Materials under irradiation

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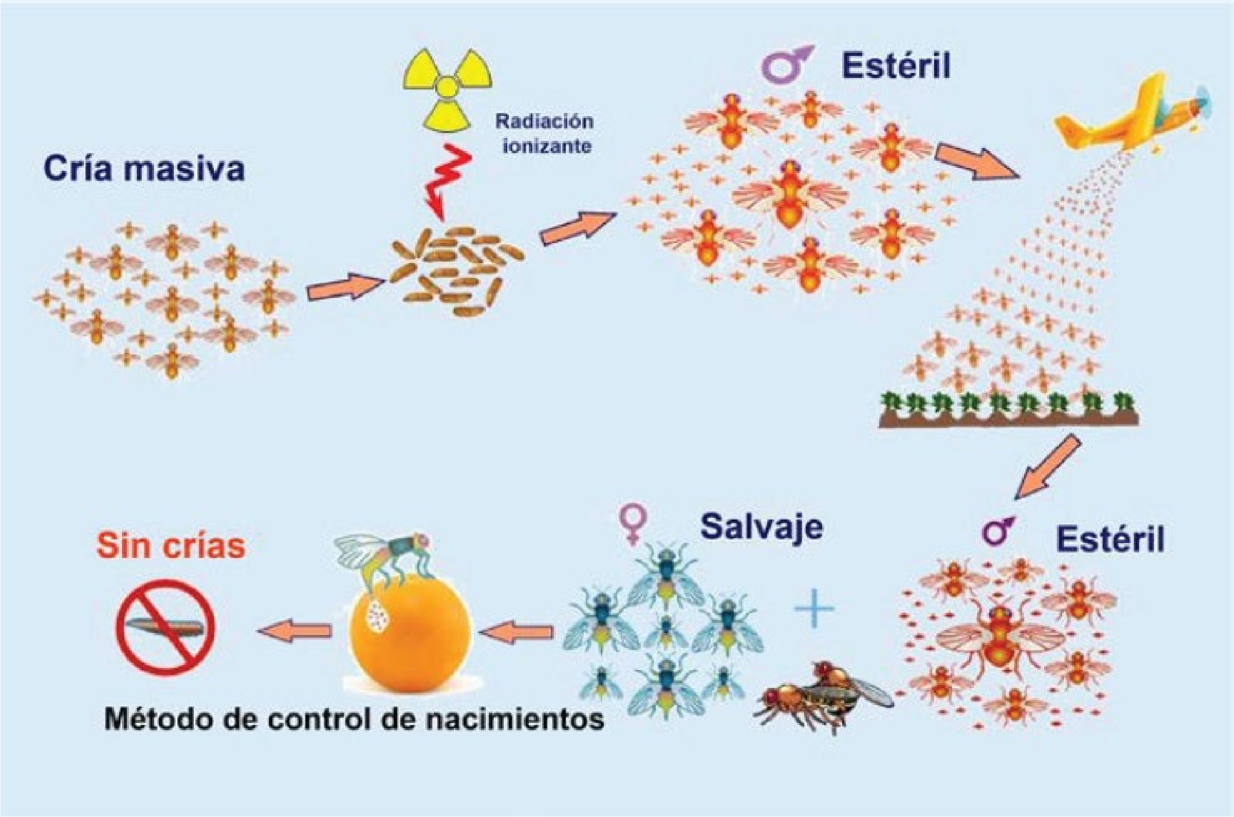
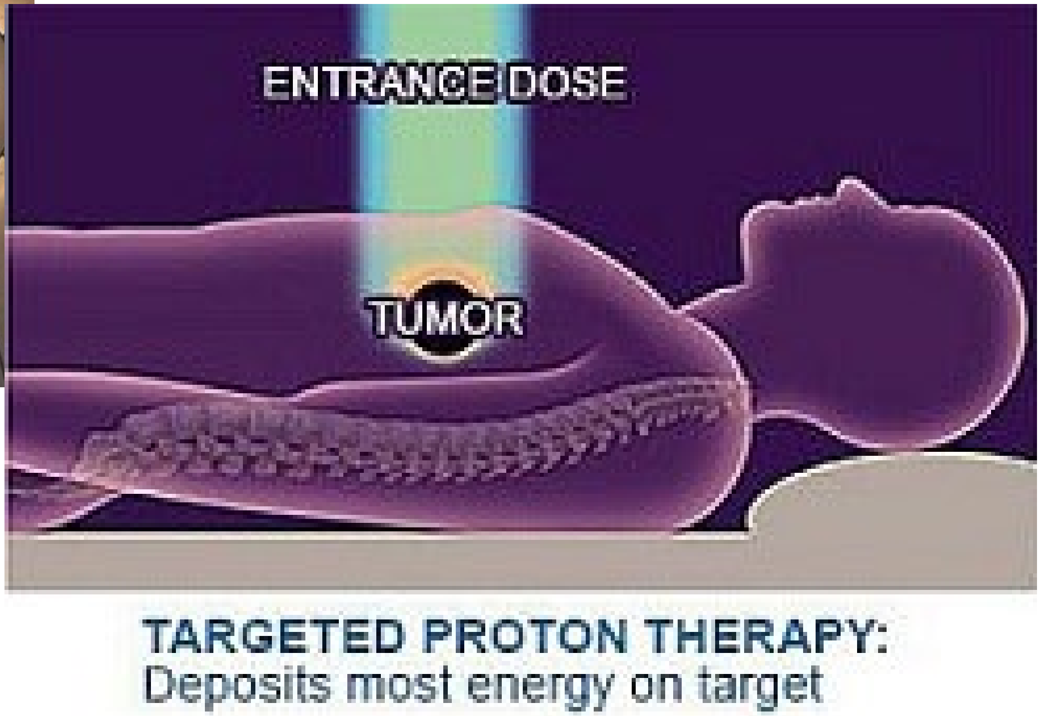
Radiation uses

Radiation uses

Radiation uses



Radiation uses



Radiation uses

http://www.catedraenresauco.com

Materials under irradiation

What does it happen when we irradiate a material?

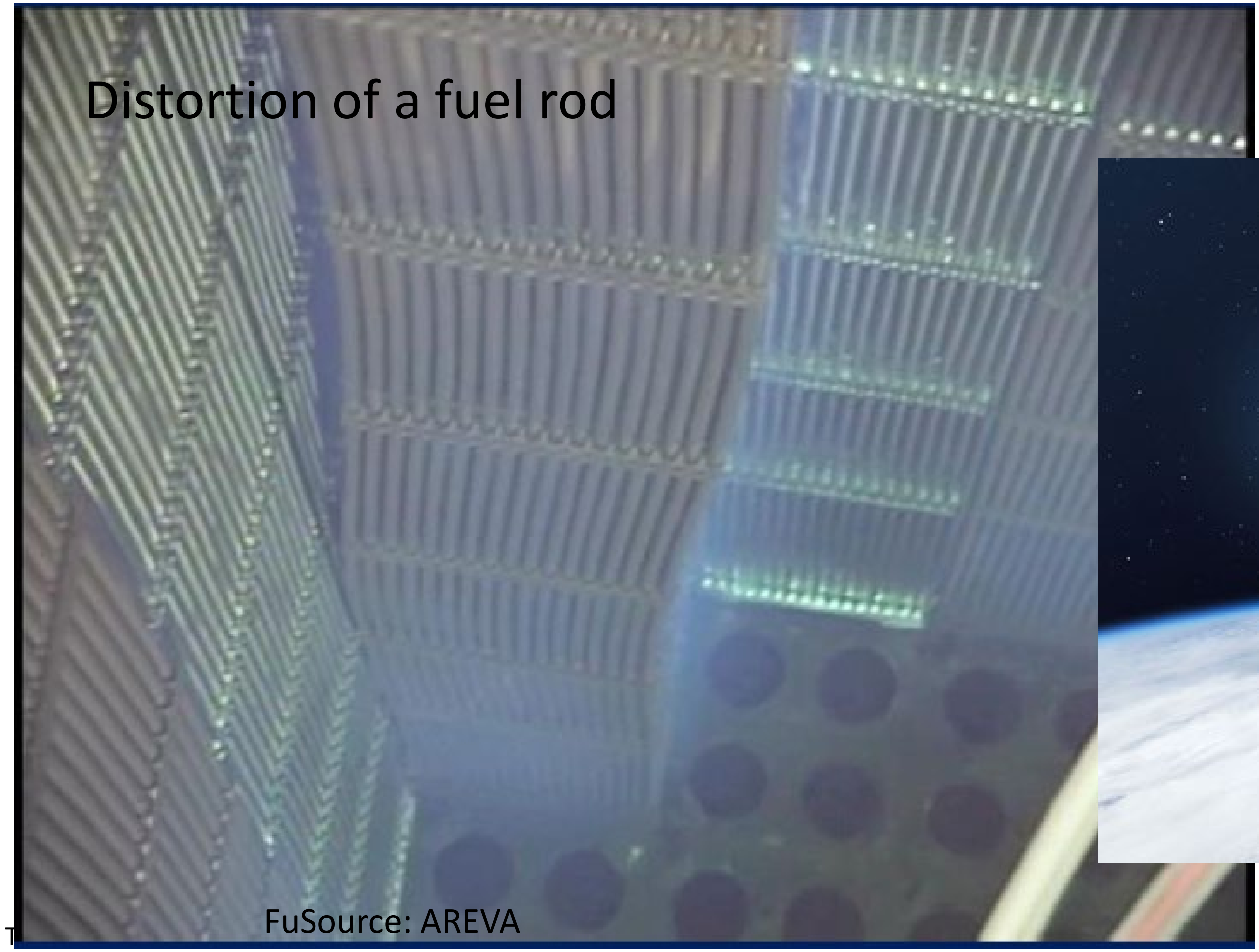
Irradiation generates damage/defects in materials. So, generally, it modifies the physical and chemical properties of the material.

Figure 6-24. Easily observed swelling ($\approx$10% linear, $\approx$33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or $\approx$75 dpa at 510 °C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

Garner, Ch. 6. Irradiation Performance of Cladding and Structural Steels in Liquid Metals Reactors, of Nuclear Materials part 1, Vol 10 A, Published by VCH, Germany

Materials under irradiation

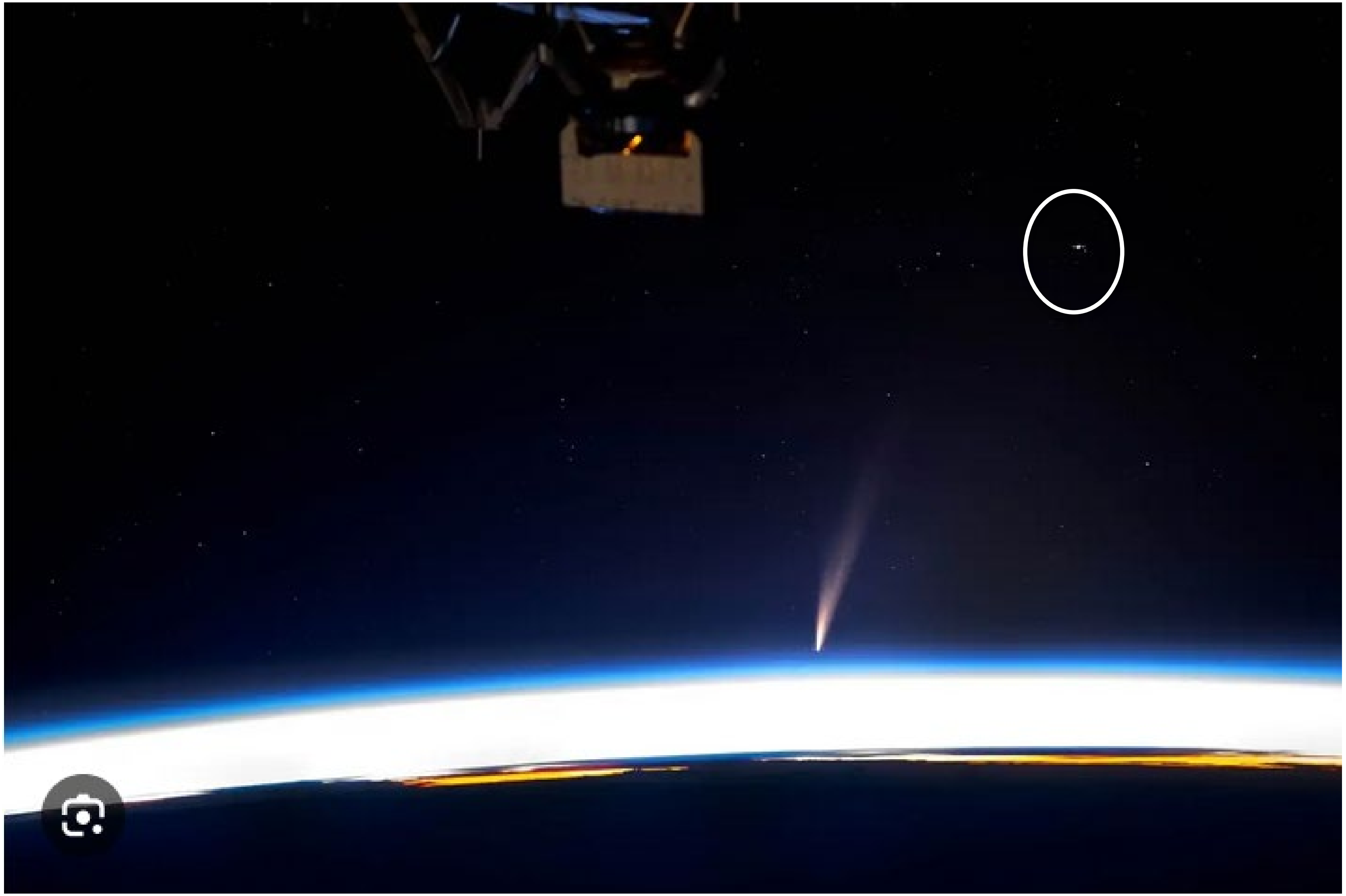
Atomistic effects lead to material properties changes/degradation



Materials under irradiation

- High definition image from the ISS

Materials under irradiation



Irradiation modifies materials properties

- What would you think as an engineer if the properties of carefully selected materials change over time?

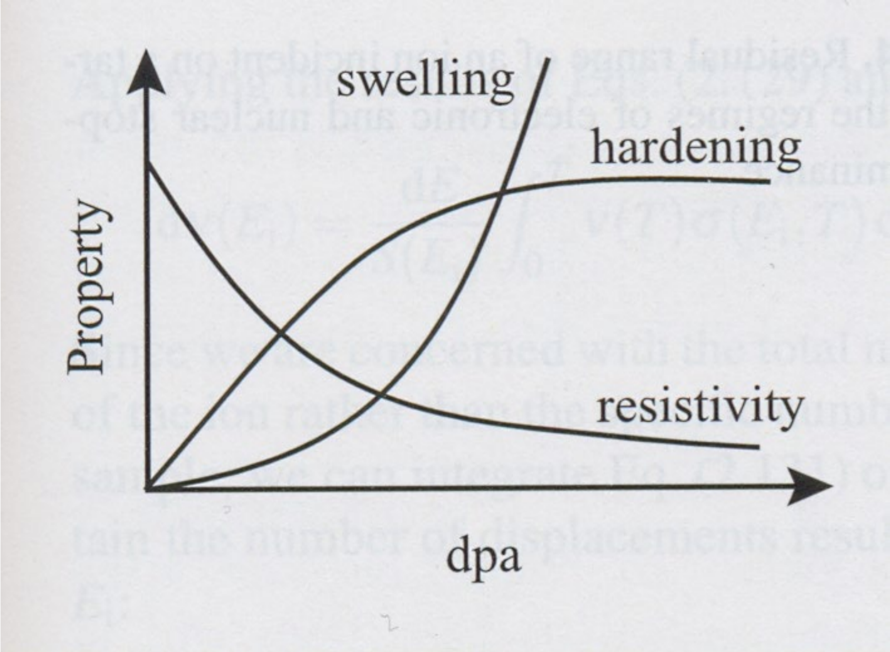
Desperate man by P. C. Robla

- What would happen if you weren't able to predict those changes?

Understanding the fundamental aspects of radiation-matter interaction is crucial to develop more radiation resistant materials.

Atomistic effects

- Origin:
  - Frenkel pairs
  - Defect clustering
  - Chemical reactions
  - Gas interaction
- Effects

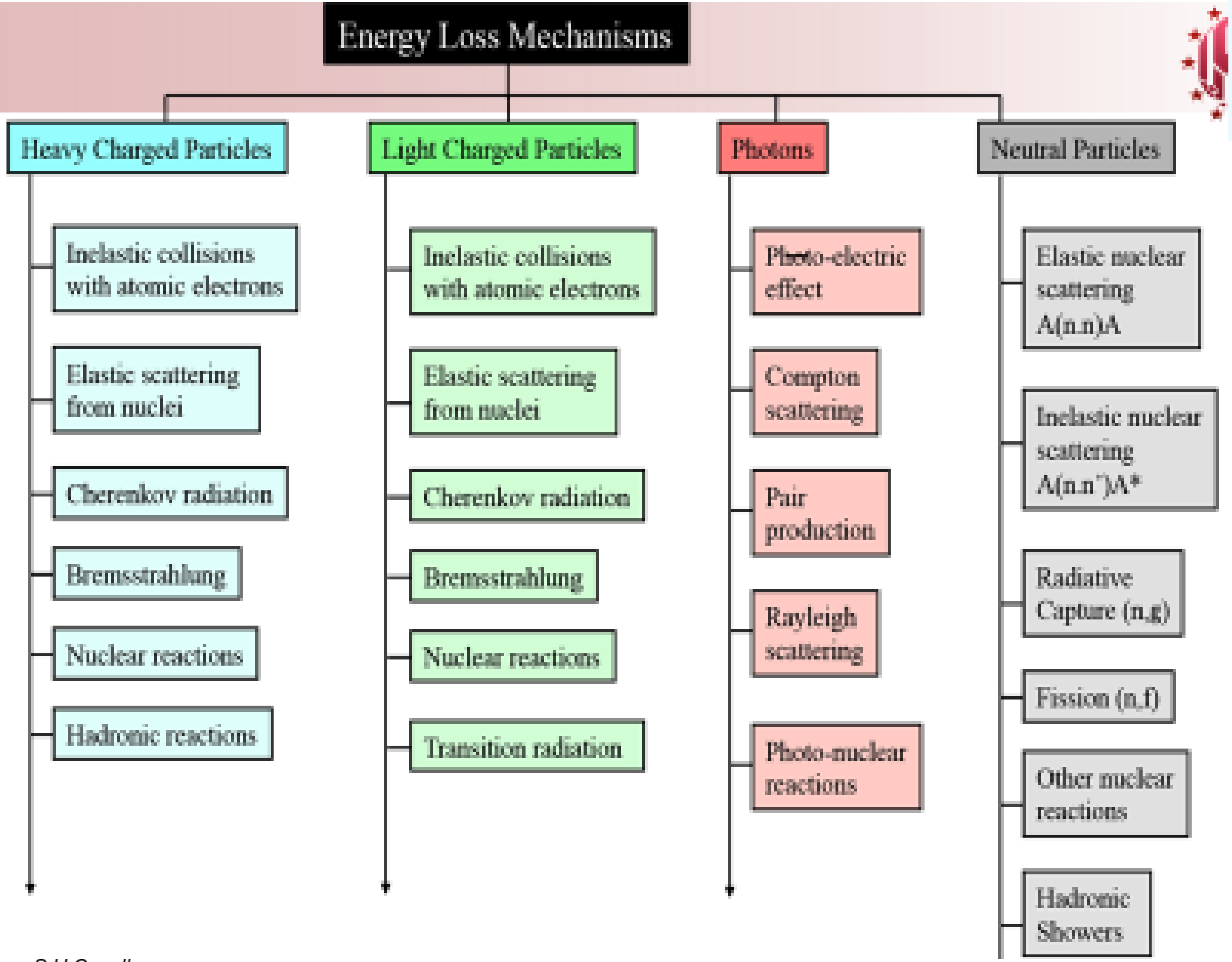


Atomistic effects

- One of the essential characteristics of ionizing radiation (photons, neutrons, charged particles, etc.) is their ability to penetrate and interact with matter.

- In these interactions, radiation loses part or all of its energy, yielding it to the medium through which it passes through different interaction mechanisms that essentially depend on:
  - The type of particle (mass and charge).
  - Particle energy.
  - Medium with which it interacts (in terms of composition, density, physical state, etc.).

- These radiation-matter interaction processes are the origin of the radiation-induced defects



Source: S H Conell

Radiation and materials

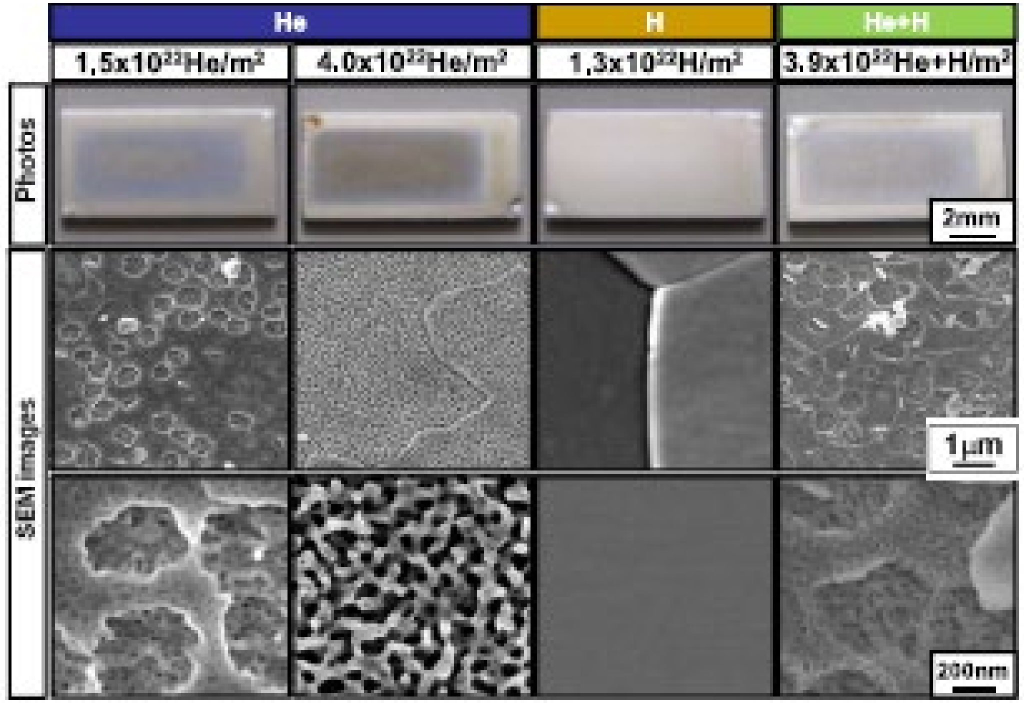
- The radiation induced changes strongly depends on the radiation environment (energy, particle, temperature..) and on the material

- The first thing that is necessary to know when one considers studying and/or predicting radiation-induced damage is the irradiation environment to which the material will face:
  - Radiation species: X-ray, neutrons, ions
  - Fluence
  - Flow
  - Temperature
  - Energy
  - Radiation nature: Pulsed or continuous
    - Pulsed: pulse duration, repetition rate, and if the samples experiment thermal loads concurrent to the pulses

Radiation species

W irradiated with

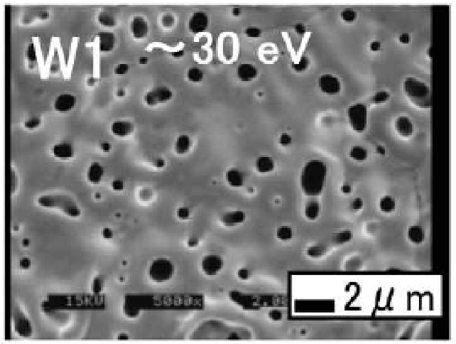
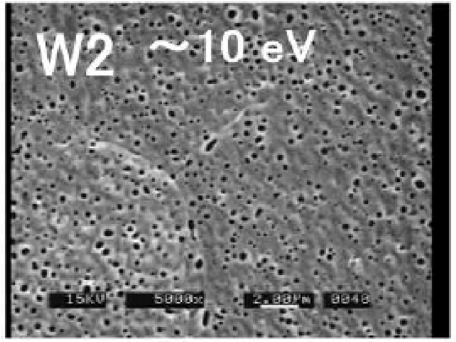
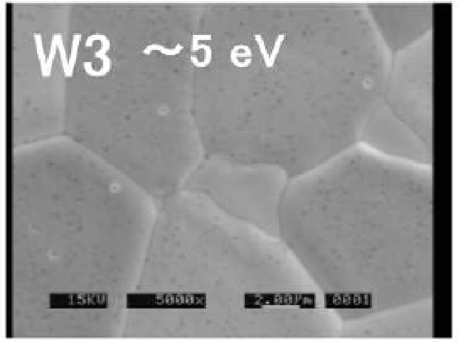
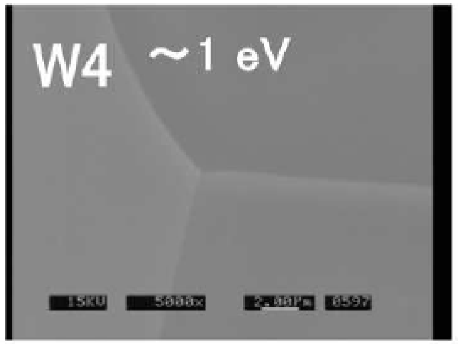
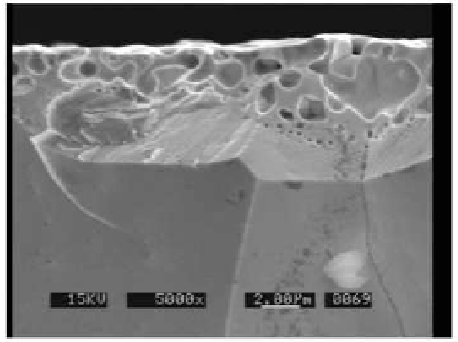
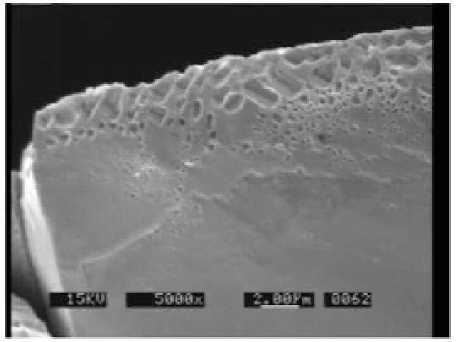
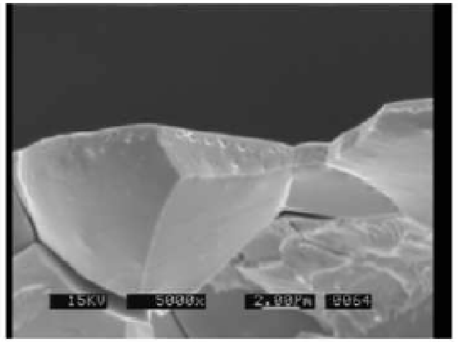
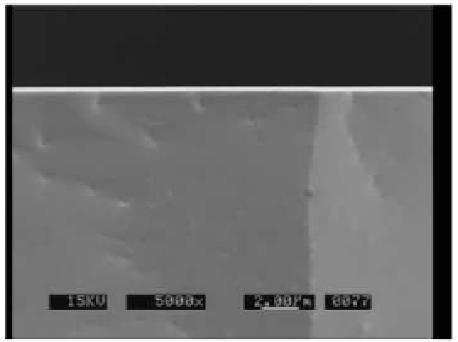
	Pulse x shot	Total irr. time	Power density	Fluence
He	~30 ms x 7 shot	171 ms	300 MW/m^2	1.5x10^{22} He/m^2
He	~30 ms x 16 shot	461 ms	300 MW/m^2	4.0x10^{22} He/m^2
H	~30 ms x 5 shot	146 ms	300 MW/m^2	1.3x10^{22} H/m^2
He+H	~30 ms x 15 shot	447 ms	300 MW/m^2	3.9x10^{22} He+H/m^2



M. Tokitani *et al.* Plasma and Fusion Research: Regular Articles Volume 5, 012 (2010)

Irradiation energy

W irradiated with He at different energies

Fluence Ion flux Time Temperature	2.6×10^{27} /m² 3.7×10^{23} /m²s 7200 s 2100 K	0.9×10^{27} /m² 1.2×10^{23} /m²s 7200 s 2600 K	0.8×10^{27} /m² 1.1×10^{23} /m²s 7200 s 2200 K	0.8×10^{27} /m² 1.1×10^{23} /m²s 7200 s 2950 K
Surface				
Cross section				

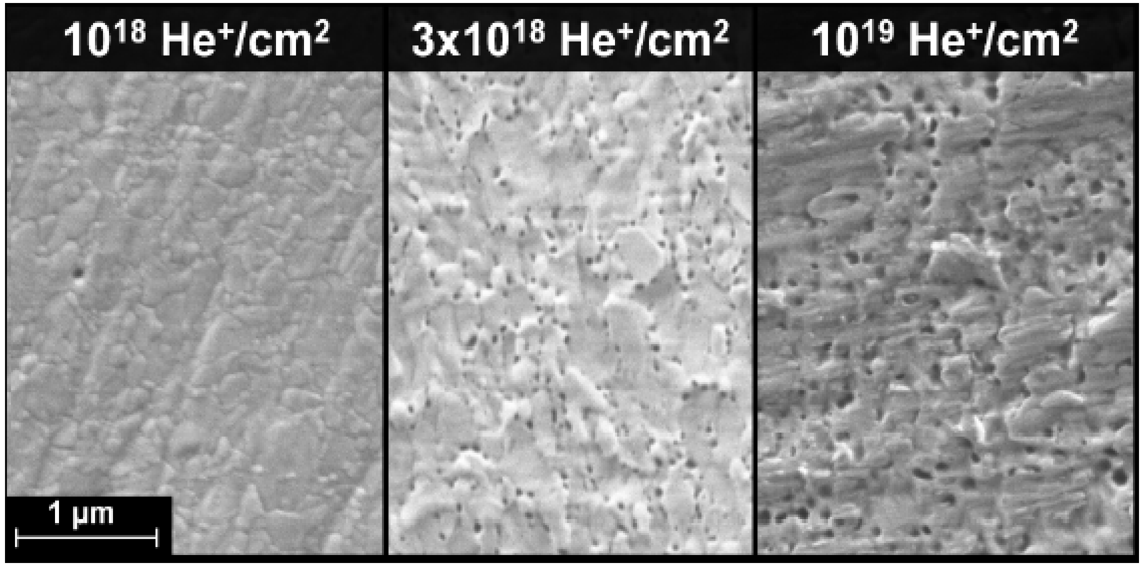
*D. Nishijima, 30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003 ECA Vol. **27A**, P-2.163*

Irradiation fluence and sample morphology

W irradiated with

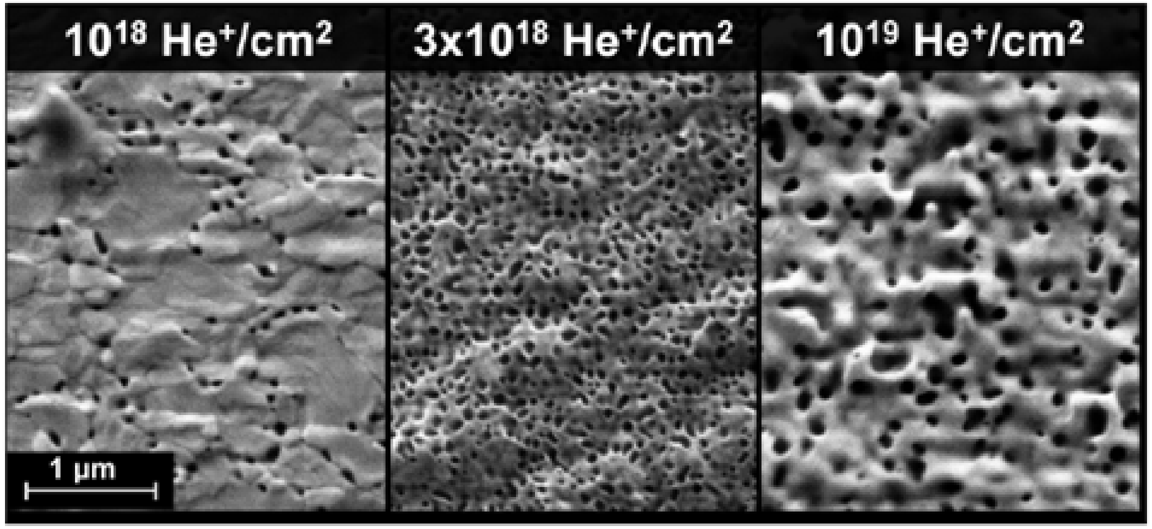
Single crystal

He 20 eV
1100ºC



Poly crystal

He 20 eV
1100ºC



The defect configuration in the as-grown sample also play a role in the radiation damage configuration

S. J. Zenobia, PhD thesis University of Wisconsin (2010)

Radiation-matter interaction: charged vs neutral particles

- **Definition:**
  - ***Charged particles:*** those that have a charge (e^-, H^+, heavy ion…)
  - ***Neutral particles***: those that have no charge (photon, neutron)

- **Differences in effective cross-sections (*σ*)**
  - ***Charged particle*** *$\sigma \sim 10^{-16}$ cm^{-2}*
  - ***Neutral particle*** *$\sigma \sim 10^{-24}$ -10^{-20} cm^{-2}*

Radiation-matter interaction: charged vs neutral particles

- **Mean free path (mfp)**

$$mfp = \frac{1}{N\sigma}$$

Where: *σ is the cross section*

N is the matter density (N~10^23 cm^-3)

– ***Charged particles:*** mfp~Å

– ***Neutral particles***: µm-cm

Charged vs neutral particles

- **Interaction**
  - ***Charged particles***
    - They interact practically with each atom along its path.
    - They lose energy in each interaction:
      - Electronic excitation
      - Ionization
    - They are characterized by their stopping power and penetration length
    - Directly ionizing.
  - ***Neutral particles***
    - They interact infrequently with the atoms of a target
    - In each collision they are absorbed or dispersed from the original beam
    - The intensity of the non-dispersed beam is attenuated proportionally to the mean free path and its intensity decreases exponentially with the crossed distance
    - Indirectly ionizing (interaction with matter can generate one or more charged energy particles (photoelectron, Compton electron)

The radiation-induced damage event

- It is defined as the energy transferred by the incident projectile to the target and the consequent distribution of the atoms in the target once the interaction has occurred.

- It is made up of different processes:
  - **The interaction of the incident energetic particle with the atom (part I).**
  - The transfer of kinetic energy to the atom giving rise to what is known as "primary Knock atom" (PKA).
  - **The displacement of the atom from its lattice position (part II)**.
  - The passage of displaced atoms through the network accompanied by the production of additional PKAs.
  - The production of the cascade (generation of point defects generated by the PKA).
  - PKA completion as interstitial

Radiation-induced damage

1. The radiation damage event
   - Neutron-nucleus interaction
   - Interaction between ions and atoms

2. The displacement of Atoms

3. The damage cascade

4. Point defect formation

Cross section

- Each type of interaction can be characterized by its cross section.
- The cross section, denoted typically by the symbol ƌ, describes the interaction probability.
- It depends on: the particle and energy the neutron energy.
- The unit of the cross section is the barn. One barn is 10^{-24} cm

Radiation-induced damage

1. The radiation damage event
   - Neutron-nucleus interaction
   - Interaction between ions and atoms

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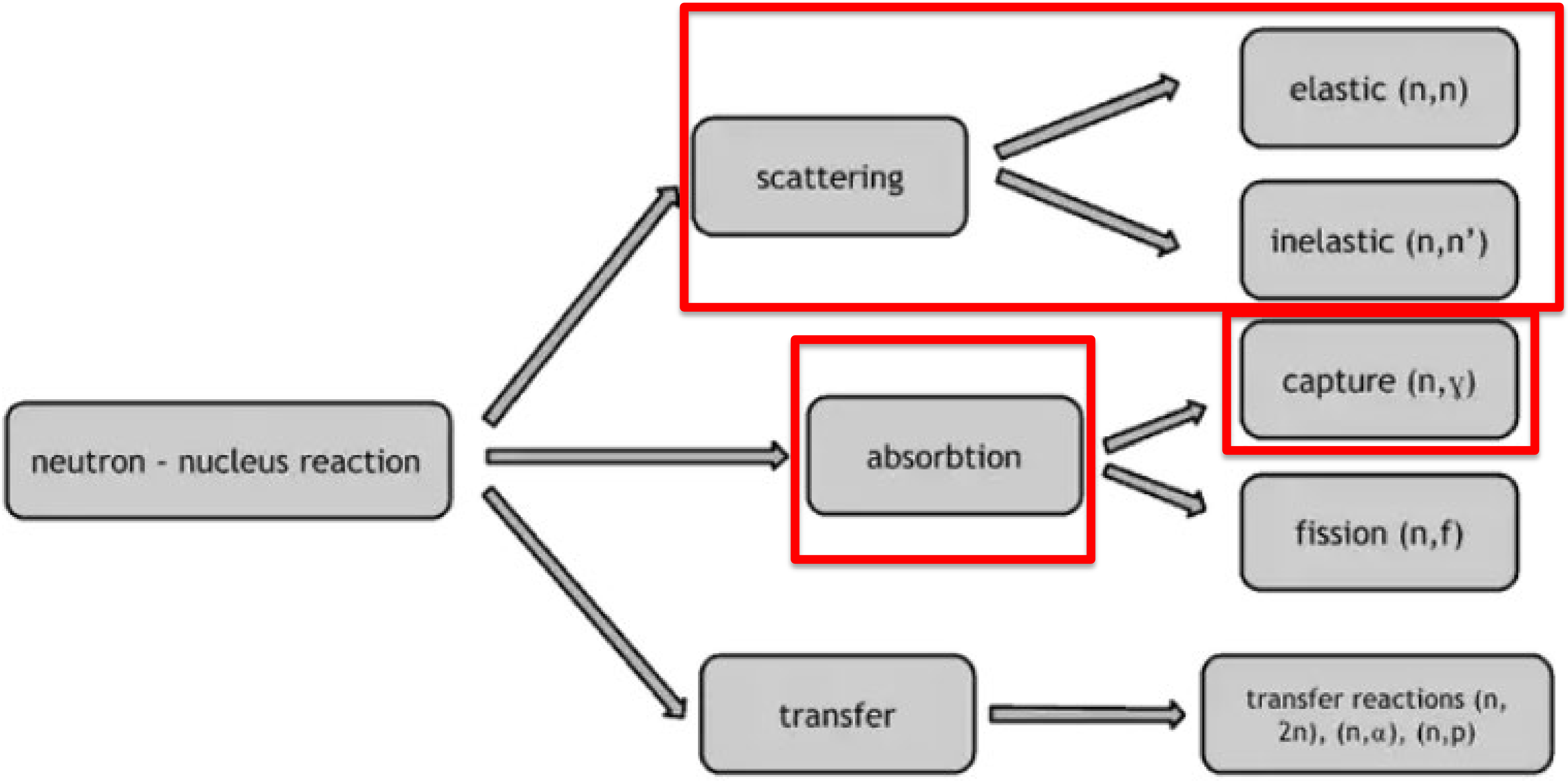
4. Point defect formation

Neutron-nucleus interaction: general

- Neutrons have no charge. They interact via physical collisions with nuclei (target nuclei).
- A neutron might scatter off the nucleus or combine with the nucleus.
- When the neutron combines with a nucleus, some type of particle might be emitted (e.g., proton, alpha particle) and/or a “prompt” gamma ray.
- Neutrons, like other indirectly ionizing radiation (e.g., ϒ rays), can travel substantial distances.

Neutron-nucleus interaction

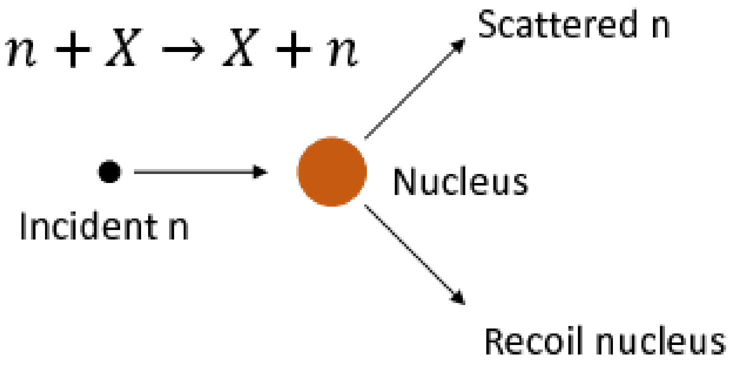


Neutron-nucleus interaction

SCATTERING INTERACTION

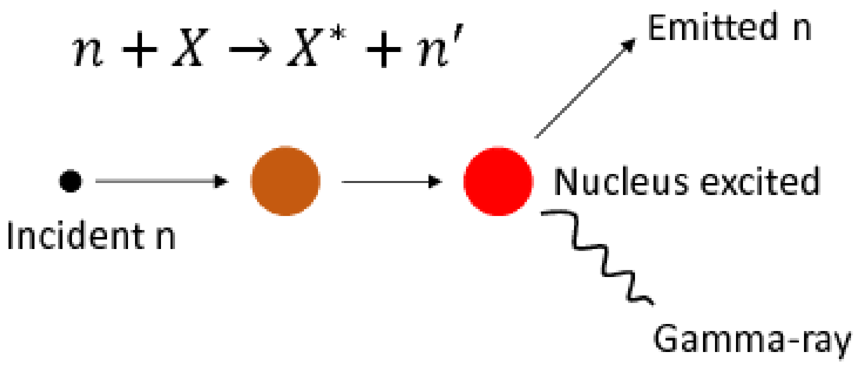
ELASTIC

$$n + X \rightarrow X + n$$



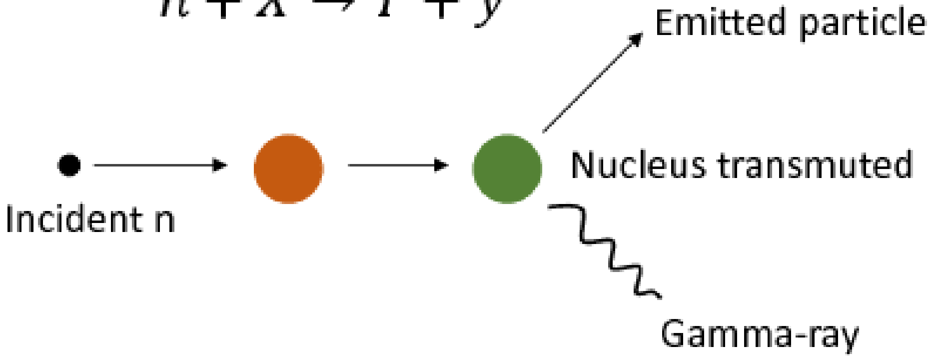
INELASTIC

$$n + X \rightarrow X^* + n'$$



ABSORPTION INTERACTION

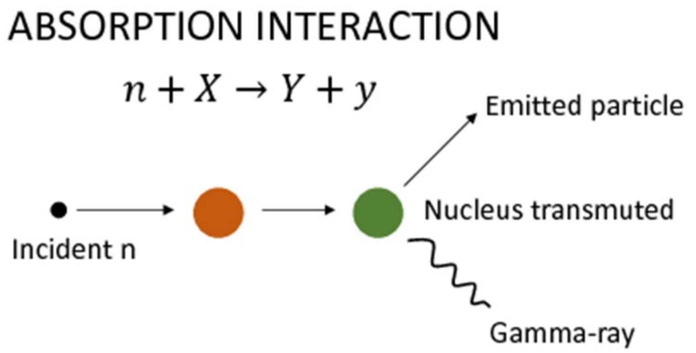
$$n + X \rightarrow Y + y$$



G. *Mauri et al.* JINST 13 (2018) no.03, P03004 arXiv:1712.05614

Neutron irradiation: transmutation reactions

- In addition to damage induced by direct collisions, neutron irradiation produces transmutation reactions.



Important issues:

1. Radioactive nuclei are produced with very different decay times $\rightarrow$ safety
2. Transmuted nucleus $\rightarrow$ changes in the elemental composition of the material $\rightarrow$ change in material properties
3. He and H accumulation inside the material $\rightarrow$ swelling

Neutron-nucleus interaction

Fundamentals of Radiation Materials Science: Metals and Alloys, Gary S. Was, Springer, ISBN 978-3-540-49471-3

Table 1.2. Energy transfer and energy transfer cross sections for various types of neutron–nuclear collisions

Type of collision	Energy transfer and energy transfer cross section	Equation in text
Elastic scattering	$T = \frac{\gamma}{2} E_\mathrm{i}(1-\cos\phi)$	(1.13)
	$\sigma_\mathrm{s}(E_\mathrm{i},T) = \frac{\sigma_\mathrm{s}(E_\mathrm{i})}{\gamma E_\mathrm{i}}$	(1.21)
Inelastic scattering	$T(E_\mathrm{i},Q_j,\phi) = \frac{\gamma}{2}E_\mathrm{i} - \frac{\gamma}{2}\left[E_\mathrm{i}\left(E_\mathrm{i}+Q_\mathrm{i}\frac{A+1}{A}\right)\right]^{1/2}\cos\phi + \frac{Q_j}{A+1}$	(1.27)
	resonance region	
	$\sigma_{\mathrm{s},j}(E_\mathrm{i},Q_j,T) = \frac{\sigma_{\mathrm{s},j}(E_\mathrm{i},Q_j)}{\gamma E_\mathrm{i}\left(1+\frac{Q_j}{E_\mathrm{i}}\frac{l+A}{A}\right)^{1/2}}$	(1.30)
	unresolved resonance region	
	$\sigma_\mathrm{is}(E_\mathrm{i},T) = \sigma_\mathrm{is}(E_\mathrm{i})\int_0^{E'^{\max}_\mathrm{m}} \frac{f(E_\mathrm{i},E'_\mathrm{m})}{4\frac{1}{A+1}(E_\mathrm{i}E'_\mathrm{m})^{1/2}}\mathrm{d}E'_\mathrm{m}$	(1.31)
(n, 2n)	$T = \frac{A}{A-1}\frac{\eta_1}{\eta_2}E''_\mathrm{m} + \frac{A-1}{A}\bar{T}_\ell - 2\left(\frac{\eta_1}{\eta_2}\right)^{1/2}(\bar{T}_\ell E''_\mathrm{m})^{1/2}\cos\phi$	(1.39)
	$\sigma_\mathrm{n,2n}(E_\mathrm{i},T) = \int_0^{E_\mathrm{i}-U}\frac{E'_\mathrm{m}}{I(E_\mathrm{i})}\mathrm{e}^{-E'_\mathrm{m}/E_\mathrm{D}} \times \int_0^{E_\mathrm{i}-U-E'_\mathrm{m}}\frac{E''_\mathrm{m}}{I(E_\mathrm{i},E'_\mathrm{m})}\mathrm{e}^{-E''_\mathrm{m}/E_\mathrm{D}}\mathrm{d}E'_\mathrm{m}\mathrm{d}E''_\mathrm{m}$	(1.40)
(n, γ)	$\bar{T} \cong \frac{E_\gamma^2}{4(M+m)c^2}$	(1.42)
	$\sigma_{\mathrm{n},\gamma}(E_\mathrm{i}) = \sigma_0\sqrt{\frac{E_0}{E_\mathrm{i}}}\left\{\frac{1}{[(E_\mathrm{i}-E_0)/(\Gamma/2)]^2+1}\right\}$	(1.44)

Radiation-induced damage

1. The radiation damage event
   - Neutron-nucleus interaction
   - Interaction between ions and atoms
2. The displacement of Atoms
3. The damage cascade
4. Point defect formation

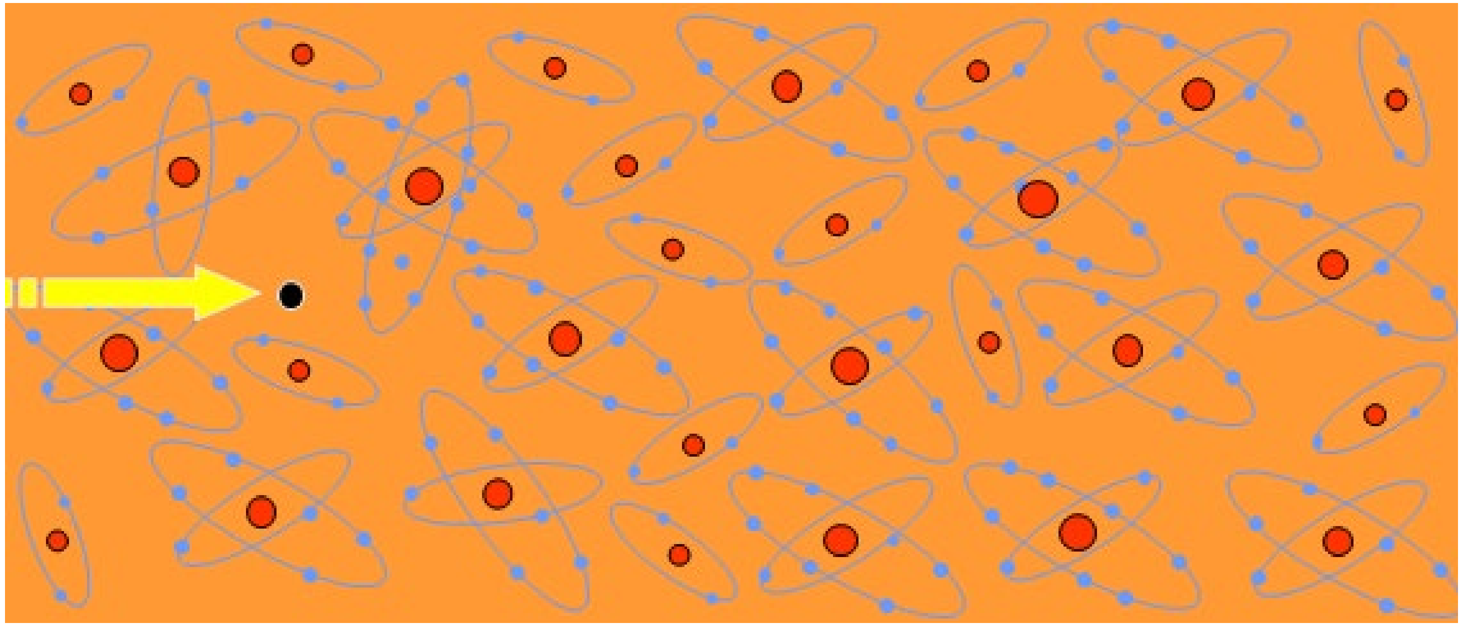
Ion irradiation

In its passage through matter, an ion may interact with:

- **THE ATOMIC ELECTRONS**

  and/or

- **THE ATOMIC NUCLEI**



Ion irradiation: stopping power S(E)

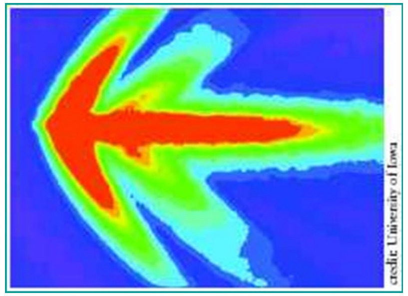
Incoming ion penetrates into the matter interacting with it and slowing down.

- **stopping power:** energy loss per unit distance traveled by the charged particle.

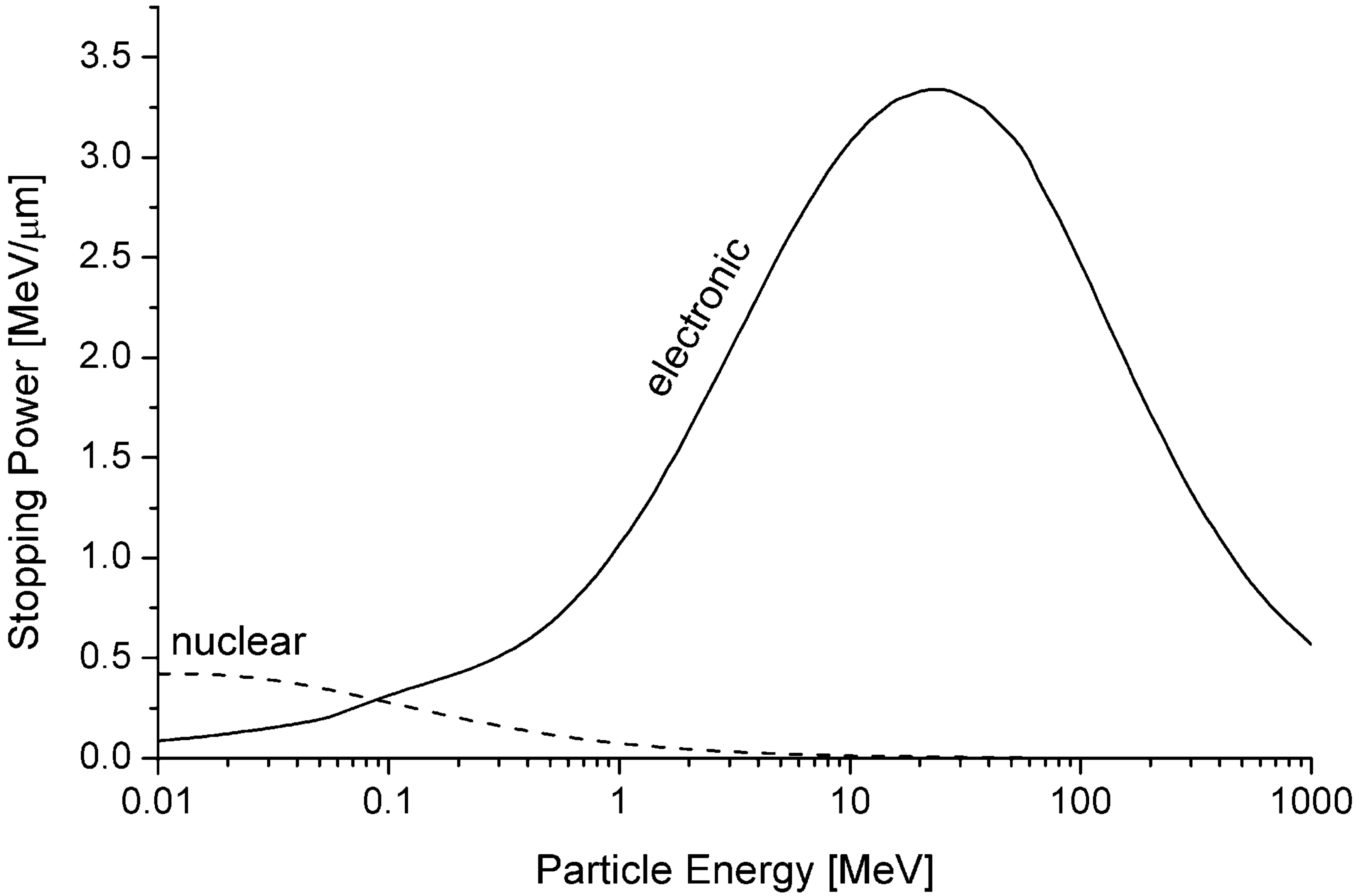
$$S(E)=\left(\frac{dE}{dx}\right)_{total}=\left(\frac{dE}{dx}\right)_{n}+\left(\frac{dE}{dx}\right)_{e}+\cancelto{0}{\left(\frac{dE}{dx}\right)_{r}}$$

  – **Nuclear stopping power, $S(E)_n$:** transfer of energy from incoming ion to target nuclei (elastic collisions)

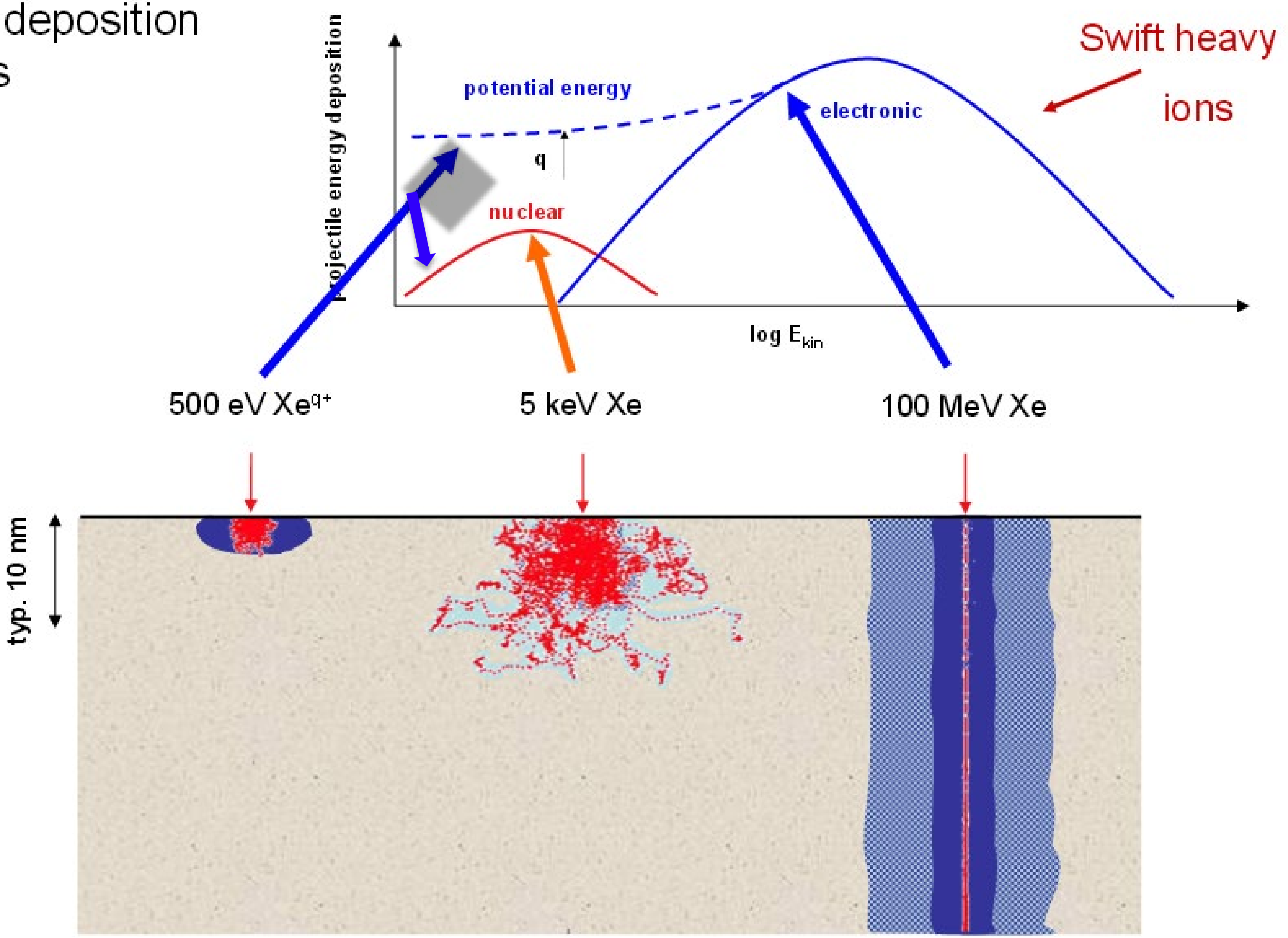
  – **Electronic stopping power, $S(E)_e$:** transfer of energy from incoming ion to the electrons of target (inelastic collisions)



Ion irradiation: stopping power *S(E)*



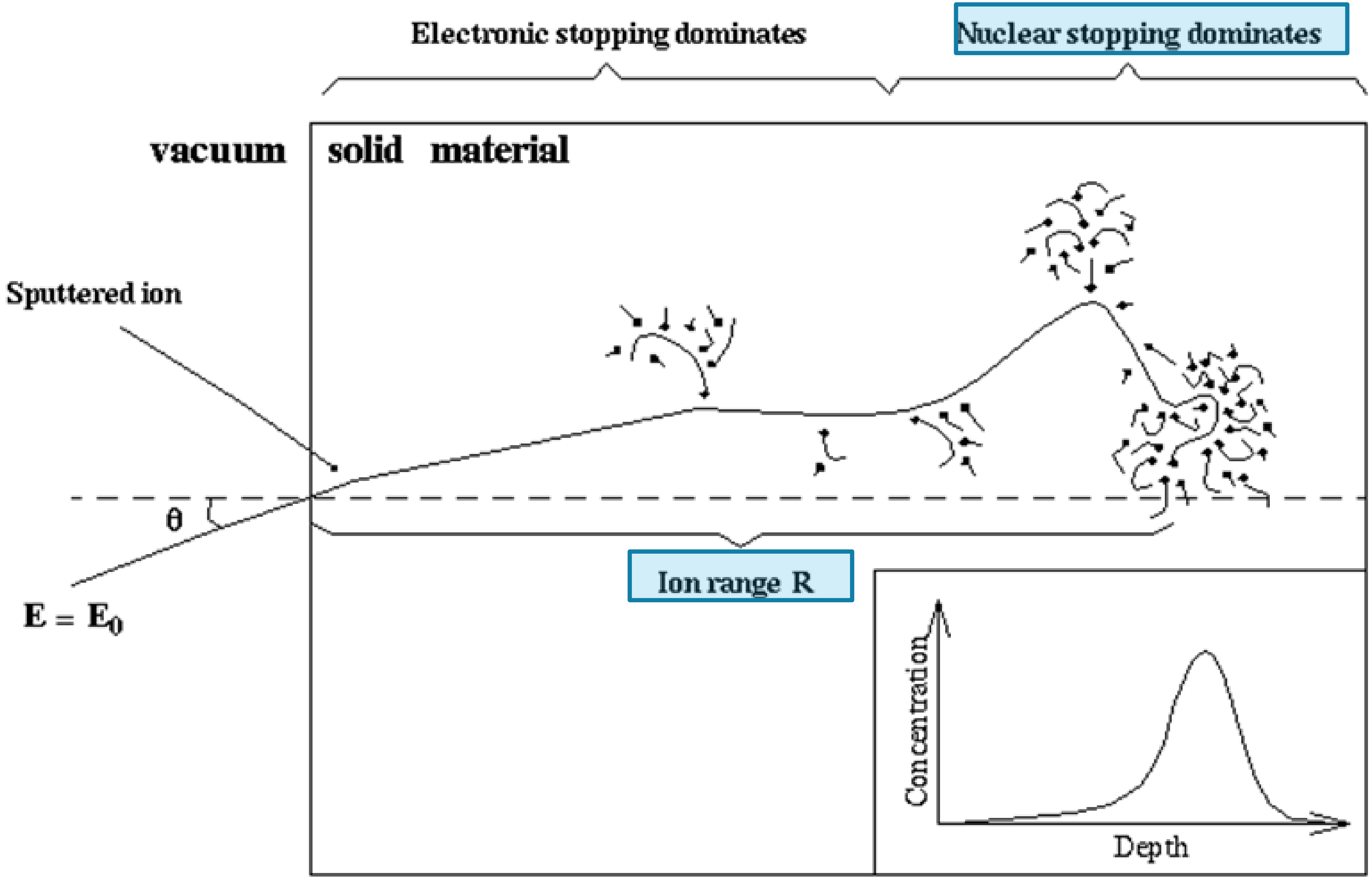
Energy deposition in solids



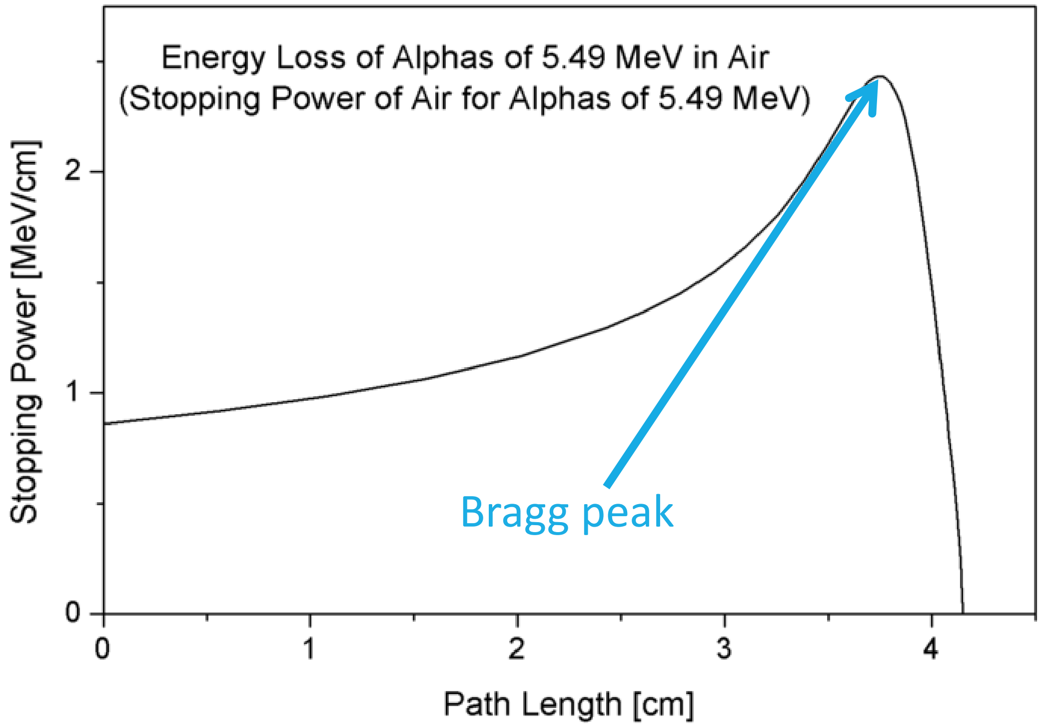
Stefan Facsko

Institute of Ion Beam Physics and Materials Research
Forschungszentrum Dresden-Rossendorf, Germany

Ion irradiation: overview of the slowing down process

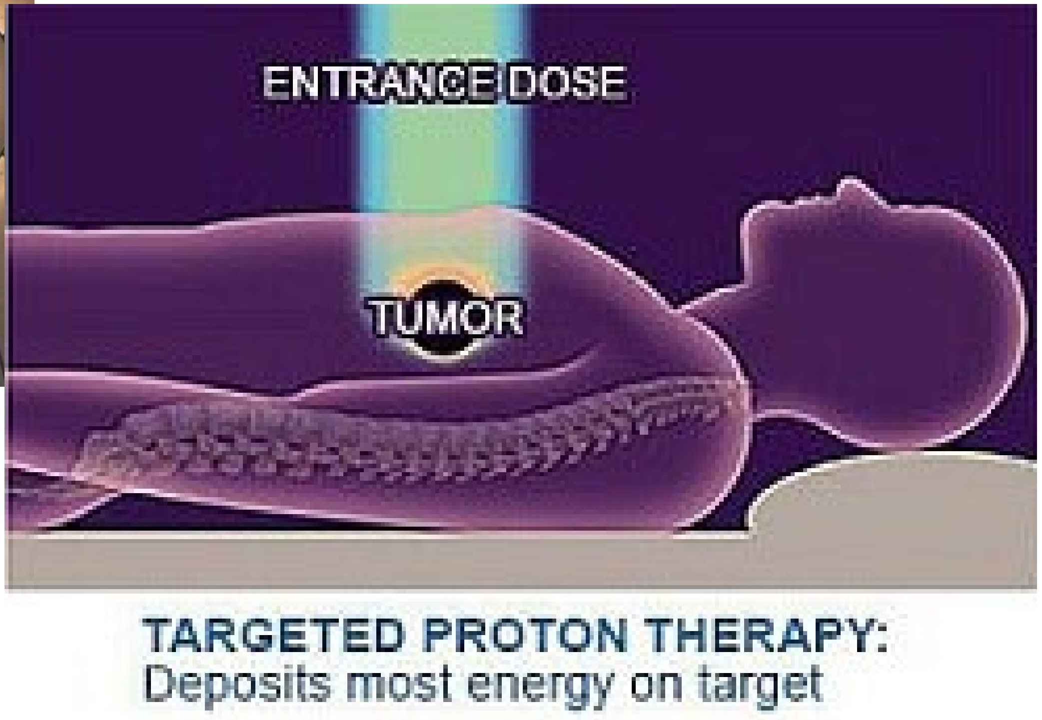


Ion irradiation: Bragg peak



- **Bragg peak occurs because the interaction cross section increases with decreasing the energy of the charged particle.**
- It occurs just before the particle comes to a complete stop because the energy lost is inversely proportional to the square of the velocity of the charged particles.

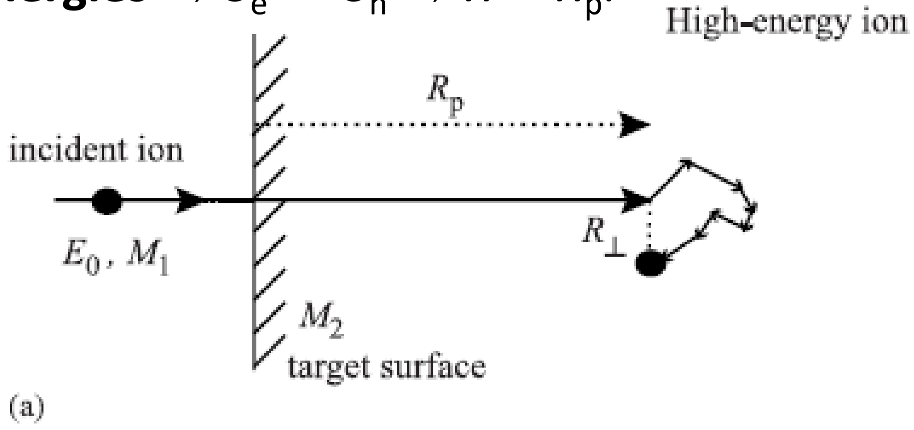
Why to measure stopping power?



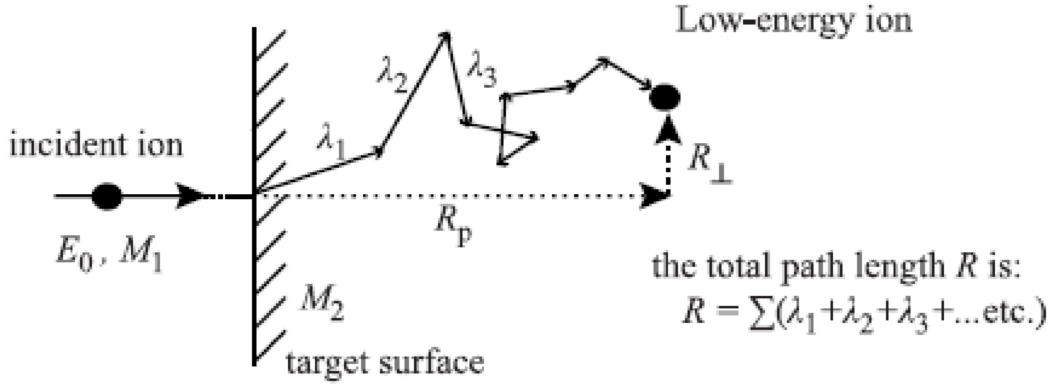
Ion irradiation: ion range

- The most interesting range quantity average projected range (R_p) and this is what is usually measured.

  - **At high energies** $\rightarrow S_e >> S_n \rightarrow R \sim R_p$.



  - **At low energies** $\rightarrow S_n \sim S_e \rightarrow R_p < R$.



Fundamentals of Radiation Materials Science: Metals and Alloys,
Gary S. Was, Springer, ISBN 978-3-540-49471-3

Ion-atom or atom/atom interaction

- These kind of collisions are governed by interactions between:
  - Electron clouds
  - Electron cloud and the nucleus
  - Nuclei.
- These interactions are described by **interatomic potentials**.
- To describe the energy transfer cross sections for interactions between atoms, we need to describe the potential function that governs that interaction.
- Unfortunately, there exists no single function that describes all interactions, but rather, the nature of the interaction is a strong function of the atom energies, and hence their distance of closest approach of their nuclei.

Summary: interatomic potentials

Table 1.3. Summary of potential functions

Potential	Equation for $V(r) =$	Range of applicability	Definitions	Eq. in text
Hard-sphere	0 for $r > r_0$; ∞ for $r < r_0$	$10^{-1} < T < 10^3$ eV	$r_0 =$ Size of atom	(1.46)
Born–Mayer	$V(r) = A\exp(-r/B)$	$10^{-1} < T < 10^3$ eV; $a_0 < r \leq r_e$	A, B determined from elastic moduli	(1.47)
Simple Coulomb	$\frac{Z_1 Z_2 \varepsilon^2}{r}$	Light ions of high energy $r \ll a_0$		(1.48)
Screened Coulomb	$\left(\frac{Z_1 Z_2 \varepsilon^2}{r}\right)\exp(-r/a)$	Light ions $R < a_0$	$a_0 =$ Bohr radius; $a =$ Screening radius	(1.49)
Brinkman I	$\frac{Z^2\varepsilon^2}{r} e^{(-r/a)}\left(1 - \frac{r}{2a}\right)$	$r < a$	$a \cong a_0/Z^{1/3}$	(1.51)
Brinkman II	$\frac{AZ_1Z_2\varepsilon^2\exp(-Br)}{1-\exp(-Ar)}$	$Z > 25$; $r < 0.7r_e$	$A = \frac{0.95\times 10^{-6}}{a_0} Z_{\text{eff}}^{7/6}$; $B = Z_{\text{eff}}^{1/3}/Ca_0$; $C \cong 1.5$	(1.52)
Firsov	$\frac{Z_1 Z_2 \varepsilon^2}{r}\chi\left[\left(Z_1^{1/2}+Z_2^{1/2}\right)^{2/3}\frac{r}{a}\right]$	$r \leq a_0$	χ is screening function	(1.56)
TFD two-center	$\frac{Z^2\varepsilon^2}{r}\chi\left(Z^{1/3}\frac{r}{a}\right) - \alpha Z + \bar{A}$	$r < r_b(3a_0)$	$r_b =$ Radius at which the electron cloud density vanishes	(1.57)
Inverse square	$\frac{2E_r}{e}(Z_1 Z_2)^{5/6}\left(\frac{a_0}{r}\right)^2$	$a/2 < r < 5a$	$E_R =$ Rydberg energy $= 13.6$eV	(1.59)

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Electrons and gammas

- Electrons *can produce Frenkel* pairs but to a much lower extend than neutrons and ions.
- Only in the case of ceramic materials when the generated electronic density is very high they can produce atom displacement by complex mechanisms (as it is the case of swift heavy ions).
- **In general we will consider them a source of energy that leads to heating of the material**

Atomistic effects: origin

- **Atomic displacements (nuclear stopping power, S_n)**
  - Dominant damage processes in metals
  - Significant for semiconductors, ceramics and polymers
  - Units- displacement per atom, dpa
- **Ionization and excitation (electronic stopping power, S_e)**
  - Generally negligible for metals
  - Important for polymers, ceramics and semiconductors
  - Units- Gray, Gy, absorbed dose 1 J / Kg.
- **Transmutation reactions**
  - Products of transmutation, especially isotopes of H, He and neutron-induced reactions
  - Units appm / dpa

Radiation-induced damage

1. The radiation damage event
   - Neutron-nucleus interaction
   - Interaction between ions and atoms

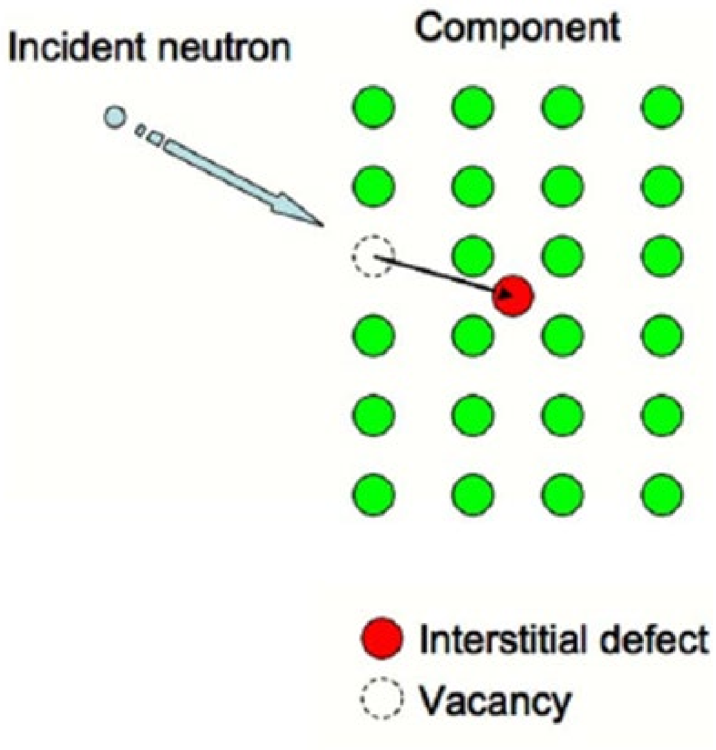
2. The displacement of Atoms

3. The damage cascade

4. Point defect formation

Displacement of atoms: ions and neutrons

- When the energy of the incoming particle (radiation) is high enough, above a certain threshold, it will produce atomic displacements leading to Frenkel pair formation (vancy-interstitial).



Cortesía de M. J. Caturla

SIAs

Vs

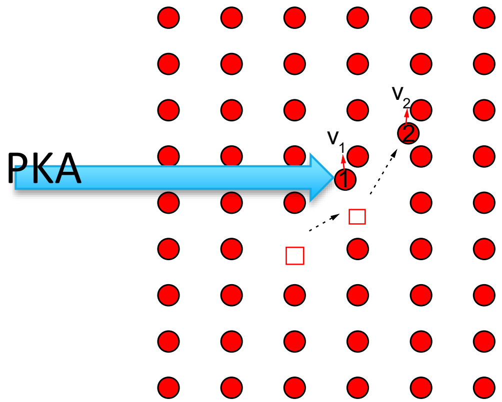
Displacement cascade damage from movement of Si atom after primary collision

The displacements of atoms: definitions

- **Primary knock-on atom (PKA):** is the first atom that an incident particle encounters in the target. After it is displaced from its initial lattice site, the PKA can induce the subsequent lattice site displacements of other atoms if it has sufficient energy, or come to rest in the lattice at an interstitial site if it does not.

- **Collision cascade**: is a spatial cluster of lattice vacancies and atoms residing as interstitials in a localized region of the lattice.

The initiation of the displacement cascade



Collision cascade

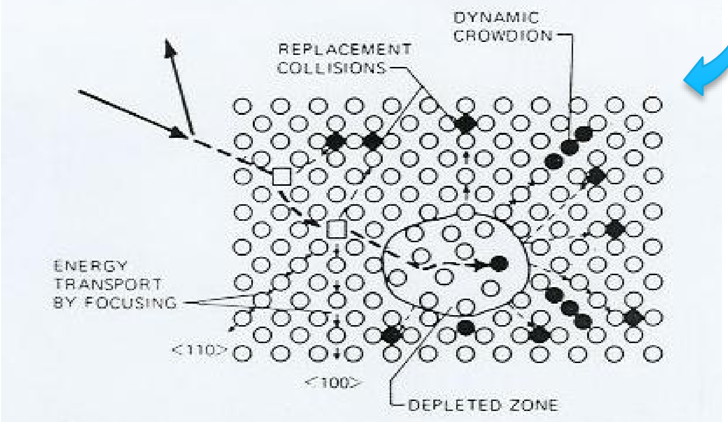


Fig. 17.25 Later version (still qualitative) of the displacement spike. □, vacancy. ●, interstitial atom. ——, path of neutron. - - -, path of PKA. (After Ref. 28.)

Seeger (1958)

Displacement per atom (dpa)

- ***1 dpa*** **means that each atom has displaced once** (on average).
  - Fusion: The half-life time of a PFM is ~ 100 dpa.

- A way to quantify radiation damage in a highly questionable and unreliable way.

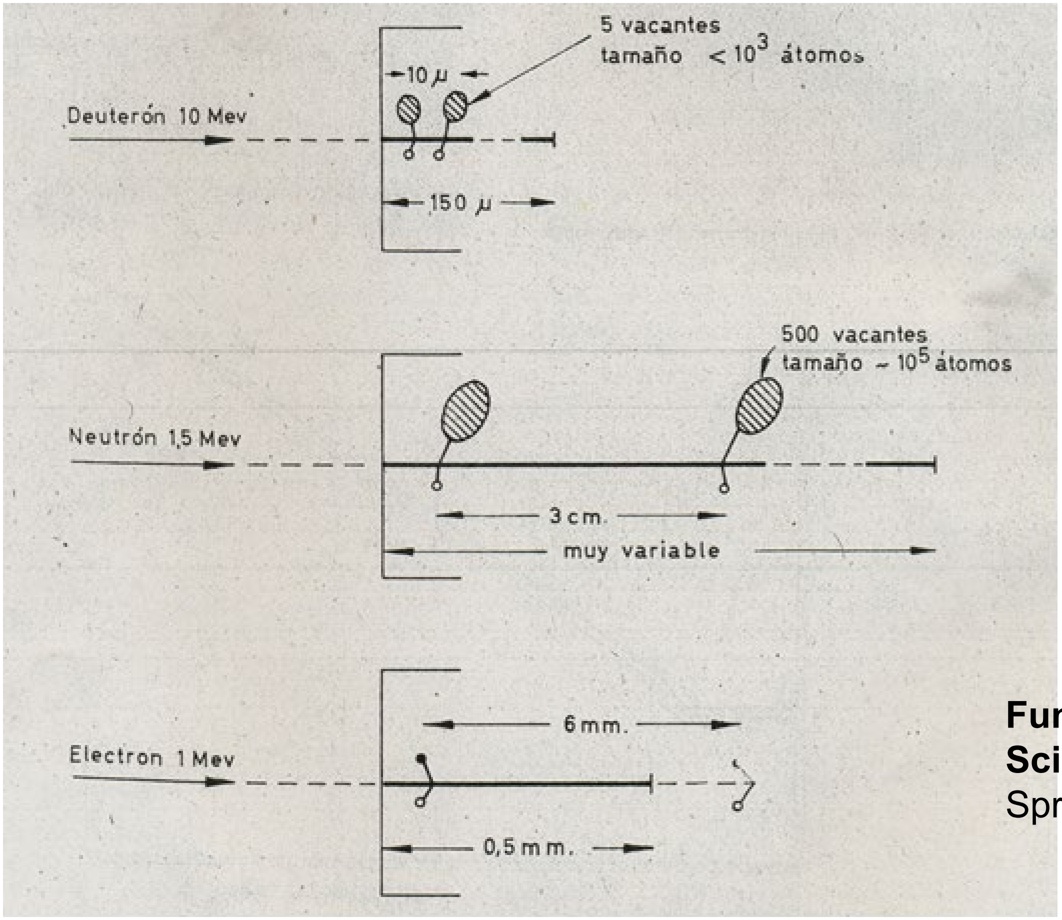
- Ignore dose rate and cascade overlap

- Stongly dependent on material

Characteristic of radiation-induced damage

- **Very important**. For similar projectile energies, The averaged energy transferred by neutrons is larger than that transferred by ions. Therefore, neutrons generate dispersed PKA, but each PKA generates a high concentration of defects (dense cascade).

Cu irradiated with:



Fundamentals of Radiation Materials Science: Metals and Alloys, Gary S. Was, Springer, ISBN 978-3-540-49471-3

But do all the created Frenkel pairs survive?

Stages of Cascade Development

- The final state of the cascade is extremely important because the end of the cascade is the starting point for defect diffusion, agglomeration and destruction that forms the basis for the observable effects of irradiation

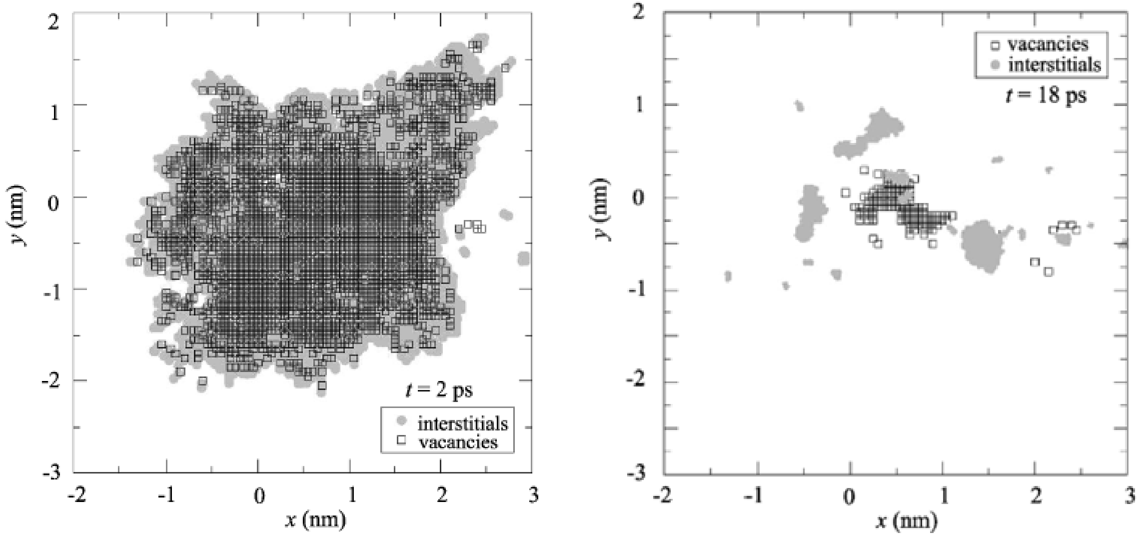
- Cascades evolve in stages given as follows:

1. **Collisional** (<1 ps)
2. **Thermal spike** (~ 0.1 ps)
3. **Quenching** (~ 10 ps)

   Not all the created Frenkel pairs survive

4. **Annealing** (ns-months**)**

End of the quench phase is completed within ~ 10ps of the initial collision event.



MD simulation of a 30keV displacement cascade in Cu at 300K at 2ps and 18ps into the collision (calculations performed at the Barcelona Supercomputer center, courtesy of M. Catula and Tomas Diaz de la Rubia)

Radiation-induced damage: time scale

Cascade Creation

10^{-13} s

↓

Unstable Matrix

10^{-11} s

↓

Interstitial Diffusion

10^{-6} s

↓

Vacancy Diffusion

10^{0} s

↓

Microstructural evolution

10^{6} s

Radiation-induced damage

1. The radiation damage event
   - Neutron-nucleus interaction
   - Interaction between ions and atoms

2. The displacement of Atoms

3. The damage cascade

4. Stable defects

Stable defects

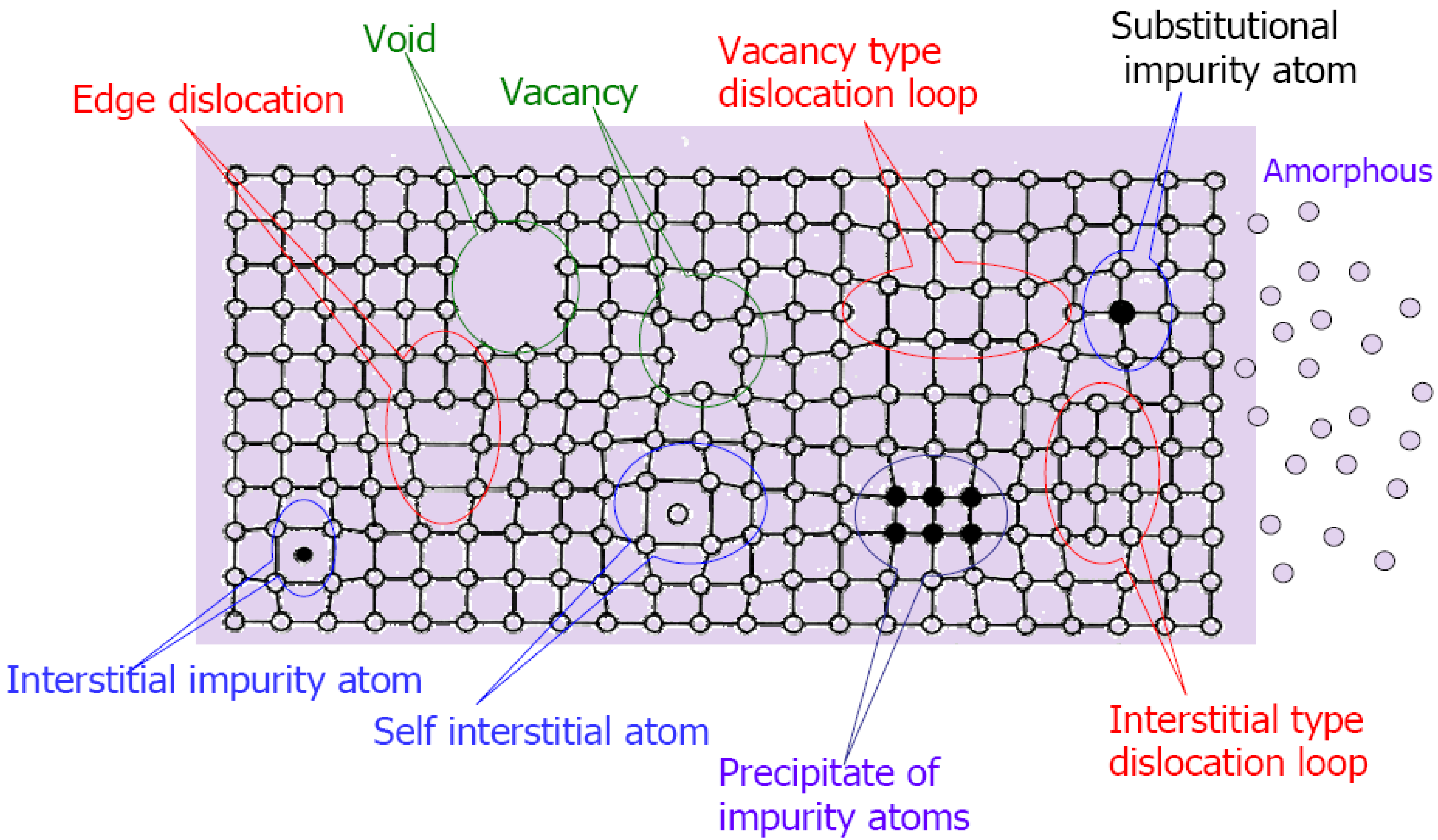
- When Frenkel pairs do not anneal (vancancy-interstial recombination) defects are generated in the material.

- These vacancies and interstitials form the foundation for all observed effects of irradiation on the physical properties of materials.

- Various types of defects exist in any crystalline lattice. These include:
  - **Point defects (0D)**: vacancies and interstitials
  - **Line defects (1D):** dislocation lines
  - **Planar defects (2D):** dislocation loops
  - **Volume defects (3D):** voids, bubbles, stacking fault tetrahedra

- Moreover, the defects generation by light ions (He, H, D) and the generation of transmutation products (neutron irradiation) is critical.

Radiation-induced damage



Summarizing

Time (s)	Event	Result
10^{-18}	Energy transfer from incident particle	Primary knock-on atom created
10^{-13}	Displacement of lattice atoms by PKA	Local melting, displacement cascade
10^{-11}	Energy dissipation, spontaneous recombination, clustering	Stable *Frenkel pairs*
$>10^{-8}$	Thermal migration of defects	Recombination, clustering, trapping

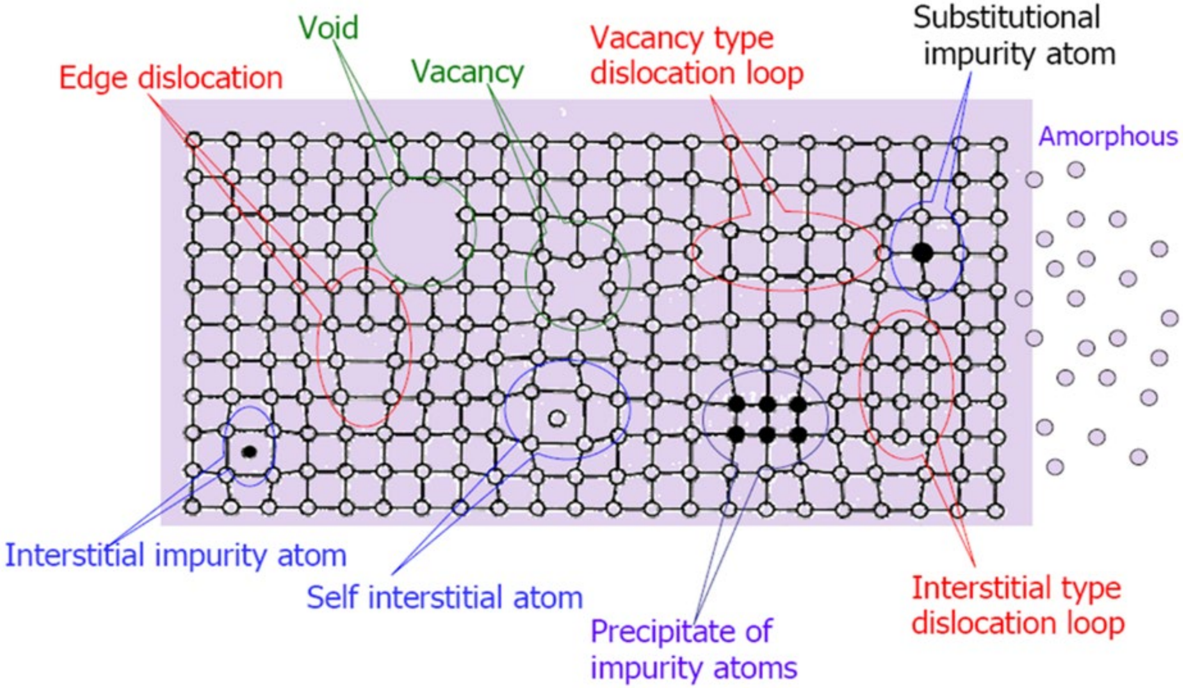
Fundamentals of Radiation Materials Science: Metals and Alloys, Gary S. Was, Springer, ISBN 978-3-540-49471-3

PartII: macroscopic effects

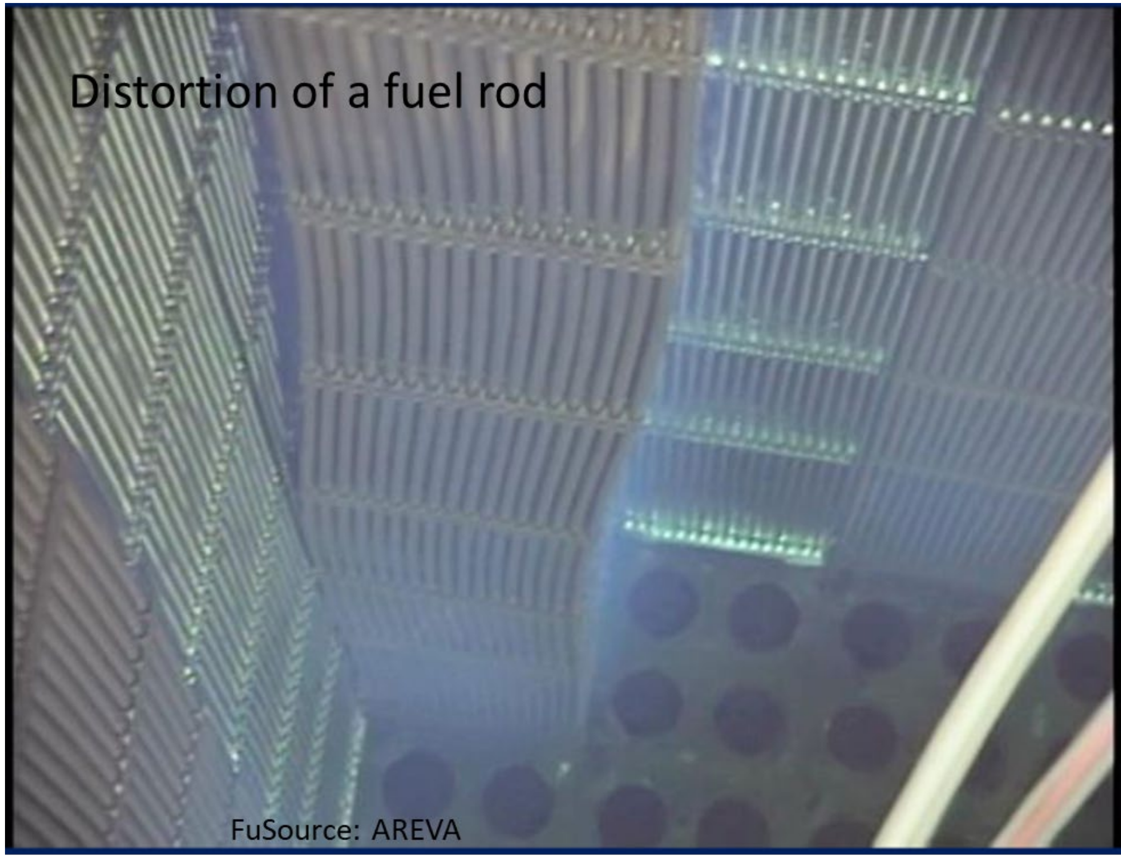
Objectives

- Relate the microscopic defects with modification in the materials (macroscopic) properties:
  - Elemental composition
  - Dimensional instabilities
    - Swelling
    - Creep
  - Thermal conductivity
  - Electrical conductivity
  - Mechanical properties
  - Optical properties

Objectives



Void
Edge dislocation
Vacancy
Vacancy type
dislocation loop
Substitutional
impurity atom
Amorphous
Interstitial impurity atom
Self interstitial atom
Precipitate of
impurity atoms
Interstitial type
dislocation loop



Distortion of a fuel rod
FuSource: AREVA

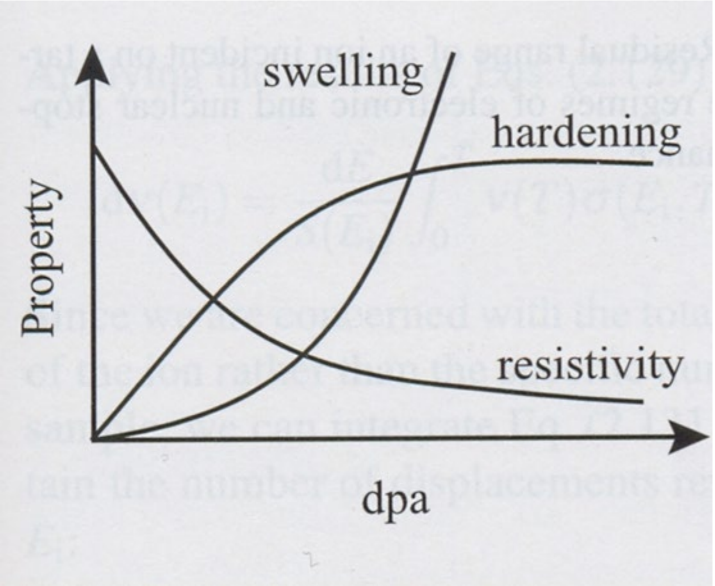
Origin of radiation effects in materials

Elemental composition

- Transmutation

Chemical composition:

- Diffusion (Formation of new chemical phase
- Segregation



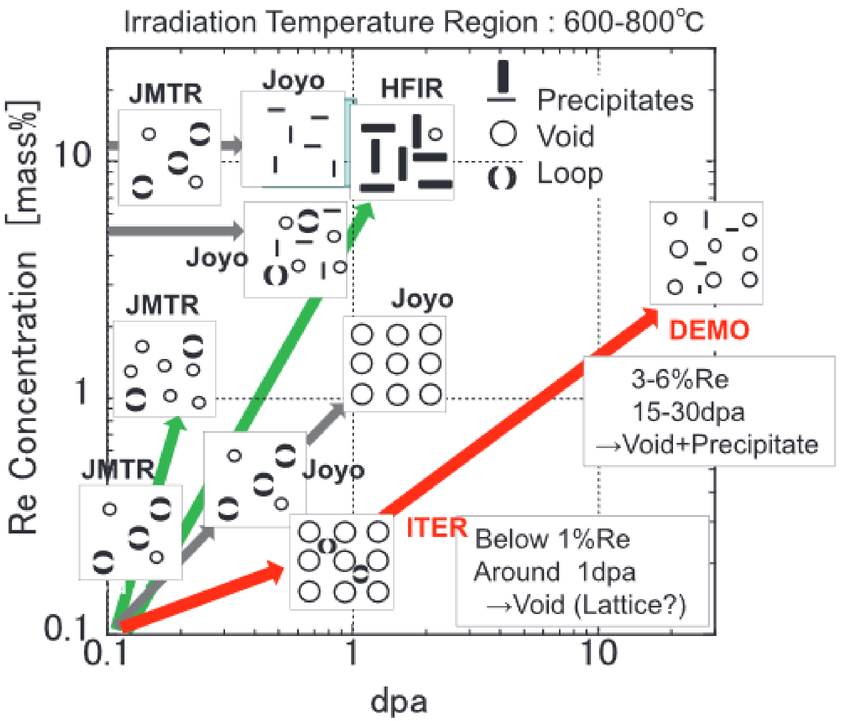
Dimensions:

- Volume change: swelling
- Shape change: creep, fuzz

Physical properties:

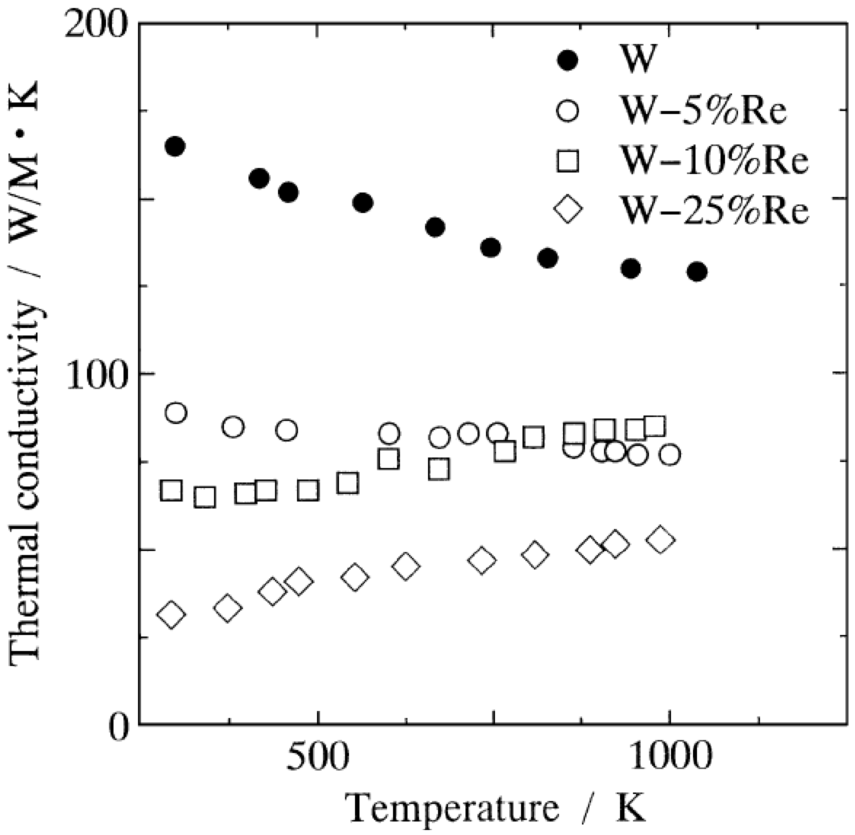
- Decease in the electrical conductivity (low temperatures)
- Decrease in the thermal conductivity (ceramic materials)

Transmutation: changes in the elemental composition



Y. Ueda *et al.* Nucl. Fusion 57 (2017) 092006

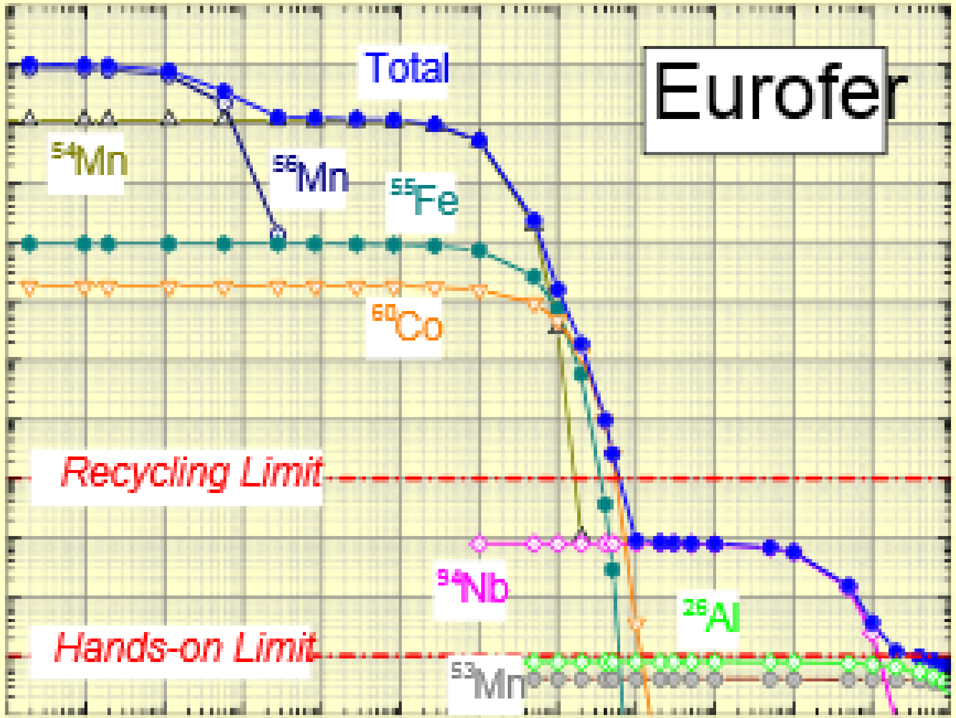
- Thermal conductivity
- Mechanical properties



T. Tanabe *et al.* Materials Letters 57 (2003) 2950–2953

Transmutation reactions: safety

- EUROFER 97:
- Recycling dose rate level of 10 mSv/h is achieved after 50-100 years
- Hands-on dose rate level of 10 μSv/h is achieved after 10^5 years

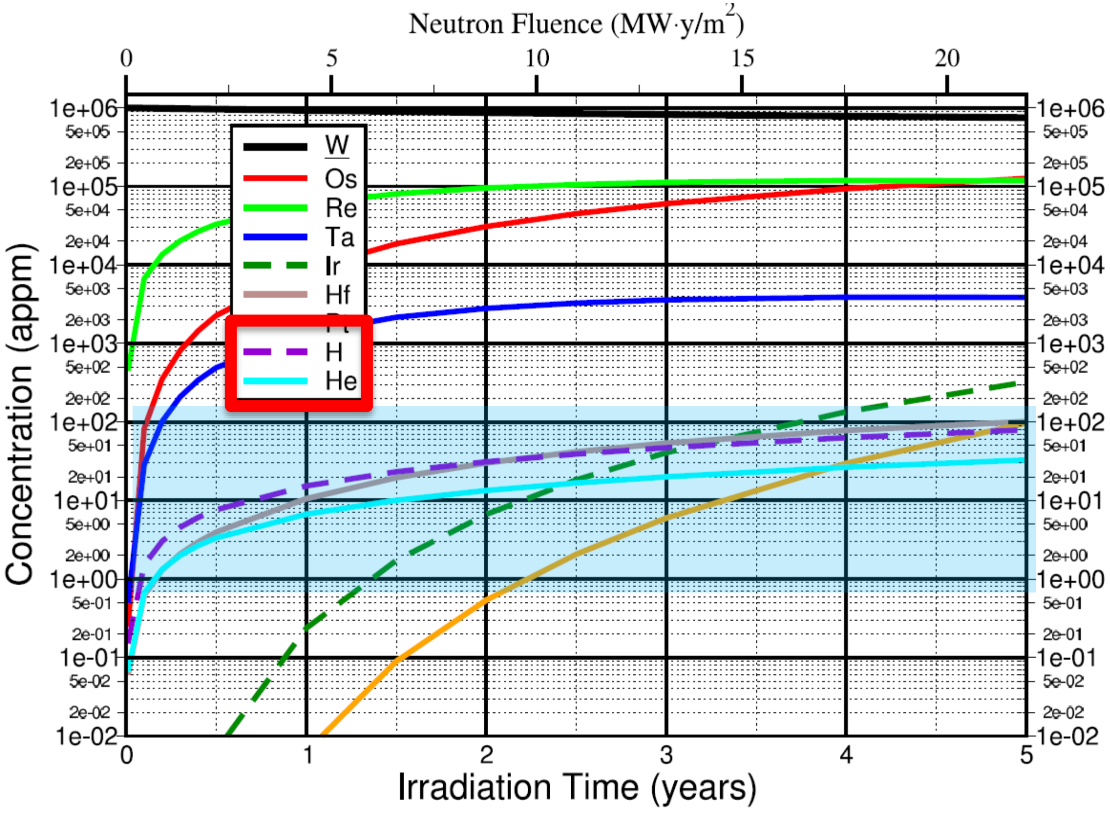


U. Fischer and S.P. Simakov, June 2003

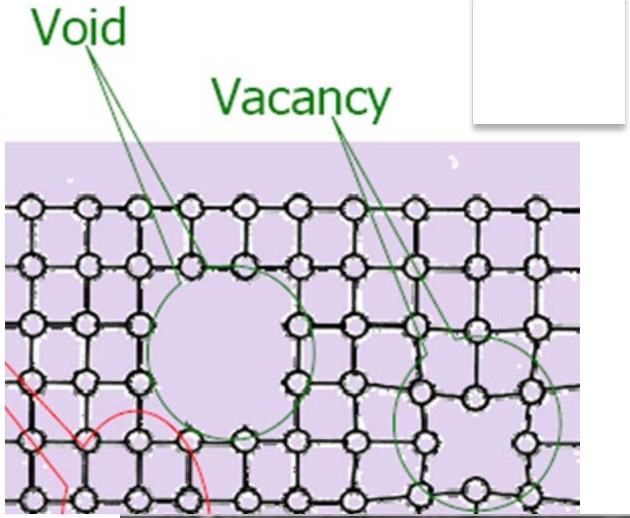
- Assumptions:
- HCLL PPCS reactor model B
- Fusion power: 3300 MW
- First wall made of EUROFER 97
- Neutron flux: 1.53×10^{15} $cm^{-2}.s^{-1}$
- 5 full power year irradiation

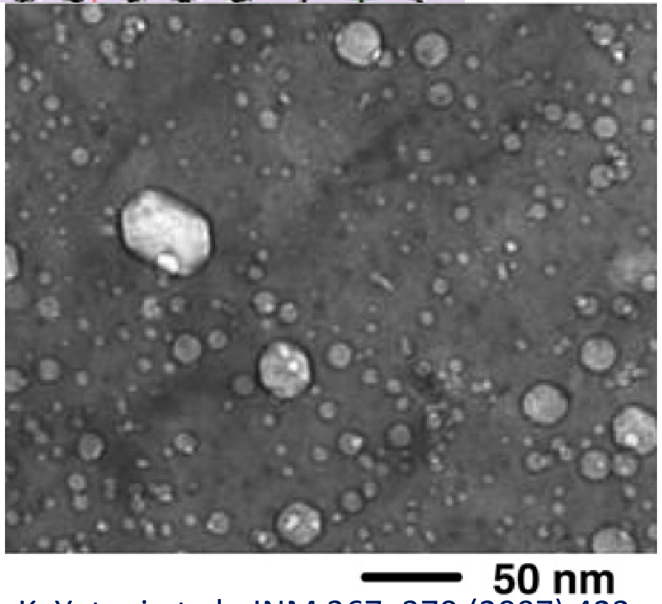
Transmutation reactions: He and H production

W irradiated with neutrons



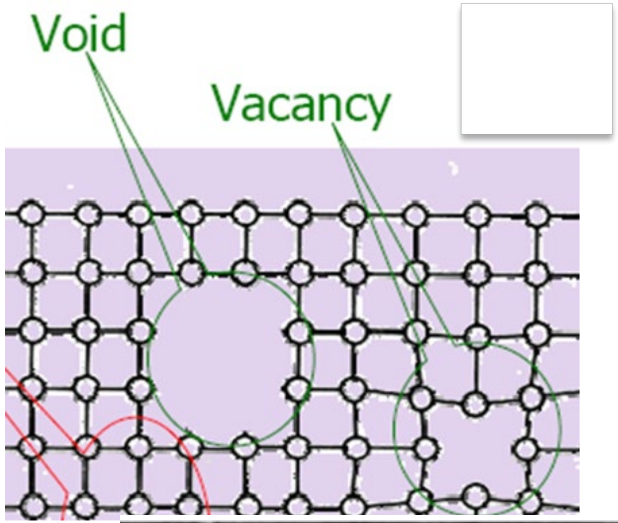
M.R.Gilbert. Transmutation and He Production in W and W-alloys

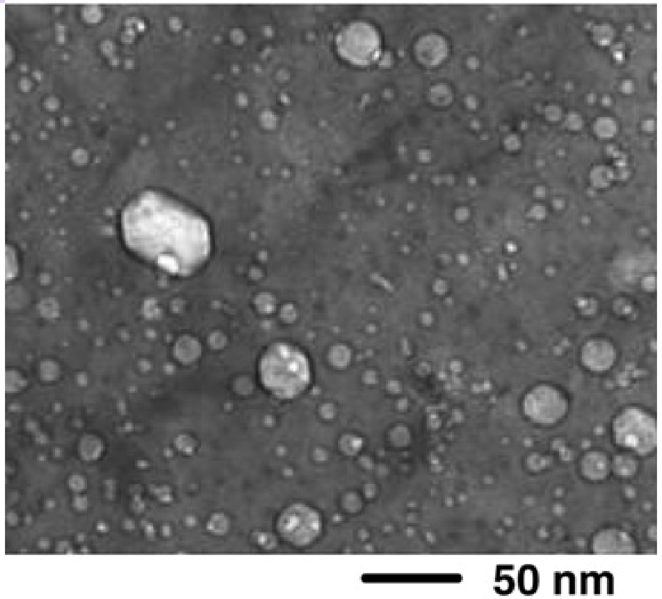




K. Yutani et al. JNM 367–370 (2007) 423

Transmutation reactions: He and H production





K. Yutani et al. JNM 367–370 (2007) 423

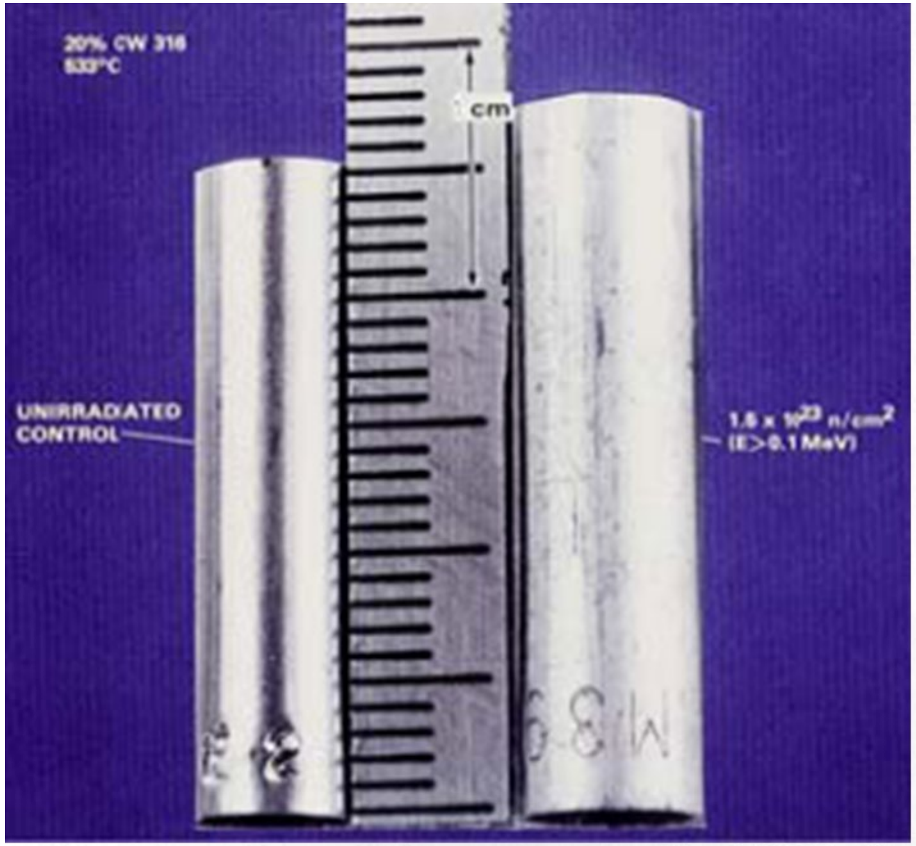


Figure 6-24. Easily observed swelling ($\approx 10\%$ linear, $\approx 33\%$ volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or ≈ 75 dpa at 510 °C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

Garner, Ch. 6. Irradiation Performance of Cladding and Structural Steels in Liquid Metals Reactors, of Nuclear Materials part 1, Vol 10 A, Published by VCH, Germany

Neutron irradiation: transmutation reactions

Important issues:

1. Radioactive nuclei are produced with very different decay times $\rightarrow$ safety
2. Transmuted nucleus $\rightarrow$ changes in the elemental composition of the material$\rightarrow$ change in material properties
3. He and H accumulation inside the material $\rightarrow$ swelling

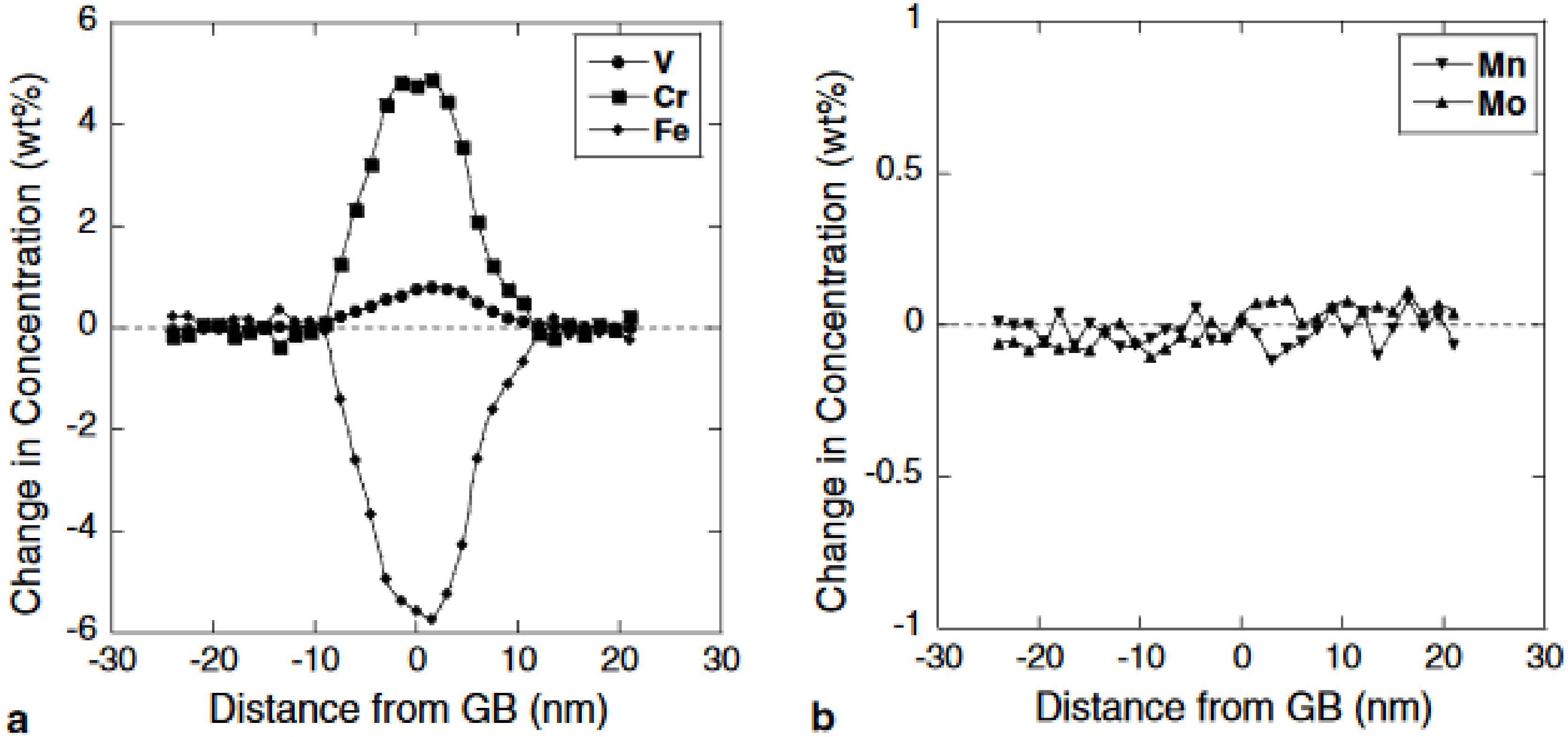
Radiation-induced segregation (RIS)

Composition of T91 Heats A and B in wt%

Heat	Cr	Mo	Mn	V	Nb	Ni	Si	Cu	C	P	Al	S	N	Fe
A[a]	8.13	0.98	0.43	0.24	0.24	0.22	0.27	0.16	0.09	0.09	0.015	<0.01	<0.005	Bal.
B[b]	8.37	0.90	0.45	0.216	0.076	0.21	0.28	0.17	0.10	0.009	0.022	0.003	0.048	Bal.

[a] Normalization: 1038 °C, 1 h; temperature: 740 °C, 45 min [2].
[b] Normalization: 1066 °C, 46 min – air cooled; temperature: 790 °C, 42 min – air cooled.

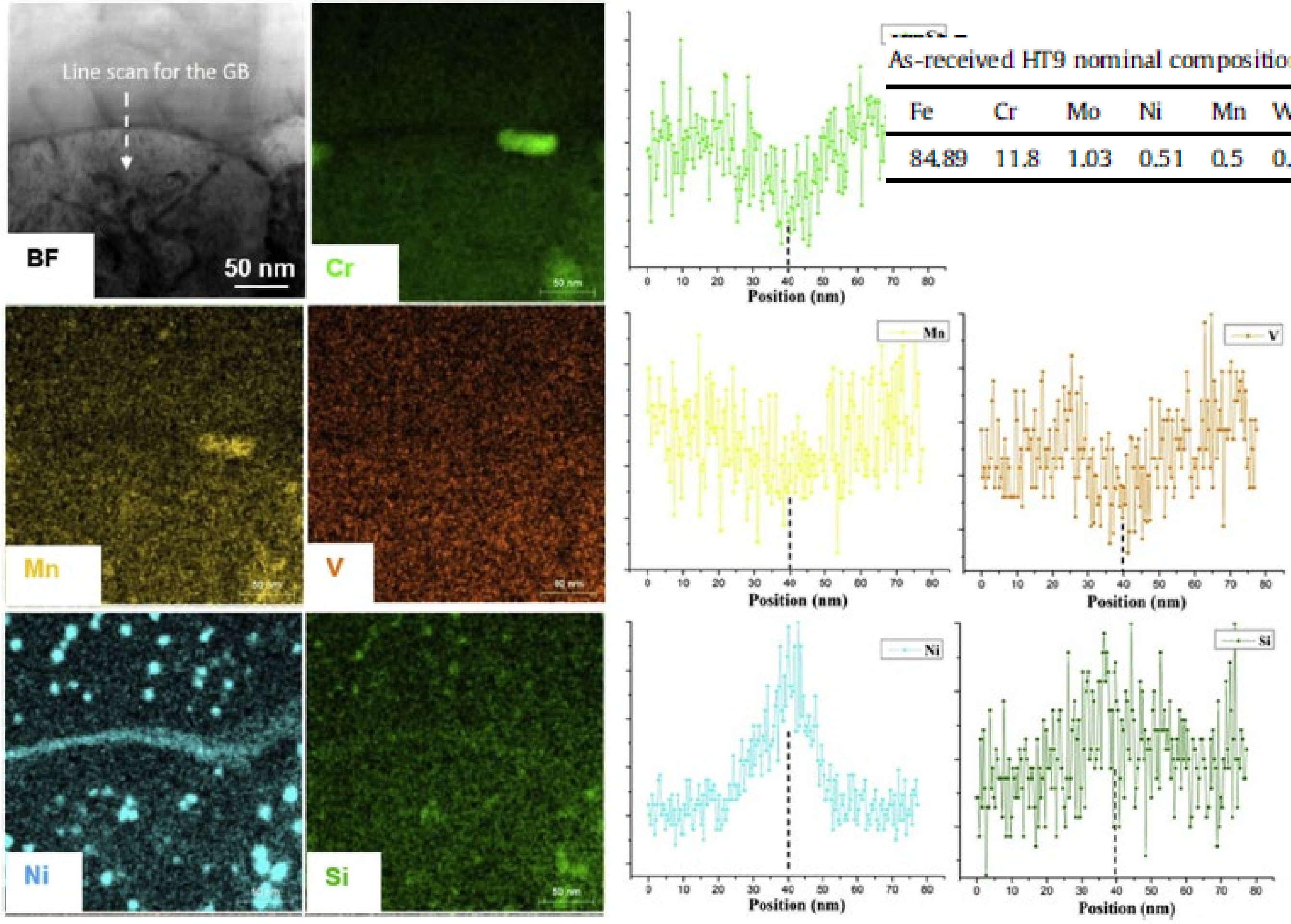
RIS after irradiation to 10 dpa at 450°C with 2.0 MeV protons



G. Gupta *et al.* Journal of Nuclear Materials 351 (2006) 162–173

Precipitate formation

HT9 irradiated with 5 MeV Fe to 20 dpa at 420ºC



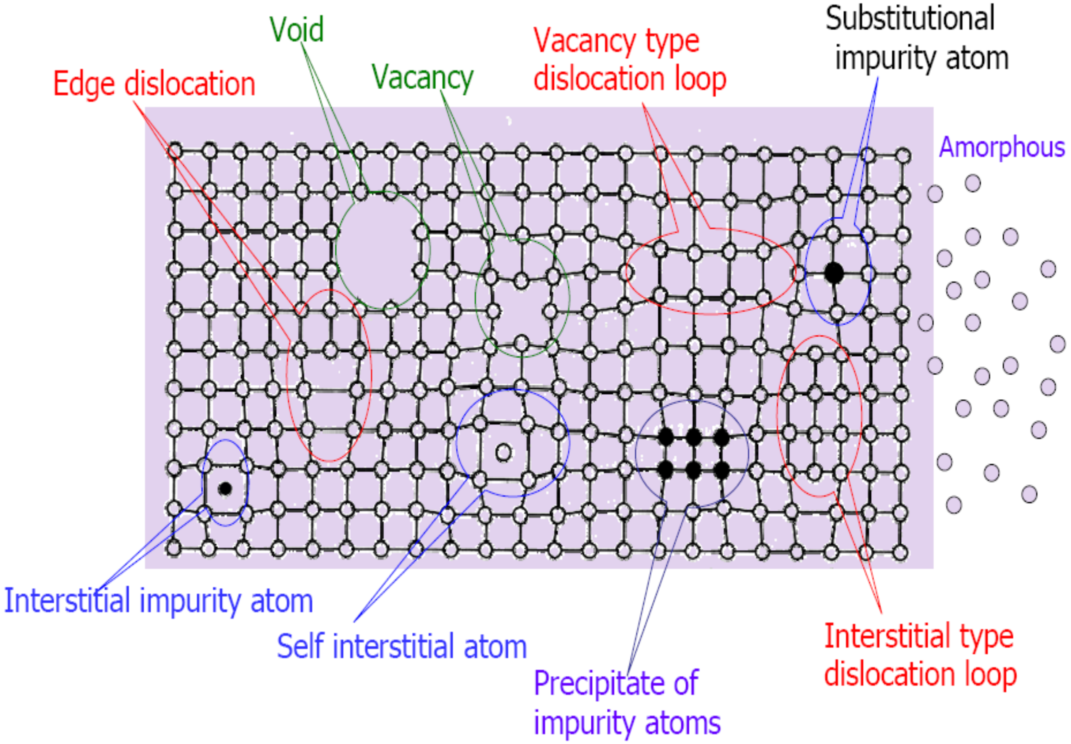
As-received HT9 nominal composition (wt.%).

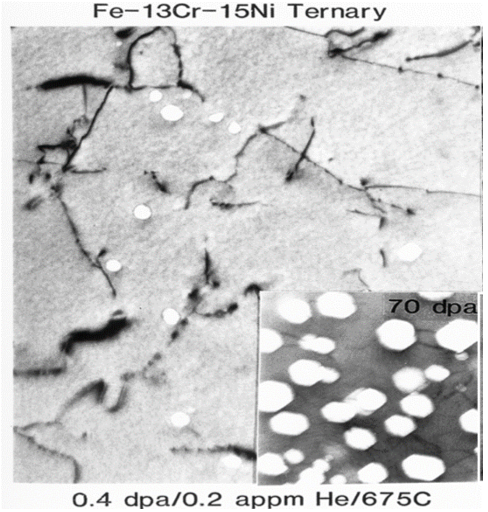
Fe	Cr	Mo	Ni	Mn	W	V	Si	C	N	P	S
84.89	11.8	1.03	0.51	0.5	0.5	0.33	0.21	0.21	0.01	0.008	0.003

C. Zheng *et al.* Journal of Nuclear Materials 491 (2017) 162-176

Swelling

Light species (H-isotopes and He) occupying cavities





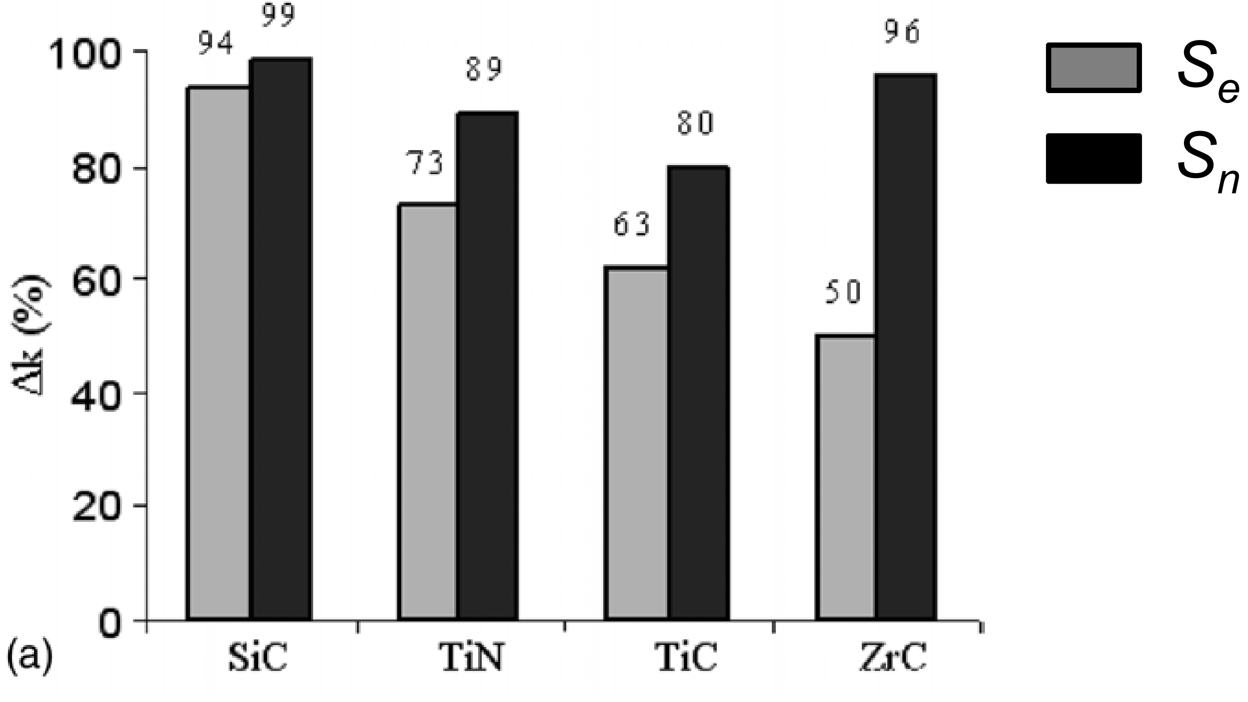
H. Lee et al. Phil Mag. A 61 (1990) 733

Figure 6-24. Easily observed swelling (≈10% linear, ≈33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or ≈75 dpa at 510 °C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

Thermal conductivity

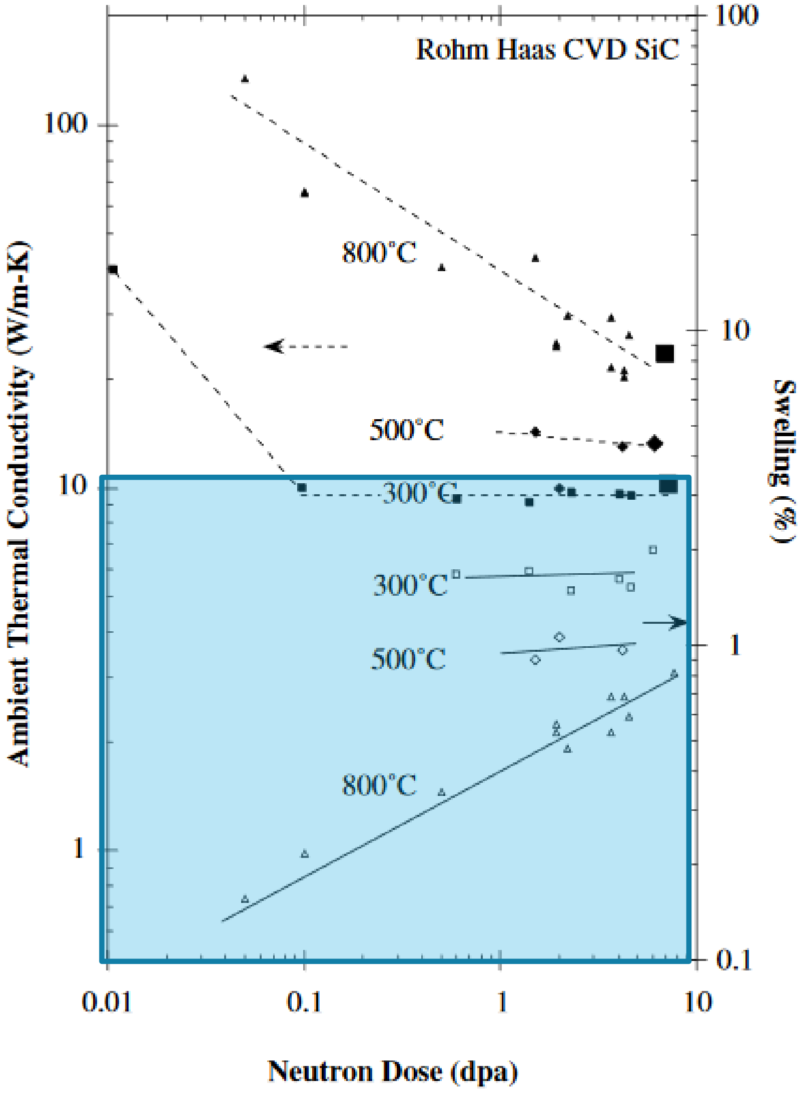
- Radiation decrease the thermal conductivity because points defects act as:
  - phonon scattering centres.
  - e^- scattering centres

25.8 MeV krypton, $10^{20} m^{-2}$, 1.77×10^{15} m^{-2} s^{-1}



L. David *et al.*, J. Phys. D: Appl. Phys. 41 (2008) 035502

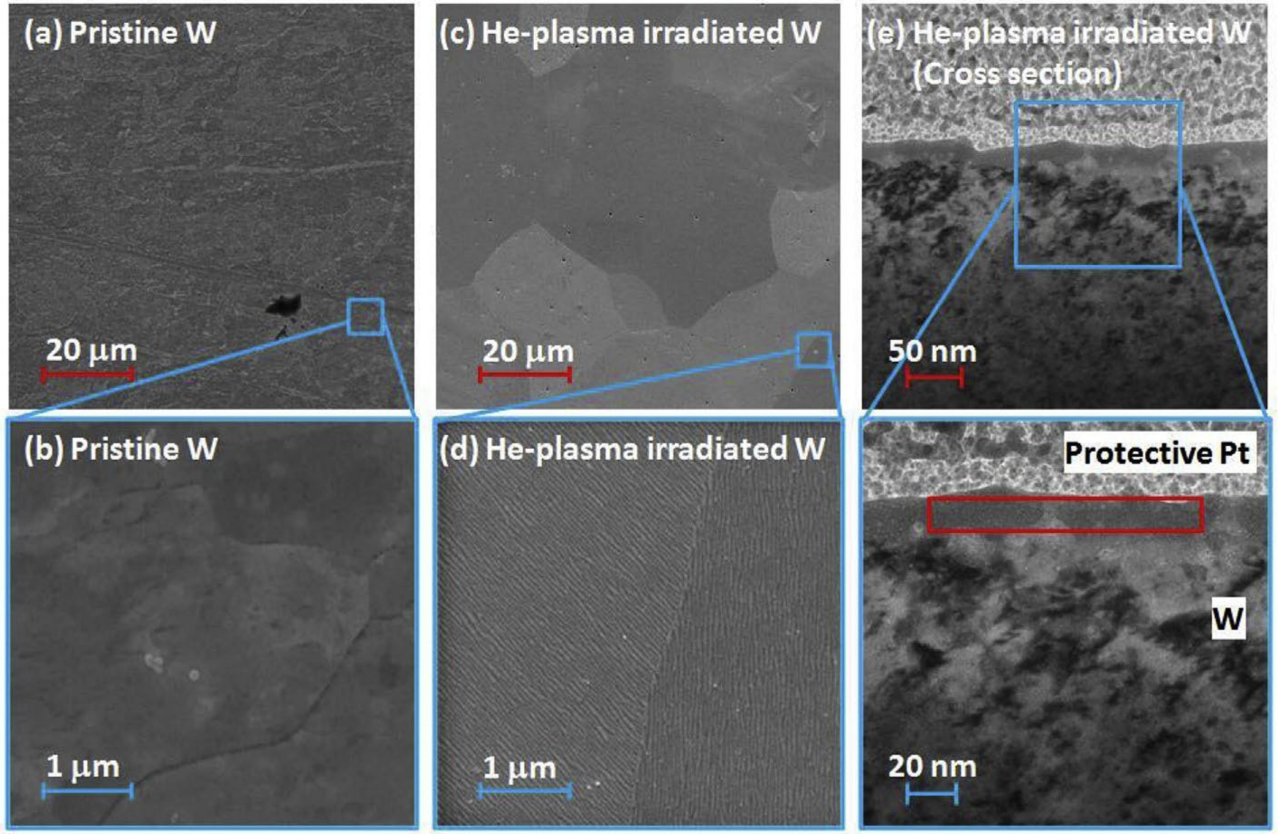
Thermal conductivity

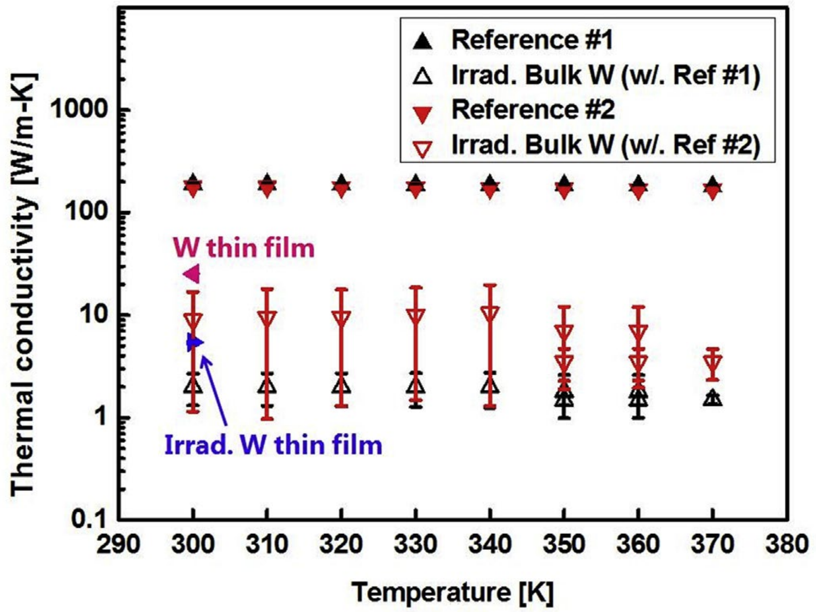


L.L. Snead *et al.* Journal of Nuclear Materials 329–333 (2004) 524–529

Thermal conductivity

He plasma irradiation: 60 eV, 1 x10^{26} m^{-2} sample temperature of 773 K





S. Cui *et al.* Journal of Nuclear Materials 486 (2017) 267e273

Radiation induced conductivity (RIC)

- RIC depends on:
  - Dose
  - Temperature

Table 1
Properties of materials studied

Material	Supplier	Processing	Density (g/cc)	Room temp. electrical conductivity $(\Omega m)^{-1}$
CVD SiC	Thermoelectron	Chemically vapor deposited (CVD)	3.1	162.0
Alpha SiC	Carborundum (Hexoloy)	Pressureless sintered	3.1	1.32×10^{-4}
Beta SiC	Kyocera (SC-221)	Hot pressed	3.0	Unknown
SiC fiber	Nippon Carbon (Nicalon)	Polymer precursor continuous fiber	2.6	1×10^{-1}

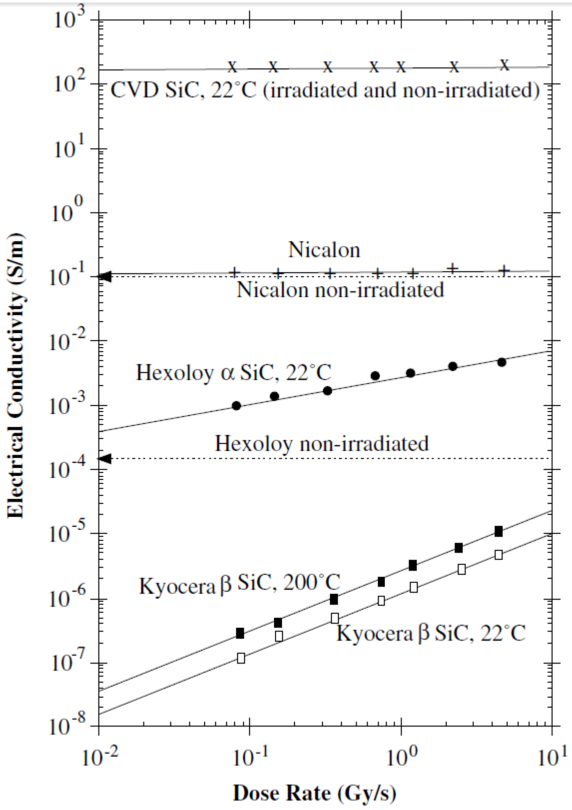


Fig. 1. Radiation enhanced conductivity of select monolithic SiC.

L.L. Snead *et al.* Journal of Nuclear Materials 329–333 (2004) 524–529

Conclusions

- The study of materials under irradiation is very important for diverse applications.

- The development of more radiation resistant materials is crucial for improving device performance.

Do you want to join our comunity?

Nuclear fusion teaching activities


El Máster tiene como principal objetivo la capacitación para el desarrollo de las metodologías de simulación, diseño y análisis avanzado, necesarios en la investigación y el trabajo profesional, en el área de la ciencia y la tecnología nuclear, esto es, de los reactores de fisión y de fusión nuclear, incluyendo aspectos de sus ciclos de combustible y de seguridad. El programa recoge tanto los contenidos básicos disciplinares, como los de desarrollo tecnológico en las diferentes áreas que dicho objetivo comprende.

El campo nuclear es especialmente activo en su contenido investigador, ya que incluye actividades, metodologías y sistemas en continuo desarrollo. Los aspectos científicos y tecnológicos son fundamentales para el futuro de las aplicaciones energéticas e industriales de la energía nuclear de fisión y de fusión, en las que existen numerosas líneas abiertas de investigación y desarrollo tecnológico, sobre distintos conceptos innovadores. Por ello, las materias que se incluyen en el Máster son las que se consideran necesarias para investigar y trabajar profesionalmente en:

- El desarrollo de reactores avanzados de fisión nuclear, con requisitos nuevos de sistemas de seguridad pasiva, combustible no-proliferante, de quemado de actínidos y de transmutación de residuos radiactivos, además de los de alta temperatura con aplicaciones industriales como la producción de hidrógeno.
- Desarrollo de sistemas de fusión nuclear, en sus versiones de confinamiento magnético e inercial, junto a las metodologías para su simulación numérica.
- Aceleradores de partículas y su utilización en la investigación física, y sus aplicaciones en la medicina e industria.

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Máster Universitario Ciencia y Tecnología Nuclear

Simulación de un núcleo PWR con COBAYA3 (código propio)

Simulación de un blanco de fusión por confinamiento inercial con ARWEN (código propio)

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Nuclear fusion teaching activities

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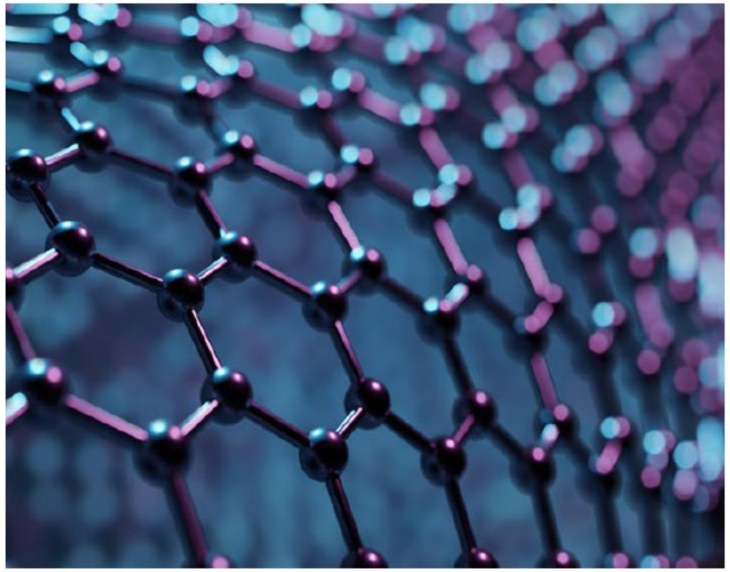

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Nanostructured W film

Upsala Glacier

Thank you for your attention