Displacement cross section measurements at HiRadMat

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- 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

Contents

- Introduction
  - Present and future plan of J-PARC
- Displacement cross section experiment at J-PARC
- Experiment at HiRadMat
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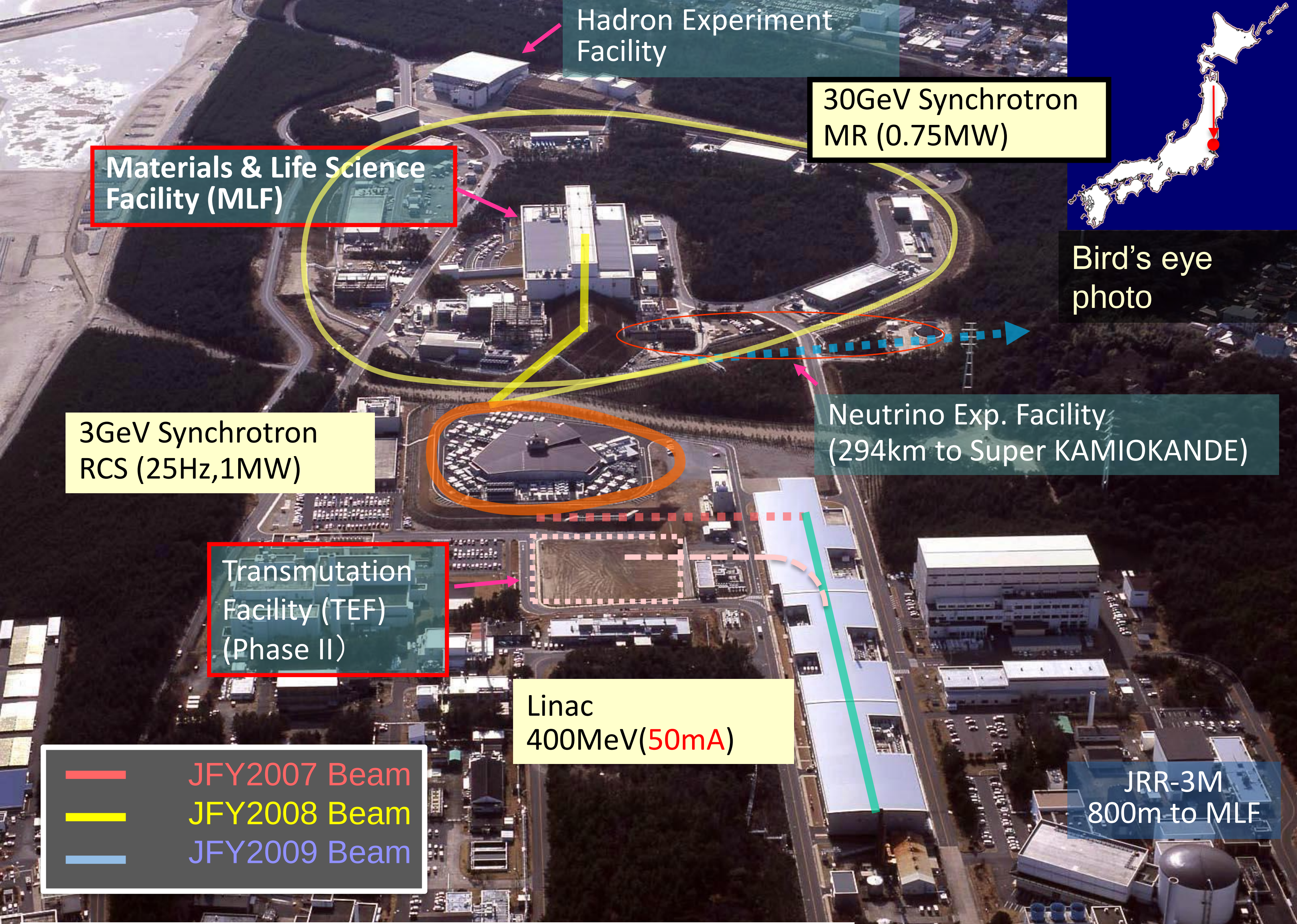
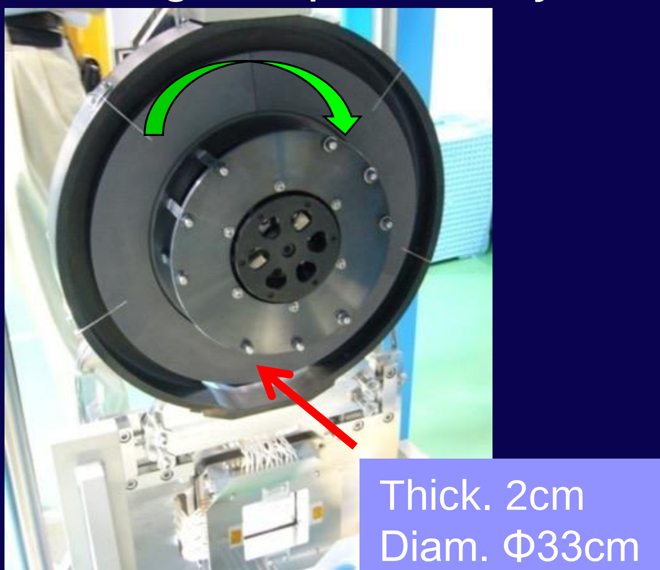


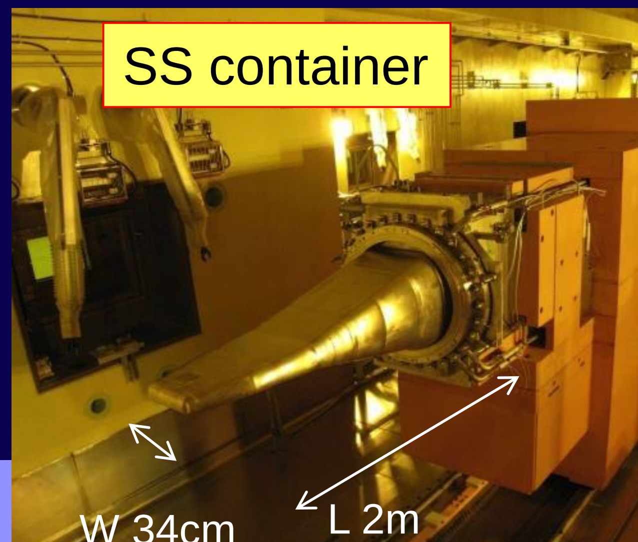
J-PARC = Japan Proton Accelerator Research Complex

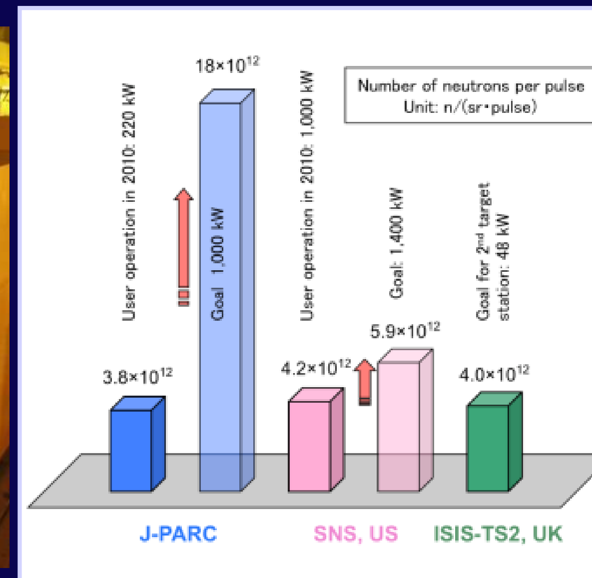
Targets in Material Life Experimental Facility (MLF)

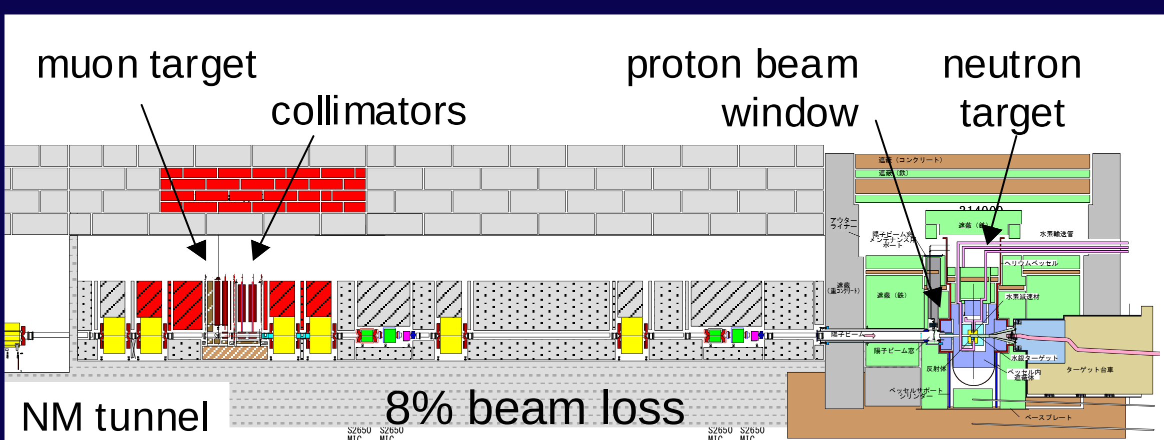
- Muon production target
  - Carbon graphite
  - Highest μ^- intensity
- Neutron production target
  - Mercury (Hg)

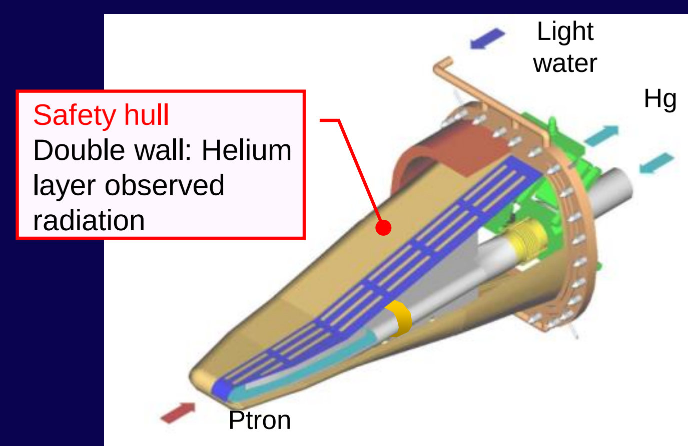
Highest pulse intensity in the world





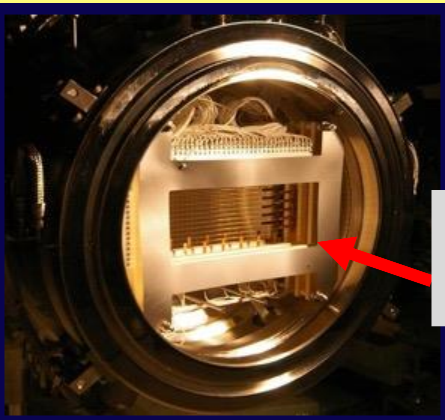






Target for high-intensity hadron accelerator and superconductor in high radiation area

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



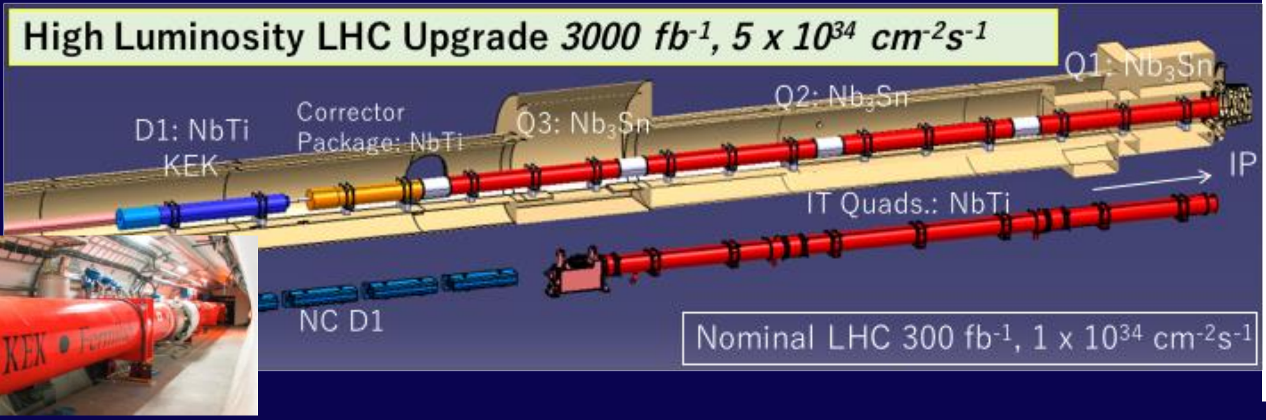
Proton
3 GeV

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

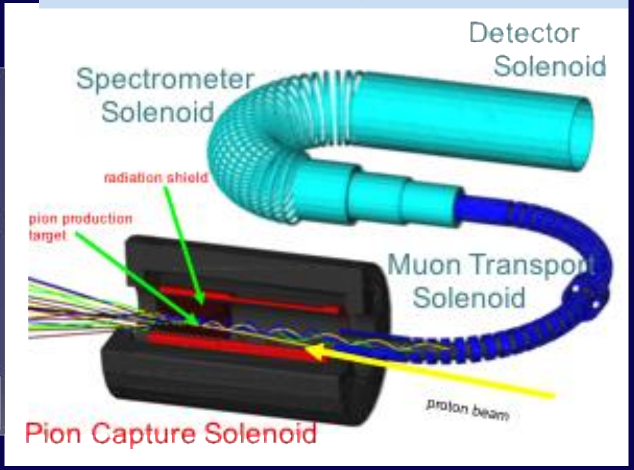
Proton
30 GeV

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

- Resistivity change due to radiation is crucial for Superconductor(SC) magnet sustaining damage.



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



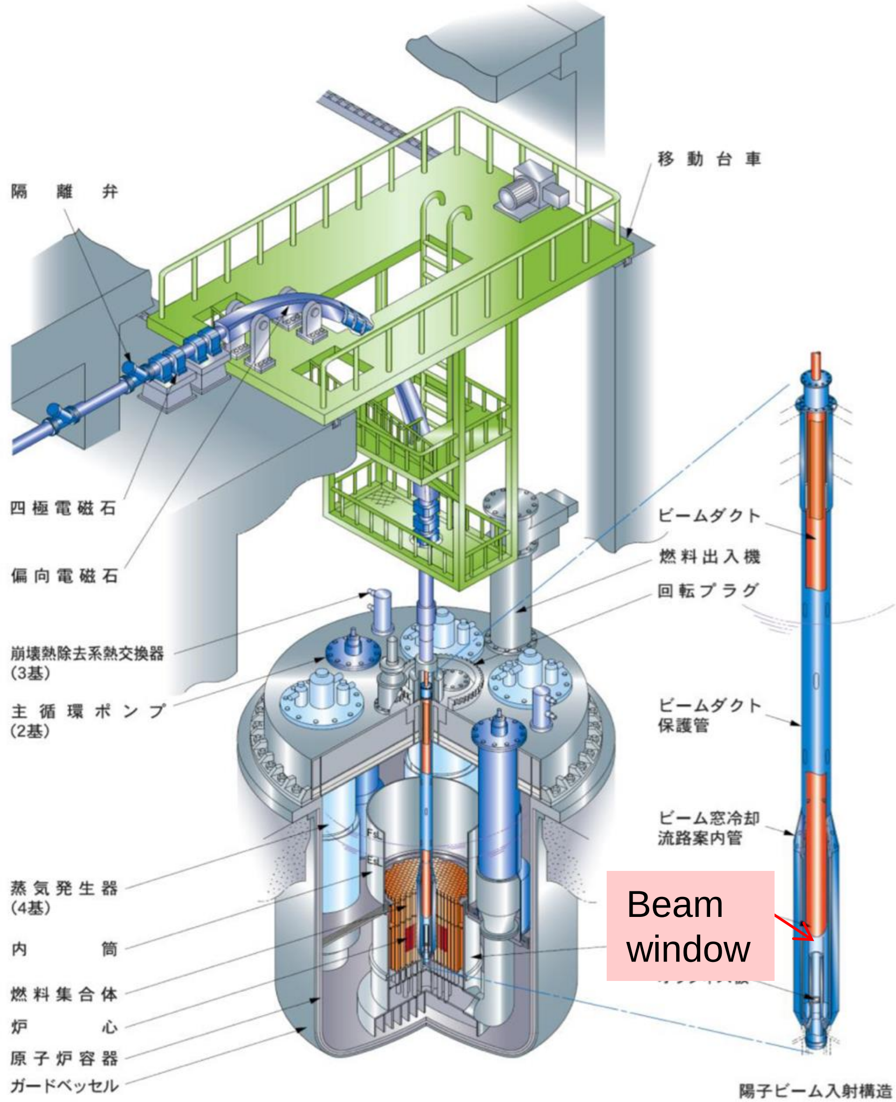
ADS Proposed by JAEA - LBE Target/Cooled Concept -

- 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 : $k_{eff} = 0.97$
- Thermal output : 800MWt
- Core height : 1,000mm
- MA initial inventory : 2.5t
- Fuel composition :

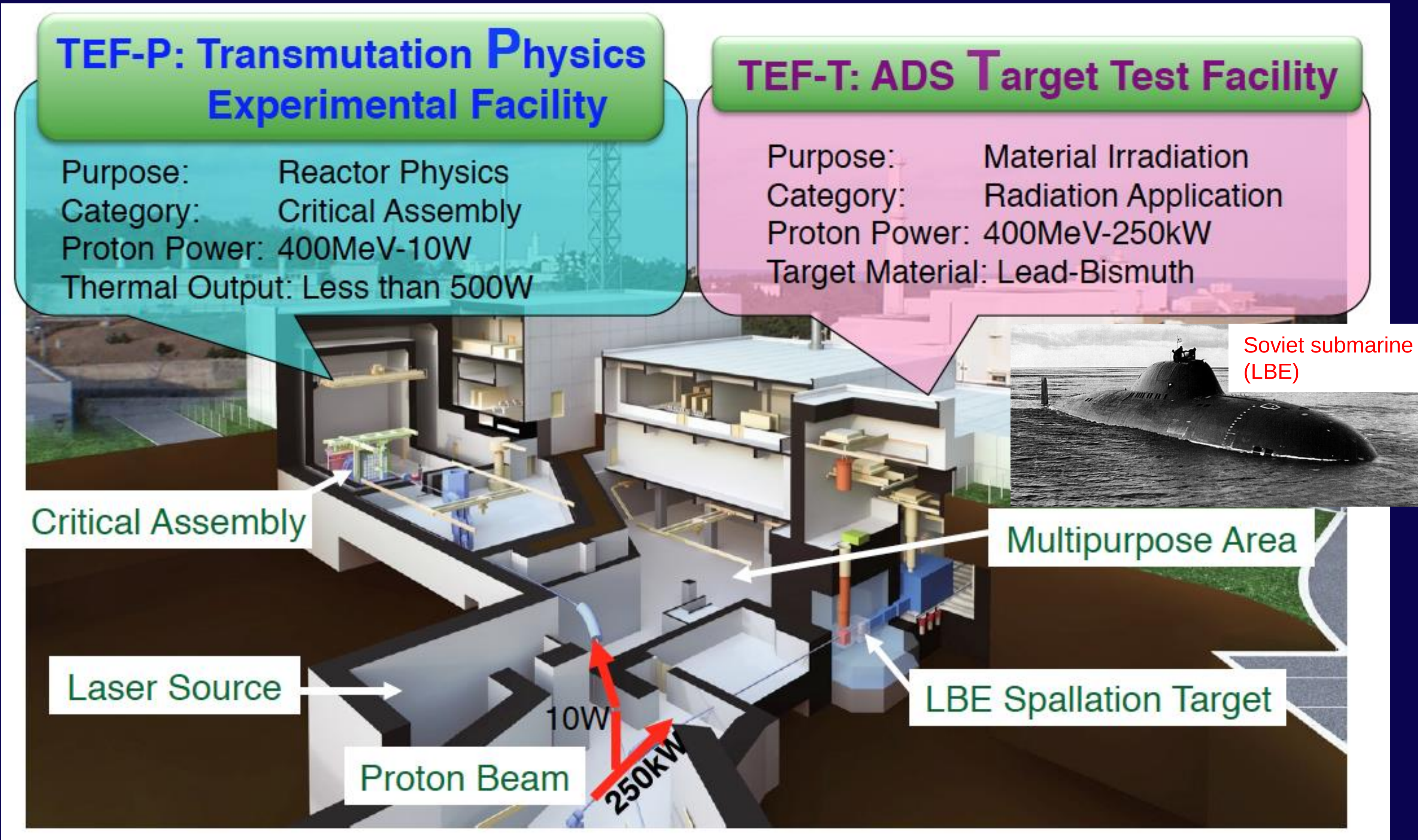
  (60%MA + 40%Pu) Mono-nitride
- Transmutation rate :

  10%MA / Year (**10 units of LWR**)
- Burn-up reactivity swing : 1.8%Δk/k



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

Transmutation Experimental Facility (TEF)

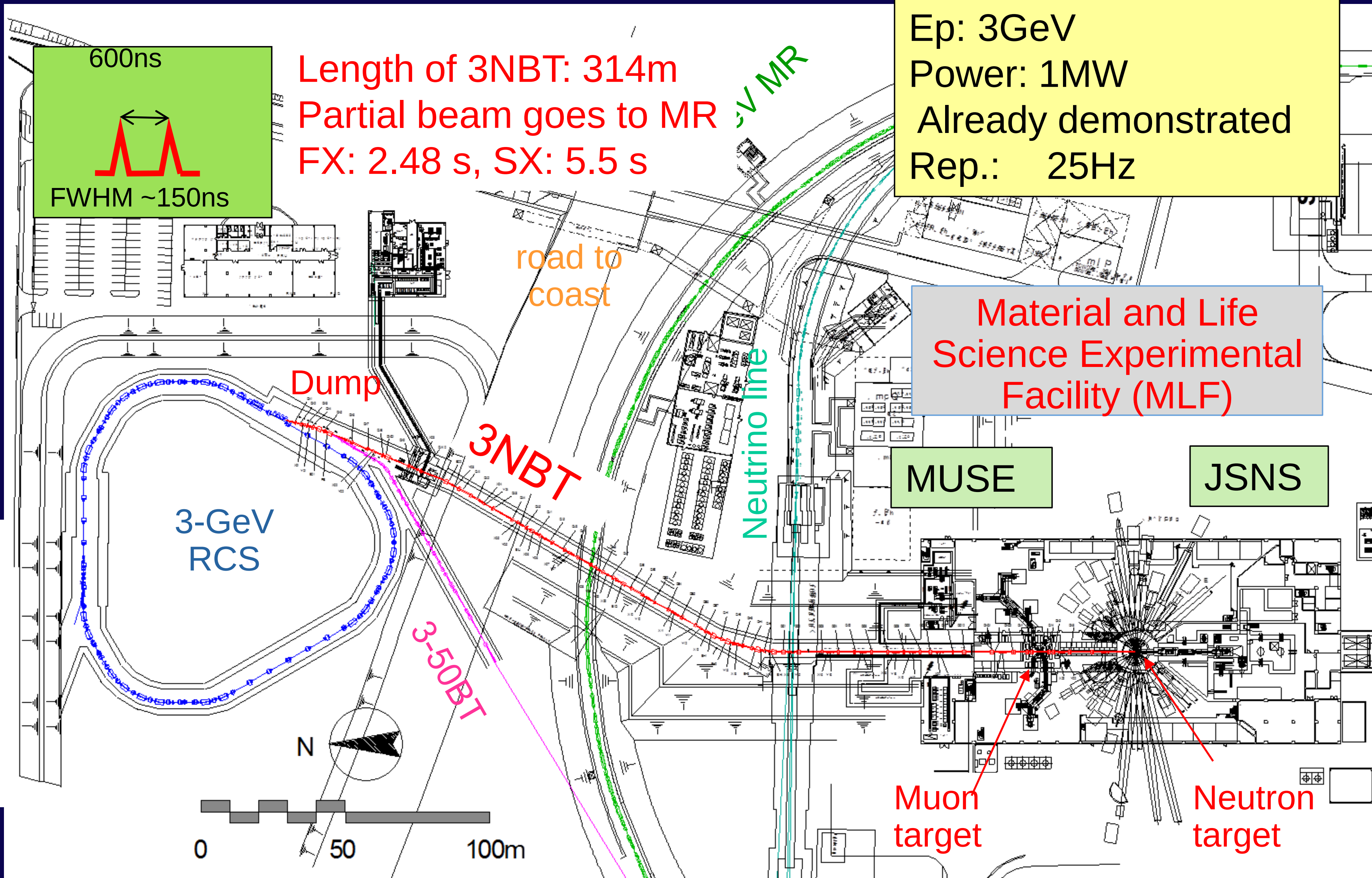


For R&D of ADS, 0.4 GeV beam by LINAC will be delivered to TEF.

Beam transport from RCS to MLF

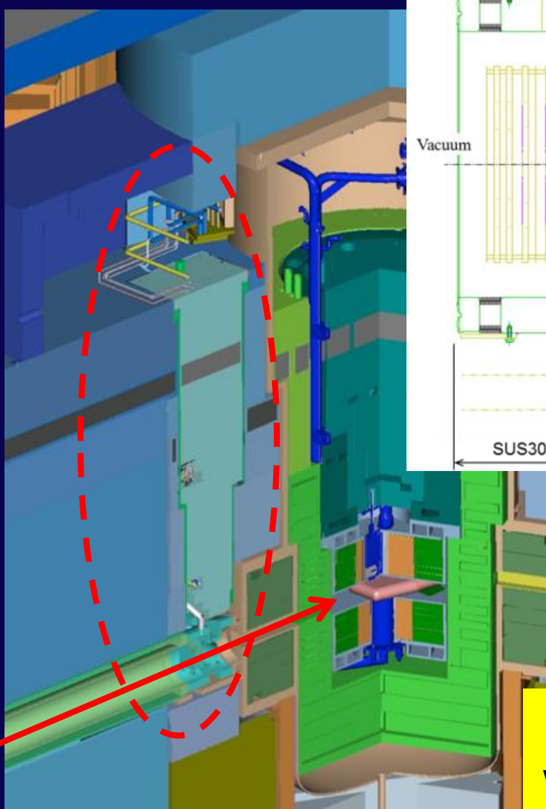
600ns

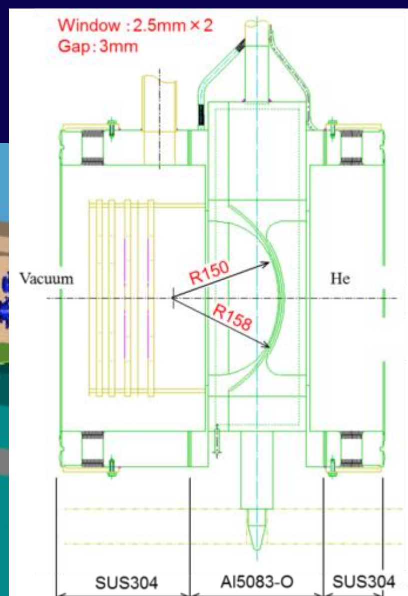
- Length of 3NBT: 314m
- Partial beam goes to MR
- FX: 2.48 s, SX: 5.5 s

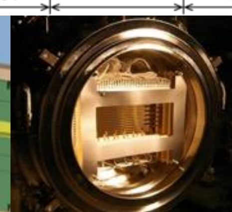


Proton Beam Window at MLF (A5083)

- Lifetime estimation based on Post Irradiation Examination (PIE) for safety shroud (AlMg3) at SINQ in PSI
- Considering difference of proton energy, to predict lifetime of the PBW with high accuracy for validation of calculation



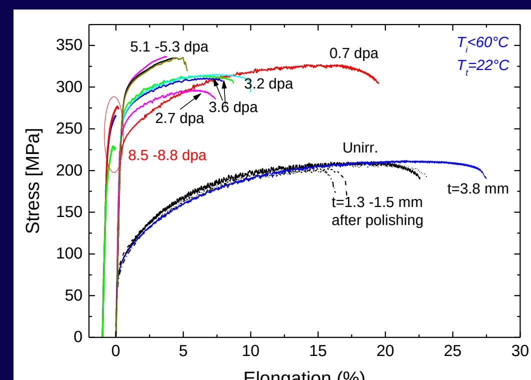


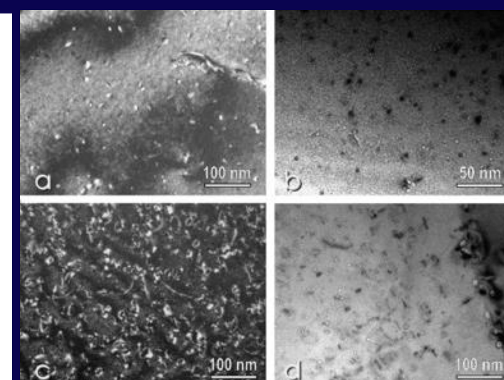


Height: 3.8m
Weight : 10t

Result at SINQ/PSI for 0.6GeV

Y. Dai, et al, J. Nucl Mat. 343 184 (2005)





Lifetime of PBW: Determined by He gas production (1200 appm) 2 years*

By recent PIE result of the SINQ (2400 apmm), lifetime may be applicable to 3 years.

* S. Meigo, et al, J. Nucl Mat. 450 141 (2012)

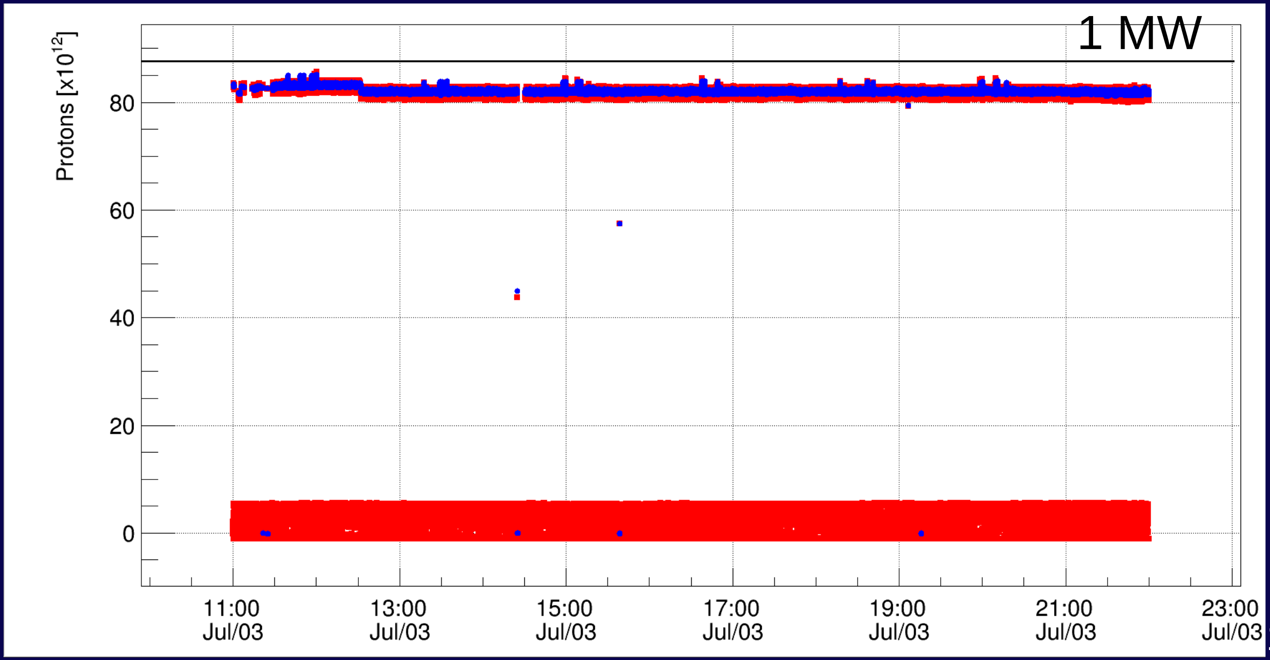
1 MW beam operation at MLF

Last year memorial snap shot at 1MW for 1 h test (2018/7/3)

Result of this year

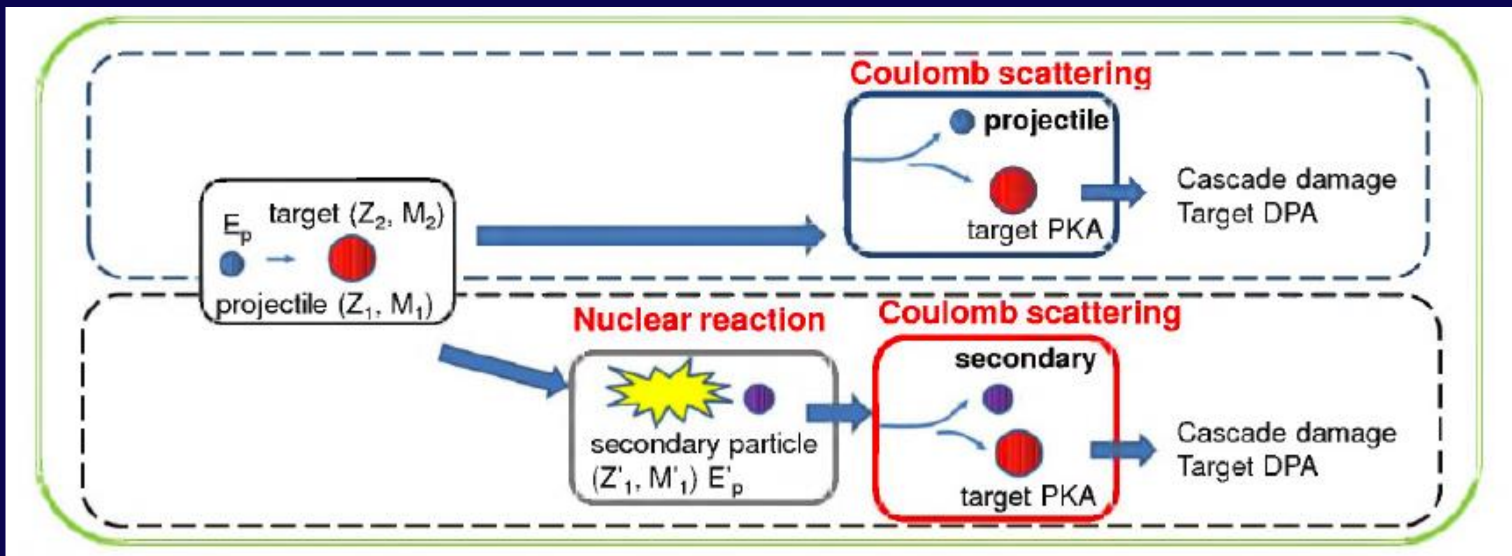
Beam intensity trend at 1MW for 10.5 h test (2019/7/3)

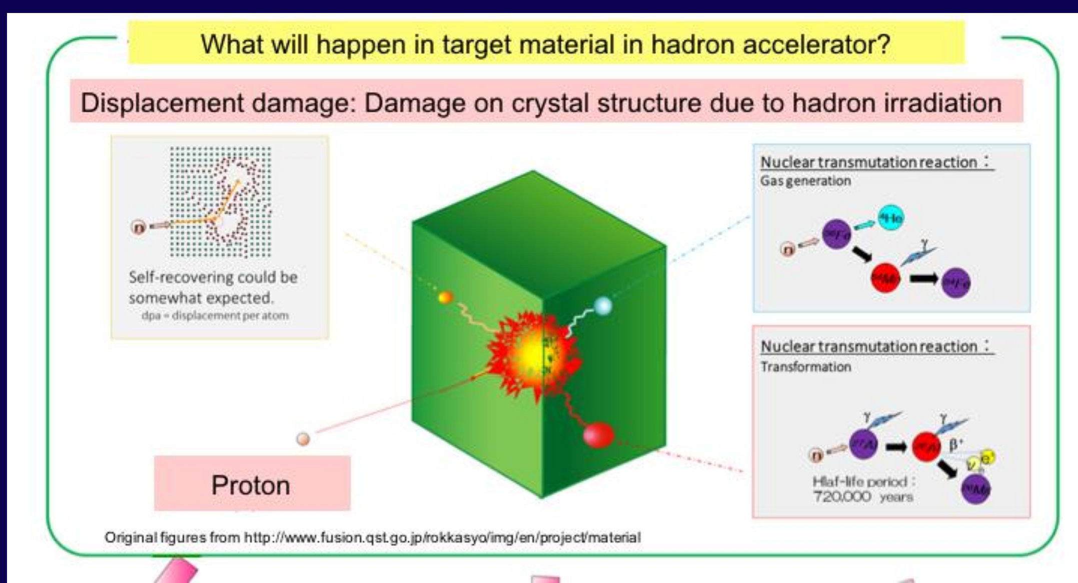
Availability ~ 99%



PKA and DPA

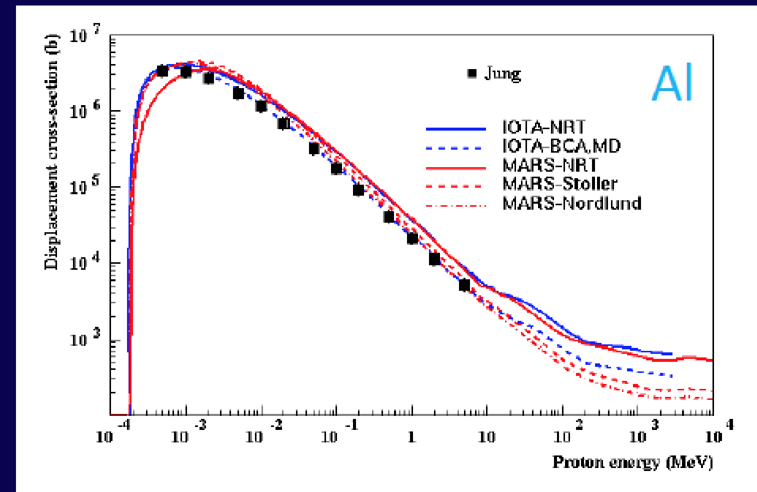
- DPA (Displacement per Atom) is estimated by calculation based on PKA.



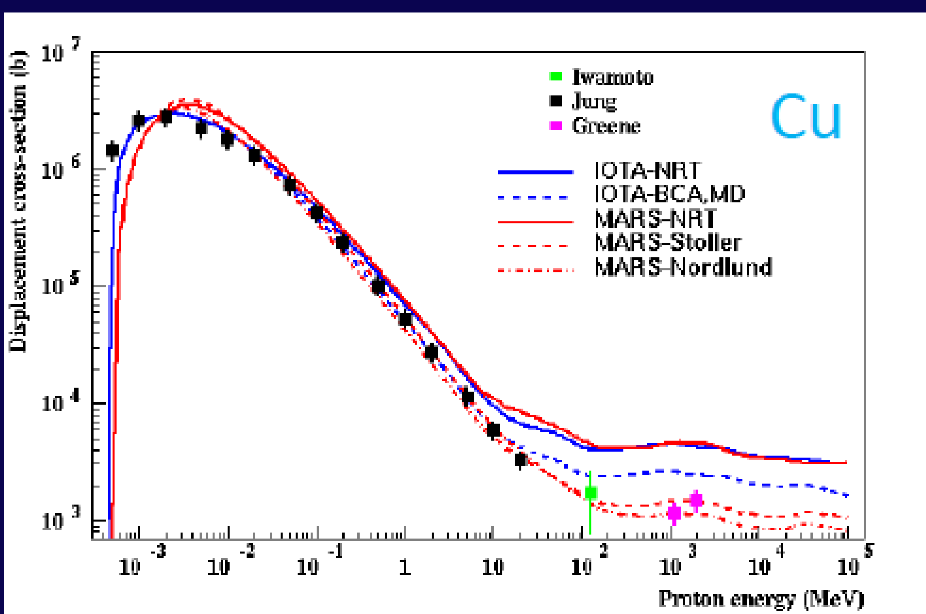


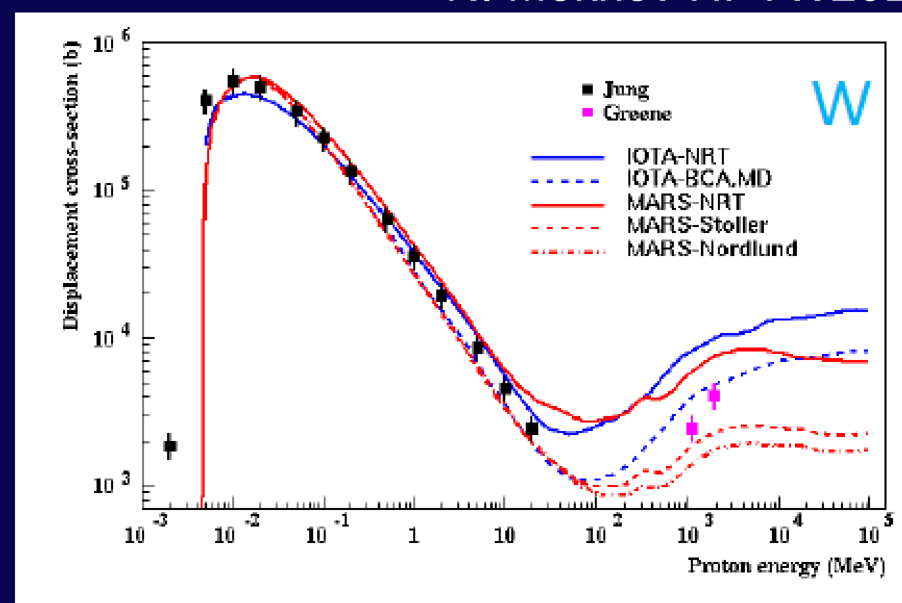
DPA and displacement cross section

- Although DPA is widely utilized for estimation of damage, displacement cross section has not been enough validated.
  - DPA = flux x Displacement cross section
- Displacement cross section has been measured only Cu and W for a few energies of protons less than 3 GeV
- Among calculations models, showing large discrepancies



N. Mokhov HPTW2016





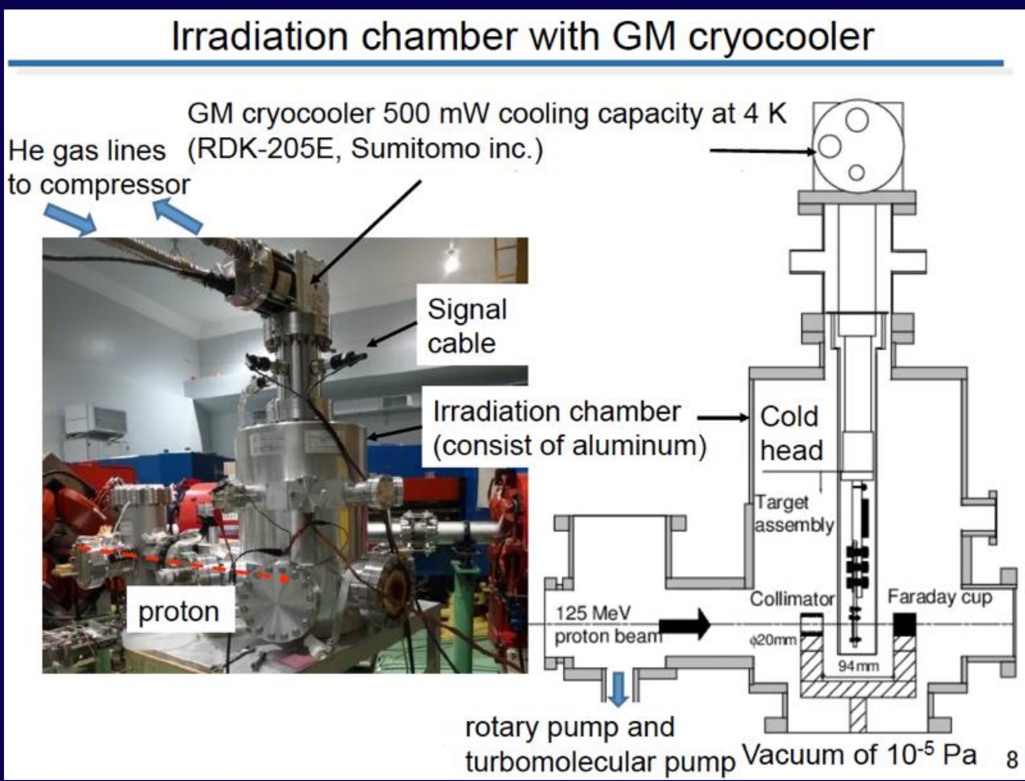
Measurement of DPA cross section at Kyoto univ.

- Irradiation on metal at cryogenic temperature with GM cryocooler
- By observing increase of electrical resistance, the cross section can be observed.

Experiment at J-PARC

- Samples and GM placed at exit of 3-GeV synchrotron for various energy of proton 0.4 to 3 GeV
- Other experiment performed at other sites for energy < 400 MeV

Measurement for Cu already performed at Kyoto university for 125 MeV proton



Damage rate

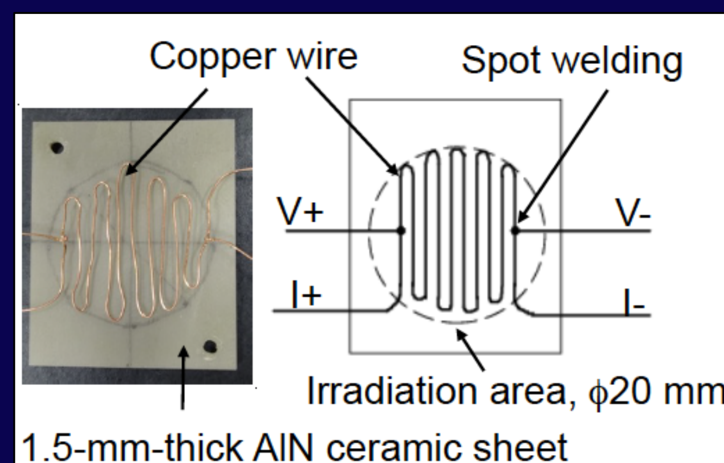
$$\sigma_{exp} = \frac{1}{\rho_{FP}} \frac{\Delta\rho_{metal}}{\phi}$$

J. Nucl. Mater. 49 (1973/74) 161.

$\Delta\rho_{metal}$: Electrical resistivity change(Ωm)

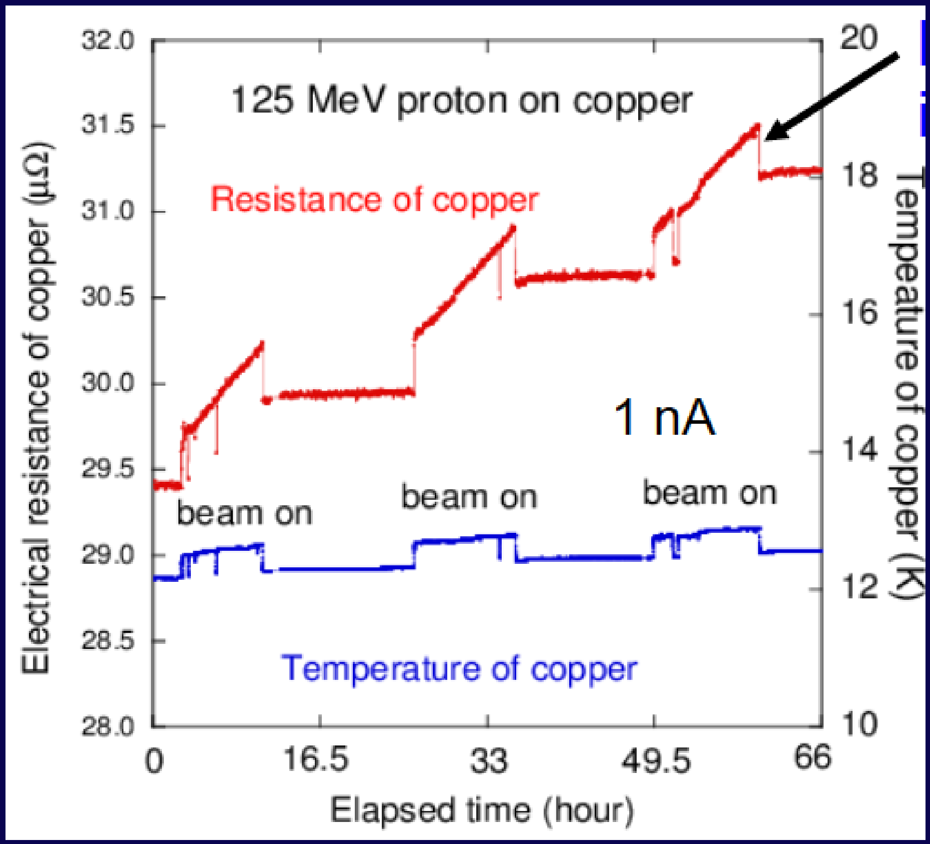
Φ: Beam fluence(1/m^2)

ρ_{FP}: Frenkel-pair resistivity (Ωm)

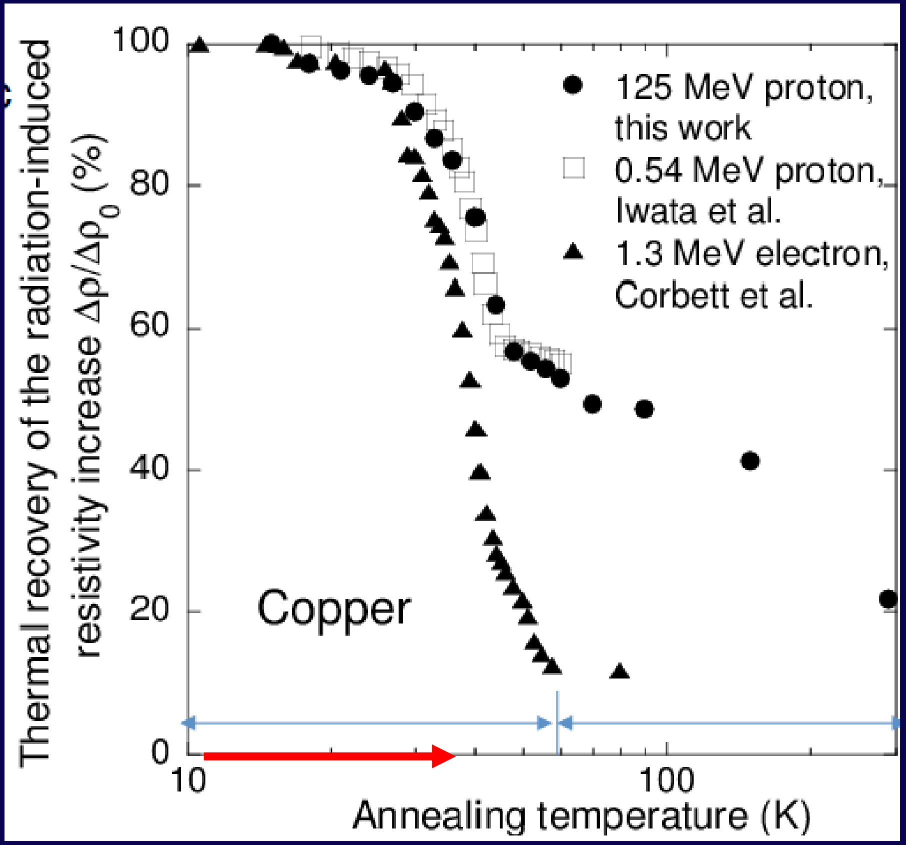


Experimental condition

Resist. and Temp. during beam irrad.



Recovering Resist. by annealing



1 nA x 12h = 3x10^{14} protons
Several shots of beam at MLF

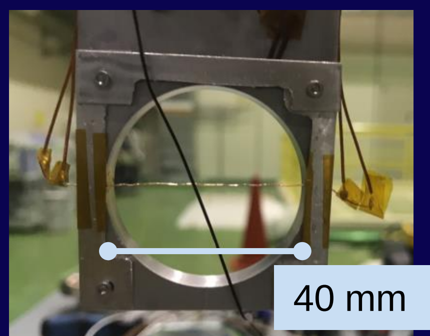
Temp rising ~20 K will be acceptable.
Lower beam intensity with accurate beam shape is preferable.
(1x10^{10} – 2x10^{13} protons/shot)

Y. Iwamoto et al.

Measurement of cross section for 0.4～3 GeV proton

- Experiment at the RCS with change of radiation license
- With changing extraction timing of RCS, kinetic energy of proton can vary from 0.4 to 3 GeV.

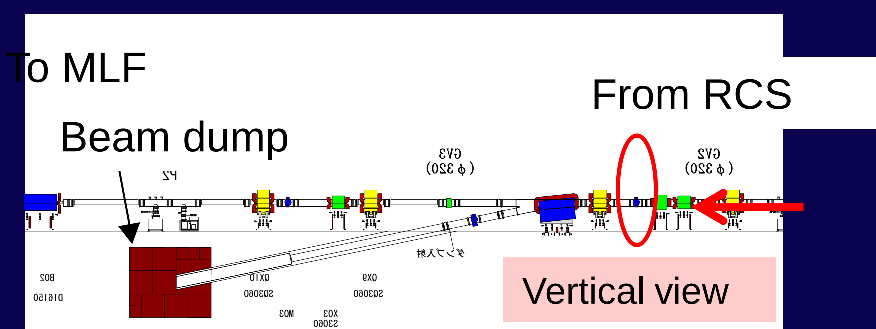
Cu wire (ϕ 0.25 mm) with purity 99.999% annealed 1,350 K

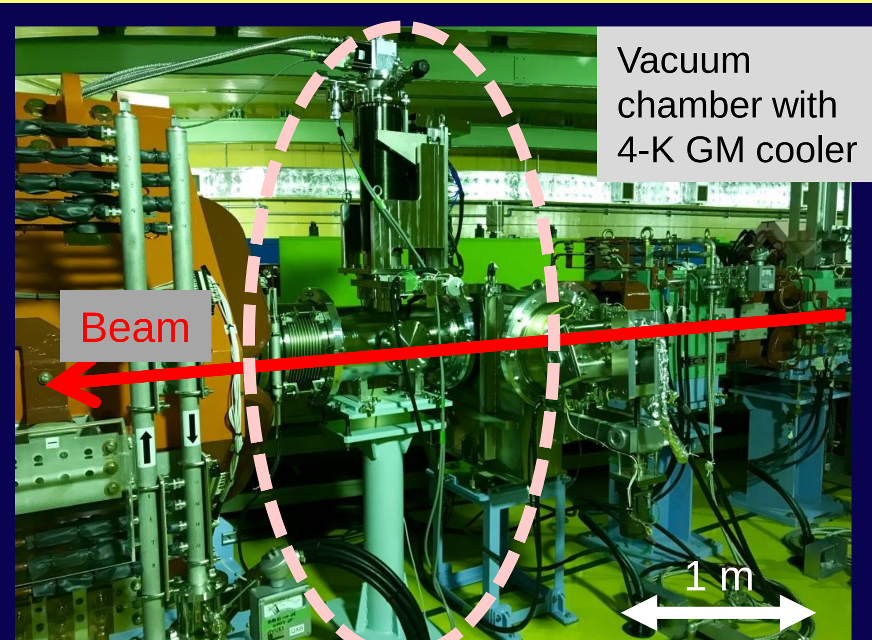


Under cryotemperature (~ 20 K), displacement cross section(σ) was obtained by increase of resistivity ($\Delta\rho_{cu}$) due to proton irradiation with average flux ($\overline{\phi(E)}$)

$$\sigma_{exp}(E) = \Delta\rho_{Cu} / (\overline{\phi(E)}\rho_{FP}),$$

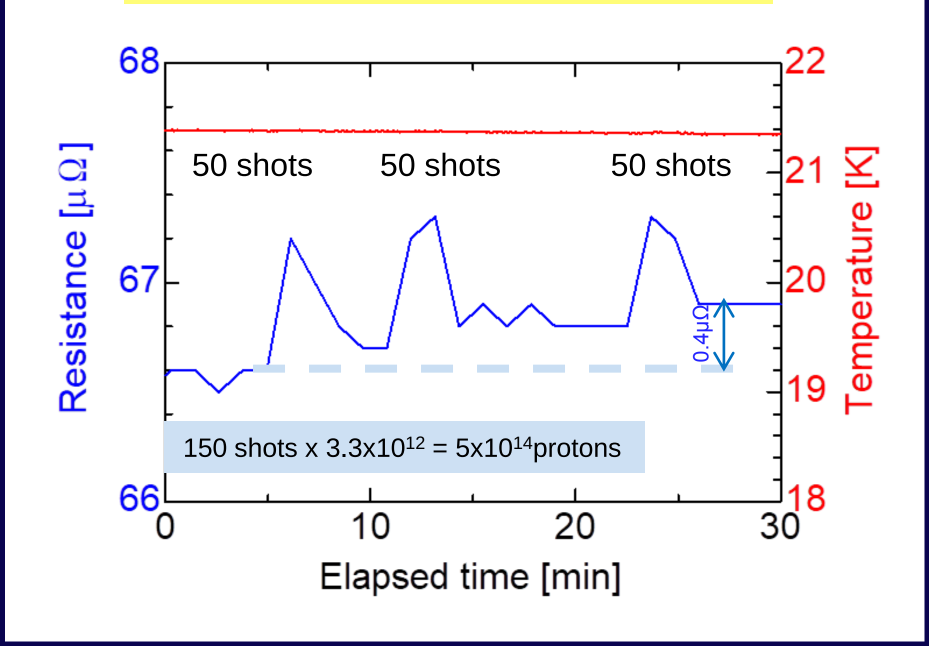
ρ_{FP}: Resistivity change by a Frankel pair (2.2x10^{-6} Ωm)

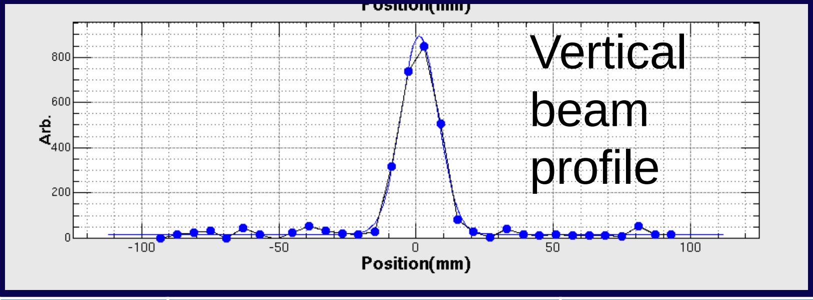




Experimental result

Resistance and temperature during irradiation





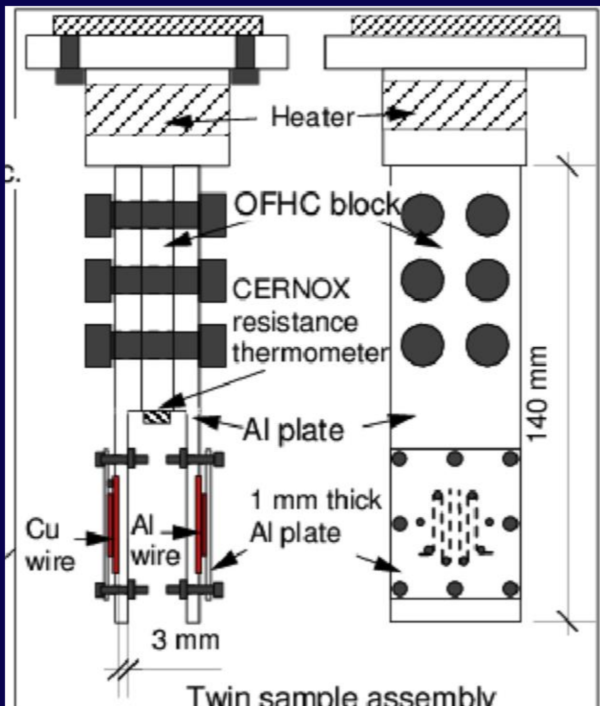
Ep (GeV)	Resistivity change ($\Delta\Omega m^3 X10^{-31}$)	σ_{dpa} (b)
0.8	2.35±0.31	1070±284
1.3	2.32±0.26	1053±270
2.2	2.49±0.21	1133±277
3.0	2.49±0.16	1010±244

$$\sigma_{exp}(E) = \Delta\rho_{Cu}/(\overline{\phi(E)}\rho_{FP}),$$

- Experiment was carried out for protons with 0.8, 1.3, 2.2 and 3.0 GeV
- To obtain resistance with high accuracy, 4 wire with delta mode with averaging was applied.
- Beam width on the sample was obtained with the beam profile monitor.
- Error is dominated with resistivity change by creation of the Frankel pair (23%).

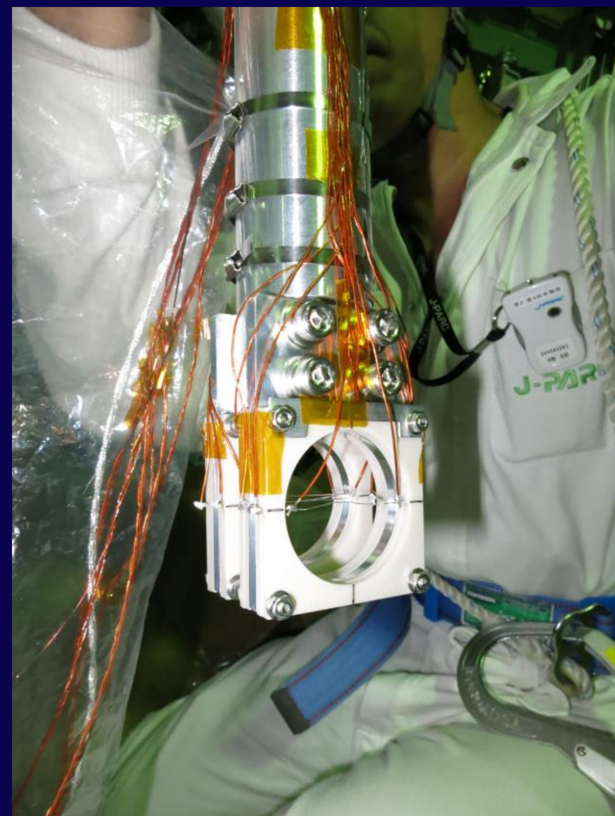
Cascade sample holder

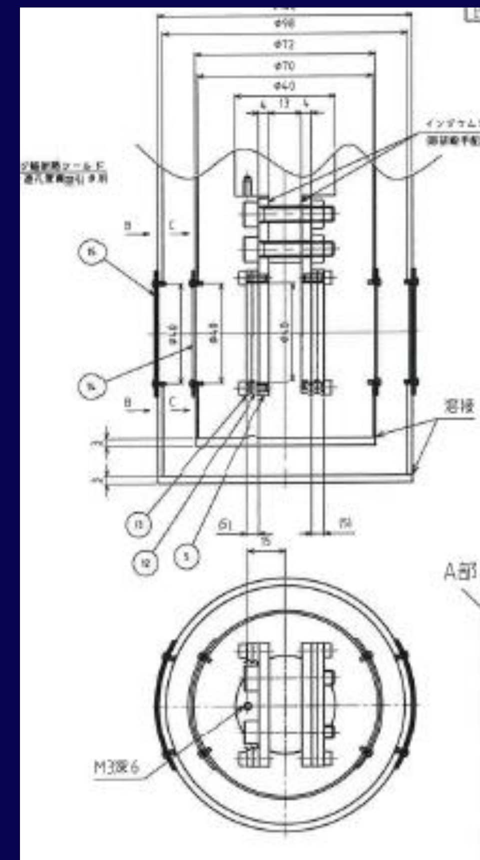
RCNP (Osaka univ.) experiment by Iwamoto



- To obtain Cu and Al data, cascade scheme applied.
- Achieved ~5 K

Experiment at 3NBT in J-PARC





- Cascade target of 4 pieces (Al, Fe, Cu, W) applied
- Temp ~19 K
- In future improved to achieve ~5K

Calculation with PHITS code

- Displacement cross section with PHITS implemented following models
  - Norgett-Robinson-Torrens (NRT) model
  - Athermal recombination corrected (arc) model (Nordlund model)
    - Nature comm. 9, 1084, 2018

NRT (Cu Ed 33 eV):

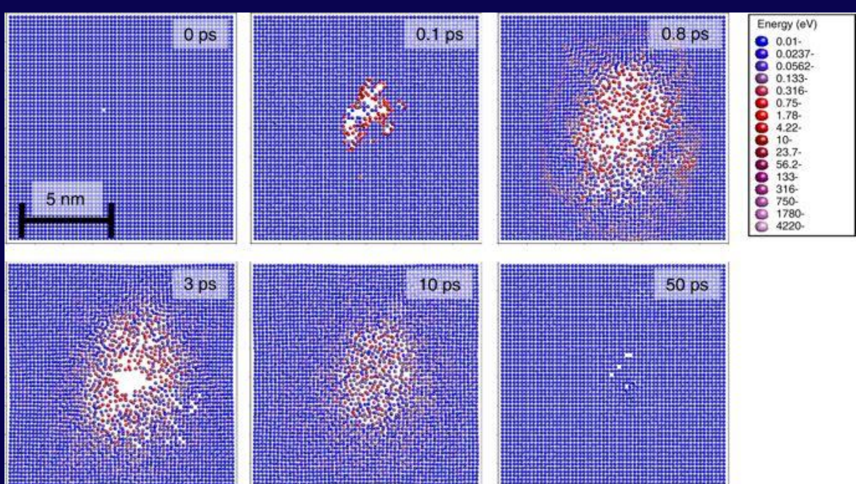
$$N_d(T_d) = \begin{bmatrix} 0 & , & T_d < E_d \\ 1 & , & E_d < T_d < \frac{2E_d}{0.8} \\ \frac{0.8T_d}{2E_d} & , & \frac{2E_d}{0.8} < T_d < \infty \end{bmatrix},$$

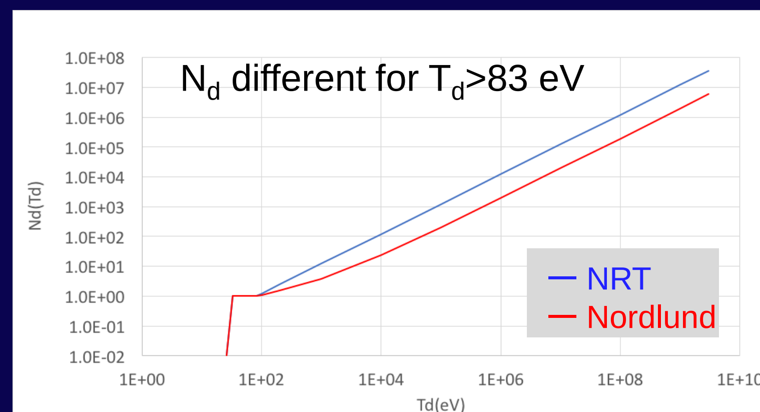
N_d: Number of displacement
T_d: Displ. energy

Nordlund (Cu Ed 33 eV):

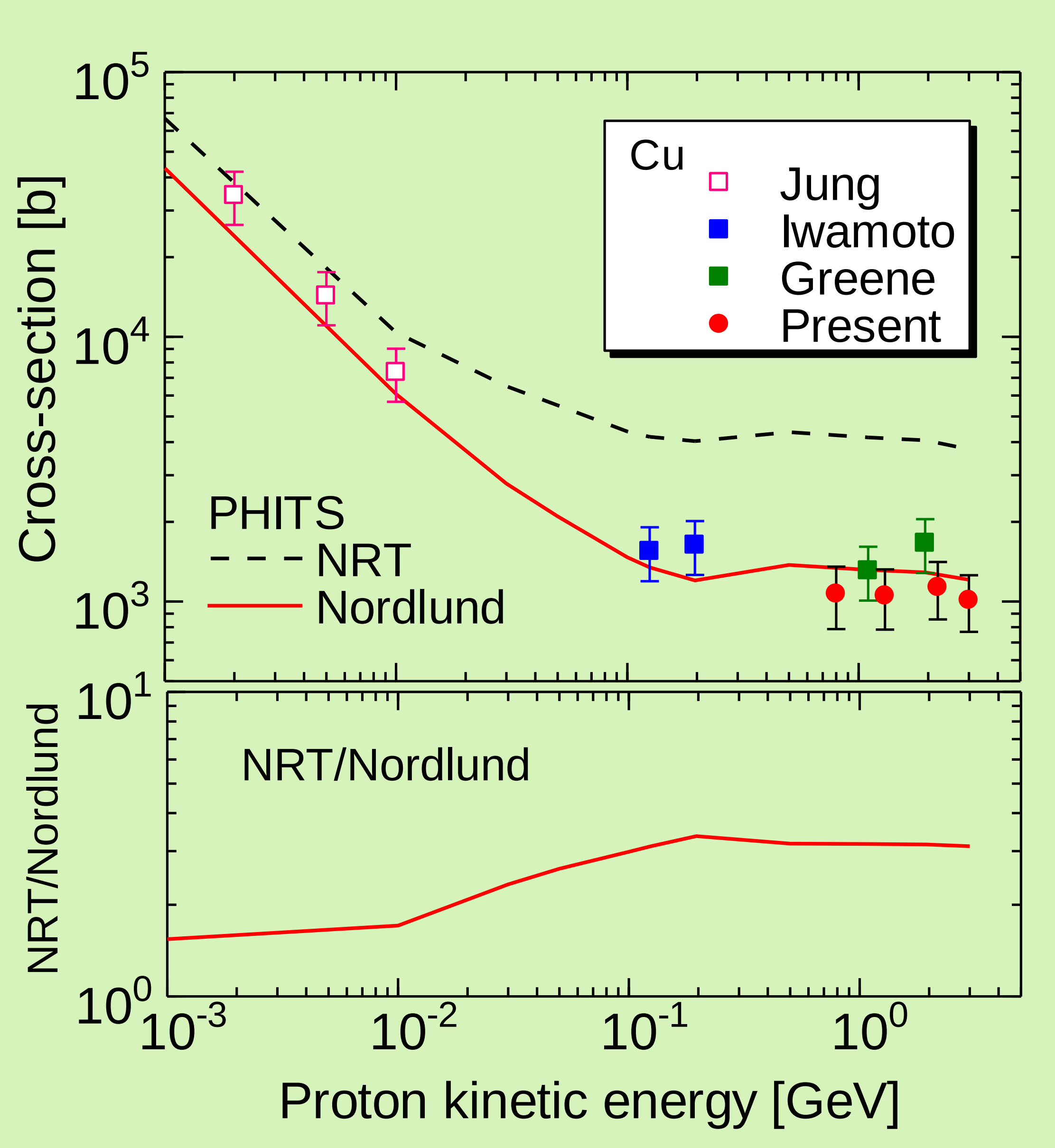
$$N_{d,\mathrm{arcdpa}}(T_d) = \begin{bmatrix} 0 & , & T_d < E_d \\ 1 & , & E_d < T_d < \frac{2E_d}{0.8} \\ \frac{0.8T_d}{2E_d}\xi_{\mathrm{arcdpa}}(T_d) & , & \frac{2E_d}{0.8} < T_d < \infty \end{bmatrix}$$

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





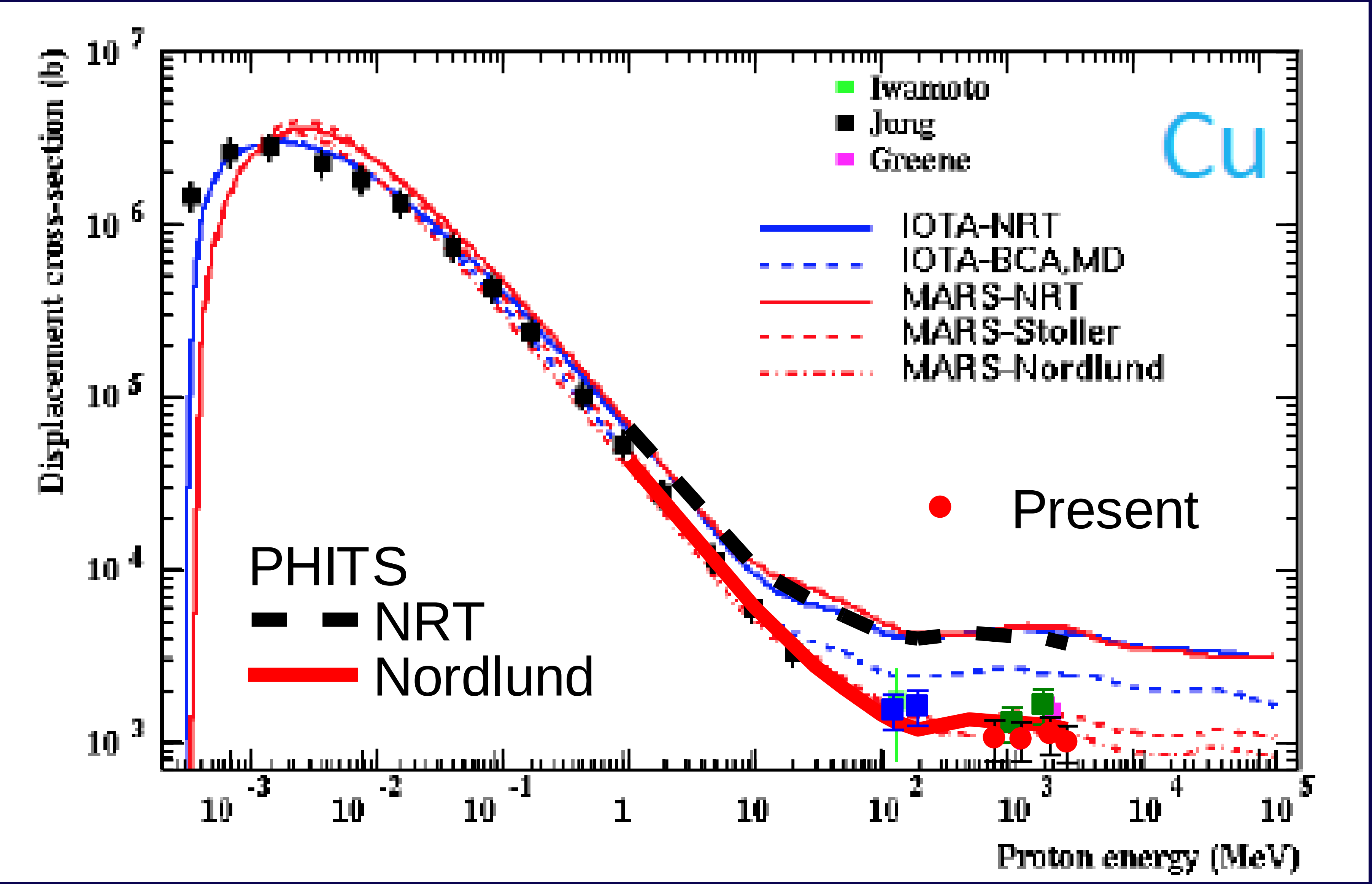
Comparison with models calculation



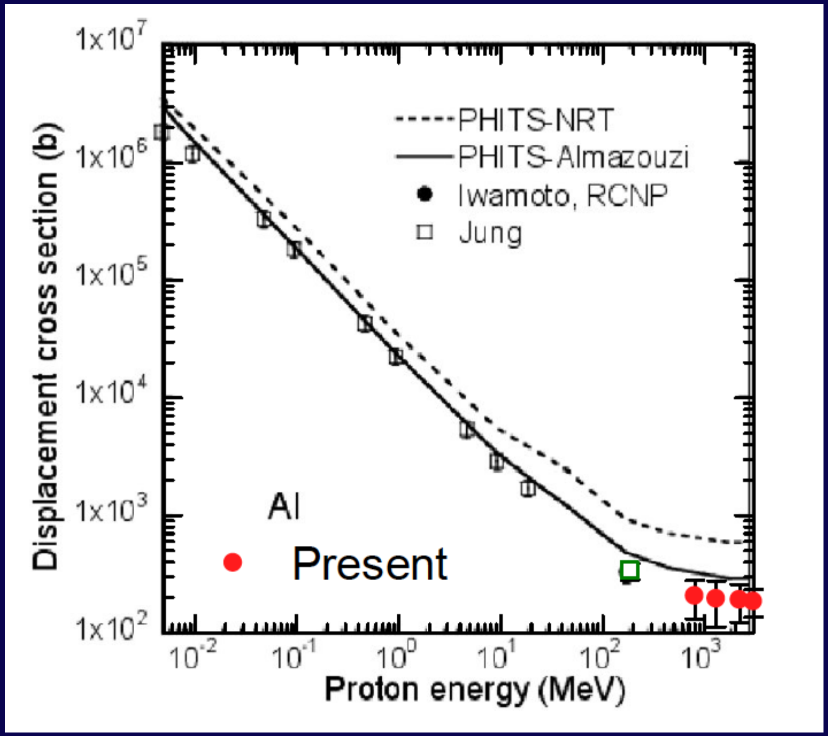
- NRT model overestimates ~ x3
- arc model of Nordlund good agreement

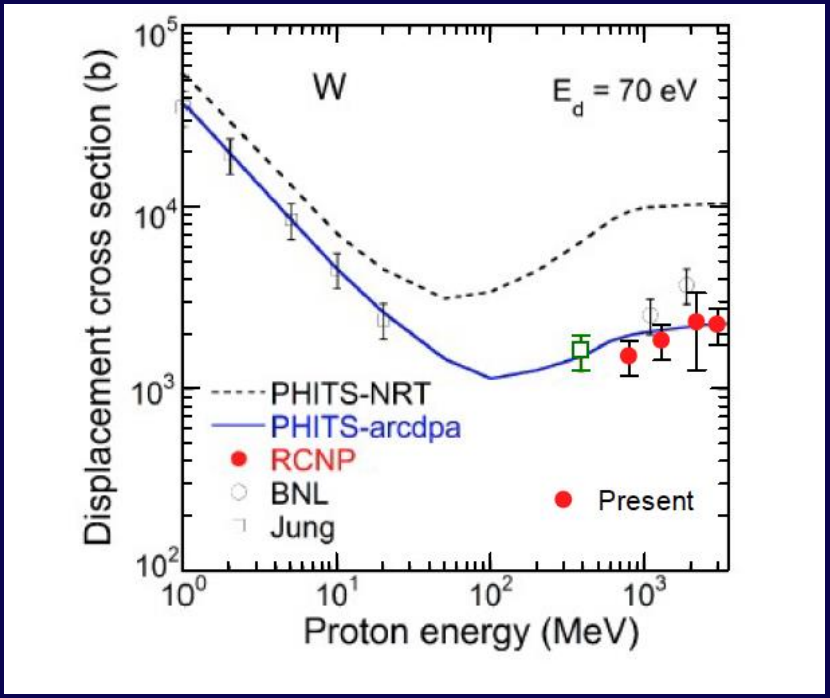
- Present data imply that the DPA should be calculated with Nordlund model.
- Ratio of NRT/Nord is constant above ~200 MeV.

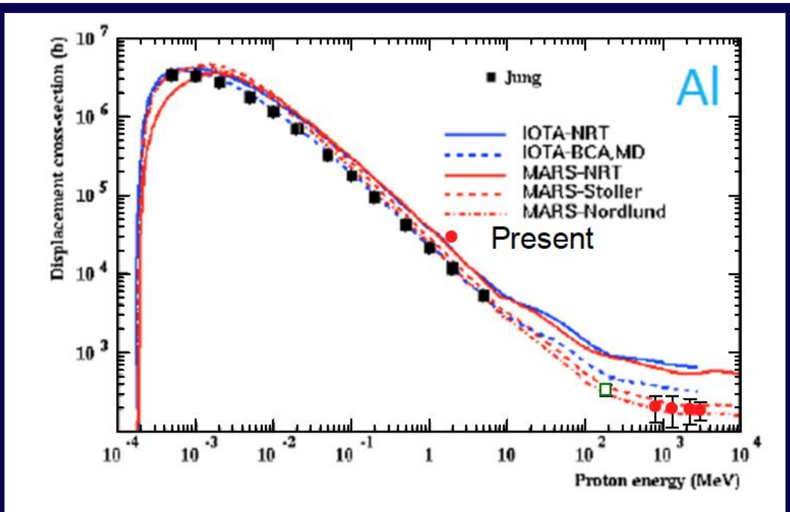
Comparison with MARS

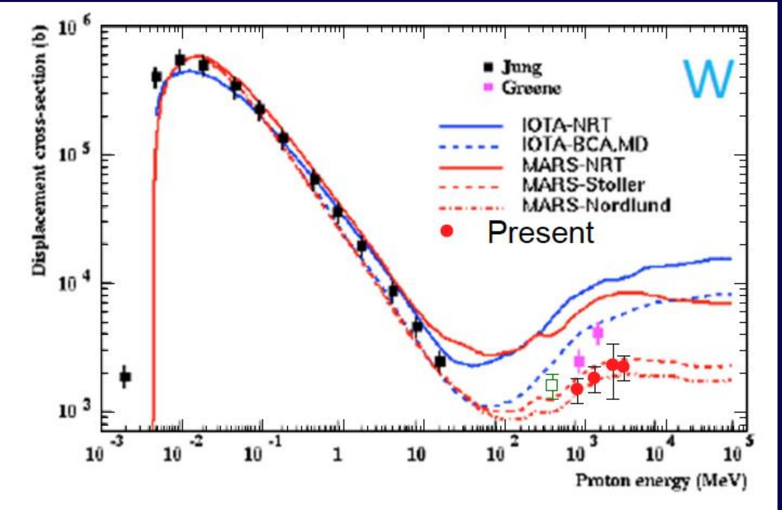


Displacement cross section for Al and W





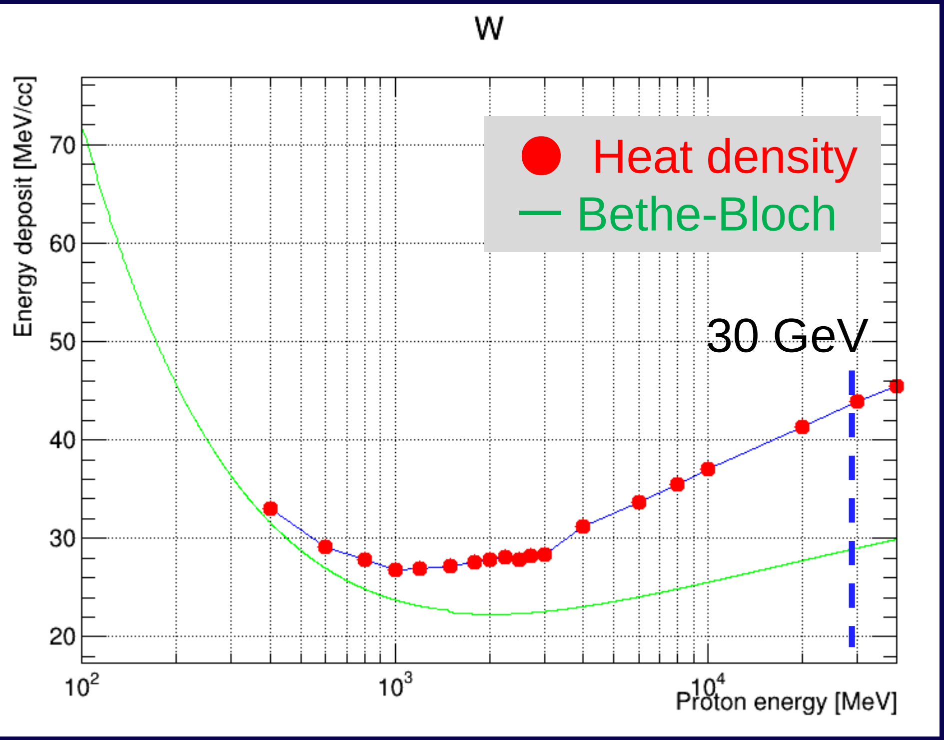


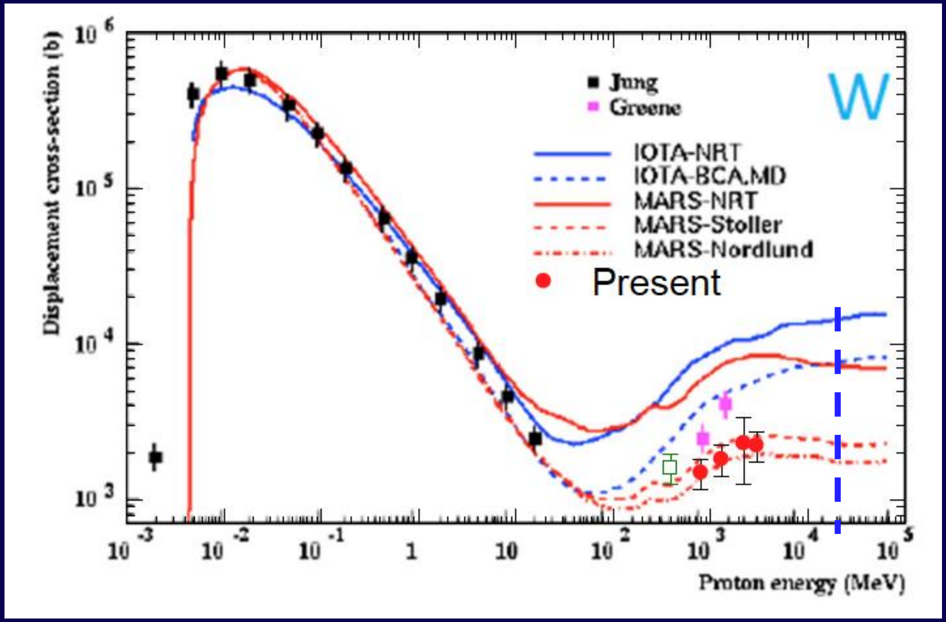


Displacement cross section above 30 GeV

As increase proton kinematic energy, heat density on material (W) increase

Regardless of the kinematic energy for Ep>30 GeV, displacement cross-section sustains almost constant

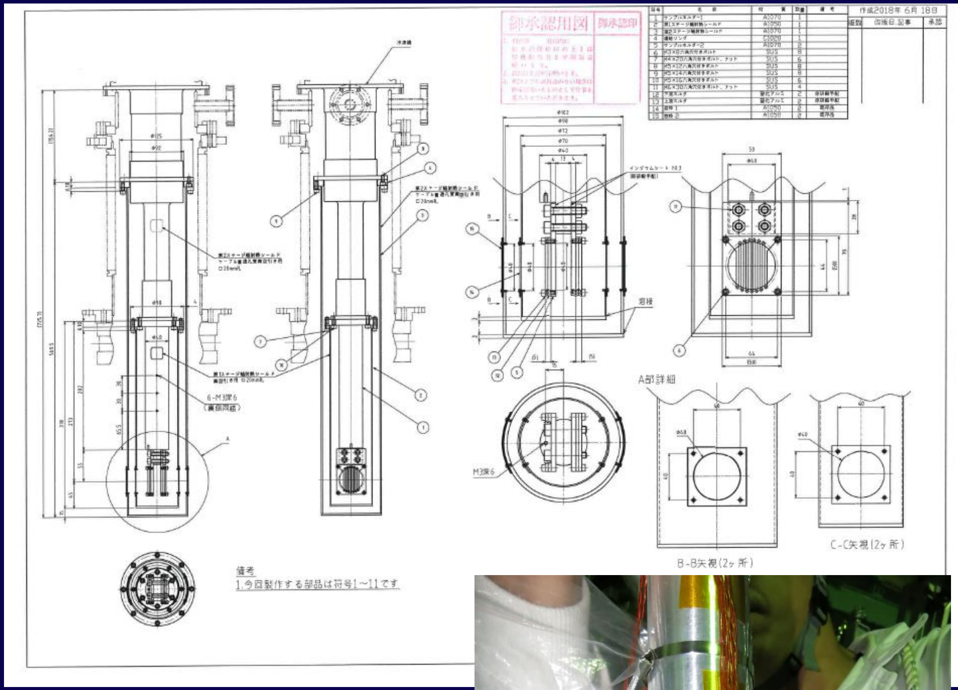


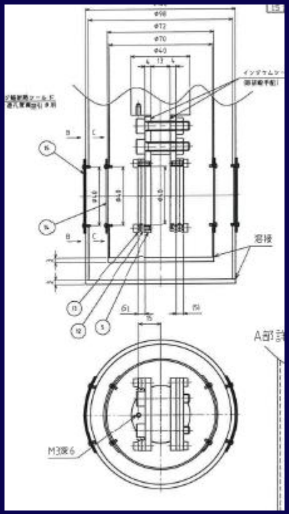


To solve the curious puzzle, the experiment should be carried out for high energy region.

Disp. cross-section experiment at HiRadMat

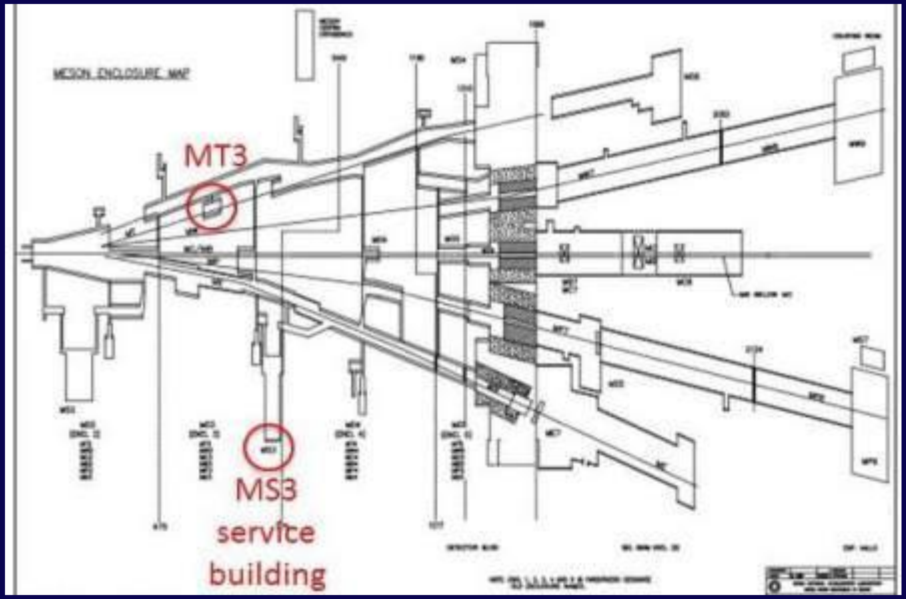
- Relatively easy experiment
- Equipment
  - GM cryo-cooler
  - Vacuum chamber
    - Those had be utilized at previous exepeiment at HiRad
  - Instruments to observe sample resistance
- Instruments can be placed at near the sample with low radiation (TT61)
- Requirement of experiment
  - Beam monitor and properties
  - Beam scan procedure
- Almost instruments are prepared. All we need is sample, sample holder and budget of travel.





Experiment at FNAL

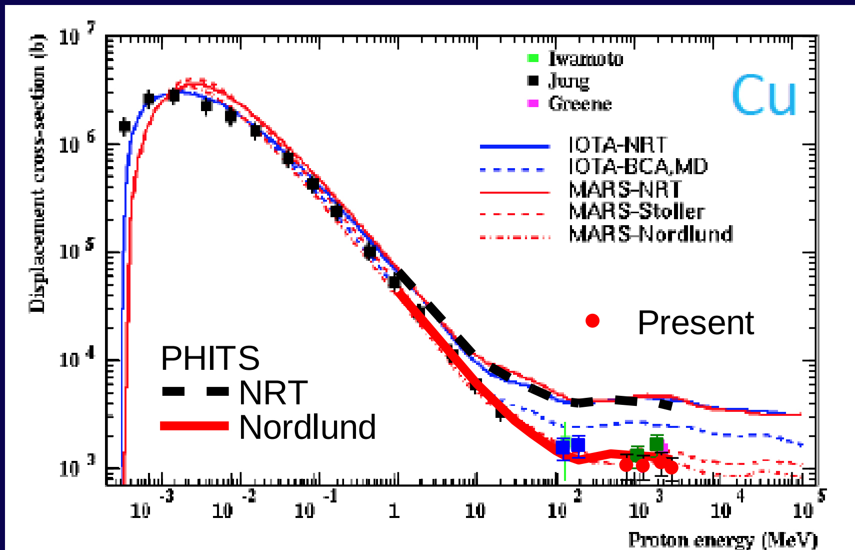
- Budget already approved by MEXT for some of our collaborators
- On 2021, the experiment will start for 120 GeV proton.

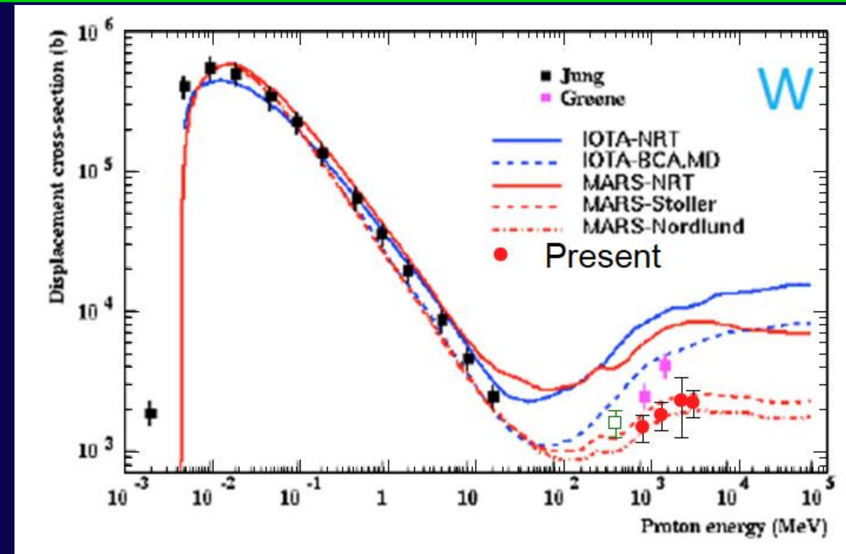


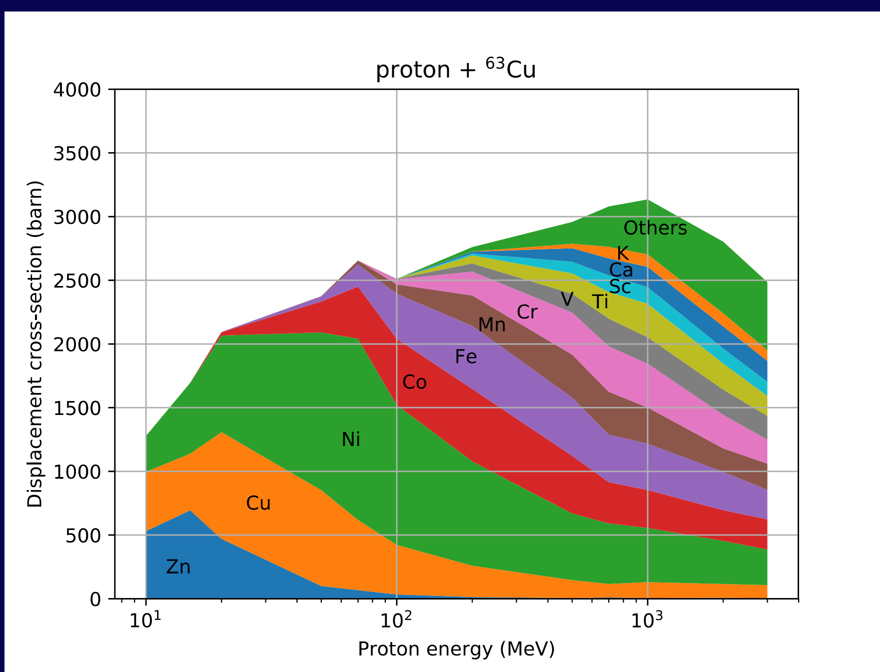
Summary

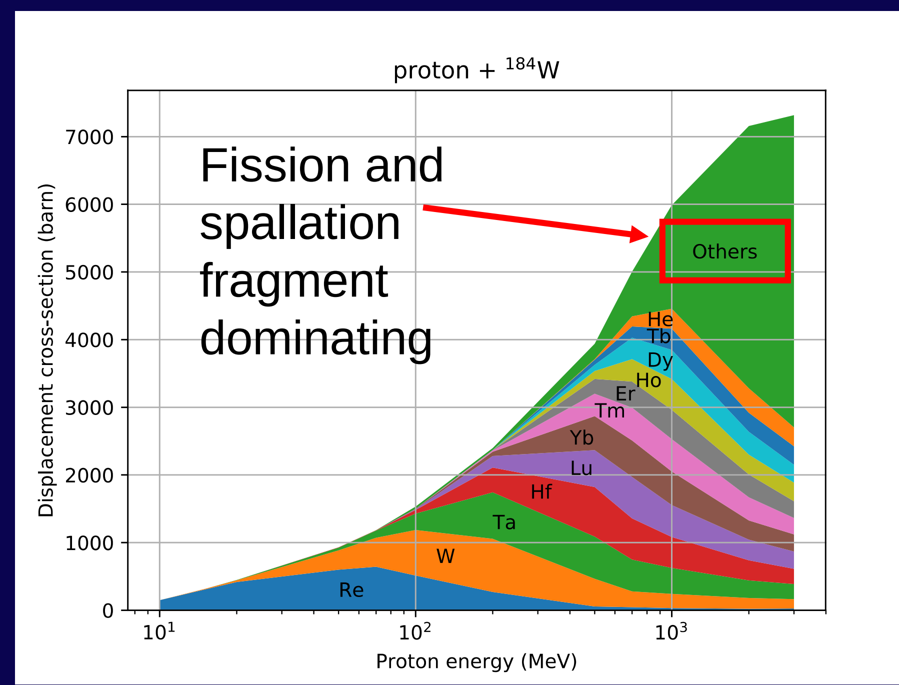
- Displacement cross section, measurement for 0.4～30 GeV protons has conducted in J-PARC.
- At FNAL, displacement cross section experiment for 120 GeV will be carried out.
- To obtain the displacement cross section at 400 GeV, which is important for HL-LHC, the experiment should be performed at HiRadMat.

Contribution for displacement







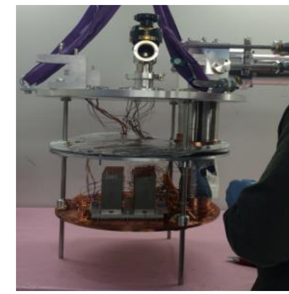


HiRadMat at a Glance

- Originated from the LHC Collimation Project, due to requirements for a facility capable for "testing accelerator equipment with beam shock impacts[1] using high power LHC type beams[2]".

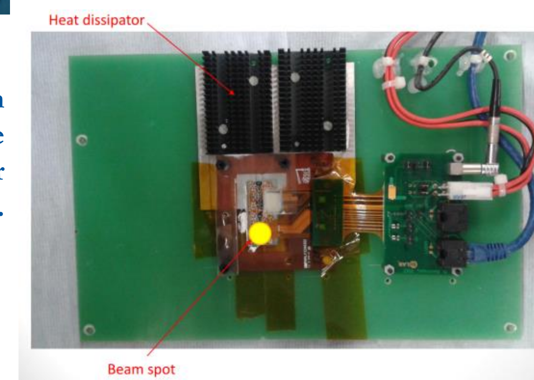
- The High Radiation to Materials (HiRadMat) testing facility took its first beam in 2012 and has continued to deliver pulsed, high intensity, LHC-type beam to over 40 experiments.

SextSc investigated damage limits of superconducting magnets, via use of cryostat to reach temperatures ~4K.



BLM2 studied the signal linearity and response, calibration, saturation and comparison of different types of Beam Loss Monitors

ATLAS investigated radiation hardness and damage threshold of pixel tracker detectors.



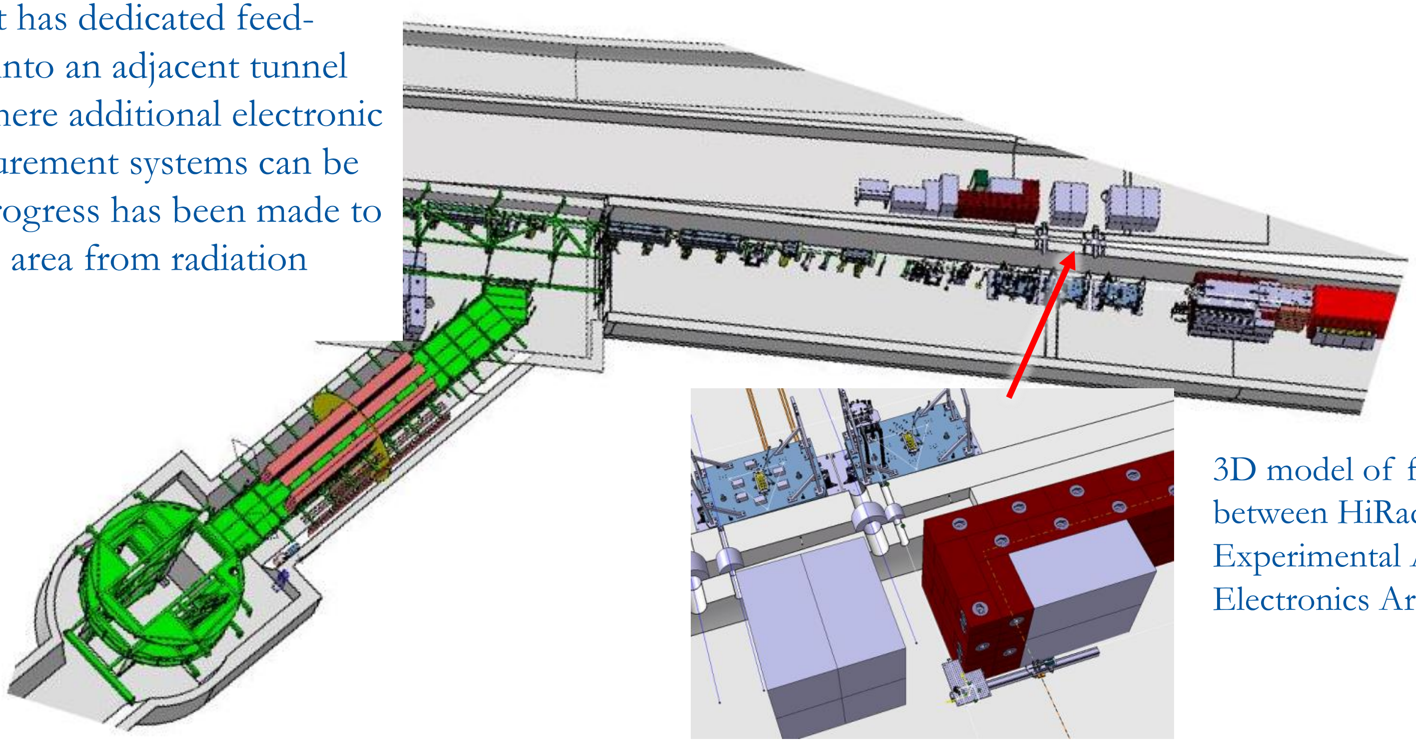
[1] http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/HiRadMat.htm

[2] R. Assmann et al., "User Requirements for a Test Facility with High Power LHC Type Beam", 2009, EDMS No: 1130296

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.



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