Measurement of displacement cross section for high-energy protons

(J-PARC/JAEA) Shin-ichiro Meigo

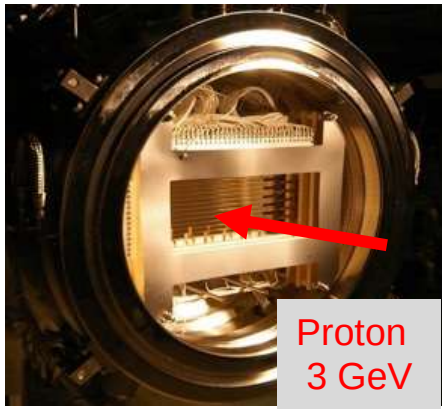
Collaborators:
(J-PARC/JAEA) Y. Iwamoto, H. Matsuda, H. Iwamoto, S. Hashimoto, F. Maekawa
(J-PARC/KEK) M. Yoshida, T. Nakamoto, S. Makimura, T. Ishida
(Kyoto Univ) A. Yabuuchi, T. Yoshiie
(FNAL) K. Yonehara, Z. Liu, K. Lynch
(CERN) N. Charitonidis, A. Goillot, P. Simon, V. Stergjou, E. Andersen

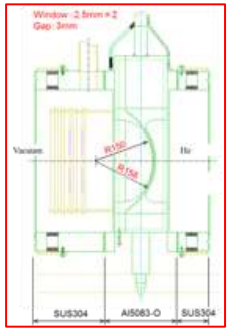
Outlook

- Introduction of displacement cross section
- Measurement of displacement cross section
  - J-PARC for 0.4 – 30 GeV
  - FNAL for 120 GeV
  - Plan at CERN for 440 GeV
- Summary

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)

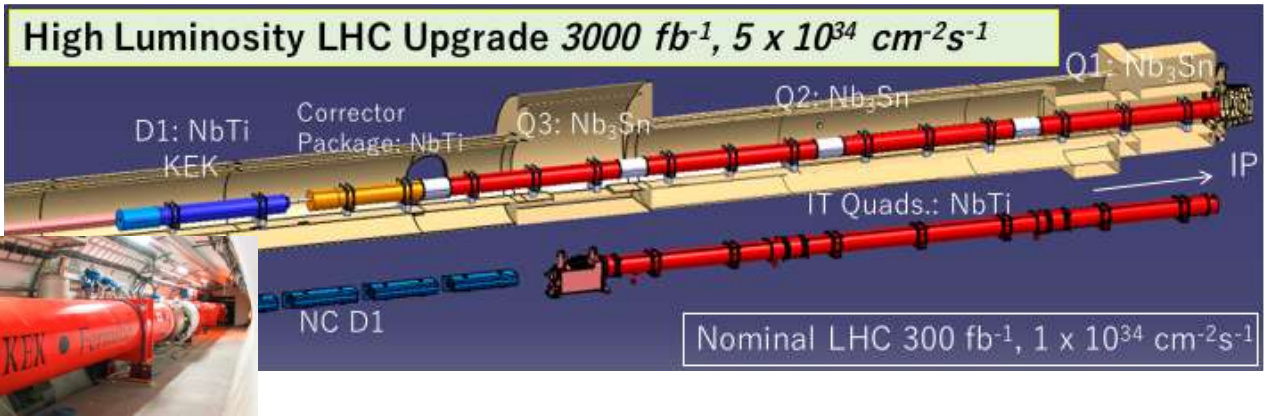




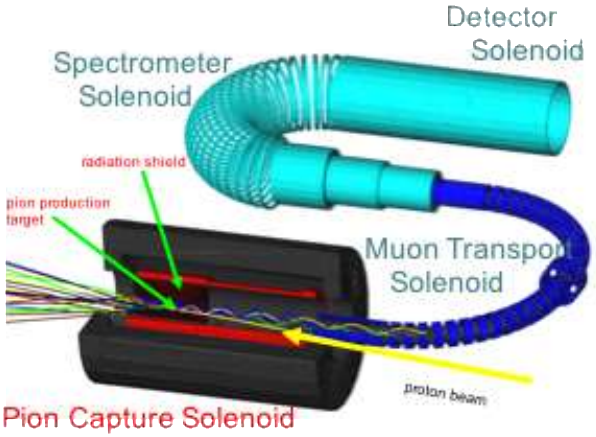
T2K beam window
Titanium alloy (Ti-6Al-4V)

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

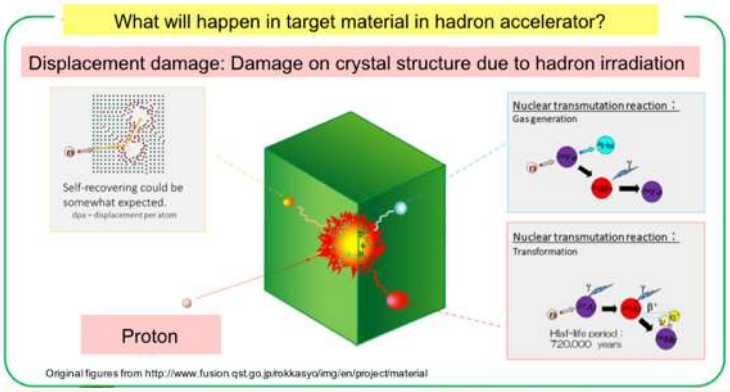
- Resistivity change due to radiation is crucial for Superconductor(SC) magnet sustaining damage.

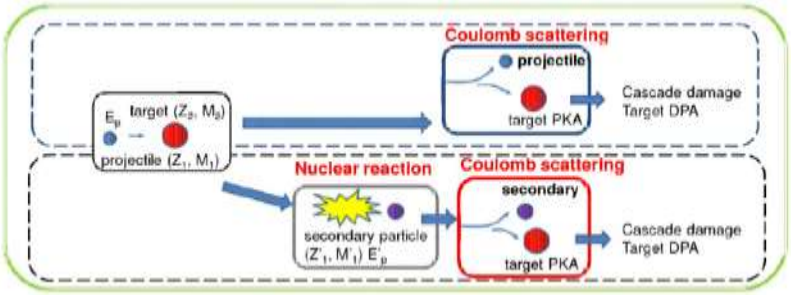


SC magnet system in beam line of COMET (J-PARC)

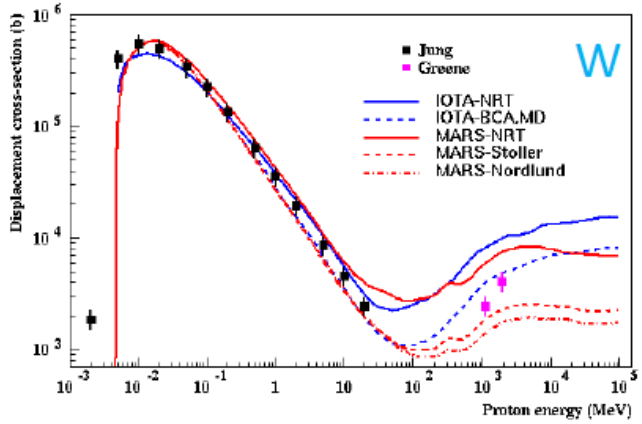


Displacement cross section (X-sec)





N. Mokhov, HPTW2016



- dpa (displacement per atom):
  Widely used as damage index for fission and fusion reactors, and accelerator fac.
  dpa = Fluence x displacement X-sec
- Lack of data above 20 MeV: Difficult validation of calculation models

⇒ Experiments started at J-PARC

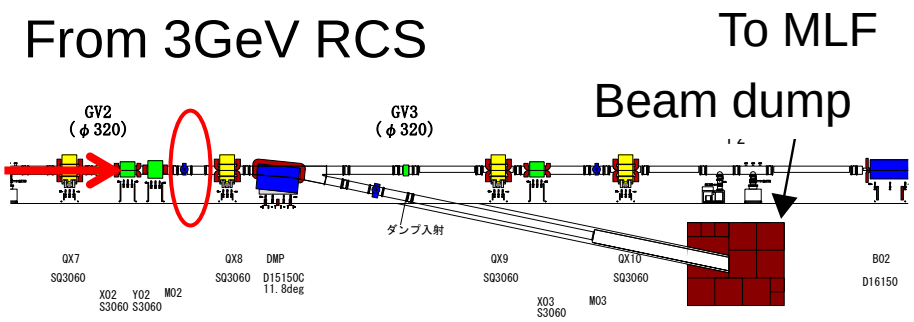
Displacement cross section:
- Following Matthiessen's low obtained by observation of electrical resistivity [Ω/m].
- To sustain the damage in sample, cryocooling is required for T < 20 K.

$$\sigma(E) = \Delta\rho/(\phi \cdot \rho_f)$$

σ(E): Displacement cross section [b]
Δρ: Change of resistivity [Ω/m]
Φ: Fluence of incident protons [/cm^2]
ρ_f: Resistivity change by Frenkel pair [Ω/m]

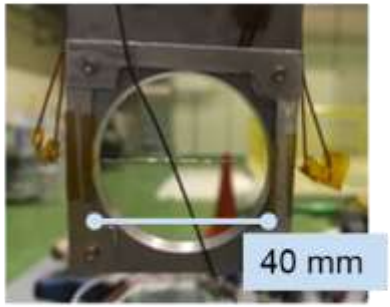
Displacement cross section at J-PARC

- Instruments equipped upstream of beam dump for 3GeV synchrotron (RCS Rapid Cycling Synchrotron) : available various kinetic energy of proton 0.4~3 GeV
  - Precious beam turning and monitor (beam scanning made for alignment)
  - Achieved ~4 K (but used ~8 K to maintain normal conducting at sample)

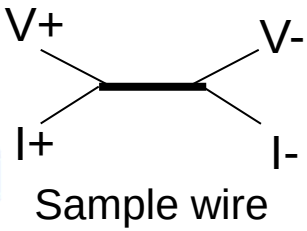


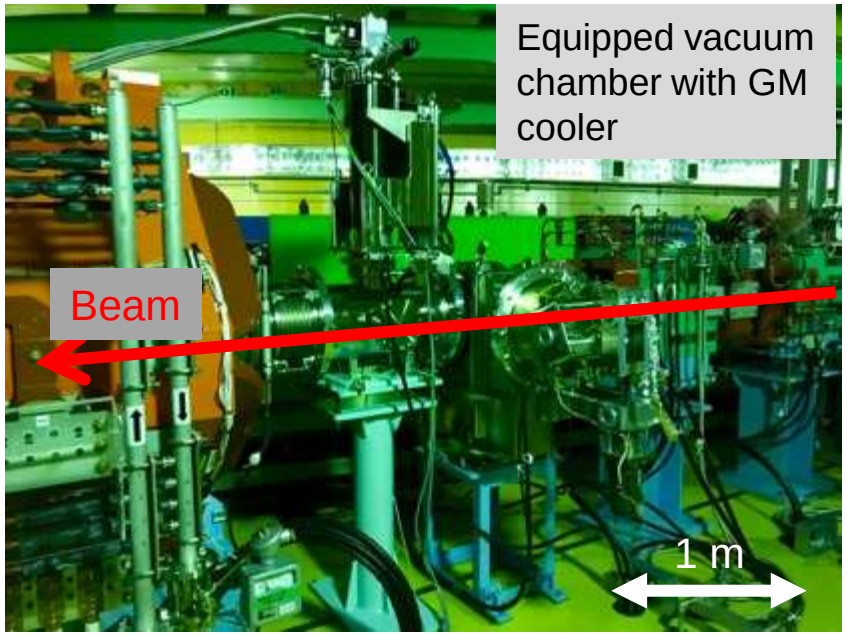
Cryocooler and sample

Nb wire (Φ 0.25 mm) 99.9%



To obtain precious resistance
4 electrodes applied

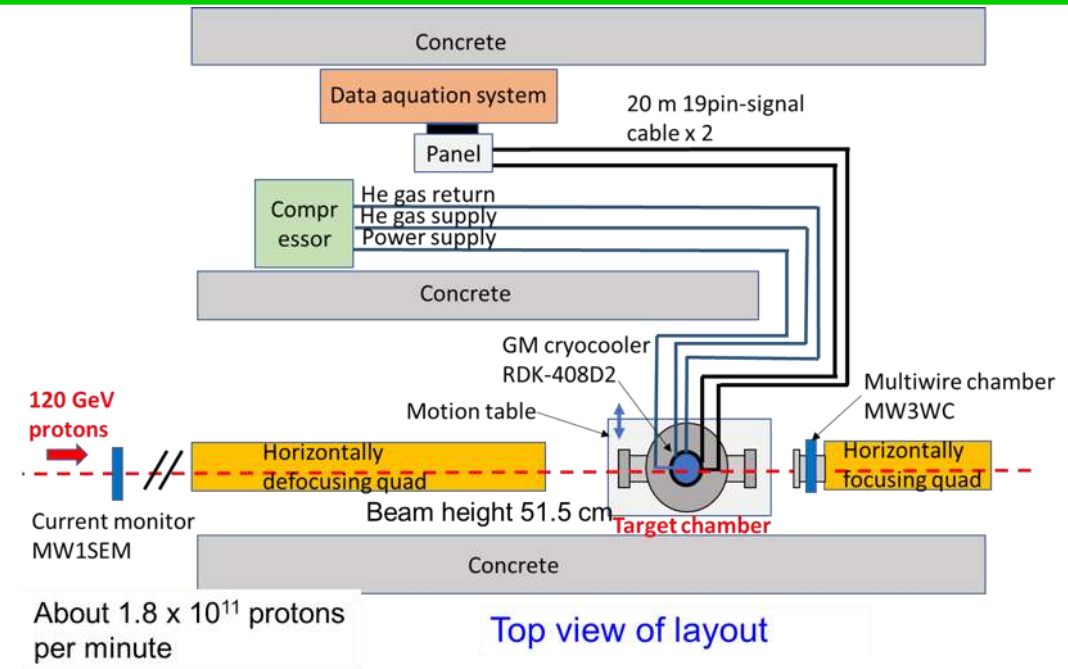




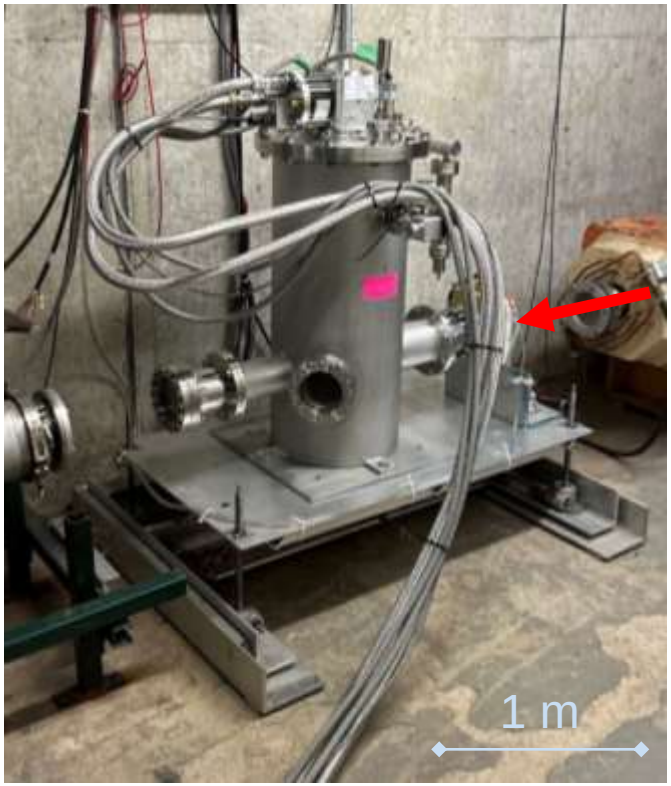
H. Matasuda, J. Nucl Sci, 57:10 1141 – 1151 (2020).

Experiment at FNAL

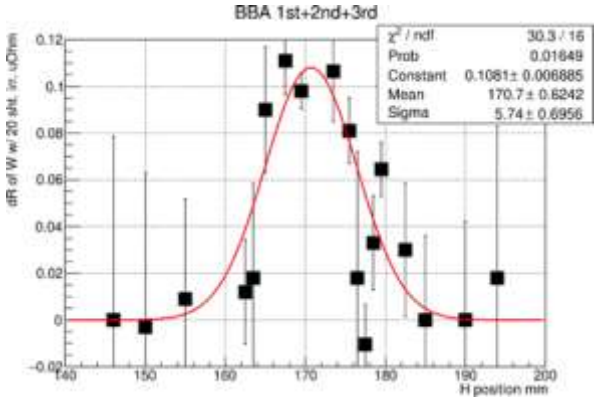
Similar manner of J-PARC experiment was applied at Fermilab Beam Test Facility (FTBF) M03.



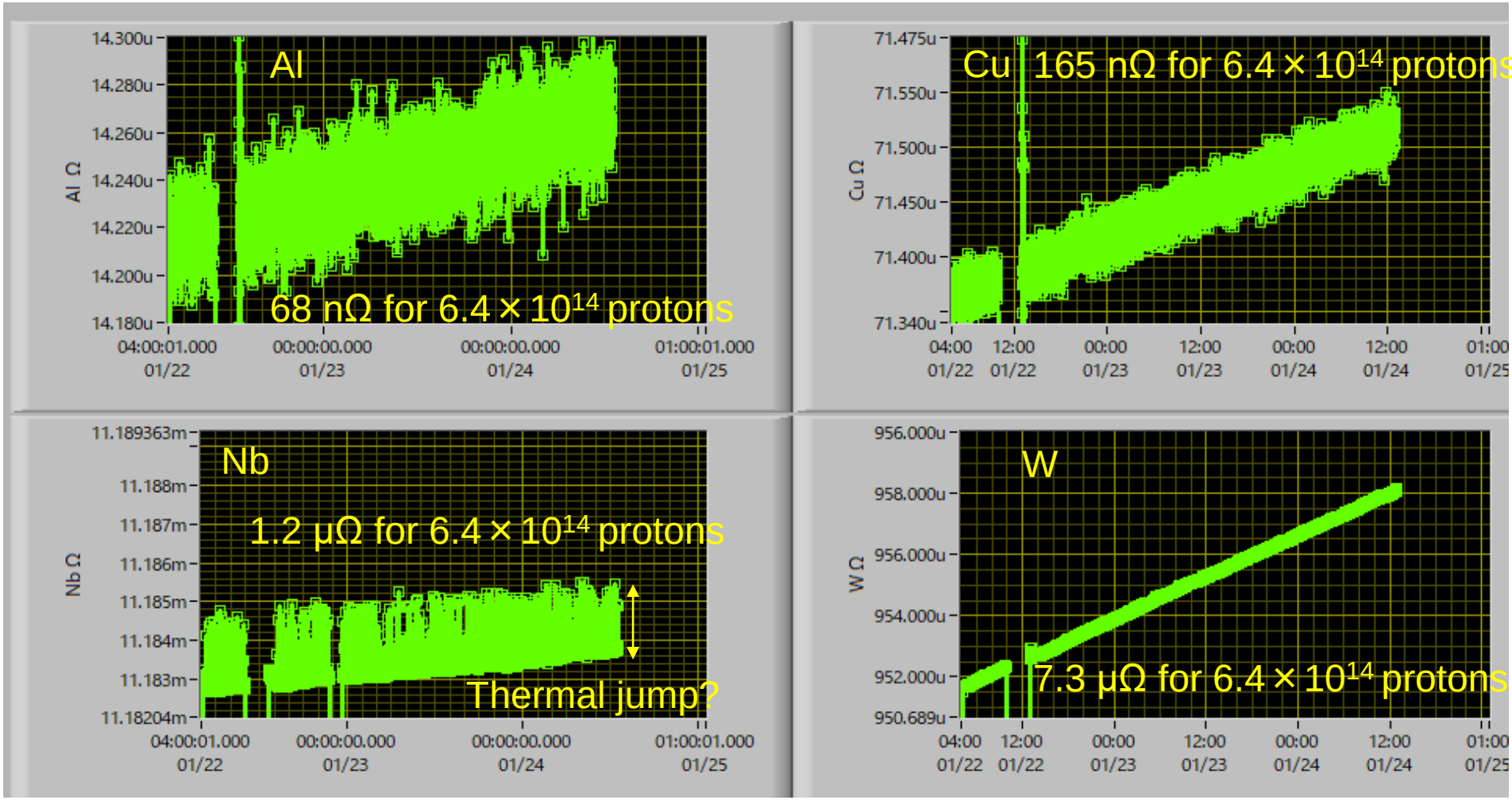
GM cooler RDK-408D2



Horizontal beam position and width were scanned by using motion table.



Electrical resistance change



Electrical resistance changes of metals at 8 K under 120 GeV proton irradiation

Disp. X-sec calculation in PHITS

- Cross section given by PHITS $\sigma_{disp-calc}(E) = \sum_i \int_{E_d}^{T_i^{max}} N_d(T_i) \frac{d\sigma}{dT_i} dT_i$,

  Displace number
  i : particle species
  - Widely utilized Norgett-Robinson-Torrens (NRT) model
  - arc-dpa model
    - Nordlund and Konobeyev's parameter applied

arc: Athermal Recombination Correction

Displace number by NRT model (N_d)

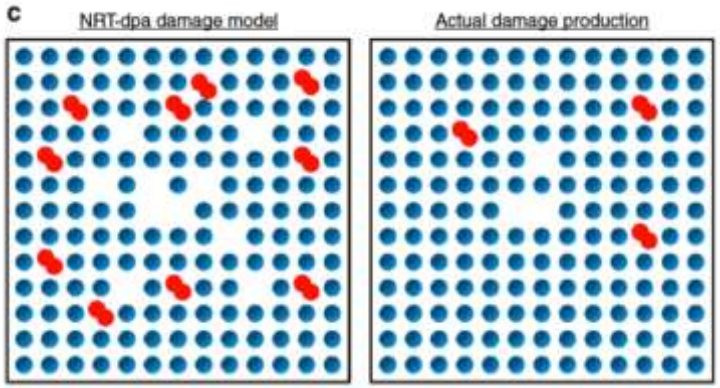
$$N_d(T_d) = \begin{cases} 0 & , \quad T_d < E_d \\ 1 & , \quad E_d < T_d < \frac{2E_d}{0.8} \\ \frac{0.8T_d}{2E_d} & , \quad \frac{2E_d}{0.8} < T_d < \infty \end{cases},$$

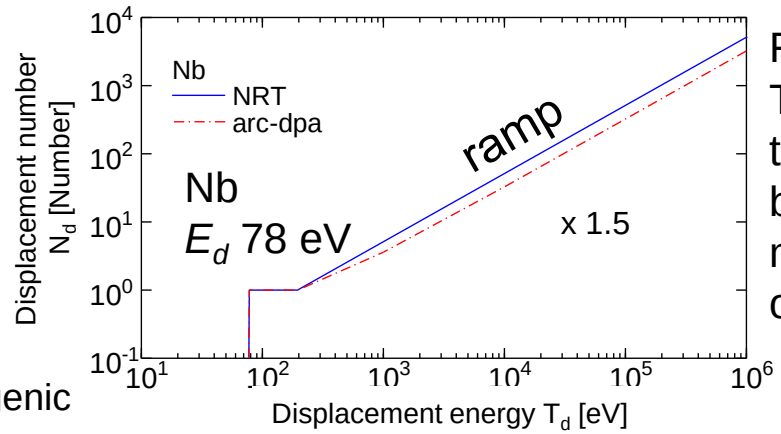
T_d: Displacement energy

Displace number by arc-dpa model ($N_{d\ arcdpa}$)

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

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

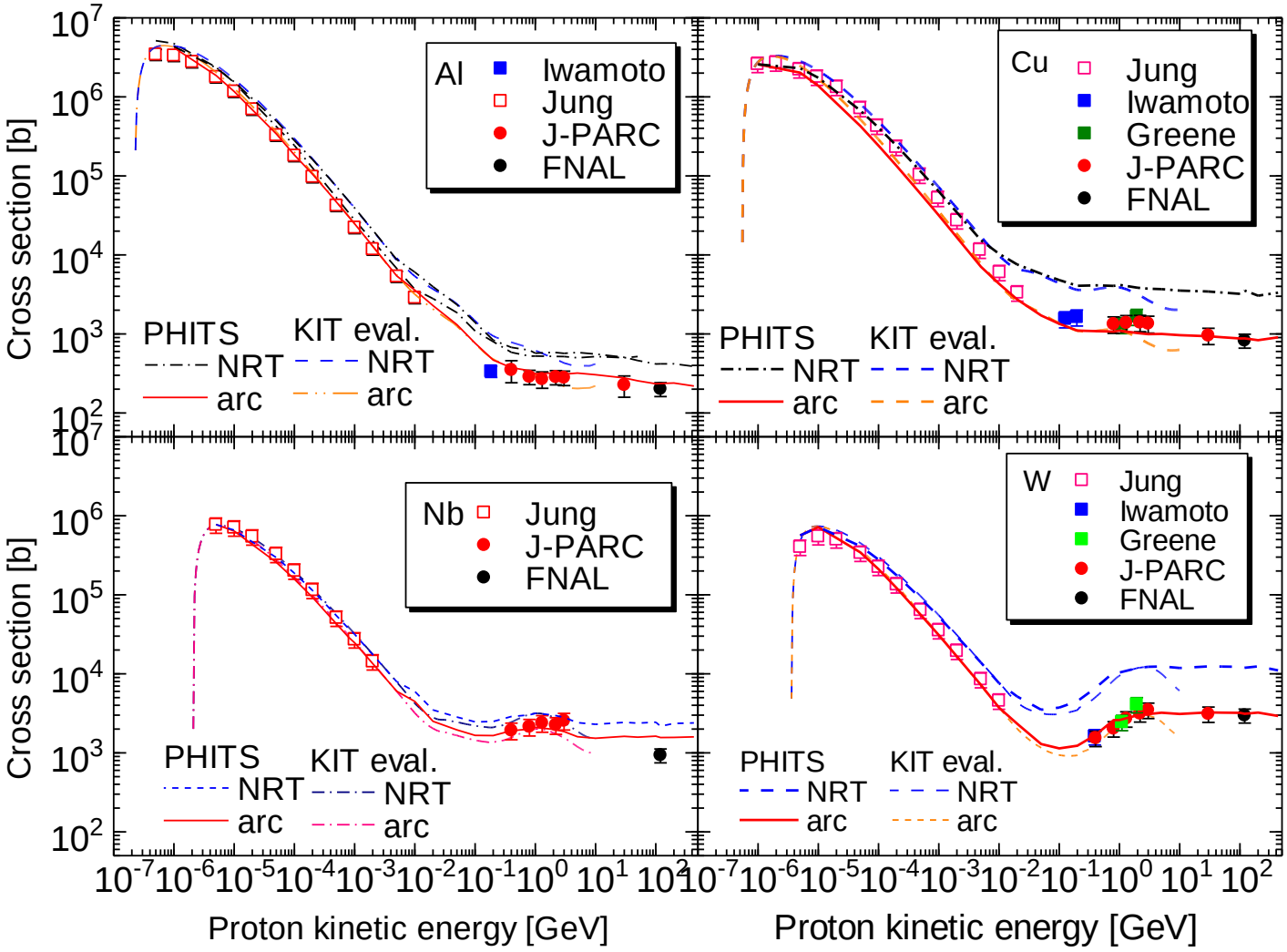




For ramp region $T_d > 2E_d/0.8$, the difference between the two models is a factor of 1.5.

arc-dpa: instantaneous recombination at cryogenic

Comparison with calculation

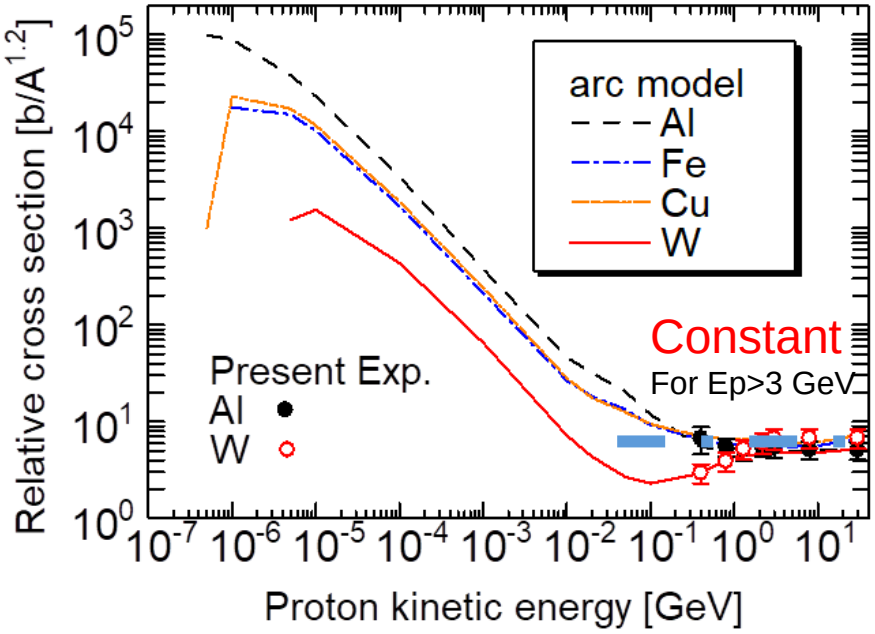


Similar tendency of NRT and arc-dpa calculation for Ep<120 GeV

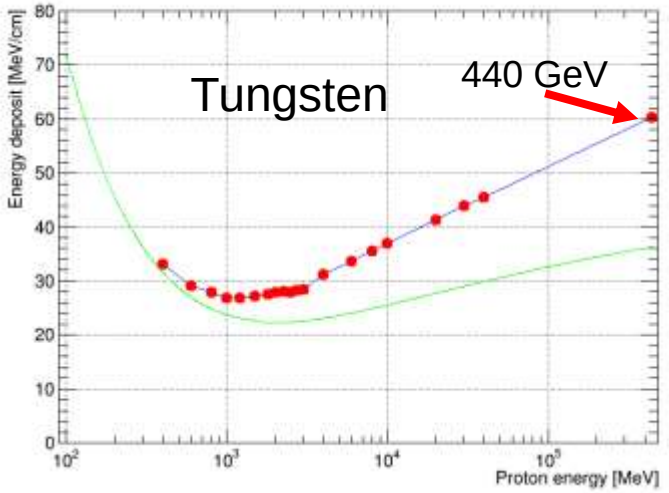
Nb ??
Hopefully try to measure by another chance

H. Matsuda, JNST 57 1141 (2020)
S. Meigo, EPJ Web of conf 239 06006 (2020)

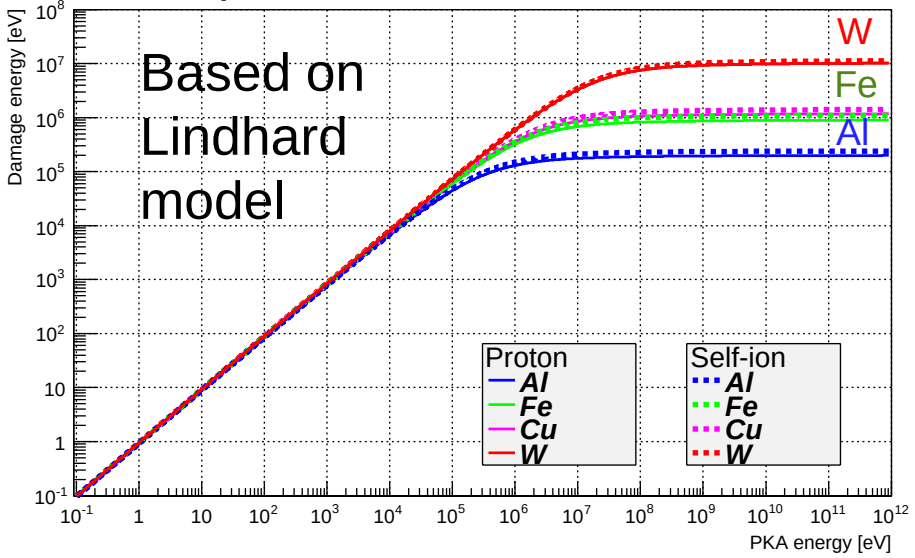
Discussion of cross section in high-energy region



Energy deposition density on materials



Displacement number v.s. PKA



Speculation of $A^{1.2}$ law

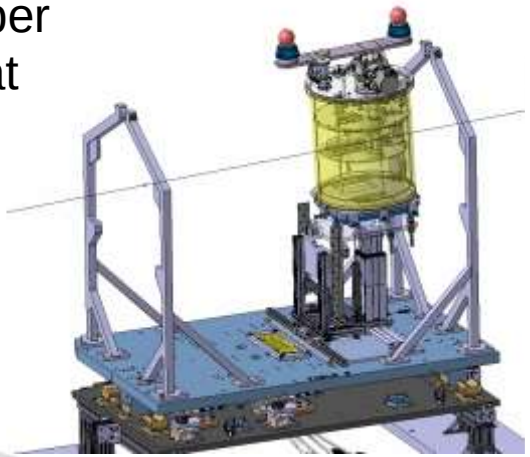
- Reaction X-sec $A^{2/3}$
- Disp. Number (Sat.) $A^{1.6}$
- Outgoing energy (PKA) A^{-1}
- Overall $\sim A^{1.2}$

Applicability should be confirmed for further higher energy (*i.e.*, Ep 440 GeV).

Ep 440 GeV at HiRadMat in CERN (plan)

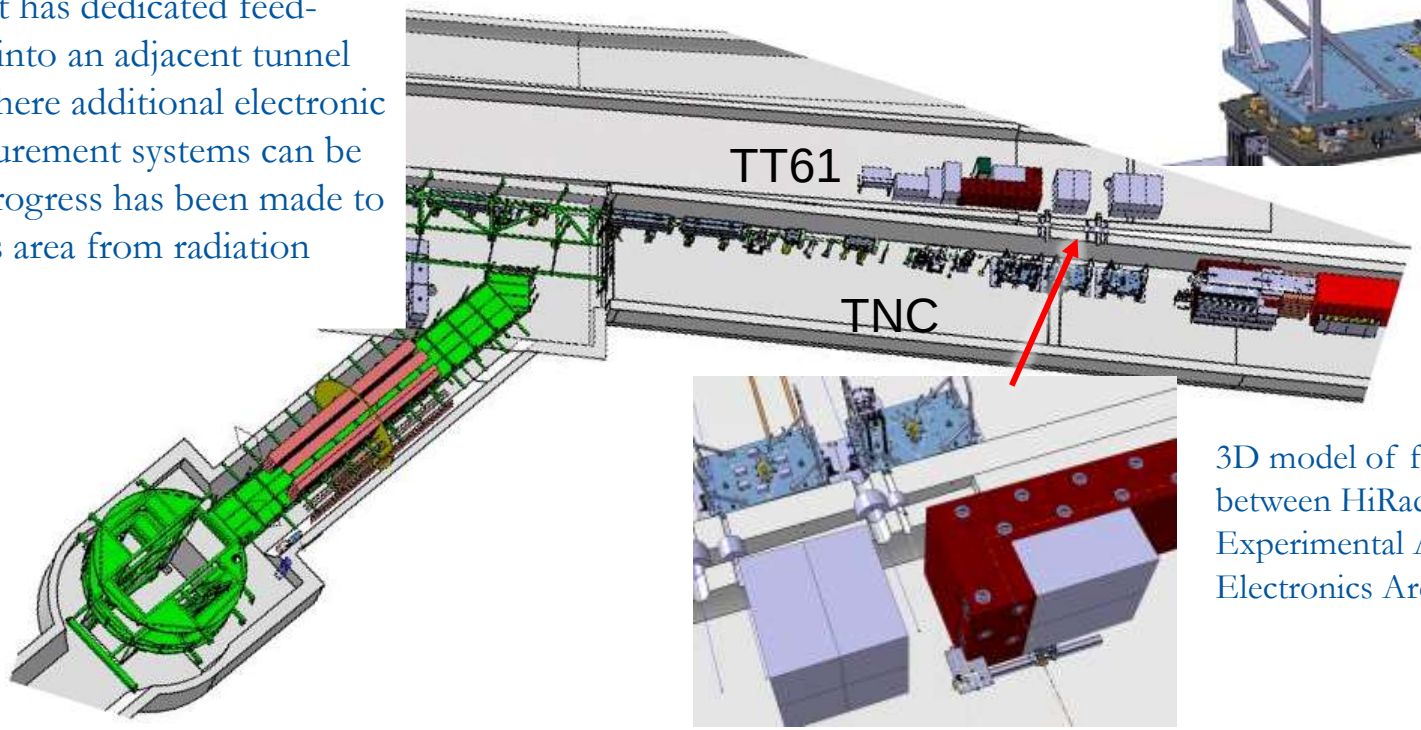
Irradiation Area

Borrowing vac. chamber and cryocooler used at HiRadMat



TT61

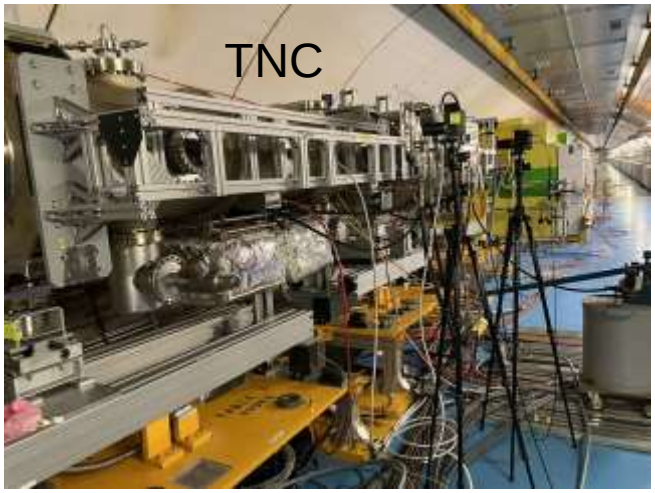
HiRadMat has dedicated feed-throughs into an adjacent tunnel (TT61) where additional electronic and measurement systems can be added. Progress has been made to shield this area from radiation effects.

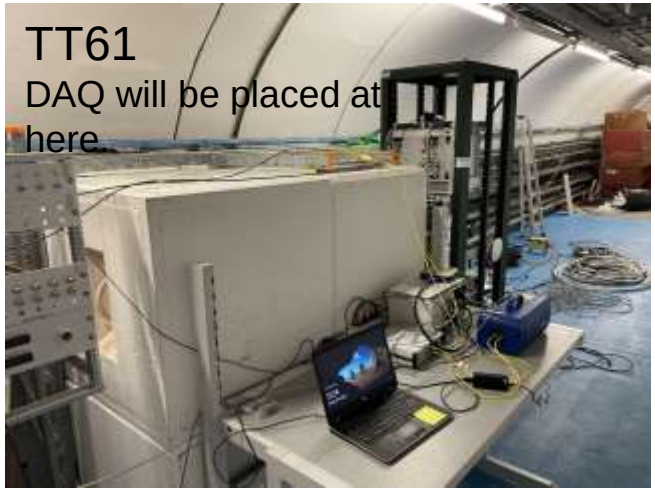


3D model of feed-through between HiRadMat Experimental Area and Electronics Area.

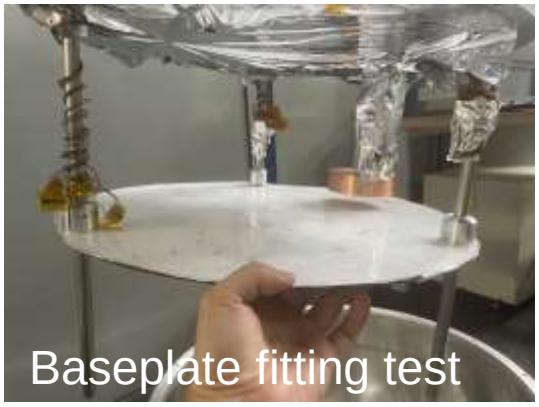
Experiment planned in 2025

Confirmation status at HiRadMat





Vessel with new base plate on movable table



- Training was completed to enter TNC
- Fitting test of baseplate was made and some revisions were found.

Summary

- 0.4 – 3 GeV proton displacement cross section:
  - Some data already published
- 120-GeV proton displacement cross section:
  - Successfully obtained the experimental data
  - arc-dpa : good agreement with experiment except for Nb (Hopefully, retry in the future)
  - NRT: Overestimate similar to the results for Ep < 30 GeV.
- 440-GeV data will be obtained in 2025.

Acknowledgements:
- This project includes the results of “Measurement of displacement cross-section at J-PARC for structural material utilized at ADS” entrusted to JAEA by the Ministry of Education, Culture, Sports, Science, and Technology of Japan (MEXT).
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