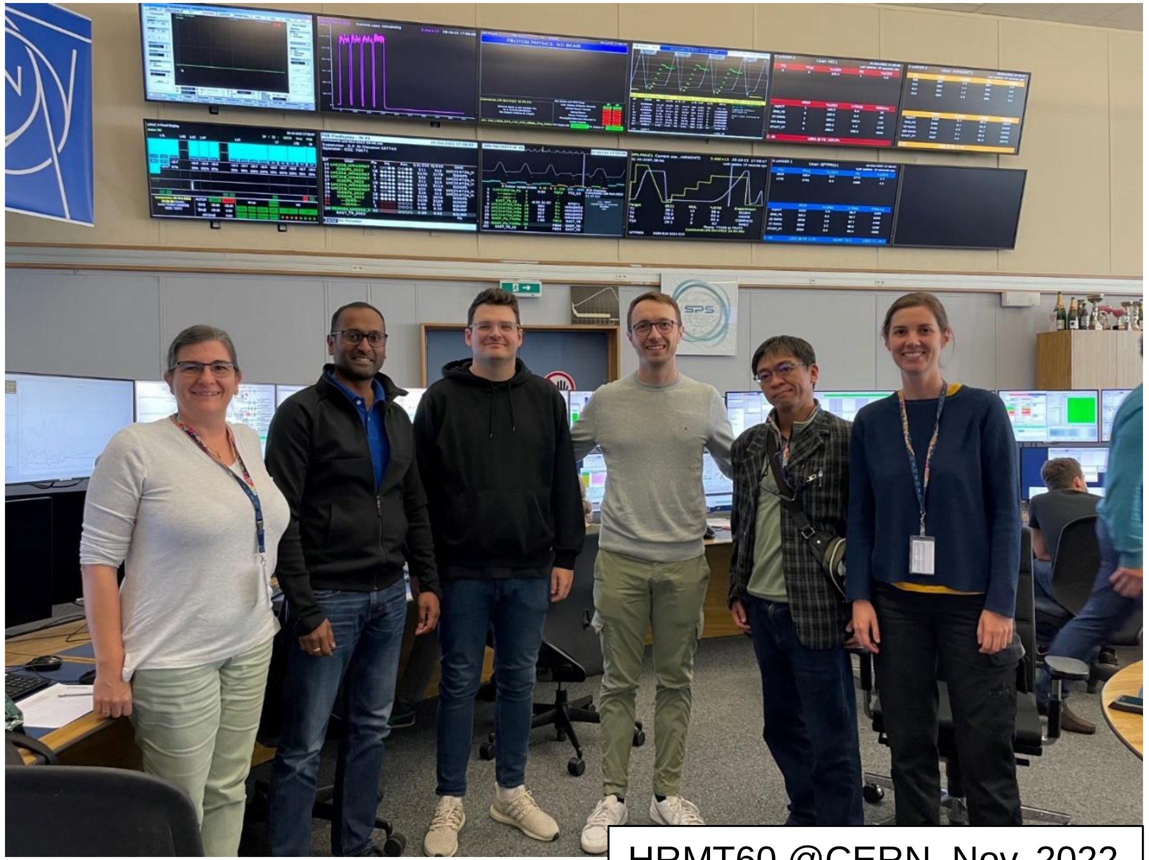
RaDIATE activities at J-PARC


HRMT60 @CERN, Nov. 2022

J-PARC, KEK & JAEA:
(KEK) Shunsuke Makimura, T Nakadaira, Taku Ishida, Shiro Matoba, Yoichi Sato, Hitoshi Takahashi, Eisuke Watanabe, Makoto Yoshida,
(JAEA) Shinichiro Meigo, Takashi Naoe, Koichi Masuyama, Takatoshi Morishita, Takamitsu Nakanoya, Shigeru Saito, Takashi Wakui,
and J-PARC RaDIATE members
Tokyo University: Sho Kano
National Institutes for Quantum Science and Technology: Hiroyuki Matsuda

Fermi National Accelerator Laboratory:
Sujit Bidhar, K. Ammigan, F. Pellemoine, K. Yonehara
Pacific Northwest National Laboratory:
D.J. Senor, A.M. Casella, A Roy, D. J. Edwards
Brookhaven National Laboratory: M. Palmer, D Kim

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE collaboration meeting at Brookhaven National Laboratory, 26th – 30th June. 2023

History of RaDIATE activities at J-PARC

J-PARC participated in RaDIATE collaboration in December 2017
- Beam window for T2K
- Target materials for pion/muon production
- DPA cross section measurements,,,

Mostly, thanks to US-JP collaboration

The activities were reviewed by an internal committee in Nov. 2022.
- The committee comprehended importance of the activities.
- So far, these activities have been individual activities by volunteer-based members.
- Now they are promoted as a J-PARC-wide mission led by the director of J-PARC Center.

<u>J-PARC-wide activities: Current activities + expansion of activities</u>

Irradiation damage studies in Targets, beam windows, and beam-intercepting components in the entire Experimental & Accelerator facilities.

New framework since April 2023

Kick-off meeting was held on 7th June.

Members from all J-PARC

- Representative (KEK): Shunsuke Makimura, Takeshi Nakadaira
- Representative (JAEA): Shinichiro Meigo, Takashi Naoe
- Experimental & Accelerator Facilities
- Fundamental technologies Gr.: Cryogenics section, Radiation Control section

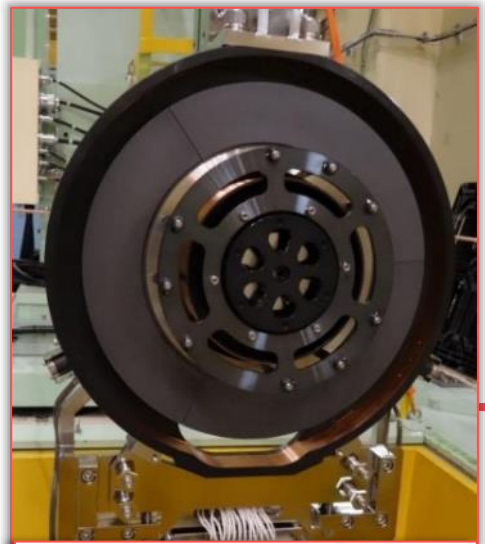
Activities

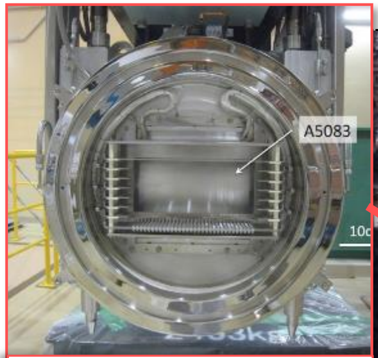
Irradiation tests & PIEs ⟺ Design of beamline components

- Quarterly core-members meeting, Annual meeting with entire J-PARC (& Japan?)
- Signing procedure: MoUs, agreement, arrangement,,,
- Report to J-PARC Directorate
- Request to Proton Irradiation Facility at J-PARC

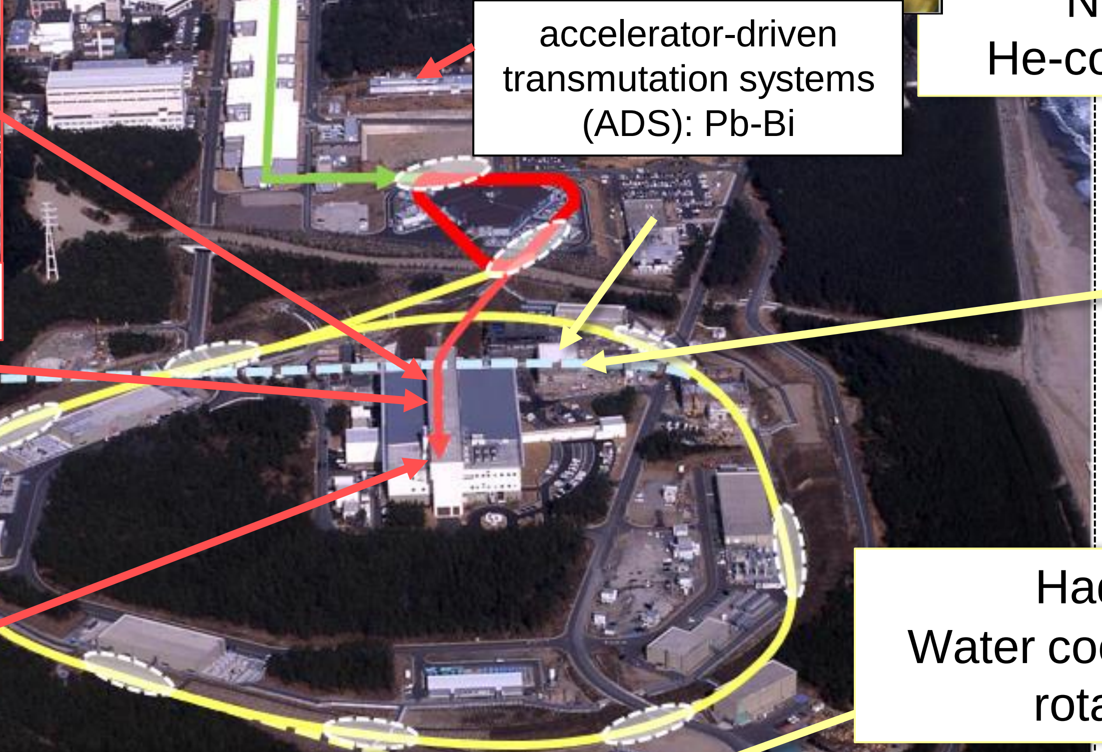
Some budget is allocated for these activities.

Targets & Beam windows at J-PARC

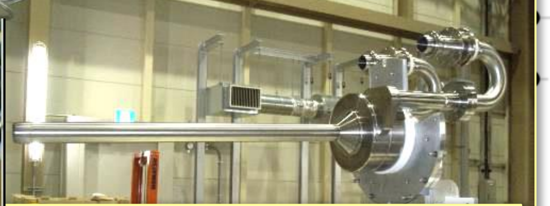

Muon [MLF-MUSE]
Rotating Graphite



Al A5083 BW

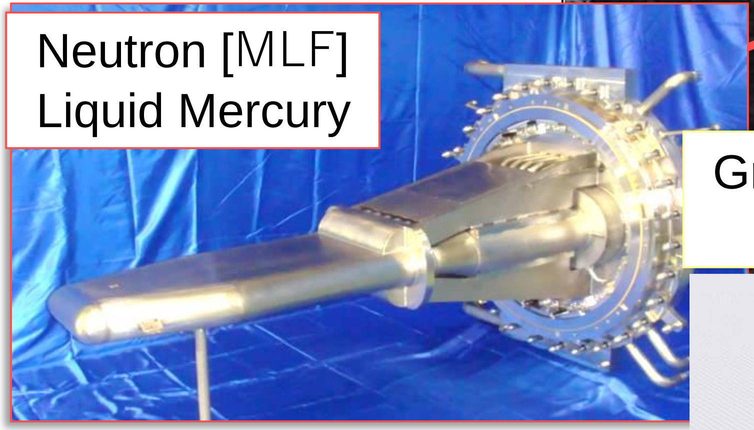



accelerator-driven transmutation systems (ADS): Pb-Bi

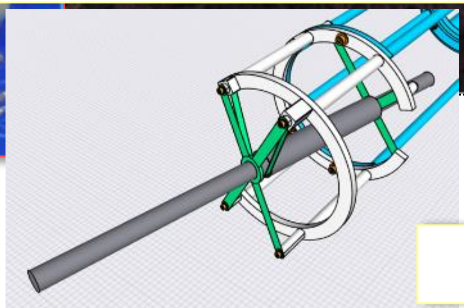

Neutrino [ν]
He-cooled graphite


Ti-6Al-4V BW

Hadron [HEF]
Water cooled gold/ high-Z rotating target


Neutron [MLF]
Liquid Mercury

Graphite (P1), SiC (P1.5), W (P2) [COMET]




3D-printed Ti-6Al-4V BW


Beryllium BW

Current activities under RaDIATE collaboration

High-energy proton irradiation at BNL-BLIP facility in 2017/2018 in partnership with the RaDIATE collaboration

Post-Irradiation Examination (PIE) at PNNL: Mech. property, Microstructure, Gas analysis,,,

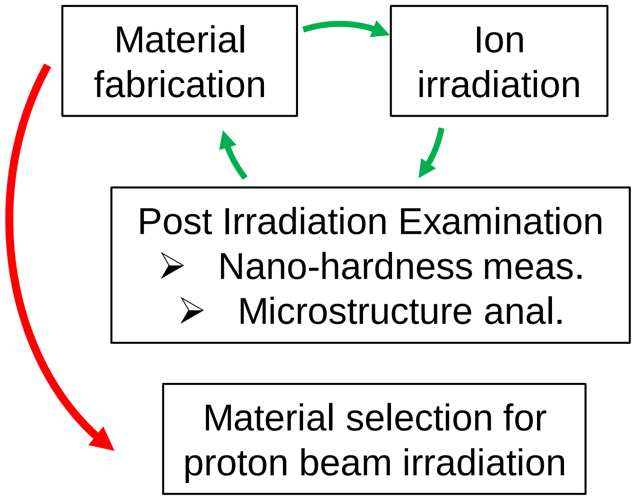
Thermal shock experiment at CERN's HiRadMat facility

Radiation damage + Thermal shock

Ion irradiation at HIT, Tokyo University

- Screening test
- High fluence & no activation, but local damage, a few μm.
- Nano-hardness, Microstructure analysis

- Beam window for next J-PARC/FNAL neutrino projects (1.2 - 2.4 MW)
  Titanium alloys (Ti): (T2HK/LBNF-DUNE)
- Development of novel materials for neutrino, muon, neutron targets
  - ✓ SiC coated graphite, SiC-SiC composite: n, μ target
  - ✓ TFGR-W-TiC: m-e conversion, neutron, anti-proton target,,,
- Other researches
  - ✓ DPA cross section measurements (presented by Meigo-san)



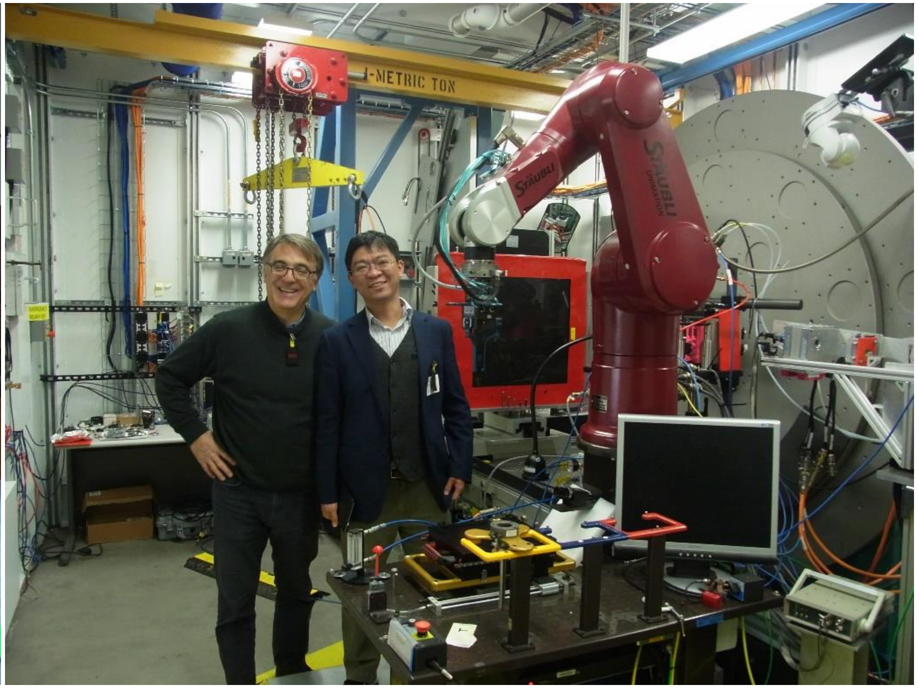
RaDIATE

Radiation Damage In Accelerator Target Environments

As a memorial of Nick Simos

- Thanks to your passion, we realized the BLIP irradiation.
- We will resume the XRD research I started with you.
- I appreciate your support of us.

Thanks for organizing a memorial session, Pat-san and Dave-san.



1. Activities since 2016

Radiation damage studies in Ti alloys, SiC coated graphite

HiRadMat experiments at CERN

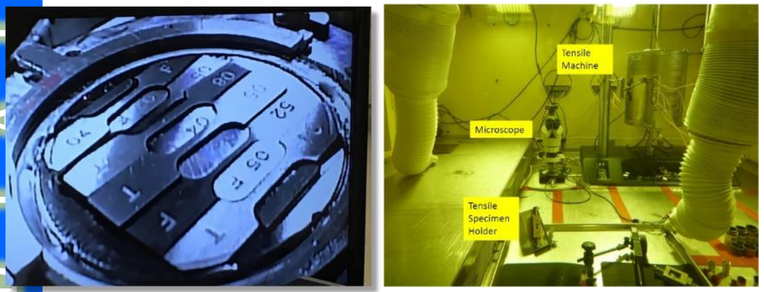
Ion irradiation at HIT facility

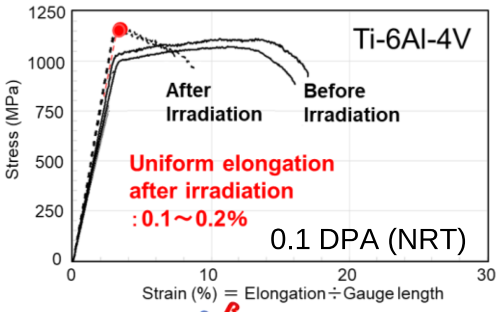
Development of novel materials

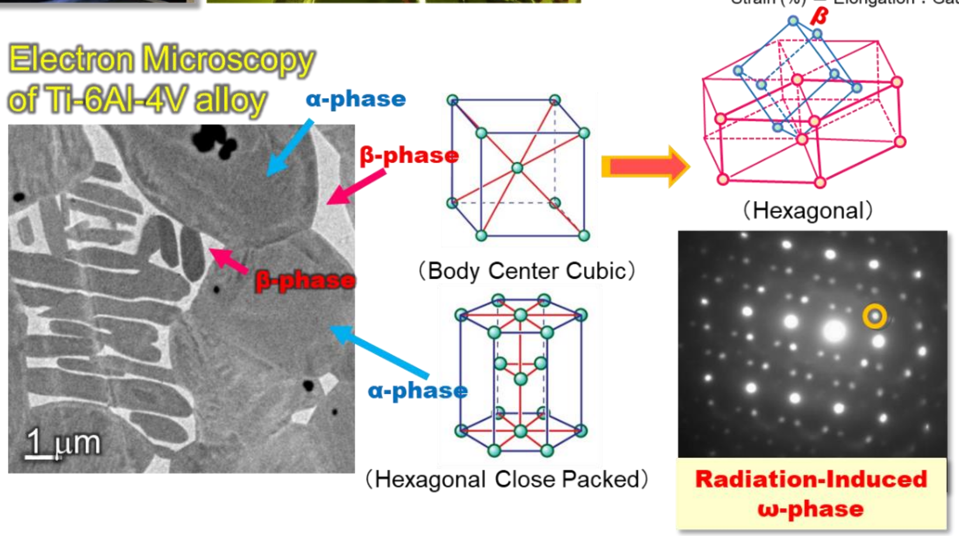
2. Expansion of activities since April 2023

Radiation damage studies in Ti-alloys

By T. Ishida







PIE in BLIP irradiated specimens at PNNL

The conventional Ti-64 alloy loses its ductility after only 0.1 dpa.

- ➢ The radiation-induced ω phase in the β matrices
- ➢ Dislocation loops in the α matrices

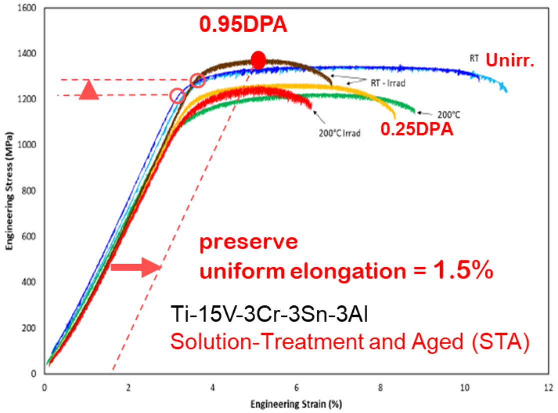
Press release Nov. 2020: “Why Does Titanium Alloy Beam Window Become Brittle After Proton Beam Exposure ?”

Ti-6Al-4V: T2K beam window material

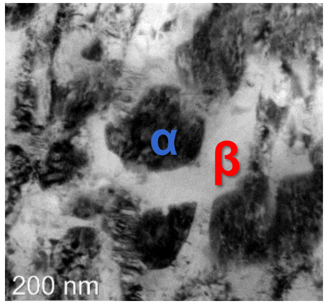
PIE in BLIP irradiated specimens at PNNL

Reduction of irradiation effect: pre-existing microstructure

- ➢ Fine-grained
- ➢ highly strained dual phase structure



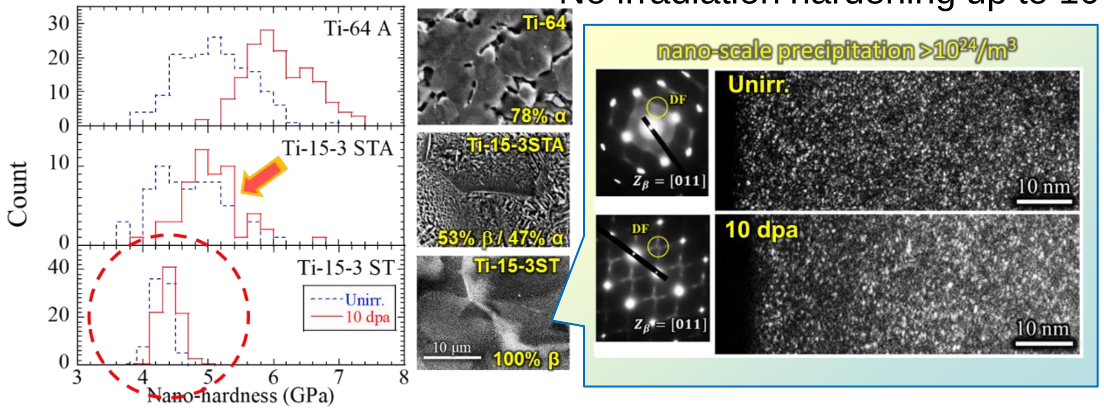
0.95 DPA (NRT)



Microstructural analysis by TEM

Ion Irradiation at Higher DPA Region in HIT

No irradiation hardening up to 10 dpa

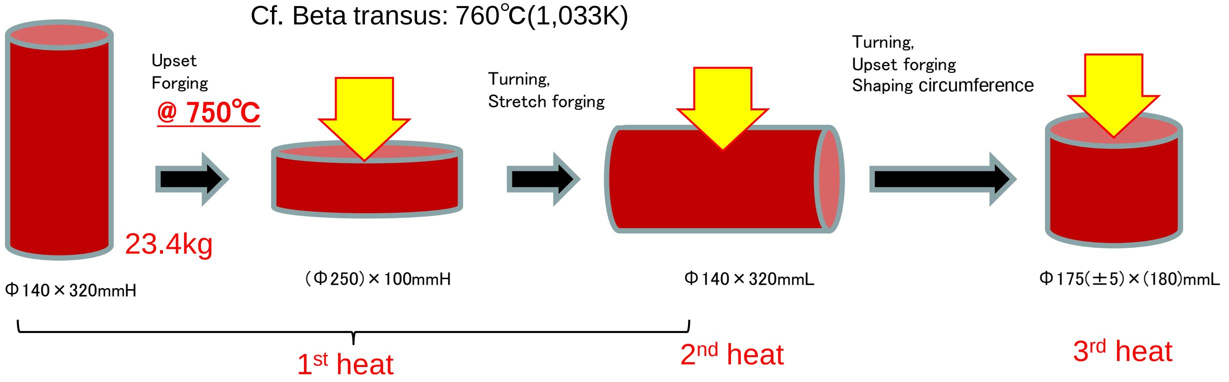


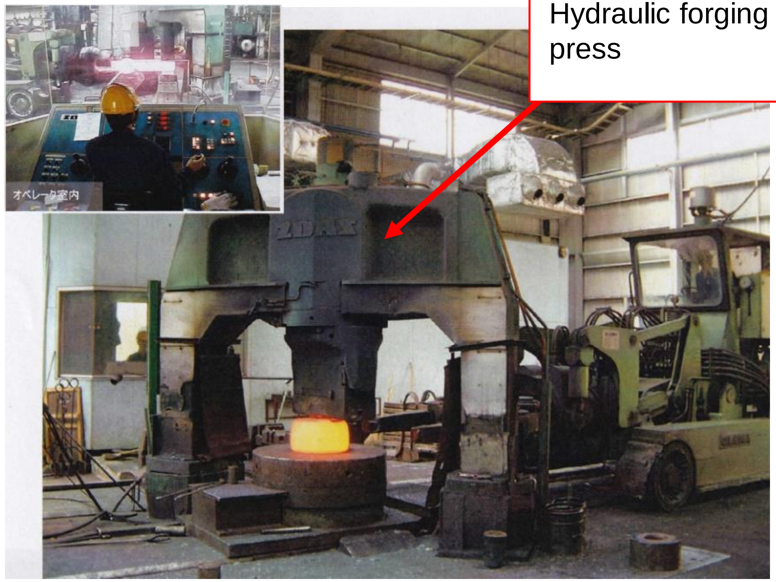
Ti-15-3-ST2A is a first choice for beam window material.

Ti-15V-3Cr-3Al-3Sn

Prototyping of Ti-15-3 ST2A Beam Window

- In the market, Ti-15-3 alloy is only available in strip form
- To manufacture T2K beam window prototype
  - Purchase intermediate billet material (140Φ×660L)
  - Apply thermo-mechanical processing (upset forging) to realize fine-equiaxed microstructure
  - Machining to beam window shape and apply two-step aging process

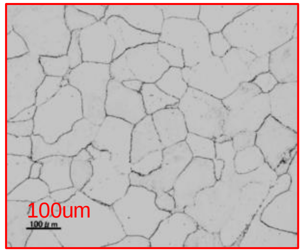




A 1,000t Hydraulic forging press

After forging

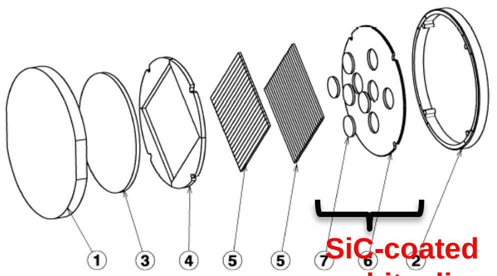
After solution treatment



These activities have led to promising selection of the material and prospect of manufacturing the actual beam window.

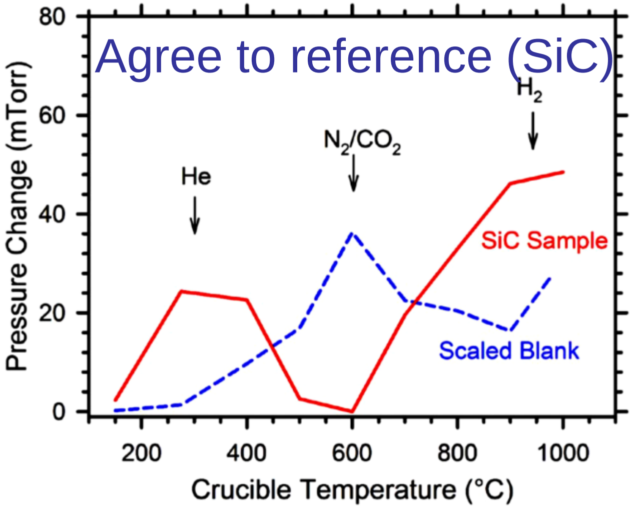
Radiation damage studies in SiC-coated Graphite

Thermal Desorption Spectroscopy (TDS) on irradiated specimen and graphite filler, to study how SiC-coating prevents radiation-produced gas release from graphite



Heating up to 1,000° C

Analysis of emitted gases by Finnigan MAT-271 magnetic sector mass spectrometer



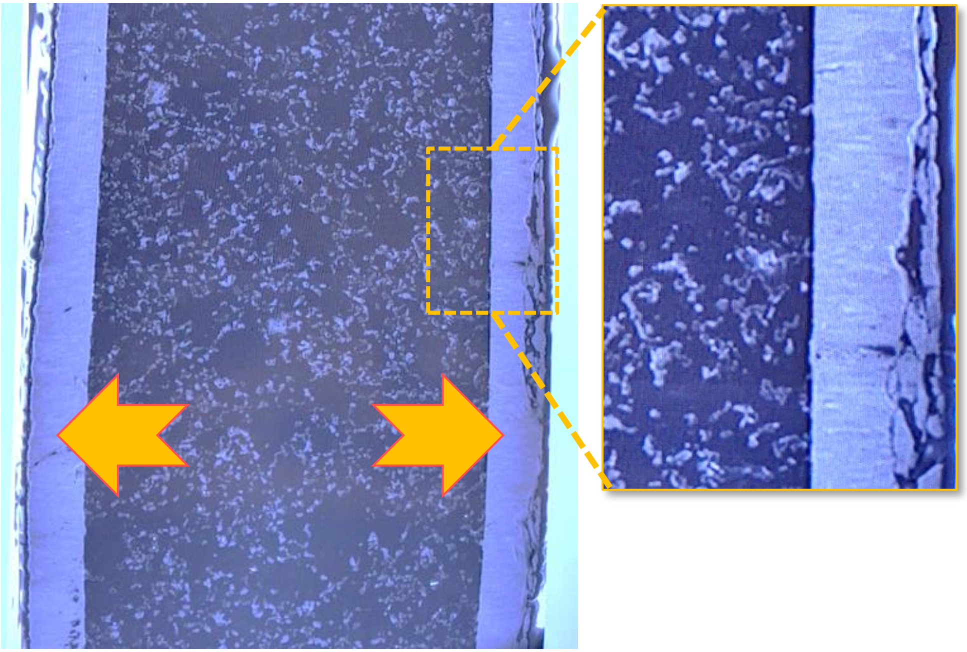
SiC-coating acts as an effective gas confinement barrier

PIE in BLIP irradiated specimens at PNNL

Estimation of Gas Production (FLUKA)

Material	Thickness (mm)	Peak DPA	H appm/DPA	He appm/DPA
Si	2.0	0.18	375	181
SiC	0.2	0.10	713	467
Graphite 1.82	0.8	0.03	2229	2481
Exp. Graph. 1	2.0	0.04	2430	2861
CAP SS316	0.3	0.32	655	194

SEM observation after TDS identified graphite swelling by 15% and crack at SiC surface



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HiRadMat Experiments (HRMT35 & HRMT48) at CERN

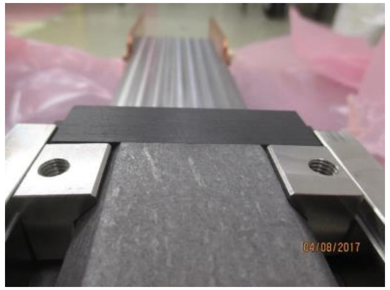
NITE SiC/SiC

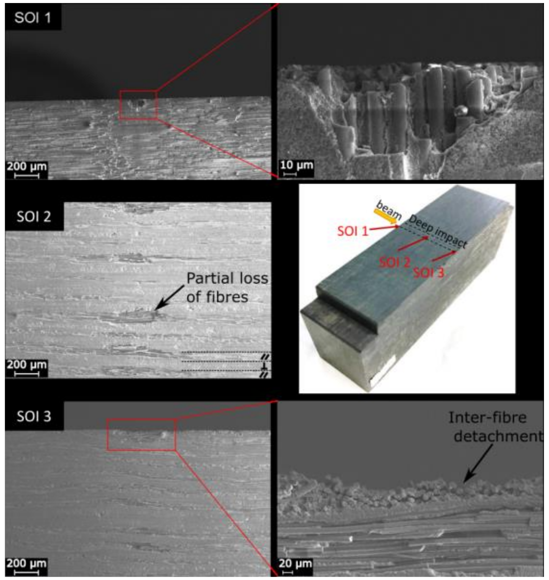
- Specimen was supplied by Muroran Institute of Technologies.
- Included in HRMT35 for Target Dump Internal, Coated low-Z absorbing material
- Different beam impact depths, beam angles
- Thermal analysis of composite material through Tsai-Wu criterion

Superficial damage for all impacts and had craters at the entrance and exit faces for deep and grazing impacts, coherent with analysis.

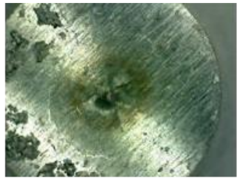
POT: 3.5×10^{13}
Beam size: 0.3 mm $\times$ 0.3 mm
288 bunches,
pulse duration 7.2 ms

dT=2100℃ J. Maestre et al.

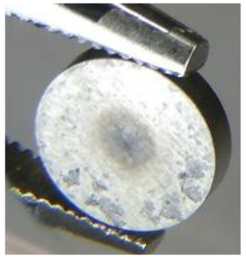


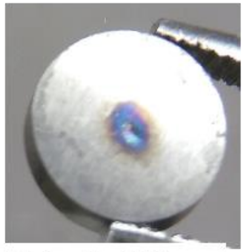


C. T. Martin et al.


hot rolled W-recrystallized


W-TiC-with GSMM


W-TiC-without GSMM


Hot rolled W

TFGR W-TiC

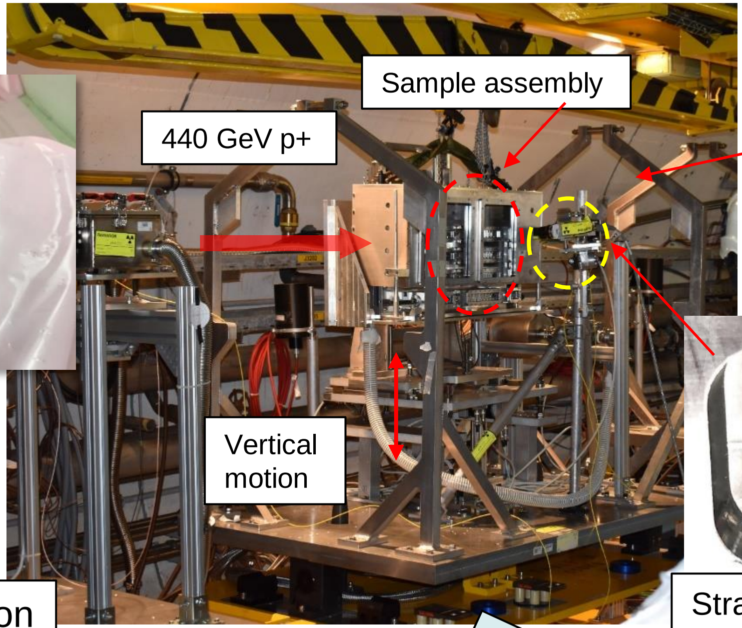
- Included in HRMT48 for AD-target design, Ir, Ta, TFGR,,,
- No noticeable damage
- Promising response

POT: $3.2 \times 10^{13} \sim 1.12 \times 10^{14}$
Beam size: 1mm $\times$ 1 mm
50 pulses, pulse duration 25 ns
dT=700℃,
Tensile stress: 1 GPa

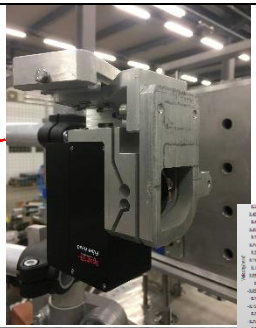
HiRadMat Experiments (HRMT43 & HRMT60) at CERN

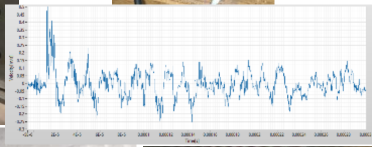
- Understand single-shot thermal shock response and limits
- Compare behavior of non-irradiated to post-irradiated materials
- Explore advanced novel materials
- Directly measure dynamic thermomechanical effects to validate numerical models

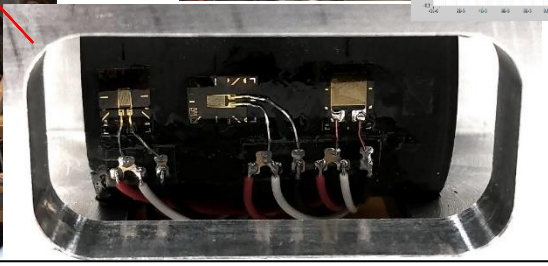
Sample preparation

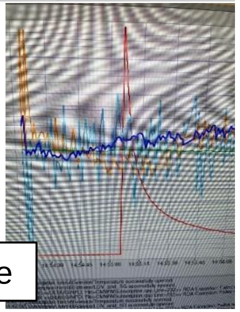


Real-time dynamic response: Laser doppler vibrometer









Strain and temperature gage response

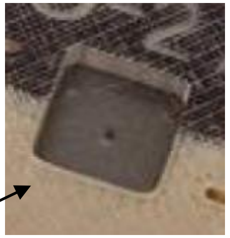
Oct. 2018, HRMT43

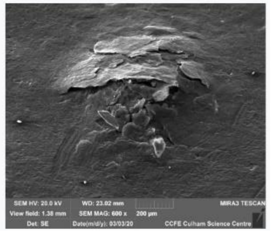
Nov. 2022, HRMT60

PIE at PNNL

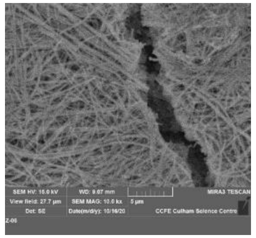
- Fractography by SEM analysis (Ti, W, SiC,,,)
- Quantification of thermals shock resistance

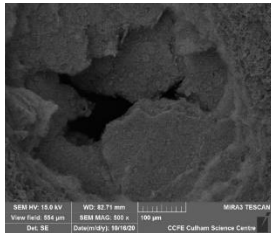
e.g. SEM analysis: HRMT43 specimens (FNAL)





Sigraflex, F. Nuiry, CERN





ZrO2 nanofiber, S. Bidhar, PRAB 24, 123001, 2021

R a D I A T E

Radiation Damage In Accelerator Target Environments

1. Activities since 2016

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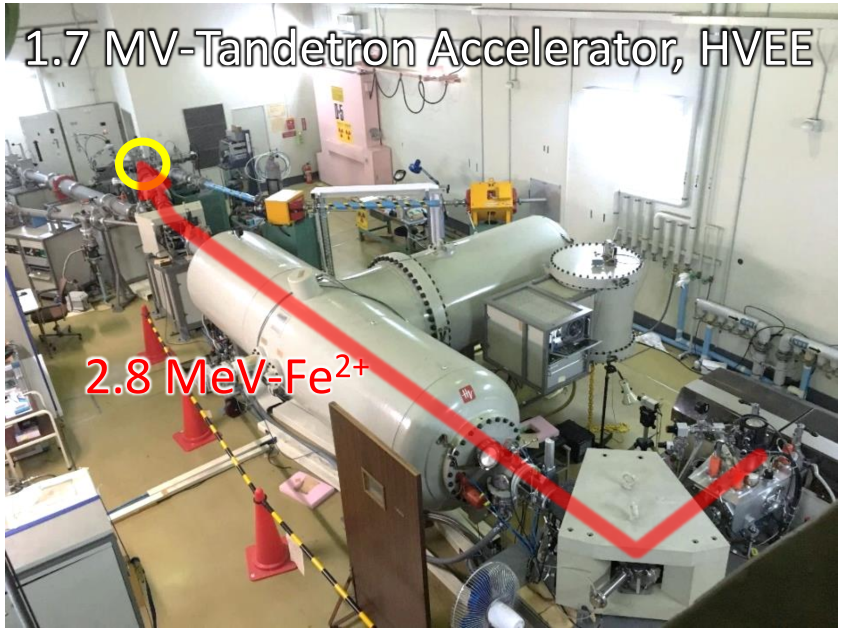
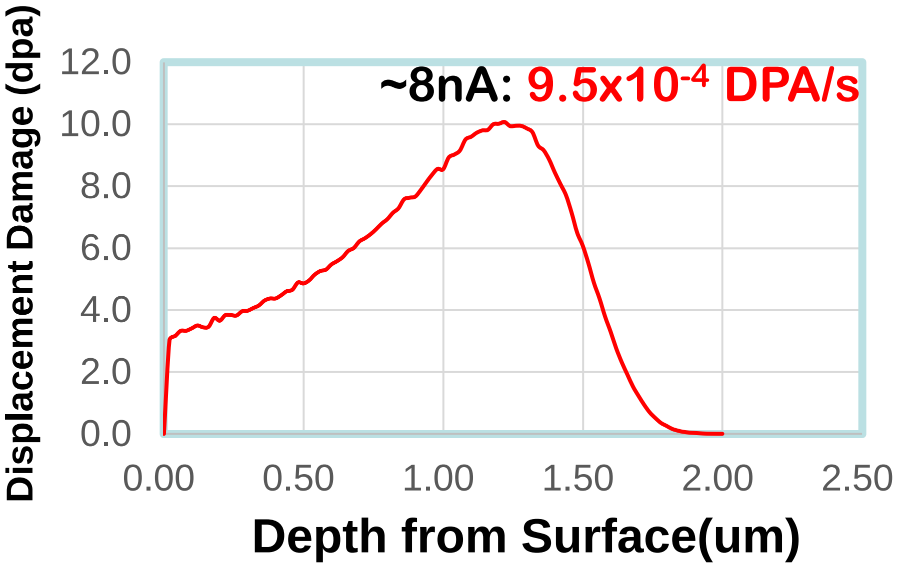
Iron Beam Irradiation at HIT Facility

High Fluence Irradiation Facility of The Univ. of Tokyo

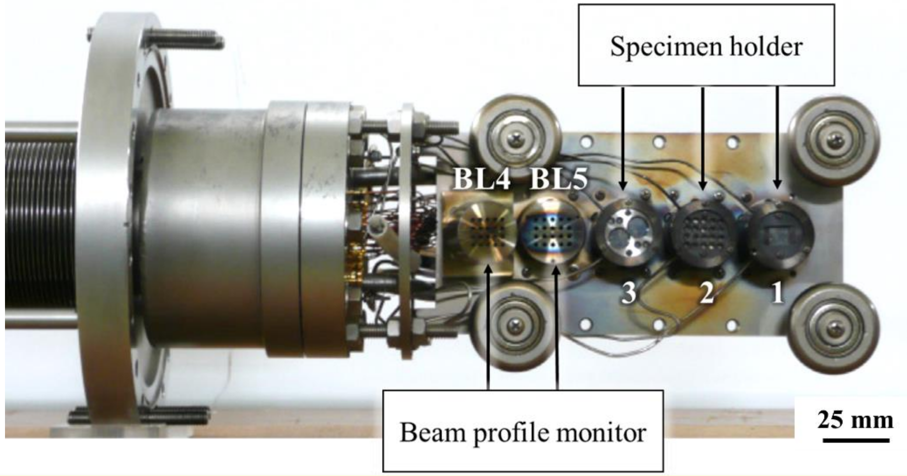
Supported by S.Kano (Univ. Tokyo)

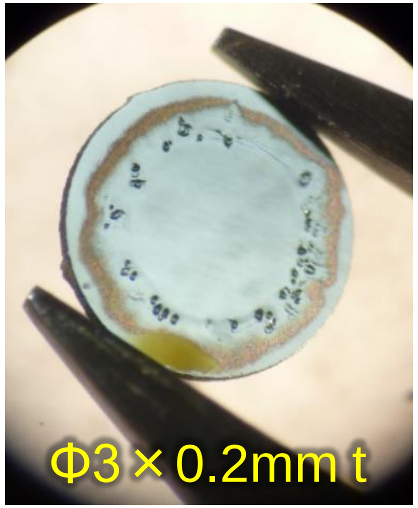




Much higher damage rate, much shorter irradiation time with higher dose, without activating the specimens

Up to 10 DPA in a few days

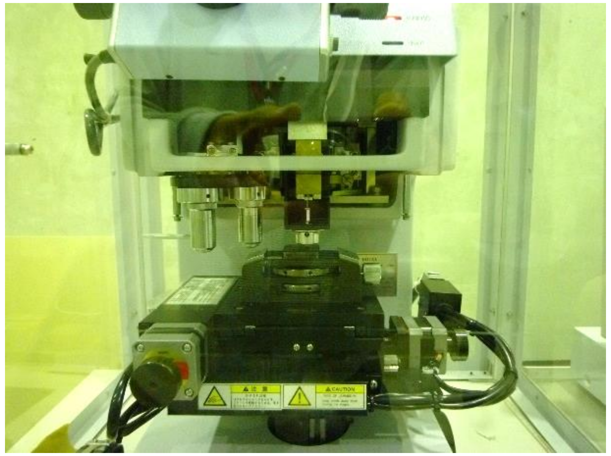




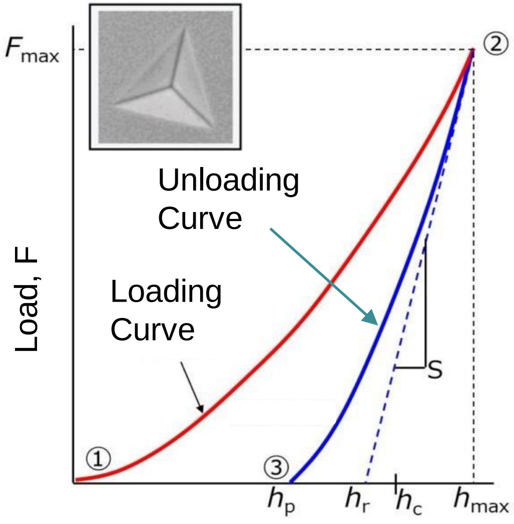
An effective and fast way to screen materials and to optimize heat treatment in higher dose region

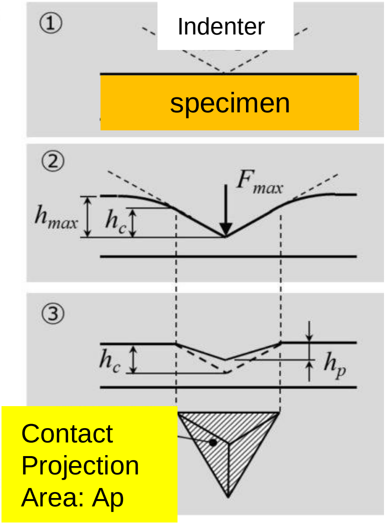
Nano-Indentation Hardness Test

Shimazu- DUH-211S



Indenter : Berkovich (115º)





$\sigma_y(\text{MPa}) ≒ 3\ H_v$

$H_v ≒ 60 \times H_{IT}(\text{GPa})$

Vickers Hardness

Indentation Testing Hardness

$$H_{IT} = \frac{F_{max}}{A_p(\boldsymbol{h_c})}$$

$$A_p(h_c) = 23.96(h_c)^2$$

$$h_c = h_{max} - \epsilon(h_{max} - h_r)$$

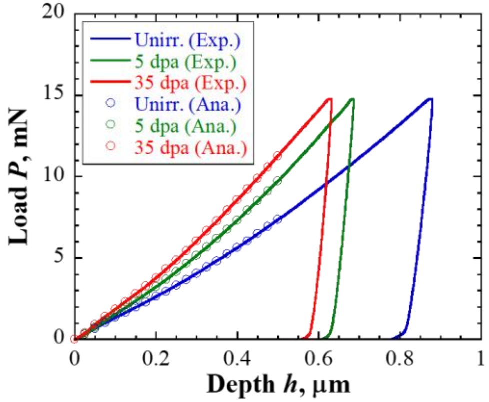
Hardness is about in proportion to Yield Strength while not easy to estimate ductility (elongation)

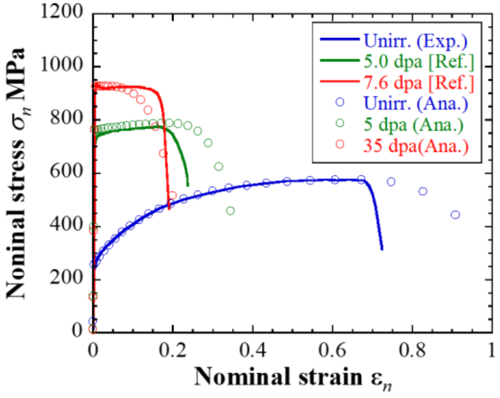
- Ti alloys, W alloys, HEAs, SS316L, Al alloys
- Participation from FNAL is planned in November 2023

March 2023 at HIT

- Inverse analysis to predict the yield strength and the elongation

By T. Wakui





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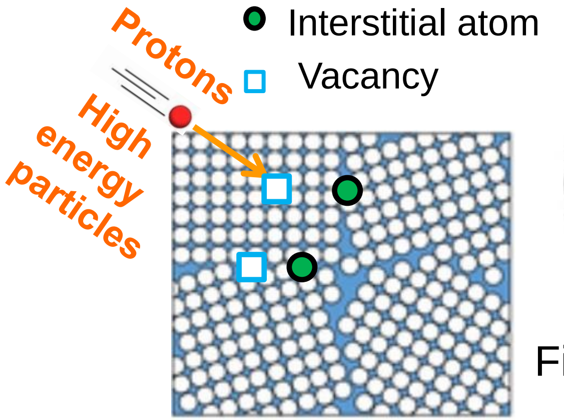
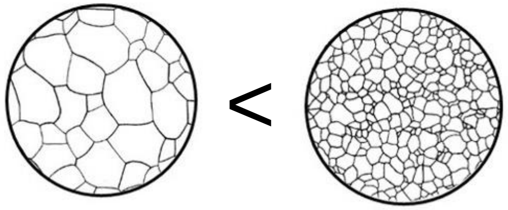
Developments of Novel materials

High-radiation-resistant material: Introduction of high dense “sink-site #”

Sink-site: Grain boundaries, precipitates, and solution atoms annihilate point defect, vacancy and interstitial atom



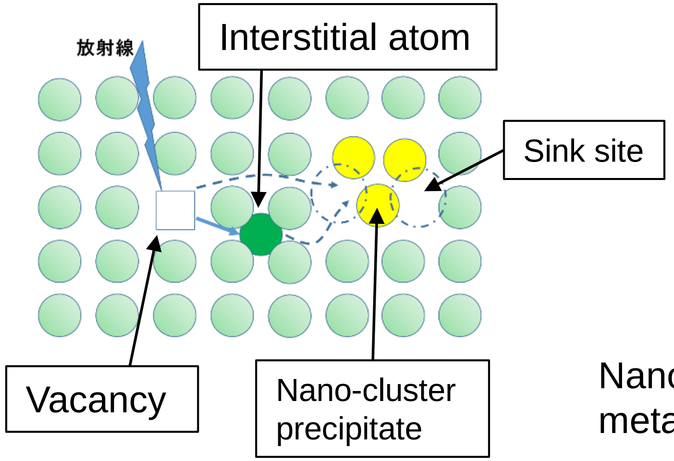


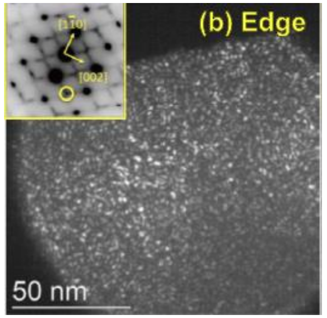
Fine-grain material is better.

- Fine grains, reinforced by TiC segregation
- Developed under KEK academic-industrial collaboration.

H. Kurishita et al. Mater. Trans. 54 (2013) 456-465.

Toughened Fine-Grained Recrystallized Tungsten



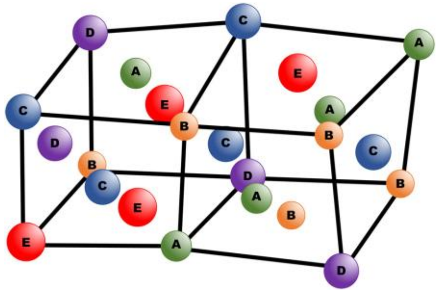


Nano-cluster precipitates at meta-stable beta titanium alloy

Lattice distortion by nano-cluster precipitate or solution atom annihilates point defect.

mixing equal or relatively large proportions of five or more elements.

In recent years, HEAs have attracted attention as radiation-resistant materials.



B.E. Macdonald et al., JOM, Vol. 69, No. 10, 2017

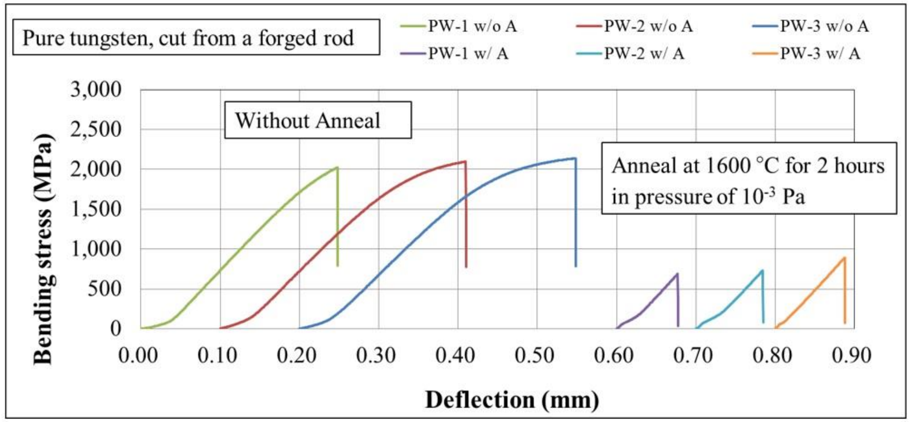
High-entropy alloys (HEAs)

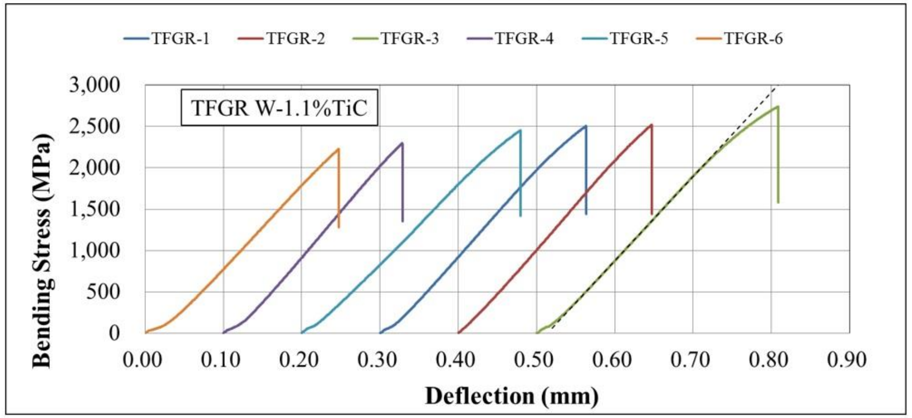
RaDIATE

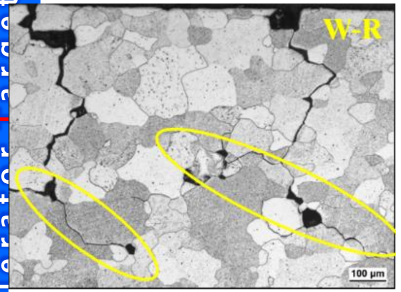
Radiation Damage In Accelerator Target Environments

Toughened Fine-Grained Recrystallized Tungsten (TFGR-W)

- ✓Tungsten is expected as a target material all over the world.
- ✓Tungsten is brittle, because grain boundary is weak.
- ✓Brittleness is improved by heavy plastic working.
- ✓Revert to the original state at recrystallization temperature (1200 ˚C at Pure W)
- ✓TFGR W overcomes recrystallization embrittlement.

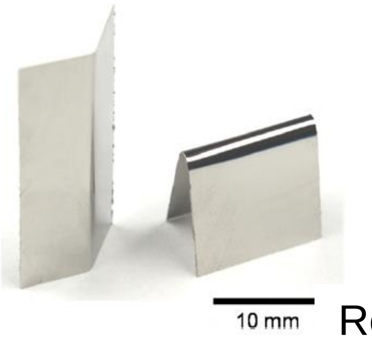


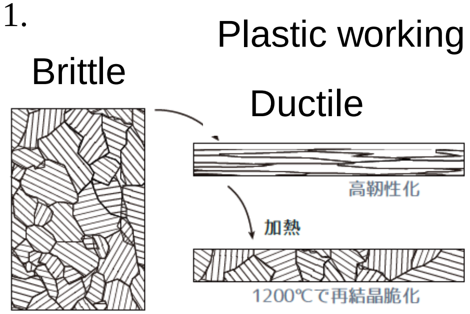




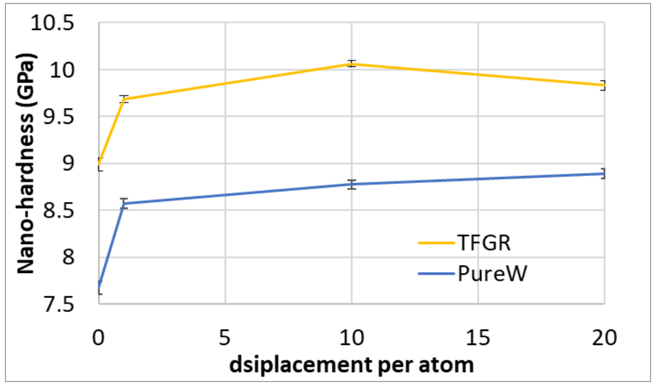
G. Pintsuk et al.

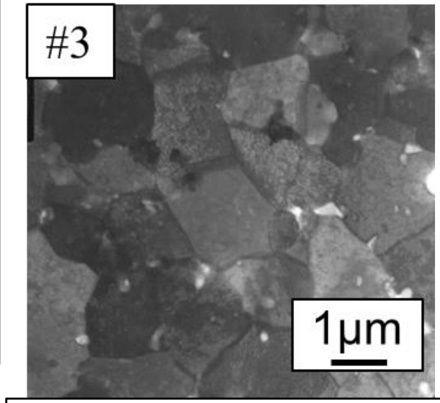
J.Reiser et al. JNM, 423 (2012) 1.





Recrystallization embrittlement





- Nano-hardness testing
- Microstructural analysis

W-ion-irradiated TFGR-W, TEM analysis at Ehime Univ.

Preliminary results of HIT irradiation

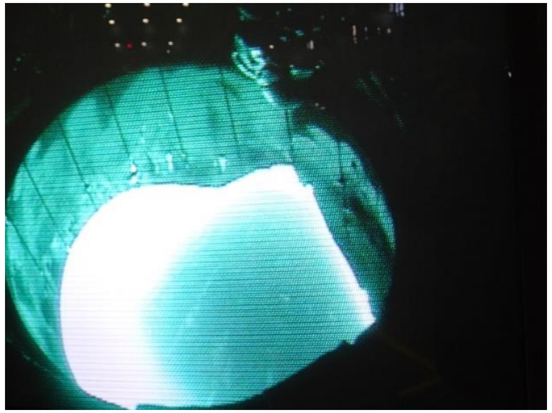
Development of High-Entropy Alloys (HEAs)

By E. Wakai

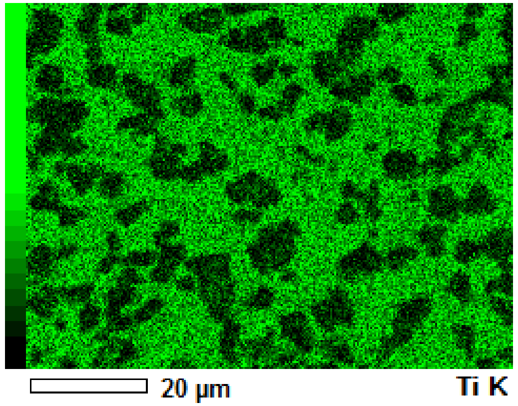
Recently, many new HEAs have been developed with combination of various elements.

Expected application:
- Ti-based HEAs: Beam window
- Fe-based HEAs: Structural material
- W-based HEAs: Target

- Forging or Hot rolling were applied.
- Radiation resistance will be confirmed.



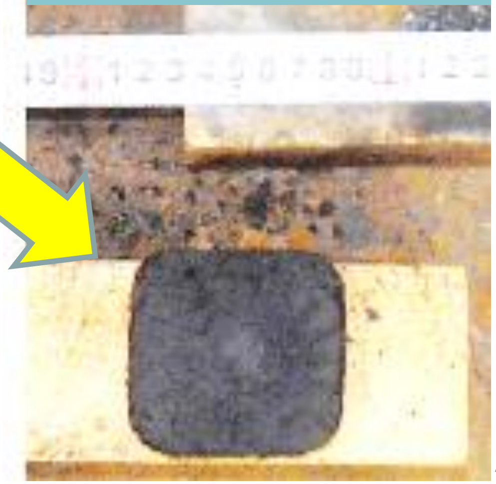
Melting in cold crucible



EDS of Ti Mapping Image

Hot Rolling

Hot Forging



1. Activities since 2016

Radiation damage studies in Ti alloys, SiC coated graphite

HiRadMat experiments at CERN

Ion irradiation at HIT facility

Development of novel materials

2. Expansion of activities since April 2023

Expansion of research area

- RCS group:
Arrangement with Los Alamos National Laboratory under RaDIATE MOU for RCS stripper foil
The process is on-going.

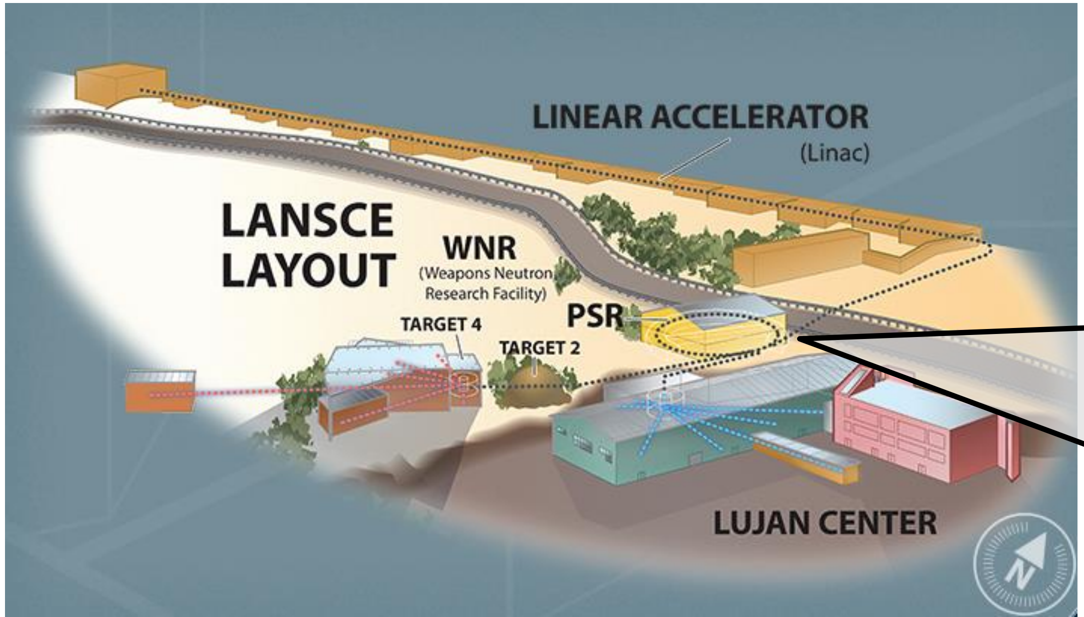
- Cryogenic section:
Neutron irradiation tests in superconducting materials at BR2 and PIE at Oarai, Tohoku university

- Proton irradiation facility at J-PARC, which will be presented by Meigo-san in this meeting

Signing of a new arrangement with LANL

By RCS gr.

- Based on the "Material Transfer Agreement" between KEK and LANL, J-PARC carbon stripper foils have been supplied to LANL.
- The supplied foils have been successfully used in actual operation.
- The manufacturing technology of the foils is transferred to J-PARC JAEA.
- A new arrangement under RaDIATE MOU is appropriate because the agreement will expire in July 2024.
- The agreement between J-PARC and LANL at the field level has been completed and will be officially signed soon.



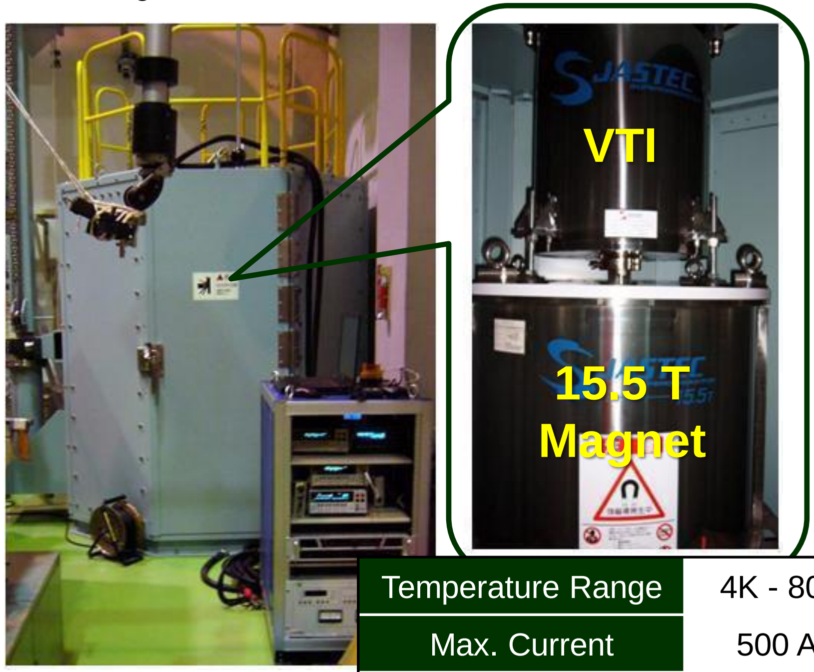
Carbon foil developed at KEK and J-PARC

Irradiation tests on Superconducting Magnet Materials

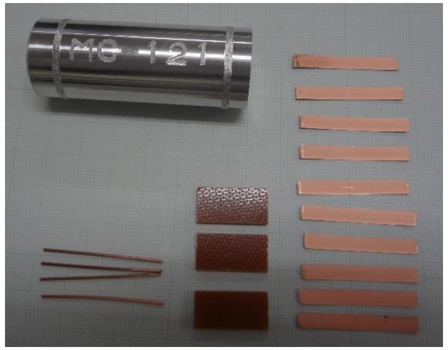
- So far, J-PARC Cryogenics Section carried out irradiation tests on superconducting magnet materials, such as superconductor, stabilizer metal, GFRP, insulation film and so on.
- Cooperation with J-PARC RaDIATE
- Tests of superconductor is performed with the collaborative research program of IMR, Tohoku University.
- Samples are irradiated by reactor neutrons of BR2 in Belgium and are sent back to IMR for PIE.
- Performance of superconductor is checked in cryogenic temperature with high field magnet installed in the hot lab.
- Status of the recent work on ReBCO coated conductor is reported.

By Cryogenic section

15.5T magnet and VTI in the hot lab of IMR



Temperature Range	4K - 80K
Max. Current	500 A
Max. External Field	15.5 T

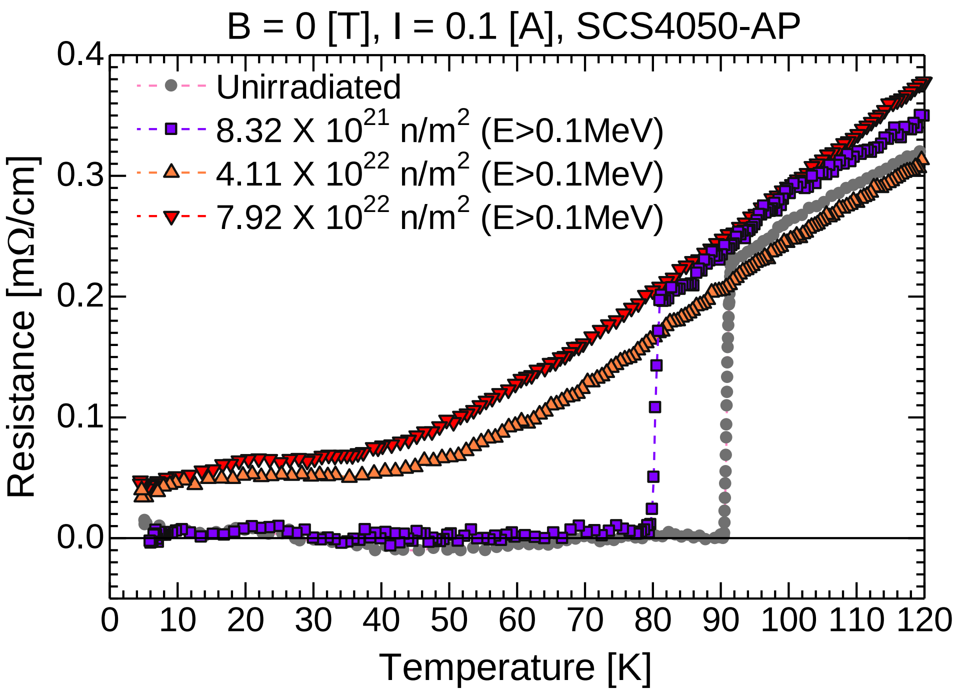


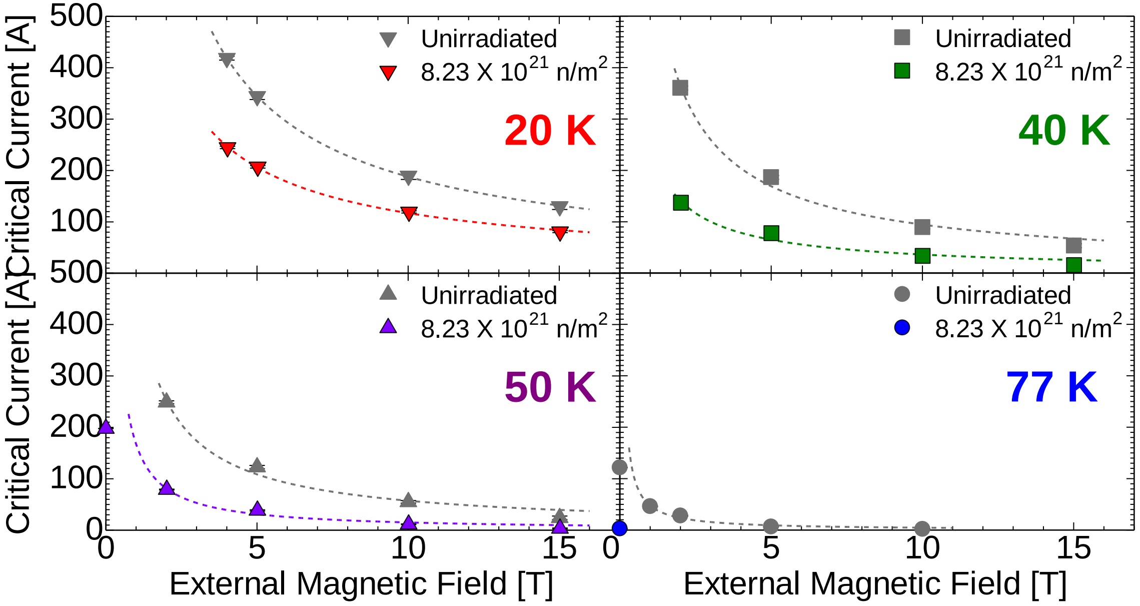
Samples to be irradiated at BR2

By Cryogenic section

Neutron irradiation effects on ReBCO

ReBCO: Rare-earth element +Ba2CuOy





Superconductivity vanished
by neutron irradiation > 4E22 n/m2

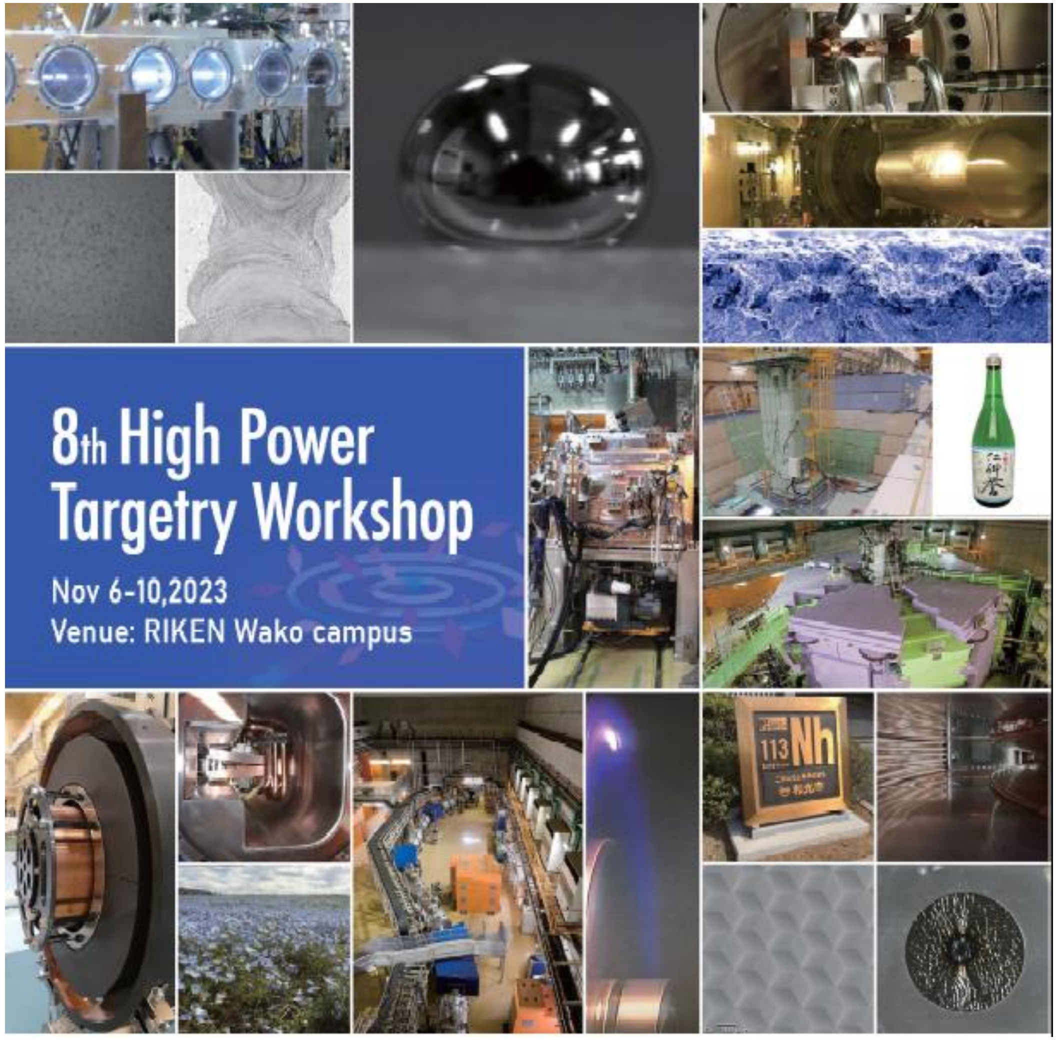
Degradation of Ic is investigated
with high field up to 15T

M. Iio, M. Yoshida, T. Nakamoto, T. Ogitsu, M. Sugano, K. Suzuki, and A. Idesaki, “Investigation of Irradiation Effect on REBCO Coated Conductors for Future Radiation-Resistant Magnet Applications,”IEEE Trans. Appl. Supercond., vol. 20, no. 6, Sep. 2022, Art. no. 6601905.

8th High Power Targetry Workshop

- RIKEN, Nishina Center for Accelerator-based Science, Wako, Saitama, Japan
- hosted by RIKEN and J-PARC
- Nov. 6th to Nov. 10th, 2023.
- Labo tour at RIKEN, and Excursion in Oedo
- https://indico2.riken.jp/event/3102/

1. R&D to support concepts
2. Radiation damage in target material and related simulations
3. Post-irradiation examination
4. Target design, analysis, and validation of concepts
5. Target facility challenges
6. Construction, fabrication, inspection, quality assurance
7. Operation of targets and beam dumps
8. Multipurpose use of targets and beam dumps



Important dates:
2023/06/10 - 08/10 Abstract submission

We are looking forward to seeing you in Japan.

J-PARC tour is under discussion.

Summary

1. J-PARC participated in RaDIATE collaboration in December 2017
   - BLIP high energy proton irradiation at BNL
   - Post Irradiation examination at PNNL
   - Thermal shock experiment at HiRadMatCERN
   - DPA cross section measurement at FNAL
   - Ion irradiation at HIT, Tokyo University
   - Development of novel materials
2. The activities were reviewed by an internal committee in Nov. 2022. Now they are promoted as a J-PARC wide mission led by the director of J PARC Center.
   - Signing of a new arrangement with LANL regarding carbon stripper foils
   - Irradiation tests on Superconducting Magnet Materials
3. Thanks to Nick Simos for his support.
4. We are waiting for you in High Power Targetry Workshop at RIKEN

Thanks for your attention.