Formation of radiation defects in a metal target by a beam of accelerated atoms

A. Pushkarev*, A. Prima*, X.P. Zhu**, C.C. Zhang**, Y. Li**, M.K. Lei**

** Tomsk Polytechnic University, Tomsk, Russia, aipush@mail.ru*

*** Dalian University of Technology, Dalian, China*

1. Methods of radiation defects formation
2. The drawbacks of imitation irradiation
3. Experimental setup
4. Thermal imaging diagnostics of radiation defects
5. Results of irradiation of samples with a pulsed beam of carbon atoms
6. Calculation of the PKA energy spectrum

Conclusions

Motivation

The active development in the outer space and nuclear industries and studies of thermonuclear fusion require the materials with a resistance to high-dose radiation.

To develop new technologies for their production an **operational method for studying the radiation resistance of materials is needed**, which makes it possible to conduct in-situ tests in the conditions of intense irradiation.

Research nuclear reactor of Tomsk Polytechnic University

1. Methods of radiation defects formation

1. Direct irradiation of structural materials with fast neutrons (irradiation in nuclear reactors)

Irradiation of samples in a nuclear reactor requires a long amount of time to process the necessary neutron fluency and post-reactor exposure of materials to reduce radiation activity.

2. Simulation irradiation

- electrons irradiation
- heavy ions irradiation

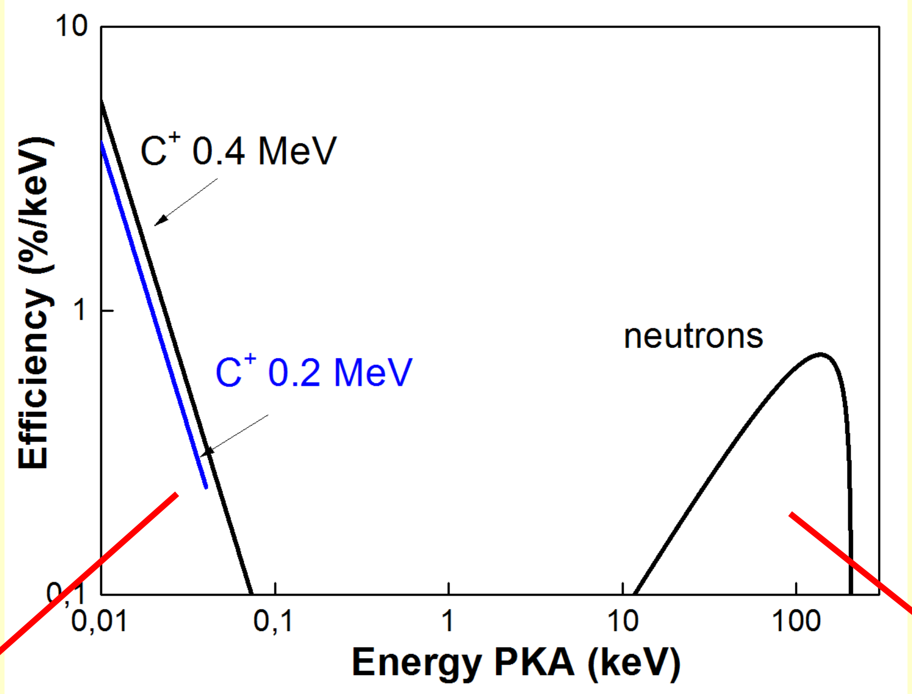
3. Computer simulation

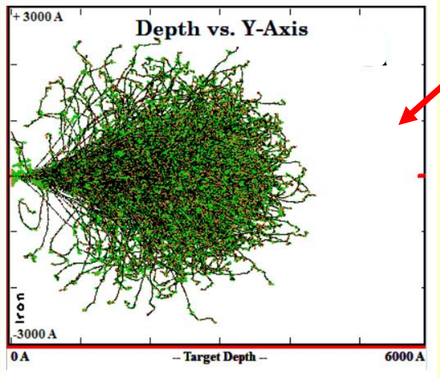
- SRIM
- Molecular dynamics simulation

2. The drawbacks of imitation irradiation

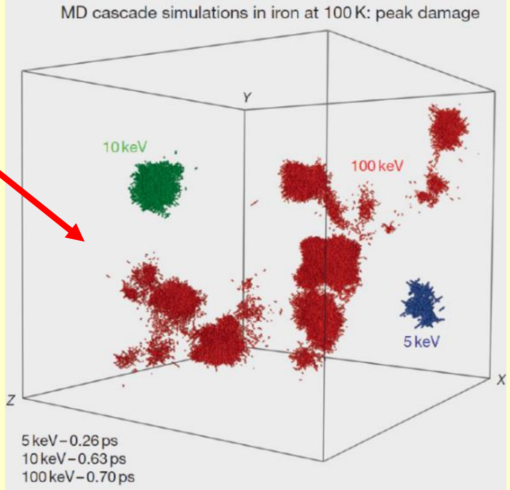
Simulated irradiation by charged-particle beams **has significant disadvantages** compared to neutron irradiation in a nuclear reactor.

1. The energy spectrum of primarily knocked-out atoms (PKA) in the target with ion irradiation is significantly different from the spectrum with irradiation by neutrons.



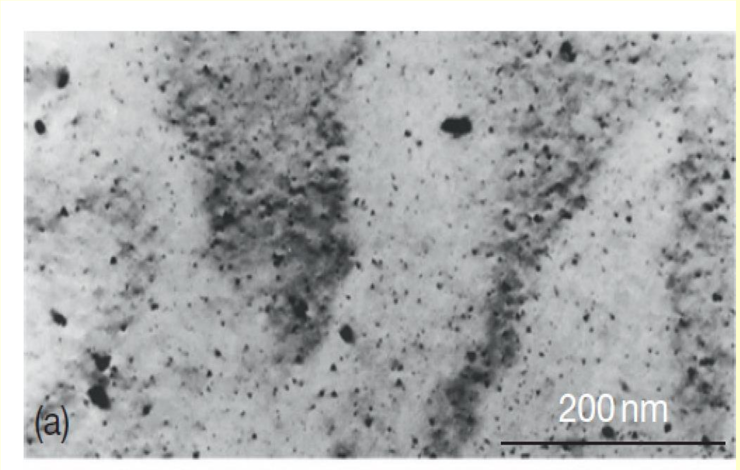


The dependence of the kinetic energy transfer efficiency from the PKA energy upon penetration in an iron target

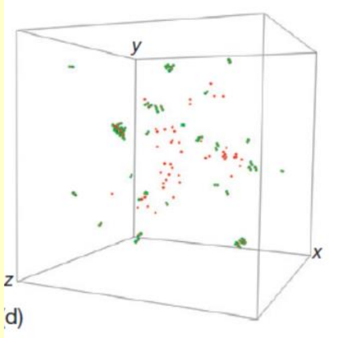


2. The drawbacks of imitation irradiation

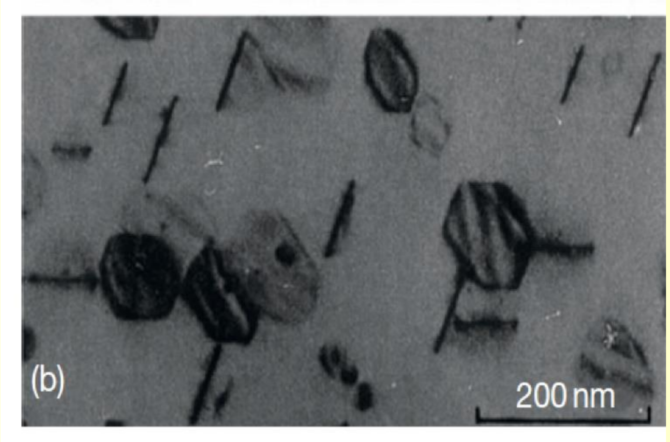
2. Different structure of defects in the target



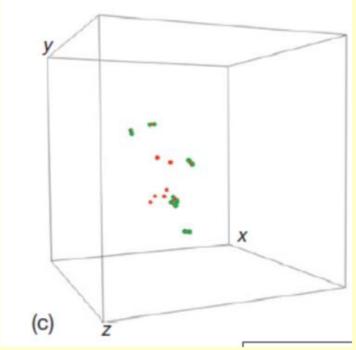
Microstructure of copper irradiated with fission neutrons



Stable configuration of defects at PKA energy 20 keV



Microstructure of copper irradiated with 1 MeV electrons



Stable configuration of defects at PKA energy 1 keV

G.S. Was, R.S. Averback. Radiation Damage Using Ion Beams. In Comprehensive Nuclear Materials. Vol. 1. Elsevier: Amsterdam. (2012):195-221.

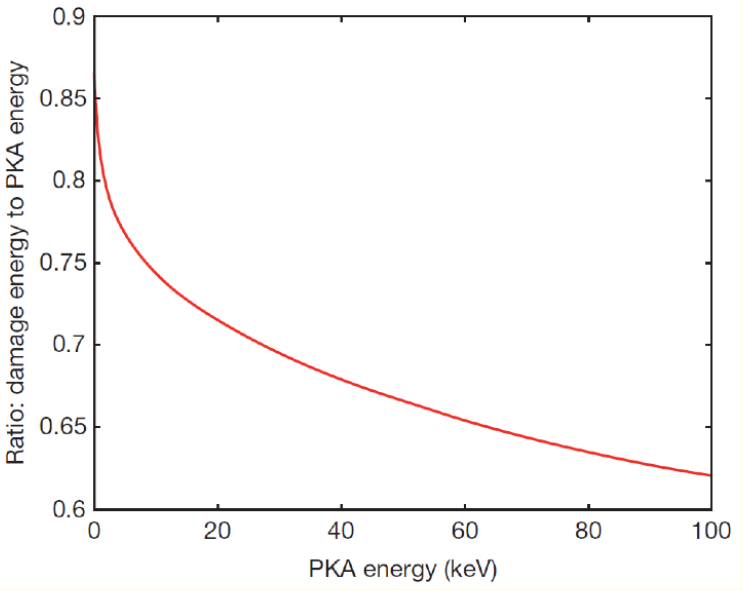
2. The drawbacks of imitation irradiation

3. Large energy losses for electronic stopping

SRIM simulation (ions)

Table 1. Loss of energy of ion C^+ with energy 250 keV in different targets

The target material	The energy loss	
	ion C^+	
	electronic stopping	phonons
Ti	84%	12%
Fe	81%	16%
Zn	77%	19%
Cu	78%	19%



Ratio of damage energy to PKA energy as a function of PKA energy

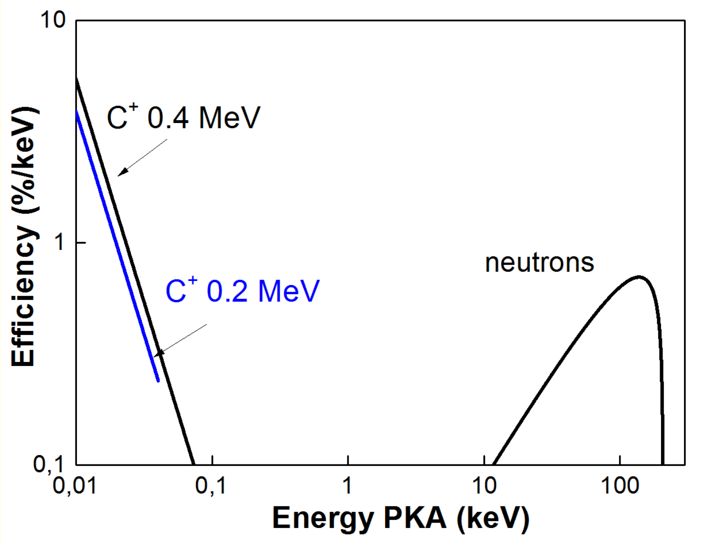
R.E. Stoller. Primary radiation damage formation. In Comprehensive nuclear materials. Vol. 1. Elsevier: Amsterdam. 2012. pp. 293-329.

2. The drawbacks of imitation irradiation

The difference between simulation (by ion or electron irradiation) and reactor radiation processes does not make accurate predictions of radiation resistance of structural materials in a nuclear reactor.

Simulated irradiation of structural materials with accelerated atoms can overcome these disadvantages, but such studies are practically absent.

The purpose of this study is to compare the effect a **fast atom beam** and ion beam on the metal target.



3. Experimental setup

Parameters of accelerator TEMP-6:

- accelerating voltage of 250-300 kV;
- pulse duration 150 ns;
- energy density up to 10 J/cm^2
- Beam composition: C$^+$ and protons

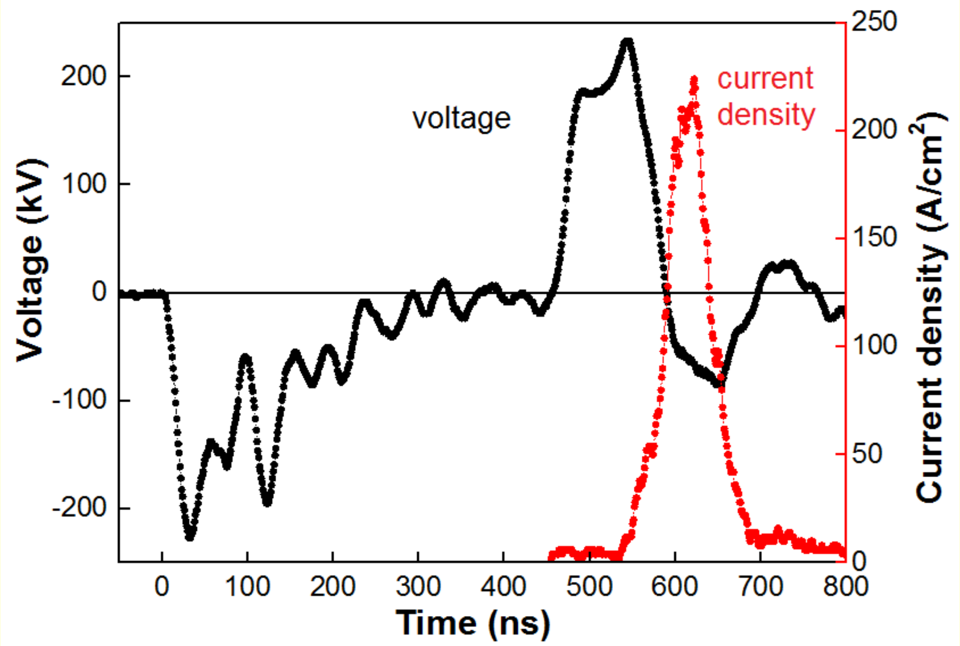
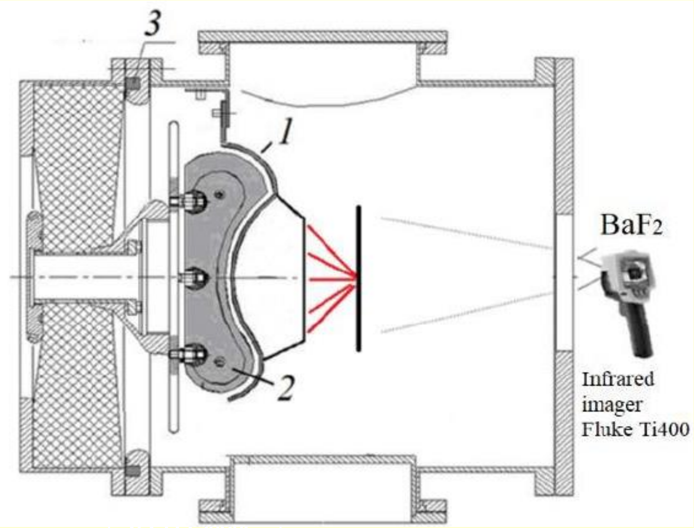


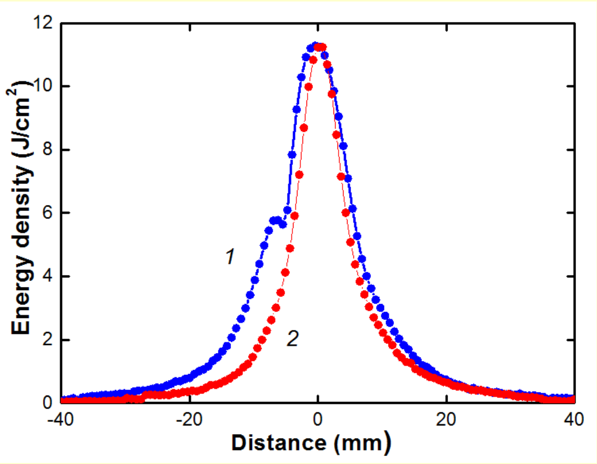
Photo of TEMP-6 accelerator. Waveforms of accelerating voltage and ion current density

3. Experimental setup

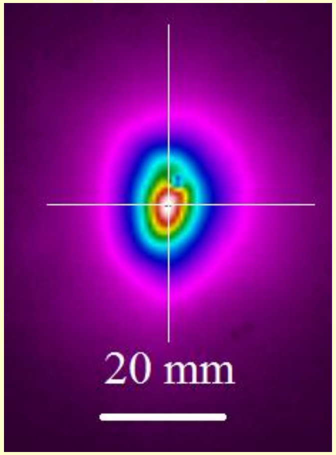


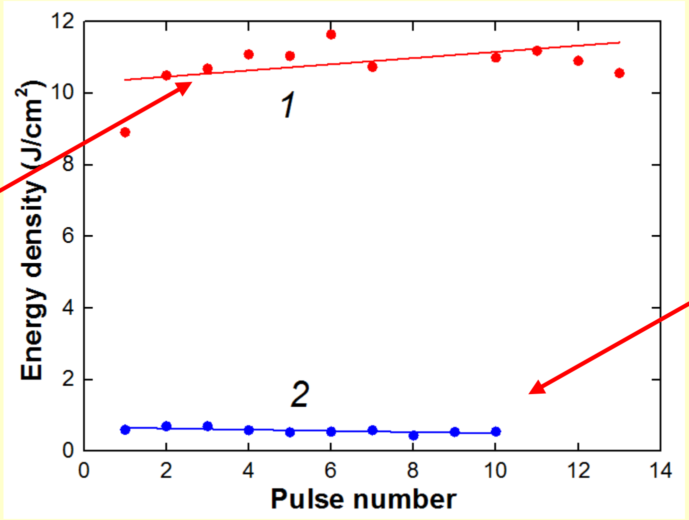
Generation of fast atoms

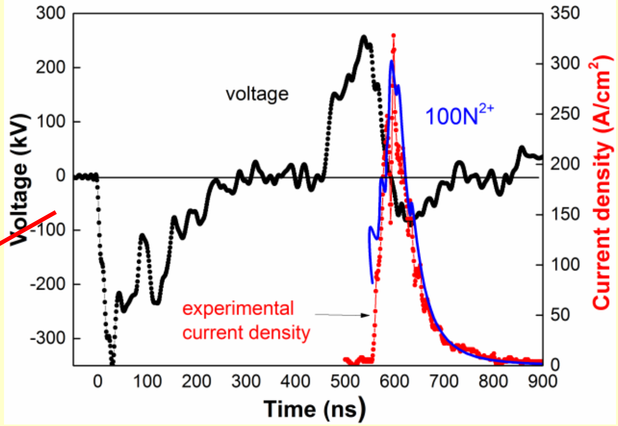
$$\frac{E_{fast\ atom}}{E_{beam}} \geq 95\%$$



Energy density distribution in focus







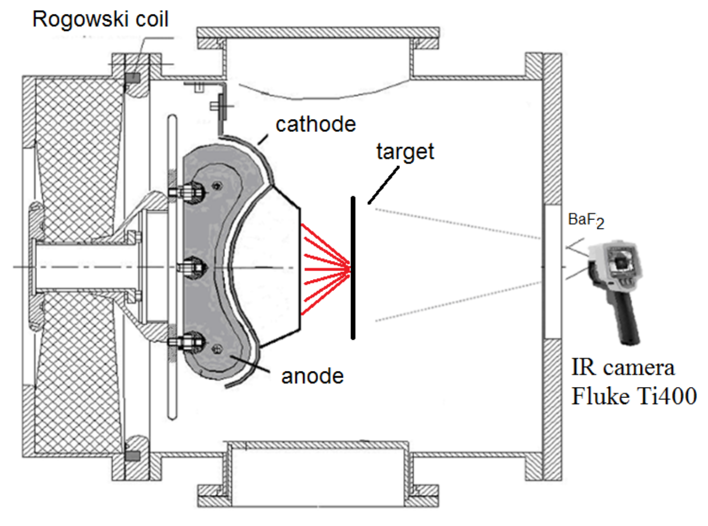
The change in the pulse series of the energy density in focus, measured using thermal imaging diagnostics (1) and calculated from the ion current density (2)

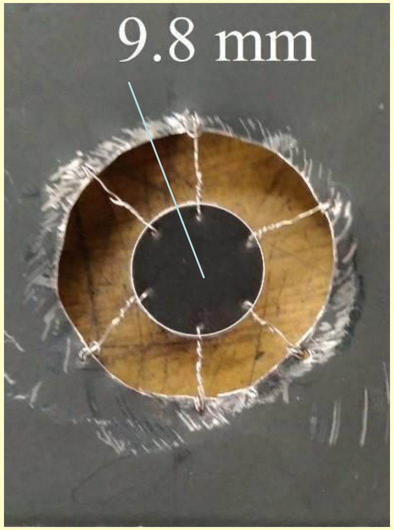
4. Thermal imaging diagnostics of radiation defects

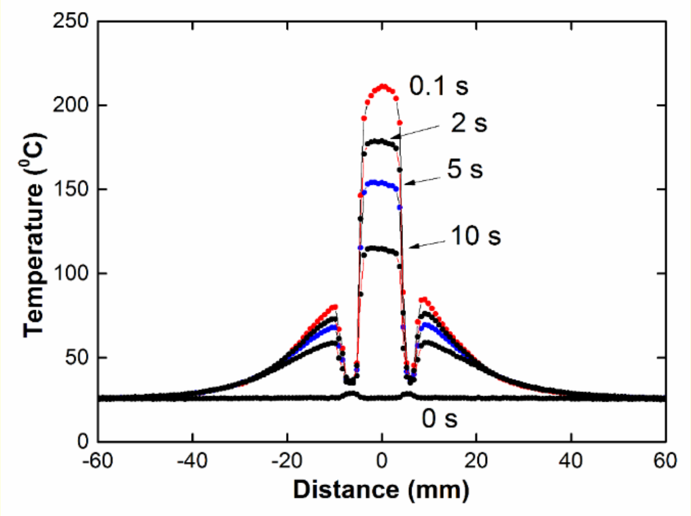
Thermal imaging diagnostics of the fast radiation processes includes

- formation of radiation-induced defects with high concentration
- in situ measurement of their parameters

To control the target cooling after irradiation, a IR camera was used.





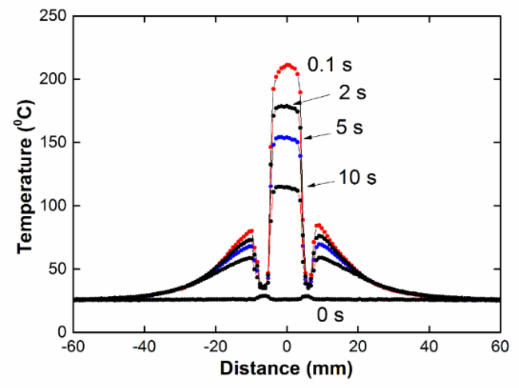


Schematic of the diode unit. Temperature distribution at different times after irradiation

4. Thermal imaging diagnostics of radiation defects

Thermal imaging diagnostics of the fast radiation processes includes

- formation of radiation-induced defects with high concentration
- in situ measurement of their parameters



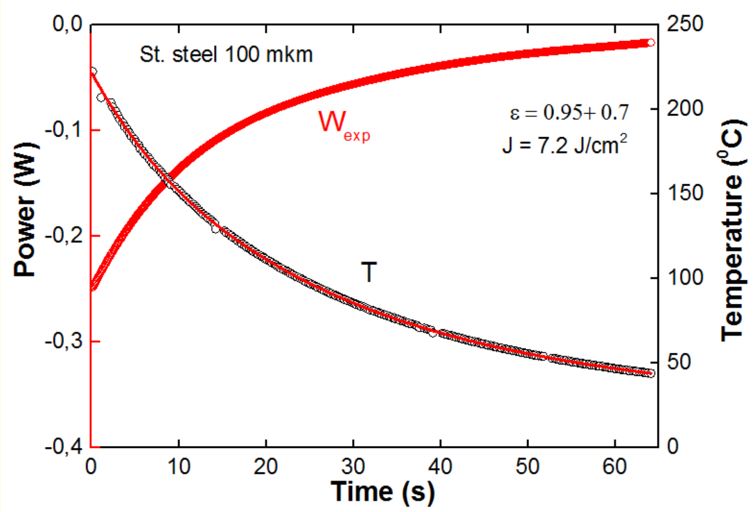
The thermal energy in the target: $$E_{\exp}(t) = c_v \cdot \rho \cdot S \cdot \Delta[T_m(t) - T_0], \quad J$$

c_v and ρ - specific heat and density of the target material, respectively;

T_0 *and* $T_m(t)$ – initial and mean temperature of the target respectively

S - area of the target,

Δ - disc thickness



Experimental power of the energy loss in target (W_{exp}<0):

$$W_{\exp}(t) = \frac{dE}{dt} = c_v \cdot \rho \cdot S \cdot \Delta \frac{dT_m(t)}{dt}, \quad W$$

Targets temperature (T) and experimental power of the energy loss in the target (W_{exp})

4. Thermal imaging diagnostics of radiation defects

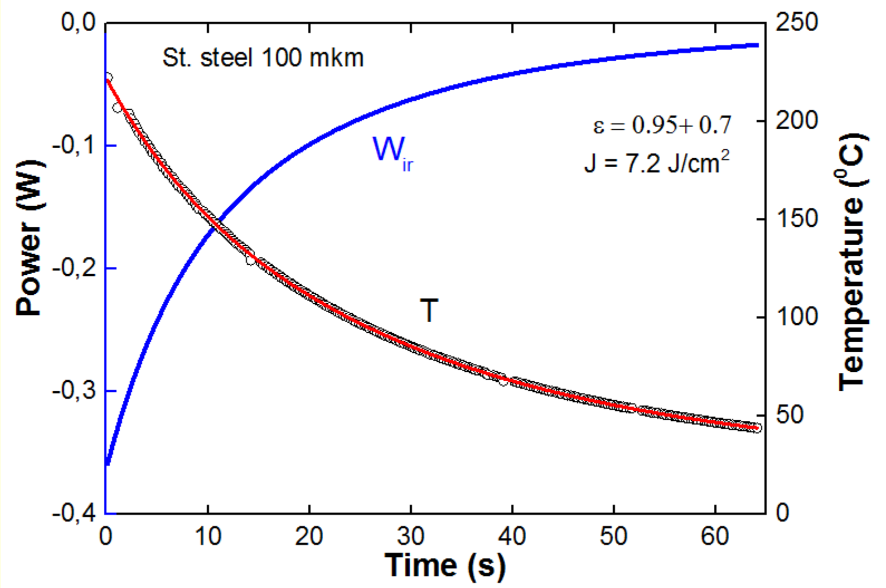
The power density of thermal radiation, given by the Stefan-Boltzmann law is:

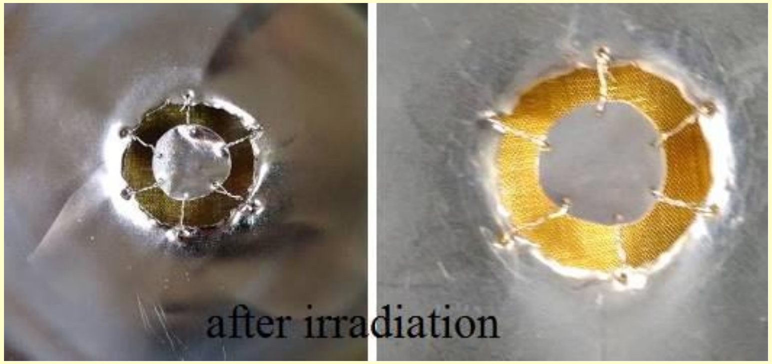
$$\mathrm{w_{ir}}(\mathrm{x},\mathrm{y},\mathrm{t}) = (\varepsilon_1 + \varepsilon_2)\cdot\sigma[T^4(x,y,t) - T_0^4], \quad W/cm^2$$

ε_1 и ε_2 are the emissivity of the front and rear sides of the target,
$\sigma = 5.67\cdot 10^{-12}$ W/(cm$^2\cdot$K^4).

Power of thermal radiation from the target:

$$\mathrm{W_{ir}}(\mathrm{t}) = -S(\varepsilon_1 + \varepsilon_2)\cdot\sigma[T_m^4(t) - T_0^4], \quad W$$



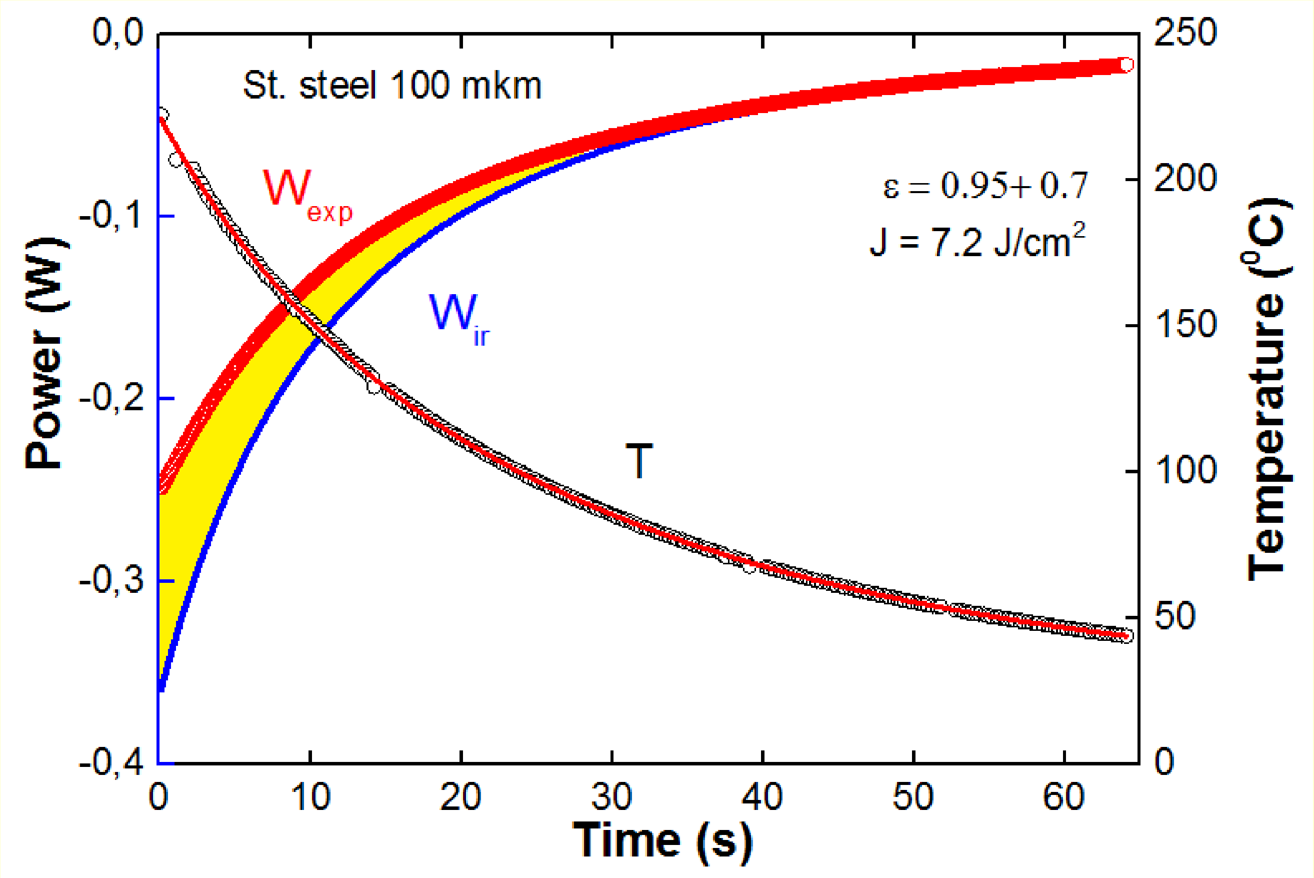


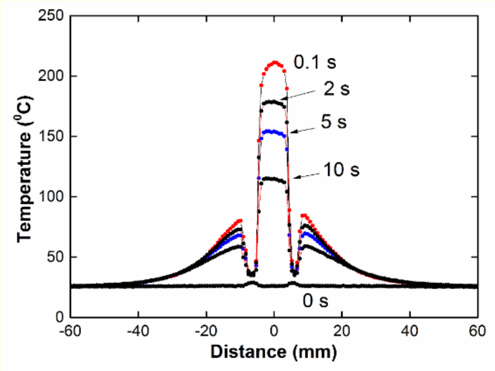
Targets temperature (T) and power of thermal radiation from the target (W_{IR})

4. Thermal imaging diagnostics of radiation defects

Cooling of a small target - thermal radiation only

$$W_{ir}(t) = S(\varepsilon_1 + \varepsilon_2) \cdot \sigma[T_m^4(t) - T_0^4], \quad W \qquad W_{exp}(t) = S \cdot c_v \cdot \Delta \cdot \rho \left| \frac{dT_m(t)}{dt} \right|, \quad W$$





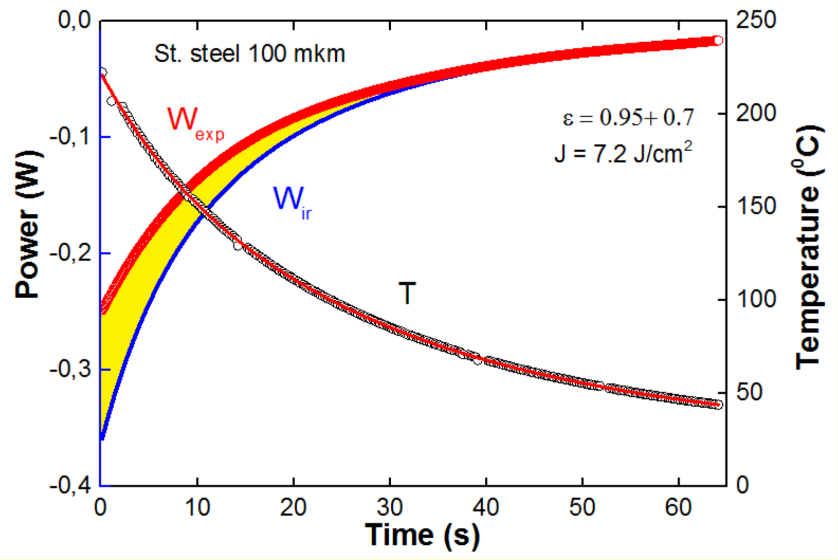
Targets temperature (T), experimental power of the energy loss in the target (W_{exp}), power of thermal radiation from the target (W_{IR})

4. Thermal imaging diagnostics of radiation defects

We assume that the source of additional energy released in the target during cooling can be **fast thermal annealing of radiation-induced defects**, formed in target during ion beam irradiation

Thermal imaging of fast radiation processes provides the ability to determine:

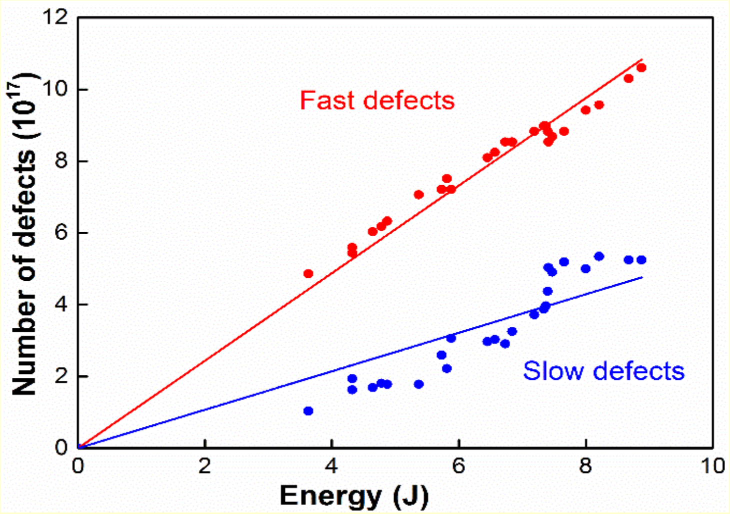
- **concentration of radiation defects**
- threshold energy of migration of radiation defects
- type of radiation defects
- duration and degree of defects annealing
- number of displacements of interstitial atoms before annihilation



5. Results of irradiation of samples with a pulsed beam of carbon atoms

Our studies have shown that radiation defects can be divided into two groups:

- **fast defects** that are annihilated before the target cooling measurement (within 0.1 s after irradiation for 150 ns)
- **slow defects** that migrate to the target from their formation point and are, then, annihilated over tens of seconds].



Dependence of the number of fast and slow defects on the absorbed beam energy in a stainless steel target.

$$n_d = K_d \cdot E_{atom},$$

E_{atom} - average energy of a fast atom in the beam

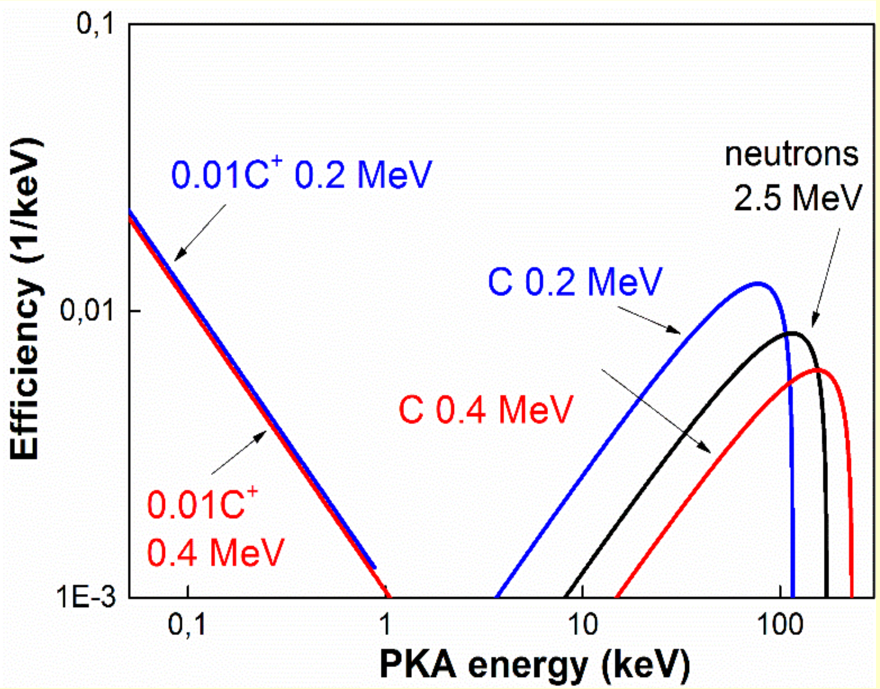
Table 1. Number of defects in the fast carbon atom cascade

Fast defects	Slow defects	N_{sum}	N_{SRIM}
4500	2025	6525	1250

6. Calculation of the PKA energy spectrum

The energy spectrum of the PKA in the target is the most important parameter, determining the spatial distribution of primary radiation defects, duration, and efficiency of their subsequent annealing. Energy spectra of PKA, when irradiating a metal target with neutrons or ions, considerably differ.

Experimental or calculated data of PKA spectra upon absorption of fast atoms in a metal target are absent.



The dependence of the kinetic energy transfer efficiency from the PKA energy upon penetration in an iron target

6.1. Calculation of the PKA energy spectrum at irradiation a metal target with ions

The energy obtained by the PKA after the collision is:

$$E_{PKA} = E_0 \frac{4m_1 \cdot m_2}{(m_1 + m_2)^2}(1 - \cos^2 \frac{\theta}{2}) \qquad (1)$$

E_0 - initial energy of a fast particle (ion, neutron, or fast atom)
θ - scattering angle of this fast particle

The probability of ion scattering by target atoms is described by the Rutherford formula:

$$f_i(\theta) = \left(\frac{4Z_1 \cdot Z_2 \cdot e^2}{E_0} \right)^2 \frac{1}{\sin^4 \frac{\theta}{2}} \qquad (2)$$

Z_1 and Z_2 - nuclei charges of an ion and PKA, respectively
e - electron charge.

6.1. Calculation of the PKA energy spectrum at irradiation a metal target with ions

The energy spectrum of the PKA is determined by the efficiency of kinetic energy transfer from the fast particle to PKA, equal to the product PKA energy on the probability of scattering.

$$F_i = f_i E_{PKA} = \frac{K}{1-\cos\theta} \quad \text{where} \quad K = \frac{4m_1 \cdot m_2 (4Z_1 \cdot Z_2 \cdot e^2)^2}{E_0 (m_1 + m_2)^2} \qquad (3)$$

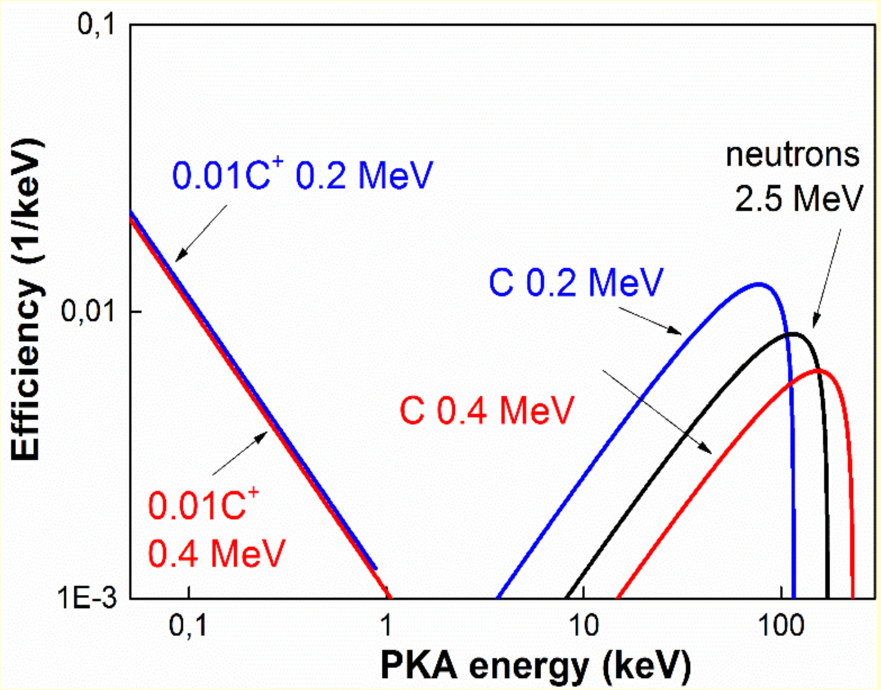
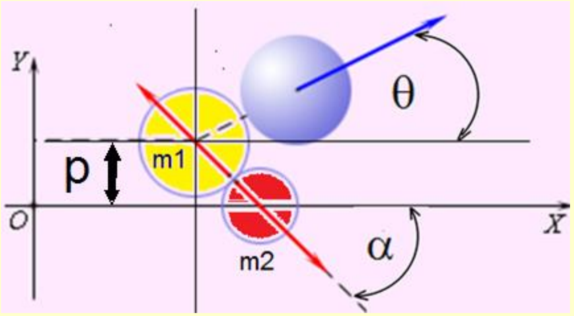


Fig. 1. The dependence of the kinetic energy transfer efficiency from the PKA energy upon penetration in an iron target

6.2. Calculation of the PKA energy spectrum at irradiation a metal target with fast atom and neutron

The process of neutron penetration in the target can also be considered with binary collisions of solid balls [13, 14], whose radii are equal to the neutron radius (3.6×10^{-5} Å) and nuclei radius of the target atom.

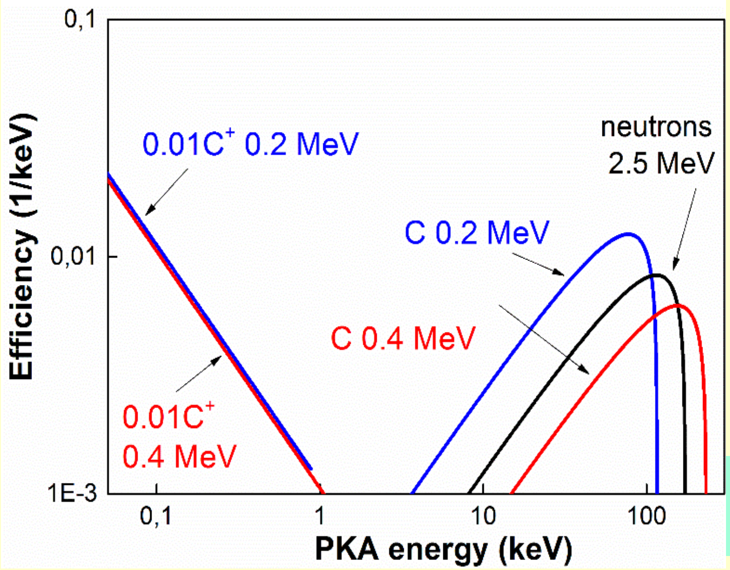
The probability of the neutron colliding with the target atom increases with the growth of the impact parameter and can be written as:



$$f_{atom}(p) = \frac{2\pi p}{\int_0^{R_1+R_2} 2\pi p dp} = \frac{p}{R_1+R_2} == \cos\frac{\theta}{2} \quad \text{at } p < R1 + R2$$

$$f(p)=0 \quad \text{at } p \geq R1 + R2$$

where p is the impact parameter,
R1 and R2 are the radii of the target atom, respectively.

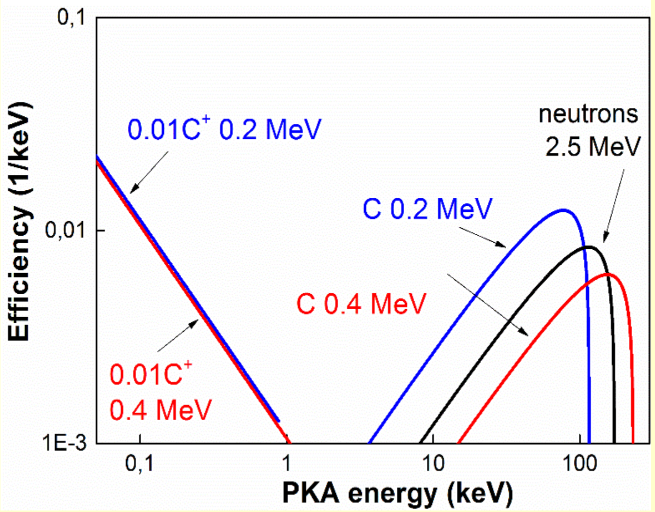


Conclussion

1. Irradiation of a metal target by fast atoms is more consistent with neutron irradiation in a nuclear reactor, according to the PKA spectrum, efficiency, and the radiation defects formation mechanism.

2. The PKA energy spectrum upon irradiation of a metal target by fast atoms, with an energy of 200–600 keV, more fully corresponds to the PKA spectrum upon irradiation by neutrons formed in the fission reaction ^{235}U in a nuclear reactor.

3. Unlike a neutron, an accelerated atom can be ionized during absorption in a target; the energy required to remove an electron is much less than its kinetic energy. However, at the energy of fast atoms, 200–600 keV, the ion charge-exchange cross section during penetration in the target is significantly higher than the ionization cross section, and the ionization probability is negligible.



The dependence of the kinetic energy transfer efficiency from the PKA energy upon penetration in an iron target