中国原子能科学研究院
CNNC CHINA INSTITUTE OF ATOMIC ENERGY

12th International Workshop on Spallation Materials Technology

19-23 October 2014, Bregenz, Austria

Development of Triple Beam Irradiation Facilities at CIAE

Shengyun Zhu

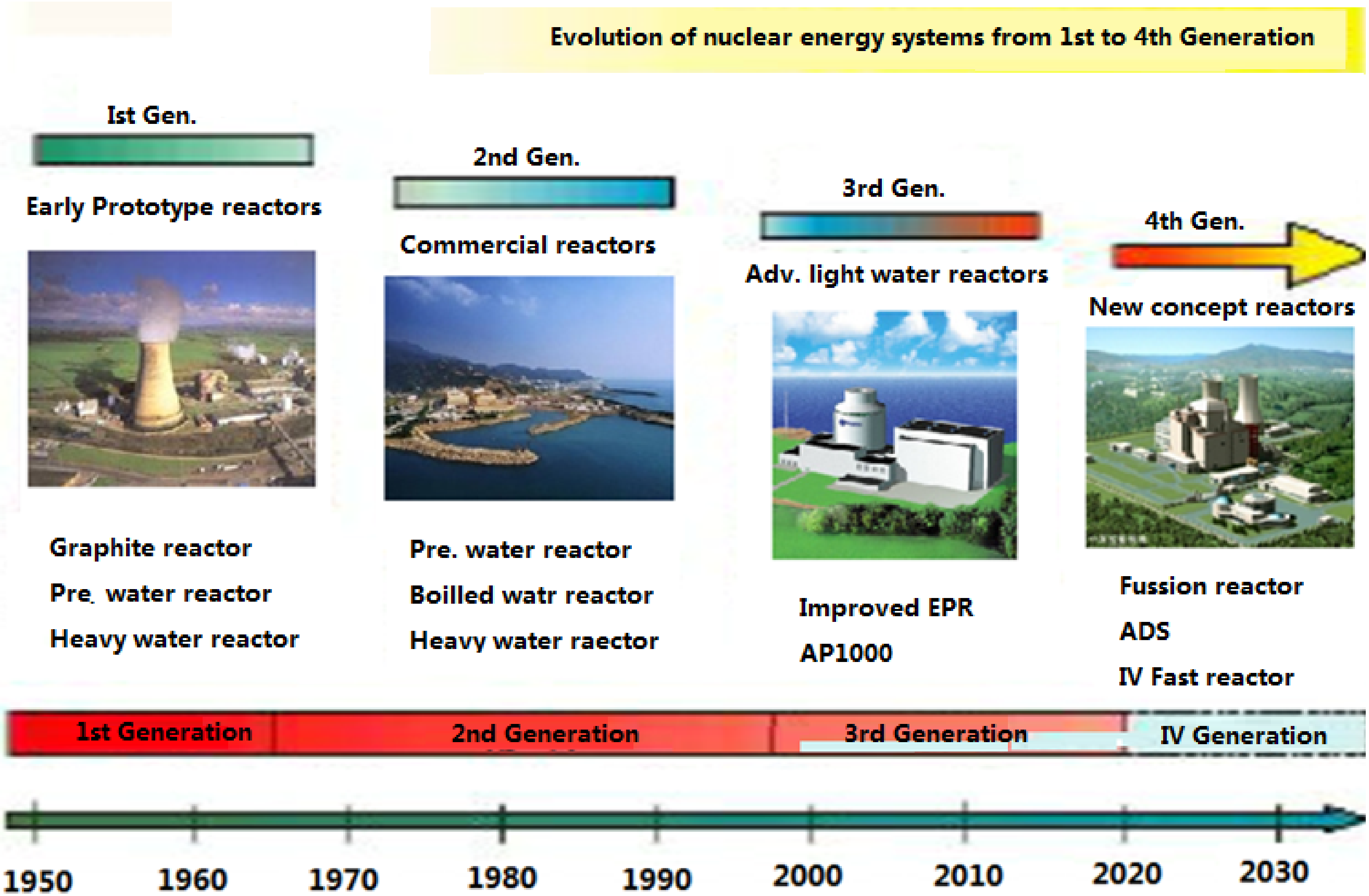
China Institute of Atomic Energy

OUTLINE

- **Background**
- **Accelerator irradiation simulation**
- **Triple beam irradiation facilities at CIAE**

- **Background**

Evolution of nuclear energy systems



Materials : one of bottle neck issues for the development of 4th Generation nuclear energy systems

Among the materials properties
Radiation property:
one of the most crucial issues to the materials needs to be examined well in advance

Present work motivated to establish in laboratory fast testing facilities of the materials radiation effects for pre-selection

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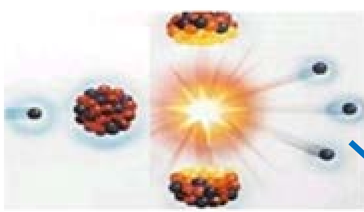
Advanced nuclear energy facilities operate with

fission neutrons with a mean energy of <3MeV

fusion neutrons of 14MeV

spallation neutrons of several hundred MeV

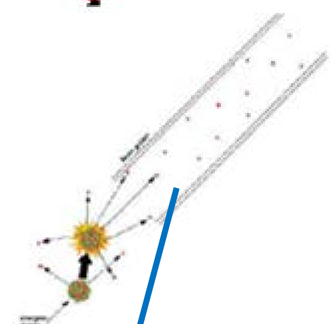
Fission



Fusion

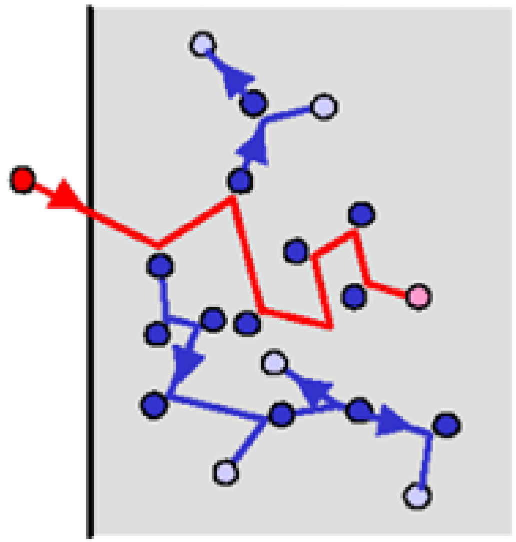
$D + T \rightarrow {}^{4}He + n$

Spallation



	Fission (Gen I)	Fission (Gen IV)	Fusion (DEMO/PROTO)	Spallation (ADS)
Neutron Energy E_{max}	<1–2 MeV	<1–3 MeV	<14 MeV	Several hundred MeV

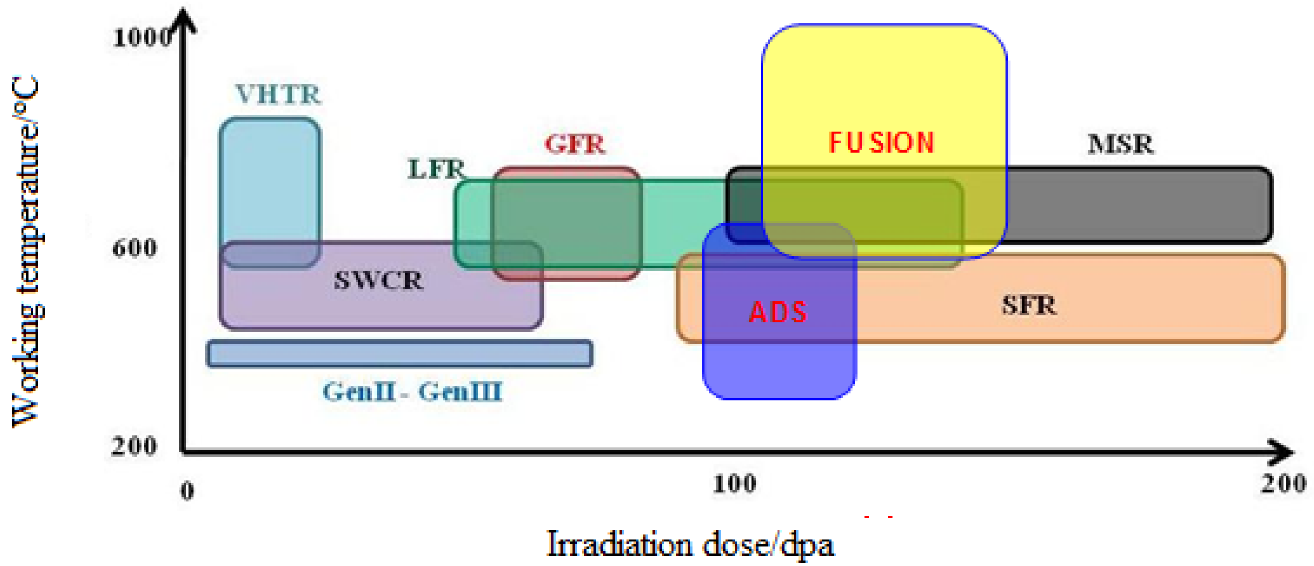
Atomic displacements



Neutron induced cascade collisions

Neuron irradiation causes atoms to be displaced from their lattice sites and
produces severe displacement damage since very high fluence of neutrons

Very high irradiation dose



Materials of 4th Generation nuclear energy facilities

suffer very high dose neutron irradiations at high temperatures

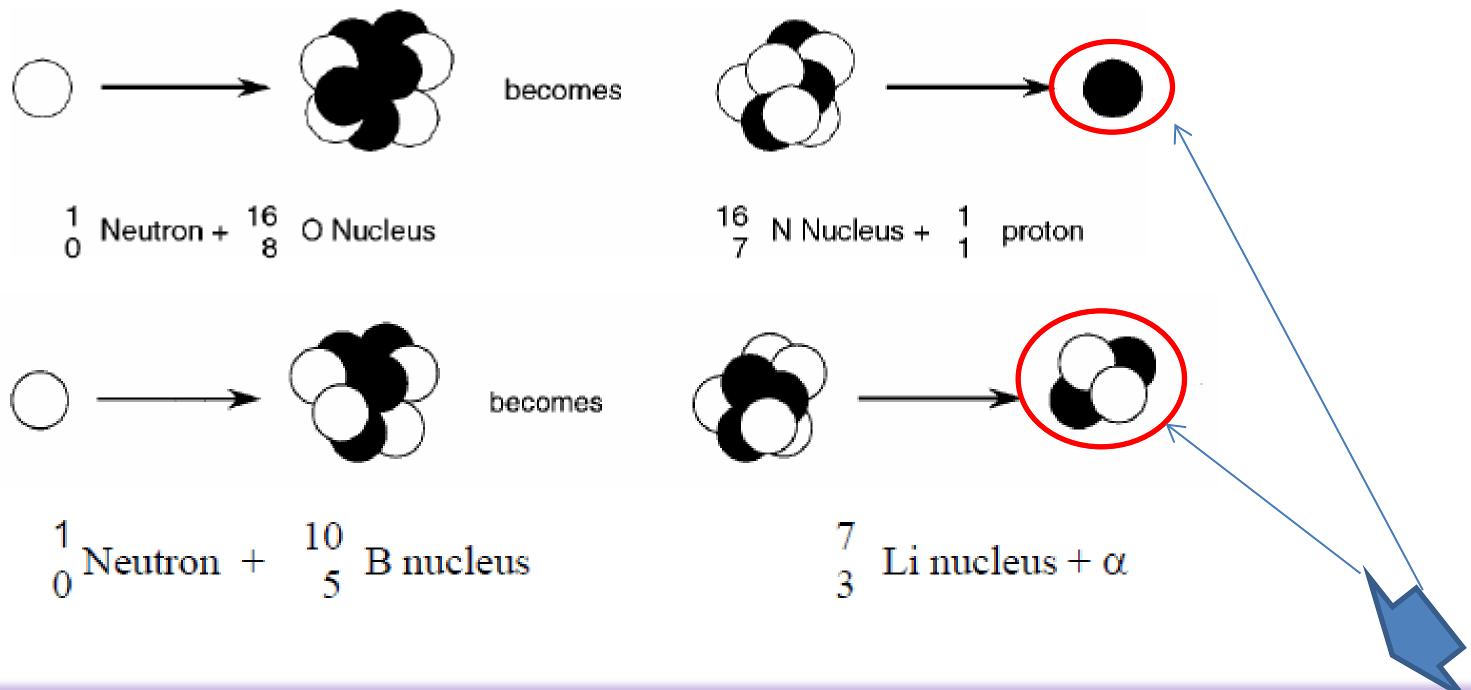
	Fission (Gen I)	Fission (Gen IV)	Fusion (DEMO/PROTO)	Spallation (ADS)
Structural alloy T_{max}	<300 °C	300–1000 °C	550–1000 °C	140–600 °C
Max dose for core internal structures	~1 dpa	~30–200 dpa	~150 dpa	50–100 dpa

Structural materials required to work in high displacement damage environment without failure

Transmutations

Transmutation resulting from (n, p), (n, α) reactions

A nucleus may absorb a neutron forming a compound nucleus which then de-energizes by emitting a charged particle either a proton or an alpha particle



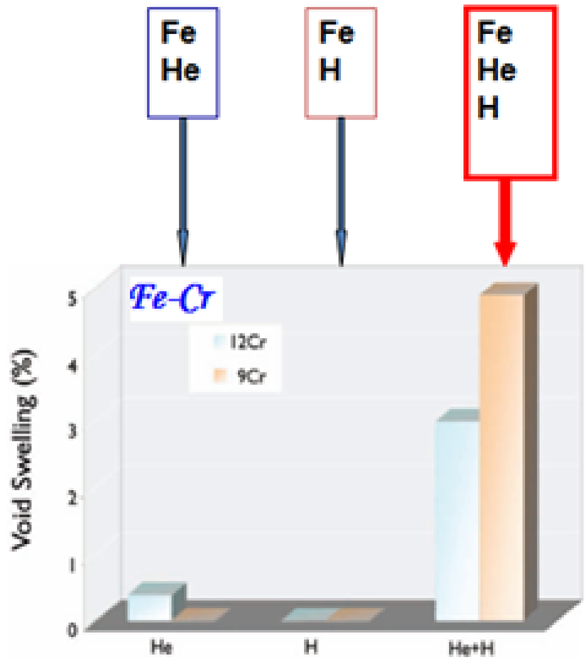
Neutron transmutations produce P (H) and α (He)

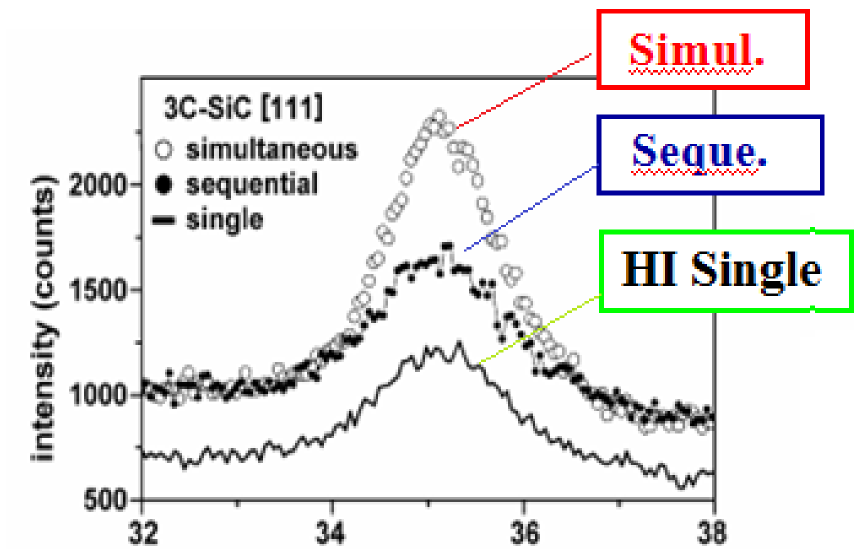
RD in structural materials of 4th Generation nuclear energy facilities arises from a combination of atomic displacements and helium and hydrogen irradiations

	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
Max helium concentration	0.1 appm	~3–40 appm	~1500 appm (~10,000 appm for SiC)	~5000 appm/fpy
Max hydrogen concentration		~20-240 appm	~6750 appm	50,000–100,000 appm/fpy
Neutron Energy E_{max}	<1–2 MeV	<1–3 MeV	<14 MeV	Several hundred MeV

Synergistic effect

In simultaneous irradiations of atomic displacements and hydrogen and helium
there is a so called synergistic effect
which can enhance or suppress RD





XRD

Synergistic effects can be seen clearly in the Fe-Cr steel and SiC irradiated simultaneously by HI, H and He

➢ Accelerator irradiation simulation

- Heavy ion irradiation simulation

- Triple beam Irradiation

	Fission (Gen IV)	Fusion (DEMO/PROTO)	Spallation (ADS)
Structural alloy T_{max}	300–1000 °C	550–1000 °C	140–600 °C
Max dose for core internal structures	~30–200 dpa	~150 dpa	50–100 dpa
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Max hydrogen concentration	~20-240 appm	~6750 appm	50,000–100,000 appm/fpy
Neutron Energy E_{max}	<1–3 MeV	<14 MeV	Several hundred MeV

Radiation effects in materials are characterized mainly by

- **High displacement rates at high temperatures**
- **Simultaneous irradiation of displacement & H & He**

Triple beam irradiations of HI, H and He are needed to simulate high dose neutron irradiation
i.e. introducing appropriate gas concentrations simultaneously with the damaging heavy ions

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Heavy Ion Irradiation Simulation

Some currently available reactor facilities used for materials testing

mixed-spectrum reactors

fast reactors

Facility	Country	Fast Flux E_n>0.1 MeV ($10^{18}/m^2s$)	Displacement damage in steel (dpa/yr)	Useful vol (cm^3)	Temp Range (°C)	Comments
BR2 Core Reflector	Germany	 1.5–3.0 0.05–1.0	 <3/yr <1/yr	 90 250	 50–1000 50–1000	• ~105 days/yr • Caps ϕ: 50–200 mm • In-situ fatigue rigs
OSIRIS	France	2.5	few/yr	230	50–1000	
HFR Core (C5)	Nether-lands	2.5	<7/yr	1540	80–1100	• 275 days/yr • In situ experiments
ATR A and H, B, I-positions Flux traps	U.S.	 2.3 0.8 0.03 2.2	 6–10/yr 6–8/yr	 240 1390 5560 5560	 50– >1500	• Caps ϕ: <127 mm • Large irrad. volume • Versatile facility
HFIR Tgt. Pos 37 RB pos 8	U.S.	 11 5.3	 18/yr 5–7/yr	 100 720	 300–1500	• Very high peak flux • Accelerated testing in smaller volumes
JOYO	Japan	5.7	~30/yr		300–700	• Temp. control +4 K • 300 days/yr
BN600	Russia	6.5	20-52	350	375–750+	• Very-high dose rate • Only passive instrumentation
BOR-60	Russia	3.0	~20	358	300–700+	• Only passive instrumentation • High level PIE

Fast reactor can reach 20-30 dpa per year

ESS 1.4dpa/GW, d

displacement rate not high enough

The heavy ion irradiation has been developed

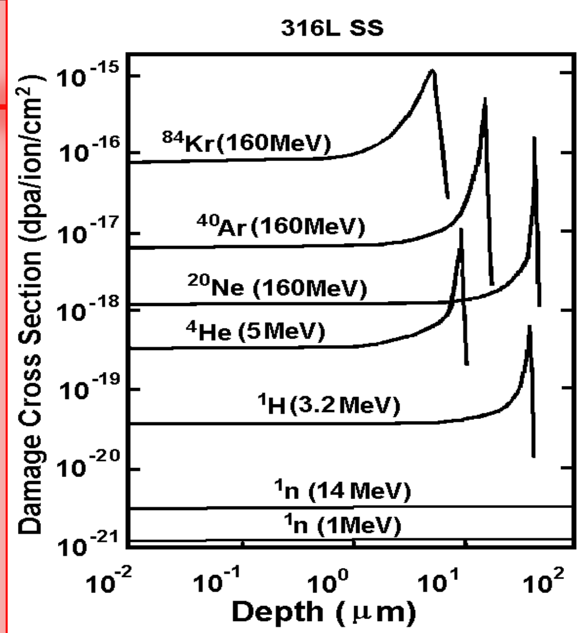
Fast way

Heavy Ion Irradiation Simulation (HIIS)

Dose Rate	Heavy Ions (Accelerator)	Fast Reactor	Reactor	ITER
dpa/s	10^{-3} -10^{-1}	10^{-6}	10^{-7}	10^{-6}

Damage rate generated by HI irradiation is much higher than that by neutron irradiations, say in the order of 10^{3-5}

HI irradiation simulation allows critical scientific studies to be performed on reasonable time scales , e.g. hours to days



Heavy Ion Simulation at CIAE HI-13 Tandem Accelerator

HI	Energy/MeV	Range/μm	RD rate(dpa/μAh)
^{12}C	70	41	2.1
^{19}F	80	21	3.9
^{36}Cl	70	7.7	11.7
^{129}I	100	6.6	26.5

for stainless steel

Providing HIs up to Au

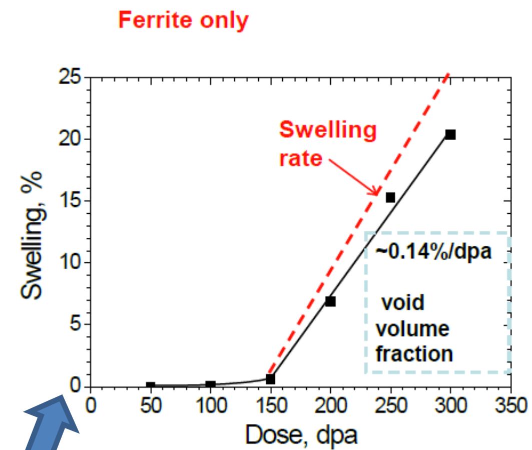
Samples irradiated by HI are not radioactive
unlike reactor irradiated samples that are highly activated requiring a very long cooling time before examination

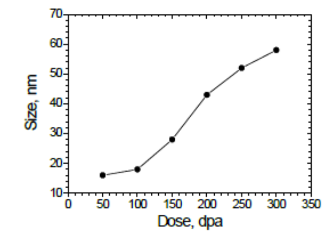
Irradiation parameters such as irradiation temperature, dose, dose rate can be well controlled in HI irradiation

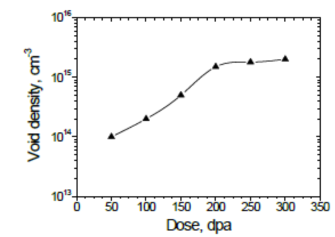
Heavy ion irradiation technique employed in many laboratories with heavy ion accelerators in the world to simulate and investigate RD produced by high dose neutrons

e.g.

- **ORNL, LLNL, USA**
- **GSI, Karlsruhe, Germany**
- **CEA-Saclay, France**
- **Kurchatov Inst., Russia**
- **JAEA, Kyoto Univ., Japan**
- **Kharkov Inst. of Phys. & Technology, Ukraine**
- **CIAE, IMP, Peking Univ., China**
- **National Tsing Hua Univ, Taipei**



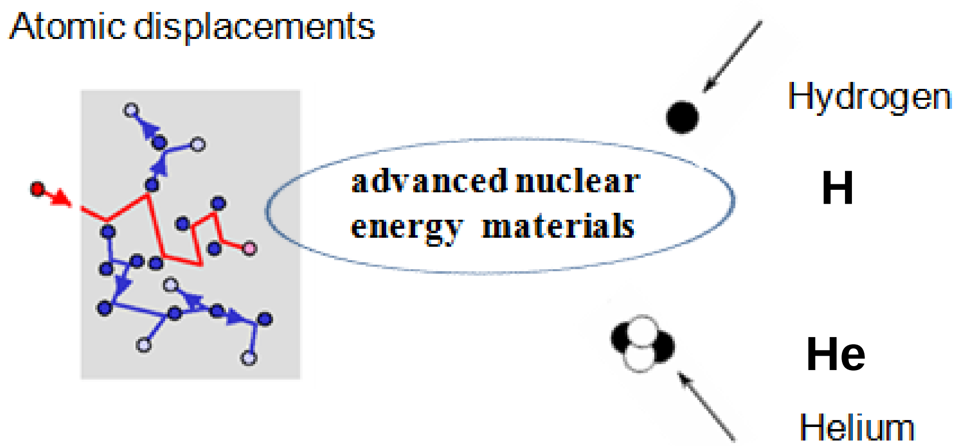




Swelling rate of 0.17 = ~0.2 %/dpa

Irradiation upto ~400 dpa well above the incubation stage, Severe swelling was observed

Triple beam irradiation



Structural materials simultaneously encounter displacement damage plus H and He

Triple-beam irradiations play a important role in investigating the RD of nuclear energy structural materials

Triple beam irradiation facilities usually composed of three accelerators or implanters, delivering heavy ion beam and hydrogen and helium ion beams independently

A list of the various multi-ion-beam facilities in the world

Laboratory	Facilities	Application field
a) dual or triple MeV ion beams		
MSD, IGCAR, Kalpakkam, India	1.7 MV Tandetron Ion implanter (30–150 keV)	Irradiation behavior of nuclear alloys
HIT, Tokyo, Japan	3.75 MV Van de Graaff 1 MV Tandetron	Irradiation behavior of nuclear alloys and ceramics
DNE, Nagoya University, Japan	2 MV Van de Graaff 200 kV ion implanter	Irradiation behavior of nuclear alloys and ceramics
FZ, Rossendorf, Germany	3 MV Tandetron 500 kV ion implanter	Synthesis of nanostructured ceramics assisted by irradiation Ion beam modification of materials
FSU, Iena, Germany	3 MV Tandetron JULIA 400 kV ion implanter ROMEO	Synthesis of nanostructured ceramics assisted by irradiation Irradiation behavior of nuclear alloys
LANL, USA	3 MV Tandem 200 kV ion implanter	Heavy ion irradiation from the tandem Simultaneous He/H implantation from the implanter
IAE, Kyoto, Japan	1.7 MV Tandetron 1 MV Van de Graaff 1 MV Singletron	Evolution of microstructure under multi-irradiation
JAEA, Takasaki, Japan TIARA	3 MV Tandem 3 MV Van de Graaff 400 kV ion implanter	Synthesis of nanostructured ceramics assisted by irradiation Behavior of alloys and ceramics under irradiation
DMN, Saclay, France JANNuS (ready to operate at the beginning of 2009)	3 MV Pelletron ÉPIMÉTHÉE 2.5 MV Van de Graaff YVETTE 2.25 MV Tandetron	Irradiation behavior of nuclear materials Ion beam modification of materials
Kharkov Institute of Physics and Technology, Kharkov, Ukraine	2 MV ESU 50 kV proton 50 kV helium	Irradiation behavior of nuclear alloys
Accelerator Lab. National Tsing Hua Univ. Taipei	HVEE 500KV ion implanter 9SDH2 Tandem Van de Graaff accelerator	Irradiation behavior of nuclear materials

Dual

Triple

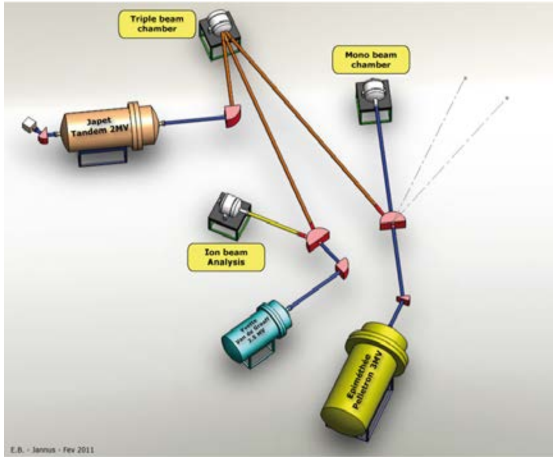
Ion-beam–TEM facilities in the world

b) mono or dual ion beams (>100 keV) coupled to a TEM

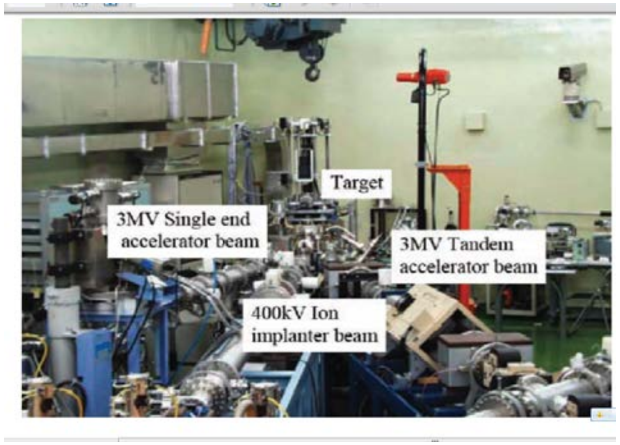
CARET, Sapporo, Japan	1.3 MV HVTEM 400 kV ion implanter 300 kV ion implanter	Synthesis of nanostructured materials assisted by irradiation Behavior of nuclear materials under irradiation
Argonne National Laboratory, USA	2 MV Tandem or 650 kV ion implanter 300 kV TEM	Irradiation behavior of nuclear ceramics
CSNSM, Orsay, France (will operate at the beginning of 2008)	2 MV Tandem Van de Graaff ARAMIS 150 kV ion implanter IRMA 200 kV TEM	Irradiation behavior of nuclear ceramics and semiconductors Ion beam modification of materials

c) dual keV ion beams coupled to a TEM

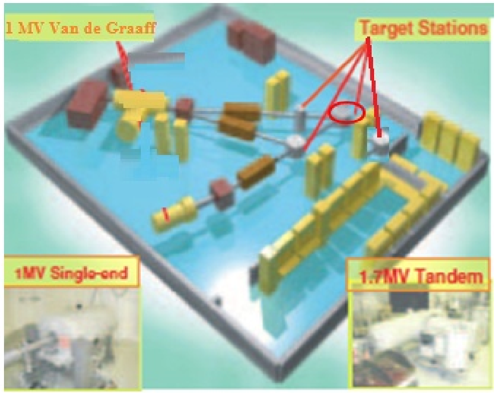
IMR, University of Salford, UK (under construction)	200 kV TEM Ion implanter (5–100 keV, A ≤ 140)	Radiation damage on nuclear reactor materials and semiconductors
JAERI DMD, Takasaki, Japan	400 kV TEM 400 kV ion implanter 40 kV ion gun	Radiation effects
JAERI DMSE, Tokai-Mura, Japan	2° — 40 kV ion guns 400 kV TEM	Irradiation behavior of nuclear alloys and ceramics



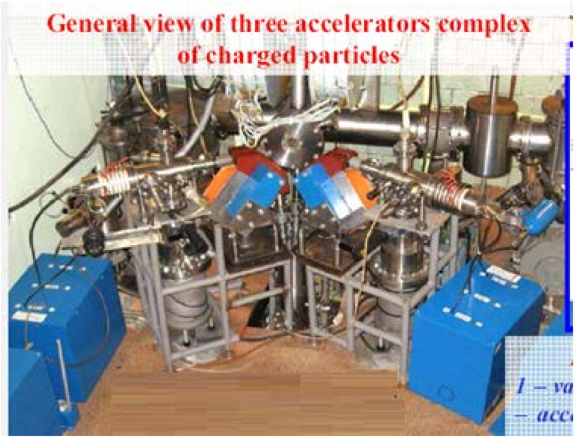
JANNuS



JAEA at Takasaki

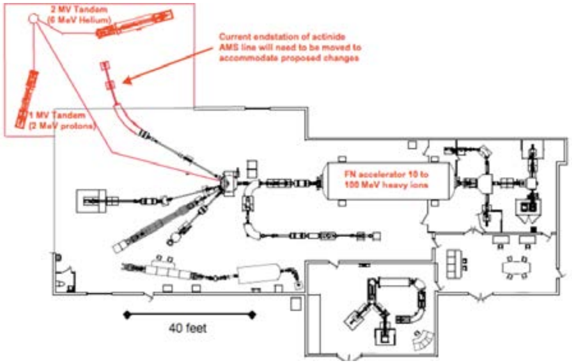


at IAE Kyoto



Kharkov Inst. Ukrain

National Tsing Hua Unversity, TW



LLNL, USA

Maximal intensities

3.9×10^{14}/s for protons, 8.8×10^{14}/s for 4He+, 2.2×10^{14}/s for $^{4}He^{2+}$

1.8×10^{12}/s for $132Xe10^{+}$, 3×10^{11}/s & 8.2×10^{12}/s for $^{40}Ar^{8+}$

2.6×10^{12} pps for $^{56}Fe^{8+}$, 1.1×10^{12} pps for

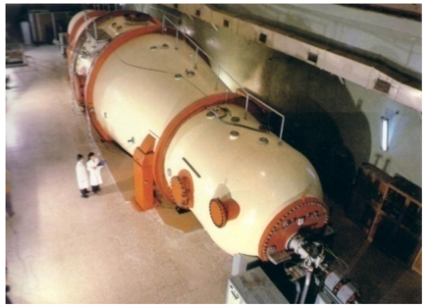
The triple beam irradiation of heavy ions & hydrogen & helium produced by accelerators or implanters
a unique way in a reasonable time period to experimentally investigate the radiation damage above several tens of dpa with appropriate H and He concentrations

➢ Triple beam irradiation facilities at CIAE

- Heavy ion irradiation facilities

- Triple beam facilities

Heavy ion irradiation facilities at the HI-13 tandem accelerator



Triple beam chamber

Irradiation terminal

Heavy Ion Simulation at CIAE HI-13 Tandem Accelerator

HI	Energy/MeV	Range/μm	RD rate(dpa/μAh)
^{12}C	70	41	2.1
^{19}F	80	21	3.9
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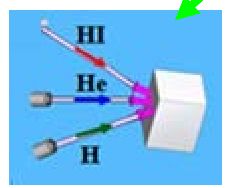
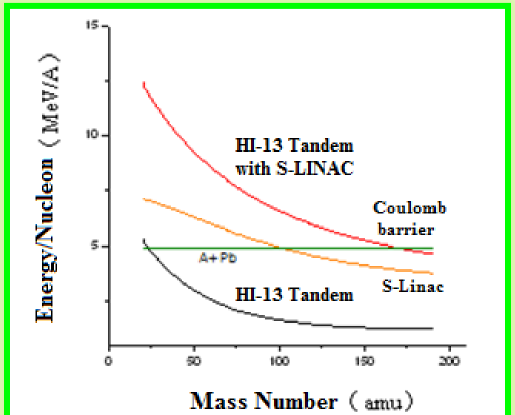
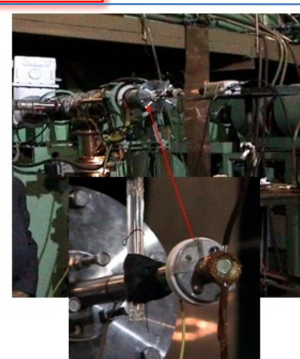
for stainless steel

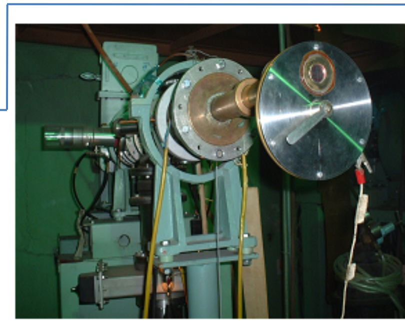
Providing HIs up to Au



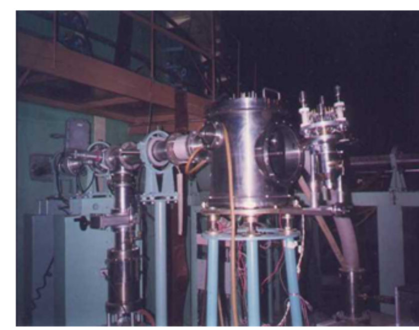




High beam current irradiation chamber
For RT irradiation
samples directly cooled by flowing water
Single sample irradiation

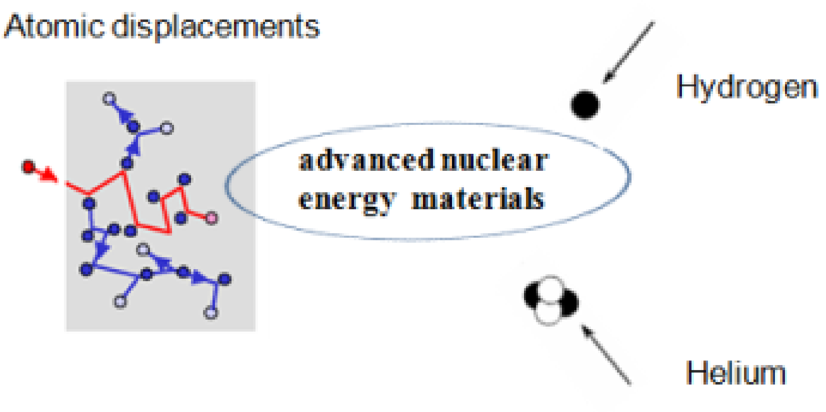


Low beam current irradiation chamber for RT irradiation
6 samples installed & irradiated in turn
without breaking vacuum

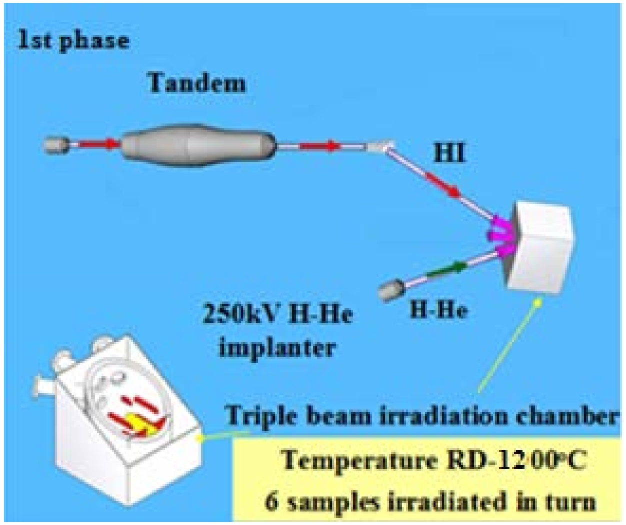


variable temperature irradiation chamber
RT to 800°C (±10°C)
6 samples mounted & irradiated in turn
without breaking vacuum

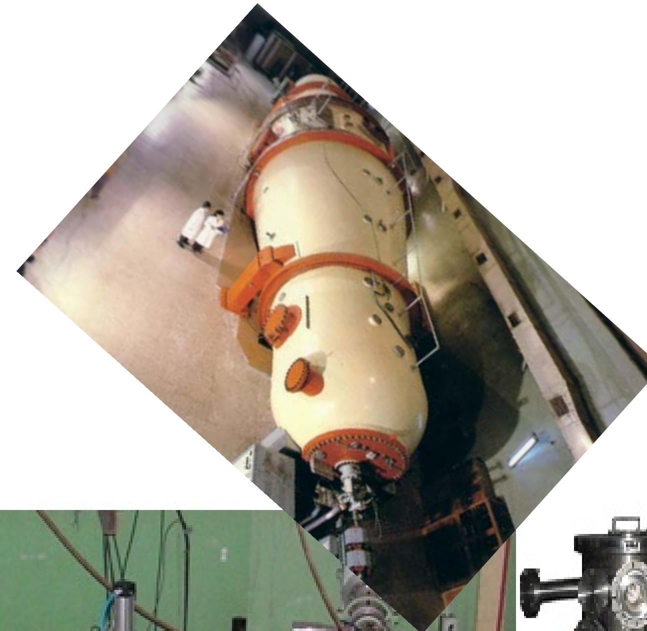
Development and Establishment of triple beam facilities at CIAE divided into three phases

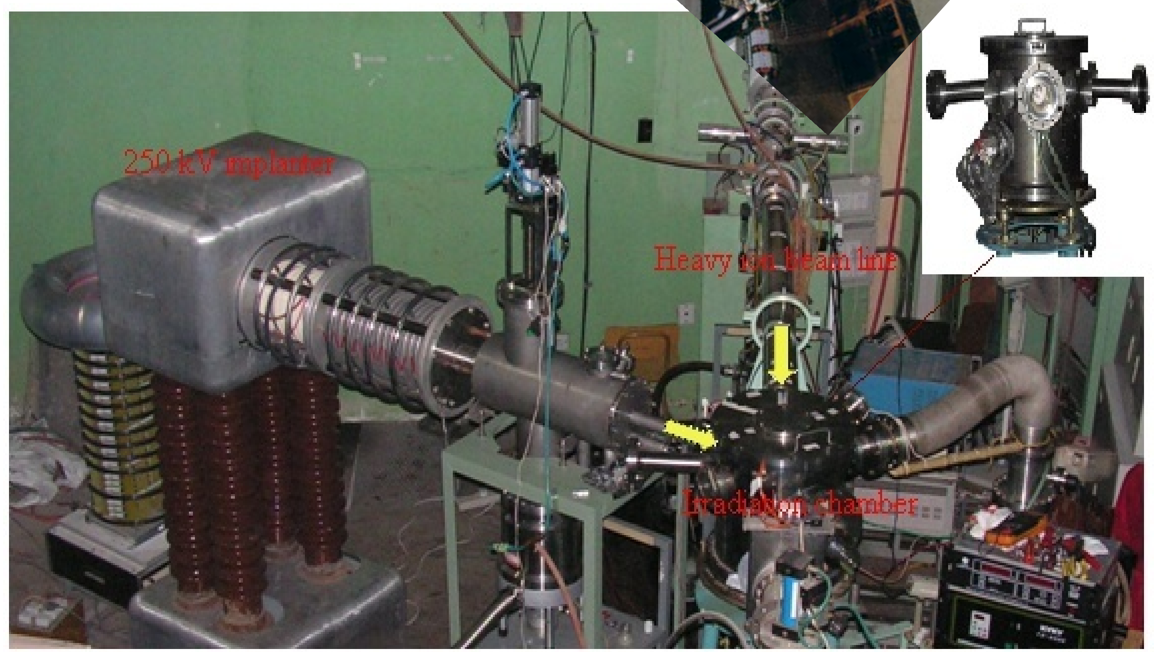


Phase 1



Early stage





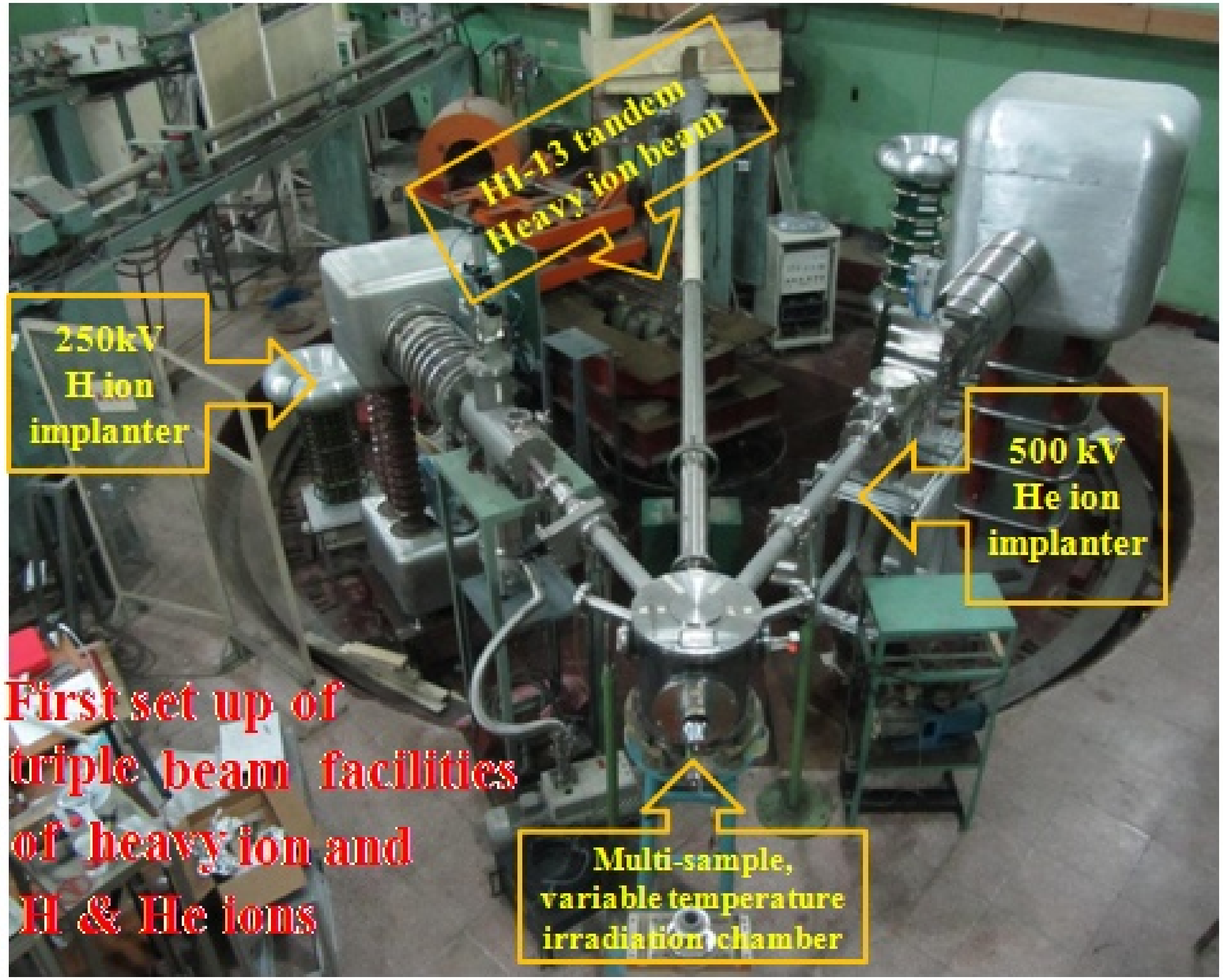
Composed of HI-13 tandem Accelerator and a 250 kV implanter

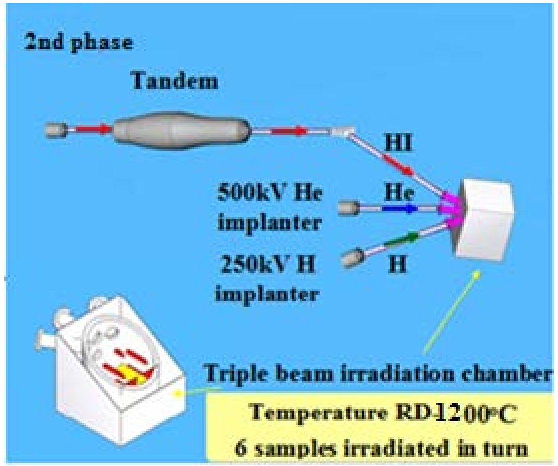
HI-13 tandem
providing various kinds of HI up to AU ions,
250 kV implanter
delivering mixed beam of H & He

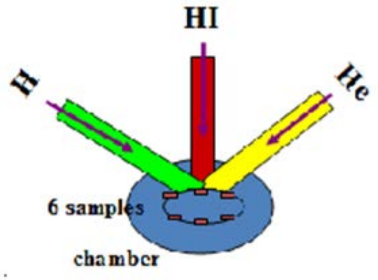
Irradiation chamber

Phase 2

Present stage







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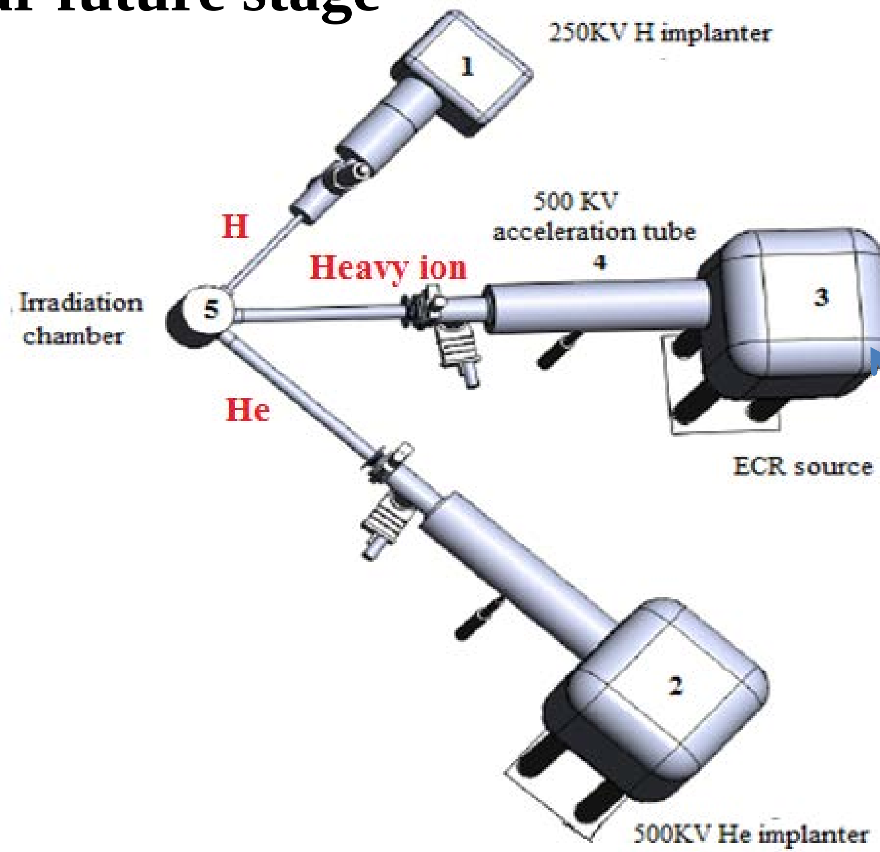
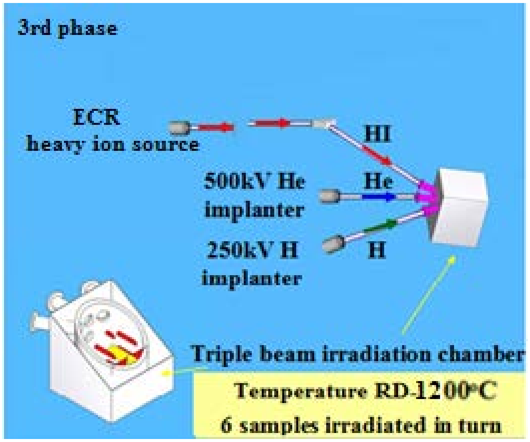
Phase 3

Near future stage





Dedicated triple beam irradiation facility

Expected to be completed in the first quarter of 2015

High-B, 10 GHz，Caprice

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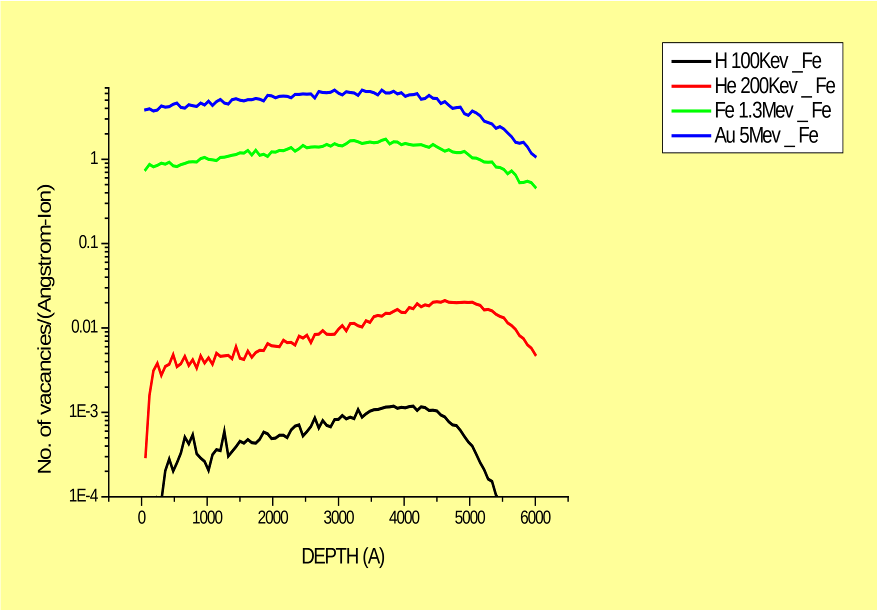
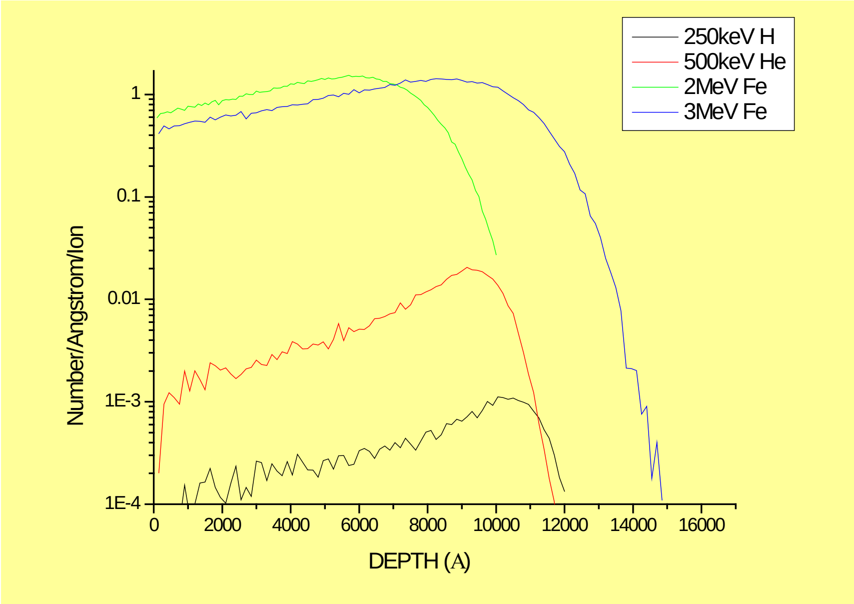


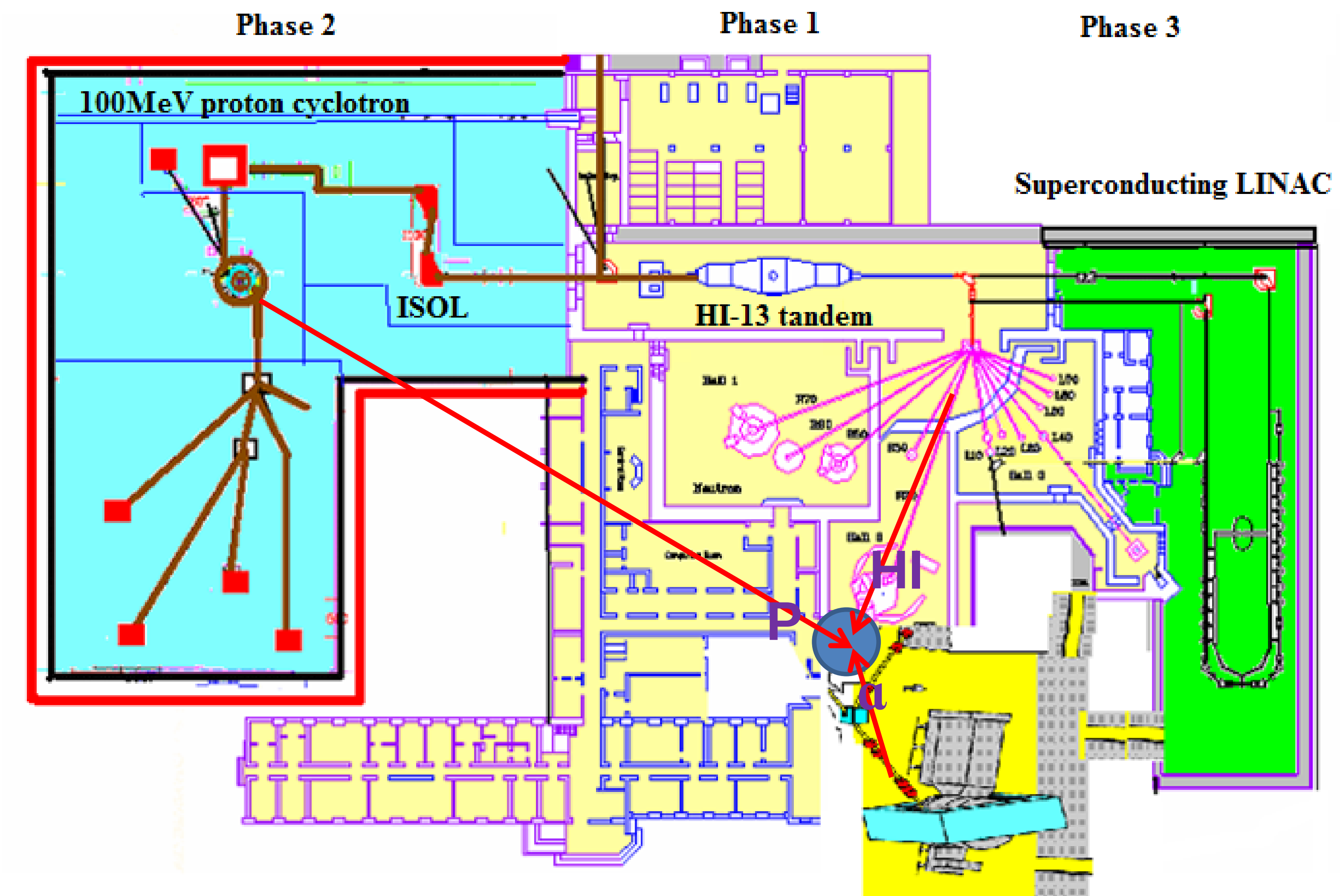
Depth distributions of displacement for 100 keV H, 200 keV He, 1.3 MeV Fe & 5 MeV Au in stainless steel



Depth distributions of displacement for 100 keV H, 200 keV He, 2 MeV and 3 MeV Fe in stainless steel

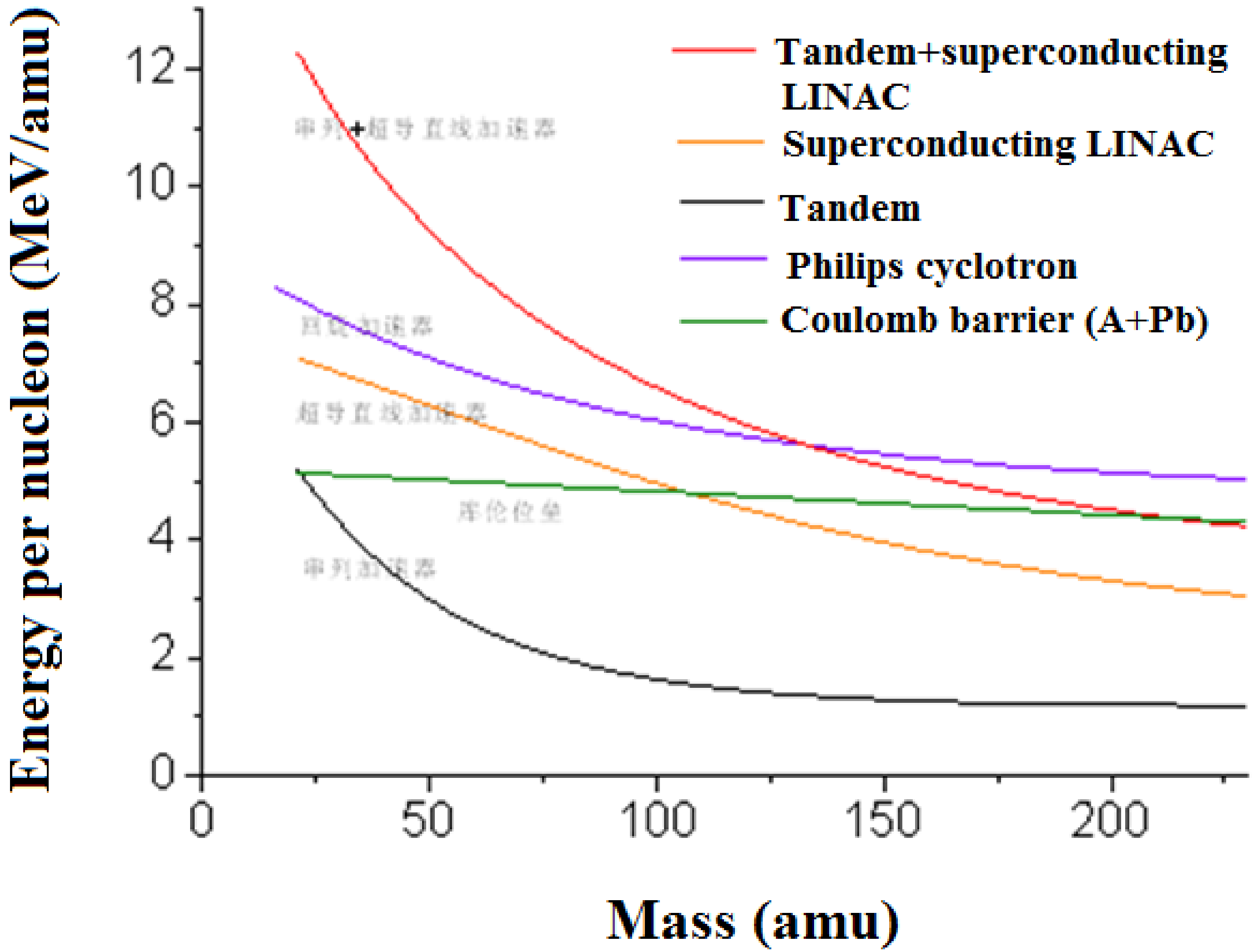
Depth distributions of heavy ion, H and He are well overlapped

High energy triple beam facilities



Plan view for the planned accelerator complex at DNP, CIAE

Philips cyclotron


Energy per nucleon (MeV/amu)
Mass (amu)
0
2
4
6
8
10
12
0
50
100
150
200
Tandem+superconducting LINAC
Superconducting LINAC
Tandem
Philips cyclotron
Coulomb barrier (A+Pb)
串列+超导直线加速器
回旋加速器
超导直线加速器
库伦位垒
串列加速器

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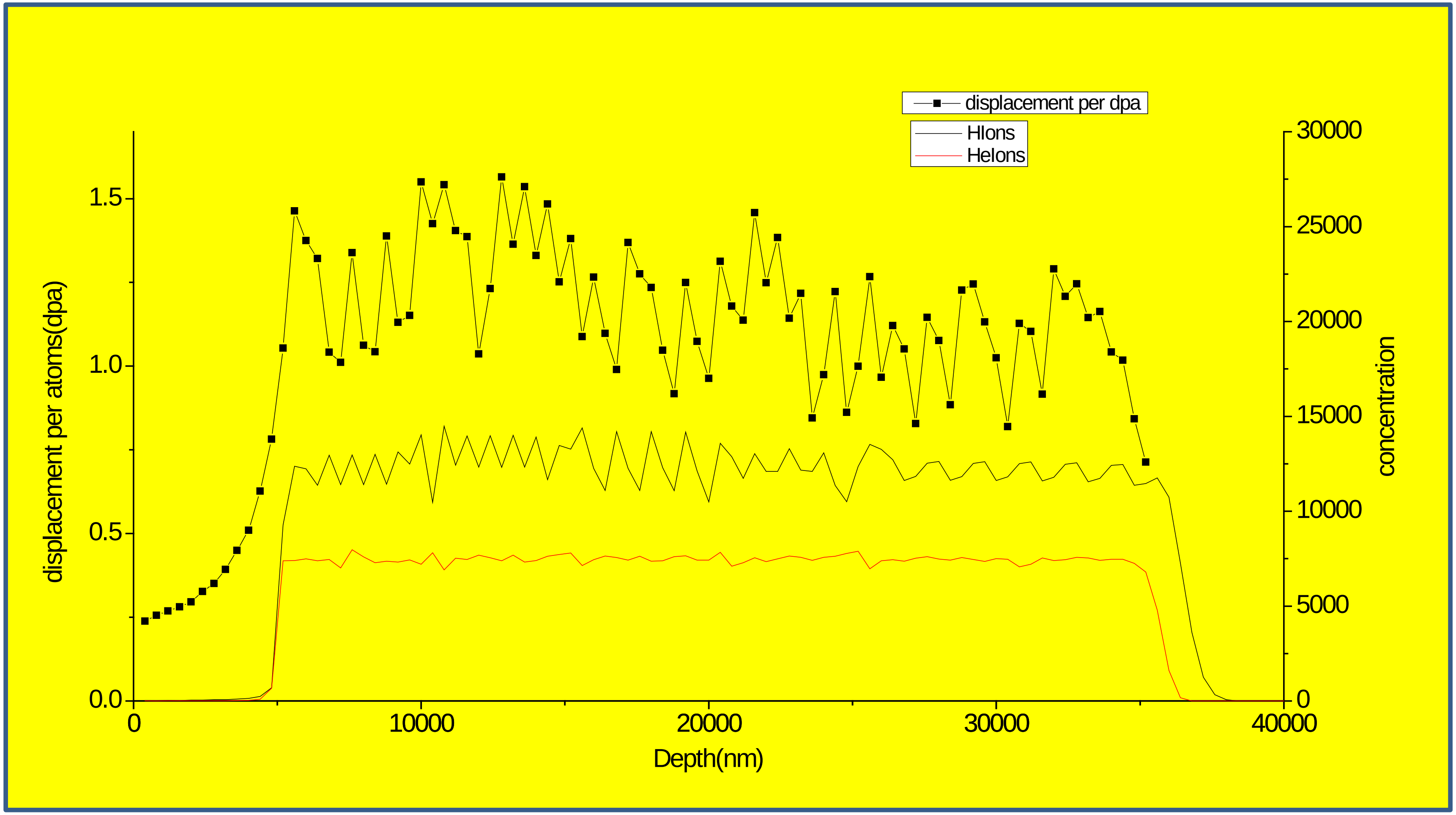
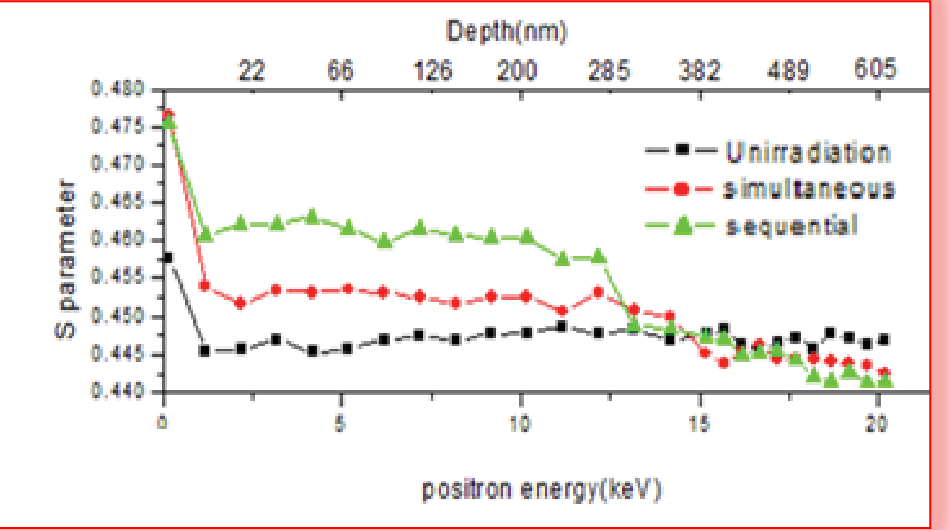


Triple beam irradiations have been carried out with the established facilities to study the radiation effects in CLAM, ODS, 304 ss, etc

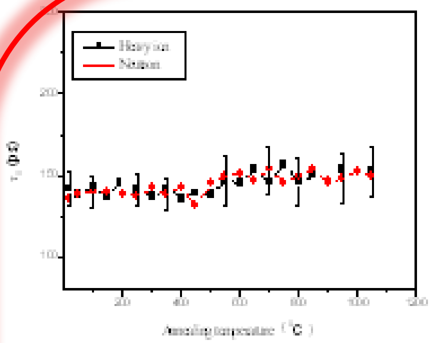
The radiation effect of simultaneous triple ion beam irradiation in CLAM

Presented by Dr. Yuan



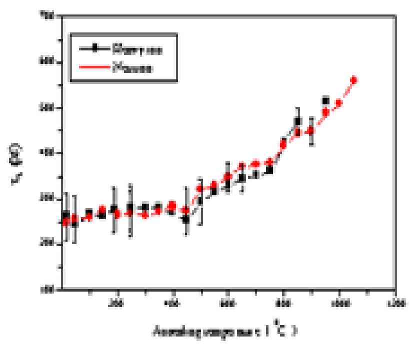
Thank you very much

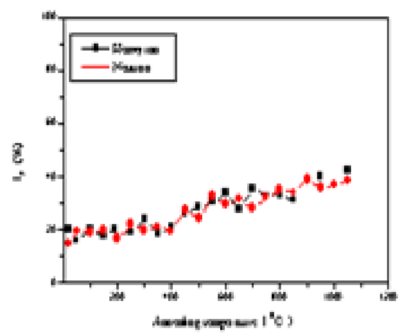
Preliminary verification

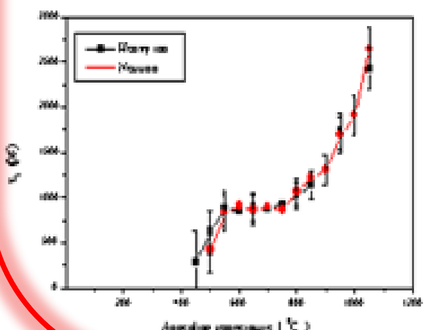


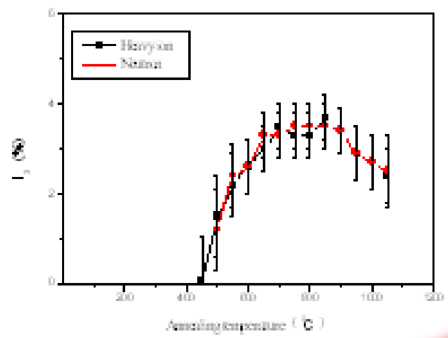
Positron lifetimes (right) and their intensities (left) as a function of annealing temperature in α-Al_2O_3 irradiated by equivalent dose neutrons or heavy ions

α-Al_2O_3









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Previous experiment proved the equivalence of the HI irradiation and the neutron irradiation for α-Al_2O_3 at the same irradiation dose

85 MeV ^{19}F ions to a fluence of 5.28×10^{15} cm^{-2} @ 60 ^{o}C, equivalent to the En ≥ 1 MeV neutron fluence of 3x10^{20} cm^{-2} @ 75 ^{o}C irradiated at JJR-2 reactor, Japan