Russian Research Center" Kurchatov Institute"

# Investigations of radiation resistance of fission and fusion structural materials in RRC KI using charged particle accelerators

Alexander Ryazanov



15 March 2010, PSI, Switzerland

# Experience of RRC KI in the Investigations of Materials for Atomic and Fusion Reactors

- **Materials for Fusion Reactors:**

  C-C, SiC, Al2O3, MgO, ZrO2,

- **Metallic Materials for Atomic Reactors:**

  Austenitic Steels

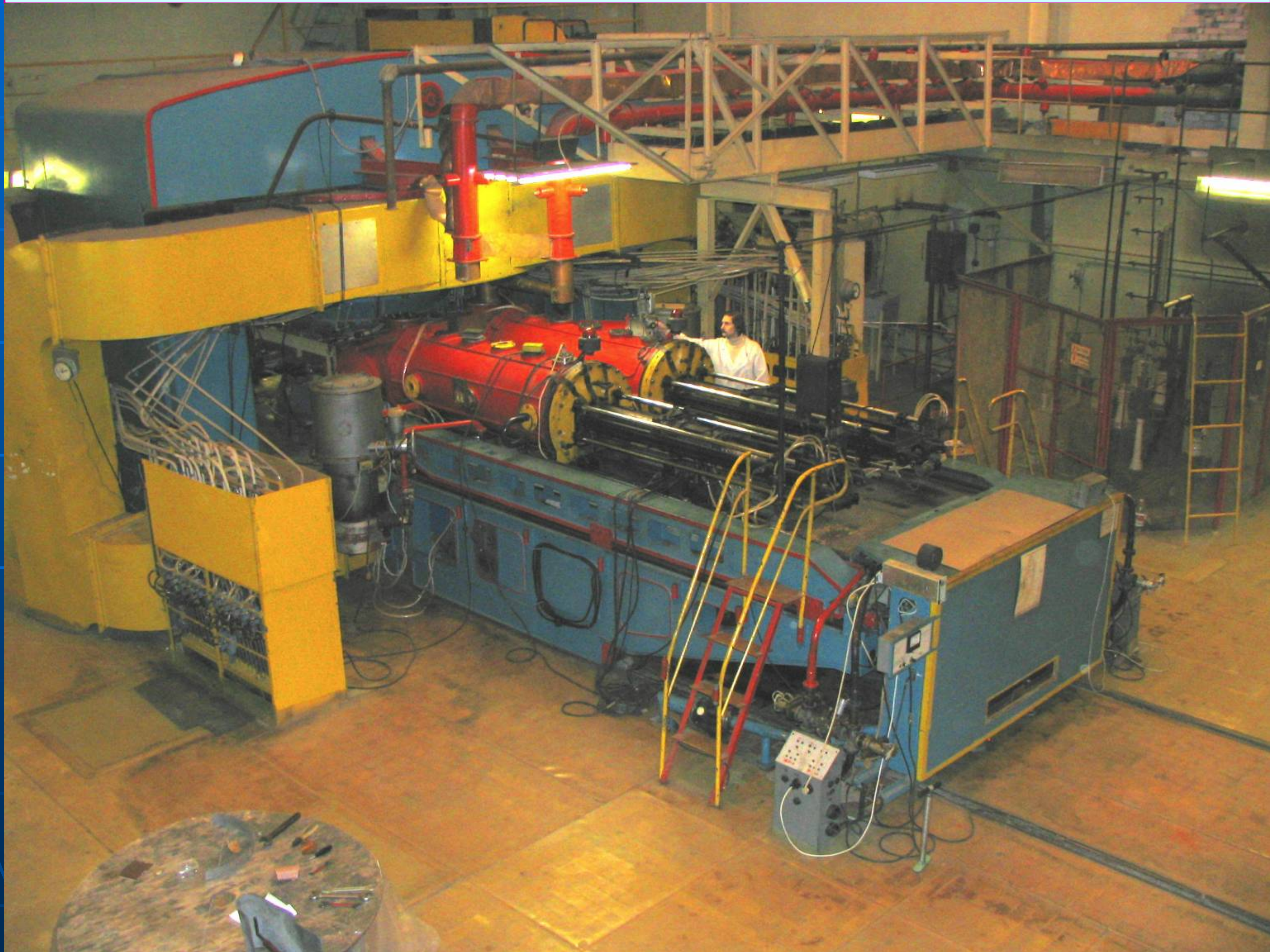
- **Atomic Reactors RBMK:**

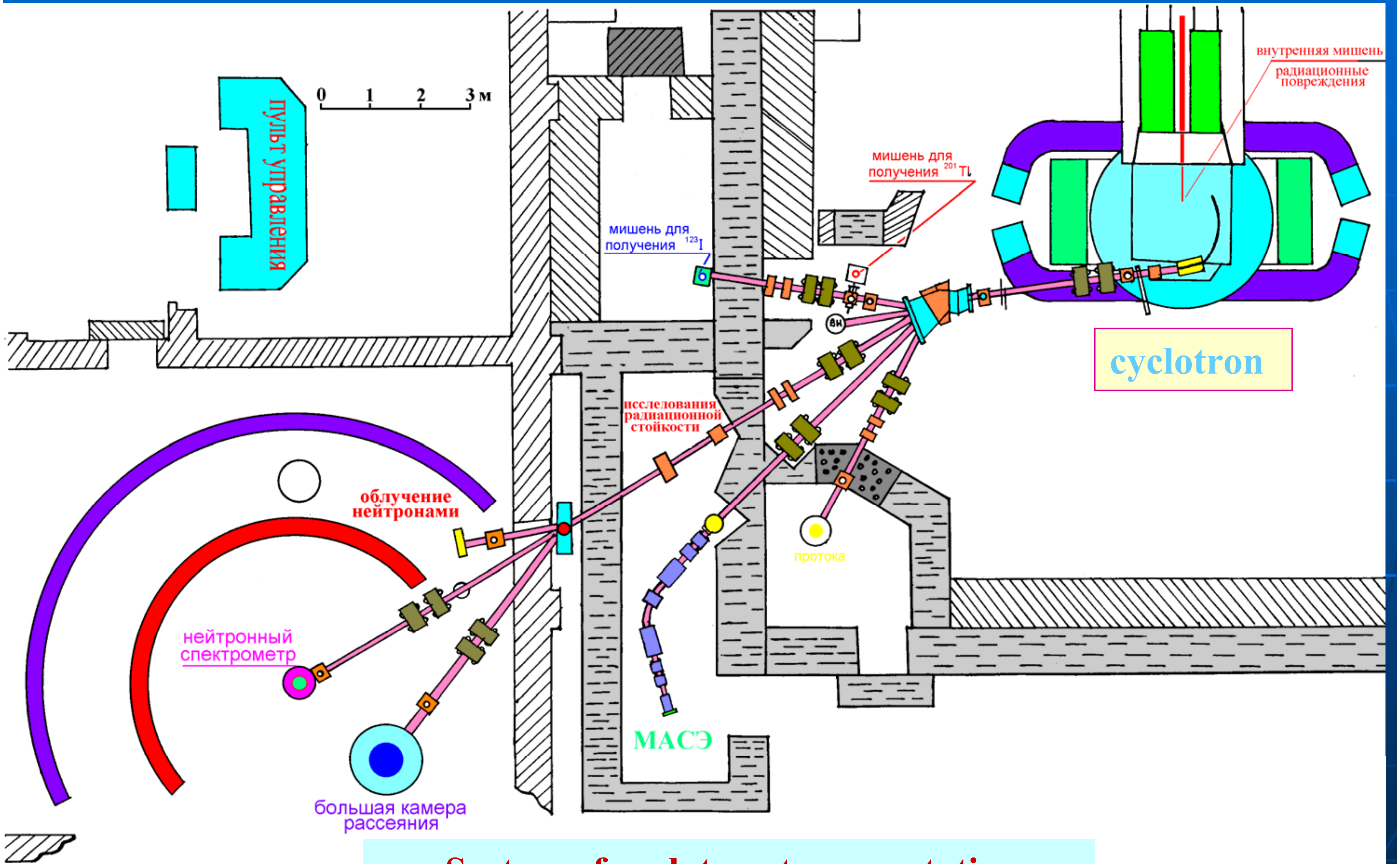
  nuclear graphite, pyrolytic graphite, Zr-Nb

- **Basic Research and Theoretical Modeling:**

  Radiation Damage Formation, Defect Cluster Growth, Radiation Swelling, Radiation Creep, Helium Ebrittlement

# Cyclotron of RRC “Kurchatov Institute”






## System of cyclotron transportation

# Accelerators of Charge Particles of Russian Research Center "Kurchatov Institute"

- **Cyclotron of RRC KI:**

  protons with energy < 35 MeV, current J < 30 mkA

  helium ions $He^4$ with energy < 60 MeV, current J < 20 mkA

  ions $O^{16}$ with energy < 120 MeV , current J < 5 mkA

  ions $C^{12}$ with energy < 80 MeV, current J < 5 mkA

# *Radiation Resistance of Graphite Materials*

# Graphite materials in Tokamaks and Fusion Reactor:

- **Limiter and/or protection plate for the inner wall**

**Exposition to:**

- Vacuum
- Intense head load
- Edge plasma
- Fast neutrons

**Important behavior:**

- Thermal shock resistance
- Thermo-mechanical properties
- Accumulation of Hydrogen and Helium in fusion reactor
- Accumulation of Radiation Damage
- Sputtering and particle emission

# Graphite Materials for Atomic Reactors :

- Reflectors and stopping system of neutrons

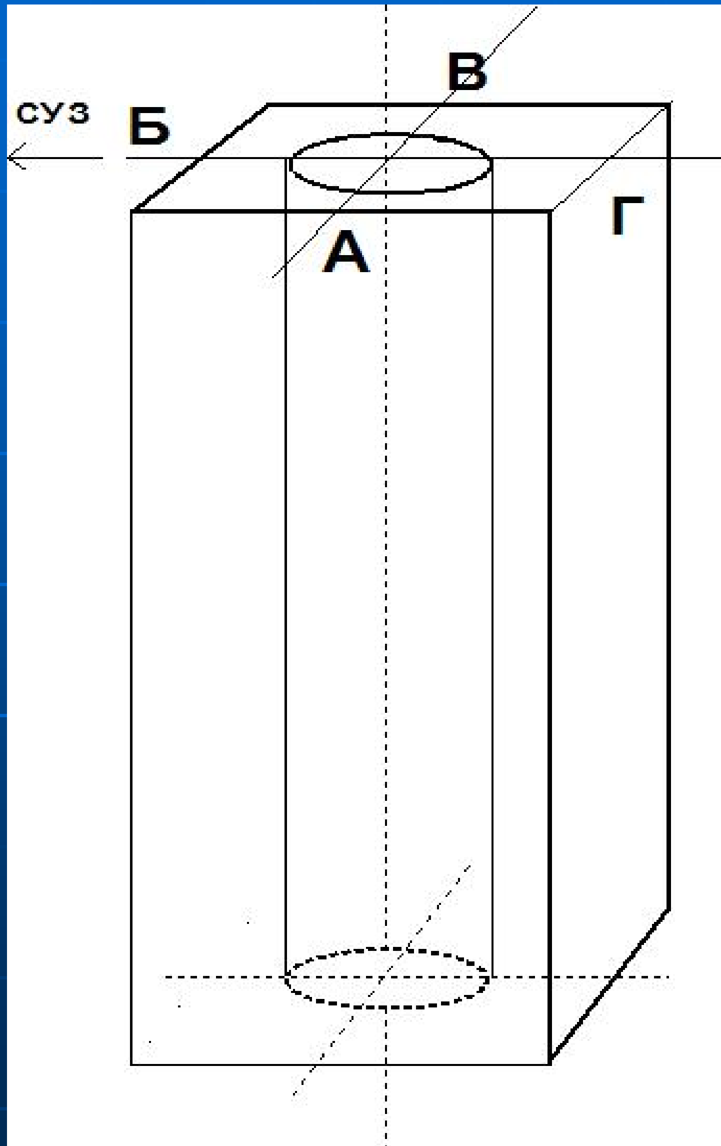
## Exposition to:

- Temperature: T = 300-750 C
- Thermal and Fast neutrons

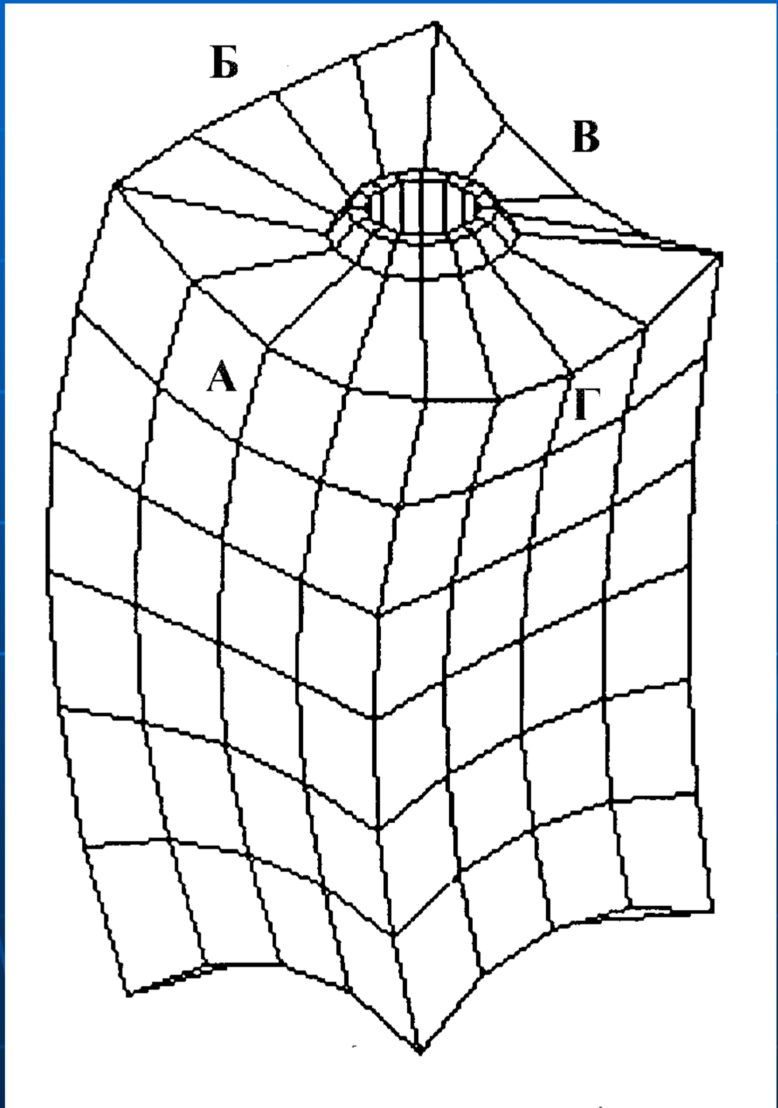
## Important behavior:

- Radiation swelling
- Degradation of thermo-mechanical properties
- Cracking and fracture

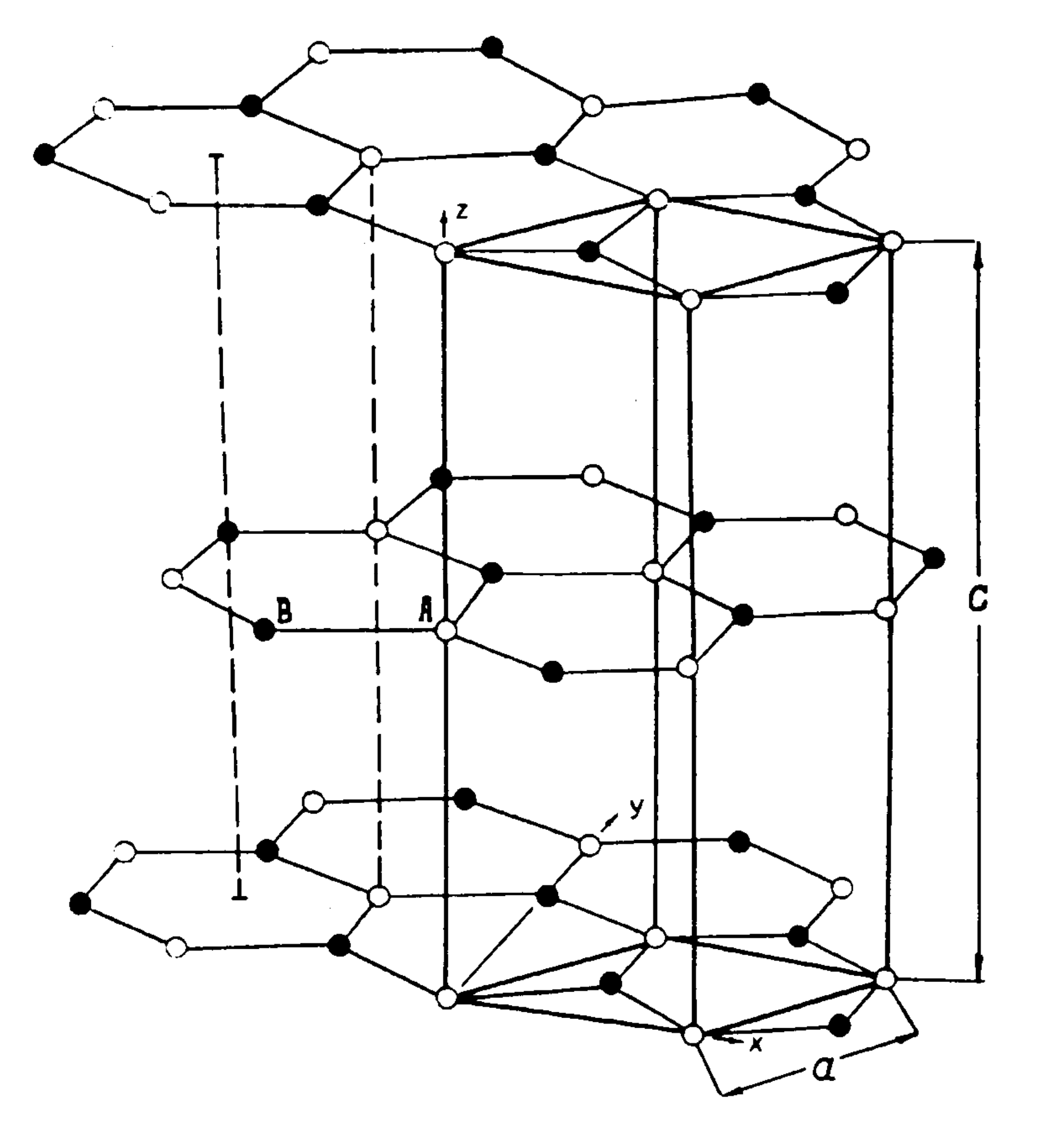
# Graphite Sheave for Atomic Station



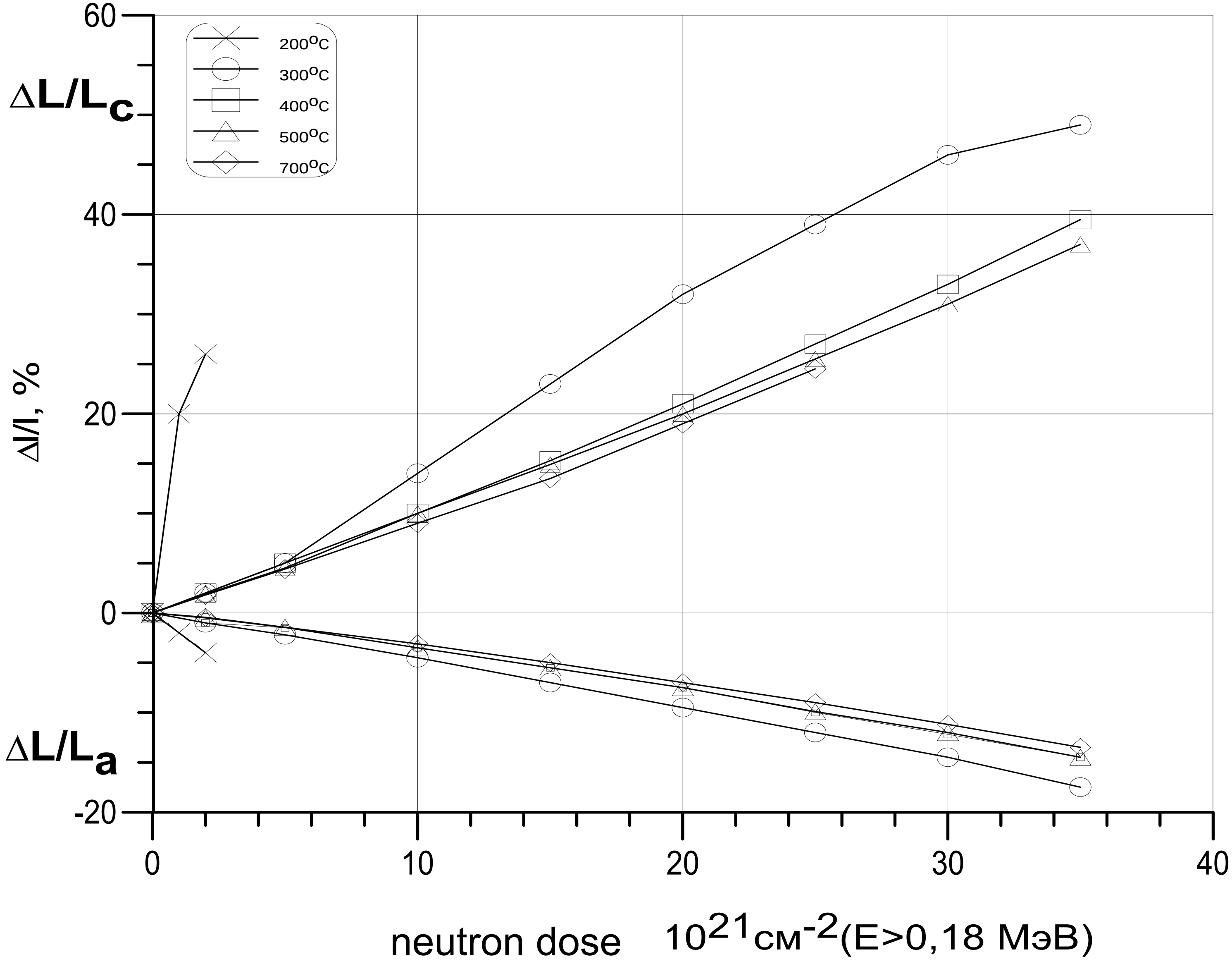
# Graphite Sheave after Irradiation in Atomic Station



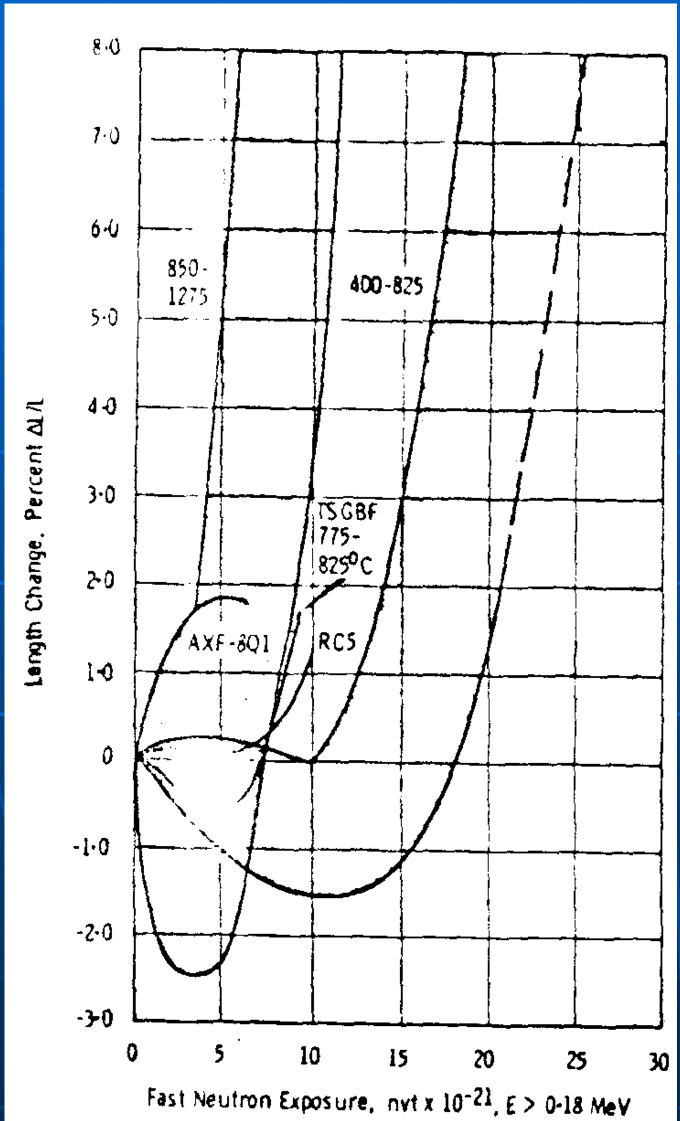
# Graphite Elementary Cell

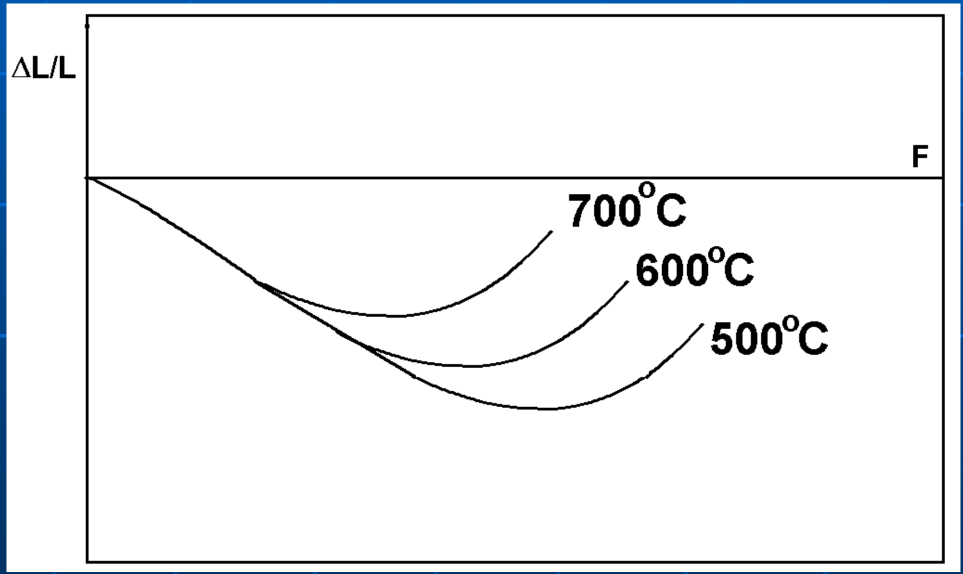


# Cell Size Change of Irradiated Pyrographite in Dependence on Irradiation Dose and Temperature

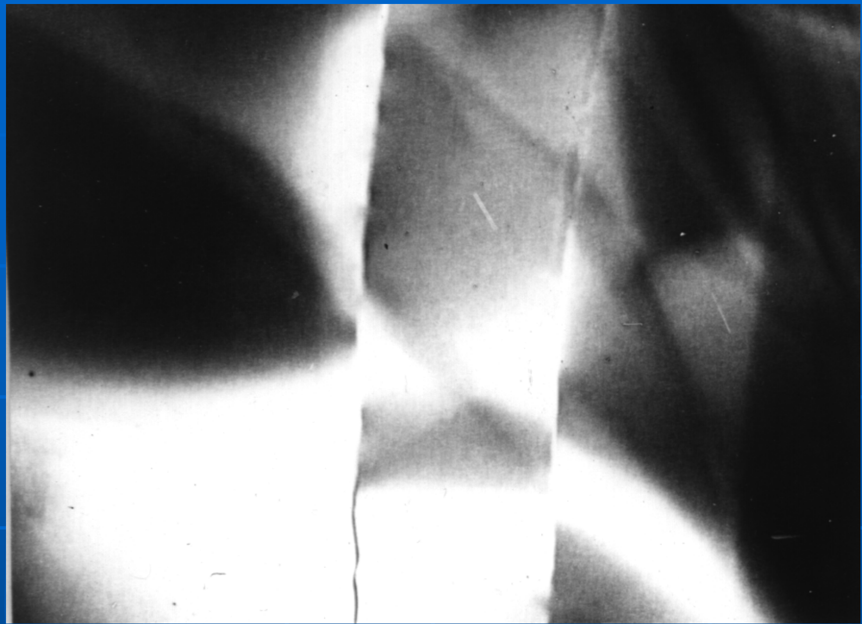


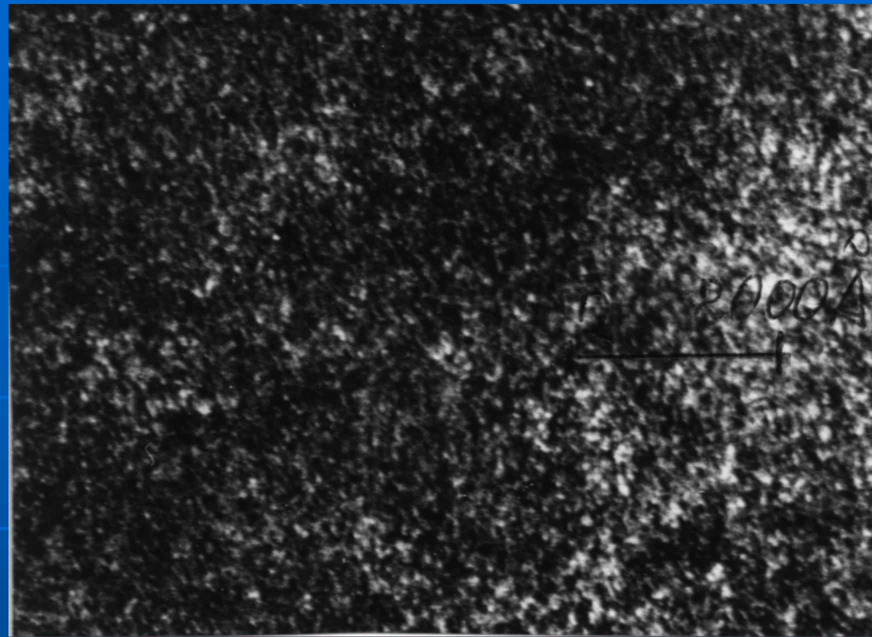
# Radiation Shrinkage and Swelling of Graphite

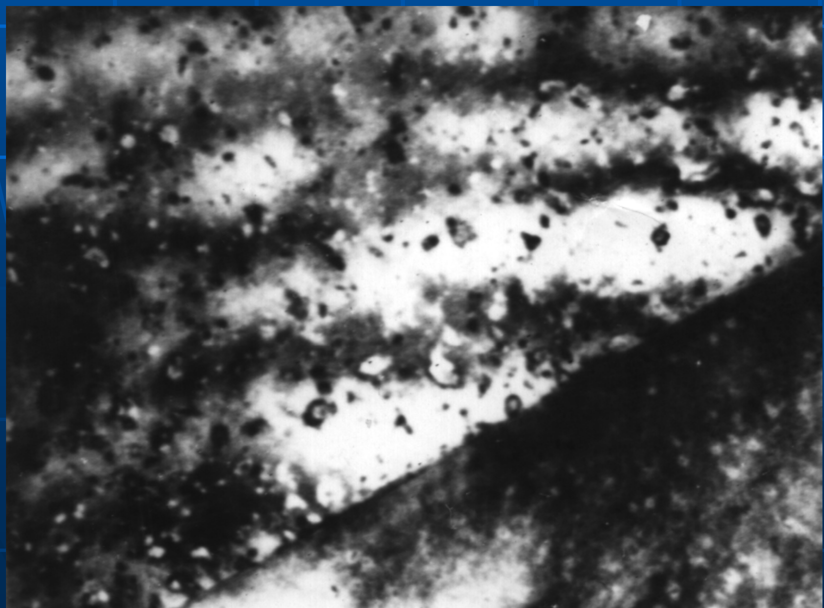


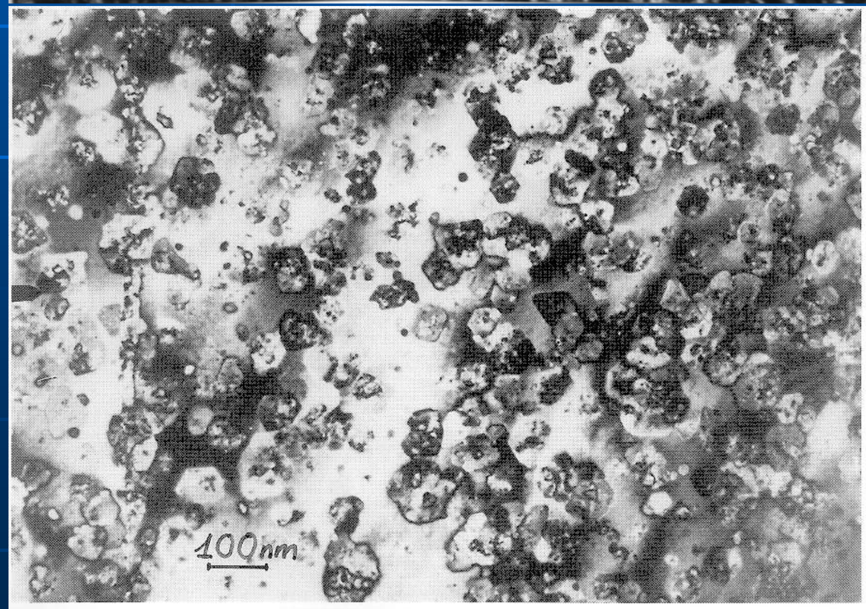



# Radiation Damage in Graphite



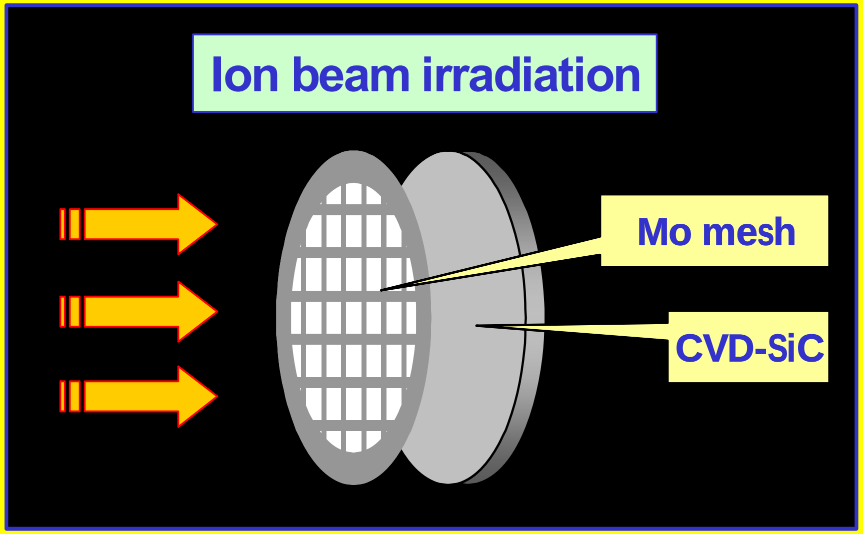


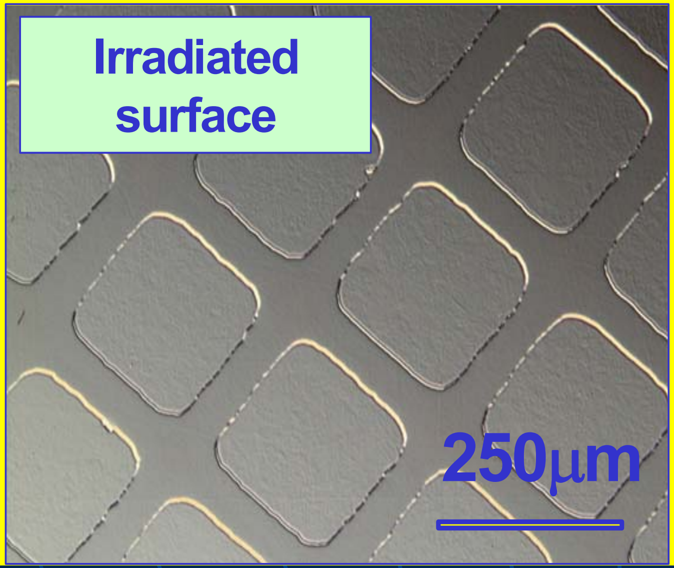



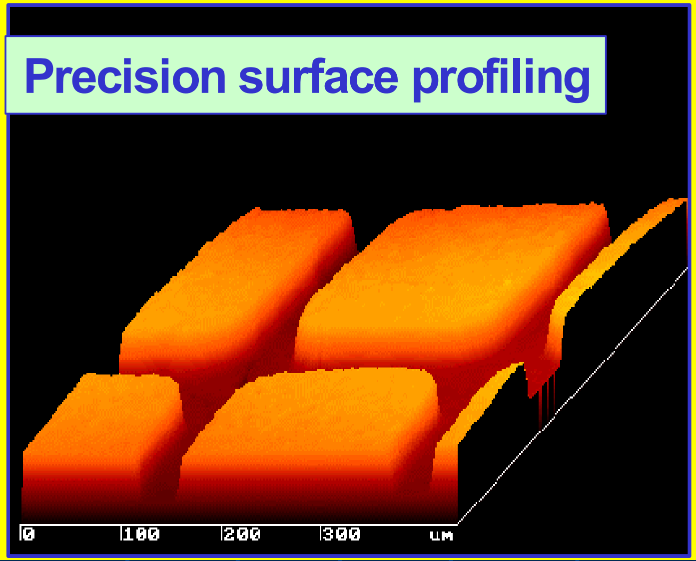


# Experimental tests of radiation resistance of SIC materials

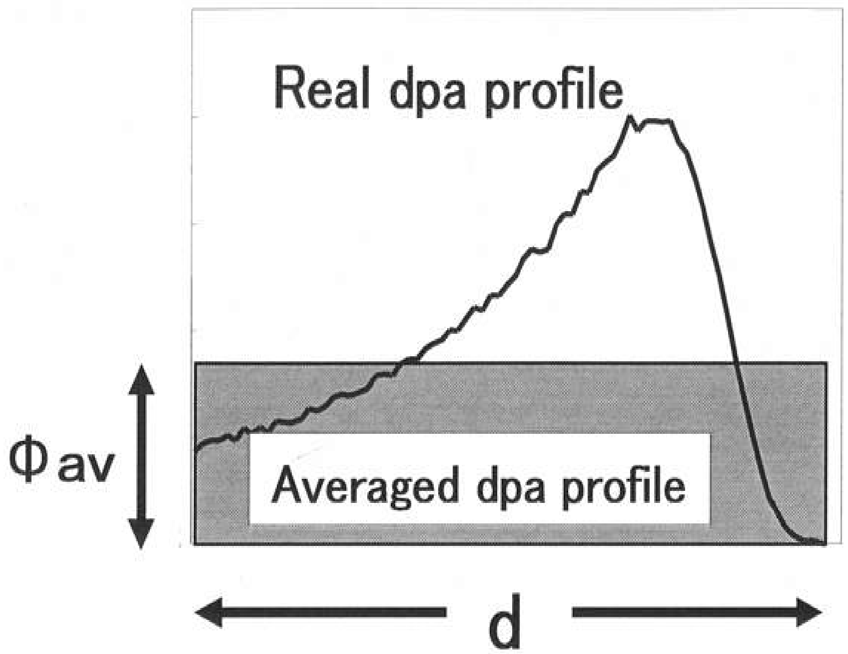
## Ion beam irradiation and Surface profile characterization

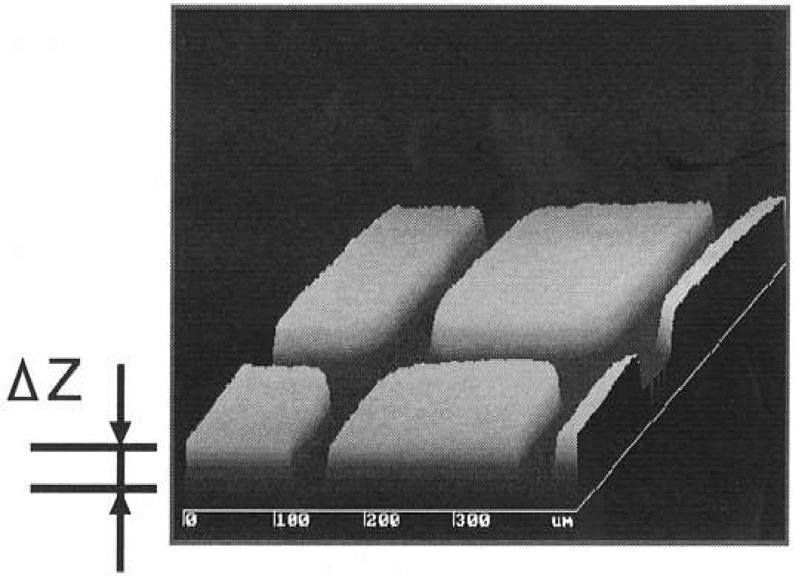


# Experimental Measurement of Radiation Swelling

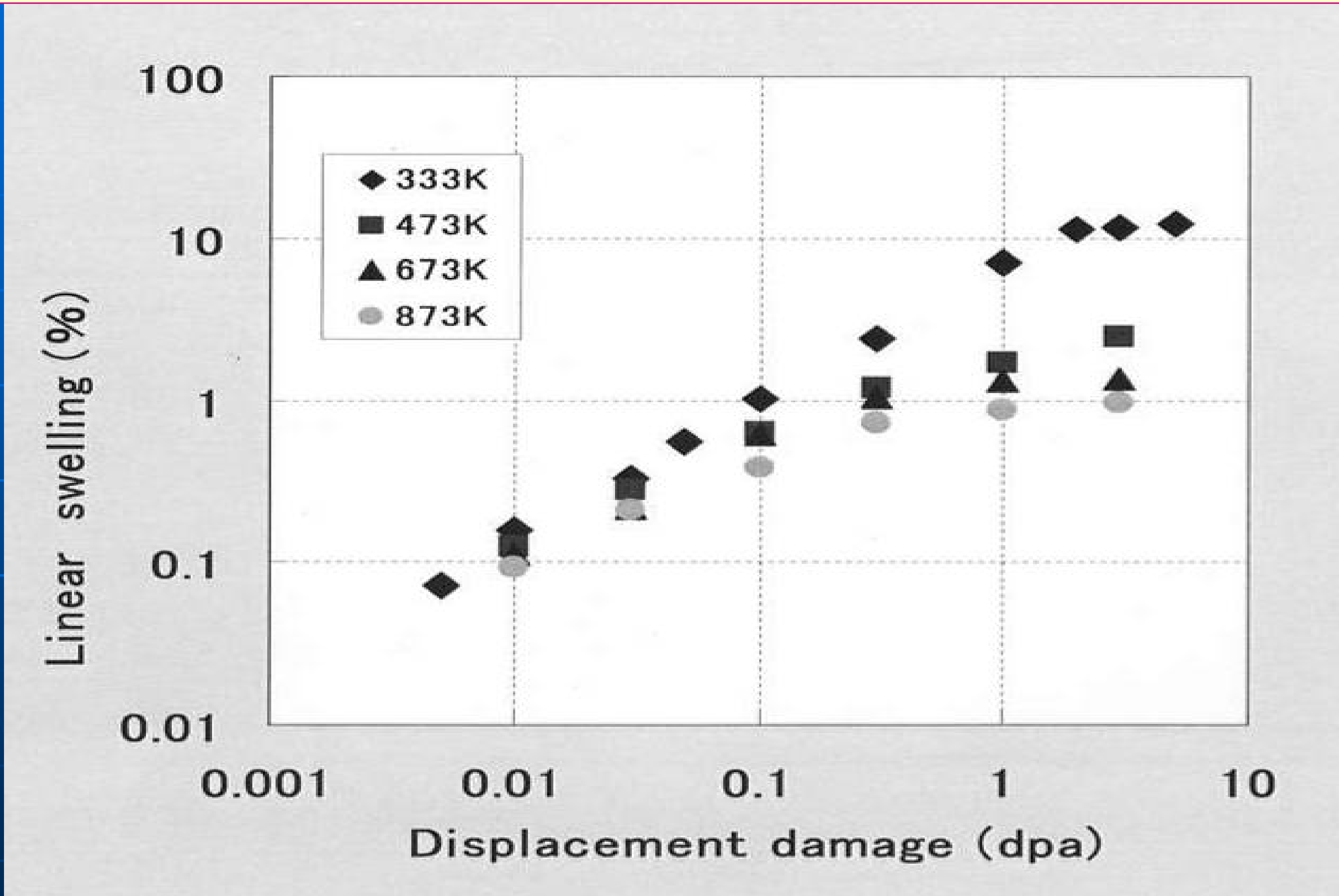


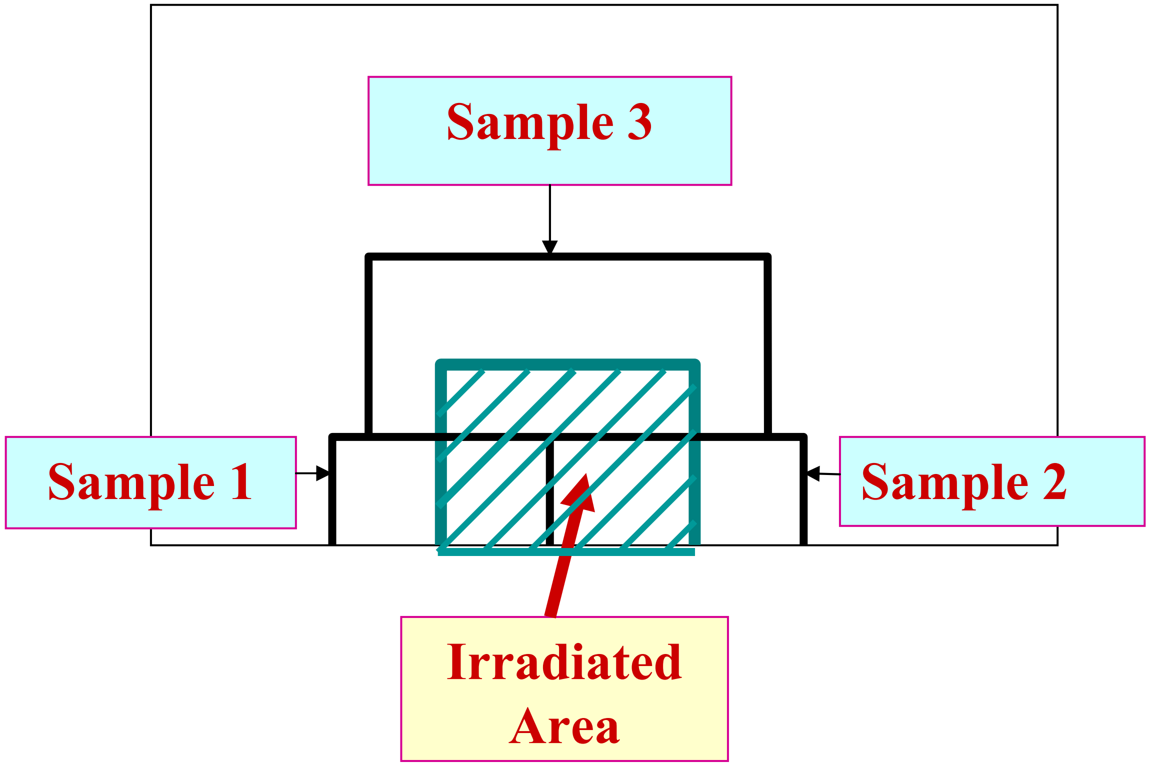

$$\Delta V / V\ (\Phi_{av}) \cong \Delta Z / d$$

**$\Phi_{av}$ – Averaged dpa profile,**
**$\Delta Z$ - Height of step between irradiated and no irradiated area,**
**d - Penetration depth of irradiated sample.**

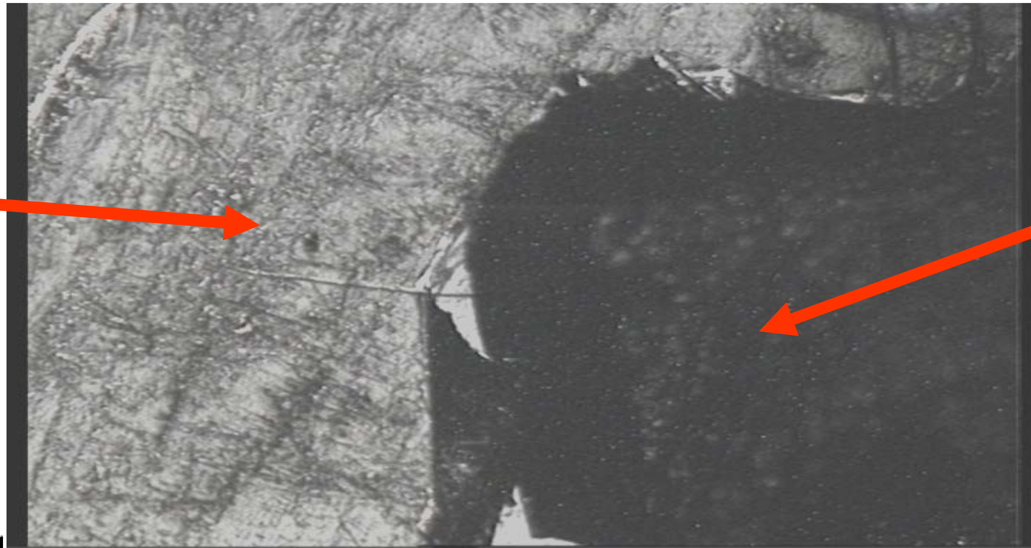
# Dose dependence of radiation swelling in SiC

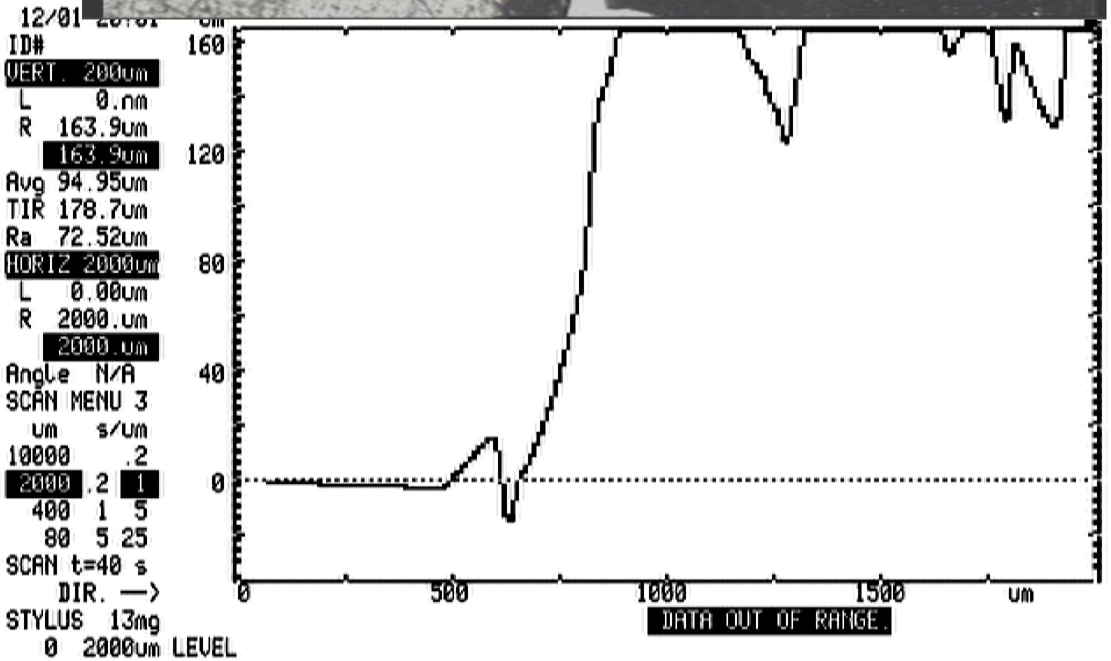


# Scheme of Irradiation of Graphite Samples by Carbon Ions

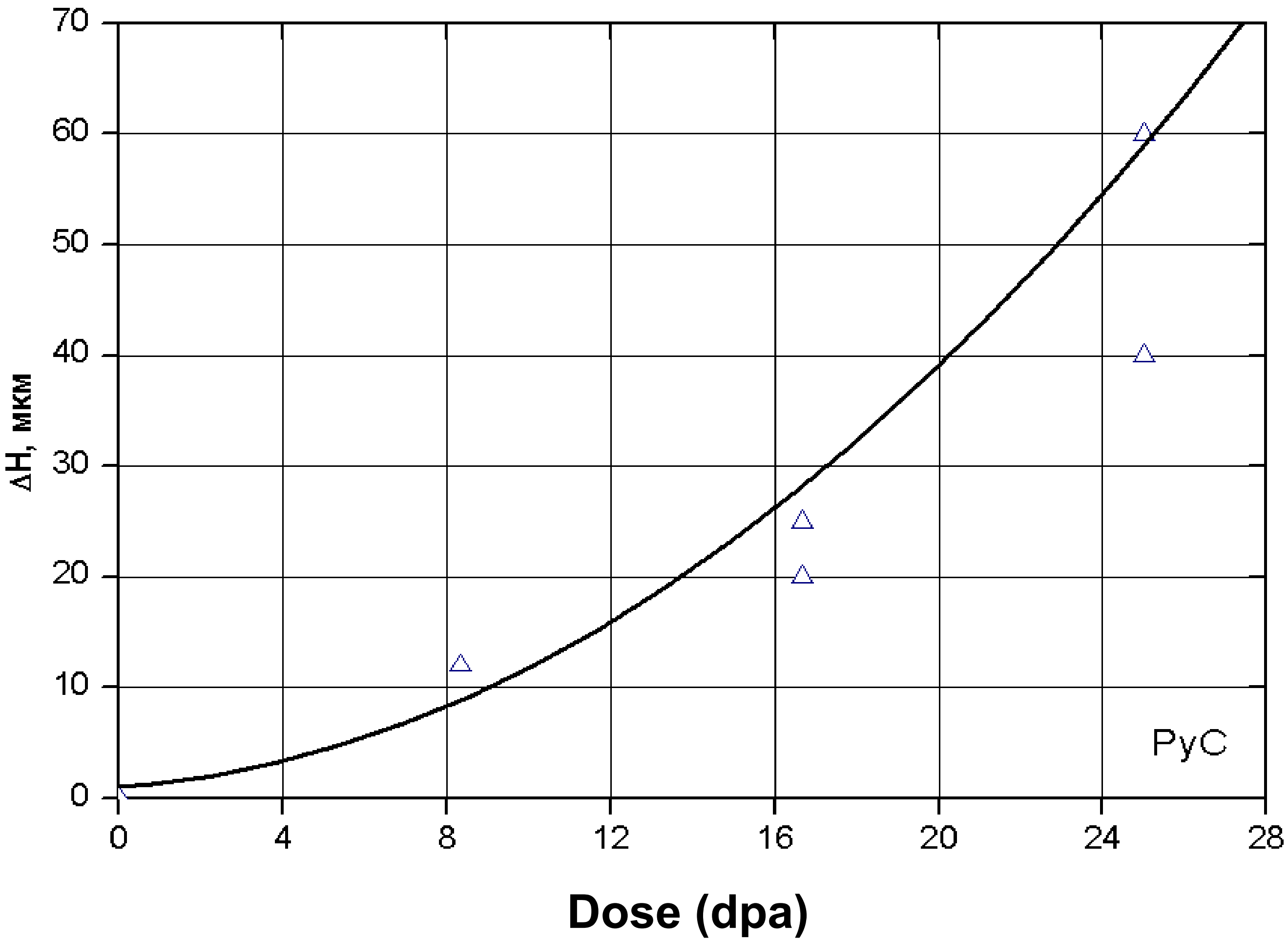


# Picture of Irradiated and Unirradiated Sample Area, Measurement of Radiation Swelling



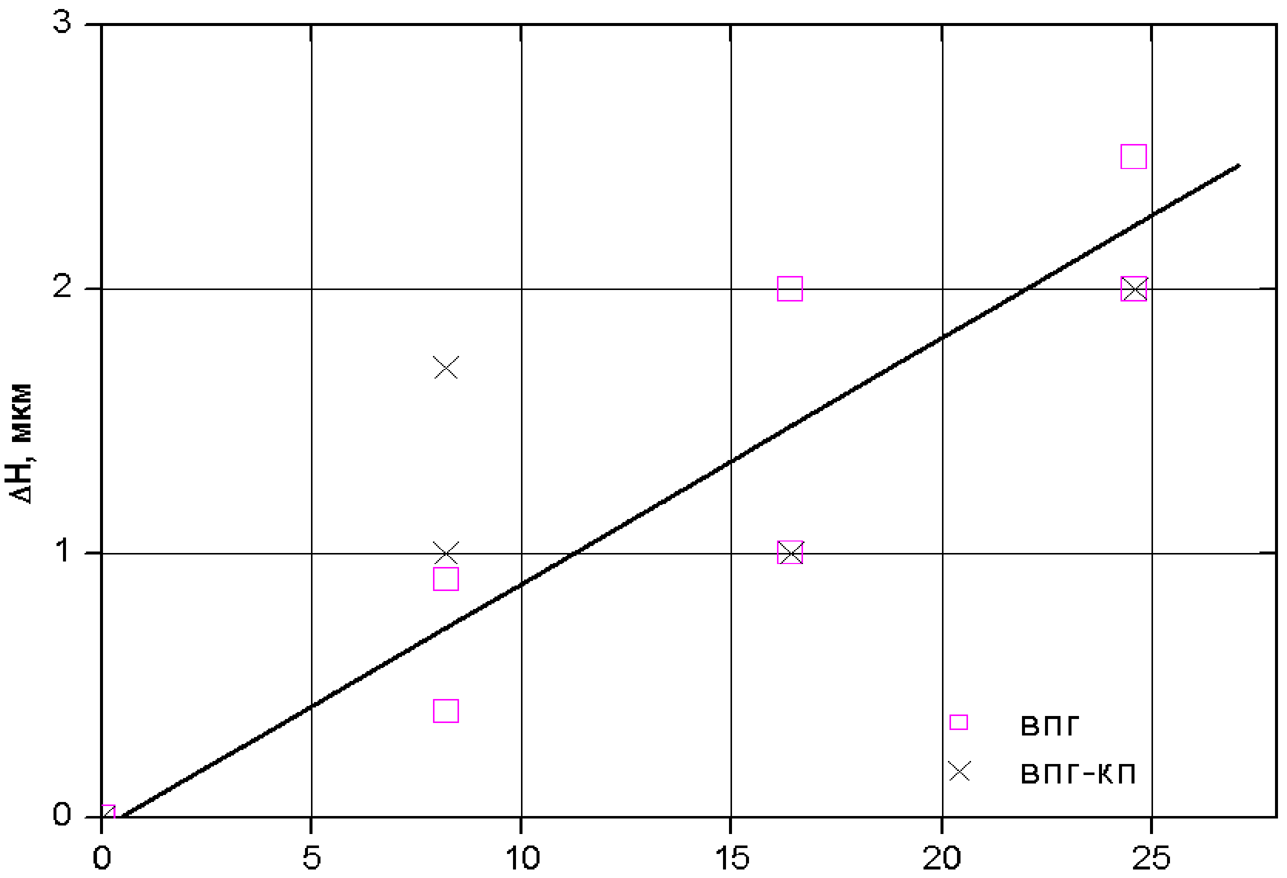



# Dose Dependence of Radiation Swelling Pyrolytic graphite at $E_c$ = 3 MeV, T=450 C



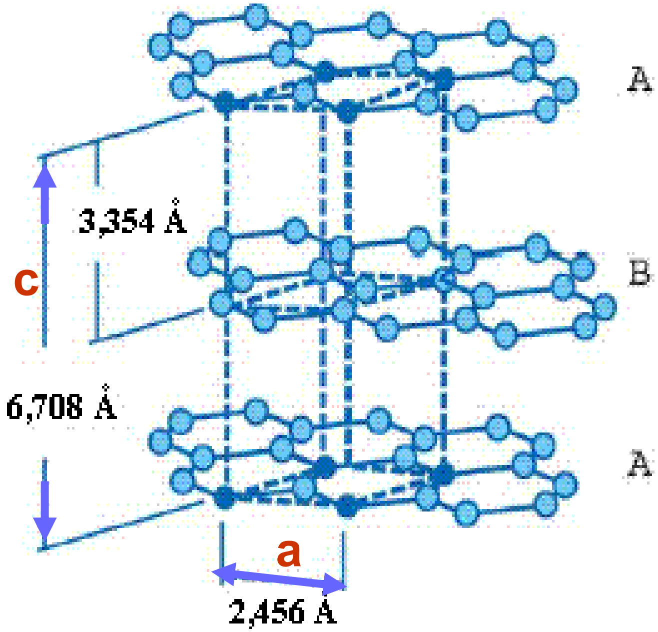

(1dpa = 10E21 n/cm2)

# Dose Dependence of Radiation Swelling Reactor Graphite at Ec = 3 MeV, T=450 C




**Dose (dpa)** **(1dpa = 10E21 n/cm2)**

# Graphite - two diamenthial anisotropic diffusivity




Crystal lattice of graphite

*Current of point defects on dislocation loop:*

$$J_L = -2\pi b Z_L D_m C_m$$

*Current of point defects on spherical void:*

$$J_V = -4\pi R_V Z_V D_m C_m$$

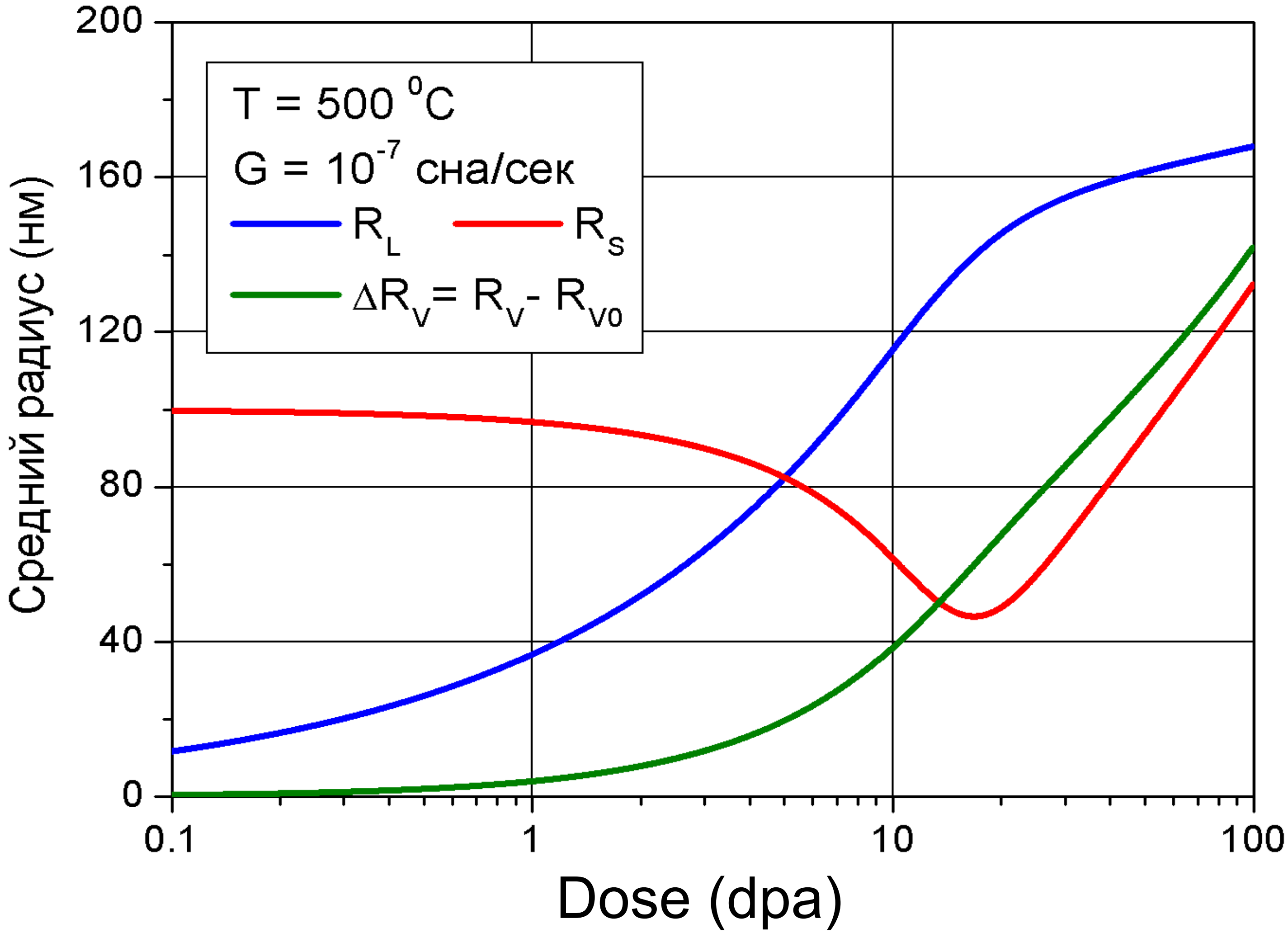
*Current of point defects on disk void:*

$$J_S = -2\pi d Z_S D_m C_m$$

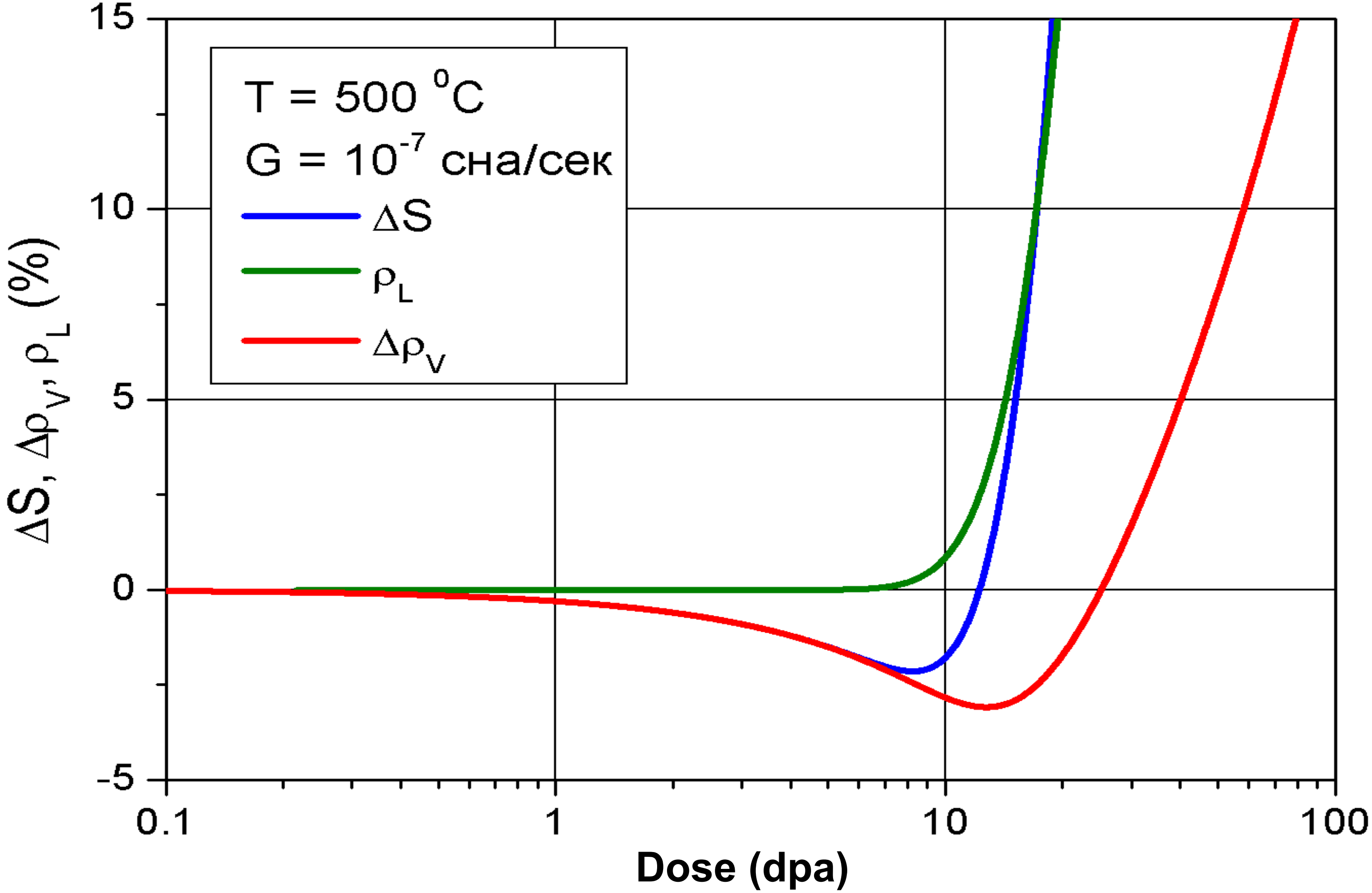
***Radiation swelling of graphite:***

$$S = 2{,}72 C_i - 0{,}08 C_v + 1{,}242 N_L V_L + \Delta\rho_V$$

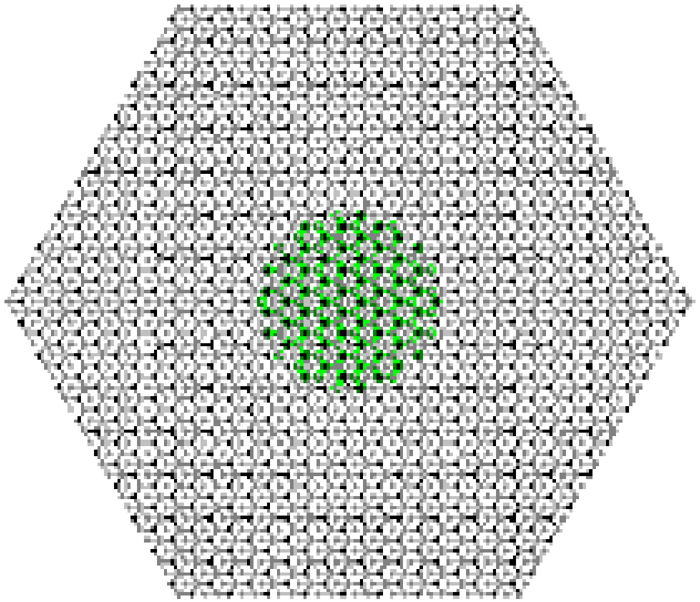
# Dose dependence of void and loop radius

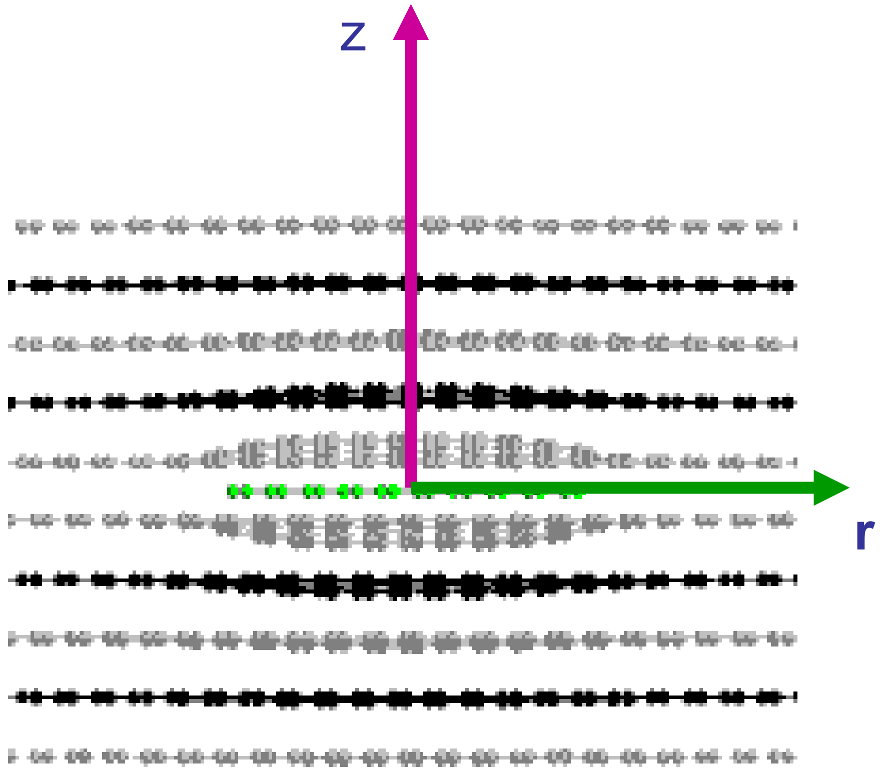


# Dose dependence of swelling

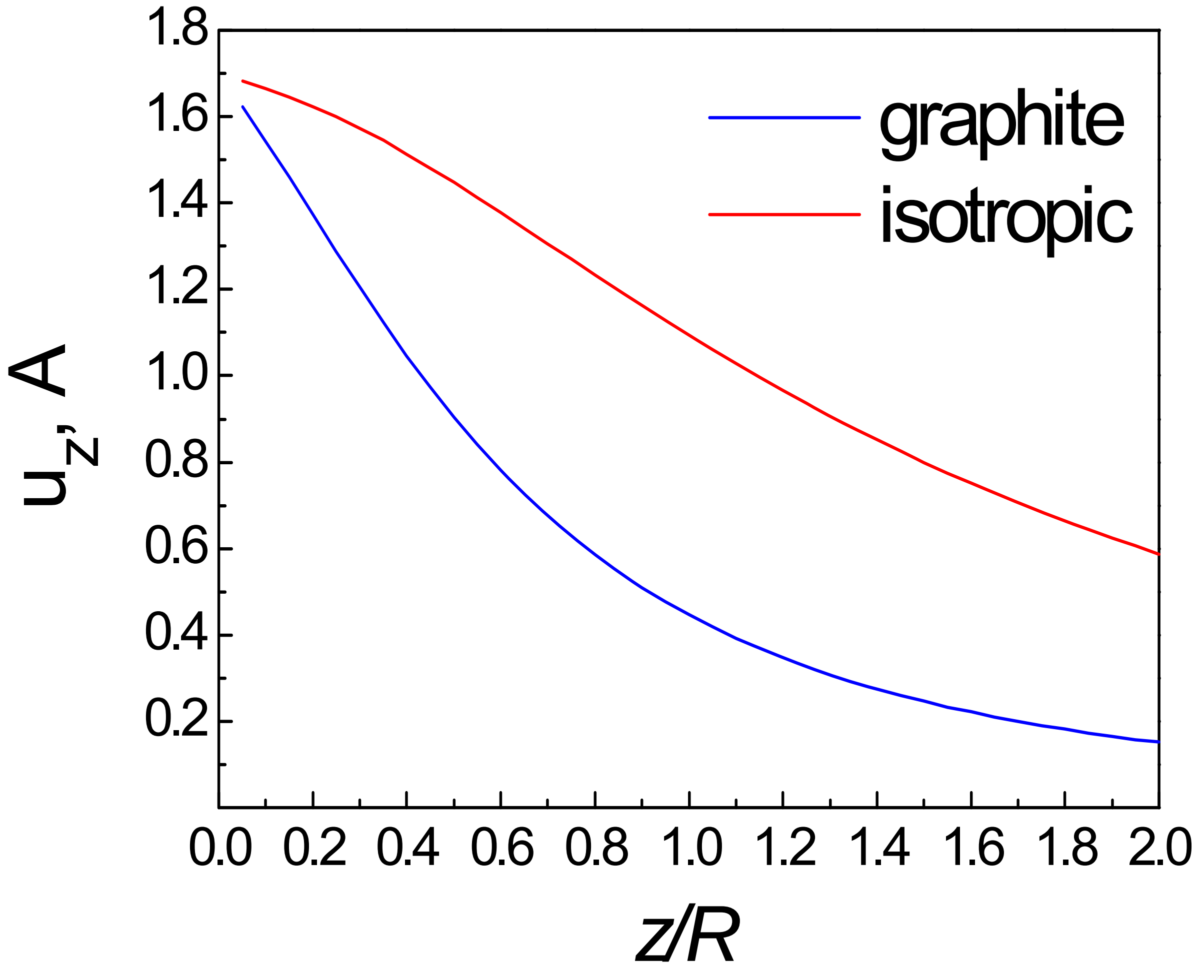


# Modeling of dislocation loops in graphite



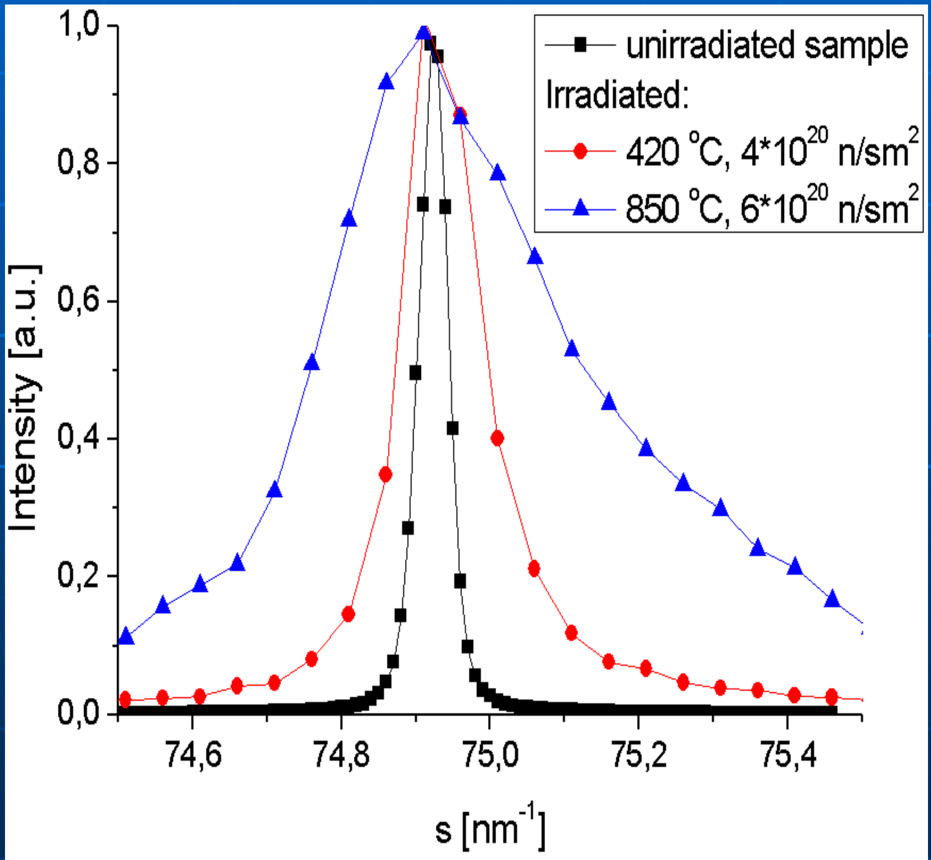


# Distribution of displacement field Uz near dislocation loop in graphite as a function of distance from loop

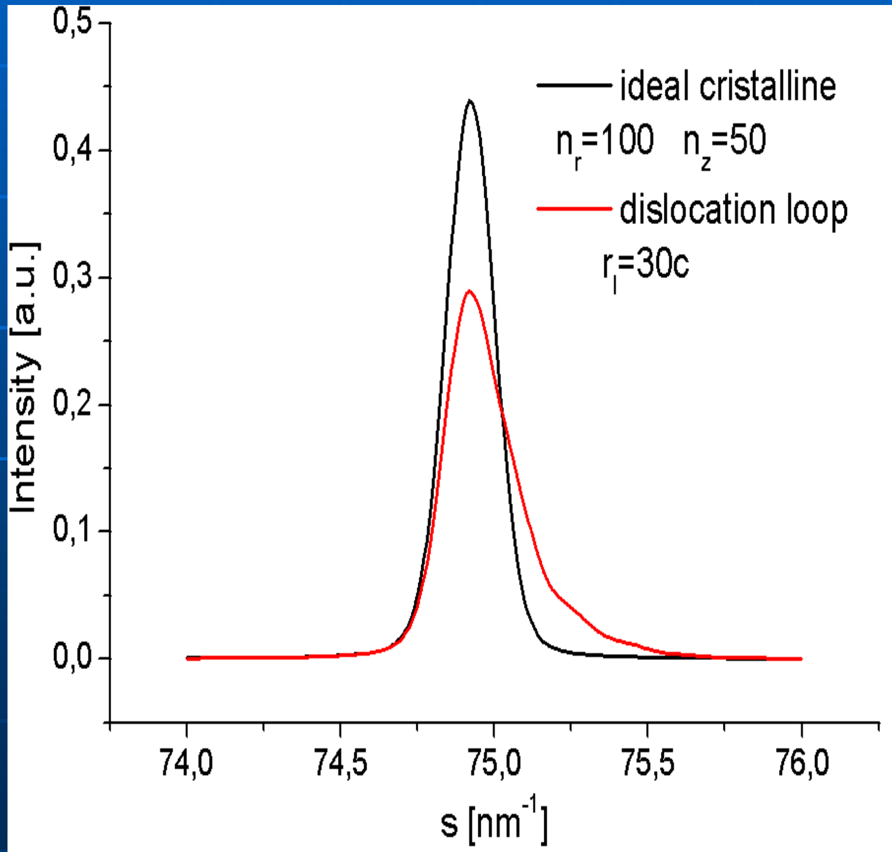


# Bragg scattering in neutron irradiated graphite

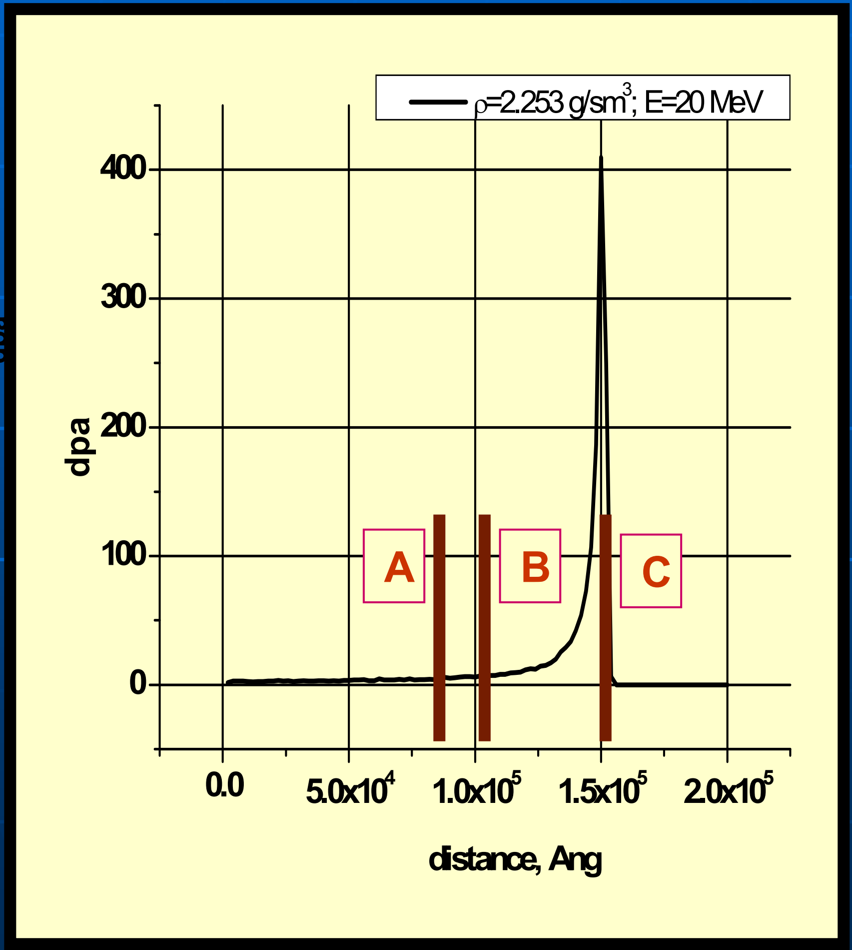
## Experimental Results

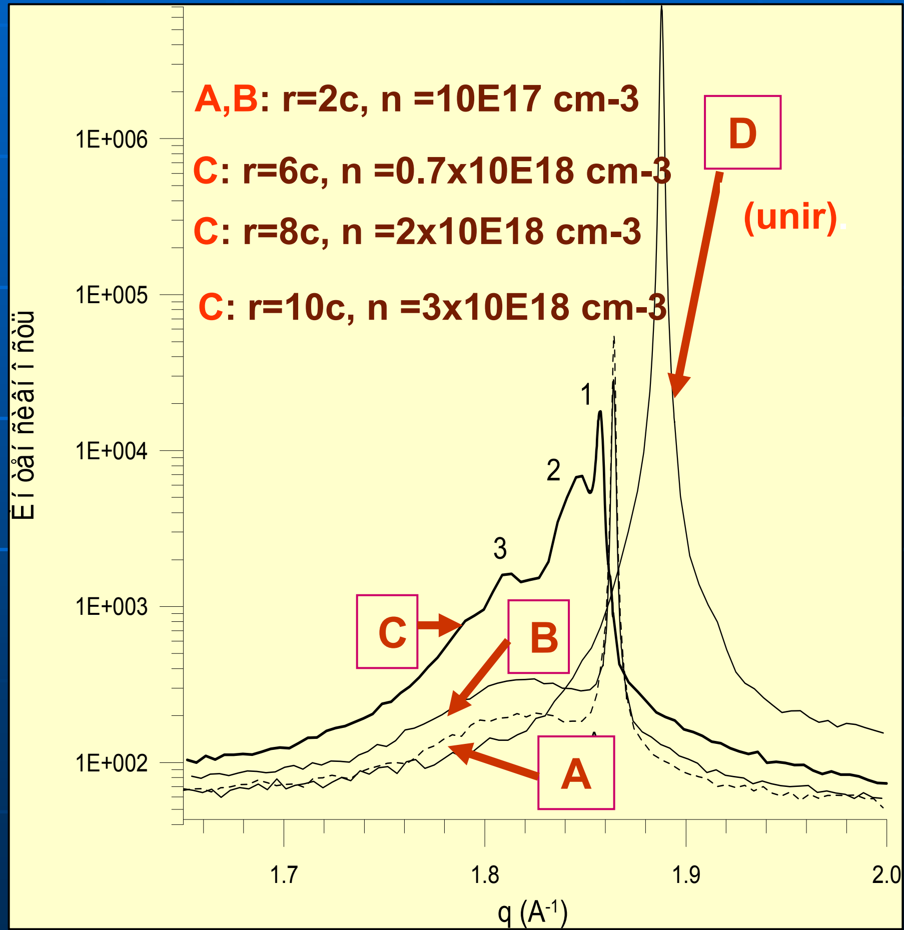



## Theoretical calculations



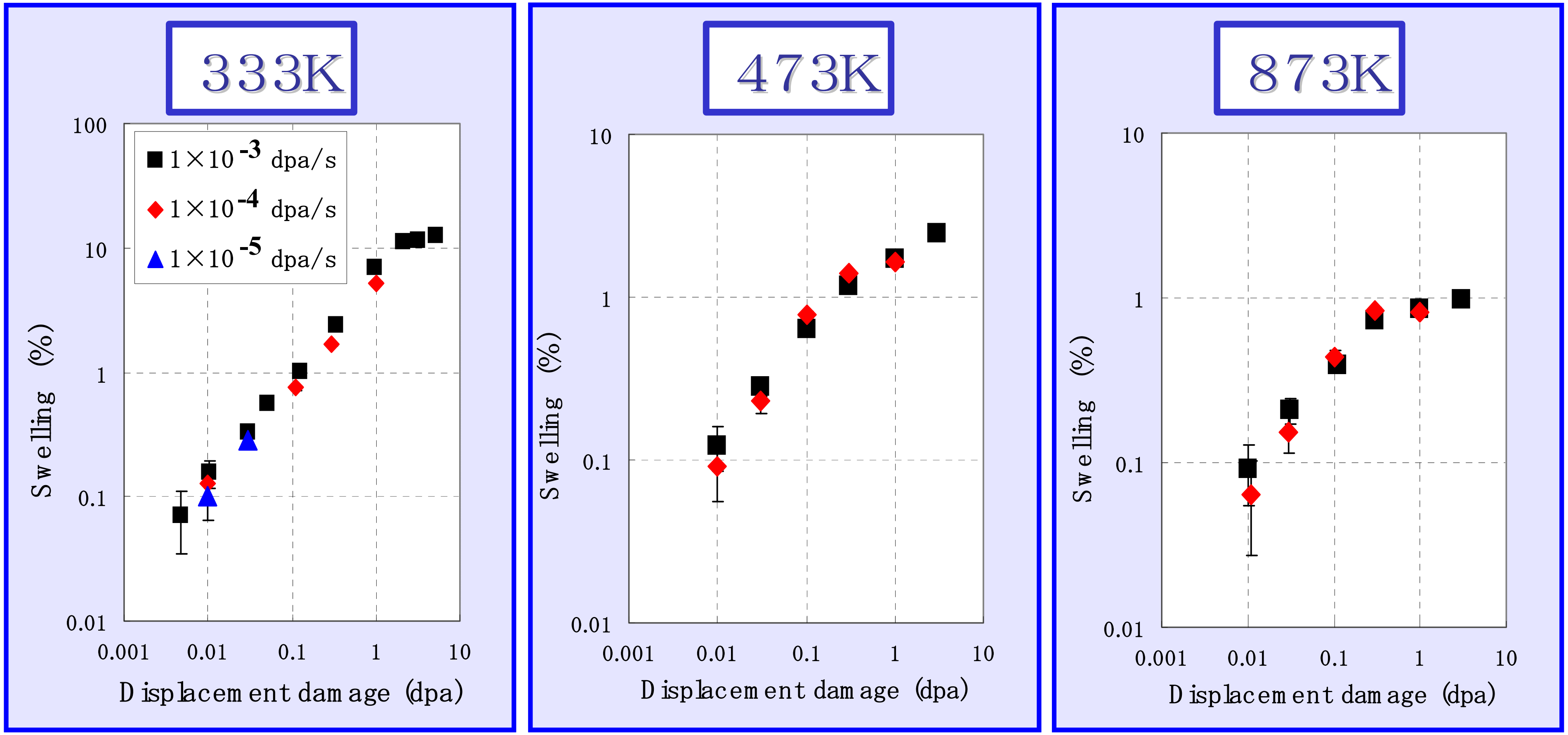
# Bragg scattering in C-ion irradiated graphite with energy 20 MeV



# *Radiation Resistance of Ceramic Materials*

# Dose rate dependence of Ion-induced swelling in CVD-SiC

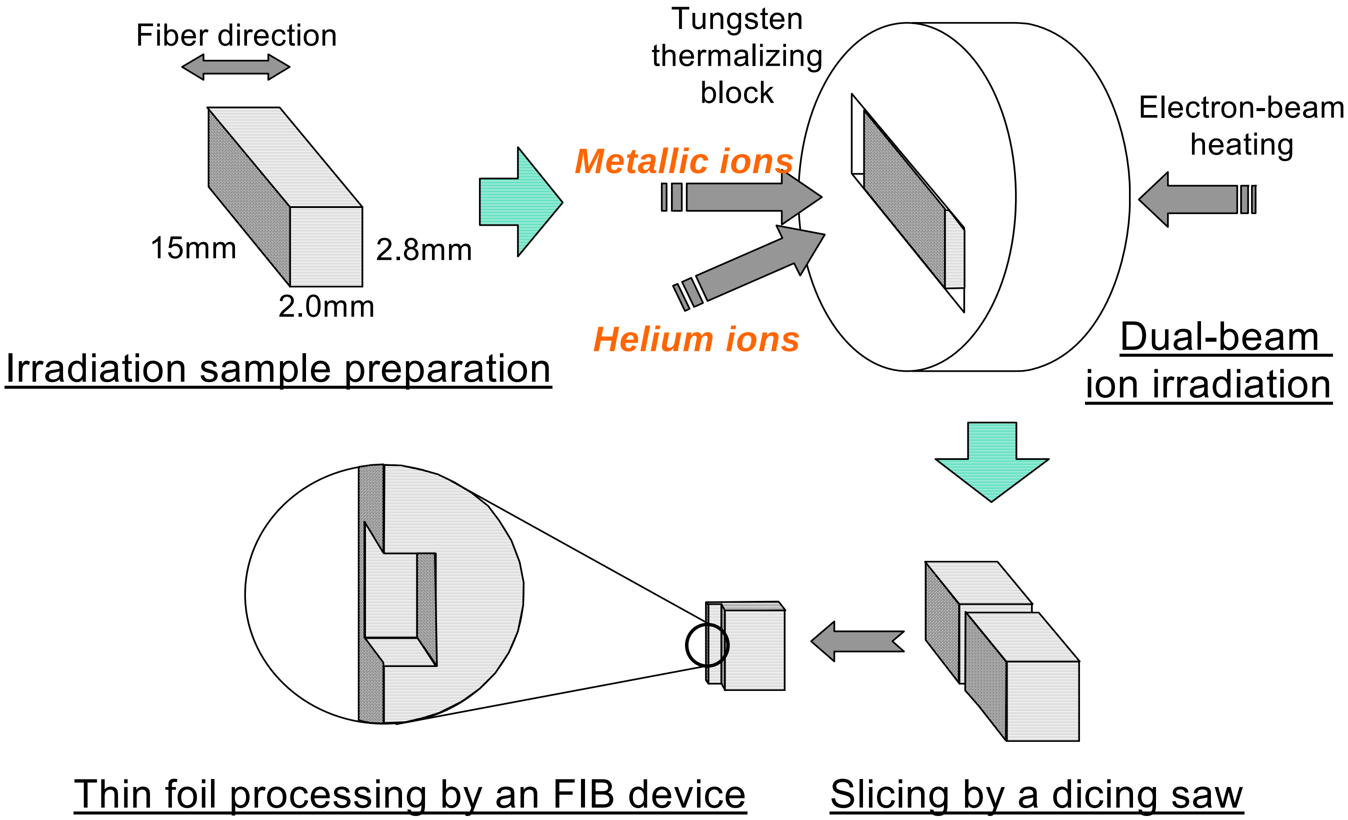



The displacement damage rates were 1×10$^{-4}$ and 1×10$^{-3}$ dpa/s at 333K-873K and 1×10$^{-5}$ dpa/s at 333K with single-beam irradiation. The error bars represent the 96% confidence limits for the Gaussian distribution. **(A. Kohyama)**

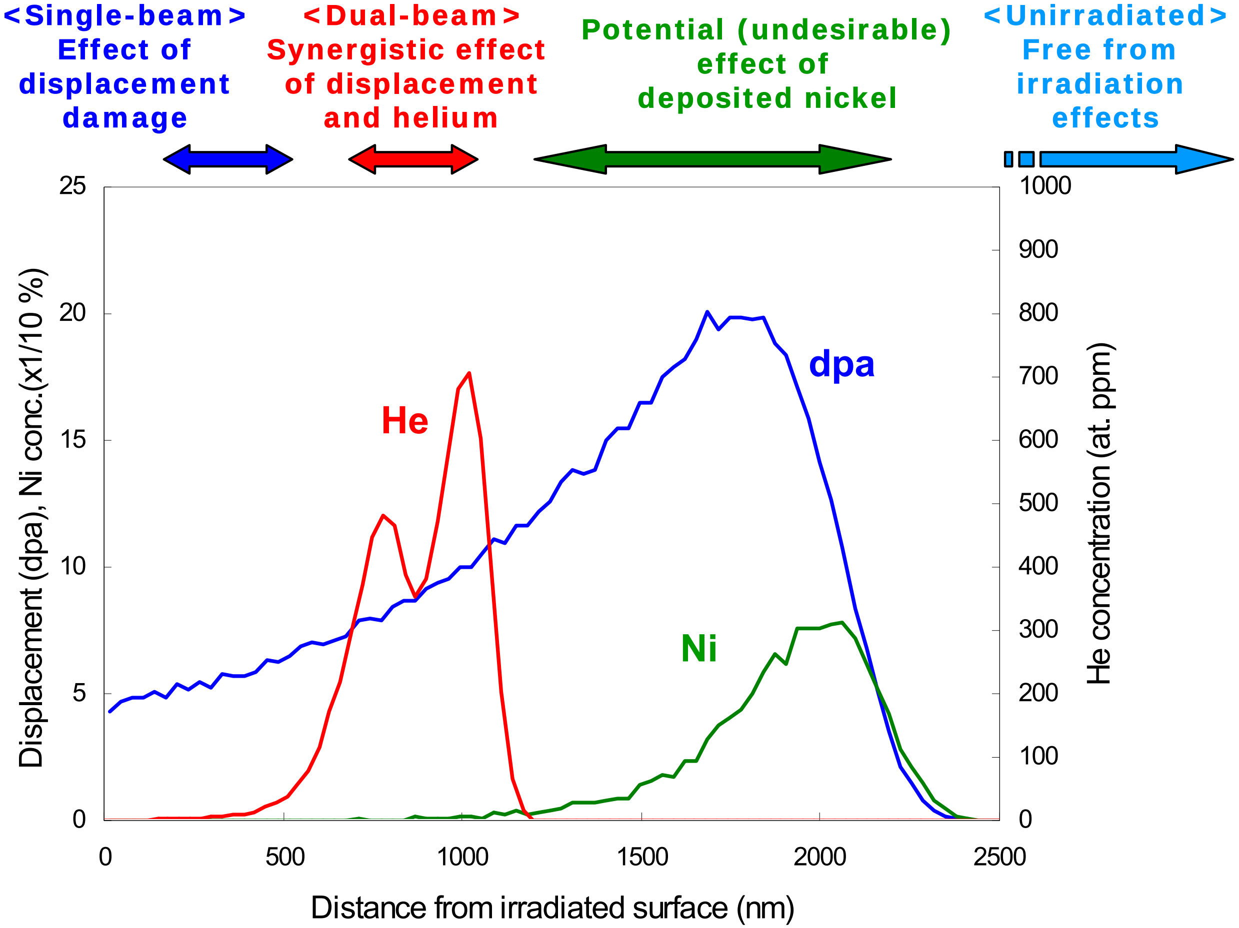
# Effect of Helium on Radiation Swelling of SiC

***Experimental procedure illustrated***

A. Kohyama
*Kyoto University*



## Profiles of displacement damage and deposited Ni in irradiated monolithic SiC. Calculated by TRIM-92 assuming Ed=35eV, $\rho$=3.21g/cm$^3$.



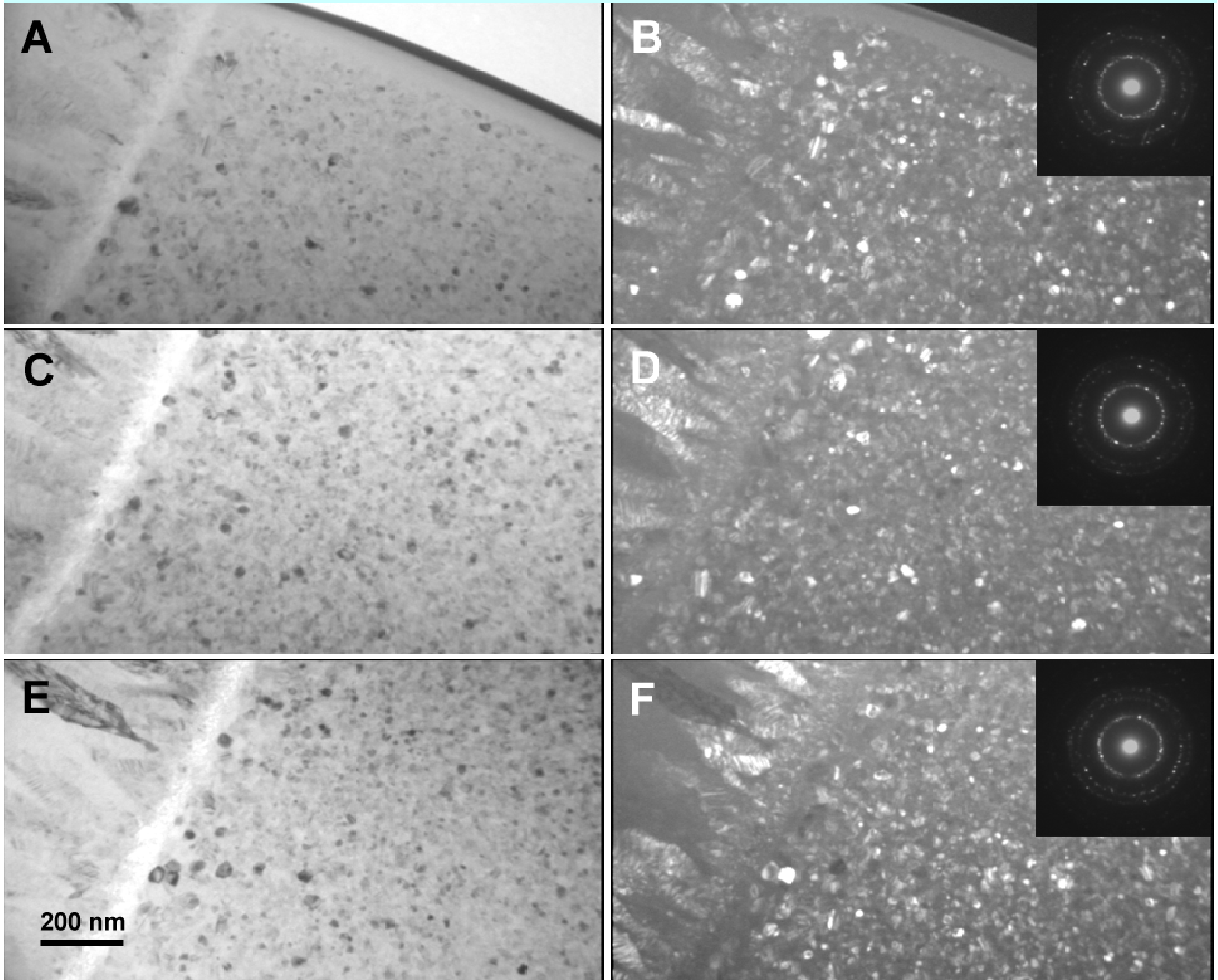

Depth-profiles of atomic displacement damage, deposited He and Ni ions in dual-beam irradiated randomly oriented micro-crystalline SiC calculated by TRIM-92 assuming target mass density of 3.21g/cm$^3$ and average displacement threshold energy of 35eV.

## *TEM images and SAD patterns for singlebeam (A,B), dual-beam (C,D) and unirradiated (E,F) regions of Hi-Nicalon® Type-S/C/SiC composite*

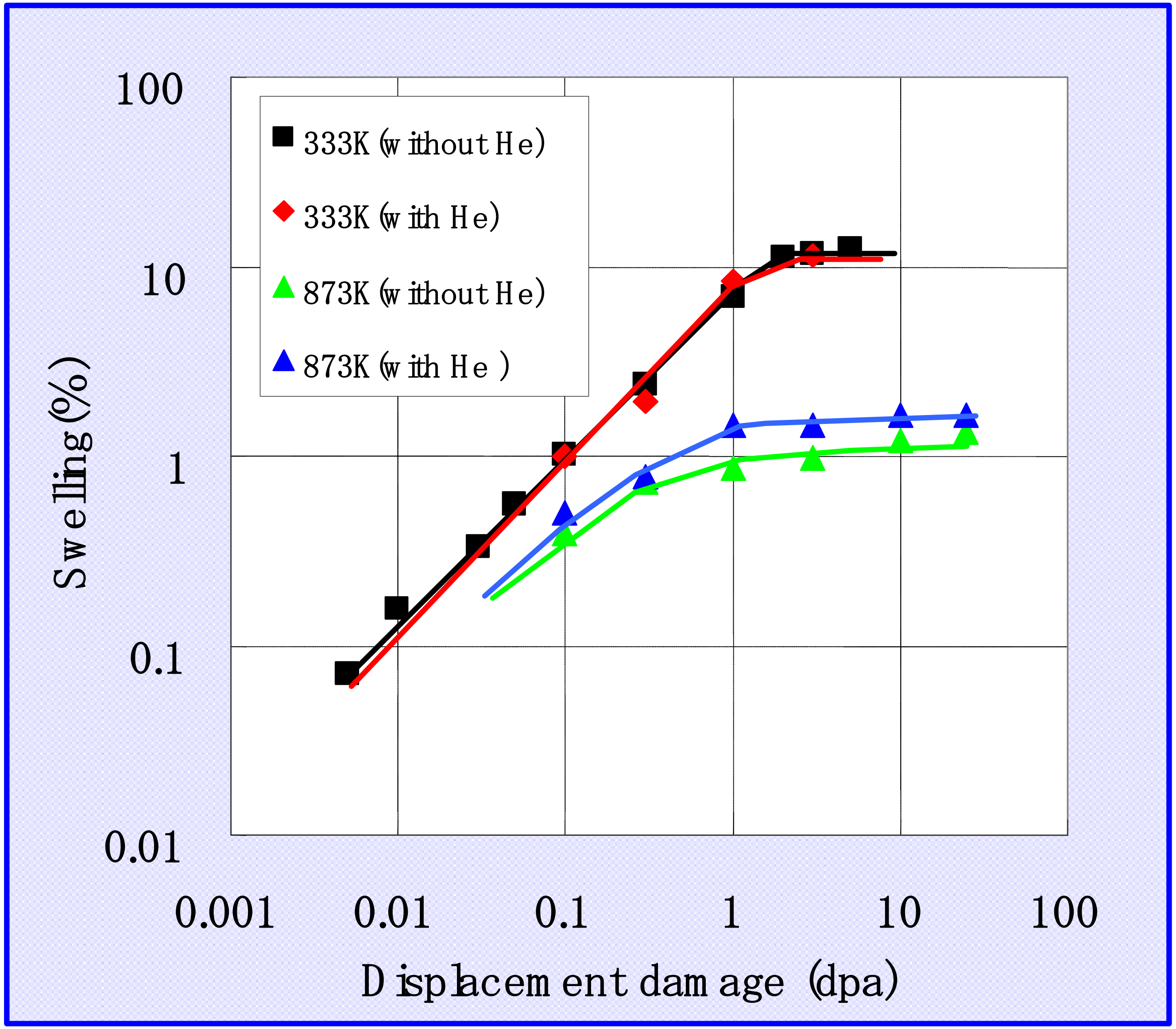
**Single-beam**
**10 dpa**
**873 K**
**$1x10^{-3}$ dpa/s**

**Dual-beam**
**10 dpa**
**873 K**
**$1x10^{-3}$ dpa/s**
**60appm-He/dpa**

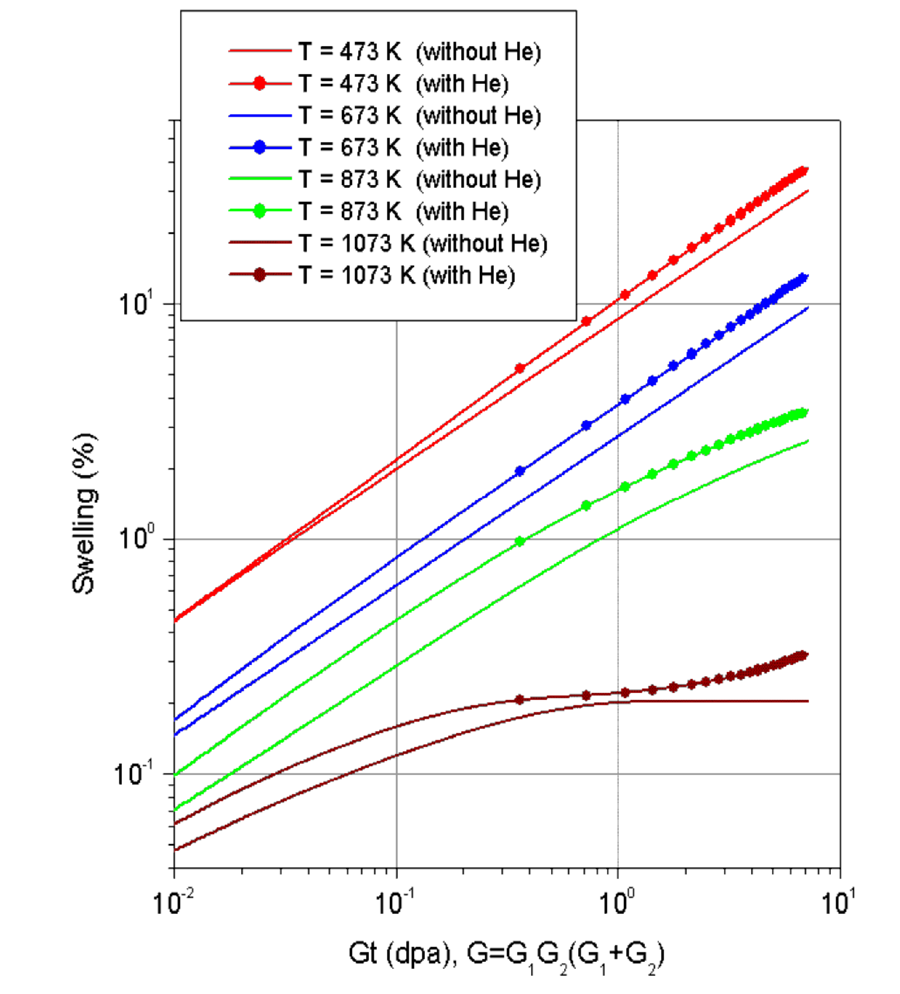
**Unirradiated**
**Dark field images from SiC <111> diffraction rings.**

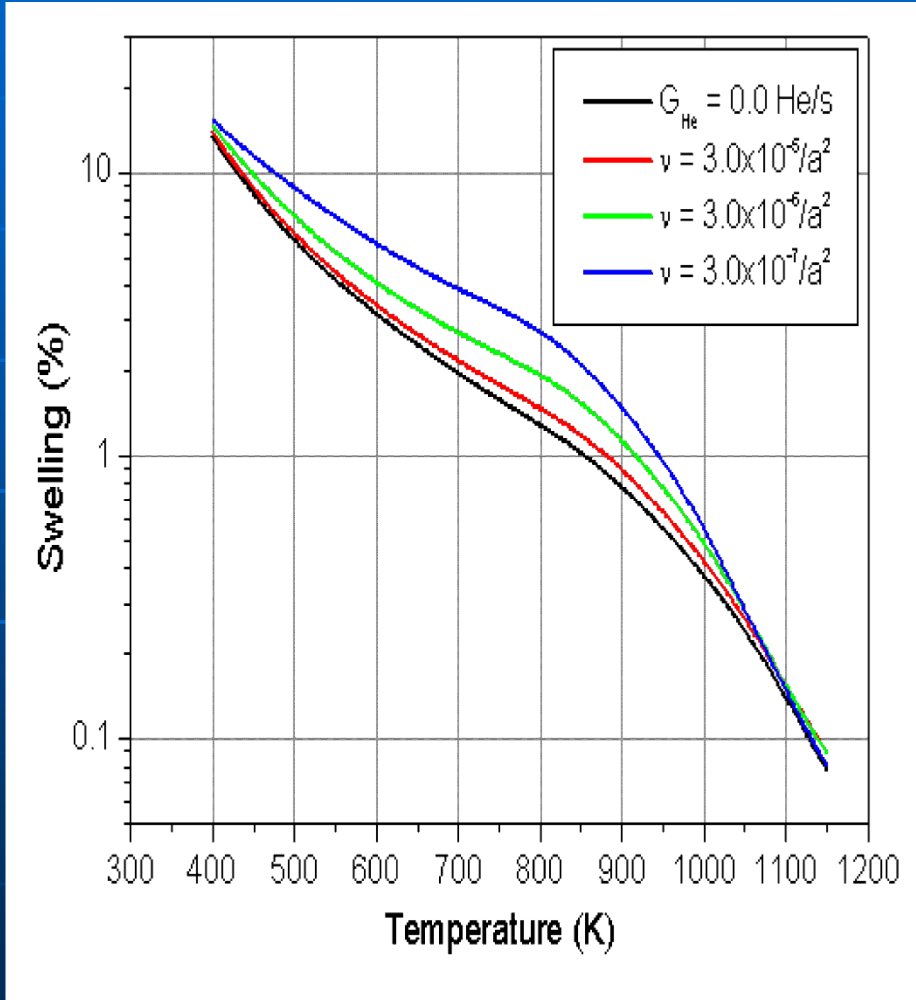


# Dual ion beam irradiation-induced swelling in CVD-SiC



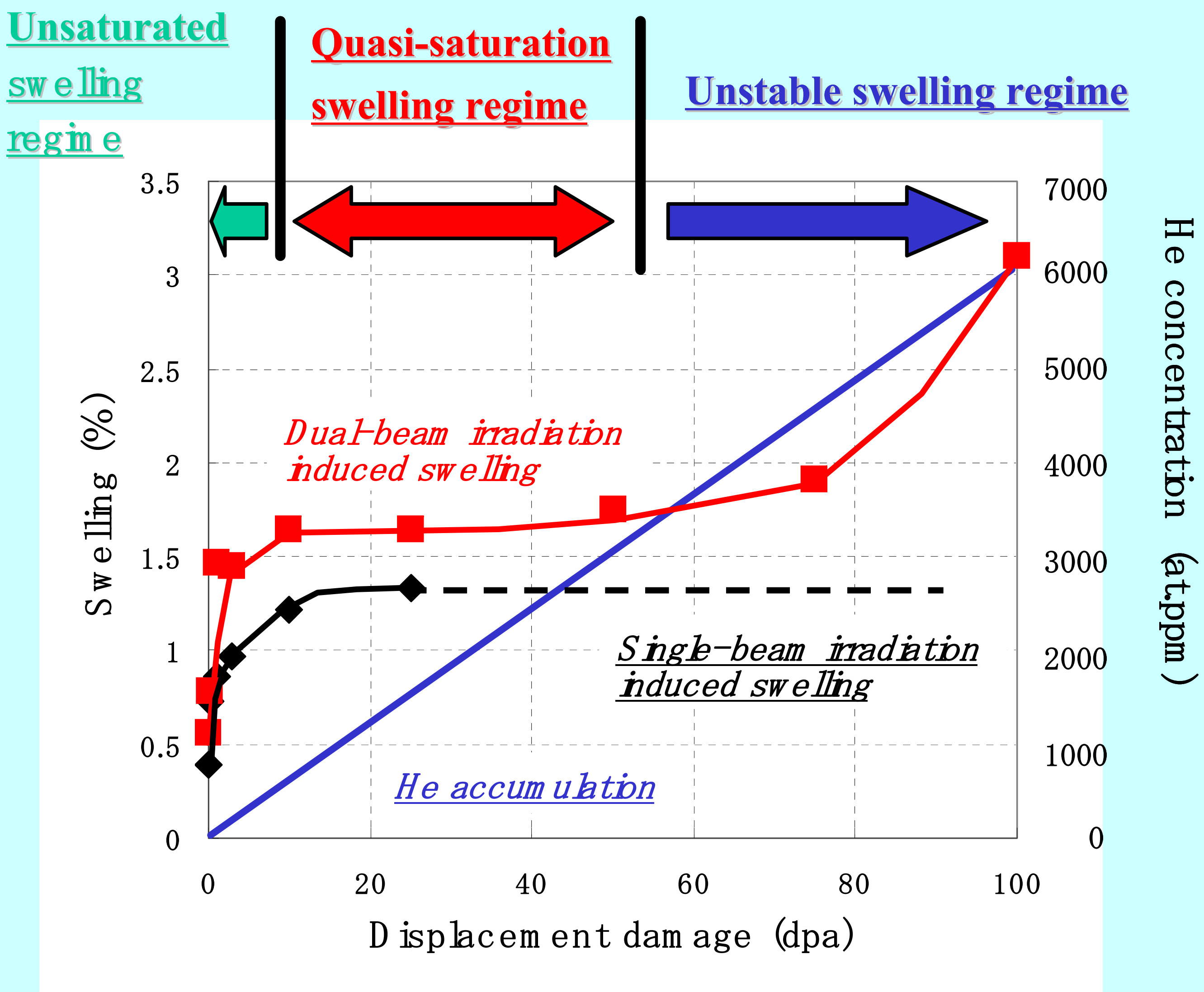
# Theoretical Calculations of effect of Helium on Radiation Swelling in SiC at RRC KI




A.Ryazanov, A.Kohyama et al

# He accumulation and irradiation-induced swelling in dual- and single-ion irradiated CVD-SiC at 873K



# Difference between metals and dielectrics

## Metals:

- Point defects are neutral

- Electric field does not exist in the matrix

## Dielectrics (Ceramic Materials):

- Point defects can have effective charge

- Electric field exists in the matrix under the influence of an applied electric field

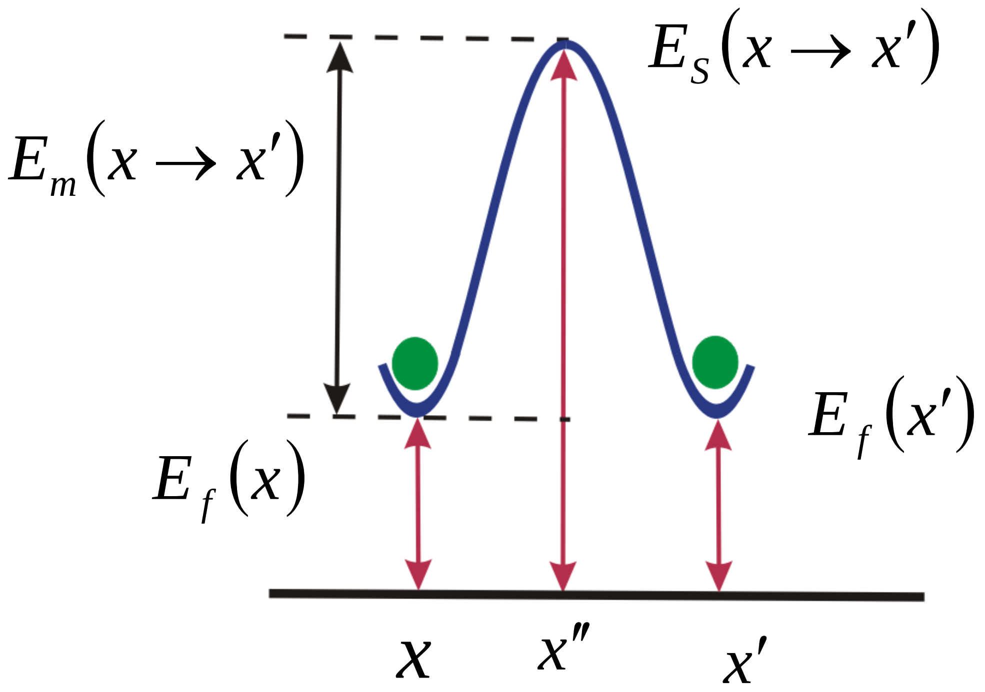
- Driving force due to an electric field can have a strong effect on diffusivity of charged point defects

# Metals $(\mathbf{E}_0 = 0)$

Interstitial

Vacancy

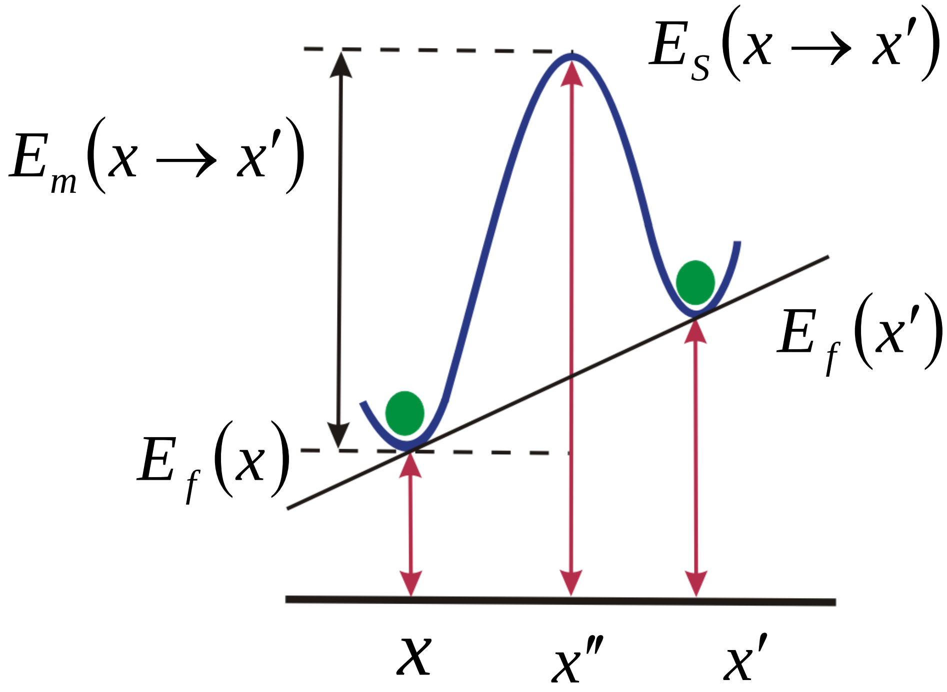
$$q_I = q_V = 0$$




$$\mathbf{J}_\alpha = -D_\alpha \nabla C_\alpha, \quad (\alpha = I, V)$$

# Dielectrics $(\mathbf{E}_0 \neq 0)$

Interstitial $q_I$ Vacancy $q_V$

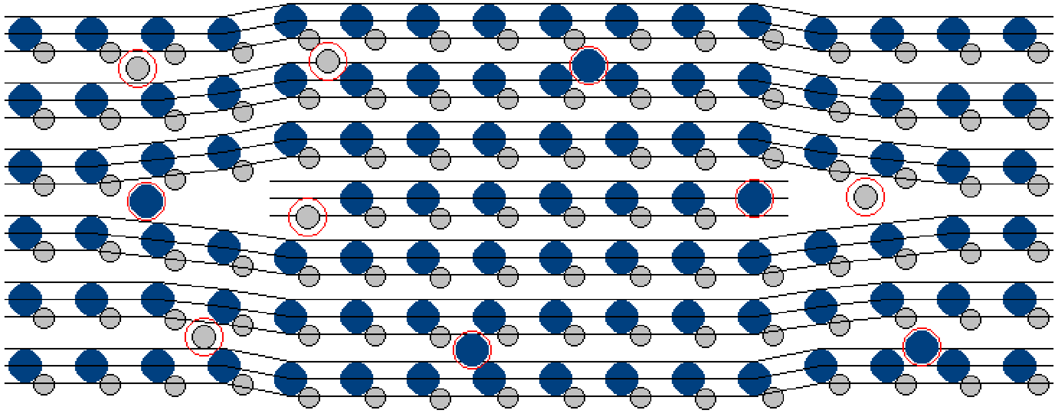



$$E_{S\alpha}(x \to x') = E_{S\alpha}^0 + q_\alpha \varphi(x) + q_\alpha (\mathbf{x}'' - \mathbf{x}) \nabla \varphi(x)$$

$$E_{f\alpha}(x) = E_{f\alpha}^0 + q_\alpha \varphi(x)$$

$$\mathbf{J}_\alpha = -D_\alpha \nabla C_\alpha - \frac{q_\alpha}{kT} D_\alpha C_\alpha \nabla \varphi, \quad (\alpha = I, V)$$

# Modeling of Dislocation Loops in Ceramics Materials (SiC)



## System of Equations

$$D_m \Delta C_m + \frac{q\nu_m}{kT} D_m \nabla\left(C_m \nabla\varphi\right) = 0$$

$$\Delta\varphi = -\frac{4\pi}{\varepsilon\omega}\left(\sum_m q\nu_m C_m + \rho\right)$$

## Boundary Conditions

$$C_m\big|_S = 0 \qquad C_m(r \to \infty) = C_{m0}$$

$$\varphi(r \to \infty) = 0 \qquad \sum_m \left(q\nu_m \mathbf{j}_m, \mathbf{n}\right)\Big|_S = 0$$

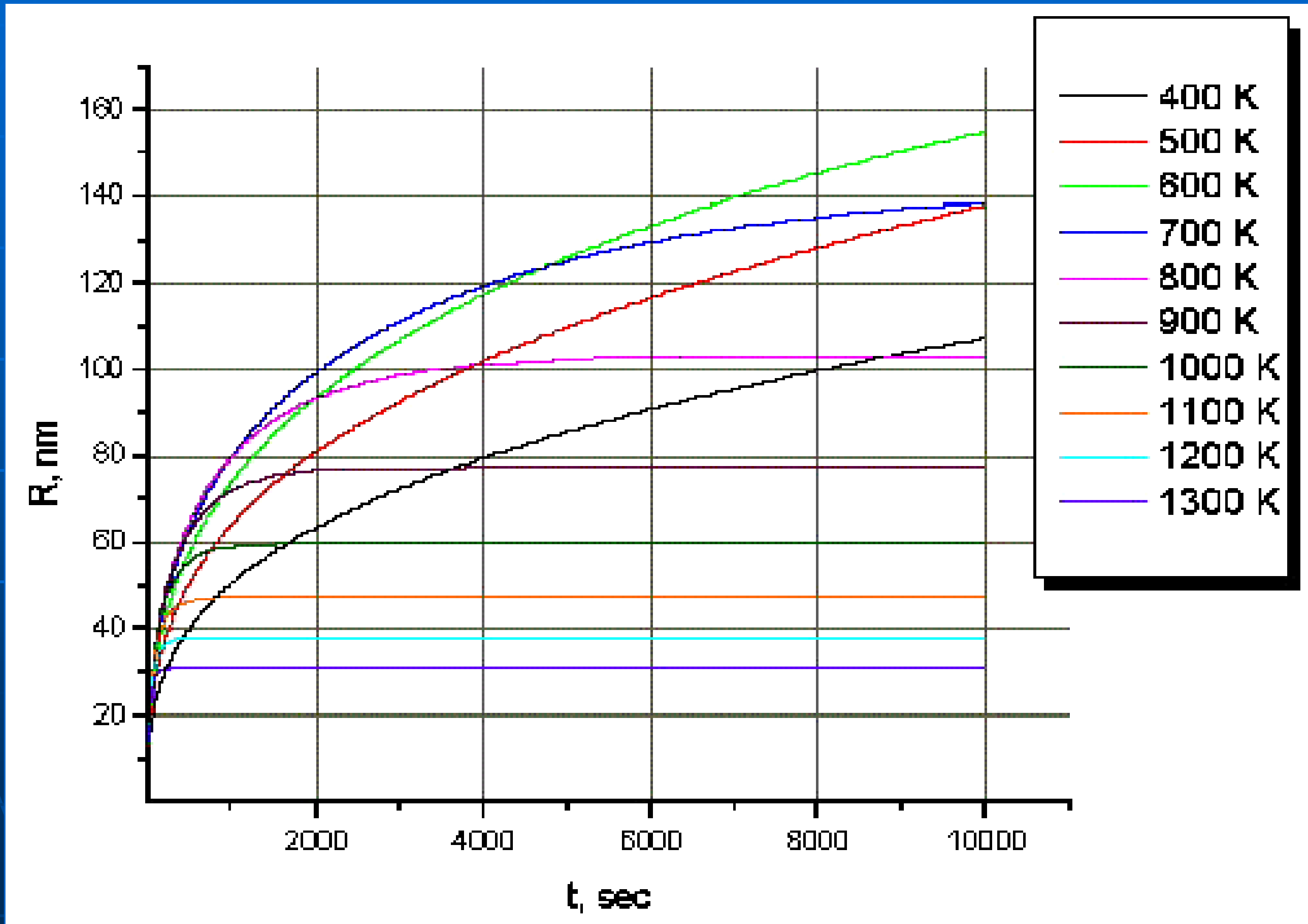
## Main parameter values used for numerical calculations of radiation swelling in SiC

| | | |
|---|---|---|
| $G_1 = G_{Si}$ | Point defect generation rate of Si atoms | $3.10^{-3}$ dpa/s |
| $G_2 = G_C$ | Point defect generation rate of C atoms | $1.10^{-3}$ dpa/s |
| $E_{mV}^{Si}$ | Silicon vacancy migration energy | 2.3 eV |
| $E_{mV}^{C}$ | Carbon vacancy migration energy | 2.0 eV |
| $E_{mI}^{Si}$ | Silicon interstitial migration energy | 0.4 eV |
| $E_{mI}^{C}$ | Carbon interstitial migration energy | 0.3 eV |
| $E_{FV}^{Si}$ | Silicon vacancy formation energy | 2.5 eV |
| $E_{FV}^{C}$ | Carbon vacancy formation energy | 2.4 eV |
| $\rho_D$ | Network dislocation density | $10^{10}$ cm$^{-2}$ |
| $e_{V1} = e_{V2}$ | Vacancy dilatation | -0.1 |
| $a$ | Lattice parameter | $5.14 \times 10^{-8}$ cm |

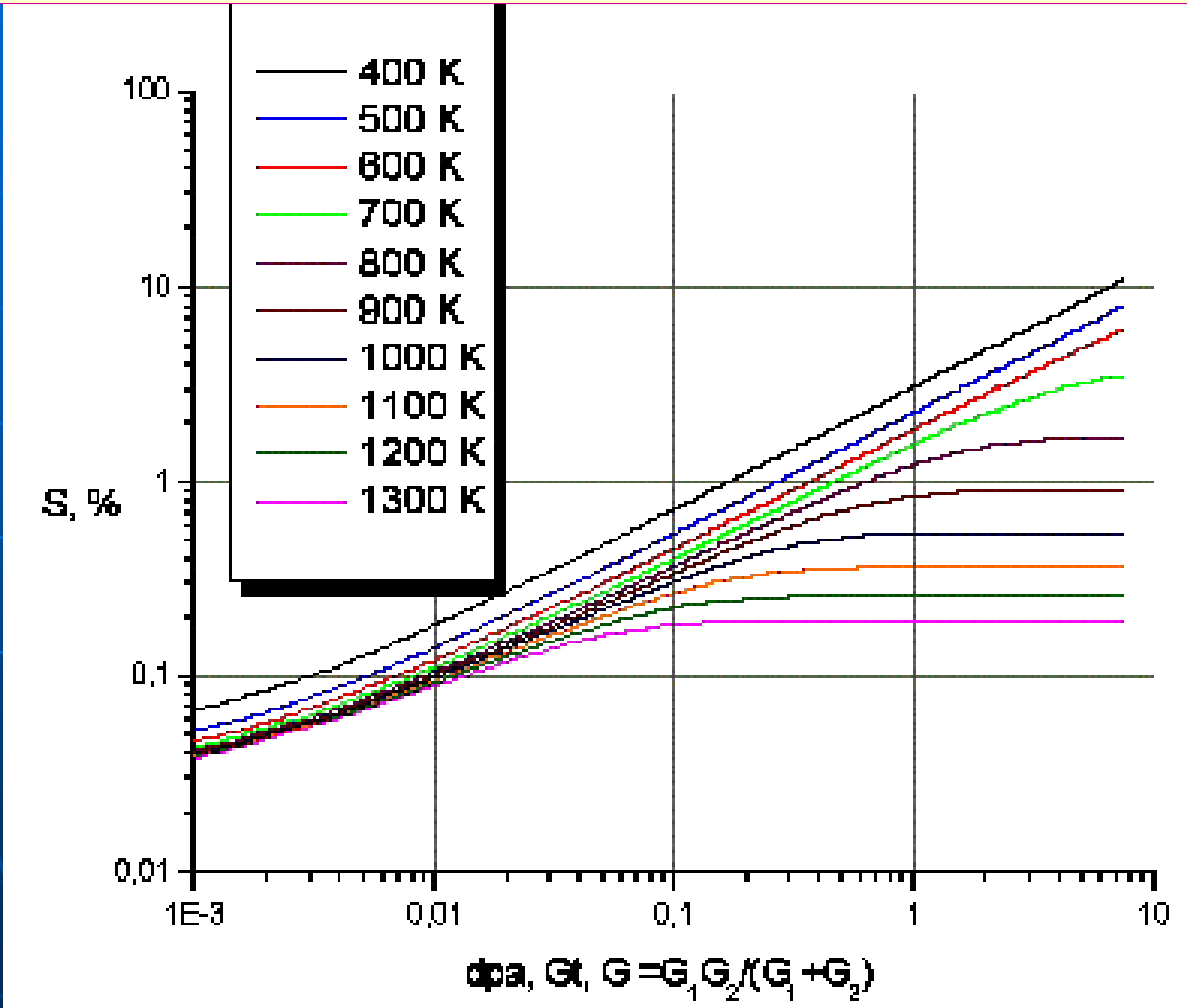
$$D_{VK} = D_{VK}^{O} \exp(-E_{mV}^{K} / T), \text{(where } D_{V1}^{O} = D_{V2}^{O} = 10^{-2} cm^{-2}\text{)},$$

$$N_L = N_L^{O} [\exp(E_{mI}^{1} / T) + \exp(E_{mI}^{2} / T)]^{1/2}, \text{(where } N_L^{O} = 3.10^{12} cm^{-3}\text{)}.$$

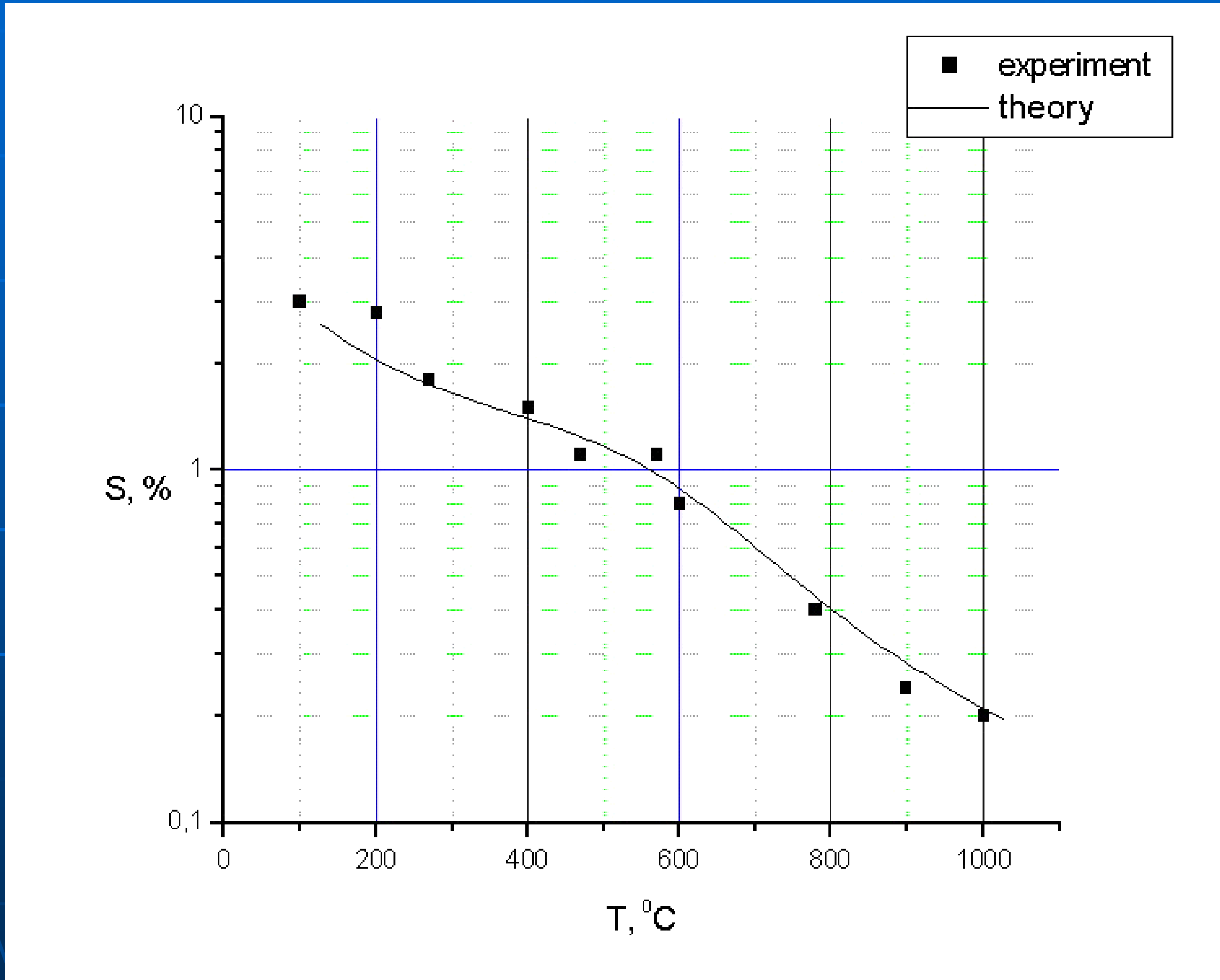
# Theoretical calculations for time dependence of dislocation loop growth at different irradiation temperatures in SiC



# Dose dependence of radiation swelling in SiC at different irradiation temperatures



# The comparison of experimental and theoretical temperature dependencies of radiation swelling in SiC.




A.I.Ryazanov,
A.V.Klaptsov,
A.Kohyama
(JNM,2002)

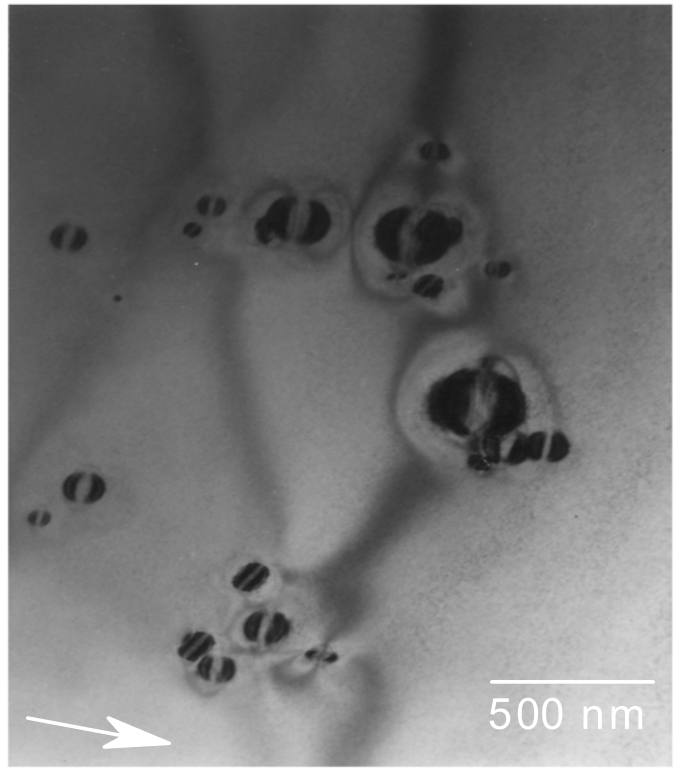
# INSTABILITY OF INTERSTITIAL CLUSTERS UNDER ION AND ELECTRON IRRADIATIONS IN CERAMIC MATERIAL

## Experimental

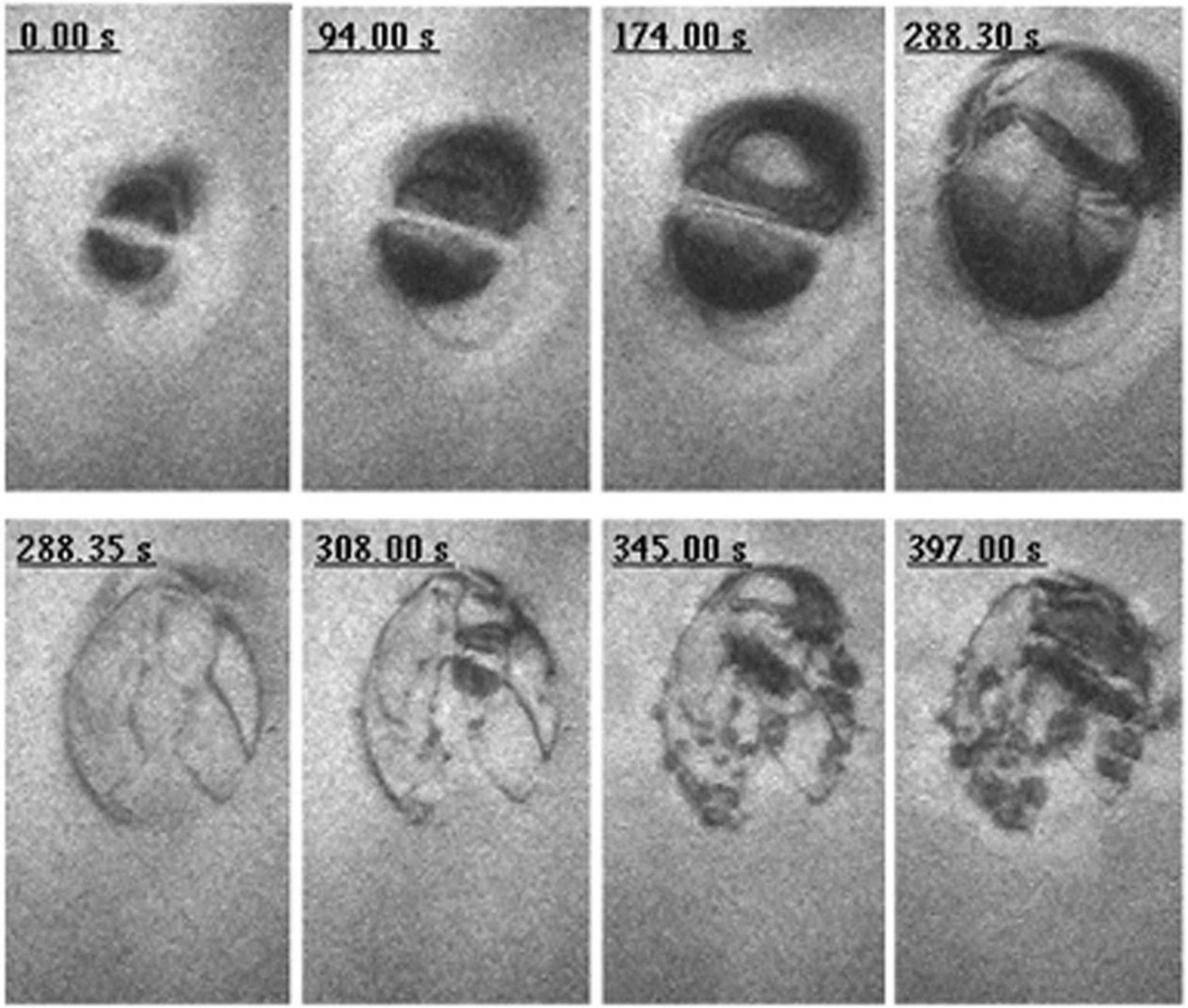
- Specimens: 13mol% Y2O3-ZrO2 single crystal (Earth Jewelry Co.)
- surface orientation: (111)
- Irradiation:
  - ions: 100 keV He+ at 870 K, up to 1x1020 ions/m2
    - 4 keV Ar+ at 300 K
    - 300 keV O+ at 470-1070 K, up to 5x1019 ions/m2
  - electrons: 1000 keV at 470-1070 K, up to 1.4x1027 e/m2
  - electron irradiation subsequent to ion irradiation:
    - 100-1000 keV electrons at 370-520 K
- Observations:
  - in situ and ex-situ TEM
    - HVEM (JEM-1000, HVEM lab., Kyushu University )
    - TEM (JEM-2000EX, HVEM lab., Kyushu University)
    - TEM-accelerator facility (JEM-4000FX, TIARA, JAERI-Takasaki)

# Defect clusters in yttrium-stabilized zirconia

-300 keV O+ions: 5.1x1017 ions/m2 at 470 K
-200 keV electrons at 370 K



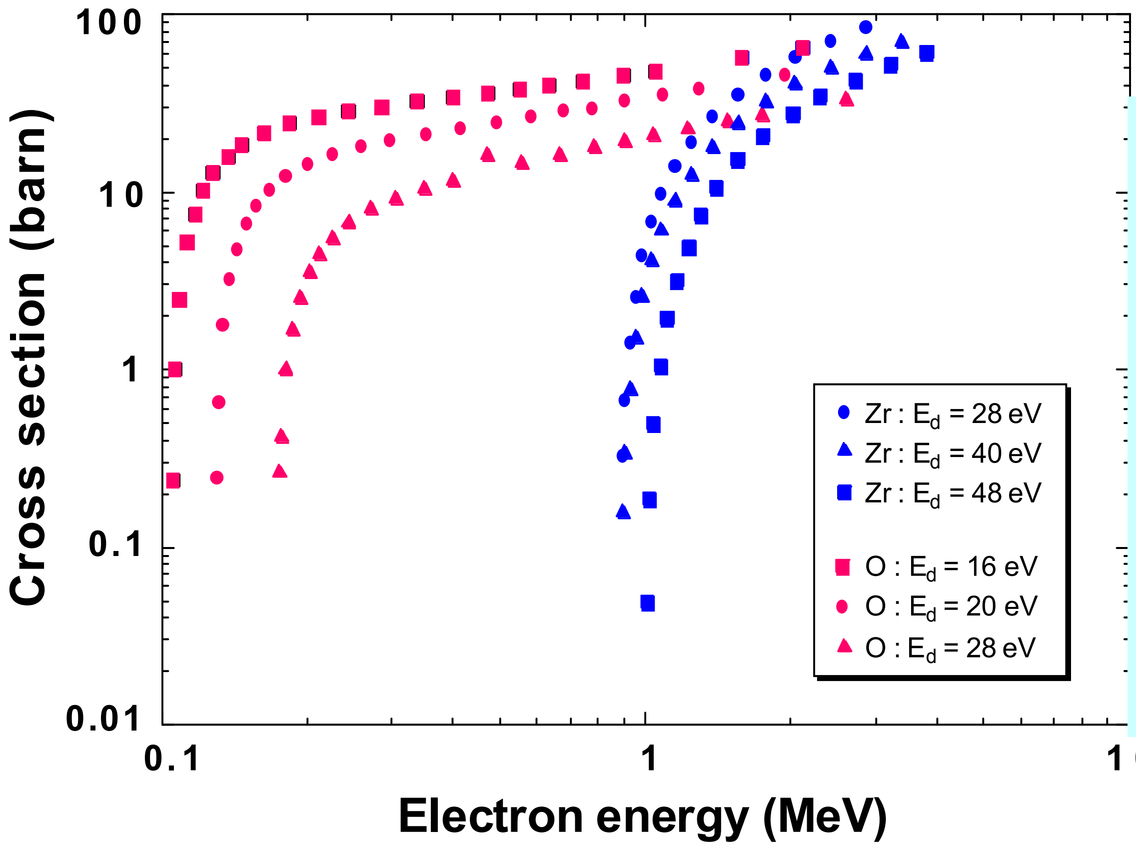
# Instability of Interstitial Clusters



# Characteristic features of the extended defects in yttrium stabilized zirconia

- irradiation condition: under 100-1000 keV electron irradiation subsequent to ion irradiation (100 keV $He^+$, 300 keV $O^+$, 4keV $Ar^+$)
- strong strain and stress fields
- very high growth rate ≈ 1-3nm/sec
- preferential formation around a focused electron beam
- preferential formation at thick regions
- critical radius: 1.2 μm
    - sudden conversion to the dislocation network
    - repeat nucleation, growth and conversion to dislocation structure on dislocation lines

# Cross section for displacement in ZrO2 under electron irradiation




**Displacement damage by elastic collisions**

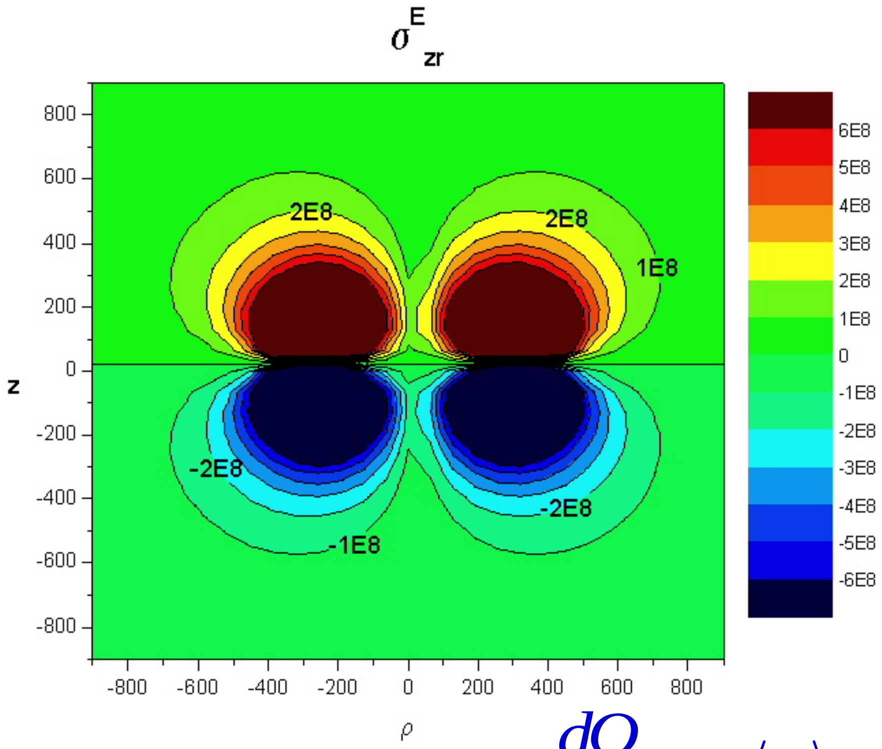
$E_d$(O)~20 eV,
$E_d$(Zr)~40 eV,

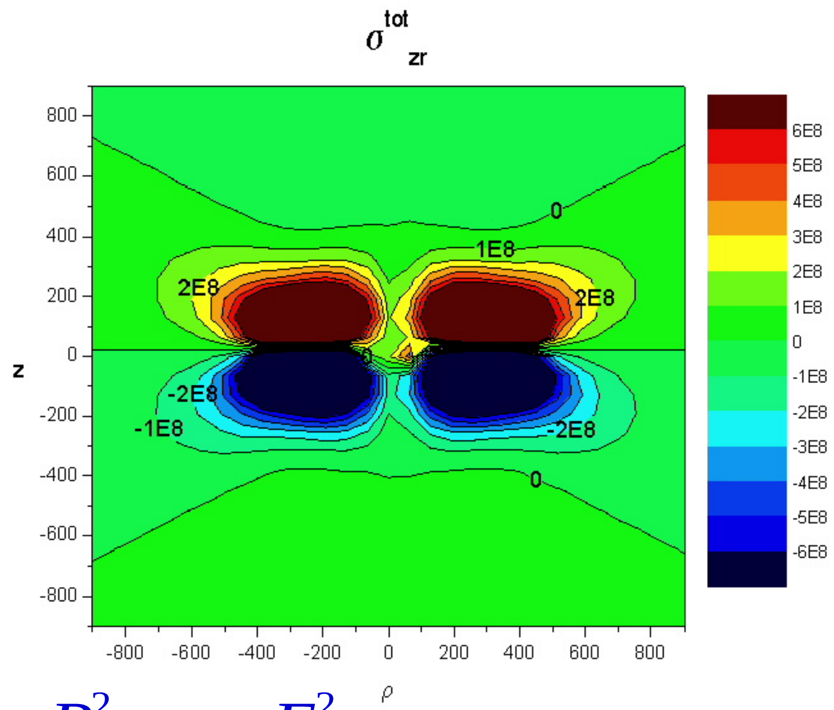
➔ 200 keV electrons :

$\sigma$(O) ~10~30 barn

➔ $\Phi$ = $10^{21}$e$^-$/m$^2$s : ~ $10^{-6}$ dpa/s

# Shear stress component induced by charged dislocation loop

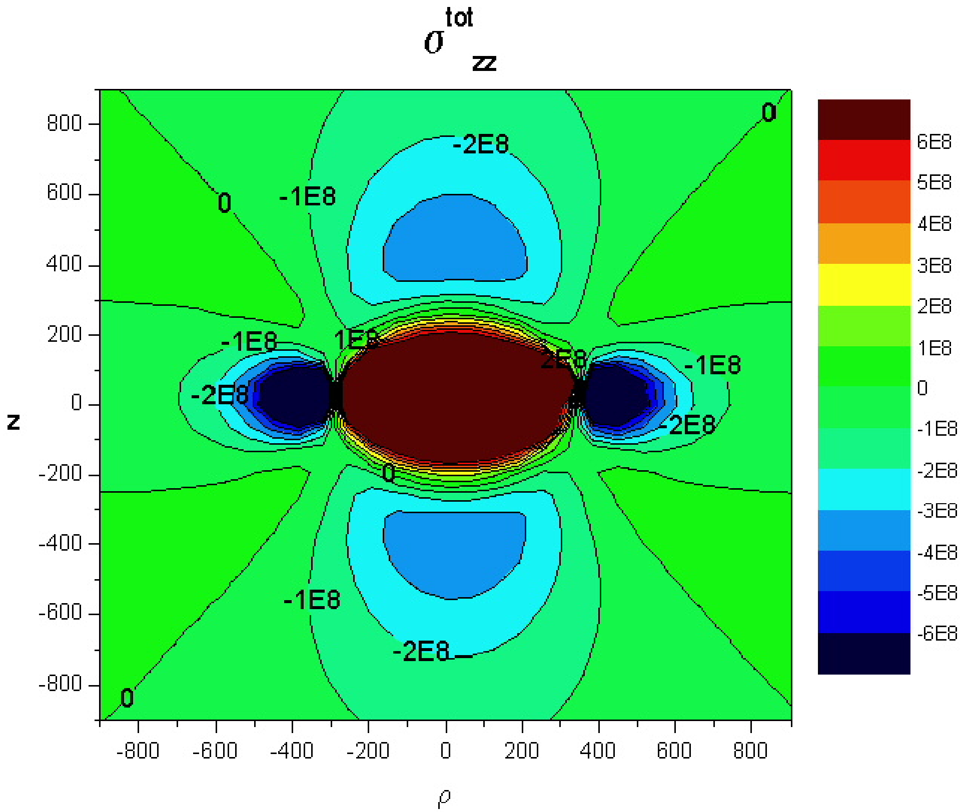



$$\frac{dQ}{dt} = N\langle\sigma\rangle_I \Phi \approx \frac{\pi R^2}{a^2} 4\pi a_0^2 \frac{E_R^2}{IE_{el}}\Phi$$

$$\sigma_{ik} = \frac{\varepsilon}{4\pi}\left(E_i E_k - \frac{E^2}{2}\delta_{ik}\right), \quad \sigma \le \sigma_{th} = \frac{\mu}{2\pi}$$

# Total normal stress component induced by charged dislocation loop



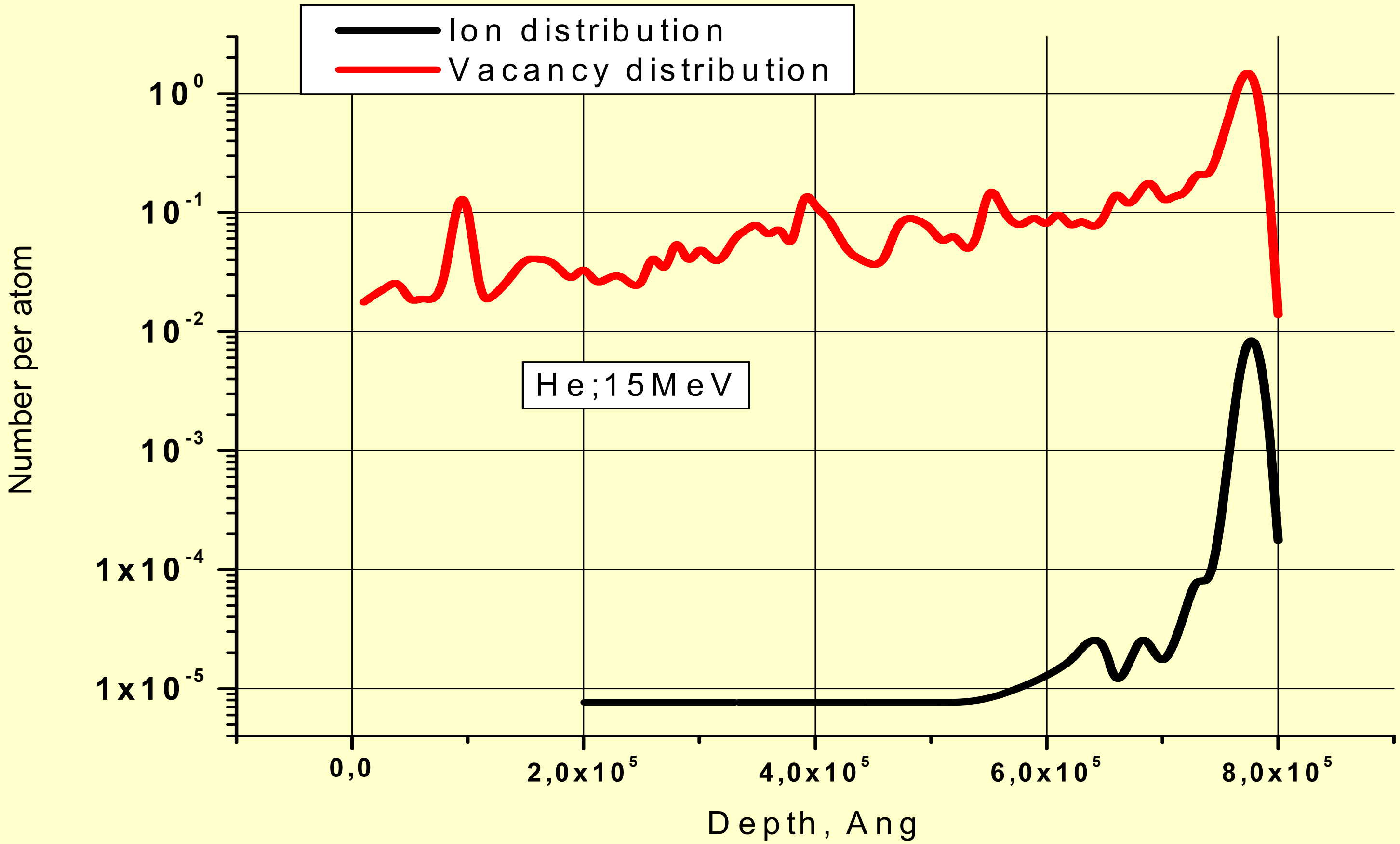
# Radiation Resistance of Zr-Alloys

A.I. Ryasanov, S.T. Latushkin, V.N. Uneghev, (RRC KI)
V.N. Shishov, V.V. Novikov, V.A. Markelov, A.A. Balashov (VNIINM)



15 March 2010, PSI, Switzerland

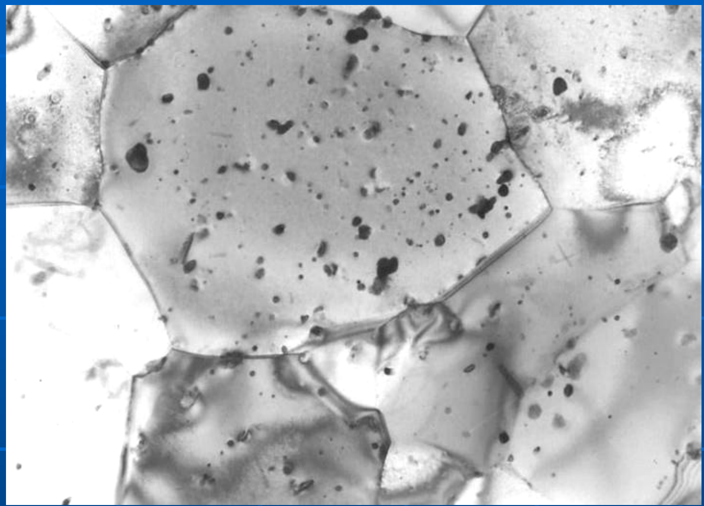
# Generation Rate of Point Defects under Irradiation of Zr alloy by 15 MeV Helium Ions at Irradiation Dose 10E17cm2



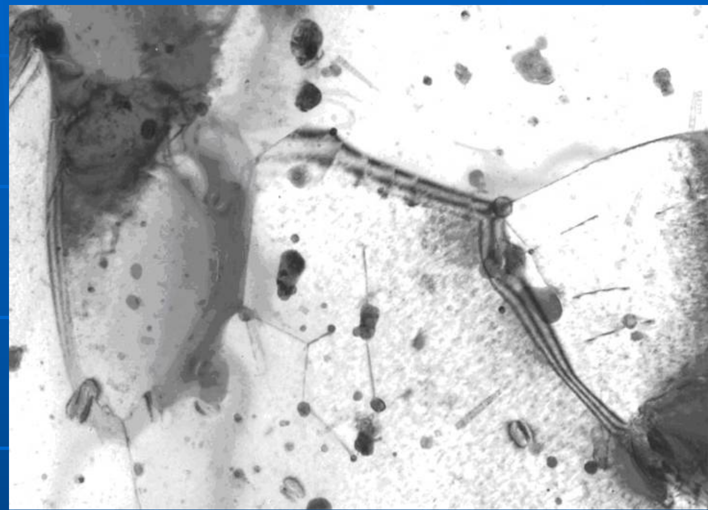
# Microstructure of Irradiated and unirradiated Zr alloys: Э110 and Э635 (Distribution of β– Nb phases, Laves phases Zr(Nb,Fe)2 and dislocations c-type)

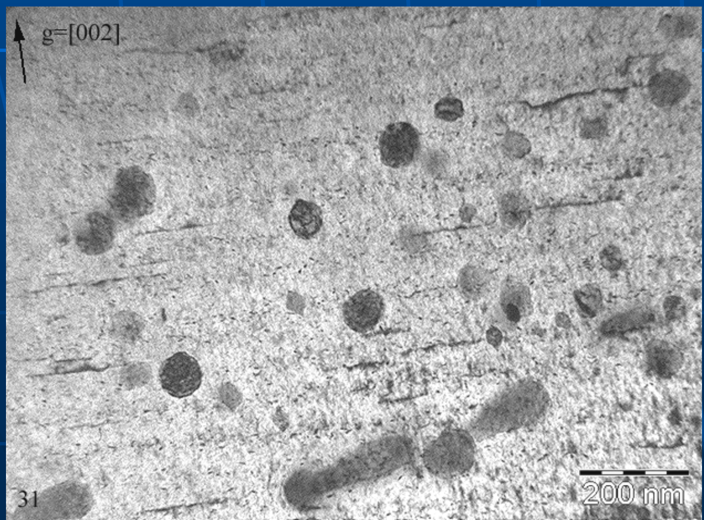
**Э110 - β-Nb**

**Э635 Laves phase Zr(Nb,Fe)2**

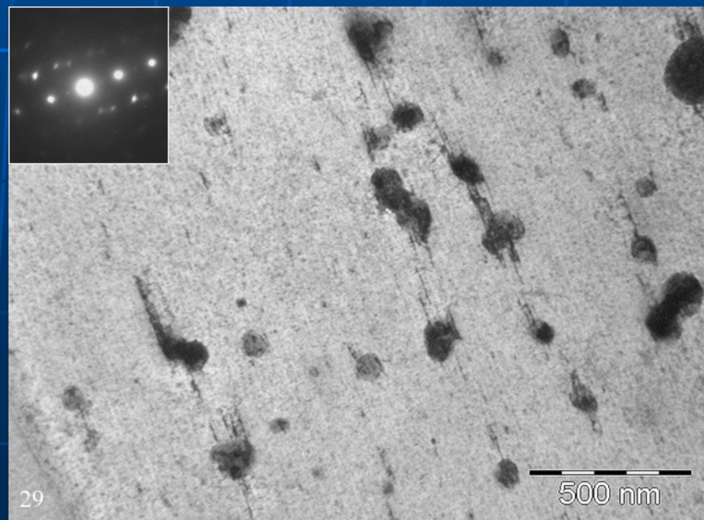


**x10 000**
**Unirrad.**

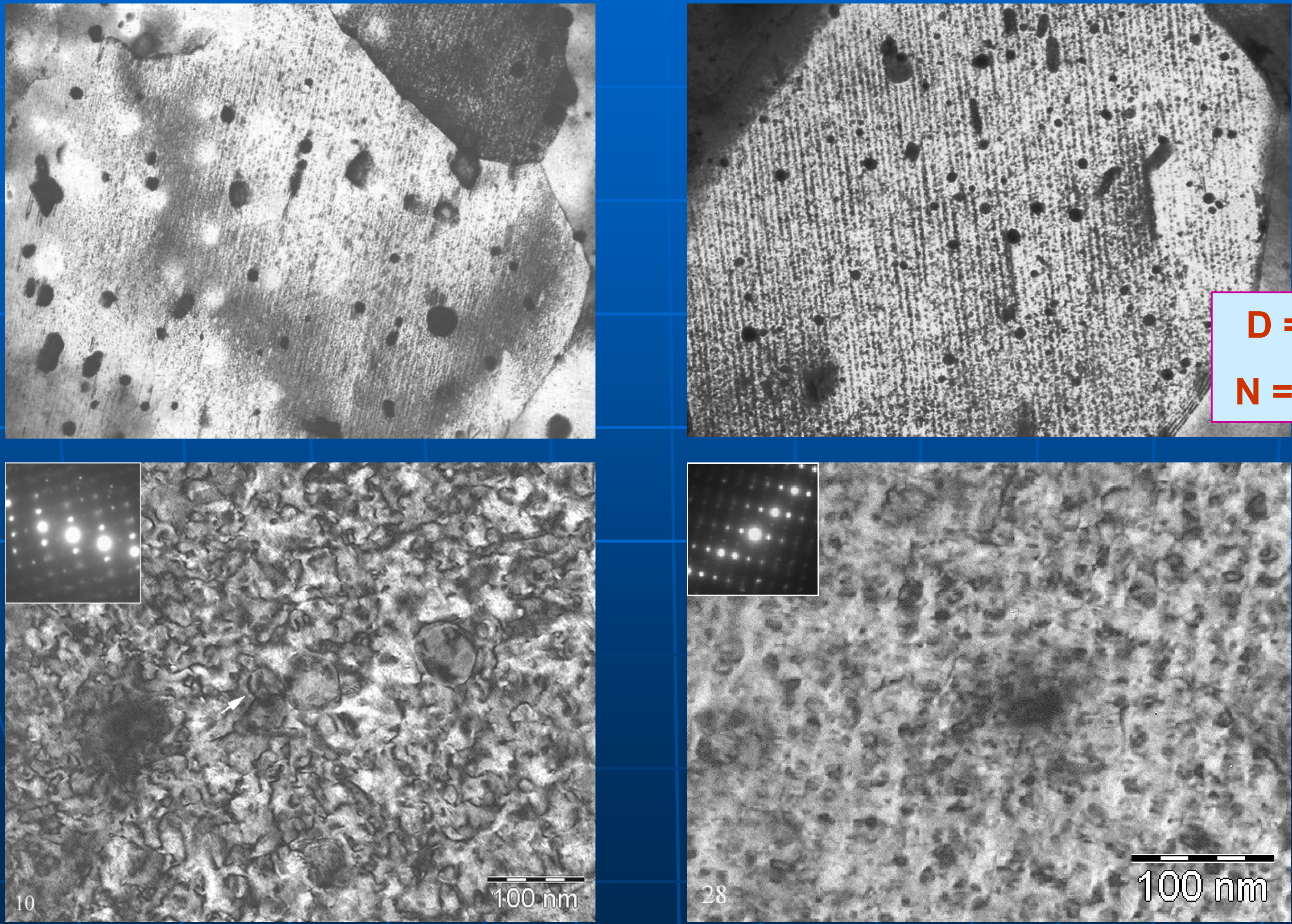





**x50 000**
**Irradiat.**



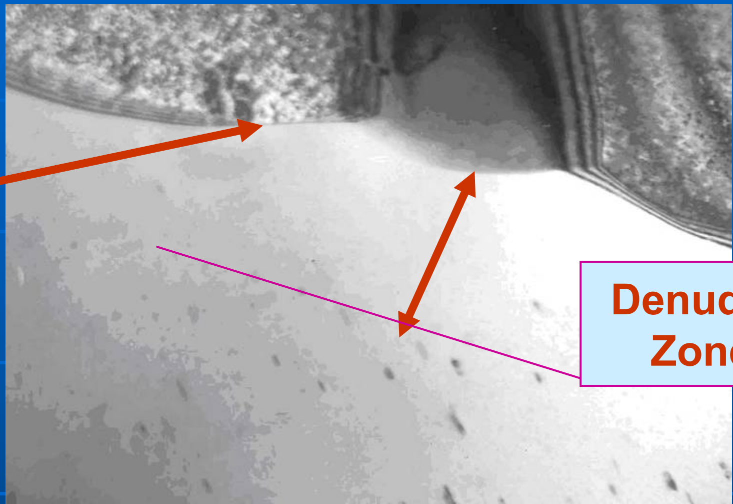
# Microstructure of neutron irradiated Zr russian alloys: Э635 и Э110 up to doses F=0,5x1026n/m2 (2 dpa): distribution of precipitates and ordered dislocation loops (a-type).

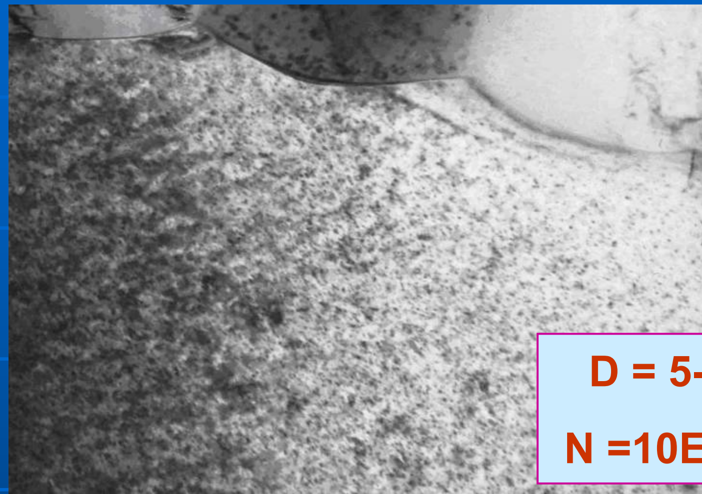


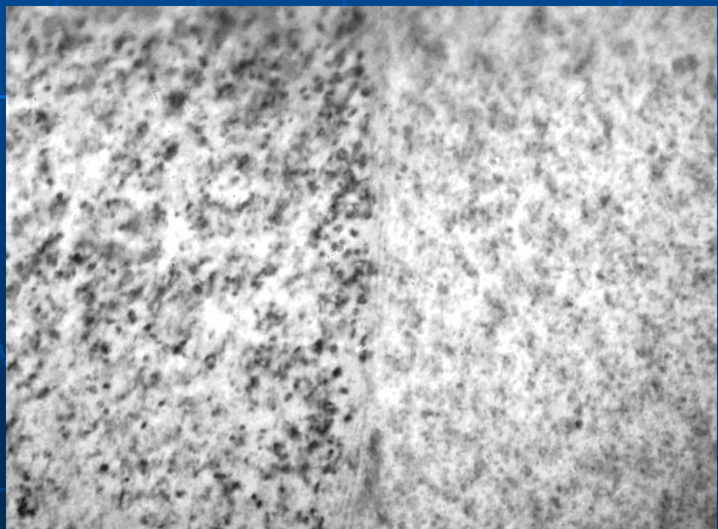

D = 10-20 nm,

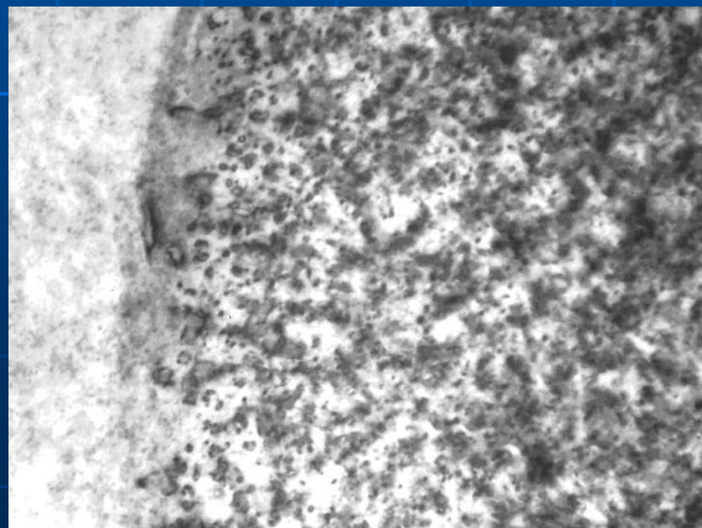
N =10E16 cm-3

# Microstructure of Zr alloy Э110 irradiated on cyclotron by helium ions with energy 10 MeV at T=350oC dose of irradiation 1 dpa (2x10E17p/cm2))

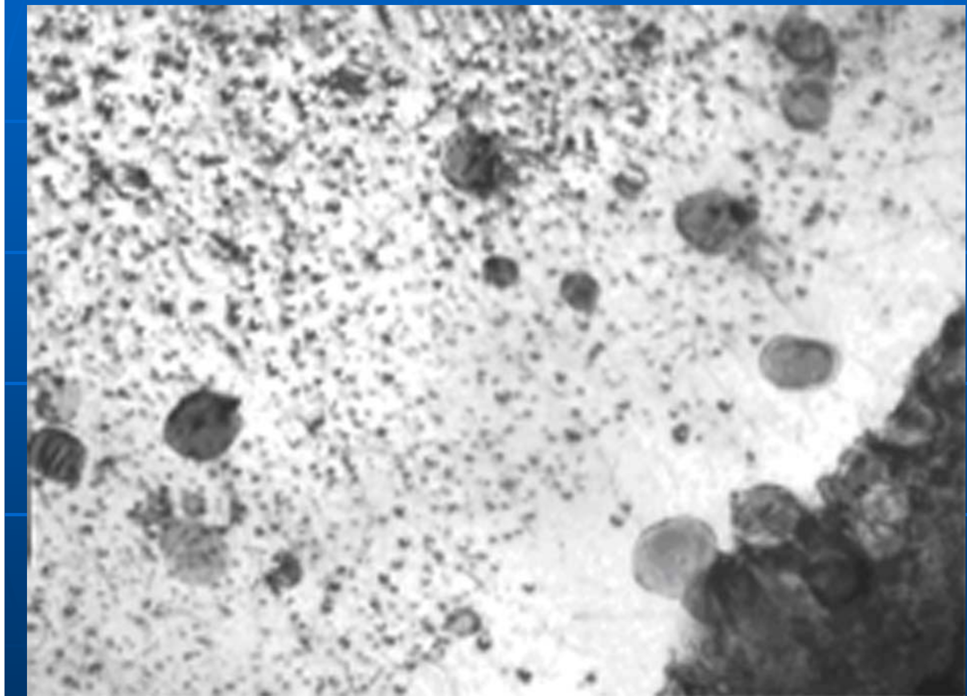


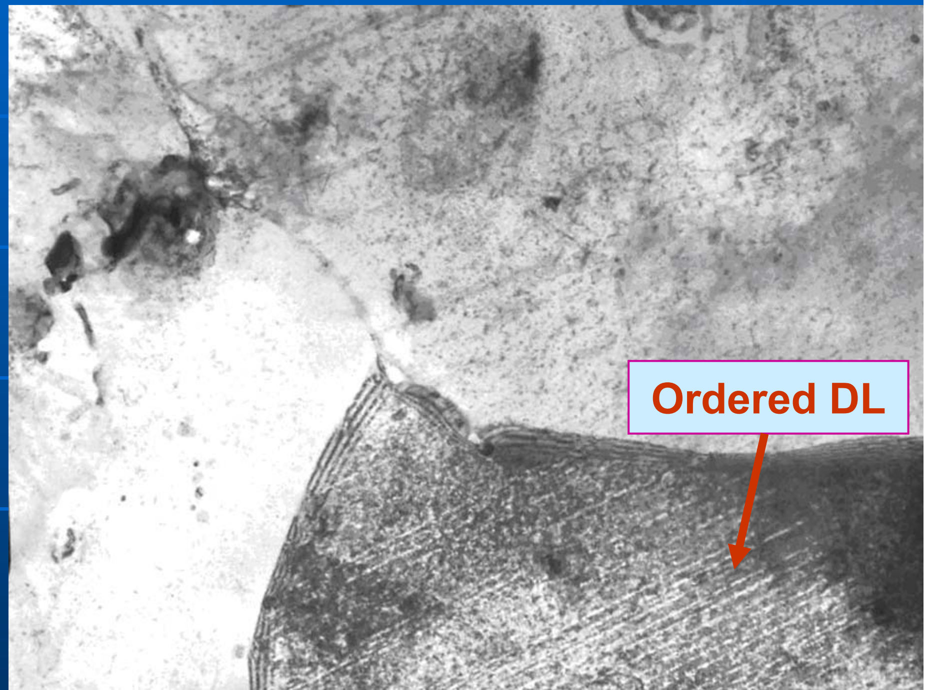





## Microstructure of Zr alloy Э635 irradiated on cyclotron by protons with energy 4 MeV at T=350oC dose of irradiation 1 dpa (2x10E17p/cm2))






Found optimal irradiation regime allowing to irradiate Zr alloys at T= 300–350 °C up to 100 μm deep to doses 10 dpa.

# Studies of proton beam irradiation on graphite collimator materials for LHC

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R.Assmann**, O.Aberle**, A.Bertarelli**, R.Schmidt**

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**CERN CH-1211 Geneva 23, Switzerland

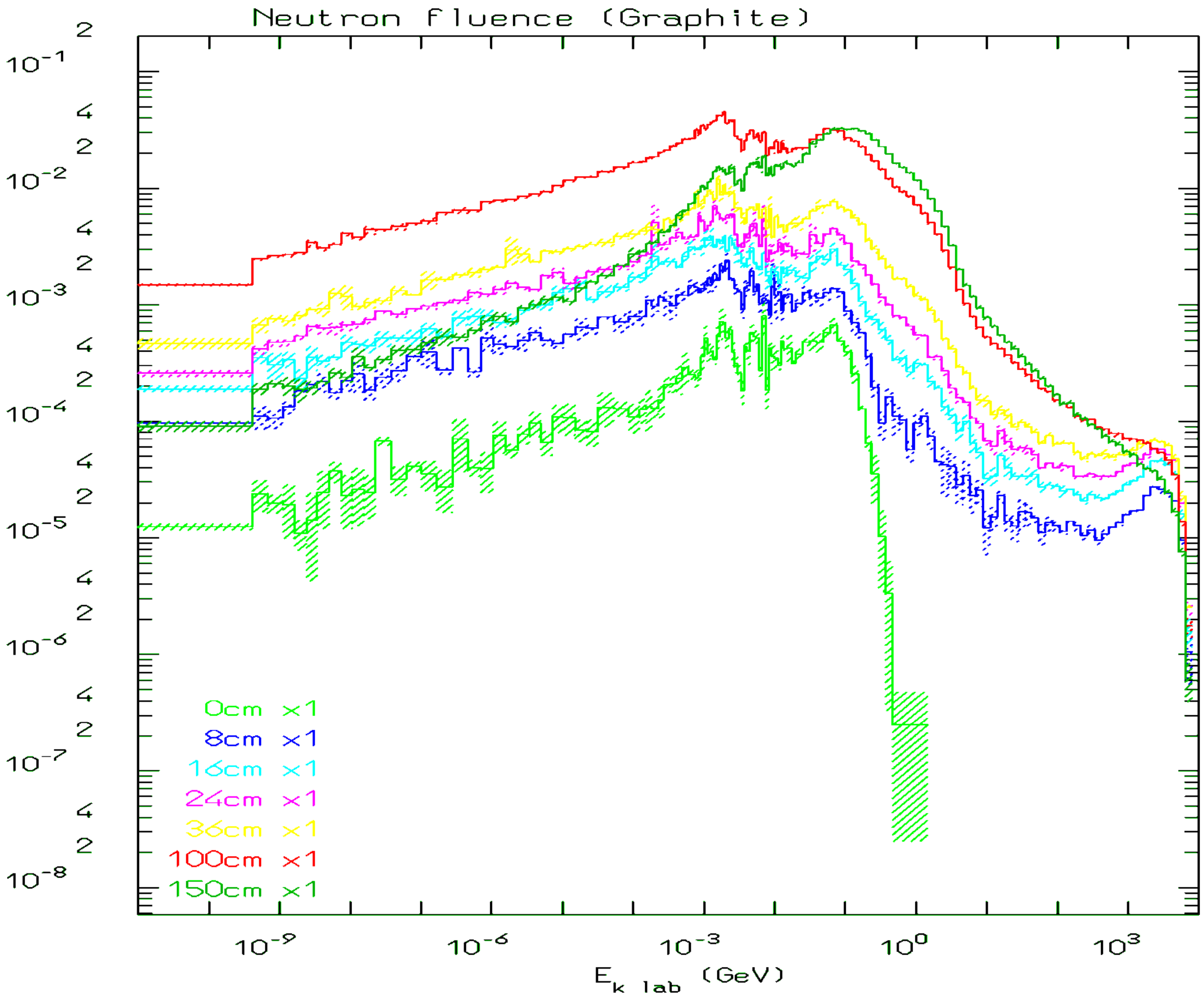
# Task: Proton Irradiation Damage Assessment of LHC Graphite Collimator Materials

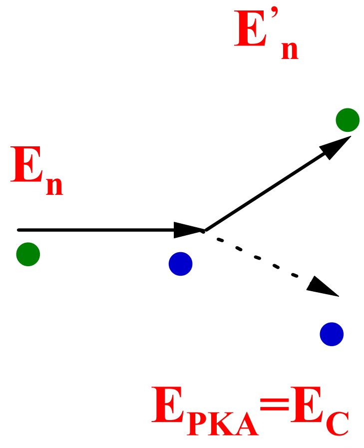
- ***Main aim of studies*** **– to measure the effect of proton irradiation on physical-mechanical material properties: thermal conductivity, thermal expansion, mechanical properties, electrical resistivity, microstructure change**

***Objective:***

- **Determine the effect of PKA proton energy spectrum near 7 TeV proton beam on physical - mechanical properties of graphite collimator material for LHC – irradiation of graphite by protons with the 35 MeV energy at different doses and theoretical modeling of main physical phenomena of radiation effects on materials**

# Neutron energy spectrum per one 7 TeV proton in graphite on the several penetration depths of proton.




$$< E_C >= 2\frac{m_n}{m_C} E_n$$

# Investigated Graphite Collimator Materials for LHC

- **C-C Composite Graphite Material**

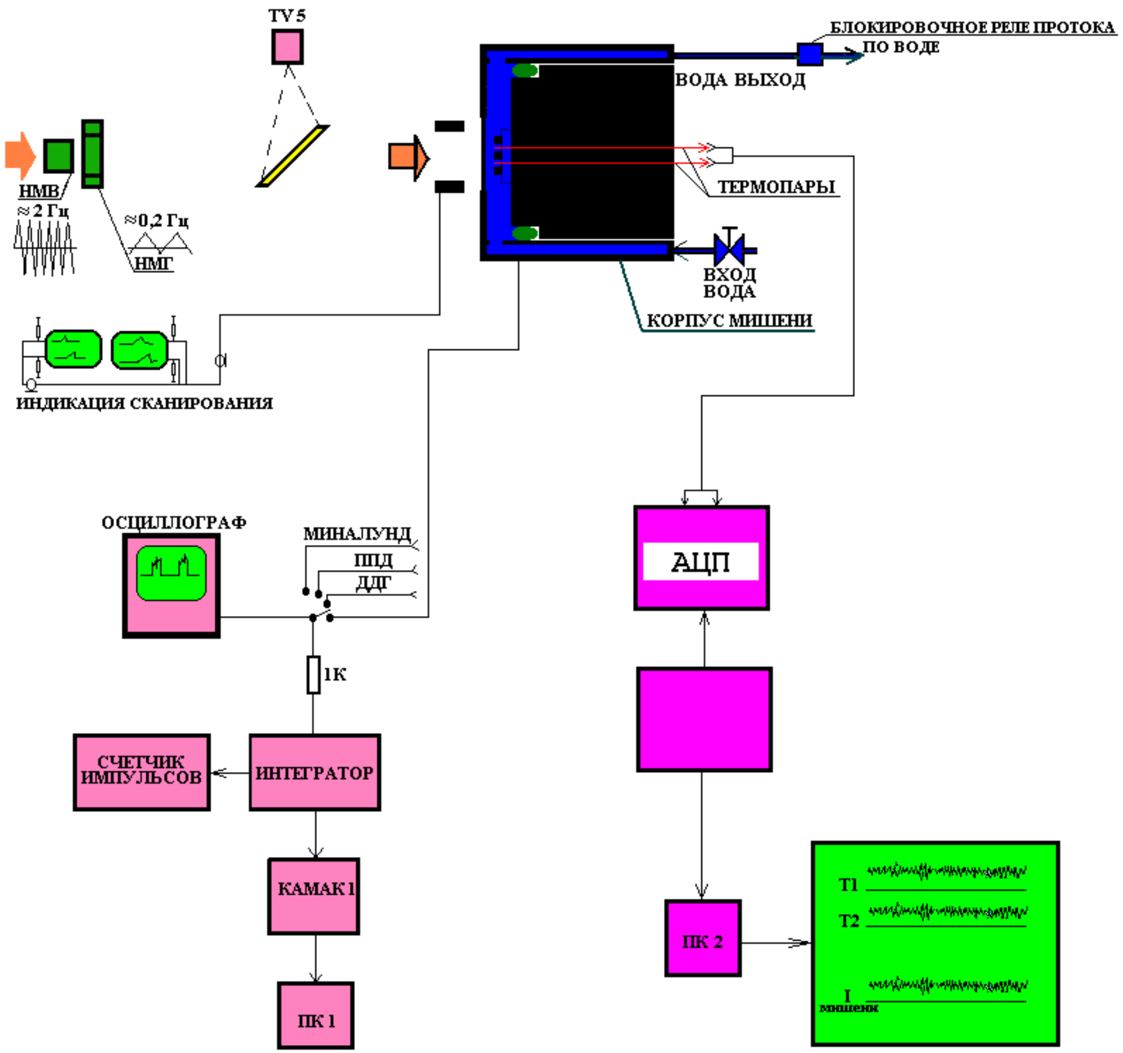
  **AC-150**

**Three orientations:**

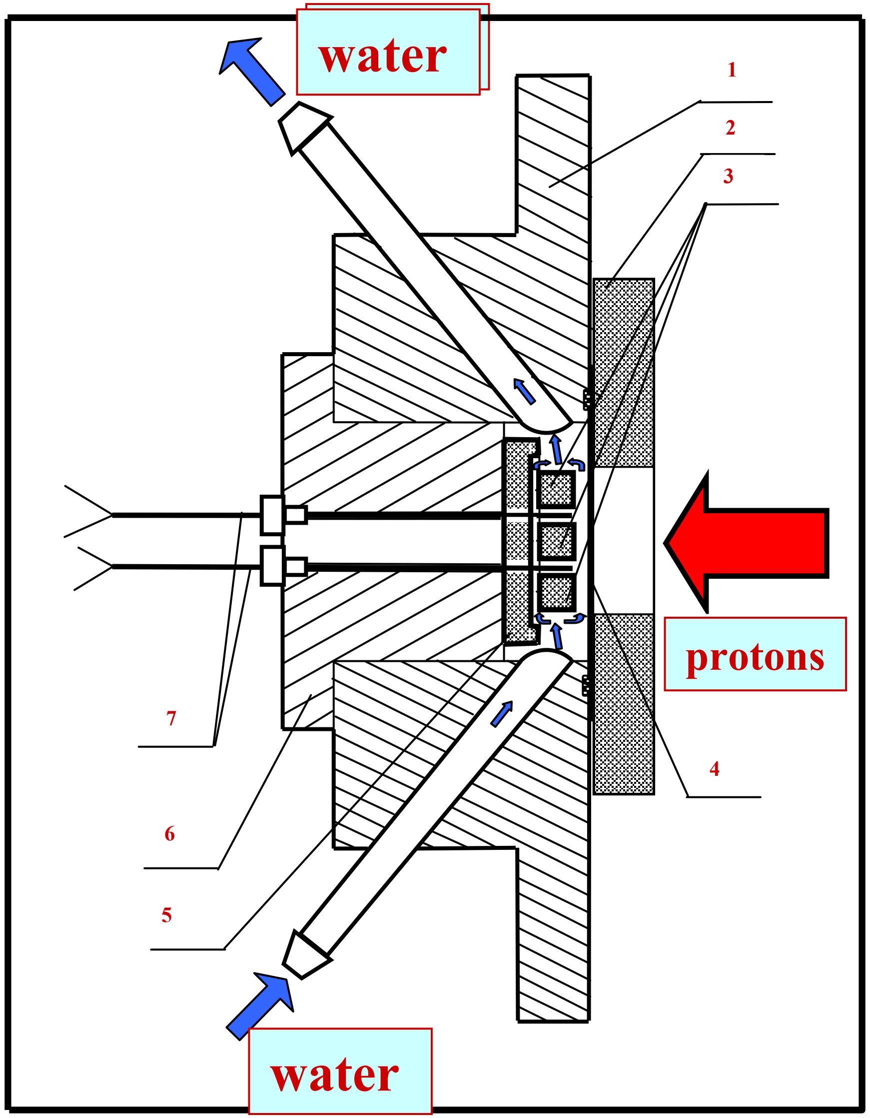
# Measured values

- *d* - density
- λ - thermal conductivity coefficient (at T < 700°C)
- ρ - electrical resistivity (at T < 700°C)
- α - thermal expansion coefficient (at T < 700°C)
- σ - compression ultimate tensile stress
- $E_d$ - dynamic elastic module
- $E_s$ - static elastic module
- *a, c* - lattice constants (X-ray method)

# Scheme of experimental tests of C-C samples on cyclotron



# Target device for proton irradiation of graphite samples on RRC KI cyclotron




1-Corps of target device

2-Graphite diaphragm

3-Irradiated samples

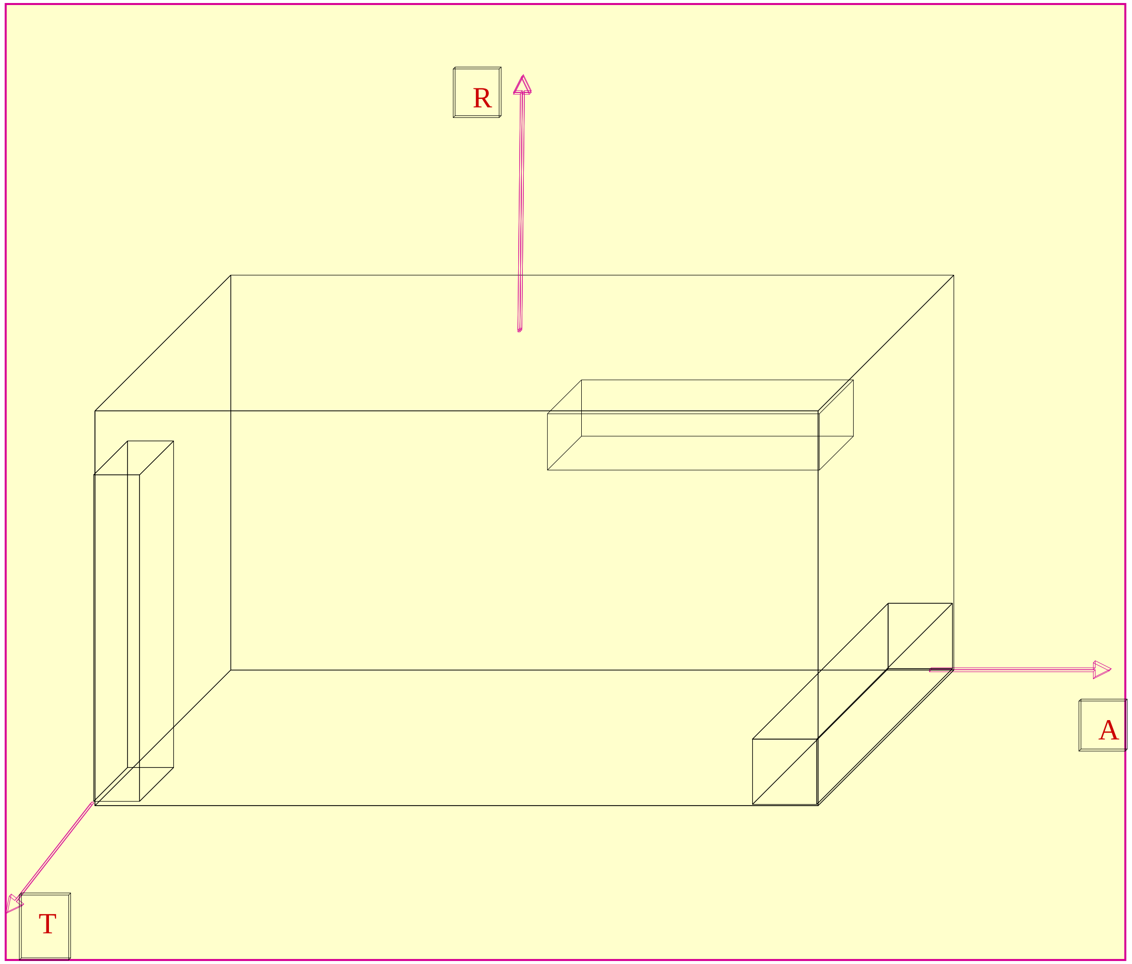
4-Foil window

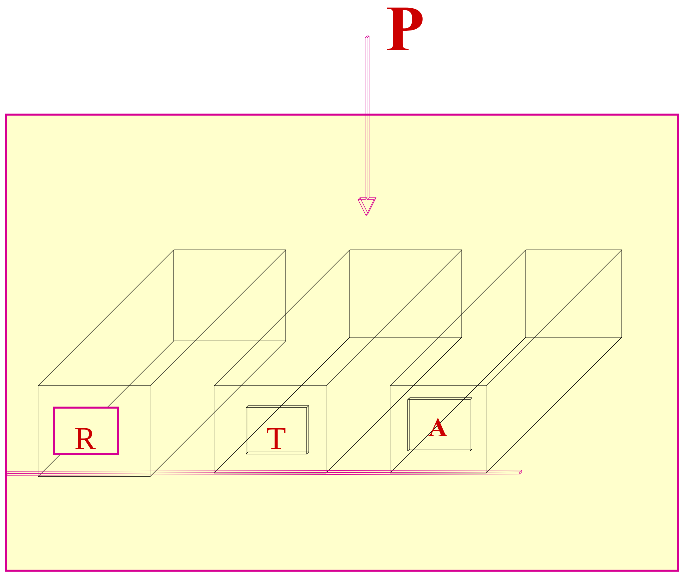
5-Holder of samples

6-Main holders

7-Thermocouples

# Preparation of three orientations of graphite samples for experimental tests

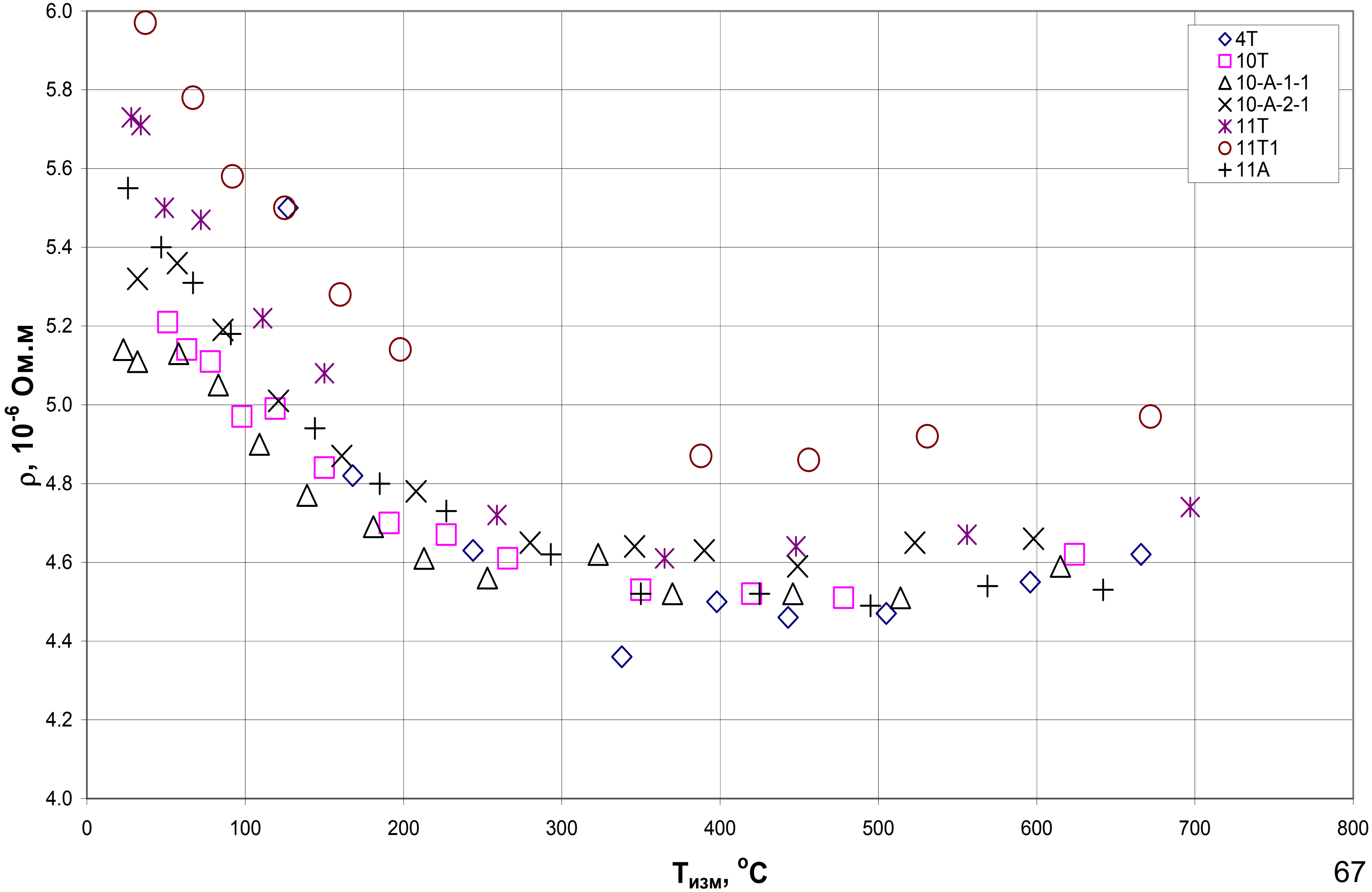


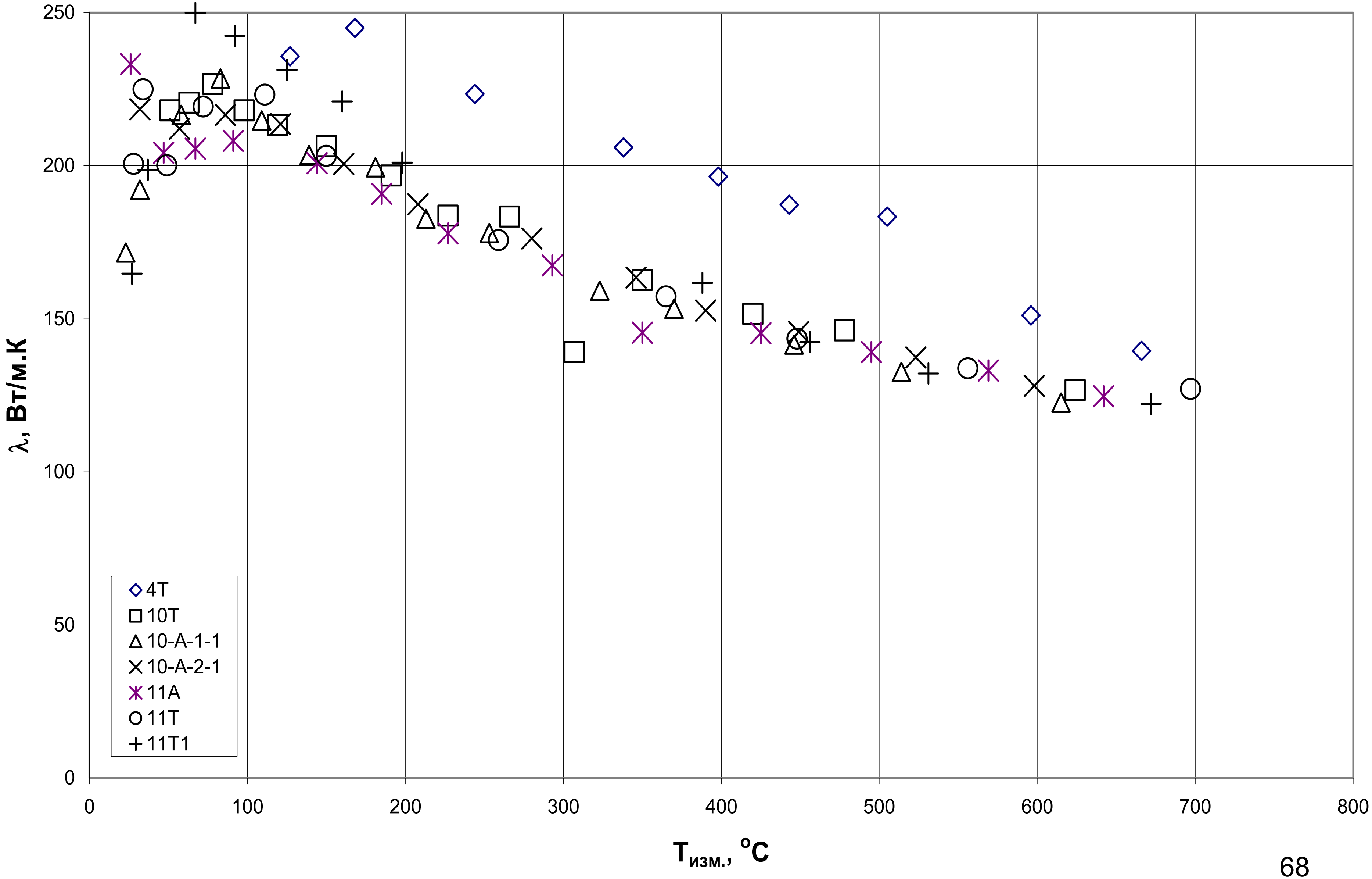
# Results of physical-mechanical tests (№10)

| № sample. | d, g/cm3 | E, GPa | ρ, $10^{-6}$ Ом.м | α, $10^{-6}$, 1/K |
|---|---|---|---|---|
| 10R(TA-1) | 1.66 | 3.2 | 27.8 | 10.31 |
| 10R(TA-2) | 1.66 | 2.96 | 30 | 10.31 |
| 10R(TA-3) | 1.66 | 3.2 | 29.1 | 10.31 |
| Average | 1.66 | 3.12 | 28.9666667 | 10.31 |
| Magnification | 0 | 0.13856406 | 1.106044 | |
| | | | | |
| 10T(AR-1) | 1.65 | 9.3 | 5.6 | 0.25 |
| 10T(AR-2) | 1.64 | 9.1 | 5.1 | 0.25 |
| 10T(AR-3) | 1.56 | 9.3 | 5.7 | 0.25 |
| Average | 1.61666667 | 9.23333333 | 5.46666667 | 0.25 |
| Magnification | 0.04932883 | 0.11547005 | 0.32145503 | |
| | | | | |
| 10A(RT-1) | 1.54 | 8.4 | 5.5 | 0.167 |
| 10A(RT-2) | 1.64 | 8.4 | 5.7 | 0.167 |
| 10A(RT-3) | 1.63 | 9.16 | 5.6 | 0.167 |
| Average | 1.603333333 | 8.653333333 | 5.6 | 0.167 |
| Magnification | 0.055075705 | 0.438786205 | 0.1 | |

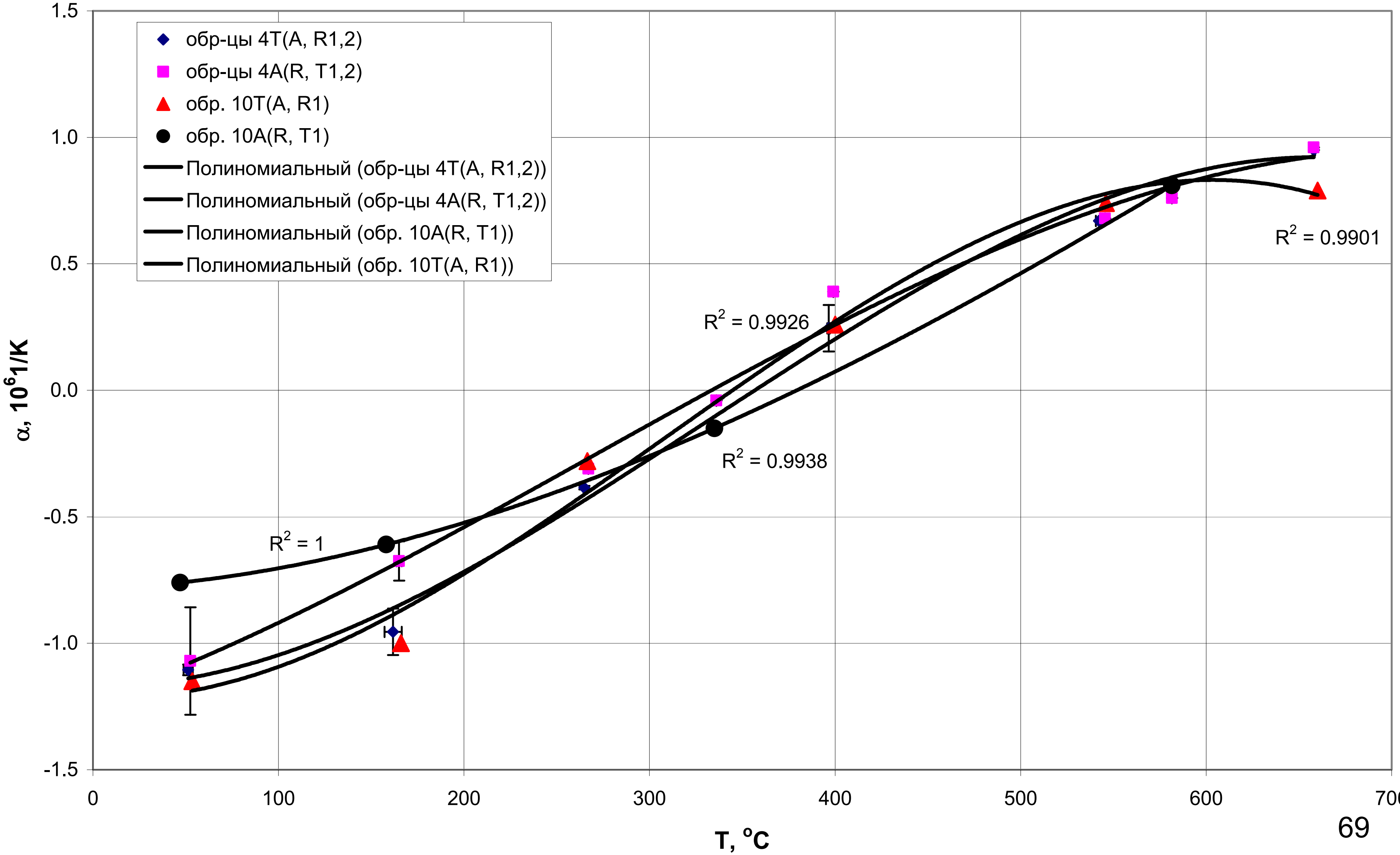
# Temperature dependence of electrical resistance for three orientations of graphite samples



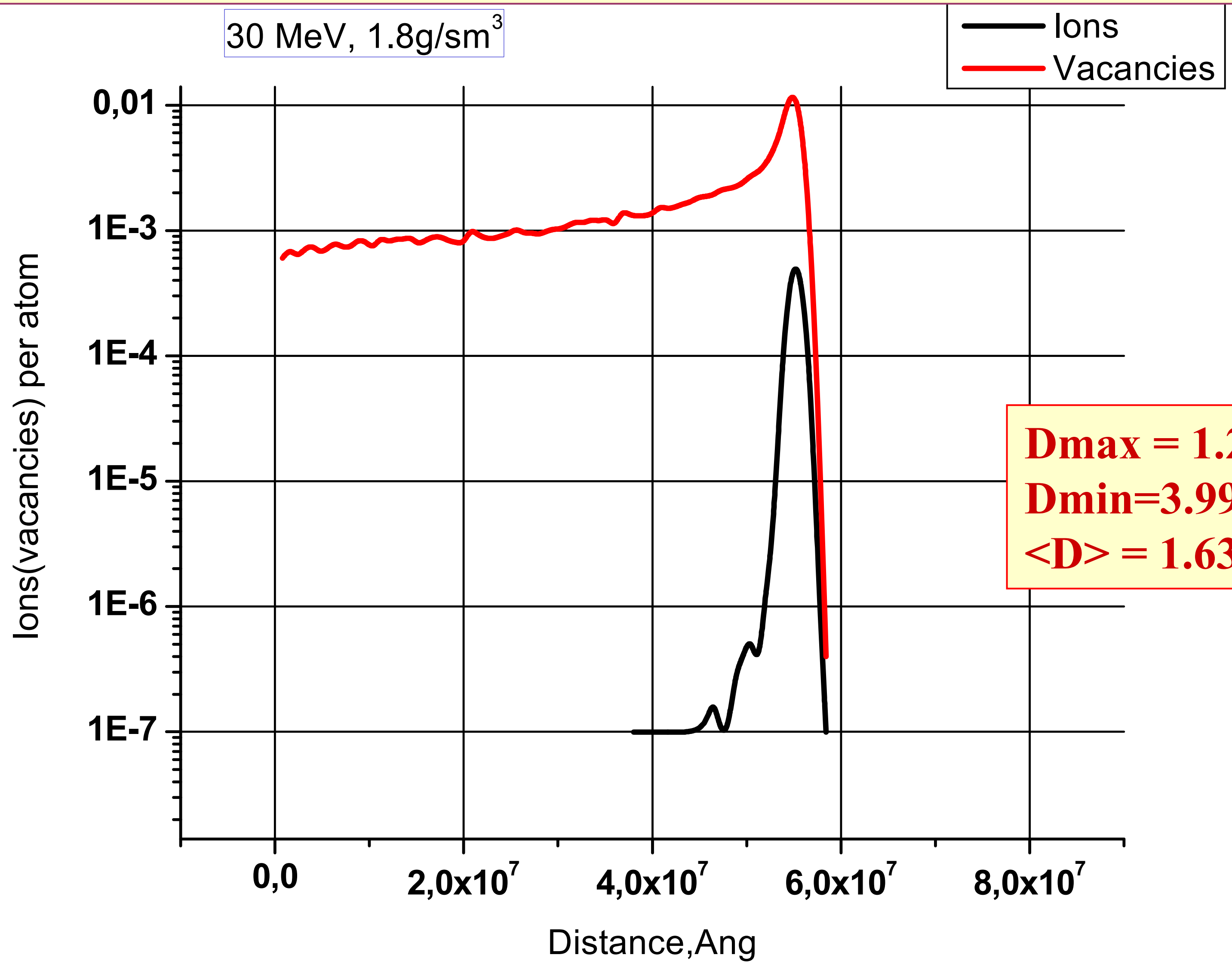
# Temperature dependence of thermal conductivity for three orientations of graphite



# Temperature dependence of thermal expansion coefficient of AC-150.



# Generation rate of point radiation defects under irradiation of graphite by 30 MeV protons at Dose 1.10E17cm2

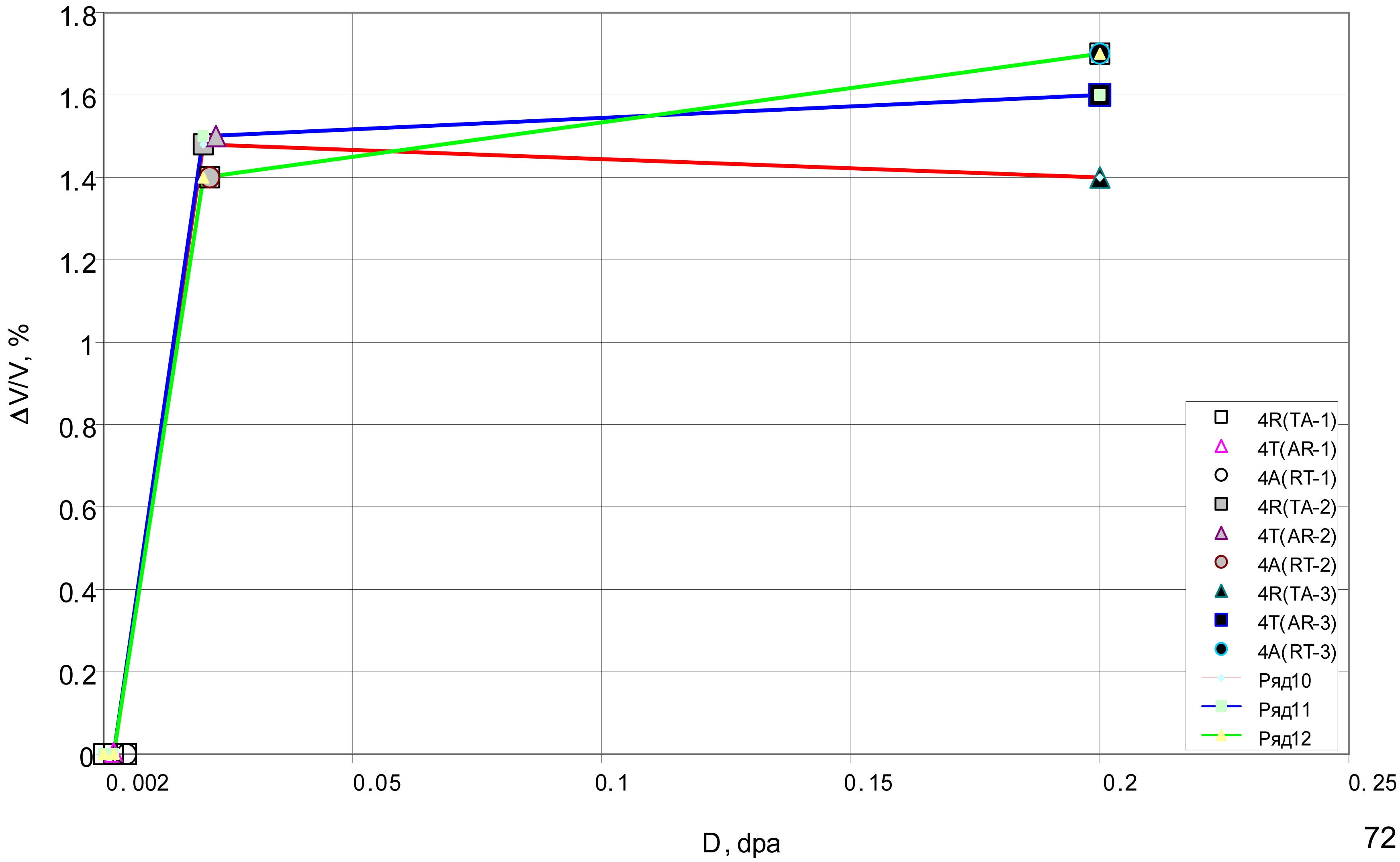



**Dmax = 1.23x10-2 dpa;**
**Dmin=3.99x10-7 dpa,**
**<D> = 1.63x10-3 dpa.**

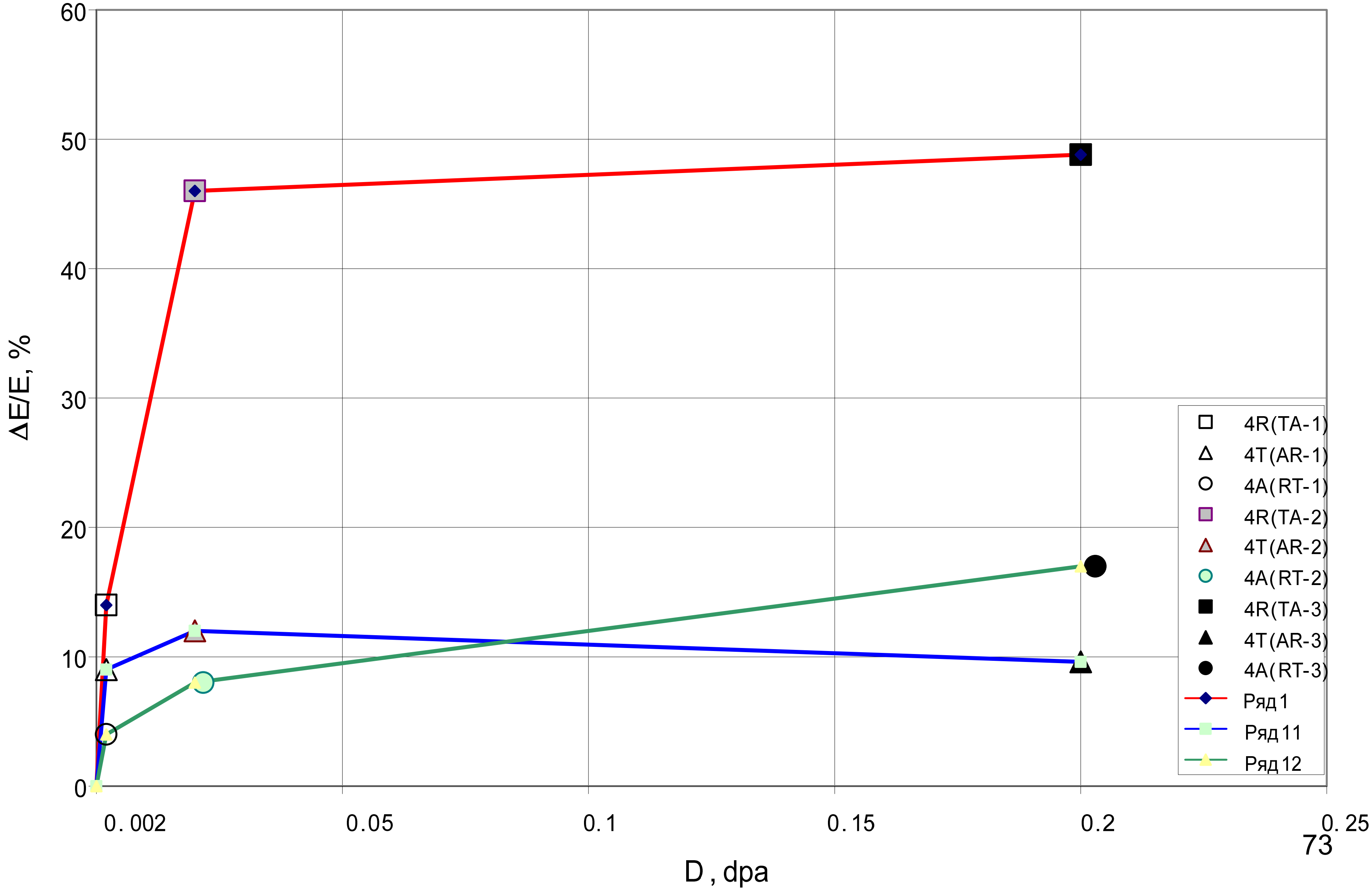
# Results of physical-mechanical property changes of graphites after proton irradiation

| № sample | $E_0/E$ GPa | ΔE/E, % | $\rho_{исх}/\rho_{обл}$, $10^{-6}$ Ом.м | Δρ/ρ, % | $\lambda_{исх}/\lambda_{обл}$ Вт/мК | Δλ/λ, % | $\sigma_{исх}/\sigma_{обл}$ МПа | Δσ/σ, % |
|---|---|---|---|---|---|---|---|---|
| First Irradiation ( 0..002dpa) | | | | | | | | |
| 4R(TA-1) | 3,5/4,0 | 14 | 28,8/29,65 | 3 | 50/48 | 6 | 61/65,3 | 7 |
| 4T(AR-1) | 8,1/8,86 | 9 | 5,65/8 | 42 | 215/150 | 30 | 57/59,9 | 5 |
| 4A(RT-1) | 9,2/9,6 | 4 | 6,2/9,4 | 52 | 215/130 | 39 | 60/61,2 | 2 |
| Second Irradiation ( 0..0.2dpa) | | | | | | | | |
| 4R(TA-2) | 4,8/6,9 | 42,7 | 29,9/62,5 | 109 | 51/25 | 51 | 61/73,8 | 21 |
| 4T(AR-2) | 9,3/10 | 7,5 | 5,7/17 | 198 | 215/80 | 62 | 57/60,4 | 6 |
| 4A(RT-2) | 8,8/9,3 | 5,7 | 5,75/12 | 109 | 215/105 | 51 | 60/62,4 | 4 |
| Third Irradiation ( 0..2dpa) | | | | | | | | |
| 4R(TA-3) | 3,7/5,5 | 48,8 | 27.6/108 | 290 | 51/15 | -70 | 61/74,4 | 22 |
| 4T(AR-3) | 8,3/9,1 | 9,6 | 5.56/26,8 | 370 | 215/55 | -74 | 57/59,9 | 5 |
| 4A(RT-3) | 9,4/10,2 | 8,5 | 5,5/26,5 | 381 | 215/56 | -72 | 60/62,4 | 4 |

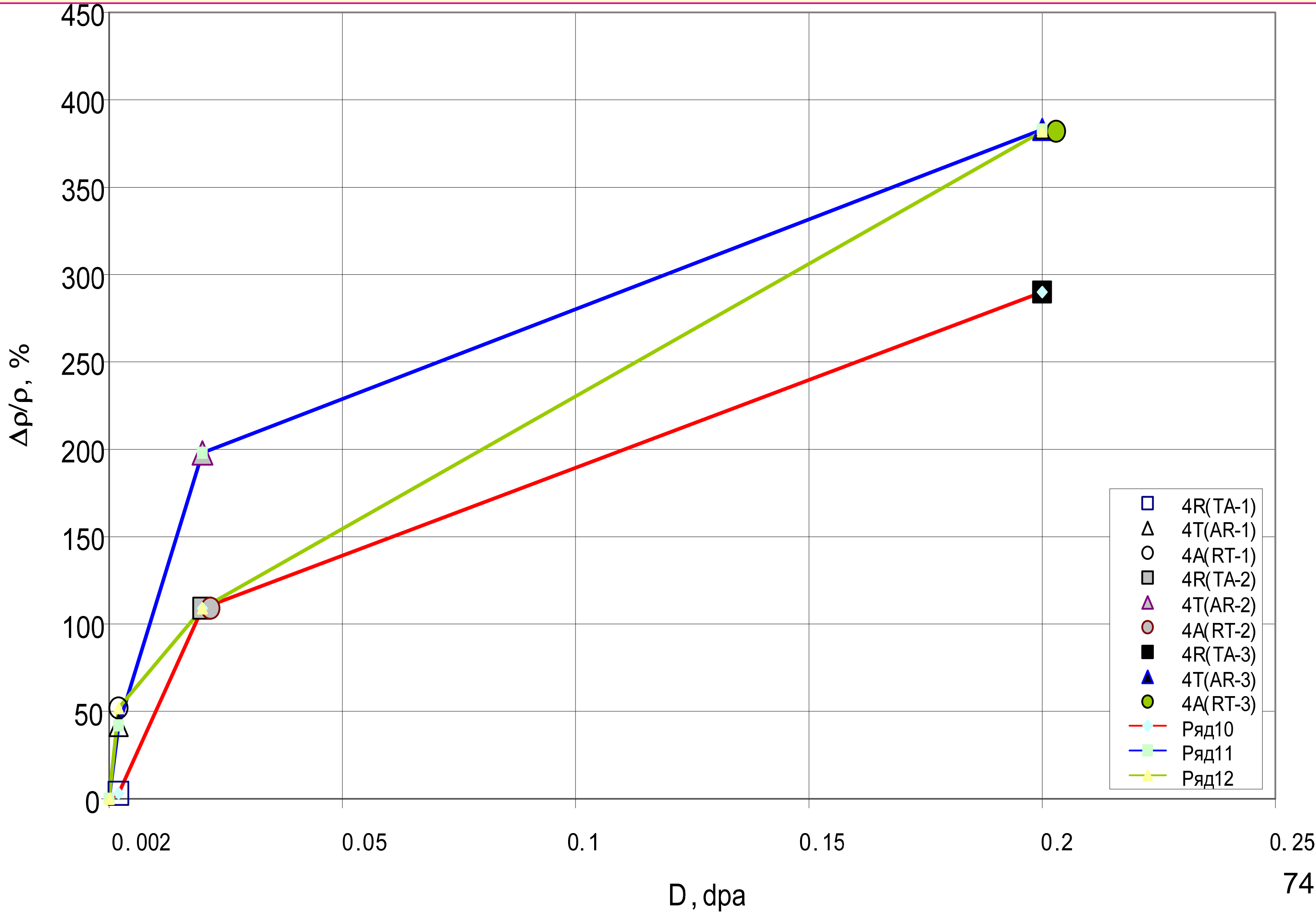
# Dose dependence of radiation swelling for three orientations of graphite.



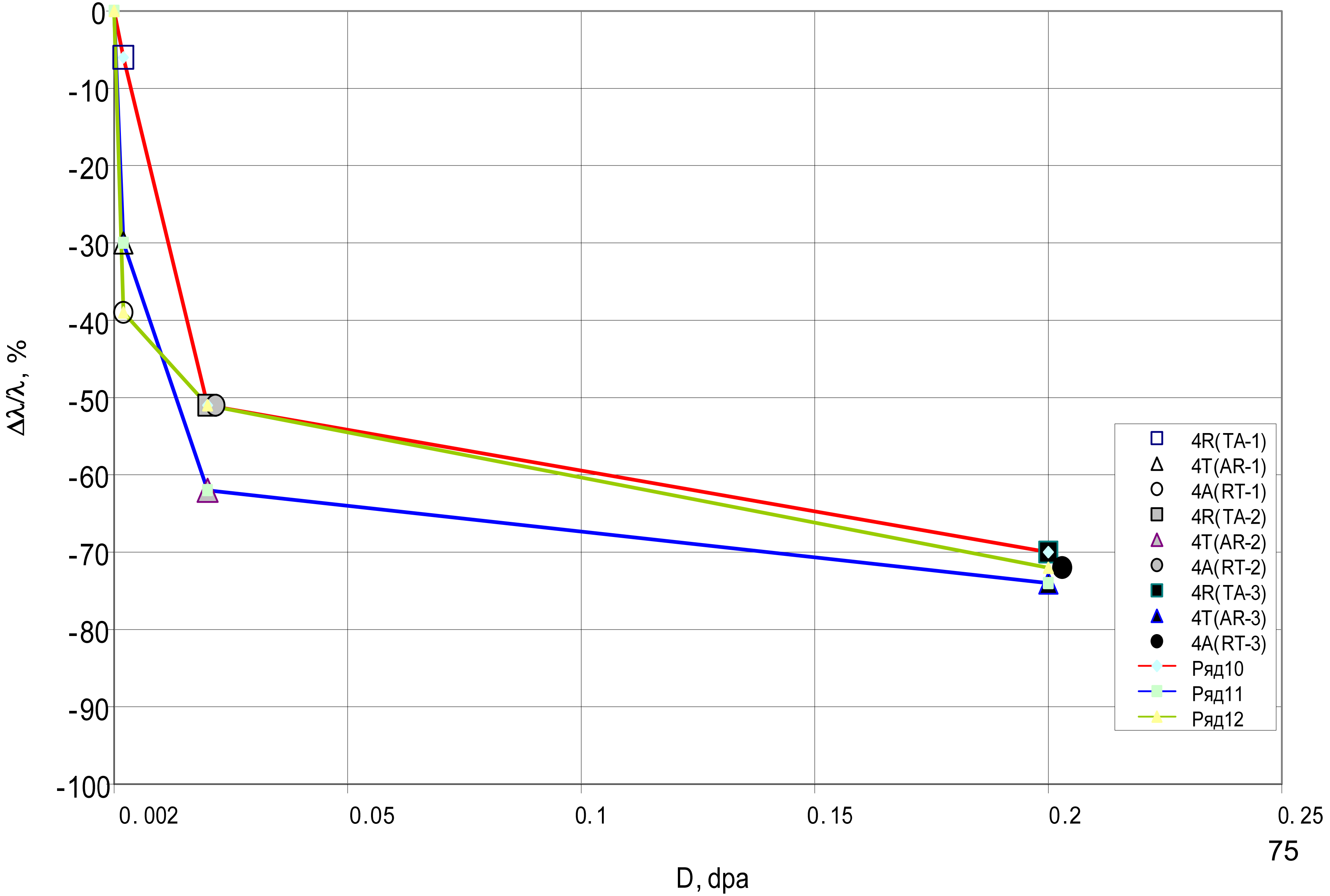
# Dose dependence of elastic Yung module for three orientations of graphite.



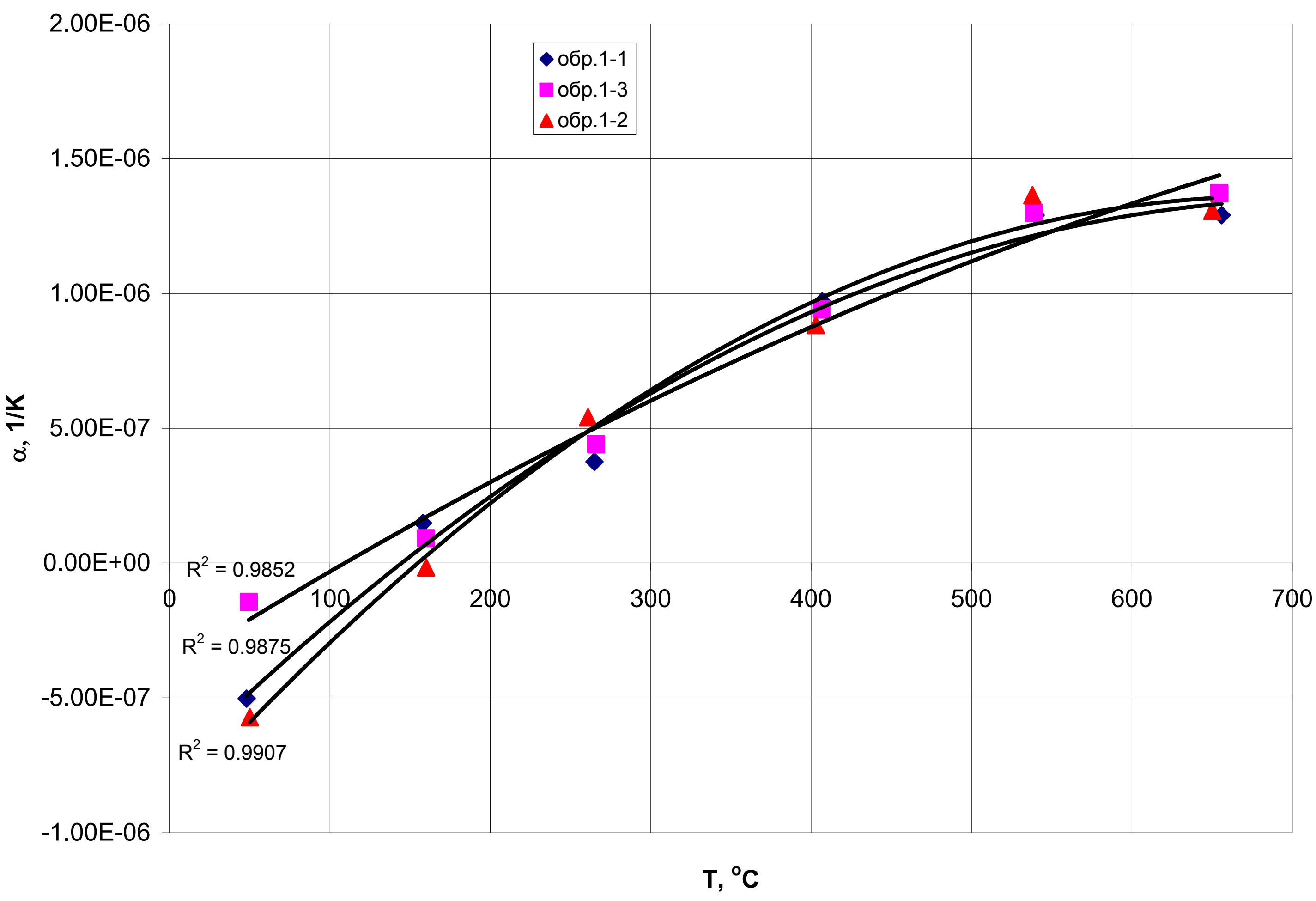
# Dose dependence of electrical resistance for three orientations of graphite.



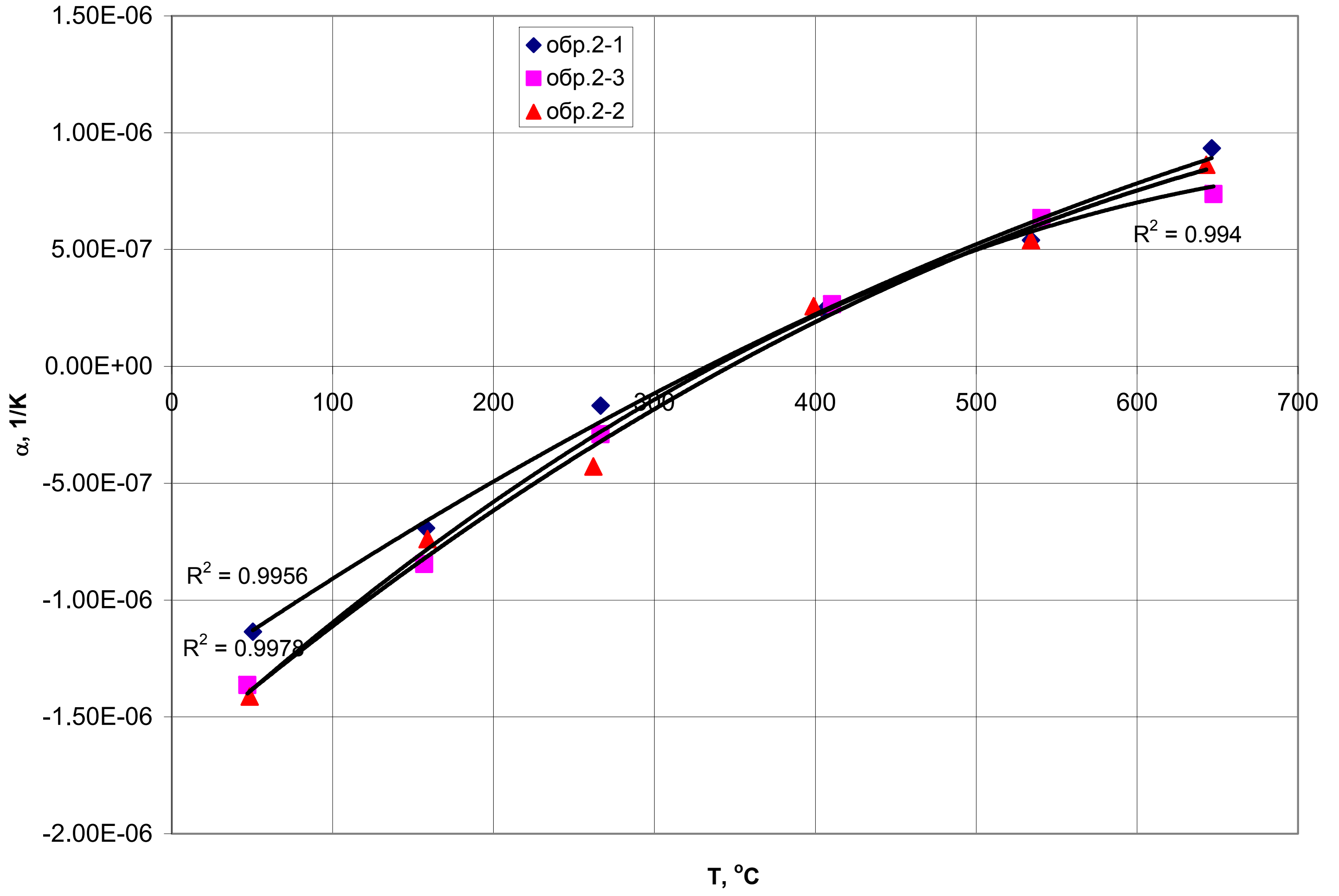
# Dose dependence of thermal expansion coefficient for three orientations of graphite.



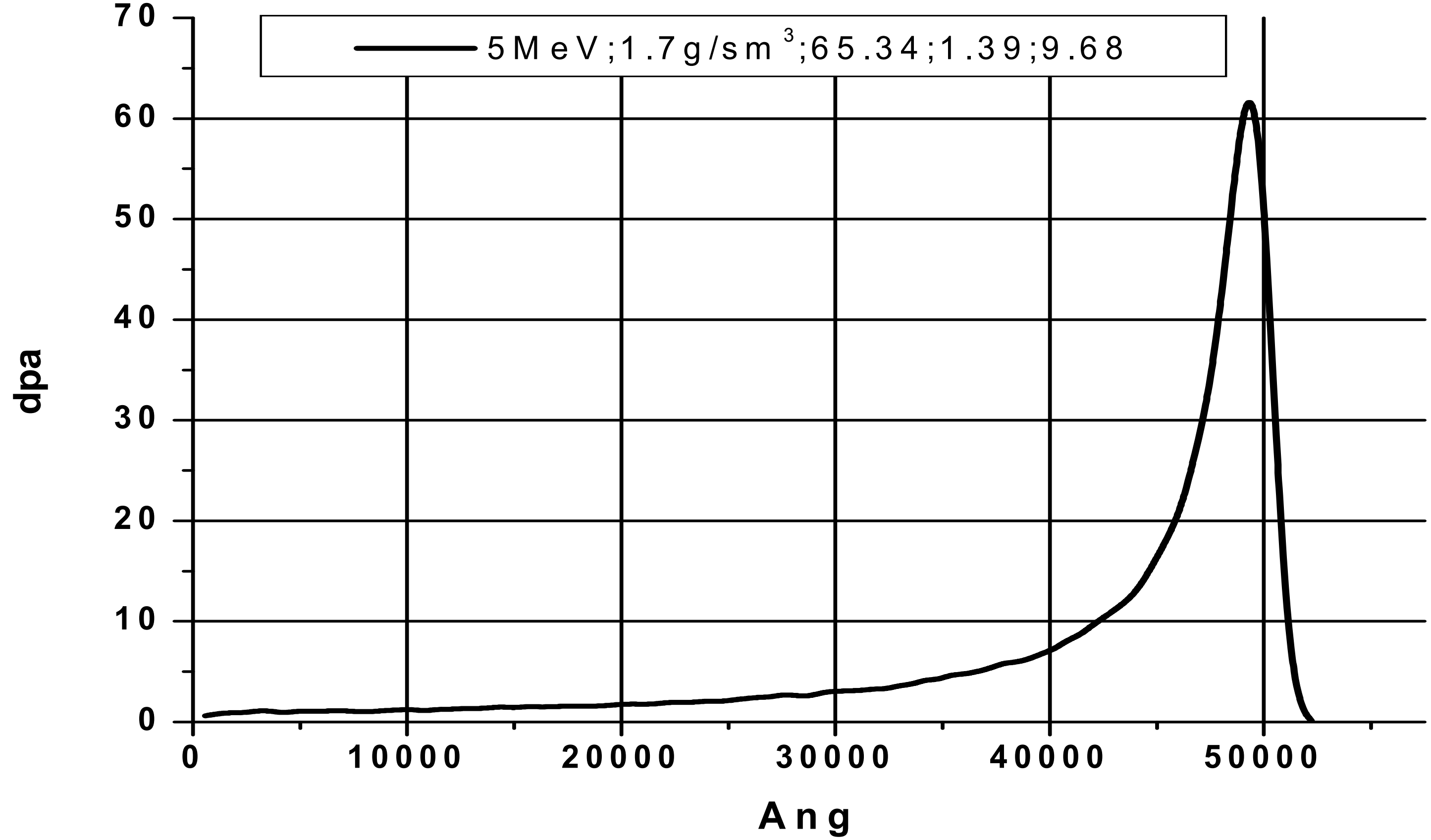
# Temperature dependence of thermal expansion coefficient **of REC.**



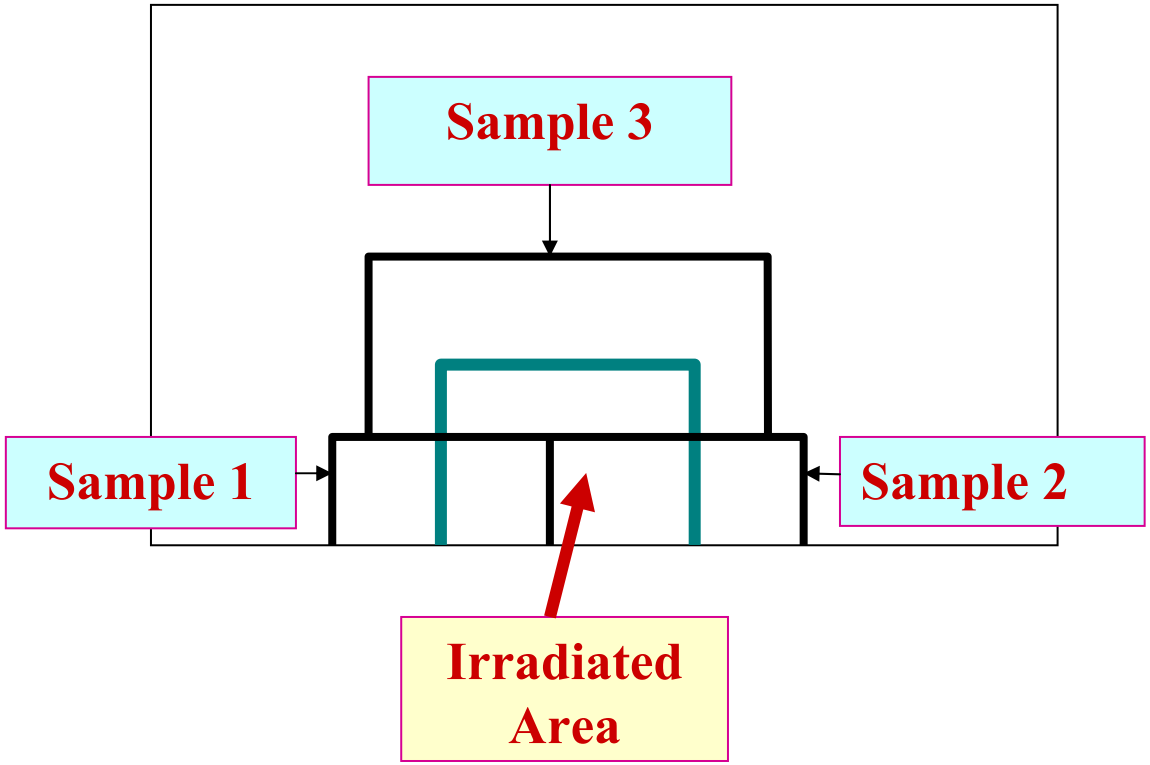
# Temperature dependence of thermal expansion coefficient **of AC 150.**



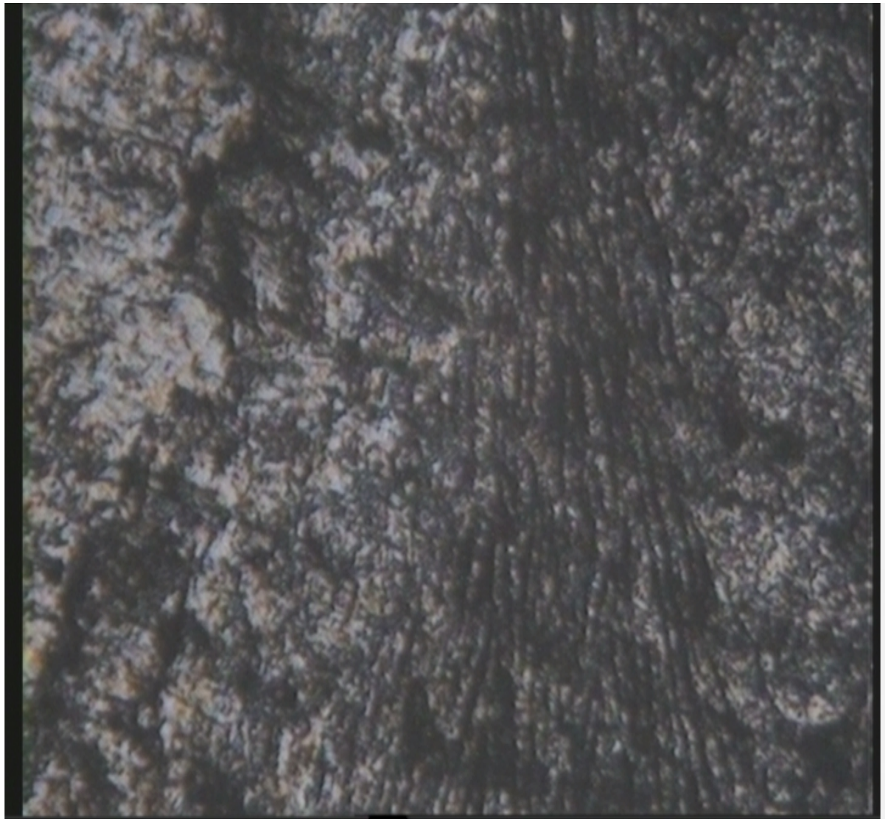
# Generation Rate of Point Defects under Irradiation of Graphite by 5 MeV Carbon Ions at Irradiation Dose 5.10E17cm2

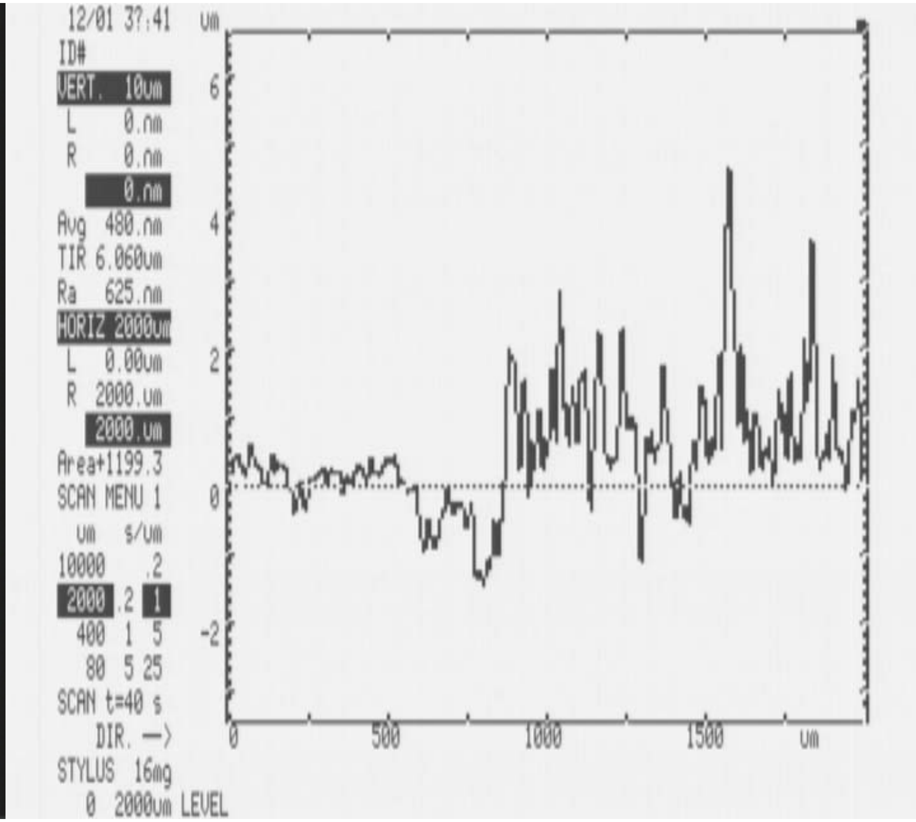


# Scheme of Irradiation of Graphite Samples

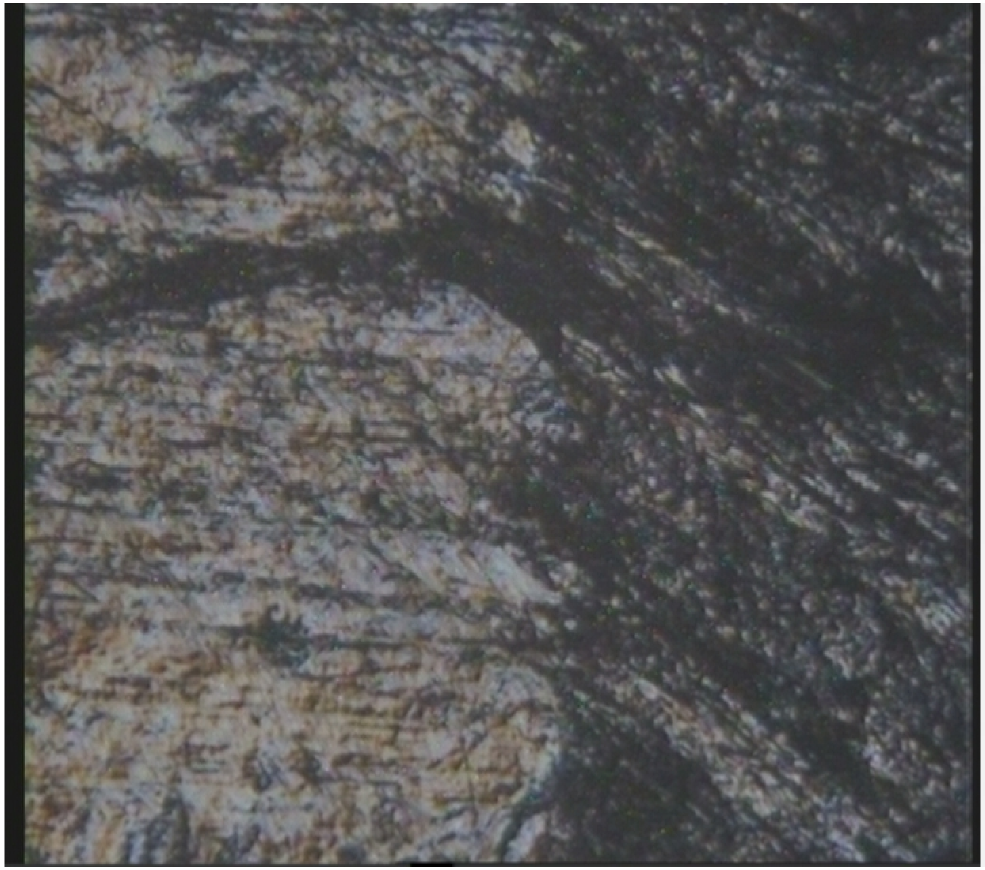


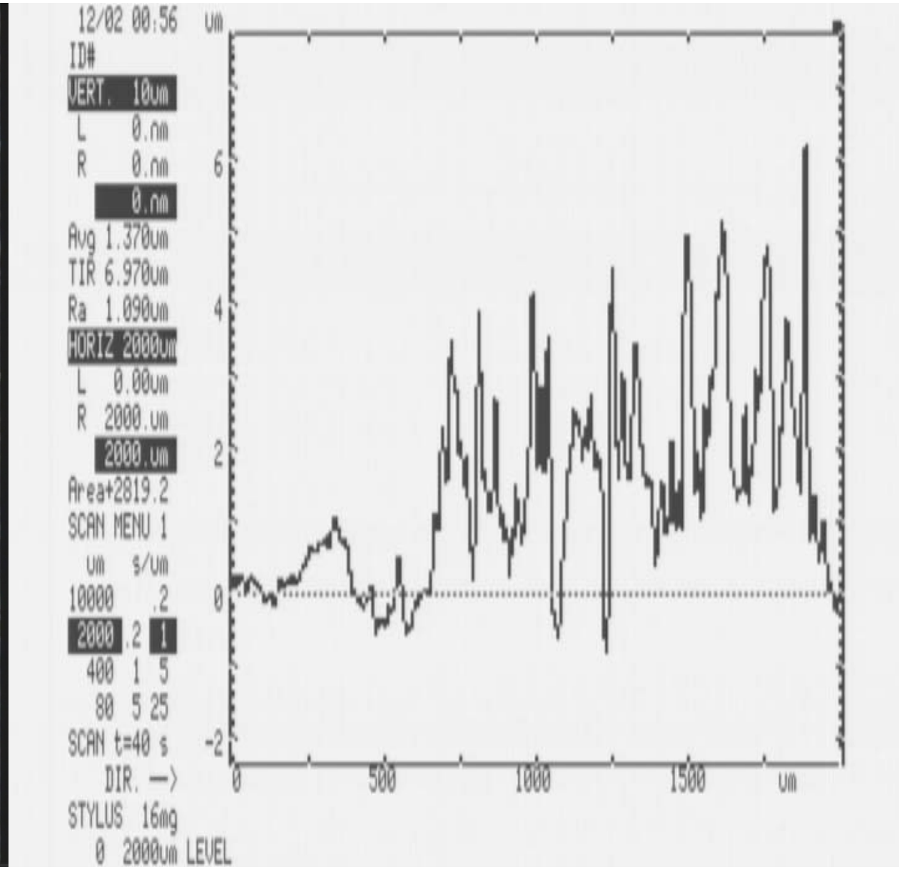
# Measurements of Radiation Induced Deformation in Graphite Composite Material REC Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 3x10 E17 p/см 2



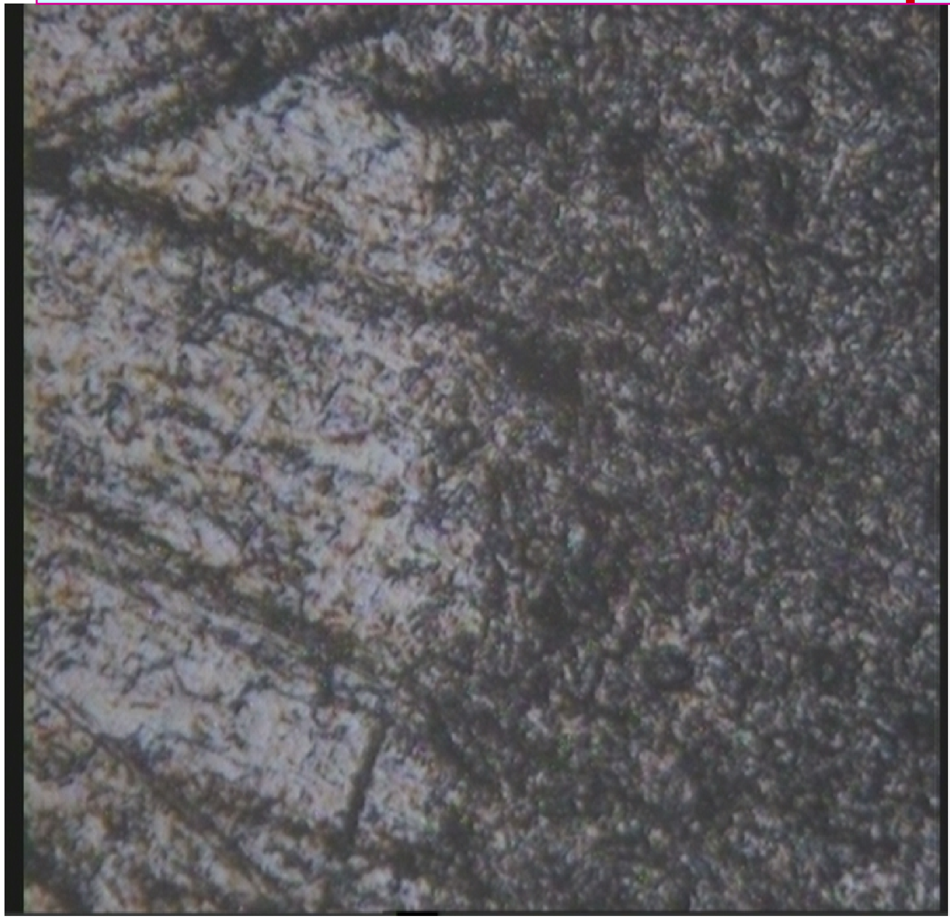


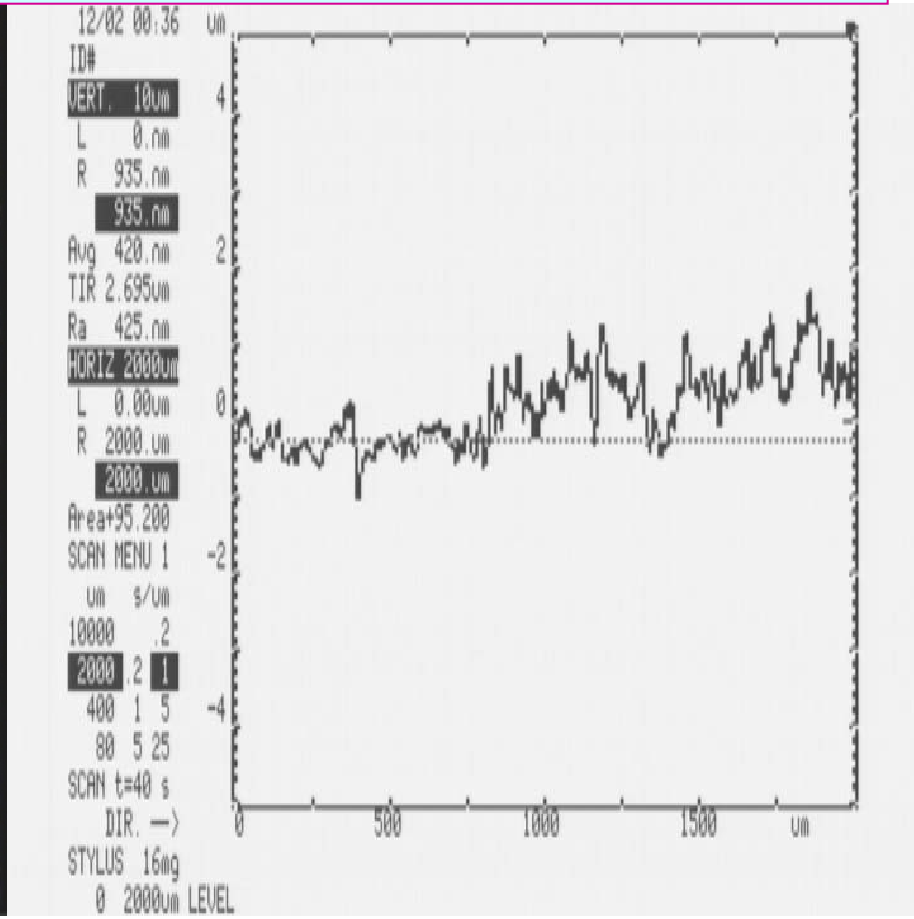
# Measurements of Radiation Induced Deformation in Graphite Composite Material AC Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 1x10 E17 p/cм 2



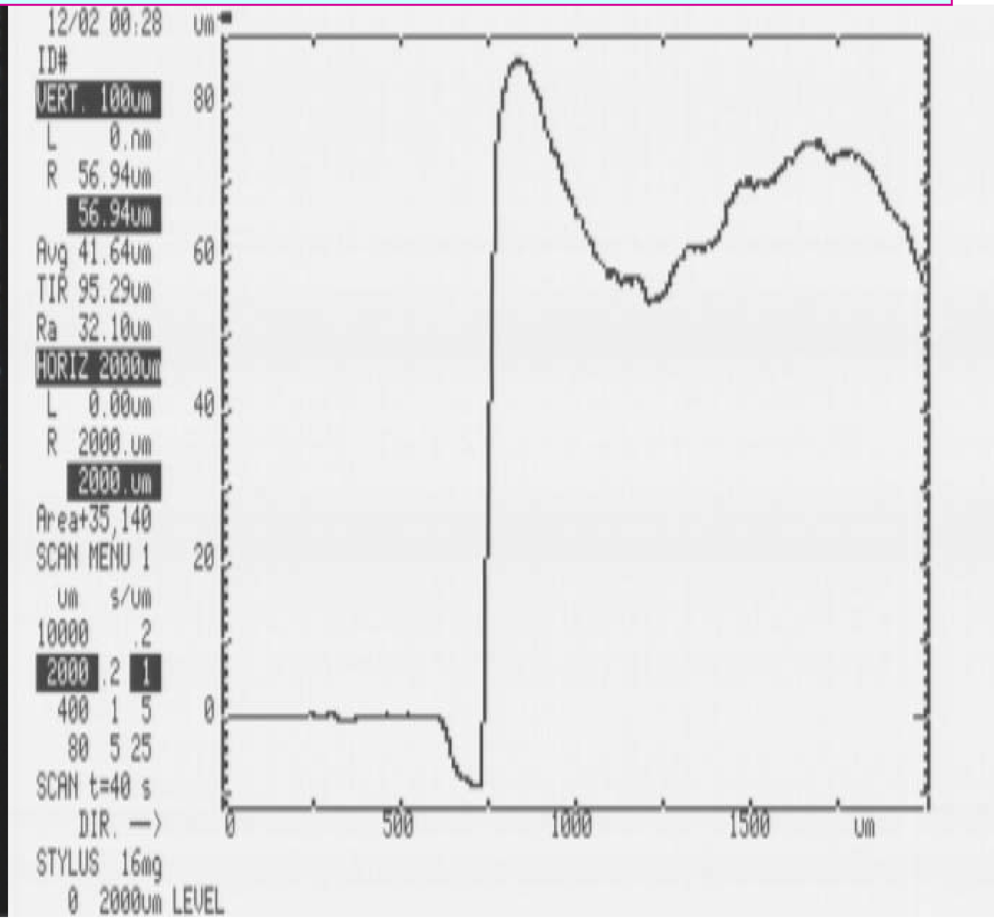


# Measurements of Radiation Induced Deformation in Graphite Composite Material R4SSO Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 3x10 E17 p/см 2

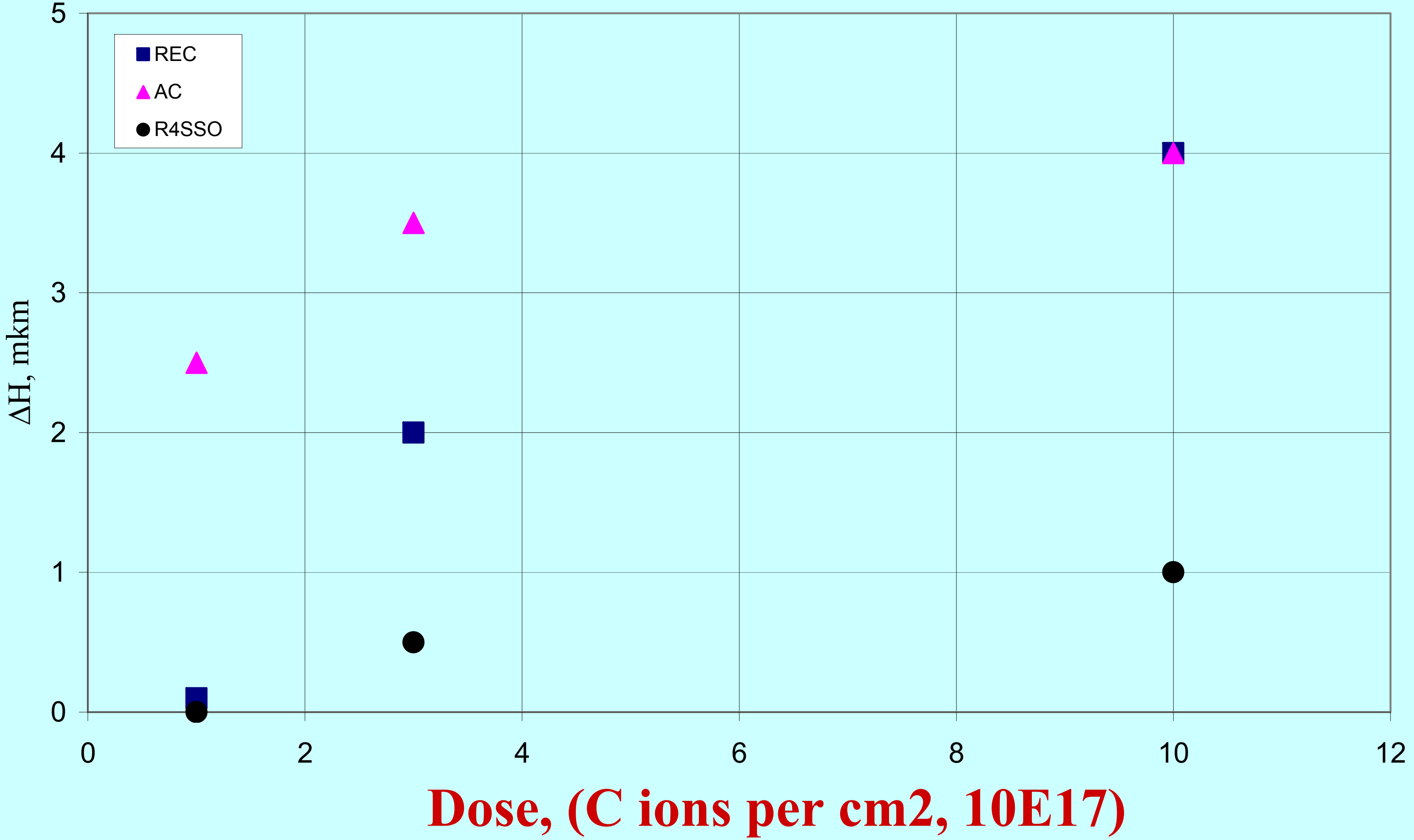




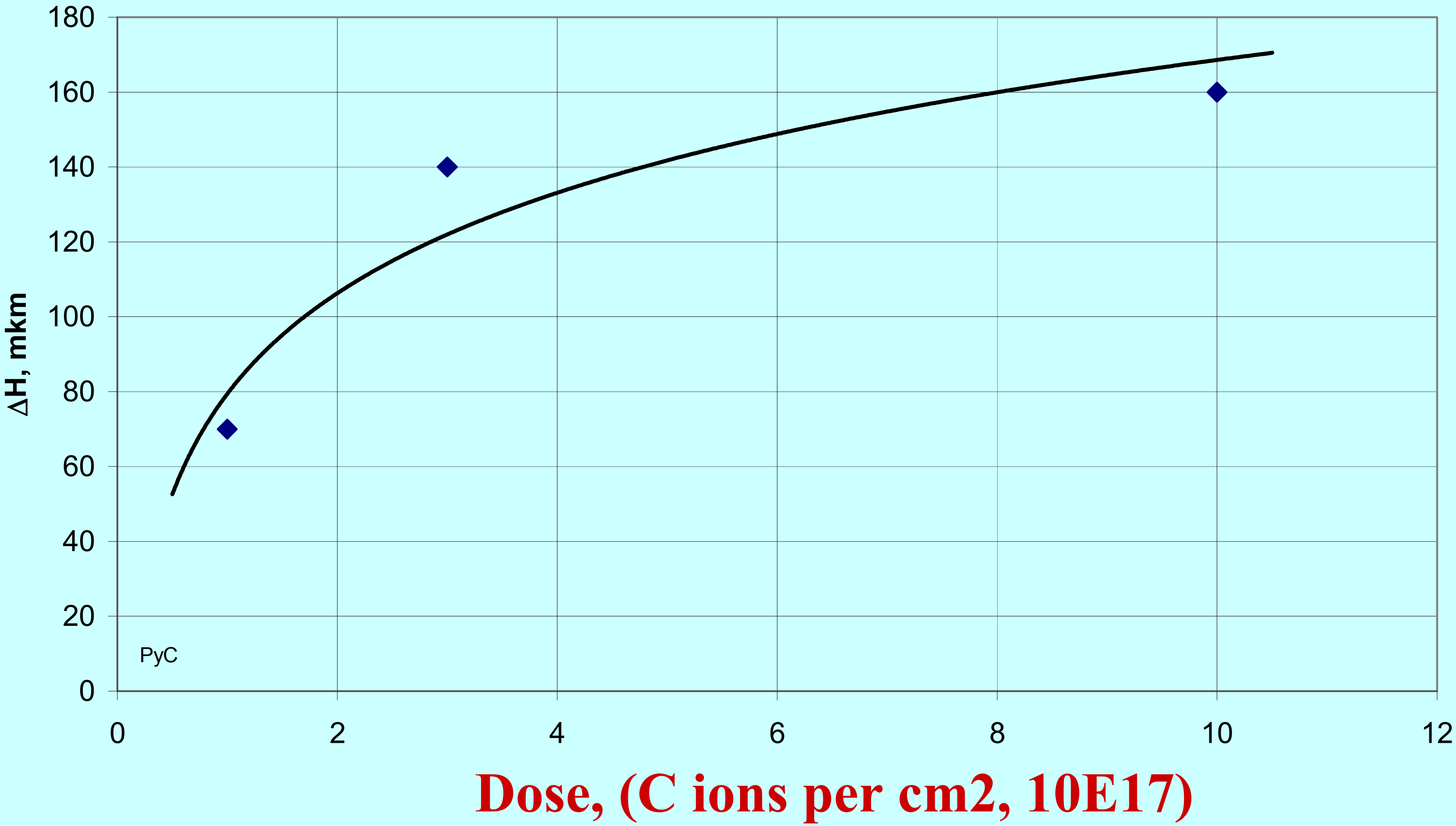
# Measurements of Radiation Induced Deformation in Pyro -Graphite Material Irradiated by Carbon Ions with the Energy 5 MeV at Irradiation Dose: 1x10 E17 p/cм 2



# Dose Dependence of Radiation Swelling of Graphite Collimator Materials of LHC



# Dose Dependence of Radiation Swelling of Pyro-graphite Material



# Future tests for of physical – mechanical properties changes on proton irradiated Graphite Collimator Materials for LHC

The following measurements shall be performed in all three directions of the irradiated C-C graphite materials (where applicable):

- Thermal conductivity (to ± 5 W/m/K).
- Electrical resistivity (to ± 1 mΩ m).
- Thermal expansion coefficient (to ± $10^{-6}$ / ºC).
- Mechanical strength (elastic modulus, deformation to rupture, ultimate tensile and compression stress, yield stress).
- Microstructure change with scale (visual analysis).
- Radiation erosion.
- Density and specific heat.
- Dimensions.

Make analysis with TEM, STEM, radiography and mechanical and electrical test equipment on irradiated and non-irradiated samples.

- Make theoretical analysis (dpa levels per sample and help in predictions for the LHC irradiation conditions).

# Theoretical modeling of shock wave formation under 450 GeV and 7 TeV proton beams in collimator materials for LHC

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**CERN CH-1211 Geneva 23, Switzerland

# Conclusion

- The results presented here allow to clarify main physical mechanisms of radiation resistance of fission and fusion structural materials using charged particle irradiation on accelerators.

- Using accelerators of charged particles allow to investigate the following physical phenomena in irradiated materials for fission and fusion reactors:

  - *Radiation hardening*
  - *Radiation swelling*
  - *Irradiation creep*
  - *Helium and hydrogen embrittlement*
  - *Fracture processes under irradiation*

  **at high irradiation doses and different temperatures.**

- The changes of physical-mechanical properties for the following fission and fusion structural materials can be analyzised:

  - **Graphite and C-C composites**
  - **Ceramic materials: SiC, MgO, ZrO2, Al2O3**
  - **Zr alloys**
  - **Ferritic / martensitic and austenitic steels**
  - **ODS materials**
  - **V alloys**

- Using accelerators can help to make chose more radiation resistance materials for fission and fusion reactors during short irradiation time comparing with atomic reactors