R a D I A T E

Radiation Damage In Accelerator Target Environments

RaDIATE activities at J-PARC

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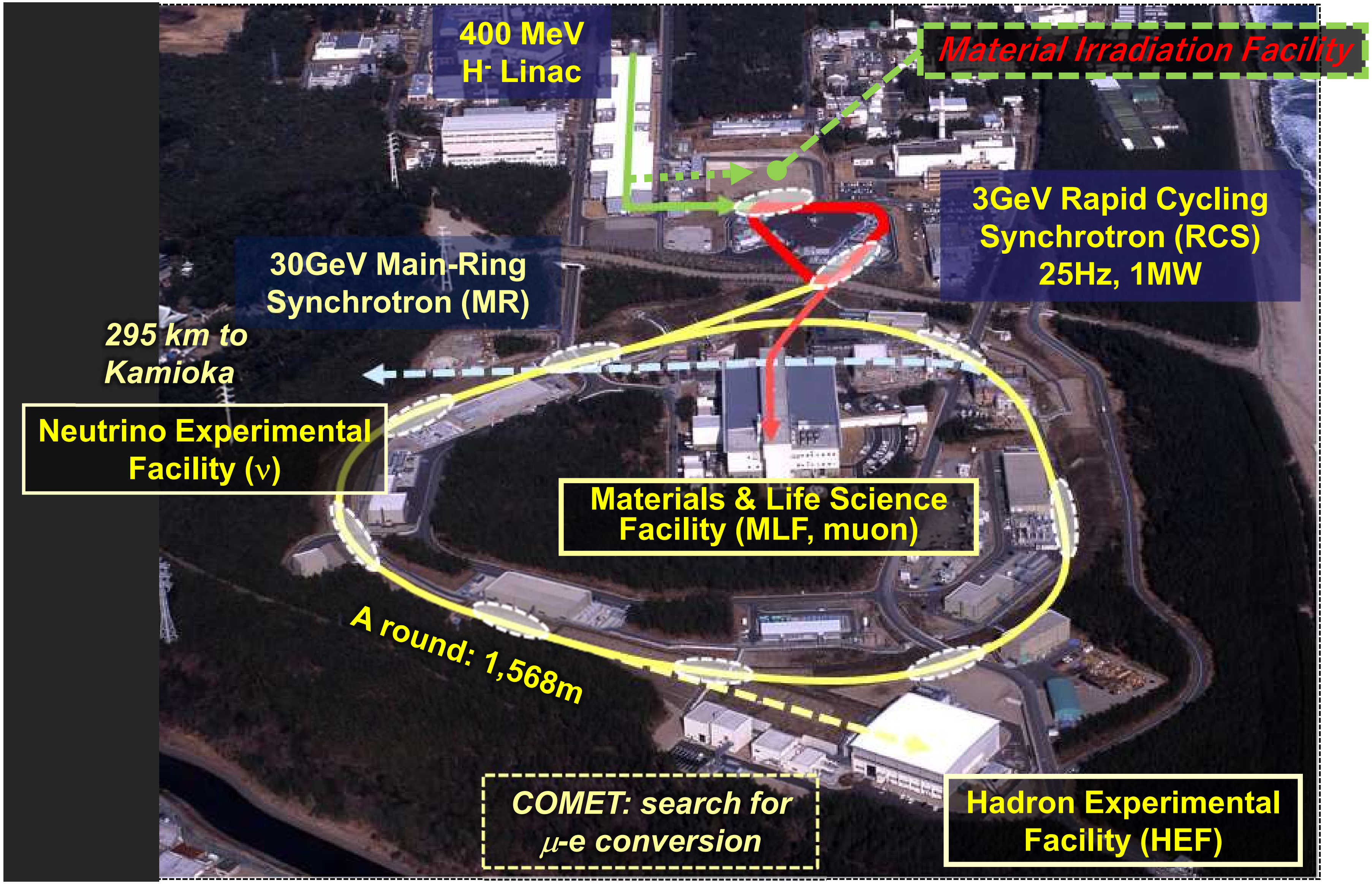
R a D I A T E Collaboration

Radiation Damage In Accelerator Target Environments

Japan Proton Accelerator Research Complex (J-PARC)



Fast Extraction(FX): 500kW → 1.3MW

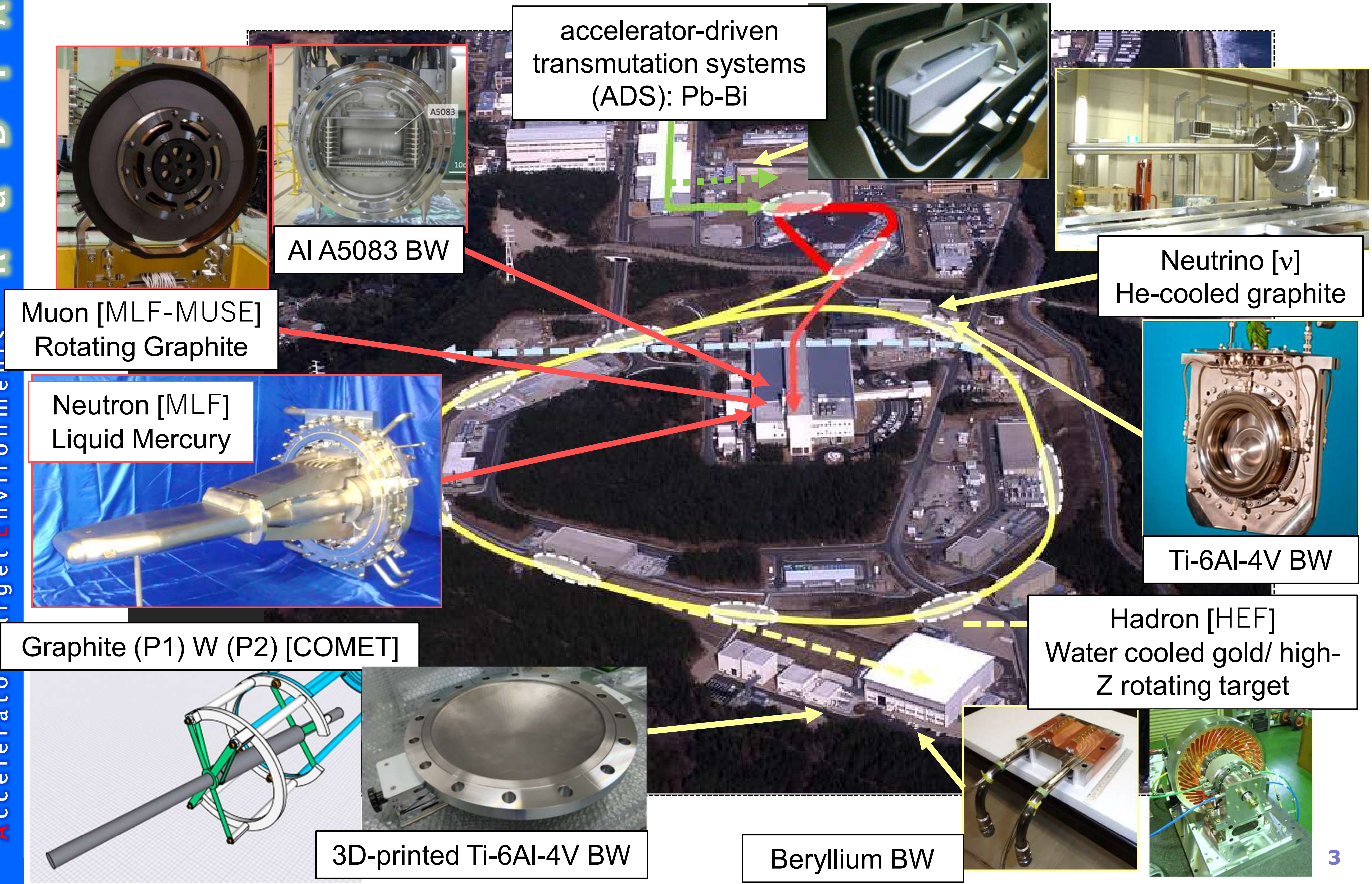
Slow Extraction(SX): 65 kW→ 100 kW (150 kW)

2

RaDIATE

Radiation Damage In Accelerator Target Environments

Targets and Beam windows at J-PARC



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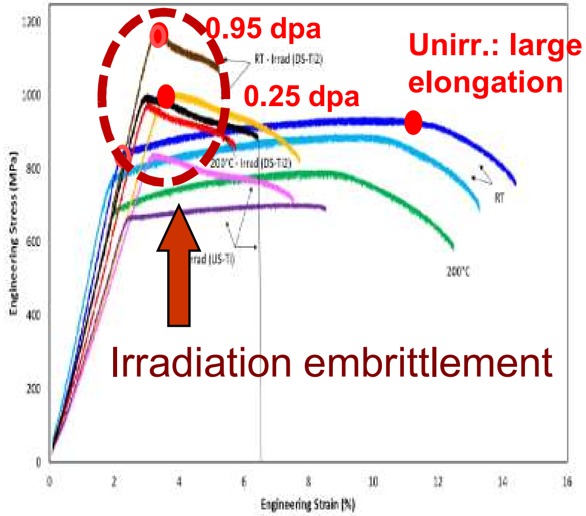
RaDIATE

Radiation Damage In Accelerator Target Environments

Research Scope

- Study **radiation damage effects** in targets & beam windows, which limits major accelerator facilities in beam power
  - Accurate lifetime prediction of target/window
  - Develop new materials & components to extend the life

T. Ishida et al., Tensile tests of Ti-6Al-4V Gr.23 A



Resent activities

- Focus upon **critical materials at J-PARC/FNAL neutrino projects** to realize high-power (+1.2MW ~ 2.4MW) operation for CPV observation
  - Titanium alloys (Ti): primary beam window (T2HK) / target containment window (T2HK/LBNF)
  - Beryllium (Be): primary window/decay pipe window (LBNF)
- Novel materials under development for, μ-e conversion, neutrino, SNS… experiments
  - NITE SiC-SiC composite, SiC coated graphite: ν, μ target
  - Ductile tungsten TFGR-W: μ-e, anti-proton target
- DPA (displacement per atom) cross section measurement,

Radiation damage effect of Ti-6Al-4V ?

Alternative Alloys ?

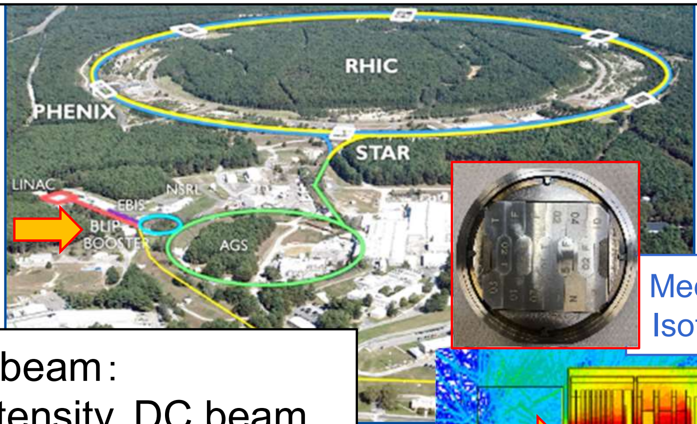
RaDIATE

Radiation Damage In Accelerator Target Environments

Research Method

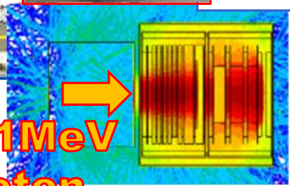
under RaDIATE collaboration

Brookhaven Linac Isotope Producer (BLIP)



Medical Isotope

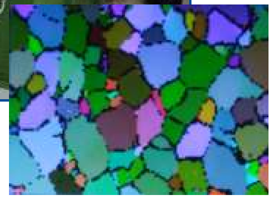
Proton beam:
High intensity, DC beam



181MeV Proton

Brookhaven National Laboratory

Post-Irradiation Examination (PIE)



Pacific Northwest NATIONAL LABORATORY

HiRadMat
High-Radiation to Materials

HiRadMat @CERN: Thermal shock experiment
- Single-shot thermal shock response and limits
- Combination of irradiation and thermal shock

- **High-intensity proton irradiation experiment at BNL-BLIP facility,**
  1st irradiation round completed in 2017-18
- **Post-Irradiation Examination (PIE) at Pacific Northwest National Laboratory (PNNL)**
- **Thermal shock experiment at CERN-HiRadMat facility**
  HRMT-43, BeGrid2 experiment, 2018
  PIE at PNNL in 2022
  HRMT-60, in October, 2022

RaDIATE

Radiation Damage In Accelerator Target Environments

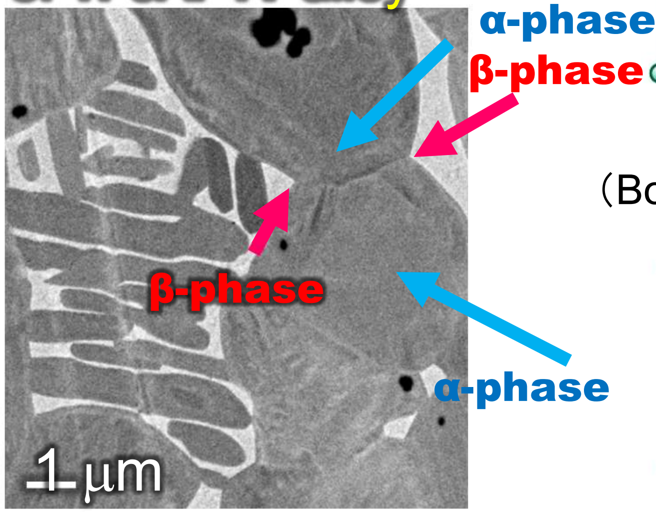
History of RaDIATE collaboration

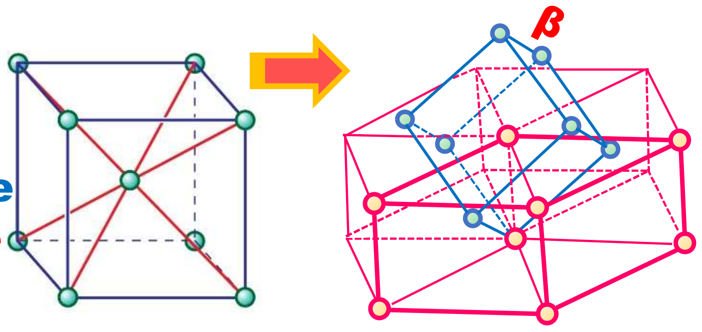
	2016	2017	2018	2019	2020	2021	2022	2023
BNL		BLIP					BNL-XRD	
PNNL				PIE			PIE	
CERN HiRadMat US-JP	US-JP start		HRMT43	cooling	transport		HRMT60	cooling
DPA meas.							FNAL	CERN
HIT irradiation				Ti alloy, TFGR W, and SS316L				w/ FNAL
CERN HiRadMat CERN-KEK	NITE SiC/SiC TFGR W	HRMT35 HRMT48	PIE	PIE	Collaboration for antiproton target			

Radiation Damage Studies on Ti-6Al-4V by BLIP specimens

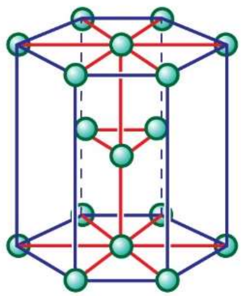
- **Ti alloys as next-generation beam window materials:**
  - Maintain enough strength & ductility
  - a few displacement-per-atom (dpa), an operational temperature of 300°C
- **The conventional two α+β phase Ti-64 alloy loses its ductility after only about 0.1 dpa**
  - the radiation-induced ω phase in the β matrices,
  - hardening caused by dislocation loops in the α matrices

Electron Microscopy of Ti-6Al-4V alloy



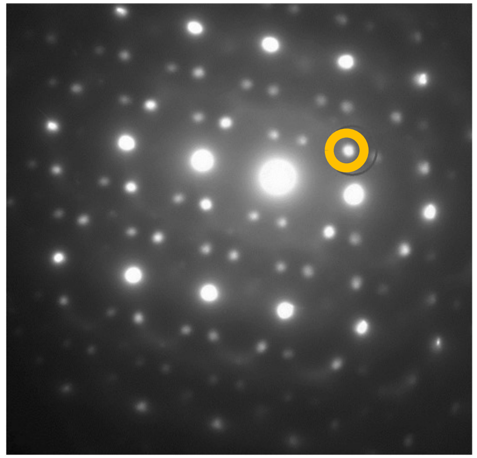


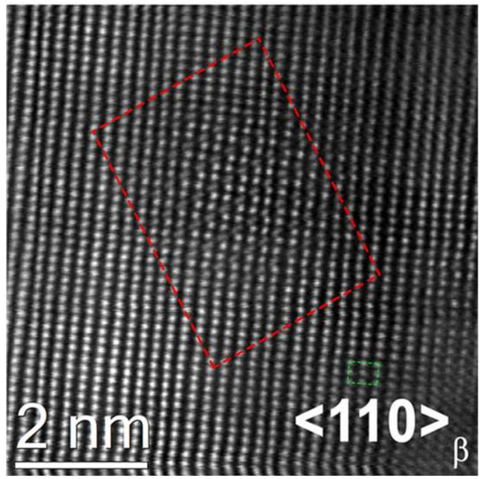
(Body Center Cubic) (Hexagonal)



(Hexagonal Close Packed)

Radiation-Induced ω-phase precipitation

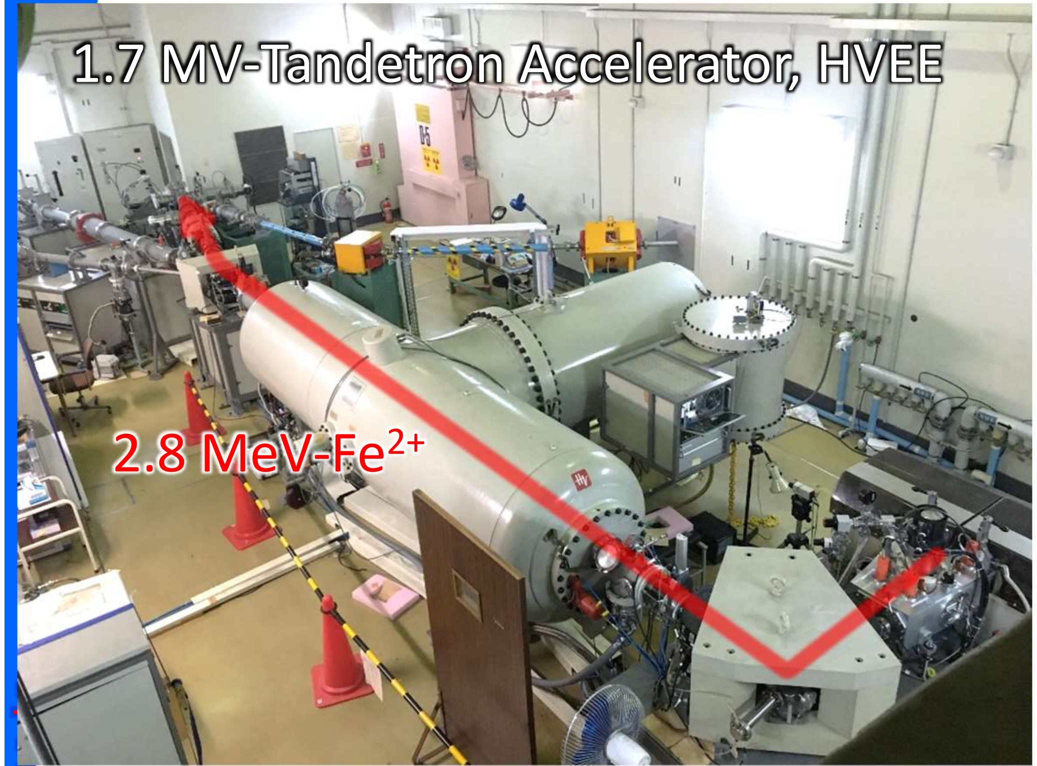




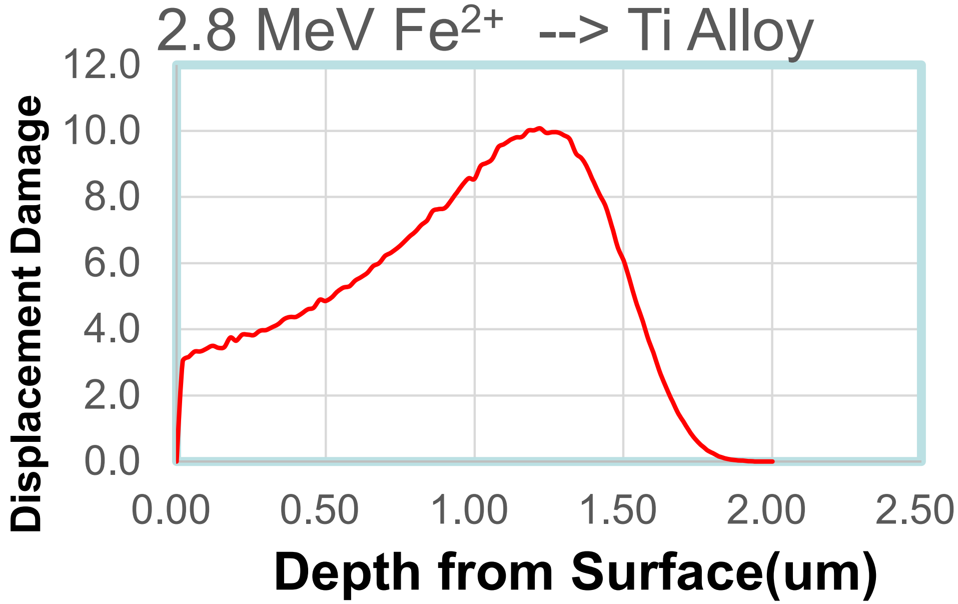
Atomic column imaging shows several omega phase zones

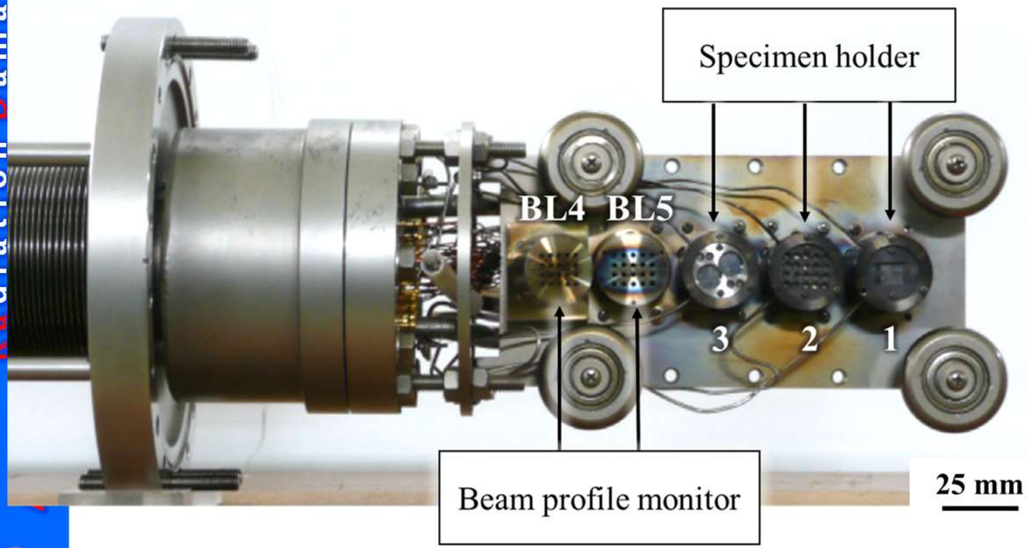
Ion irradiation at HIT facility

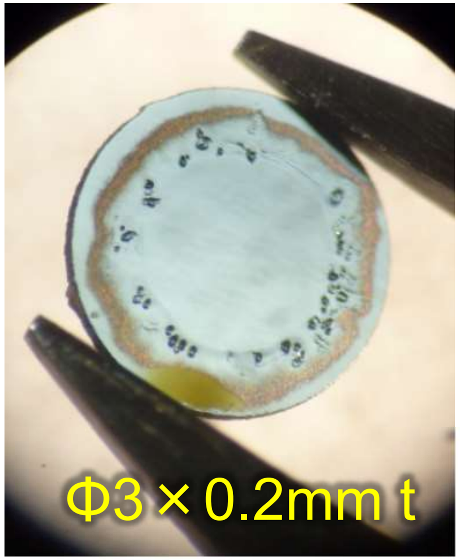
HIT: High Fluence Irradiation Facility of The Univ. of Tokyo



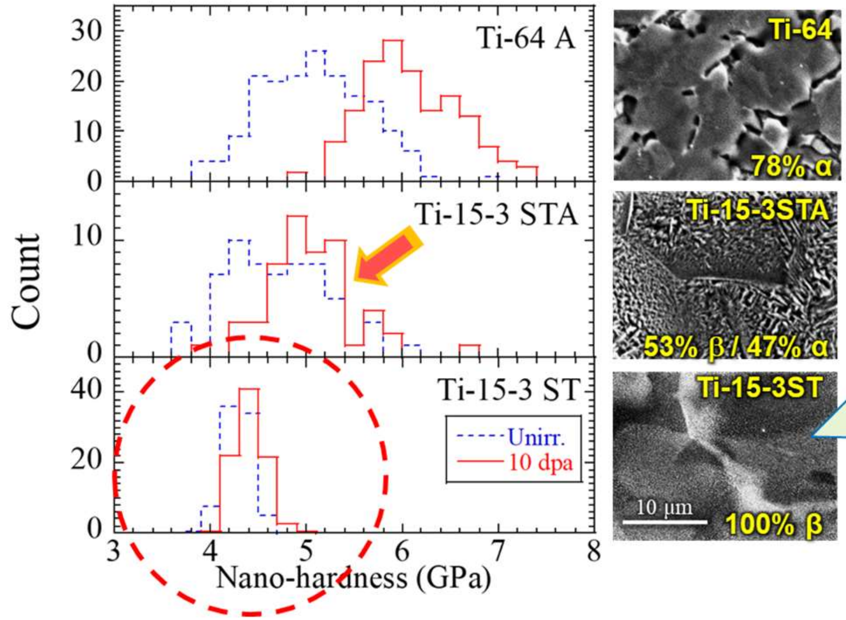
$\alpha+\beta$ 64Ti and **metastable-β 15-3Ti** were irradiated to 1, 5, and **10 DPA**

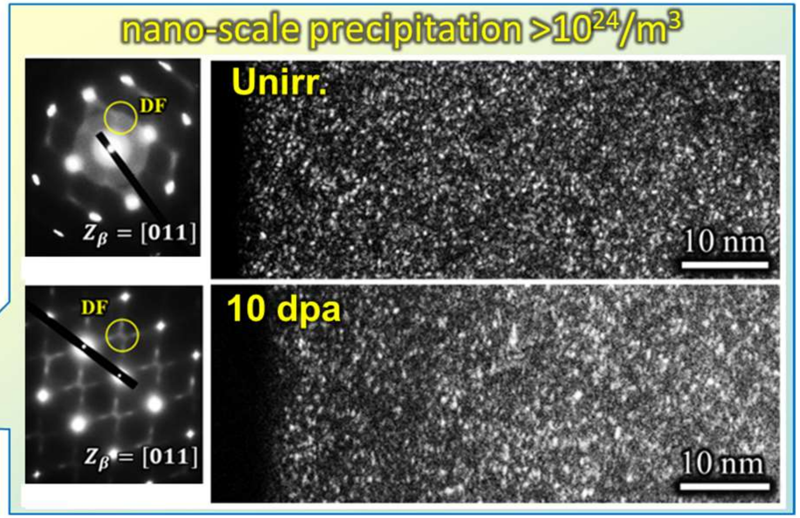






Study on Ti-15-3 alloy by ion irradiation at HIT facility





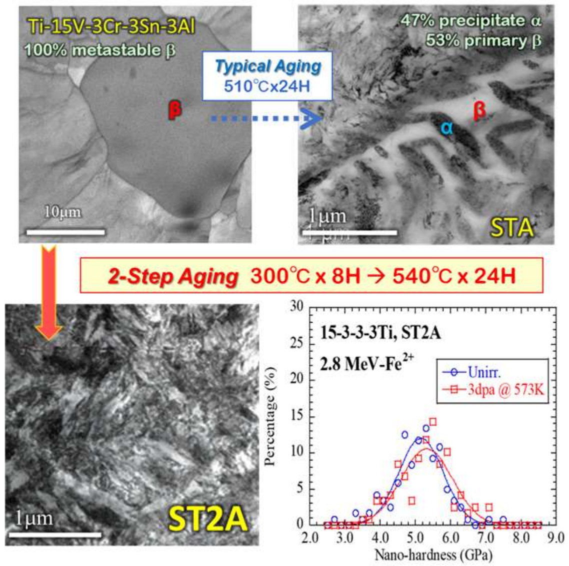
Effective sink site

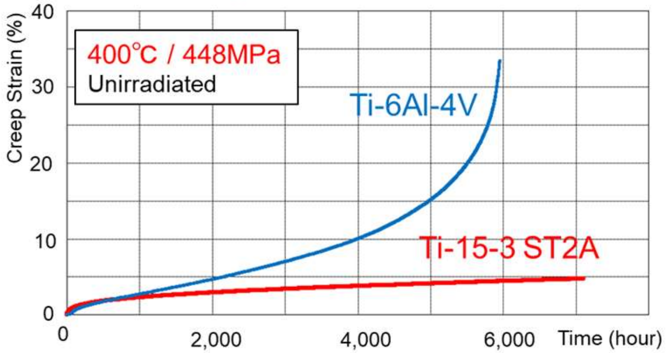
- **The single metastable β phase Ti-15-3 alloy exhibits high radiation damage tolerance, that does not undergo irradiation hardening up to 10 dpa at room temperature**

Ti-15-3 is typically aged at ~500°C for high temp. usage.

Two-step aging treatment from low temperature to high temperature (ST2A)

- α-phase precipitation to become very fine
- Preserving irradiation resistance at 300^{o}C



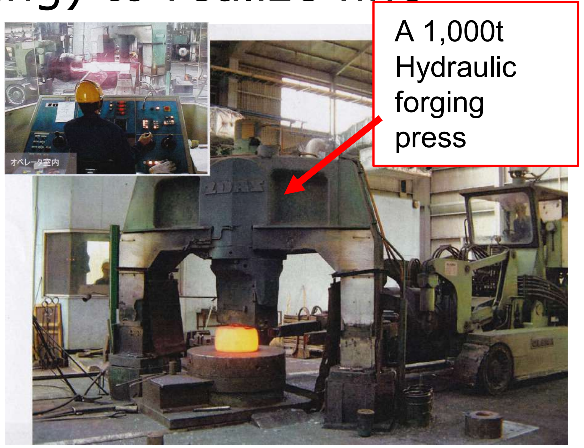


Confirmation of creep resistance

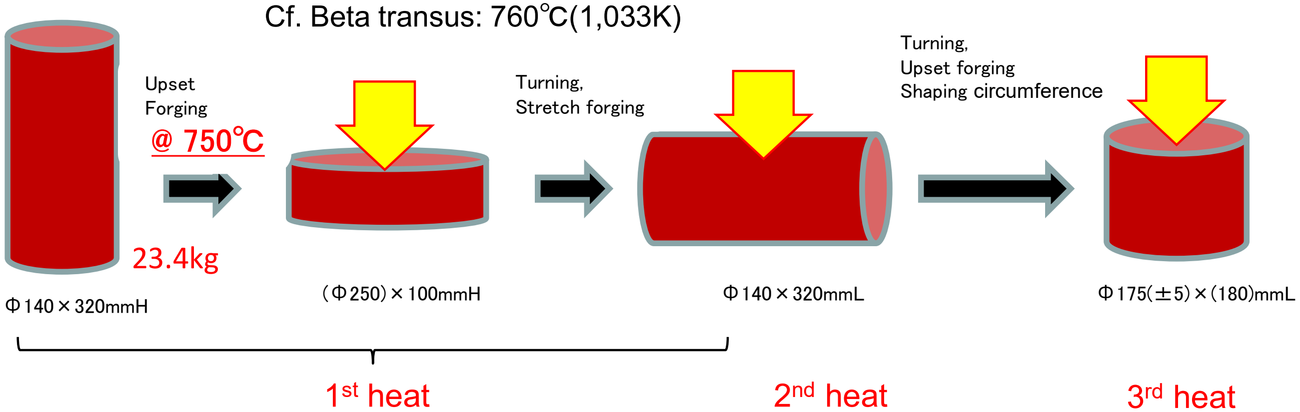
Ti-15-3 ST2A can be used at higher temperatures than Ti-64

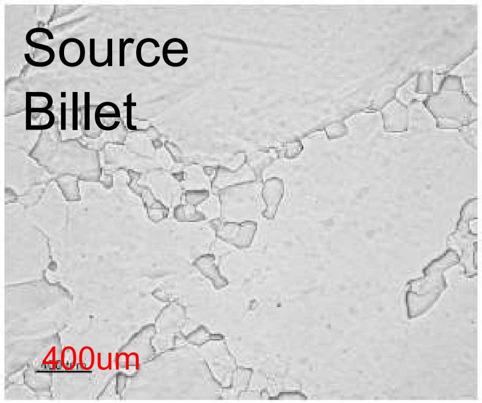
Beam window manufacturing

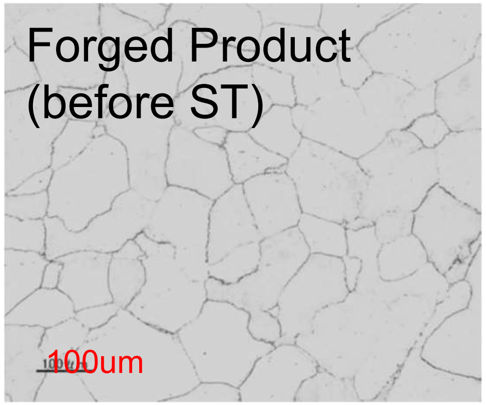
- In the market, Ti-15-3 alloy is only available in strip form
- To manufacture T2K beam window prototype
  - Purchase (intermediate) billet material (140Φ×660L)
  - Apply thermo-mechanical processing (upset forging) to realize fine-equiaxed microstructure
  - Machining to beam window shape
  - Apply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



Cf. Beta transus: 760℃(1,033K)



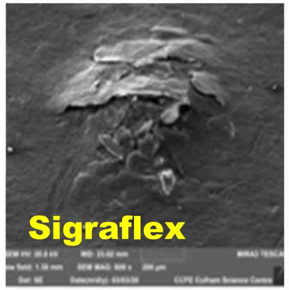




1st Ti-15-3 beam window prototype manufactured successfully !

CERN HiRadMat under US-JP collab.

Iridium



- Beam energy: 440GeV, size: σ_r = 0.25 ~ 4 mm (rms)
- 1.2 x 10^{11} / b x (1 ~ 288) = 3.46 x 10^{13} ppp in 7.95us (max)

Pre-irradiated specimens

ARRAY 1	Irradiated specimen box											
	A1.1	A1.2	A1.3	A1.4	A1.5	A1.6	A1.7	A1.8	A1.9	A1.10	A1.11	A1.12
288b, 1.2e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite (NT-02)	POCO ZXF-5Q graphite (NT-02)	POCO ZXF-5Q graphite (NT-02)	IG-430 graphite (BLIP)	IG-430 graphite (BLIP)	IG-430 graphite (BLIP)	Mo-coated CfC	Mo-coated CfC	Mo-coated MoGr	Mo-coated MoGr	Sigraflex flexible graphite	Sigraflex flexible graphite

ARRAY 1	Non-irradiated specimen box																		Slug
	A1.13	A1.14	A1.15	A1.16	A1.17	A1.18	A1.19	A1.20	A1.21	A1.22	A1.23	A1.24	A1.25	A1.26	A1.27	A1.28	A1.29	A1.30	A1s
288b, 1.2e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite	POCO ZXF-5Q graphite	IG-430 graphite	IG-430 graphite	Mo-coated CfC	Mo-coated CfC	Mo-coated MoGr	Mo-coated MoGr	Sigraflex flexible graphite	Sigraflex flexible graphite	ZrO	ZrO	ZrO2-SiO2	ZrO2-SiO2	WO3	WO3	ZrO (higher density)	ZrO (higher density)	Beryllium S-200-FH

ARRAY 2	Irradiated specimen box											
	A2.1	A2.2	A2.3	A2.4	A2.5	A2.6	A2.7	A2.8	A2.9	A2.10	A2.11	A2.12
216b, 1.2e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite (NT-02)	POCO ZXF-5Q graphite (NT-02)	POCO ZXF-5Q graphite (NT-02)	IG-430 graphite (BLIP)	IG-430 graphite (BLIP)	IG-430 graphite (BLIP)	Mo-coated CfC	Mo-coated CfC	Mo-coated MoGr	Mo-coated MoGr	Sigraflex flexible graphite	Sigraflex flexible graphite

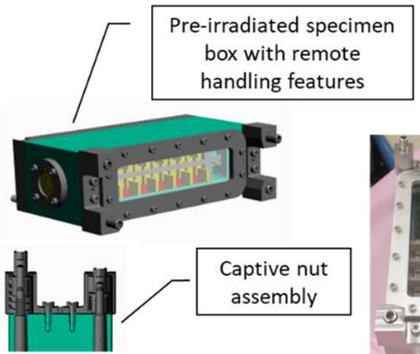
ARRAY 2	Non-irradiated specimen box																		Slug
	A2.13	A2.14	A2.15	A2.16	A2.17	A2.18	A2.19	A2.20	A2.21	A2.22	A2.23	A2.24	A2.25	A2.26	A2.27	A2.28	A2.29	A2.30	A2s
216b, 1.2e11 ppb, σ: 0.25 mm	POCO ZXF-5Q graphite	POCO ZXF-5Q graphite	IG-430 graphite	IG-430 graphite	Mo-coated CfC	Mo-coated CfC	Mo-coated MoGr	Mo-coated MoGr	Sigraflex flexible graphite	Sigraflex flexible graphite	ZrO	ZrO	ZrO2-SiO2	ZrO2-SiO2	WO3	WO3	ZrO (higher density)	ZrO (higher density)	Beryllium S-200-FH

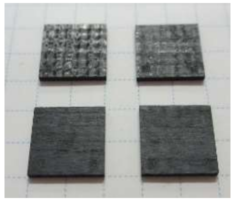
ARRAY 3	Irradiated specimen box											
	A3.1	A3.2	A3.3	A3.4	A3.5	A3.6	A3.7	A3.8	A3.9	A3.10	A3.11	A3.12
72b, 1.3e11 ppb, σ: 0.25 mm	Ti 15-3 STA	Ti-6Al-4V A (Gr23)	Ti-6Al-4V STA (Gr23)	Ti-6Al-4V UFG (Gr5)	Ti (Gr2)	Ti-5Al-2.5Sn (Gr6)	Ti 15-3 STA	Ti-6Al-4V A (Gr23)	Ti-6Al-4V STA (Gr23)	Ti-6Al-4V UFG (Gr5)	Ti (Gr2)	Ti-5Al-2.5Sn (Gr6)

ARRAY 3	Non-irradiated specimen box																		Slug
	A3.13	A3.14	A3.15	A3.16	A3.17	A3.18	A3.19	A3.20	A3.21	A3.22	A3.23	A3.24	A3.25	A3.26	A3.27	A3.28	A3.29	A3.30	A3s
72b, 1.3e11 ppb, σ: 0.25 mm	Ti-6Al-4V 3D	Ti IMI829	Ti Timet 1100	Ti IMI834	Ti-6-2-4-6	Ti 15-3 ST	Ti 15-3 ST2A	Ti beta 21s	Ti-17	Ti DAT54	HEA1 - CrMnV	HEA2 - CrMnTiV	HEA3 - AlCrMnTiV	HEA4 - AlCoCrMnTiV	NITE SiC-SiC	NITE SiC-SiC	Free slot	Free slot	NITE SiC/SiC

ARRAY 4	Irradiated specimen box											
	A4.1	A4.2	A4.3	A4.4	A4.5	A4.6	A4.7	A4.8	A4.9	A4.10	A4.11	A4.12
24b, 1.2e11 ppb, σ: 0.25 mm	Ti 15-3 STA	Ti-6Al-4V A (Gr23)	Ti-6Al-4V STA (Gr23)	Ti-6Al-4V UFG (Gr5)	Ti (Gr2)	Ti-5Al-2.5Sn (Gr6)	Ti 15-3 STA	Ti-6Al-4V A (Gr23)	Ti-6Al-4V STA (Gr23)	Ti-6Al-4V UFG (Gr5)	Ti (Gr2)	Ti-5Al-2.5Sn (Gr6)

ARRAY 4	Non-irradiated specimen box																		Slug
	A4.13	A4.14	A4.15	A4.16	A4.17	A4.18	A4.19	A4.20	A4.21	A4.22	A4.23	A4.24	A4.25	A4.26	A4.27	A4.28	A4.29	A4.30	A4s
24b, 1.2e11 ppb, σ: 0.25 mm	Ti-6Al-4V 3D	Ti IMI829	Ti Timet 1100	Ti IMI834	Ti-6-2-4-6	Ti 15-3 ST	Ti 15-3 ST2A	Ti beta 21s	Ti-17	Ti DAT54	HEA1 - CrMnV	HEA2 - CrMnTiV	HEA3 - AlCrMnTiV	HEA4 - AlCoCrMnTiV	TFGR W-1.1%TiC	TFGR W-1.1%TiC	TFGR W-3.3%TaC	Pure W	Titanium (Ti6Al4V)





NITE SiC/SiC, SiC coated graphite, TFGR W

NITE SiC/SiC

Efficient transport of Pions/Muons due to higher density

- Density:
SiC 3.2 g/cc
Graphite: 1.8 g/cc
- Developed at Muroran Institute of Technologies
- Overcome of brittleness by composite material

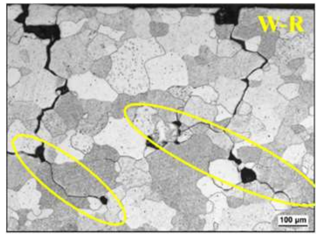
SiC coated graphite

- Improvement of oxidation resistance in graphite target
- Effect of tritium shielding in SiC coated graphite

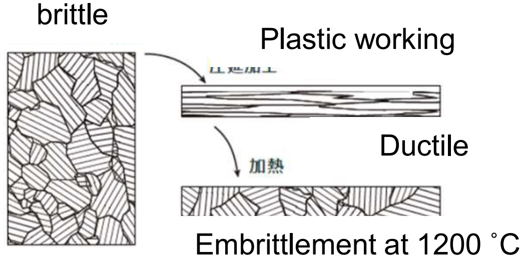
Production of tritium by proton irradiation @BNL
The release rate in temperature dependence up to 1000 ºC was measured by temperature programmed desorption @PNNL

TFGR W-TiC

- ✓ Tungsten is brittle, because grain boundary is weak.
- ✓ Brittleness is improved by heavy plastic working.

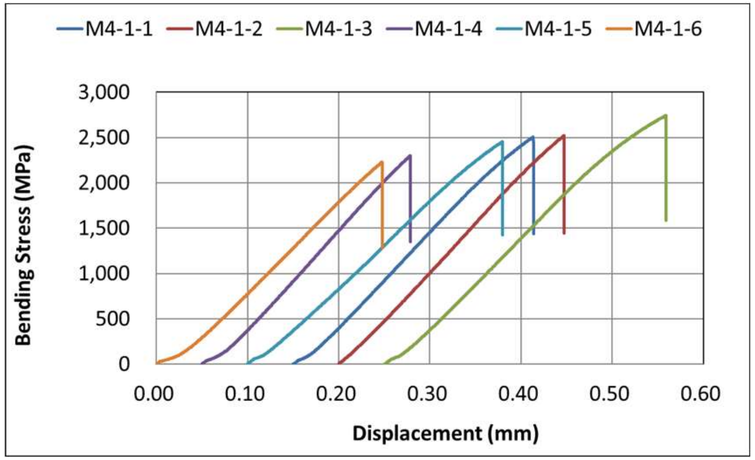


G. Pintsuk et al.



Recrystallization embrittlement at high temperature

The grain boundary of TFGR W-TiC is reinforced by TiC segregation.



TFGR W-TiC shows ductility after recrystallization.

HiRadMat under CERN-KEK collaboration

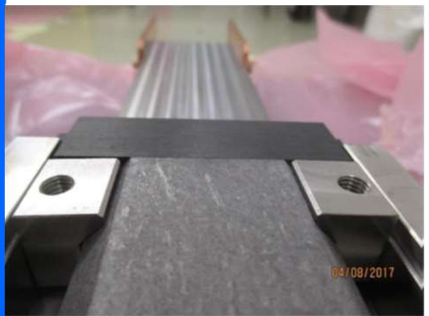
NITE SiC/SiC

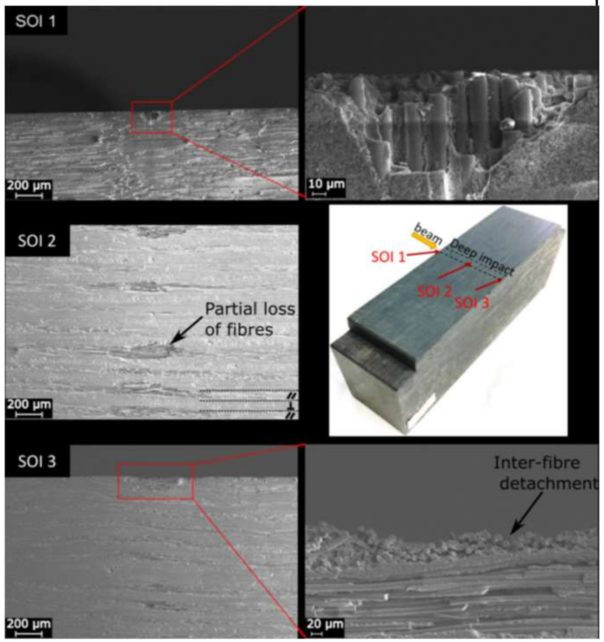
- Specimen was supplied by Muroran Institute of Technologies.
- Included in HRMT35 for Target Dump Internal, Coated low-Z absorbing material
- Different beam impact depths, beam angles
- Thermal analysis of composite material through Tsai-Wu criterion

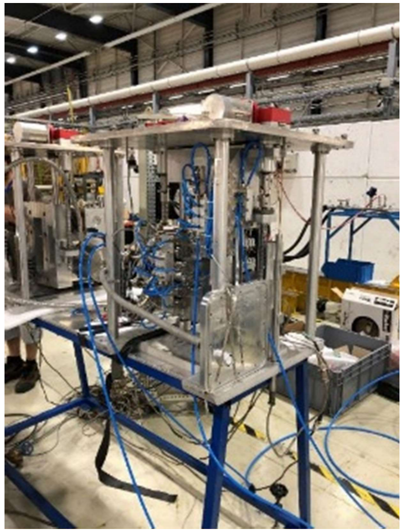
Superficial damage for all impacts and had craters at the entrance and exit faces for deep and grazing impacts, coherent with analysis.

J. Maestre et al.

POT: 3.5×10^{13}
Beam size:
0.3 mm × 0.3 mm
288 bunches, pulse duration 7.2 μs
dT=2100℃

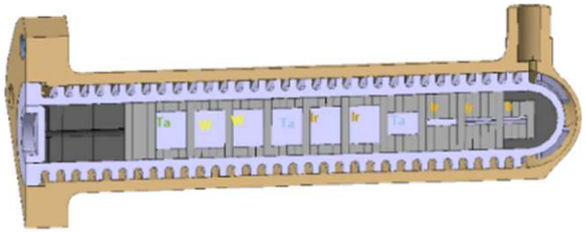




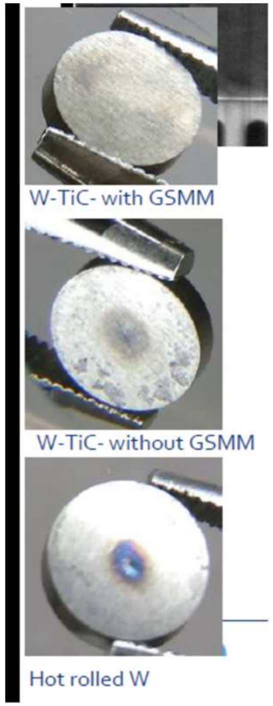


TFGR W-TiC

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



POT: $3.2\times10^{13}\sim1.12\times10^{14}$
Beam size: 1mm × 1 mm
50 pulses, pulse duration 25 ns
dT=700℃,
Tensile stress: 1 GPa

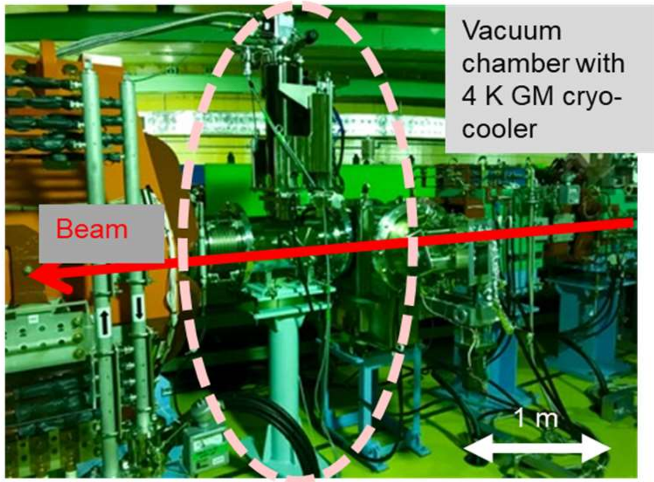


C. T. Martin et al.

dpa measurement

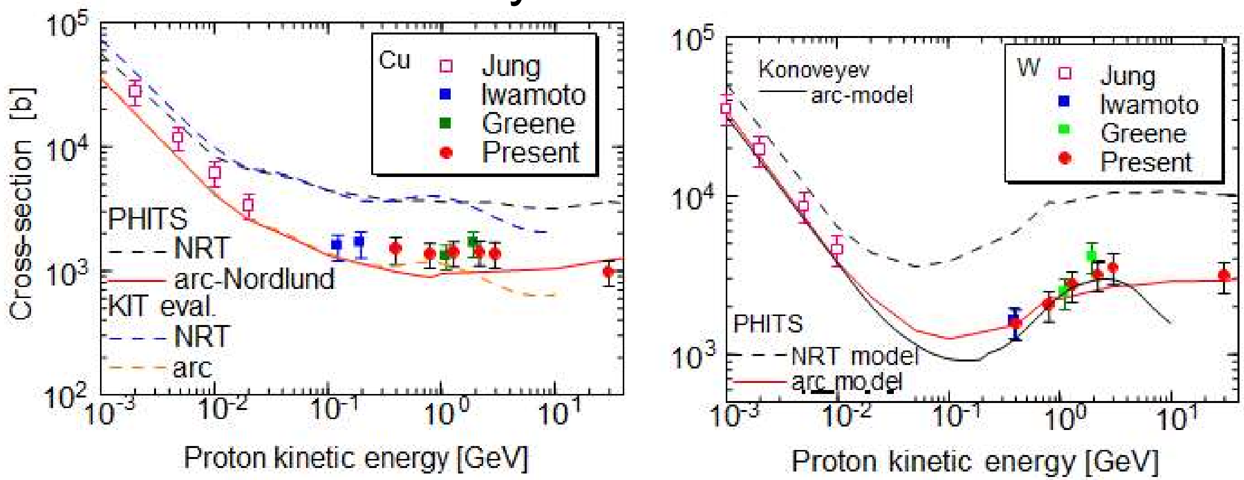
- Displacement per atom (dpa) : given multiplication of the particle flux and displacement cross section (dpa X-sec)
- No experimental dpa X-sec data above 10 MeV energy region, the measurements were conducted at J-PARC.
- dpa X-sec can be obtained by the change of electrical resistance under cryo-temperature irradiation.
- Awarded:
  - Best paper award by atomic energy society of Japan
  - Most popular article by JNST (Journal of Nucl. Sci. and Technol.)

Vac. chamber installed at J-PARC



H. Matsuda et al., JNST 57, 1141 (2020)
M. Yoshida et al., IEEE Trans. App. SC. 32 (2022)

dpa X-sec experimental data for Ep < 30 GeV were successfully obtained at J-PARC.

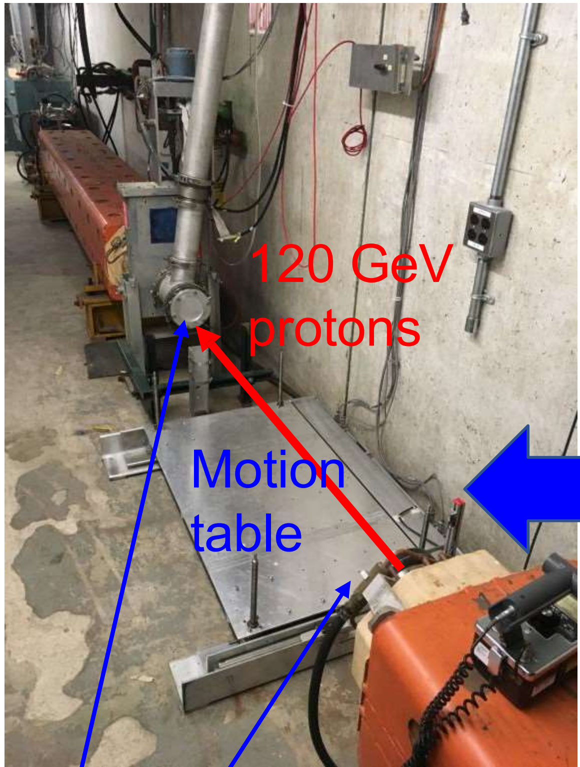


Exp. data helped revision of calc. model.

dpa measurement in the future

- To obtain the dpa X-sec for high energy region E>30 GeV, we will carry out the experiment at FNAL FTBF and CERN HiRadMat using the similar manner at J-PARC
- Budget and program were already approved.

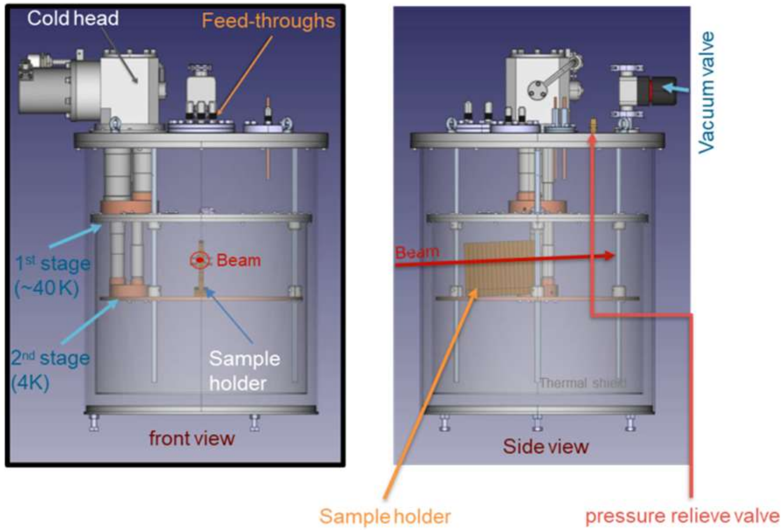
FNAL BT-FT (by Y. Iwamoto)

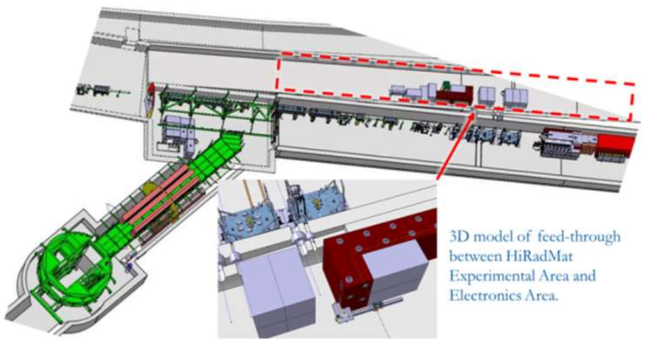


Vacuum chamber with GM cryo-cooler

Experiment will be carried out January 2023.

CERN HiRadMat (by S. Meigo)

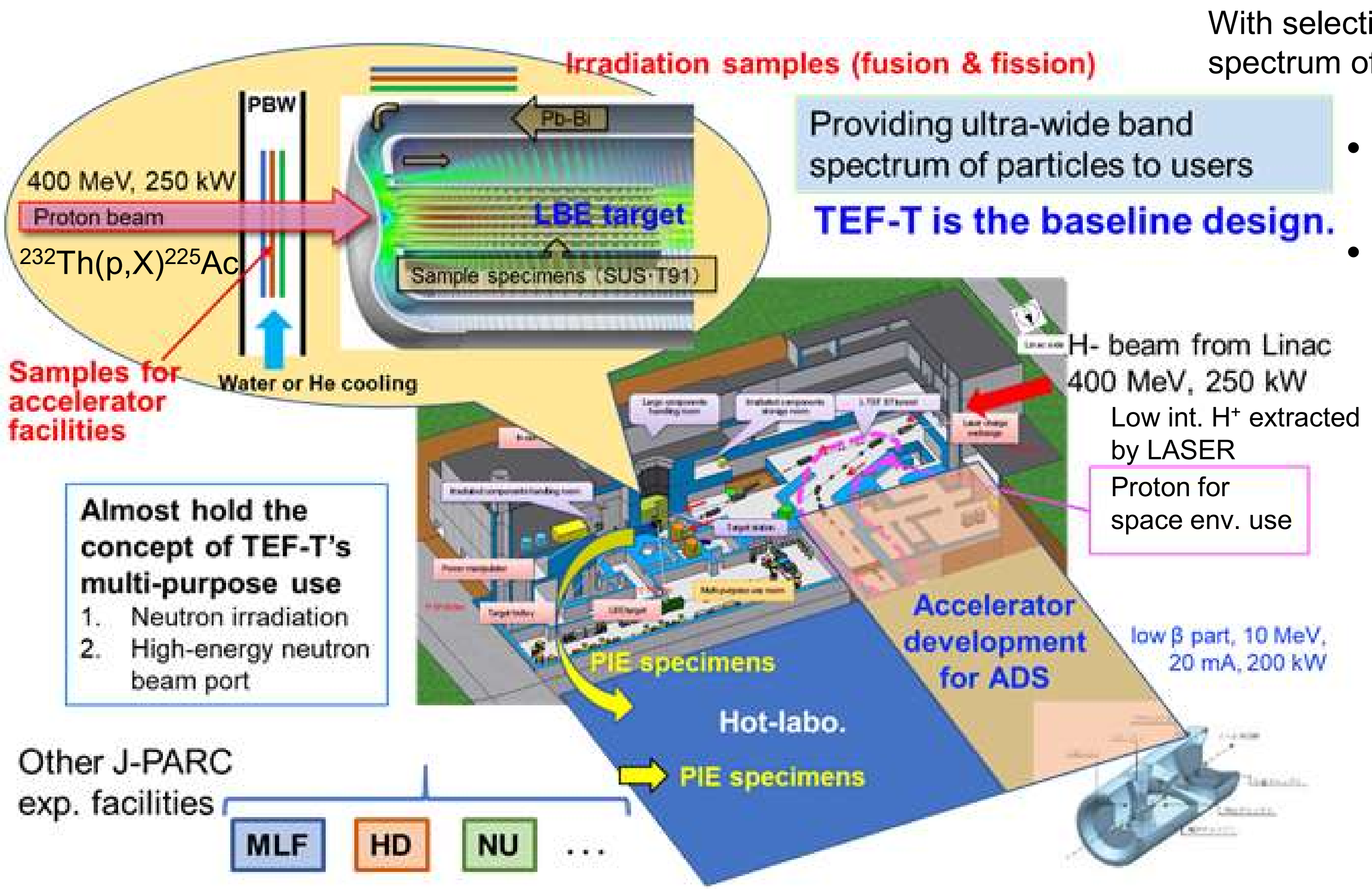




Experiment: planned on 2024

J-PARC proton beam irradiation facility

- Proton beam irradiation facility planned at J-PARC
  - H^- beam 0.4 GeV, Power >250 kW with 25 Hz of long pulse (0.5 ms)
  - Dose >20 dpa/year at the Pb-Bi (LBE) target
- User communities established for multi-purpose
  - RaDIATE users are welcome to join the community, which enhances to build of the new facility.



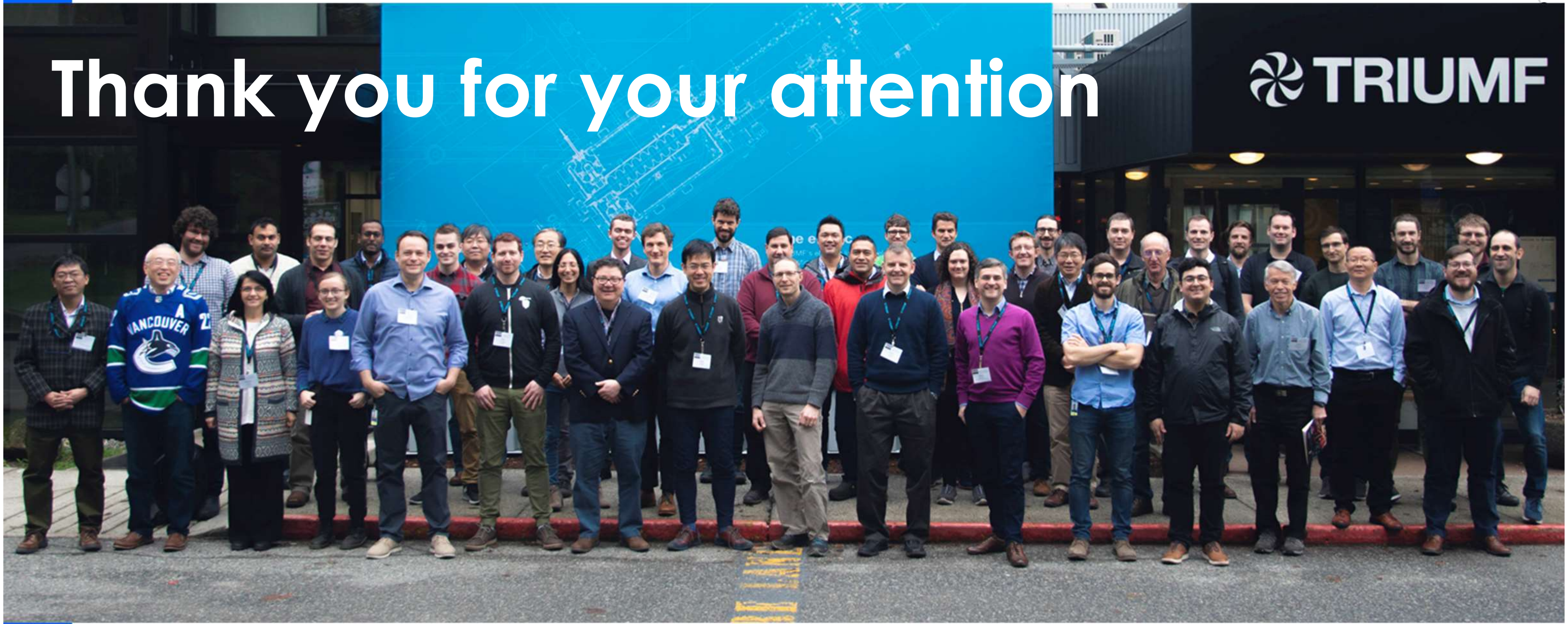
- Building Hot-labo is also planned for PIE.
- Multi-purpose use
  1. Irradiation fac.
  2. Neutron for soft error
  3. RI medicine ^{225}Ac
  4. Space env. use

ADS: accelerator driven system
TEF-T: ADS Target Test facility
(JAEA Tech 2017-3)

Summary

- J-PARC participated in RaDIATE collaboration since 2017.
- BLIP irradiation, PIE at PNL, and CERN HiRadMat irradiation is in progress.
- PIEs in Titanium alloy, NITE SiC/SiC, SiC coated graphite, and TFGR W-TiC have been conducted.
- DPA cross section measurement contributes the improvement in Monte Carlo simulation.
- A user community for J-PARC proton beam irradiation facility was established to include the request from users all over the world.

Thank you for your attention



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

List of related publications and presentations (FY2021)

- T. Ishida et al., "Investigation into Contrasting Radiation Damage Behavior between High-Strength Titanium Alloy Classifications and Micro-Structural Optimization", 20 International Conference on Fusion Reactor Materials (ICFRM20), Oct. 25-29, 2021. Online Event (Poster).
- F. Pellemoine, "RaDIATE collaboration recent results", International Particle Accelerator Conference, May 24-28, 2021. Online Event (Poster).
- T. Ishida et al., "Progress of Radiation Damage Studies on Ti Alloys as High-Intensity Proton Accelerator Beam Window Materials", the US-Japan Mini-Symposium, Apr. 21-23, 2021. Online Event (Poster). Awarded as Poster with an Honorable Mention.
- S. Bidhar et al., "Extreme beam-induced thermal shock on materials for future high intensity multi-MW accelerator components", US-Japan Mini-Symposium, Apr. 21-23, 2021. Online Event (Poster).
- S. Meigo et al., "Measurement of displacement cross-section at J-PARC, FNAL and CERN", US-Japan Mini-Symposium, Apr. 21-23, 2021. Online Event (Poster).
- K. Ammigan et al., "Advanced material studies for high intensity proton production targets and windows", invited talk at the US-Japan Mini-Symposium, Apr. 21-23, 2021. Online Event (Invited Talk).
- S. Meigo et al., "Measurement of Displacement Cross Section for Proton in the Kinetic Energy Range from 0.4 GeV to 3 GeV", JPS Conf. Proc. 33, 011050 (2021).
- E. Wakai et al., "Irradiation damages of structural materials under different irradiation environments", J. Nucl. Mat 543 (2021), 152503.
- S. Makimura et al., "Development of Toughened, Fine Grained, Recrystallized W-1.1%TiC", Materials Science Forum, Spallation Materials Technology, Vol. 1024, pp 103-109, ISSN: 1662-9752 (2021)
- K. Ammigan et al., "Recent studies of radiation damage effects in high-power accelerator target materials", Joint Experimental and Theoretical Physics seminar, Fermilab, Dec. 18, 2020. Online Event (Talk).