NONLINEAR EFFECTS IN MATERIALS UNDER IRRADIATION

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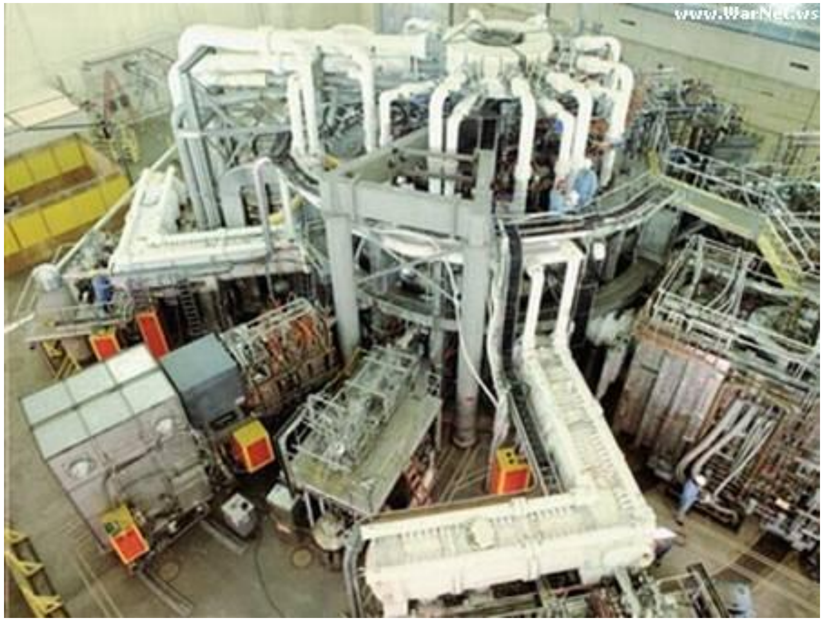
Materials under irradiation

Problems of the radiation materials science are of both fundamental and technological importance in the fields of nuclear materials, space applications, nanotechnologies, modification of the material properties and so on.



- **All properties of material are changed under irradiation**

Mechanical, Thermal, Electric, Magnetic and so on

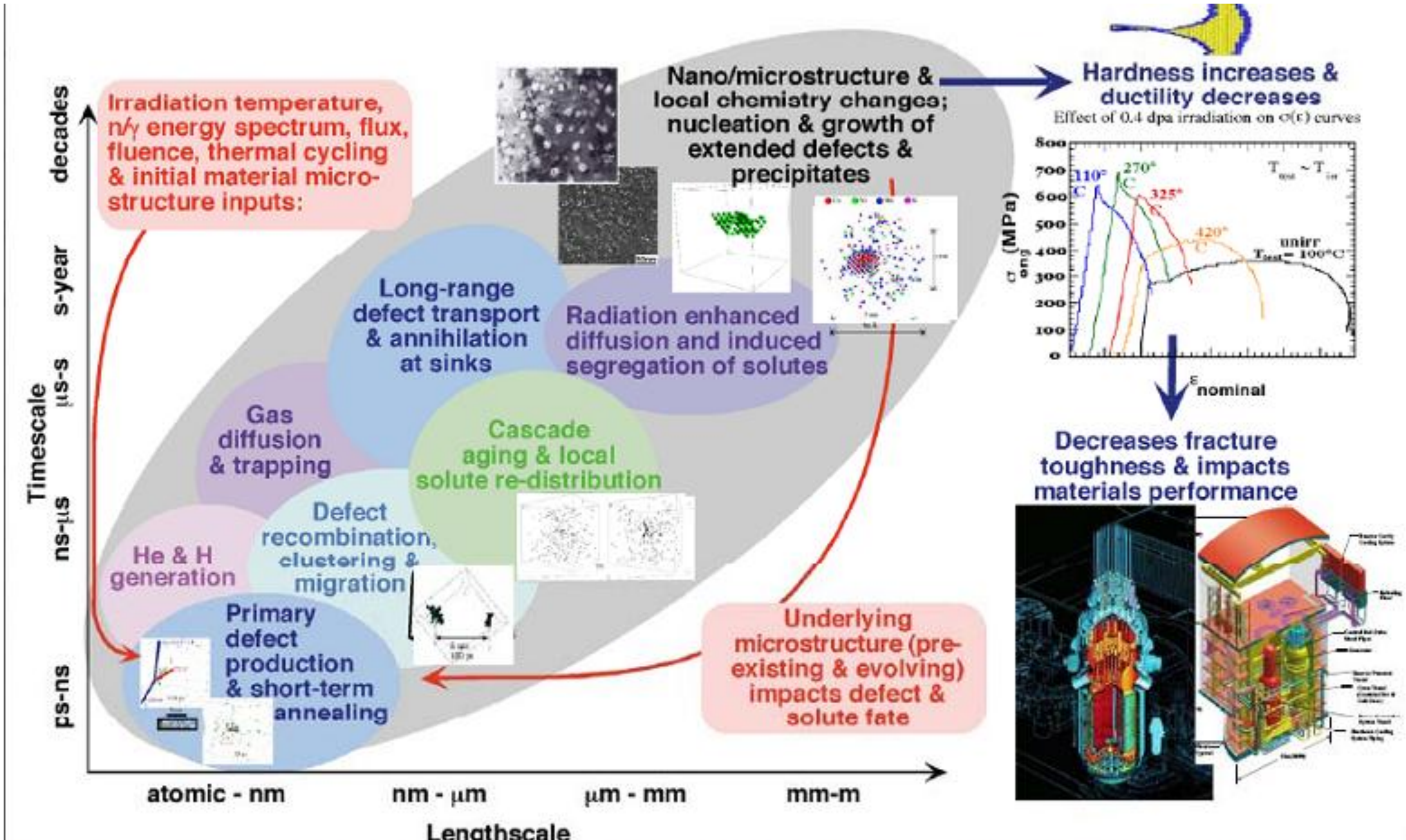
- **New effects arise under irradiation**

Surface effects
Different excitations and heating
Dimensional changes
Effect of long-range action
Irradiation induced phase transformation

- **Radiation damage as evolution of a nonlinear complex system**

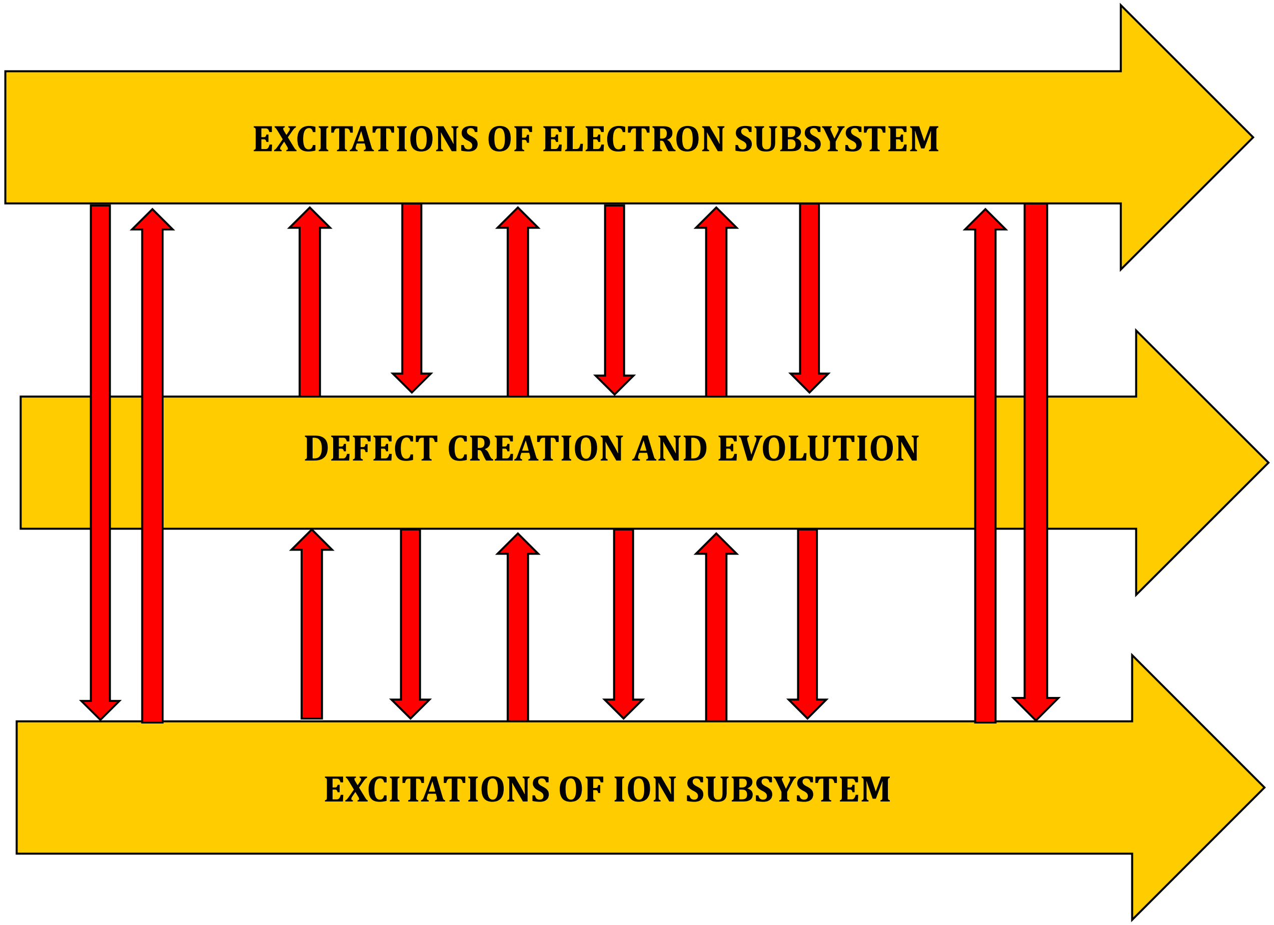
Formation of new structures
Complex time evolution of defect structures under irradiation

Materials behavior is inherently multi-scale



Radiation damage produces atomic defects and transmutants at the shortest time and length scales, which evolve over longer scales to produce changes in microstructure and properties through hierarchical and inherently multiscale processes

Influence of irradiation



Radiation effects

Phenomena
of the radiation effects are

open,

non-equilibrium,

synergetic,

multi-scale,

non-linear

and

stochastic

Radiation effects

There are still a lot of phenomena, which cannot be explained in the conventional frameworks:

- **passage of heavy fast ions that cause treks,**
- **interaction of slow multi-charged ions with surface,**
- **sub-threshold effects,**
- **long-range effects,**
- **radiation-induced diffusion,**
- **self-organization of defects and complex time evolution of defect structures under irradiation**

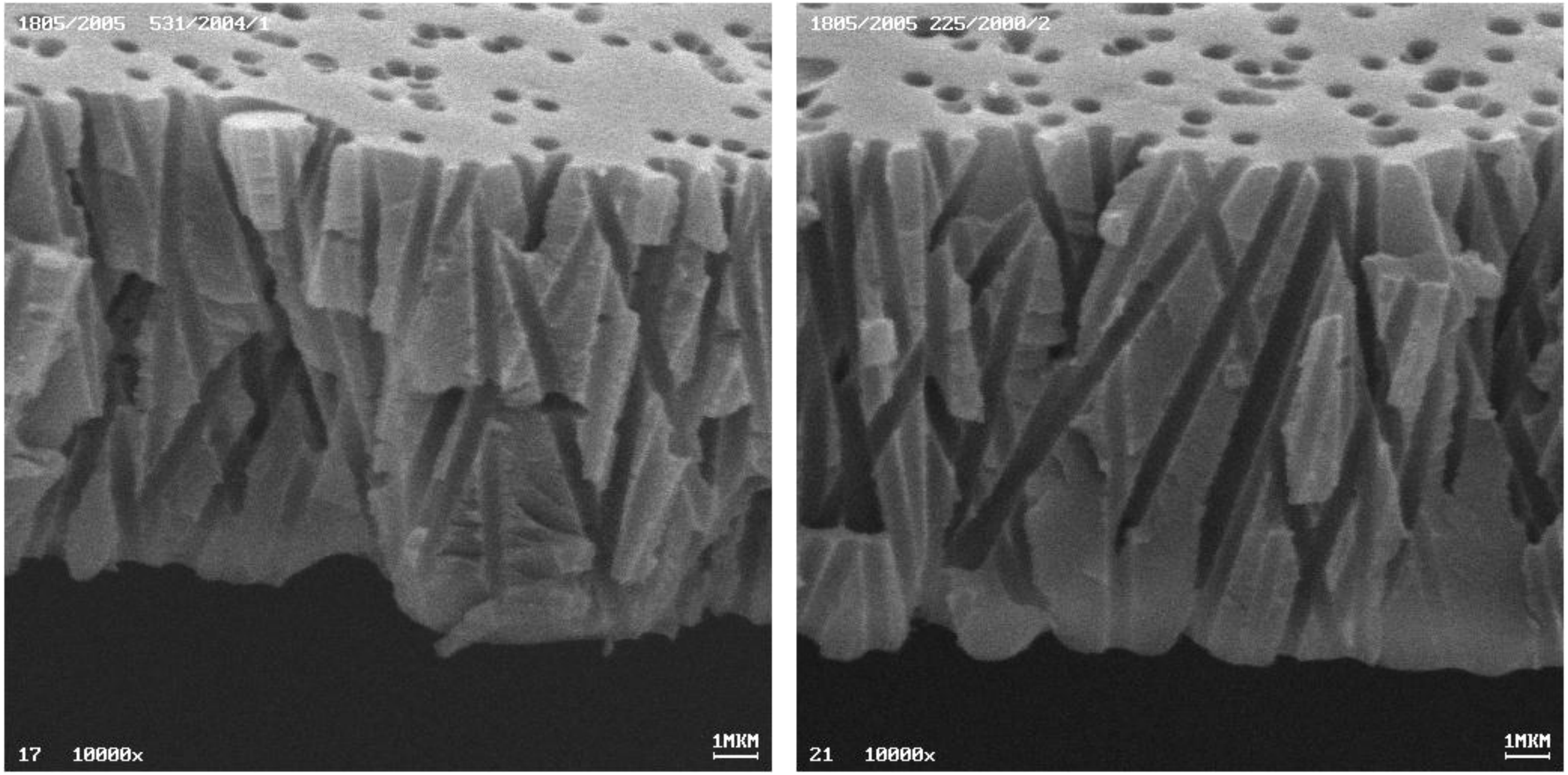
We need more sophisticated multi-disciplinary methods to deal with these problems.

Radiation effects

The mechanisms distinguish the field of radiation effects from the field of classical materials science:

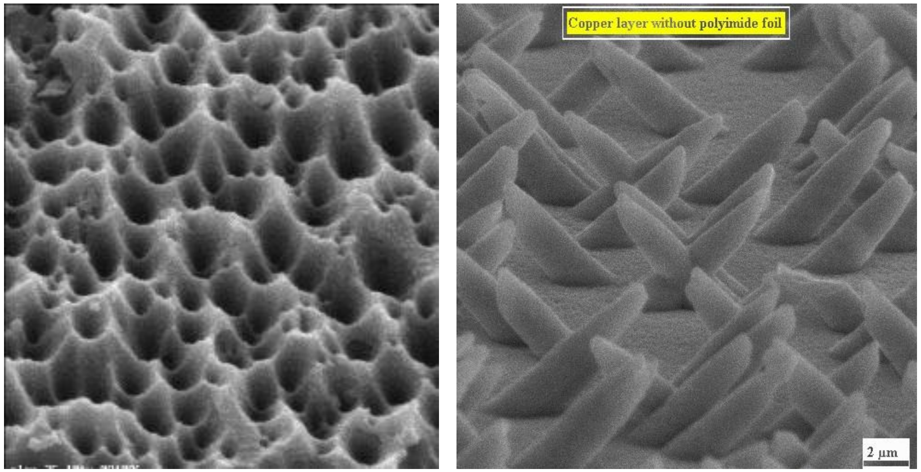
1. **Formation of self-interstitial atoms**
2. **New types of radiation-induced excitations in electron and ion systems**
3. **Interaction of these radiation-induced excitations with "static" crystal defects.**

Structure of tracks

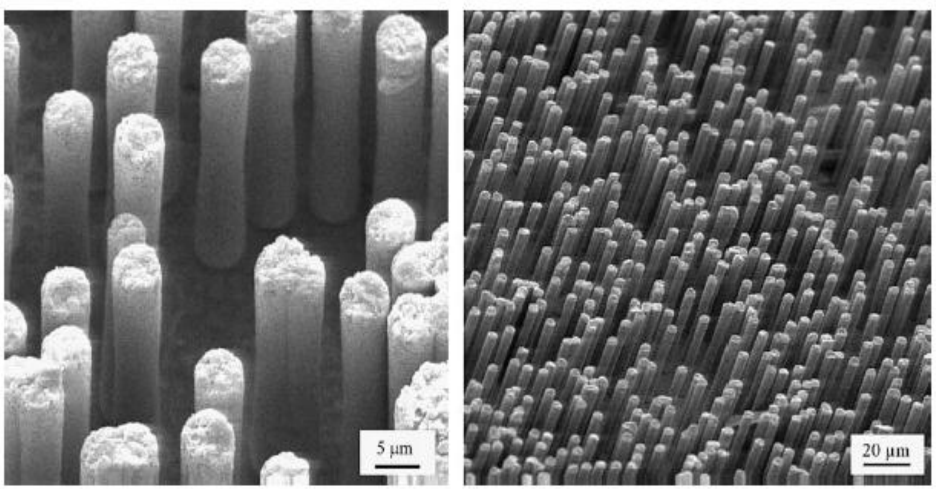


- **SEM data: track membrane with pore size of 0.4 um, Skuratov V., Dubna**

Nano-structure formation by means irradiation



M.Danziger, W.Votius. In: Proc. 2nd Intern. Symp. On Polyimides and Other High Temperature polymers. Newark, 2003, Vol. 2, p. 1.

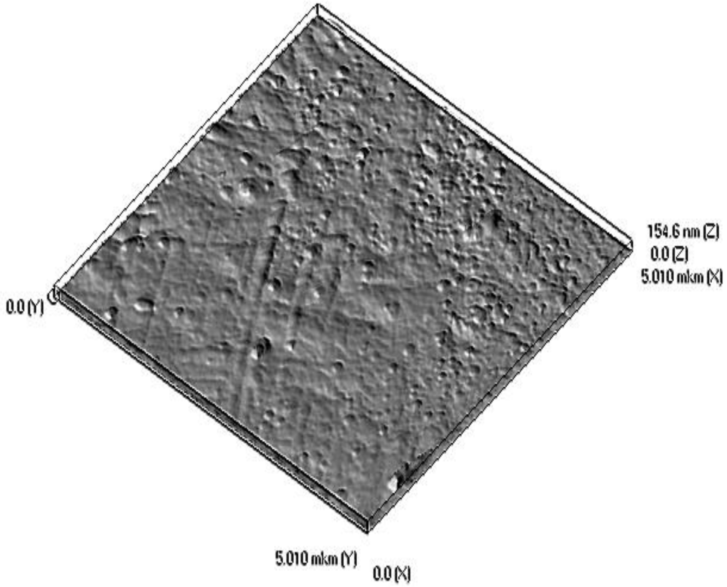


A.Schulz et al. / NIM B 236(2005) 254

Structure of surface after irradiation

Ni 41%Cr, 600C

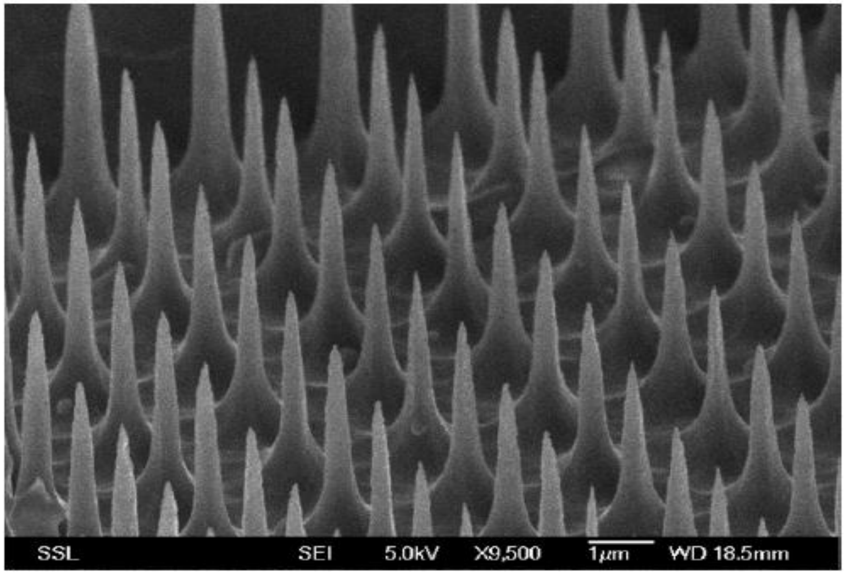
Before irradiation

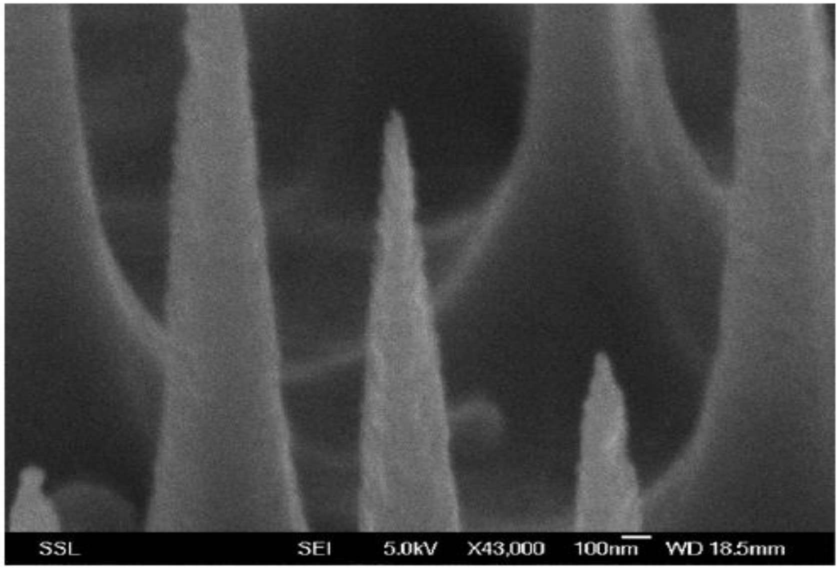


After irradiation

Kulikova N.V., Khmelevskaya V.S., Bondarenko V.V., Obninsk, 2009

Experimental facts: spatial organization

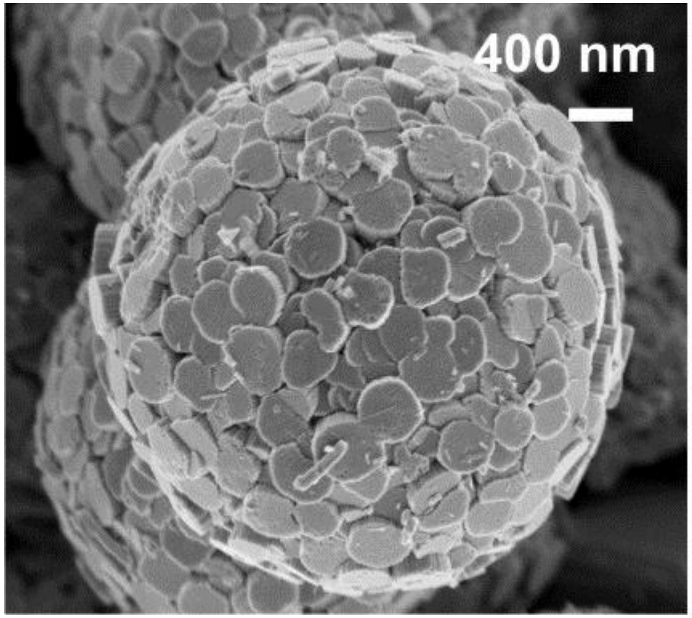


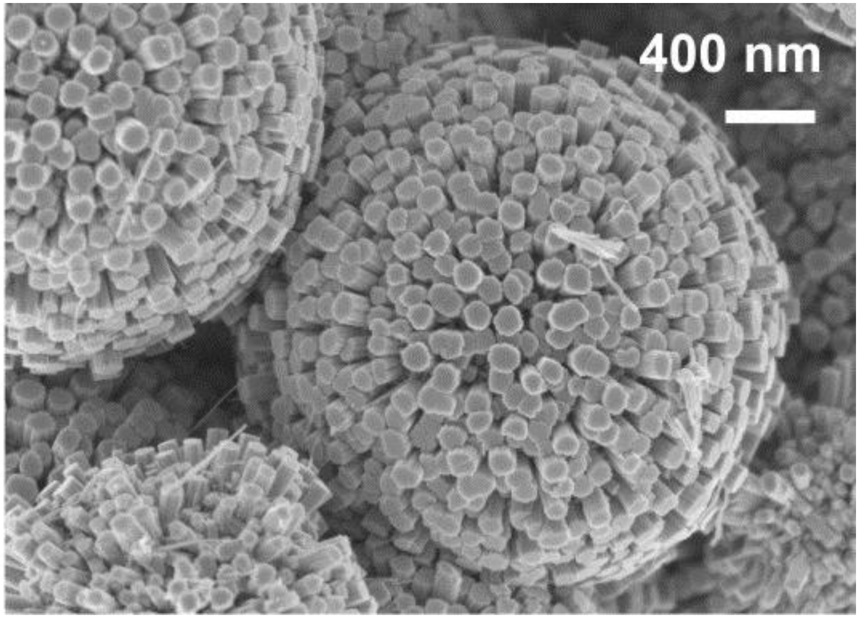


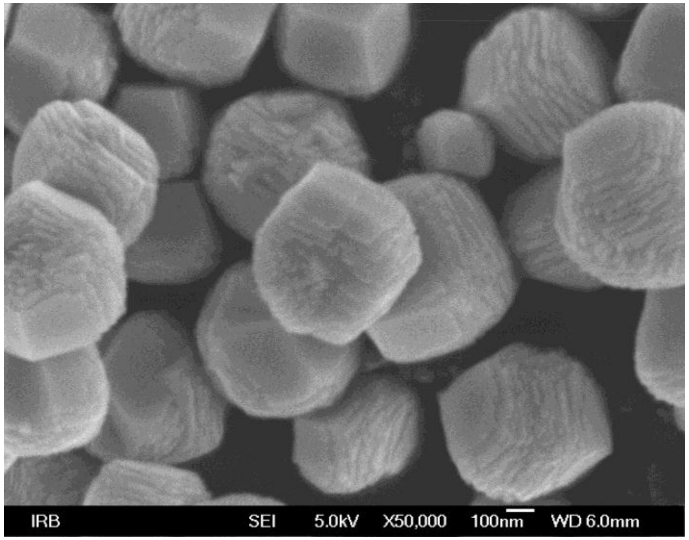
- Align the [100] crystal plane to the beam direction
- Regular array of nanotips
- Each spike measuring 2 μm has a 10nm radius of curvature

[Mark Breese et al. "Fabrication of patterned porous silicon microstructures using proton beam writing" (Centre for Ion Beam Applications, Department of Physics, National University of Singapore)]

Structure formation

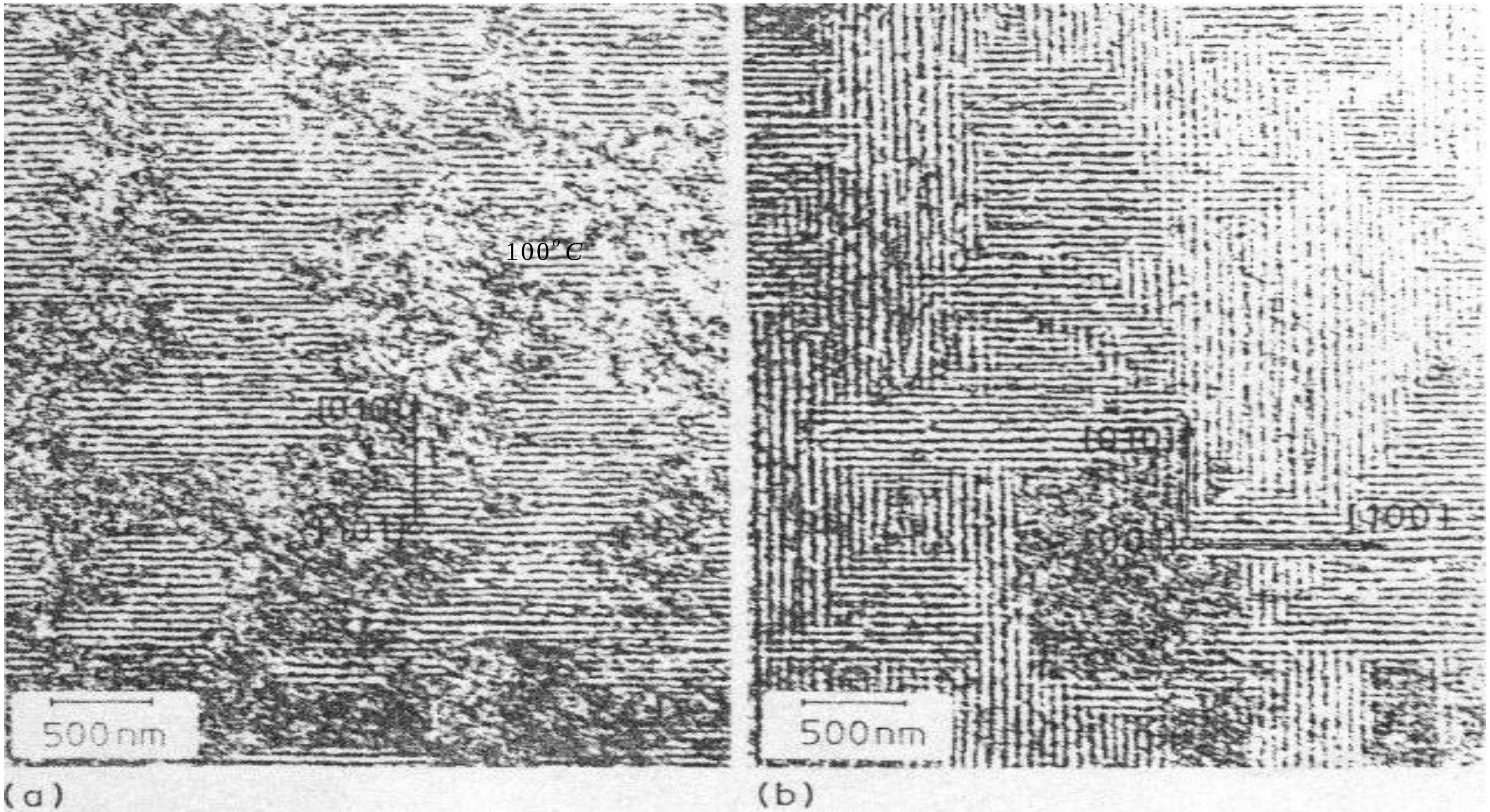






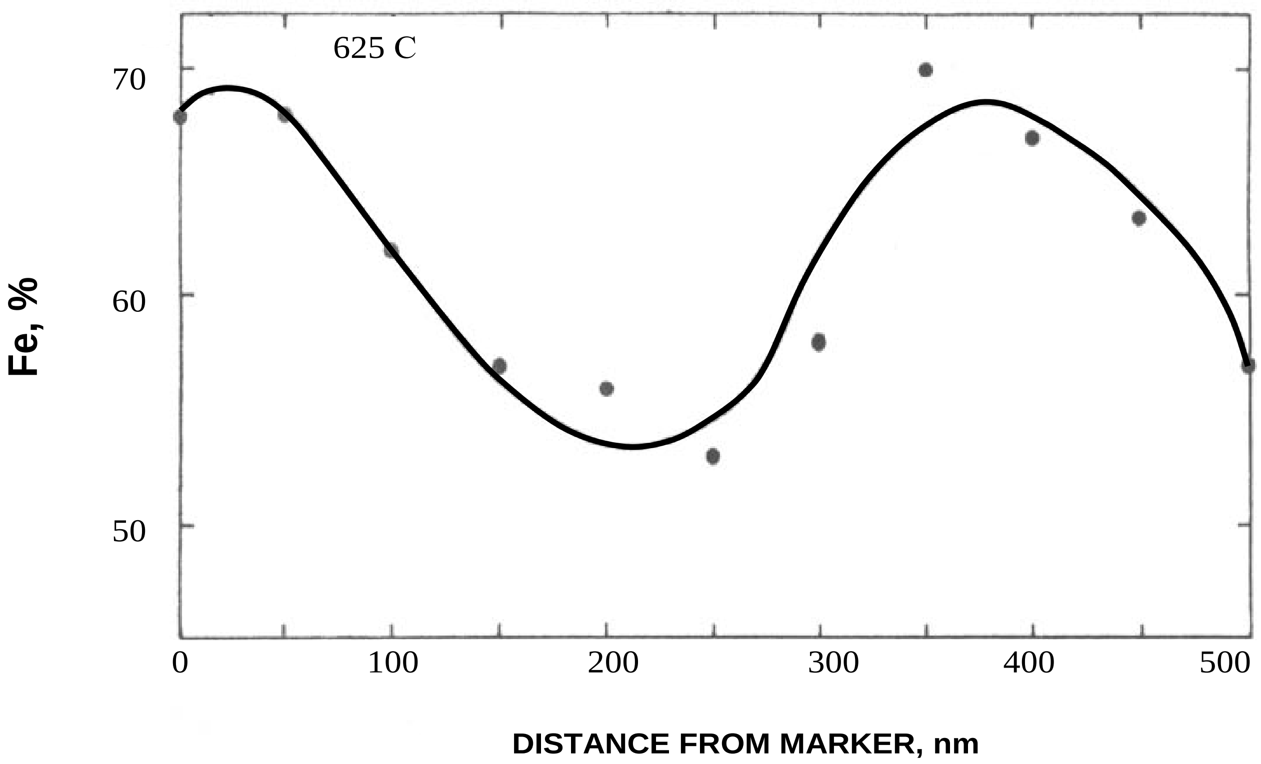
Formation of second phase segregations (separation of chemical element or point defects from main matrix) in multi-component systems under irradiation

Experimental facts: spatial organization



- Formation of planar periodic walls of defects in 3 MeV proton-irradiated copper (100C^o, **2** dpa. Imaging is in the $\{11\bar{0}\}$ projection in **(a)** and in the {100} projection in (b) – *Walgraef D., Ghoniem N.M. Nonlinear dynamics of microstructure under irradiation // Phys. Rev.. 1995. V. B52. P. 3951-3962*

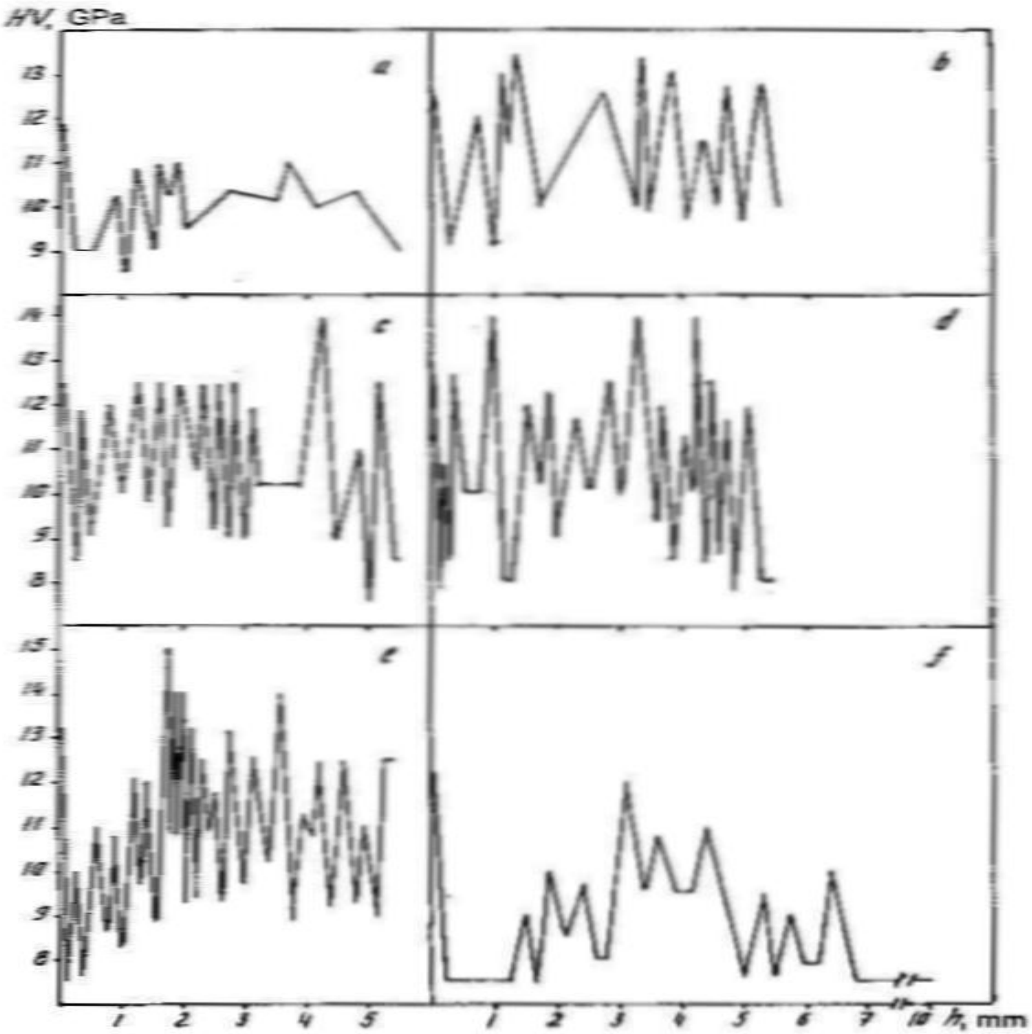
Experimental facts: spatial organization



Oscillation of iron level in ***Fe-35Ni*** irradiated to **117** dpa by 5 MeV ***Ni***$^{+}$ ions at 625C^{o}.

Garner F.A., Brager H.R., Hamilton M.L., Dodd R.A., Porter D.L. New developments in irradiation-induced microstructural evolution of austenitic alloys and their consequences on mechanical properties // Radiat.Eff. - 1986. - V.101. - P.37-53.

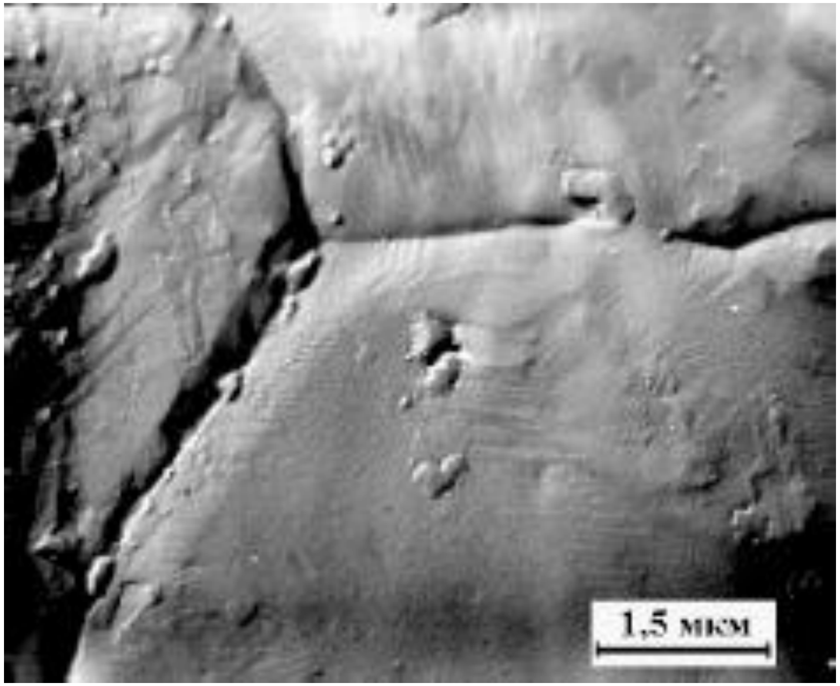
Experimental facts: spatial organization

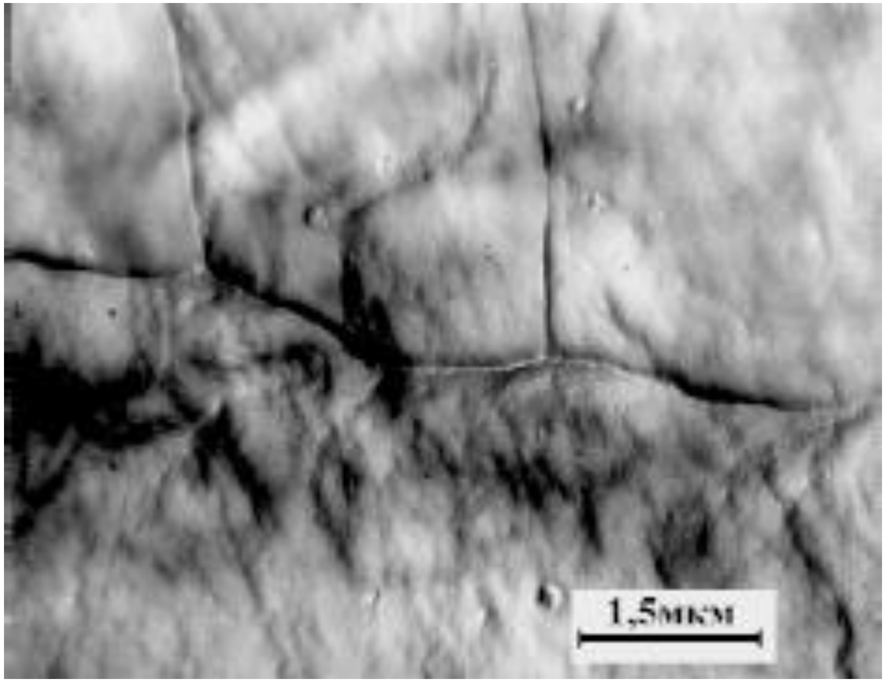


Microhardness vs depth in electron irradiated WC-steel ($40\ J/cm^2$) at different number of pulses *a – 3, b – 6, c, f - 10, d – 20, e – 50.*

S.F.Gnjusov, Yu.F.Ivanov, D.I.Proskurovskiy, V.P.Rotshteyn Pisma v ZhTF, 1999, v. 25, N30, p.30-59

Long-range effects under ion irradiation

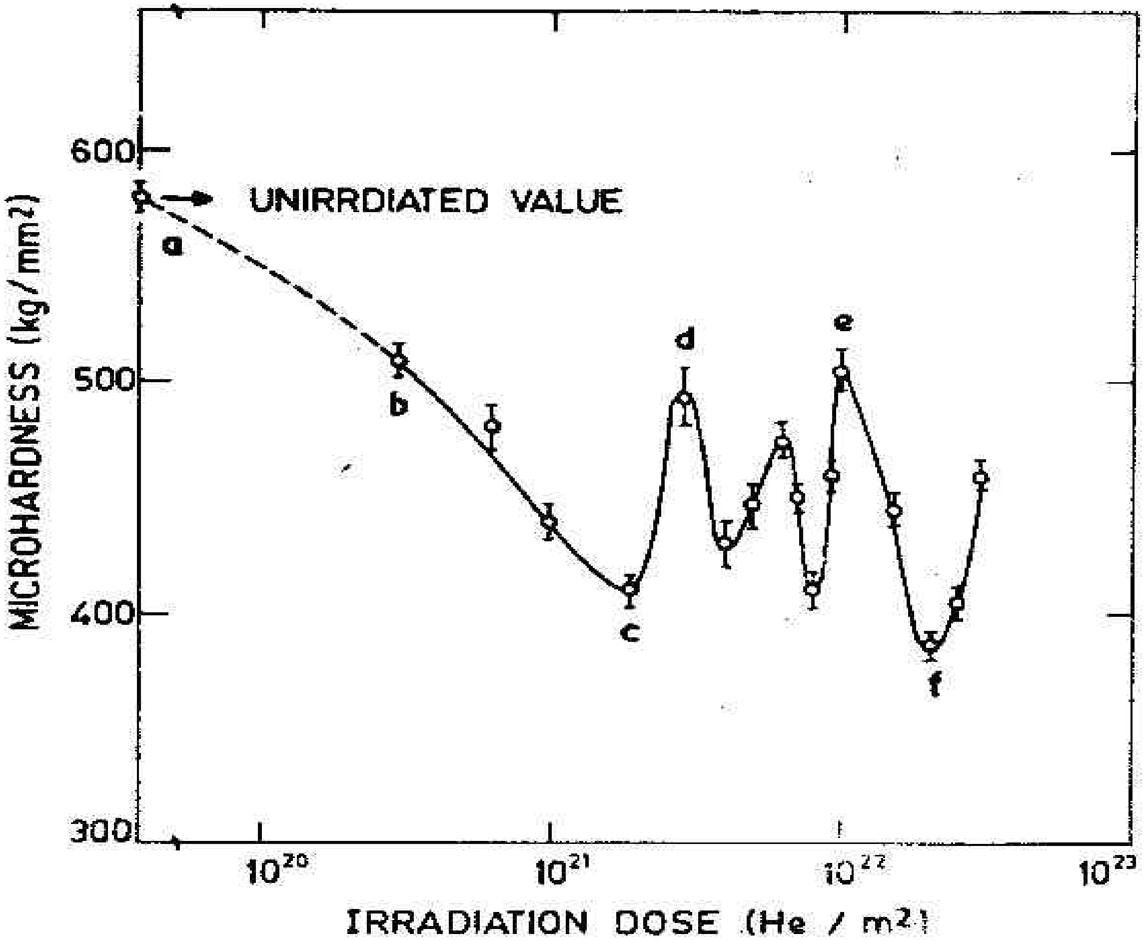




On depth of the zone of modification of properties (hardening) of materials under irradiation at t < 100 °c with low-energy plasma of the glow discharge . Microstructure of alpha-Fe in the annealed state before (left) and after (right) irradiation. Formation of dense dislocation networks around grain boundaries can be seen far away from the irradiated surface

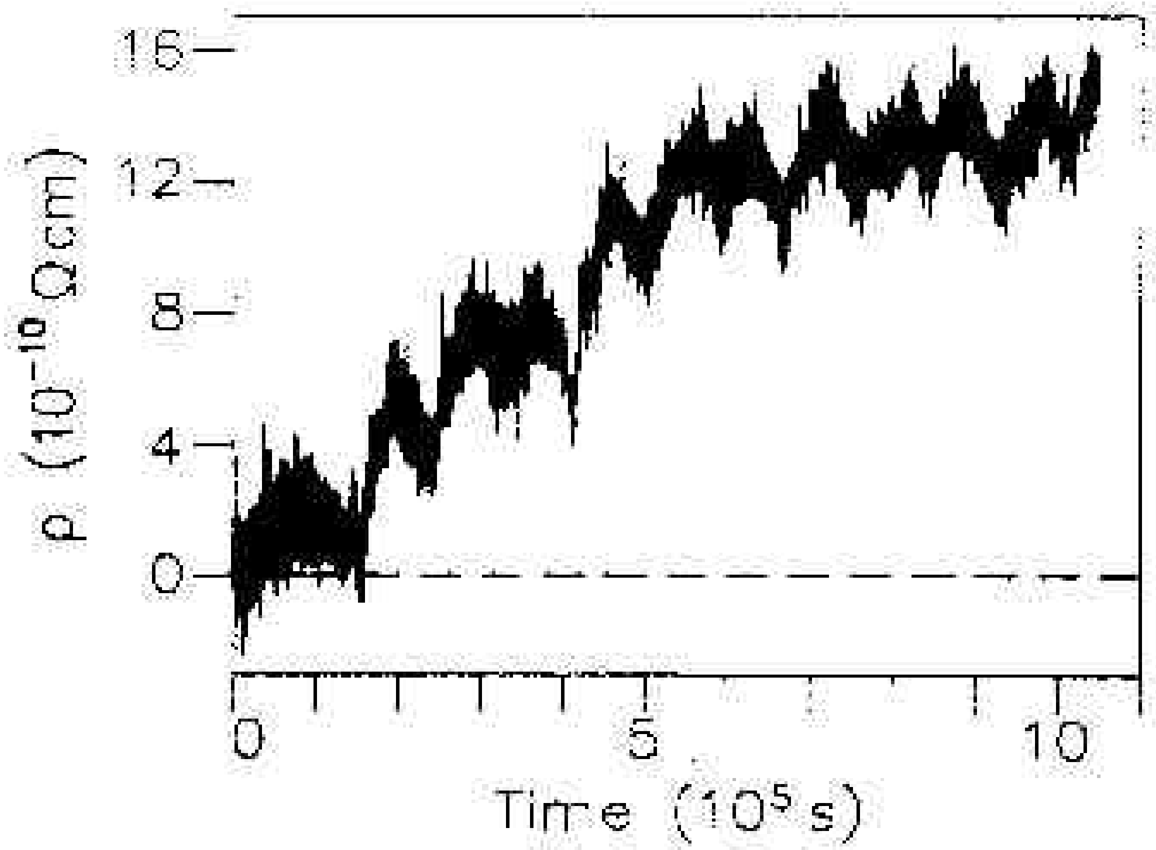
Y.V. Kunchenko, V.V. Kunchenko, G.N. Kartmazov
NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

Experimental facts: temporal oscillation



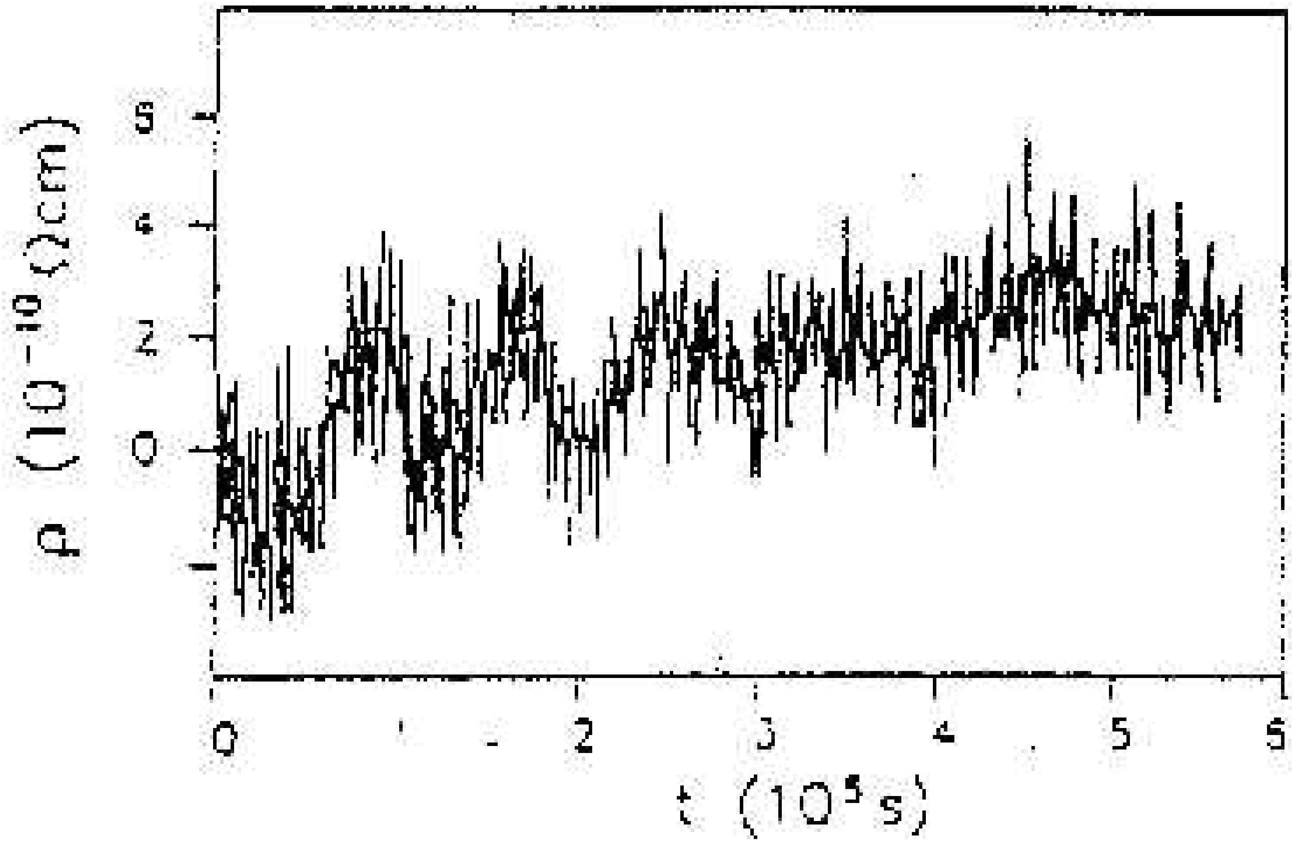
Variation of microhardness as a function of 50 keV Helium ion irradiation dose on Nimonic 90 containing γ-precipitates (~300K) Varatharajan K., Nandedkar R.V. Microhardness-microstructure study of aged nimonic 90 irradiated with helium // Effects of Radiation on Materials. R.E.Stoller Edr. - Philodelphia, 1989. - P.263-270

Experimental facts: temporal oscillation



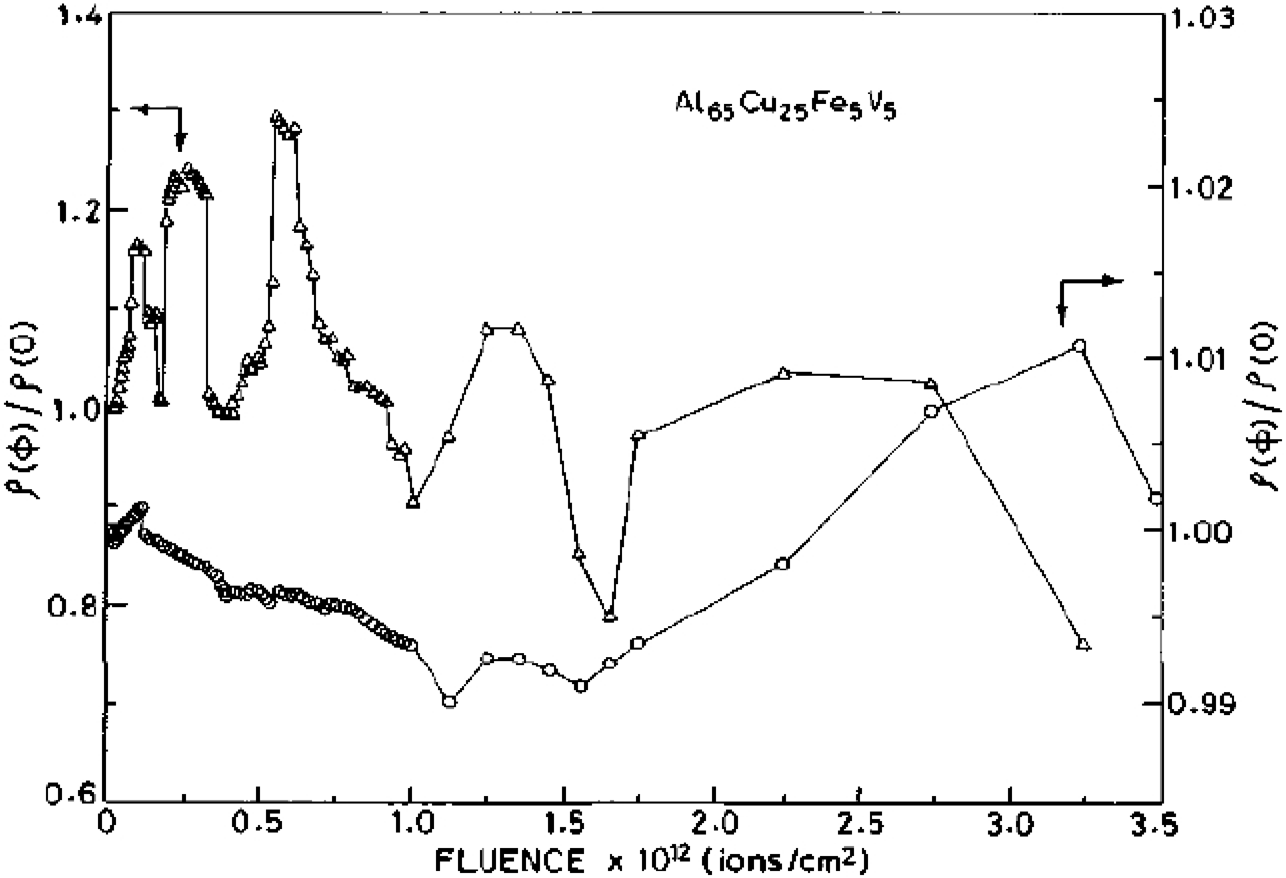
Oscillations of the electrical resistivity of electron irradiated copper (T= -80°C, Φ=2.24 μA·cm^{-2}, 2.2 MeV)
Schule W. Radiation-enhanced diffusion due to interstitials and dynamic crowdions // J. Nucl.Mater. - 1996 - V.233-237. - P.964-968.

Experimental facts: temporal oscillation



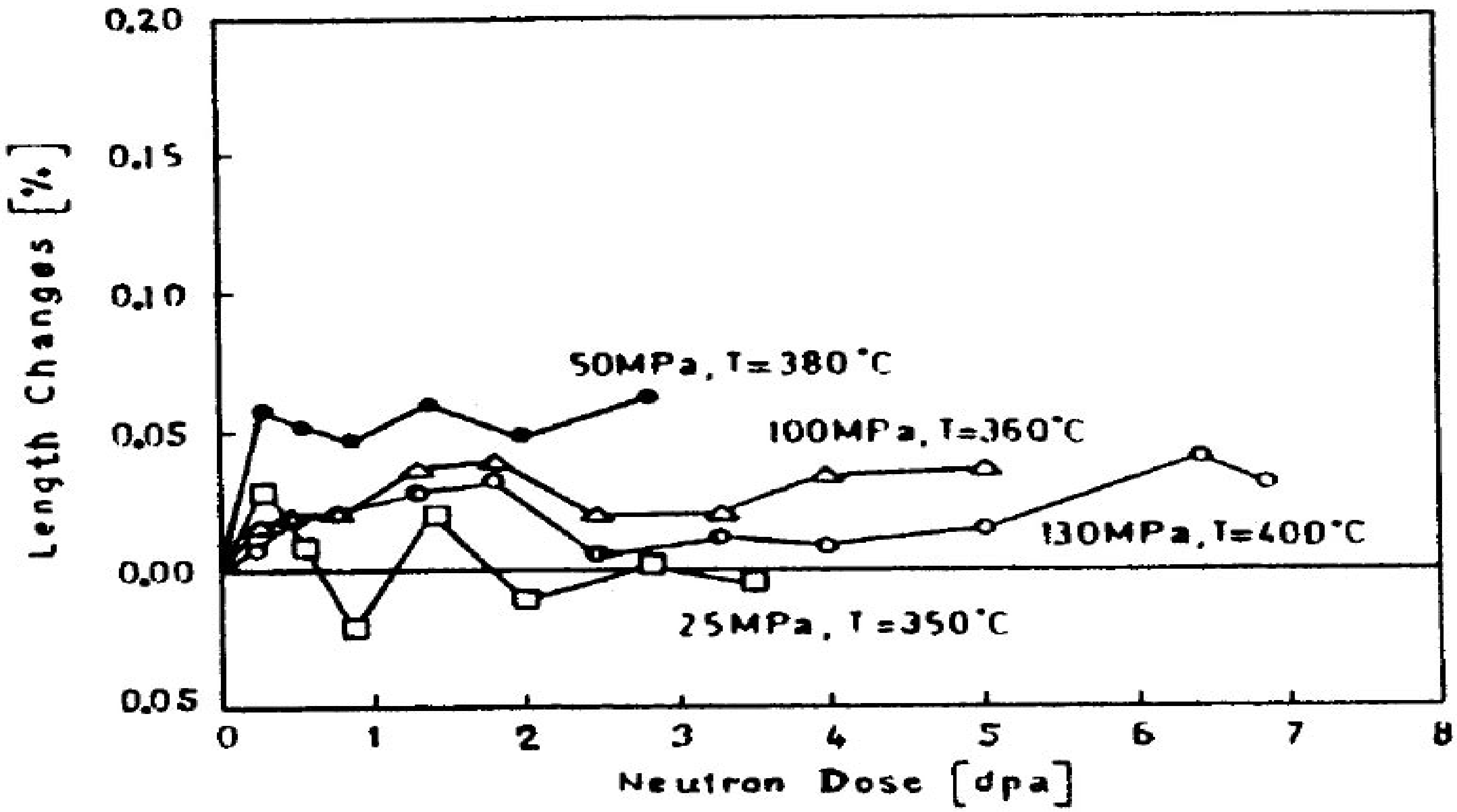
Oscillations of the electrical resistivity of electron irradiated gold (T=197 K, Φ=1.15 μA·cm^{-2}, 2.3 MeV)
Schule W. Radiation-enhanced diffusion due to interstitials and dynamic crowdions // J. Nucl.Mater. - 1996 - V.233-237. - P.964-968.

Experimental facts: temporal effects



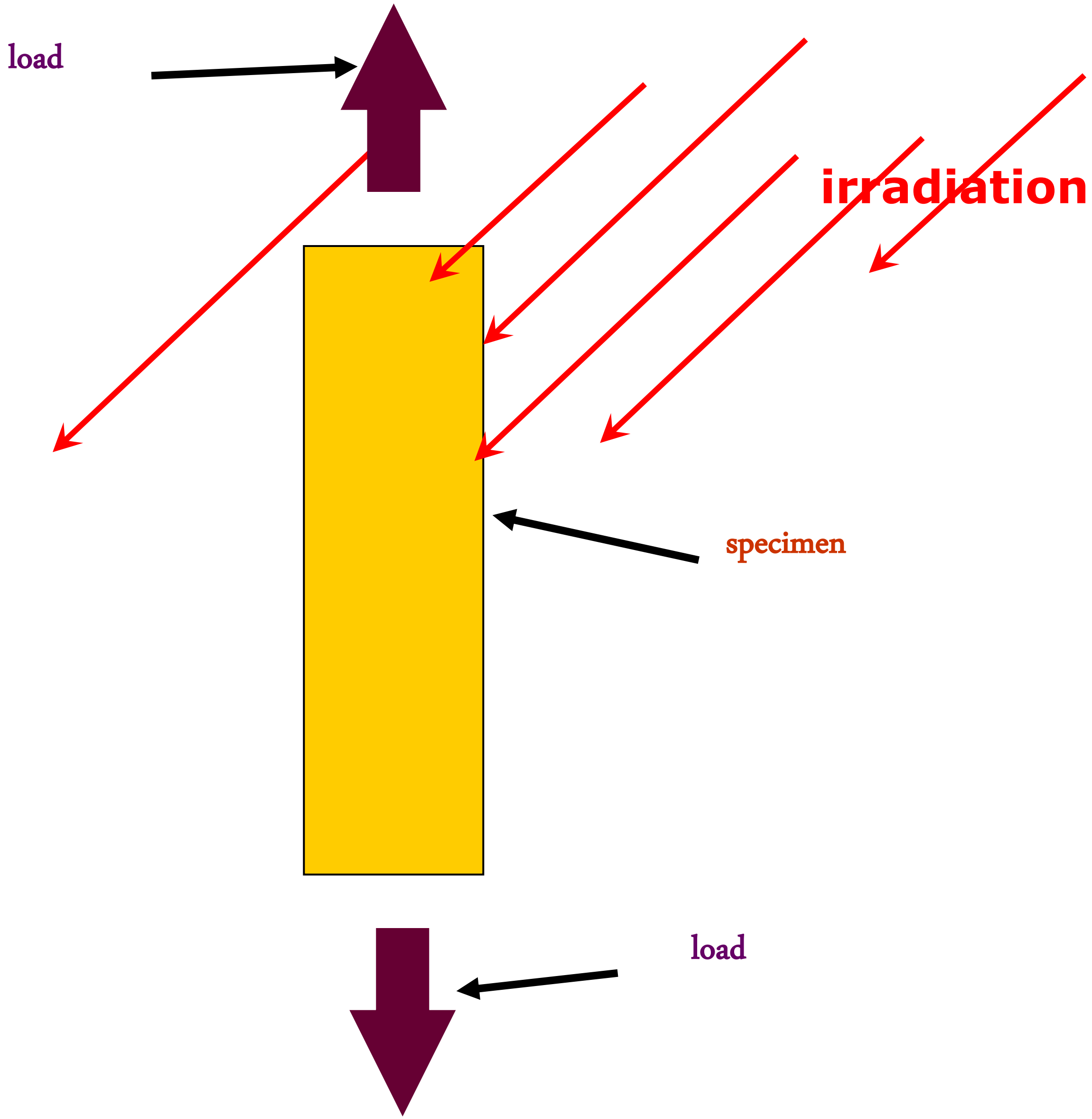
- **Oscillations of relative resistance** R.Chatterjee, A.Kanjilal, A.Dunlop, U.Tiwari, J.M.Ramillon The observation of oscillatory behaviour in swift heavy ion irradiated quasicrystals. Solid State Communications 120(2001) 289-293

Experimental facts: temporal oscillation

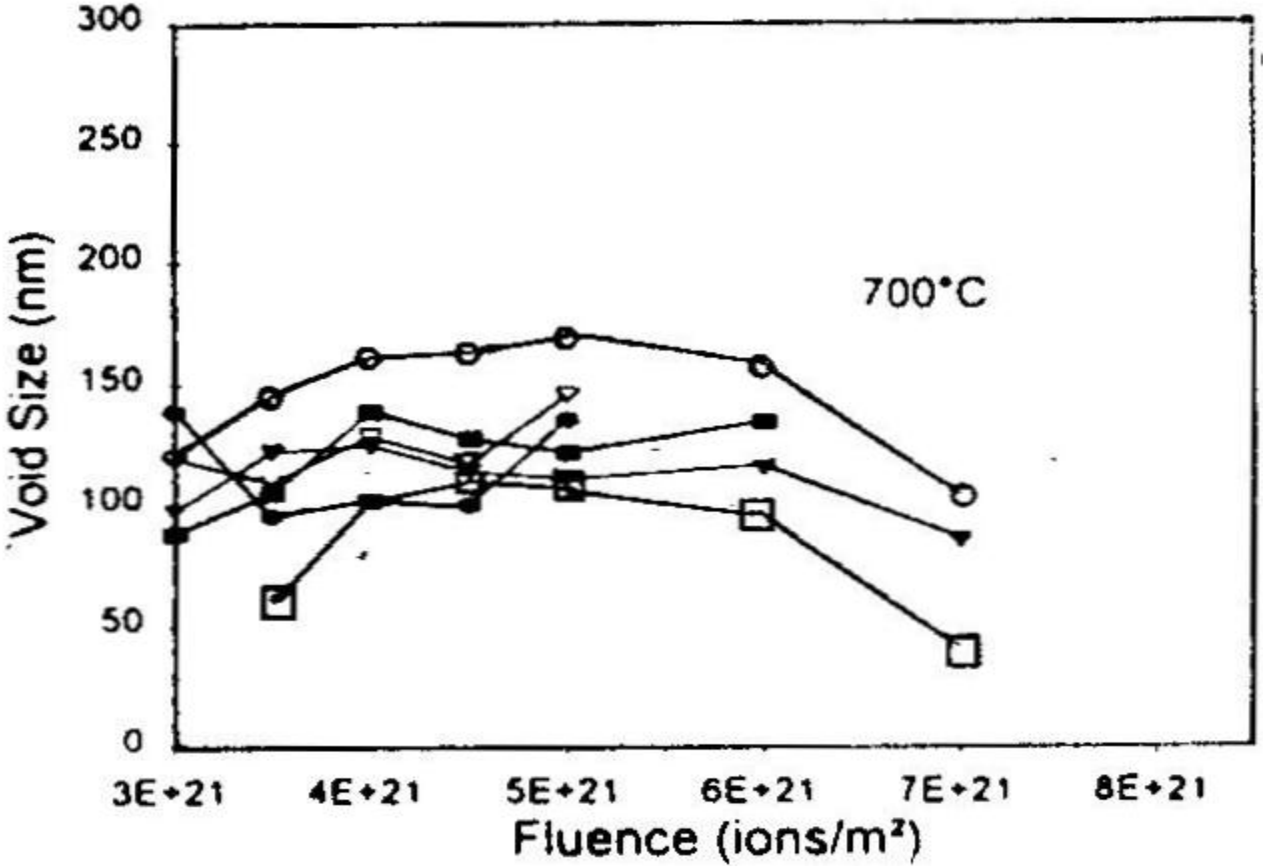


Oscillations of the length of steel specimens *versus* the neutron irradiation dose. Schule W., Hausen H. Neutron irradiation creep in stainless steel alloys// J.Nucl.Mater.-1994. - V.212-215.-P.388 – 392

Creep: oscillation of the length of specimen

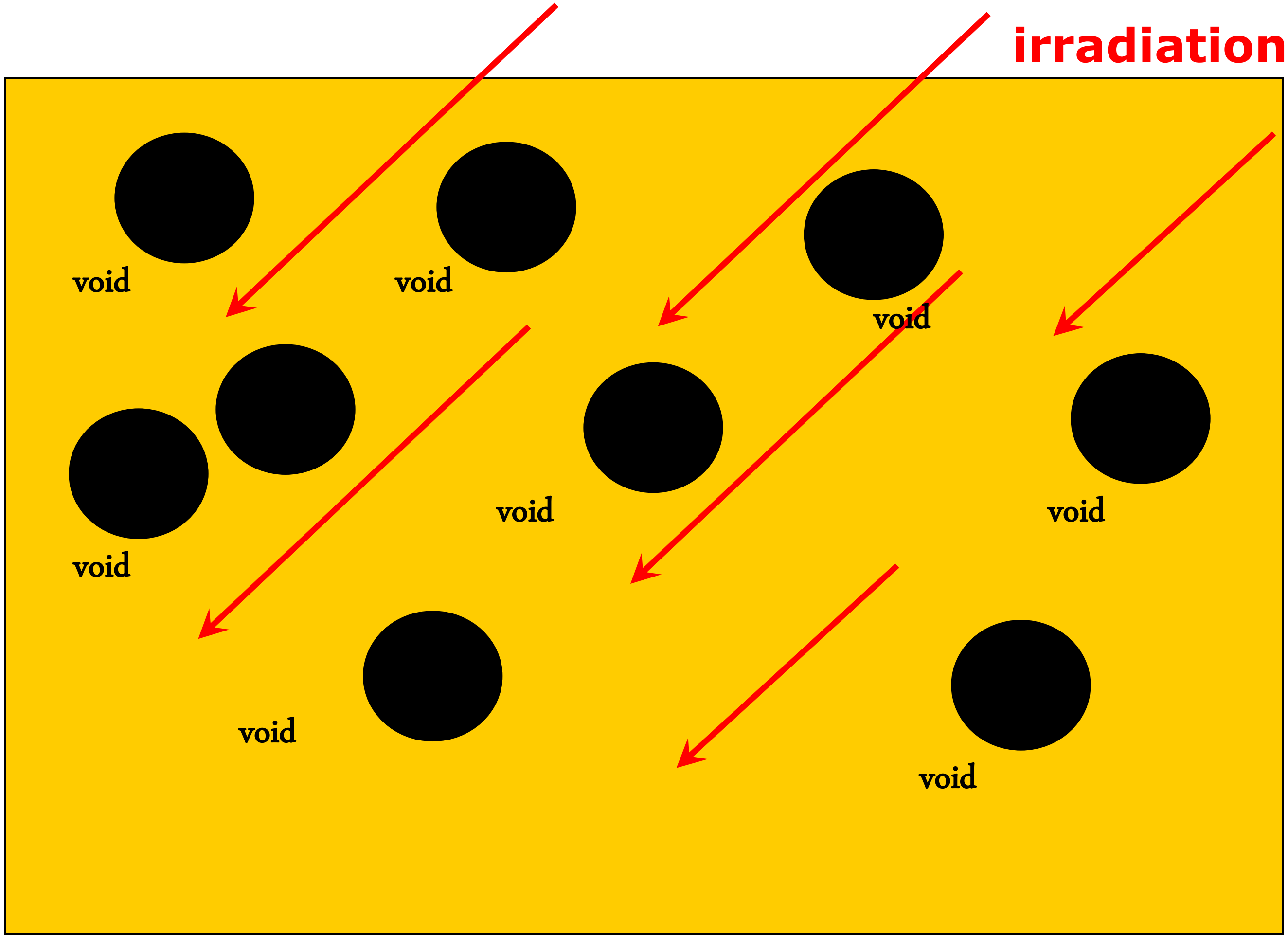


Experimental facts: temporal oscillation

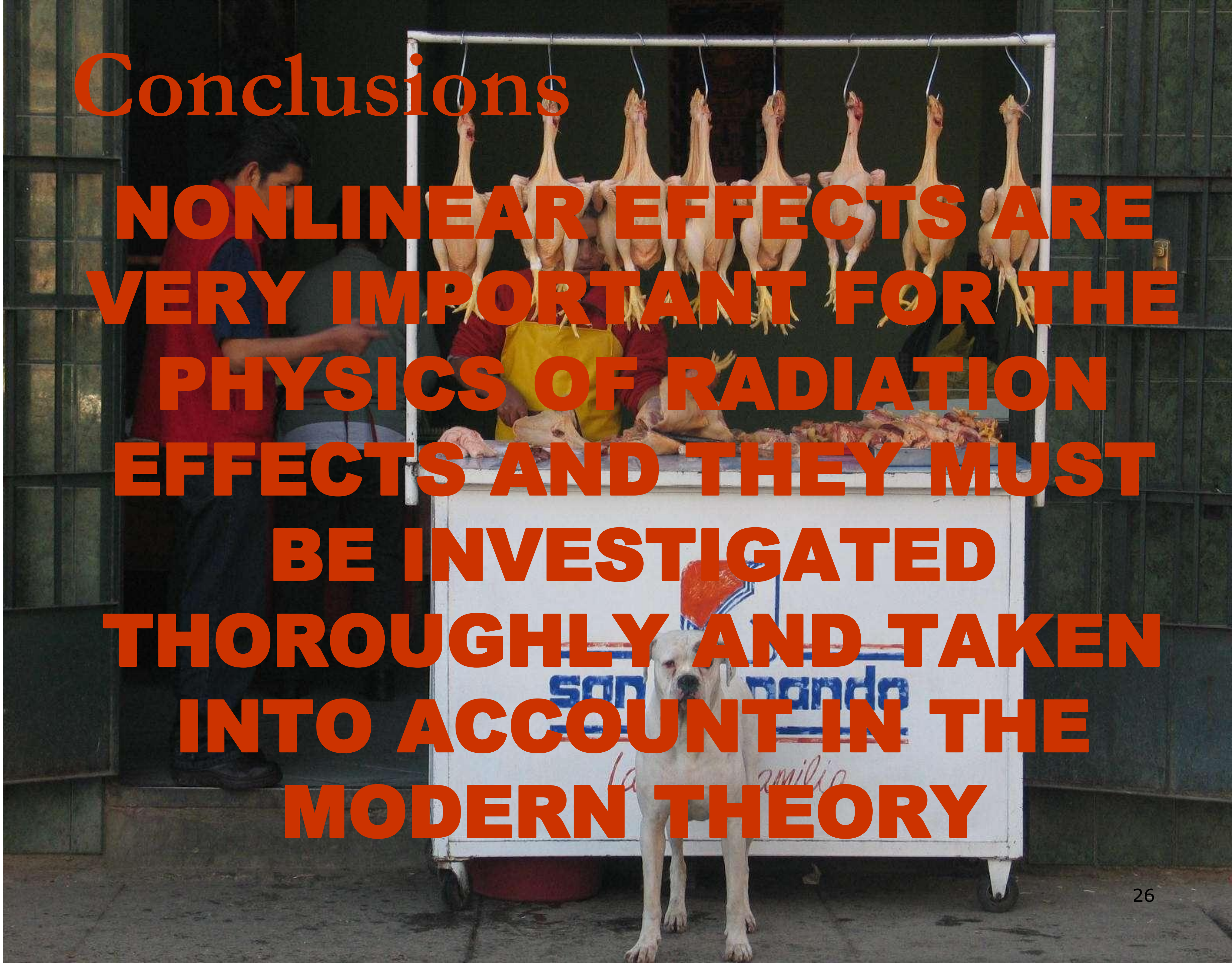


Non-monotonous dose dependence of the size of vacancy voids. *Steele J.K., Potter D.I. The disappearance of voids during 180 keV Ni+ bombardment of nickel // J.Nucl.Mater. -1995. - V.218. - P.95-107.*

Swelling: self-oscillation of void size

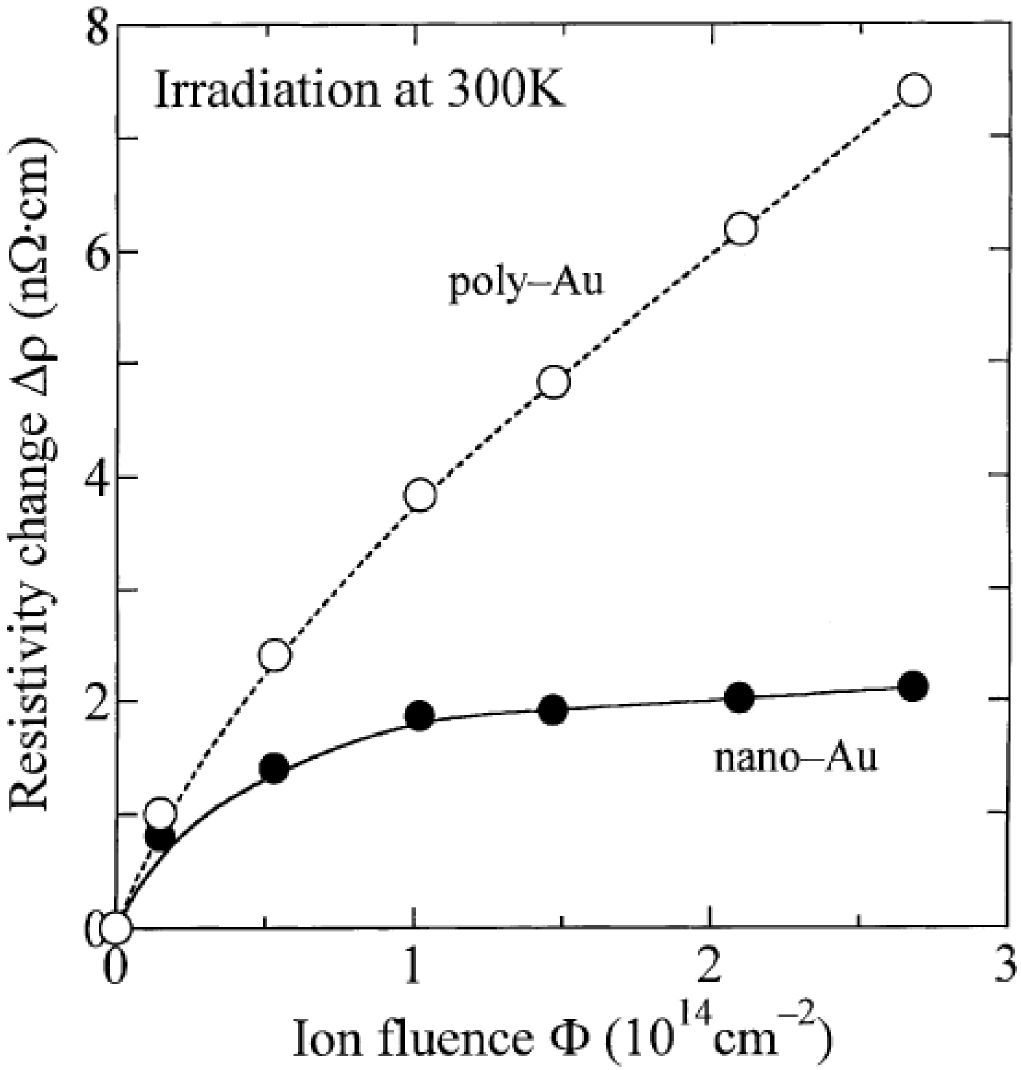


Conclusions



NONLINEAR EFFECTS ARE VERY IMPORTANT FOR THE PHYSICS OF RADIATION EFFECTS AND THEY MUST BE INVESTIGATED THOROUGHLY AND TAKEN INTO ACCOUNT IN THE MODERN THEORY

Nanocrystalline gold



The relative change in electrical resistivity of nanocrystalline gold compared to polycrystalline depending on the dose of 12C with energy of 60MeV

[Y. Chimi, A. Iwase, N. Ishikawa, et al. // *J. Nucl. Mater.*, 297 (2001)]

F.M. Russell

Quodons in mica moscovite

Black tracks: Fe_3O_4

Cause:

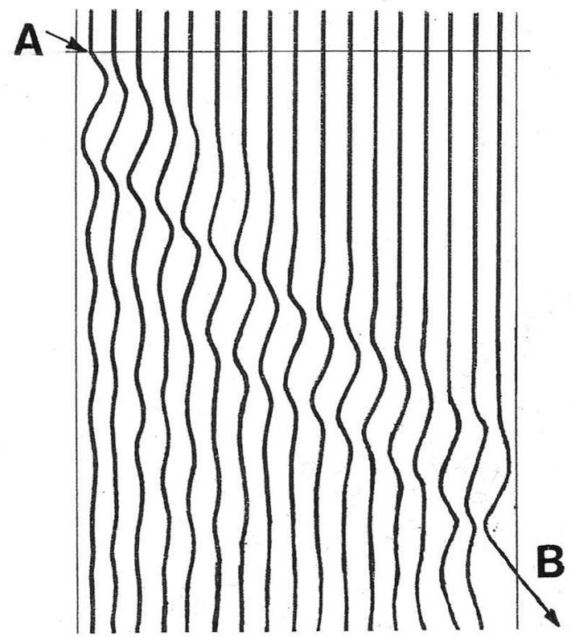
- 0.1% Particles:
  - •muons: produced by interaction with neutrines
  - • Positrons: produced by muons' electromagnetic interaction and K decay

- 99.9% **Unknown**

¿Lattice localized vibrations: quodons?

F.M. Russell, J.C. Eilbeck, Evidence for moving breathers in a layered crystal insulator at 300 K,

Europhysics Letters 78, 10004, 2007.

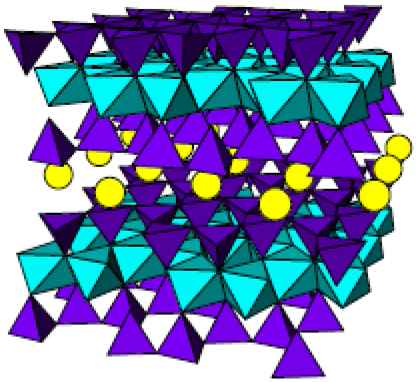


Sputtering

Trayectories along lattice directions within the K^+ layer

Evidence for moving breathers in a layered crystal insulator at 300K
FM Russell and JC Eilbeck, Europhysics Letters 78, 10004, 2007.

Ejection of atoms at a crystal surface caused by energetic breathers which have travelled more than 10^7 unit cells in atomic chain directions. The breathers were created by bombardment of a crystal face with heavy ions. This effect was observed at 300K in the layered crystal muscovite, which has linear chains of atoms for which the surrounding
lattice has C2 symmetry.



K^+