Operational Status and Upgrade of the J-PARC Neutrino Experimental Facility

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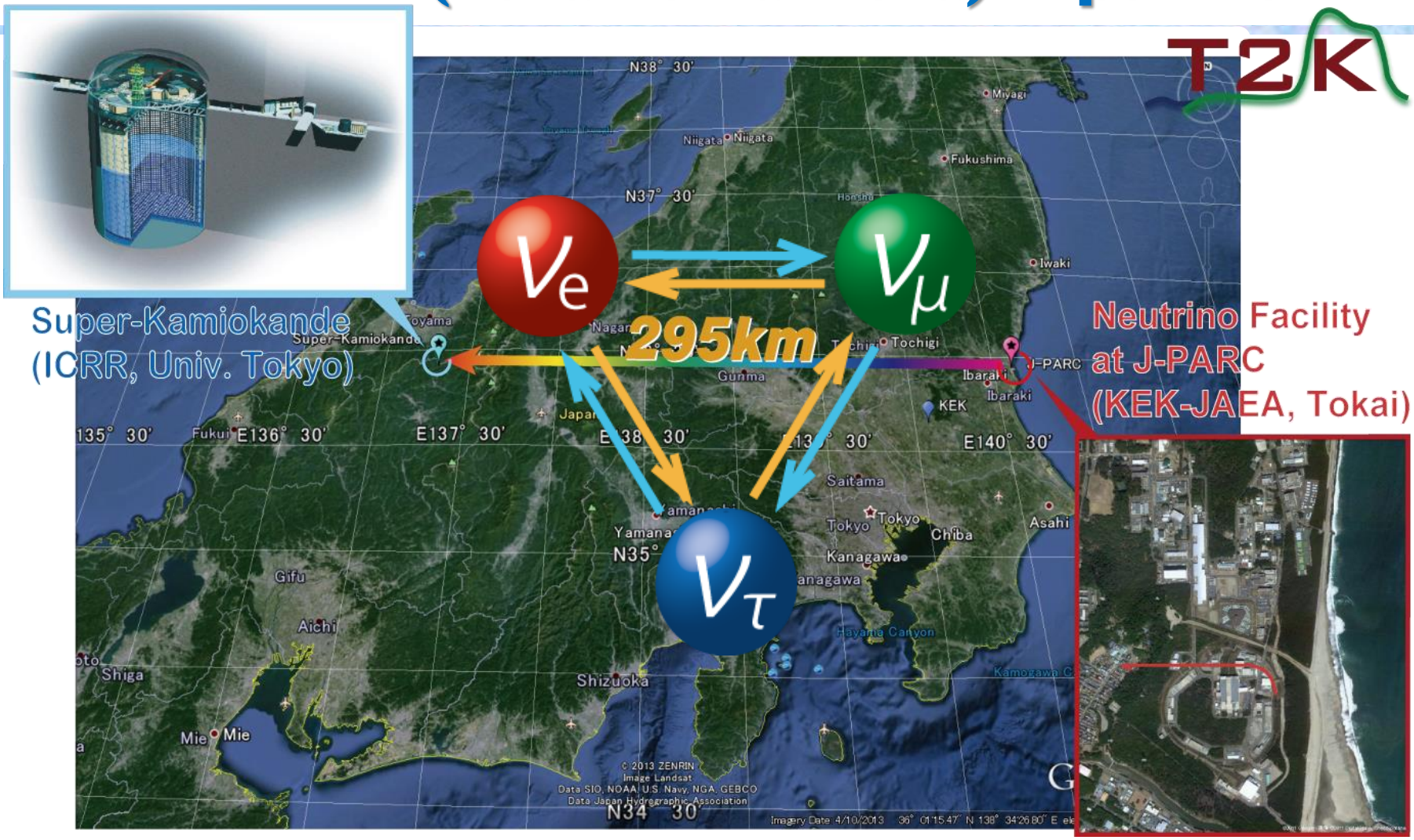
RaDIATE2018 Collaboration Meeting
CERN December 17, 2018

Table of Contents

Happy to be CERN again since exciting stay in Oct.

1. The T2K (Tokai-to-Kamioka) Experiment

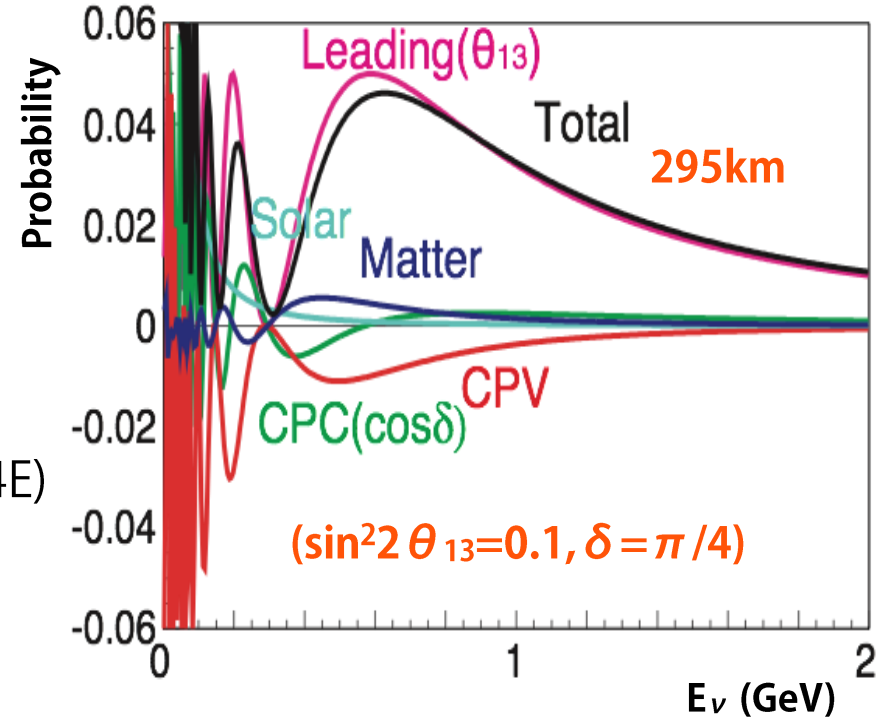


- **A Long-Baseline neutrino oscillation experiment connecting Neutrino Experimental Facility at J-PARC (Tokai village) and Super-Kamiokande**

Motivation

- **Discovery of $\nu_\mu \rightarrow \nu_e$**
  - Direct detection of neutrino flavor mixing in "appearance" mode
  - ν_μ to ν_e plays an important role to study CP violation (and mass hierarchy)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$
$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$



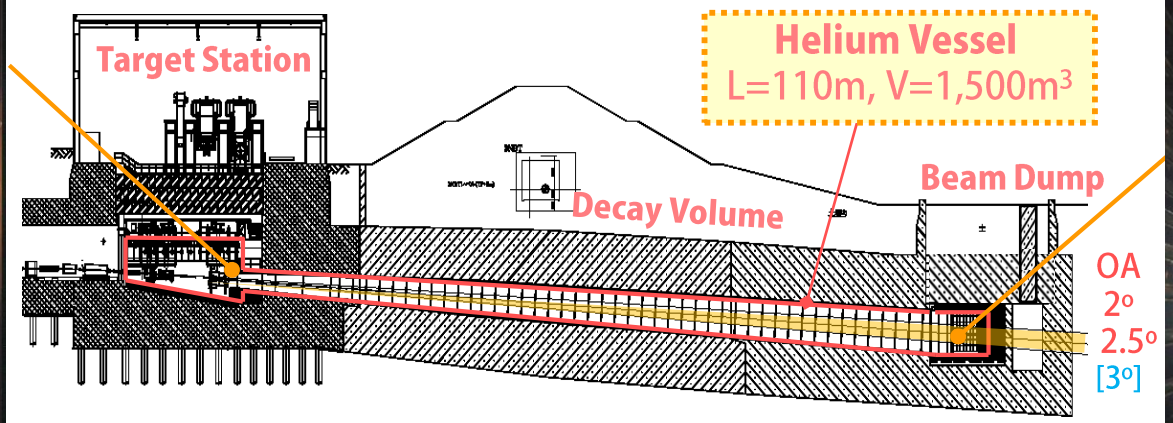
- **Exploring CP Violation** becomes possible by comparing ν_e and anti-ν_e appearance in case **large θ_{13}**

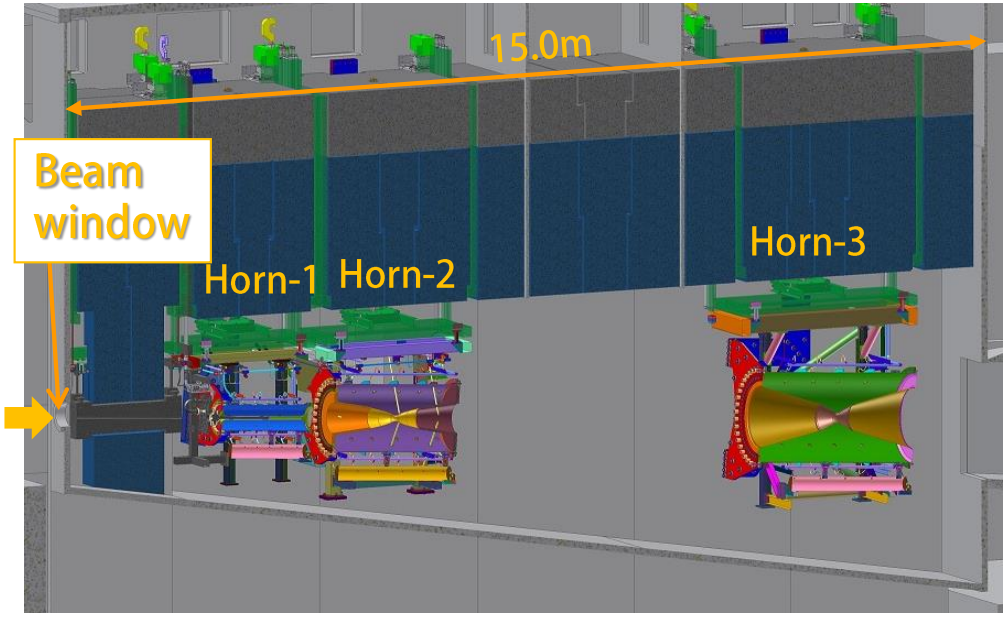
$$\text{CPV} \propto \sin\theta_{12} \times \sin\theta_{13} \times \sin\theta_{23} \times \sin\delta$$

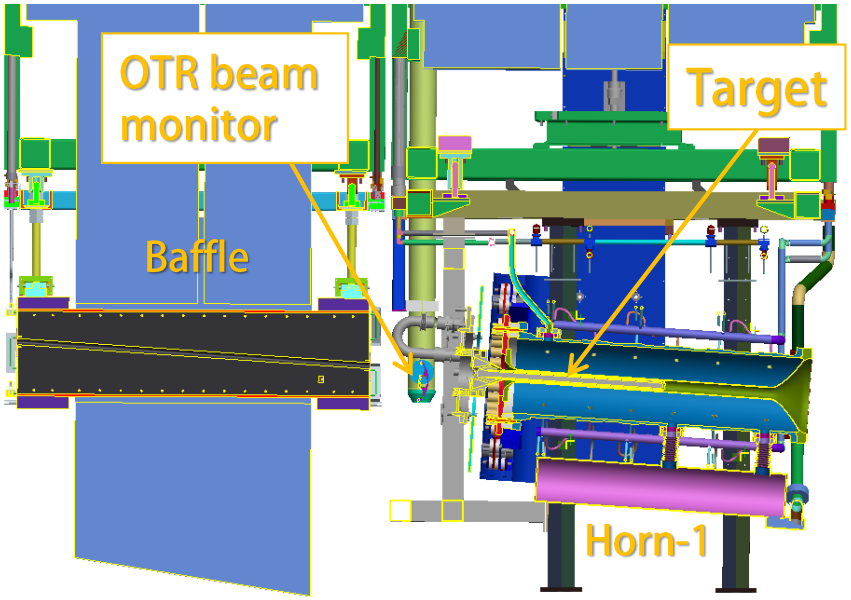
The idea firstly claimed in 1996 by J.Sato and J.Arafune
Phys.Rev. D55 (1997) 1653-1658.


Japan Proton Accelerator Research Complex
J-PARC
400 MeV H- Linac
FY01~08 Construction
Nov. 2006~ LINAC
Oct. 2007~ RCS
May 2008~ MLF/MR
Dec. 2008~ MR@30GeV
Jan. 2009 Hadron
Apr. 2009 Neutrino
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]

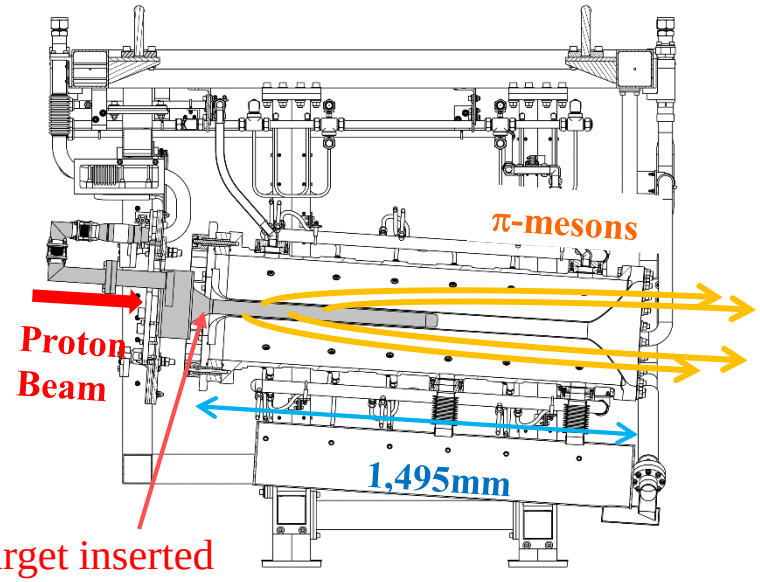
Neutrino Secondary Beam-line



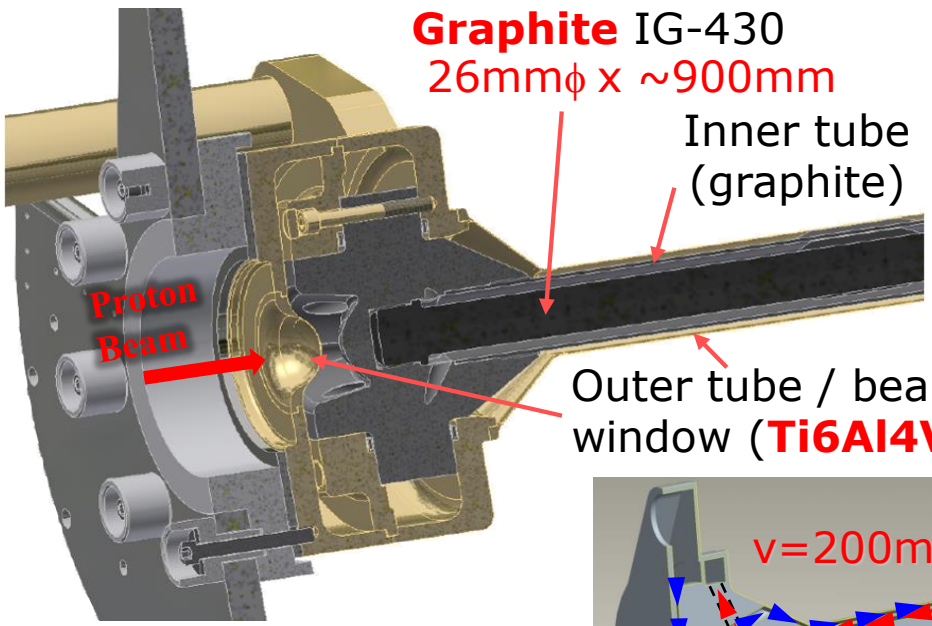


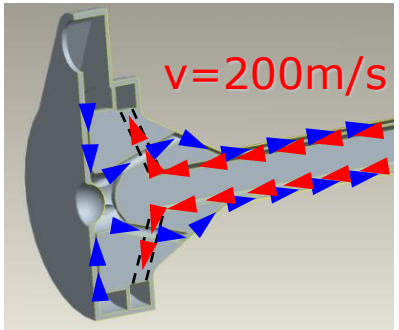


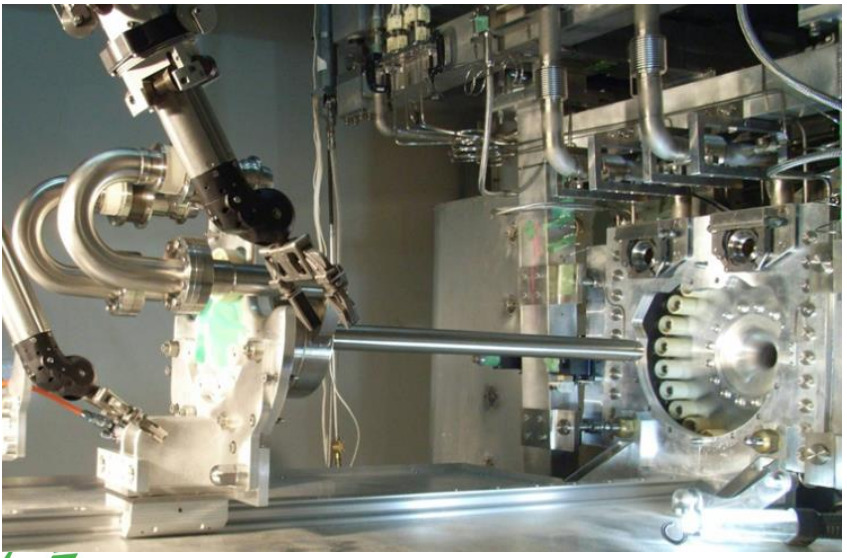
Neutrino Facility Target



Target inserted to horn inner conductor (54mm-dia.)



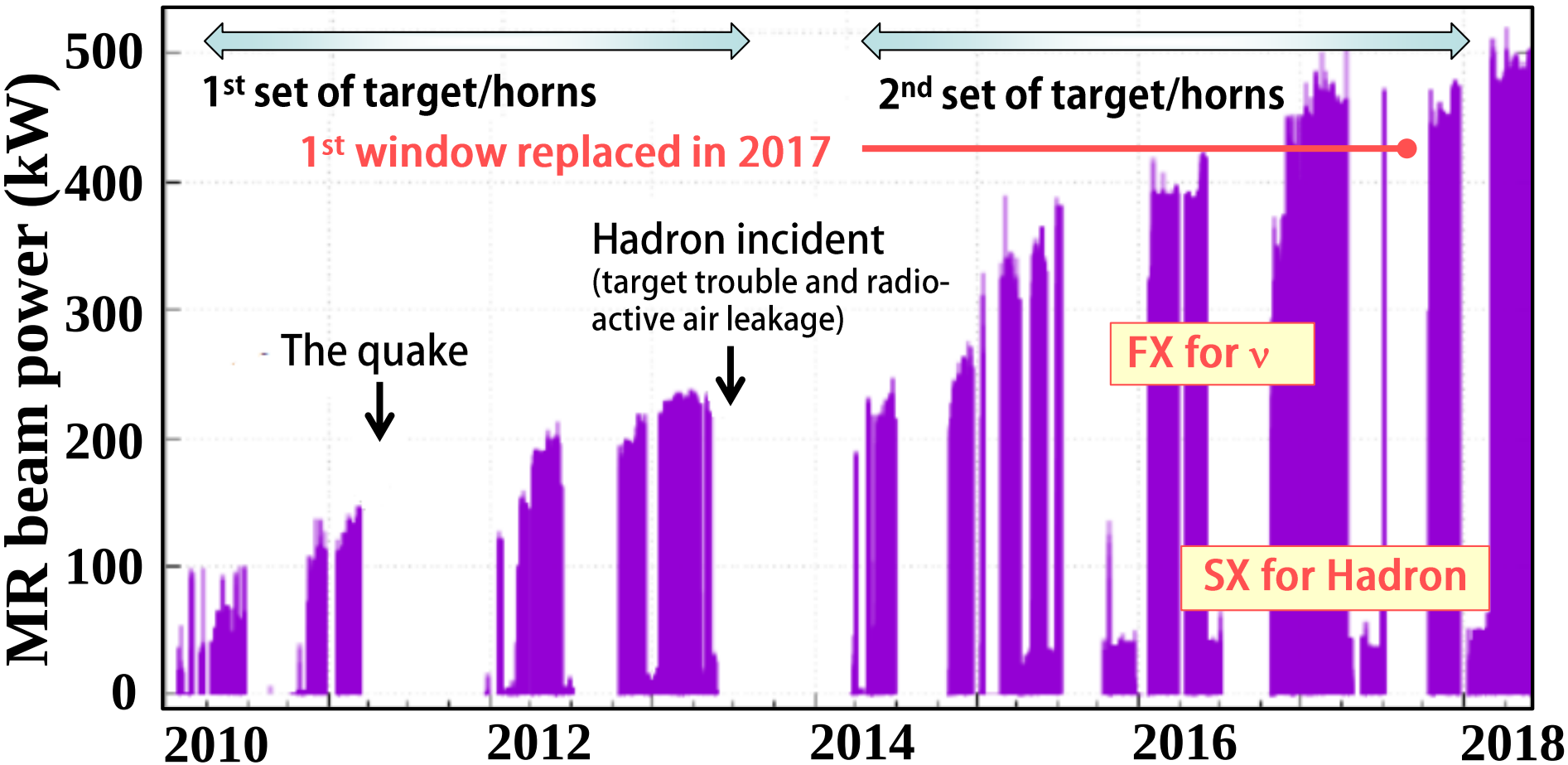




Design Beam Power: 750kW (3.3×10^{14}ppp / 2.1s)

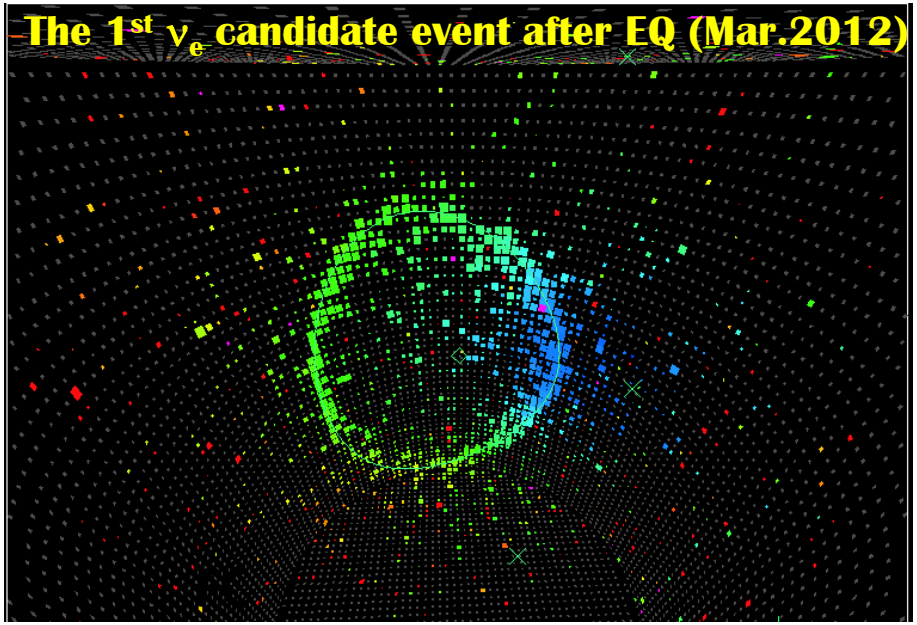
- Small diameter of target (26mm) : small beam size (σx, σy=4.2mm)
- Low-Z isotropic graphite: low thermal shock, less absorption of pions
- Helium gas cooling: keep high temperature, to mitigate radiation damage of graphite

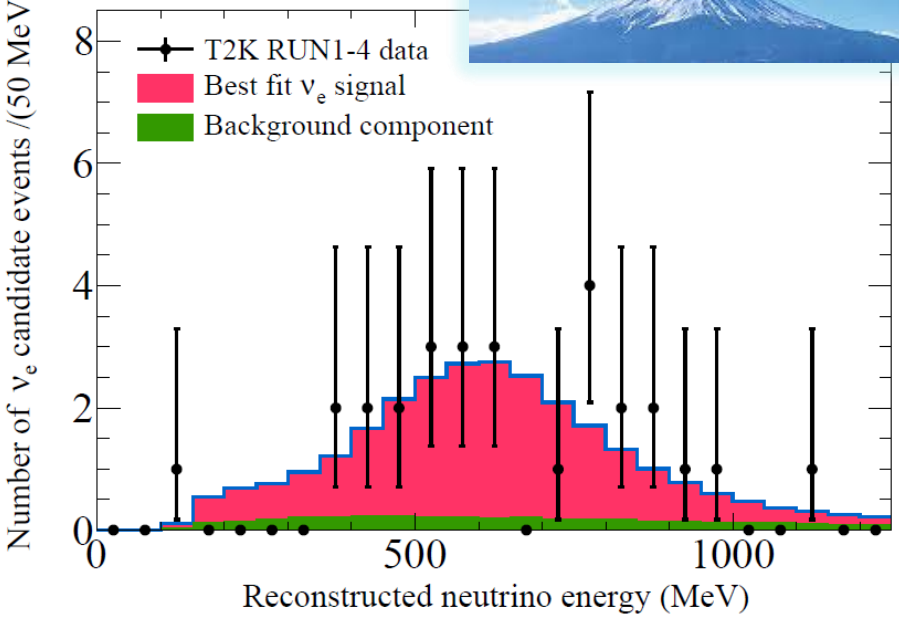
Main Ring Beam Power Trend



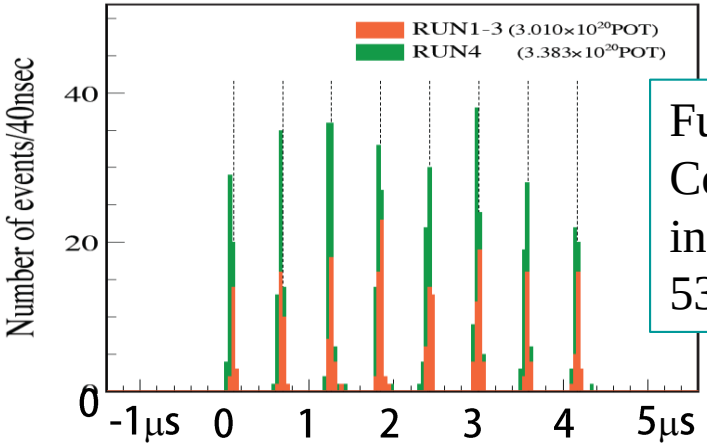
- Max. delivered power: World record of FX'd # of protons from synchrotron
  - Fast eXtraction to Neutrino ~485kW (2.5×10^{14}ppp / 2.48s)
  - Slow eXtraction to Hadron ~51kW (5.4×10^{13}ppp / 5.52s)

T2K ν_e appearance (Jul.2013)





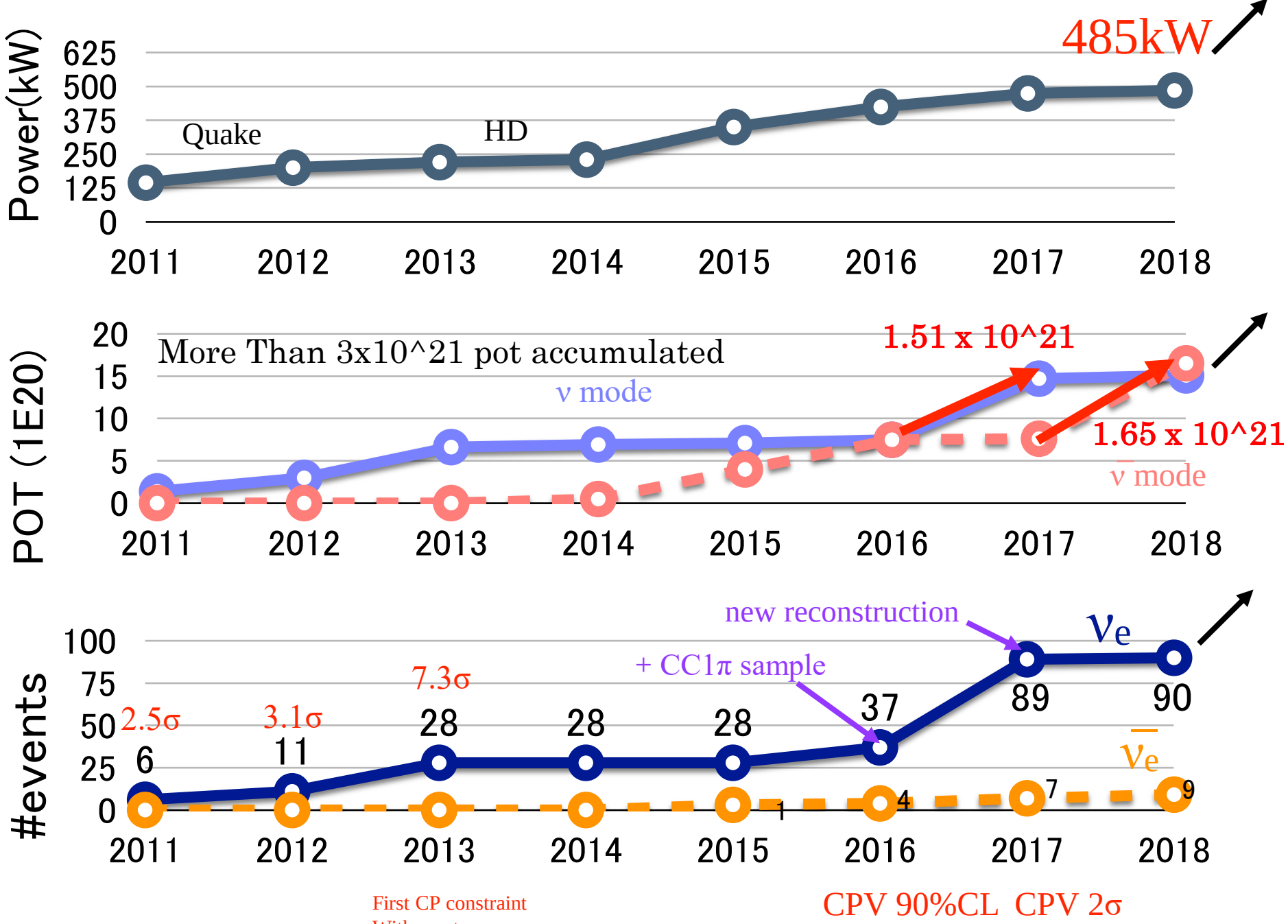
$\Delta T_0 = T_{SK} - T_{J\text{-}PARC} - TOF$



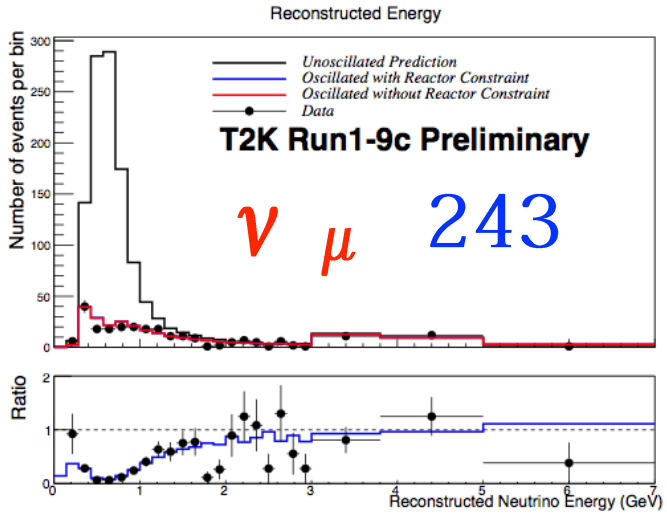
Fully Contained in ID 532 events

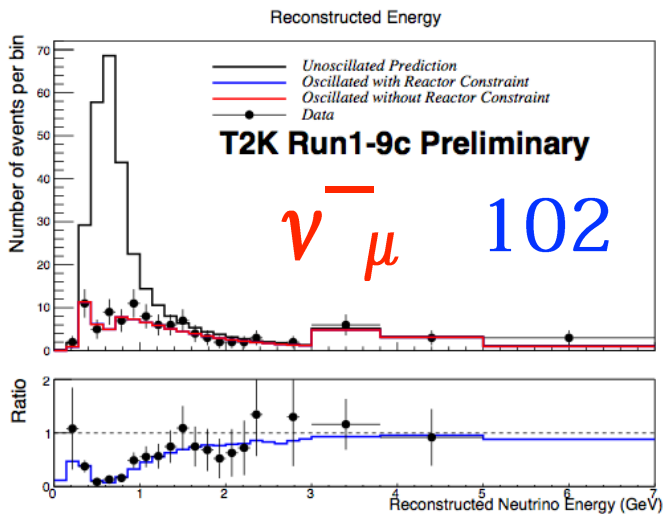
- 28 candidate events are observed with 6.39×10^{20}pot
- $N_{exp}=4.64\pm0.52(\sin^2 2\theta_{13}=0)$
  20.44 ± 1.80 ($=0.1$)
- Significance=7.5σ

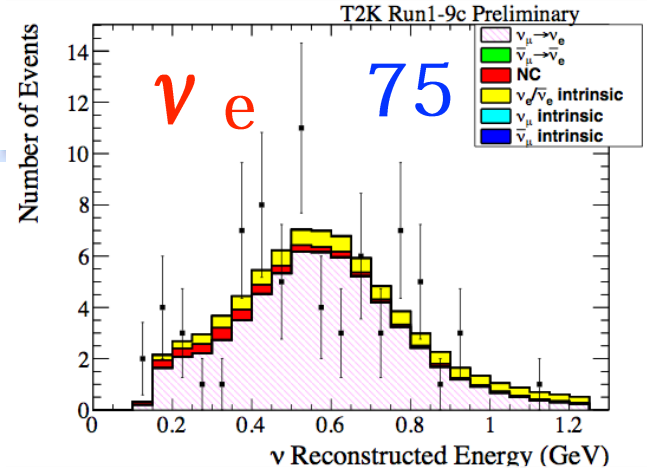
http://jnusrv01.kek.jp/public/t2k/sites/default/files/130719-KEK-seminar.pdf

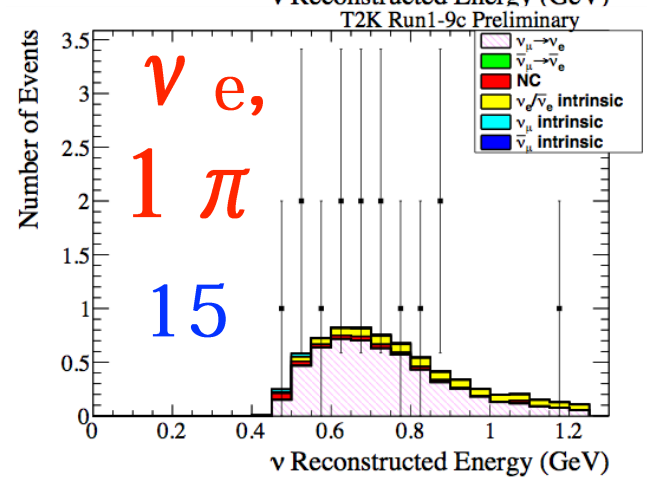

Power(kW)
625
500
375
250
125
0
Quake
HD
485kW
2011
2012
2013
2014
2015
2016
2017
2018
POT (1E20)
20
15
10
5
0
More Than 3x10^21 pot accumulated
ν mode
1.51 x 10^21
1.65 x 10^21
ν̄ mode
#events
100
75
50
25
0
2.5σ
3.1σ
7.3σ
6
11
28
28
28
37
89
90
1
4
7
9
new reconstruction
+ CC1π sample
νe
ν̄e
First CP constraint
With reactor
CPV 90%CL CPV 2σ

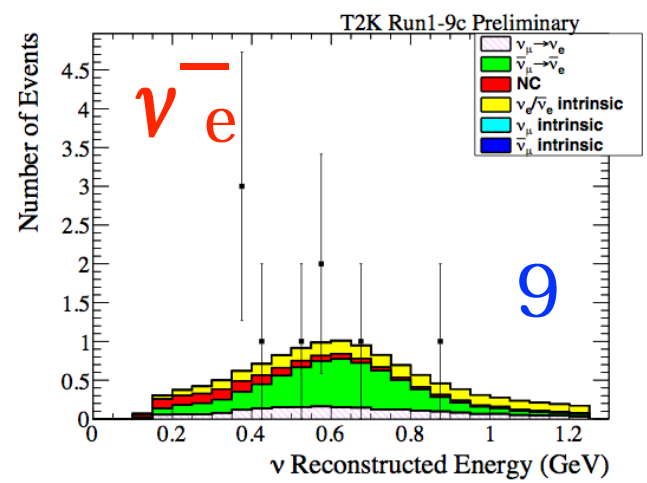
T2K SK events











Analyzed: ν: 1.49×10^{21} POT

$\bar{\nu}$: 1.12×10^{21} POT

Neutrino Conference 2018

Update with full-dataset will soon be issued at NuPhys2018

T2K ν&ν̄ oscillation anal

- Compare observed rates at SK to predictions under oscillation hypothesis, tuned with observed ND rates

Oscillation Probability *Constrained by near detector fit*

$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)=\sum_i^{E_\nu\ \mathrm{bins}}\sum_j^{flavors} P_{\nu_j\to\nu_i}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)\,\Phi_j^{far}(E_{\nu,i})\,\sigma_k(E_{\nu,i},p_k,\theta_k)\,\epsilon(p_k,\theta_k)\,M_{det}$$

SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
>>> FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75 νe
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
<<< RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9 $\overline{\nu e}$

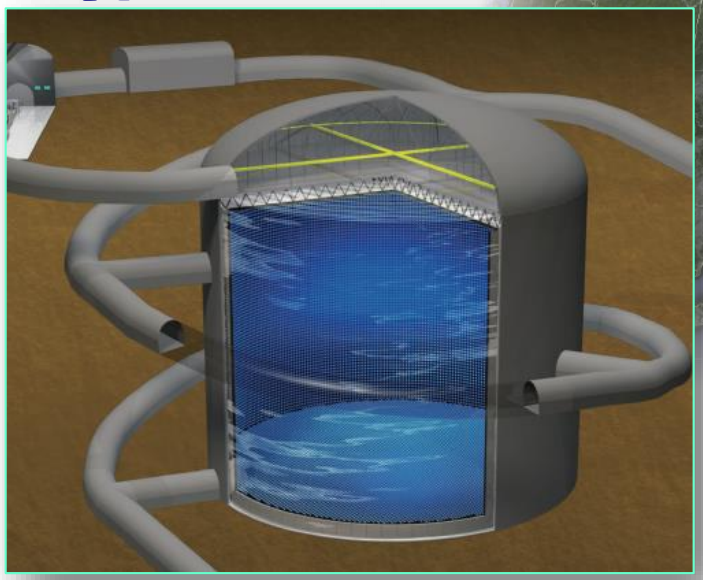
- **$\sin\delta_{CP}=0$ ($\delta=0$, π) outside of 2σ CL interval**
- **First hint of CP violation in the lepton sector**

3. Accelerator and Facility Upgrade to > Mega-Watt Beam Power

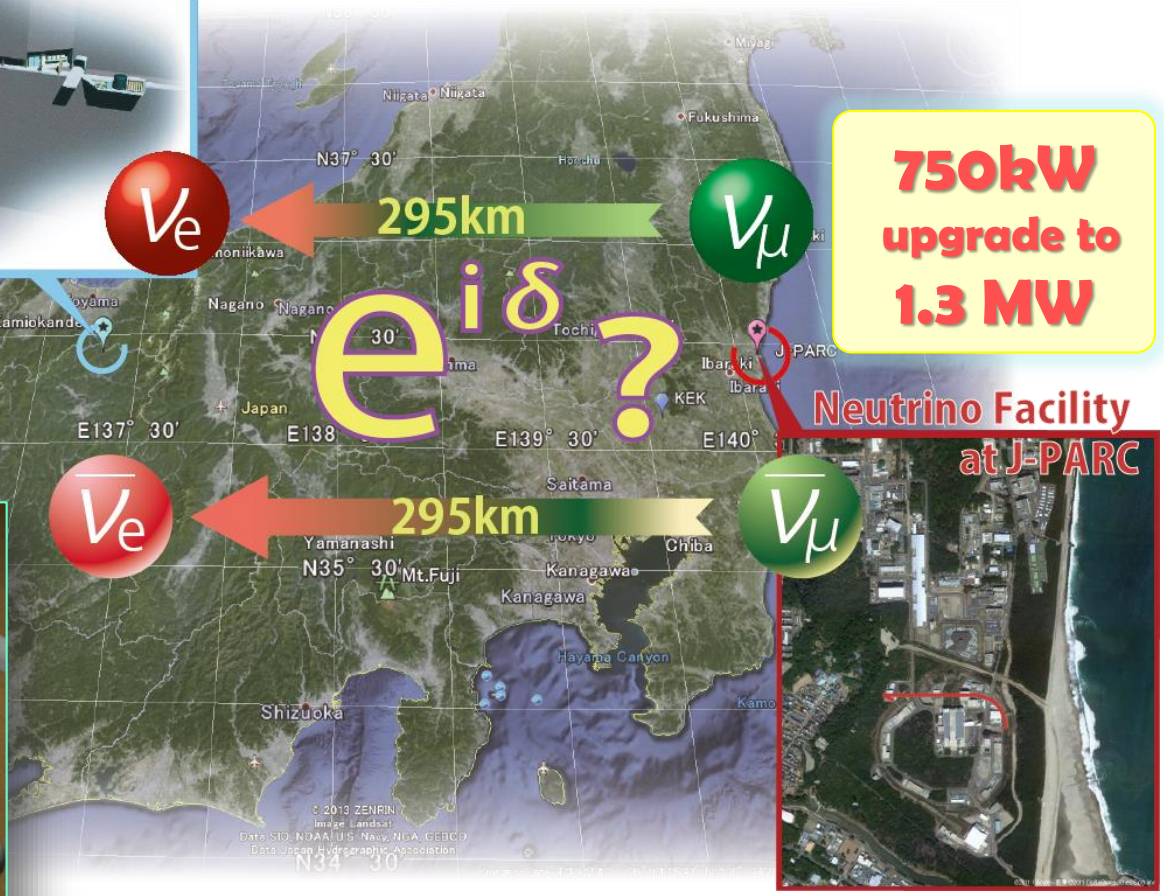
39mϕ x 41mH
Total[Fiducial]
Volume
= 50[22.5]kt

x ~10 of Super-K

Hyper-Kamiokande



74mϕ x 60mH = 258[187]kt

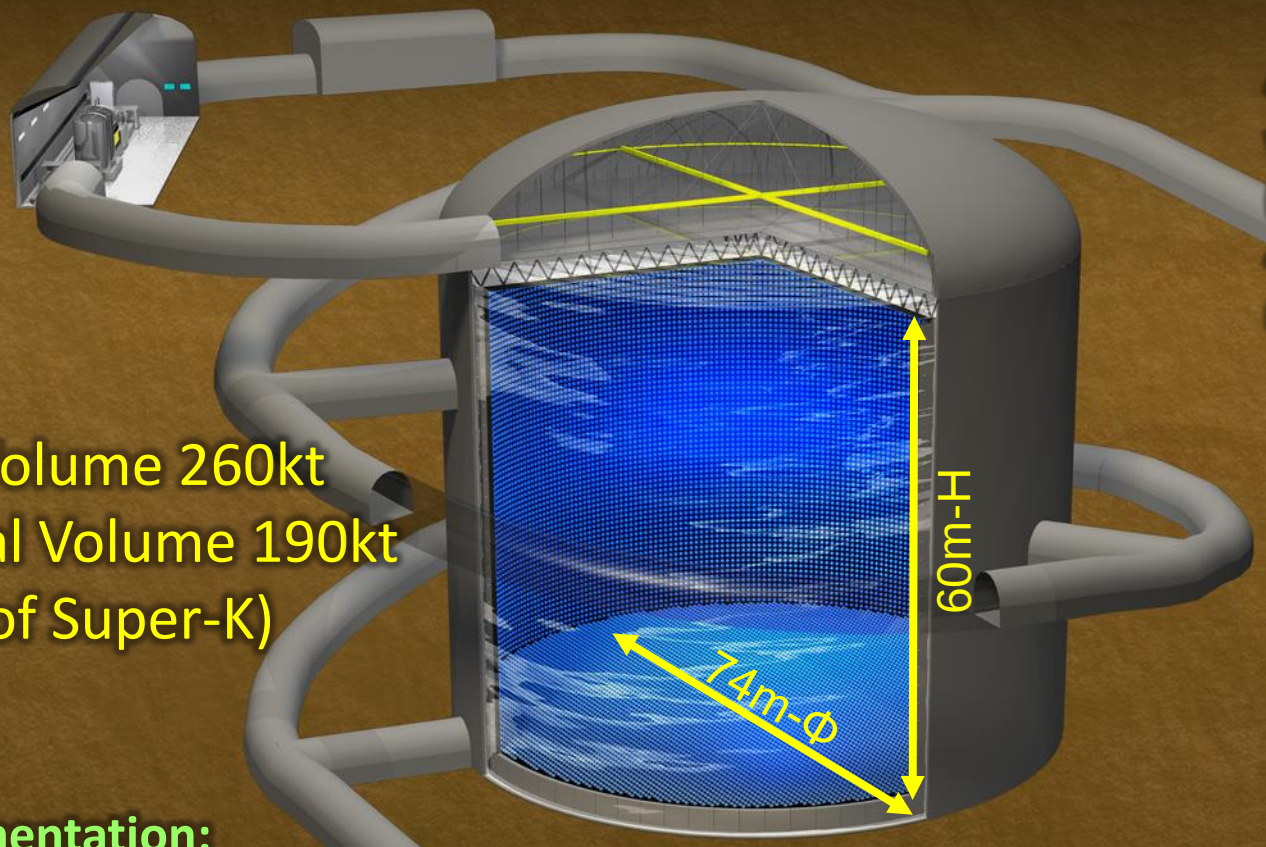


750kW
upgrade to
1.3 MW

Exploring CPV in Lepton Sector

Hyper-Kamiokande Detector

- Larger mass for more statistics
- Better sensitivity by more photons with improved PMTs



40% coverage
with new sensor
(x2 photon sensitivity)
40,000 20in ID PMT
6,700 8in OD PMT

Total Volume 260kt
Fiducial Volume 190kt
(~x10 of Super-K)

Documentation:
Letter Of Intent https://arxiv.org/abs/1412.4673
HK Design Report https://arxiv.org/abs/1805.04163

Construction will start on Apr. 2020 to start experiment from 2027

Hyper-K Construction Starts in Apr.2020

- "Japan's main science ministry last week proposed an ambitious budget for basic research that would… push ahead with a massive new particle detector."
  - SCIENCE 7 SEPTEMBER 2018 • VOL 361 ISSUE 6406 pp. 954-955
    DOI: 10.1126/science.361.6406.954

- Followed by Decision by Univ. of Tokyo President M.Gonokami (Sep.12)

Concerning the Start of Hyper-Kamiokande

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

http://www.hyper-k.org/news/news-20180912.html

J-PARC Main Ring Upgrade

- The original target beam power of 750 kW is planned with the higher repetition 2.48 s → 1.32 s
- Upgrading the following hardware are going on
  - Main magnet power supplies
  - 2nd harmonic RF systems (2nd harmonic voltage 110~120kV)
- The possibility of the beam power of 1.3 MW is being explored with higher repetition of 1.16 s.
  - Reinforce RF system (7→9, acc. voltage 300~390 → 510kV)
  - Anode power supply upgrade

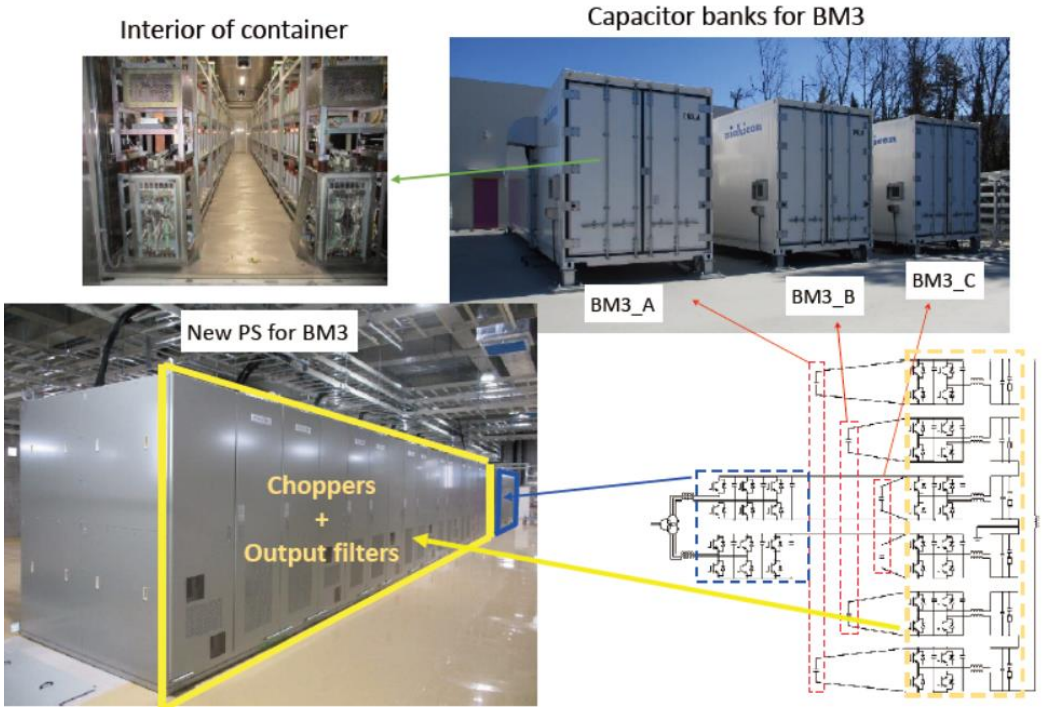
Beam power	485 kW (achieved)	750 kW (proposed)	1.3 MW (proposed)
Beam energy	30 GeV	30 GeV	30 GeV
Beam intensity (ppp)	2.5×10^{14}	2.1×10^{14}	3.3×10^{14}
Repetition cycle	2.48 s	1.32 s	1.16 s

New Magnet PS for the Higher Repetition

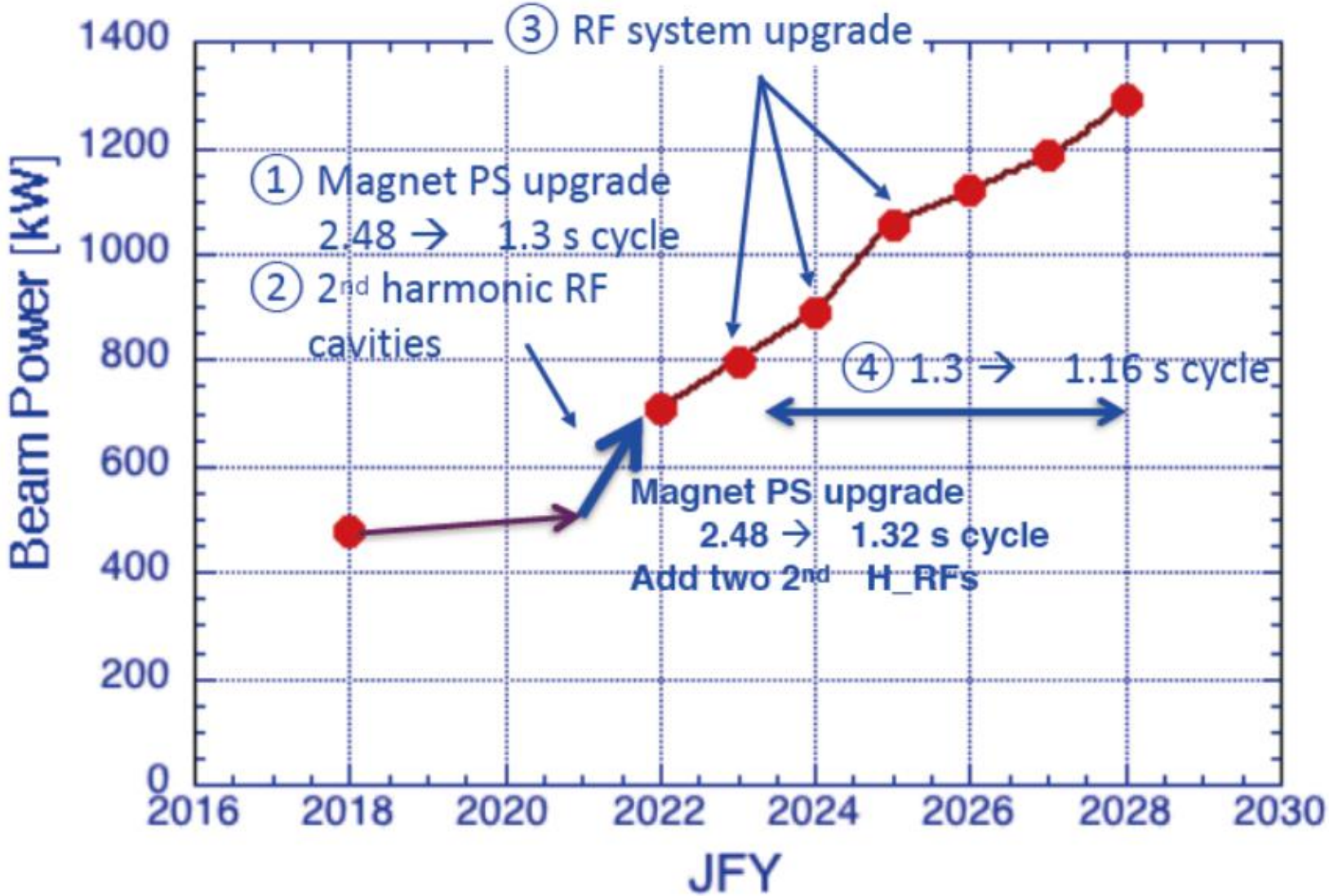
- The new magnet power supplies adopt energy recovery system with the capacitor banks
- Mass production/installation/commissioning will finish in 2021.

New buildings (D4/5/6) for new PS's have been constructed.

Complete set of Bending Magnet 3 PS in D4 under commissioning.



J-PARC Main Ring operates beyond 1 MW

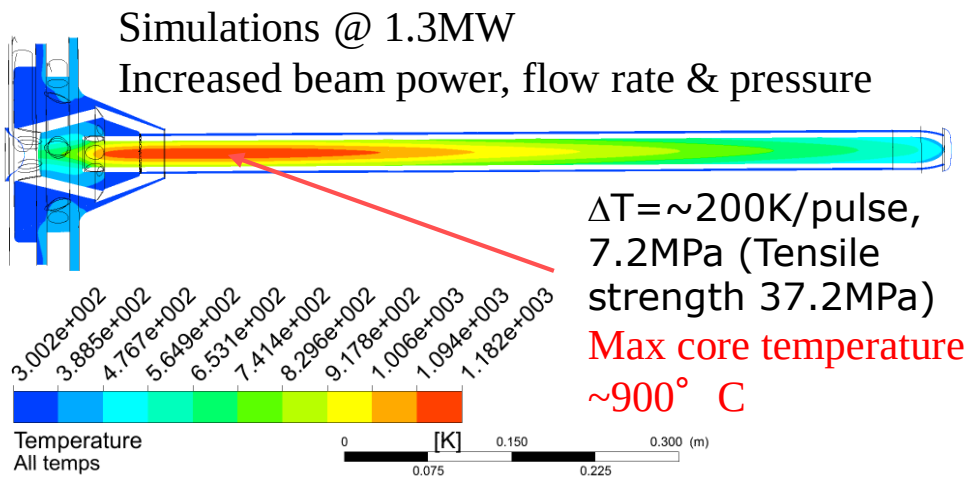


Neutrino Beam-line Upgrade

- Primary beamline
  - Beam monitor upgrade
  - Remote maintenance scheme in FF section
  - Larger aperture magnets and/or upgraded collimators
- DAQ/control system
  - Upgrade for higher rep. rate and safety operation
- Secondary beamline
  - Target/beam window upgrade
  - Higher current horn operation (250→320kA)
  - Capacity upgrade for cooling facilities
  - Upgrade for radiation protection / waste treatment
- Upgrade is technically feasible, to be completed in FY2021
- Radiation damage studies / develop radiation-thermal shock tolerant materials for beam intercepting devices (target /beam window…) can be bottleneck of our facility operation

1.3 MW Target Upgrade

- The facility aims to increase beam power from 750kW to 1.3MW to explore CP violation in lepton sector
- It will increase the integrated heat load on the target (approx. 23kW → 41kW)
- Need to increase helium mass flow rate to keep outlet temperatures within range
- Necessary to increase operating pressure to keep velocities and pressure drops within range

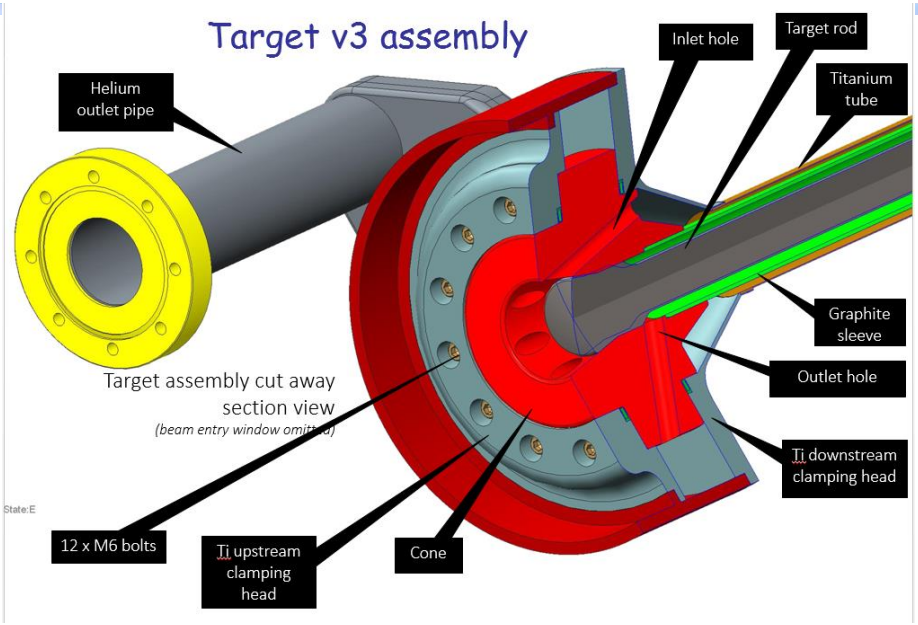


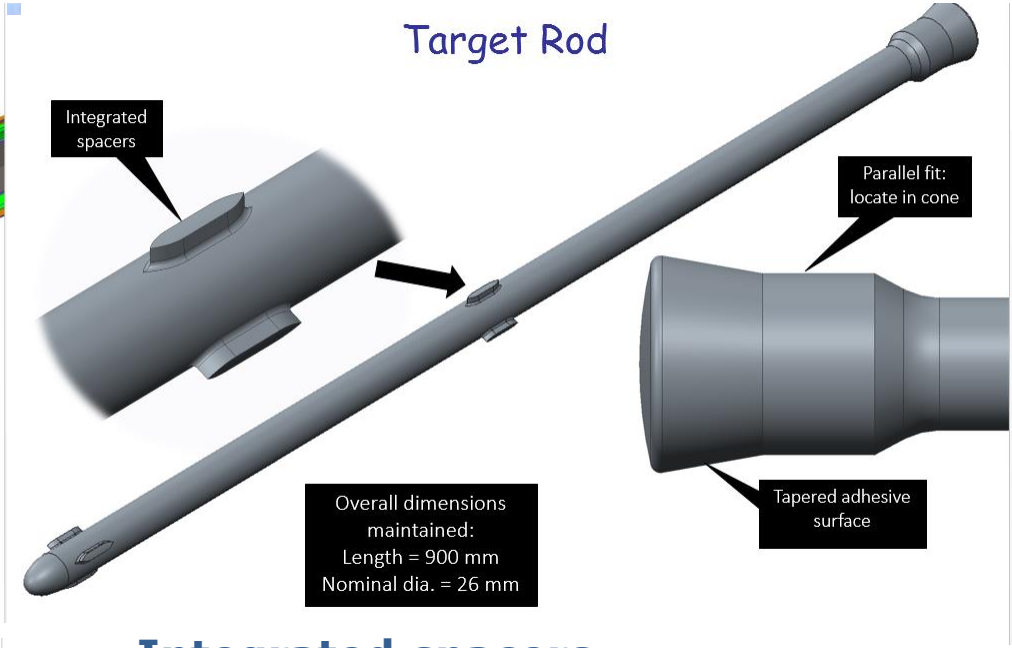
	750kW (designed)	1.3 MW
Proton kinetic energy	30GeV	
Protons per pulse	3.3e14	3.2e14
Rep. cycle	2.1s	1.16s
Helium pressure	1.6 bar	**5 bar**
Pressure drop	0.83 bar	0.88 bar
Helium mass flow	32 g/s	**60 g/s**
Heat load	23.5 kW	**40.8 kW**
US window temp.	105 ° C	157 ° C
DS window temp.	120° C	130° C
Graphite Max. temp.	736° C	**909° C**

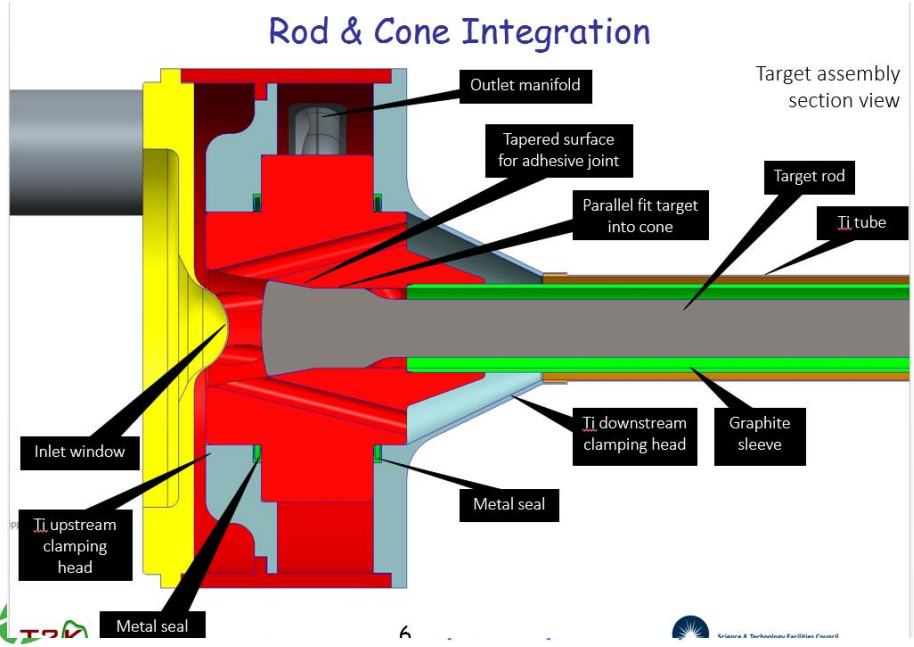
Lifetime 5years under 100ppm-O2

- Some target modifications needed to operate at higher pressure (e.g. window geometry, weld design, target pipes – bellows & isolators)
- Need high helium purity to avoid oxidation of graphite (+ SiC coating on Graphite ?)

Version-3 Target Assembly

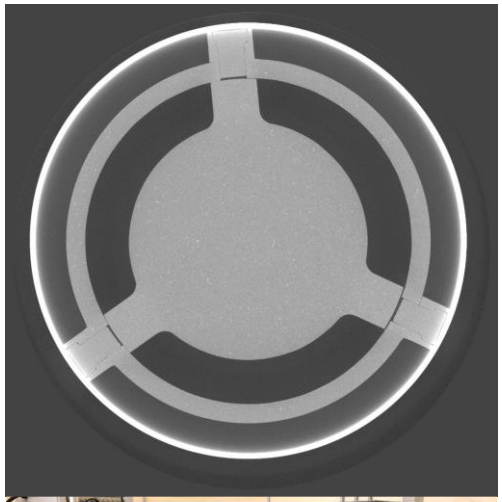


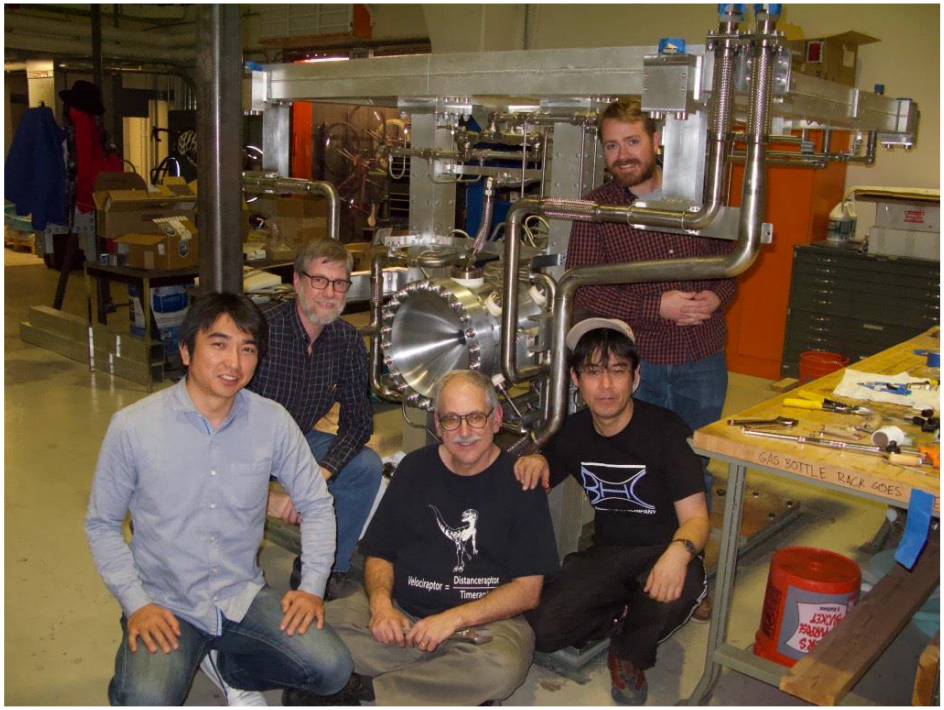




- **Integrated spacers**
- **Target rod locates in cone by parallel fit**
- **Widened central bore of cone**
- **Bolted design with metal seals (like v1 and v1a)**
- **No diffusion bond as in target v2 (current spare)**
- **Thicker Ti shell / window for high pressure operation**

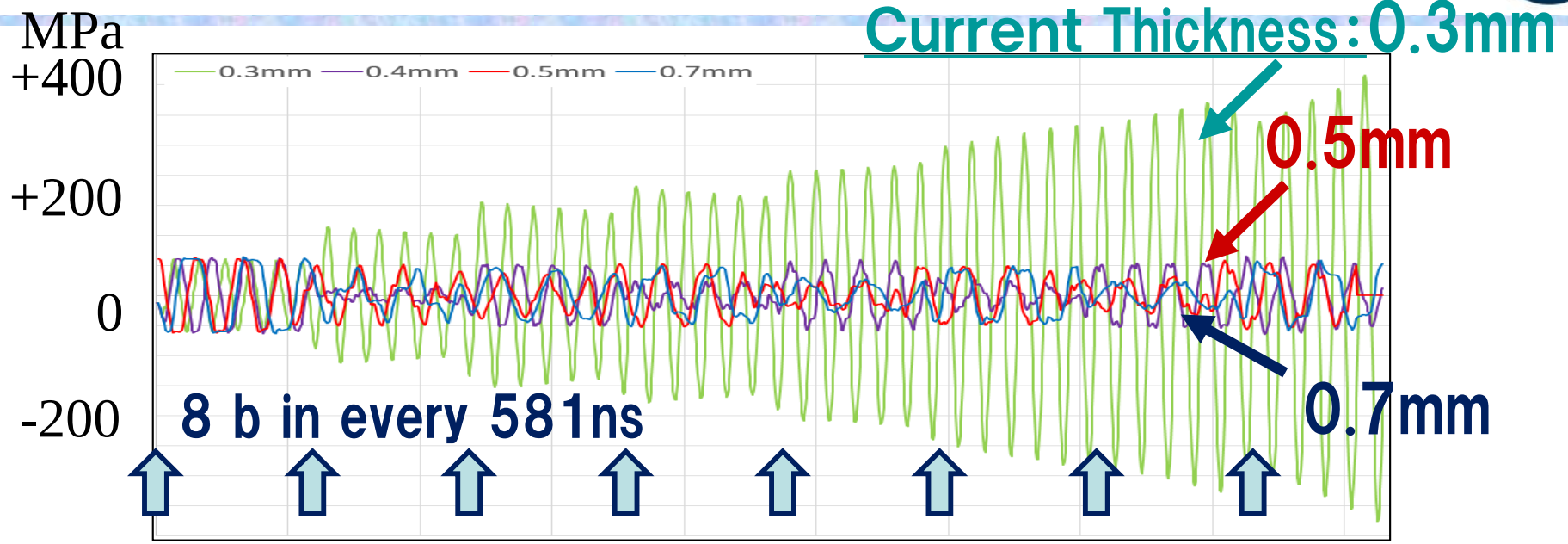
Target & Horn Production



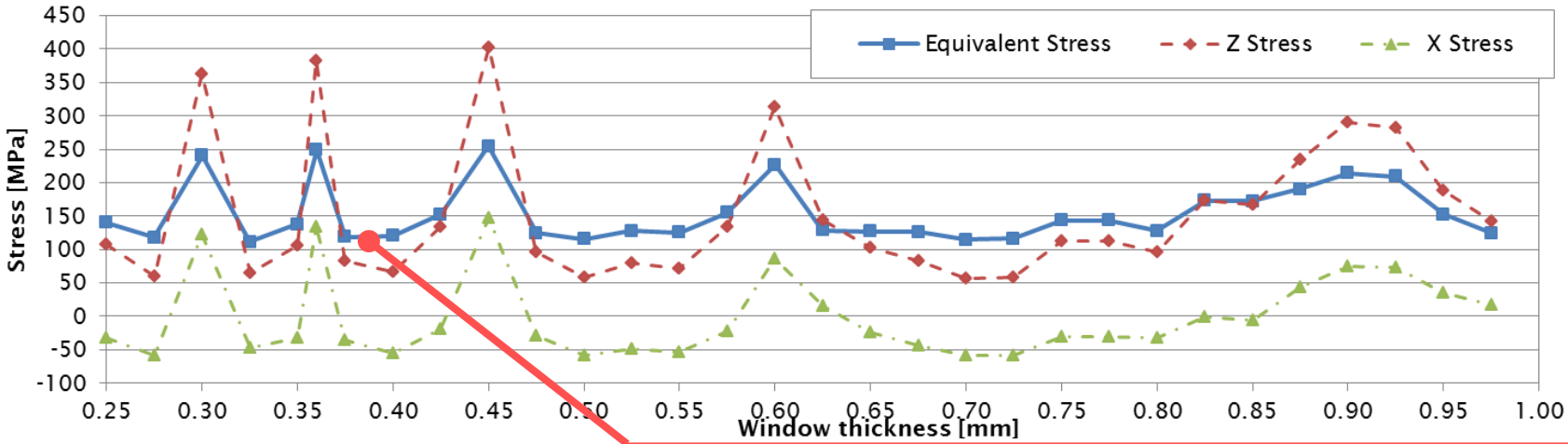


- Upgrade horn production at Univ. Colorado completes soon
- Target production/QA, support plate completed at RAL
- Integration work will be on coming January at J-PARC with RAL team

Stress Wave Analysis for Ti window



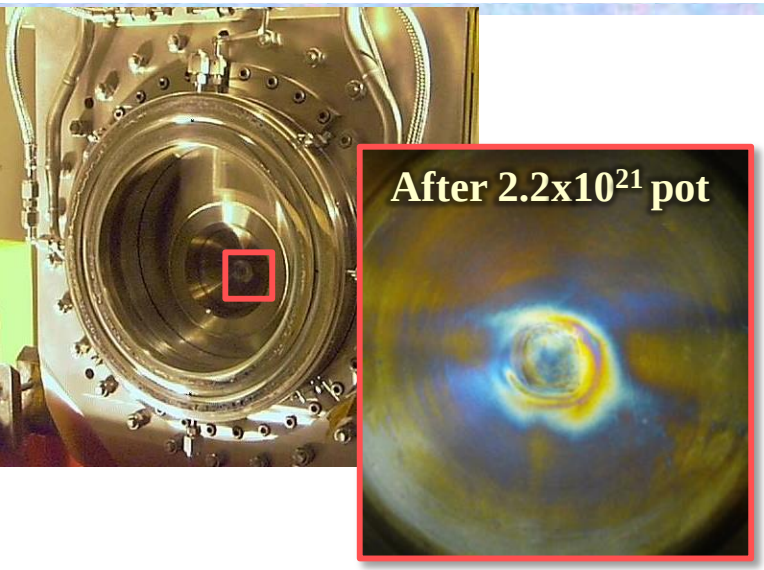
N.B. SZ = through thickness stress, SX = radial stress



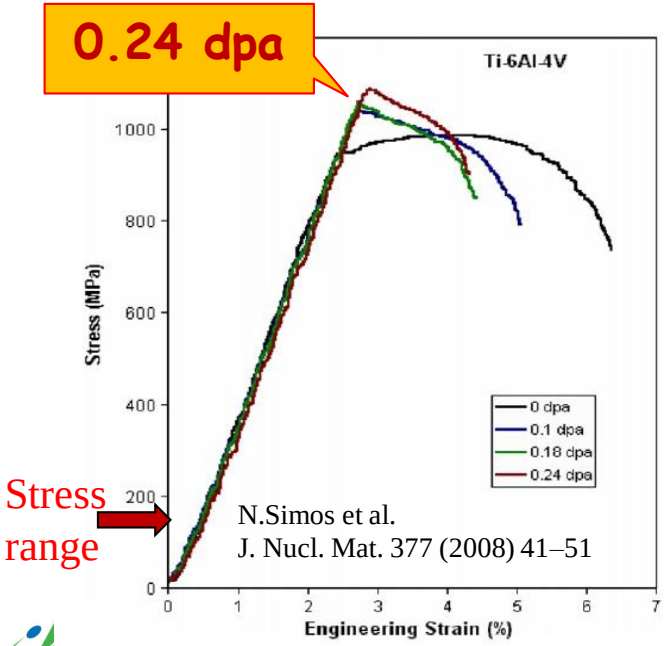
0.39+-0.1mm to be adopted for ver2 window

Radiation Damage on Ti-6Al-4V Window ?

→ T.I.19a
→ D.Senor19a



- 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 0.1~0.3DPA (*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
485kW (achieved)	2.5 x 10^{14}	2.48 sec	0.9 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}

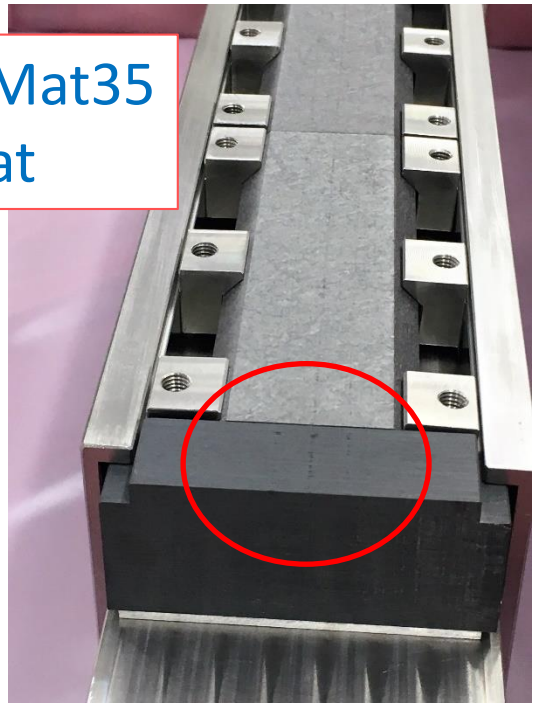
designed **~8M pulses/yr** **~1DPA/yr**

New Target Materials tested at HiRadMat

→ N.Nakazato20a

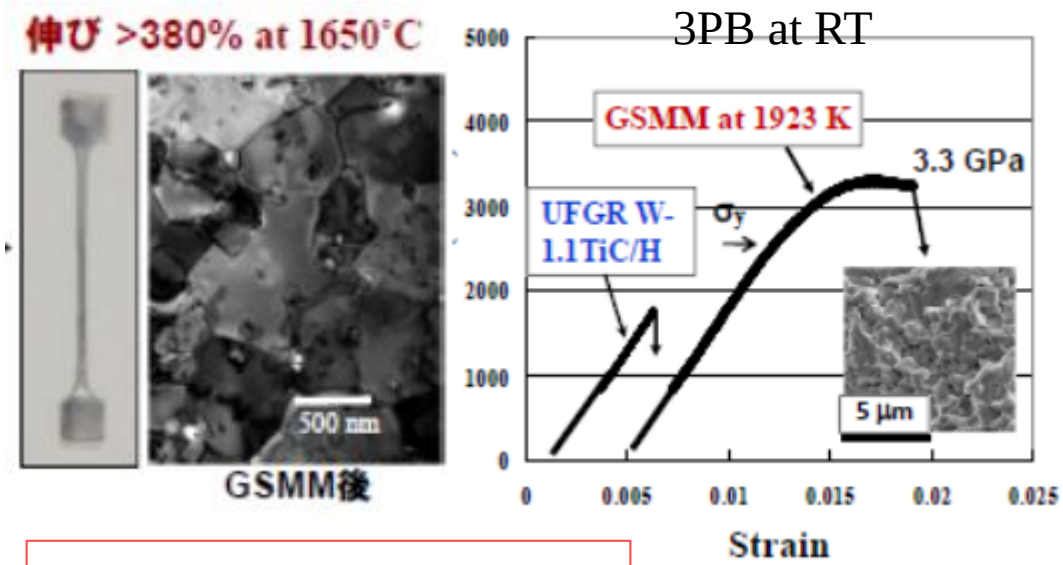
- NITE-SiC/SiC
  - Density 3.2 g/cc (SiC) → more secondary emission than graphite
  - SiC fibers + matrix, control mechanical properties / to replicate ductility

HiRadMat35
TDICoat



→ S.Makimura20a

- Highly-Ductile W (TFGR W-1.1TiC)
  - Tungsten: high density/melting point, but become brittle by recrystalization at 1200'C
  - 3D MA (FineGrain) → HIP → recrystallization under grain boundary sliding (GSMM): segregation / precipitation of TiC at grain boundary

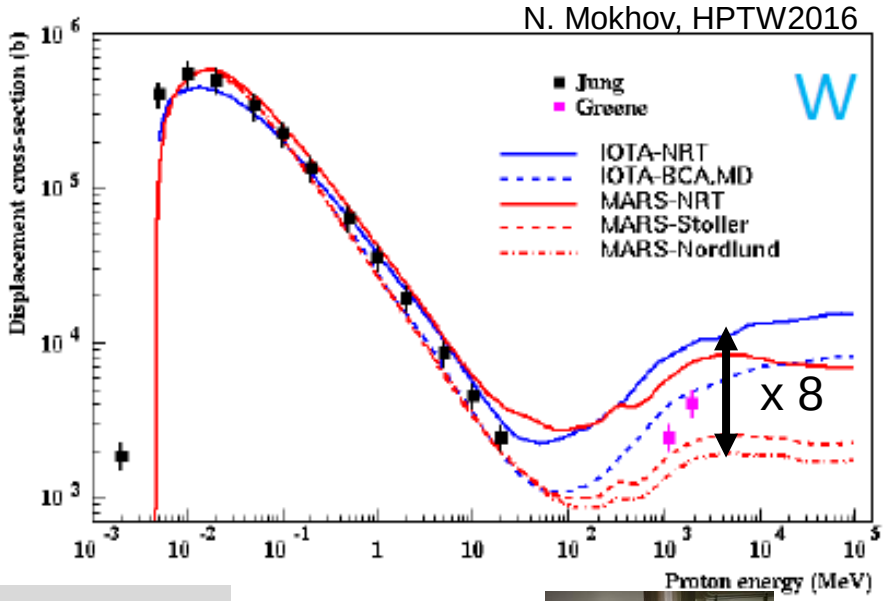


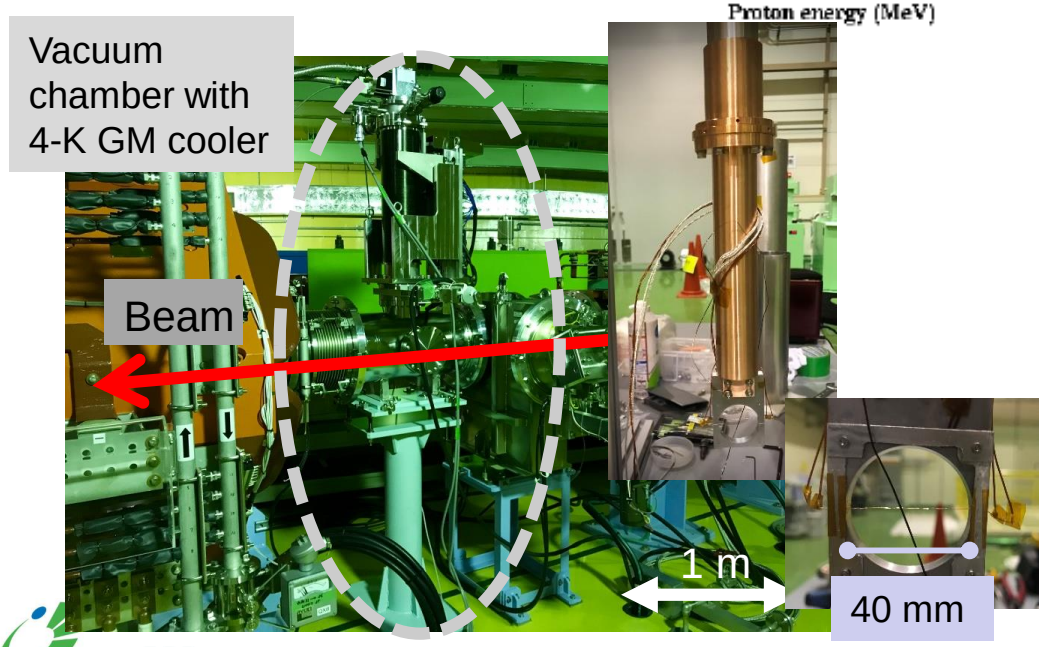
HiRadMat48 PROTAD

Measurement of Displacement Cross-section

→ S.Meigo20p

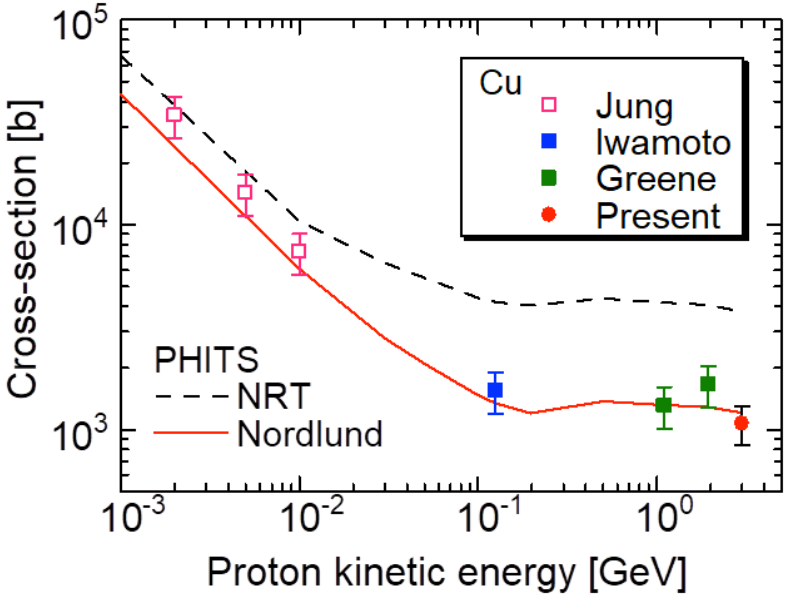
N. Mokhov, HPTW2016





- 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 ($\overline{\phi(E)}$)

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



4. Summary

- J-PARC Neutrino Experimental Facility accepts world's most intense fast-extracted proton beam pulse from synchrotron (2.5×10^{14} ppp) for T2K experiment.
- Until 2018 T2K accumulates > 3×10^{21} pot with about even amounts of neutrino and anti-neutrino mode data.
- The analysis clearly indicates the possibility that the CP symmetry in the lepton sector can be maximally broken.
- To confirm this, construction of Hyper-Kamiokande and power upgrade of J-PARC are both urgency.
- For Hyper-K, seed funding is going to be allocated from JFY2019 by government, and U-Tokyo pledges to start construction from April 2020.
- The J-PARC Main Ring power upgrade to ~1.3 MW will be realized by doubled rep-rate scenario. Magnet power supply upgrade is in good progress to be completed in JFY2021.
- The Neutrino Experimental Facility upgrade is going to be completed also in the JFY.
- Radiation damage / thermal shock studies on the beam window can be the bottleneck of the facility operation.
- J-PARC will continue to contribute to RaDIATE collaboration activities. Wide variety of interesting studies are going on to provide critical inputs to MW target / window design, fabrication and operation.

Thank you for your attention