Displacement cross section measurements in J-PARC and potential for 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

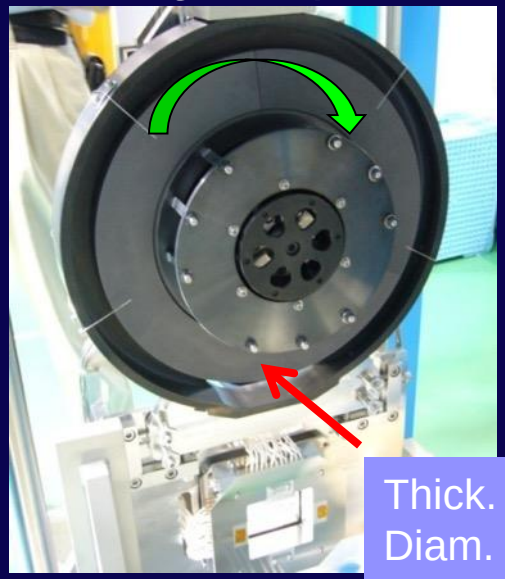
- Introduction
  - Present and future plan of J-PARC
- Experiment for measurement displacement (DPA) cross section at J-PARC
  - Experiment Ep 0.4 to 3 GeV at 3NBT
  - Comparison with calculation model
- Summary

J-PARC = Japan Proton Accelerator Research Complex

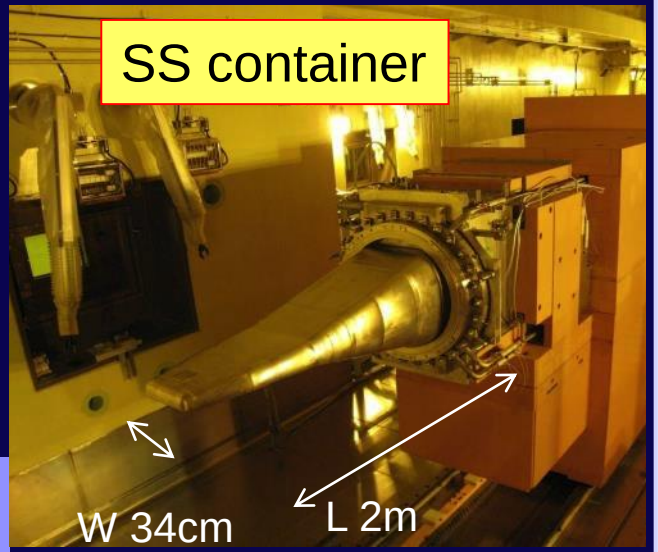
Targets in Material Life Experimental Facility (MLF)

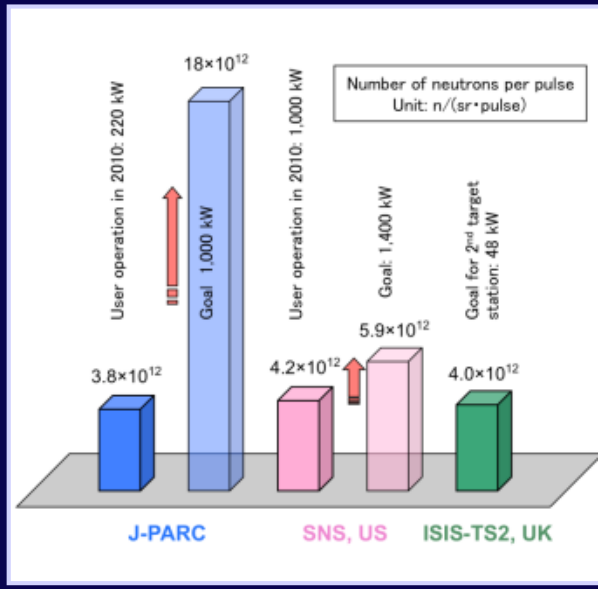
- Muon production target
  - Carbon graphite
  - Highest μ^- intensity
- Neutron production target
  - Mercury (Hg)

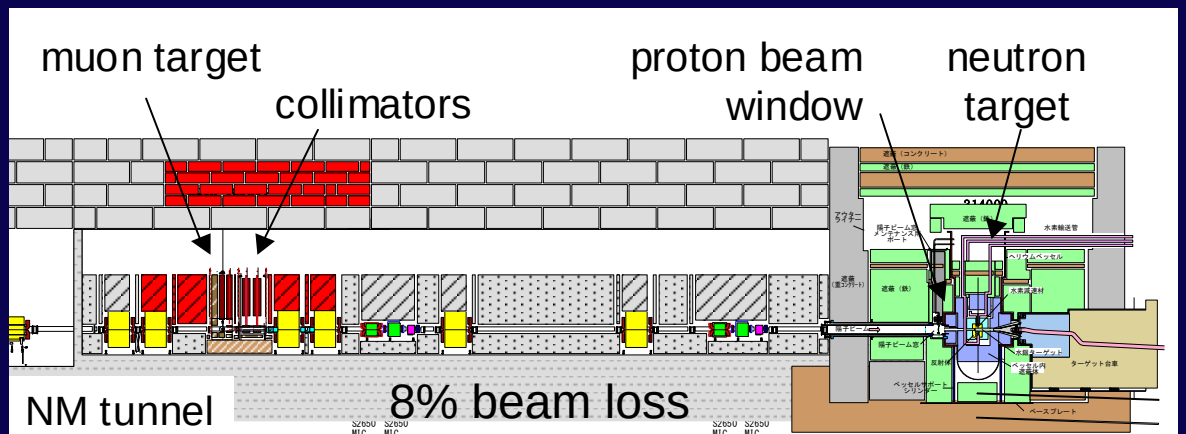
Highest pulse intensity in the world



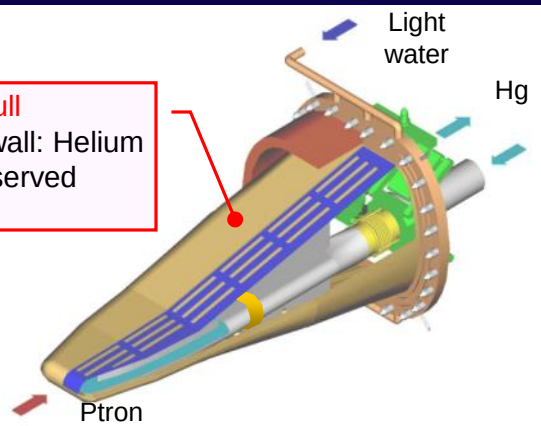
Thick. 2cm
Diam. Φ33cm





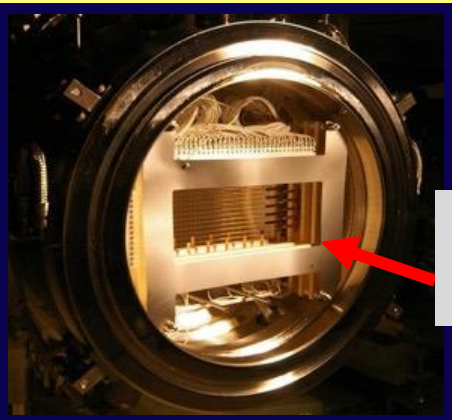


Safety hull
Double wall: Helium layer observed radiation



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)

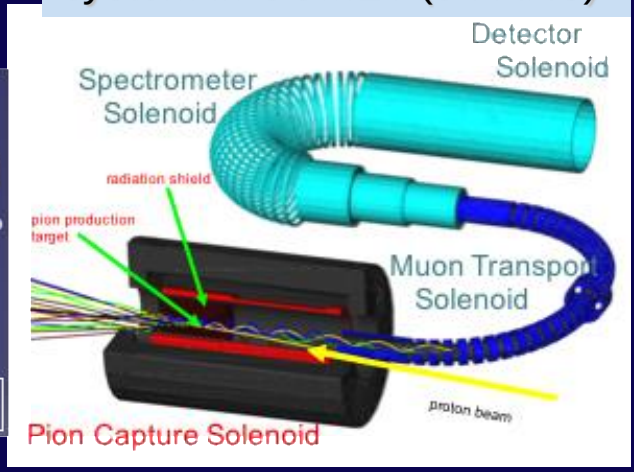


T2K beam window
Titanium alloy (Ti-6Al-4V)

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

- Superconductor resistivity change due to radiation is crucial for superconducting magnet.

Superconducting magnet system in COMET (J-PARC)



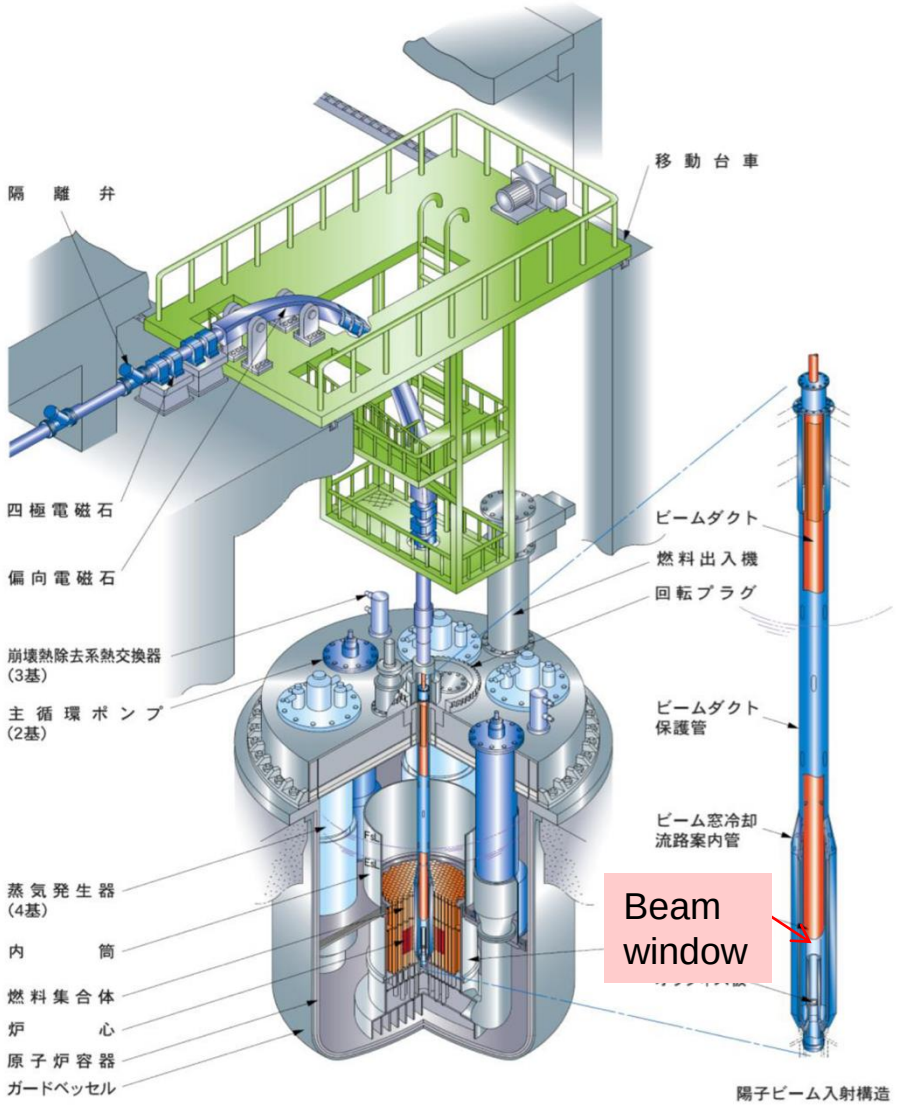
ADS Proposed by JAEA - LBE Target/Cooled Concept -

➢ 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)

TEF-P: Transmutation Physics Experimental Facility

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

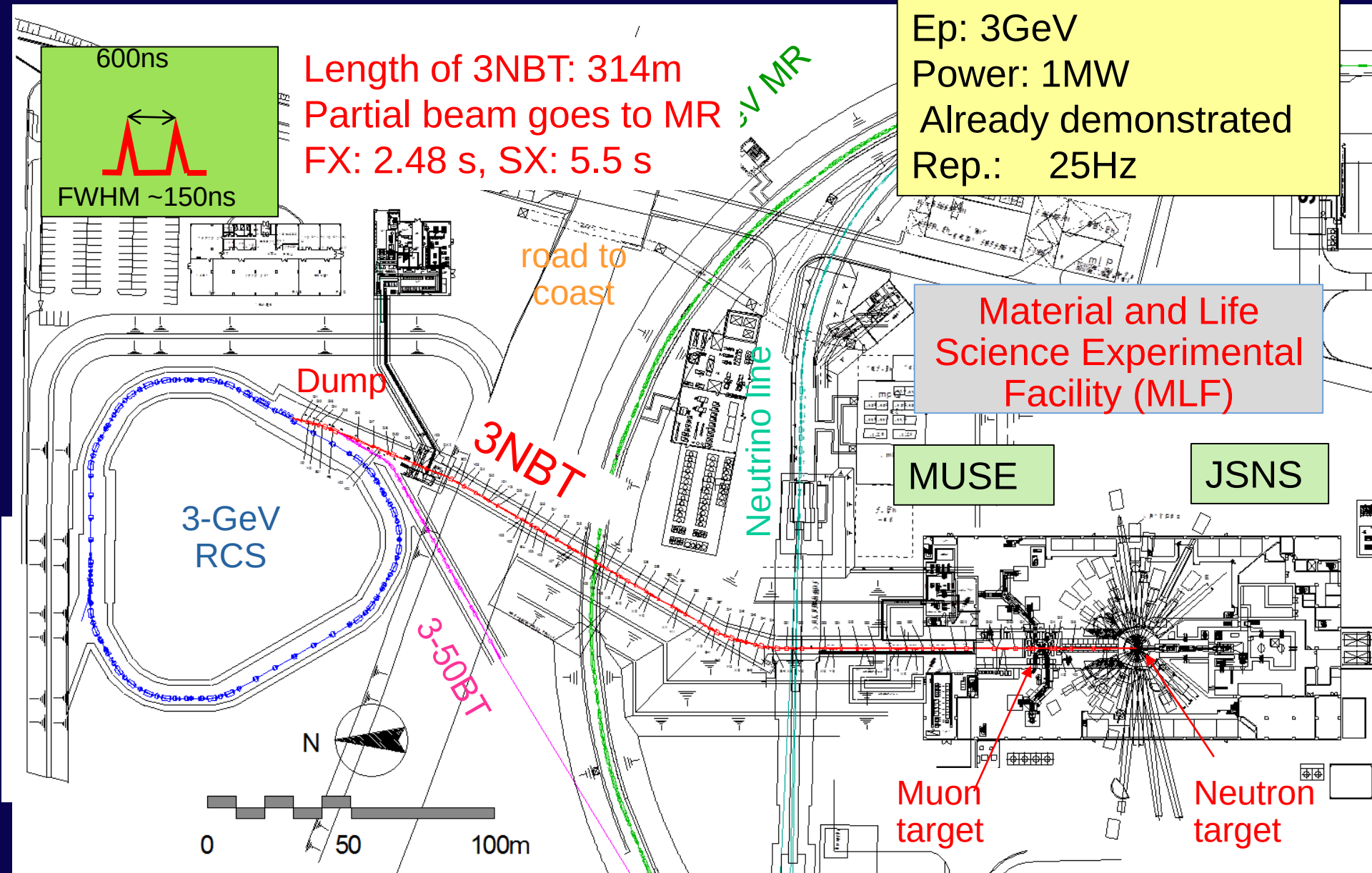
TEF-T: ADS Target Test Facility

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

Soviet submarine (LBE)

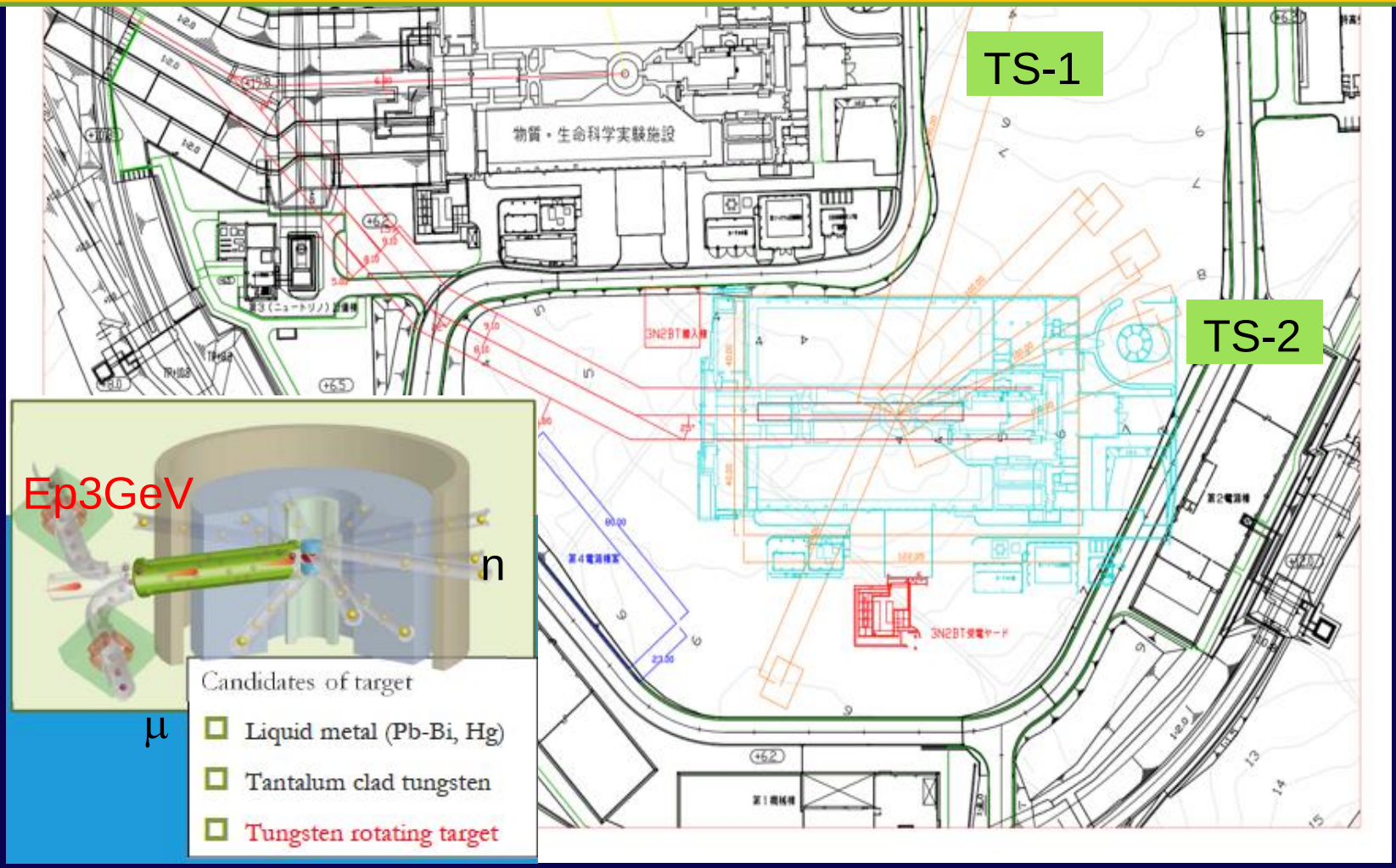
For R&D of ADS, 0.4 GeV beam by LINAC will be delivered to TEF.

Beam transport from RCS to MLF



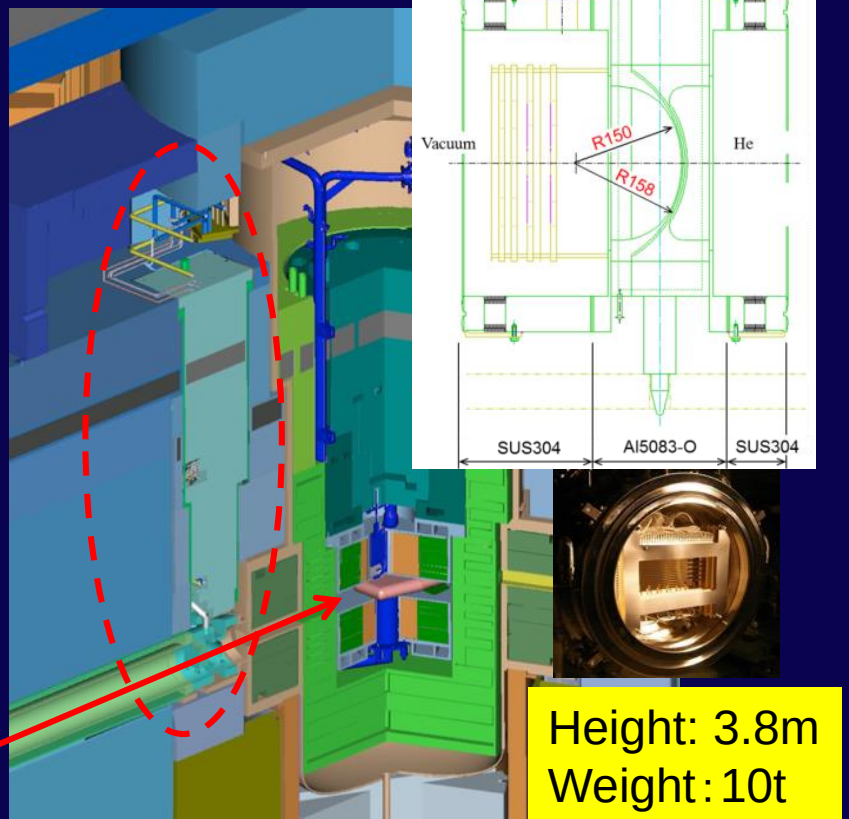
Second target station plan

1st target ST (TS-1): 24 Hz: 1MW
2nd target ST (TS-2) 1Hz : 42kW (Designed to accept 1 MW)



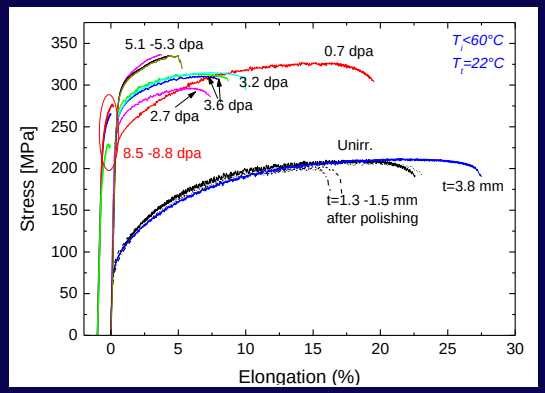
Proton Beam Window at MLF (A5083)

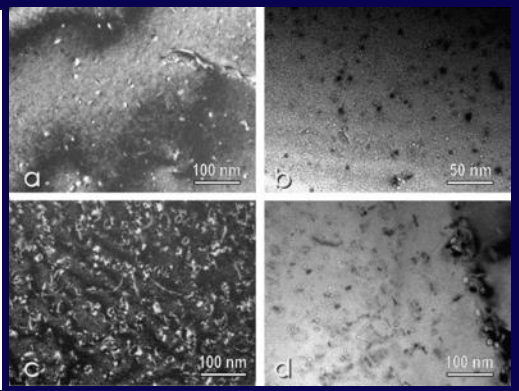
- Lifetime estimation based on Post Irradiation Examination (PIE) for safety shroud (AlMg3) at SINQ in PSI
- Considering difference of proton energy, to predict lifetime of the PBW with high accuracy for validation of calculation



Result at SINQ/PSI for 0.6GeV

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





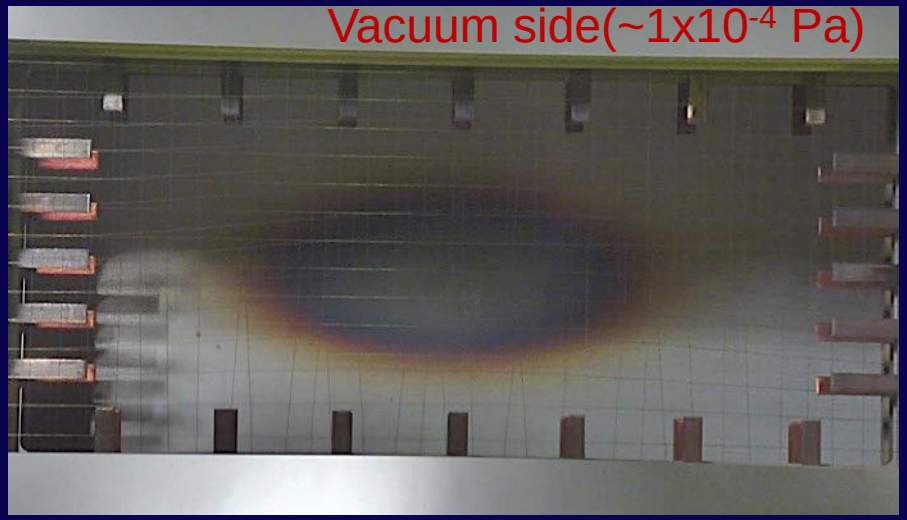
Lifetime of PBW: Determined by He gas production (1200 appm) 2 years*

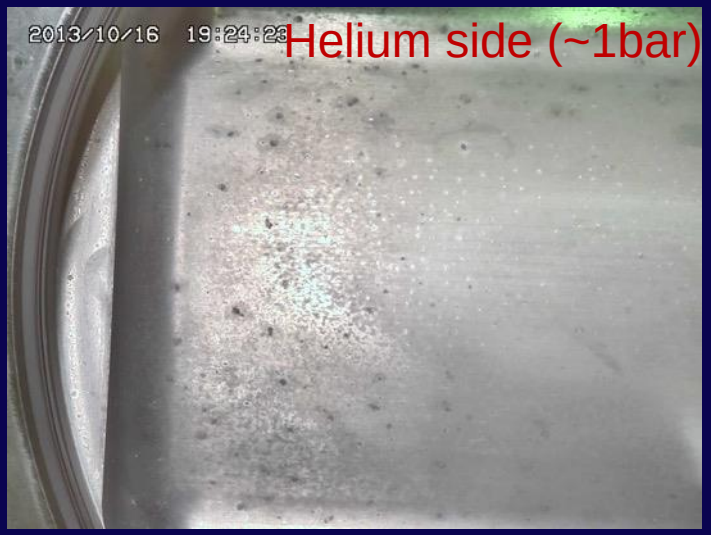
By recent PIE result of the SINQ (2400 apmm), lifetime may be applicable to 3 years.

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

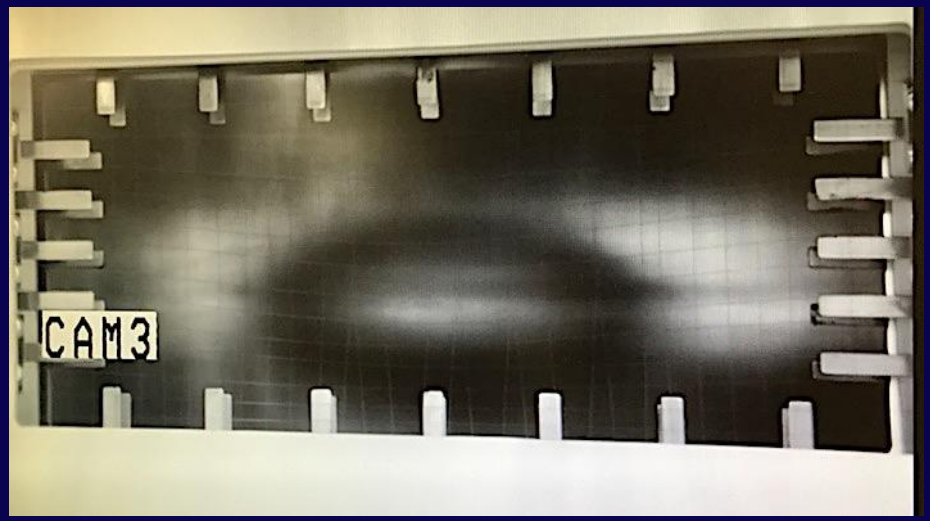
Inspection spent PBW

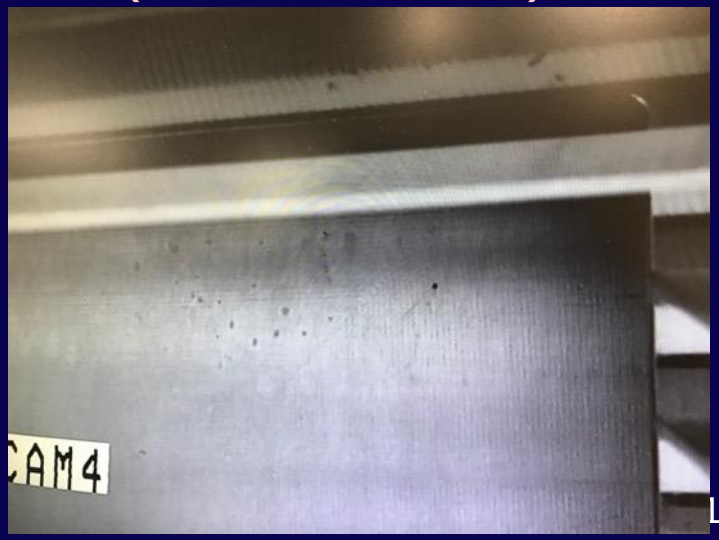
PBW #1 (obs. 2013 Oct) 1916 MWh (1.4×10^{22} POT)





PBW #2 (obs. 2017 Aug) 2510 MWh (1.9×10^{22} POT)





Beam peak density reduction with octupole magnet

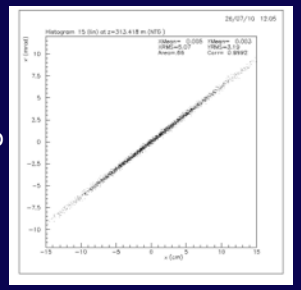
- Normal optics (i.e. linear) → Gaussian
  - Nonlinear optics with OCT shaping flat beam to reduce the peak

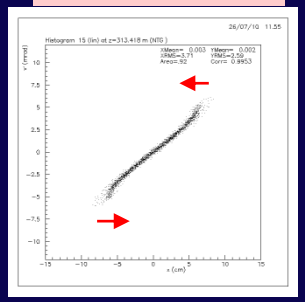
Linear

With OCT

Phase space

Divergence



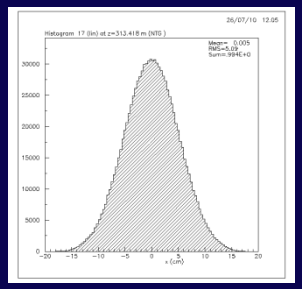


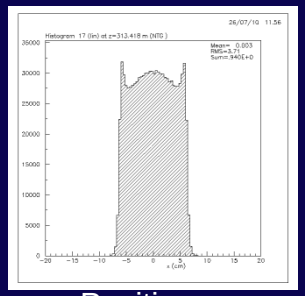
Position

Position

Spatial distribution

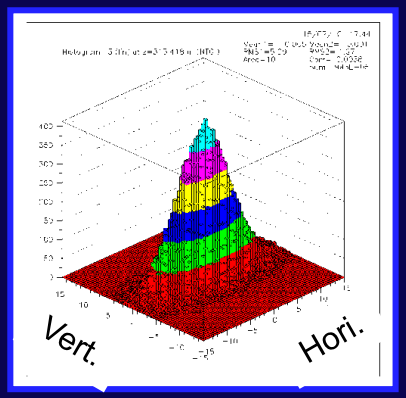
Intensity

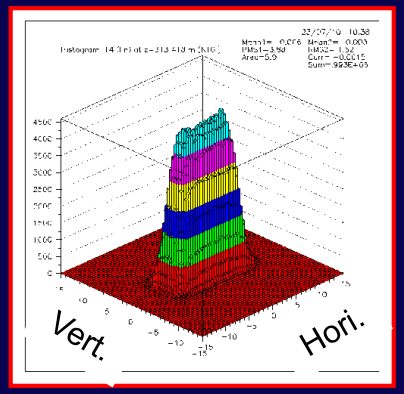




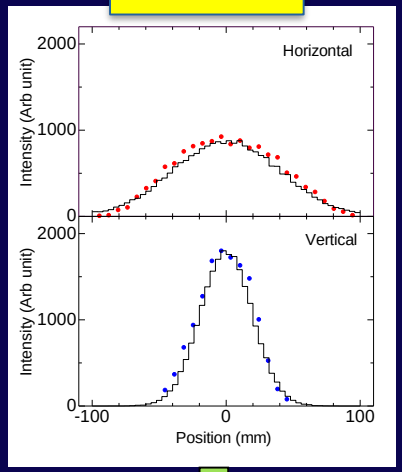
Position

Position

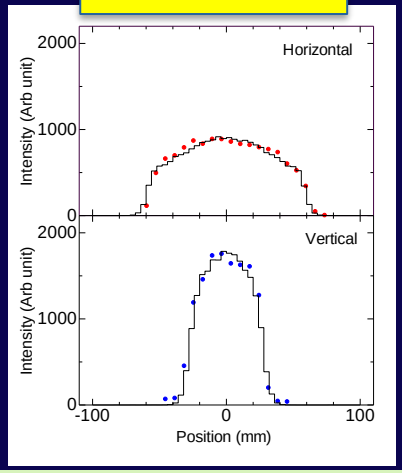




OCT 0A



OCT 698A

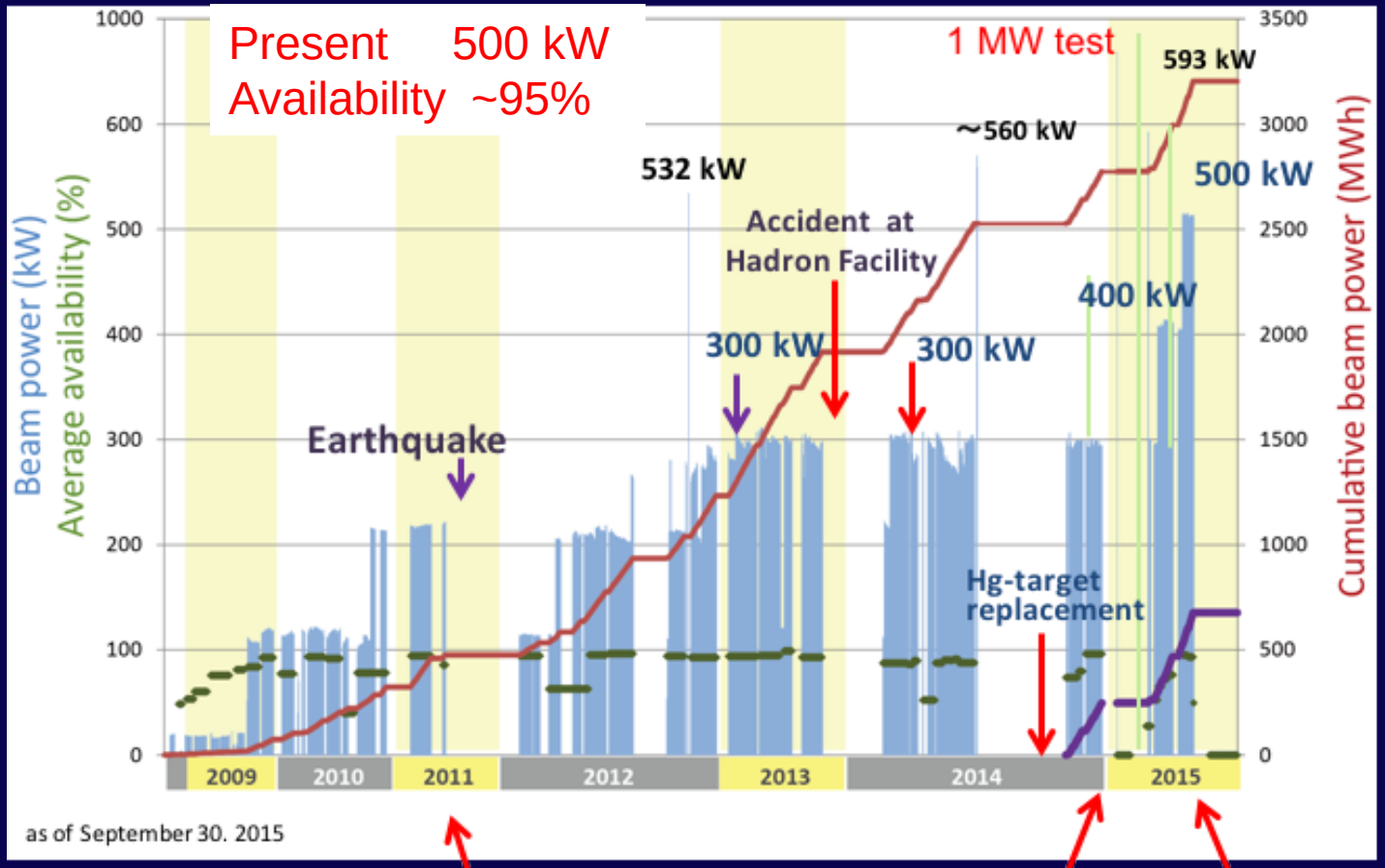


Principal: Folding edge to center

Reduction ~40% (10→6 μA/cm² at 1MW)

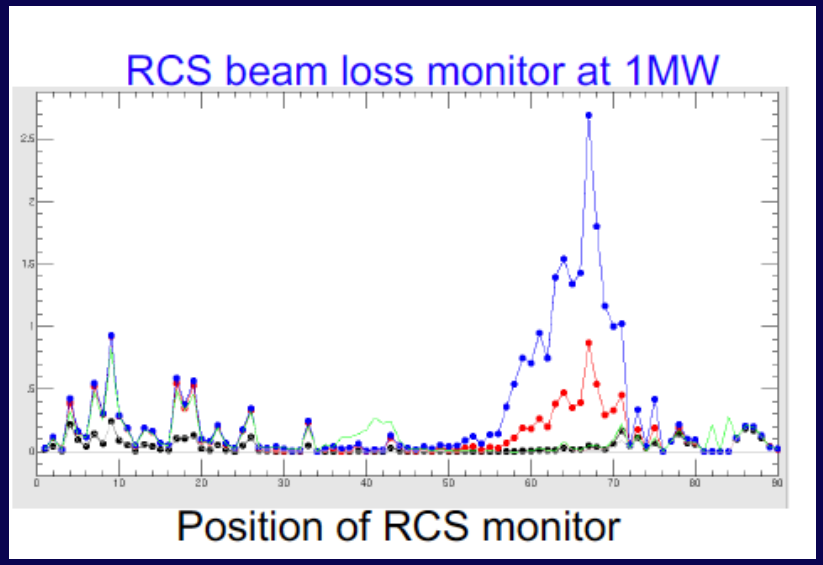
Beam operation at MLF

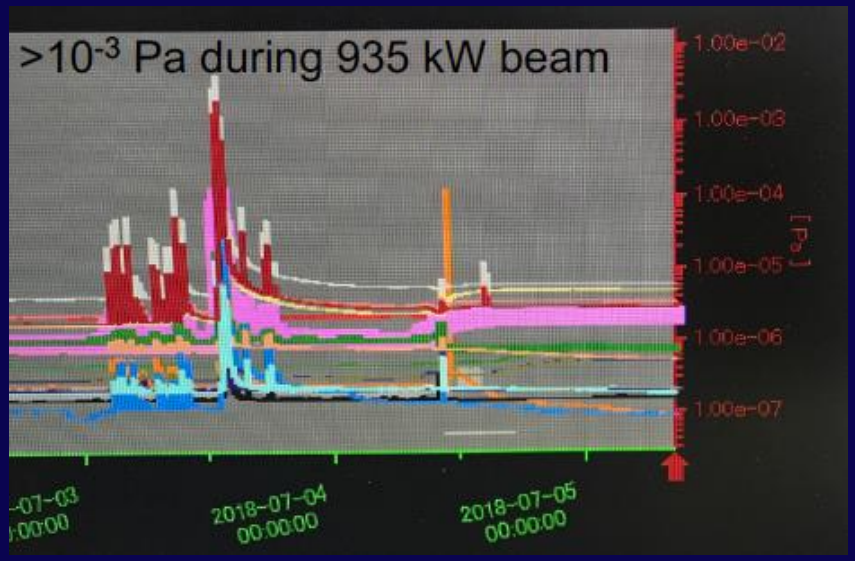
- Major interruption : Earthquake, Hadron facility accident, Water leak Hg target (x2)
- Kicker magnet (KM) failed. But keep operation w/o failed KM (2 of KM failed out of 8)
- Helium bubbler flow choking. Mirror for LDV came off due to welding issue.



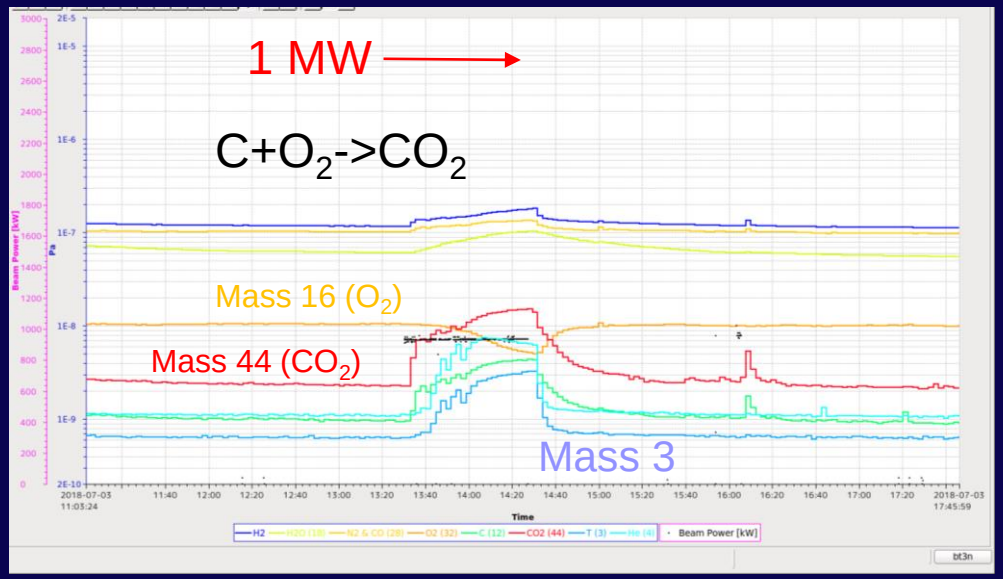
Demonstration of 1 MW for 1h

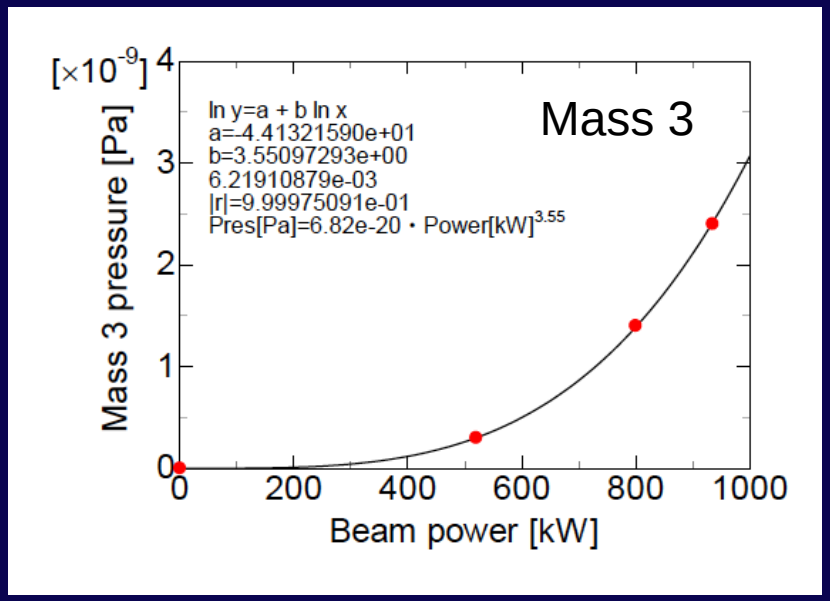
- On July 2018 4th, 1 MW beam test for 1h
- Once chance per year before outage
- Vacuum worse found at RCS
- W/O failed one quadrupole magnet operated





Vacuum at BT during 1 MW

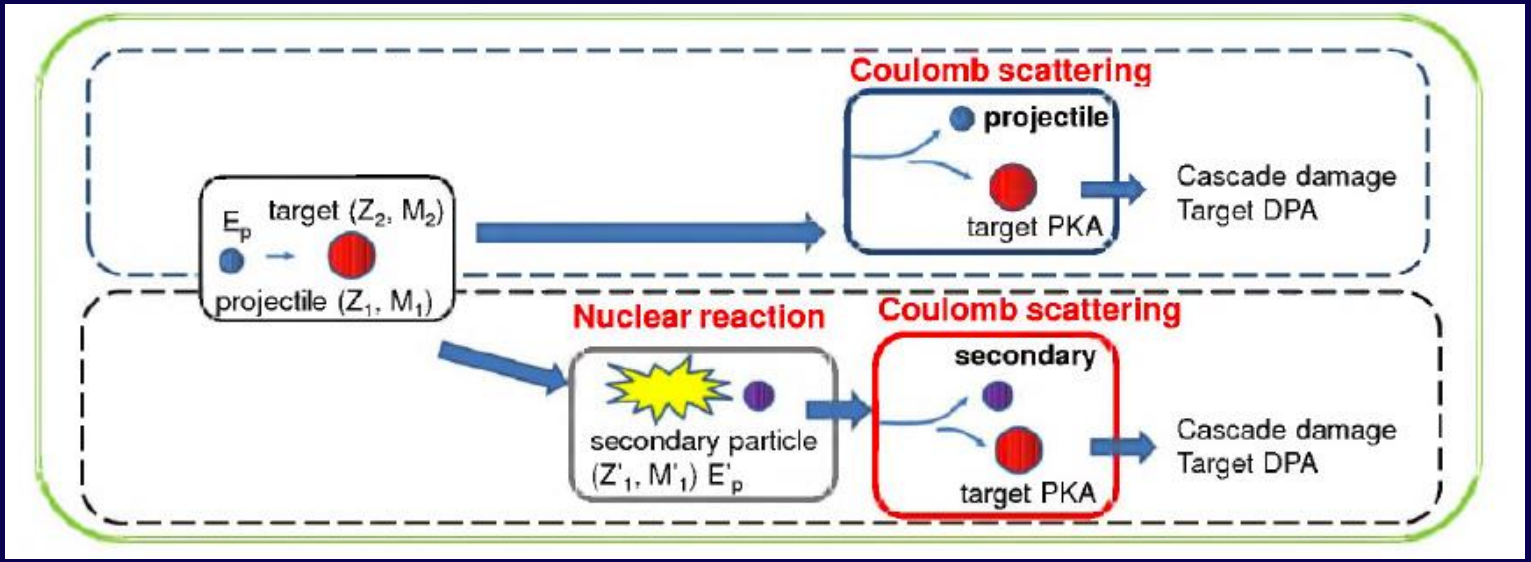


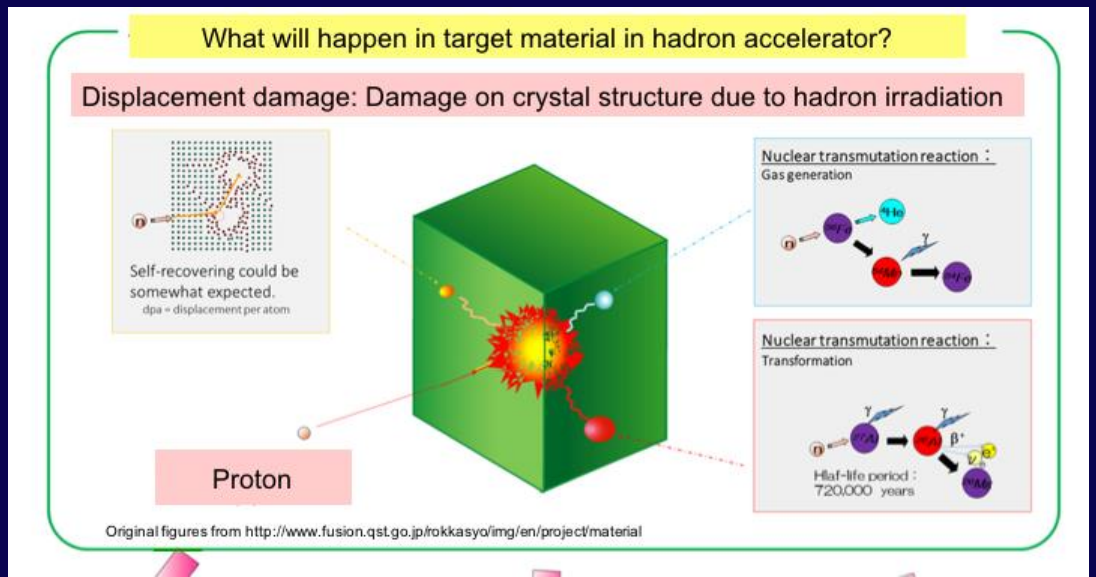


- Overall vacuum pressure was low.
- Drastically increase pressure of mass number 3 (probably T) as increase of beam power. (1 MW: ~12 times of 500 kW)
- Gas treatment system for exhaust of pump was implemented on summer 2018.
- Tritium production in cooling water for magnets and beam scraper is an another issue.

PKA and DPA

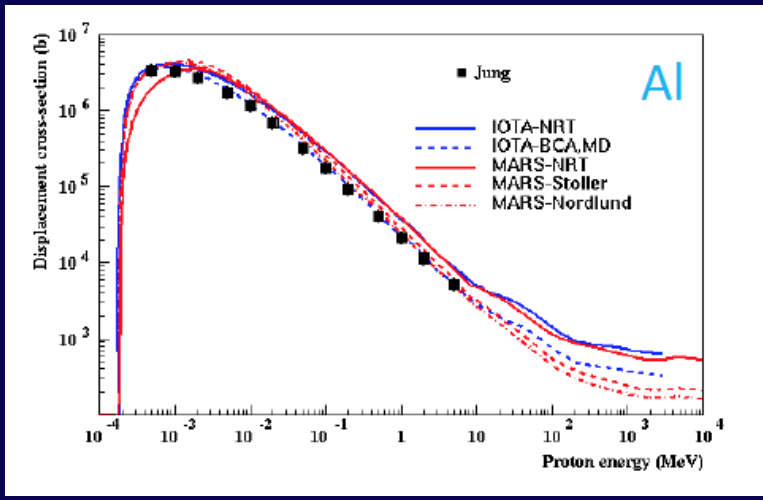
- DPA (Displacement per Atom) is estimated by calculation based on PKA.



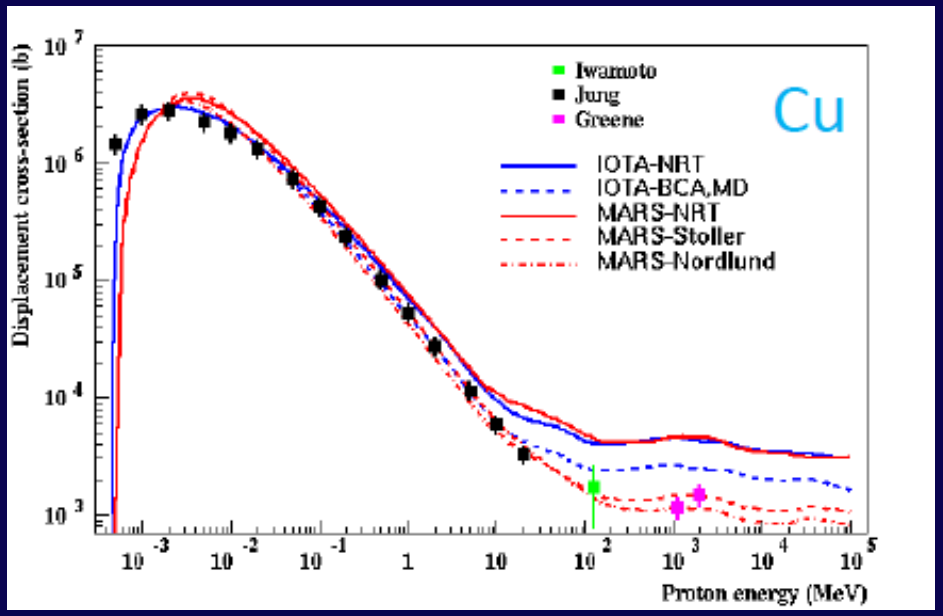


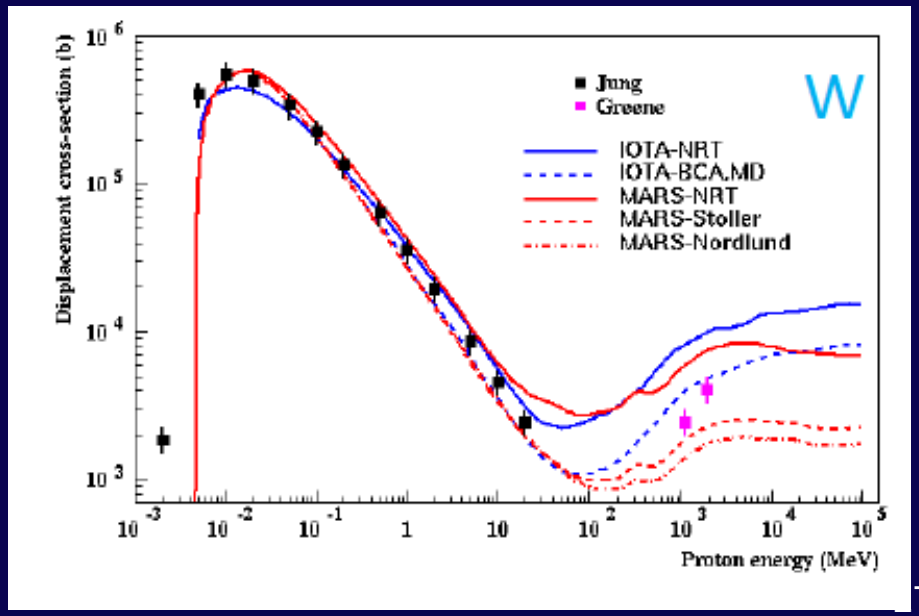
DPA and displacement cross section

- 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
  - Among calculation showing large discrepancies among models.



N. Mokhov HPTW2016



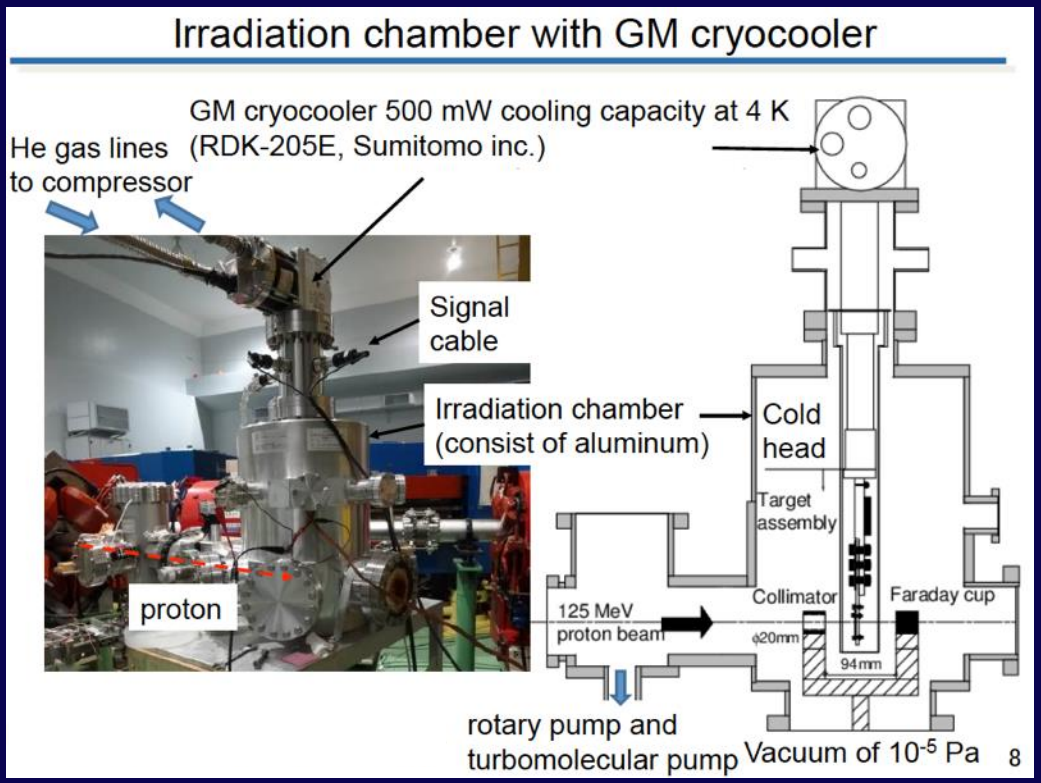


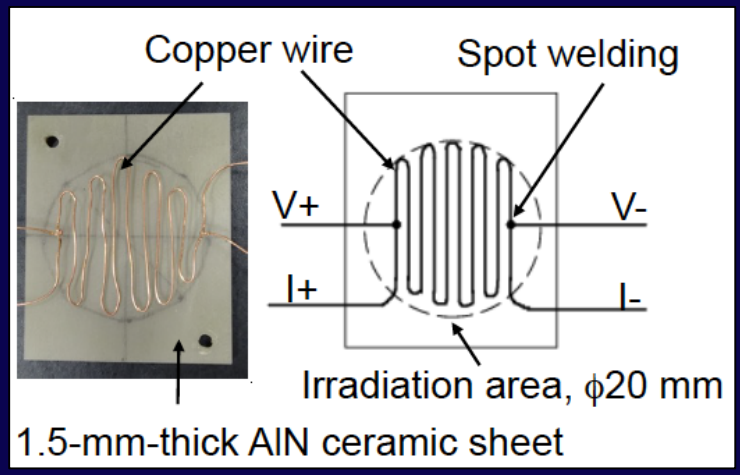
Measurement of DPA cross section at Kyoto univ

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

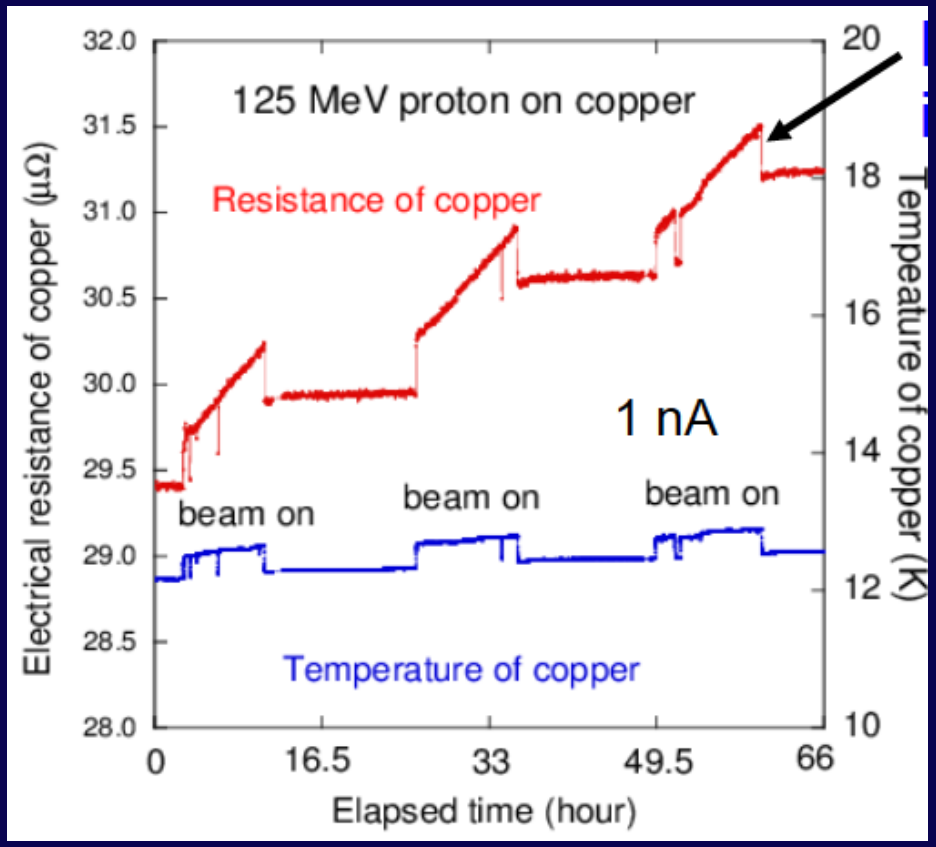
Measurement for Cu already performed at Kyoto university for 125 MeV proton

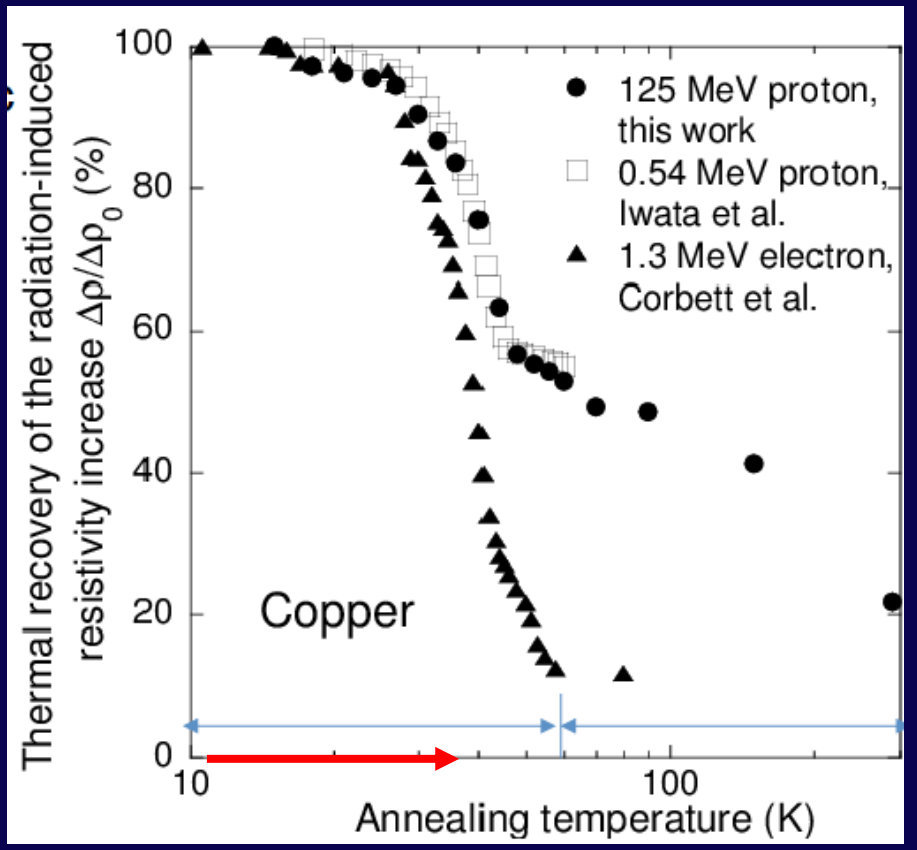
Experiment at J-PARC
- Samples and GM placed at exit of 3-GeV synchrotron for various energy of proton 0.4 to 3 GeV
- Other experiment performed at other sites for energy < 400 MeV





Experimental condition





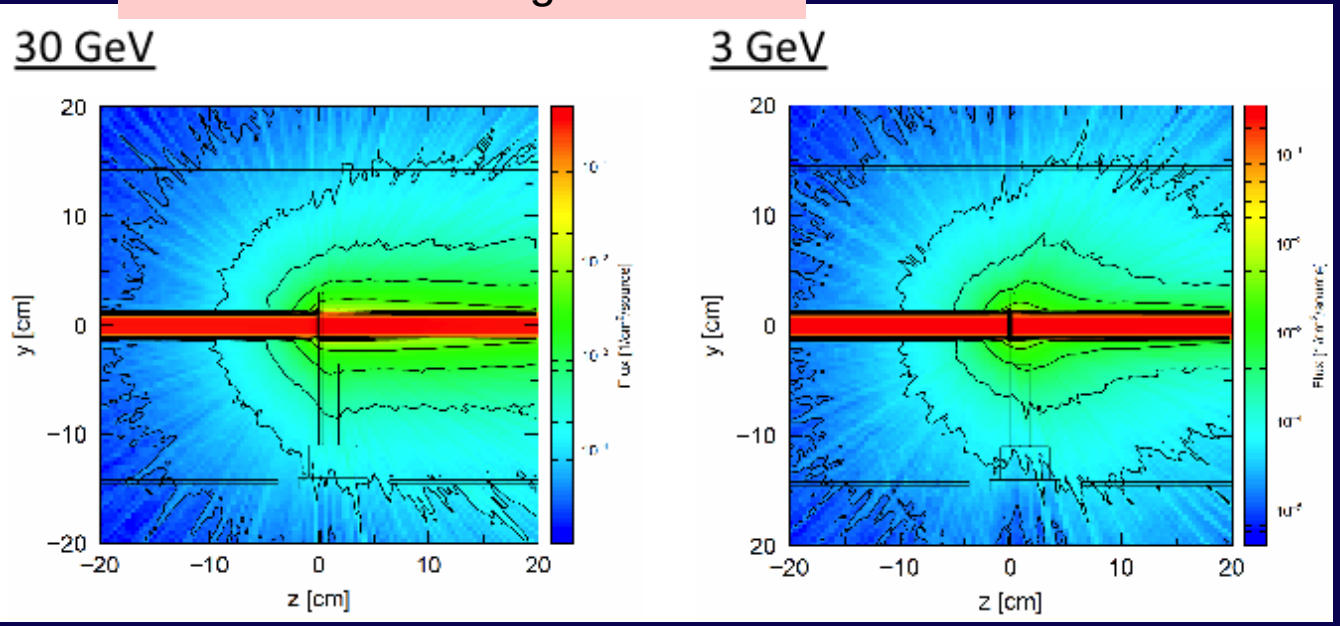
1 nA x 12h = 3×10^{14} protons
Several shots of beam at MLF

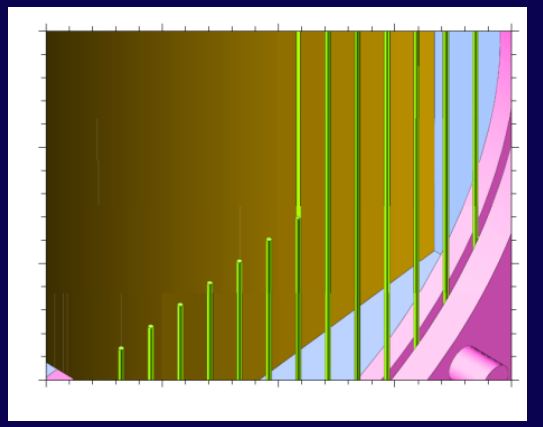
Y. Iwamoto et al.

Temp rising ~20 K will be acceptable.
If time permits, lowest beam is preferable.
However, it makes worse accuracy of beam charge. (Vary 1×10^{10} – 2×10^{13} protons/shot)

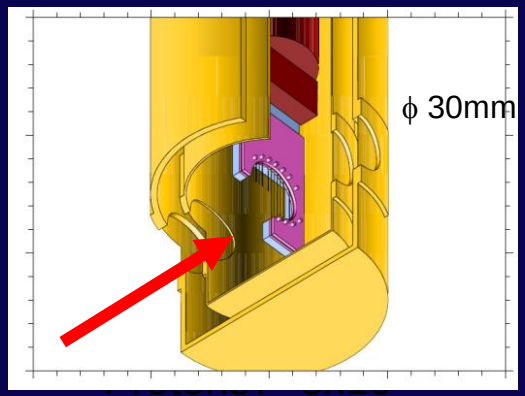
Radiation safety for J-PARC exp.

Particles flux during irradiation





Calc. geom. model



Residual dose at 0.3 m of sample

Incident energy	Cooling 4h (μSv/h)	Cooling 7d (μSv/h)
3 GeV	19	0.01
30 GeV	29	0.02

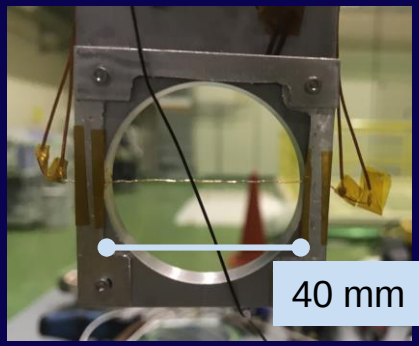
- Residual dose: Confirmed enough small for handling
- Confirmed to fit criteria of beam loss (1 W/m) for maximum beam to dump (8 kW)

Measurement of cross section for 0.4～3 GeV proton

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

Cold head and sample

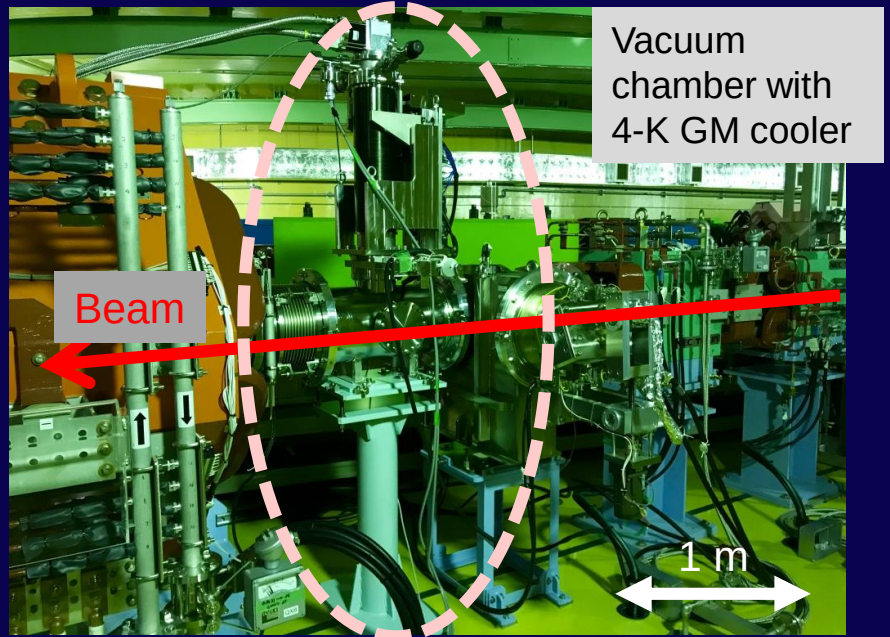
Cu wire (ϕ 0.25 mm)
with purity 99.999%
annealed 1,350 K



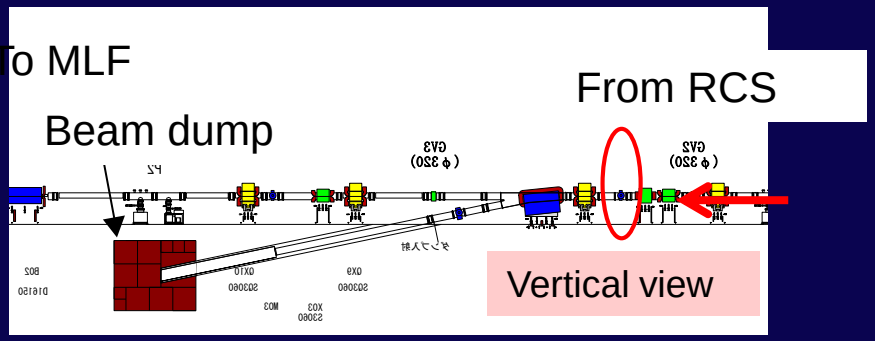
Under cryotemperature (~ 20 K), displacement cross section(σ) was obtained by increase of resistivity ($\Delta\rho_{cu}$) due to proton irradiation with average flux ($\overline{\phi(E)}$)

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

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

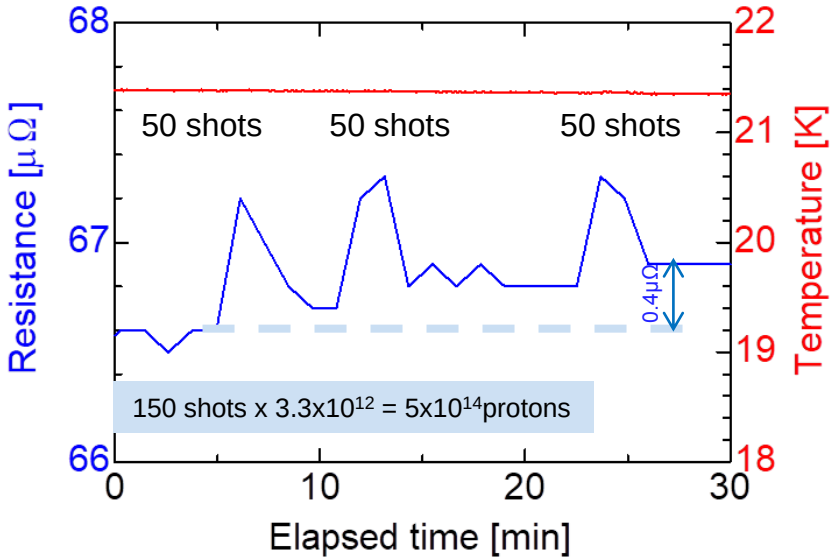


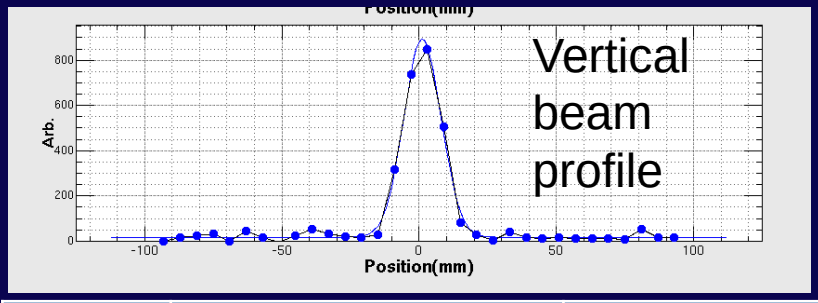
Vacuum chamber with 4-K GM cooler



Experimental result

Resistance and temperature during irradiation





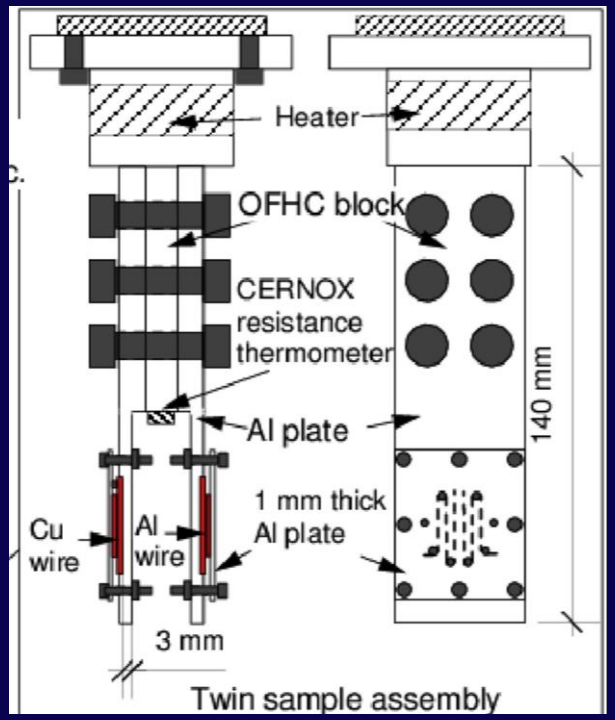
Ep (GeV)	Resistivity change ($\Delta\Omega m^3 X10^{-31}$)	σ_{dpa} (b)
0.8	2.35±0.31	1070±284
1.3	2.32±0.26	1053±270
2.2	2.49±0.21	1133±277
3.0	2.49±0.16	1010±244

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

- 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%).

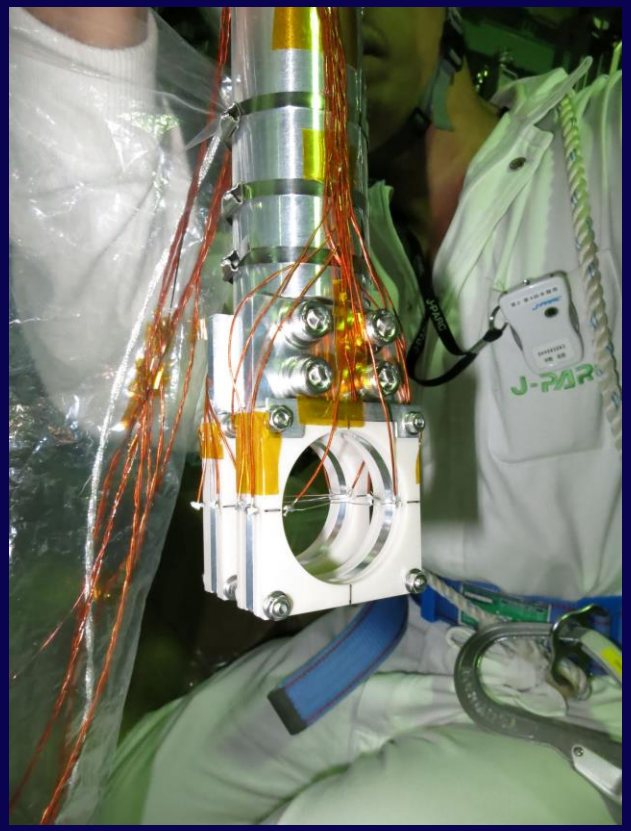
Cascade sample holder

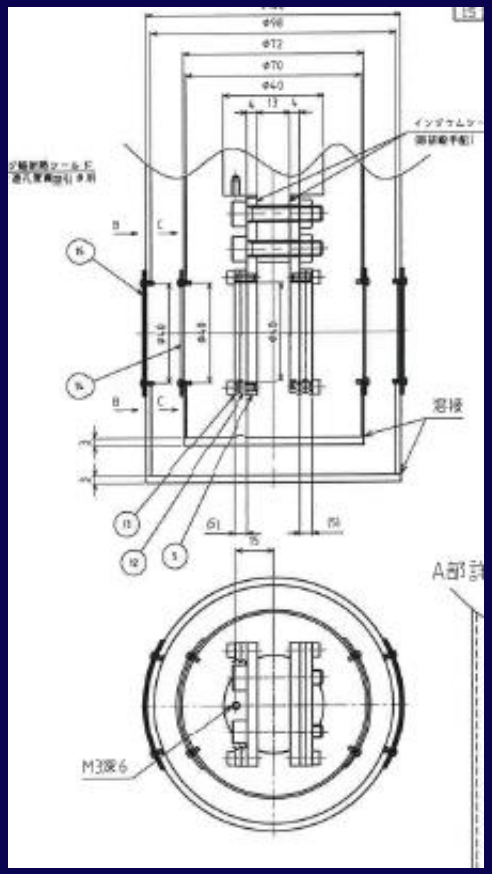
RCNP (Osaka univ.) experiment by Iwamoto



- 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

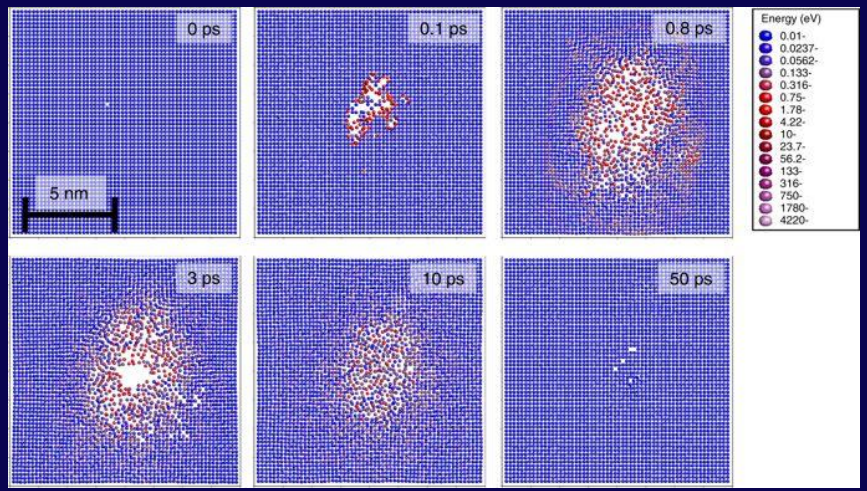
Calculation with PHITS code

- 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):

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

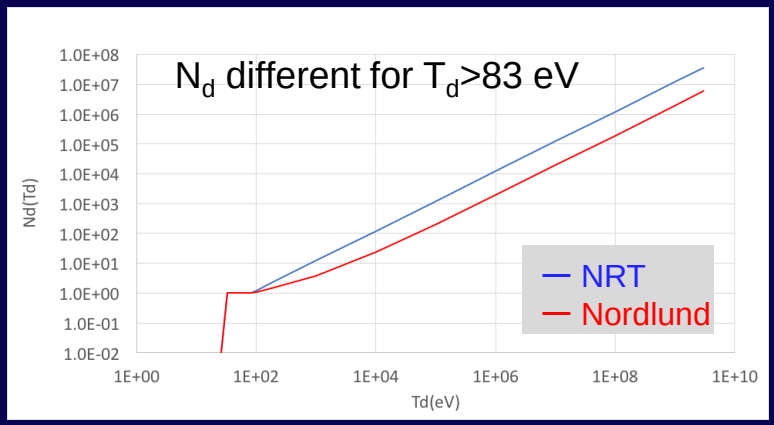
N_d: Number of displacement
T_d: Displ. energy



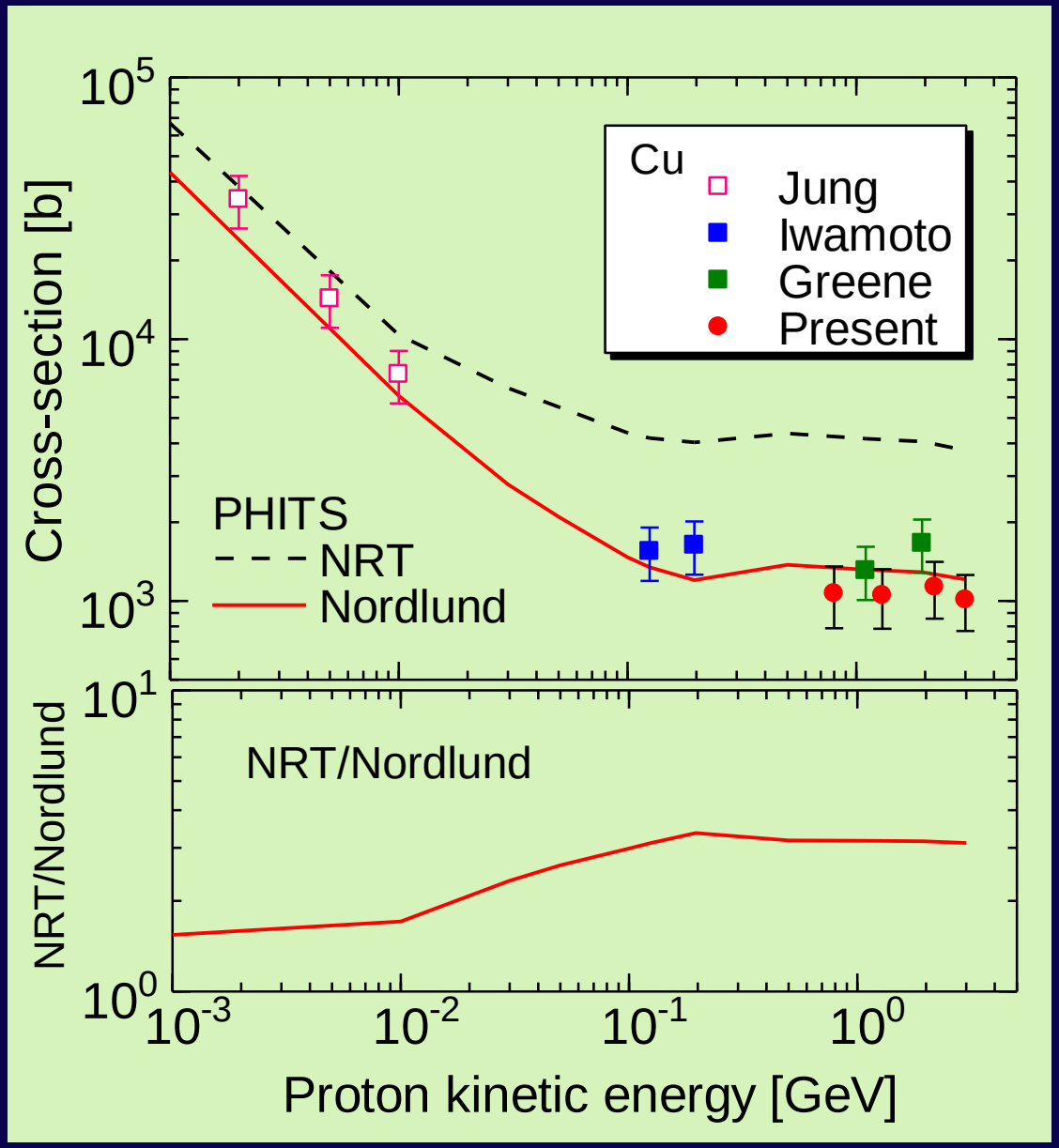
Nordlund (Cu Ed 33 eV):

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

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



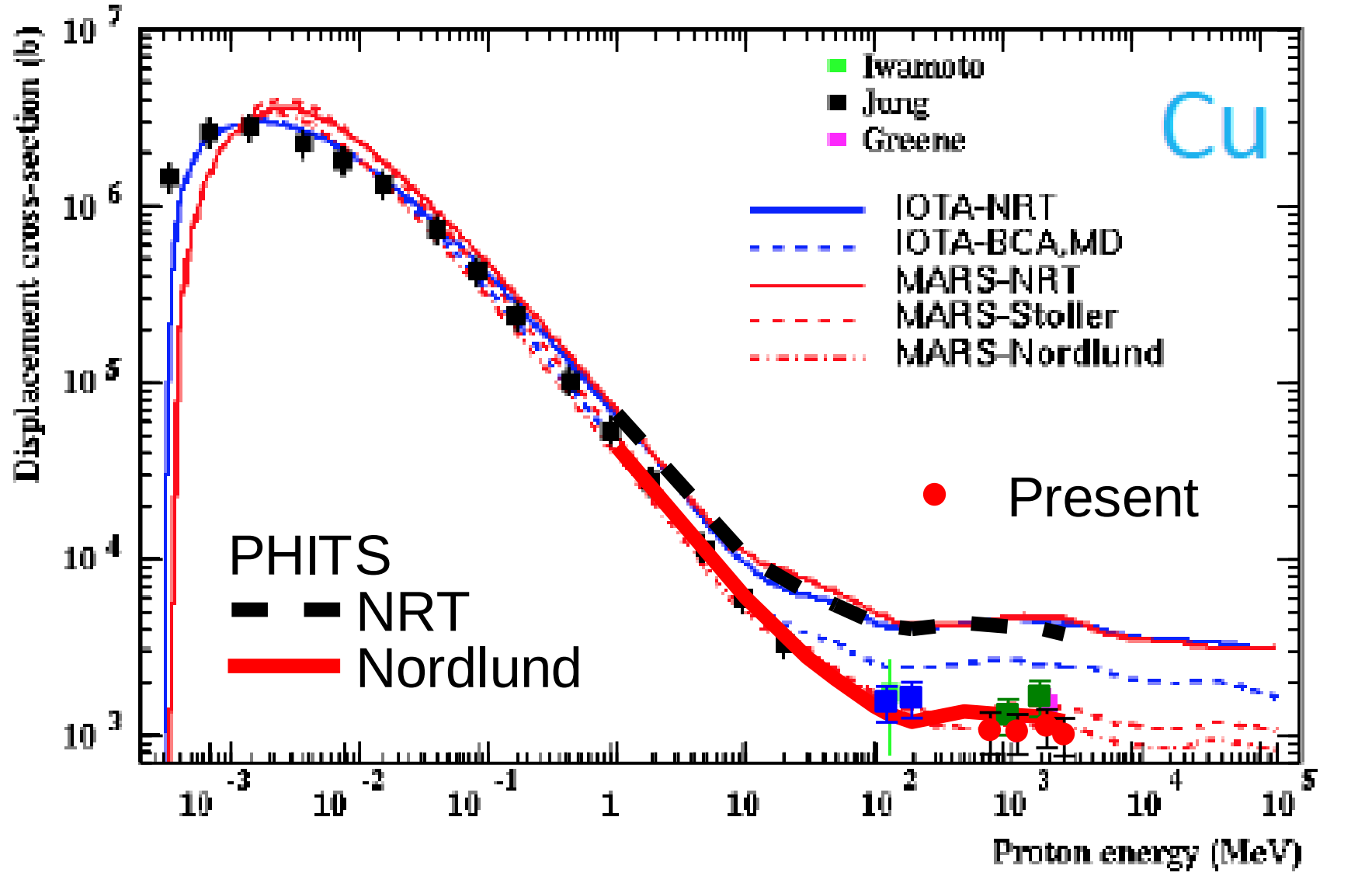
Comparison with models calculation



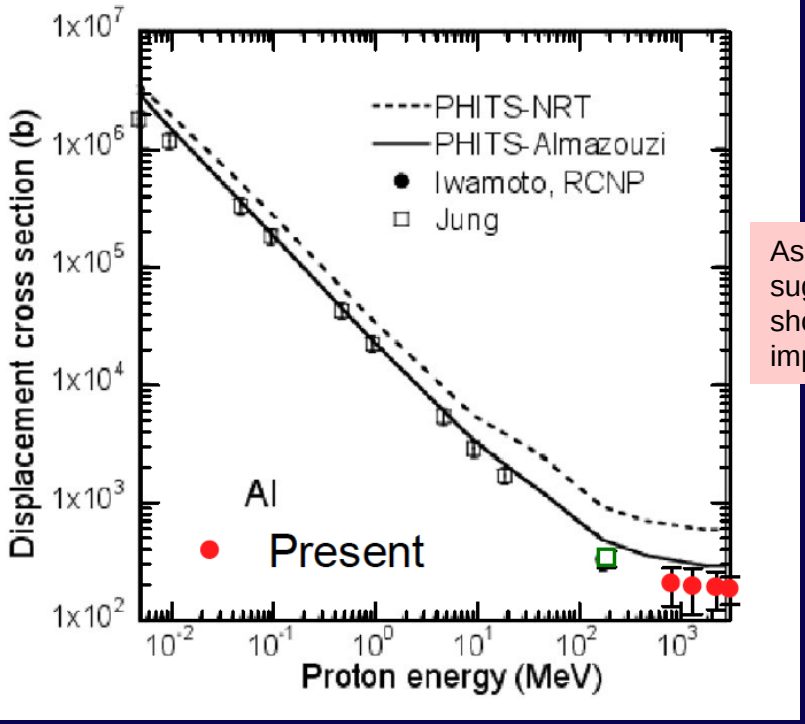
- NRT model overestimates ~ x3
- Nordlund model good agreement

- Present data imply that the DPA should be calculated with Nordlund model.
- Ratio of NRT/Nord is constant above ~200 MeV.
- If the displacement cross section sustains to NRT for Ep< 10 MeV, the cross section for Ep>100 MeV is ~2 times.

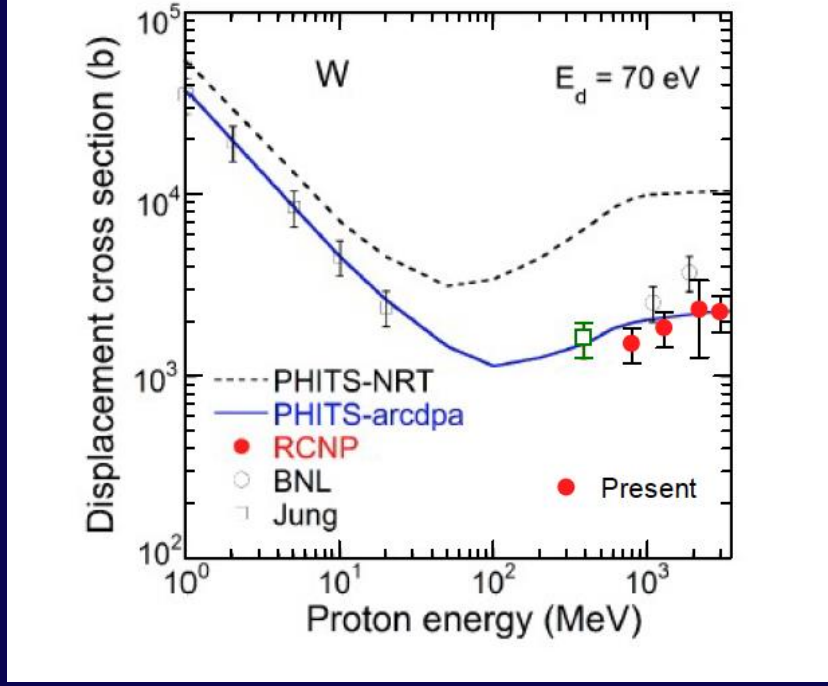
Comparison with MARS

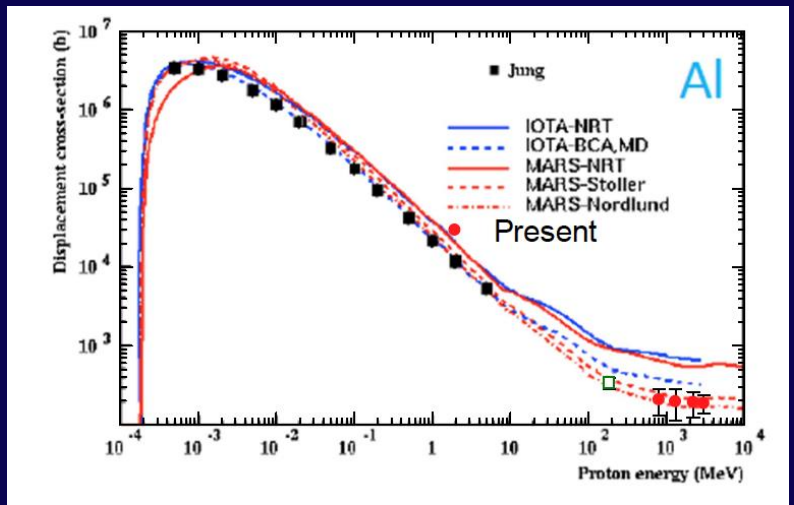


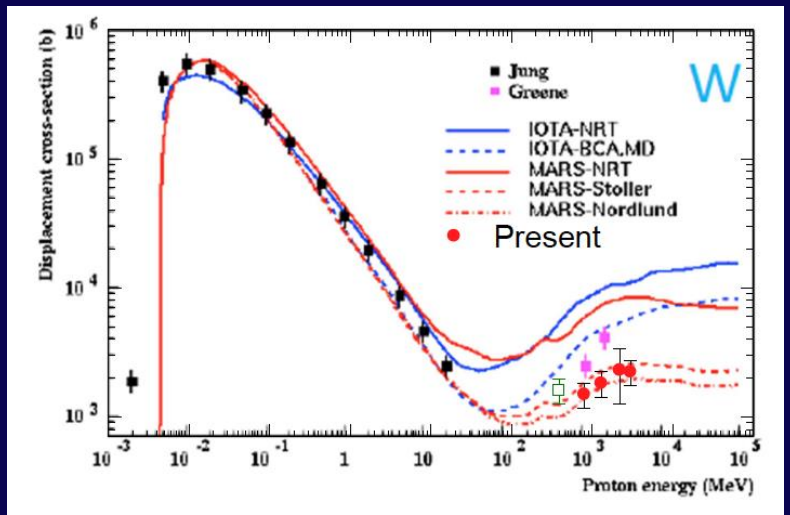
Al and W results



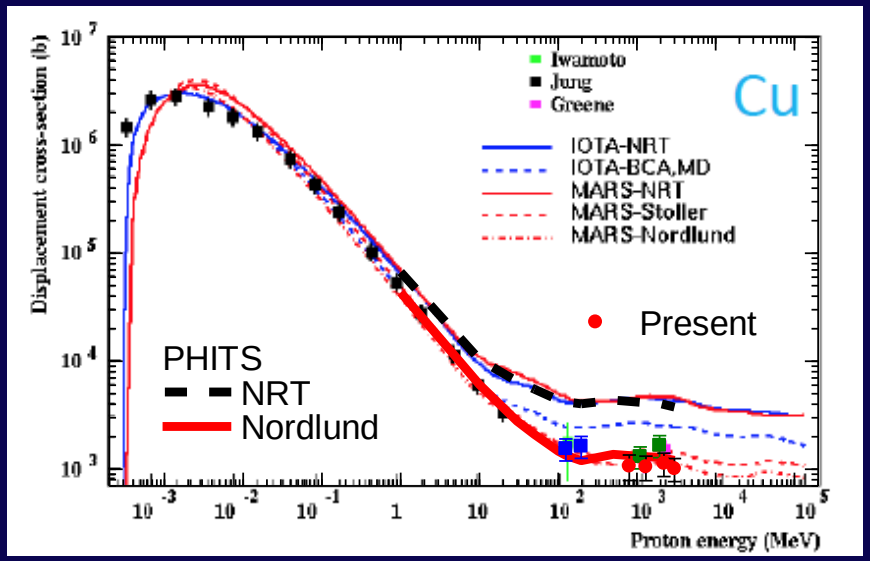
As Mokhov suggestion, should be improved

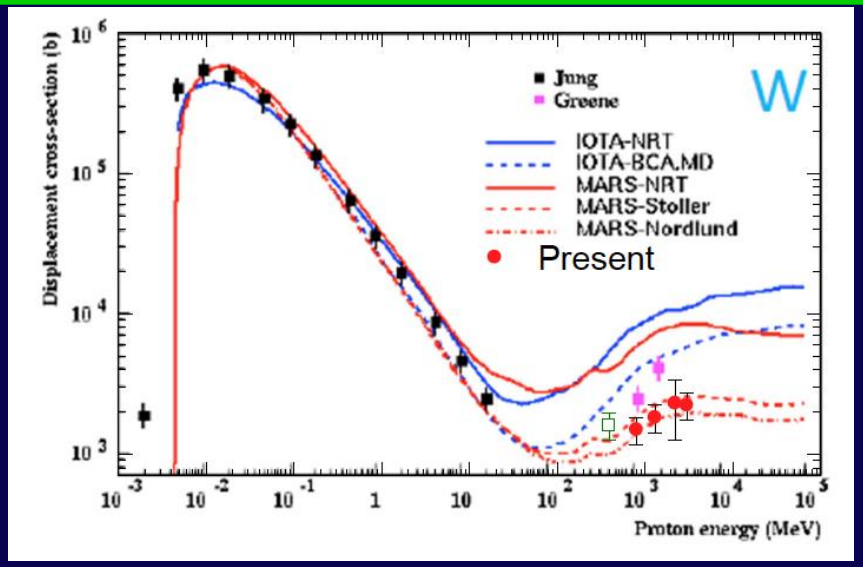


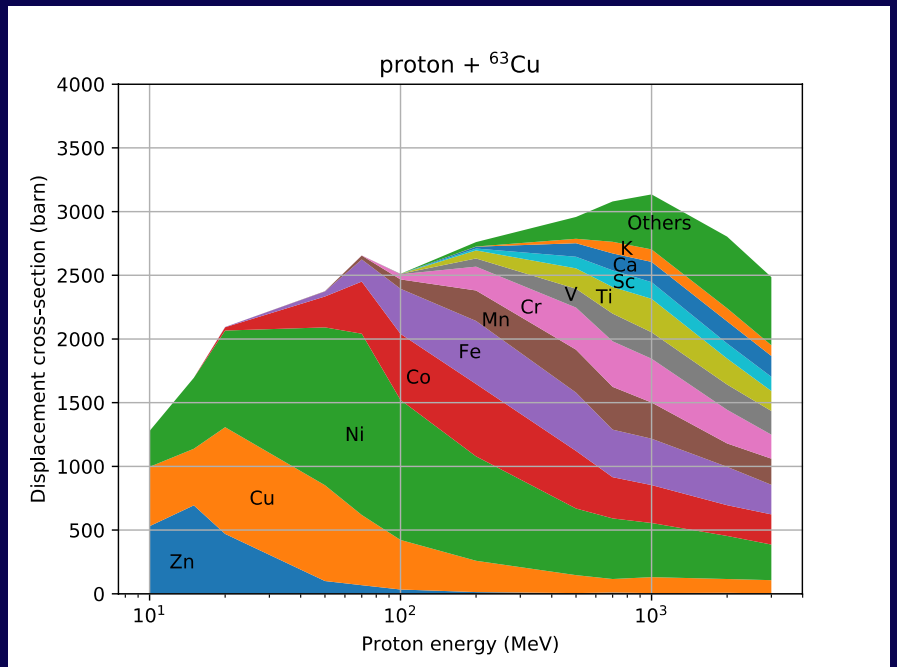


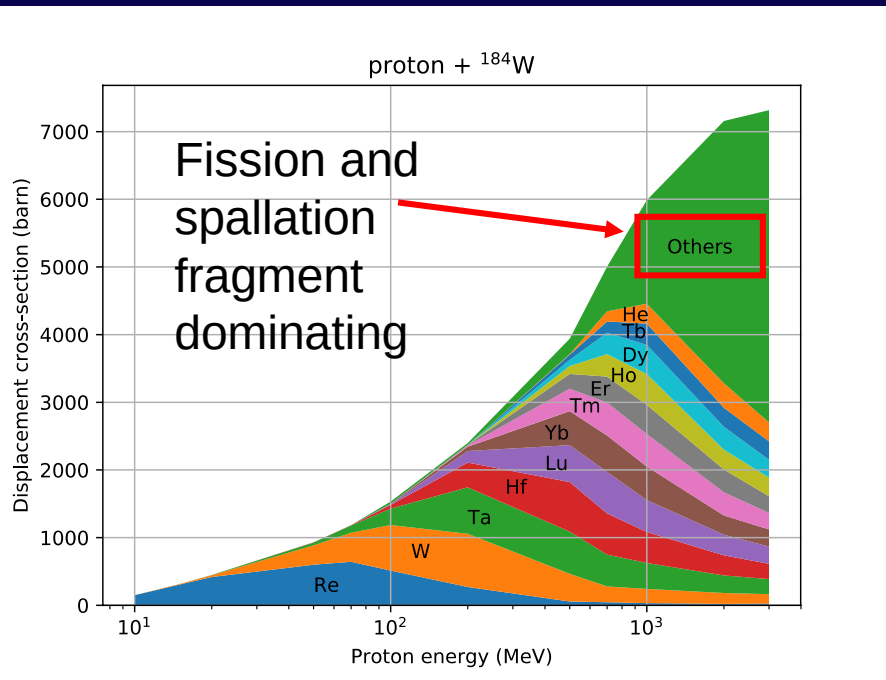


Analysis of contribution for DPA



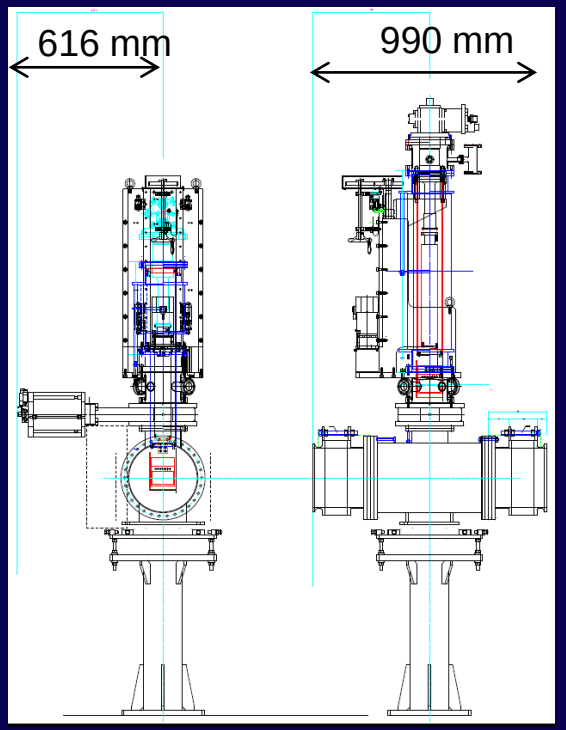


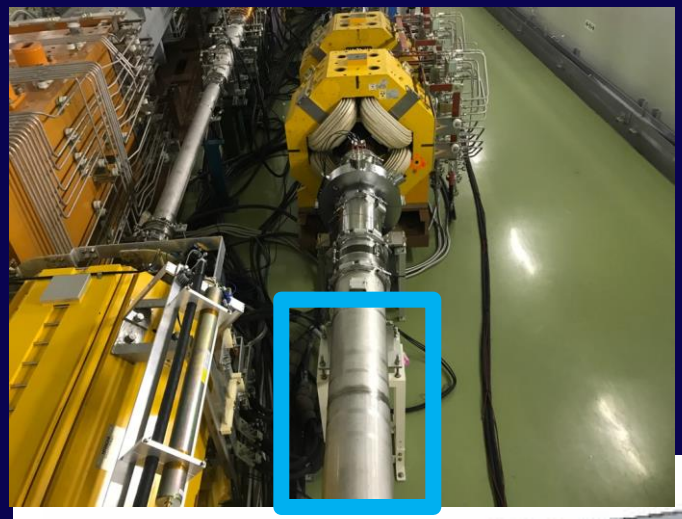


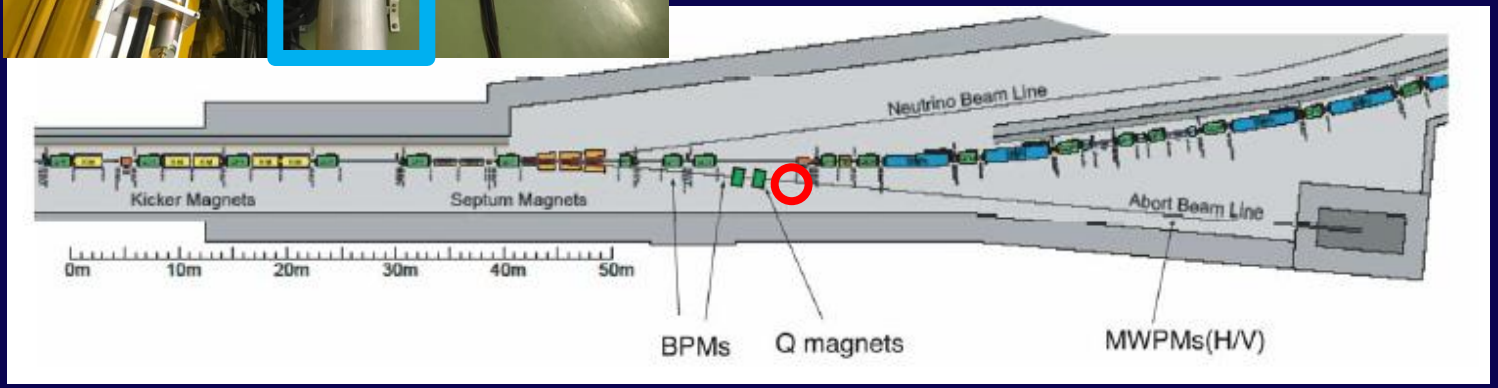


Plan at MR for 3～30 GeV

- MR abort dump
  - PAC will approve soon
  - Next year will be performed.

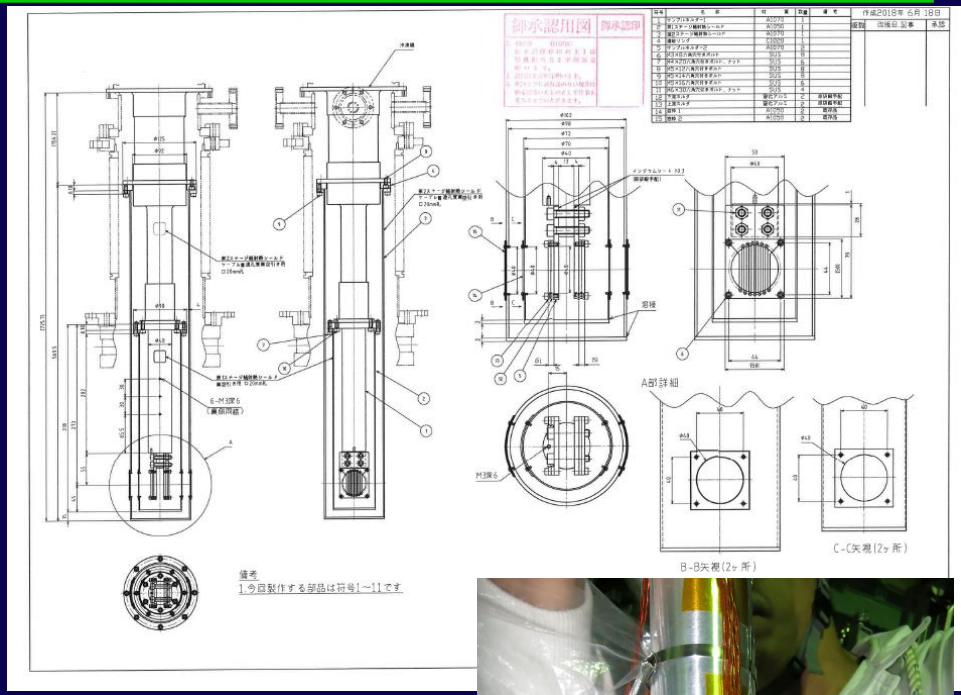


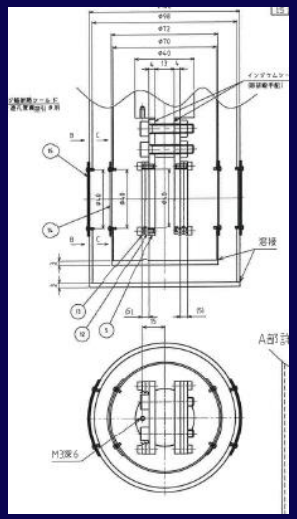




Possibility at FNAL and HPTW

- Relatively easy experiment
- Equipment
  - GM cooler
  - Vacuum chamber
  - Instruments to observe sample resistance
- Instruments should be placed at near the sample with low radiation
- Requirement of experiment
  - Beam monitor and properties
    - not only for beam position but also width and Twiss parameter
  - Beam scan procedure
  - If beam loss allowed, thick sample holder should be applied to cool the sample





Impact on material property analysis

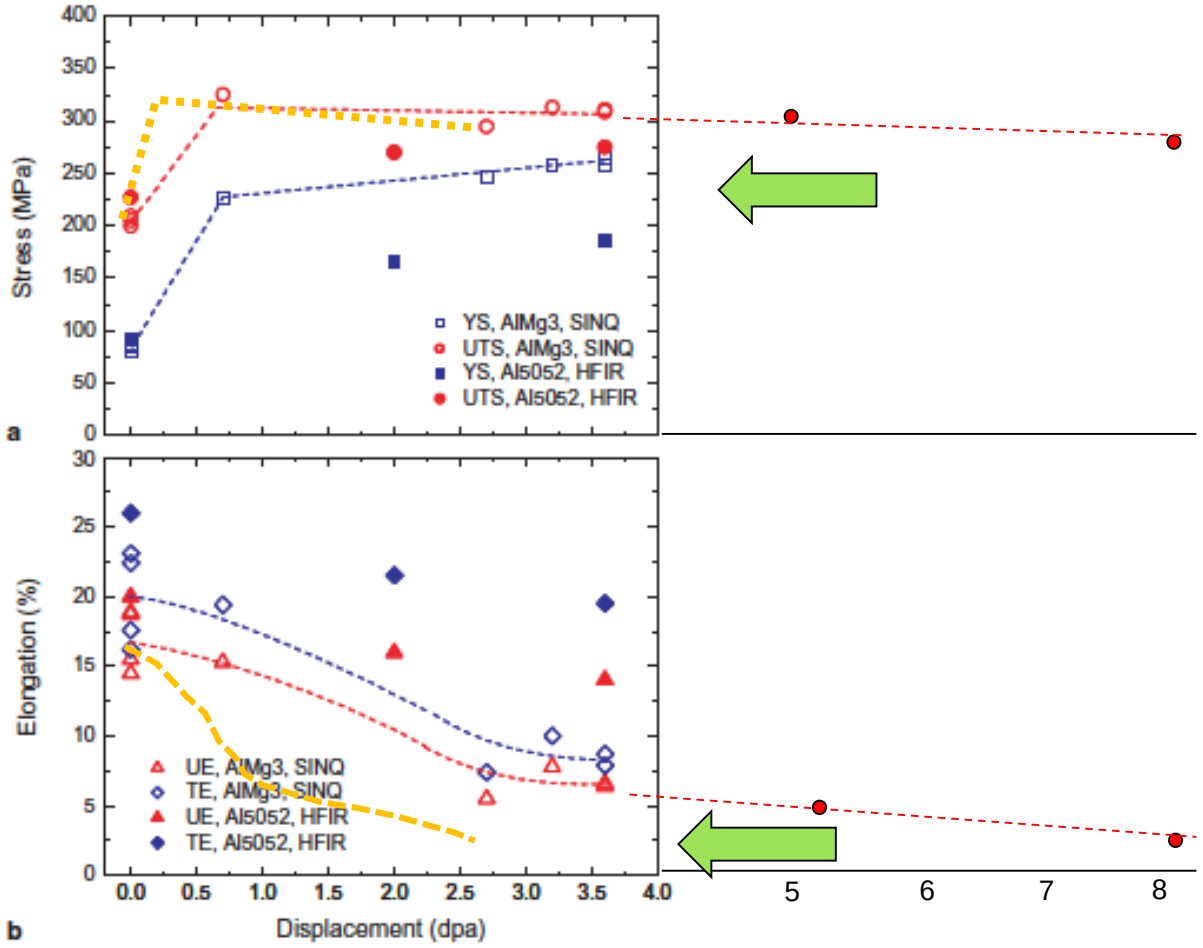


Fig. 9. The irradiation dose dependence of (a) yield stress (YS) and ultimate tensile strength (UTS), (b) uniform elongation (UE) and total elongation (TE). For a comparison, a few data of Al-5052 irradiated in the HFIR [8] were included.

Gas production is good index to determine the lifetime

Summary

- Displacement cross section, measurement for 0.4～30 GeV protons has conducted in J-PARC.
  - Experiment performed for Al, Fe, Cu and W with 0.8, 1.2, 2.2 and 3 GeV protons.
  - Calculation compared with the present data.
    - NRT: ~3 times overestimation
    - Arc-dpa (Nordlund) : pretty good agreement
- NRT cross section will be discussed in IAEA.
- In future, similar experiment will be performed at FNAL and HiRatMat.