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J-PARC

RaDIATE
Collaboration

J-PARC Neutrino Beam-line Status & Radiation Damage Studies on Titanium Alloys

Current and Future J-PARC-Based Long-Baseline Neutrino Oscillation Experiments

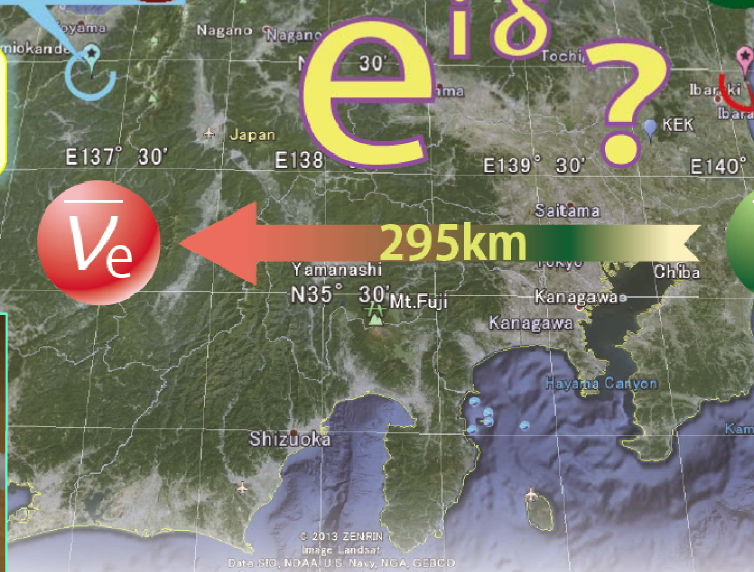
T2K
Tokai-to-Kamioka

Kamioka Mine
Nucleon Decay Exp.
Neutrino Detection Exp.
39mϕ x 41mH
Total[Fiducial] Volume
= 50[22.5]kt

$\pi^{\pm} \rightarrow \mu + \nu_{\mu}$

485kW achieved

upgrade to **1.3 MW**



ν_e ← 295km ← ν_μ

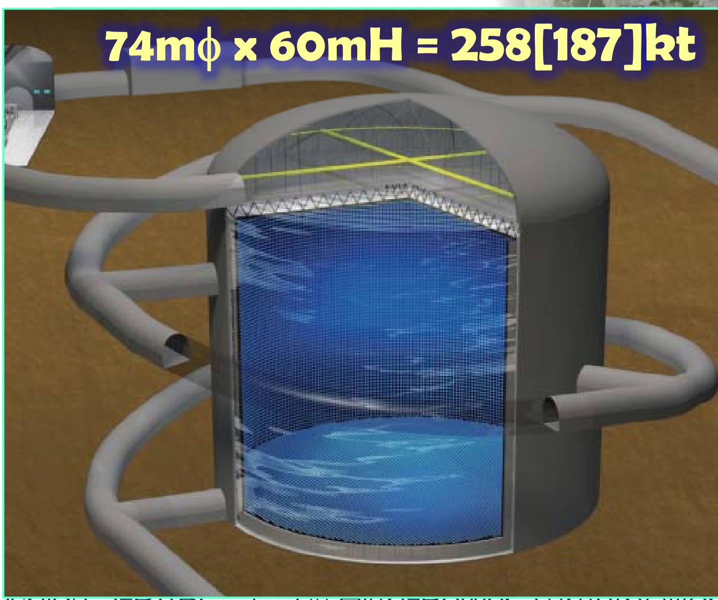
$e^{i\delta}$?

$\bar{\nu}_e$ ← 295km ← $\bar{\nu}_\mu$

x ~10 of Super-K

Hyper-Kamiokande

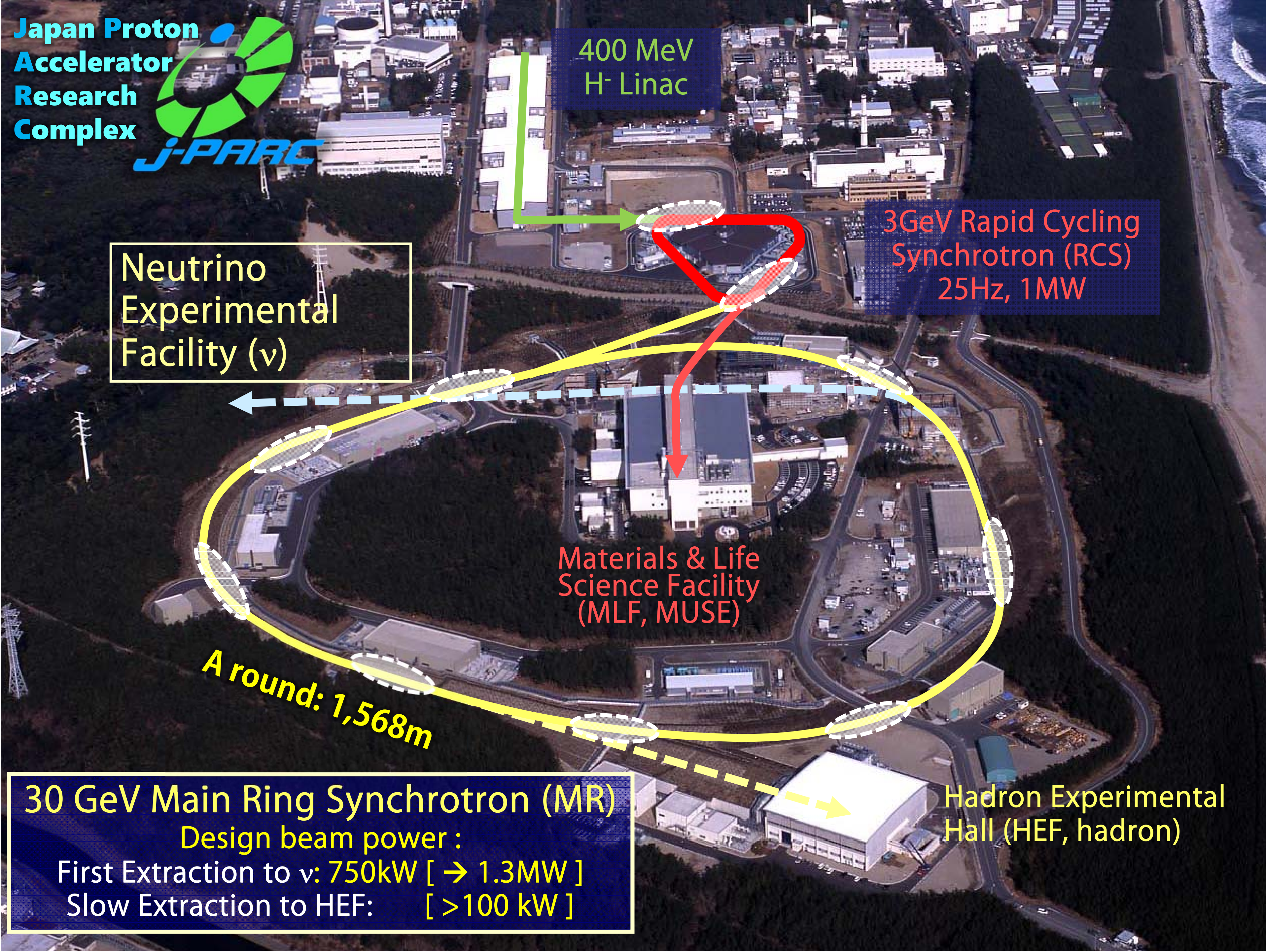
74mϕ x 60mH = 258[187]kt



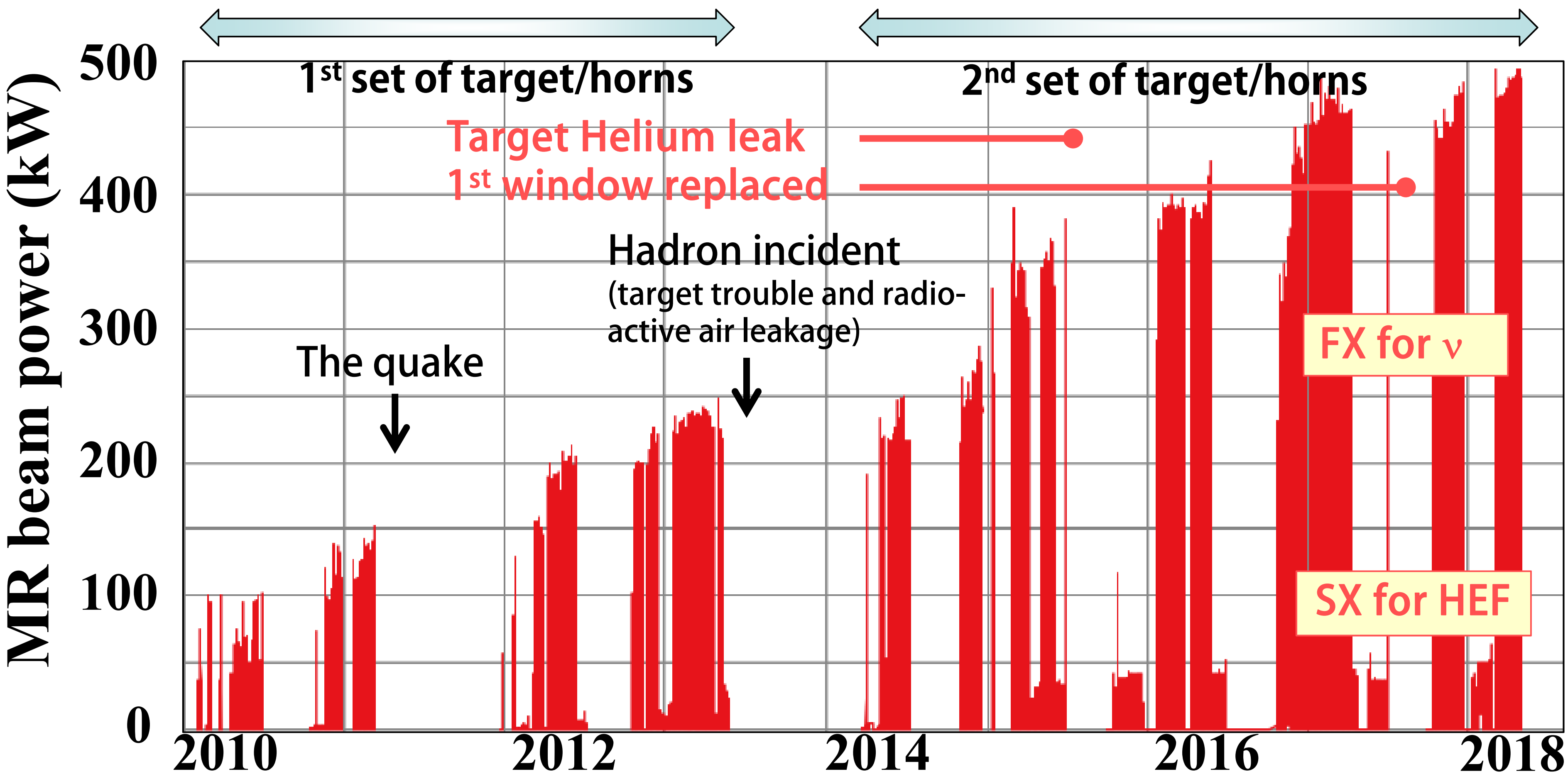
Neutrino Facility at J-PARC

Tokai village

Discovery of CPV in Lepton Sector

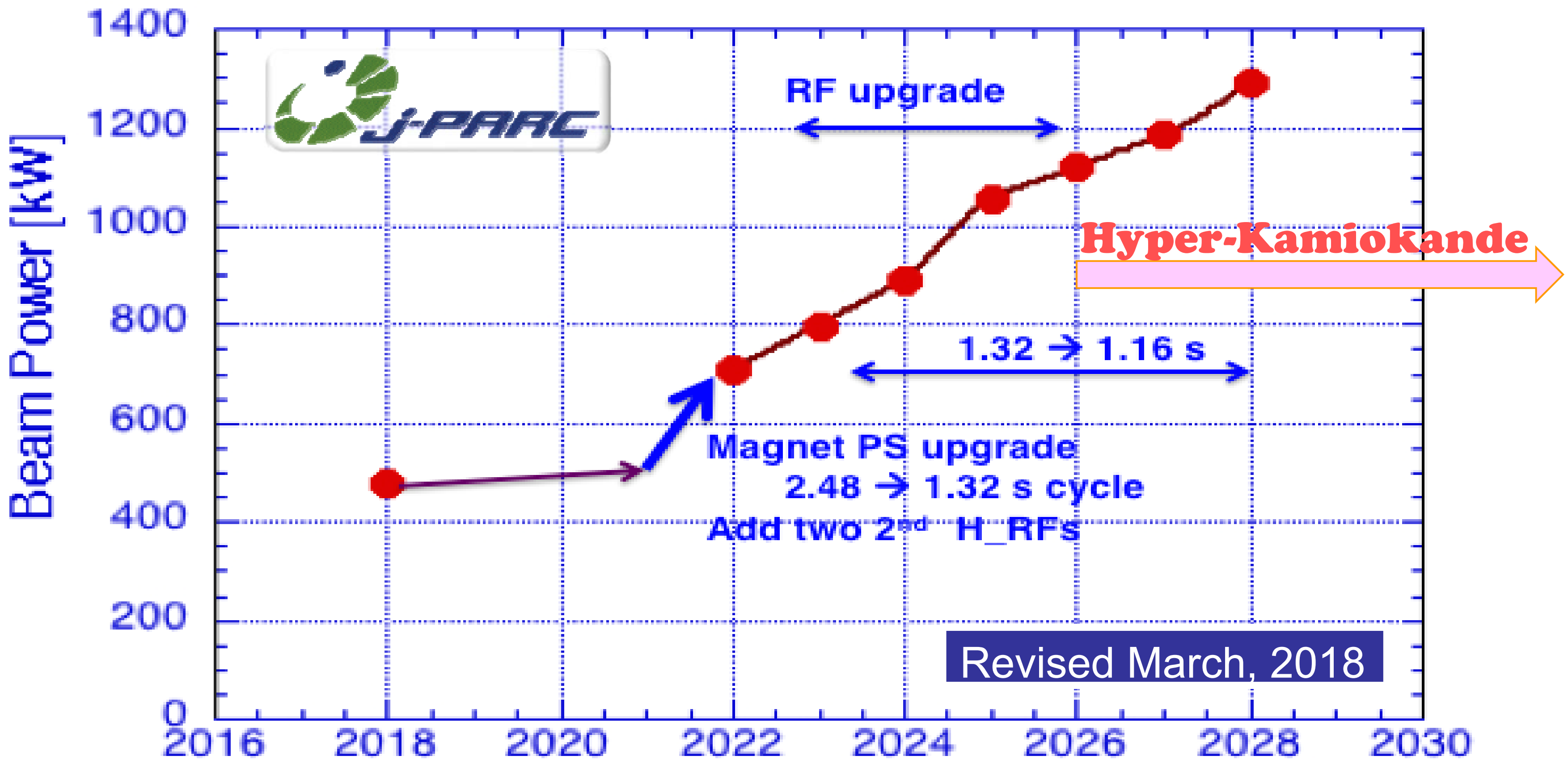

Japan Proton Accelerator Research Complex
J-PARC
400 MeV
H⁻ Linac
3GeV Rapid Cycling Synchrotron (RCS)
25Hz, 1MW
Neutrino Experimental Facility (ν)
Materials & Life Science Facility (MLF, MUSE)
A round: 1,568m
Hadron Experimental Hall (HEF, hadron)
30 GeV Main Ring Synchrotron (MR)
Design beam power :
First Extraction to ν: 750kW [→ 1.3MW]
Slow Extraction to HEF: [>100 kW]

Operational History of Main Ring



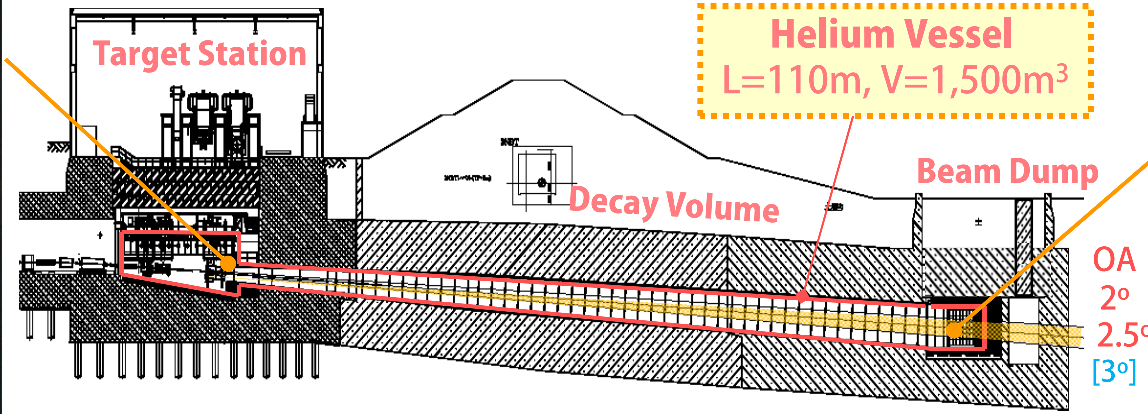
- The 485 kW beam power has been achieved with 2.5×10^{14} ppp/2.48sec
- No major problems on neutrino facility target and beam-window
  - He leak at target outlet pipe → fixed by remote handling
  - The 1st beam window is replaced to (nearly) identical 2nd window

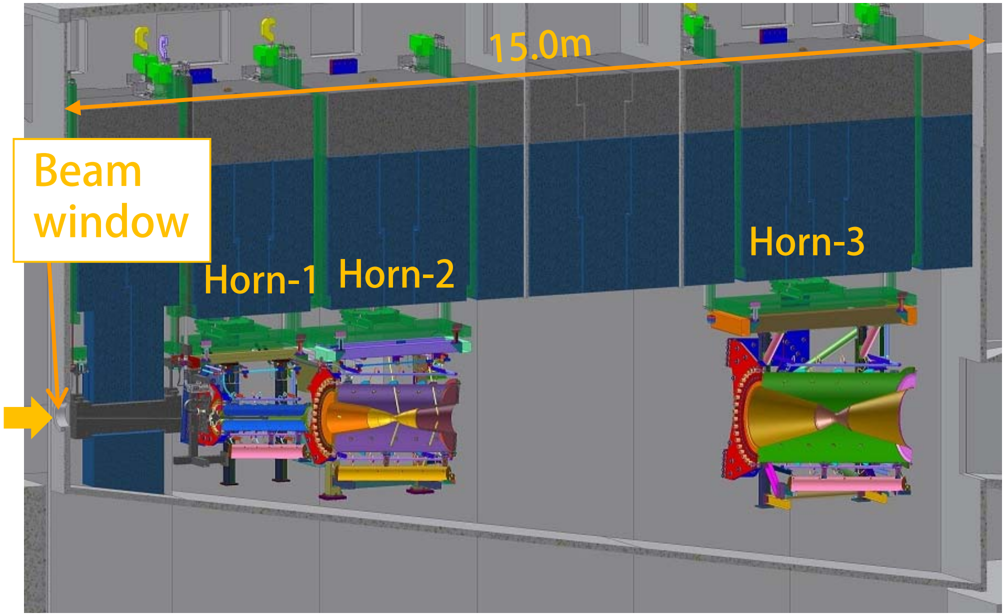
MR beyond 1 MW with Doubled Rep-rate

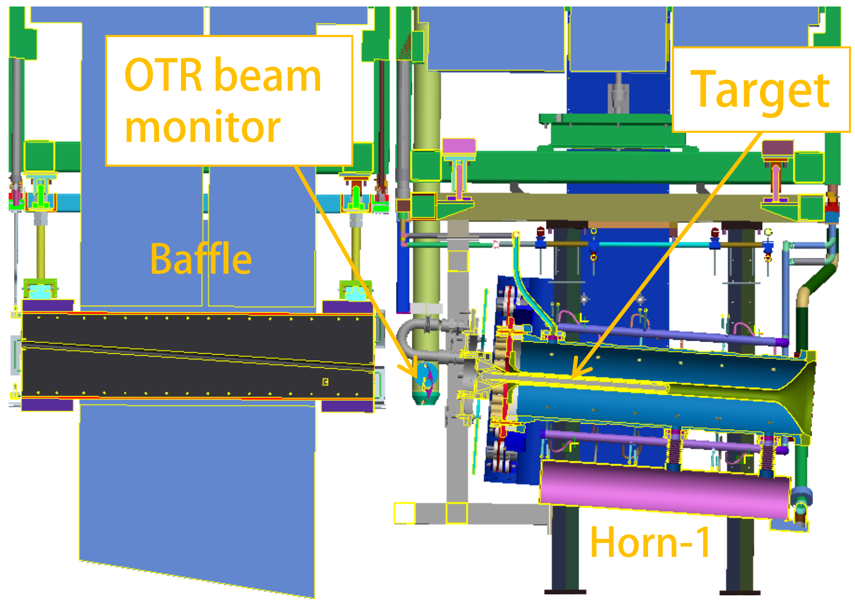


Beam power	485 kW (achieved)	750 kW (proposed)	1.3 MW (proposed)
Beam energy	30 GeV	30 GeV	30 GeV
Beam intensity (ppp)	2.5×10^{14}	2.0×10^{14}	3.2×10^{14}
Repetition cycle	2.48 s	1.32 s	1.16 s

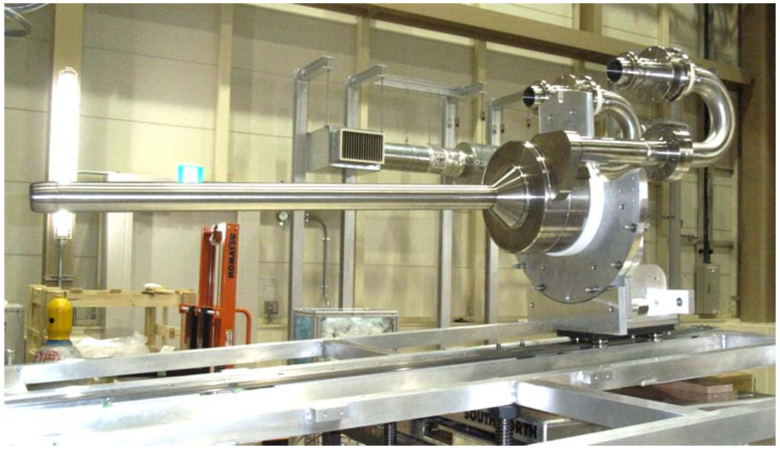
Neutrino Secondary Beam-line

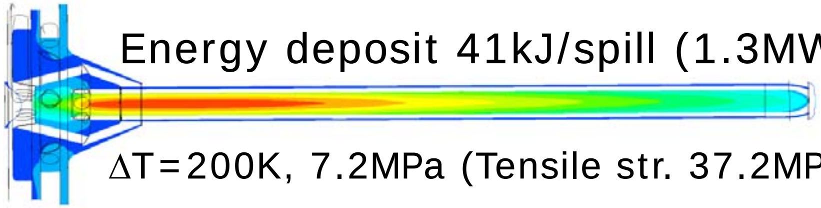


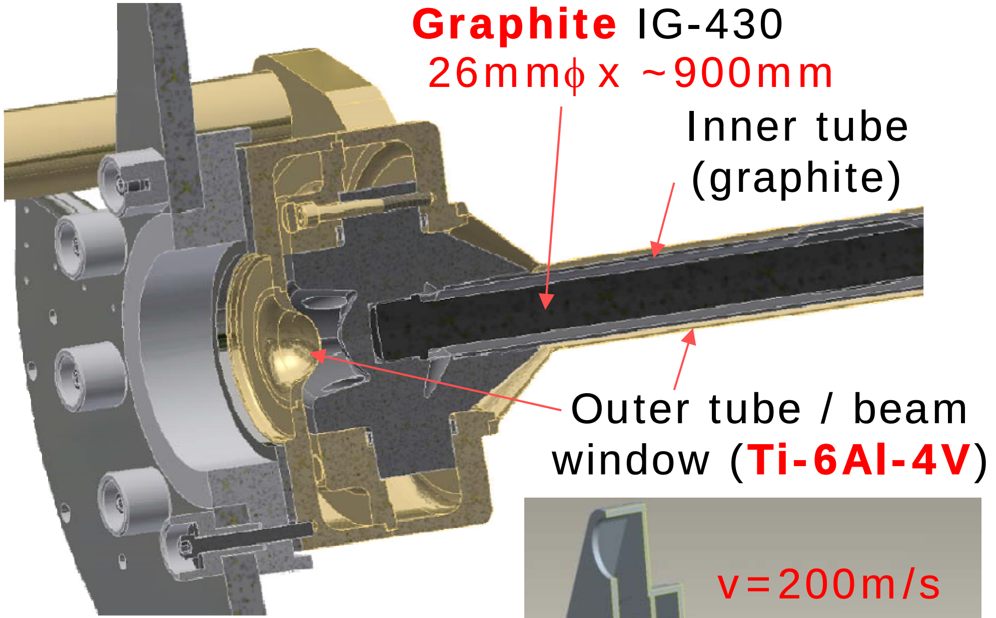


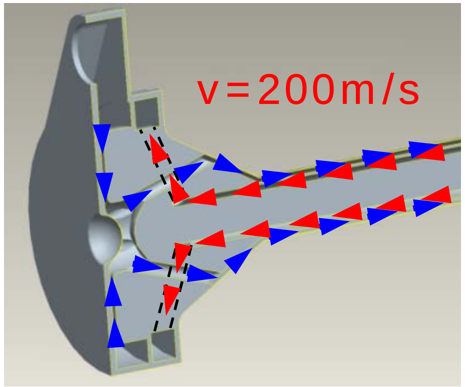


1.3 MW Target Upgrade – Graphite & Ti







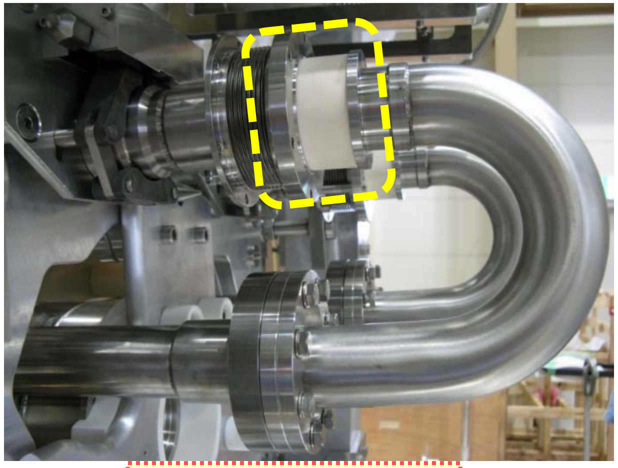


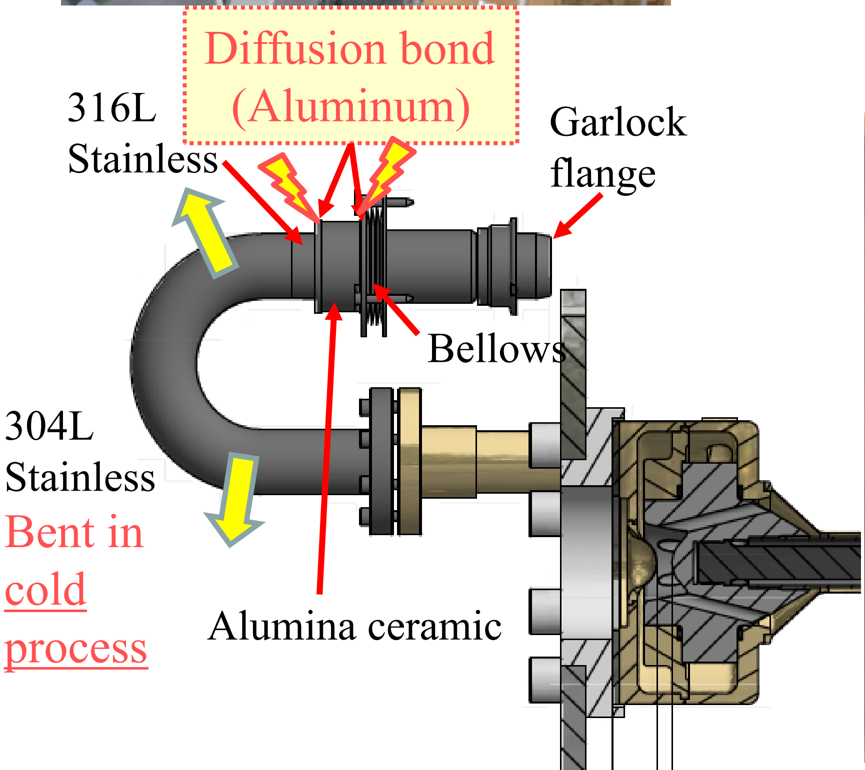
	0.75 MW	1.3 MW
Helium pressure	1.6 bar	**5 bar**
Pressure drop	0.83 bar	0.88 bar
Helium mass flow	32 g/s	**60 g/s**
Heat load	23.5 kW	40.8 kW
US window temp	105°C	157°C
DS window tem	120°C	130°C
Graphite Max. temp.	736°C	**909°C**

Lifetime 5years under 100ppm

- High Temperature：Oxidization of graphite will be the limiting factor on target lifetime
  - CVD-SiC coated graphite in BLIP/HiRadMat
- Radiation damage on Ti beam window under higher pressure

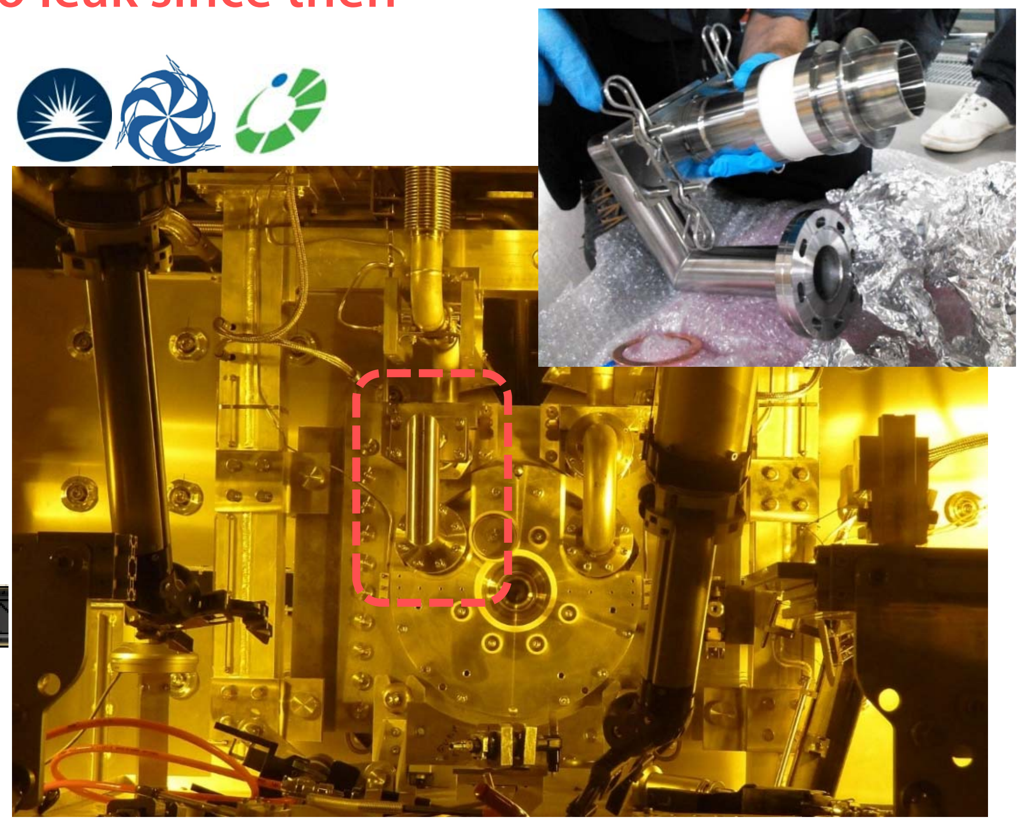
Leak at Helium Outlet Pipe & Remote Handling





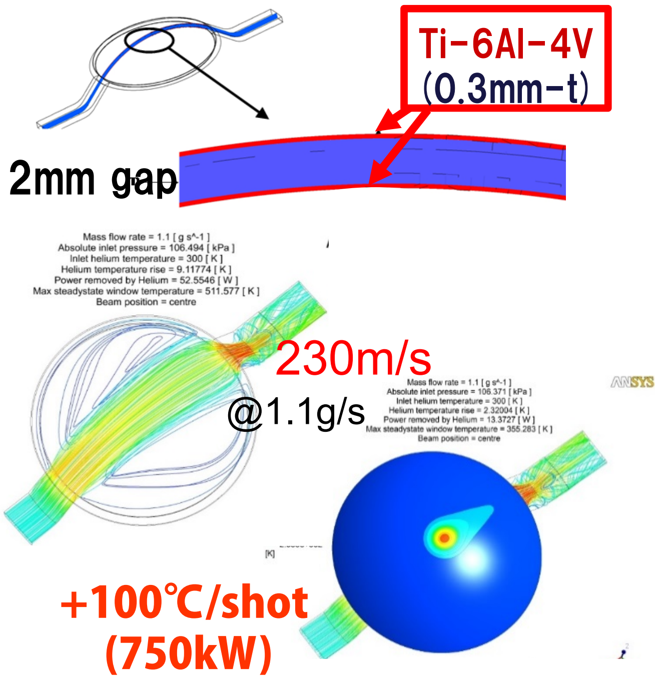
- Failure of joint/ceramic from movement of stainless pipes (stress relieving)
- Thermal fatigue failure of the diffusion bonded joint/ceramic
- Remote Exchange in 2015
- No leak since then

(A.Atherthon HPTW16)



Ti-6Al-4V Beam Window

- Periodic thermal stress wave caused by the intense proton beam energy deposition
- 750kW operation will cause radiation damage of ~1DPA/ops-year, whereas significant irradiation hardening and loss of ductility has been reported with 0.3DPA (no higher DPA data exists)
- No known data exists on high cycle fatigue (>10^3 cycles) of irradiated titanium alloys



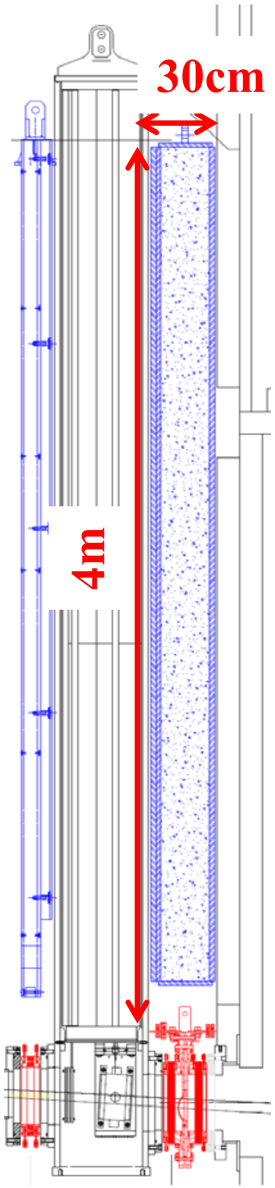
Beam Power	PPP	Rep. cycle	POT / 100 days
470kW (achieved)	2.4 x 10^{14}	2.48 sec	(0.8 x 10^{21})
750kW (proposed)	2.0 x 10^{14}	1.3 sec	1.3 x 10^{21}
750kW [original plan]	3.3 x 10^{14}	2.1 sec	1.3 x 10^{21}
1.3 MW (proposed)	3.2 x 10^{14}	1.16 sec	2.4 x 10^{21}

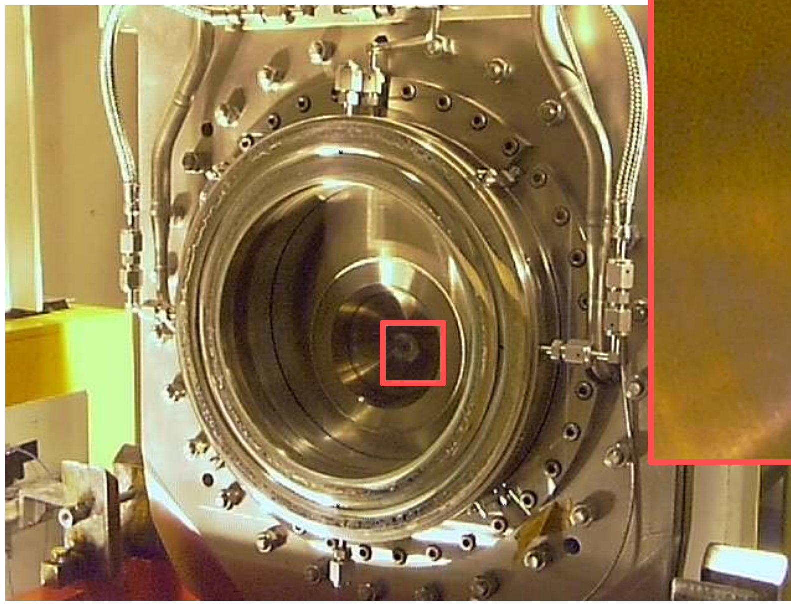
designed

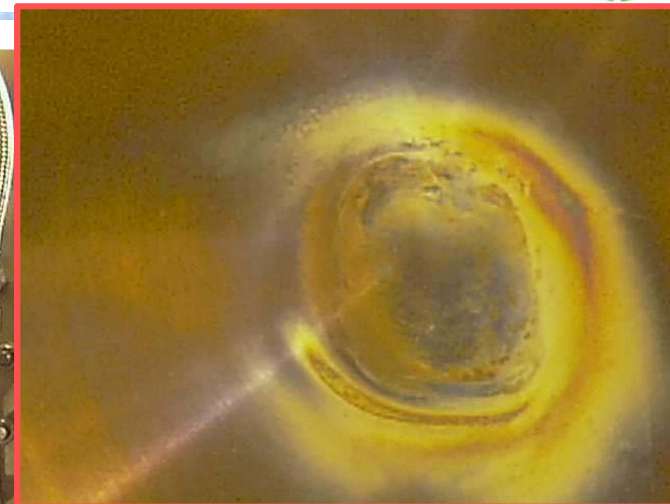
~8M pulses/yr

~1DPA/yr (MARS)

Window Remote Maintenance (2017 summer)





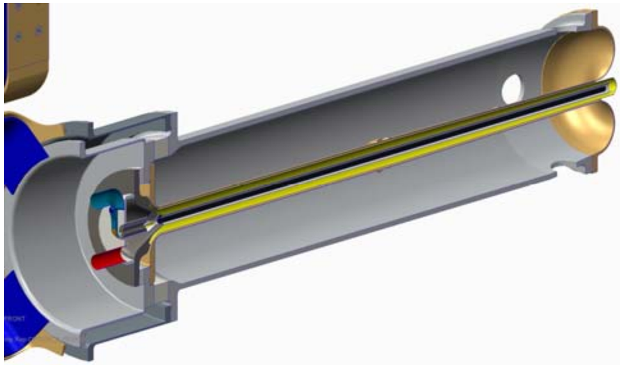


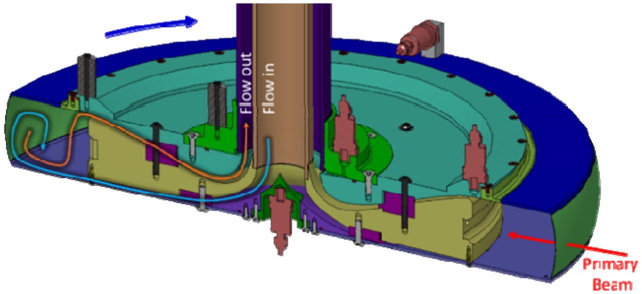
After 2.2 x 10^{21} pot
~2DPA(NRT)

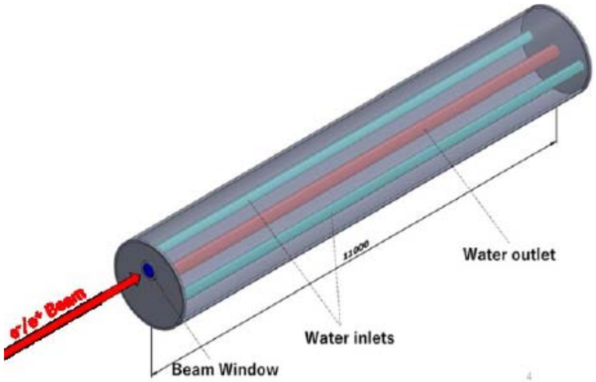
- The 1st window survives to the 2.2x10^{21} POT comparable to 1.3MW/ops-yr
- Discoloration/deposit/damage of Ti-6Al-4V on TS vessel side visually identified
  - Helium in TS vessel was humid, and the damage can be from radio-chemical reaction (accelerator vacuum side show less signatures)
  - Need to improve helium circulation system to remove the humidity
- We wish to perform PIE at JAEA's hot-lab, while it will take time to clear radiation safety regulations and license problems at J-PARC

Radiation damage studies on Ti-alloys

- Titanium alloy Ti-6Al-4V is widely adopted as a targetry material:
  - J-PARC neutrino primary beam window, target window & containment vessel
  - J-PARC hadron facility target chamber window
  - LBNF reference design target window and target containment vessel
  - MSU-FRIB Beam Dump
  - ILC 14MW main water dump beam window
- Relatively little known on how this Ti alloy is affected by high energy proton irradiation
- Imperative to research radiation damage effects to enable :
  - Accurate component lifetime prediction
  - Design of robust multi-MW components, and
  - Choice of better alloy or development of new materials to extend lifetimes



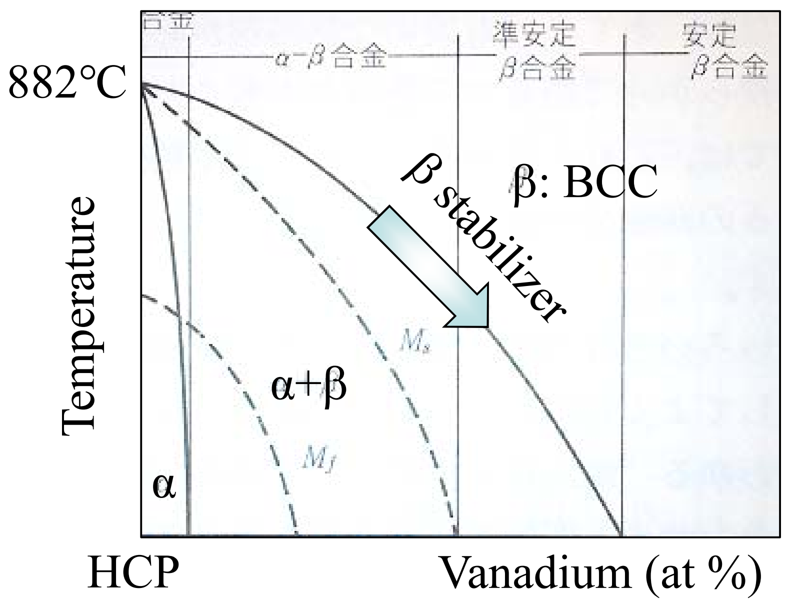




Classification of Ti-alloys & BLIP specimens

Comprehensive understanding on radiation damage effects for different Ti alloys

- β and α+β alloy require proper heat treatment to reinforce strength by precipitation of alloy elements:
  1. Solution Treatment: Keep proper high temp to solute more alloy element than RT
  2. Rapid Cooling to RT keeping the condition
  3. Aging treatment: Keep temp moderately higher than RT to precipitate the alloying components as fine intermetallic compound



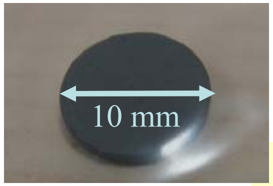
□ : Samples in BLIP capsules

組　成	熱処理	引張性質		
		引張強さ (MPa)	耐力 (MPa)	伸び (%)
純チタン(α) Comercially Pure Ti				
JIS 1 種 Gr1(α)	A	270～410	≧165	≧27
JIS 2 種 Gr2(α)	A	340～510	≧215	≧23
JIS 3 種	A	480～620	≧345	≧18
JIS 4 種	A	550～750	≧485	≧15
α 合金				
Ti-5 Al-2.5 Sn Gr6(α)	A	862	804	16
α リッチ α-β 合金				
Ti-8 Al-1 Mo-1 V	A	1 000	951	15
Ti-6 Al-2 Sn-4 Zr-2 Mo	A	980	892	15
α-β 合金				
Ti-3 Al-2.5 V Gr9(α+β)	A	686	588	20
Ti-6 Al-4 V	A	980	921	14
Gr5/23(α+β), α'-UFG	STA	1 170	1 100	10
Ti-6 Al-6 V-2 Sn	A	1 060	990	14
	STA	1 270	1 170	10
Ti-6 Al-2 Sn-4 Zr-6 Mo	STA	1 270	1 180	10
Ti-10 V-2 Fe-3 Al	STA	1 270	1 200	10
β 合金 Meta-stable β				
Ti-13 V-11 Cr-3 Al	STA	1 220	1 170	8
Ti-3 Al-8 V-6 Cr-4 Mo-4 Zr	STA	1 440	1 370	7
Ti-11.5 Mo-6 Zr-4.5 Sn	STA	1 380	1 310	11
Ti-15 Mo-5 Zr-3 Al	STA	1 470	1 450	13
Ti-15 V-3 Cr-3 Al-3 Sn	STA	1 230	1 110	10

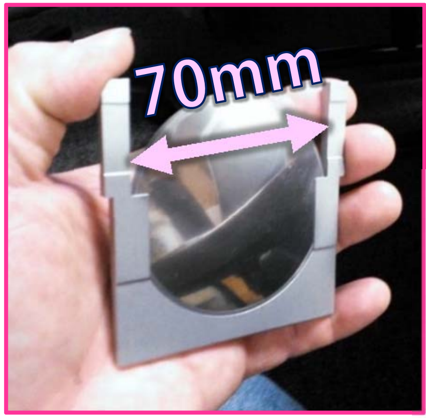
15-3Ti(β)

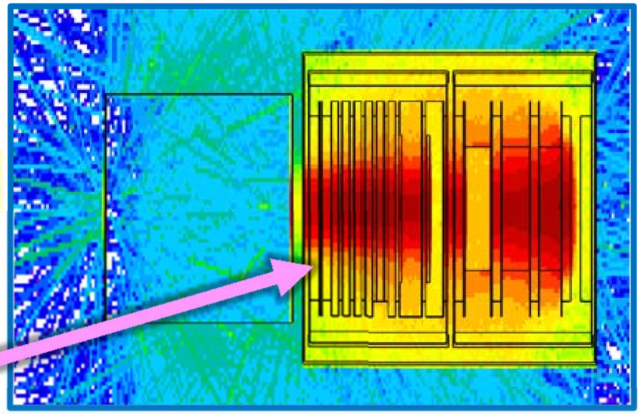
RaDIATE Irradiation Runs at BNL-BLIP Facility

SiC-coated graphite



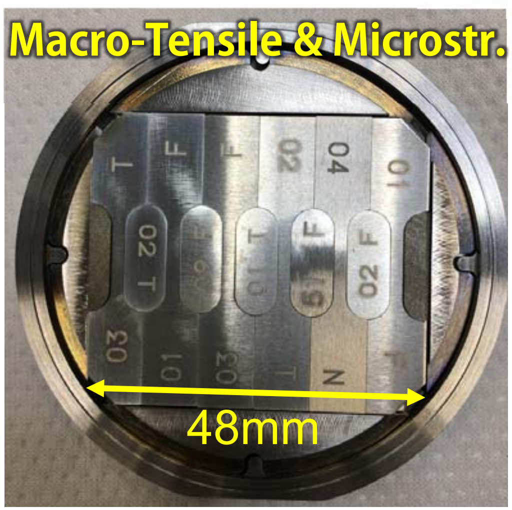
→ D.Senor

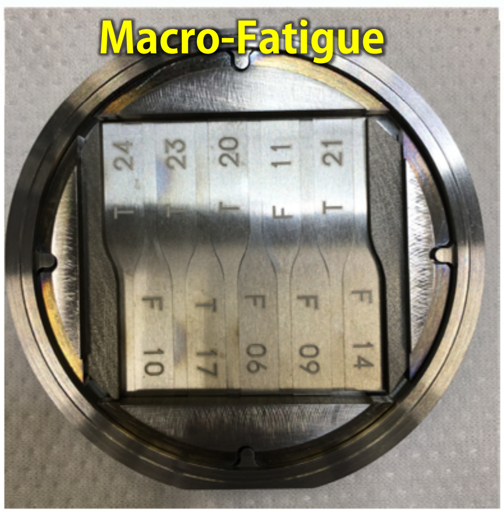


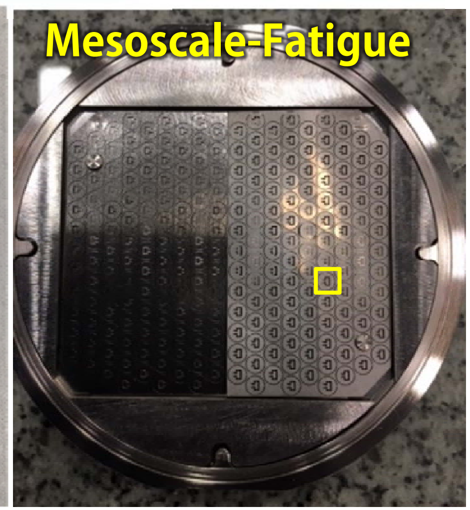


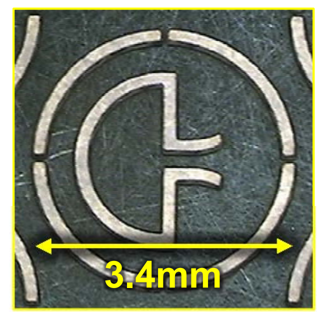
Accumulated Damage
Ti : 1.52 DPA peak (NRT)
0.93 DPA peak (Stoller)

- 1st phase irradiation (2017)
  - Total POT: 1.76×10^{21} in 22 days @ 146μA average
  - Capsules shipped to PNNL
  - Tensile testing → A.Casella
  - 2 capsules newly installed
- 2nd phase irradiation(Jan-Mar 2018)
  - 2.81×10^{21} in 33 days @ 158uA average
  - Capsules to be shipped to PNNL soon.







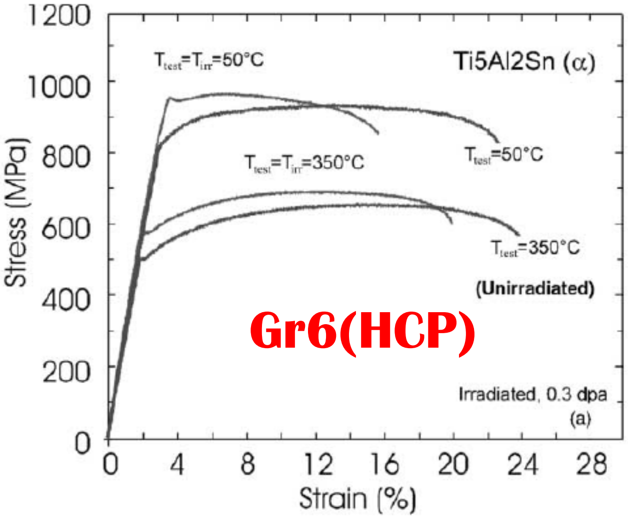


UNIVERSITY OF OXFORD

Damage-tolerant Candidates in BLIP Irradiation

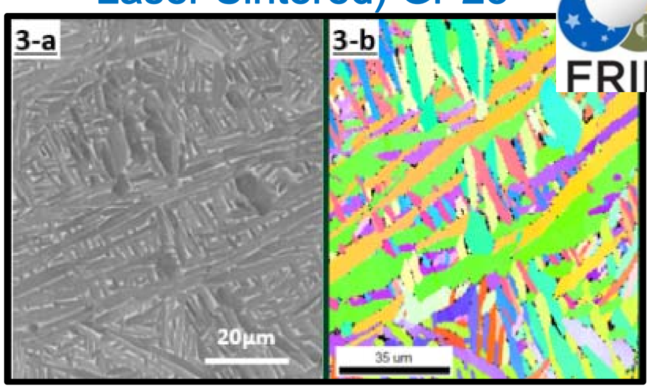
HCP α alloy Gr6

Better ductility (n 0.3DPA)



S. Tähtinen et al., JNM 307-311 (2002) 416

3D printing (Direct Metal Laser Sintered) Gr-23

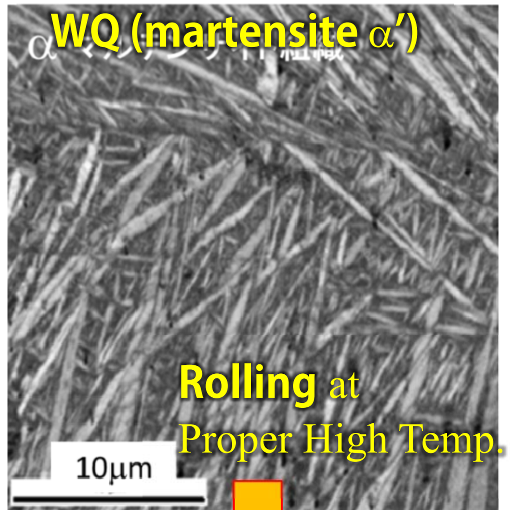


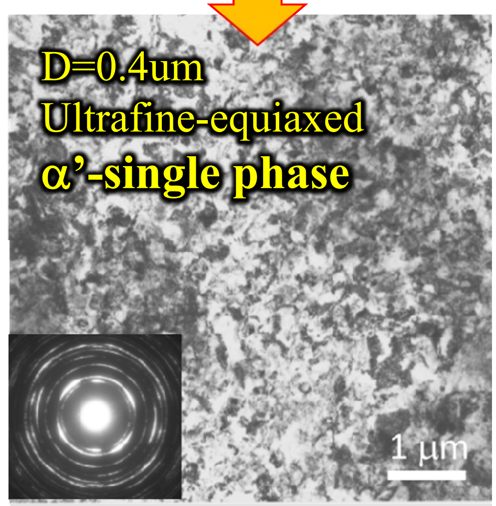
FRIB

F.Pellemoine, NBI2017+RaDIATE

64Ti α'-Ultra FineGrain

Rich grain boundaries

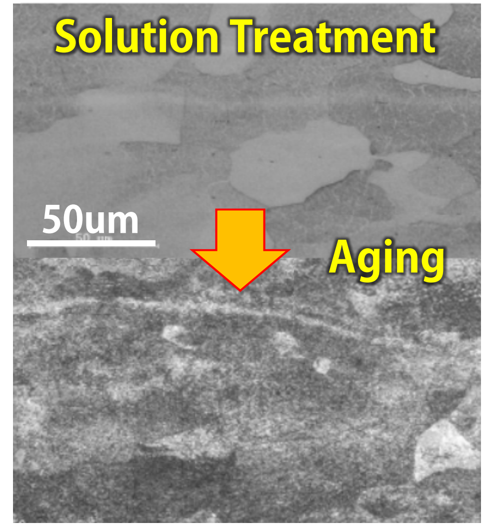


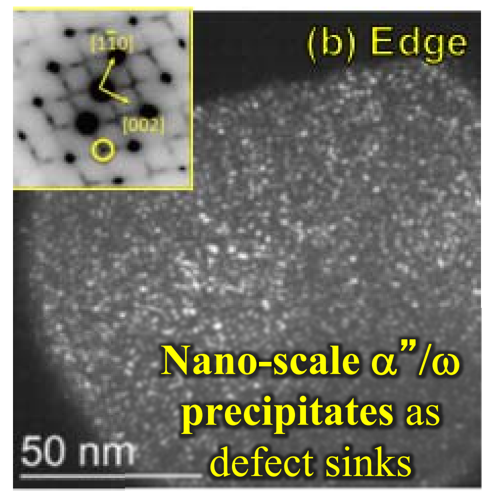


H.Matsumoto et al., Adv.Eng.Mat.13 (2011) 470

Metastable β 15-3Ti

Nanoscale precipitates





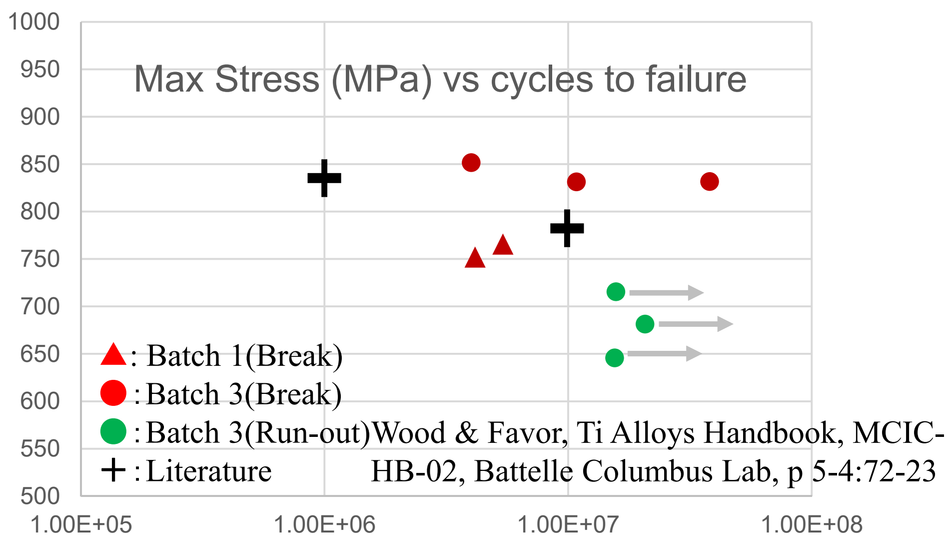
T.Ishida et al, NME (2018) in press

→ D.Senor

High-Cycle Fatigue Data on Ti alloys to be Available

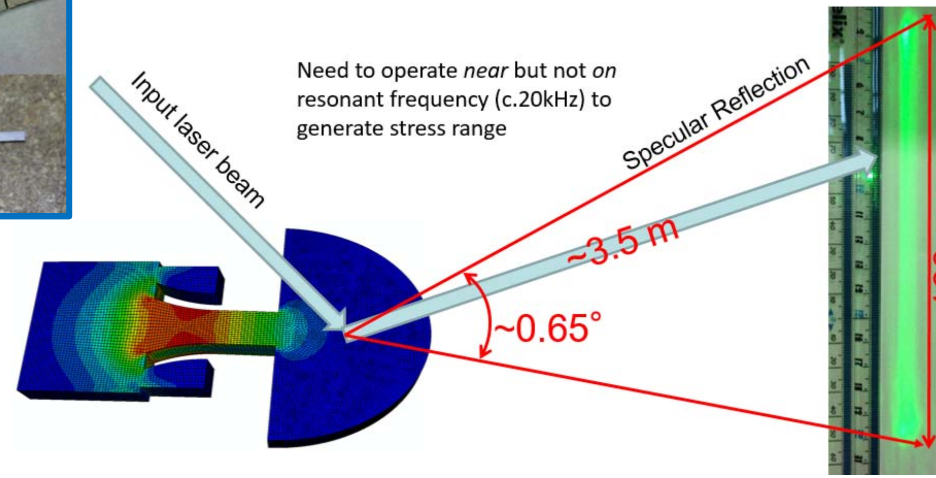
Macro-scale Fatigue Testing

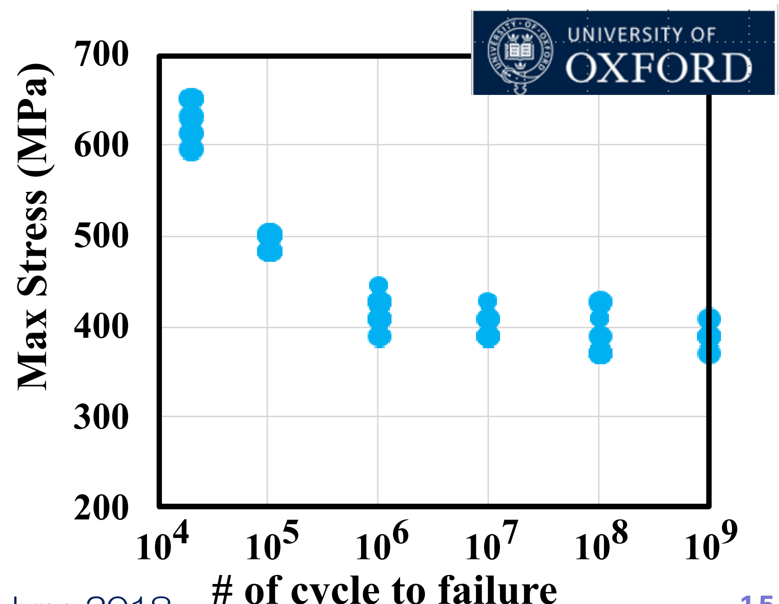
- Gr5/23



Meso-scale Fatigue Testing

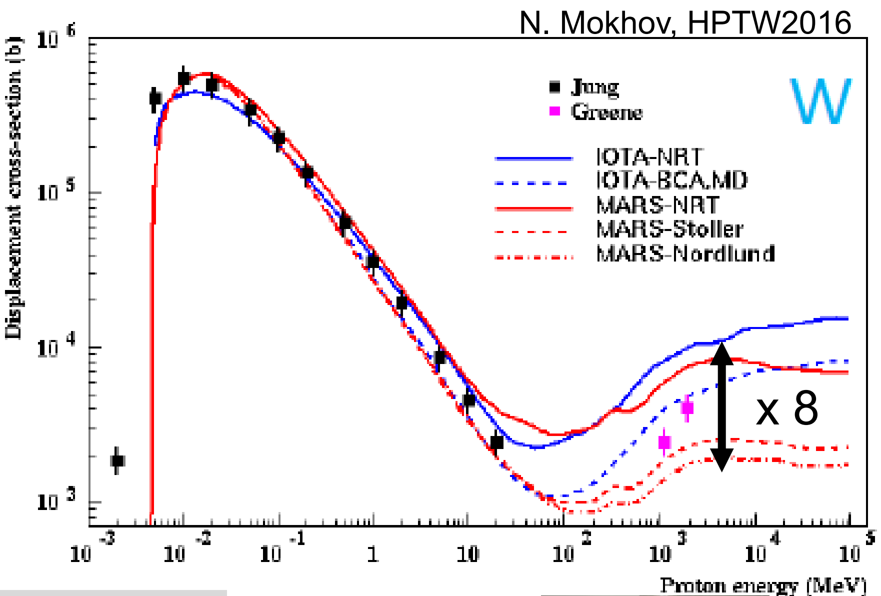
- Gr23 A&STA, Gr2, 15-3Ti





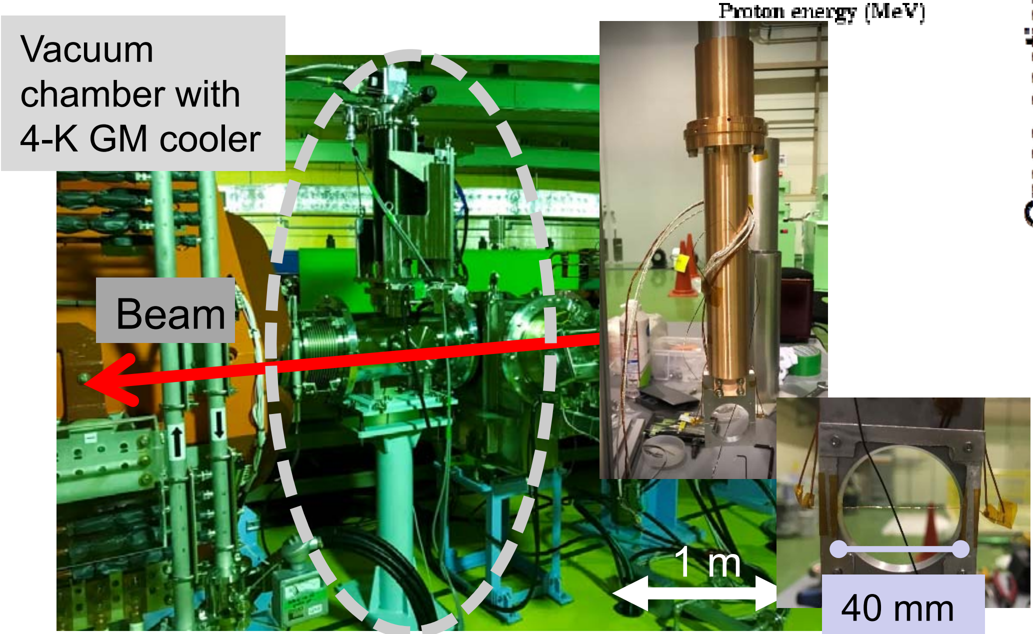
Measurement of displacement cross-section for 3-GeV proton at J-PARC

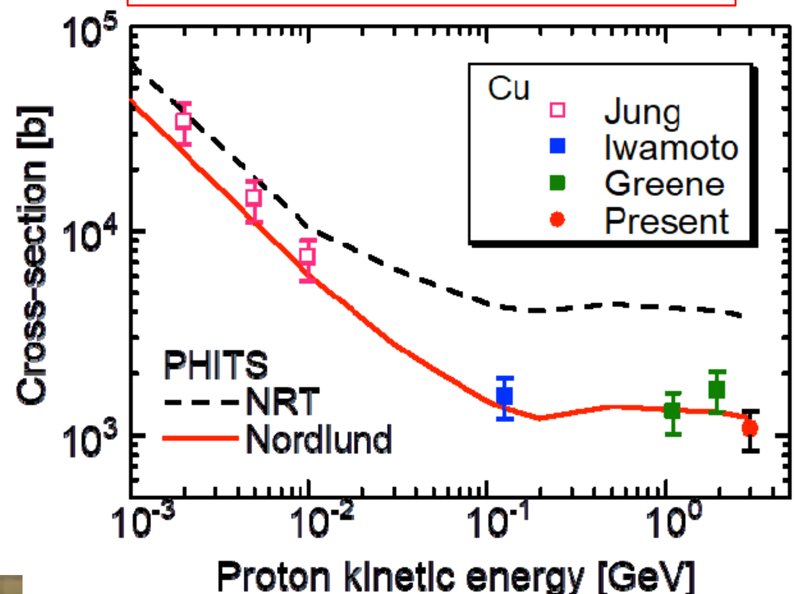
S.Meigo et al., IPAC2018, MOPML045



- Experiment at 3-GeV Rapid Cycling Synchrotron (RCS)
- Under cryotemperature (~ 20 K), displacement cross section(σ) was obtained by increase of resistivity ($\Delta\rho_{cu}$) due to proton irradiation with average flux ($\overline{\phi(E)}$)

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





NRT overestimates about 4 times of the present data, while Nordlund model drastically improves.

Summary

- J-PARC Neutrino target/window : designed with 3.3 x 10^{14} ppp, hopefully applicable for coming 750kW→1.3MW operation with minor upgrades
  - Oxidization of graphite will determine the life of target. SiC-coated graphite specimen provided for BLIP irradiation / HiRadMat test
  - Beam window survived after 2.2×10^{21} pot. Need PIE to evaluate damage while it requires time to clear rad.safety regulations & license problems
- Study on radiation damage effect of Titanium alloys with a few DPA region is critical to determine/improve service life of targetry applications
  - BLIP irradiation run will provide data upto 1.5DPA (NRT)
  - 1st HCF data with both macro-bend and mesoscale tests
  - Damage-tolerant candidates: Gr-6/Gr-23 DMLS/Gr-5 α'-UFG/15-3Ti
  - Comprehensive understanding of radiation damage effect on different type of Titanium alloys and different heat treatments will be obtained.
- Displacement xsec. measurement for 3GeV proton carried out at J-PARC.
  - NRT overestimates about 4 times. Nordlund model agrees.
  - 30GeV at J-PARC MR approved. Collab. with Fermilab/ CERN underway.