Experimental plan for displacement damage cross sections using 120-GeV protons at FNAL

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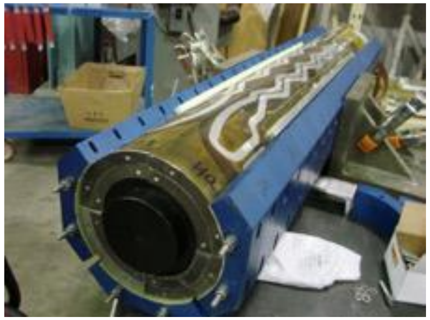
Introduction

Prediction of usable lifetime of materials under high-energy (E>100 MeV) proton irradiation is essential for the design.



CERN LHC superconducting magnet (Nb alloy)

Beam window in neutrino facility (Ti alloy)

Displacement per atom (DPA) value is used as a damage-based exposure unit.

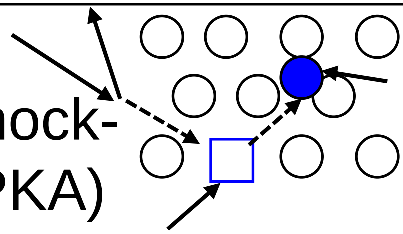
DPA: average number of displaced atoms per atom of a material

DPA $= \sigma_d \phi$

σ_d : **displacement cross-section (m^2)**

ϕ: irradiation fluence (particles/m^2)

Displacement cross section and number of displacements



Frenkel-pairs cause cascade damage.

The number of atomic displacement Nuclear Engineering and Design 33 (1975) 50.

Conventional method: NRT model

$$N_{\mathrm{NRT}} = \frac{0.8}{2E_{\mathrm{D}}} T_{\mathrm{d}}$$

T_{d} ← Damage energy transferred to lattice atoms

E_{D} ← Threshold displacement energy 15 – 90 eV

New method: athermal recombination correction (arc)

$$N_{\mathrm{arc}} = \frac{0.8}{2E_{\mathrm{d}}} T_{\mathrm{d}} \zeta_{arc}(T_{\mathrm{d}})$$

K. Nordlund et al., Nature Communications 9 (2018) 1084.

Experimental data: Irradiation on metal at cryogenic temperature

Recombination of Frenkel pairs by thermal motion is well suppressed.

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

Damage rate

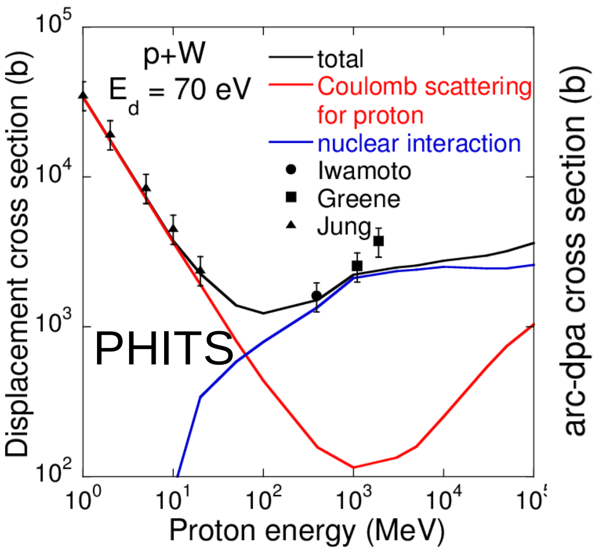
$\Delta\rho_{\mathrm{metal}}$: Electrical resistivity change(Ωm)

Φ: Average Beam fluence(1/m^2)

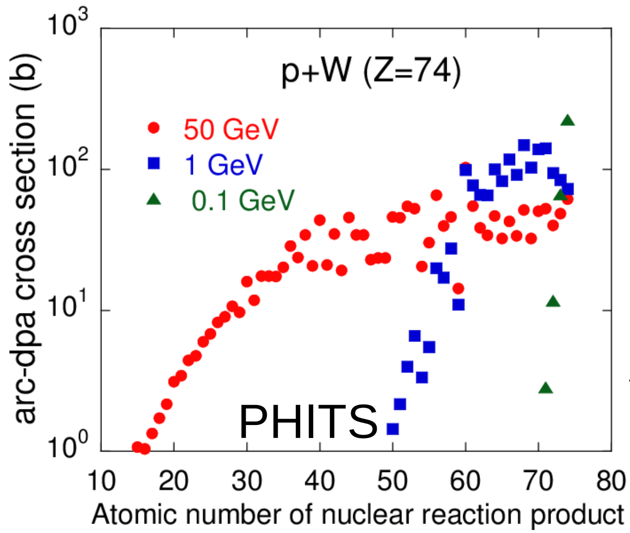
ρ_{FP}: Frenkel-pair resistivity (Ωm)

Resistivity increase is the sum of resistivity per Frenkel pair

Strategy and purpose of dpa measurements



Arc-dpa cross section for p+W



Arc-dpa of nuclear interaction products

Kinetic energies of products for 50 GeV are a few MeV.

Radiation damage models were developed in MC codes (PHITS,FLUKA,MARS,…).

Cross sections of metals were measured with 0.1 – 30 GeV.

Arc-dpa reproduces the data well.

There is no data over 30 GeV.

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

JSPS Kakenhi budget project (2013-2022)

- Development of calculation method
- Development of device
- 125 MeV p on Cu at FFAG
- 200, 389 MeV p on Al,Cu,W at RCNP
- **120 GeV p on Al,Fe,Cu,Ti,Nb,W… at FNAL**

MEXT budget project, 原シス (2016-2019)

- 0.4-30 GeV p on Al,Cu,Fe,W … at J-PARC

International collaboration

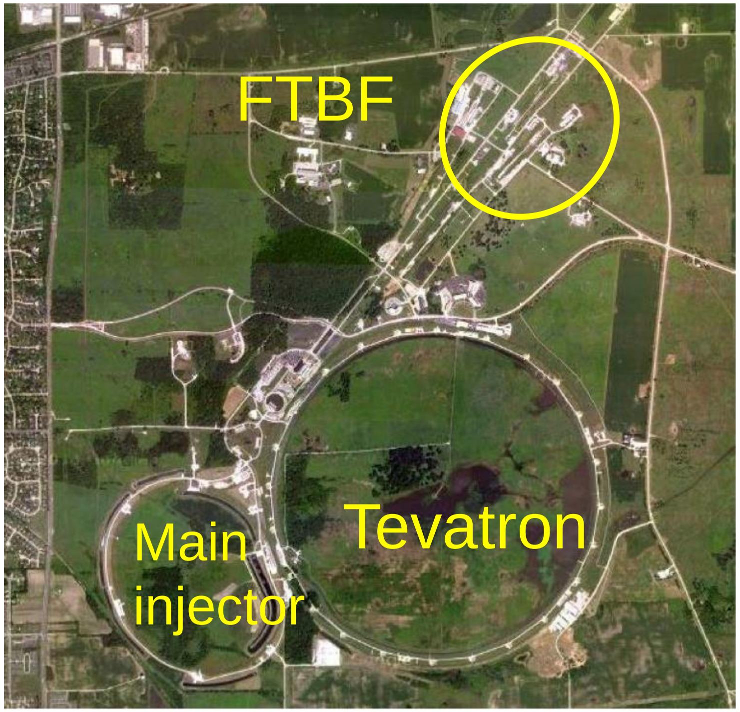
IAEA CRP: Primary radiation damage cross sections

Radiation Damage In Accelerator Target Environments (RaDIATE)

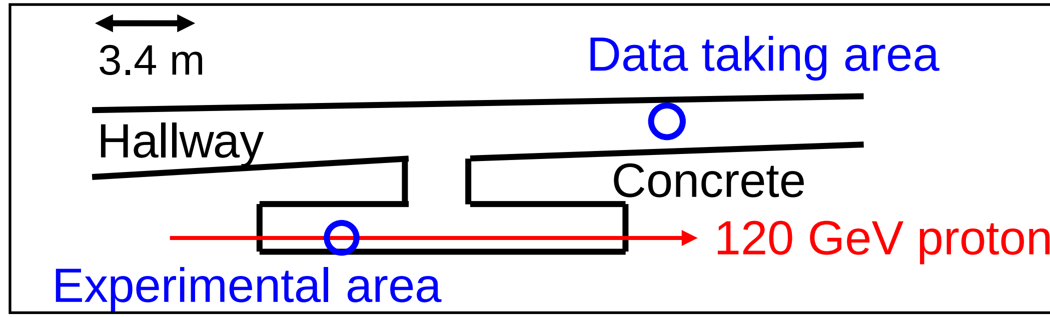
Purpose: Preparing for DPA cross section measurements with 120 GeV proton

Fermilab Test Beam Facility (FTBF) located on FNAL

Experiment was approved at meeting in FNAL on Feb. 4th 2020 and was scheduled in Nov. 2020. But we decided to photophone it 1 year later due to the spread of COVID-19.



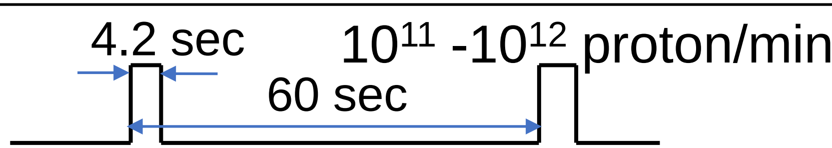
Bird’s eye view of FNAL



M03 in FTBF

Experimental area

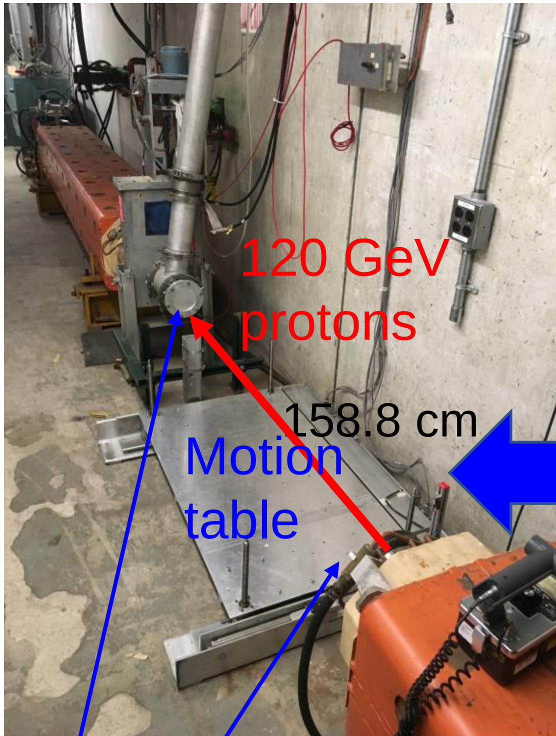
Data taking area



Root mean square (RMS) beam size can be 4 mm for protons.
Beam scan is possible for horizontal and vertical directions.

Beam structure

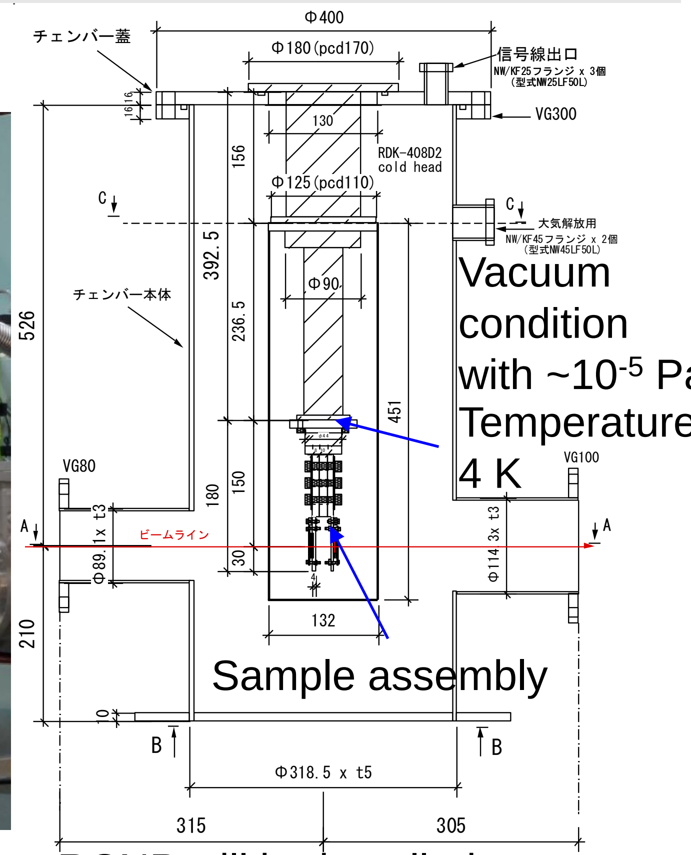
Irradiation chamber with GM cryocooler



Segmented Wire Ionization Chambers (SWICs) will be installed for beam profile.

Experimental area

Gifford-McMahon (GM) cooler RDK-408D2



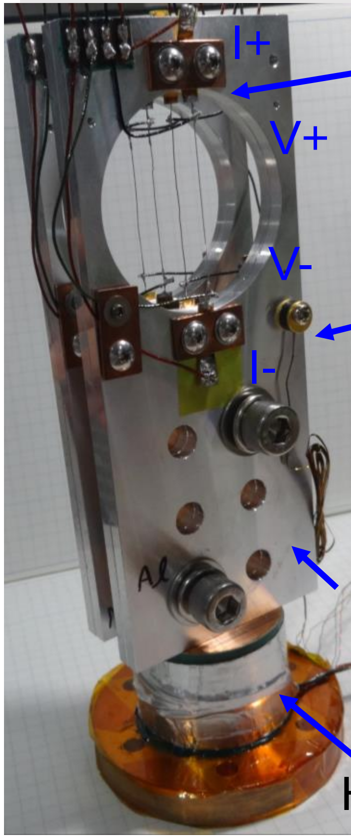
The chamber used at RCNP will be installed.

Irradiation chamber with GM cryo cooler

1. Set the chamber on the motion table.
2. The chamber is set on the beam line.
3. Beam alignment. The target is on the beam line during the beam alignment.
4. 40 hours irradiation
5. Move the chamber from the beam line.
6. Annealing test with keeping vacuum condition and cryogenic temperature.

Heat damage recovery measurements

Sample assembly for FNAL experiment



Sample assembly

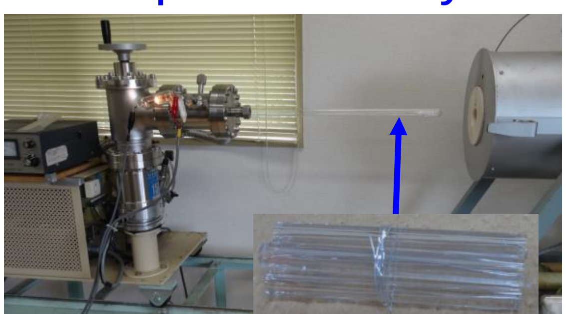
- The aluminum plate is a support plate of a wire sample and a beam hole is a free space for a beam.
- A 5-sigma of beam size or more should be needed for the beam clearance.

Beam hole: 48 mm diameter (6-sigma)

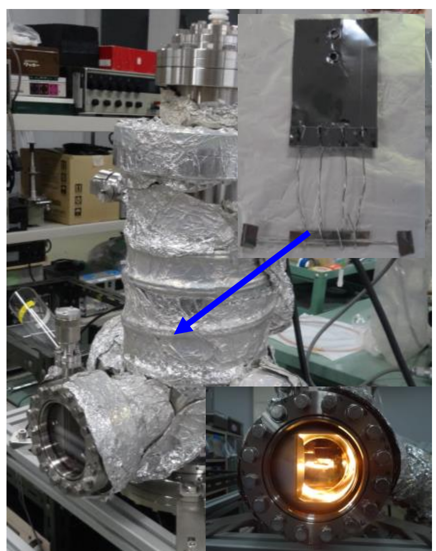
- Beam loss permits less than 3 % of interaction length in area at M03: 1.2 cm for 120 GeV proton on Al.

Wire sample with 250 micro-meter diameter.

- Samples were annealed to decrease defects before irradiation.



Vacuum electric furnace for Al and Cu

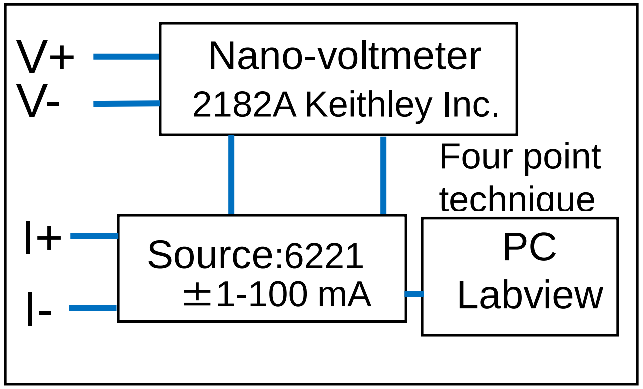


Electron gun for Nb and W

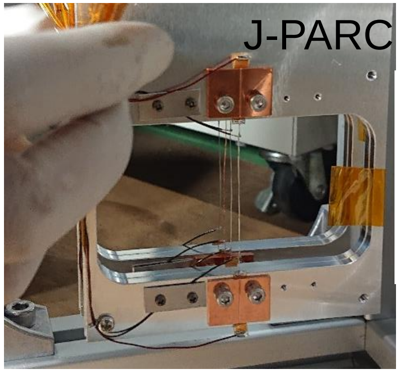
Annealing temperature for samples

	Melting point (K)	Annealing temperature (K)	Time (min.)
Al	933.5	840	30
Cu	1358	1289	30
Nb	2750	1923	15
W	3695	2473	15

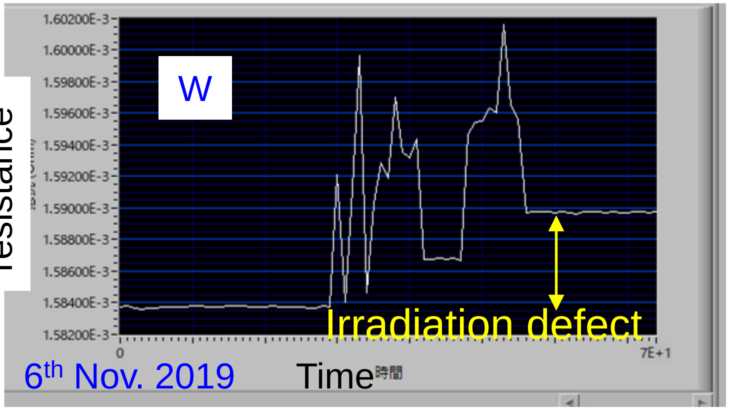
Data taking system and estimation of beam time



Data taking system



Sample assembly similar with FNAL samples



Trend of resistance with 30 GeV protons

- Electrical resistivity change of a cryogenic sample during beam irradiation is measured using four-terminal method.
- Electrical resistivities of FNAL samples will be measured soon.

Estimation of beam time

	Al	Cu	Nb	W
Estimated DPA cross section (m^2)	1.67E-26	1.41E-25	1.85E-25	3.33E-25
Frenkel pair resistivity (μΩm)	3.7	2.2	14	27
Geometry factor (A/L) (m)	4.91E-06	5.24E-06	5.10E-06	5.24E-06
Resistance increase (μΩ)	0.3	1.2	10	35
Estimated beam fluence ($1/m^2$)	2.38E+19	2.03E+19	1.97E+19	2.04E+19

Estimated beam area (m^2)	5.03E-05
protons/min.	5.00E+11
protons/min/m^2	9.95E+15
Beam fluence for 40 h ($1/m^2$)	2.39E+19

Approximately 40 hours irradiation is needed to measure resistance increase in Table.

Summary and future plan

- We planed measurements of displacement cross sections for metals at cryogenic temperature with 120 GeV protons.
- The experimental arraignment of irradiation chamber and data taking system at FTBF was decided.
- The sample assembly was developed. The electrical resistivity at cryogenic temperature will be measured soon.
- The first experiment at FTBF will be scheduled during the period between Nov. 2021 and April 2022.

References related with our studies

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Y. Iwamoto et al., Estimation of reliable displacements-per-atom based on athermal-recombination-corrected model in radiation environments at nuclear fission, fusion, and accelerator facilities, J. Nucl. Mater. 538 (2020) 152261.

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