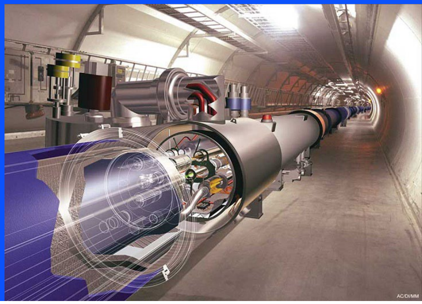
Superconductivity & Particle AcceleratorS 2024
Polish Academy of Sciences

PREDICTING LIFETIME OF IRRADIATED METASTABLE MATERIALS AT EXTREMELY LOW TEMPERATURES

Błażej Skoczeń

Research Centre
Laboratory of Extremely Low Temperatures
Cracow University of Technology



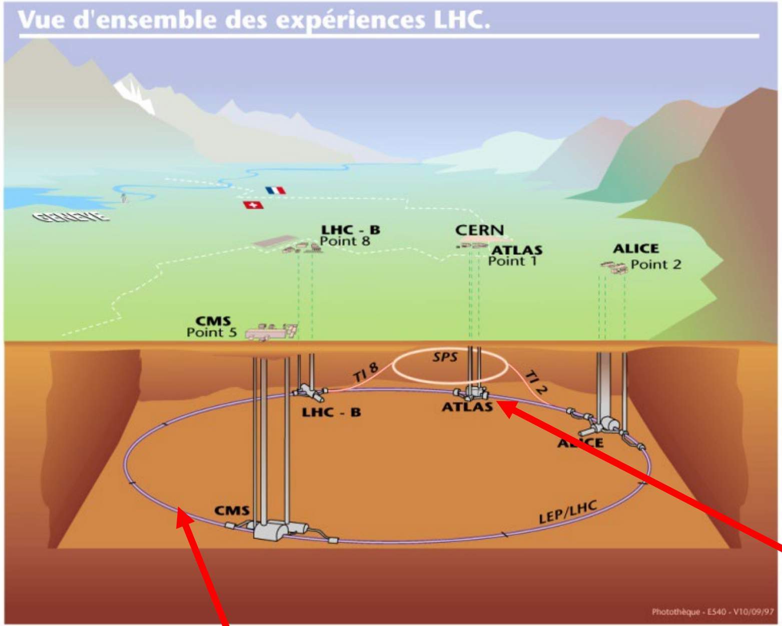
Outline:

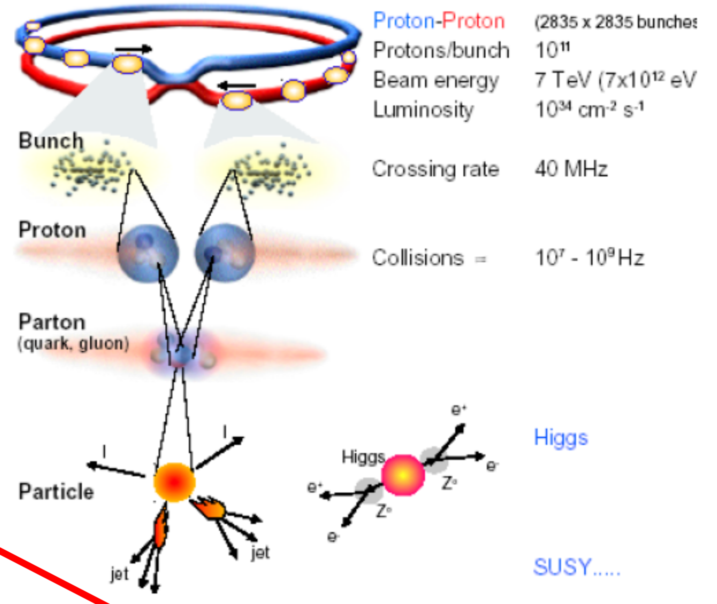
1. Motivation: radiation sources at cryogenic temperatures
2. Strain induced fcc-bcc phase transformation
3. Radiation induced damage
4. Radiation induced hardening
5. Conclusions

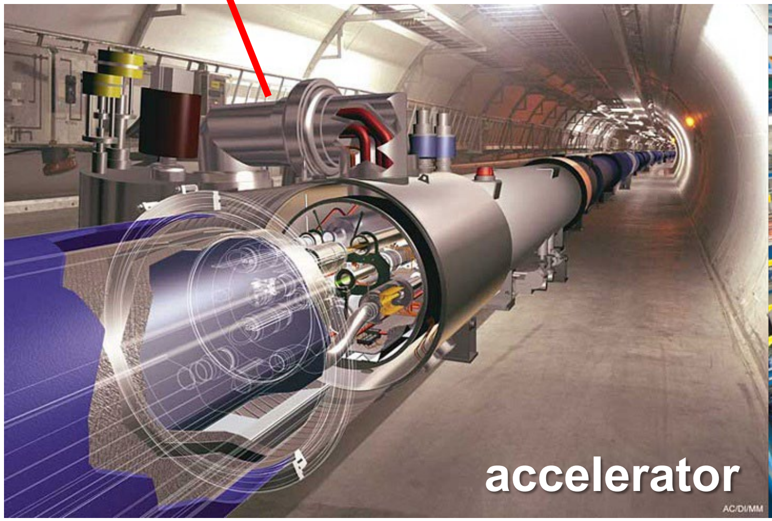
Research Centre –

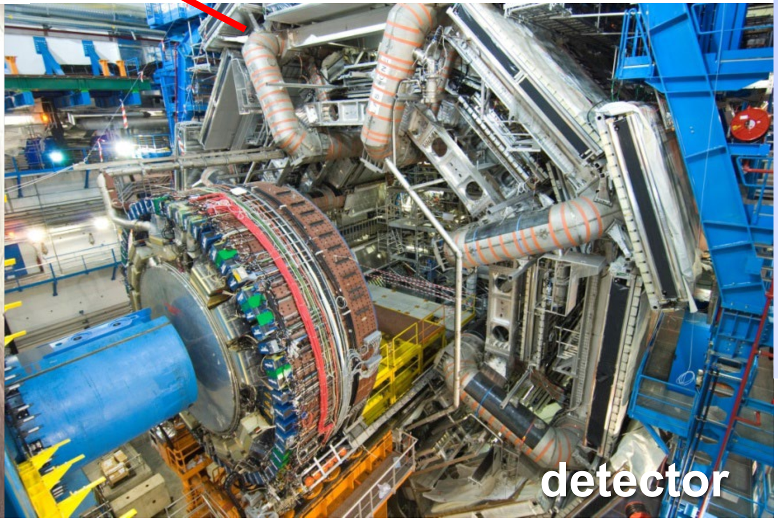
Laboratory of Extremely Low Temperatures (RC-LENT)

Motivation: CERN Large Hadron Collider





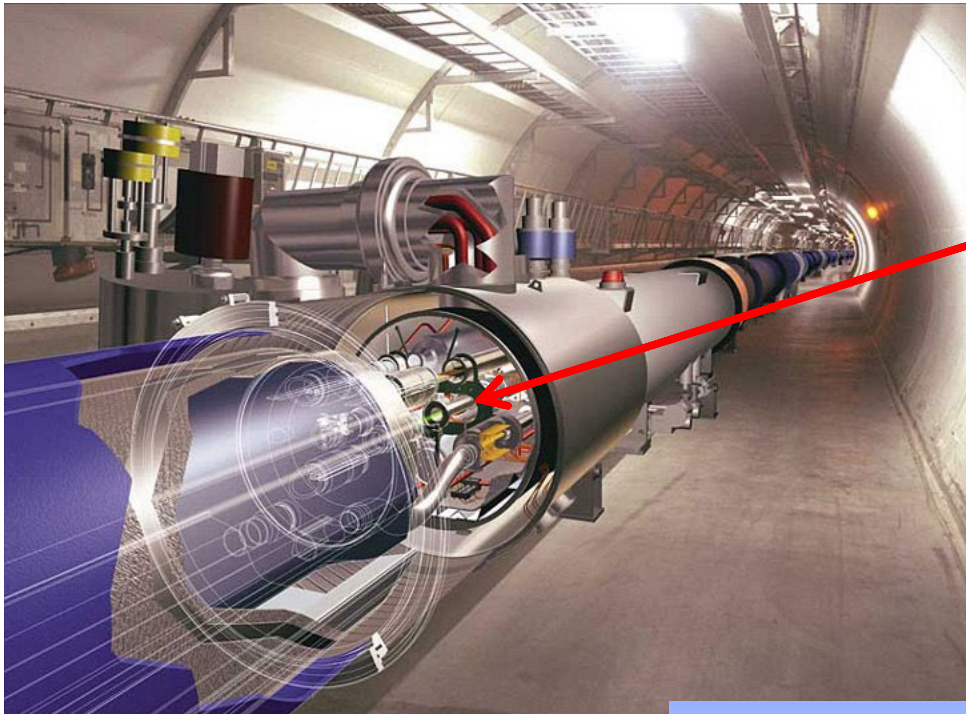


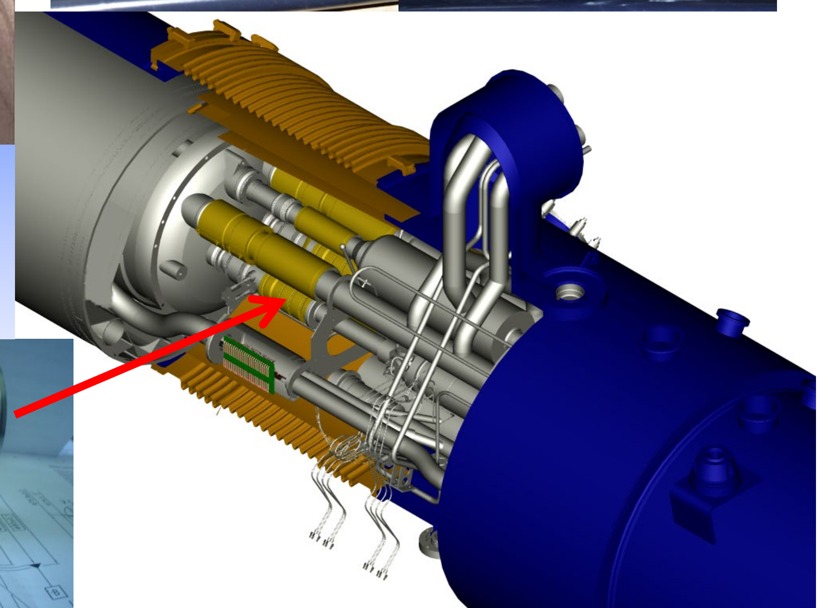


LHC is the largest scientific instrument in the world based on the principle of super-conductivity!

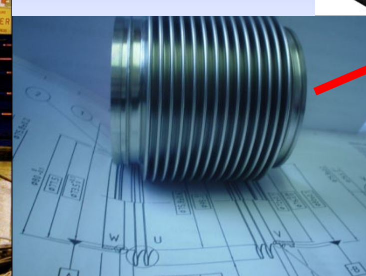
LHC operates in super-fluid helium at 1.9 K

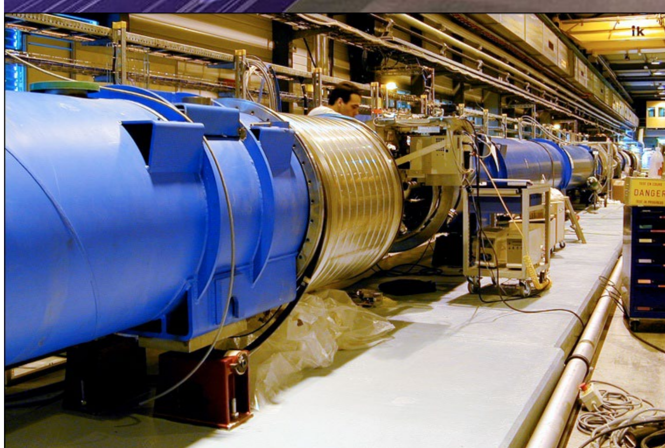
Motivation: CERN Large Hadron Collider





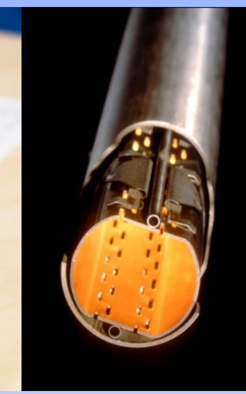
20000 expansion bellows





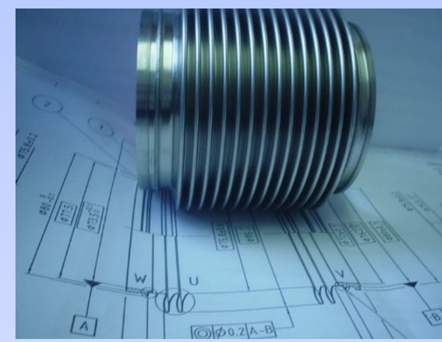
Materials used at low temperatures: LHC, FCC, ITER

Modern materials for extremely low temperatures (0-5 K):



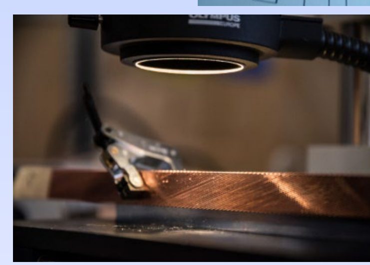
I Metals:

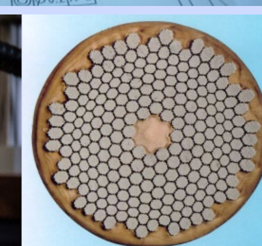
Al, Ag, Be, Cu, Sn, Ta, Ti, Zr, etc.



II Alloys:

304L, 316L, 316LN, 316Ti, P506, JK2LB, etc.





III Composites:

NbTi, NbAl, Nb_3Sn, MgB_2, Bi2212, etc.

General program of research

I constitutive models of single phenomena

Strain induced phenomena at extremely low temperatures

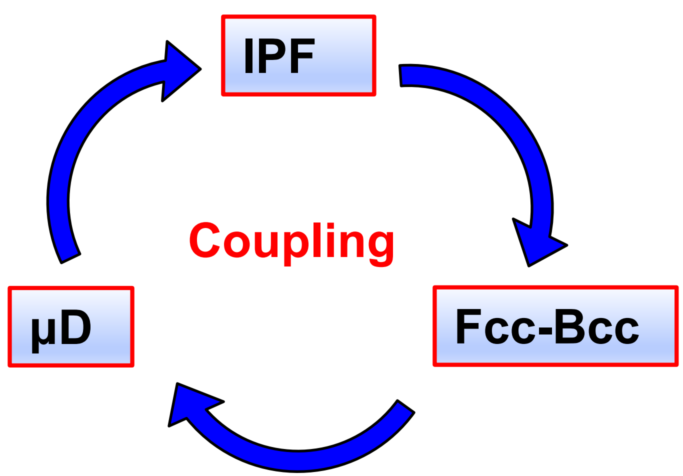
- Intermittent plastic flow **IPF**
- Plastic strain induced **Fcc-Bcc** phase transformation
- Nucleation and evolution of micro-damage **µD**

Done

- Fracture at low temperatures **LTF**
- Creep at low temperatures **LTC**

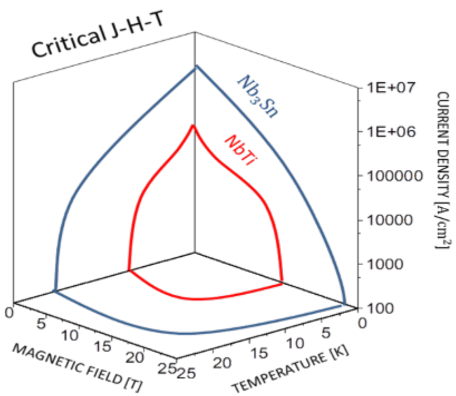
In progress

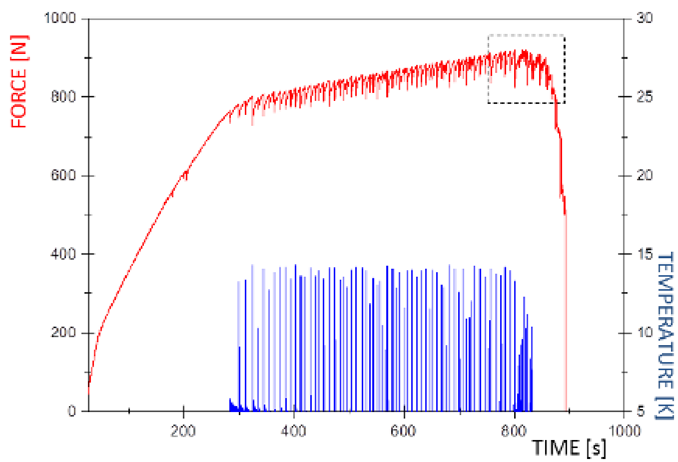
II coupling between the phenomena

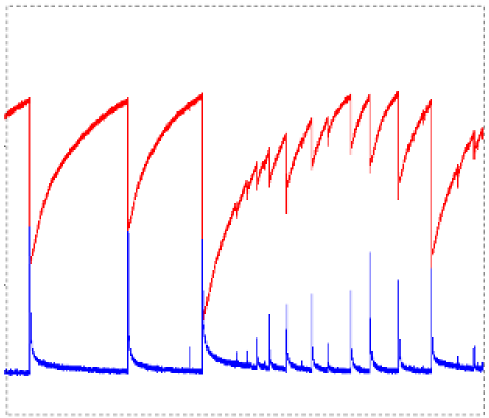


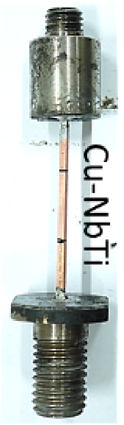
In progress

Problem 8: IPF in the intermetallic composites (superconductors)



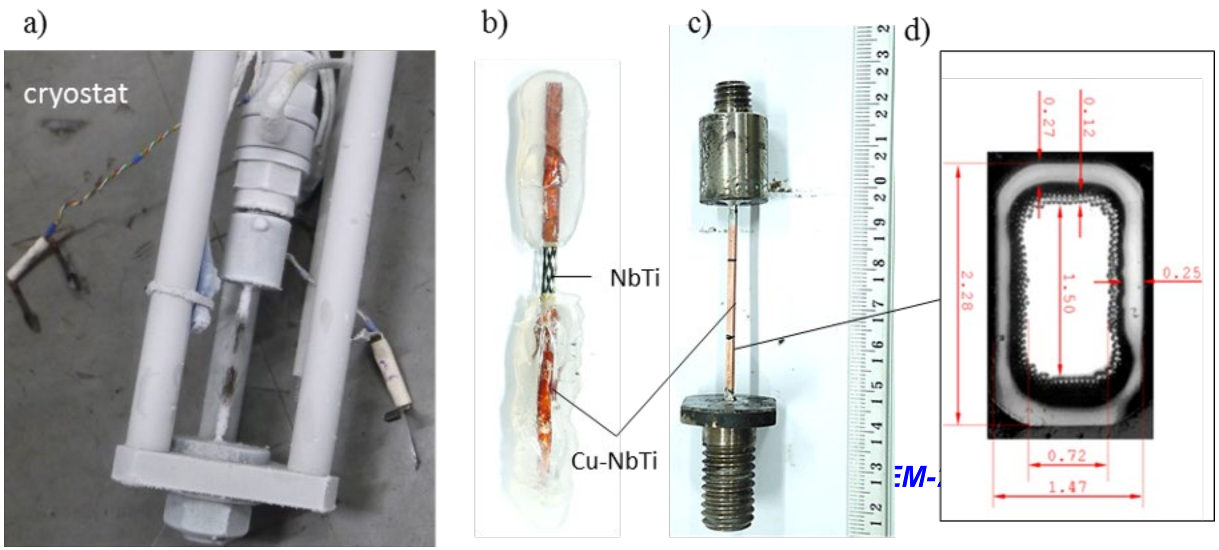






The critical surface for NbTi and Nb_3Sn filaments

The intermittent plastic flow in NbTi specimen in LHe (4.2 K)



Superconducting multifilament composite based on NbTi wires:

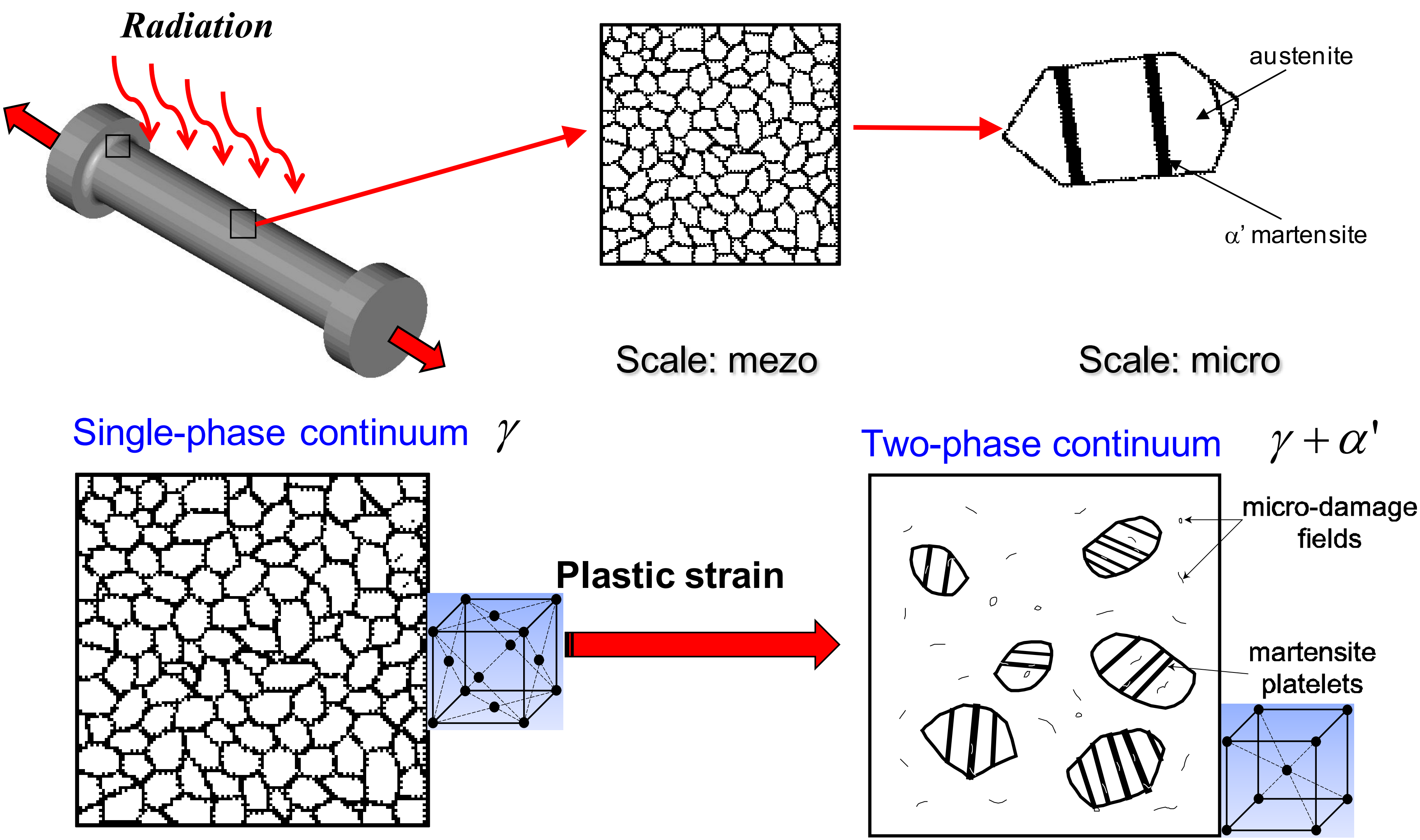
a) the specimen in the test set-up (cryostat insert),

b) NbTi filaments extracted from the copper matrix,

c) the NbTi specimen ready for testing,

d) the cross section of the NbTi specimen.

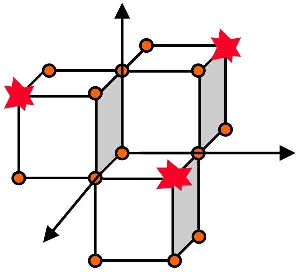
Coupled field problems: radiation versus phase transformation



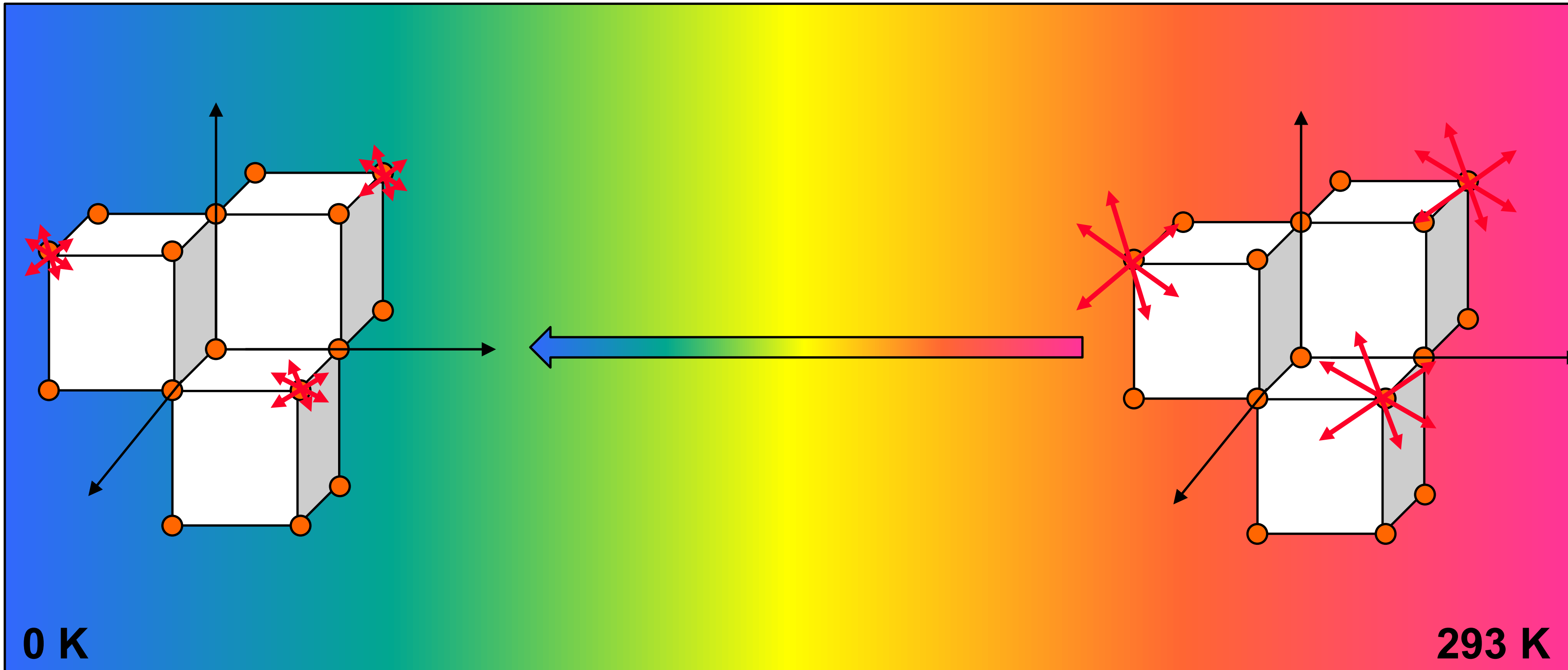
Laboratory of Extremely Low Temperatures RC-LENT

genic temperatures

Thermodynamics in the proximity of absolute zero



Thermodynamics of lattice at low temperatures



Temperature = measure of lattice excitation

$$\lim_{T \to 0} S(T, V, N) = 0$$

III-rd law of thermodynamics (Nernst; for perfect crystals)

Thermodynamics of lattice at low temperatures

Hamilton operator of lattice vibrations:

$$H = H_0 + \sum_{\alpha,\underline{k}} \hbar\omega_\alpha(\underline{k}) a_\alpha^+(\underline{k}) a_\alpha(\underline{k})$$

Number of phonons operator and its eigenvalues:

$$a_\alpha^+(\underline{k}) a_\alpha(\underline{k}) \longrightarrow N_\alpha(\underline{k})$$

Energy of lattice vibrations:

$$E = E_0 + \sum_{\alpha,\underline{k}} \hbar\omega_\alpha(\underline{k}) N_\alpha(\underline{k})$$

Phonon energy of lattice:

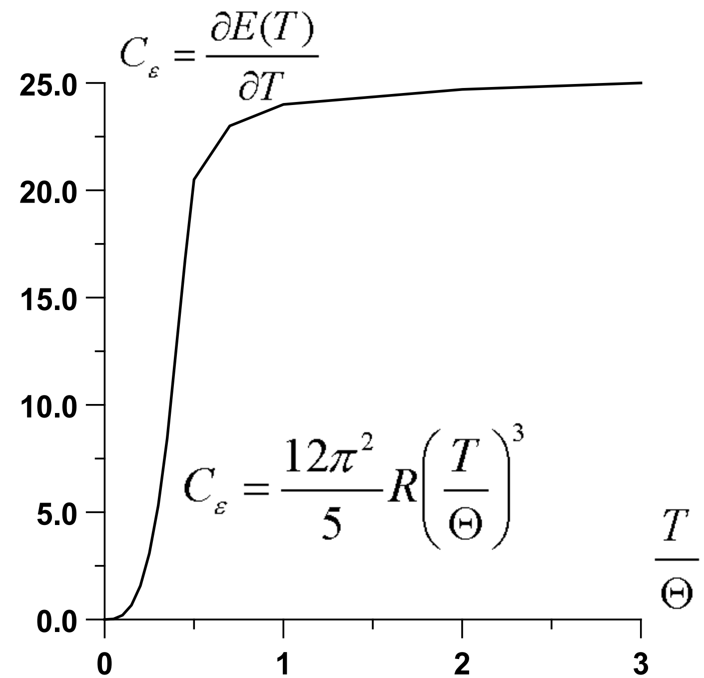
$$\Delta E = \sum_{\alpha,\underline{k}} \hbar\omega_\alpha(\underline{k}) f_0(\omega_\alpha) \Rightarrow \int_0^{\omega_{\max}} f_0(\omega)\nu(\omega)\hbar\omega d\omega$$

$$E_{ph} \sim N\left(\frac{T}{\Theta}\right)^3 T$$

Thermodynamics of lattice at low temperatures

Specific heat at constant volume:

$$\left(C_{ph}\right)_V = \left(\frac{\partial E_{ph}}{\partial T}\right)_V \sim N\left(\frac{T}{\Theta}\right)^3 \qquad \left(C_{el}\right)_V \sim \frac{T}{T_F}$$



$$C_V = \left(C_{el}\right)_V + \left(C_{ph}\right)_V \sim aT + bT^3$$

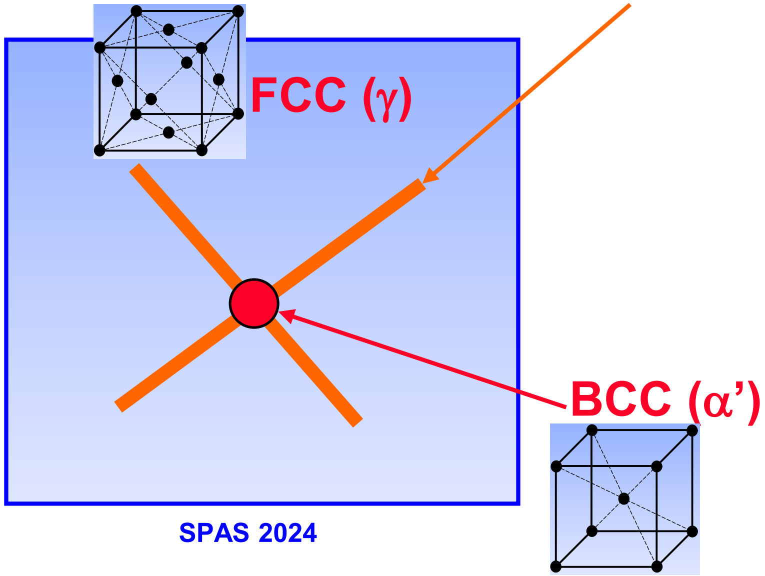
$$\lim_{T\to 0} C_V = 0$$

$$dQ = mC_V dT \qquad \frac{dT}{dQ} = \frac{1}{mC_V}$$

$$T \to 0 \Rightarrow \frac{dT}{dQ} \to \infty$$

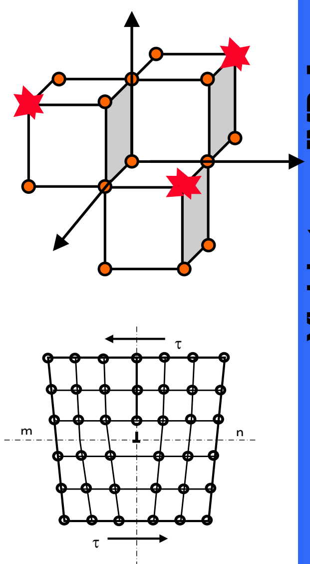
Quantum ΔQ causes large ΔT → "thermodynamic instability"

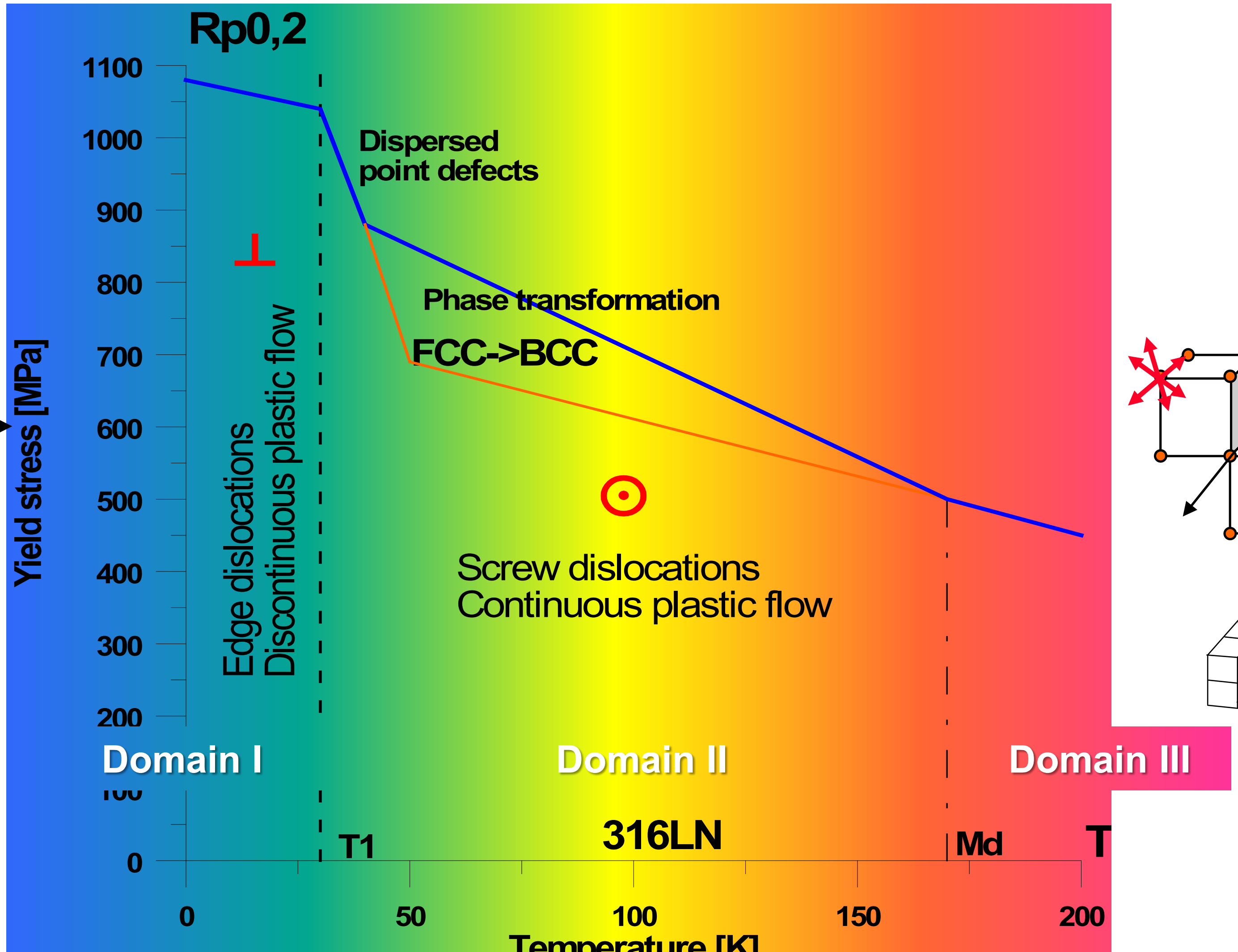
Strain induced fcc-bcc phase transformation

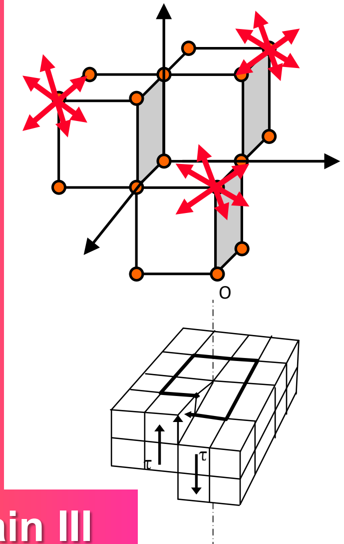


Mechanisms of plastic flow at cryogenic temperatures

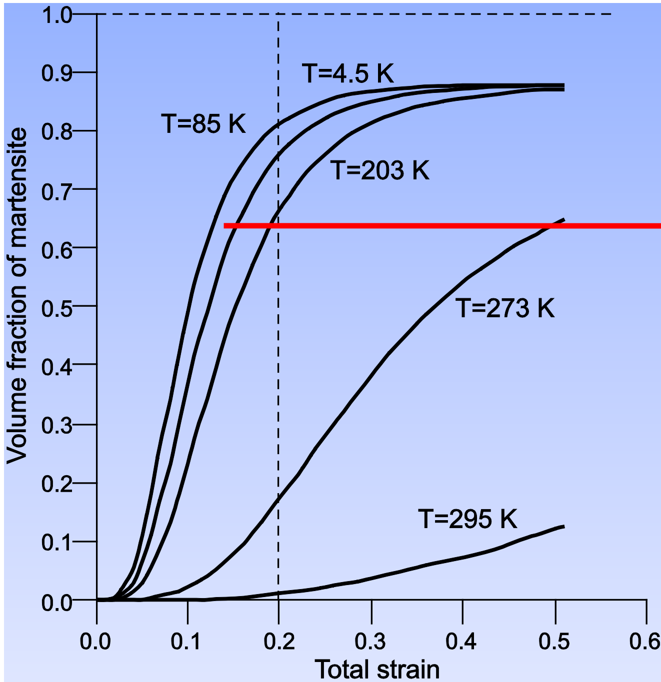
nic temperatures

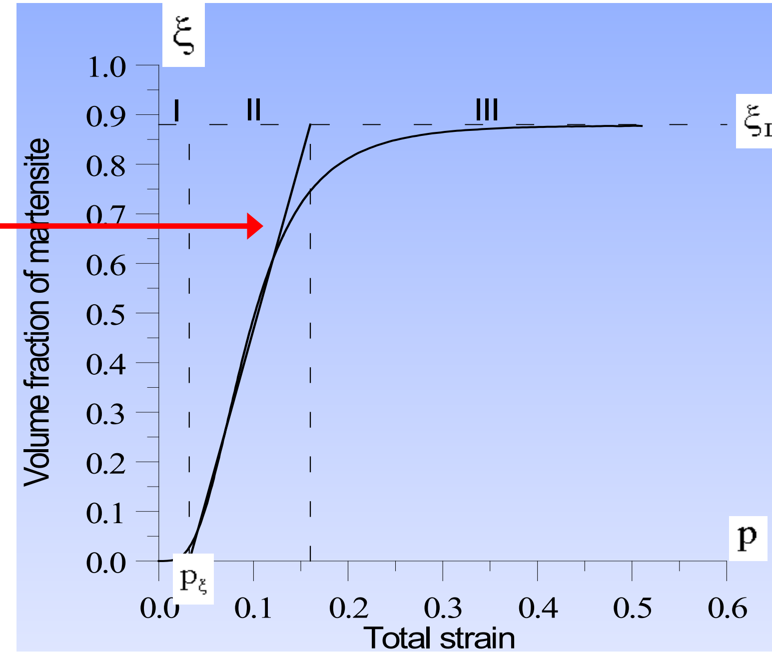


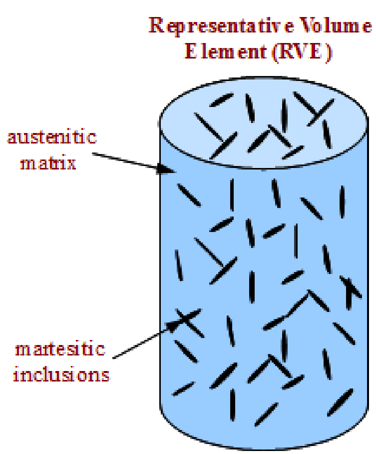




Kinetics of Fcc-Bcc phase transformation







$$\xi = \frac{dV_\xi}{dV} \quad ; \quad 0 \le \xi \le 1$$

$$\dot{\xi} = A\left(T, \dot{\underline{\underline{\varepsilon}}}^p, \underline{\underline{\sigma}}\right) \dot{p} H\left(\left(p - p_\xi\right)\left(\xi_L - \xi\right)\right)$$

ξ – volume fraction of α' phase

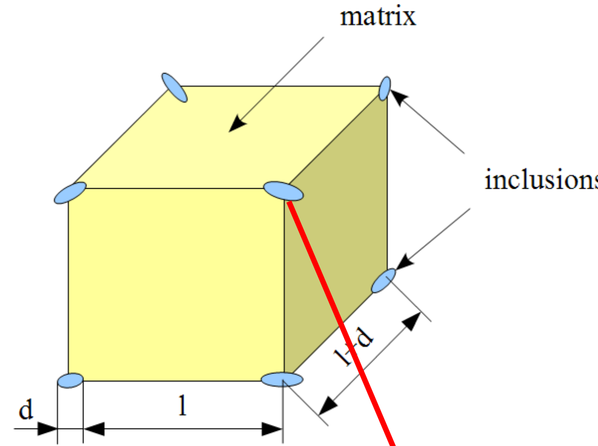
Micromechanics: transformation strain

$$\underline{\underline{\varepsilon}}^{bs} = \frac{1}{V}\int_V \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV$$

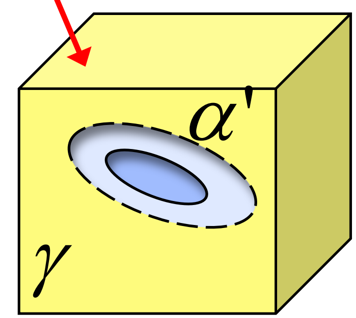
$$\underline{\underline{\varepsilon}}^{bs} = \underbrace{\frac{V_\gamma}{V}\frac{1}{V_\gamma}\int_{V_\gamma} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV}_{\approx 0} + \frac{V_\alpha}{V}\frac{1}{V_\alpha}\int_{V_\alpha} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV$$

$$\underline{\underline{\varepsilon}}^{bs} = \frac{V_\alpha}{V}\frac{1}{V_\alpha}\int_{V_\alpha} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV = \xi \frac{1}{V_\alpha}\int_{V_\alpha} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV = \xi \left\langle \underline{\underline{\varepsilon}}_{\mu}^{bs} \right\rangle$$

$$\underline{\underline{\varepsilon}}_{\mu}^{bs} = \begin{pmatrix} 0 & 0 & \frac{\gamma}{2} \\ 0 & 0 & 0 \\ \frac{\gamma}{2} & 0 & \Delta\upsilon \end{pmatrix}_{(\vec{x},\vec{y},\vec{z})} \qquad \left\langle \underline{\underline{\varepsilon}}_{\mu}^{bs} \right\rangle = \frac{1}{3}\Delta\upsilon \underline{\underline{I}}$$



Type Eshelby ellipsoidal inclusion



$$\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{E}}}} : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{p} - \underline{\underline{\varepsilon}}^{th} - \xi \underline{\underline{\varepsilon}}^{bs}\right)$$

$$\underline{\underline{\varepsilon}}^{bs} = \xi \frac{1}{3}\Delta\upsilon \underline{\underline{I}}$$

Constitutive description of two-phase continuum

Yield condition:

$$f_c\left(\underline{\underline{\sigma}}, \underline{\underline{X}}, R\right) = J_2\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right) - \sigma_y - R = 0 \qquad J_2\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right) = \sqrt{\frac{3}{2}\left(\underline{\underline{s}} - \underline{\underline{X}}\right):\left(\underline{\underline{s}} - \underline{\underline{X}}\right)}$$

Mixed hardening depending on the phase transformation parameter:

$$d\underline{\underline{X}} = d\underline{\underline{X}}_a + d\underline{\underline{X}}_{a+m} = \frac{2}{3} C_X(\xi)\, d\underline{\underline{\varepsilon}}^p$$

$$dR = C_R\left(\xi\right) dp$$

Hardening of two-phase continuum

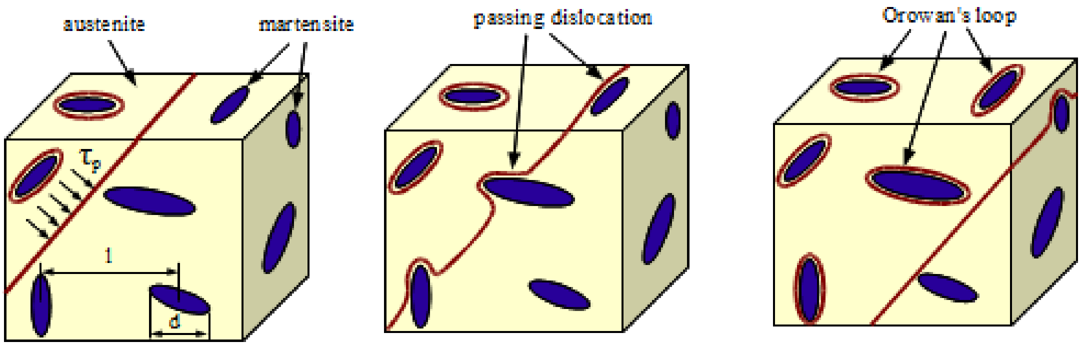
Scale Micro:
Interaction of dislocations with inclusions

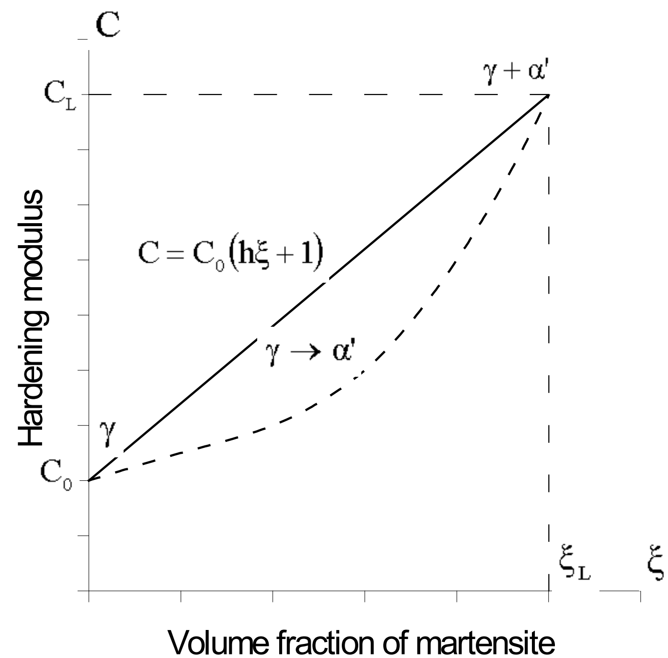
→ **Method:**
Micromechanics analysis transferred to RVE

Scale Macro:
Evolution of stiffness due to evolution of proportion between phases

→ **Method:**
Mean field approach
Mori Tanaka homogenization

Scale Micro: interaction of dislocations with inclusions





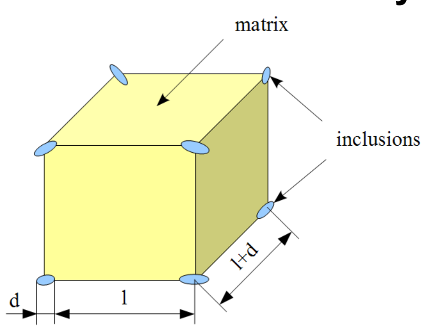
$$d\underline{\underline{X}}_a = \frac{2}{3} C_0 d\underline{\underline{\varepsilon}}^p$$

Initial hardening of matrix (austenite)

$$d\underline{\underline{X}}_a = \frac{2}{3} C_0 \phi(\xi) d\underline{\underline{\varepsilon}}^p$$

Hardening of matrix containing inclusions

Micromechanics analysis



$$\tau_p = \frac{Gb}{d}\left(\frac{6\xi_0}{\pi}\right)^{\frac{1}{3}}\left(1 + \frac{\xi - \xi_0}{3\xi_0}\right)$$

$$\phi(\xi) = 1 + h\xi\,; \quad 0 \le \xi \le 1$$

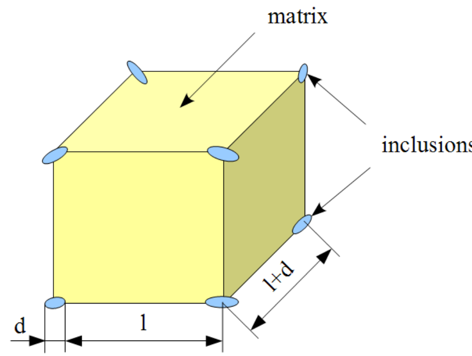
$$C = C_0 \phi(\xi)$$

Scale Macro: evolution of proportion between phases

Elastic-plastic matrix:

$$\Delta\underline{\underline{\sigma}}_a = \underline{\underline{\underline{\underline{E}}}}_{ta} : \Delta\underline{\underline{\varepsilon}}$$

$$\underline{\underline{\underline{\underline{E}}}}_{ta} = 3k_a \underline{\underline{\underline{\underline{J}}}} + 2\mu_a \underline{\underline{\underline{\underline{K}}}} - 2\mu_a \frac{\underline{\underline{n}} \otimes \underline{\underline{n}}}{1 + \frac{C(\xi)}{3\mu_a}}$$



Elastic inclusions:

$$\Delta\underline{\underline{\sigma}}_m = \underline{\underline{\underline{\underline{E}}}}_m : \Delta\underline{\underline{\varepsilon}}$$

$$\boxed{\underline{\underline{\underline{\underline{E}}}}_m = 3k_m \underline{\underline{\underline{\underline{J}}}} + 2\mu_m \underline{\underline{\underline{\underline{K}}}}}$$

$$\mu_m = \frac{E}{2(1+\nu)} \qquad k_m = \frac{E}{3(1-2\nu)}$$

„Linearization": extraction of isotropic part of tangent stiffness operator

$$\boxed{\underline{\underline{\underline{\underline{E}}}}_{ta} = 3k_{ta} \underline{\underline{\underline{\underline{J}}}} + 2\mu_{ta} \underline{\underline{\underline{\underline{K}}}}}$$

$$\mu_{ta} = \frac{E_t}{2(1+\nu)} \quad k_{ta} = \frac{E_t}{3(1-2\nu)} \quad \boxed{E_t = \frac{EC}{E+C}}$$

Homogenization:

$$\boxed{\Delta\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{E}}}}_H : \Delta\underline{\underline{\varepsilon}}}$$

Constitutive description of two-phase continuum

$$\beta = \frac{\sigma' + \sigma'^{-}}{2(\sigma' - \sigma_0)}$$

Kinematic hardening

Isotropic hardening

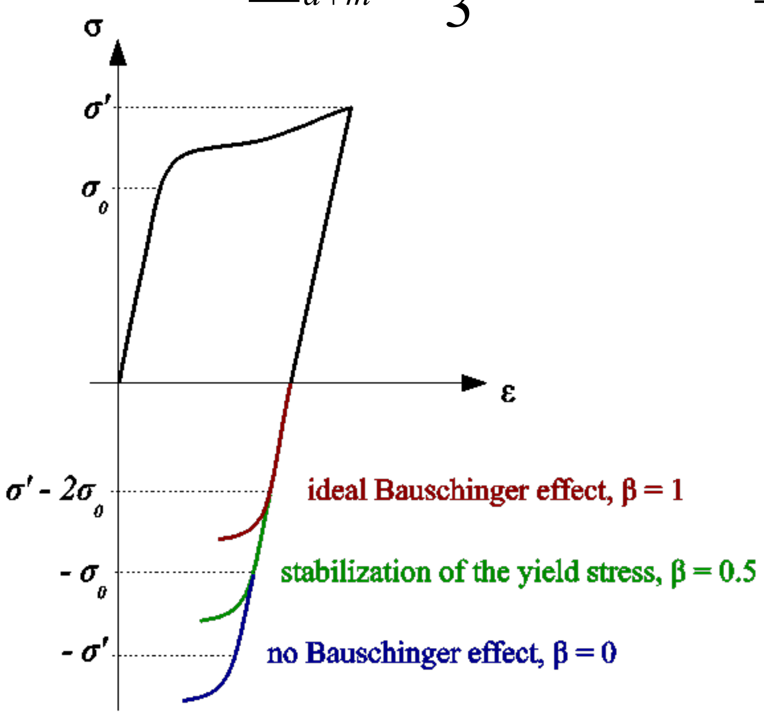
$$\Delta \underline{\underline{X}}_{a+m} = \Delta \underline{\underline{\sigma}}_{a+m}$$

Parametization: ***Życzkowski, 1981***

$$\Delta R = \left\| \Delta \sigma_{a+m} \right\|$$

$$d\underline{\underline{X}}_{a+m} = \frac{2}{3}\beta C_{a+m}(\xi)\, d\underline{\underline{\varepsilon}}^p$$

$$dR = (1-\beta) C_{a+m}(\xi)\, dp$$

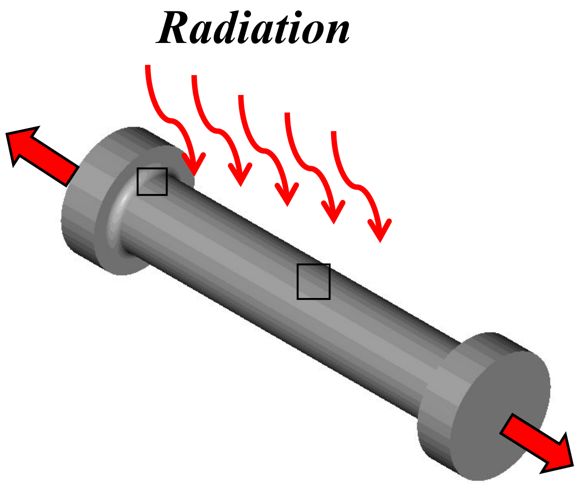


Evolution laws of hardening parameters

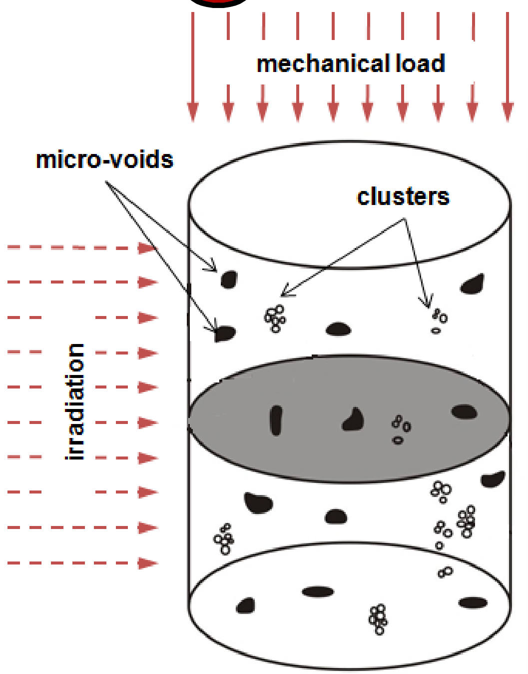
$$dR = C_R(\xi)\, dp = (1-\beta) C_{a+m}(\xi)\, dp$$

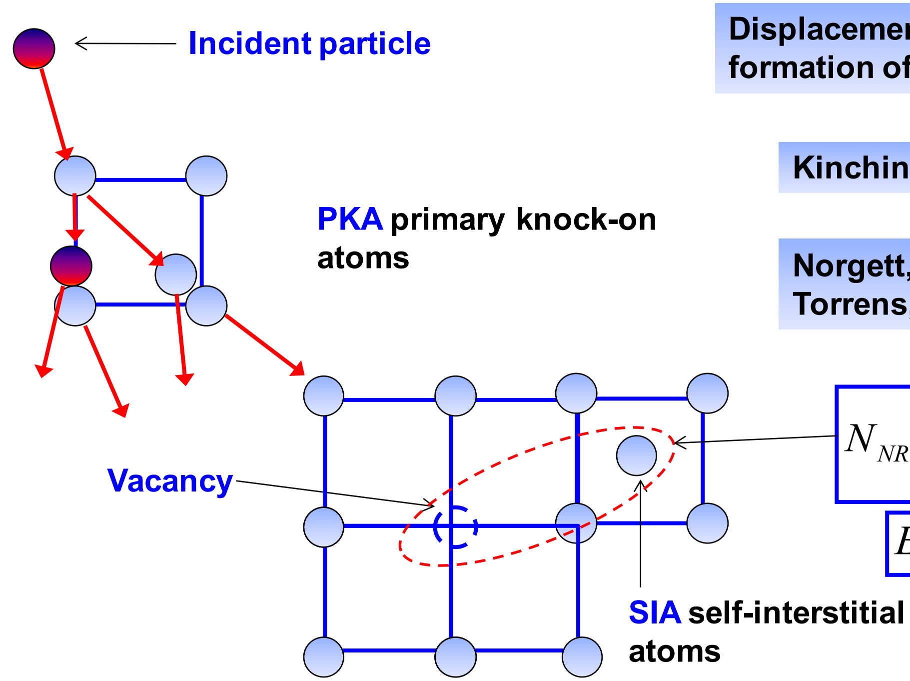
$$d\underline{\underline{X}}_{a+m} = \frac{2}{3} C_X(\xi)\, d\underline{\underline{\varepsilon}}^p = \frac{2}{3}\beta C_{a+m}(\xi)\, d\underline{\underline{\varepsilon}}^p$$

Radiation induced damage



Radiation induced micro-damage





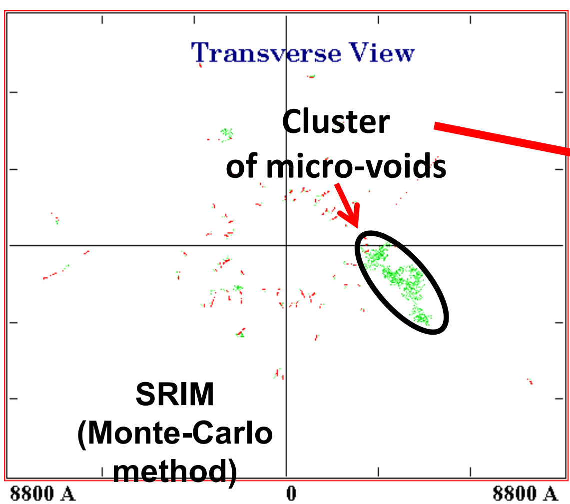
Displacement cascade and formation of Frenkel pairs

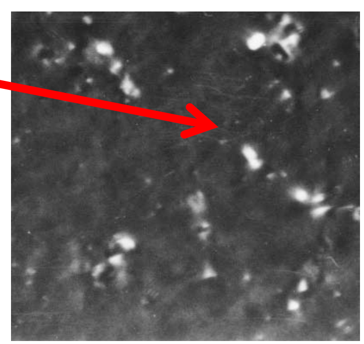
Kinchin & Pease, 1955

Norgett, Robinson, Torrens, 1975

$$N_{NRT} = \frac{0.8 E_{dam}}{2\overline{E}_d}$$

$$E_{dam} = NIEL$$



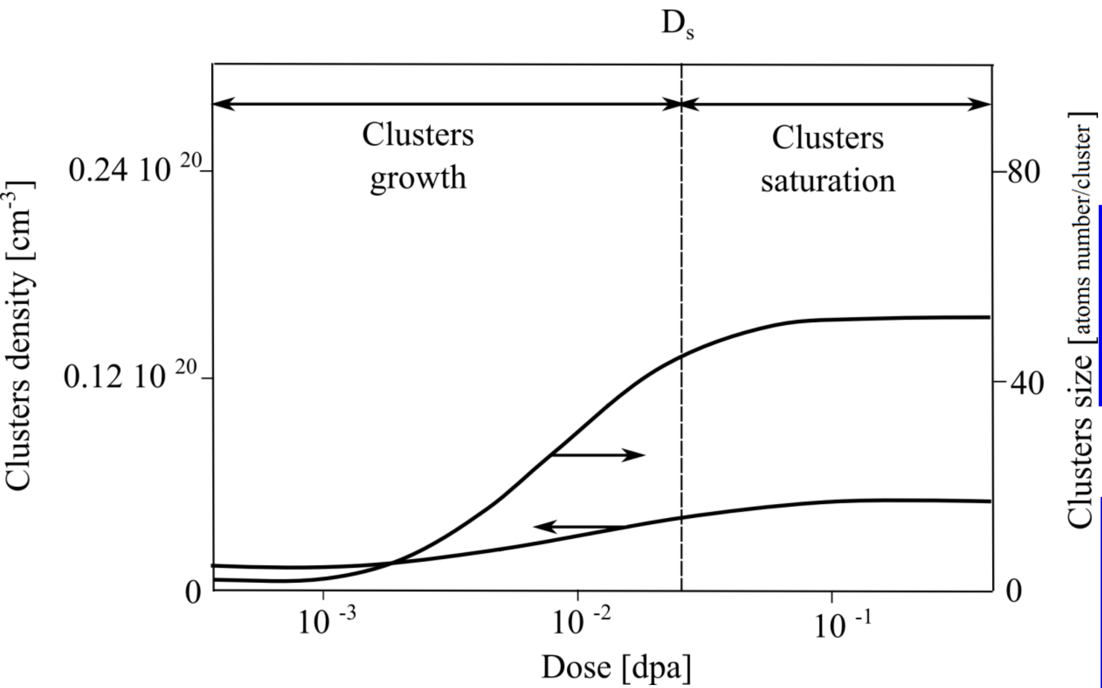


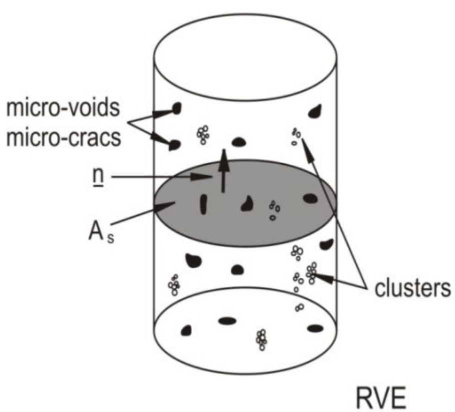
Defects due to irradiation:

1. SFT – stacking fault tetrahedron
2. Faulted or perfect dislocation loops
3. Voids – 3D vacancy clusters
4. Cavities – 3D vacancy clusters with impurities (He)

Lattice defects after irradiation

Coupled dissipative phenomena at cryogenic temperatures





q_c – number of clusters per unit volume
r_c – average radius of clusters

$$D = \frac{dS_D}{dS} \quad ; \quad 0 \le D \le 1$$

$$\xi = \frac{dV_D}{dV} \quad ; \quad 0 \le \xi \le 1$$

Physics

$$dpa$$

$$q_c = \begin{cases} C_{qI}(dpa)^{n_{qI}} & for \quad dpa < D_S \\ C_{qII}(dpa)^{n_{qII}} & for \quad dpa \ge D_S \end{cases}$$

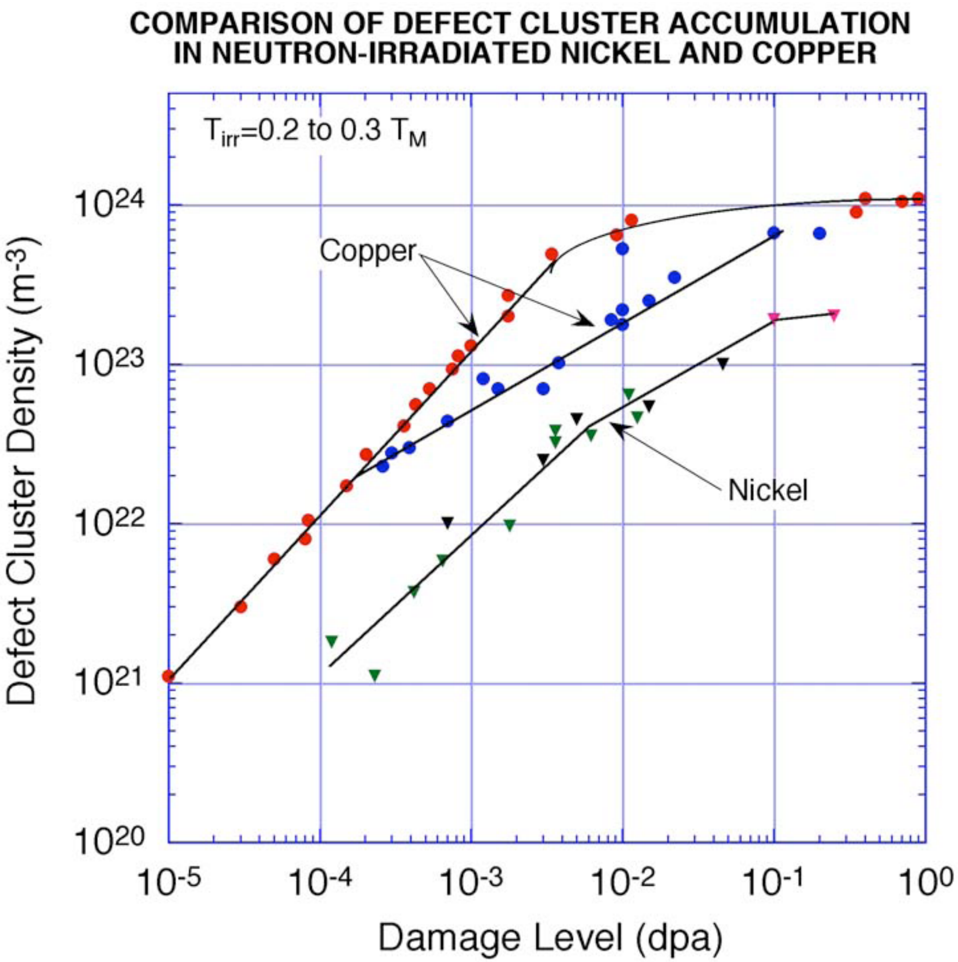
$$r_c = \begin{cases} C_r(dpa)^{n_r} & for \quad dpa < D_S \\ r_{cr} & for \quad dpa \ge D_S \end{cases}$$

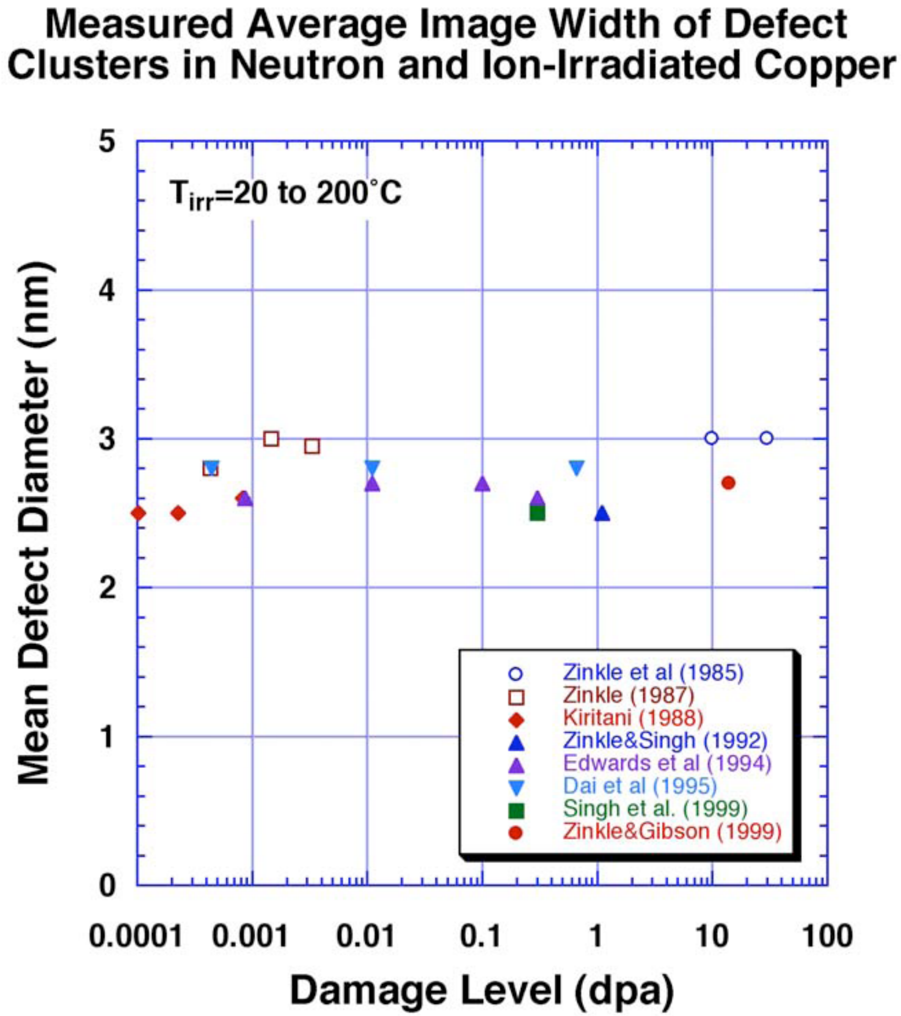
$$q_A = \left(\sqrt[3]{q_V}\right)^2 = q_c^{\ 2/3}$$

$$D_{r0} = q_A \pi r_{c0}^{\ 2}$$

Mechanics

Irradiated metals and alloys: Nickel and Copper

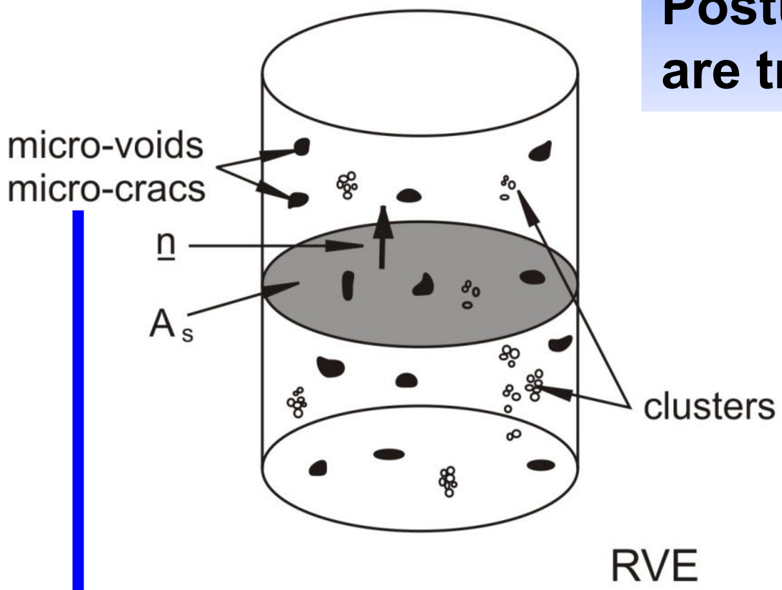




Source: S.J. Zinkle „Microstructure evolution in irradiated metals and alloys: fundamental aspects", Italy, 2004.

Radiation and mechanical damage: additive formulation

Postulate: both micro-damage components are treated in additive way



$$D_r = D_{r0} + \int_0^{\hat{p}} dD_{rm}$$

radiation induced damage

$$\underline{\underline{D}}_r = \frac{D_r}{3}\underline{\underline{I}}$$

isotropic

$\underline{\underline{I}}$ **- identity tensor**

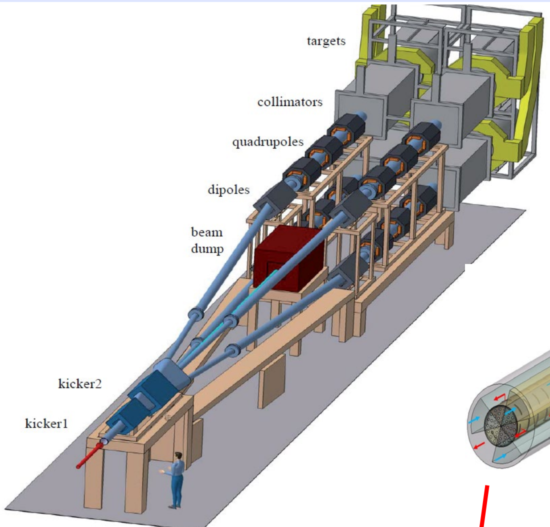
$$d\underline{\underline{D}}_m = \underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^T dp$$

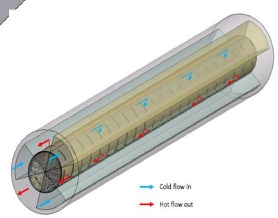
anisotropic

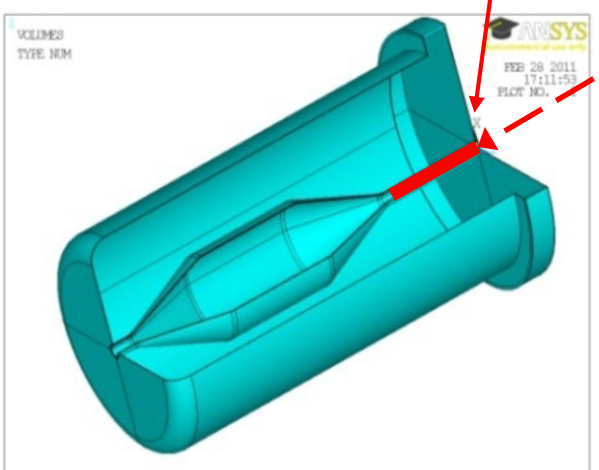
$$\underline{\underline{D}} = \underline{\underline{D}}_m + \underline{\underline{D}}_r = \underline{\underline{D}}_m + \frac{1}{3} D_r \underline{\underline{I}}$$

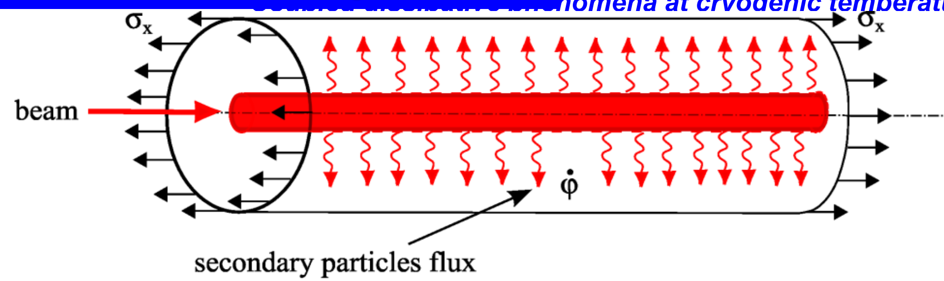
Lifetime estimation for irradiated components

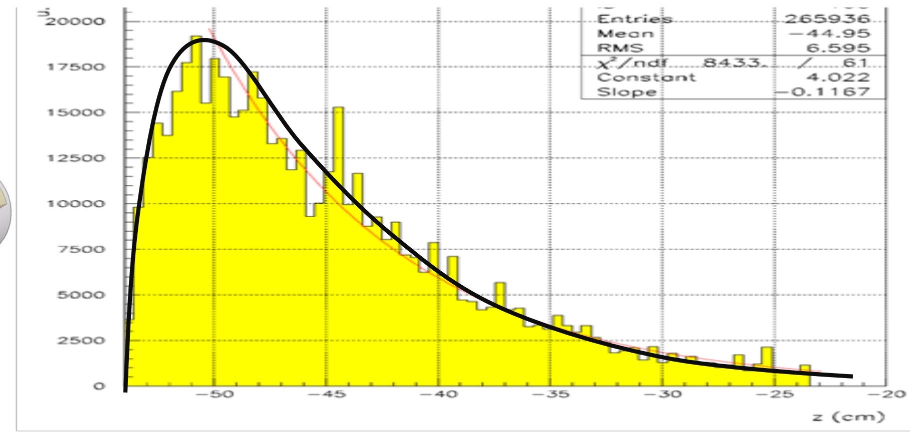
Secondary particles flux: γ, n, p+, π± and e±





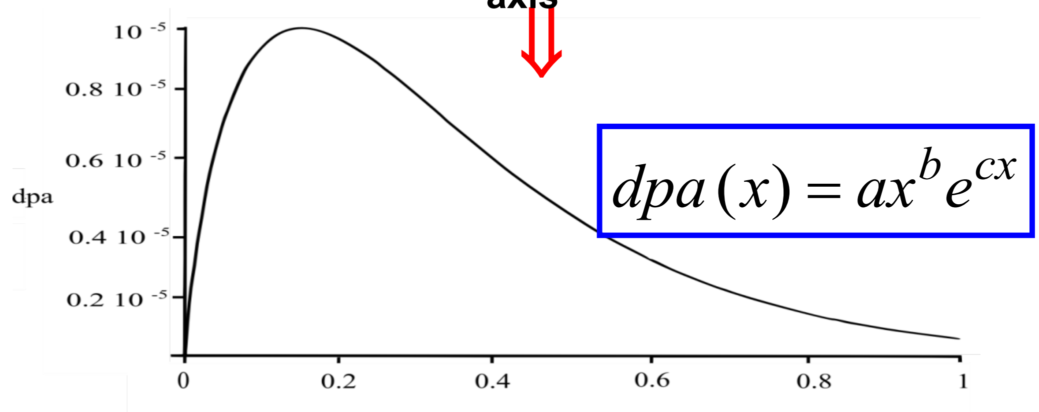






Typical distribution of particle flux along the target axis

⇓



$$dpa\,(x) = ax^{b}e^{cx}$$

Kinetics of evolution of radiation induced damage (clusters of voids) under mechanical loads

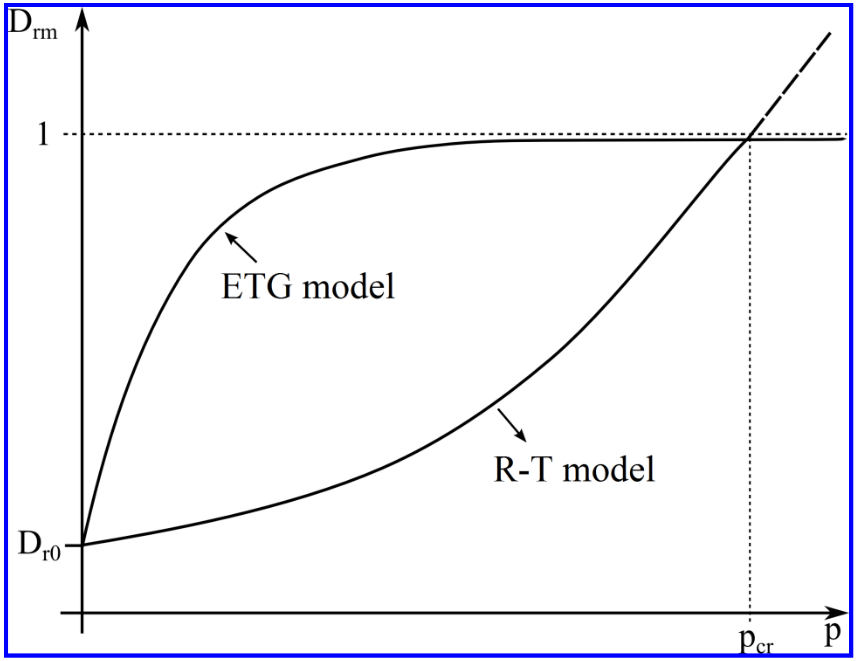
Rice&Tracey (R-T) model:

$$dr_c = r_c \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp$$

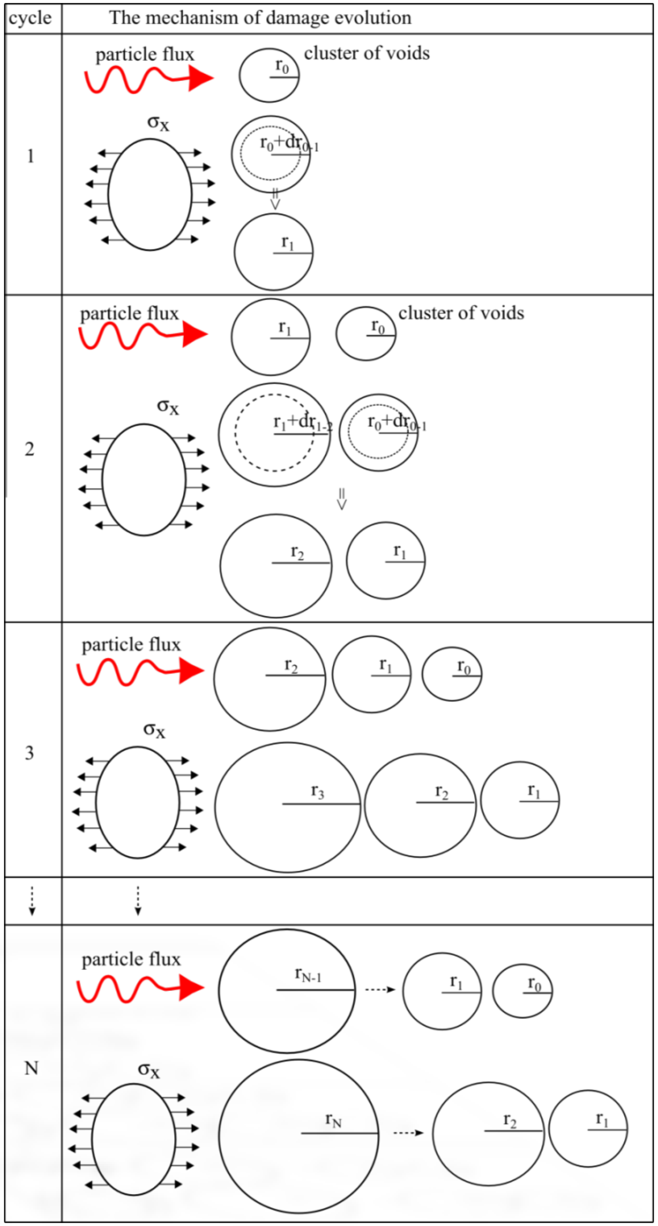
Gurson (ETG) model:

$$d\xi = (1-\xi)dp$$

$$\dot{p} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}}$$



Lifetime estimation for irradiated components



Rice & Tracey law

$$\int_{D_i}^{D_{i+1}} dD = q_A 2\pi \int_{r_i}^{r_{i+1}} r\, dr$$

$$\Delta D_{i\rightarrow i+1} = q_A \pi \left(r_{i+1}^2 - r_i^2\right)$$

$$\int_{r_i}^{r_{i+1}} \frac{dr_c}{r_c} = \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right)\int_0^{\tilde{p}} dp$$

$$r_{i+1} = r_i\, e^{A\tilde{p}} \qquad A := \alpha_r \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right)$$

$$\Delta D_{i\rightarrow i+1} = q_A \pi r_i^2 \left(e^{2A\tilde{p}} - 1\right)$$

Lifetime estimation for irradiated components

$$D_{r0} = q_A \pi r_{c0}^2$$

$$D_{rm1} = D_{r0} + \Delta D_{rm(0\to1)} = D_{r0} + q_A \pi r_{c0}^2 \left(e^{2A\tilde{p}} - 1\right)$$

$$D_{rm2} = D_{rm1} + \Delta D_{rm(1\to2)} + D_{r0} + \Delta D_{rm(0\to1)} = 2D_{r0} + q_A \pi r_{c0}^2 e^{2A\tilde{p}} + q_A \pi r_{c0}^2 e^{4A\tilde{p}} - 2q_A \pi r_{c0}^2$$

$$\vdots$$

$$D_{rm_{i+1}} = D_{rm_i} + D_{r0} + \Delta D_{rm(i\to i+1)} + \Delta D_{rm(i-1\to i)} + \ldots + \Delta D_{rm(0\to1)}$$

$$D_{rmN} = \underbrace{q_A \pi r_{c0}^2 e^{2A\tilde{p}} + q_A \pi r_{c0}^2 e^{4A\tilde{p}} + q_A \pi r_{c0}^2 e^{6A\tilde{p}} + \ldots + q_A \pi r_{c0}^2 e^{2NA\tilde{p}}}_{\text{Geometric series}}$$

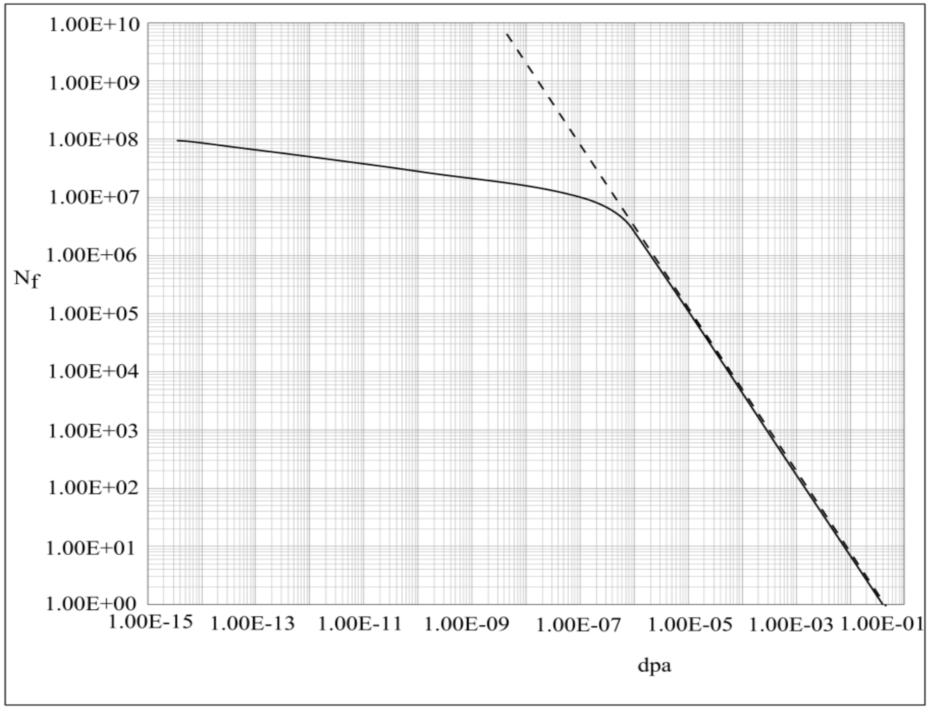
Number of cycles to failure N_f based on the critical damage criterion: $D_{rm}=D_{cr}$

$$D_{rmN} = q_A \pi r_{c0}^2 \sum_{n=1}^{N} e^{2nA\tilde{p}}$$

$$S_N = a_1 \frac{1-q^N}{1-q} \qquad S_N = q_A \pi r_{c0}^2 e^{2A\tilde{p}} \frac{1-e^{2ApN}}{1-e^{2Ap}}$$

$$\boxed{D_{rmN} = q_A \pi r_{c0}^2 e^{2A\tilde{p}} \frac{1-e^{2ApN}}{1-e^{2Ap}}}$$

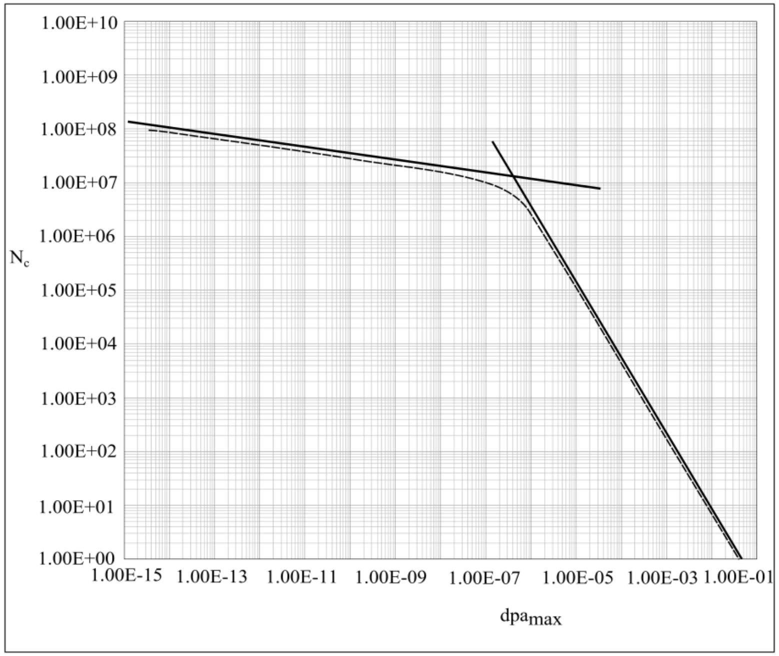
$$\boxed{D_{rmN_f} = q_A \pi r_{c0}^2 e^{2A\tilde{p}} \frac{1-e^{2A\tilde{p}N_f}}{1-e^{2A\tilde{p}}} = D_{cr}}$$



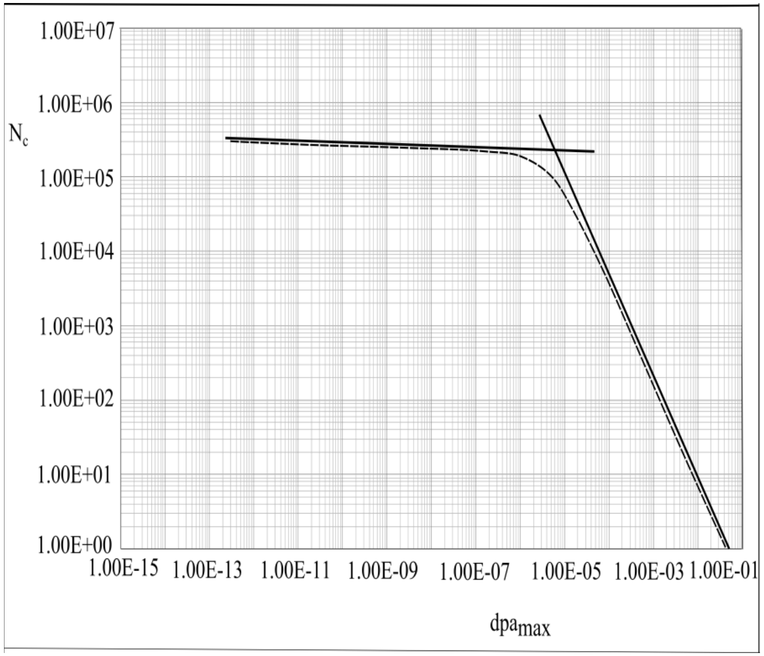
Bilinear approximations for R-T and Gurson models

peratures

Rice & Tracey model



Gurson model



$$\log(N_c) = a + b\log(dpa_{max})$$

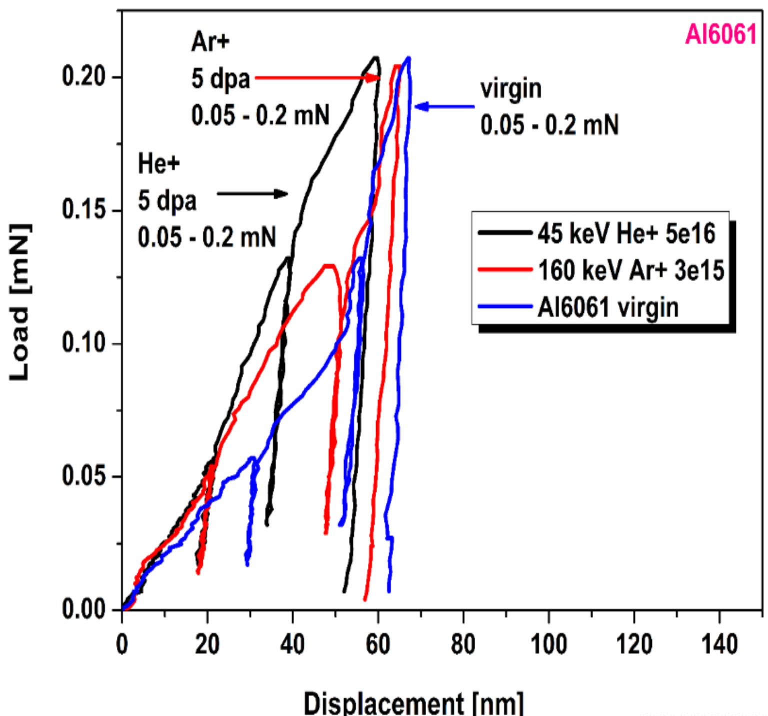
Analytical formula - useful tool for estimation of number of cycles to failure

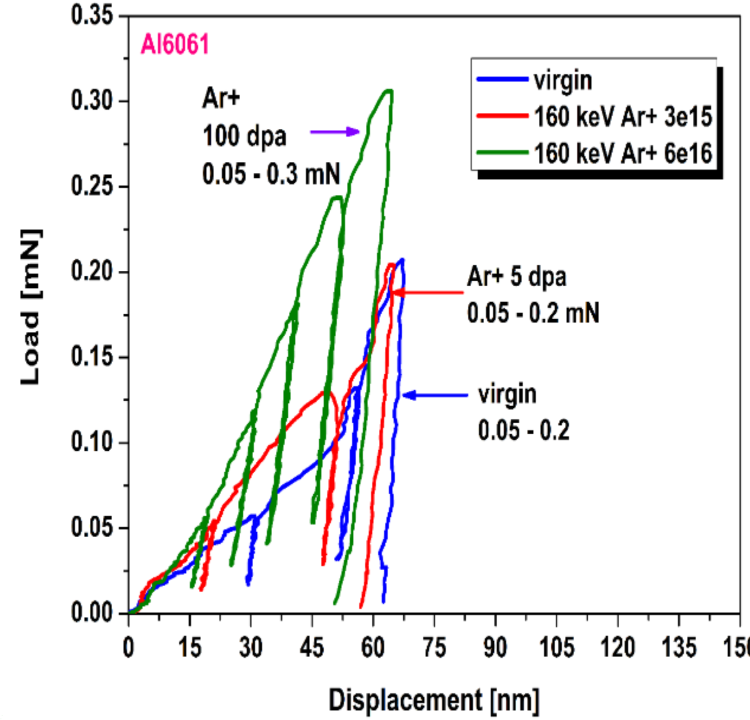
$$N_c = 10^a dpa_{max}^b$$

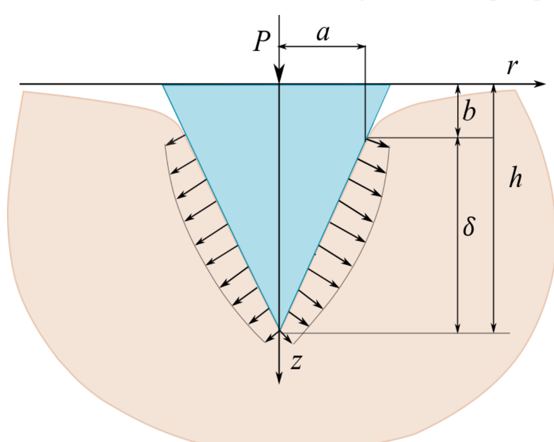
$$N_c = \begin{cases} 10^{-1.9} dpa_{max}^{-1.4} & for \quad dpa_{max} \geq 10^{-6} \\ 10^{6.1} dpa_{max}^{-0.13} & for \quad dpa_{max} < 10^{-6} \end{cases}$$

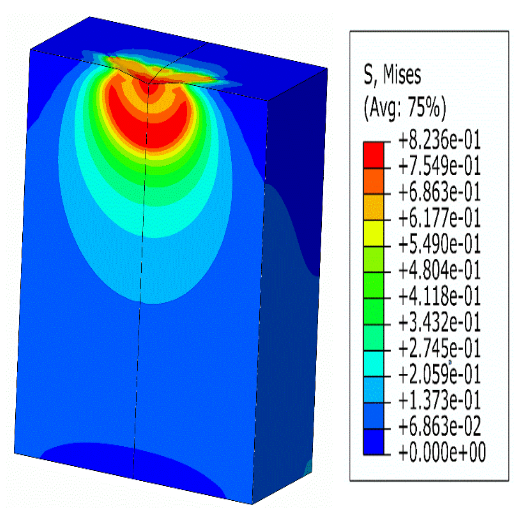
$$N_c = \begin{cases} 10^{-1.9} dpa_{max}^{-1.4} & for \quad dpa_{max} \geq 10^{-5} \\ 10^{5.43} dpa_{max}^{-0.016} & for \quad dpa_{max} < 10^{-5} \end{cases}$$

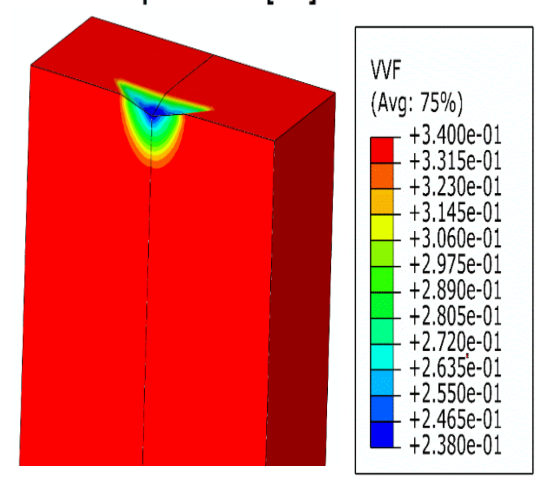
Nanoindentation of irradiated Al6061



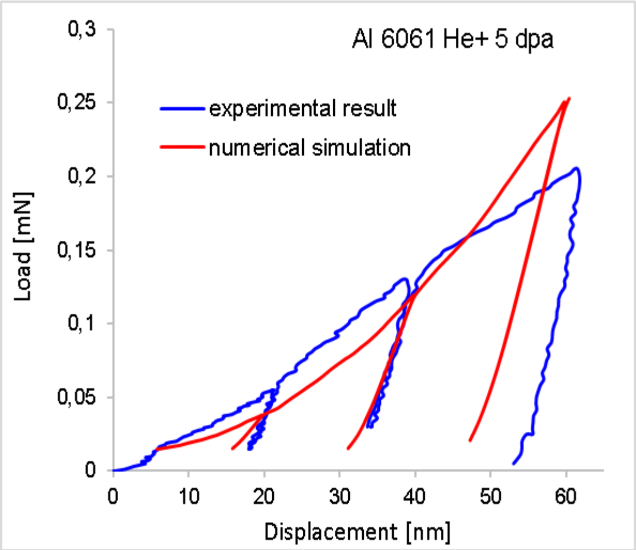


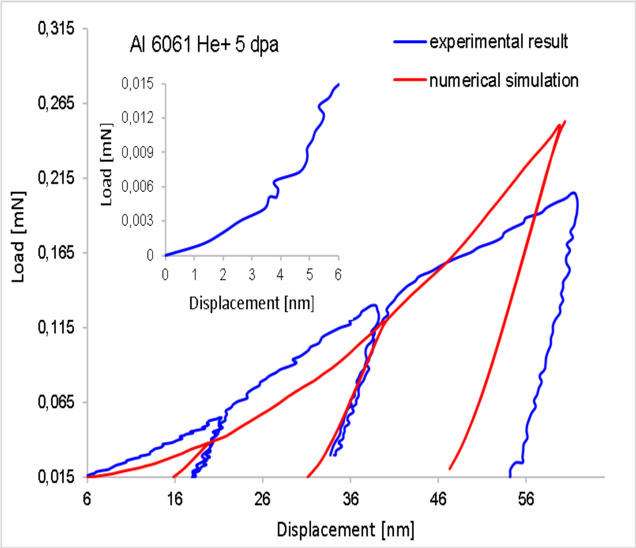


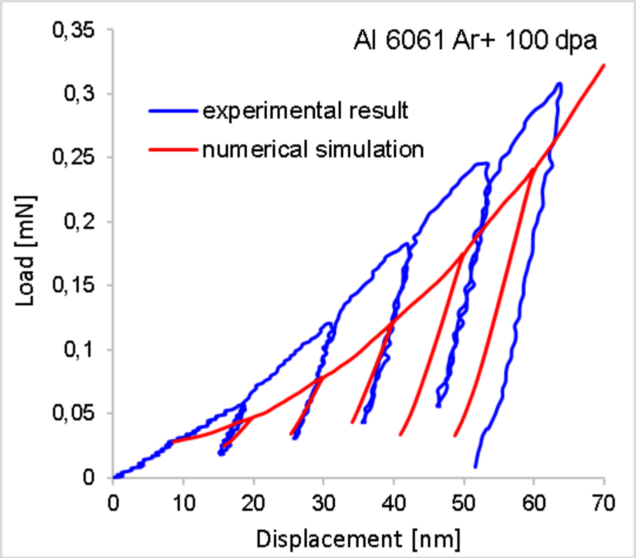


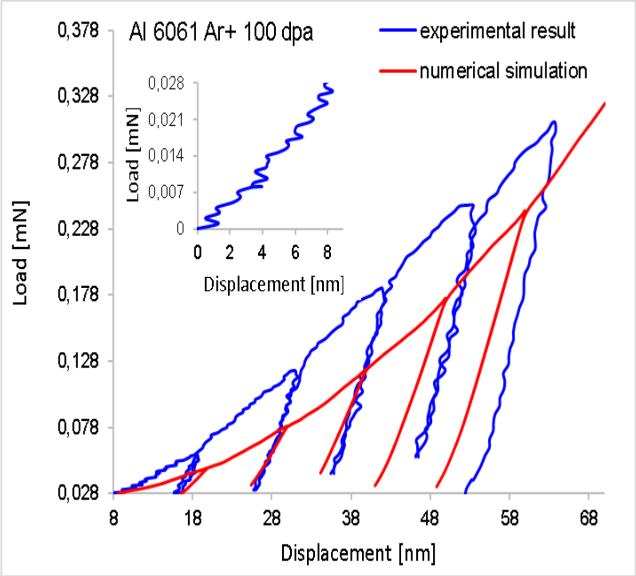


Nanoindentation of irr. Al6061: experiment vs. Gurson model

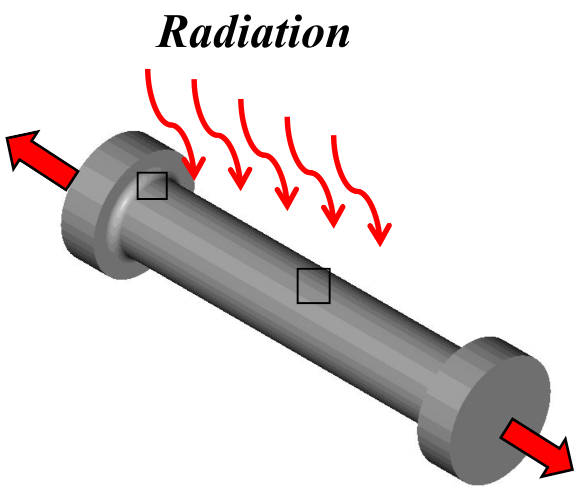






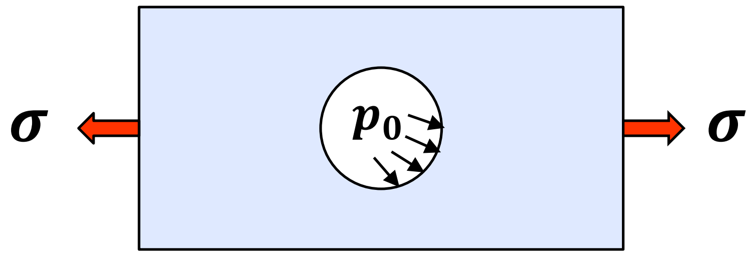


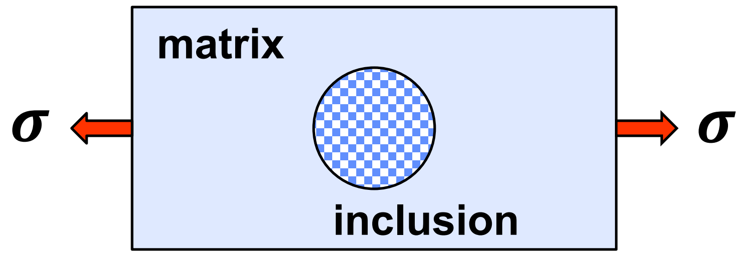
Radiation induced hardening



Type Eshelby entities: the equivalent inclusion

Assumptions:
- small strains approach
- perfect gas inside the void at a constant temperature T
- pressurized void is equivalent to inclusion subjected to hydrostatic stress





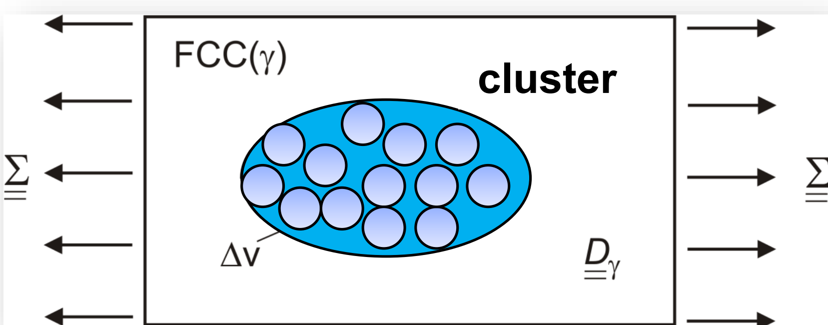
$$\Delta p = -3p_0\Delta\varepsilon$$

$$E_{p_{ijkl}} = 3k_pJ_{ijkl} + 2\mu_pK_{ijkl}$$

$$\mu_p = 0 \;\; ; \;\; \nu_p = 0 \;\; ; \;\; k_p \neq 0$$

$$\Delta\sigma = E_p\Delta\varepsilon \;\; ; \;\; E_p = -3p_0$$

$$\Delta\sigma = -3p_0\Delta\varepsilon$$



Interaction of dislocations with voids

The Orowan mechanism:

$$\tau_p = \frac{\mu b}{d}\sqrt[3]{\frac{6\xi_0}{\pi}}\left(1 + \frac{1}{3}\frac{\Delta\xi}{\xi_0}\right)$$

$$\Delta\xi = 3C_1\xi_0\Delta p$$

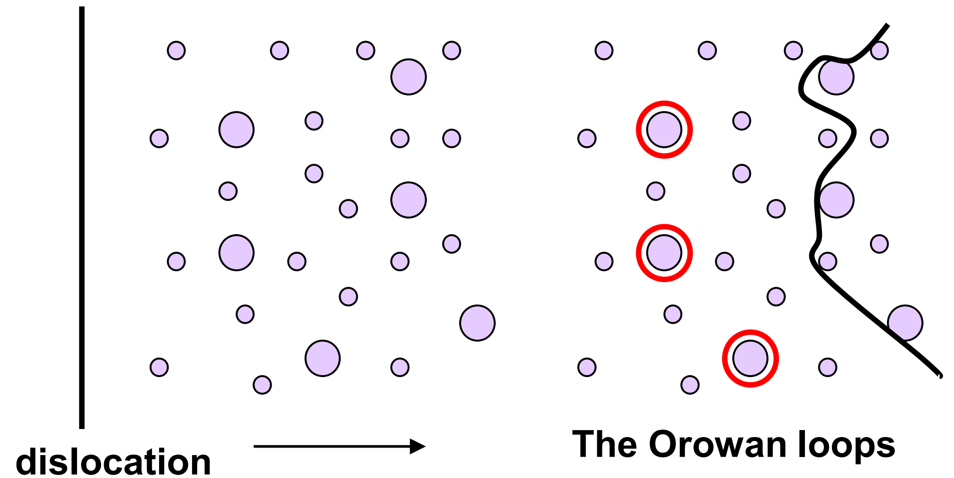
$$\tau_p = \frac{\mu b}{d}\sqrt[3]{\frac{6\xi_0}{\pi}}(1 + C_1\Delta p)$$

Using the Taylor factor:

$$\sigma_p = M\tau_p = MA_0\sqrt[3]{\xi_0}\left(1 + \frac{1}{3}\frac{\Delta\xi}{\xi_0}\right)$$

Hardening modulus:

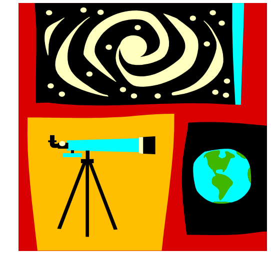
$$C = C_0\left(1 + \frac{1}{3}\frac{\Delta\xi}{\xi_0}\right)$$



$$C = C_0\,(1 + h\Delta\xi)$$

Uniaxial case – tension/compression

dissipative phenomena at cryogenic temperatures



$$\mathrm{d}\sigma = \mathrm{d}\sigma_i + \mathrm{d}\sigma_{MT}$$

General

$$\mathrm{d}\sigma_i = C_0(1 + h\Delta\xi)d\varepsilon^p \quad ; \quad \mathrm{d}\sigma_{MT} = E_H\, d\varepsilon^p = C_{MT}\, d\varepsilon^p$$

$$\Delta\sigma_i = C_0(\xi_0)\left(\varepsilon^p + \frac{1}{2}C_1(\varepsilon^p)^2\right)$$

Interaction

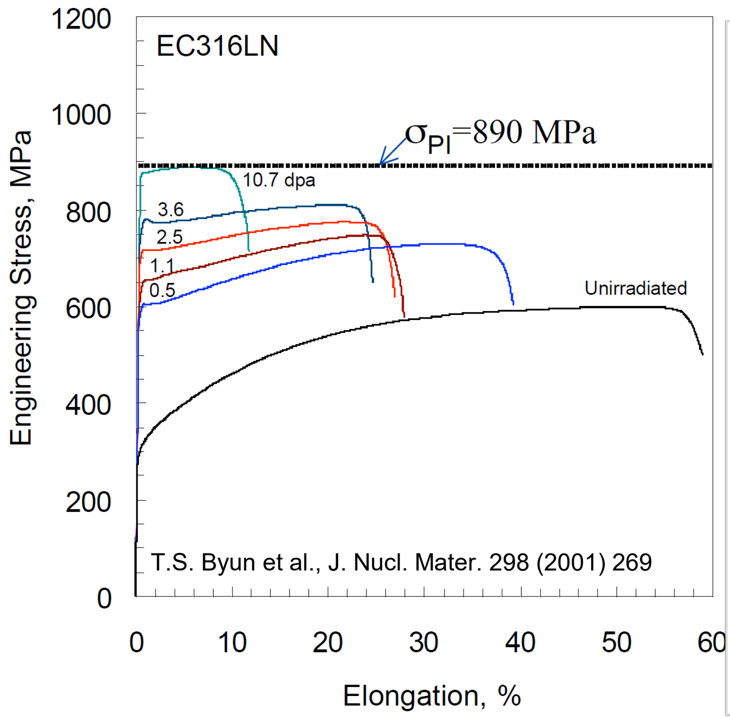
$$\Delta\sigma_{MT} = -\frac{5}{2}\mu\eta_0\frac{\xi_0}{C_1}\left[\frac{1}{4}(\chi^2 - 1) - \frac{4}{81}\xi_0(\chi^3 - 1) + -\frac{2}{81}{\xi_0}^2(\chi^4 - 1)\right]$$

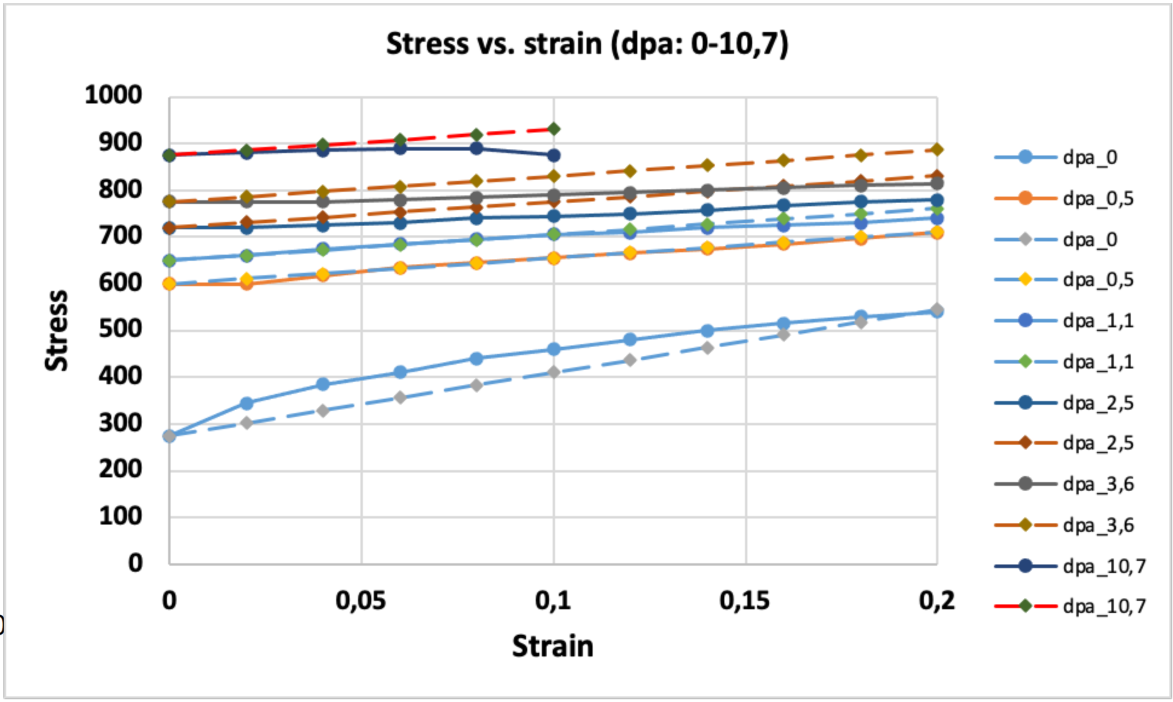
$$\chi = 1 + 3C_1\varepsilon^p \qquad \eta_0 = \frac{C_i}{E} = \frac{M\frac{\mu b}{d}\sqrt[3]{\frac{6}{\pi}}\sqrt[3]{\xi_0}}{E}$$

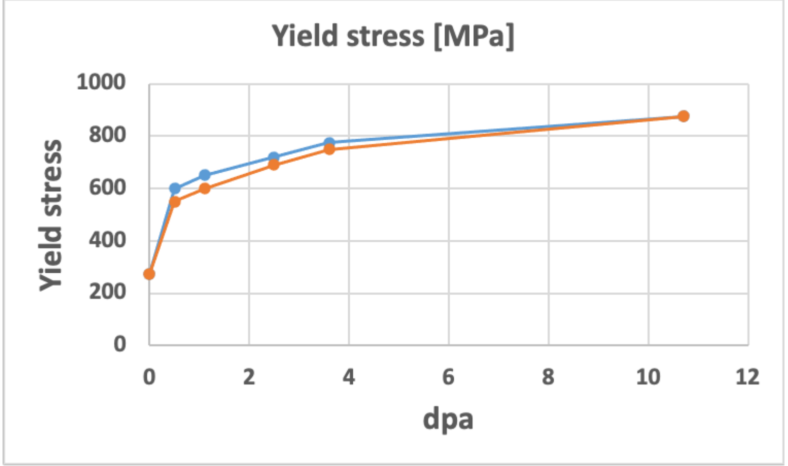
MT homogenization

$$\sigma = \sigma_0 + C_0(\xi_0)\left(\varepsilon^p + \frac{1}{2}C_1(\varepsilon^p)^2\right) - \frac{5}{2}\mu\frac{C_i(\xi_0)}{E}\frac{\xi_0}{C_1}\left[\frac{1}{4}(\chi^2 - 1) - \frac{4}{81}\xi_0(\chi^3 - 1) + -\frac{2}{81}{\xi_0}^2(\chi^4 - 1)\right]$$

Uniaxial case: 316LN stainless steel



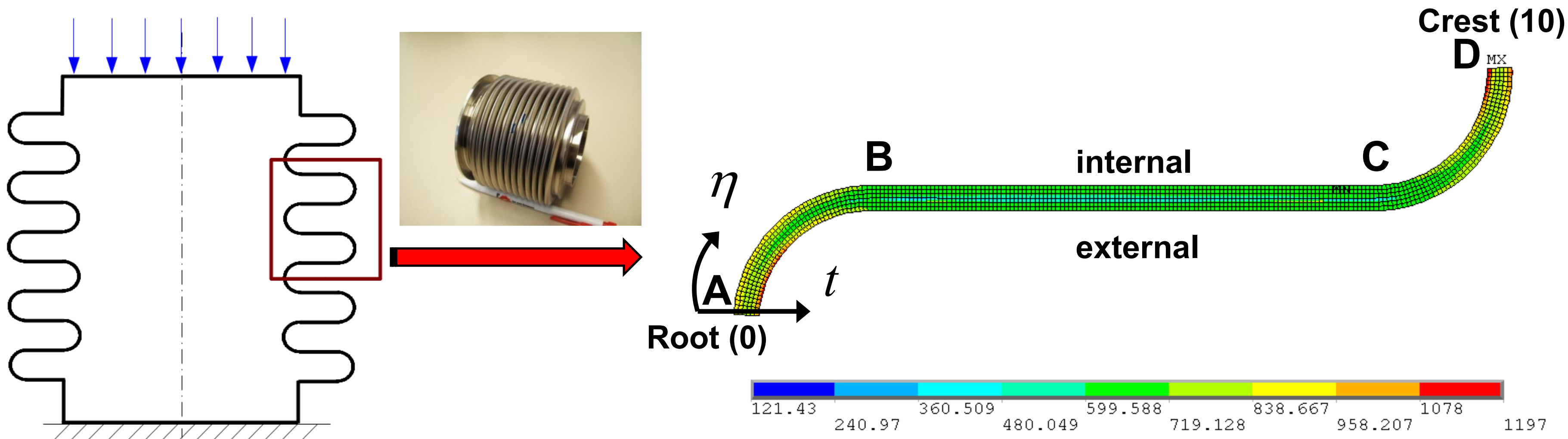




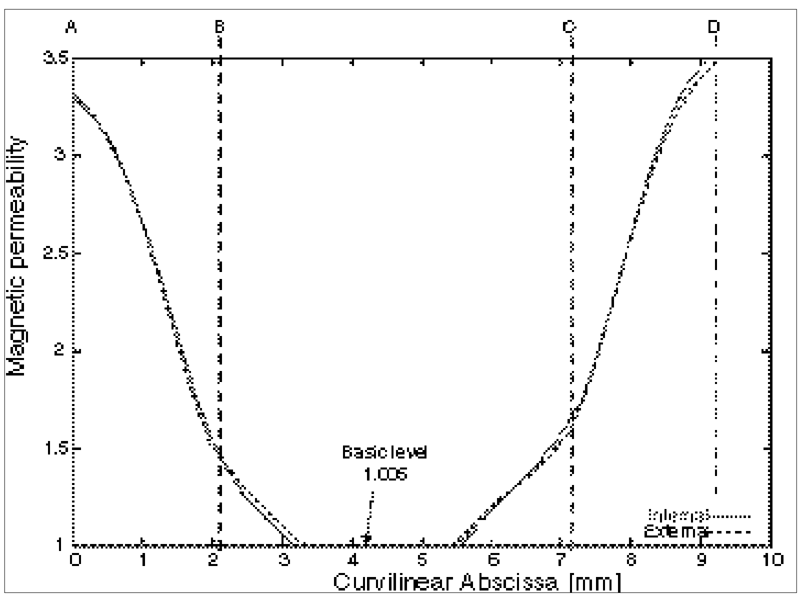
Radiation induced hardening comprising:

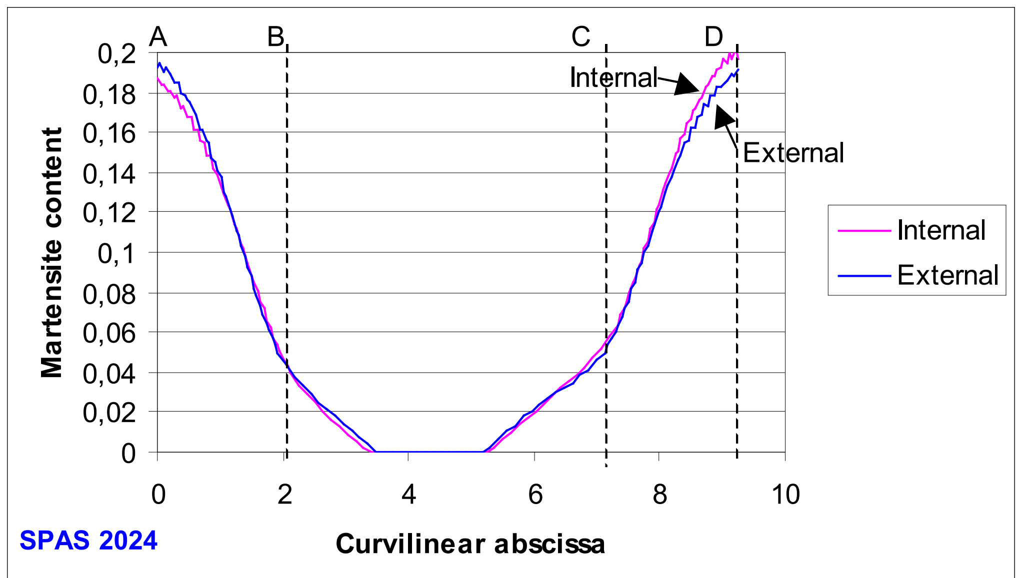
- **massive interaction of dislocations with the pressurized voids,**
- **evolution of tangent stiffness expressed by the Mori-Tanaka homogenization.**

Problem 10: Compensation system of Large Hadron Collider (LHC)



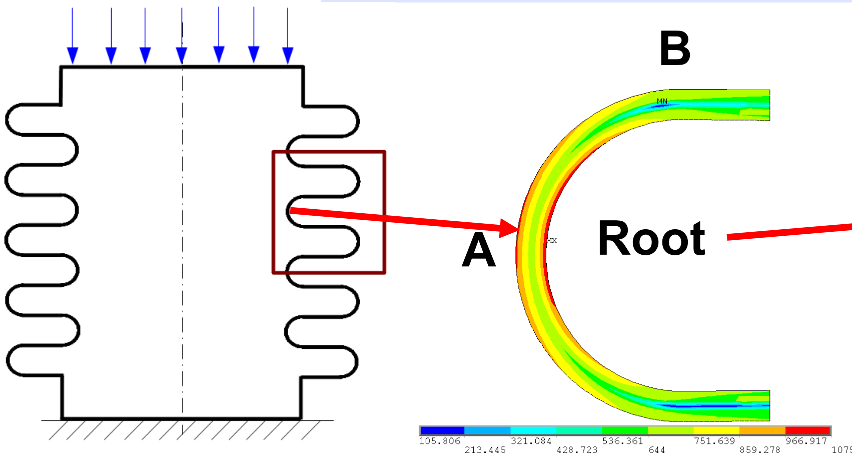
Profile of α' phase at 77 K

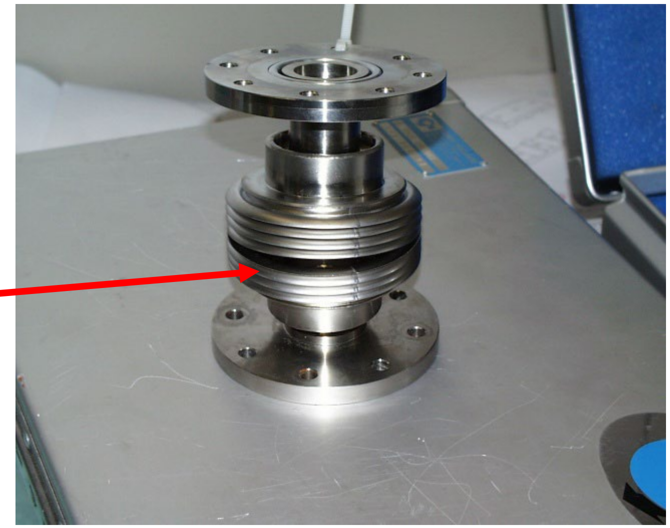


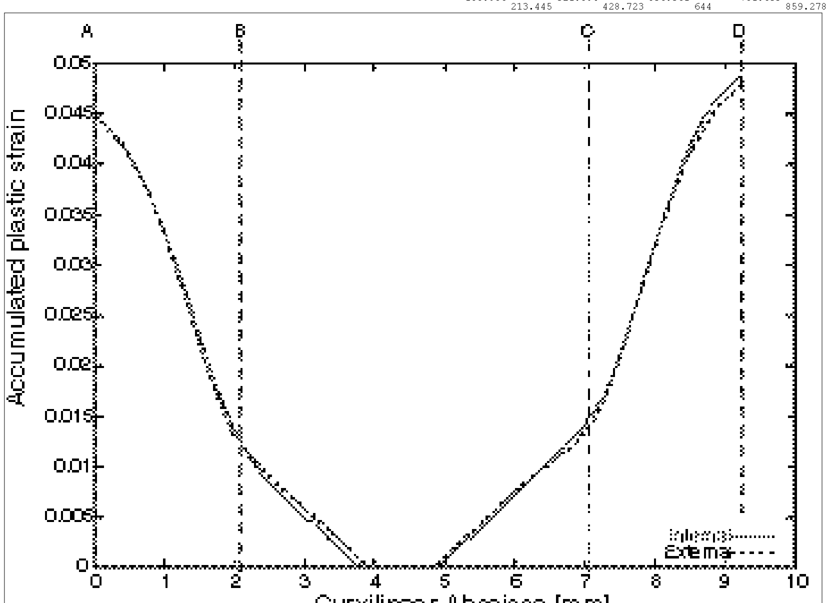


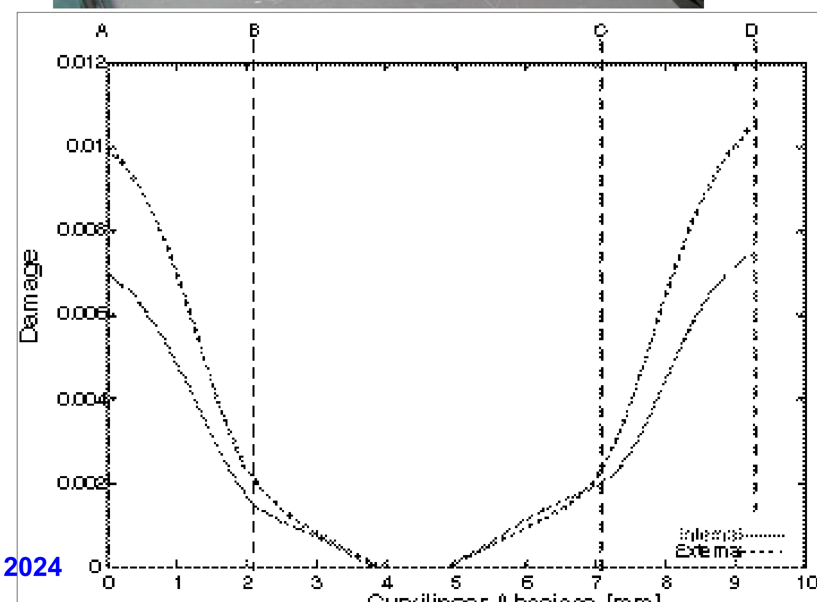
Problem 10: Compensation system of Large Hadron Collider (LHC)

Evolution of microdamage









Conclusions:

1. Radiation induced defects in the lattice constitute obstacles for the motion of dislocations.
2. Microvoids filled with impurities (gas) induce two physical effects: hardening and swelling.
3. Hardening is related to the interaction of dislocations with the defects, in particular with voids filled with impurities.
4. Tangent stiffness corresponds to the proportion between the volume fraction of matrix, and the volume fraction of voids with impurities.
5. Good correlation between the experiment and the numerical results was obtained.

Thank you for your attention!