中國原子能科學研究院
CNNC CHINA INSTITUTE OF ATOMIC ENERGY

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Radiation Damage and Synergistic Effect in CLAM steel

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Outline

- ✓ **Background**
- ✓ **Dependences of Radiation Damage in CLAM on Irradiation Temperature and Dose**
- ✓ **Synergistic Effect of RD in CLAM Studied by Triple beam irradiation**

Background

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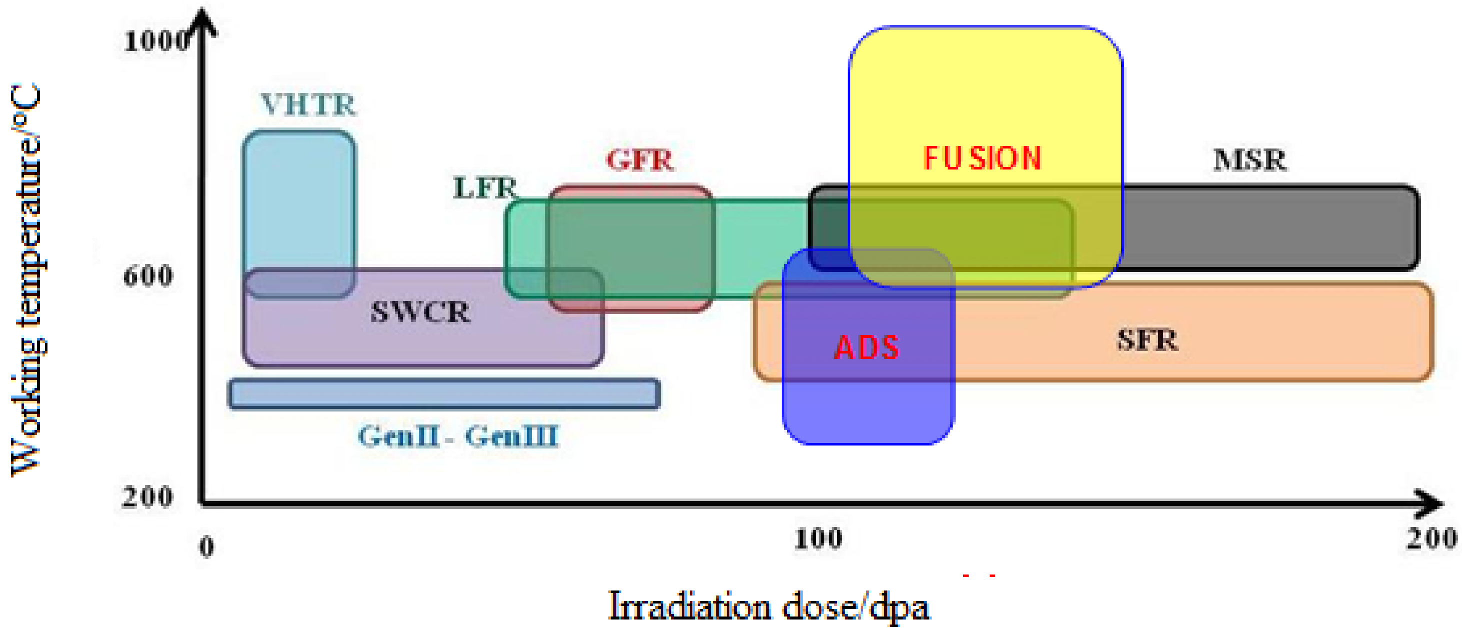
- **Nuclear energy materials**

  withstand constant bombardment of neutrons

  work in high dose and temperature environment



Structure materials for advanced nuclear energy system are required to be able to work in such extreme environments of high dose irradiation for more than one hundred dpa without failure.

Irradiation resistance of structure materials is one of key properties.

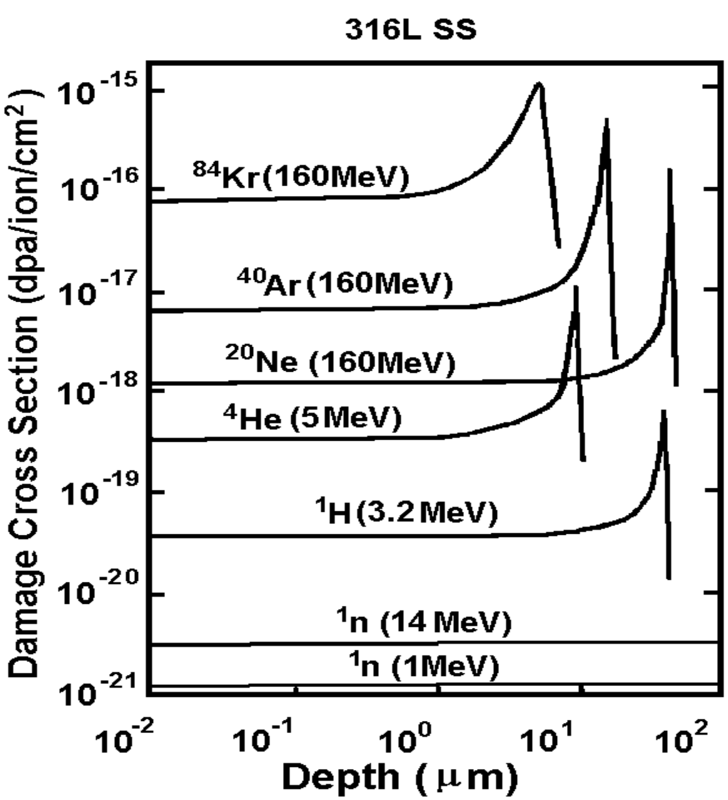
	Fission (Gen I)	Fission (Gen IV)	Fusion (DEMO/PROTO)	Spallation (ADS)
Structural alloy T_{max}	<300 °C	300–1000 °C	550–1000 °C	140–600 °C
Max dose for core internal structures	~1 dpa	~30–200 dpa	~150 dpa	50–100 dpa

It needs very long time, say years, to perform irradiations in laboratories up to several tens or hundreds of dpa by using currently available reactors or accelerators neutron sources.

Accelerator simulation of heavy ion irradiation developed

study of radiation damage produced by high dose neutron irradiations

Dose Rate	Heavy Ions (Accelerator)	Fast Reactor	Reactor	Fusion
dpa/s	10^{-3}	10^{-6}	10^{-7}	10^{-6}



Radiation damage rate (dpa/μAh)
HI-13 Tandem Accelerator

HI	Energy	Range	Charge state	dpa/μAh
^{12}C	70 MeV	41μm	5+	0.83
^{19}F	80 MeV	21μm	5+	2.44
^{36}Cl	70 MeV	7.7μm	7+	6.1
^{56}Fe	110 MeV	7.9 μm	9+	7.8
^{129}I	100 MeV	6.6μm	10+	14.1

for stainless steel

HIs up to Au

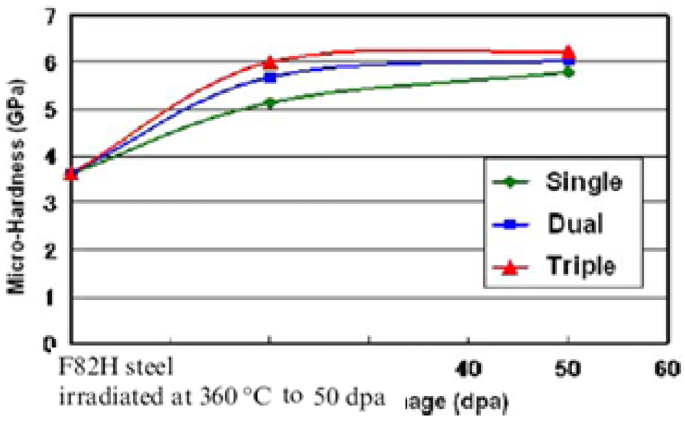
- **The displacement rate of heavy ions is a magnitude of $>10^3$ higher than that of neutrons**
- **Hence, significantly reduces the irradiation time**

Triple ion beam irradiation

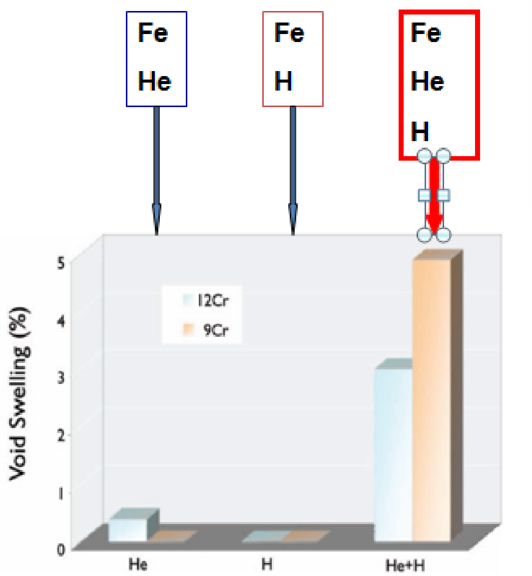
	FAST REACTOR	ADS	FUSION
working temperature (°C)	400～1000	250～600	550～1000
dose rate (dpa/year)	~40	~100	~30
He (appm/year)	40	~5000	~450
H (appm/year)	240	~30000	~1500

Fast neutron irradiation:
Nuclear energy materials suffer continuous neutron irradiation inducing severer displacement damage plus gas production of hydrogen and helium produced by (n,α) and (n,p) transmutation reactions

In simultaneous irradiations of triple ion beams there is the so called synergistic effect that may enhance or suppress radiation damage



E. Wakai, JNM, Vol 307-311(2002) 278
JNM ,Vol 356(2006) 95



T. Tanaka JNM Vol 329-333 (2004) 294

Important to investigate the combined radiation effect of the displacement damage coupled with gas production of hydrogen and helium

The CLAM (China Low Activation Martensitic) Steel has been developed in China for use as structural materials in ITER, fast reactors, ADS, etc

Present work motivated to examine its radiation properties through measuring the dependences of radiation damage on irradiation temperature up to 700°C and irradiation dose up to 100 dpa by heavy ion irradiations and
studying the synergistic effect of radiation damage by simultaneous irradiations of heavy ions and hydrogen and helium

Dependences of radiation damage in CLAM on irradiation temperature and dose

Chemical composition of CLAM Steel in wt%

Element	C	Cr	W	V	Ta	Mn	Y	Fe
Content	0.1	9.0	1.5	0.20	0.15	0.45	0.2	Bal.

1, For low activation

W, Ta and V adopted to replace Mo, Nb, and Ni in RAFM

2, For improving its physical, mechanical, radiation-resistant properties

Cr, Y and Mn added

Size of the samples used in the experiment ϕ15mm×0.5mm

Mechanically polished to mirror like surface

Irradiation terminal

performed using the variable temperature irradiation chamber set at the HI-13 Tandem Accelerator irradiation terminal in CIAE

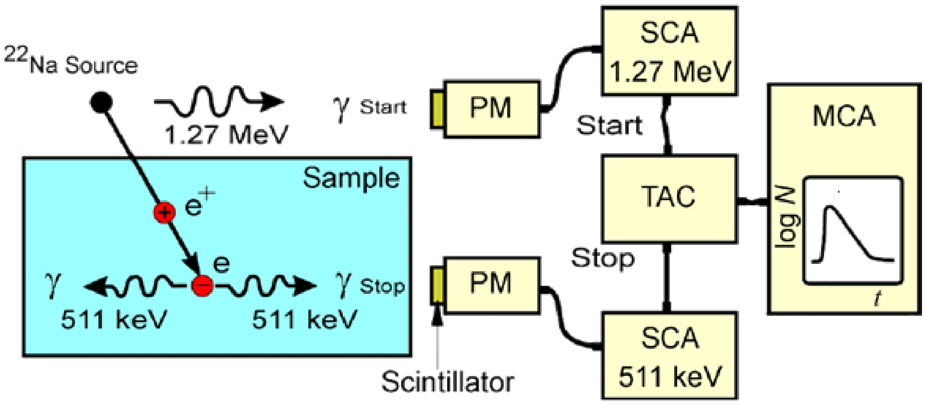
variable temperature irradiation chamber
RT to 800°C (±10°C)
6 samples mounted & irradiated in turn without breaking vacuum

Positron Annihilation Spectroscopy (PAS)

Radiation induced defects in structural materials particularly in the early stage are mainly atomic-scale vacancy type defects PAS is a powerful & indispensable tool for the study of vacancy type defects in an atomic scale

PAS was employed in the present work
for examining the RD induced by irradiations

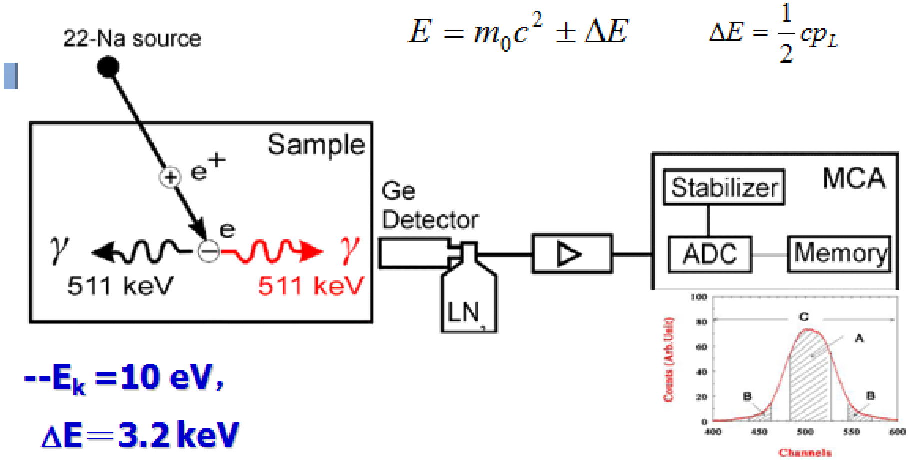
The Positron Lifetime Measurement



^{22}Na positron source is usually used.
The positron emitted is accompanied by a 1.27 MeV γ ray.
One PMT detector detects 1.27 MeV γ ray as a start signal of TAC and the other 0.511 MeV annihilated γ ray as a stop signal.

Measurement of Doppler Broadening

$$E = m_0c^2 \pm \Delta E \qquad \Delta E = \frac{1}{2}cp_L$$



--E_k =10 eV,
ΔE=3.2 keV
-- HPGe in order of~ 1 keV, Ek detectable

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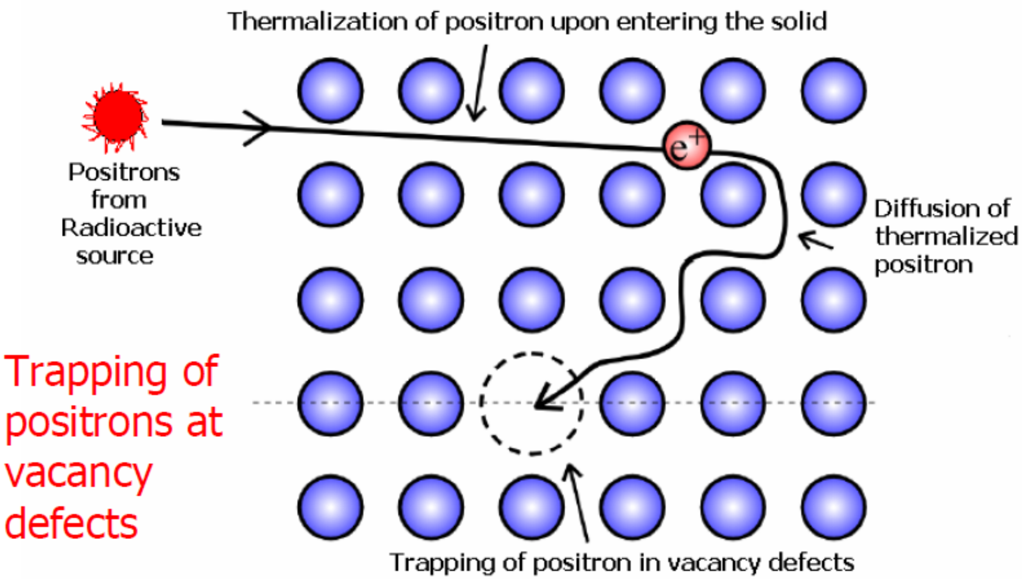
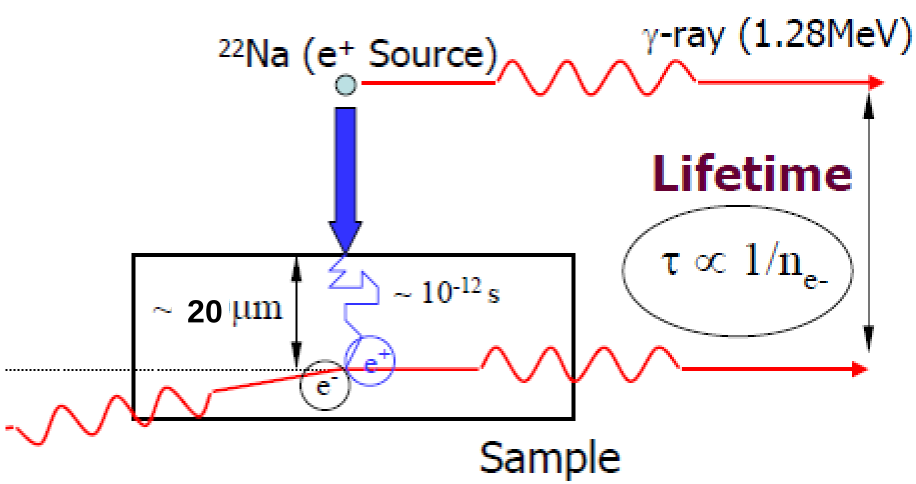
Positron Lifetime Measurement

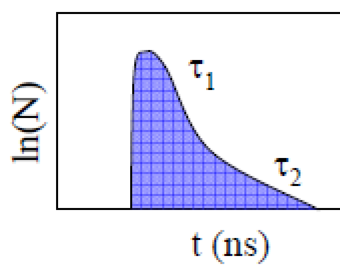


Using positrons, one can get defect information.

The lifetime of positron is determined by the local electron density at the annihilation site. The annihilation rate (inverse of positron lifetime) is proportional to the local electron density at the site of annihilation.

Positron lifetime is deduced by measuring the time delay between the birth signal of a positron (1.28MeV) and annihilation signal (511keV)

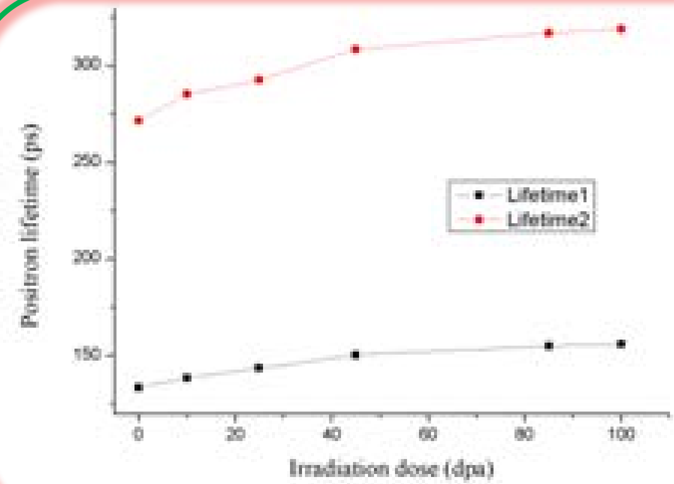




τ1: short lifetime component positron annihilation with bulk and mono-vacancy

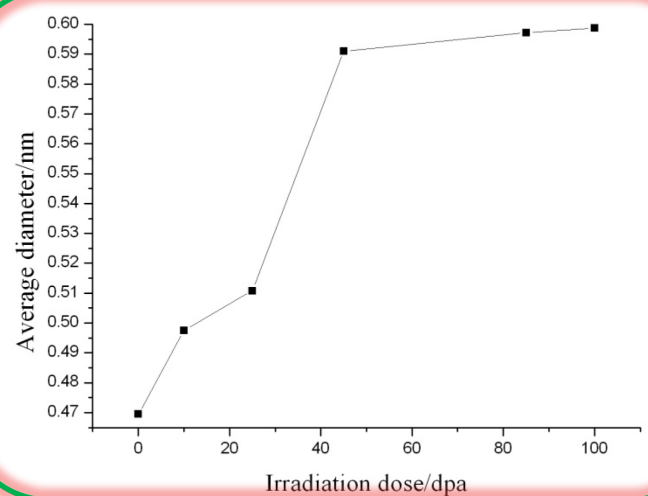
τ2: long lifetime component positron annihilation with vacancy clusters

Dependence of RD on irradiation dose



Positron lifetime spectra were measured and analyzed by two lifetime **components model**

Lifetime1: short lifetime component
positron annihilation with bulk and mono-vacancy
Lifetime 2: long lifetime component
positron annihilation with vacancy clusters



Size of vacancy clusters were calculated from lifetime2

Size of the vacancy clusters increases with increasing the irradiation dose, and the vacancy cluster reaches at 100 dpa a size of ~0.6 nm with 9 vacancy clusters.

irradiated by 80 MeV ^{19}F ions to 100 dpa at RT

Dependence of RD on irradiation temperature

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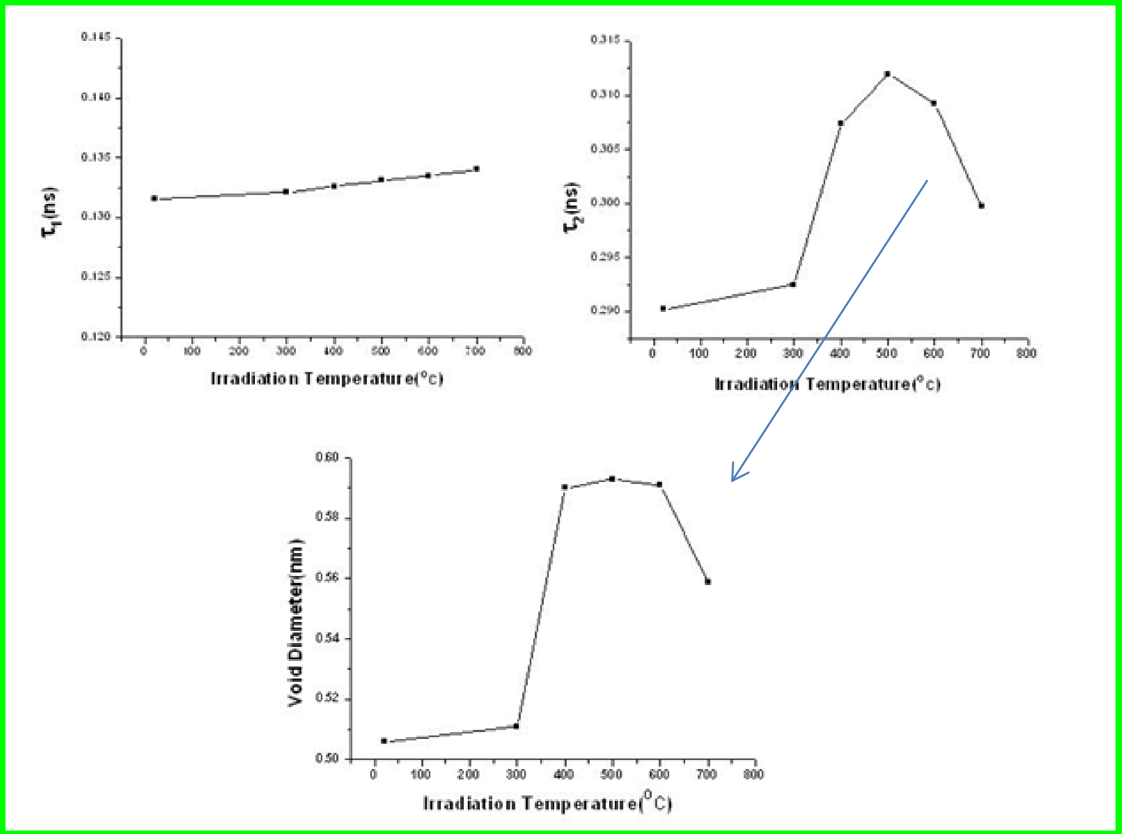

a peak at ~500°C where the maximum vacancy cluster contains 9 vacancies with an average diameter of 0.59 nm.

The experimental results indicate that this CLAM steel has good radiation resistant properties

irradiated by 80 MeV ^{19}F ions from RT to 700°C at 15 dpa

Synergistic effect of RD in CLAM steel studied by triple beam irradiation

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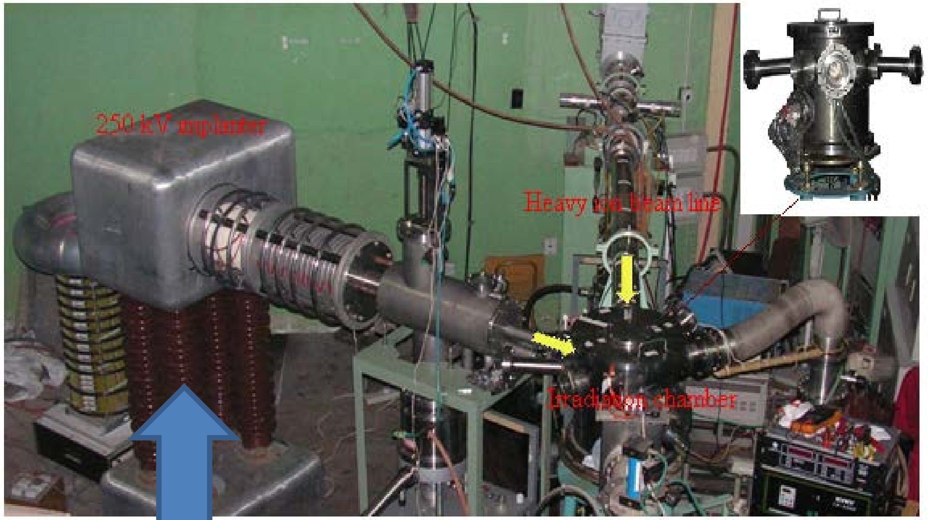
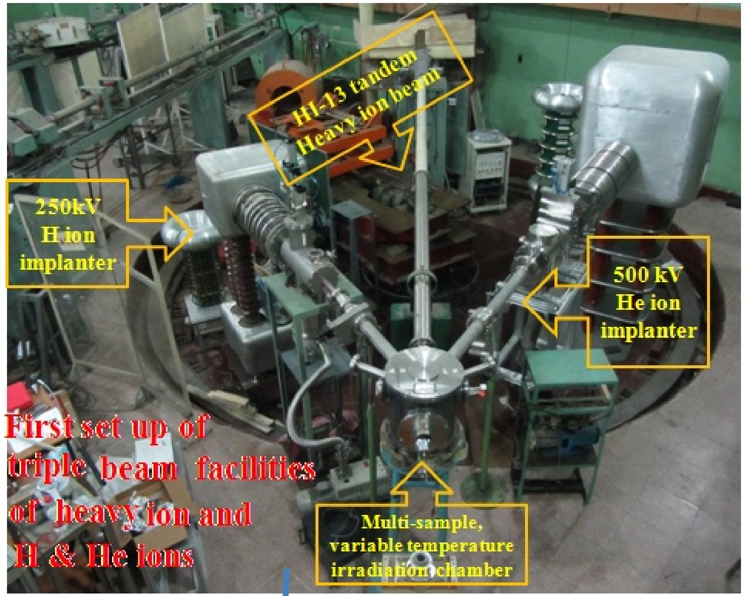
Temperature RT-1200ºC (±10ºC)
6 samples irradiated in turn





H and He mixed beam

Irradiation terminal

Triple beam irradiation parameters

	Energy/keV	Irradiation fluence /cm^{-2} A	Irradiation fluence /cm^{-2} B	Irradiation fluence /cm^{-2} C
Hydrogen	100	0	2.42×10^{16}	4.84×10^{16}
Helium	200	0	7.89×10^{15}	1.66×10^{16}
Gold	70000	0	5.37×10^{13}	1.07×10^{14}

Three different fluence of triple beam for irradiation:
A: un-irradiation sample
The fluence of triple beam of C is about twice higher than one of B
For fluence B: **sequentially and simultaneously irradiation were performed**

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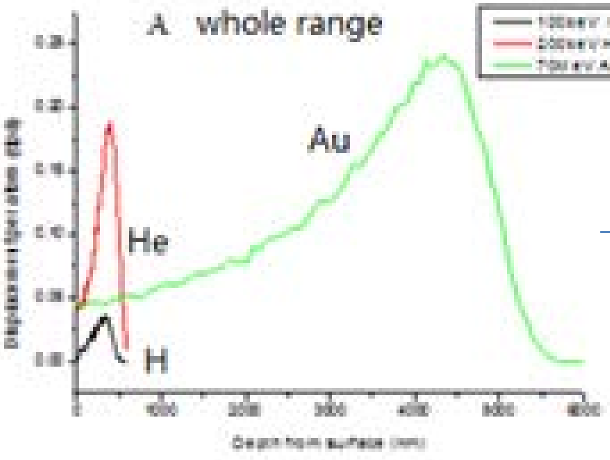
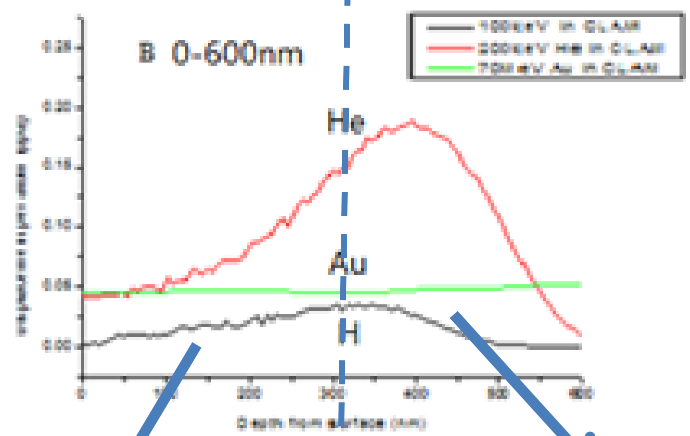
Depth distributions of Au and H and He for irradiation fluence B calculated by SRIM code

range from the surface to 600 nm

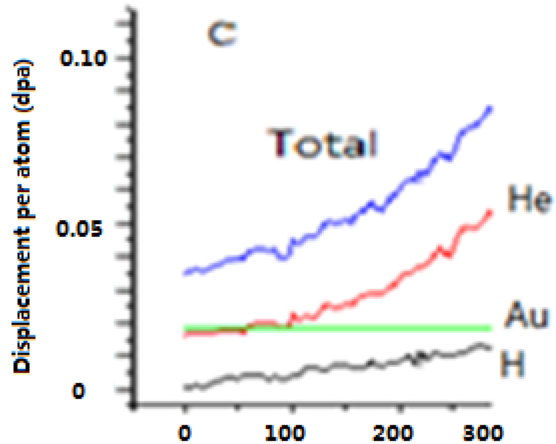


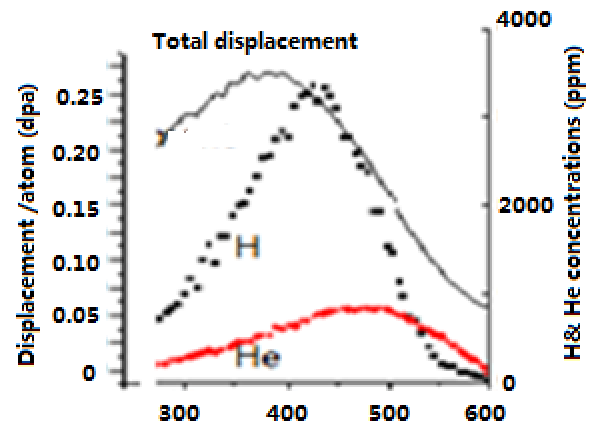


Depth distributions of displacement for H, He and Au ions in whole range

Distributions of total displacement H & He concentration distributions

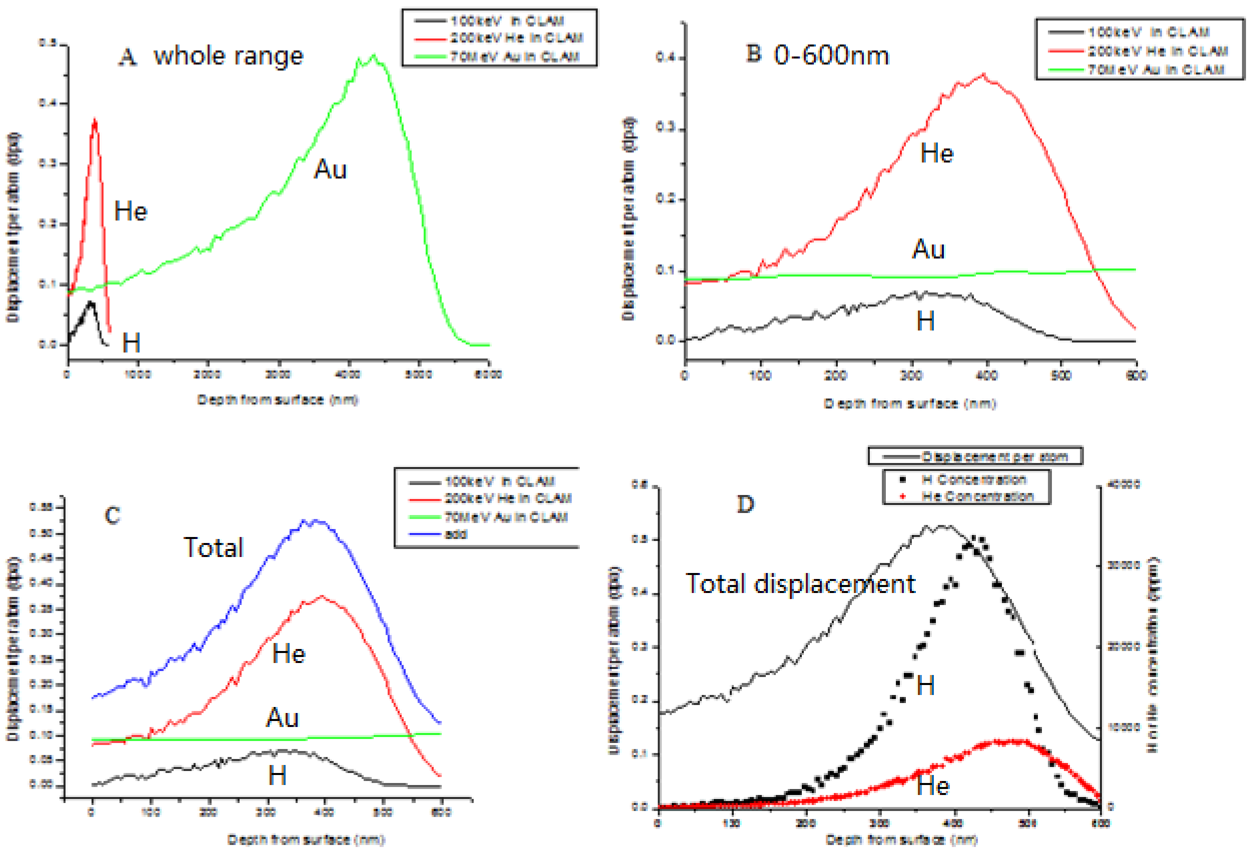
Depth distributions of total and respective displacements





Synergistic effect of HI,H & He

Severer effect of H & He



A and B: Depth distributions of displacement for H, He and Au ions in whole range and range from the surface to 600 nm

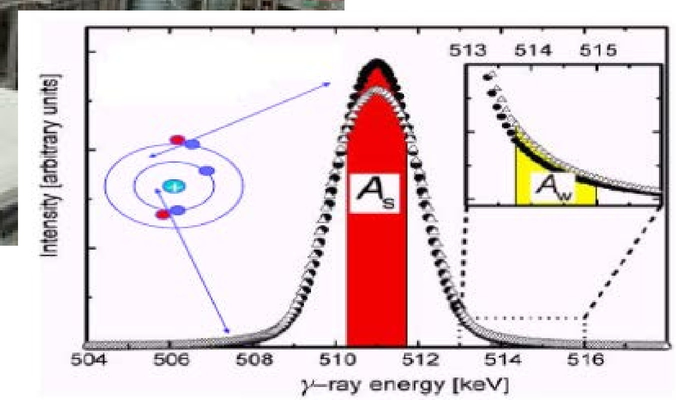
C: Depth distributions of total and respective displacements

D: Distributions of total displacement and H and He concentrations

Distribution of displacements and H and He concentrations for irradiation fluence C

Since the implanted ion range is less than 1 μm. Variable mono-energetic slow positron beams used to detect RD by depth profiling measurements of Doppler broadening

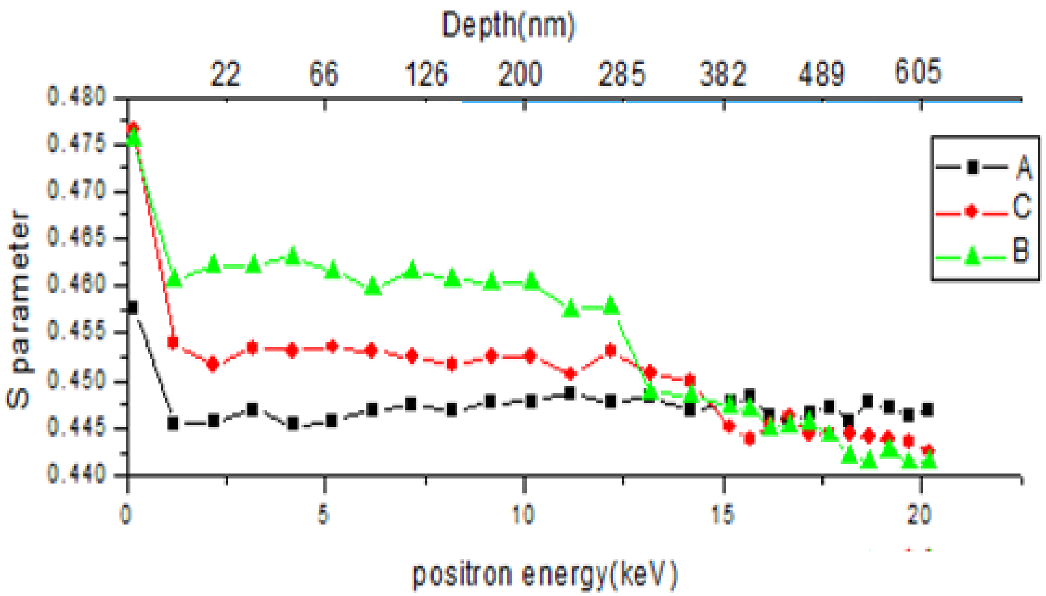
S parameter
=As/gross count of peak



Slow positron beam facility based on 1.3 GeV Linac of BEPC at IHEP Provideing mono-energy positrons up to 30 keV (±10 eV) with intensity of $6x10^5e^+s^{-1}$

The range of 20keV positron is ~600nm in CLAM, so the slow positron beam facility is enough to detect the depth profile of radiation damage.

Depth region up to 300nm



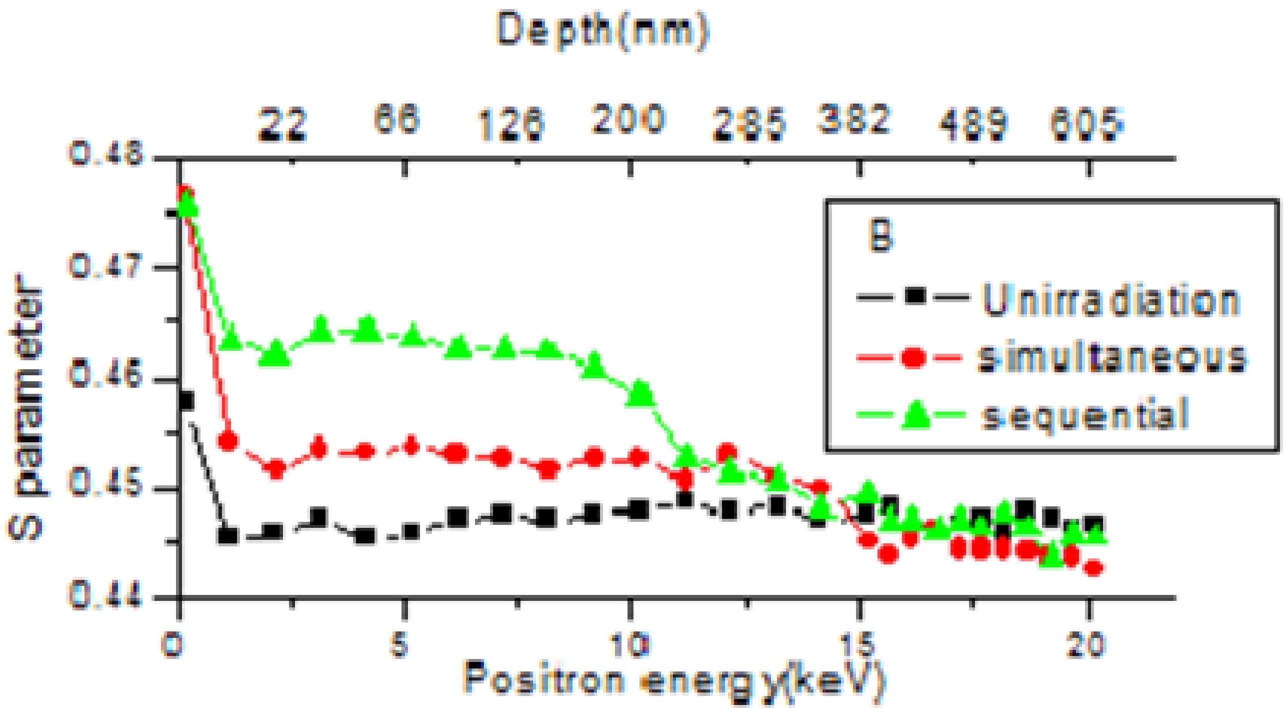
Depth profiles of *S* parameter for the un-irradiated sample (A) for the samples triple beam simultaneously irradiated to fluences B and C

triple beam irradiations create vacancy type defects cause an increase of *S* para. compared to un-irradiation sample.

***S* para. of the sample irradiated to the high fluence C are lower than those of the sample irradiated to the low fluence B in the depth up to 300 nm**

Explained by the synergistic Effect of displacement , H and He

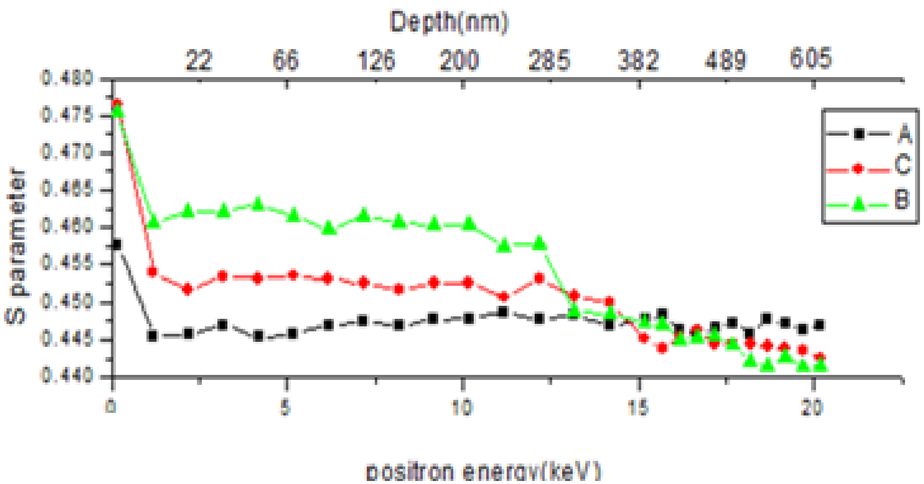
Depth region up to 300nm



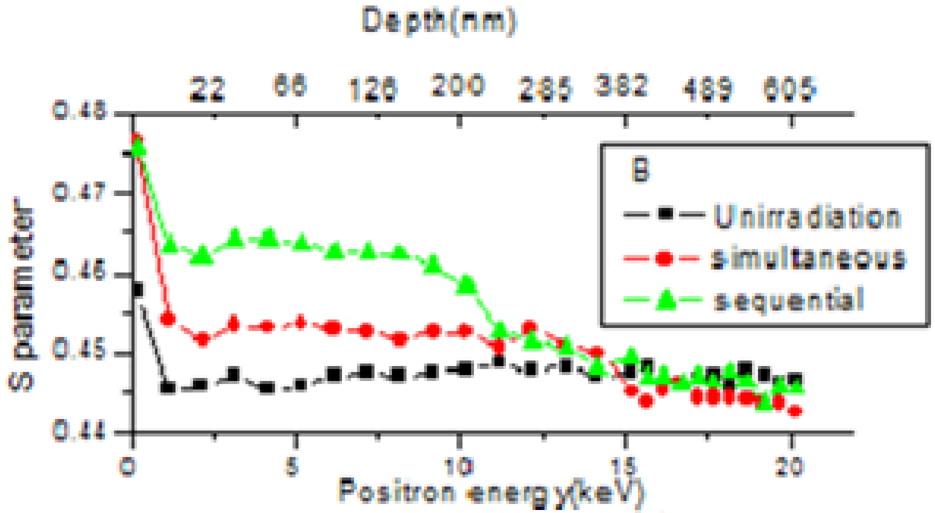
Depth profiles of *S* parameters for the un-irradiated sample, and the samples sequentially and simultaneously irradiated to fluence B

***S* parameters for the simultaneous irradiation are lower than those for the sequential irradiation duo to the synergistic effect of H and He that reduces the *S* parameters**

Synergistic effect of Heavy ion and H and He suppress the *S* parameter in the present experiment

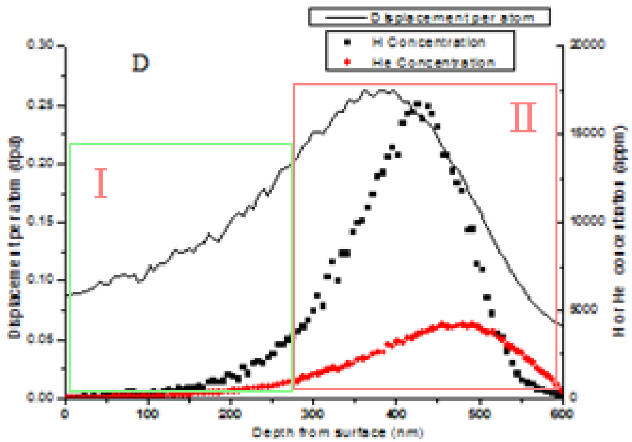


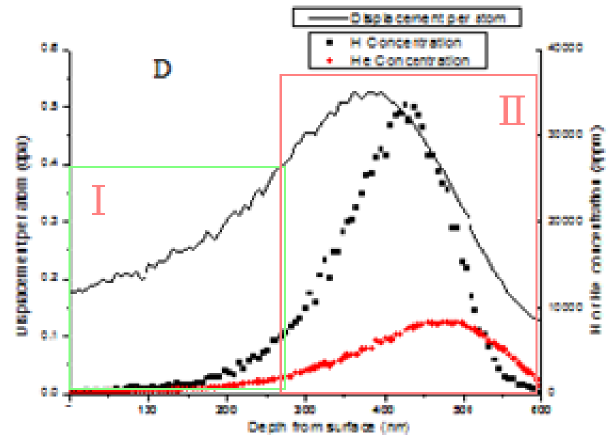
_S_ parameters for simultaneous irradiation to higher fluence C are lower than those to low fluence B



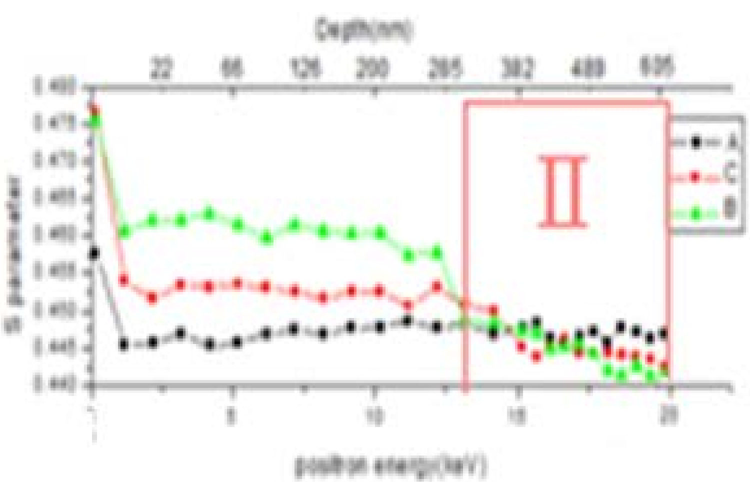
_S_ parameters for simultaneous irradiation are lower than those for the sequential irradiation

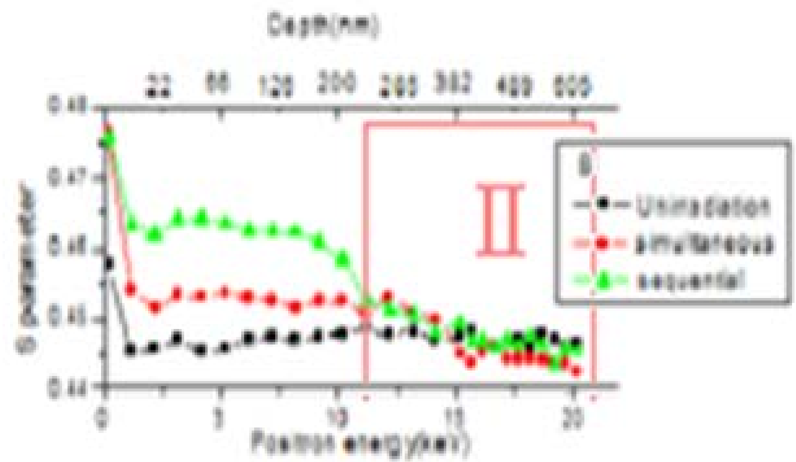
Depth region between 300nm and 600 nm





Concentration peaks of H and He located in the depth region II between 300 & 600 nm





Strong He & H effects greatly reduce the *S* parameters for both simultaneous and sequential irradiations to the irradiation fluences B and C to those of the un-irradiated sample

- **Implanted He and H atoms are mobile at first and then subsequently trapped by vacancies located in the centers of the vacancy clusters or voids As a result, positrons are trapped in a smaller space or at the inner surface of the voids**
  - **The He and H filling lowers the available positron trap volume and leads to a significant reduction of the *S* parameter**
- **In the peak region of the H and He concentration distribution the He and H effect is so strong that the *S* parameters are greatly reduced**

Experimental results exhibit clearly the synergistic effect of displacement damage and H and He on the formation of radiation damage in CLAM steel

Thank you