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Investigation of Radiation Hardening in Metastable Materials for Cryogenic Applications

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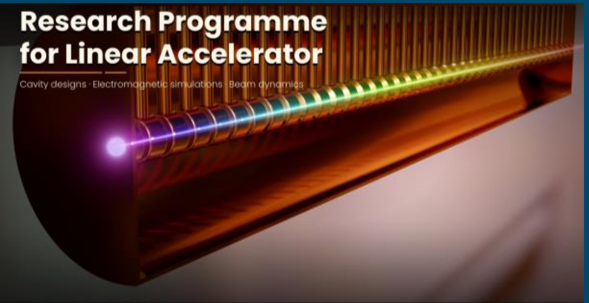


2nd Workshop on Research & Innovation in Poland
IFJ PAN, Krakow, 26-27 May, 2026

Research Centre – Laboratory of Extremely Low Temperatures

Research Programme including irradiated materials

I constitutive models of single phenomena

Strain induced phenomena at extremely low temperatures

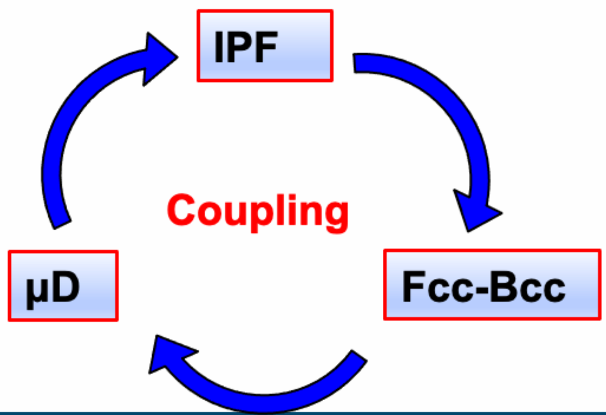
Done

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

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

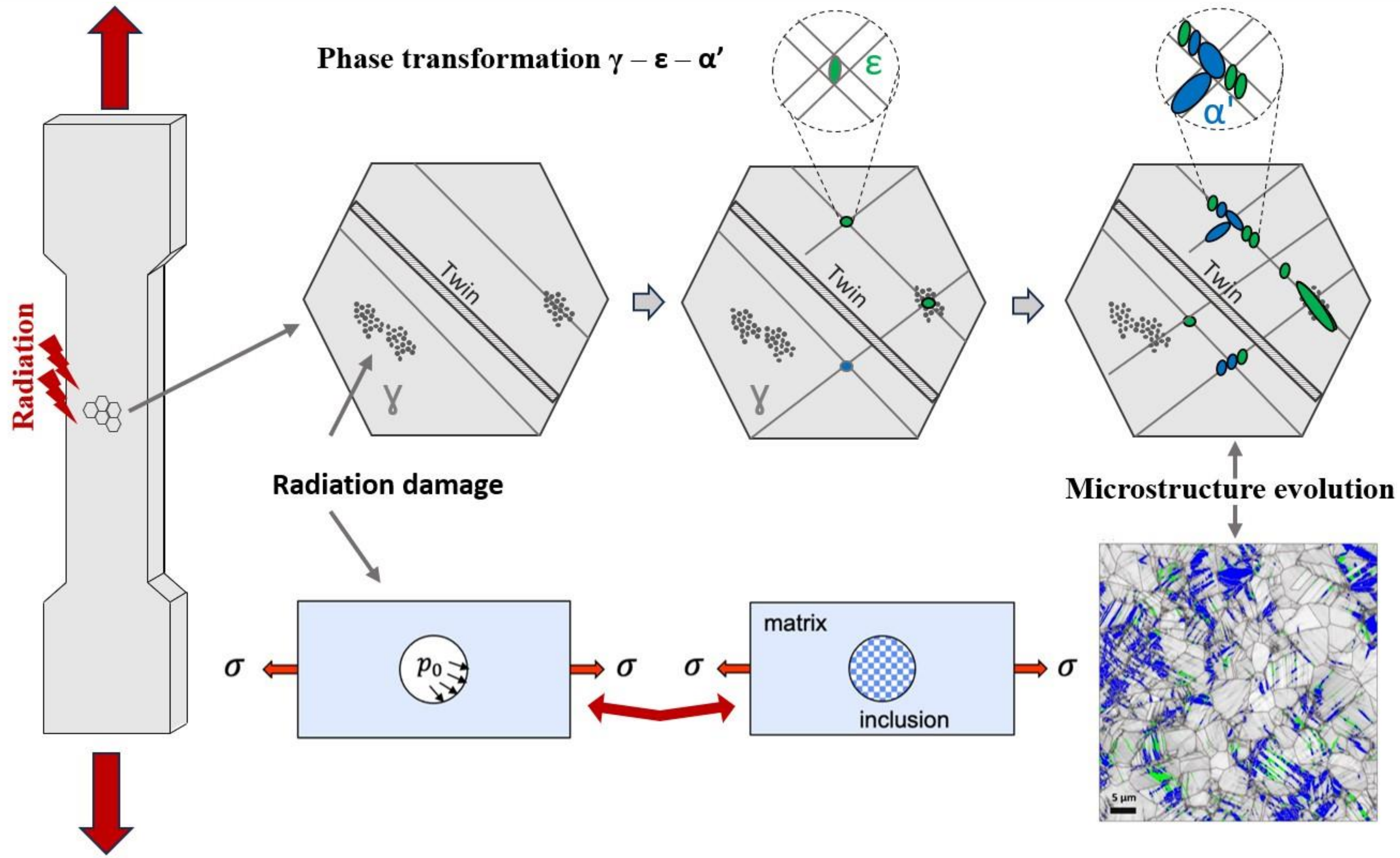
In progress

II coupling between the phenomena

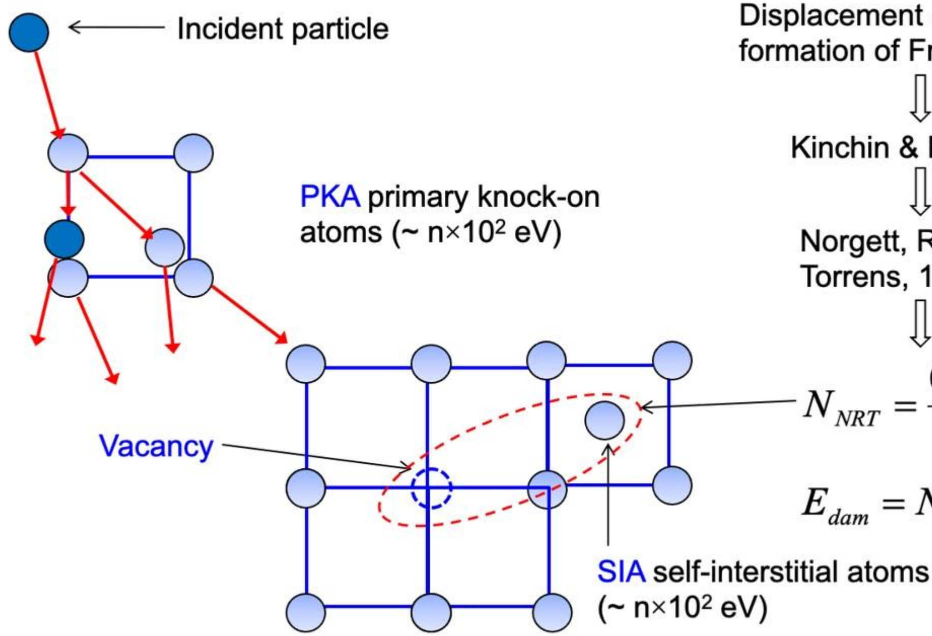


In progress

Research programme – irradiated materials



Research programme – defects due to irradiation



Displacement cascade and formation of Frenkel pairs

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Kinchin & Pease, 1955

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Norgett, Robinson, Torrens, 1975

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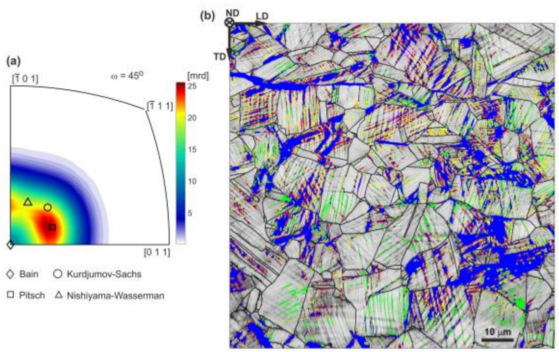
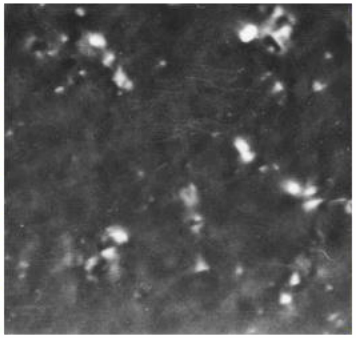
$$N_{NRT} = \frac{0.8E_{dam}}{2\overline{E}_d}$$

$$E_{dam} = NIEL$$

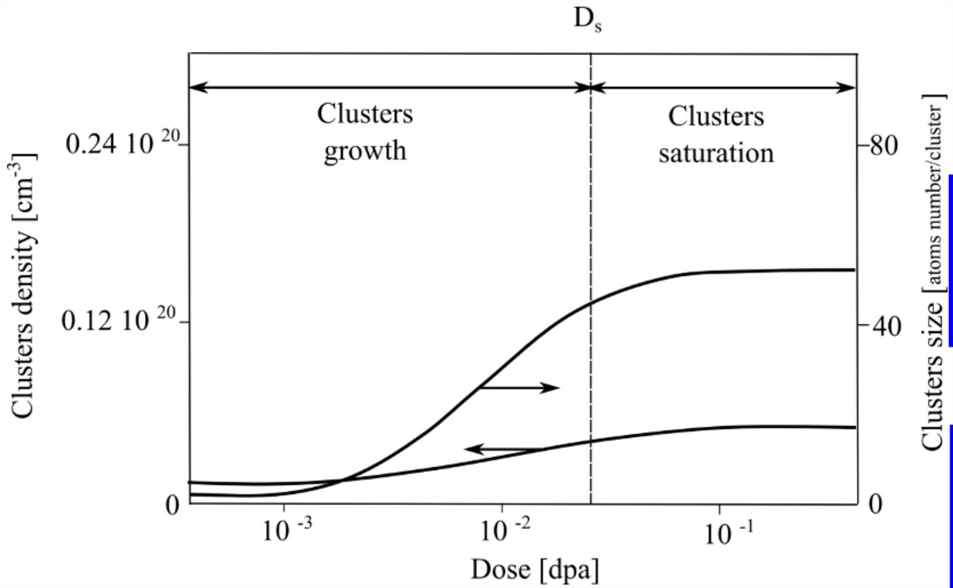


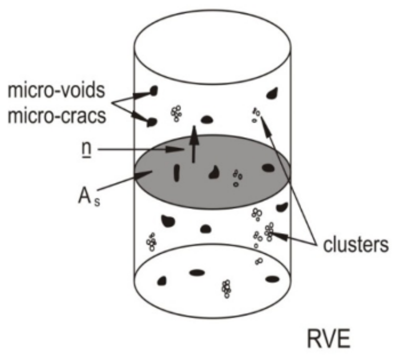


Defects due to irradiation:

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

Research programme – from dpa to damage parameter





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

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

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

dpa

Physics

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

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

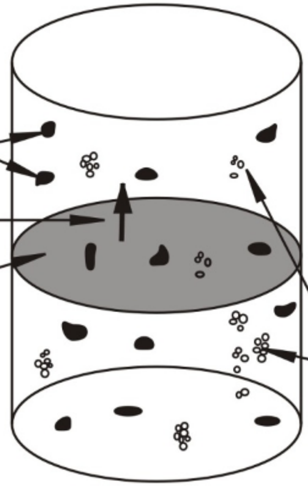
$$q_A = \left(\sqrt[3]{q_V}\right)^2 = q_c^{\,2/3}$$

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

CDM

Research programme – additive decomposition of damage tensor

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

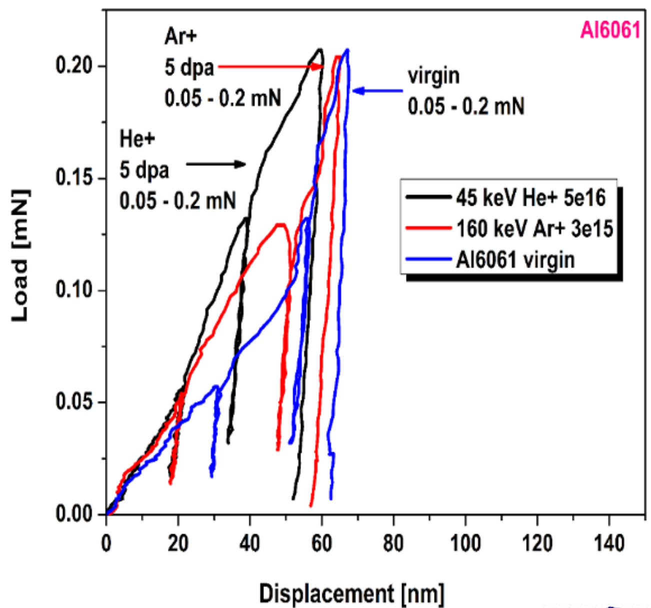
$\underline{\underline{I}}$ **- identity tensor**

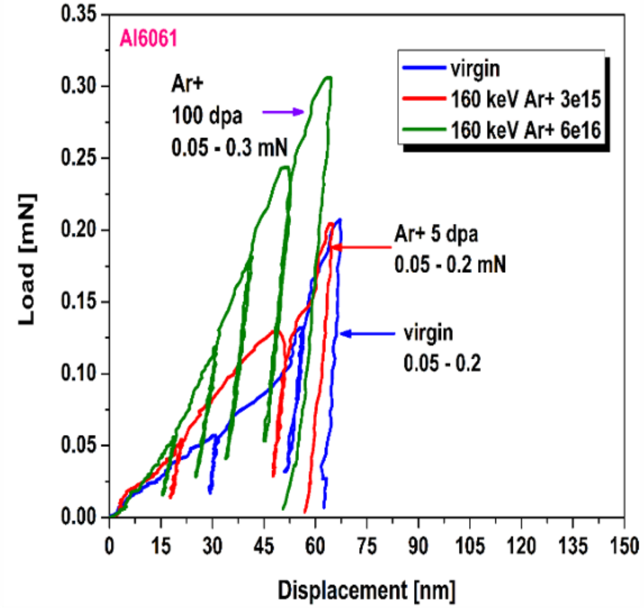
$$d\underline{\underline{D}}_m = \underline{\underline{C}}\,\underline{\underline{Y}}\,\underline{\underline{C}}^T dp$$

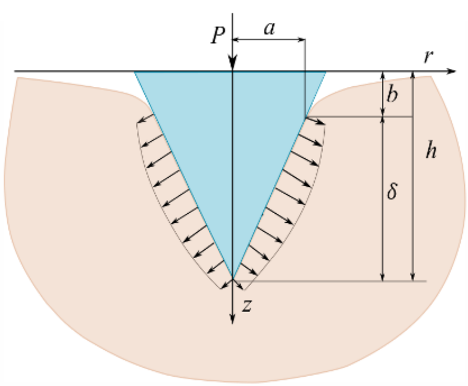
anisotropic

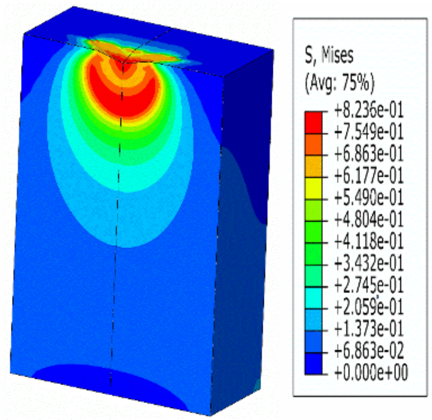
$$\underline{\underline{D}} = \underline{\underline{D}}_m + \underline{\underline{D}}_r = \underline{\underline{D}}_m + \frac{1}{3} D_r \underline{\underline{I}}$$

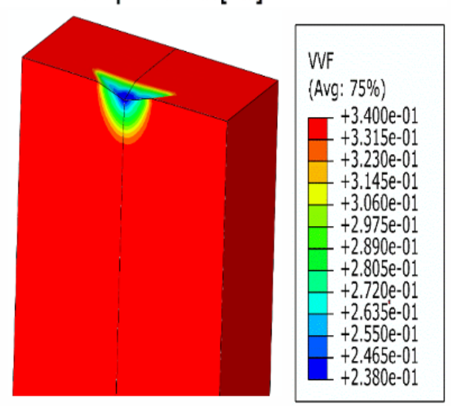
Research programme – He^{+} and Ar^{+} irradiated materials



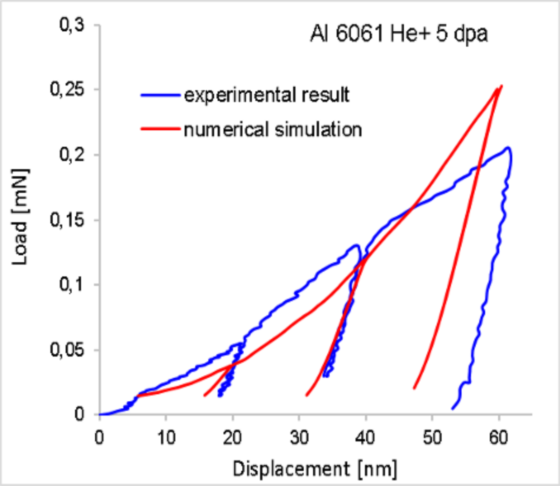


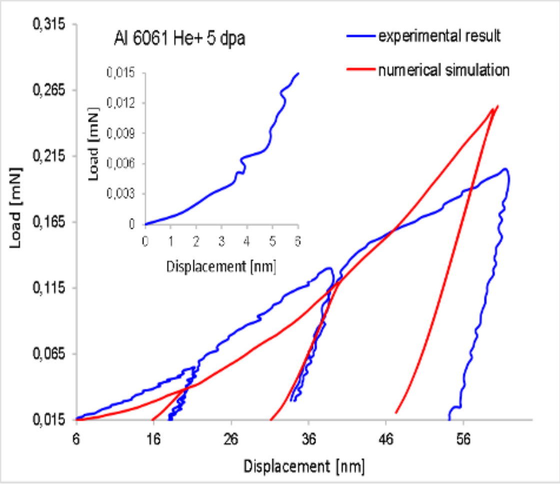


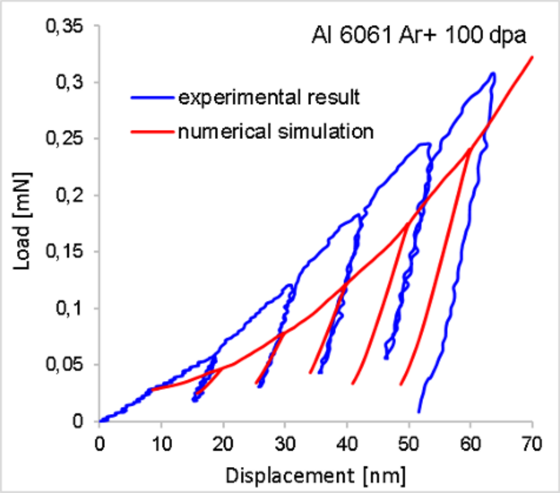


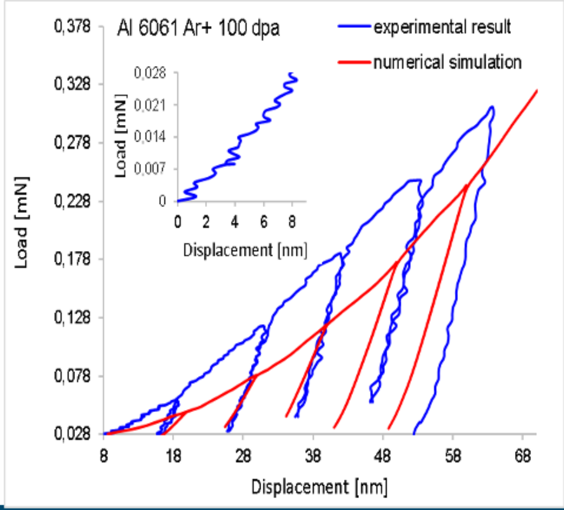


Research programme – nanoindentation vs Gurson model





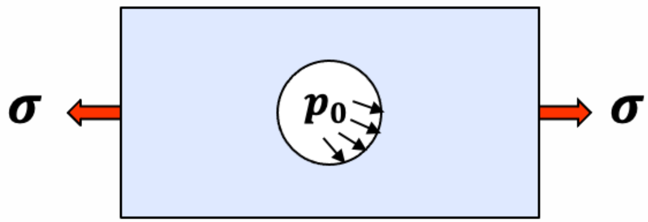


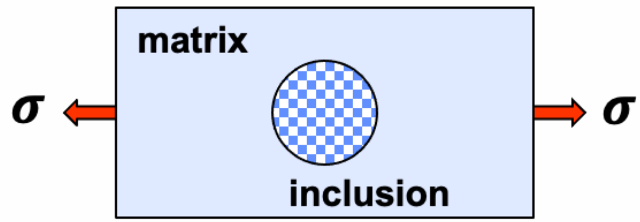


Research programme – radiation hardening model

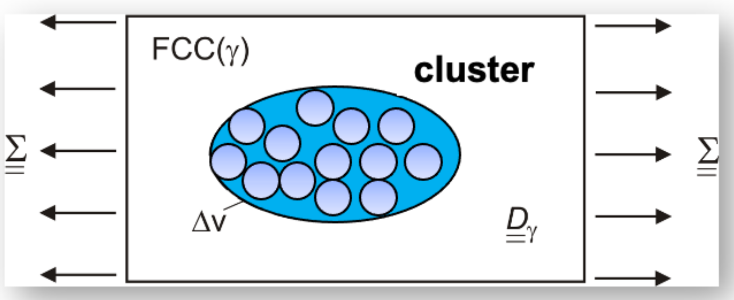
Assumptions:

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





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



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

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

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

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

Research programme – radiation hardening model

The Orowan mechanism:

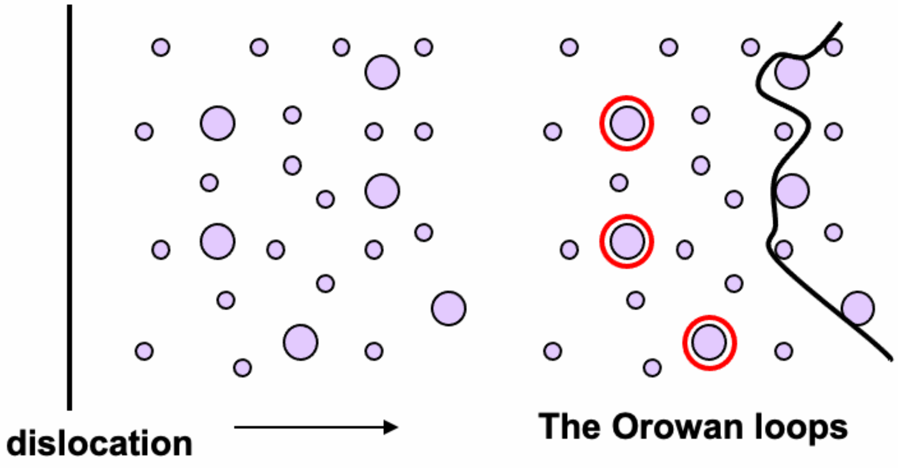
$$\tau_p = \frac{\mu b}{d}\sqrt[3]{\frac{6\xi_0}{\pi}}\left(1 + \frac{1}{3}\frac{\Delta\xi}{\xi_0}\right)$$

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

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

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:

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

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

Research programme – radiation hardening model

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

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

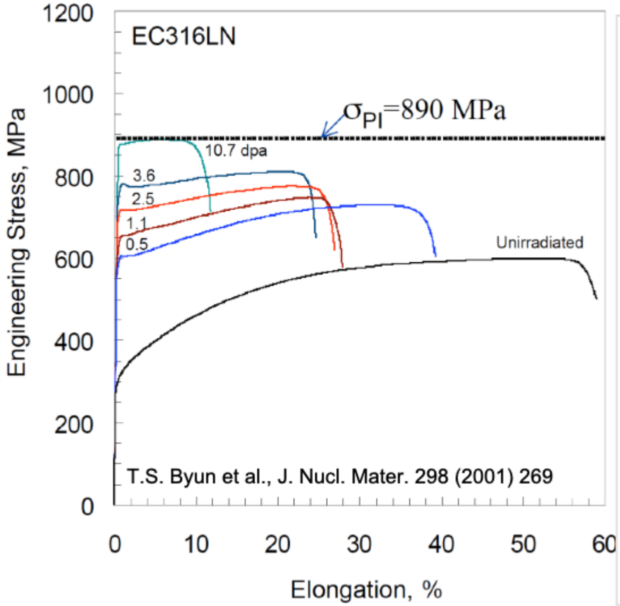
$$\Delta\sigma_{MT} = -\frac{5}{2}\mu\eta_0\frac{\xi_0}{C_1}\left[\frac{1}{4}(\chi^2 - 1) - \frac{4}{81}\xi_0(\chi^3 - 1) + -\frac{2}{81}{\xi_0}^2(\chi^4 - 1)\right]$$

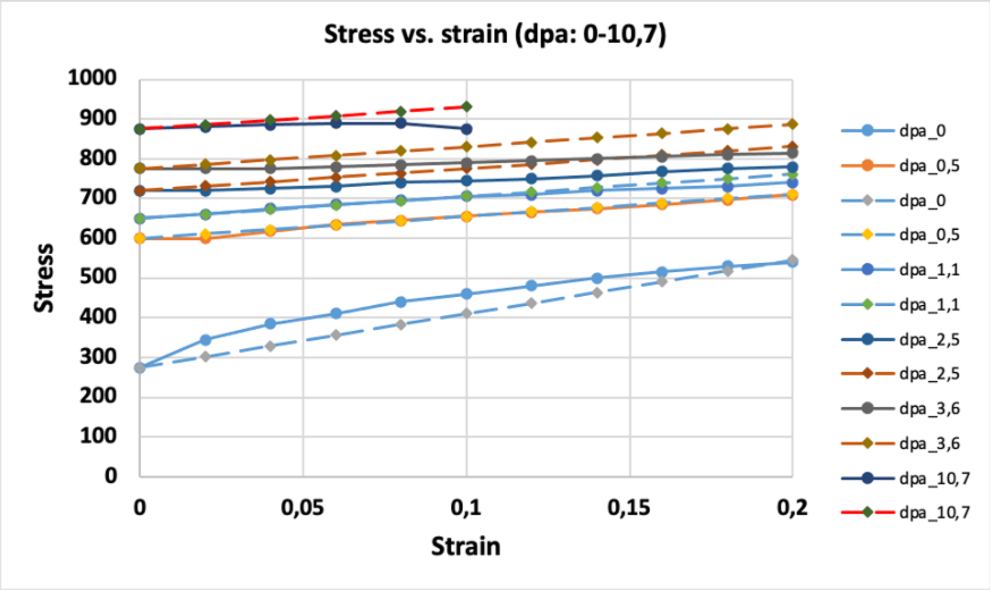
$$\chi = 1 + 3C_1\varepsilon^p \qquad \eta_0 = \frac{C_i}{E} = \frac{M\frac{\mu b}{d}\sqrt[3]{\frac{6}{\pi}}\sqrt[3]{\xi_0}}{E}$$

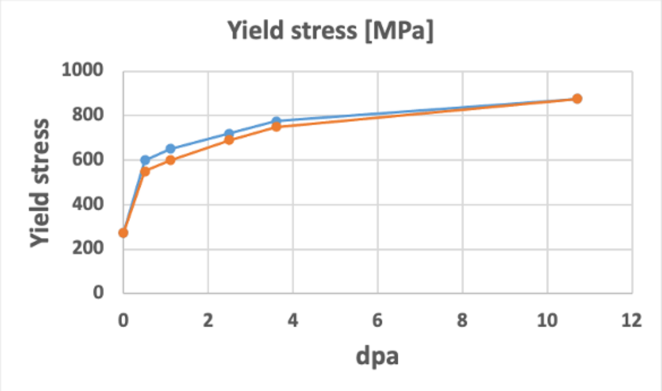
MT homogenization

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

Research programme – experiment versus rad. hardening model







Radiation induced hardening comprising:

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

Required beam: particle, energy and properties

Sections 1, 2 and 3

Protons with energies in the range of:

- **1 – 2.5 MeV**
- **2.5 – 12.5 MeV**
- **12.5 – 250 MeV**

Typically:

Proton energy: 12.5 MeV

Average beam current: 1–20 mA

Peak beam current: 20–80 mA

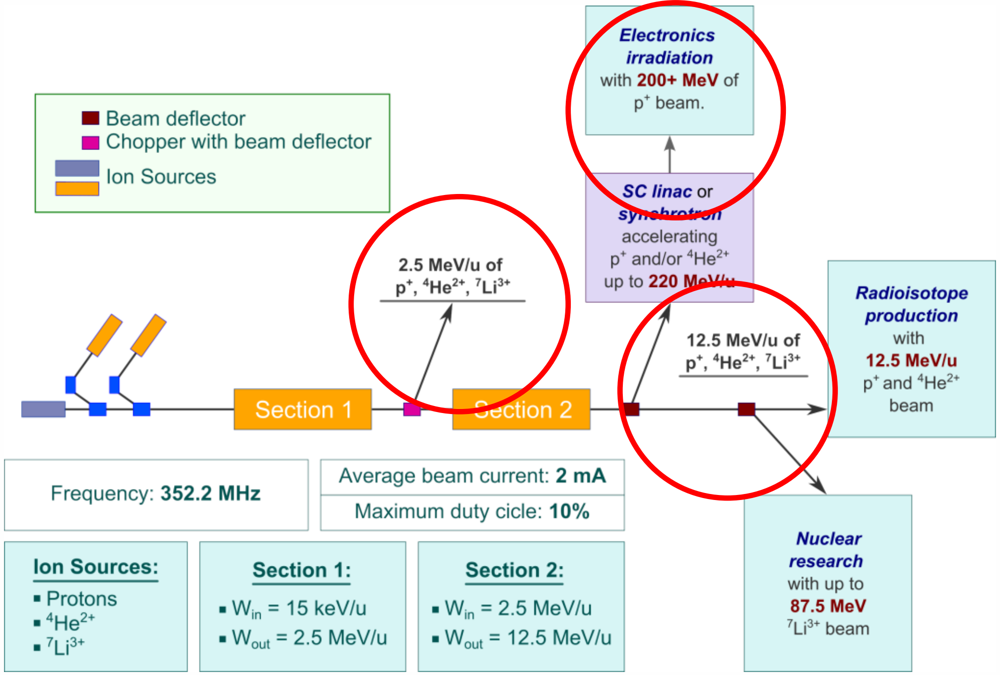
Average beam power (1 mA): 12.5 kW

Normalized RMS emittance: 0.1–0.4 π·mm·mrad

Full bunch length: 0.1–0.3 ns

Other requirements:

- Cryogenic installation to maintain target (specimen) at low temperature during beam-solid interaction (Cu, Al, Nb, Ti, AISI 316L, AISI 316LN etc.)
- Installation for irradiation of low and high-temperature superconductors (NbTi, Nb_3Sn, MgB_2, Bi-2212, REBCO etc.)
- Possibility of using He^+ and Ar^+ in the research program



SWOT analysis for the project

S (Strengths): Unique capability on a global scale; research program spanning a broad temperature range; ability to evaluate the performance of LTS and HTS after irradiation to high dpa levels.

W (Weaknesses): Stringent technical requirements for the experimental setup, including cryogenic systems and the handling of superconducting materials.

O (Opportunities): Development of a dedicated expert team, including doctoral students actively participating in the experiments, with strong potential for international research collaborations and patent generation.

T (Threats): Challenges associated with securing sustained long-term funding for the design, prototyping, and fabrication of LINAC systems, including cryogenic detector infrastructure; and the risk that competing groups may complete similar research within the project's timeframe, potentially diminishing its 'first-in-the-world' advantage.

Conclusions

- Project focused on the investigation of radiation hardening in metastable and intermetallic materials for cryogenic applications.
- The subject is well aligned with the research profile of the group working at the Laboratory of Extremely Low Temperatures at CUT.
- Excellent opportunity to explain the mechanisms of radiation hardening in materials widely used under cryogenic conditions, including superconductors.
- Cryogenic installation at the target station enabling reduction of defect recombination after irradiation.
- Possibility to investigate the effect of irradiation on the critical surface of low- and high-temperature superconductors.
- Development of robust and reliable constitutive models for irradiated materials, including radiation hardening associated with all types of radiation-induced defects in a weakly excited crystal lattice.

Thank you for your attention!