

ADS Material Irradiation Facility in J-PARC

(JAEA/J-PARC) Shin-ichiro Meigo

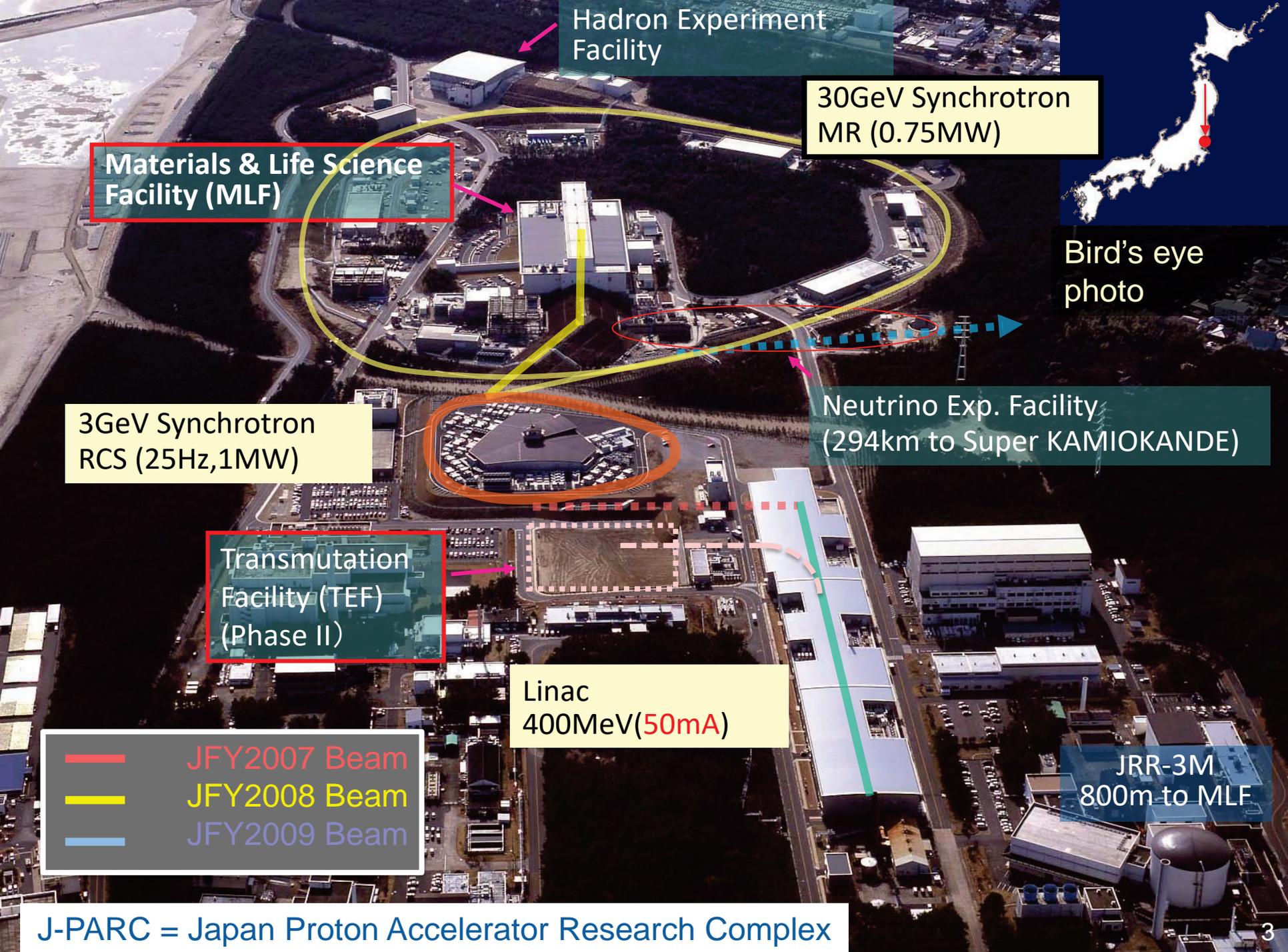
Collaborators:

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E. Wakai, K. Haga, N. Ohkubo

(KEK/J-PARC) M. Yoshida, T. Nakamoto, T. Ishida,
and S. Makimura

- Present study includes the results of “Measurement of displacement cross section at J-PARC for structural material utilized at ADS” entrusted to JAEA by MEXT

- Introduction:
 - J-PARC
 - Accelerator Driven System (ADS)
- Plan of a new facility for materials R&D for ADS
- Research activity materials at J-PARC:
 - Experiment of displacement cross-section at J-PARC
- Summary



Hadron Experiment Facility

30GeV Synchrotron MR (0.75MW)

Materials & Life Science Facility (MLF)



Bird's eye photo

3GeV Synchrotron RCS (25Hz,1MW)

Neutrino Exp. Facility (294km to Super KAMIOKANDE)

Transmutation Facility (TEF) (Phase II)

Linac 400MeV(50mA)

JRR-3M 800m to MLF

- JFY2007 Beam
- JFY2008 Beam
- JFY2009 Beam

J-PARC = Japan Proton Accelerator Research Complex

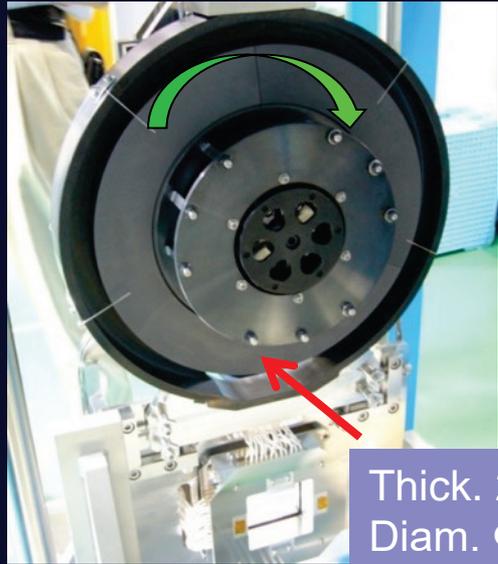
Targets in Material Life Experimental Facility (MLF)



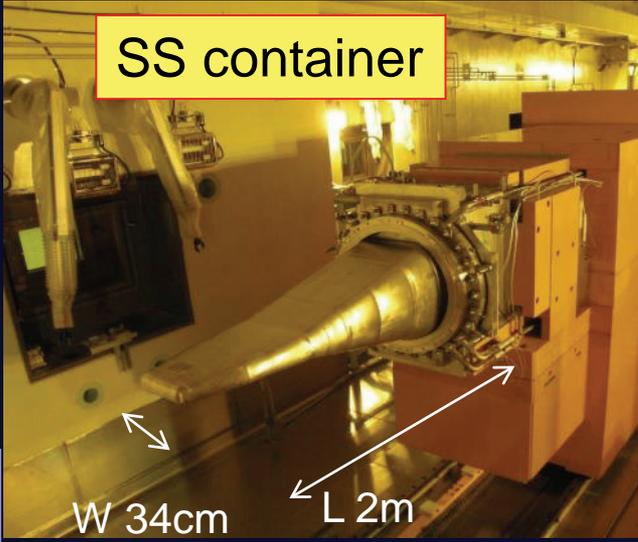
- Muon production target
 - Graphite IG430U
 - Highest μ^- intensity

- Neutron production target
 - Mercury (Hg)

Highest pulse intensity in the world

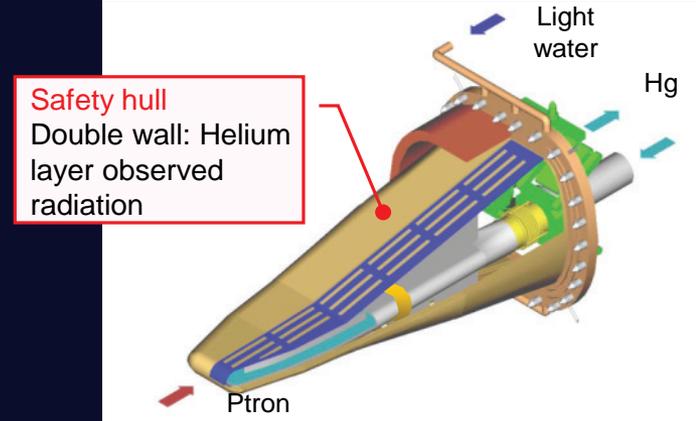
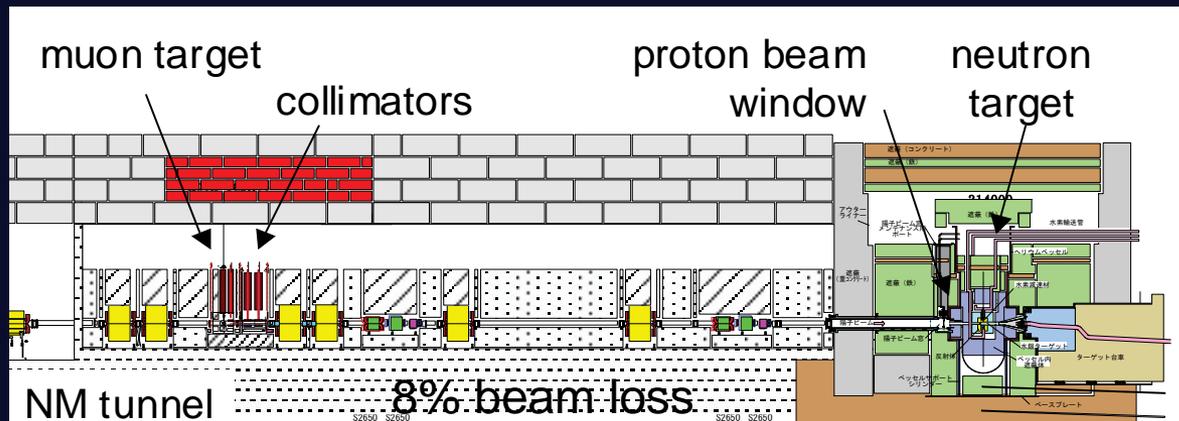
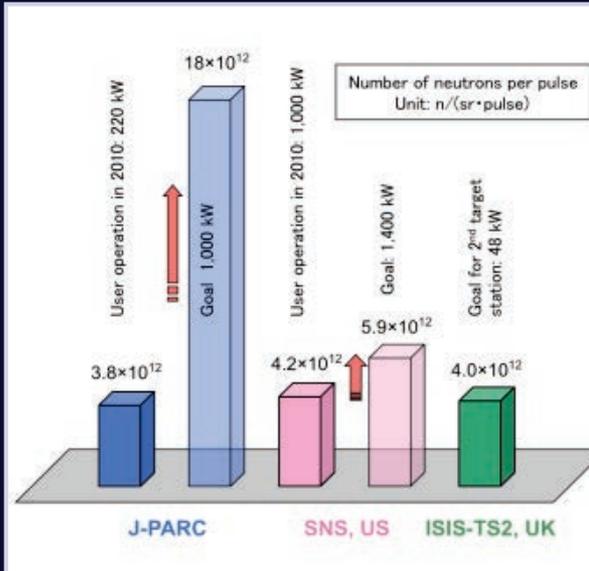


Thick. 2 cm
Diam. Φ 33cm



SS container

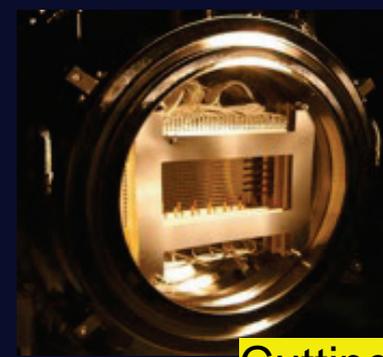
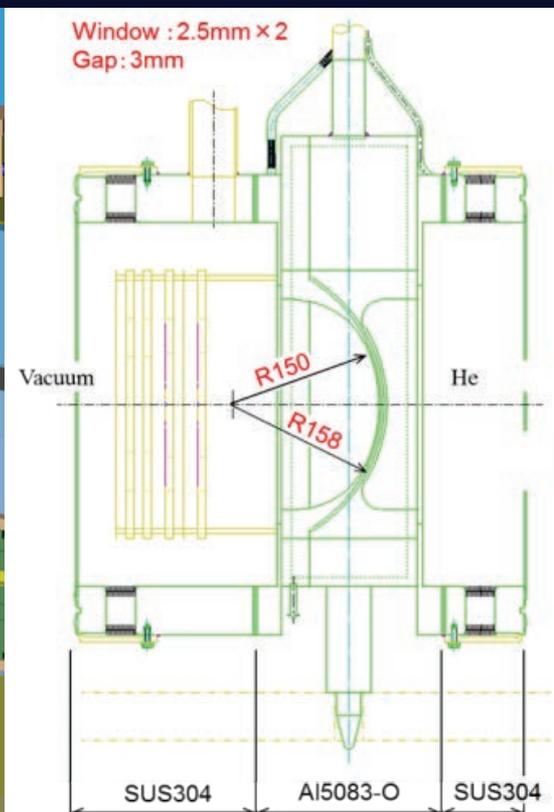
W 34cm L 2m



Proton Beam Window at MLF (A5083)

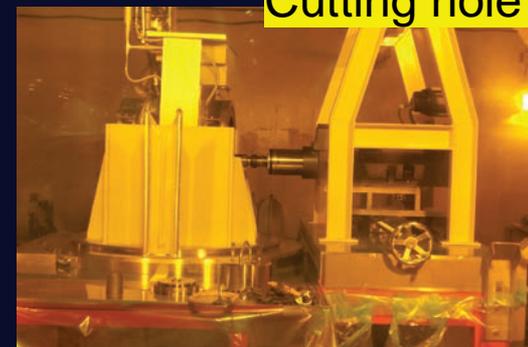
- Lifetime estimation based on Post Irradiation Examination (PIE) for safety shroud (AlMg3) at SINQ in PSI
- Due to the law related to activated materials, PIE is difficult using the present hot cell at JAEA.
- Considering difference of proton energy, to predict lifetime of the PBW with high accuracy for validation of calculation

Height: 3.8m
Weight: 10t



Front
Diam 0.6 m

Cutting hole saw



Cut out specimen waiting for PIE ₅

1 MW beam operation at MLF



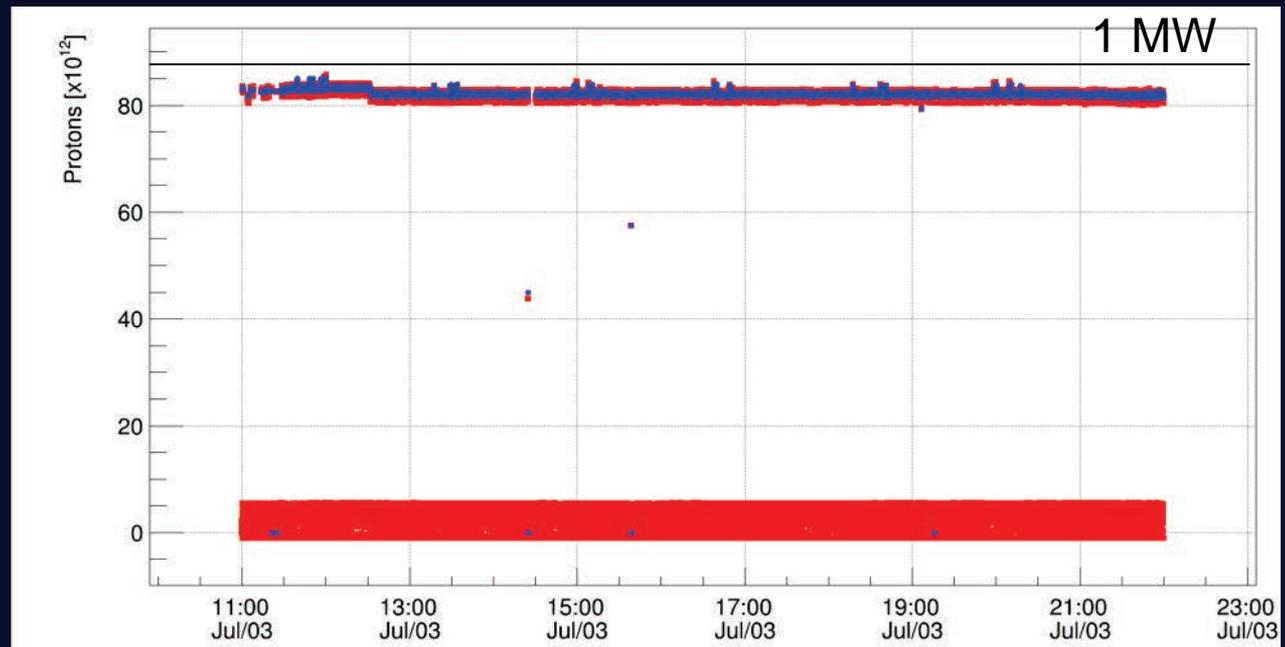
Memorial shot at 1MW for
1 h test (2018/7/3)

2019 test

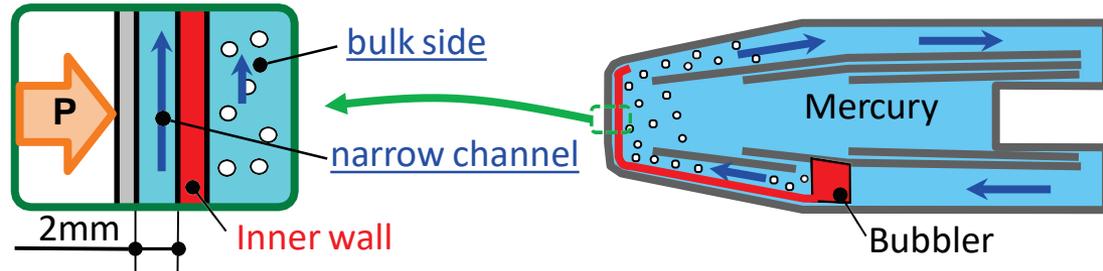
- Beam intensity trend at 1MW for 10.5 h test Availability ~ 98%

1 MW user run
for 2 days on 2020

- Found good status of target
- Insufficient of cooling water capability for RF was found.



Specimens Cut Out of Target Vessels



Bulk side of inner wall

Target #8 :
 $P_{avg} = 434 \text{ kW}$
 $E_{total} = 1812 \text{ MWh}$

Max. depth
0.286 mm

Target #9 :
 $P_{avg} = 529 \text{ kW}$
 $E_{total} = 2104 \text{ MWh}$

Max. depth
3.3mm

Influenced
by gas flow
reduction?

$\Phi: 50 \text{ mm}$
5 mm-t

Target #11 :
 $P_{avg} = 568 \text{ kW}$
 $E_{total} = 1660 \text{ MWh}$

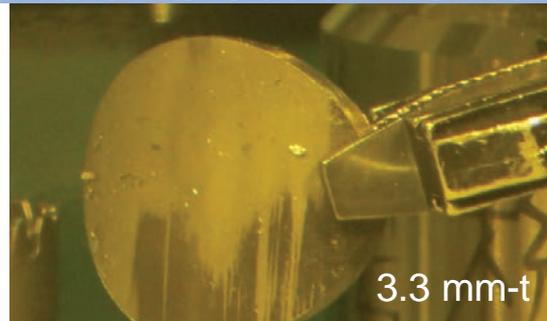
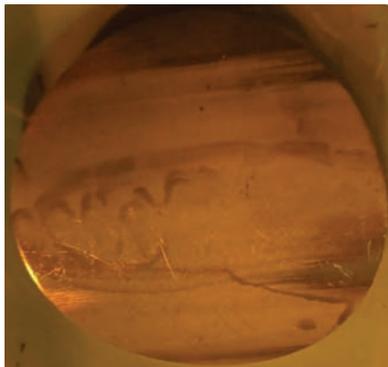
Max. 0.43 mm

0.16 mm

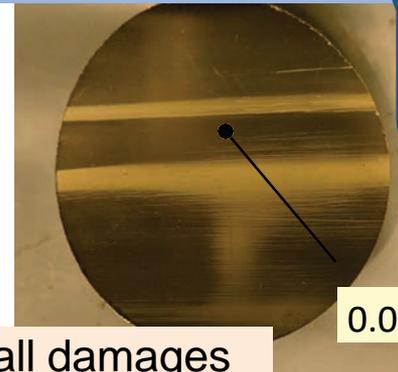
0.26 mm

Probably due to improve on helium flow of bubbler

Narrow channel side of inner wall

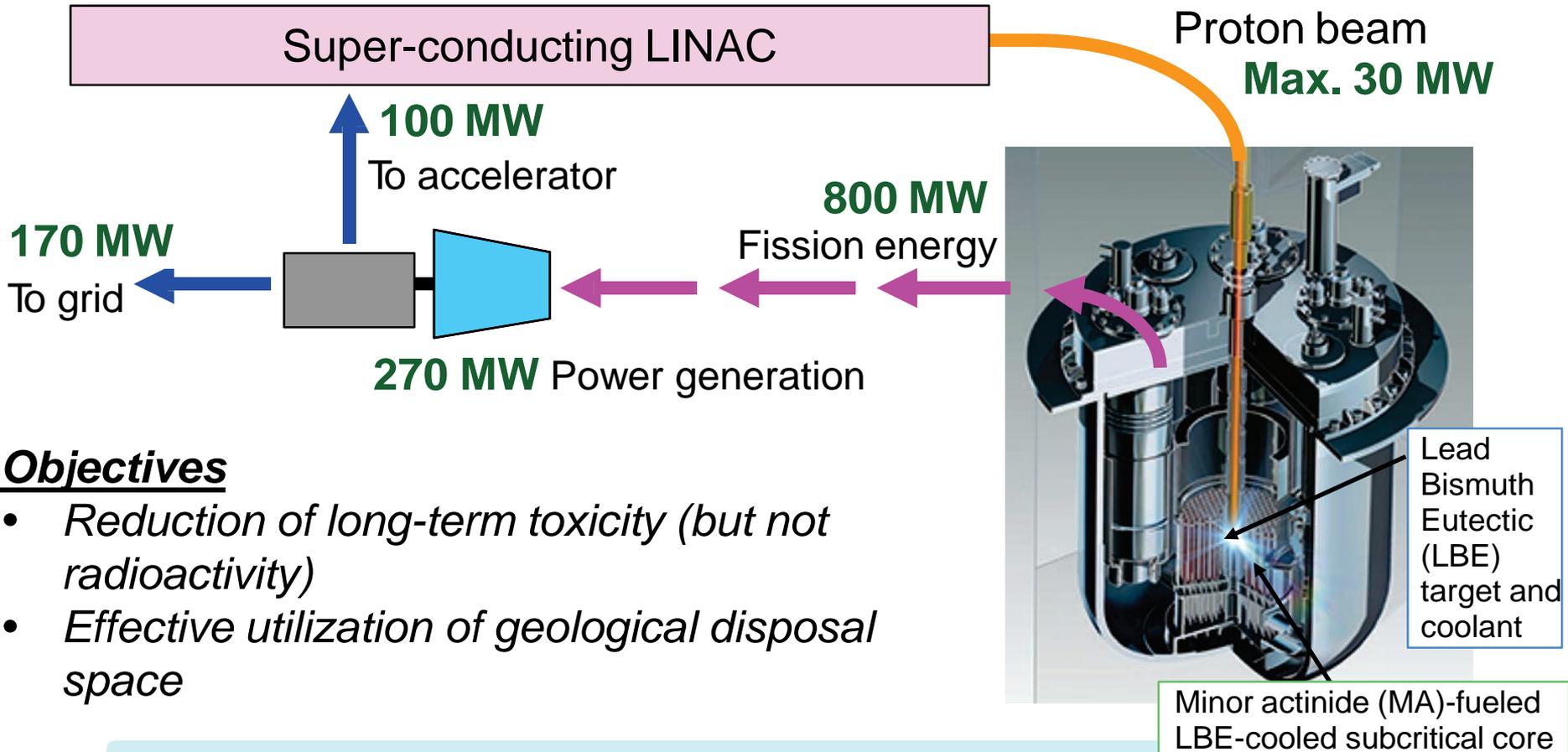


Negligibly small damages



- ¼ of damage depth estimation.
- Promising result for further power ramp-up.

Accelerator driven system (ADS)



Objectives

- *Reduction of long-term toxicity (but not radioactivity)*
- *Effective utilization of geological disposal space*

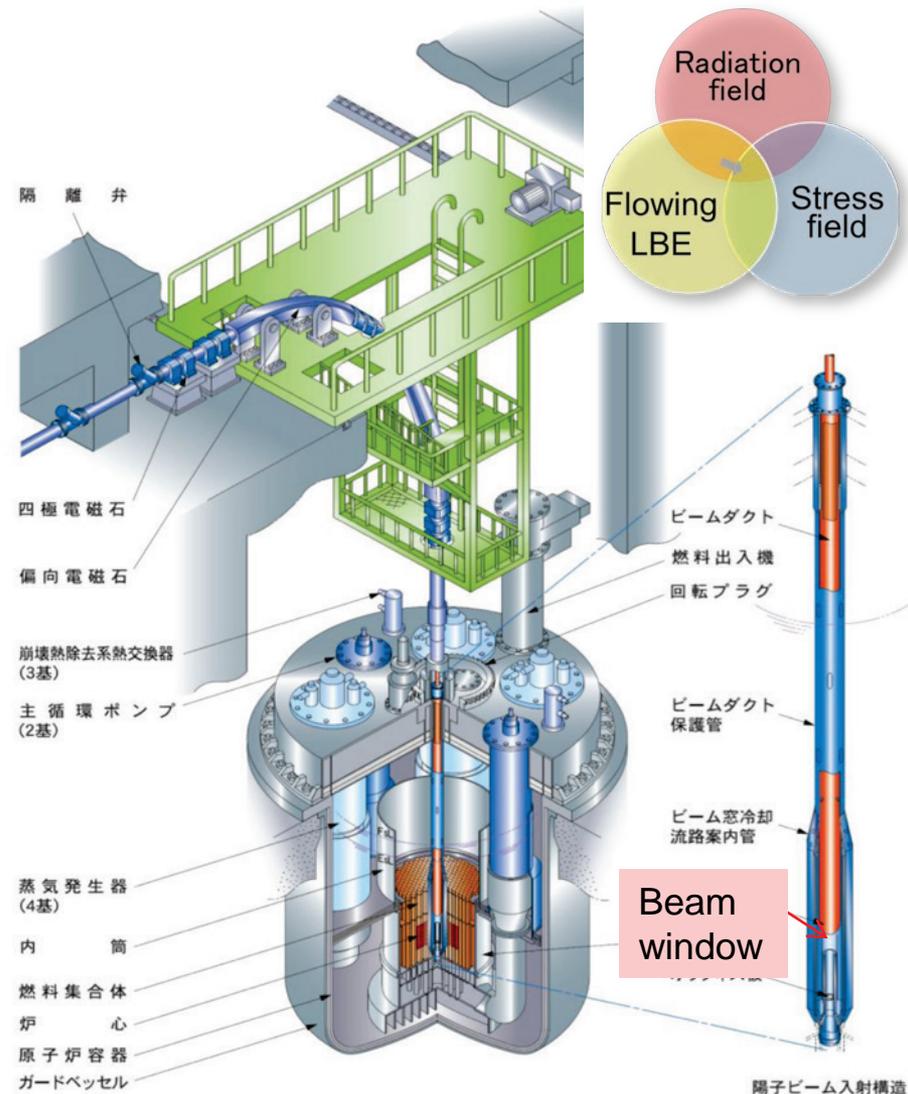
Features of ADS:

- Chain reactions stop when the accelerator is turned off.
- LBE is chemically stable. → **High safety is expected.**
- High MA-bearing fuel can be used. → MA from **10 reactors** can be transmuted.

ADS Proposed by JAEA - LBE Target/Cooled Concept -

➤ Belgium ADS program MYRRHA at SCK·CEN (Mol) approved 558 M€

- Proton beam : 1.5GeV 20MW ~ 30 MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : $k_{\text{eff}} = 0.97$
- Thermal output : 800MWt
- Core height : 1,000mm
- MA initial inventory : 2.5t
- Fuel composition :
(60%MA + 40%Pu) Mono-nitride
- Transmutation rate :
10%MA / Year (10 units of LWR)
- Burn-up reactivity swing : 1.8% $\Delta k/k$



• Beam window: 20 dpa/year. Accuracy of dpa is required for damage estimation.

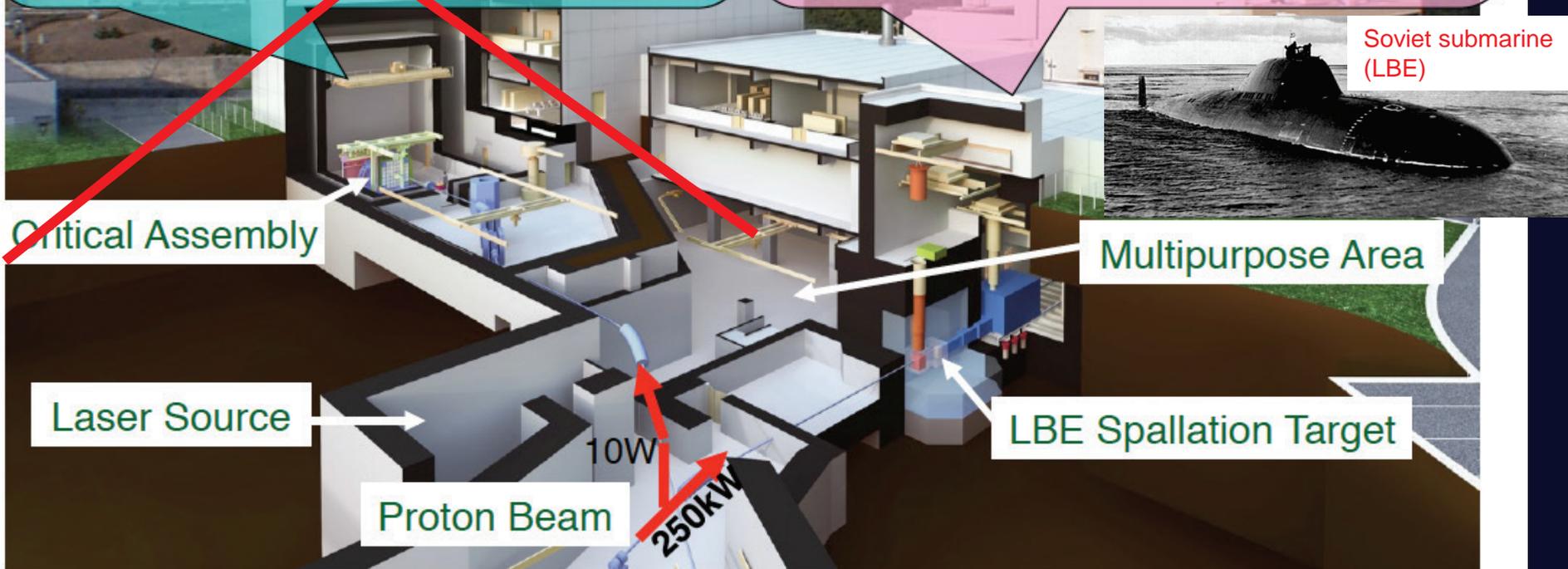
Transmutation Experimental Facility (TEF)

TEF-P: Transmutation Physics Experimental Facility

Purpose: Reactor Physics
Category: Critical Assembly
Proton Power: 400MeV-10W
Thermal Output: Less than 500W

TEF-T: ADS Target Test Facility

Purpose: Material Irradiation
Category: Radiation Application
Proton Power: 400MeV-250kW
Target Material: Lead-Bismuth



For R&D of ADS, 0.4 GeV beam by LINAC will be delivered to TEF.



Hadron Experiment Facility

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Bird's eye photo

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Linac 400MeV(50mA)

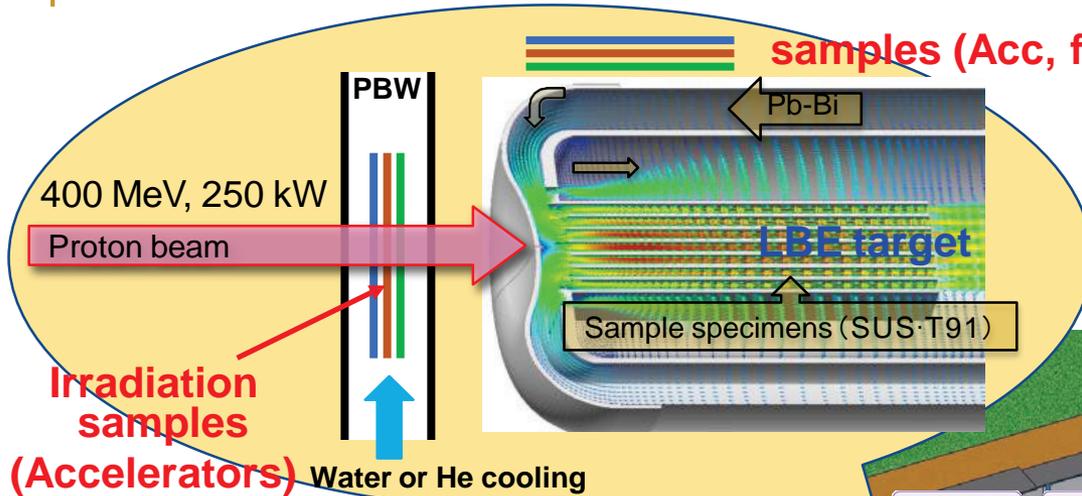
JRR-3M 800m to MLF

- JFY2007 Beam
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J-PARC = Japan Proton Accelerator Research Complex

Purpose of the new facility

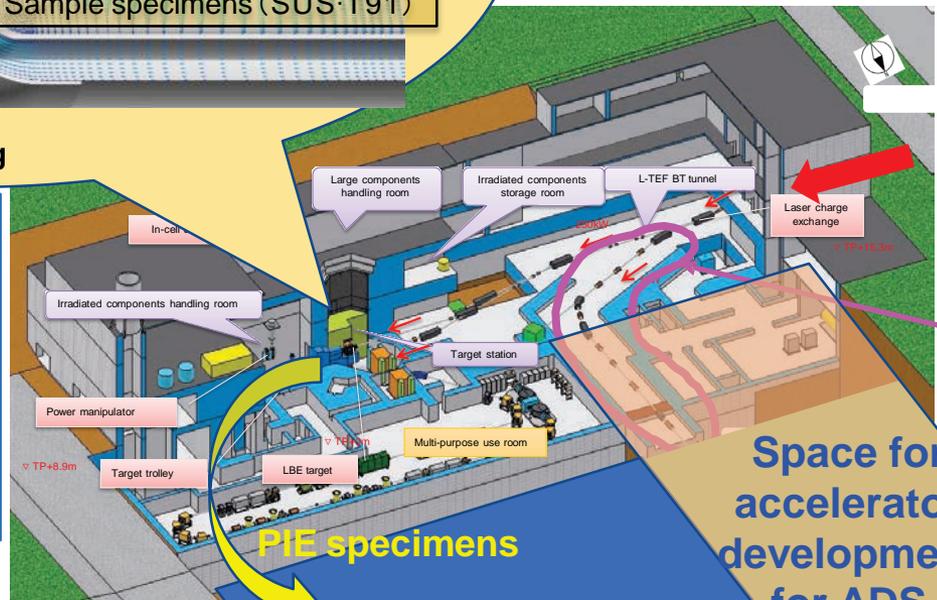
Cost estimation
 ~\$250 M in phase 1



A new facility based on TEF-T design with small modification

H- Beam
 Linac 400 MeV
 250 kW

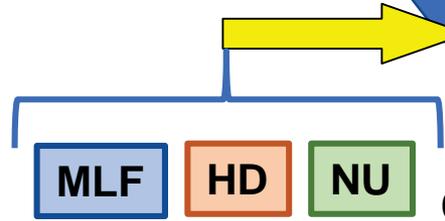
- Holding concept of multi-purpose use**
1. Neutron irradiation
 2. High-energy neutron beam
 3. ~~Use of a small fraction of the proton beam (ex. ISOL)~~



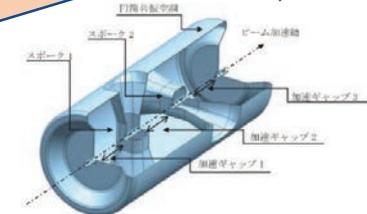
Eliminate BT-line to TEF-P

Space for accelerator development for ADS
 low β part, 10 MeV
 20 mA, 200 kW

N.B.: Storage will be fully occupied by the MLF target in ~13 years with the present exchange pace (1 time/year).



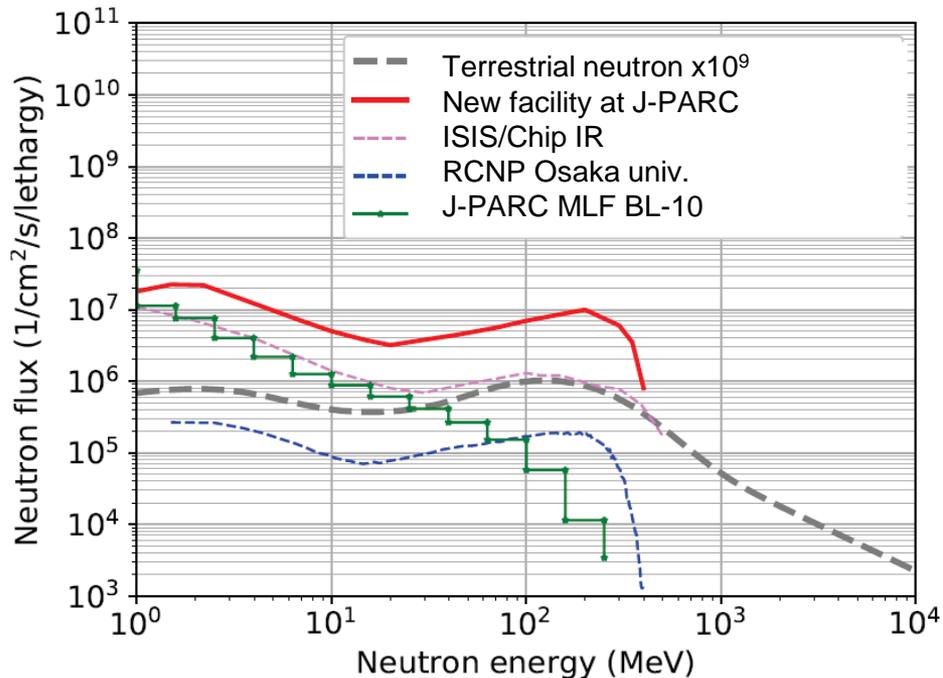
Other facilities at J-PARC



Multi-purpose use of the facility

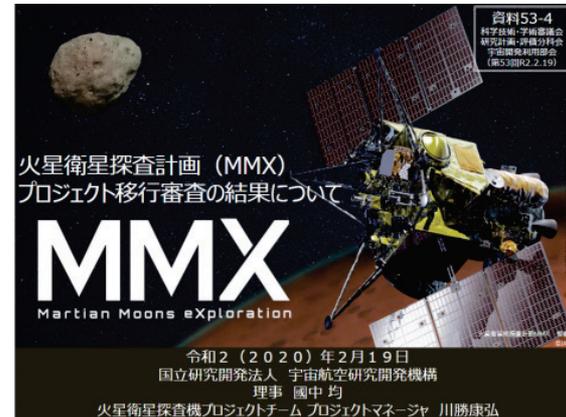
To enhance the construction of the new facility, exploring the multi-purpose use such as study for soft error and use of proton with low intensity extracted by laser.

- Terrestrial neutron spectrum has a peak ~ 150 MeV.
- Required to be at least 150 MeV in standard of power device (JEP151).

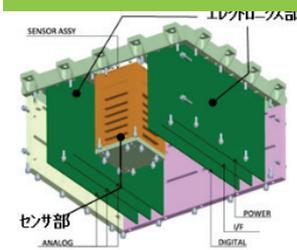


- Giving the best circumstance for semiconductor & soft error research.

JAXA: **MMX** (MMX: Martian Moons Exploration)



Interplanetary Radiation Environment Monitor (IREM)

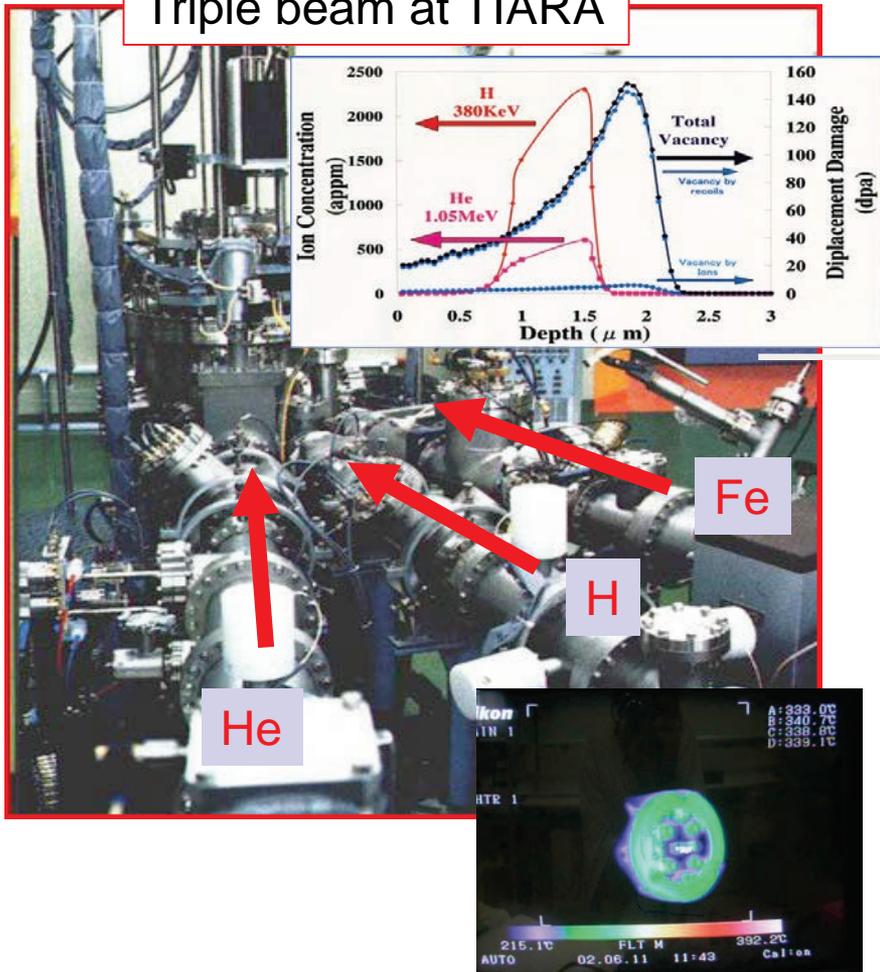


- JAXA asked J-PARC to use the protons $E_p \sim 0.4$ GeV with low intensity beam for R&D of IREM.
- Use of the primary beam is difficult to provide the users.
- Secondary protons of the existing beam dump or primary proton extracted by laser can be applied for this aim.

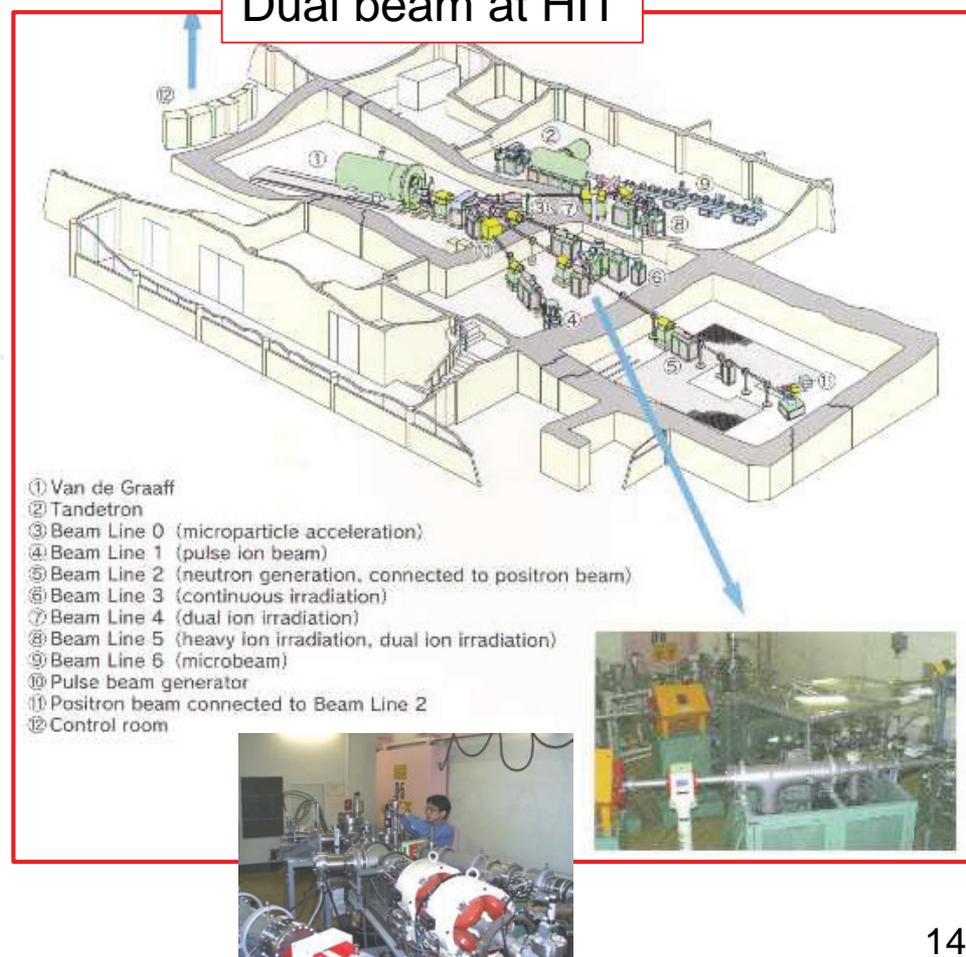
Other facilities for material test for J-PARC

- Acceleration damage using low energy heavy ion beam
- HIT: High Fluence Irradiation Facility Tokyo University (Tokai)
- TIARA: Takasaki Ion Accelerators Advanced Radiation Application (Takasaki)

Triple beam at TIARA



Dual beam at HIT



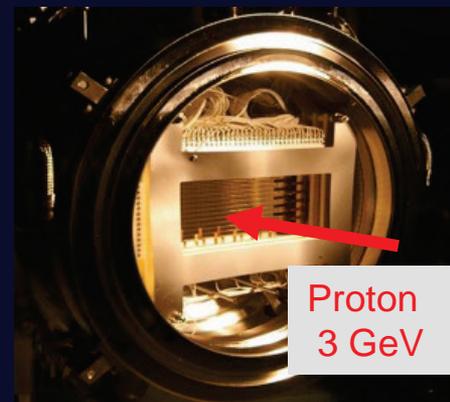
Target for high-intensity hadron accelerator and superconductor in high radiation area



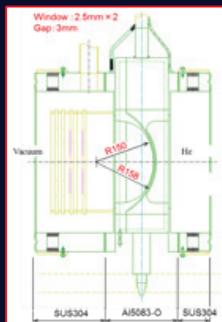
Proton beam window in J-PARC spallation neutron source:
Aluminum alloy (ϕ 0.6 m)

T2K beam window
Titanium alloy (Ti-6Al-4V)

- ⊕ For damage estimation of beam intercepting material, DPA is utilized based on displacement cross section.
- ⊕ High accuracy of the displacement cross section is required.



Proton
3 GeV

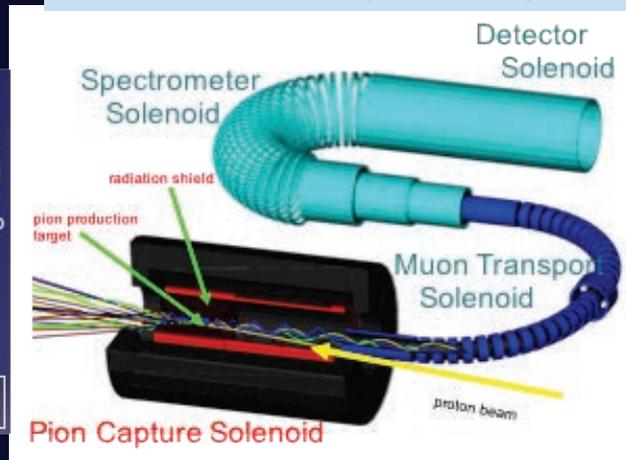
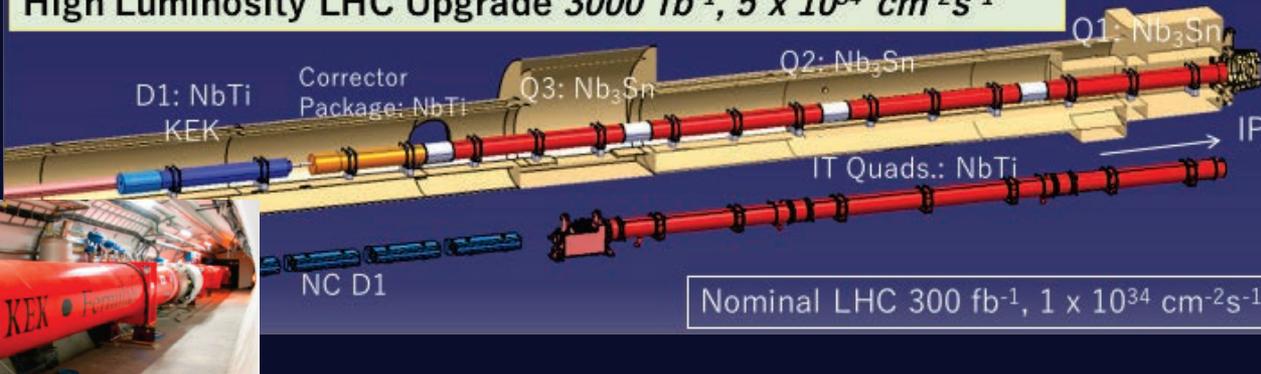


Proton 30 GeV

⊕ Resistivity change due to radiation is crucial for Superconducting (SC) magnet sustaining damage.

SC magnet system in beam line of COMET (J-PARC)

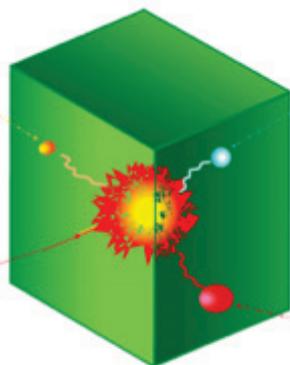
High Luminosity LHC Upgrade 3000 fb^{-1} , $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



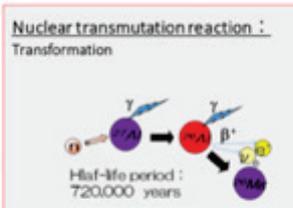
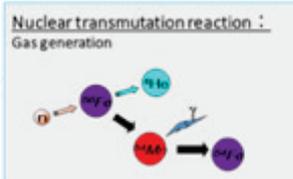
DPA and PKA

What will happen in target material in hadron accelerator?

Displacement damage: Damage on crystal structure due to hadron irradiation



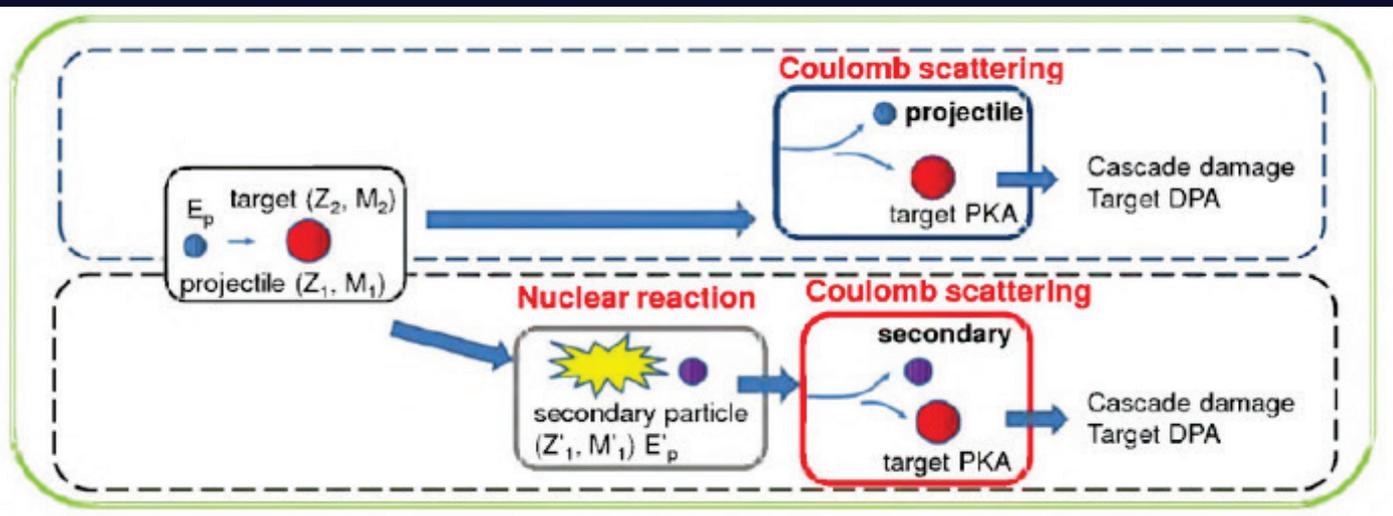
Proton



Original figures from <http://www.fusion.qst.go.jp/rokkasyo/img/en/project/material>

Damage characteristics may be described as a function of DPA, gas production and temperature.

$$\text{DPA} = \text{flux} \times \text{Displacement cross section}$$



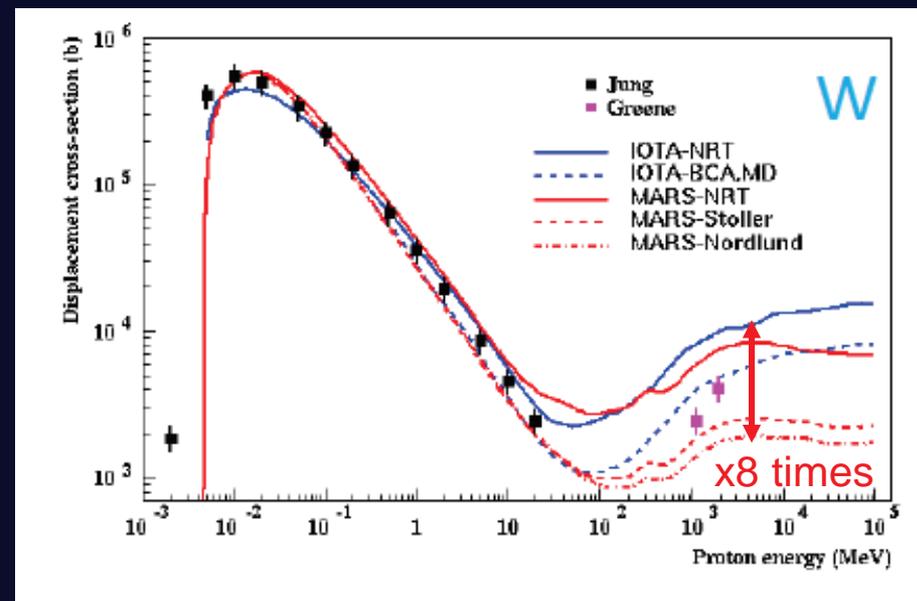
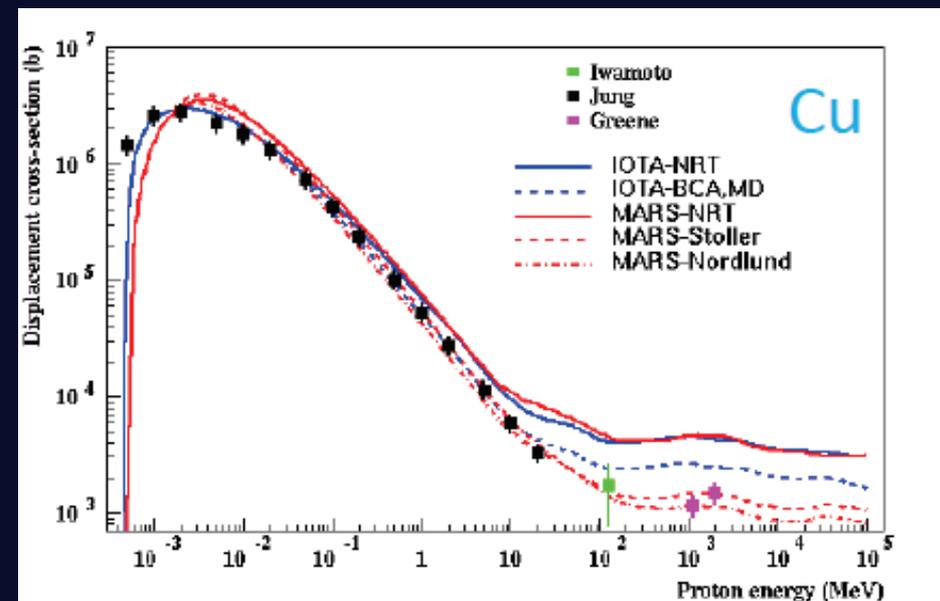
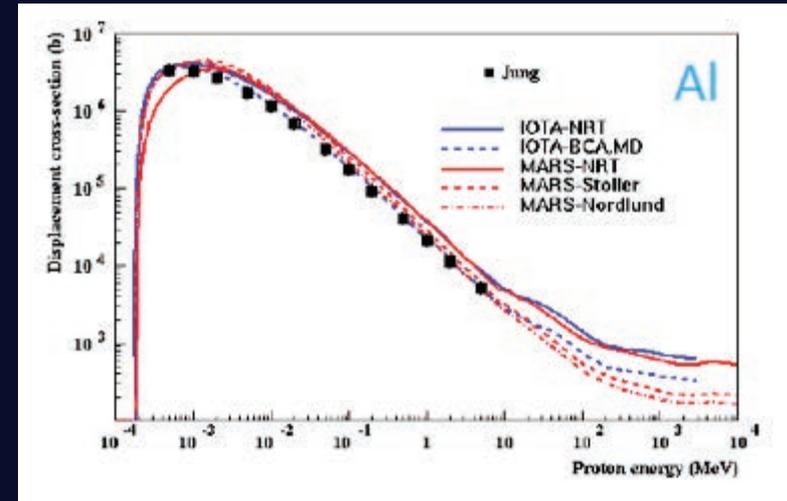
Displacement cross section is estimated by calculation based on PKA (Primary Knock-on Atom)

DPA and displacement cross section

Although DPA is widely utilized to estimate damage, displacement cross section has not been enough validated.

- Cross section exp. data for $E_p > 20$ MeV are scarce.
- Only 5 Data (Cu: 3, W: 2)
- No data for Al, Fe (important for ADS)
- Showing large discrepancies among calculation models

N. Mokhov HPTW2016



Displacement cross section experiment at J-PARC

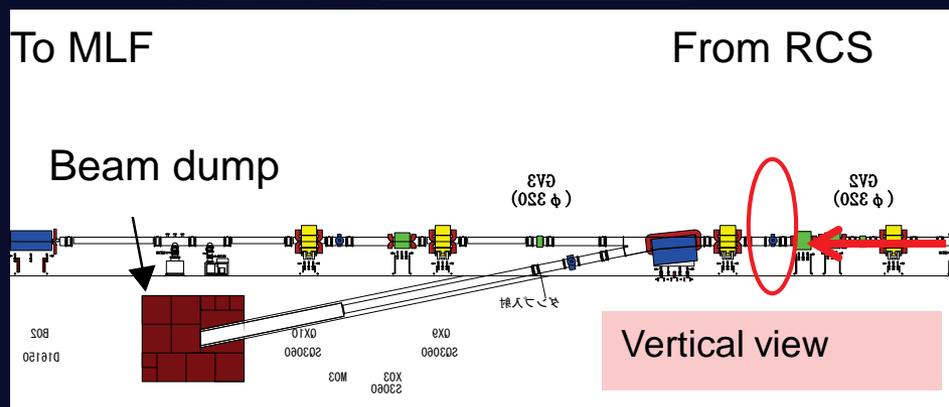
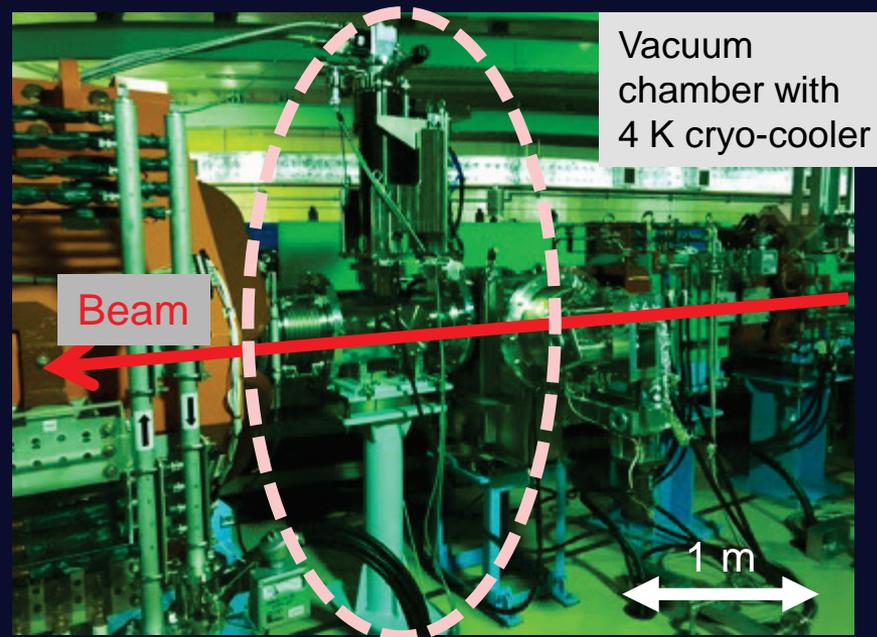
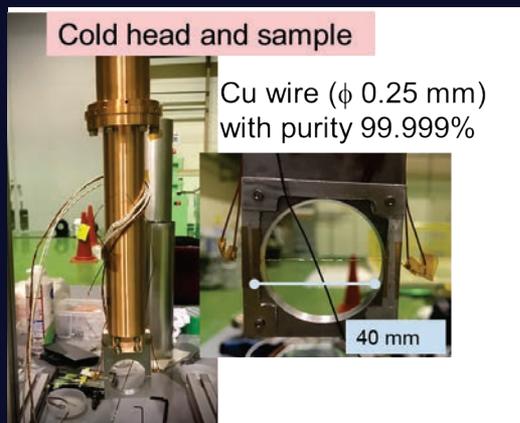
- Experiments were conducted at RCS (0.4 - 3 GeV) and at MR (3 - 30 GeV)

To sustain damage, sample was cooled to **cryo-temperature** (~ 4 K).

Displacement cross section (σ) can be obtained by increase of resistivity ($\Delta\rho = \Delta R \cdot A/L$) due to proton irradiation with average flux ($\overline{\phi(E)}$).

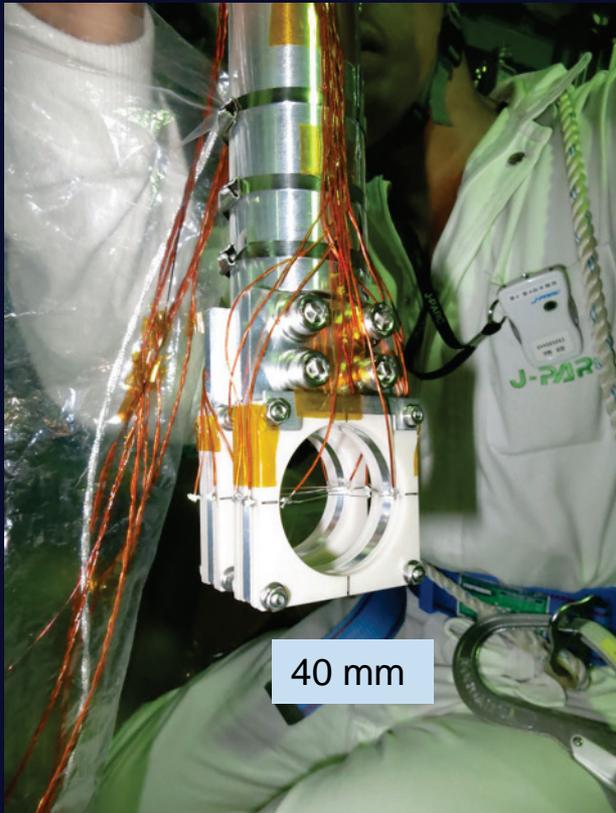
$$\sigma(E) = \Delta\rho / \left(\overline{\phi(E)} \rho_{FP} \right)$$

ρ_{FP} : Resistivity change by a Frankel pair (Cu: $2.2 \times 10^{-6} \Omega\text{m} \pm 23\%$)

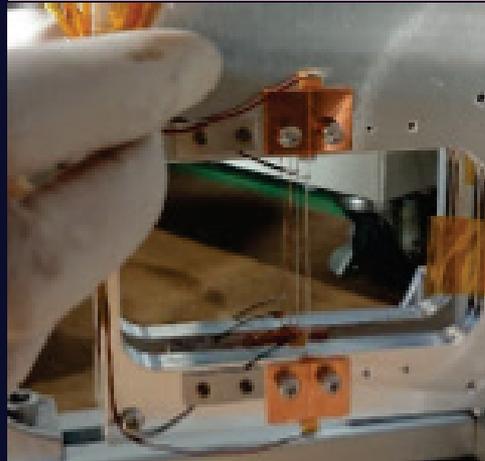


Samples

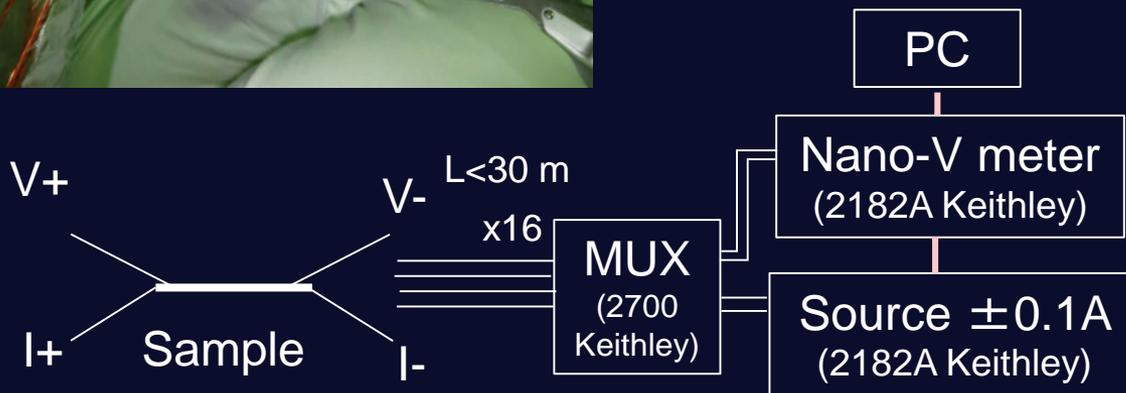
3NBT for 0.4 – 3 GeV



MR for 3 – 30 GeV



- Cascade scheme of 4 pieces (Al, Fe, Cu, W) with $\Phi 0.25$ mm were applied
- Samples were annealed $\sim T_{\text{melt}}$ before installation.
- After trial and error, the temperature was achieved < 4 K.
- To obtain accurate resistance, 4 wires terminal scheme with delta mode switching polarity with 10 Hz and averaging was applied.



Calculation of the cross section with PHITS code

- PHITS implemented the following models for calculation of the displacement cross-section
 - Norgett-Robinson-Torrens (NRT) model: Widely utilized
 - Athermal recombination corrected (arc) model
 - Nordlund parameter : Nature comm. 9 1084 (2018)

NRT (Cu Ed 33 eV):

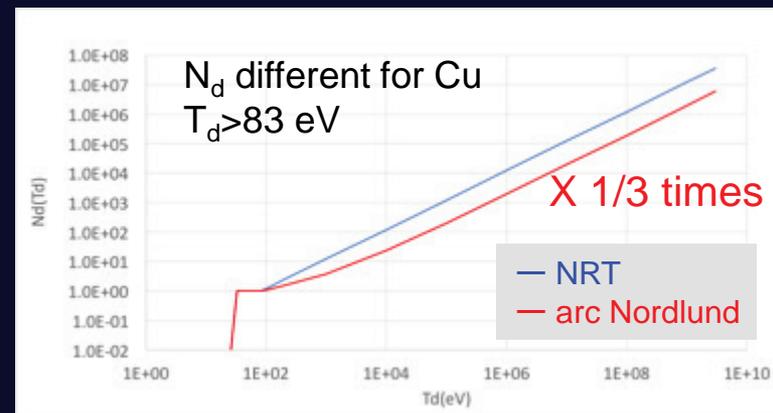
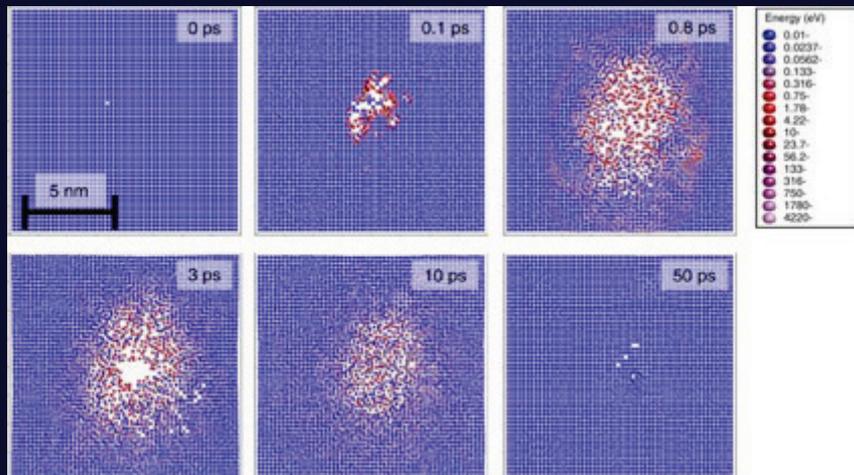
$$N_d(T_d) = \begin{cases} 0 & , T_d < E_d \\ 1 & , E_d < T_d < \frac{2E_d}{0.8} \\ \frac{0.8T_d}{2E_d} & , \frac{2E_d}{0.8} < T_d < \infty \end{cases},$$

N_d : Number of displacement
 T_d : Displ. energy

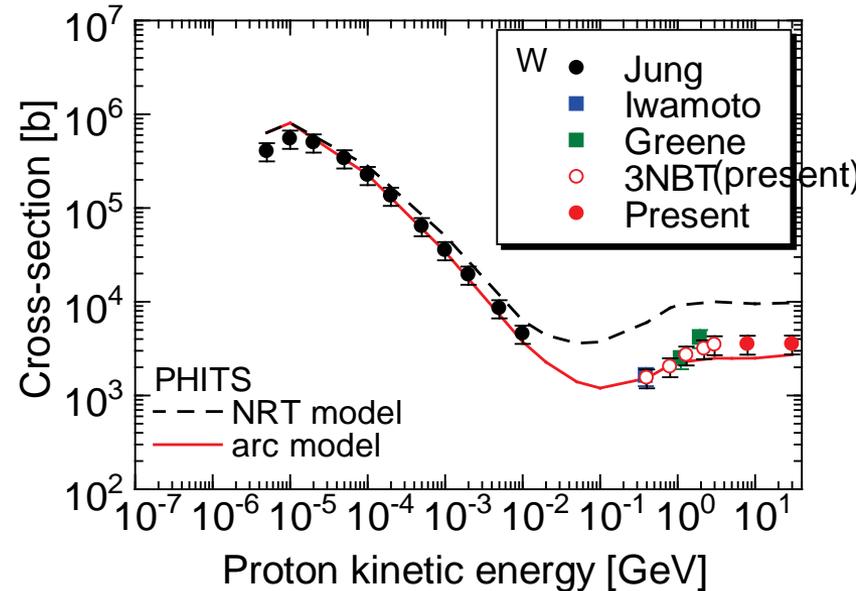
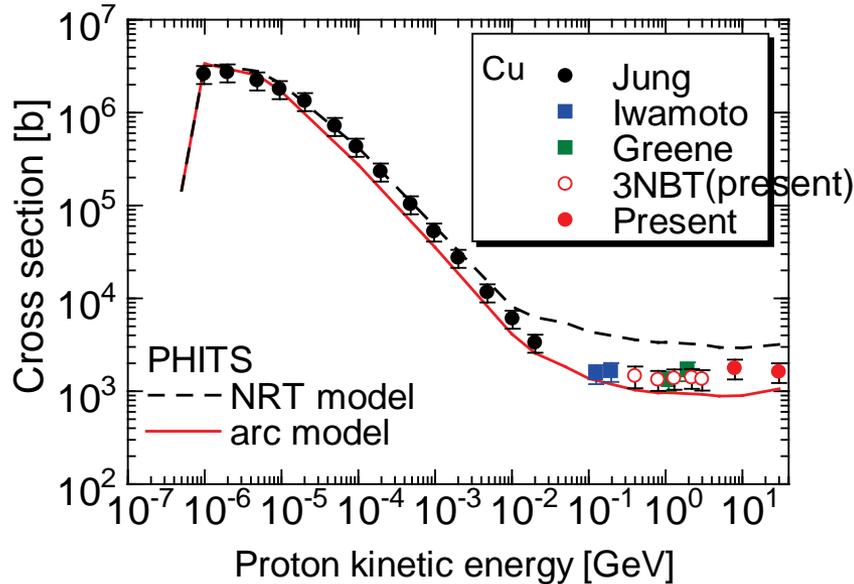
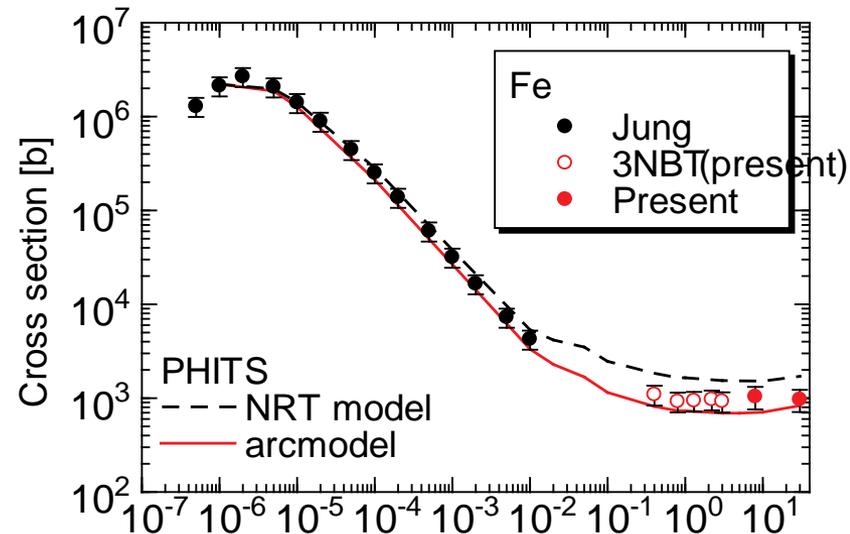
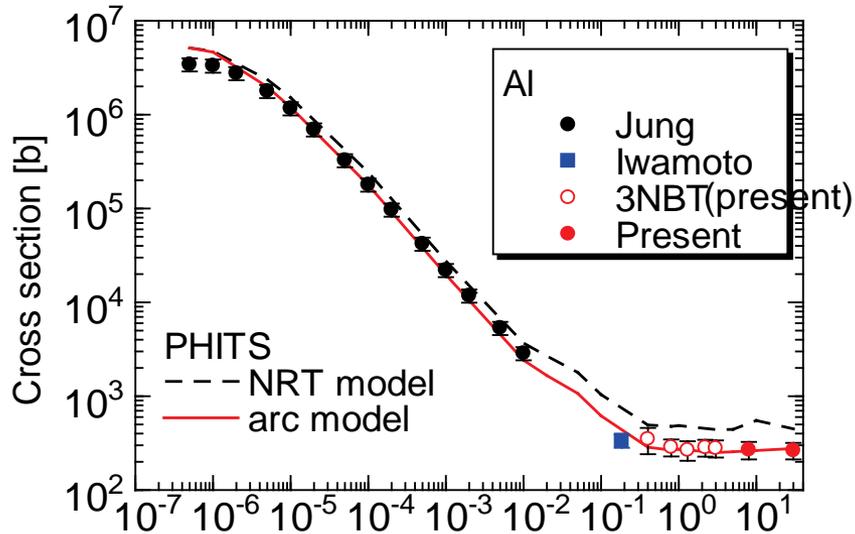
arc-Nordlund (Cu Ed 33 eV):

$$N_{d,arc\text{dpa}}(T_d) = \begin{cases} 0 & , T_d < E_d \\ 1 & , E_d < T_d < \frac{2E_d}{0.8} \\ \frac{0.8T_d}{2E_d} \xi_{arc\text{dpa}}(T_d) & , \frac{2E_d}{0.8} < T_d < \infty \end{cases}$$

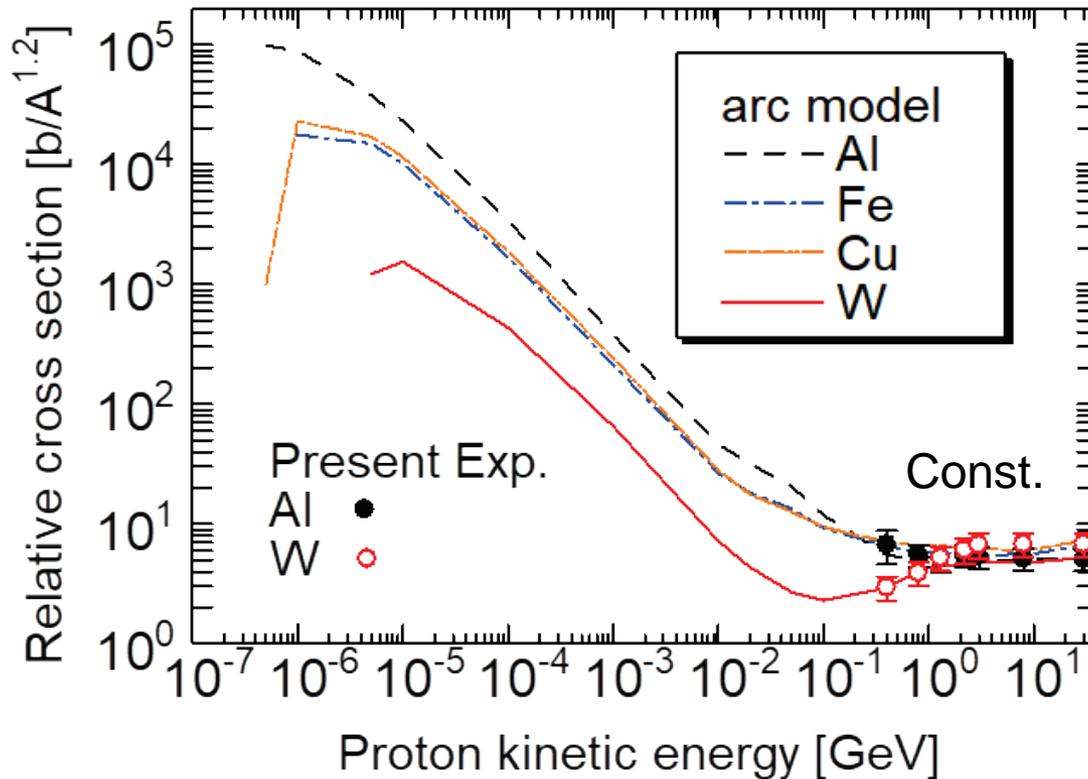
$$\xi_{arc\text{dpa}}(T_d) = \frac{1 - c_{arc\text{dpa}}}{(2E_d/0.8)^{b_{arc\text{dpa}}}} T_d^{b_{arc\text{dpa}}} + c_{arc\text{dpa}}$$



Comparison calc. vs exp.



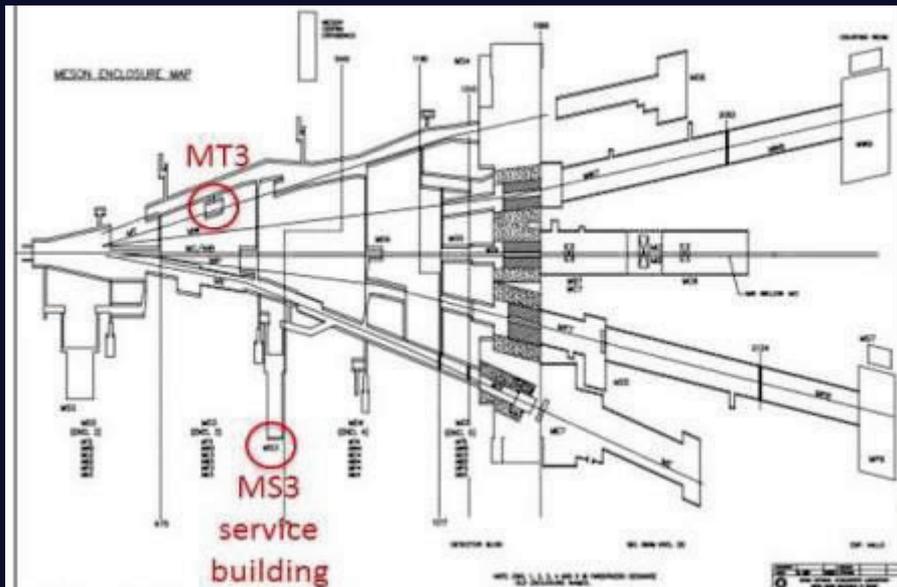
Requirement to extend high energy region



- The cross section was found to be saturated with proportional of $A^{1.2}$ (A = target mass) in high energy region.
- We want to experimentally confirm this tendency.

Experiment at FNAL for 120 GeV

- Budget already approved by MEXT to Iwamoto-san
- Experiment will be conducted for 120 GeV proton at FTBF FNAL on November 2022.

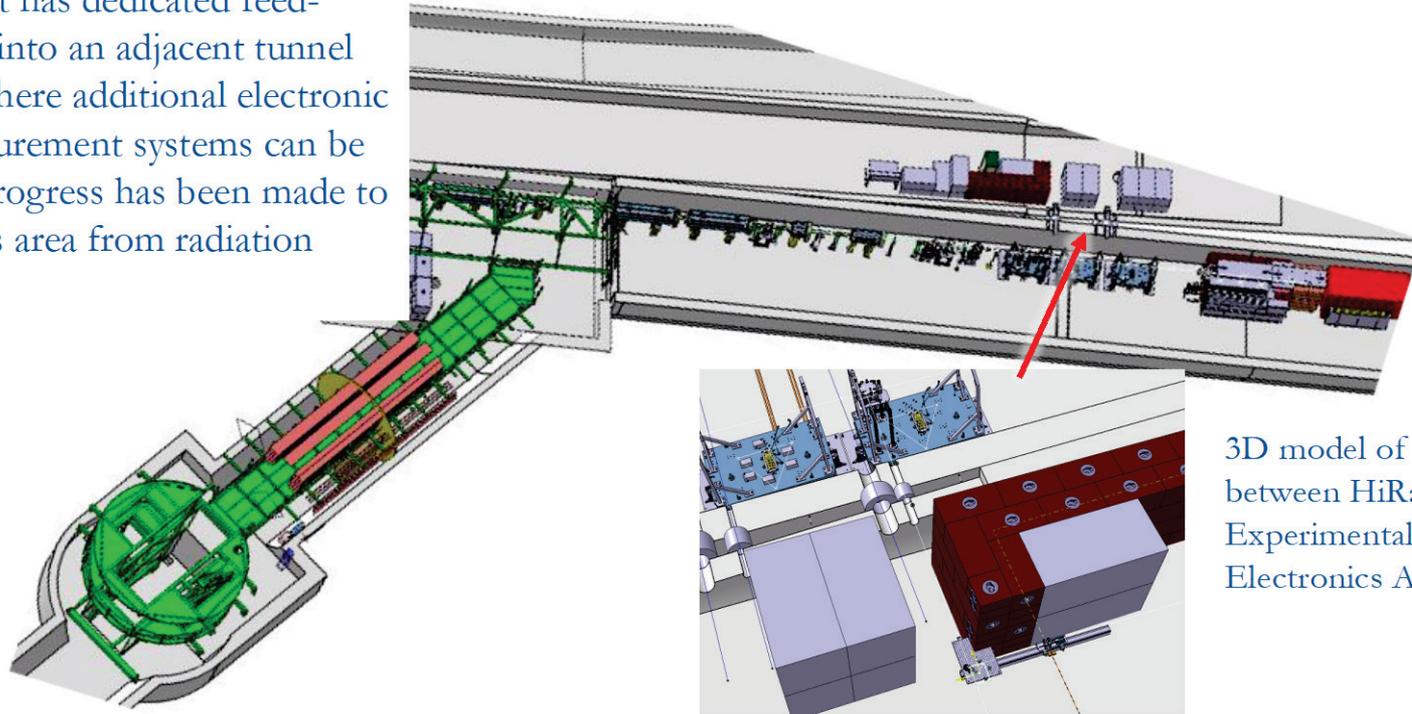


Irradiation Area

TT61

HiRadMat has dedicated feed-throughs into an adjacent tunnel (TT61) where additional electronic and measurement systems can be added. Progress has been made to shield this area from radiation effects.

Scientific committee of HiRadMat has approved the proposal of the experiment, which will be conducted on 2023.



3D model of feed-through between HiRadMat Experimental Area and Electronics Area.

Summary

- J-PARC has a plan to build a new facility for R&D of materials of ADS.
 - Irradiation facility
 - Multipurpose use such as soft error
 - Hot cell for PIE as Phase 2
- To understand the damage on beam intercepting materials correctly, displacement cross sections were obtained for protons 0.4 - 30 GeV.
 - NRT model: 4 times overestimation
 - arc model: good agreement with present results.
 - To extend energy region, similar experiment will be carried out at FNAL and HiRadMat for 120 and 440 GeV protons.

Thank you for attention

