Observation and Analysis of Defect Cluster Production and Interactions with Dislocations

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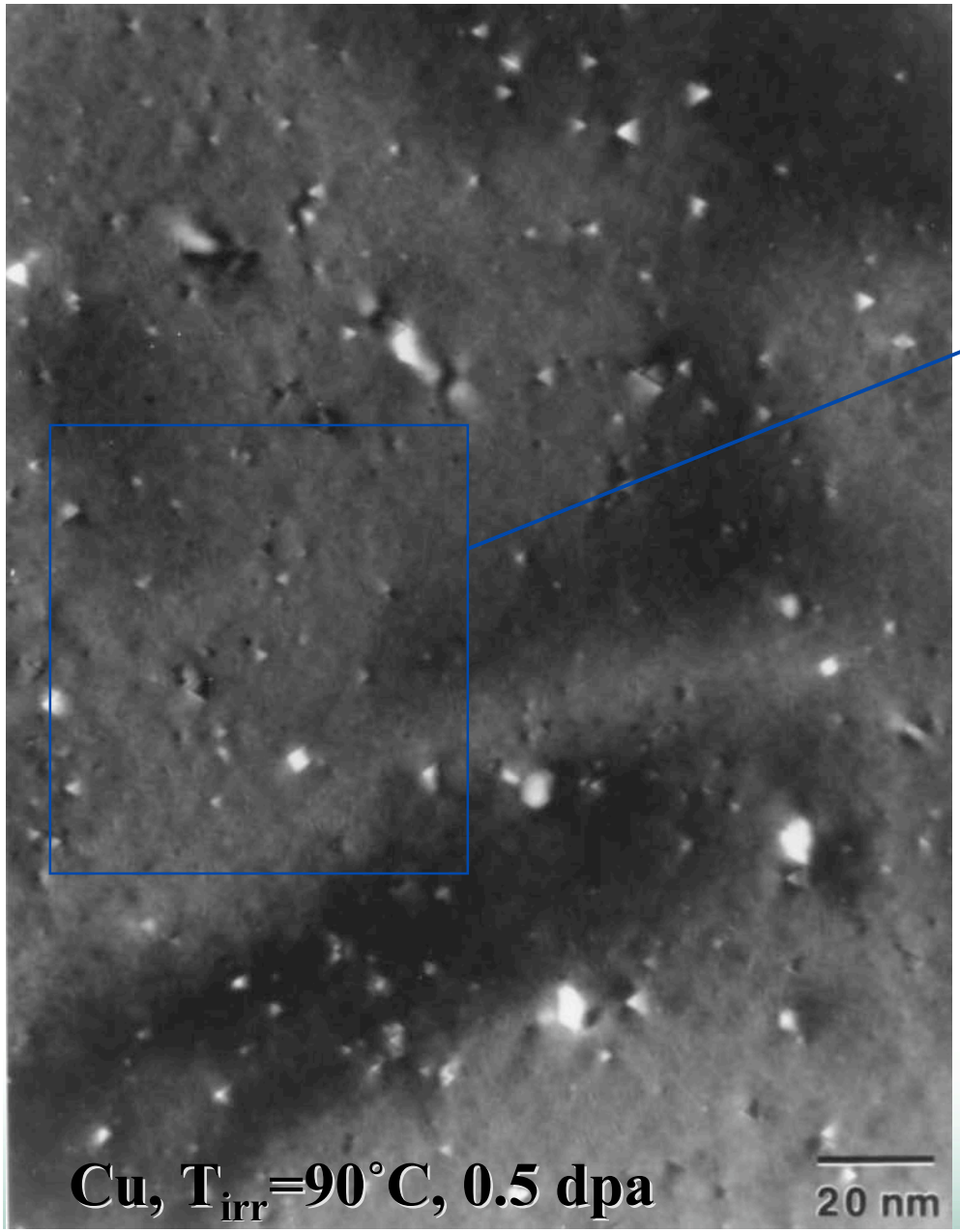
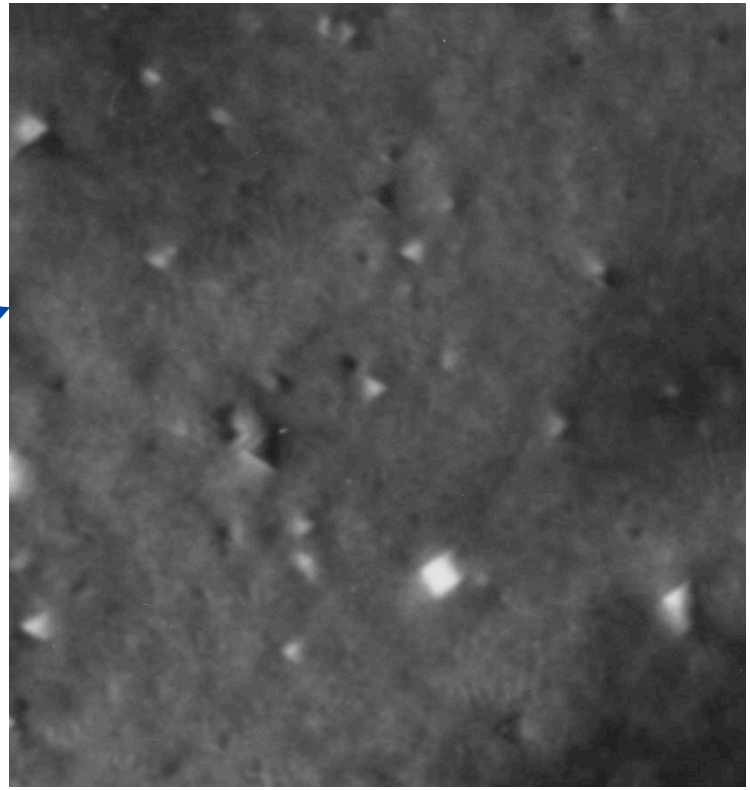
Quantification of small defect clusters is best performed using weak beam microscopy





- Dark-diffracting defects are visible in suitably-thin foil regions
- Differentiation between SFTs and partially dissociated loops requires observation at B=001 and B=110

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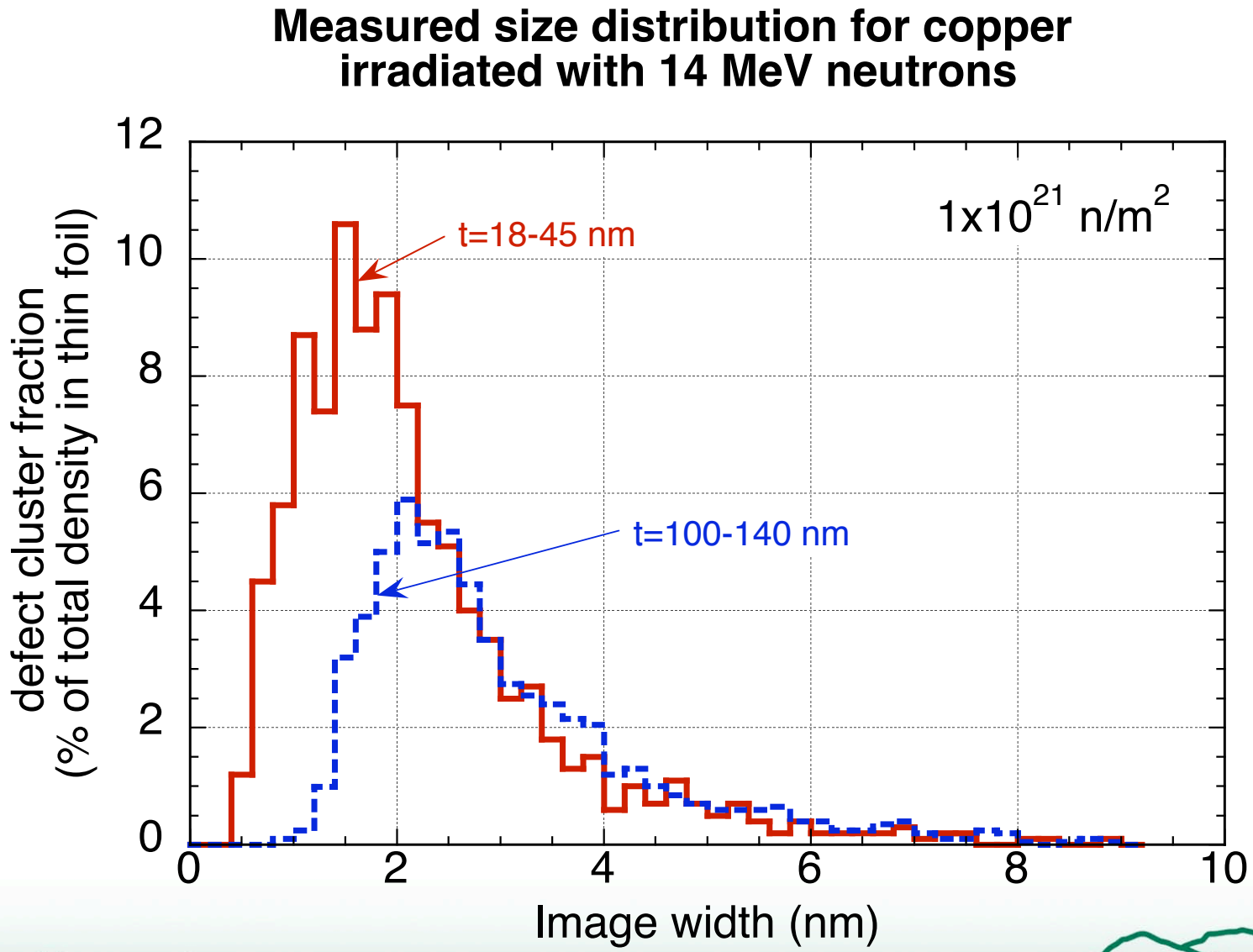
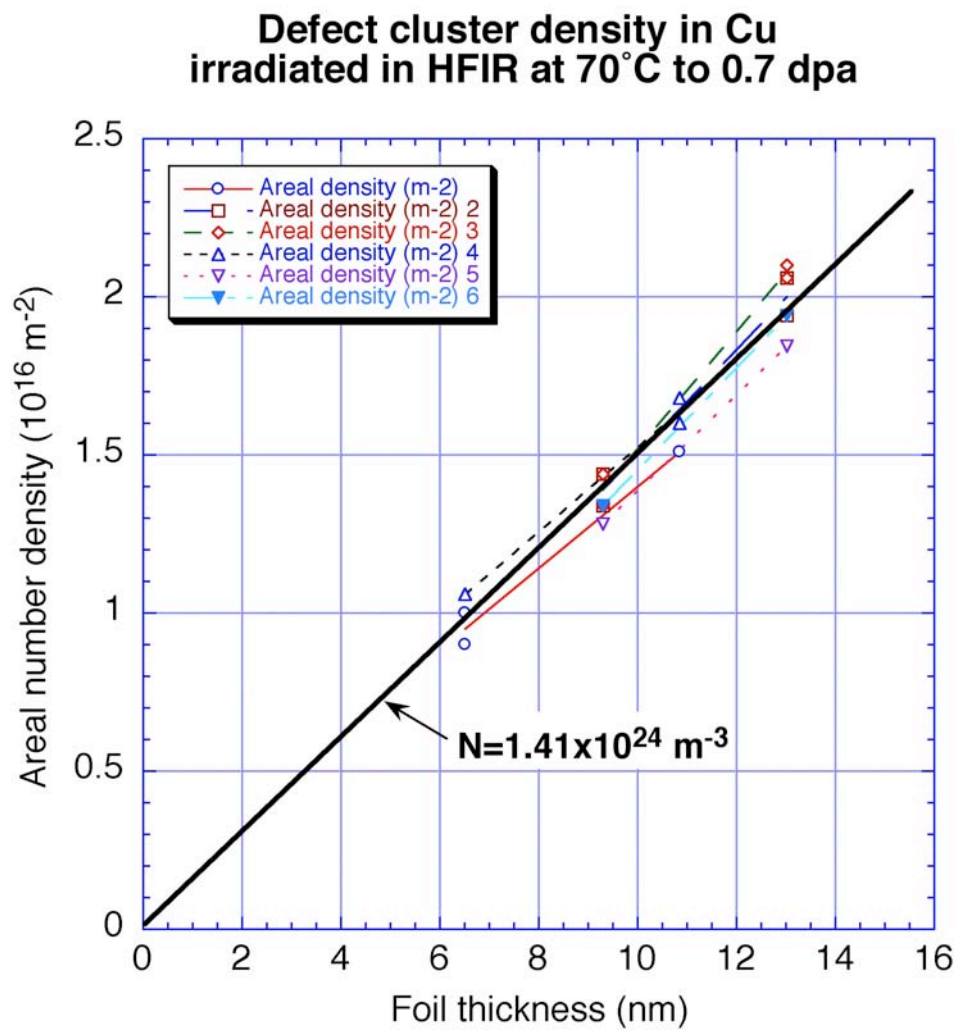
Small defect clusters are not visible in foils with thickness above ~40 nm



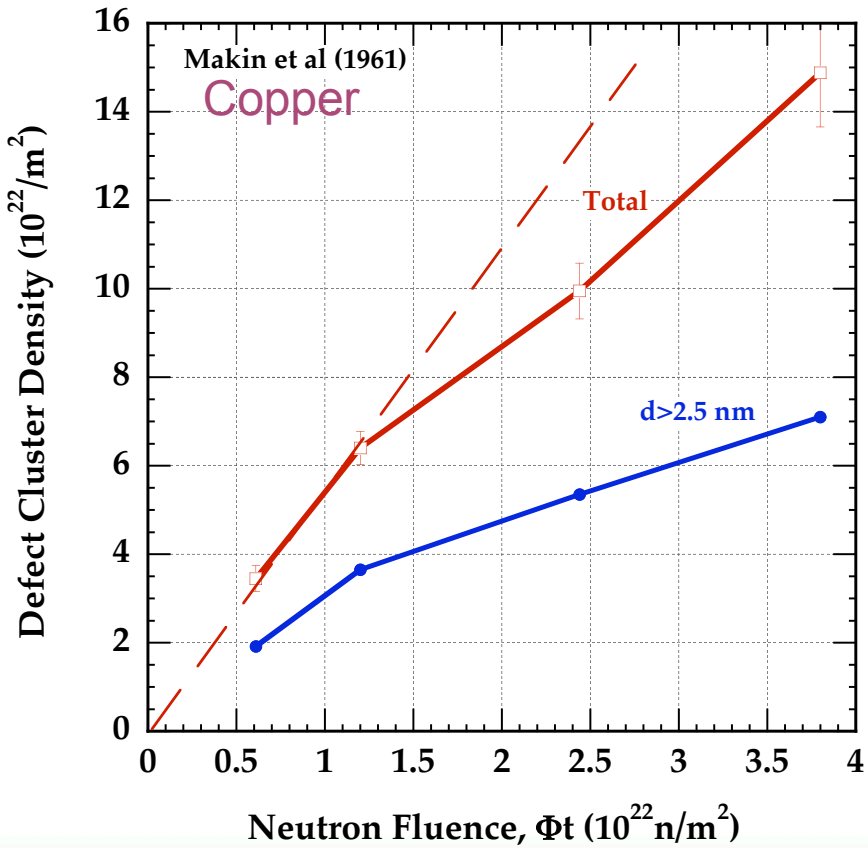
Essential steps for accurate measurement of defect cluster densities

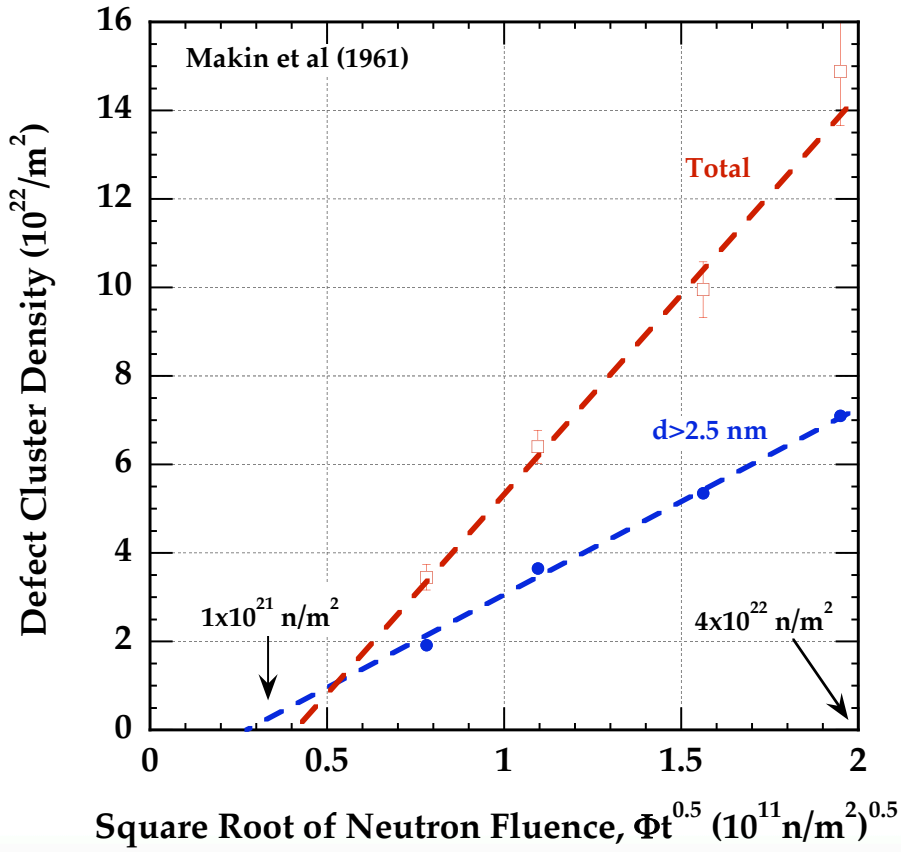
- Use very thin regions (t<40 nm) to count SFTs and small defect clusters (d<3 nm), using total magnifications >500 kx
- Count larger (d>3 nm) defect clusters vs. foil thickness in "thicker" foil regions (50-200 nm)
- Check for possible defect cluster invisibility and/or loss of glissile clusters to foil surface by analyzing areal cluster density vs. foil thickness
  - Plot should linearly extrapolate to the origin



Dose Dependence of Defect Cluster Accumulation

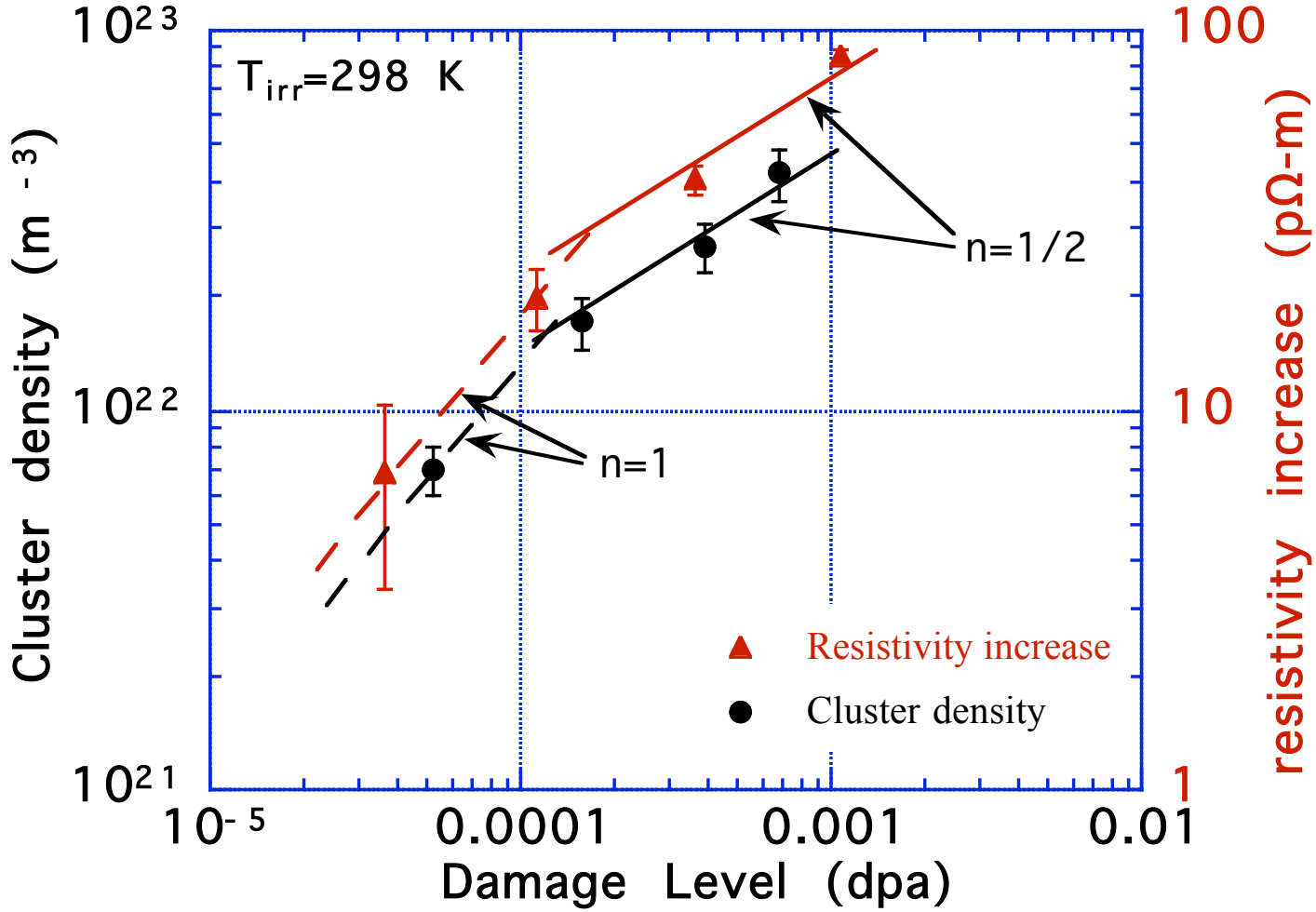
- Early studies reported "nearly linear" dose dependence despite significant deviation from linearity
- Dose dependence even for early studies of irradiated pure metals is better described by square root accumulation behavior





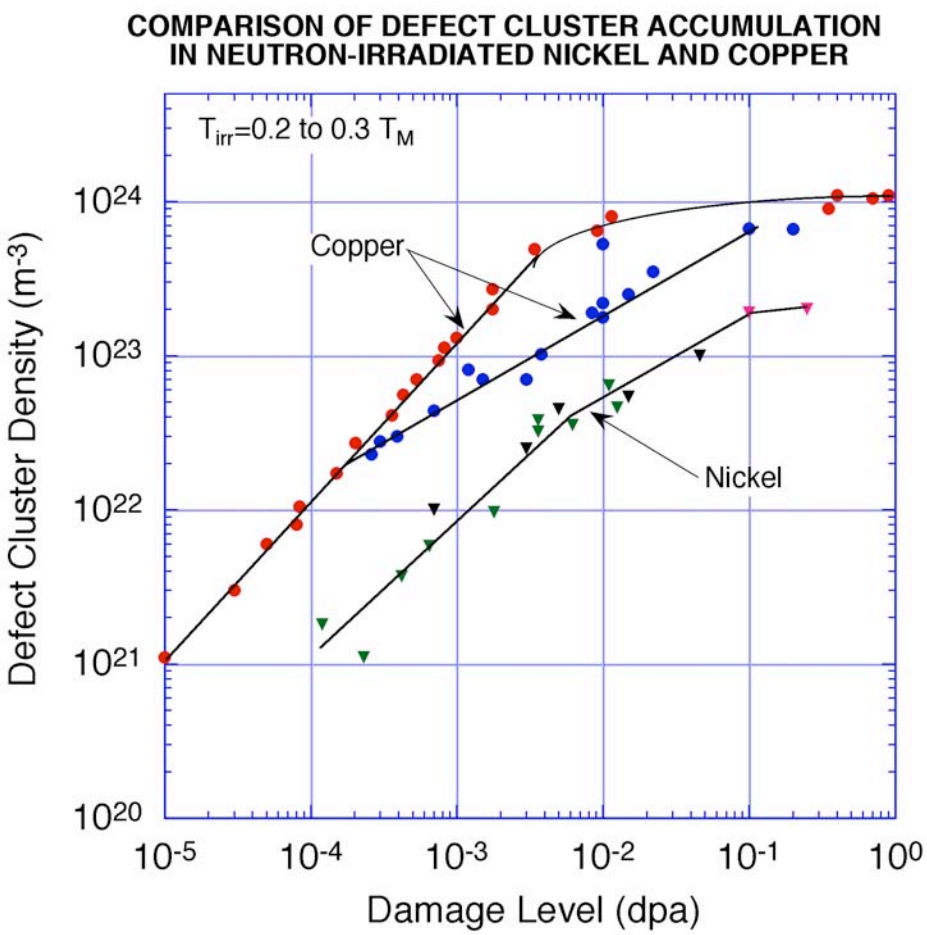
Dose Dependence of Defect Cluster Accumulation

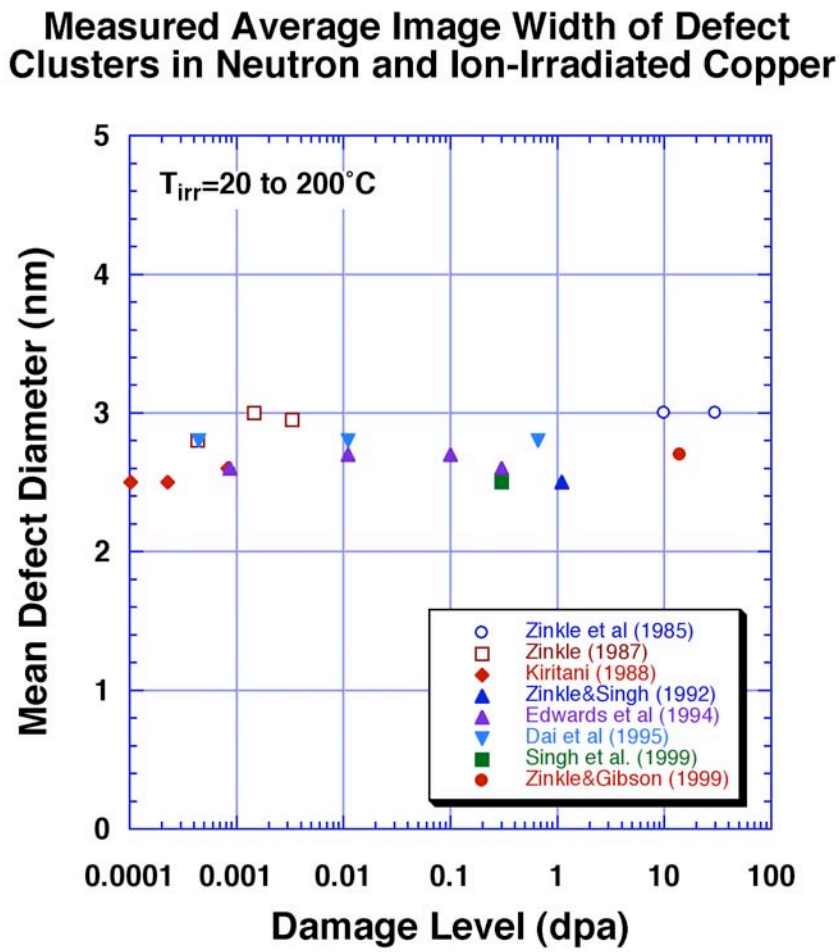
Comparison of Dose Dependence of Electrical Resistivity and Defect Cluster Density in 14 MeV Neutron Irradiated Copper



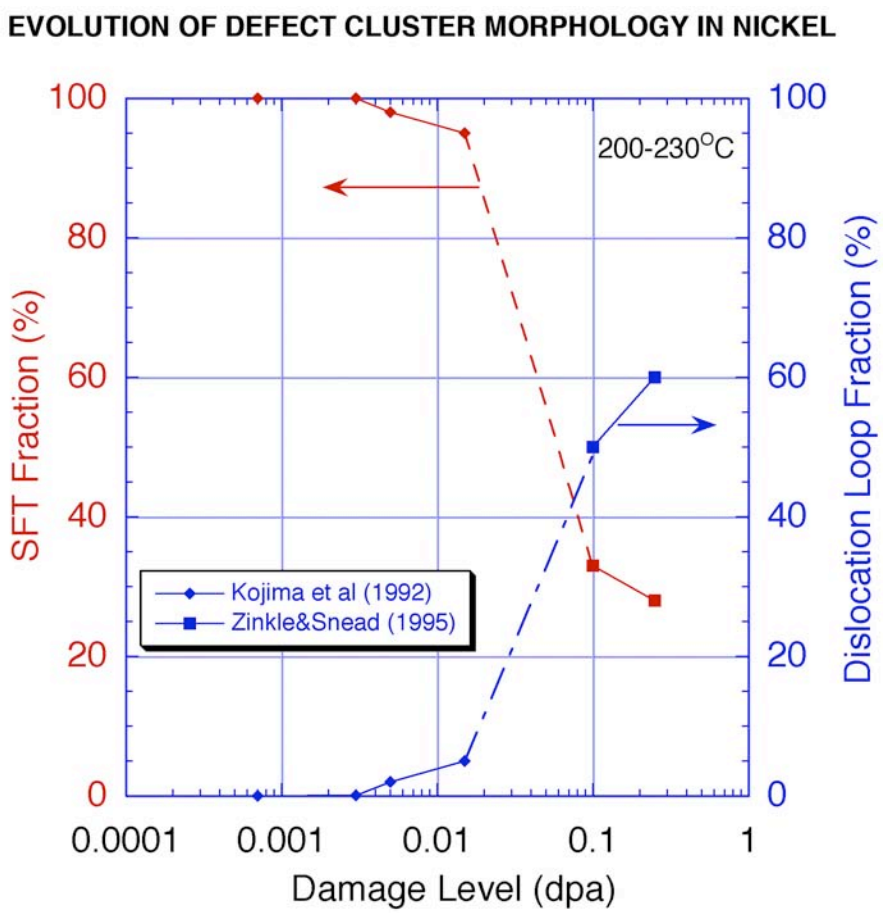
- Data analysis based on unsaturable trap model indicates freely migrating interstitial fraction is f_i~11%

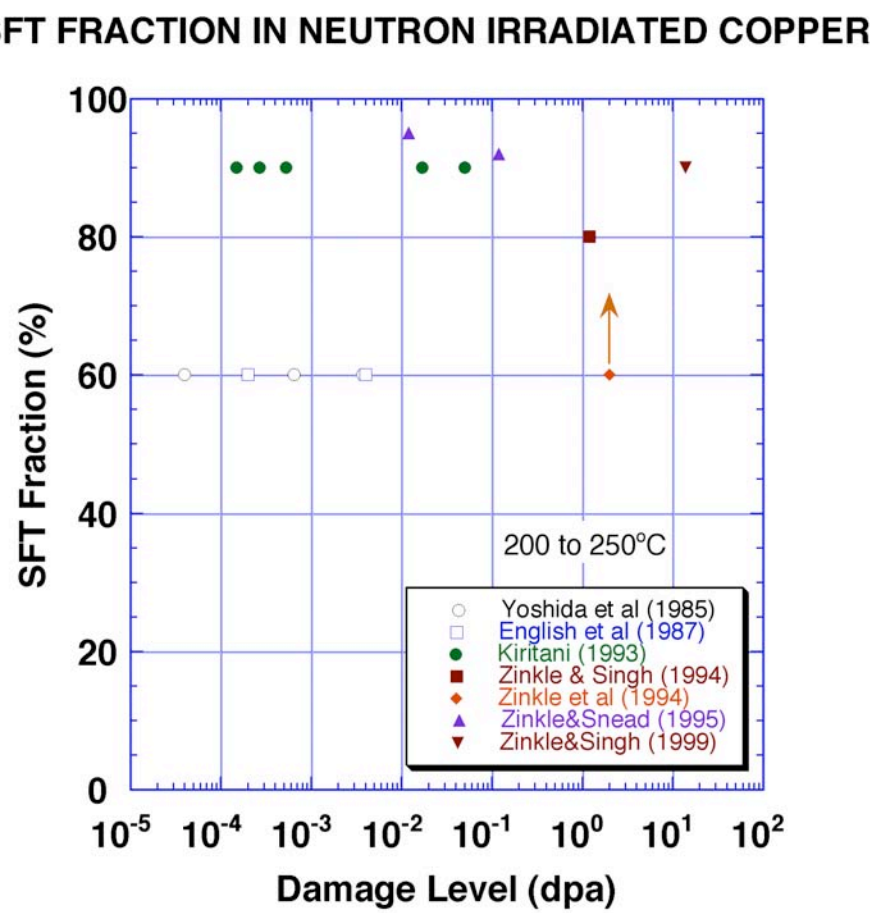
Defect clusters in neutron irradiated copper (low T)



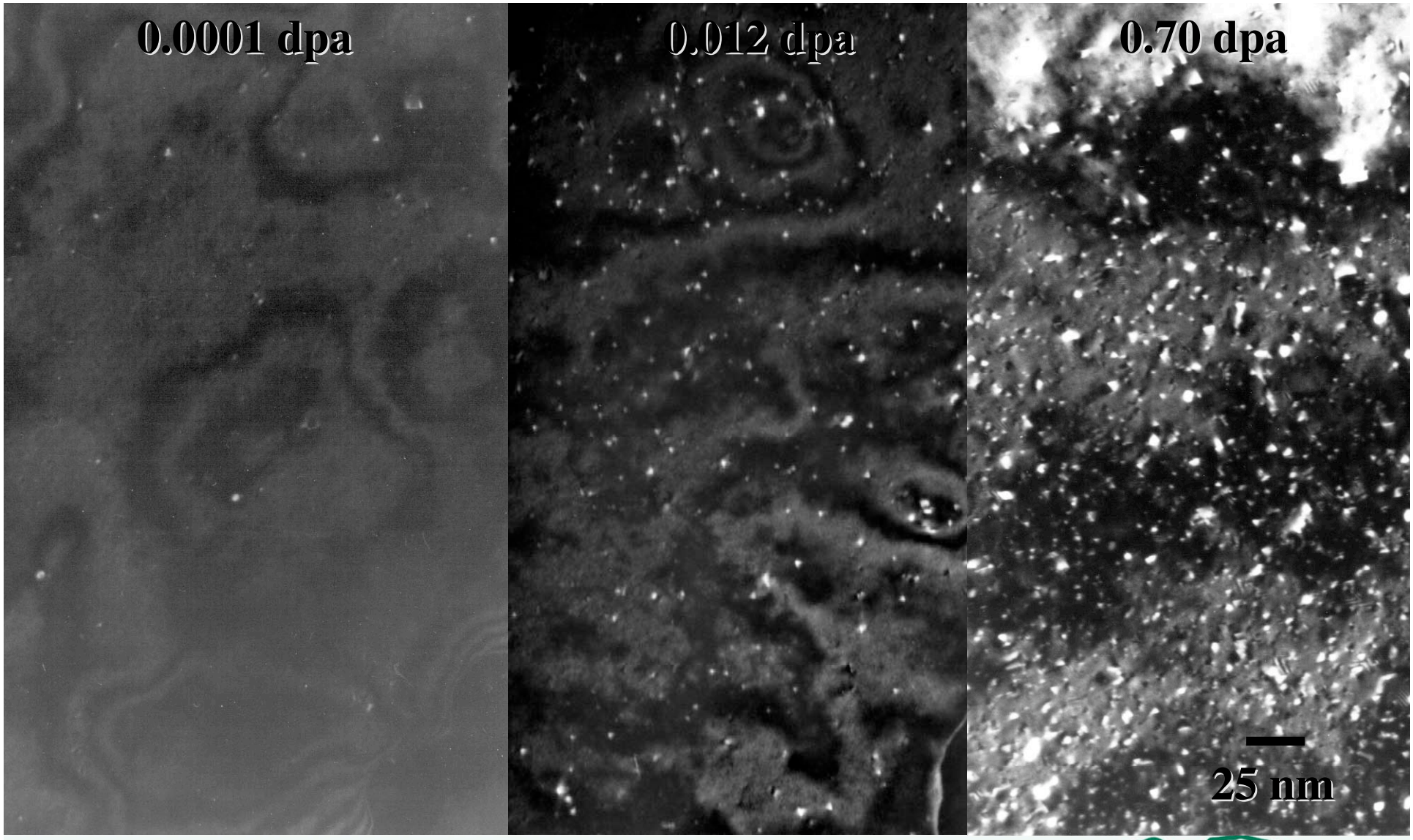


Comparison of defect cluster evolution in neutron irradiated Cu and Ni (low T)

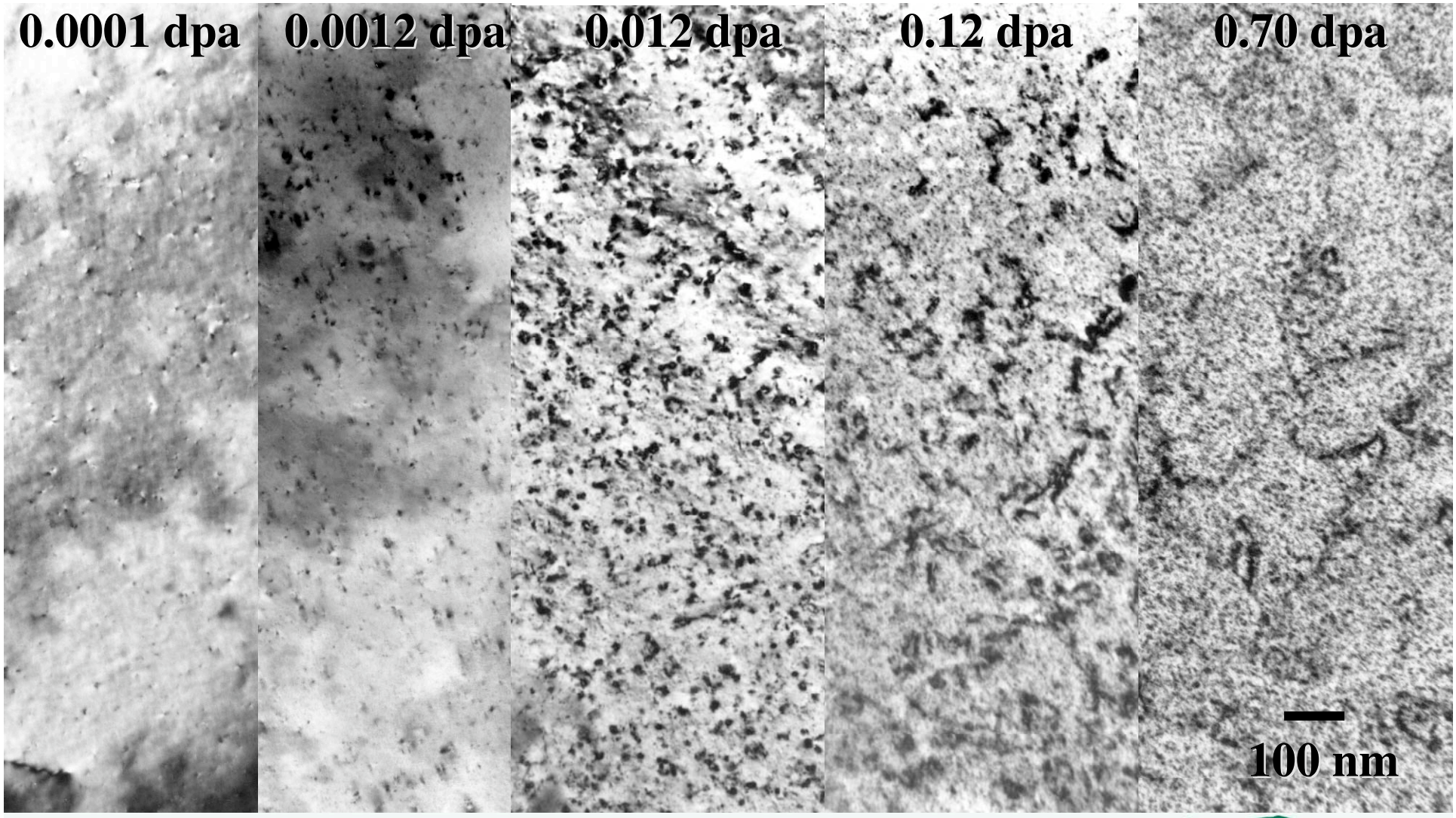




Black Spot Defect Cluster evolution in neutron-irradiated Cu at 70˚C

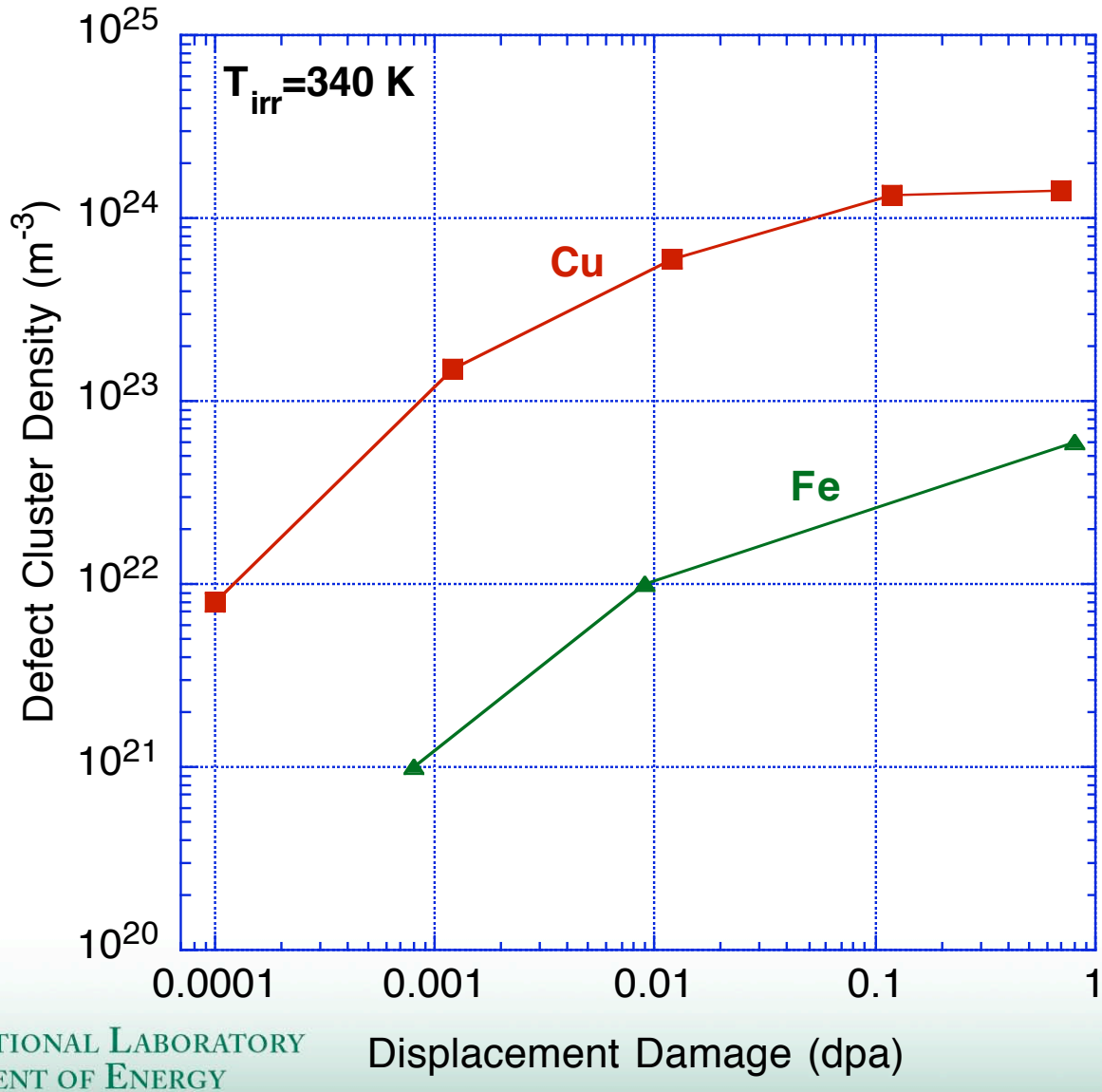


Dislocation loop evolution in neutron-irradiated Cu at 70°C

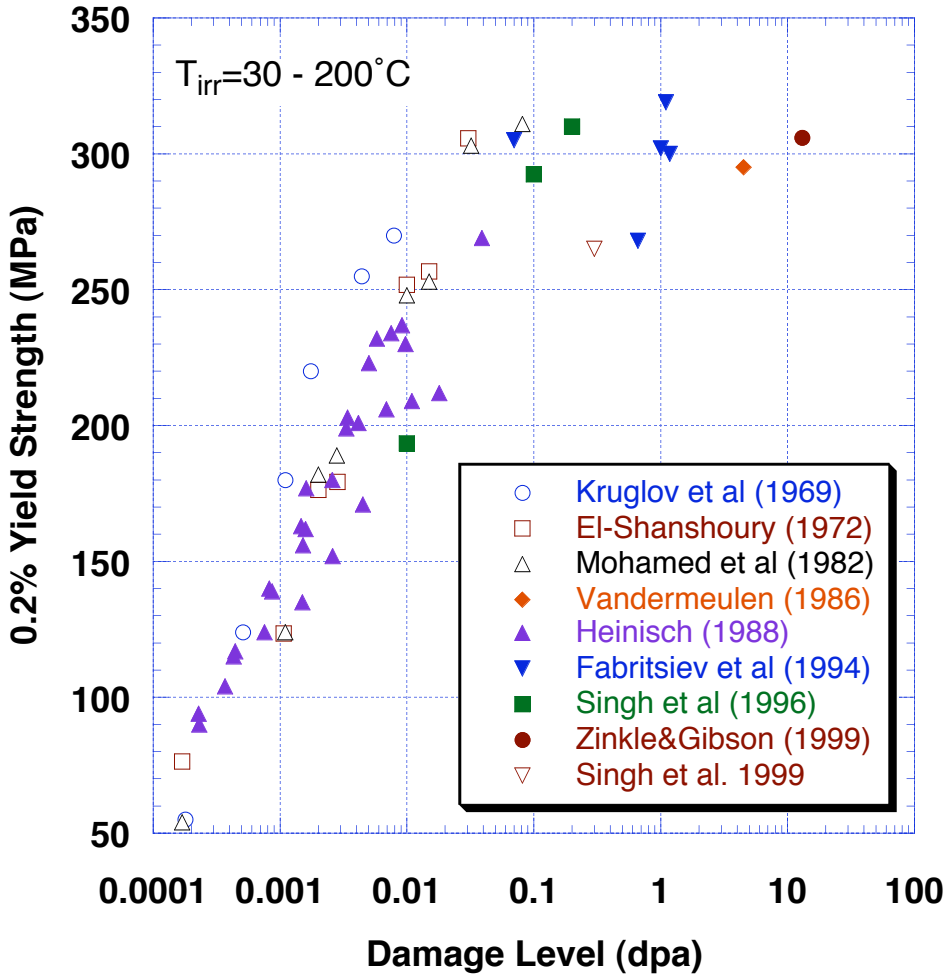


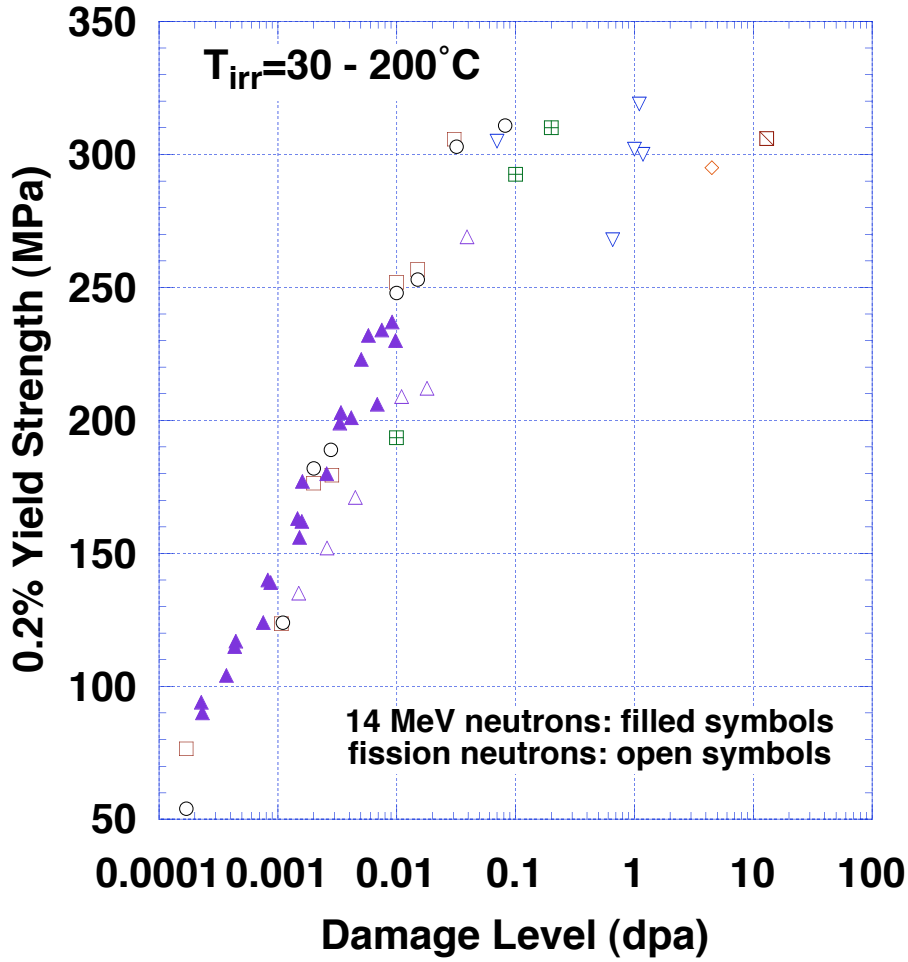
Peak loop density occurs at ~0.01 dpa

Comparison of the defect cluster accumulation behavior of irradiated Cu and Fe



Dose Dependence of Radiation Hardening in Copper





- Fission and fusion neutron radiation hardening behavior are in good agreement

Radiation Hardening in Copper: Seeger vs. Friedel relationships

- Two general models are available to describe radiation hardening ($\Delta\sigma$) in metals:
  - Dispersed barrier model (Seeger, 1958)--valid for strong obstacles

$$\Delta\sigma = M\alpha\mu b\sqrt{Nd}$$

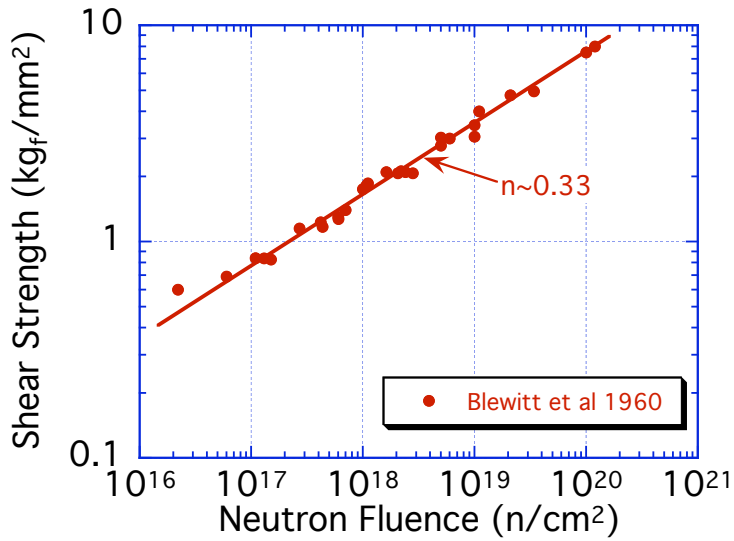
Where M=Taylor factor
α=defect cluster barrier strength
μ=shear modulus
b=Burgers vector of glide dislocation
N, d=defect cluster density, diameter

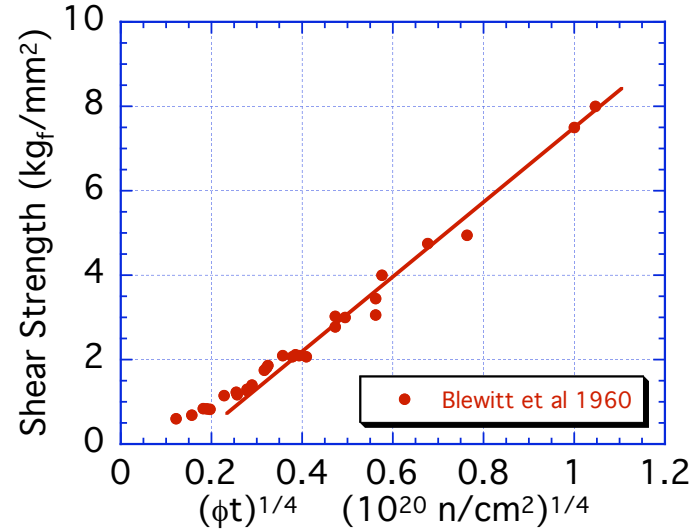
  - Friedel 1963 (also Kroupa and Hirsch 1964) weak barrier model:

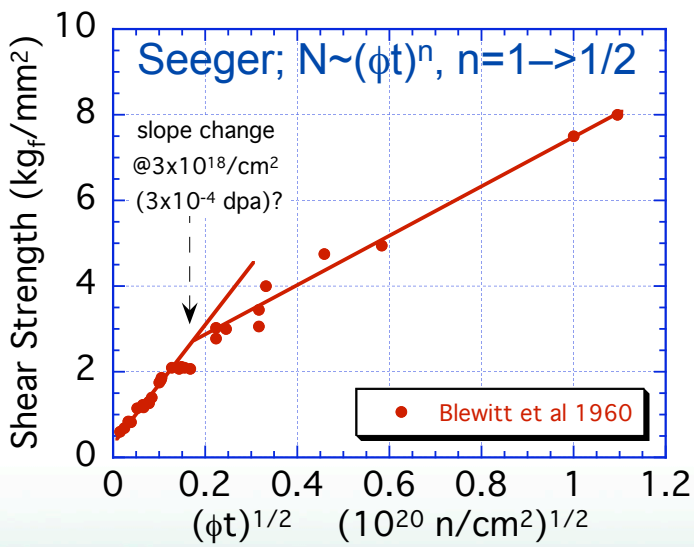
$$\Delta\sigma = \frac{1}{8} M\mu b d N^{2/3}$$

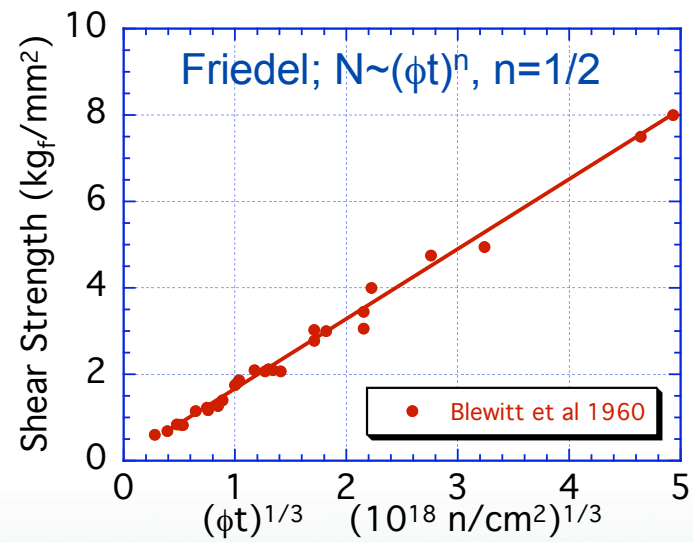
$$\Delta\sigma = M\alpha\mu b\sqrt{Nd} \quad \text{vs.} \quad \Delta\sigma = \frac{1}{8}M\mu bdN^{2/3}$$

Shear Strength of Cu Single Crystals Irradiated and Tested Near Room Temperature

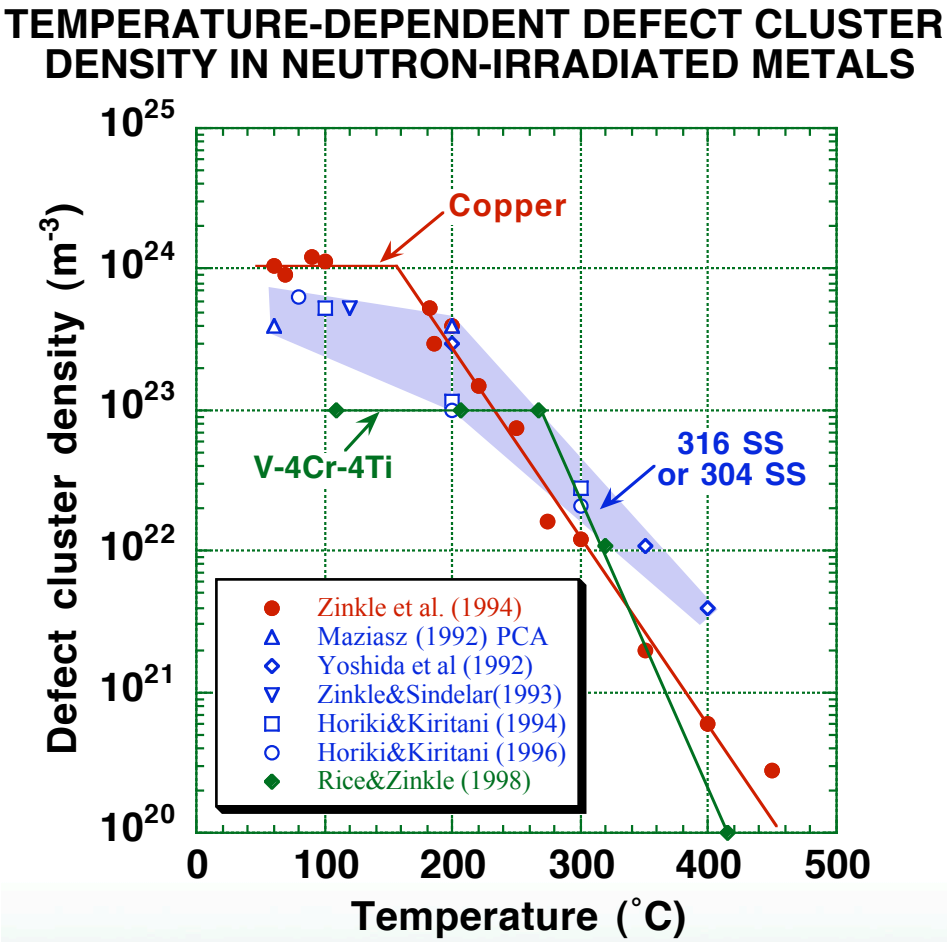


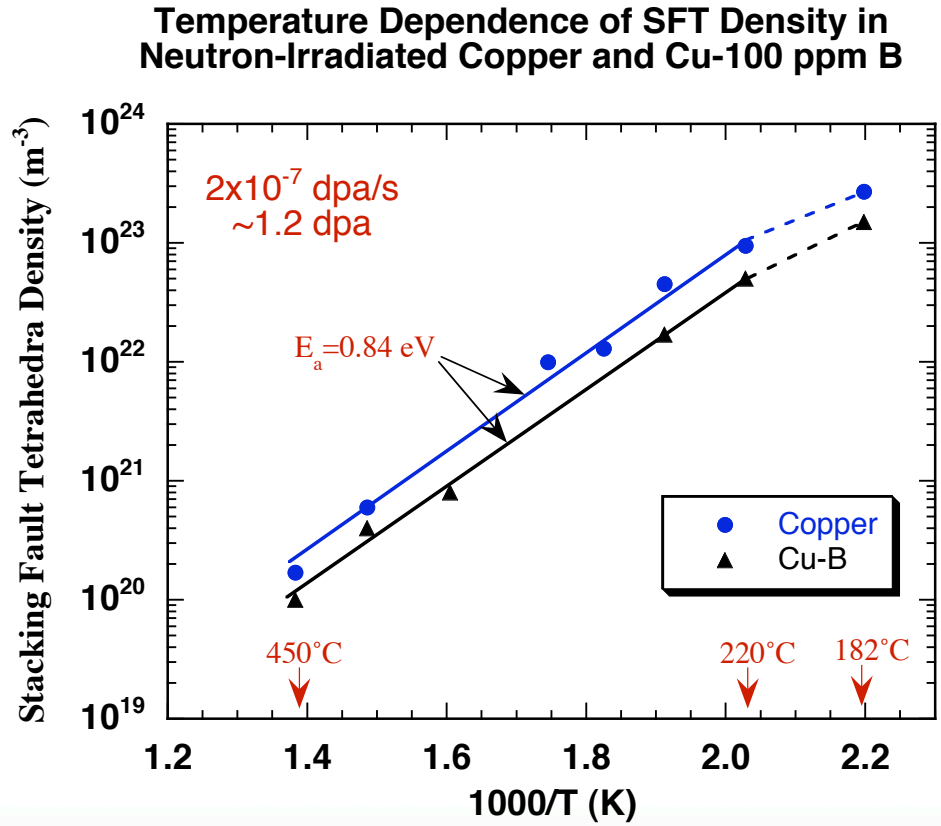




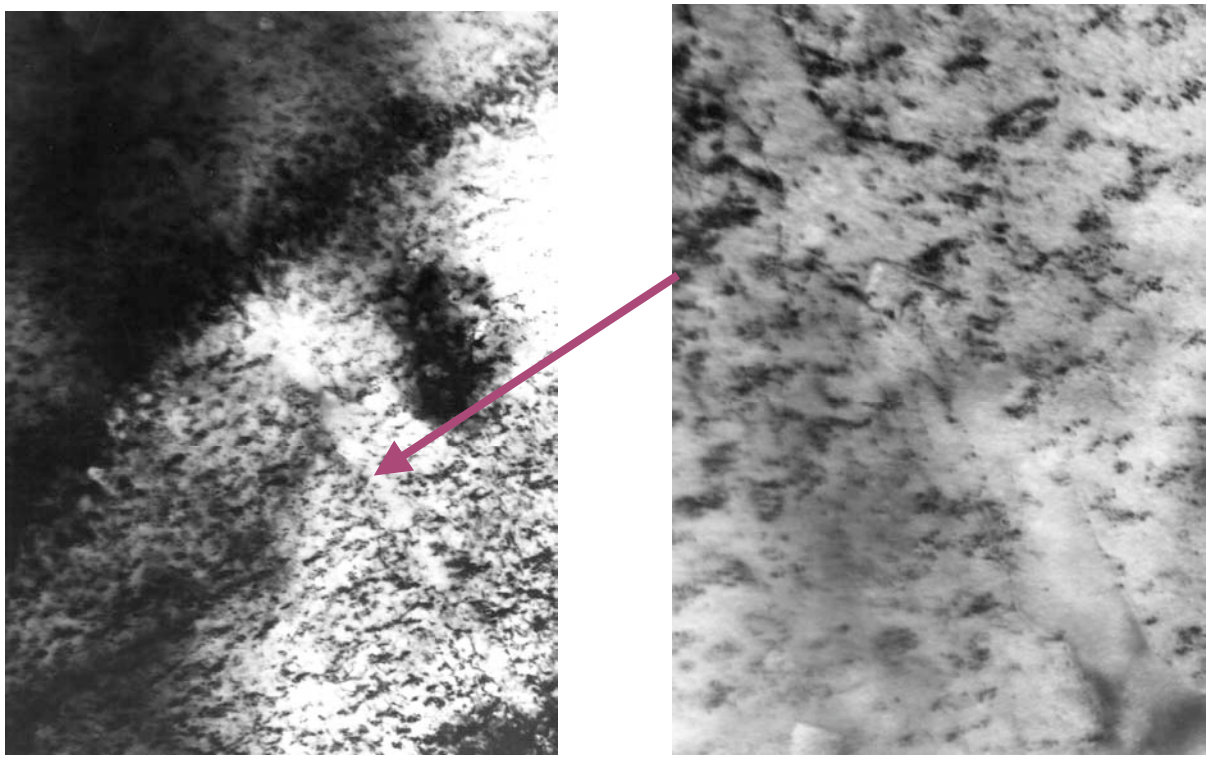


Temperature dependence of defect cluster density in neutron irradiated metals





Dislocation channeling in Fe deformed following neutron irradiation at 70˚C to 0.8 dpa



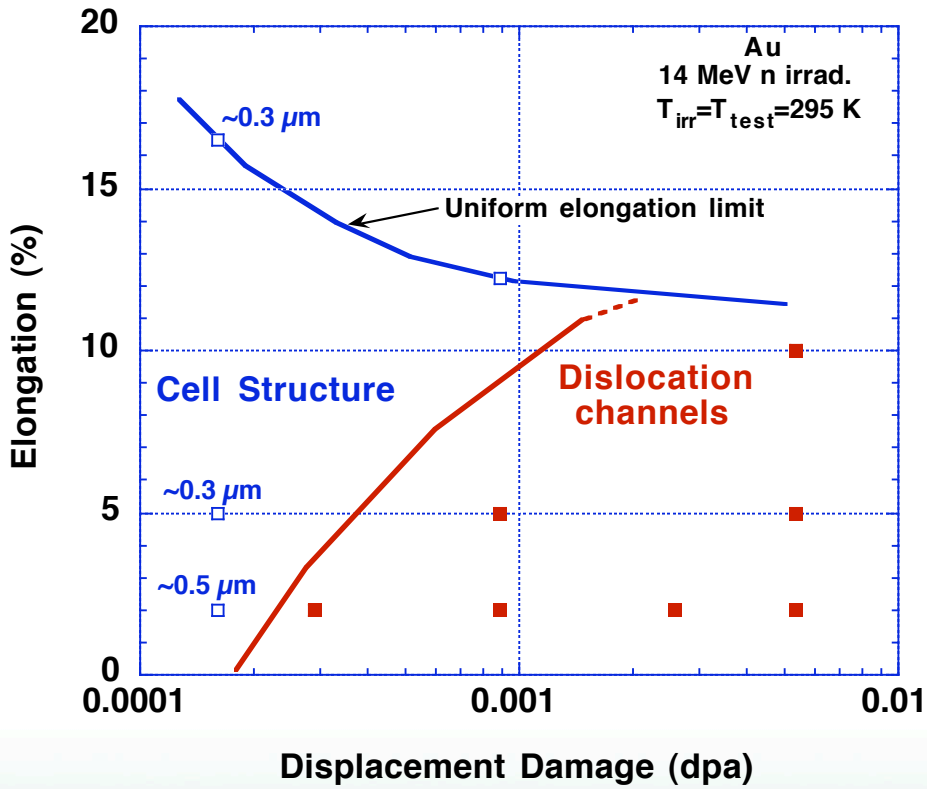
Uniform strain region

Necked region

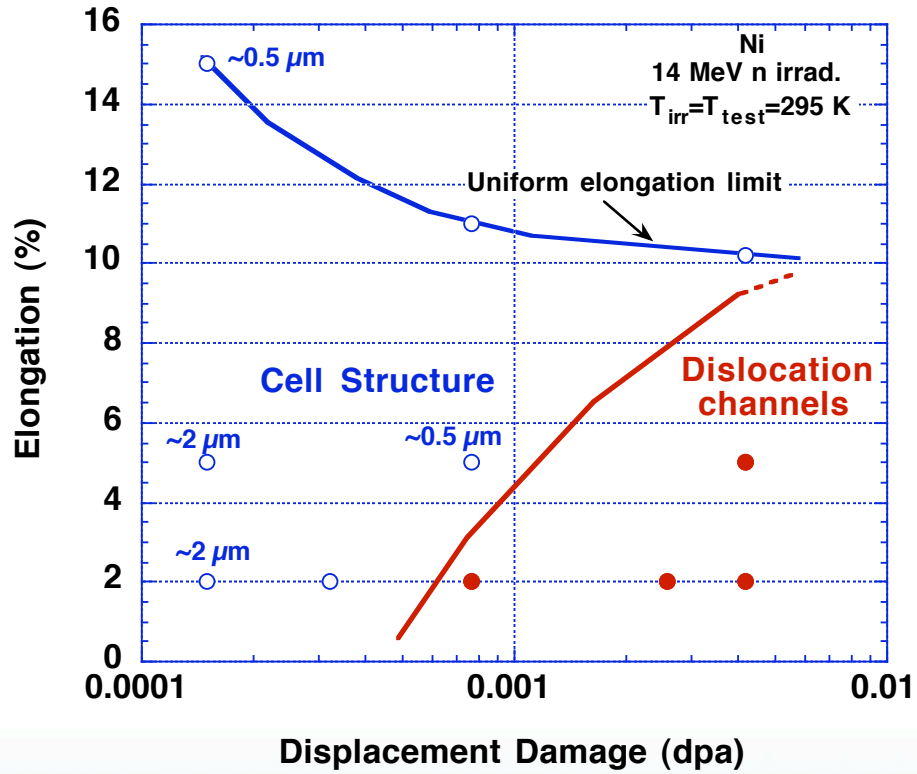
Effect of Irradiation Dose and Strain on Deformation Modes of FCC Metals

A. Okada et al. Mater. Trans. JIM 30 (1989) 265

Deformation Mode Diagram for Neutron-irradiated Au

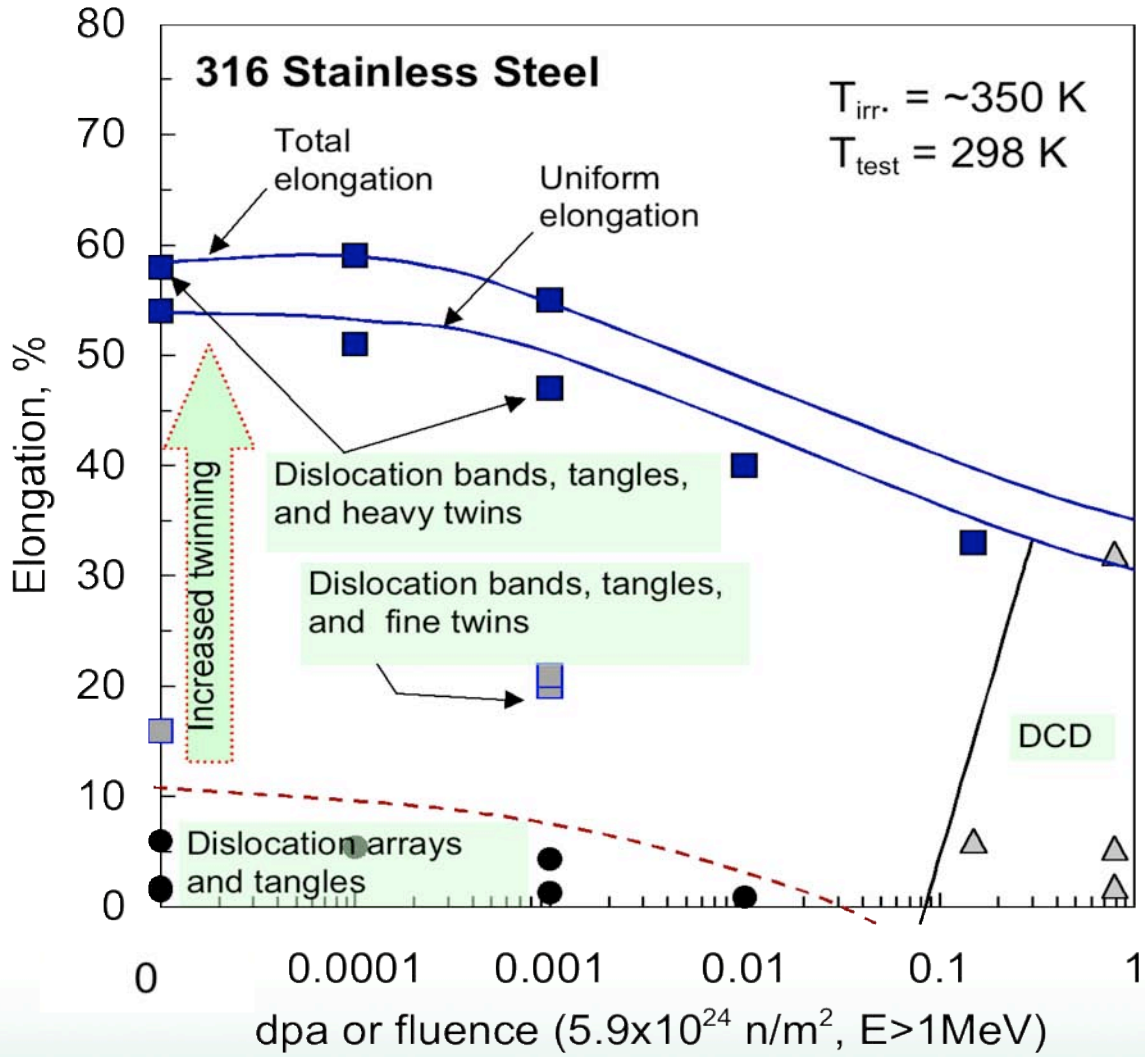


Deformation Mode Diagram for Neutron-irradiated Ni

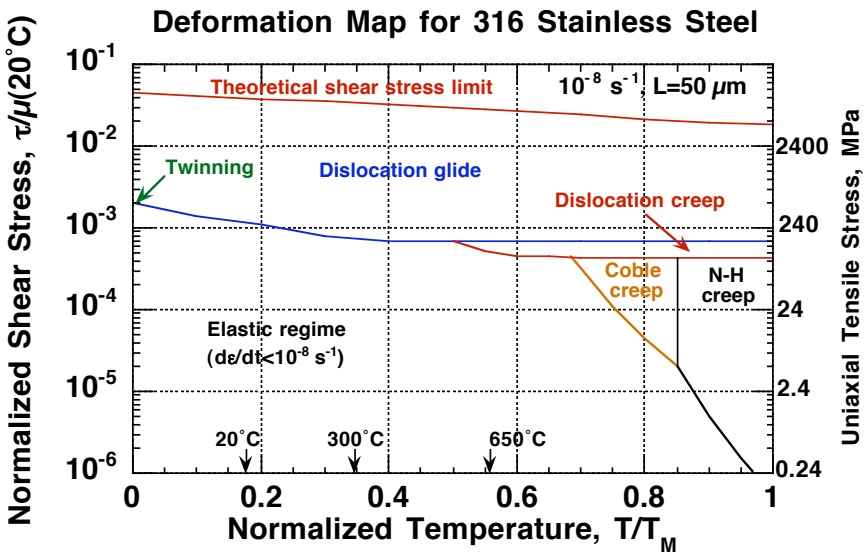


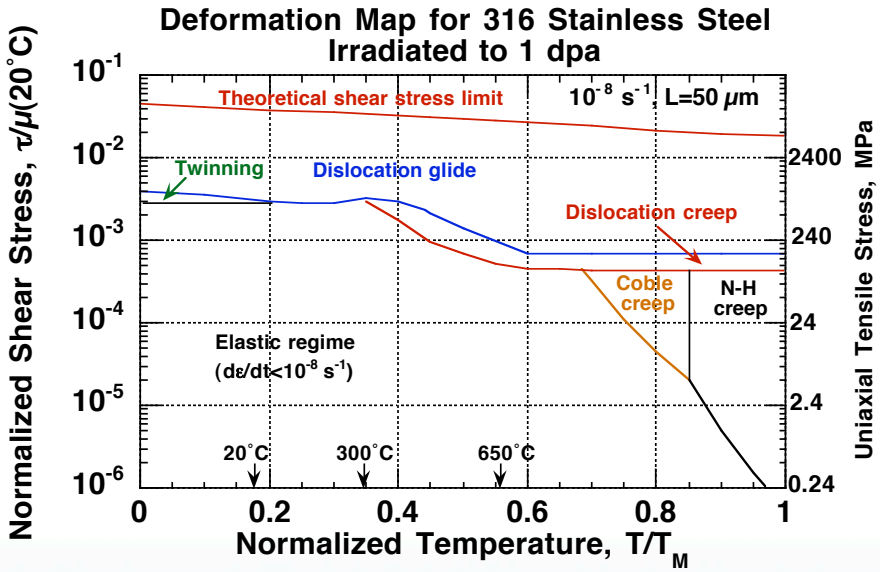
Deformation mode map for 316 SS neutron-irradiated at 65-100°C and tested at 25°C

K. Farrell et al. ORNL/TM-2002/66 (2002)

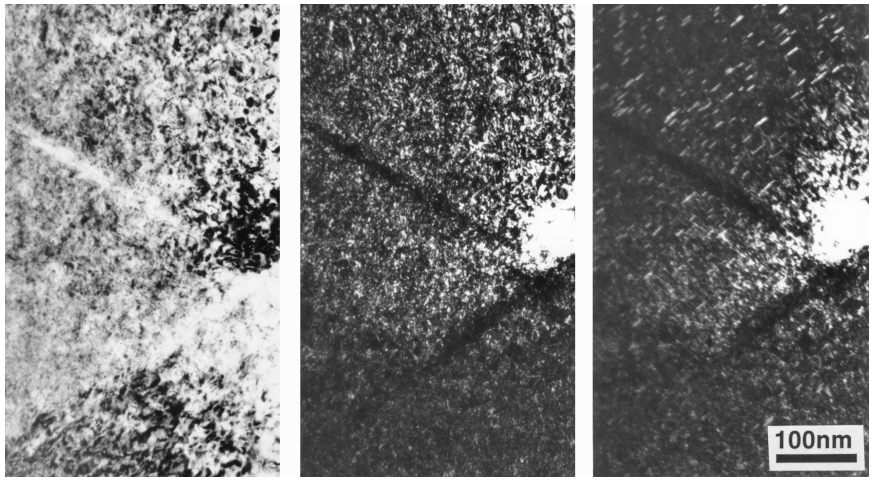


Deformation mechanisms in FCC metals

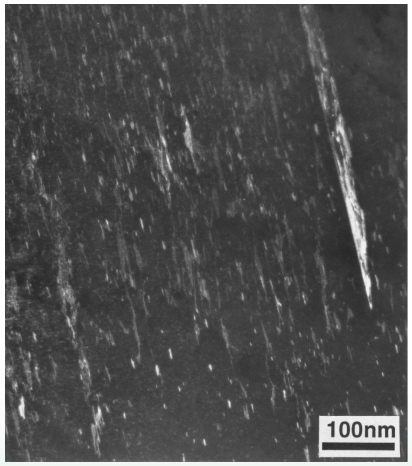




Dislocation channels, twins and martensite are observed in irradiated 316SS after deformation



Channeling (Disln glide) occurs at higher temperatures (~300˚C)

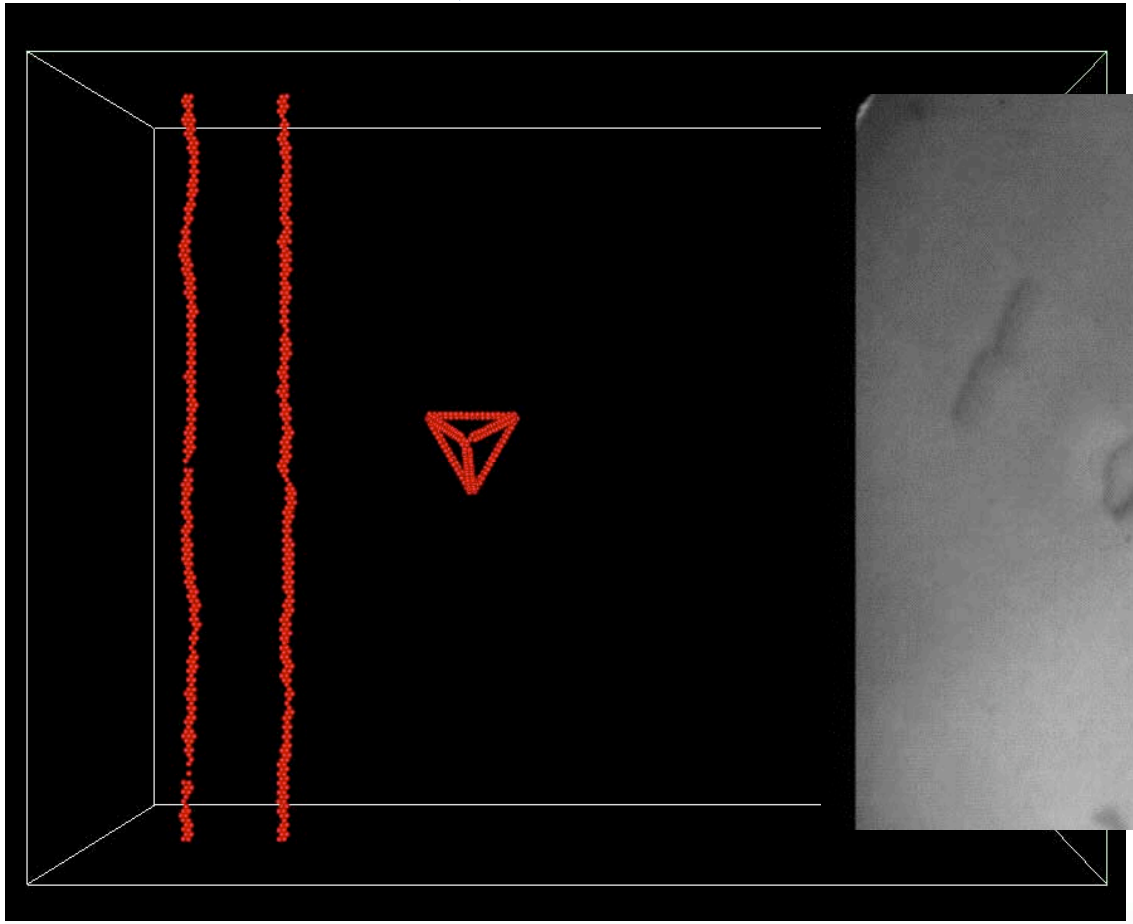


Twinning occurs at lower temperatures (<200˚C) and high strain rates

MD and TEM in-situ deformation studies are investigating fundamental dislocation-defect cluster interactions

- Dislocation pinning and defect cluster annihilation

3.5e6 Cu atoms, 136 vac SFT (L=4nm),
T=300 K, strain rate=5e6/s



Molecular Dynamics simulation (Y. Osetsky)

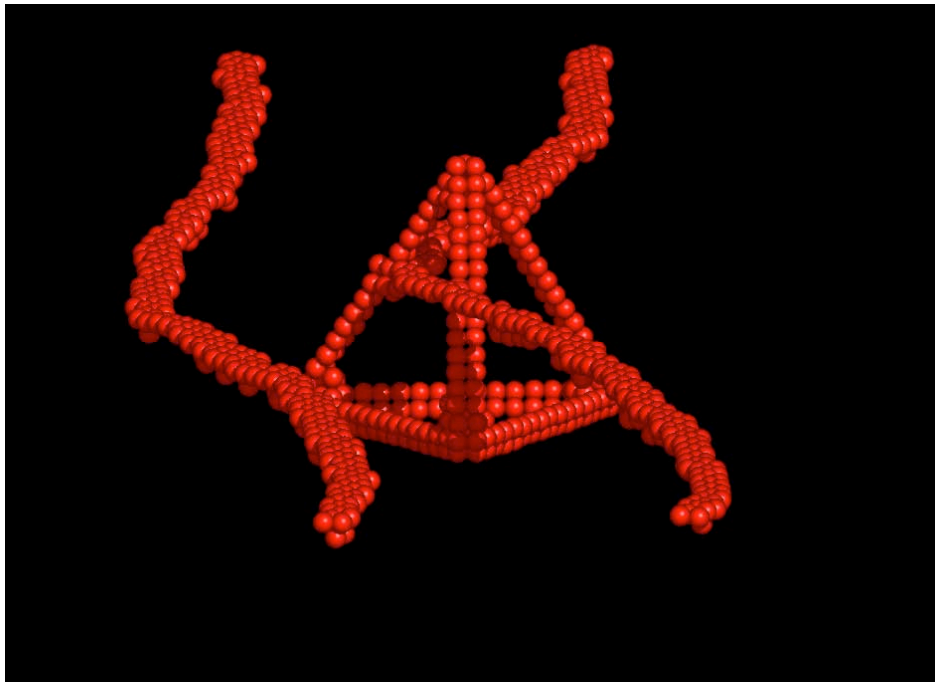
In-situ TEM observation
(Y. Matsukawa)

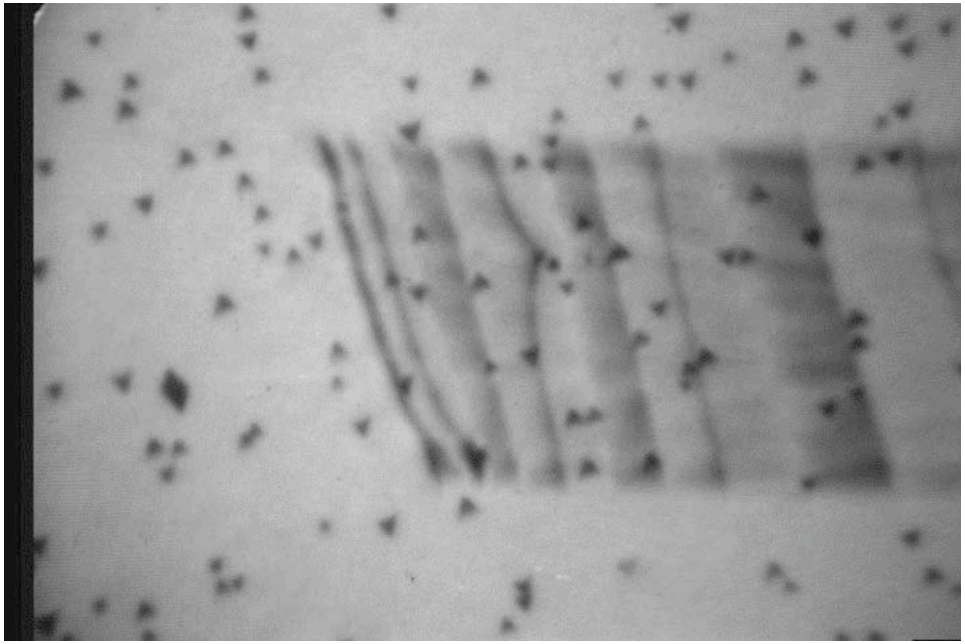
Investigation of dislocation interactions with SFTs

SFT annihilation by a single dislocation

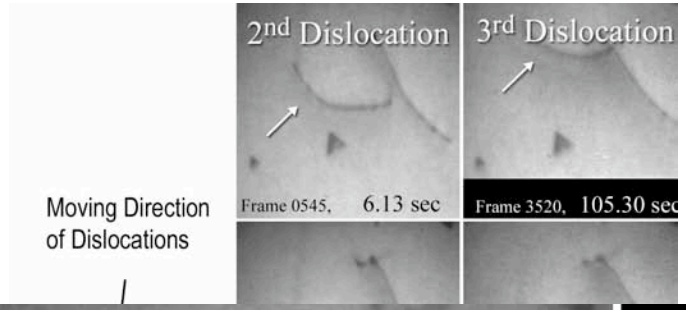
Investigation of dislocation interactions with SFTs

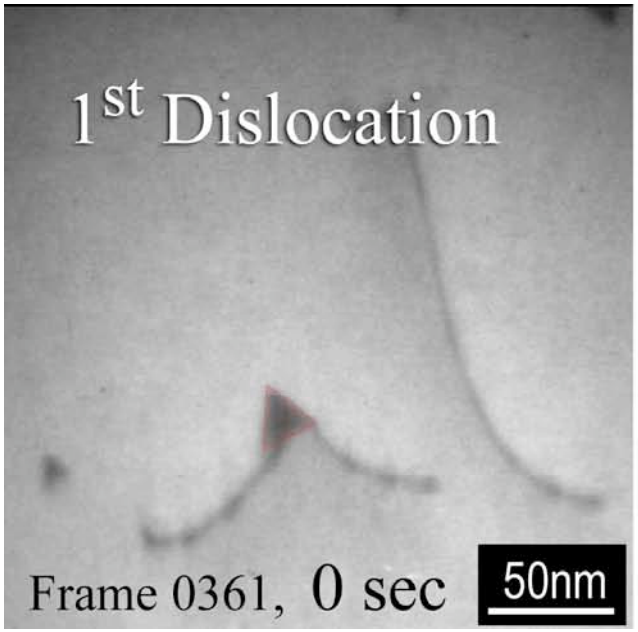
Dislocation pinning by small SFTs (no annihilation)

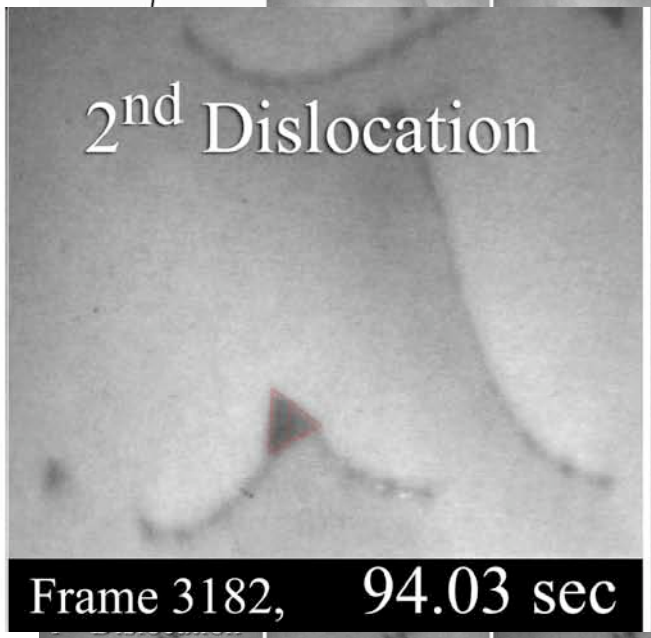


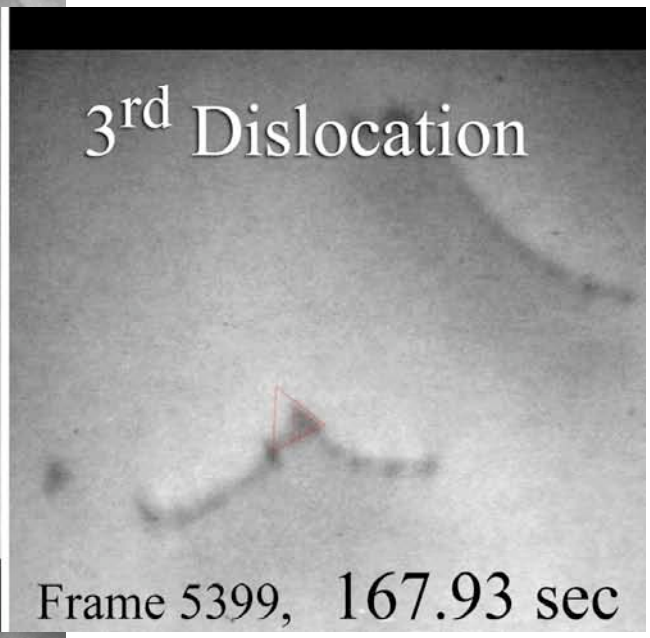


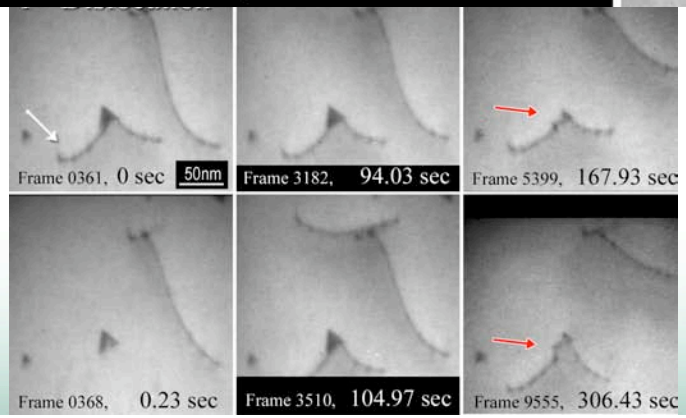
Investigation of dislocation annihilation of SFTs



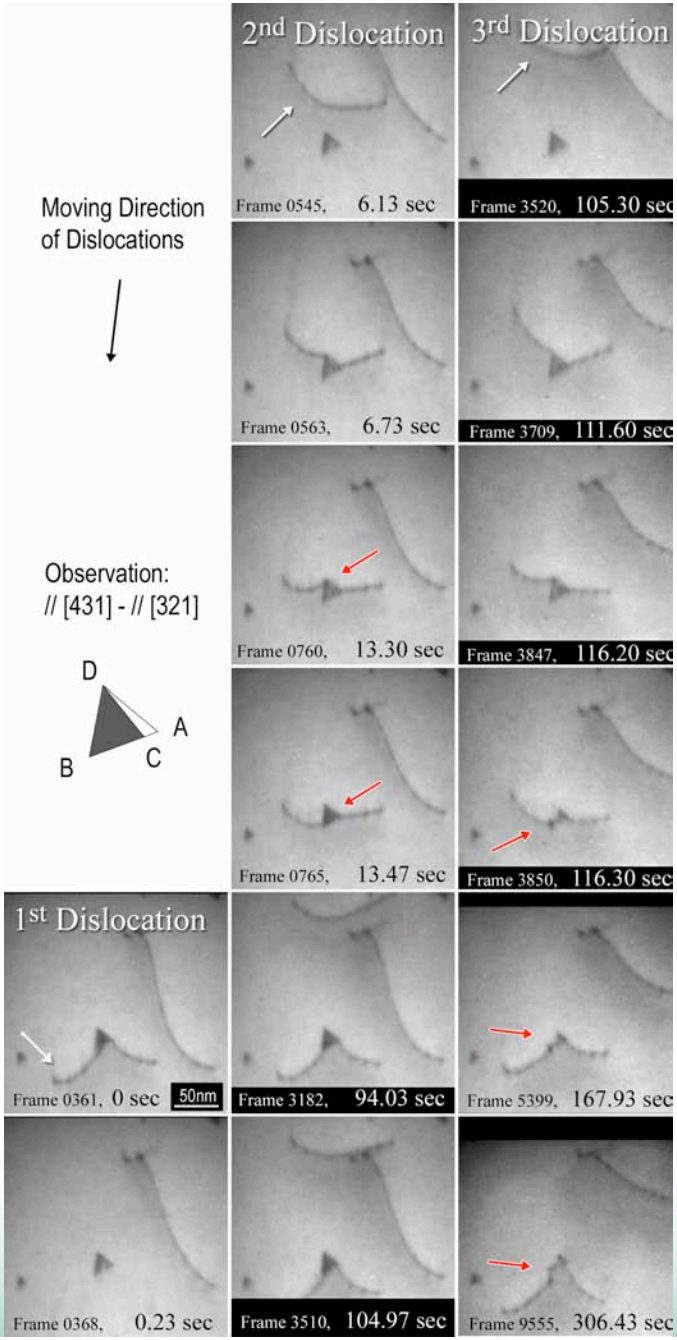


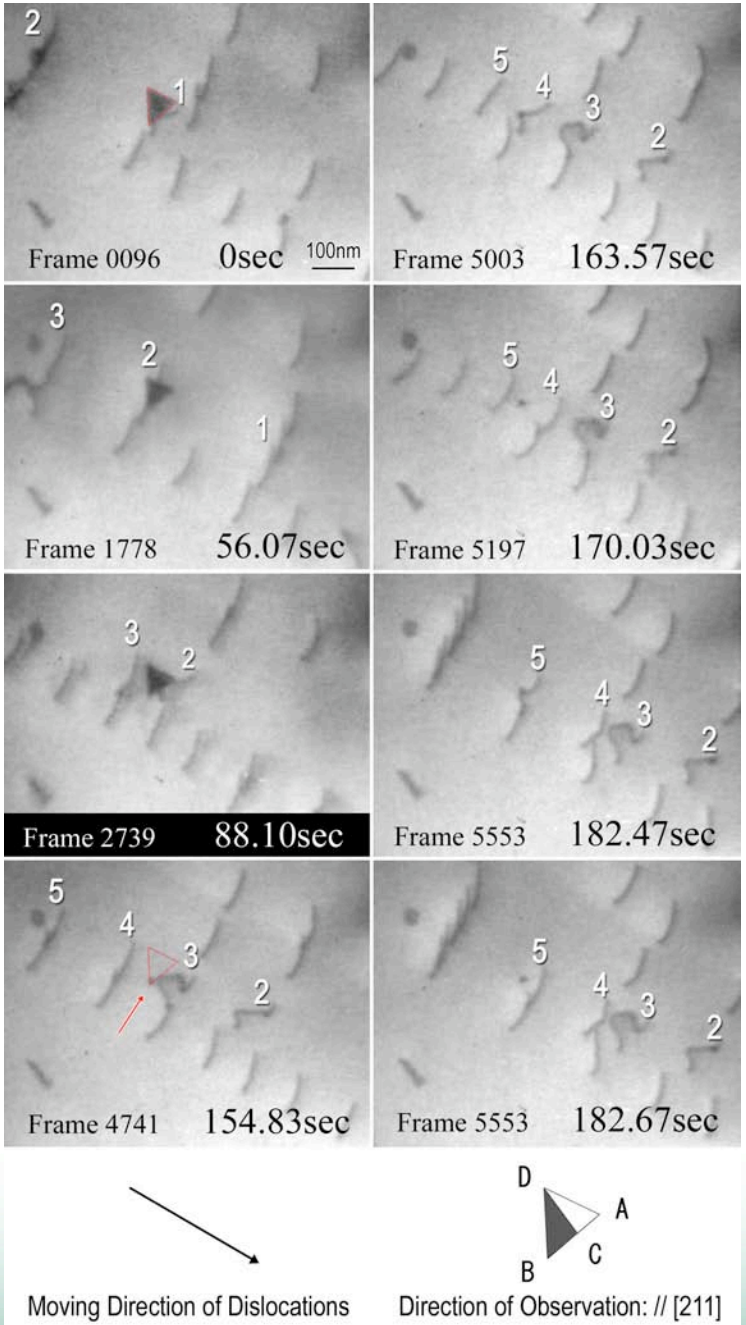




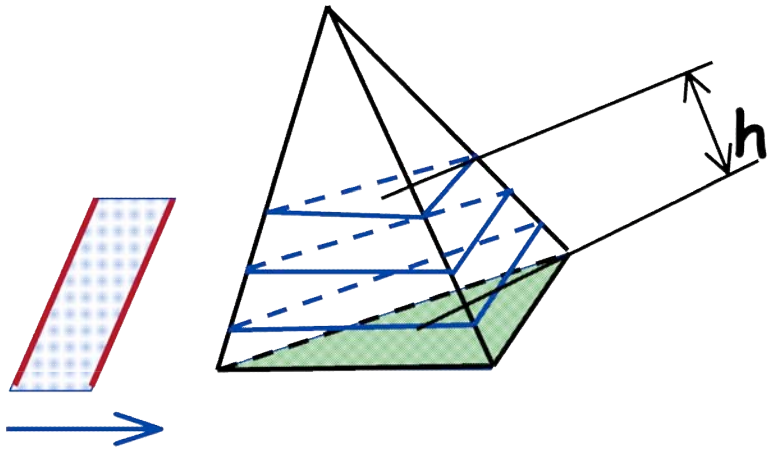


Investigation of dislocation annihilation of SFTs

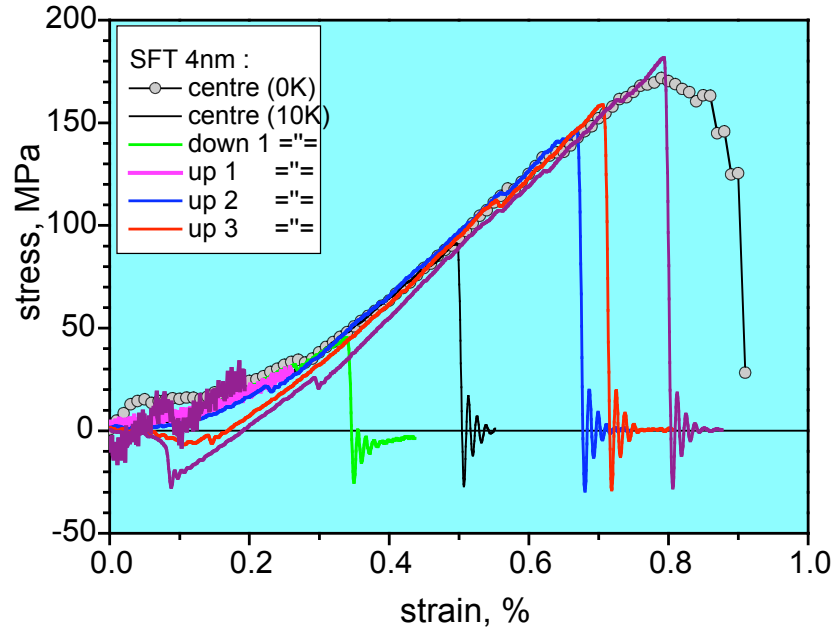


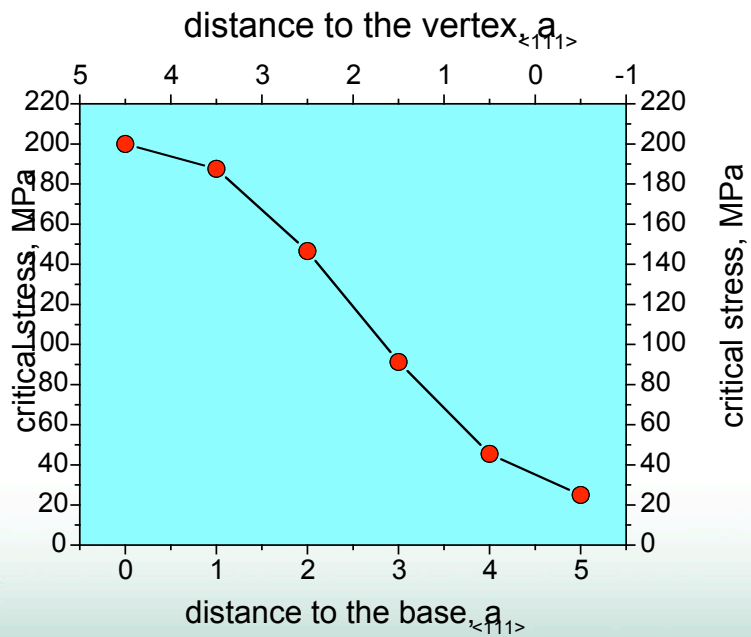


Effect of Dislocation-SFT Interaction Height (136-vacancy SFT, T=10K)



B=1/2<110>

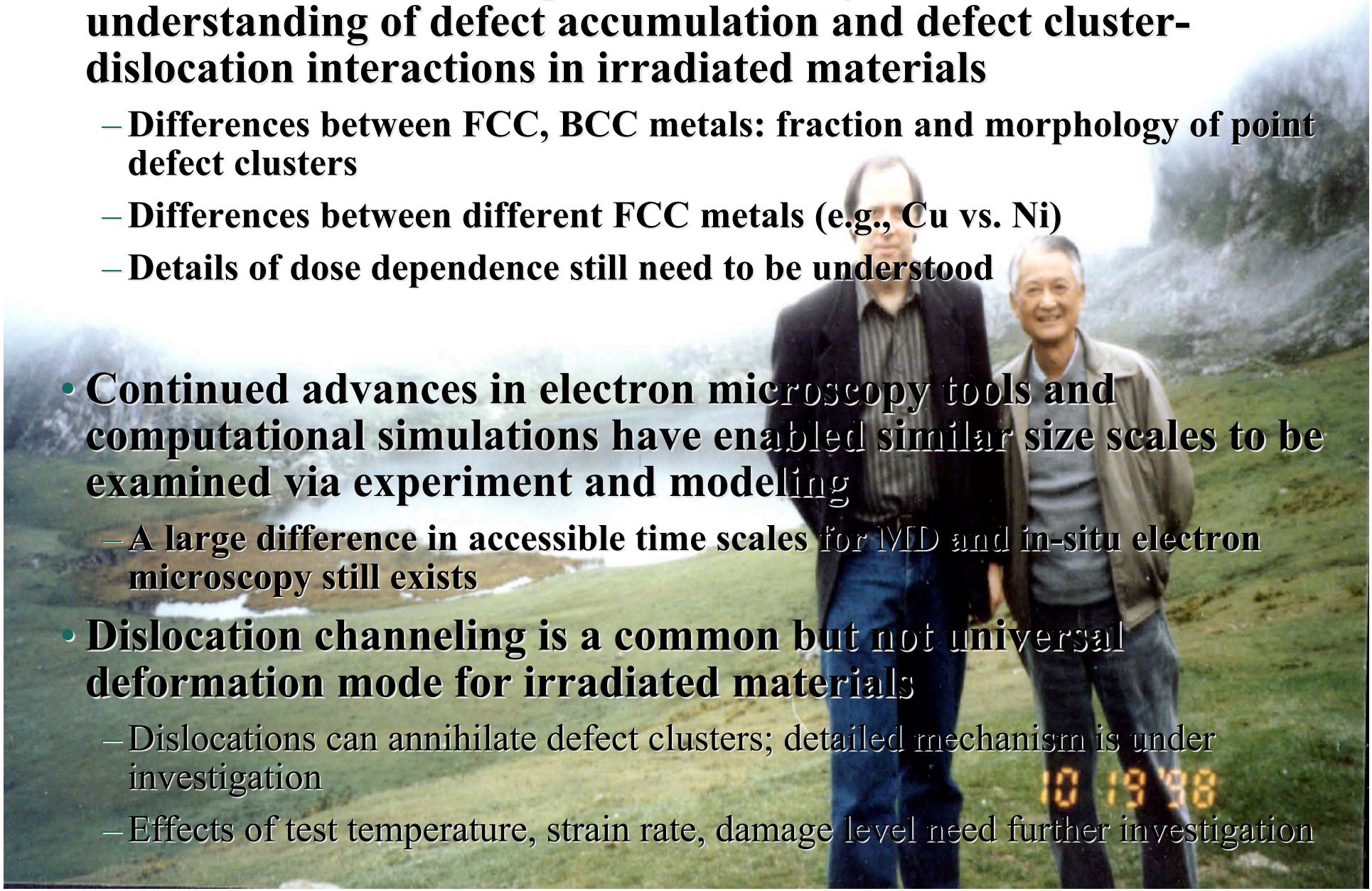




Y Osetsky et al.
ICFRM-11

Conclusions

- **Microstructural investigations are a key tool for fundamental understanding of defect accumulation and defect cluster-dislocation interactions in irradiated materials**
  - **Differences between FCC, BCC metals: fraction and morphology of point defect clusters**
  - **Differences between different FCC metals (e.g., Cu vs. Ni)**
  - **Details of dose dependence still need to be understood**



- **Continued advances in electron microscopy tools and computational simulations have enabled similar size scales to be examined via experiment and modeling**
  - **A large difference in accessible time scales for MD and in-situ electron microscopy still exists**
- **Dislocation channeling is a common but not universal deformation mode for irradiated materials**
  - Dislocations can annihilate defect clusters; detailed mechanism is under investigation
  - Effects of test temperature, strain rate, damage level need further investigation