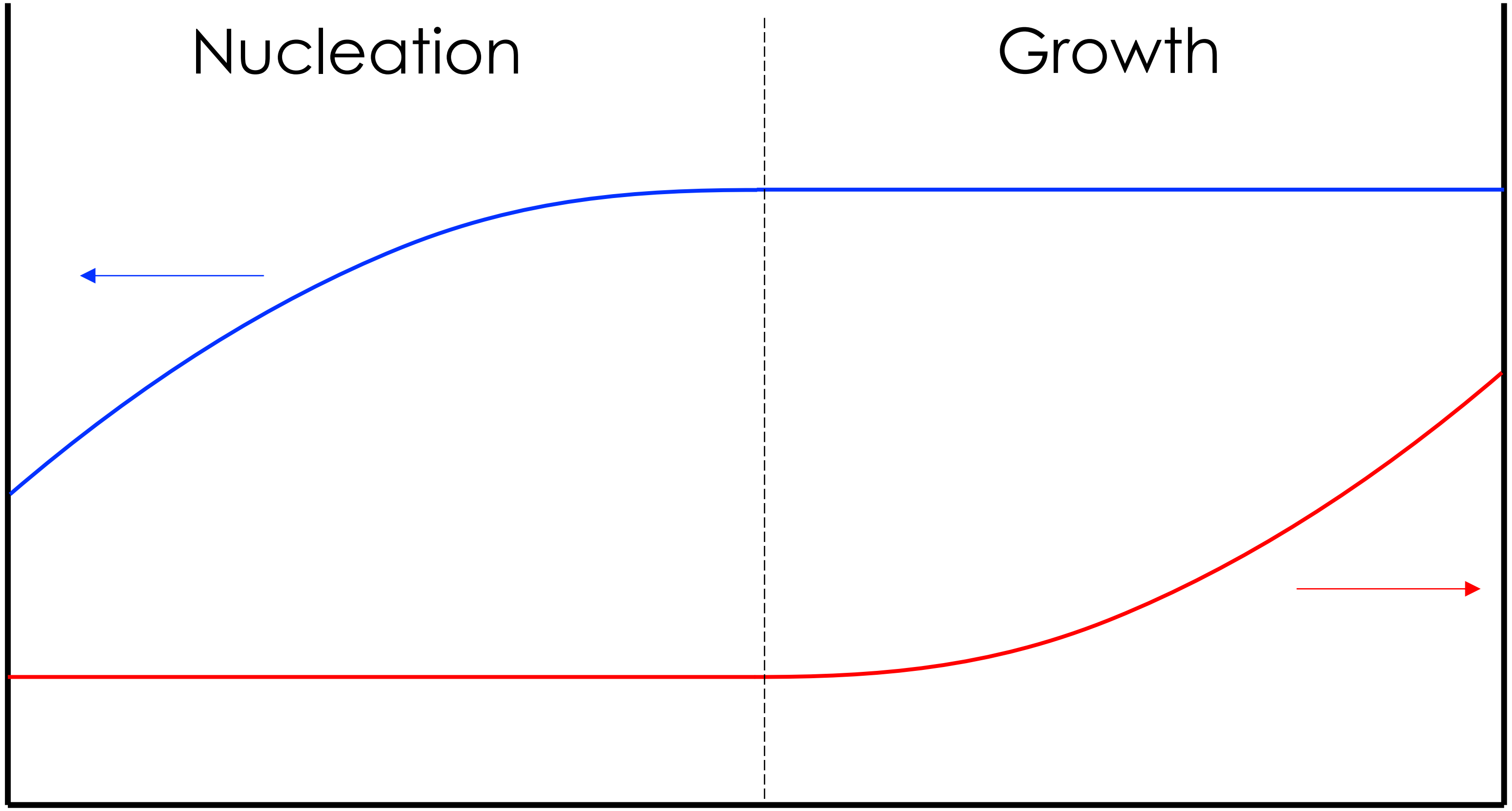
# Nucleation vs. Growth

Void Number Density




Void Size

Time (or dose)

# Questions?