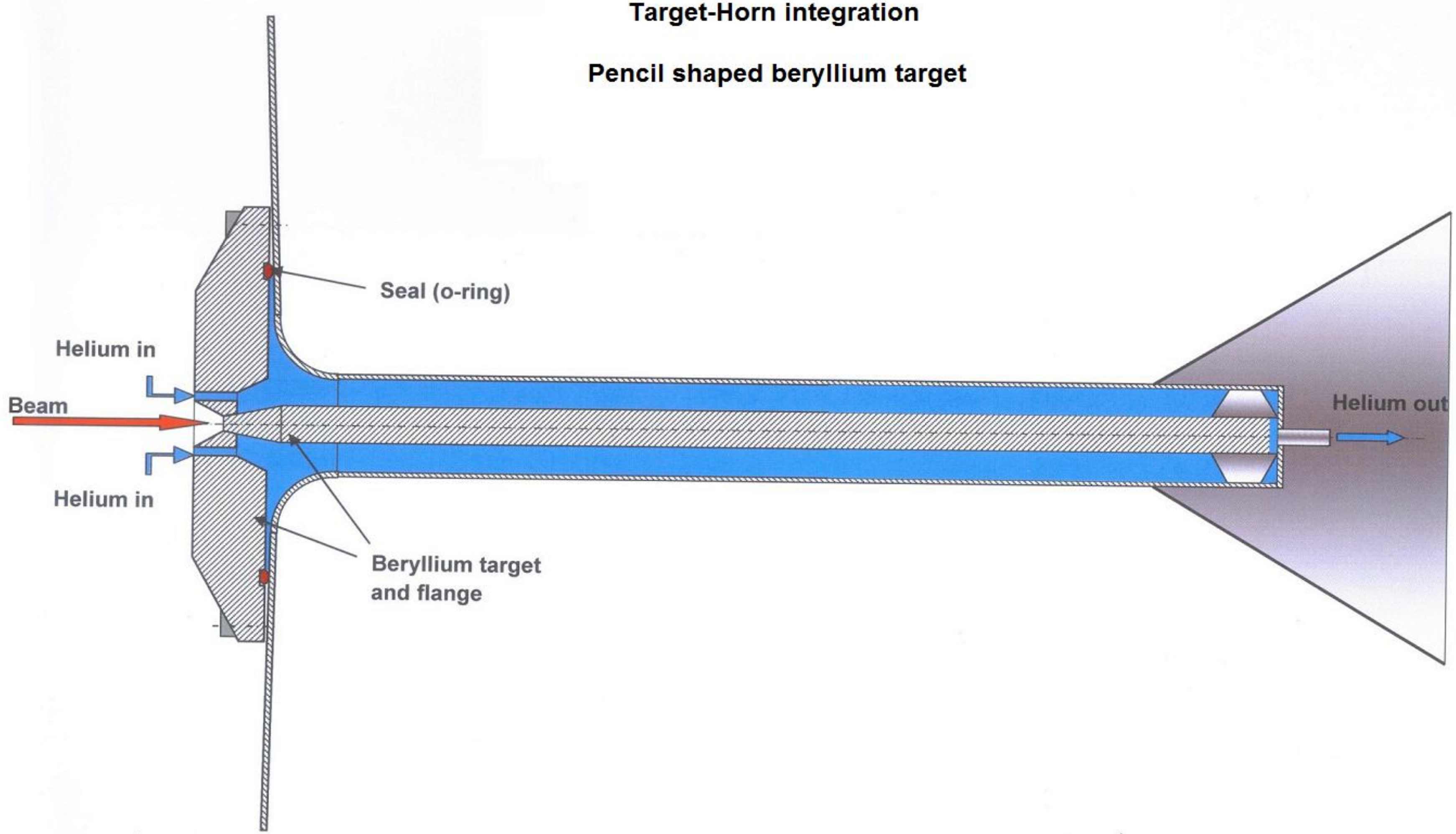
Target-Horn integration

Pencil shaped beryllium target



Evolution of radiation micro-damage in aluminum horn subjected to plastic straining

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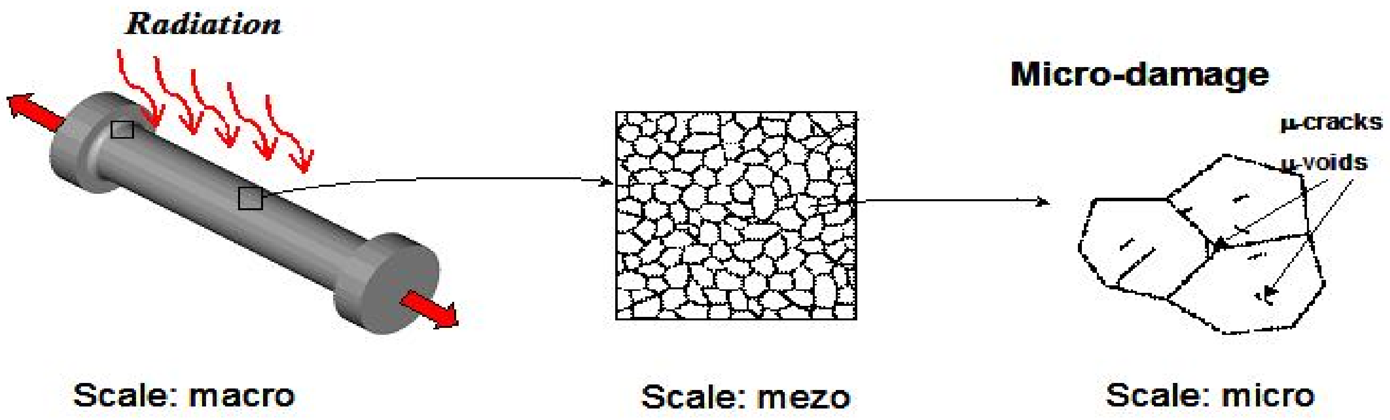
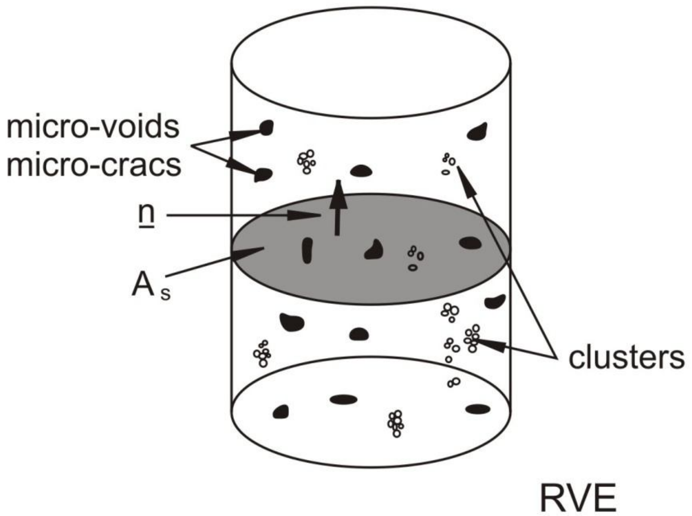
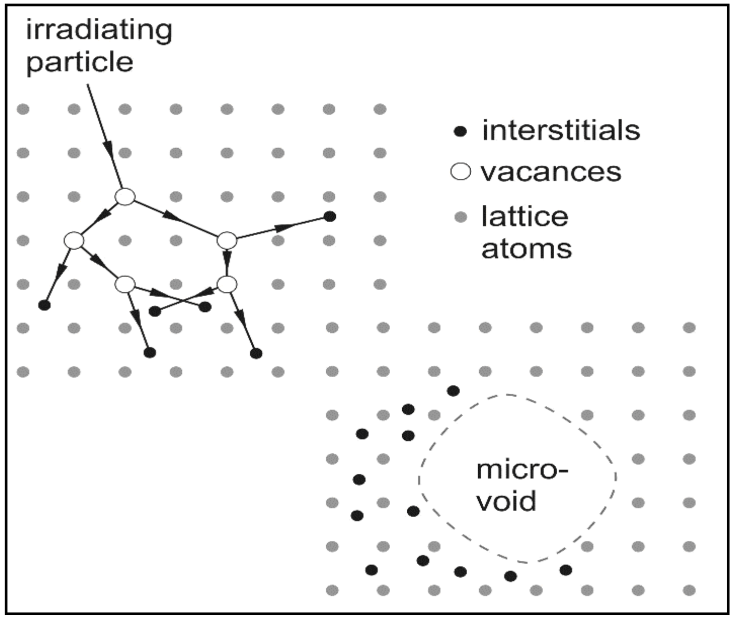
Cracow University of Technology

Institute of Applied Mechanics

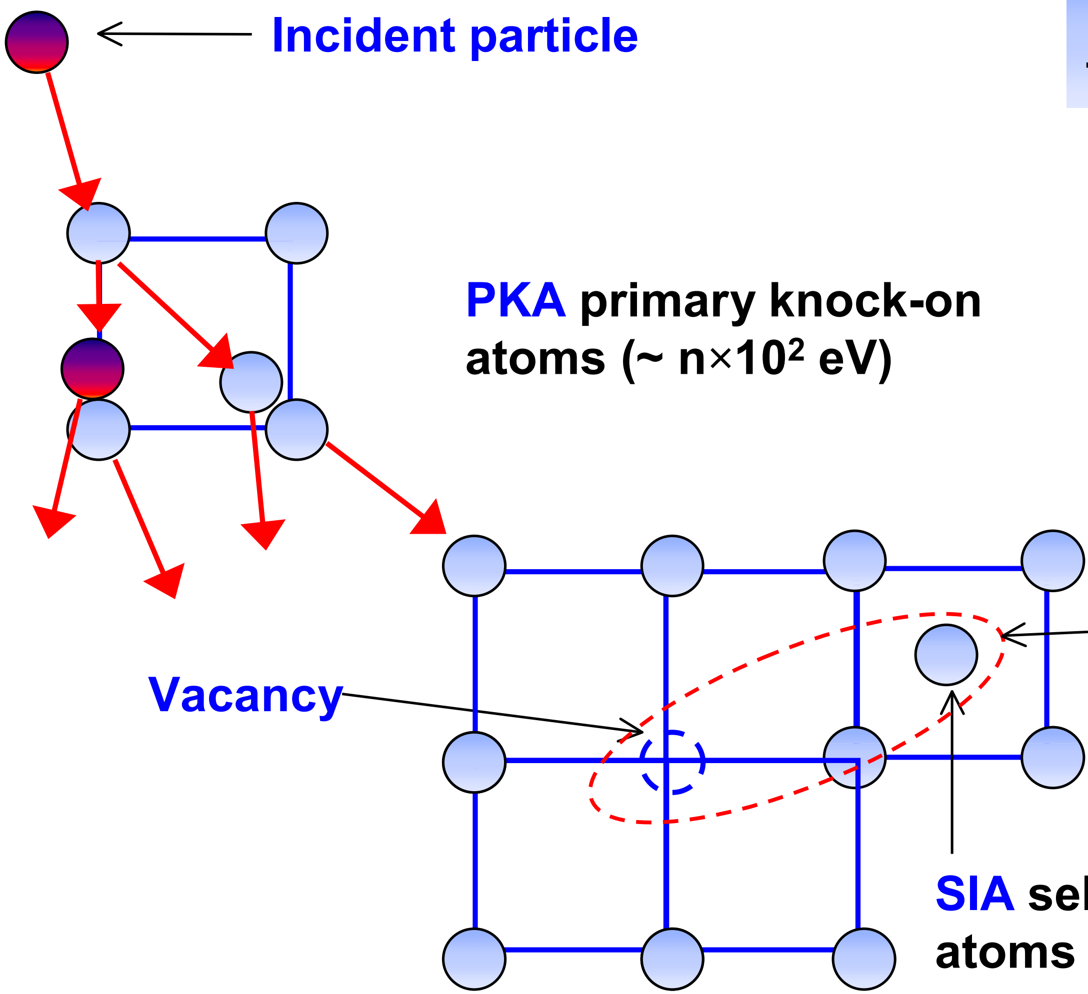
Irradiation induced micro-damage – types of defects







Irradiation induced defects in the lattice



Displacement cascade and formation of Frenkel pairs

↓

Kinchin & Pease, 1955

↓

Norgett, Robinson, Torrens, 1975

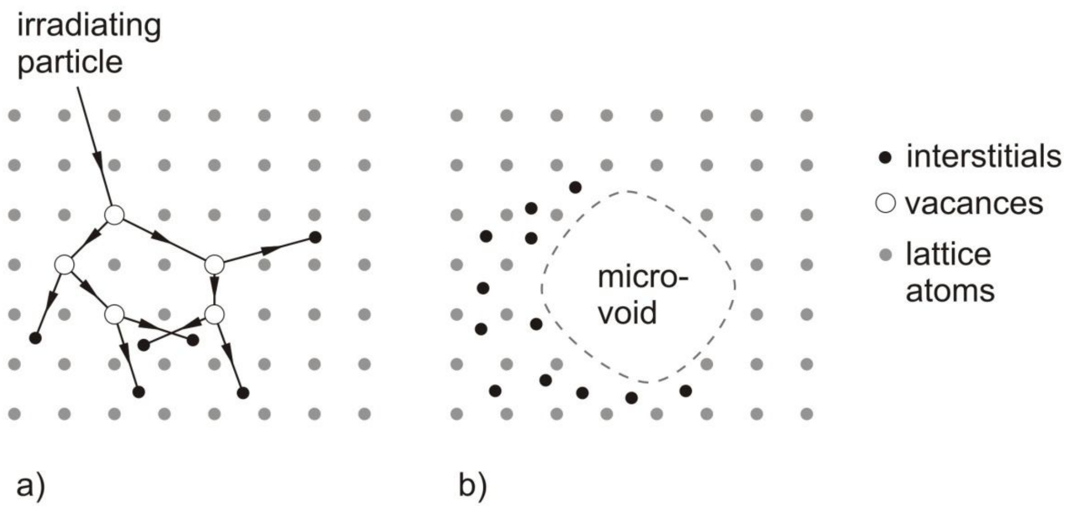
↓

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

$$E_{dam} = NIEL$$

Measure of irradiation induced damage

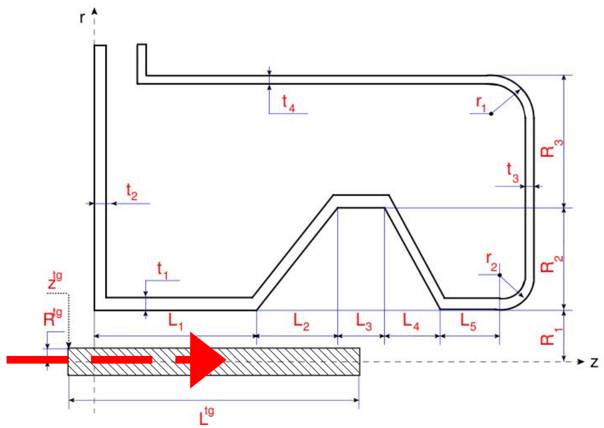
1 displacement per atom (dpa) corresponds to stable displacement from their lattice site of all atoms in the material during irradiation near absolute zero (no thermally-activated point defect diffusion).



Pulsed current & irradiation

For n pulses we assume that:

$$D_{rm}^{n} = n \times D_{rm}^{1}$$



i=i+1 pulse

Algorithm for structures subjected to pulsed irradiation

$$NIEL^{i} \Rightarrow dpa^{i}$$

$$D_{r0}^{i} = q_{A} \pi r_{c0}^{\;2}$$

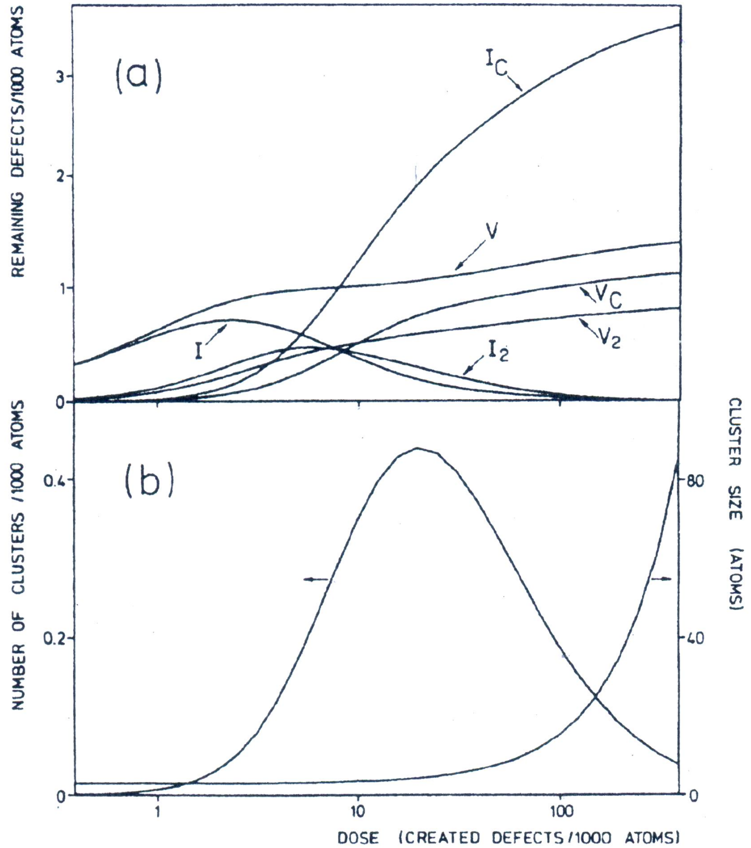
irradiation

Quasi-static and cyclic loads

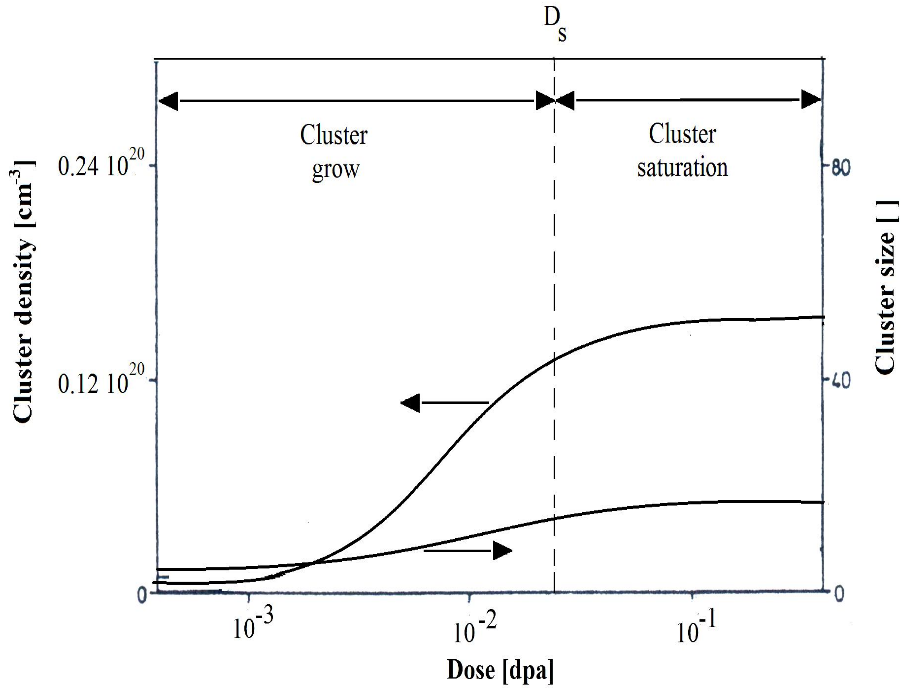
$$dD_{rm}^{i} = 2 q_{A} \pi r_{c0}^{\;2} \exp\left[\alpha_{r} \int_{0}^{p} \exp\left(\frac{3\sigma_{m}}{2\sigma_{eq}} \right) dp \right]$$

$$D_{rm}^{i} = D_{r0}^{i} + \int_{0}^{\hat{p}} dD_{rm}^{i}$$

Damage production during the irradiation



$\upsilon_R(=\upsilon_{IV})$	400	
υ_{II}	200	$\upsilon_R/2$
υ_{VV}	133	$\upsilon_R/3$
υ_{V_2I}	210	$3/2\ \upsilon_{I_2I}$
υ_{I_2V}	140	$3/2\ \upsilon_{V_2V}$
υ_{CI}	250	
υ_{CV}	50	$\upsilon_{CI}/5$



Properties of Aluminium

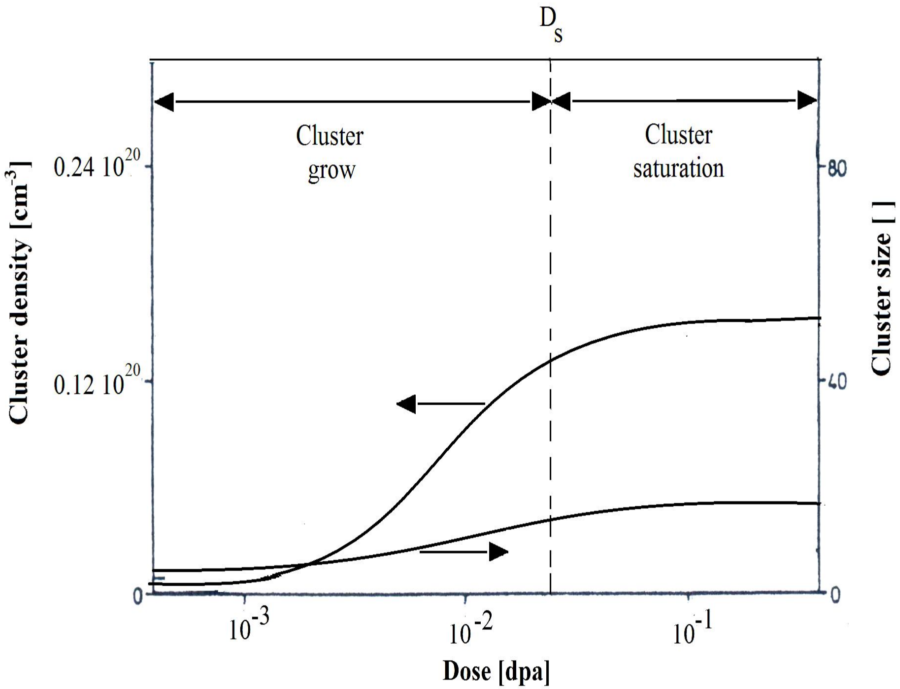
Atomic mass 26.982 g mol^{-1}

density 2.7 g cm^{-3}

Avogadro constant $N_A = 6.02 \cdot 10^{23} mol^{-1}$

Source: E. Verbiest, H. Pattyn „Study of radiation damage in aluminium", Physical Review B, 1982.

Clusters density and average cluster size at irradiation



$D_s = 2 \cdot 10^{-2}$

size of clusters $1.05\ nm - 14\ defects\ per\ cluster$

$$NIEL \Rightarrow dpa$$

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

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

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

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

Post-irradiation evolution of micro-damage (after recombination)

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

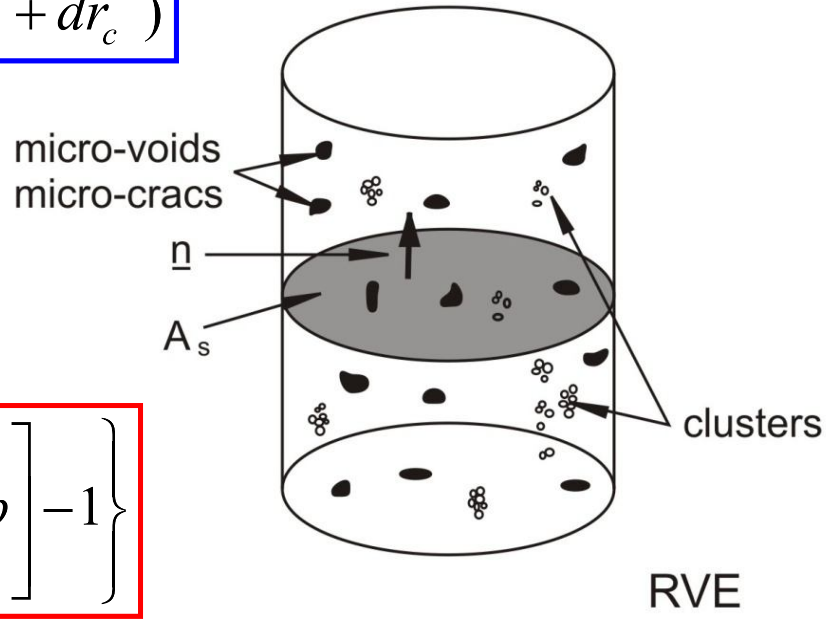
Rice & Tracey 1969, Beremin 1981, Huang 1991, Pardoen et al. 1996.

Typical value of α_r for Al is equal to 0.283

$$dA_{rm} = \pi((r_{c0} + dr_c)^2 - r_{c0}^2) = \pi(2r_{c0}dr_c + dr_c^2)$$

$$dD_{rm} = q_A dA_{rm} = q_A 2\pi r_{c0} dr_c$$

$$dD_{rm} = 2q_A \pi r_{c0}^2 \left\{ \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp \right] - 1 \right\}$$



Kinetic law of evolution of post-irradiation micro-damage (porosity)

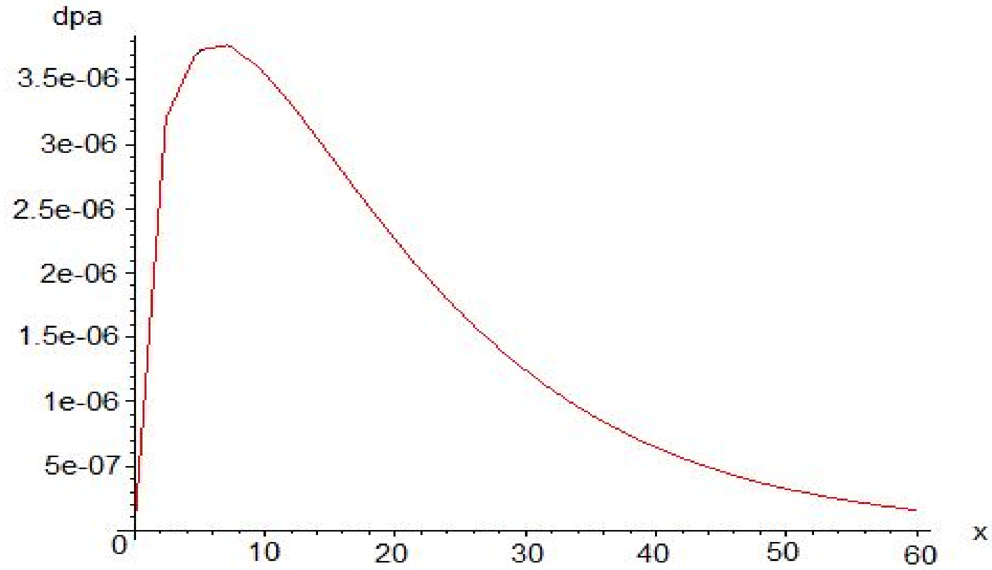
dpa distribution in target-horn integration

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

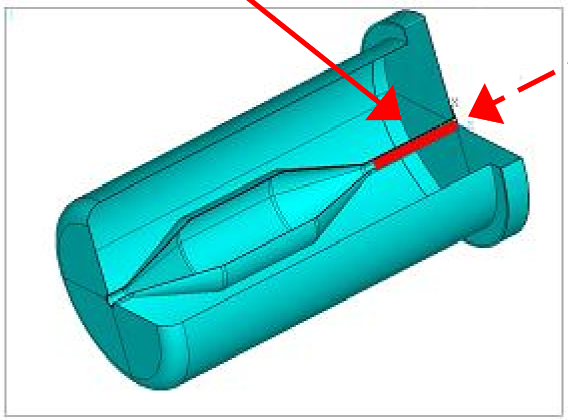
where: $a = 0.0000025$

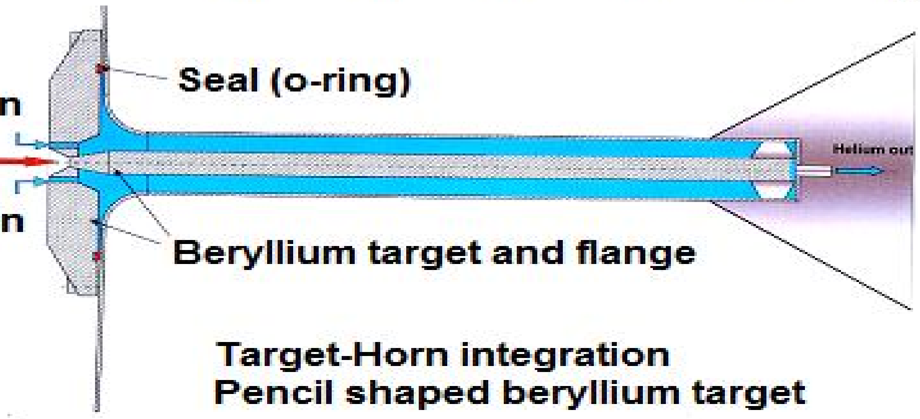
$b = 0.5$

$c = -0.08$



NIEL
⇩
dpa
⇩
D=Dr+Dm

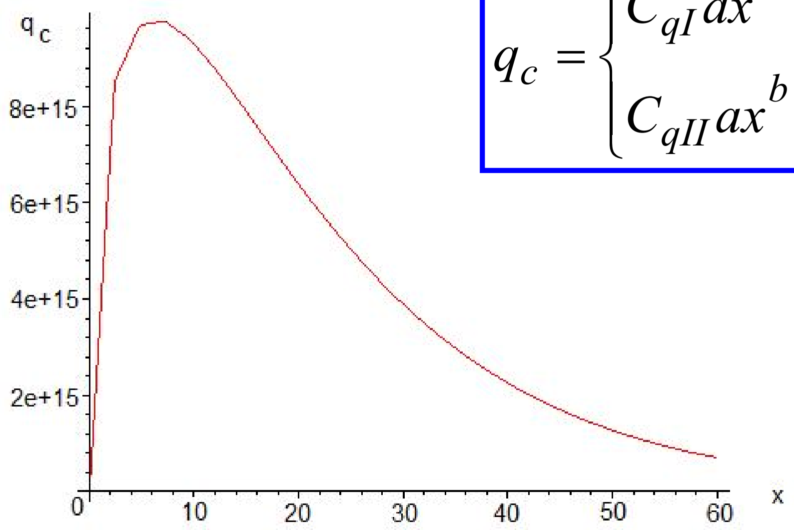




Target-Horn integration
Pencil shaped beryllium target

Horn Pulsed current & irradiation

Clusters density at irradiation

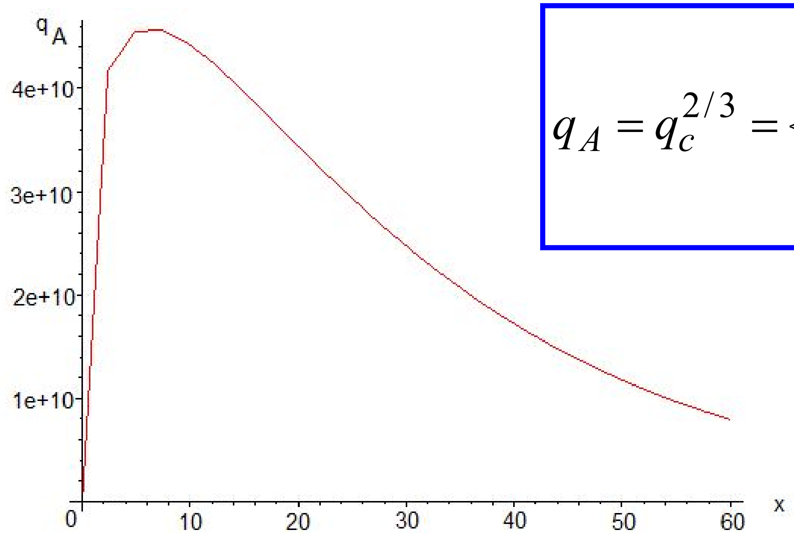


$$q_c = \begin{cases} C_{qI} a x^{b\, n_{qI}} e^{c\, n_{qI} x} & for \quad dpa < D_S \\ C_{qII} a x^{b\, n_{qII}} e^{c\, n_{qII} x} & for \quad dpa \geq D_S \end{cases}$$

where:

$C_{qI} = 0.3 \cdot 10^{20}$ $n_{qI} = 0.83$

$C_{qII} = 0.2 \cdot 10^{20}$ $n_{qII} = 0.145$



$$q_A = q_c^{2/3} = \begin{cases} \left(C_{qI} a x^{b\, n_{qI}} e^{c\, n_{qI} x}\right)^{2/3} & for \quad dpa < D_S \\ \left(C_{qII} a x^{b\, n_{qII}} e^{c\, n_{qII} x}\right)^{2/3} & for \quad dpa \geq D_S \end{cases}$$

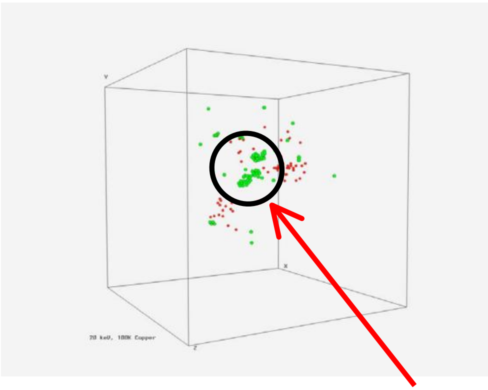
Cluster size at irradiation

$$r_{c0} = \begin{cases} C_r a\, x^{b\, n_r} e^{c\, n_r x} & for \quad dpa < D_S \\ r_{cr} & for \quad dpa \geq D_S \end{cases}$$

where:

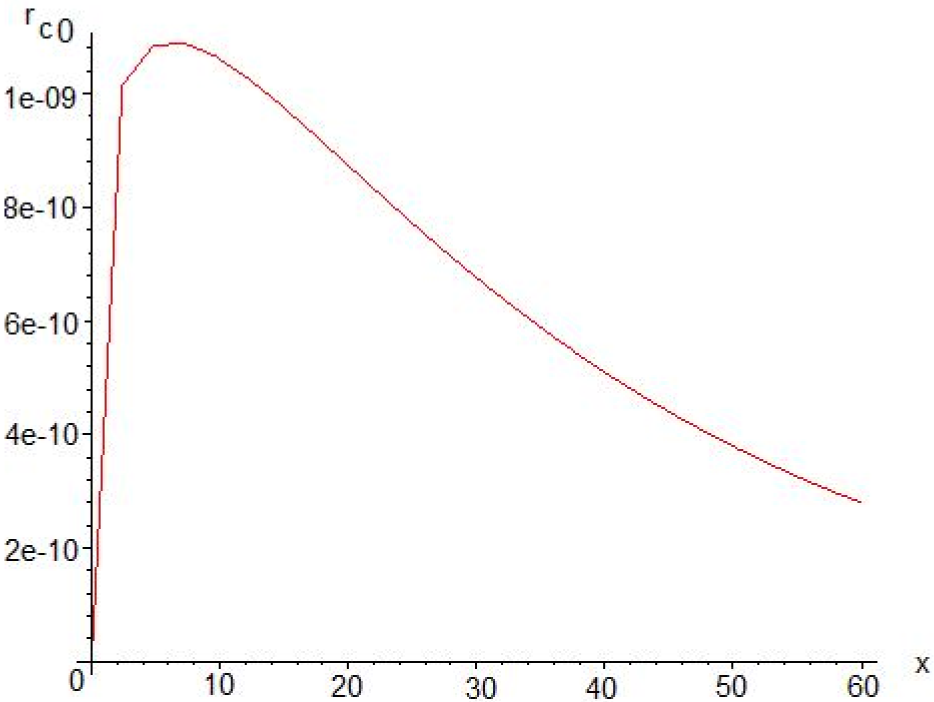
$C_r = 0.1 \cdot 10^{-6}$ $\quad n_r = 0.15$

$r_{cr} = 0.11 \cdot 10^{-6}$



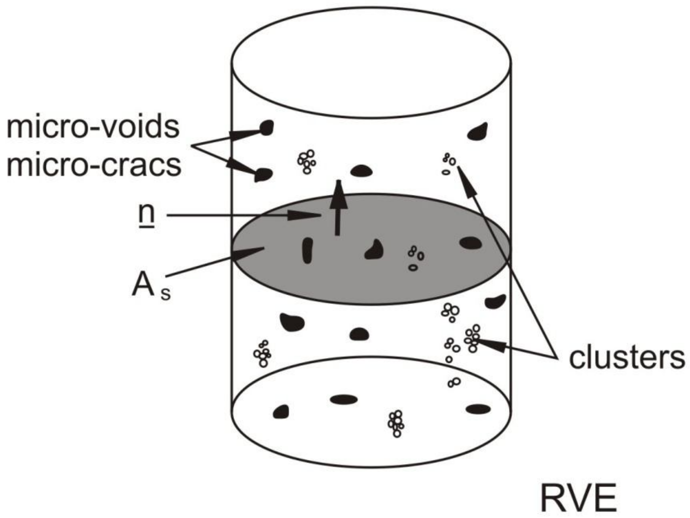
Cluster

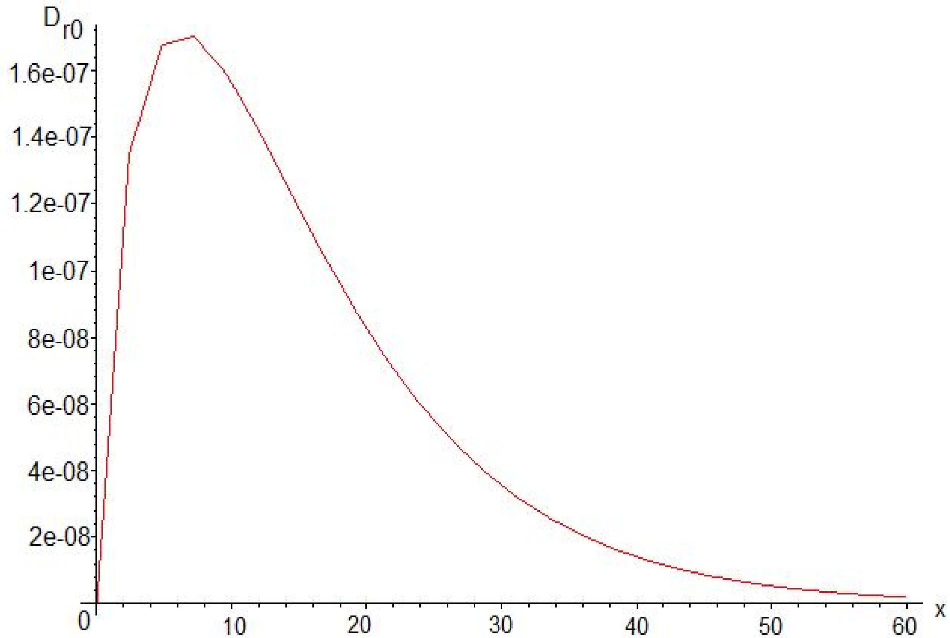
of micro-voids

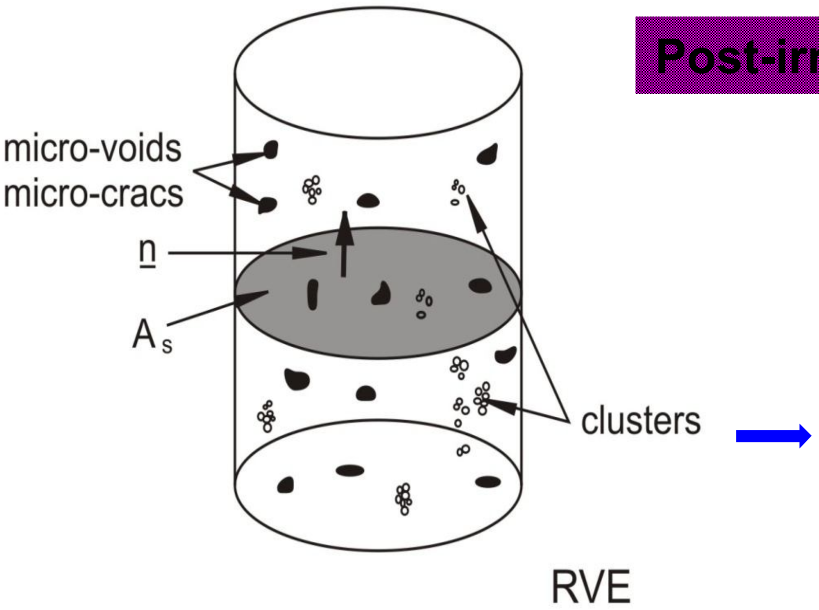


Irradiation damage

$$D_{r0} = \begin{cases} \left(C_{qI}\, a x^{b\, n_{qI}}\, e^{c\, n_{qI}\, x}\right)^{2/3} \pi\, r_{c0}^2 & for \quad dpa < D_S \\ \left(C_{qII}\, a x^{b\, n_{qII}}\, e^{c\, n_{qII}\, x}\right)^{2/3} \pi\, r_{c0}^2 & for \quad dpa \geq D_S \end{cases}$$







Post-irradiation evolution of micro-damage

$$dD_{rm} = 2q_A \pi r_{c0}^{\ 2} \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) dp\right]$$

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

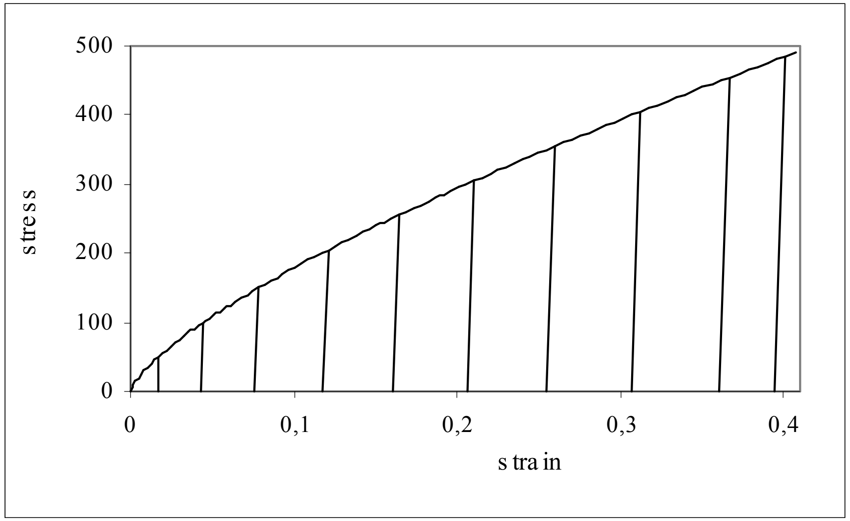
Power law:

$$\varepsilon = \frac{\sigma}{\widetilde{E}} + K\left(\frac{\sigma}{\widetilde{E}}\right)^n$$

Parameters of the power law: $n = 0.7 \quad K = 63$

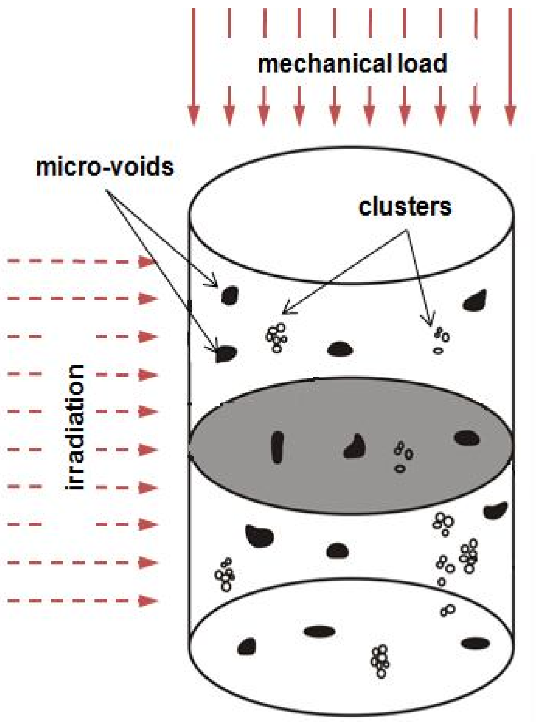
Effective Young Modulus: $\widetilde{E} = E(1-D)$

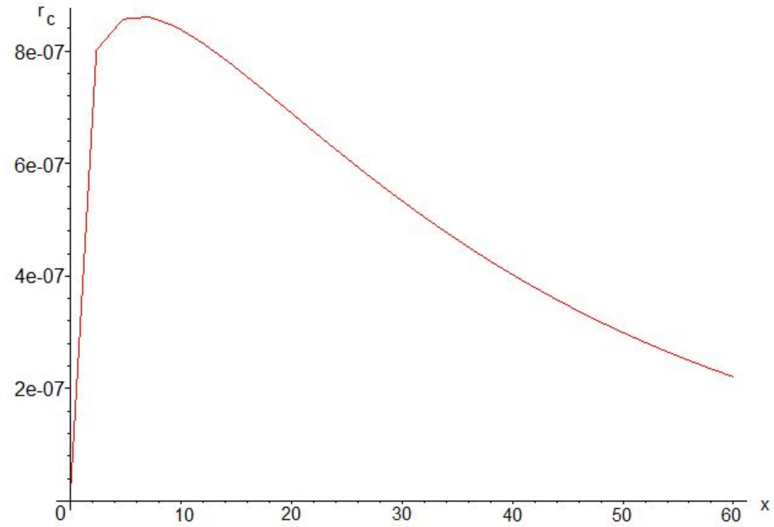
Unloading law: $\hat{\sigma} - \sigma = E(\hat{\varepsilon} - \varepsilon)$

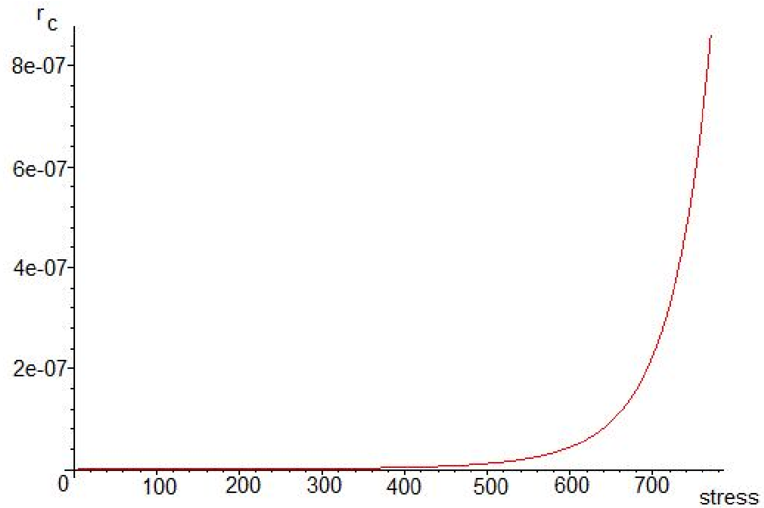


Post-irradiation evolution of micro-damage

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



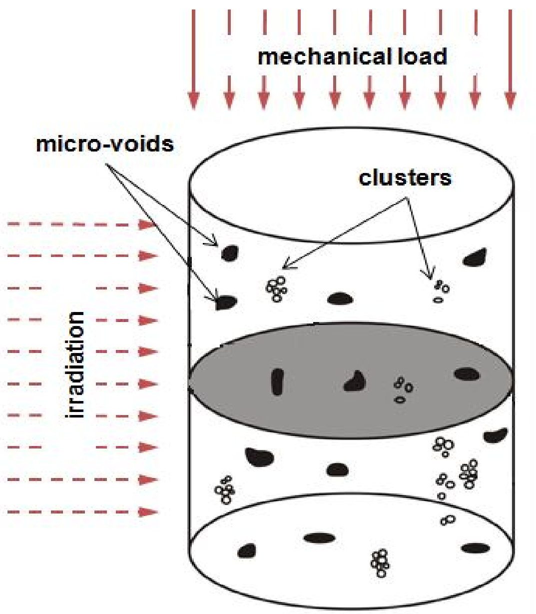


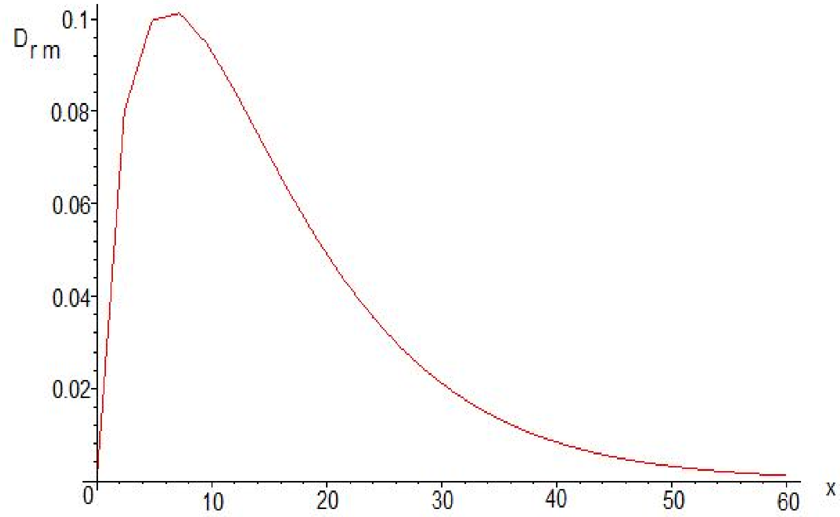


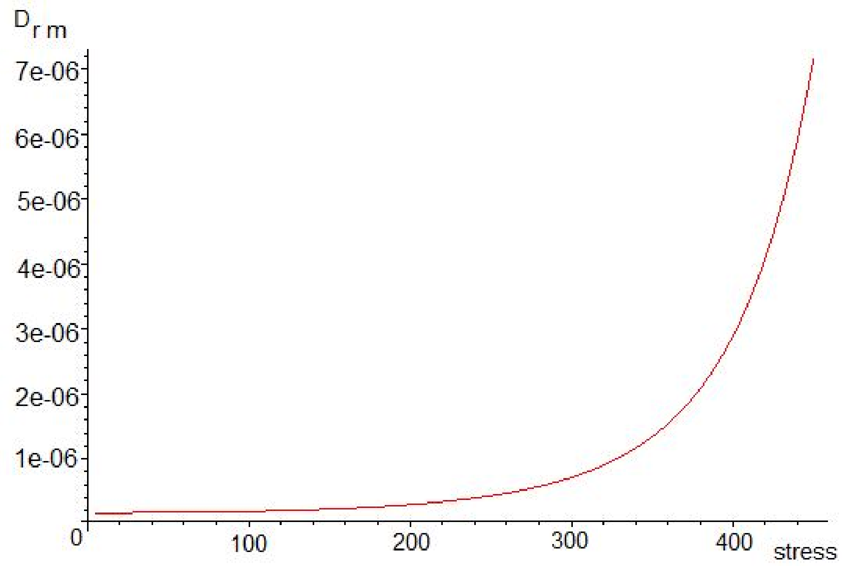
Post-irradiation evolution of micro-damage

$$dD_{rm} = 2q_A \pi r_{c0}^{\;2} \left\{ \exp\left[\alpha_r \int_0^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}} \right) dp \right] - 1 \right\}$$

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







Conclusions

1. Irradiation induced damage measured in „dpa" has to be converted to classical micro-damage parameter D. Evolution of D is governed by type Rice-Tracey kinetic law of damage evolution and is expressed in terms of stress state and strains.

2. Evolution of micro-damage can be simulated as a function of static, cyclic or dynamic loads imposed on the analysed structure.

3. In particular, lifetime of horn can be determined by means of the above presented approach.