EVOLUTION OF RADIATION INDUCED POROSITY IN METASTABLE MATERIALS APPLIED AT CRYOGENIC TEMPERATURES

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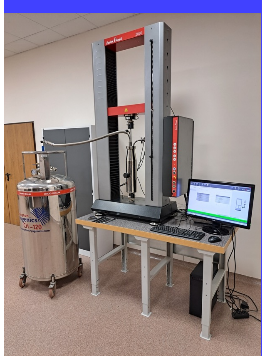
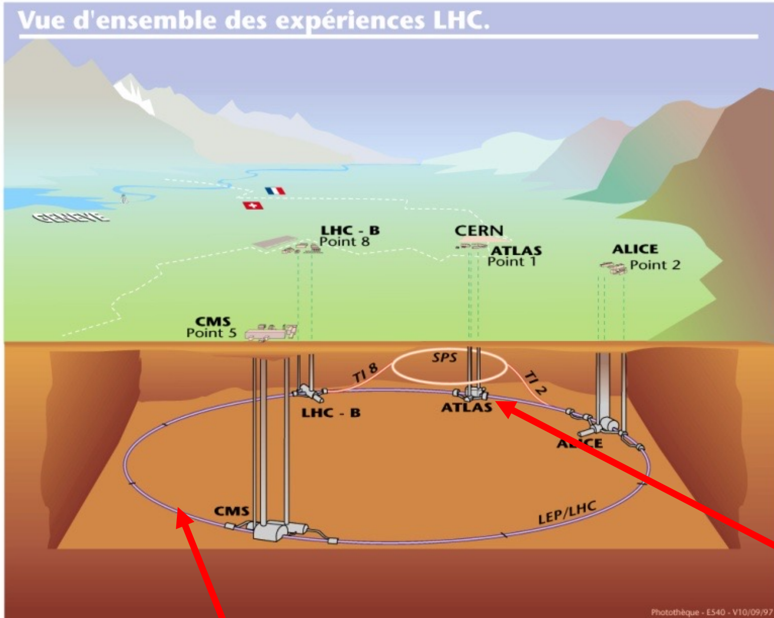
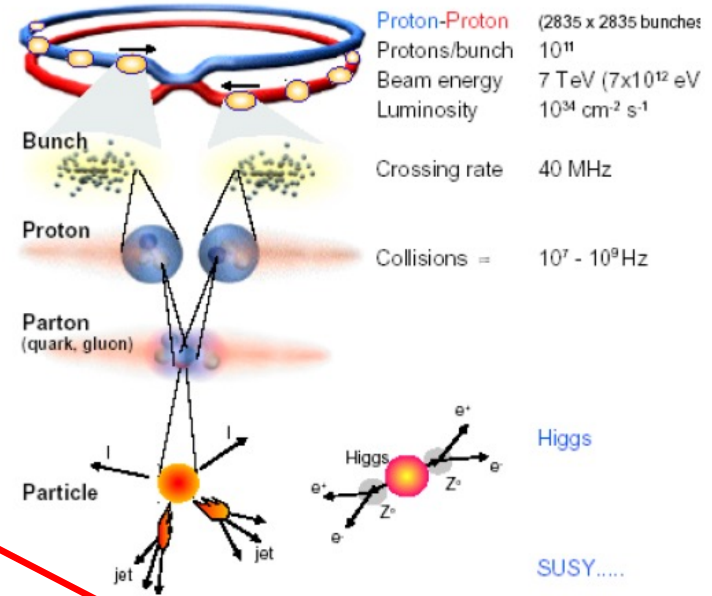


Outline:

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

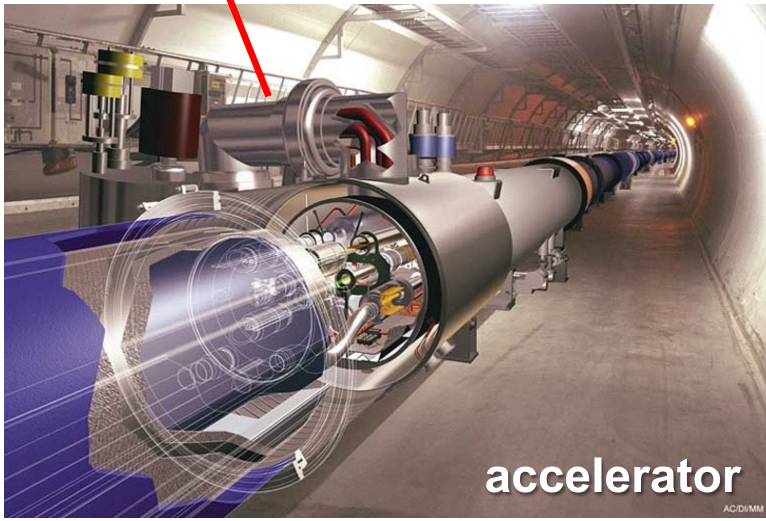
Motivation: CERN Large Hadron Collider

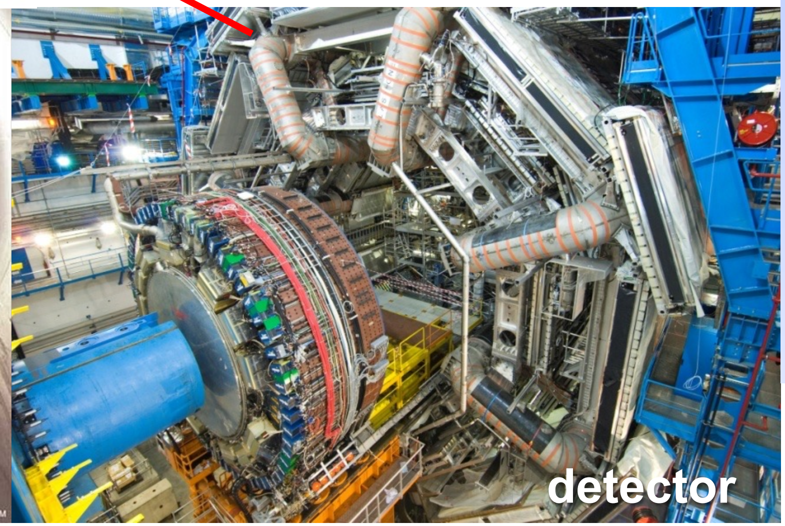




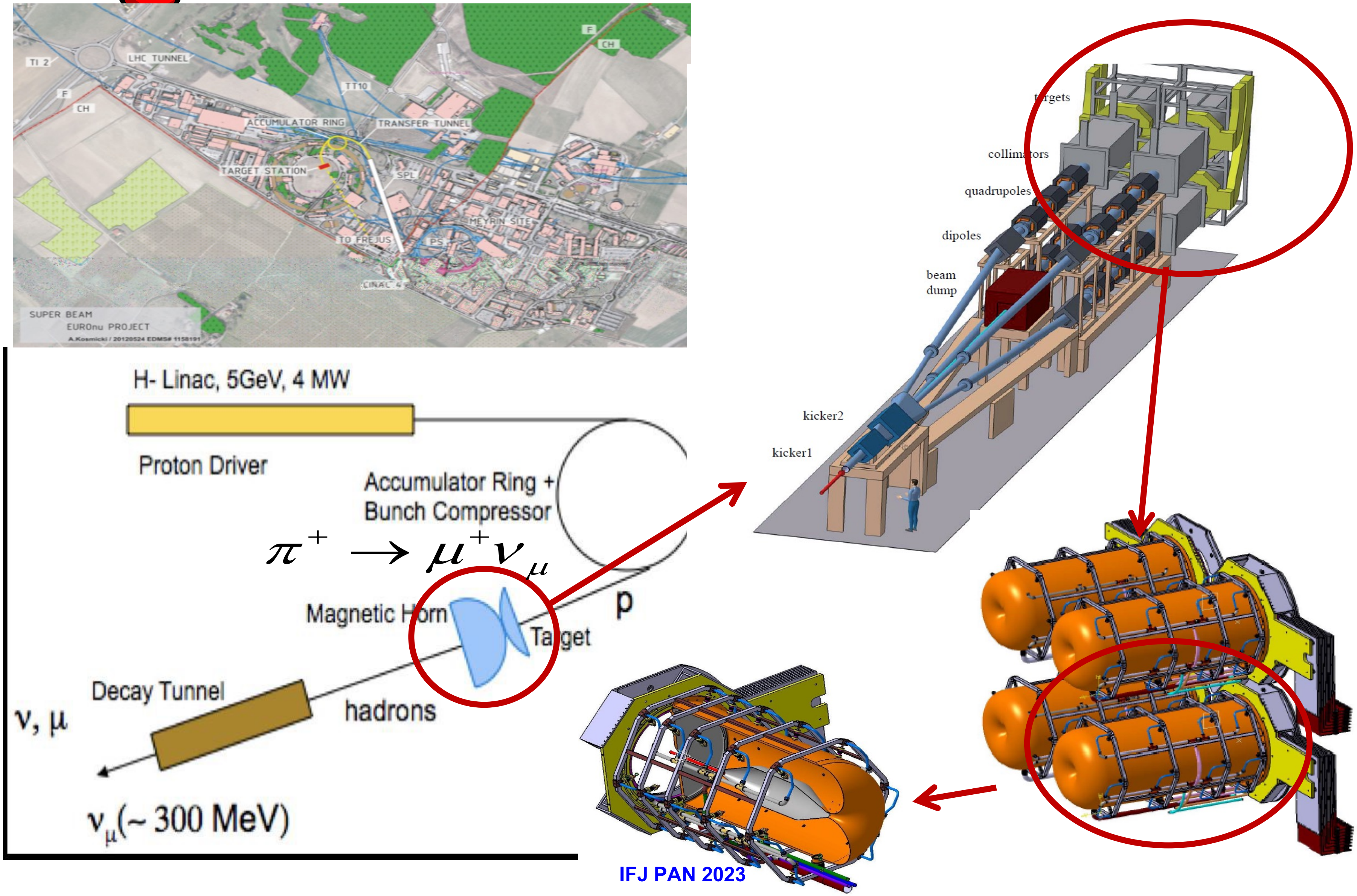
LHC
is the largest scientific instrument in the world based on the principle of super-conductivity!

LHC
operates in super-fluid helium at 1.9 K





EUROnu: High Intensity Neutrino Oscillation Facility in EU



International Thermonuclear Experimental Reactor ITER

Central Solenoid
Nb_3Sn 6 modules

Toroidal Field Coil
Nb_3Sn 18,

Poloidal Field Coil
NbTi, 6

Correction Coils
NbTi, 18

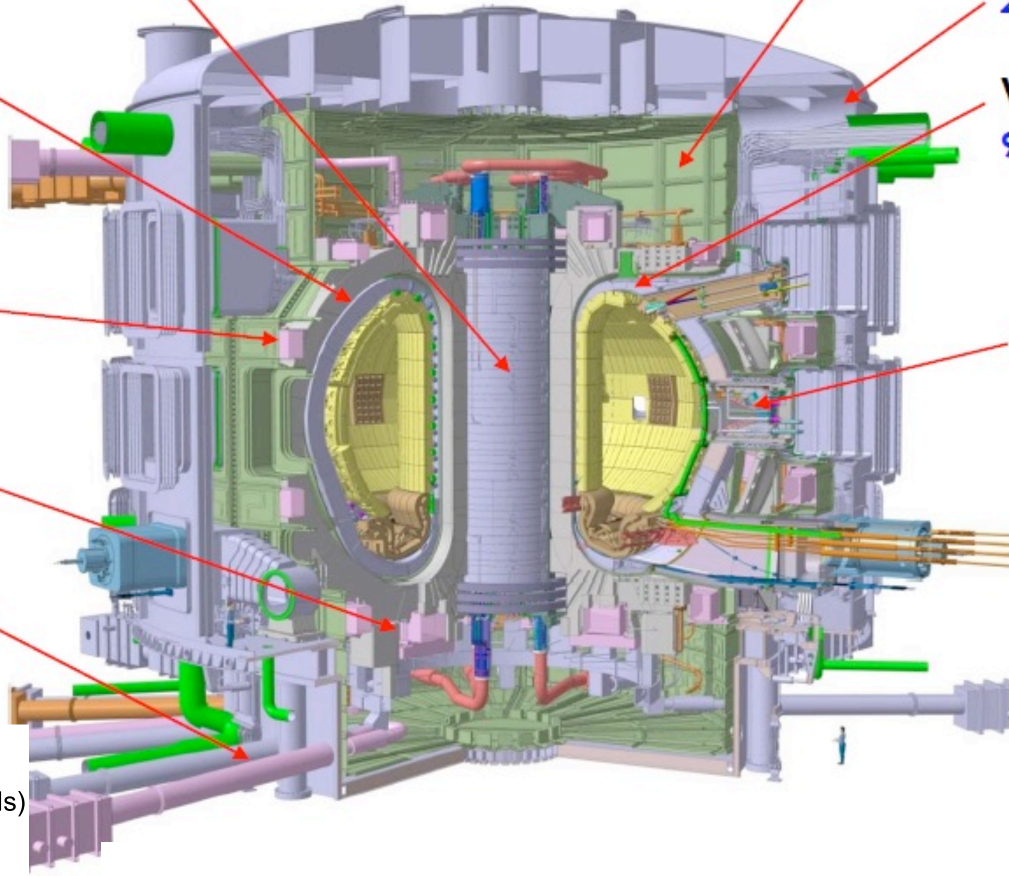
Feeders
NbTi, 31

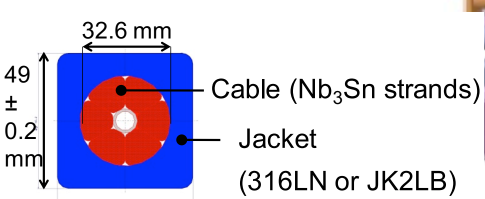
Cryostat Thermal shields

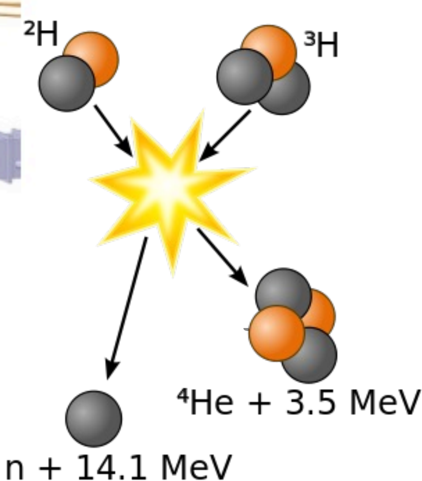
Cryostat
24 m high x 28 m dia.

Vacuum Vessel
9 sectors

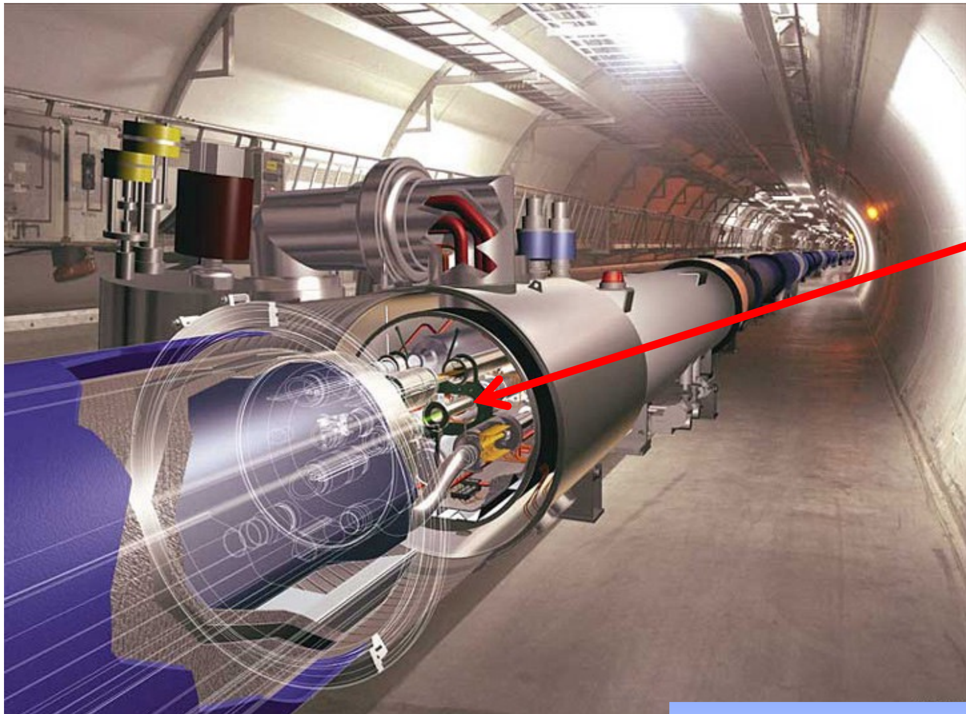
Port Plug
heating/current drive, test blankets limiters/RH diagnostics

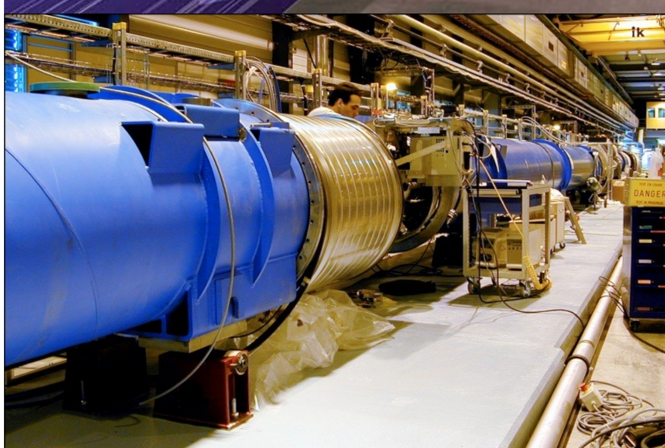




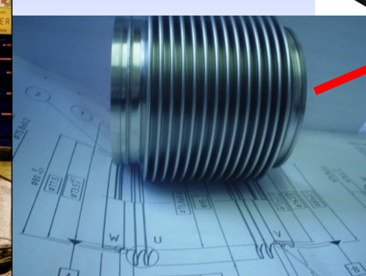


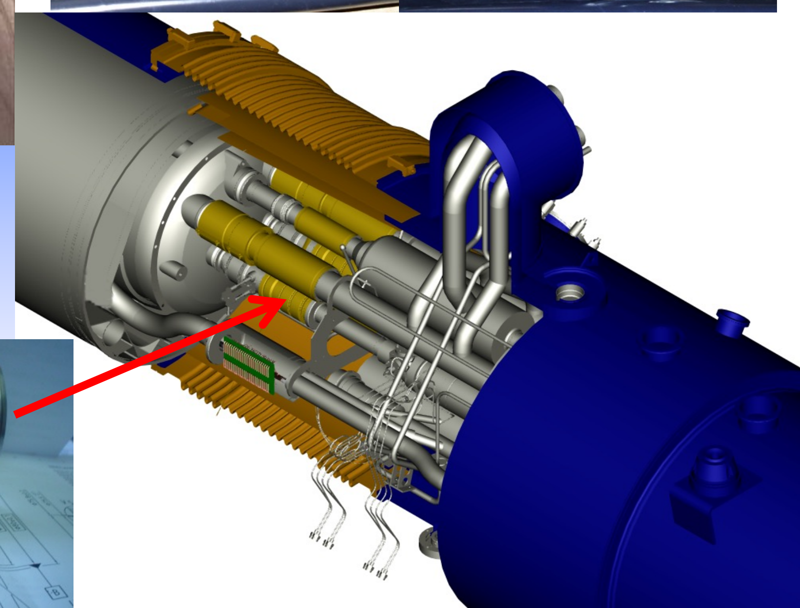
Motivation: CERN Large Hadron Collider



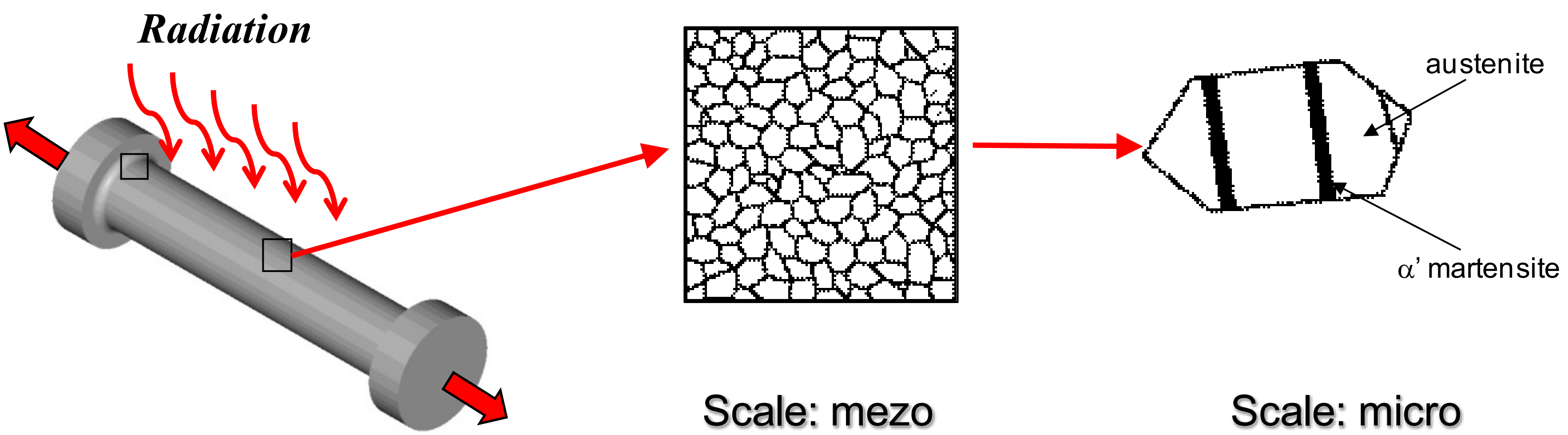


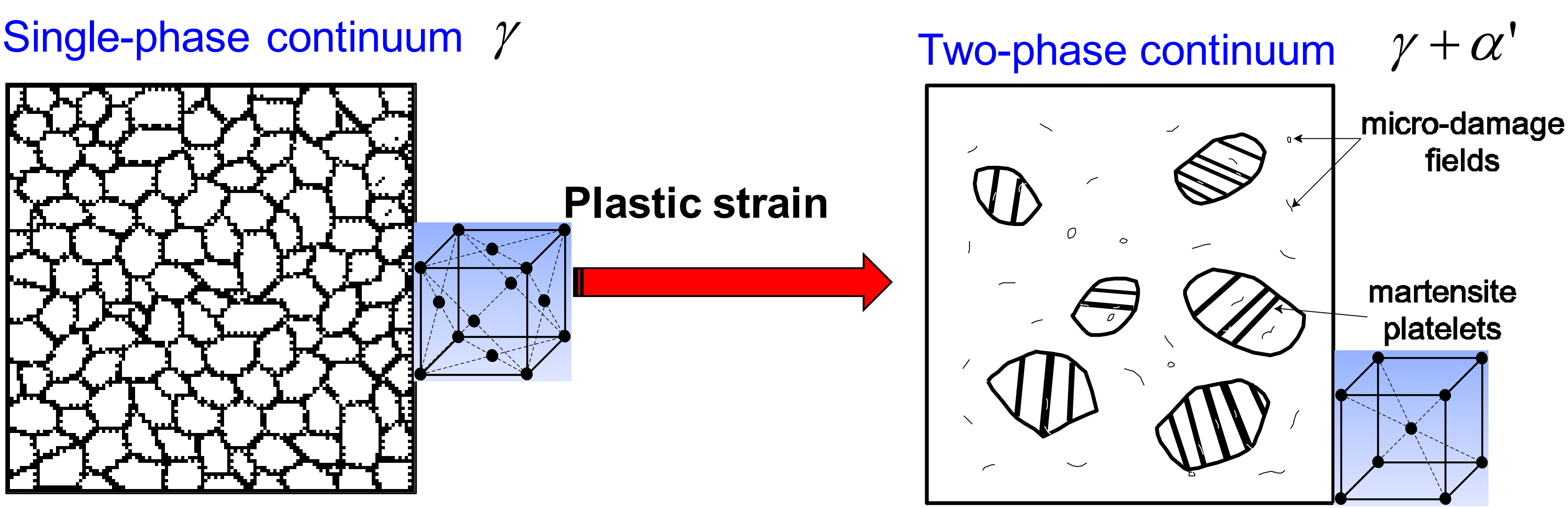
20000 expansion bellows



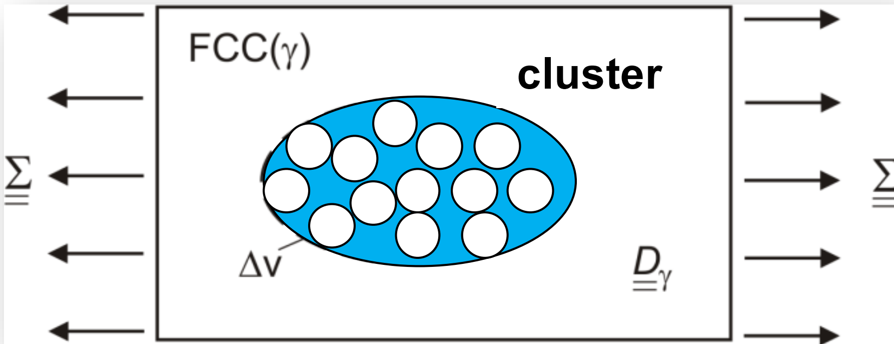


Coupled field problems: radiation versus phase transformation

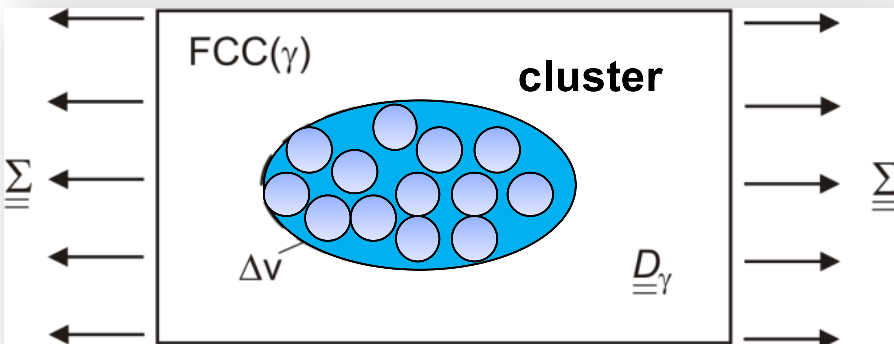




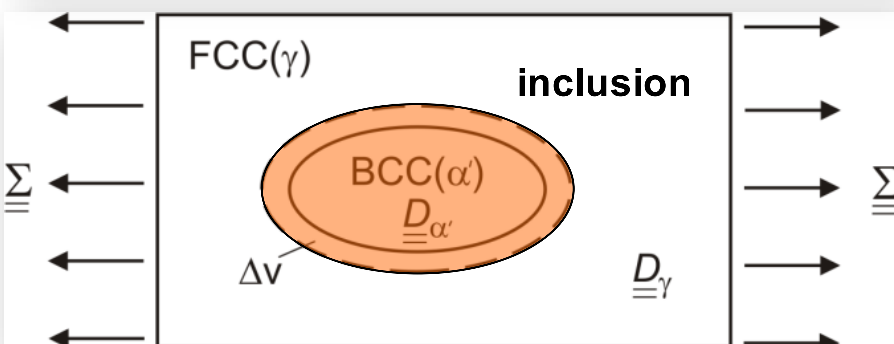
Coupled field problems: radiation versus phase transformation



3D vacancy clusters: ξ_c

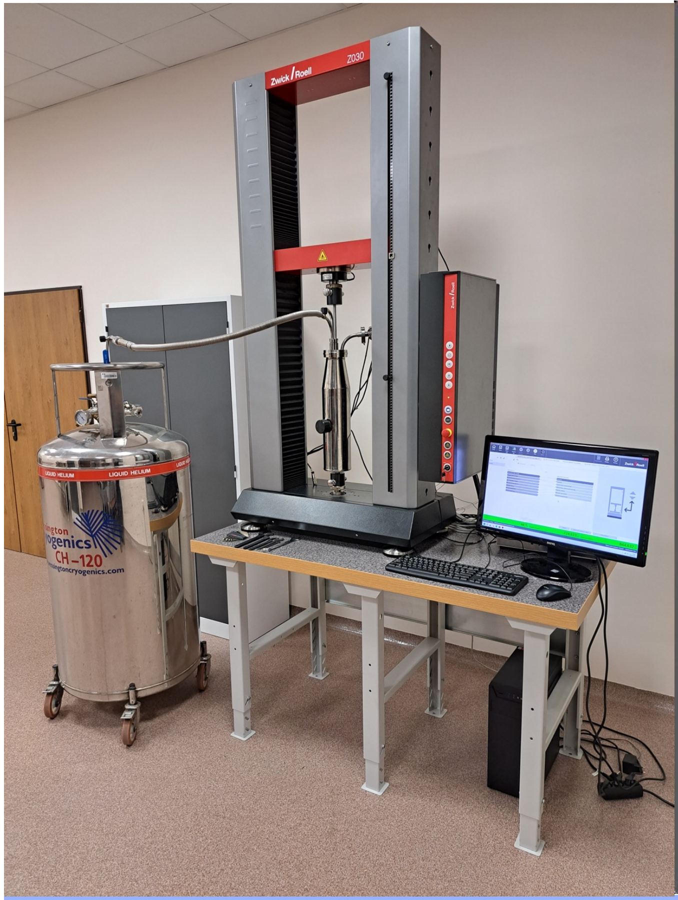


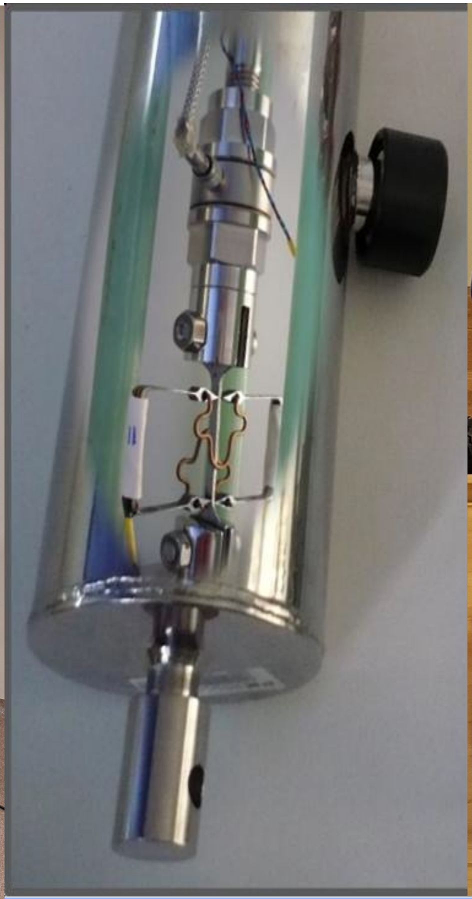
3D vacancy cluster with impurities (He): ξ_c

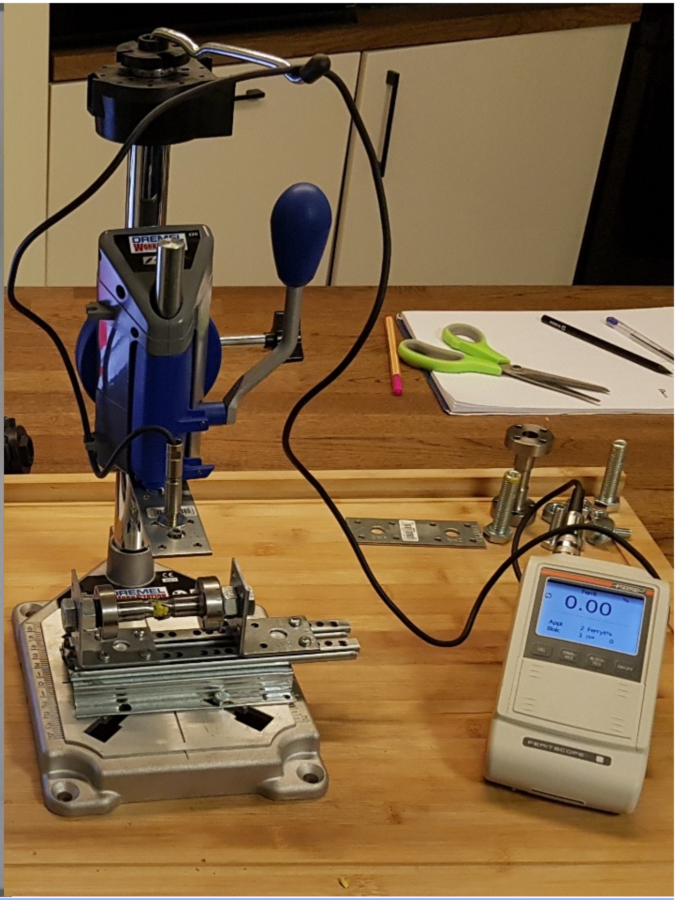


Inclusions of secondary phase: ξ_α

Experiments at extremely low temperatures (77 K, 4.2 K)

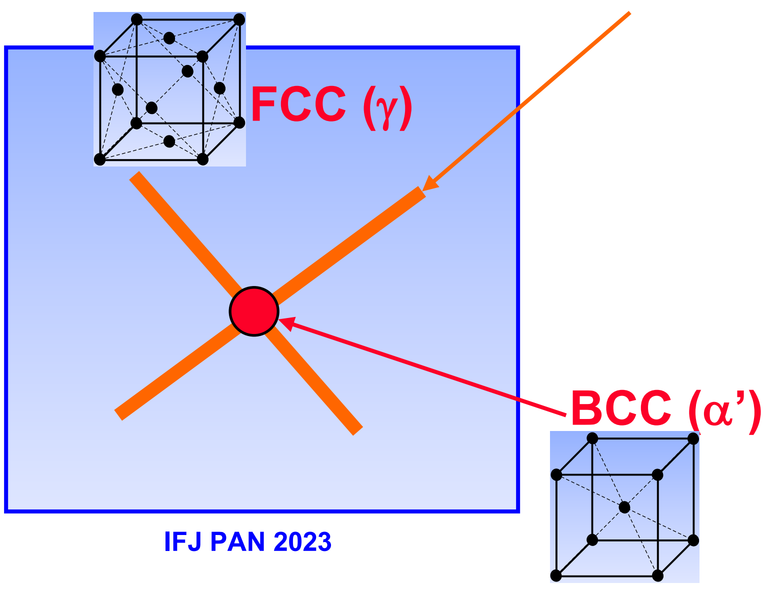




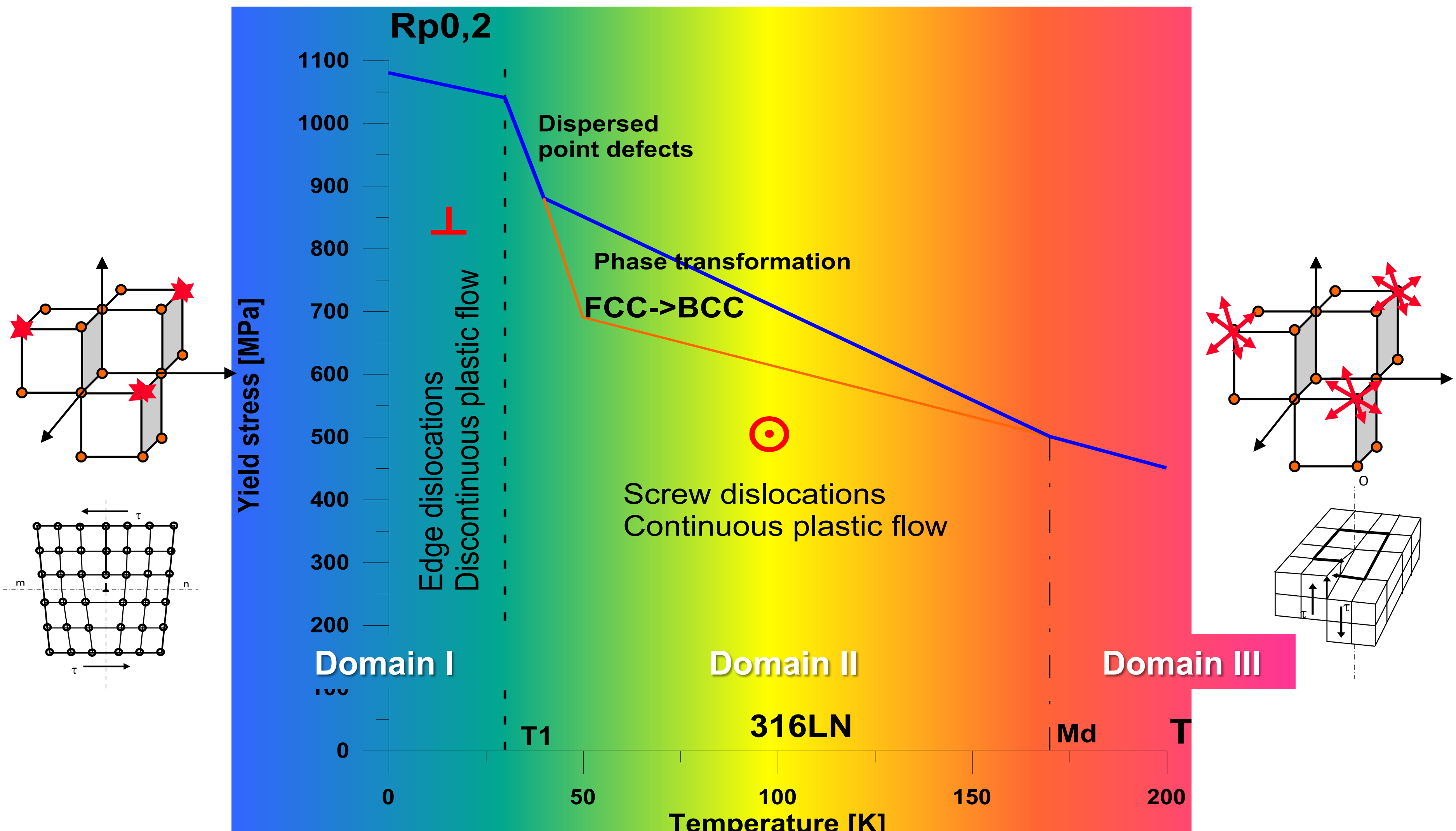


Dedicated cryogenic set-up for materials testing at extremely low temperatures (liquid nitrogen 77 K, liquid helium 4.2 K)

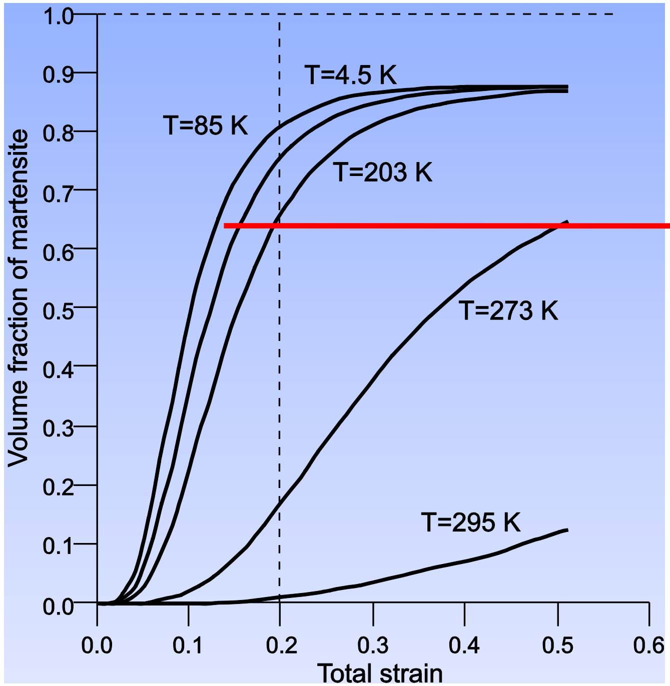
Plastic strain induced fcc-bcc phase transformation

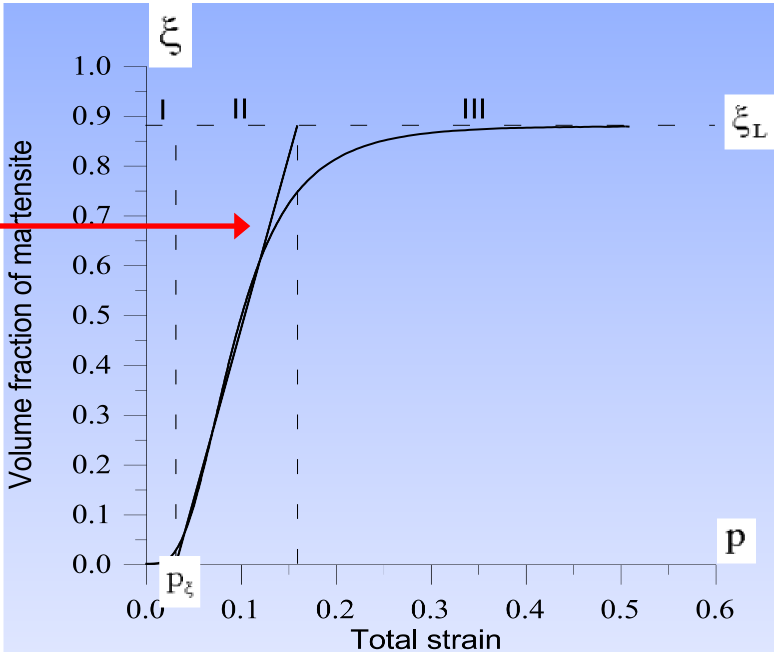


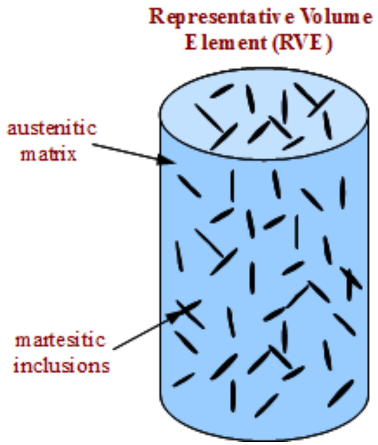
Mechanisms of plastic flow at cryogenic temperatures



Kinetics of Fcc-Bcc phase transformation







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

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

ξ – volume fraction of α’ phase

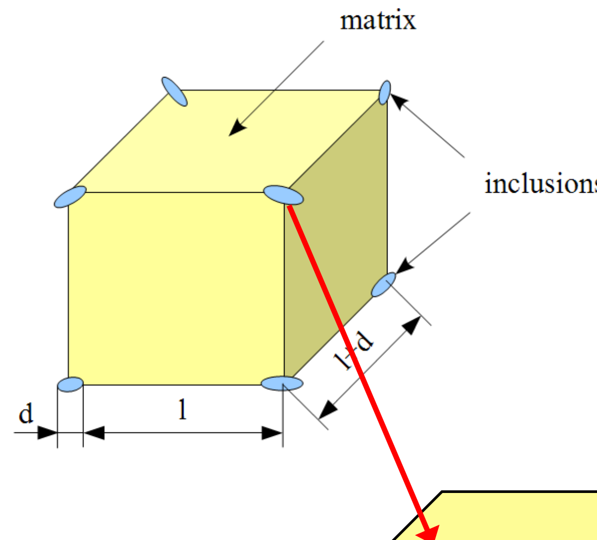
Micromechanics: transformation strain

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

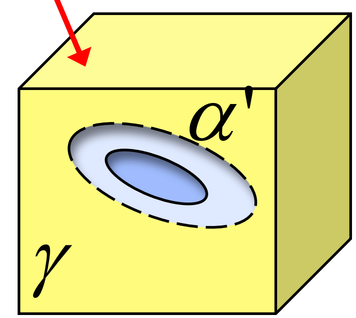
$$\underline{\underline{\varepsilon}}^{bs} = \underbrace{\frac{V_\gamma}{V}\frac{1}{V_\gamma}\int_{V_\gamma} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV}_{\approx 0} + \frac{V_\alpha}{V}\frac{1}{V_\alpha}\int_{V_\alpha} \underline{\underline{\varepsilon}}_{\mu}^{bs}\, dV$$

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

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



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

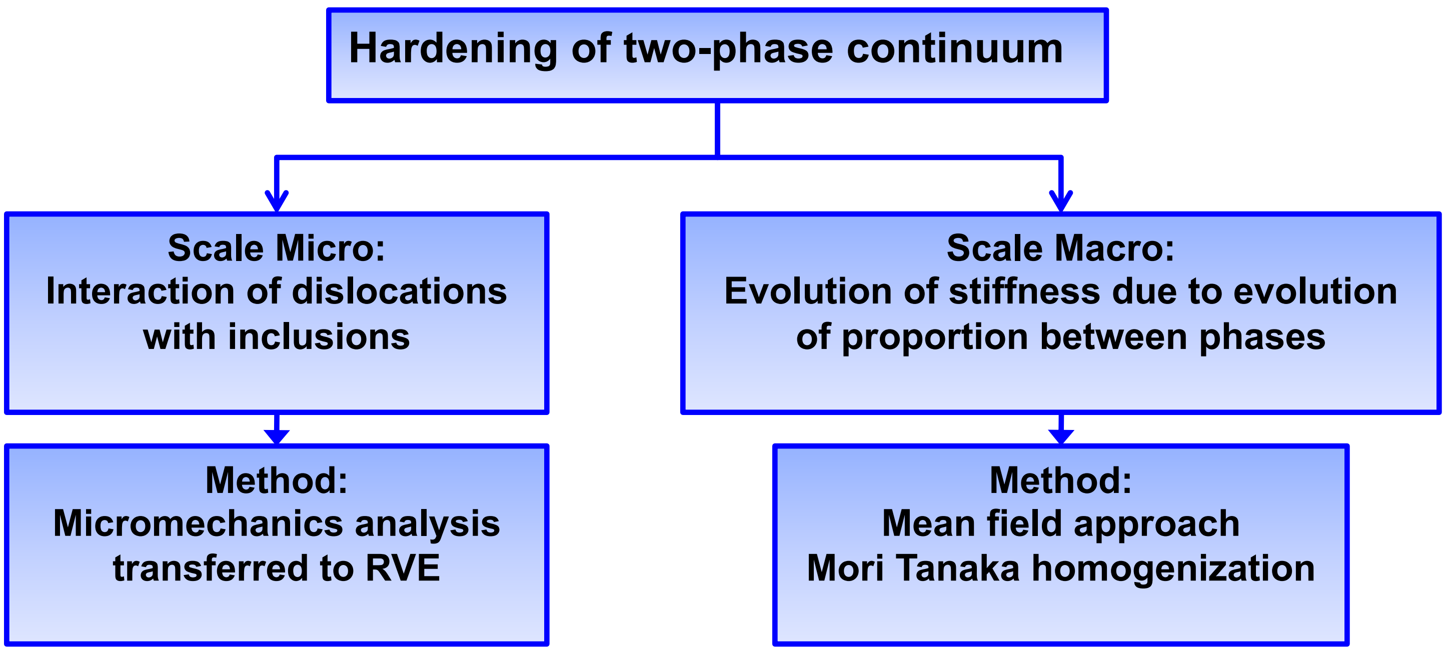
Yield condition:

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

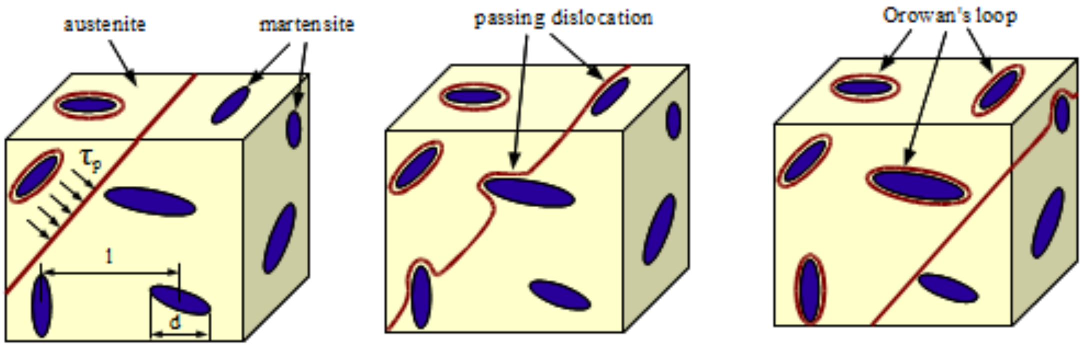
Mixed hardening depending on the phase transformation parameter:

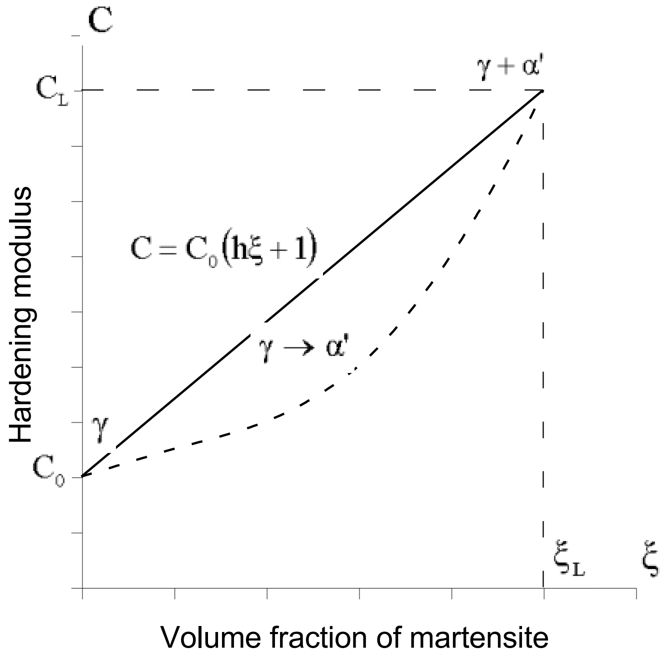
$$d\underline{\underline{X}}=d\underline{\underline{X}}_a+d\underline{\underline{X}}_{a+m}=\frac{2}{3}C_X(\xi)d\underline{\underline{\varepsilon}}^p$$

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



Scale Micro: interaction of dislocations with inclusions





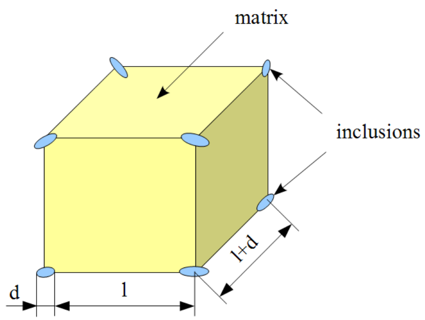
$$d\underline{\underline{X}}_a = \frac{2}{3} C_0 d\underline{\underline{\varepsilon}}^p$$

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

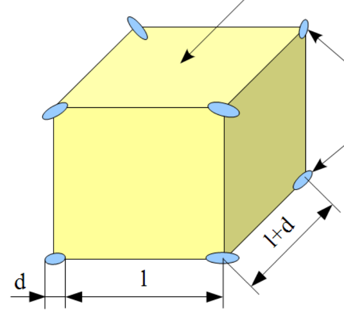


$$\tau_p = \frac{Gb}{d}\left(\frac{6\xi_0}{\pi}\right)^{\frac{1}{3}}\left(1 + \frac{\xi - \xi_0}{3\xi_0}\right)$$

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

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

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:

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

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

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

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

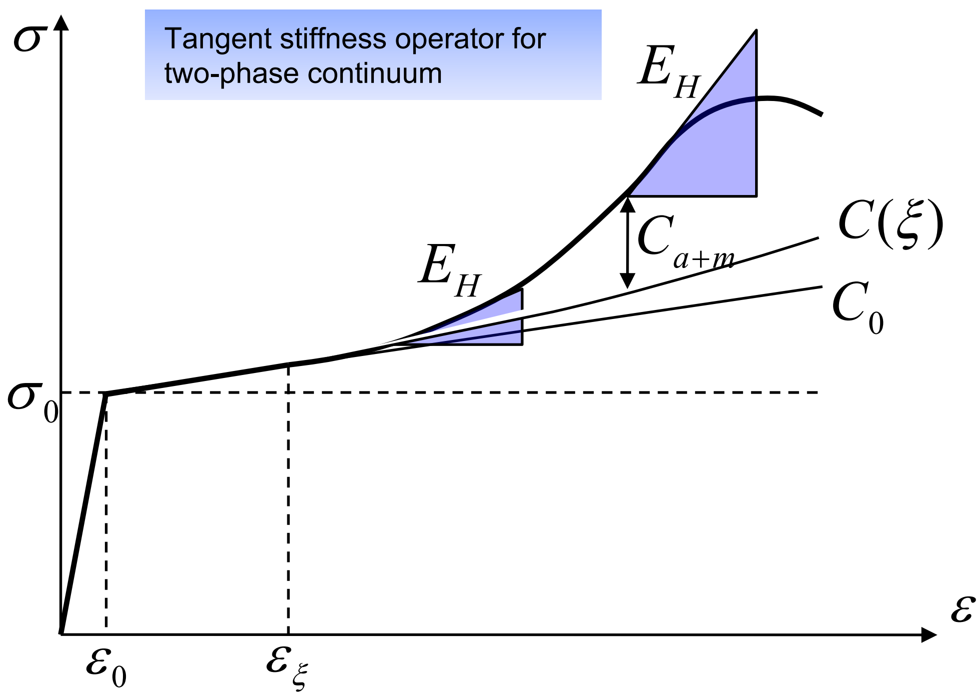
$$\underline{\underline{\underline{\underline{E}}}}_{ta} = 3k_{ta} \underline{\underline{\underline{\underline{J}}}} + 2\mu_{ta} \underline{\underline{\underline{\underline{K}}}}$$

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

Homogenization:

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

Scale Macro: evolution of proportion between phases



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

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

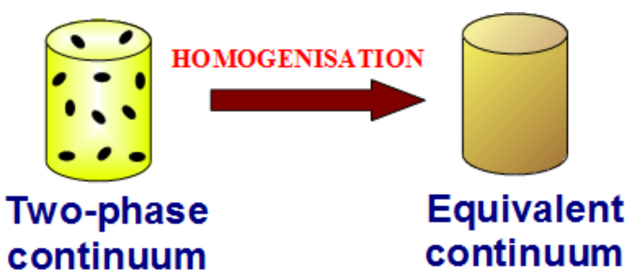
$$\underline{\underline{E}}_{H} = \underline{\underline{E}}_{MT} = 3k_{MT}\,\underline{\underline{J}} + 2\mu_{MT}\,\underline{\underline{K}}$$

$$\left[\underline{\underline{E}}_{MT} + \underline{\underline{E}}^*\right]^{-1} = \sum_{i=a,m} f_i \left[\underline{\underline{E}}_i + \underline{\underline{E}}^*\right]^{-1}$$

$$\underline{\underline{E}}_{MT} = \left[(1-\xi)\left(\underline{\underline{E}}_a + \underline{\underline{E}}^*\right)^{-1} + \xi\left(\underline{\underline{E}}_m + \underline{\underline{E}}^*\right)^{-1}\right]^{-1} - \underline{\underline{E}}^*$$

$$3k_{MT} + 3k^* = \left[\frac{1-\xi}{3\left(k_{ta} + k^*\right)} + \frac{\xi}{3\left(k_m + k^*\right)}\right]^{-1} \qquad k^* = \frac{4}{3}\mu_{ta}$$

$$2\mu_{MT} + 2\mu^* = \left[\frac{1-\xi}{2\left(\mu_{ta} + \mu^*\right)} + \frac{\xi}{2\left(\mu_m + \mu^*\right)}\right]^{-1} \qquad 2\mu^* = \frac{\mu_{ta}\left(9k_{ta} + 8\mu_{ta}\right)}{3\left(k_{ta} + 2\mu_{ta}\right)}$$



Constitutive description of two-phase continuum

Kinematic hardening

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

Isotropic hardening

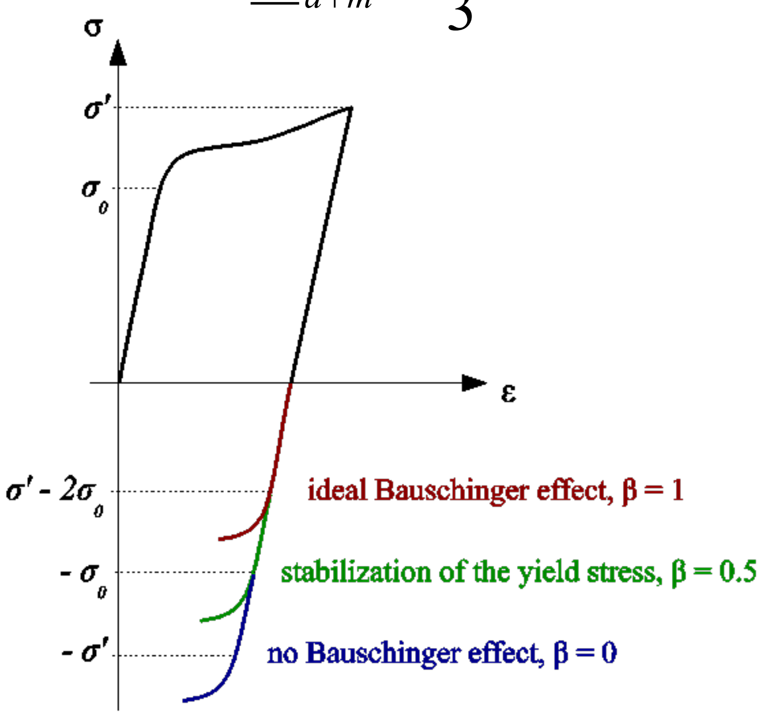
$$\Delta \underline{\underline{X}}_{a+m} = \Delta \underline{\underline{\sigma}}_{a+m}$$

Parametization: ***Życzkowski, 1981***

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

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

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

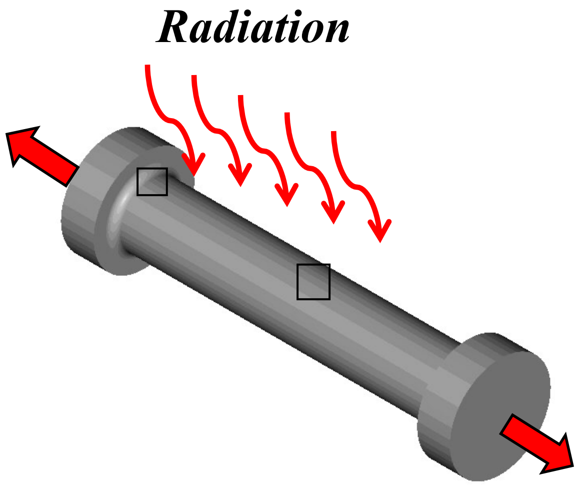


Evolution laws of hardening parameters

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

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

Radiation induced damage



Research program

Experiments including proton and neutron irradiated samples subjected to loading/unloading technique

⬇

Building well calibrated multi-scale 3D constitutive models of damage/ porosity evolution in the framework of CDM

⬇

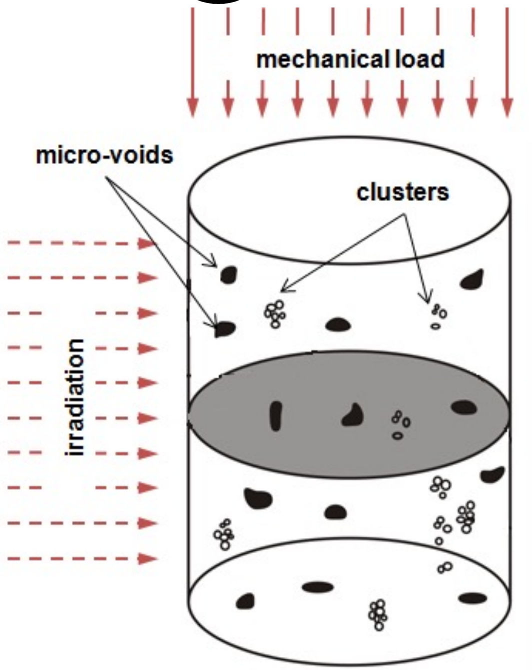
Combining CDM with fracture mechanics in order to predict transition from critical damage/porosity to fracture

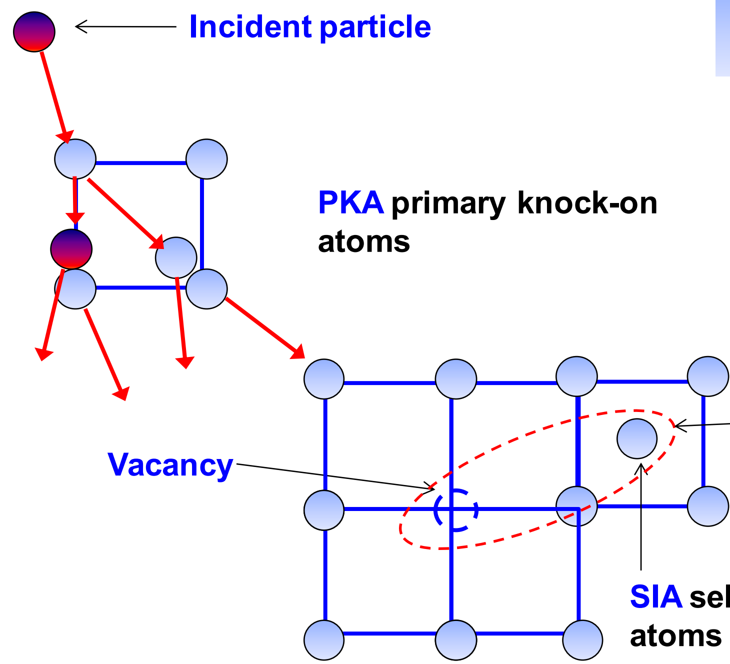
⬇

Computing evolution of nano/micro damage fields and macro-crack propagation in the irradiated components

Lifetime prediction

Radiation induced micro-damage





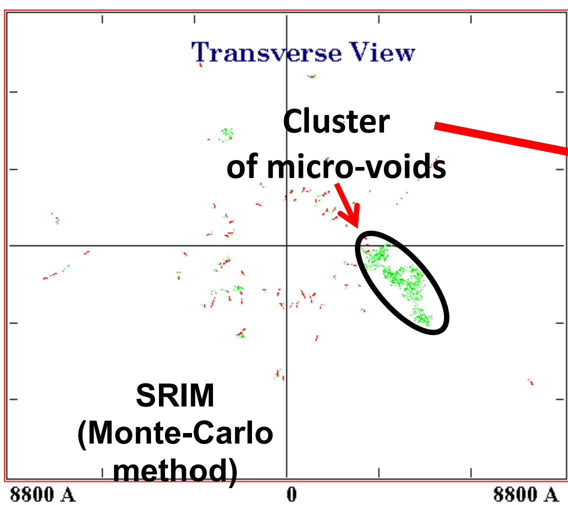
Displacement cascade and formation of Frenkel pairs

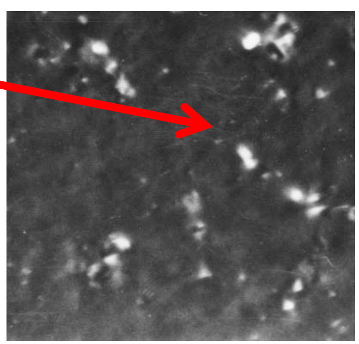
Kinchin & Pease, 1955

Norgett, Robinson, Torrens, 1975

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

$$E_{dam} = NIEL$$



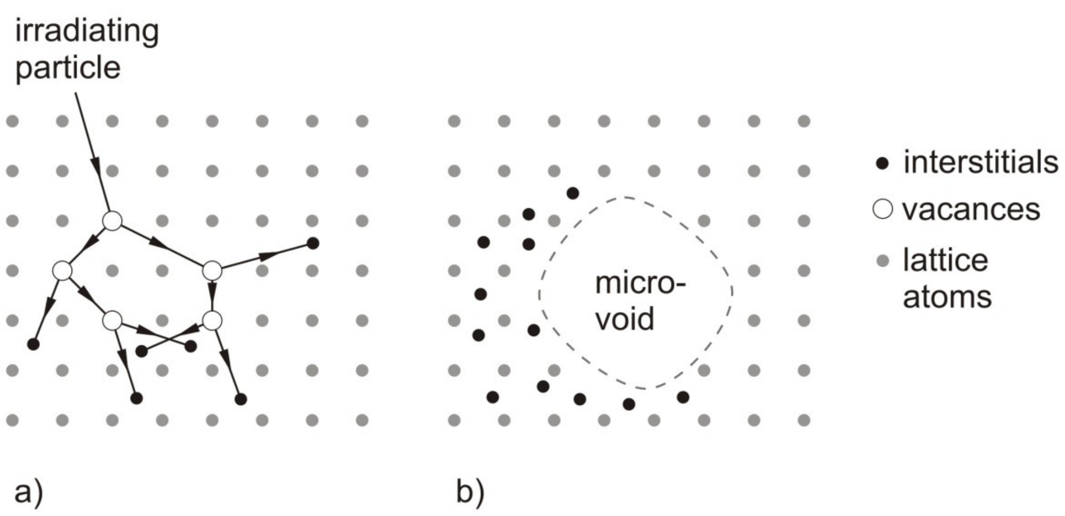


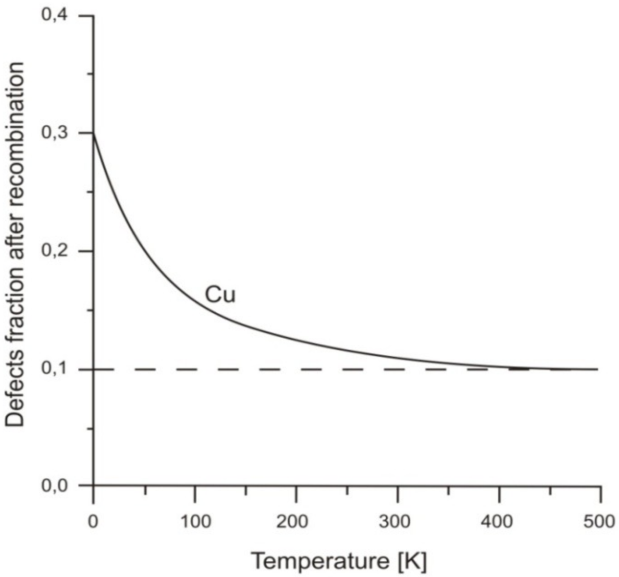
Defects due to irradiation:

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

Measure of irradiation induced damage

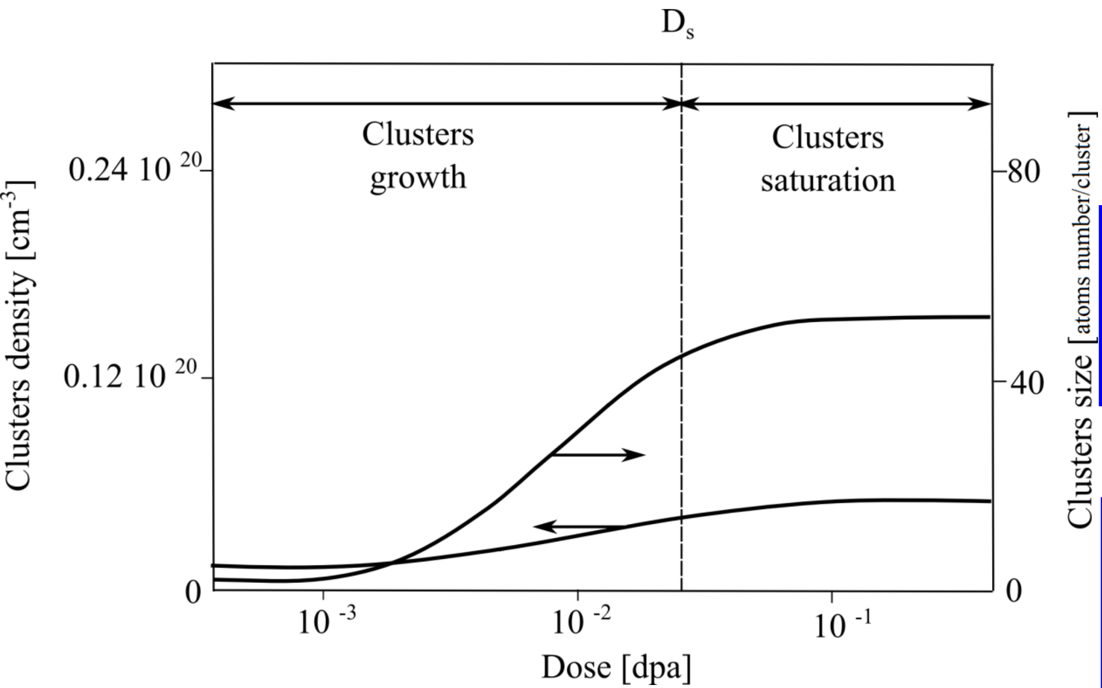
1 displacement per atom (dpa):
corresponds to stable displacement from their lattice site of all atoms in the material during irradiation near absolute zero (no thermally-activated point defect diffusion)





Lattice defects after irradiation

Coupled dissipative phenomena at cryogenic temperatures



dpa

Physics

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

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

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

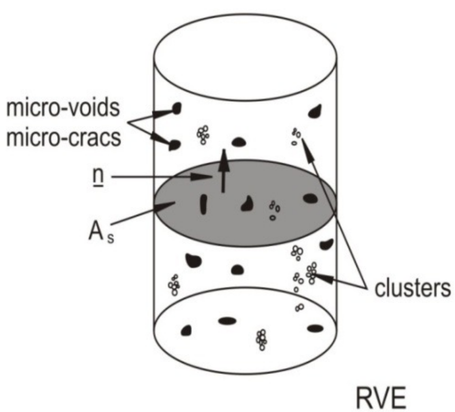
$$D_{r0} = q_A \pi r_{c0}^{\;2}$$

Mechanics

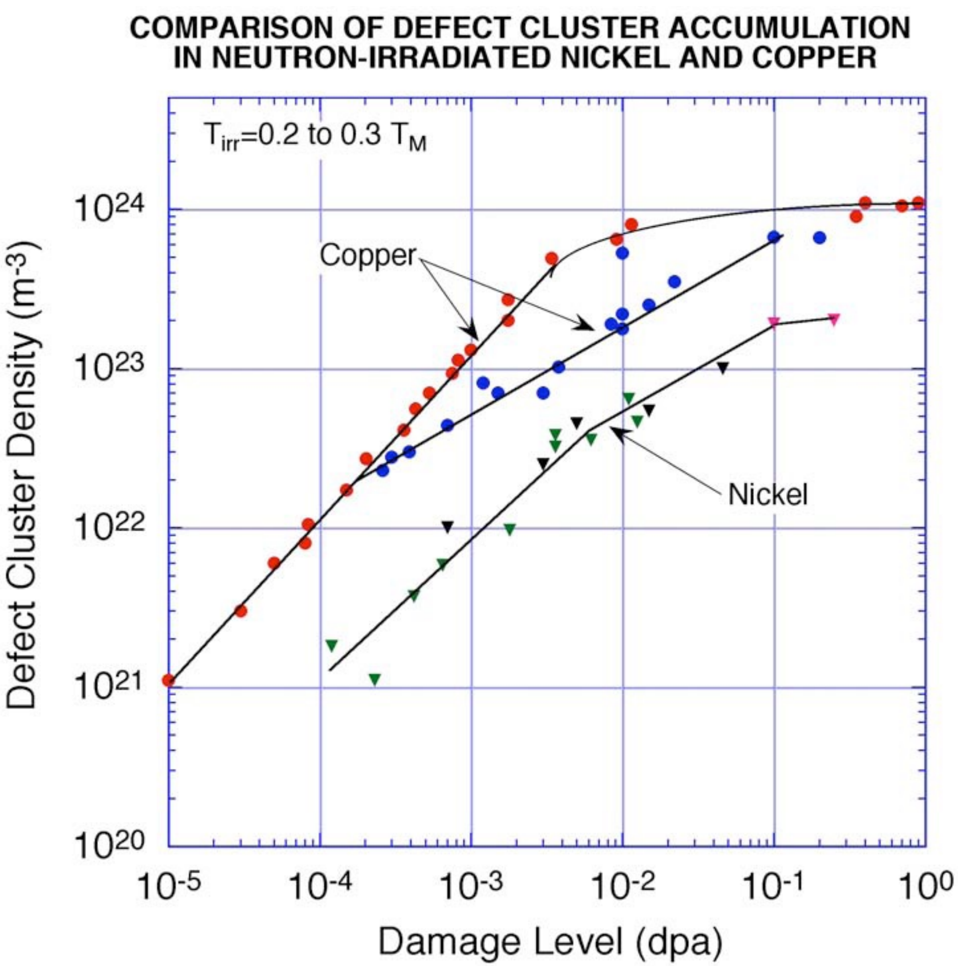
q_c – number of clusters per unit volume
r_c – average radius of clusters

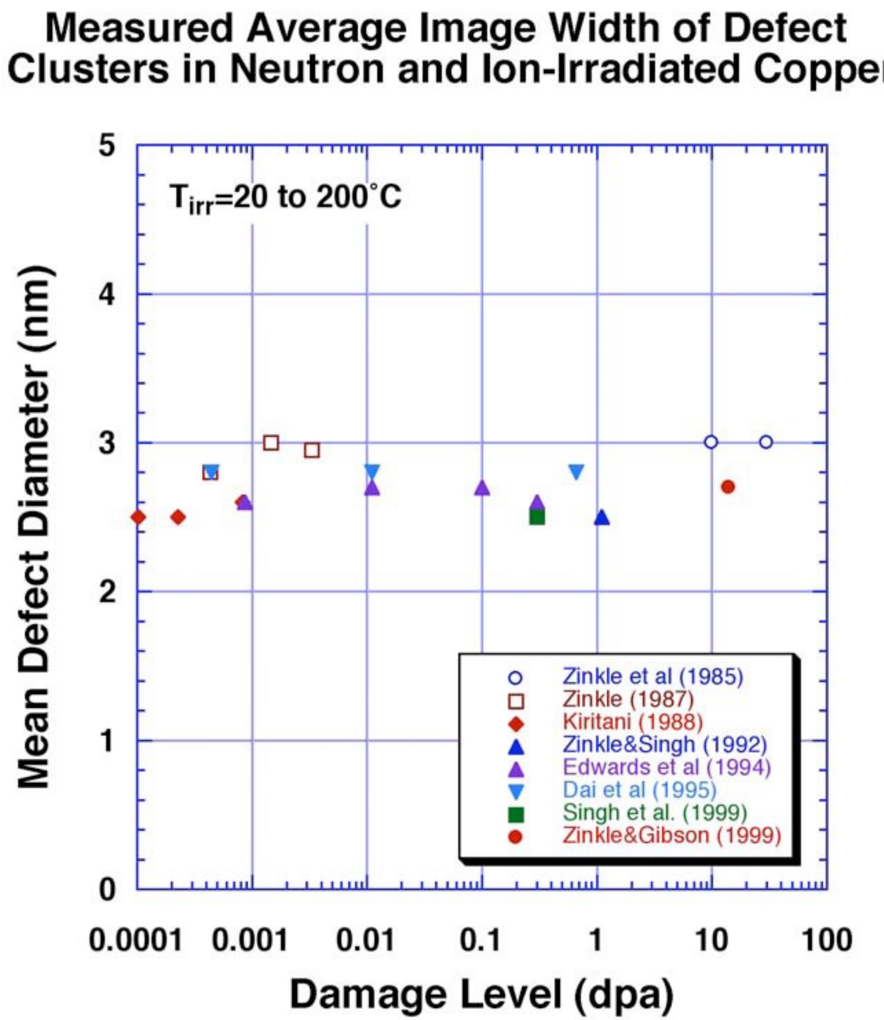
$$D = \frac{dS_D}{dS} \quad ; \quad 0 \leq D \leq 1$$

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



Irradiated metals and alloys: Nickel and Copper

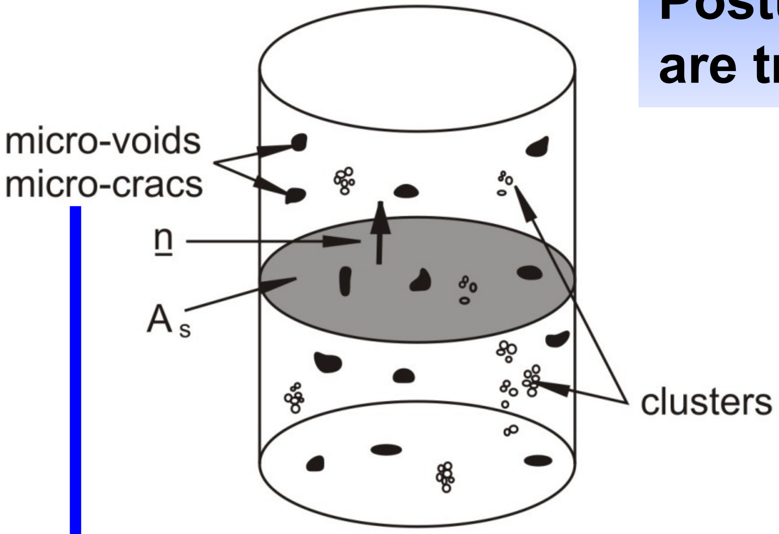




Source: S.J. Zinkle „Microstructure evolution in irradiated metals and alloys: fundamental aspects", Italy, 2004.

Radiation and mechanical damage: additive formulation

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



RVE

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

radiation induced damage

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

isotropic

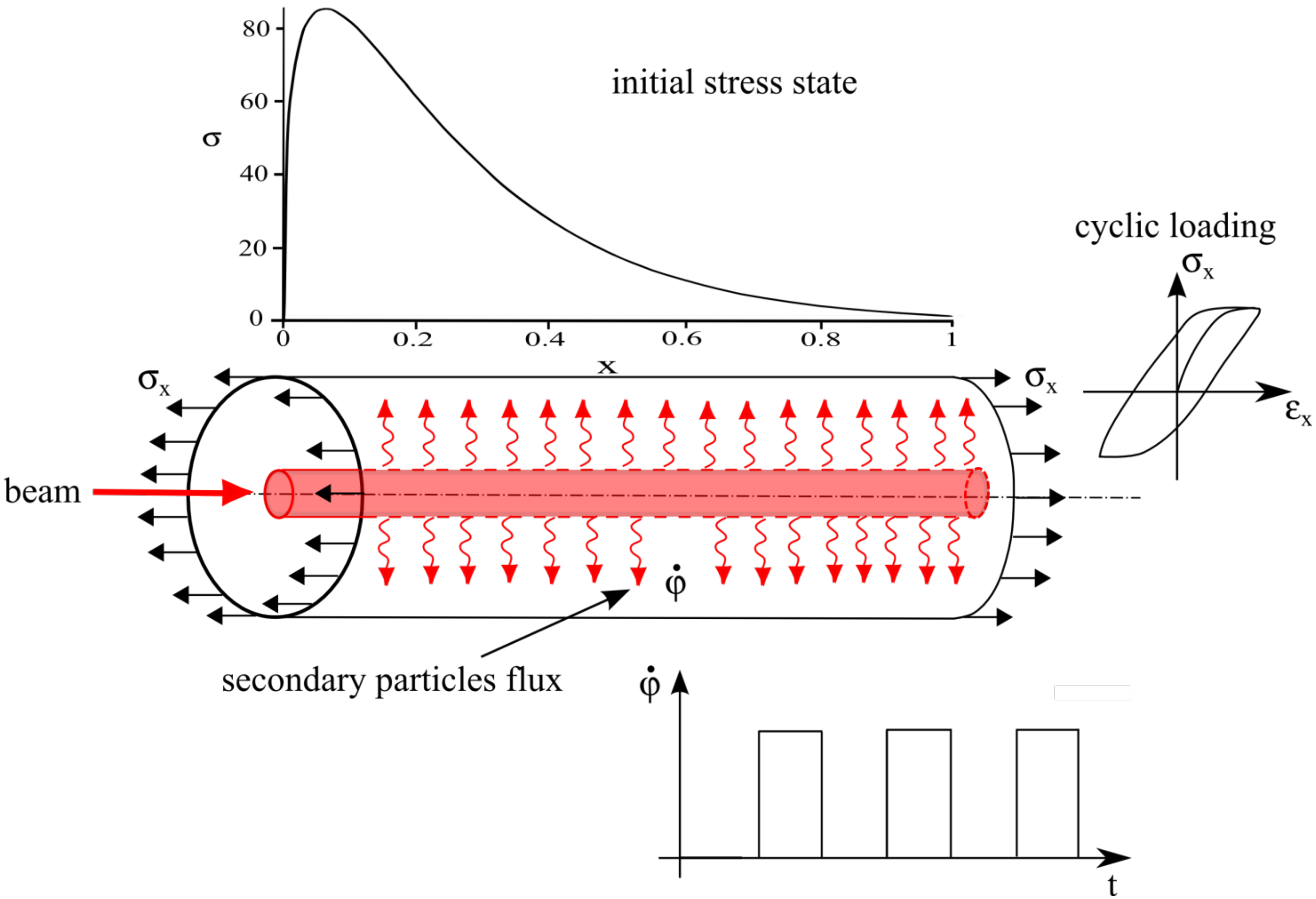
$\underline{\underline{I}}$ **- identity tensor**

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

anisotropic

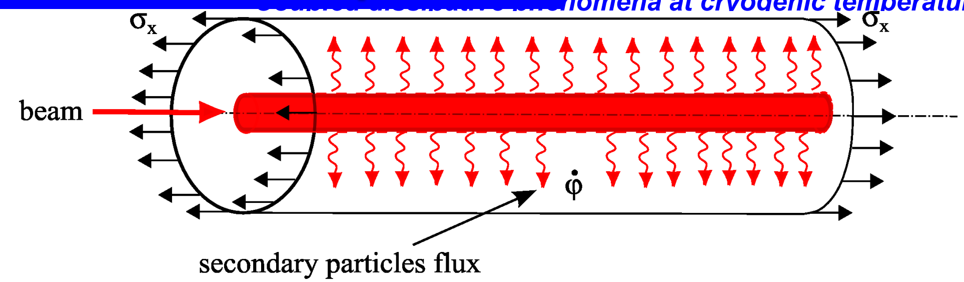
$$\underline{\underline{D}} = \underline{\underline{D}}_m + \underline{\underline{D}}_r = \underline{\underline{D}}_m + \frac{1}{3} D_r \underline{\underline{I}}$$

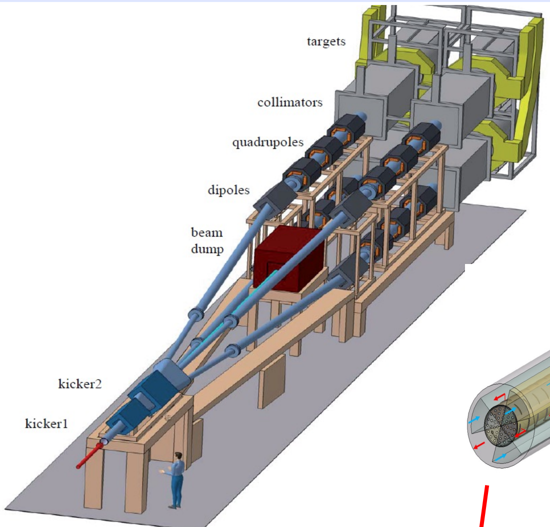
Lifetime estimation for irradiated components

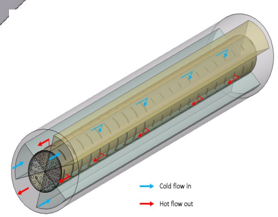


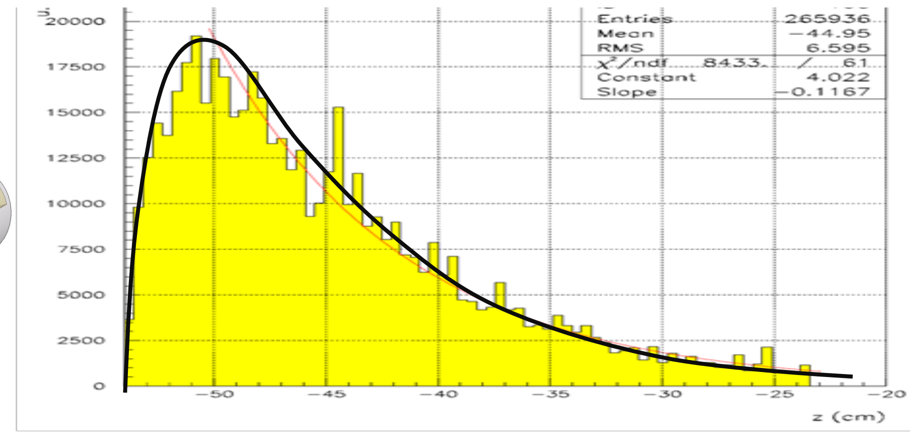
Lifetime estimation for irradiated components

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



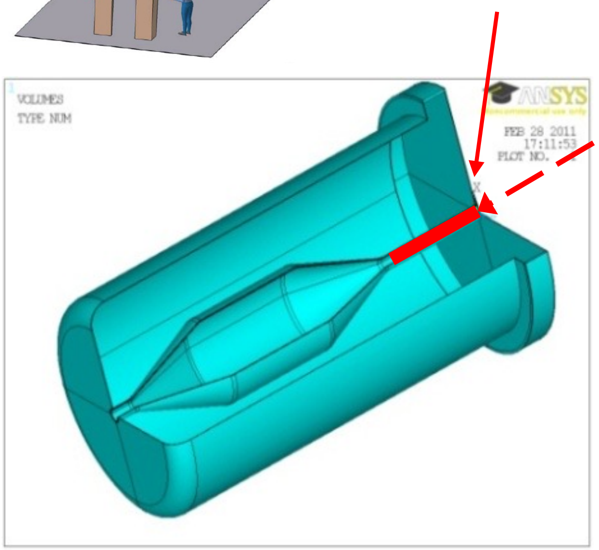


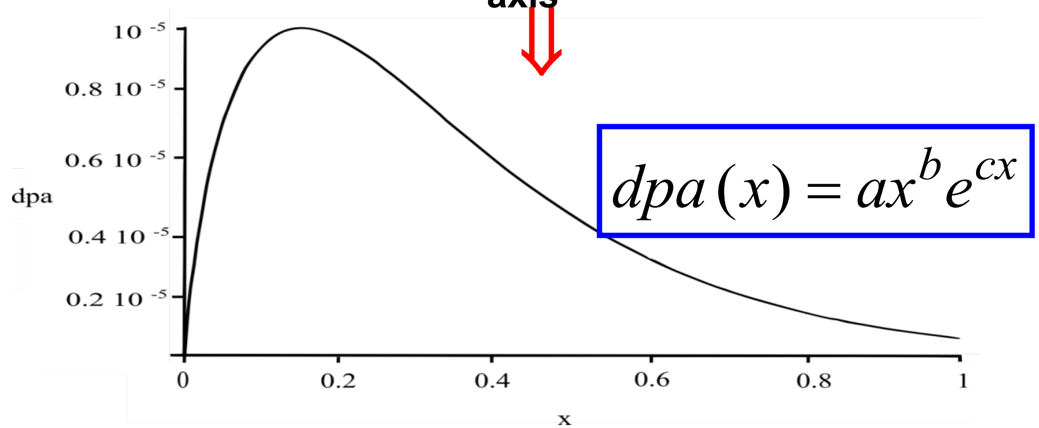




Typical distribution of particle flux along the target axis

⇓





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

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

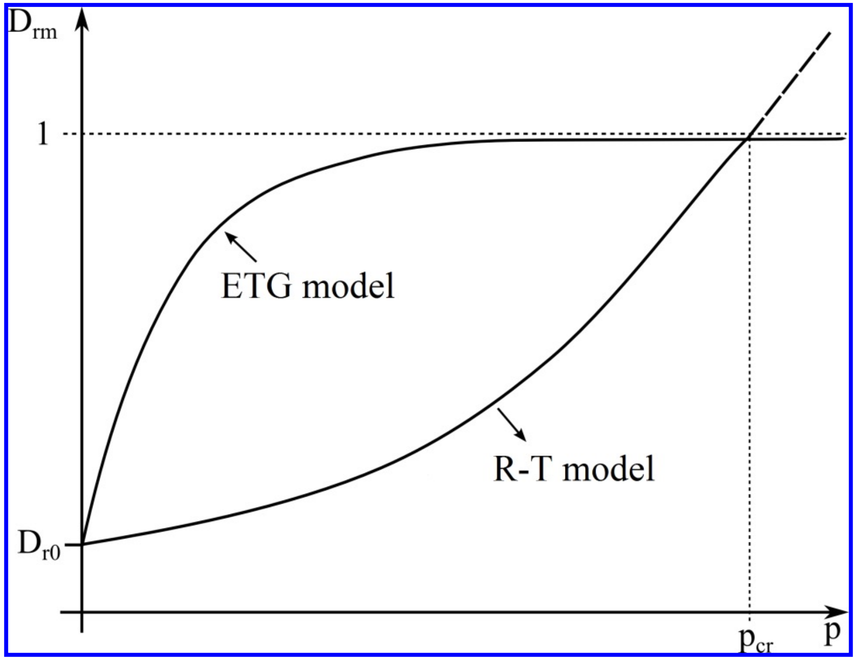
Rice&Tracey (R-T) model:

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

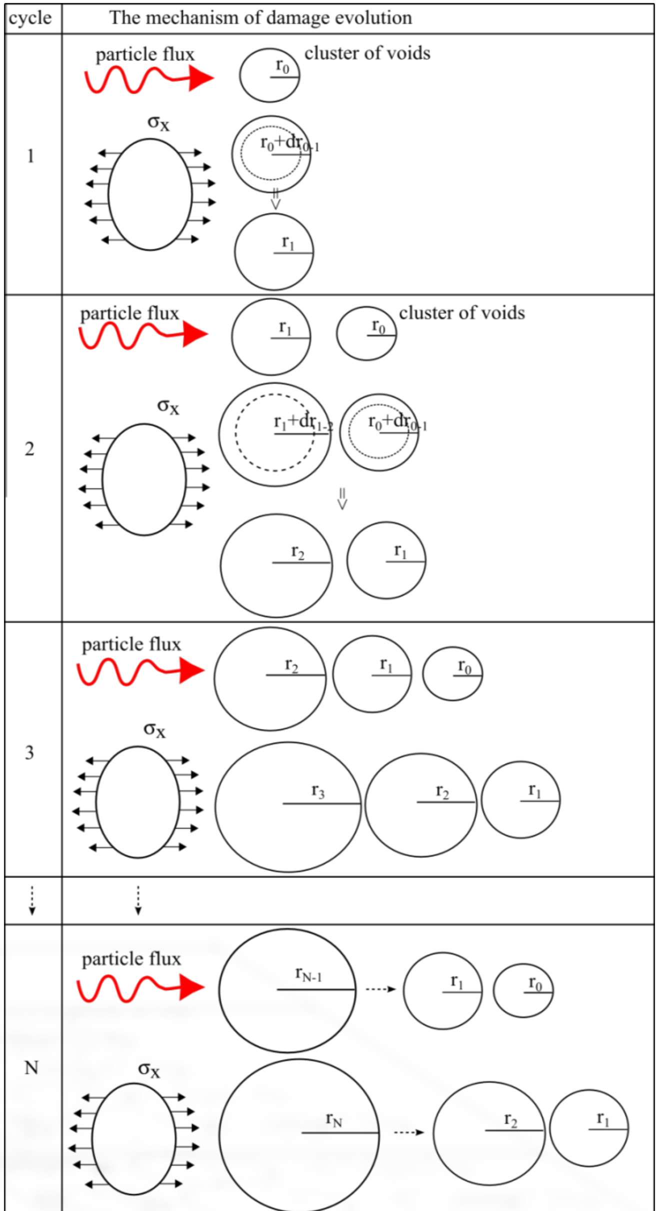
Gurson (ETG) model:

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

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



Lifetime estimation for irradiated components



Rice & Tracey law

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

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

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

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

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

Lifetime estimation for irradiated components

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

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

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

$$\vdots$$

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

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

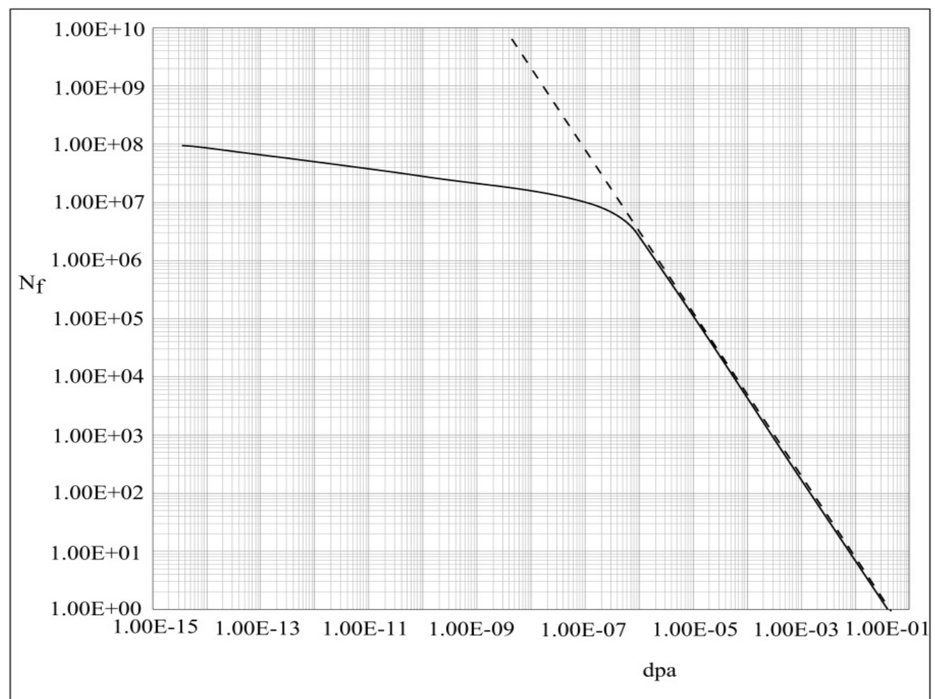
Number of cycles to failure N_f based on the critical damage criterion: $D_{rm}=D_{cr}$

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

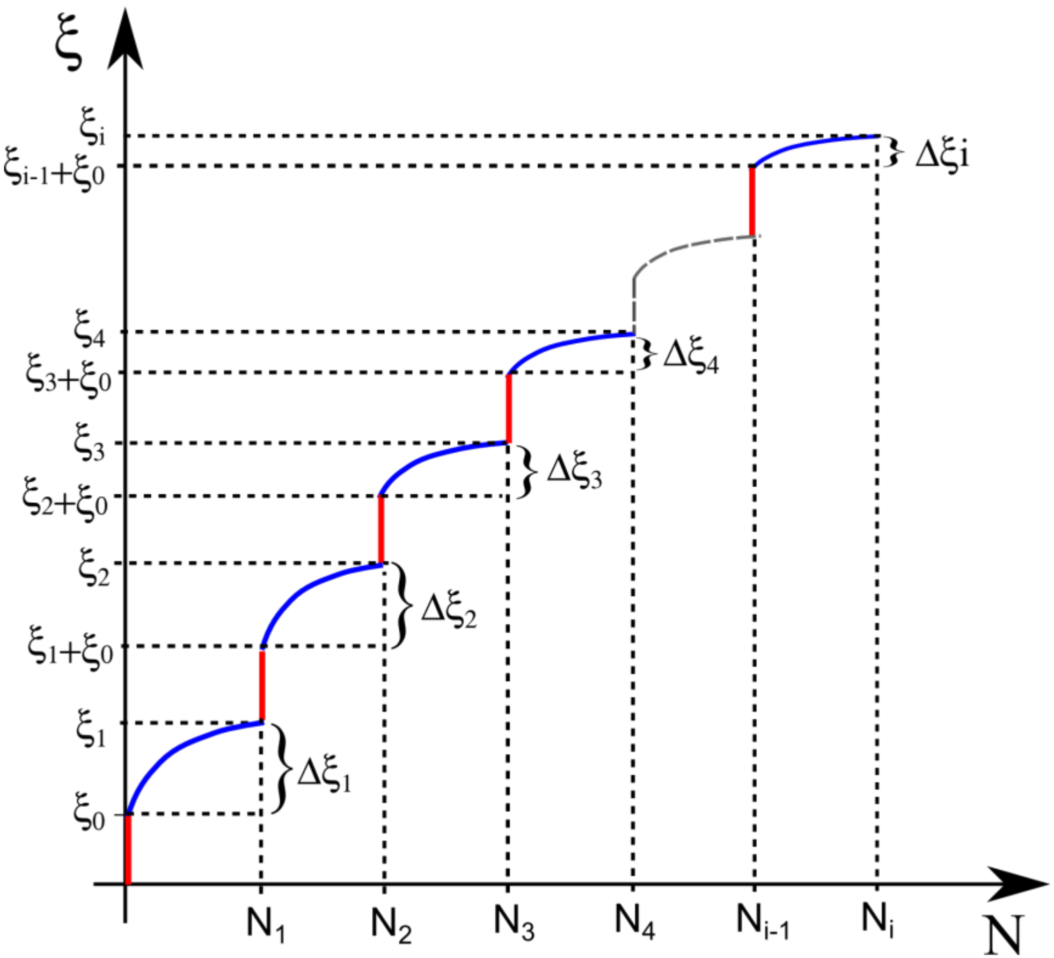
$$S_N = a_1 \frac{1-q^N}{1-q} \qquad S_N = q_A \pi r_{c0}^2 e^{2A\tilde{p}} \frac{1-e^{2ApN}}{1-e^{2Ap}}$$

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

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



Lifetime estimation for irradiated components



Gurson law

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

$$\int_{\xi_i+\xi_0}^{\xi_{i+1}} \frac{d\xi}{1-\xi} = \int_0^{\tilde{p}} dp \qquad K := e^{-\tilde{p}}$$

$$\xi_{i+1} = 1 - (1 - \xi_0 - \xi_i)\, K$$

Porosity parameter ξ_i increases from cycle to cycle by ξ_0 due to emission of secondary particles flux

Lifetime estimation for irradiated components

nomena at cryogenic temperatures

$$\xi_1 = 1-(1-\xi_0)K = 1+\xi_0 K - K$$

$$\xi_2 = 1-(1-\xi_0-\xi_1)K = 1+\xi_0 K + \xi_0 K^2 - K^2$$

$$\xi_3 = 1-(1-\xi_0-\xi_2)K = 1+\xi_0 K + \xi_0 K^2 + \xi_0 K^3 - K^3$$

$$\xi_4 = 1+\xi_0 K + \xi_0 K^2 + \xi_0 K^3 + \xi_0 K^4 - K^4$$

$$\vdots$$

$$\xi_i = (1-K^i) + \xi_0 \sum_{n=1}^{i} K^n$$

$$\xi_N = 1 + \underbrace{\xi_0 K + \xi_0 K^2 + \xi_0 K^3 + \xi_0 K^4 + \ldots + \xi_0 K^N}_{\text{Geometric series}} - K^N$$

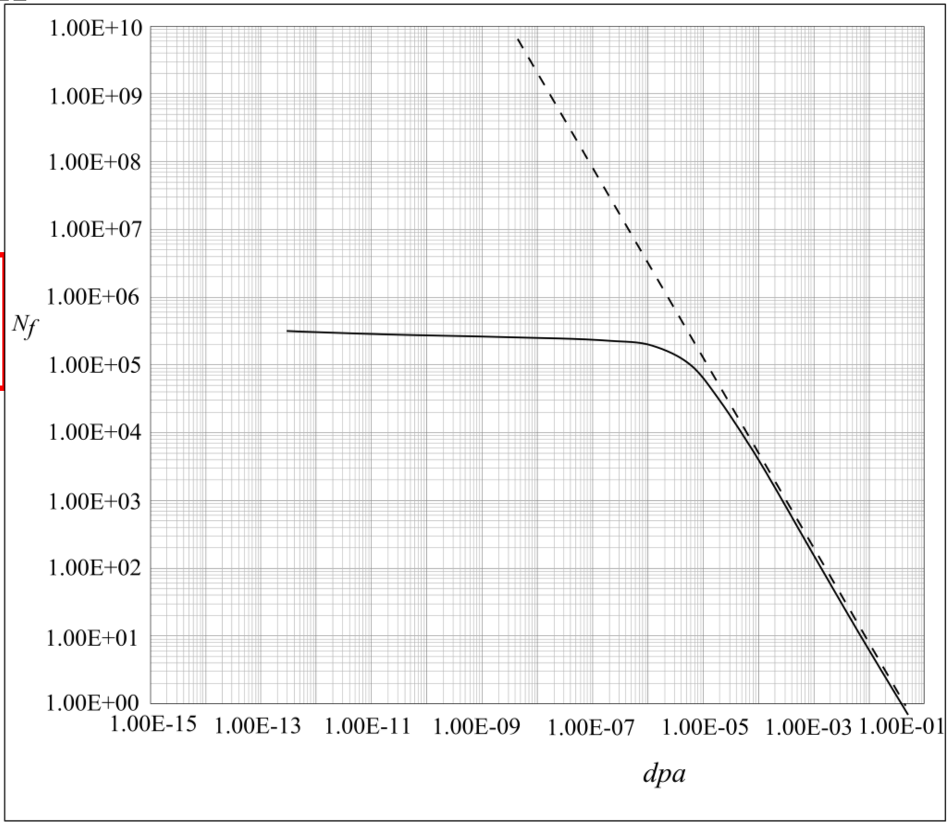
$$\xi_N = (1-K^N) + \xi_0 \sum_{n=1}^{N} K^N$$

$$S_N = \xi_0 K \frac{1-K^N}{1-K}$$

$$\xi_N = 1 + \xi_0 K \frac{1-K^N}{1-K} - K^N$$

$$\xi_N = 1 + \xi_0 K \frac{1-K^N}{1-K} - K^N = \xi_{cr}$$

Number of cycles to failure N_f is based on the criterion $\xi_N = \xi_{cr}$



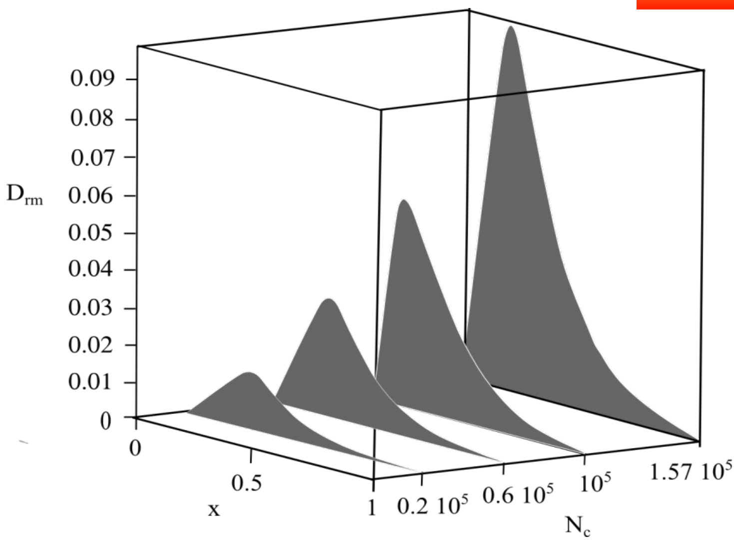
Mechanical loads have significant impact below *dpa*≈10^{-5}

Evolution of damage parameter in the horn (magnetic lense)

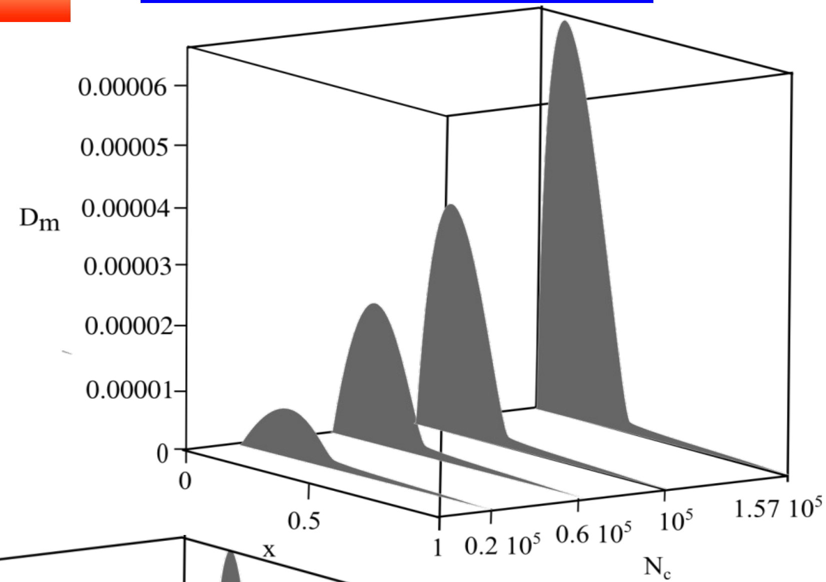
Coupled dissipative phenomena at cryogenic temperatures

D_{cr}=0.1

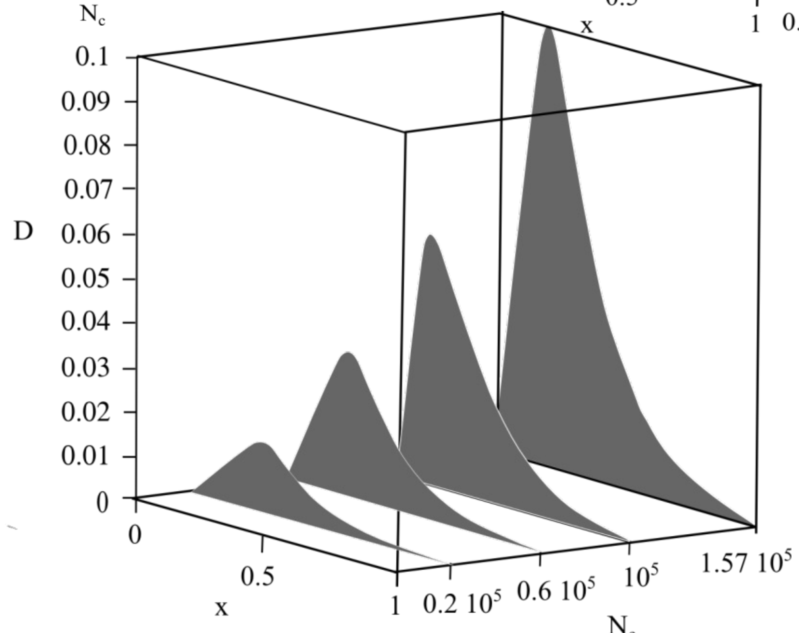
radiation induced damage



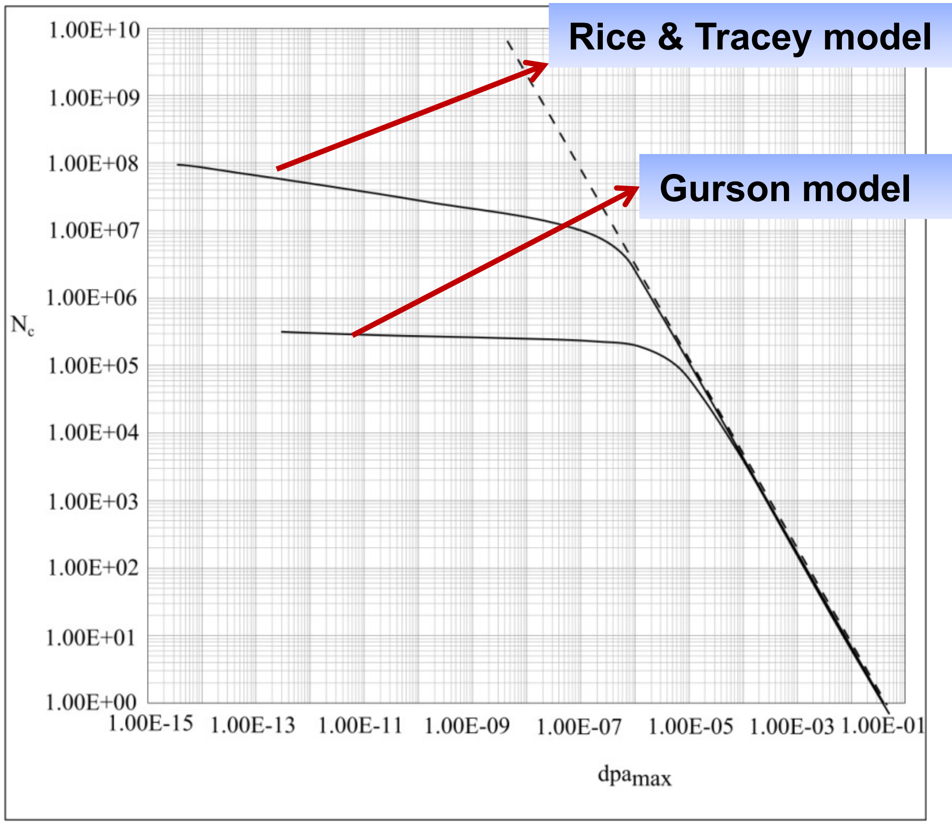
mechanical damage

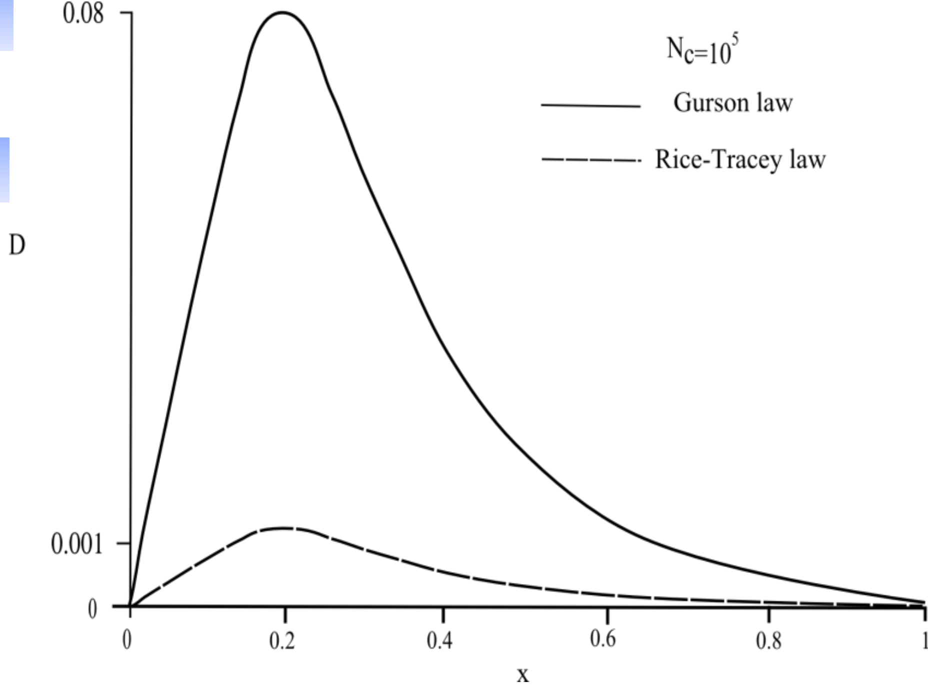


total damage parameter



Performance of Rice-Tracey and Gurson models (log-log)



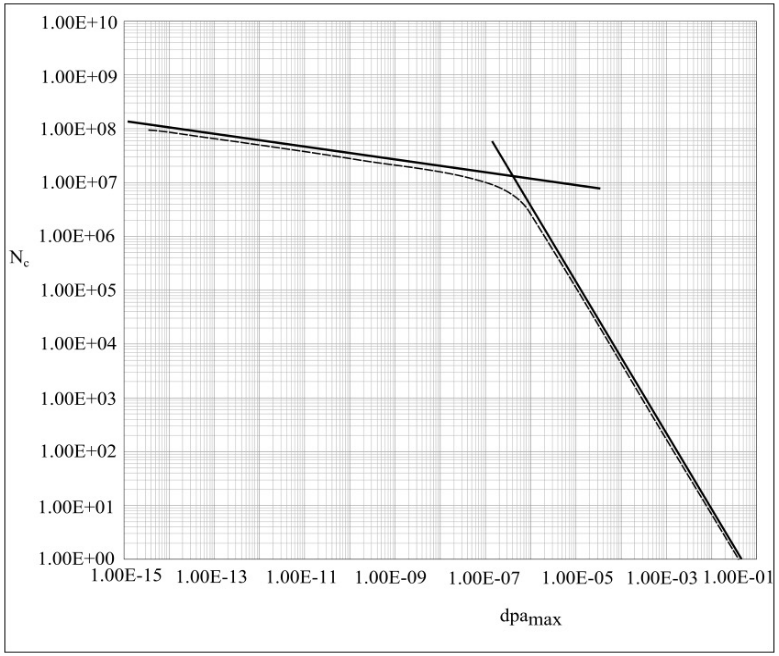


different sensitivity of both models

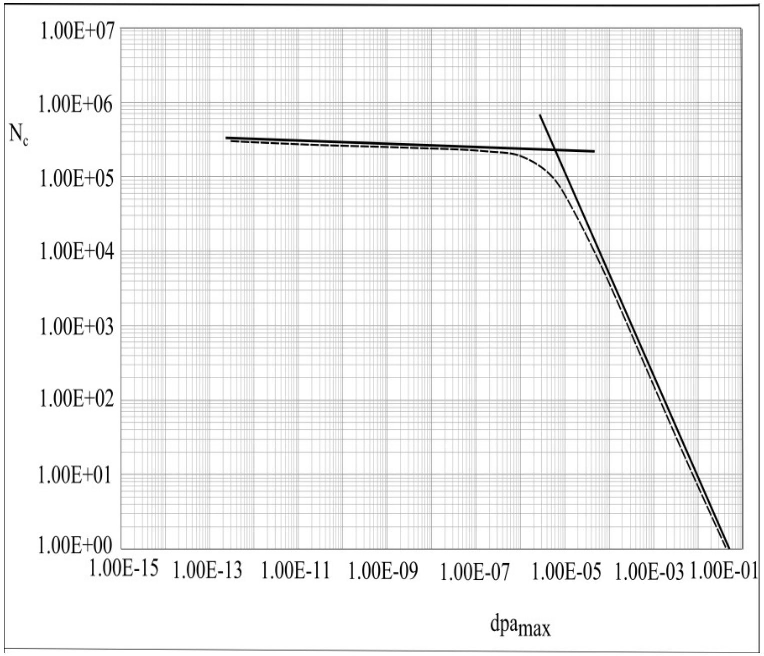
Rice & Tracey model predicts lower values of damage

Bilinear approximations for R-T and Gurson models

Rice & Tracey model



Gurson model



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

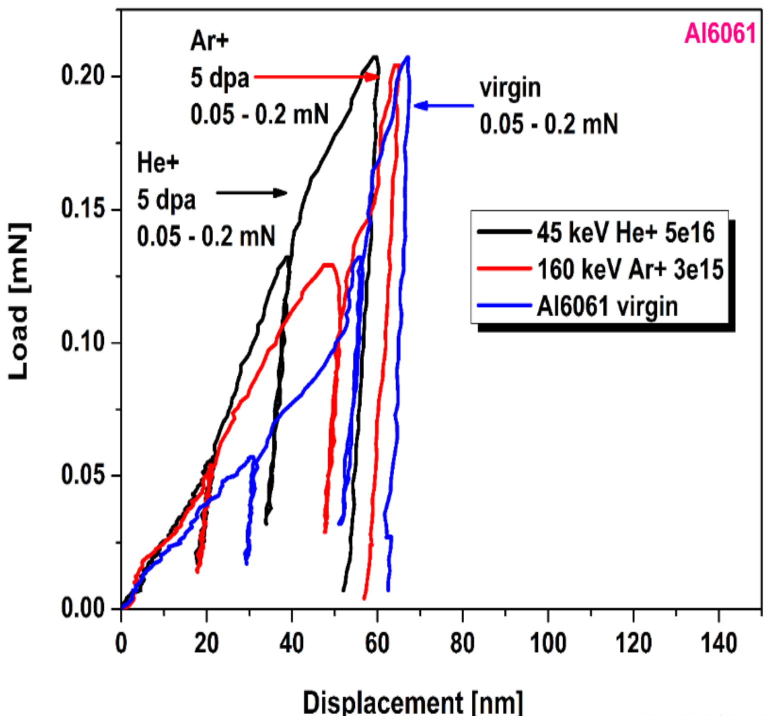
Analytical formula - useful tool for estimation of number of cycles to failure

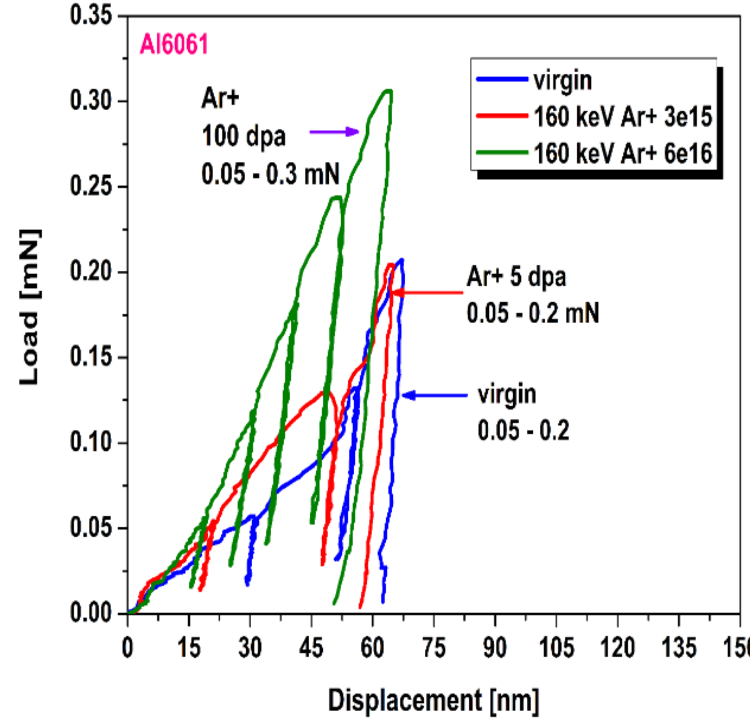
$$N_c = 10^a\, dpa_{\max}^b$$

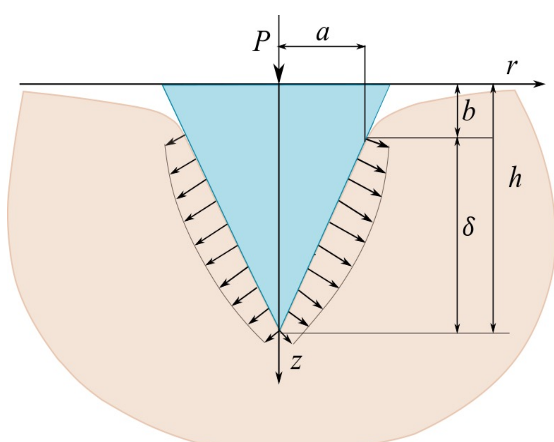
$$N_c = \begin{cases} 10^{-1.9}\, dpa_{\max}^{-1.4} & \text{for} \quad dpa_{\max} \geq 10^{-6} \\ 10^{6.1}\, dpa_{\max}^{-0.13} & \text{for} \quad dpa_{\max} < 10^{-6} \end{cases}$$

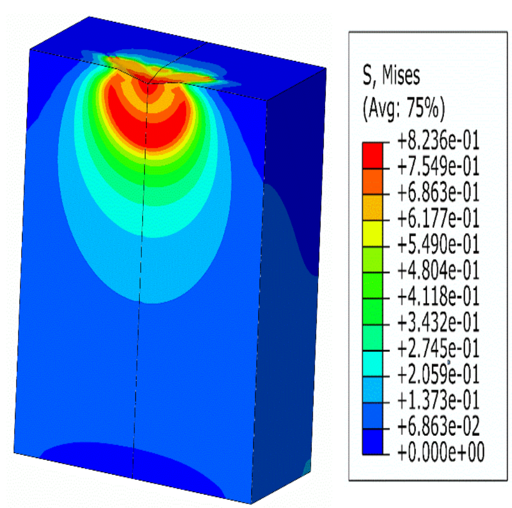
$$N_c = \begin{cases} 10^{-1.9}\, dpa_{\max}^{-1.4} & \text{for} \quad dpa_{\max} \geq 10^{-5} \\ 10^{5.43}\, dpa_{\max}^{-0.016} & \text{for} \quad dpa_{\max} < 10^{-5} \end{cases}$$

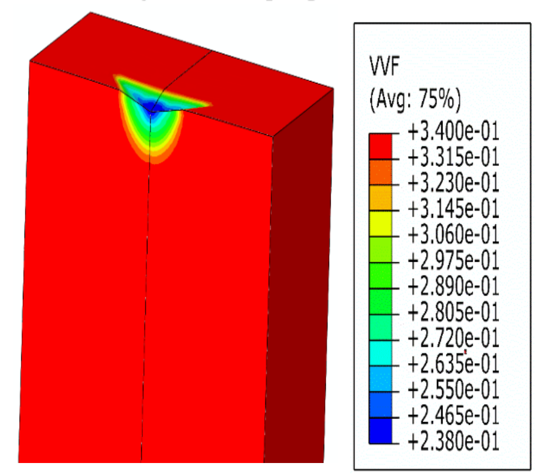
Nanoindentation of irradiated Al6061



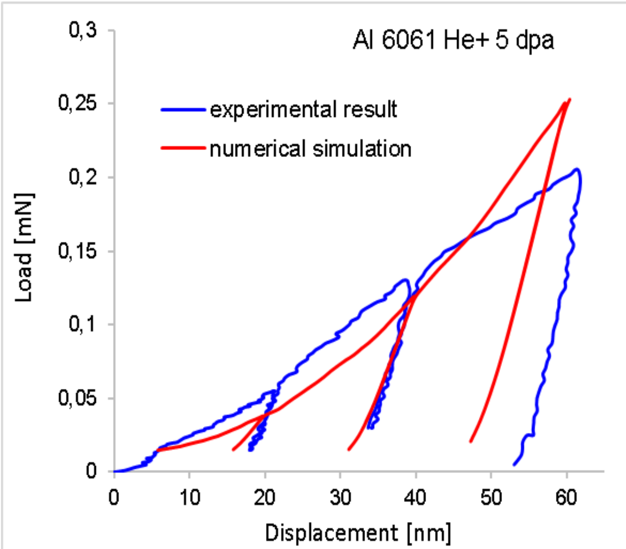


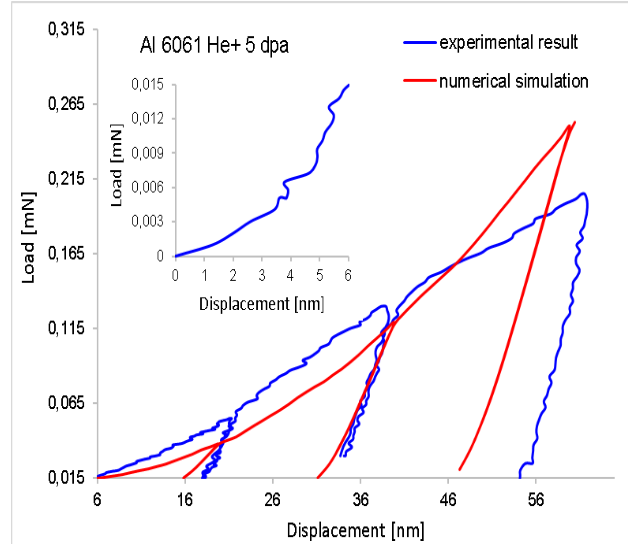


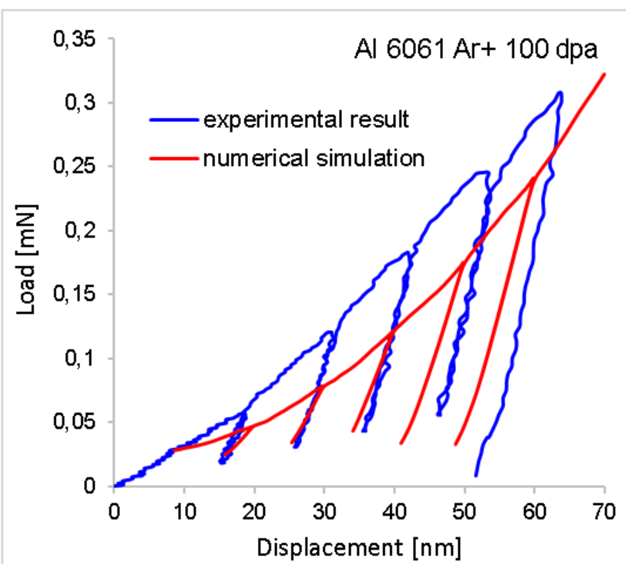


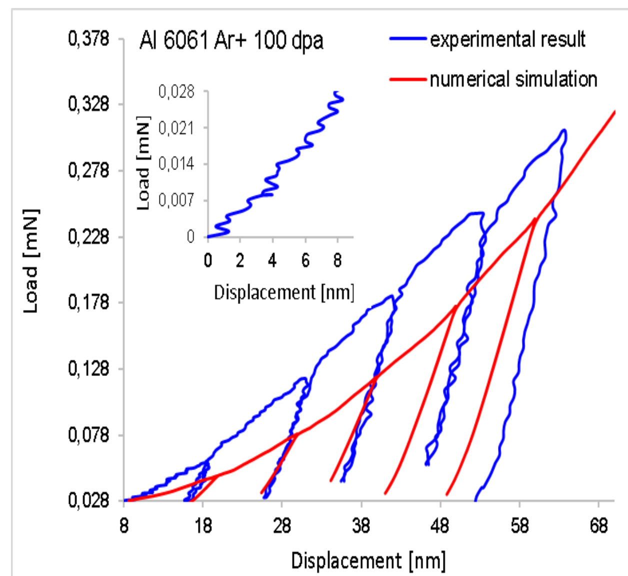


Nanoindentation of irr. Al6061: experiment vs. Gurson model

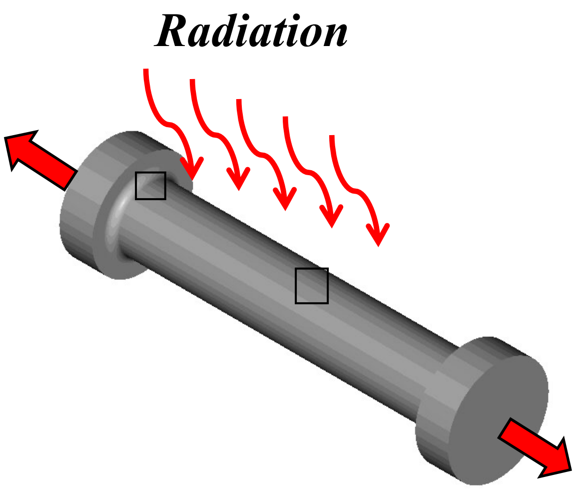






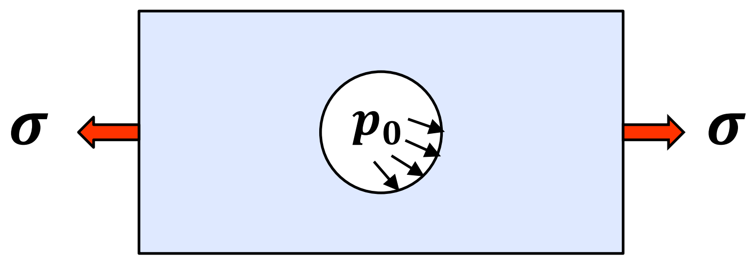


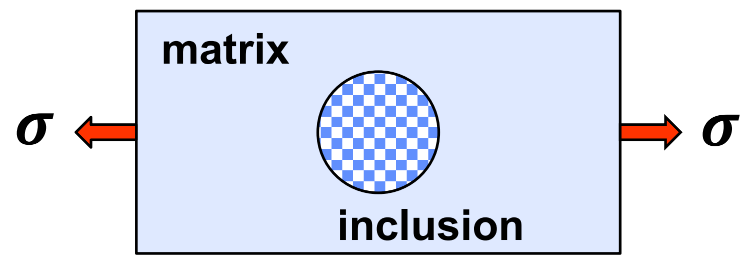
Radiation induced hardening



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





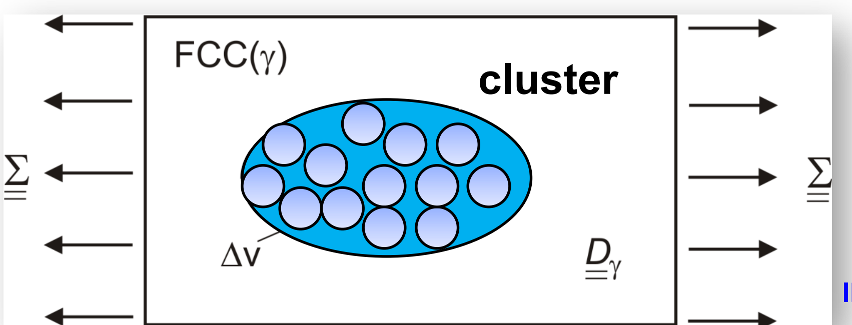
$$\Delta p = -3 p_0 \Delta\varepsilon$$

$$E_{p_{ijkl}} = 3k_p J_{ijkl} + 2\mu_p K_{ijkl}$$

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

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

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



Evolution of voids – Rice & Tracey kinetics

Evolution of voids corresponding to the far stress field: R&T kinetics

$$\frac{\dot{r}}{r} = \alpha_r exp\left(\frac{3\sigma_m}{2\sigma_i}\right)\dot{p}$$

$$\int_{r_0}^{\tilde{r}} \frac{dr}{r} = \alpha_r \int_0^{\tilde{p}} exp\left(\frac{3\sigma_m}{2\sigma_i}\right) dp$$

For the uniaxial stress state:

$$\tilde{r} = r_0\left[\alpha_r exp\left(\frac{3\sigma_m}{2\sigma_i}\right)\tilde{p}\right]$$

$$\tilde{r} = r_0[C_1\tilde{p}]$$

$$r = Re^{C_1 p}$$

$$\Delta\xi = \frac{n(V_d - V_D)}{V}$$

$$\Delta\xi = \xi_0\left(e^{3C_1\Delta p} - 1\right)$$

Linearization:

$$\xi = \xi_0 + \Delta\xi = \xi_0(1 + 3C_1\Delta p)$$

Interaction of dislocations with voids

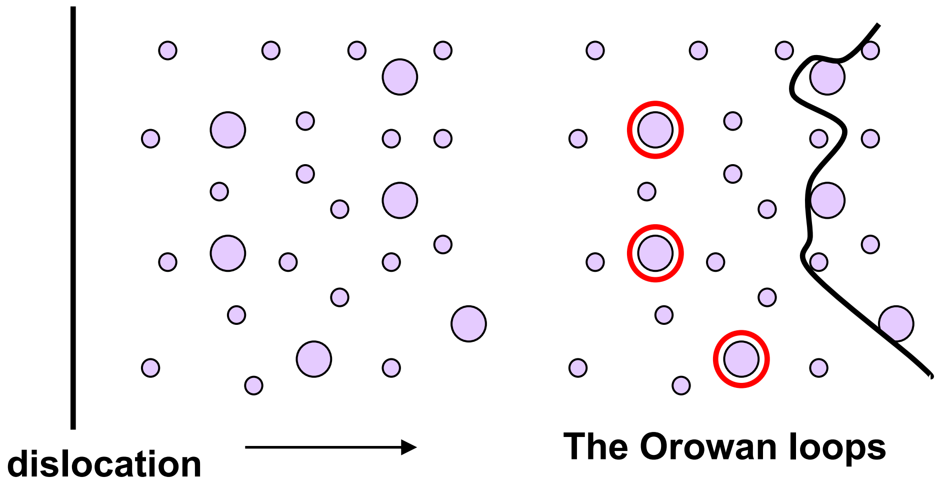
The Orowan mechanism:

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

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

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:

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

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

Mean field methods: homogenization

Stiffness of the matrix:

$$\Delta\sigma_{a_{ij}} = E_{ta_{ijkl}}\Delta\varepsilon_{kl}$$

$$E_{ta_{ijkl}} = 3k_{ta}J_{ijkl} + 2\mu_{ta}K_{ijkl}$$

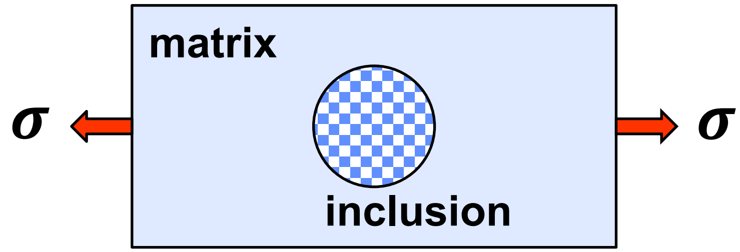
$$\mu_{ta} = \frac{E_t}{2(1+\nu)} \qquad k_{ta} = \frac{E_t}{3(1-2\nu)} \qquad E_t = \frac{EC}{E+C}$$

Stiffness of the inclusion:

$$\Delta\sigma_{p_{ij}} = E_{p_{ijkl}}\Delta\varepsilon_{kl}$$

$$E_{p_{ijkl}} = 3k_pJ_{ijkl}$$

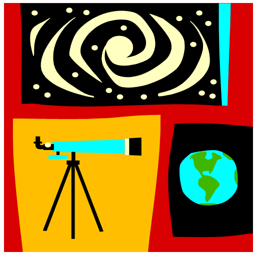
$$\mu_p = 0 \;;\; \nu_p = 0 \;;\; k_p = \frac{E_p}{3(1-2\nu_p)} = \frac{E_p}{3}$$



Mori-Tanaka homogenization:

$$\Delta\sigma_{ij} = E_{H_{ijkl}}\Delta\varepsilon_{kl}$$

Uniaxial case – tension/compression



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

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

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

Interaction

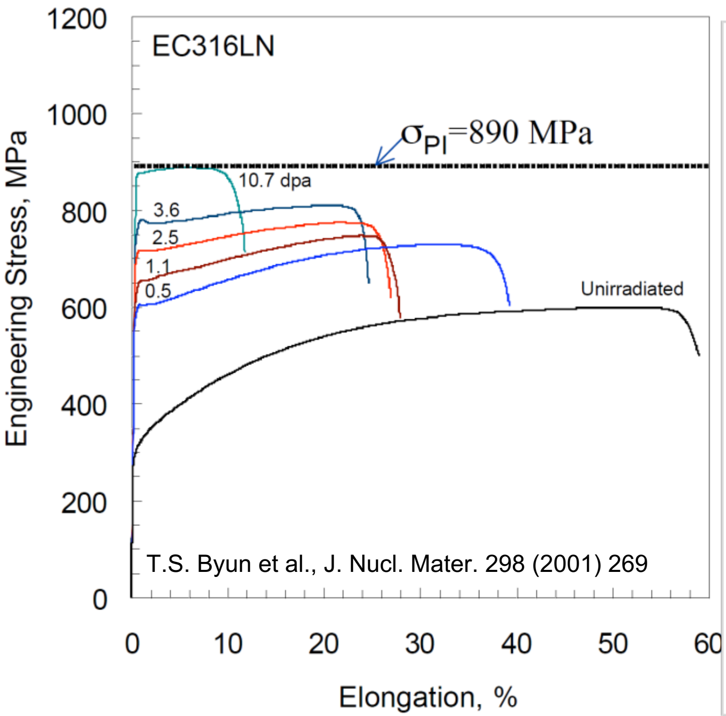
$$\Delta\sigma_{MT} = -\frac{5}{2}\mu\eta_0\frac{\xi_0}{C_1}\left[\frac{1}{4}(\chi^2 - 1) - \frac{4}{81}\xi_0(\chi^3 - 1) + -\frac{2}{81}{\xi_0}^2(\chi^4 - 1)\right]$$

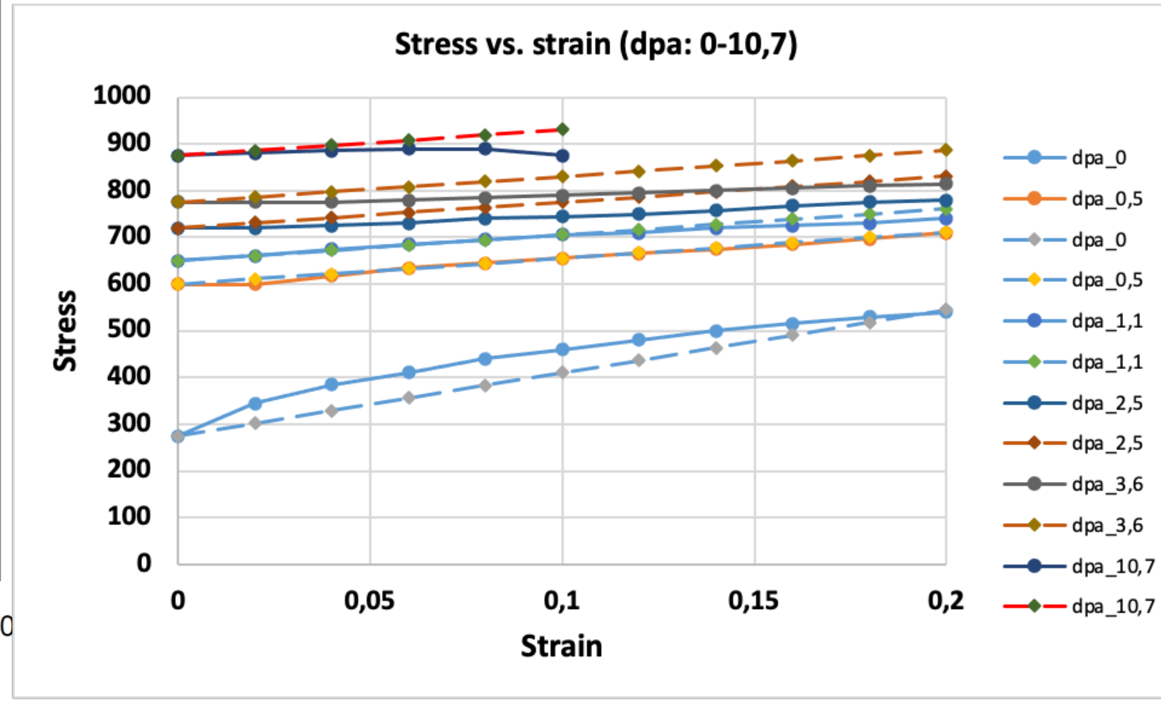
$$\chi = 1 + 3C_1\varepsilon^p \qquad \eta_0 = \frac{C_i}{E} = \frac{M\frac{\mu b}{d}\sqrt[3]{\frac{6}{\pi}}\sqrt[3]{\xi_0}}{E}$$

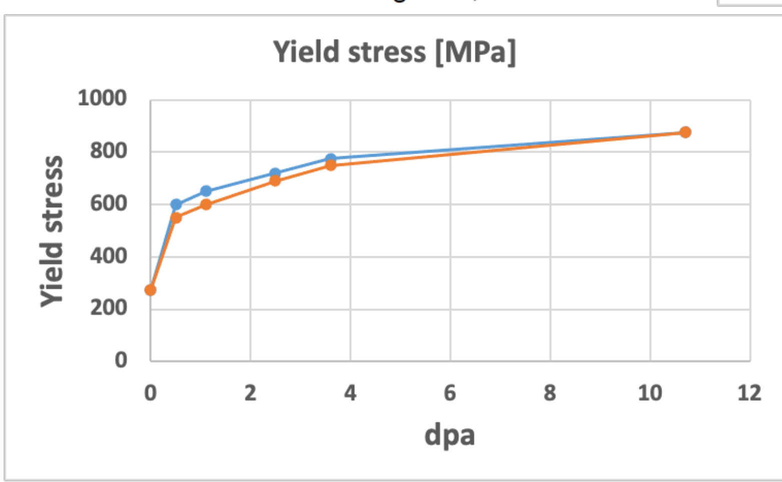
MT homogenization

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

Uniaxial case: 316LN stainless steel



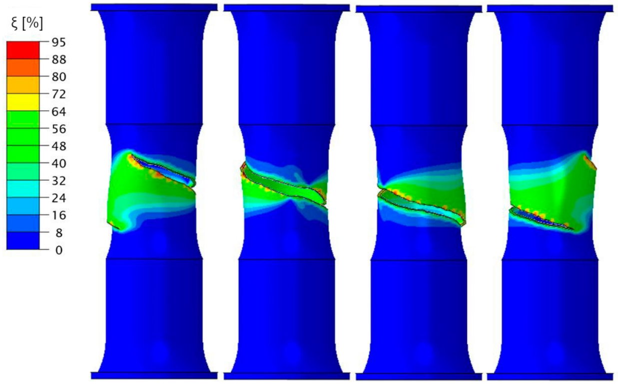




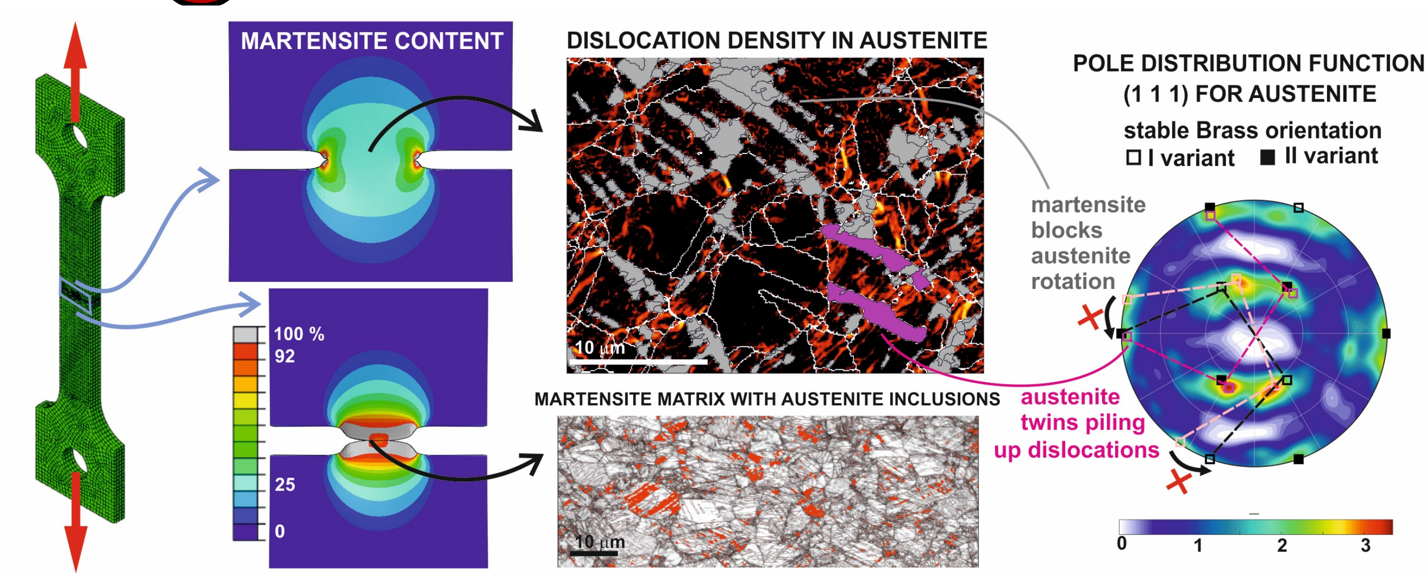
Radiation induced hardening comprising:

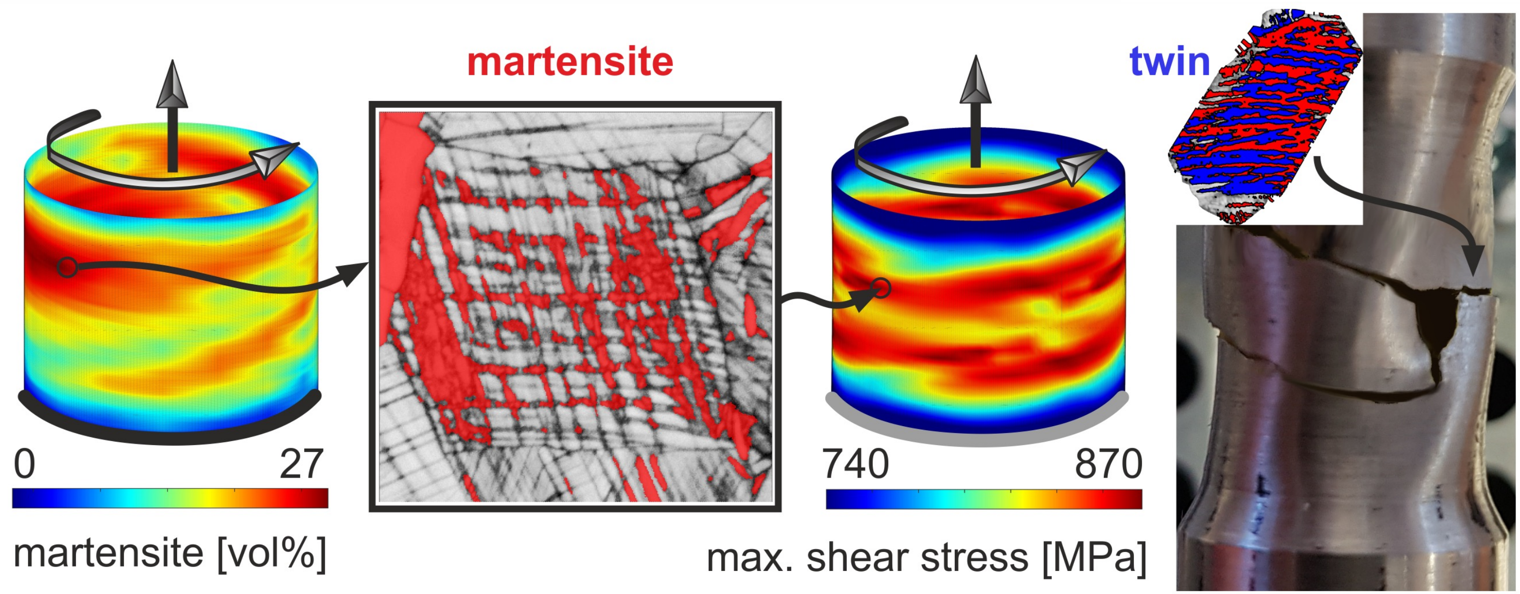
- **massive interaction of dislocations with the pressurized voids,**
- **evolution of tangent stiffness expressed by the Mori-Tanaka homogenization.**

Fracture at extremely low temperatures



Fracture at extremely low temperatures





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!