Neutrino Experimental Facility: Challenges towards Observation of CP Violation in Lepton Sector

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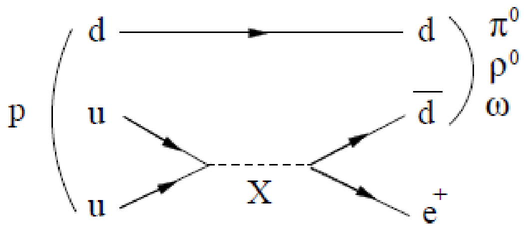
1. Introduction to Japan LBL Neutrino Experiments

- In 1998, the evidence of the neutrino oscillation was obtained through the observation of atmospheric neutrinos by Super-Kamiokande
  - This was "*intended* ", since the anomaly was clearly indicated by the first-generation Kamokande detector

- To confirm the anomaly by accelerator, the first-ever long-baseline neutrino oscillation experiment, K2K, connecting 250km from KEK Proton Synchrotron (12GeV-5kW) to Super-Kamiokande was commenced in 1999
  - This was the revival of the "conventional" neutrino beam technique, established in 1960s at CERN

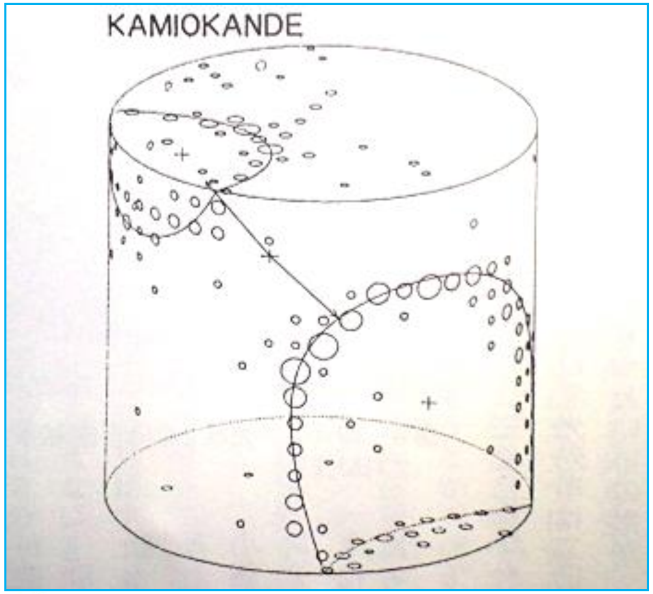
Kamiokande (1983~)

GUT predicts nucleon decay with life > 10^{30} yr



To observe nucleon decay of life time of 10^{33}yr,

$$10^{33} \text{ nucleons} \approx \frac{10^{33}}{6 \cdot 10^{23}} \text{ gr} \approx 1700 \text{ t},$$

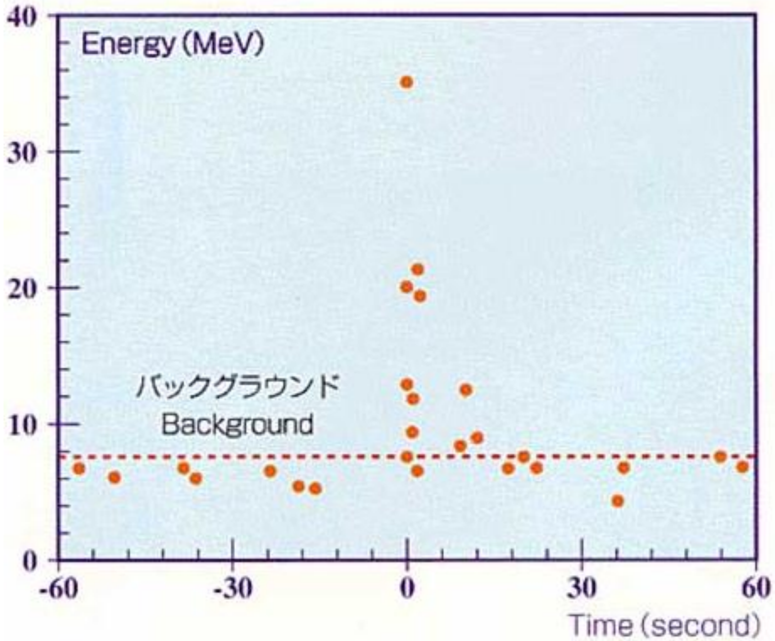


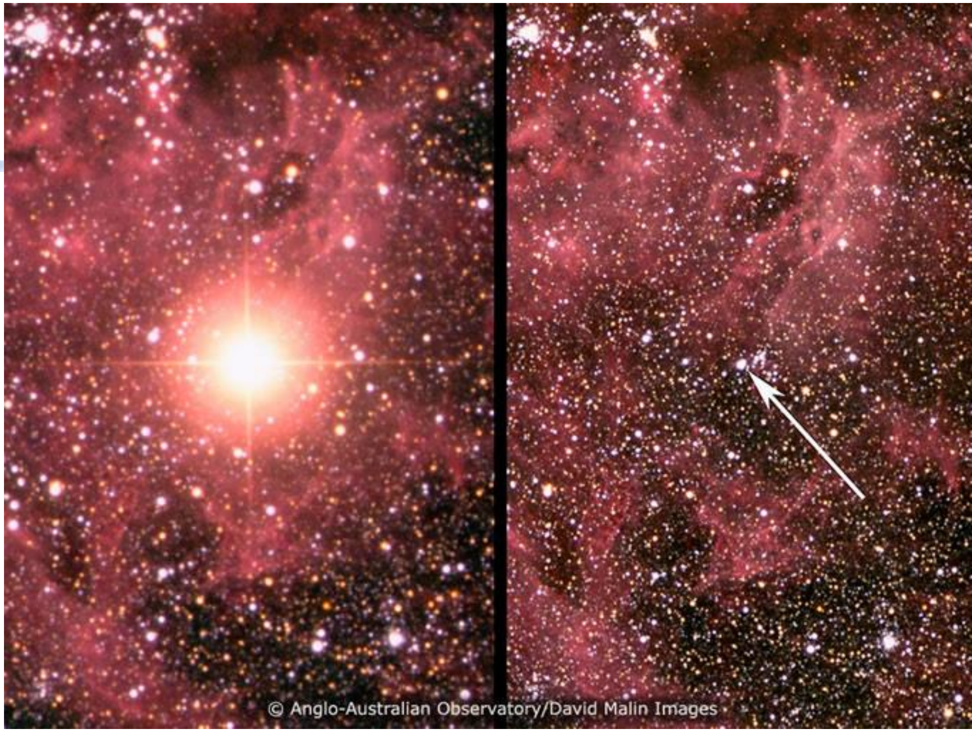
- Locates Kamioka mine underground, 1,000 overburden
- Detect Cherenkov light emission in purified water
- 15.6mφ × 16mH
- 3,000t (680t fiducial)
- 1,000 20-in PMTs (1/m^2)
- μ-like/e-like event separation

NDE= *Nucleon Decay Experiment*

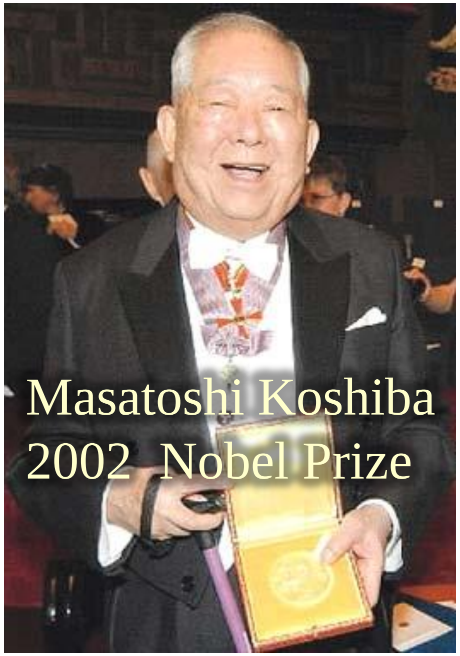
$P \rightarrow e+\pi^0$ > 2.5×10^{32} yr
Denial of minimal SU(5) theory

SN1987a





- Feb.23 1987, 11 events of neutrino burst from a supernova in Large Magellanic Cloud (50kpc/160kLY away) was detected.
- Good agreement to the Type-II supernova theory prediction (neutrinos take almost all energy of gravitational collapse / birth of neutron star with radii 10km, total energy 3×10^{46}J, in 10 sec. x500 of total energy sun was emitted in its life.)
- Upper limit of neutrino mass (<20eV)



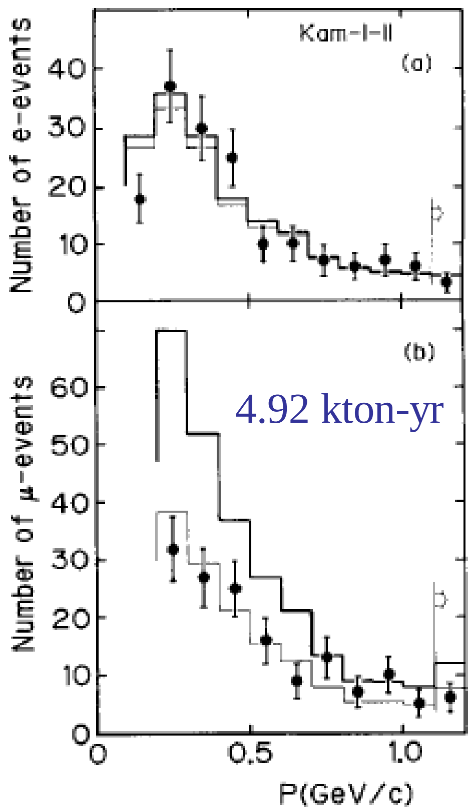
Atmospheric Neutrino

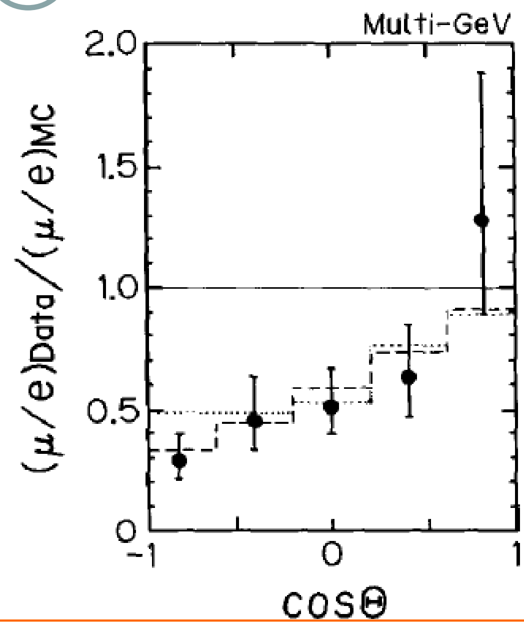
Neutrinos produced in the earth's atmosphere through the interactions of primary cosmic rays with nuclei in the air, energy ranging 0.1GeV～1 TeV.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Produced ν_μ to ν_e ratio ~ 2 : 1

Major background source of nucleon decay

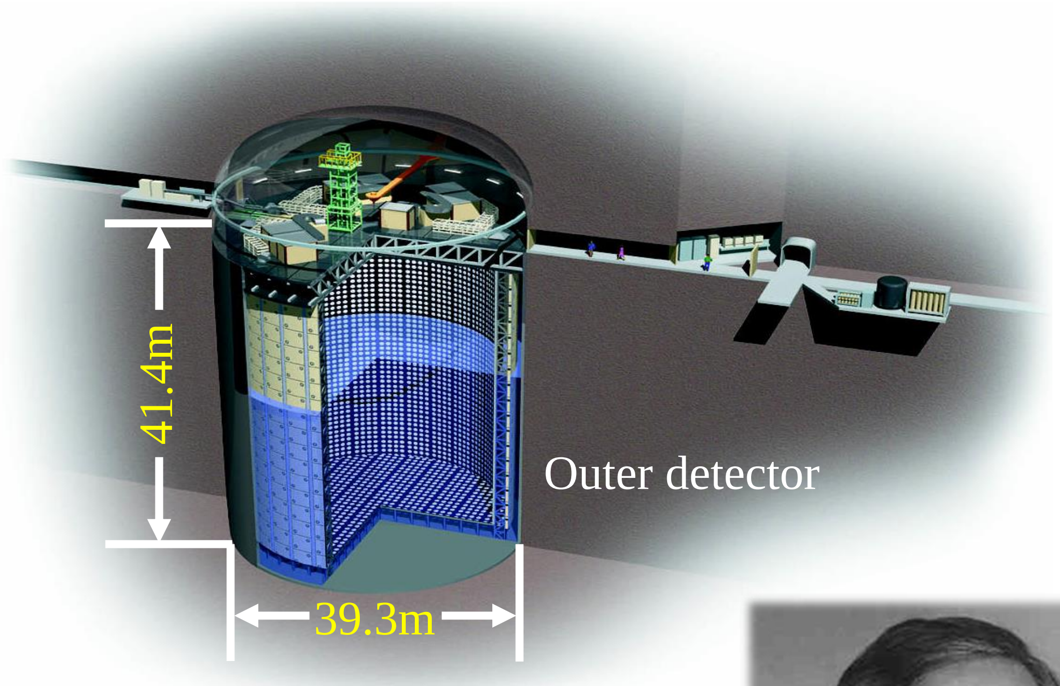




$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.57^{+0.08}_{-0.07}(\text{stat.}) \pm 0.07(\text{syst.})$$

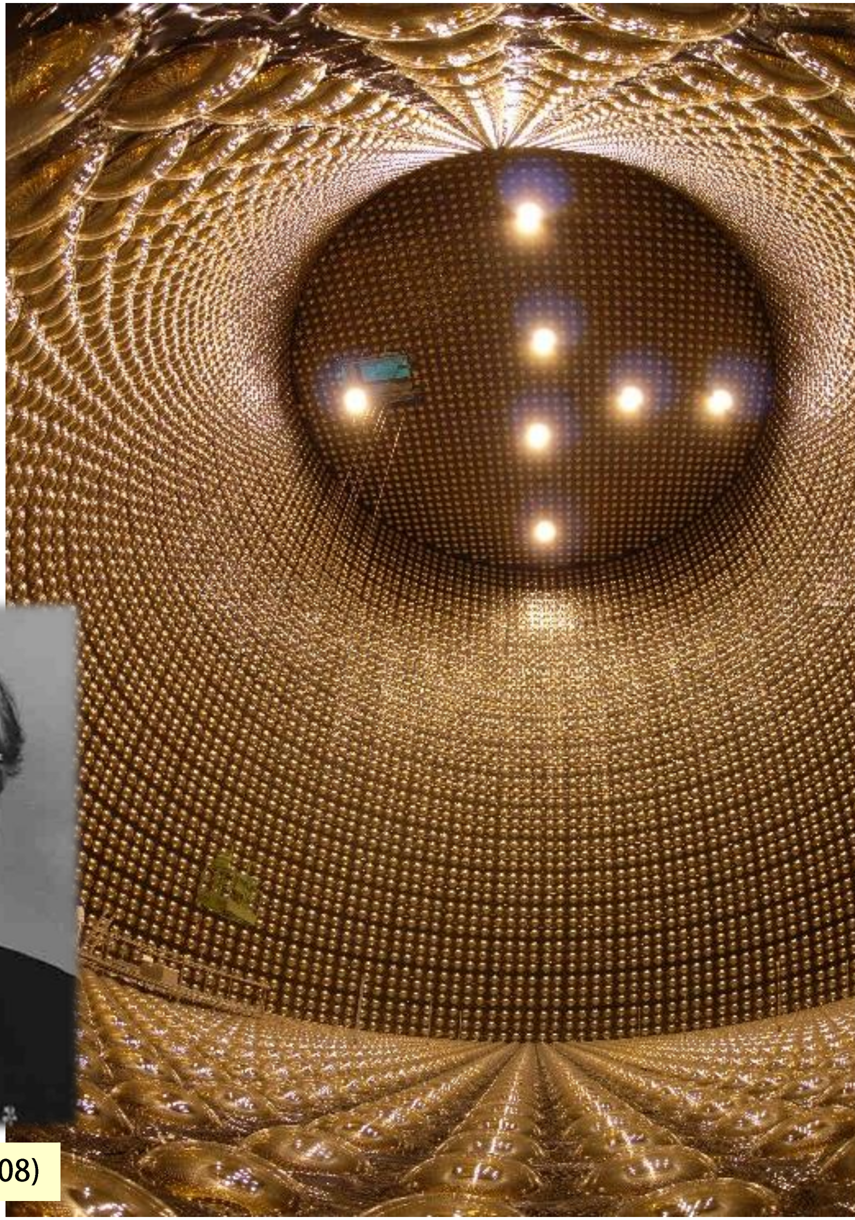
PLB280(1992)146/ B335(1994)237

The Second Generation: Super-Kamiokande (1996~)

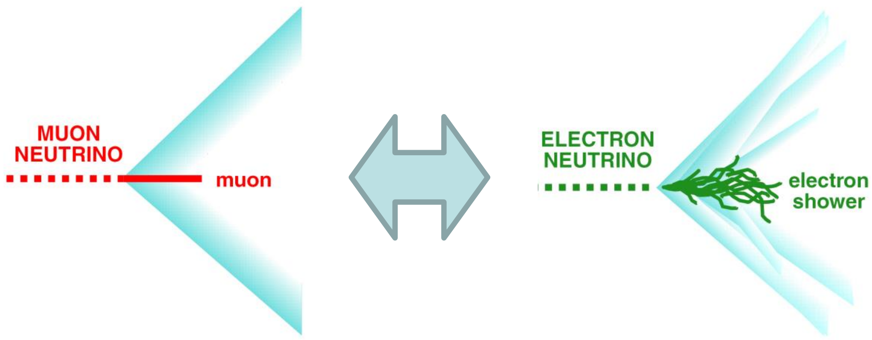


- 50,000 t (22,500t fiducial, x 33 of Kamiokande)
- Inner Detector: 11,129 20” PMTs (2/m^2)
- Outer Detector: 1,885 8” PMTs
- Construction: 1993~96

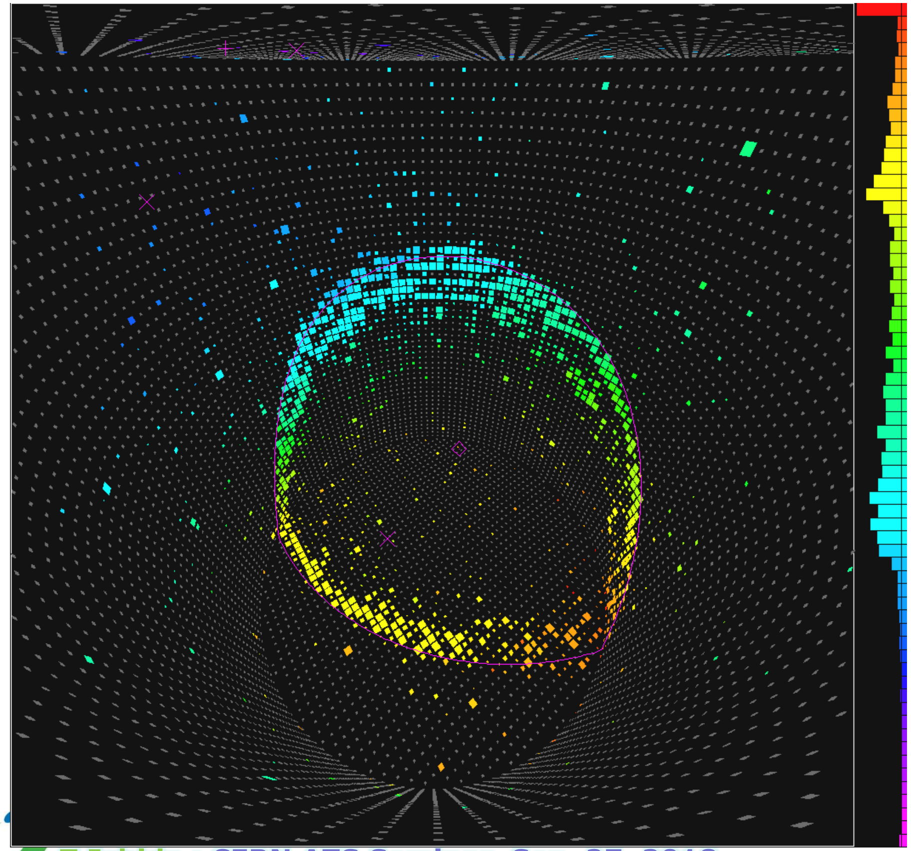
Y.Totsuka (1942-2008)

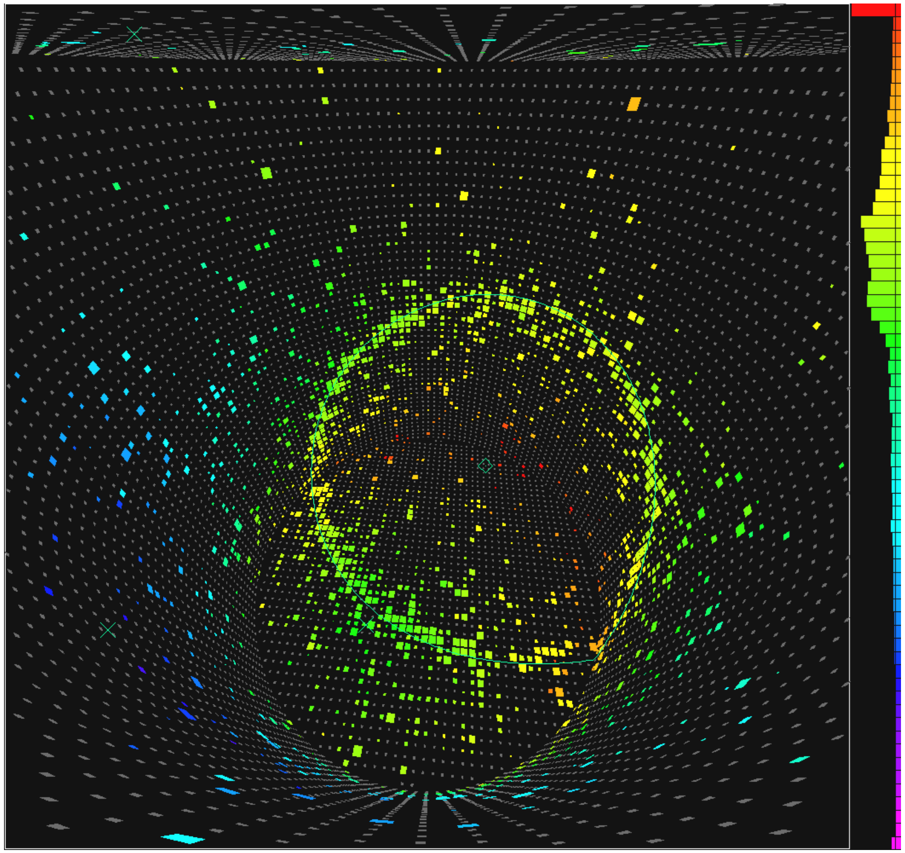


Mu-like / e-like identification



- Cherenkov ring for electron is more blurred than that for muon, due to EM shower
  - Mis-identification:
    <1GeV：0.6%
    a few GeV：≲2%

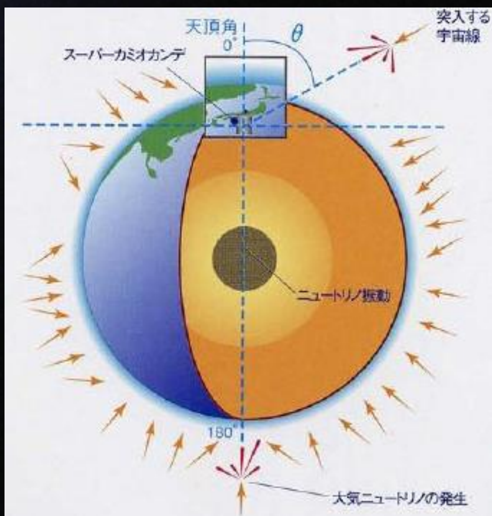


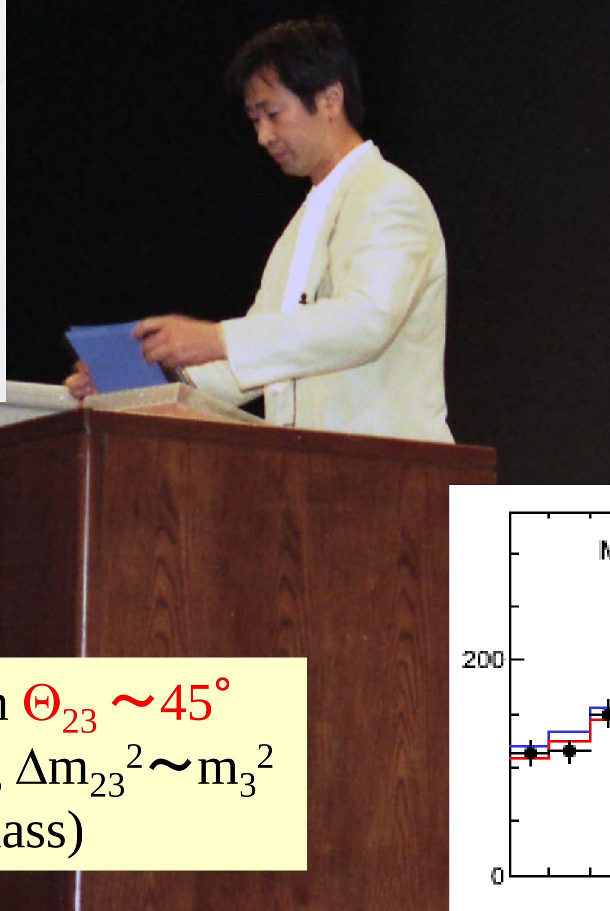


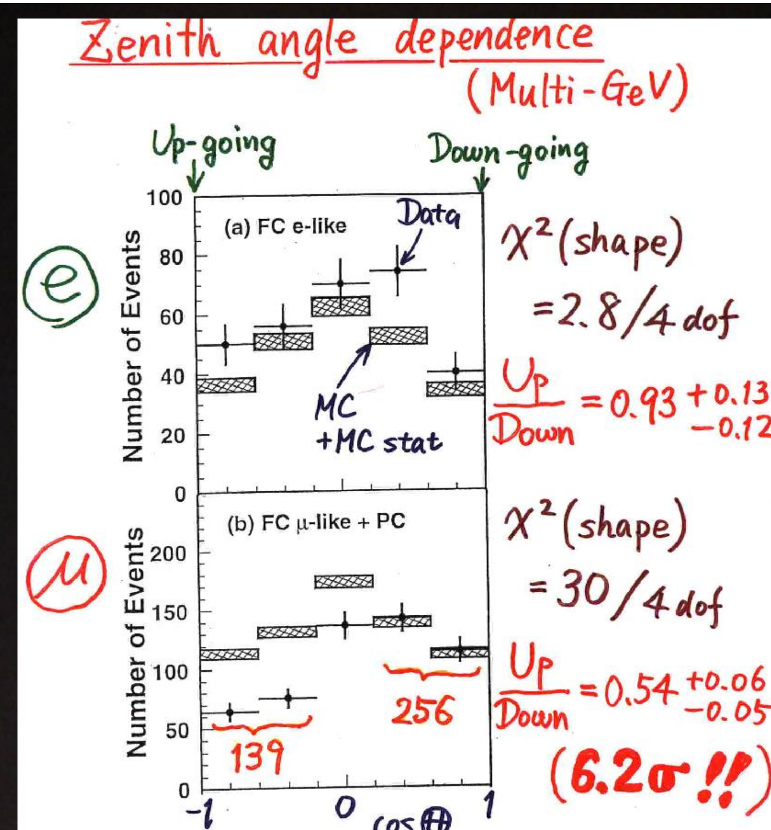
2018: 20th anniversary of neutrino oscillation discovery

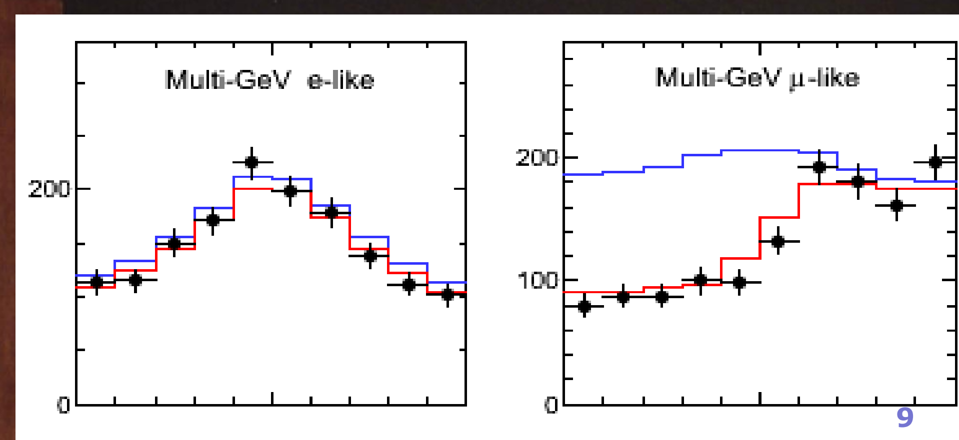
NEUTRINO1998
June 5, 1998 @Takayama

Takaaki Kajita
2015 Nobel Prize



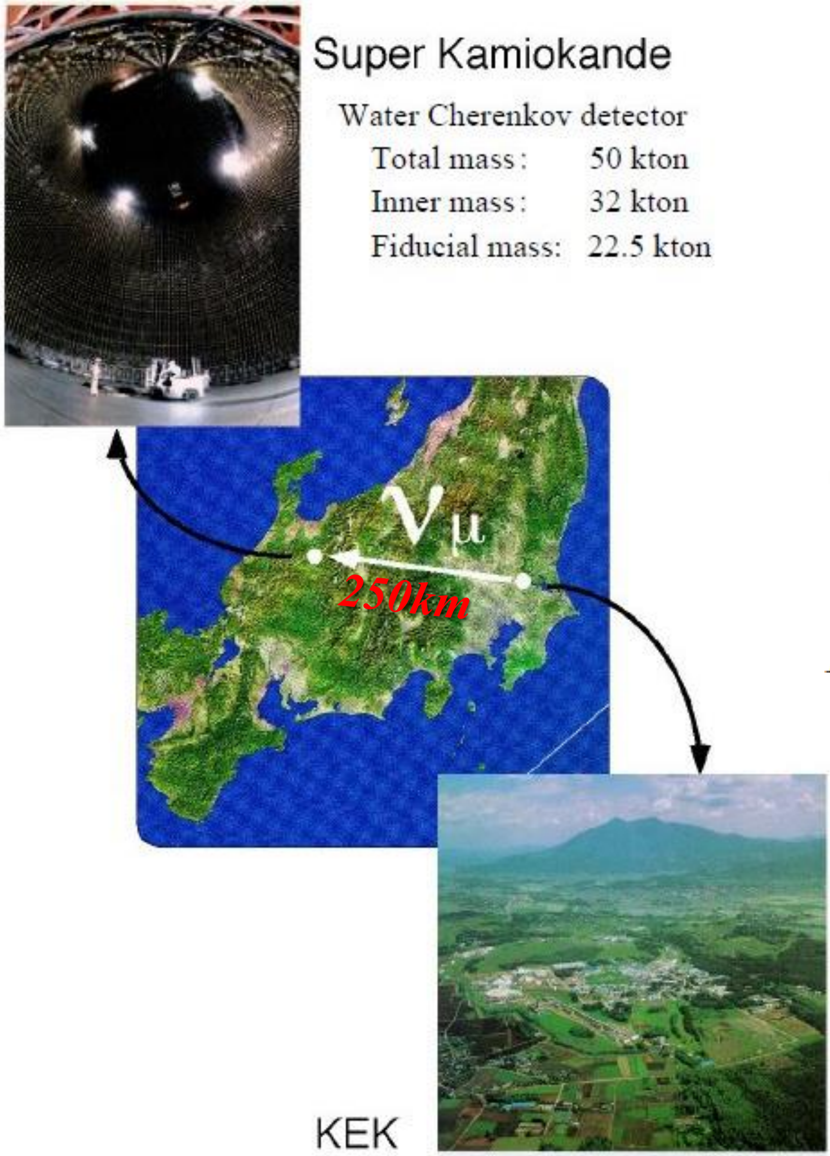






Maximal mixing with $\Theta_{23} \sim 45^\circ$
$m_3 \sim 0.05$eV assuming $\Delta m_{23}^2 \sim m_3^2$
(1/10M of electron mass)

Long-baseline Neutrino Experiment:
Revival of Conventional Neutrino Beam



- KEK 12GeV proton synchrotron (5kW) ⇒ Super-Kamiokande (250km)
- Validate atmospheric neutrino $\nu_\mu \Rightarrow \nu_\tau$ oscillation
- Distance between KEK-PS and SK was just the right number !
- 1996~1998: Beam-line / Near detector construction

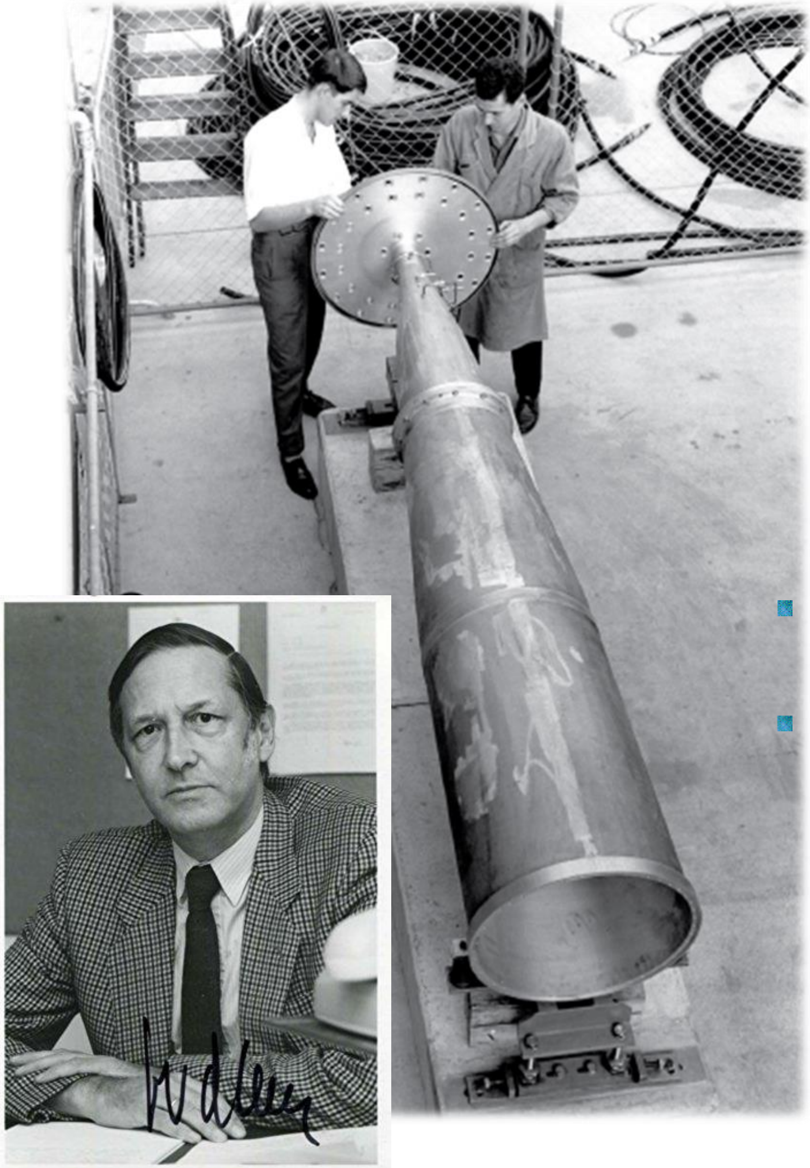
$$P_{\nu_e \to \nu_\mu} \sim \sin^2 2\theta \sin \frac{\delta m^2 t}{4E}$$

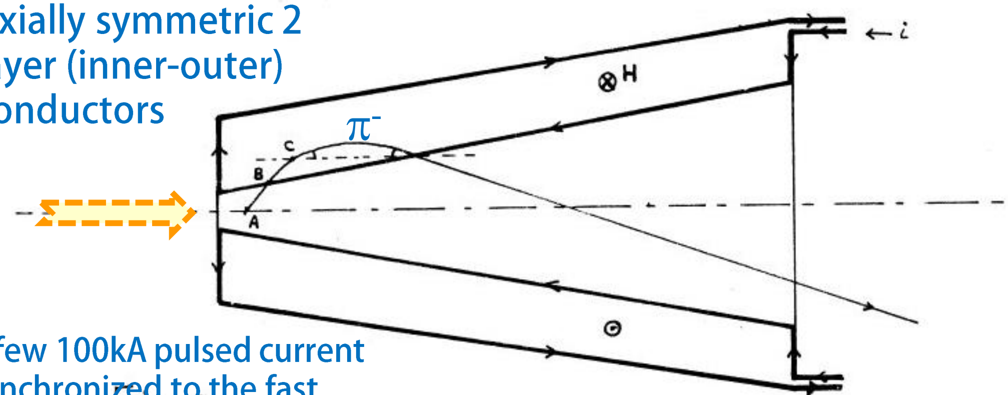
$$\delta m^2 \equiv |m_1^2 - m_2^2|$$

$L = vt \sim ct = t$

	Atm-ν	K2K
L	15~13,000*km*	250*km(fix.)*
Eν	0.1~1,300GeV	~ 1.3GeV
Δm^2	10^{-1} ~10^{-4}eV^2	> 10^{-3} eV^2
ν_e/ν_μ	50 %	~1%

Conventional Neutrino Beam (1968~)





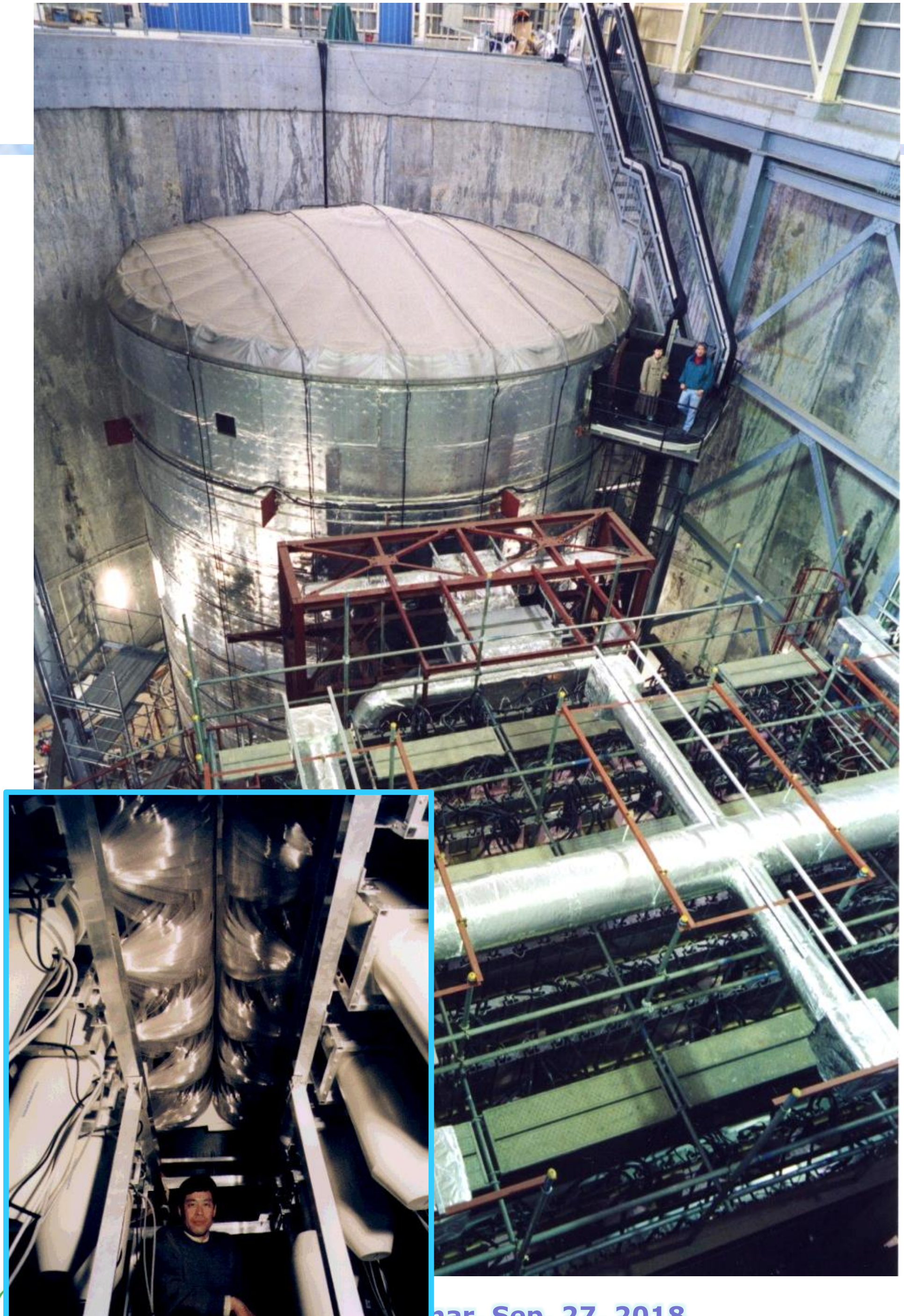
Axially symmetric 2 layer (inner-outer) conductors

A few 100kA pulsed current Synchronized to the fast beam extraction orbits through inner to outer conductor

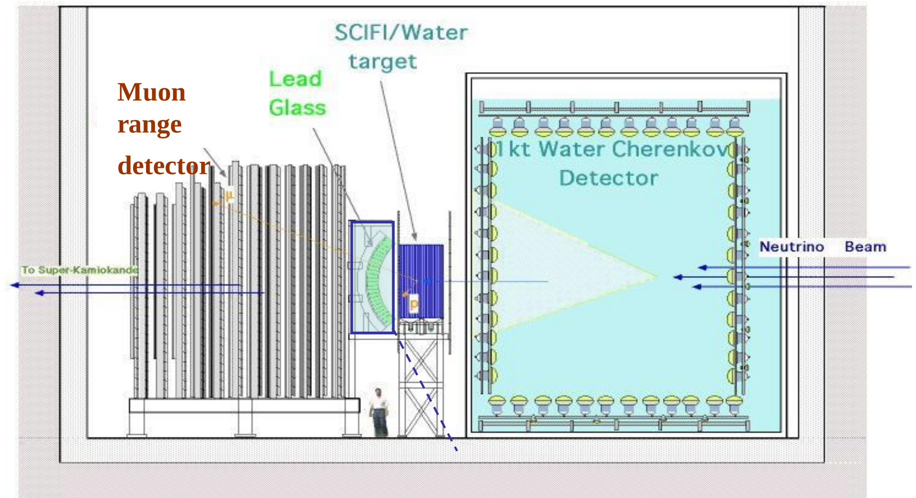
A few Tesla of Toroidal magnetic field Btw. conductors

- Fast extraction from accelerator
  - A few us beam pulse extracted with a few sec cycle
- Electromagnetic horn "van der Meer Horn"
  - Focus secondary charged mesons ($\pi^{\pm} \rightarrow \mu + \nu_{\mu}$ 100%)
  - By focusing parents before their decay, neutrino flux can be amplified by 1 order of magnitude
  - Parent mesons produced at the target with various momenta and scattering angles are focused at once ⇒ Neutrino energy spreads widely (Wide Band Beam)
  - Choice of current direction (polarity) changes the charge of parents to be collected ⇒neutrino/anti-neutrino can selectively be produced (not in perfect manner)


1.1 μs pulse/2.2s
6~7×10^12 ppp
TRISTAN RING
(B-factory)
East
Counter Hall
Al target
Double HORNs
π-monitor(pπ,θπ)
Primary Beam-line
12GeV PS
P
Target Station
North
Counter Hall
Decay Section
(200m)
π+ → μ+ + νμ
Muon Pit
Direction(μ)
Front Detectors
Direction(ν)
ν Spectrum/Rate
νμ



Near Detectors

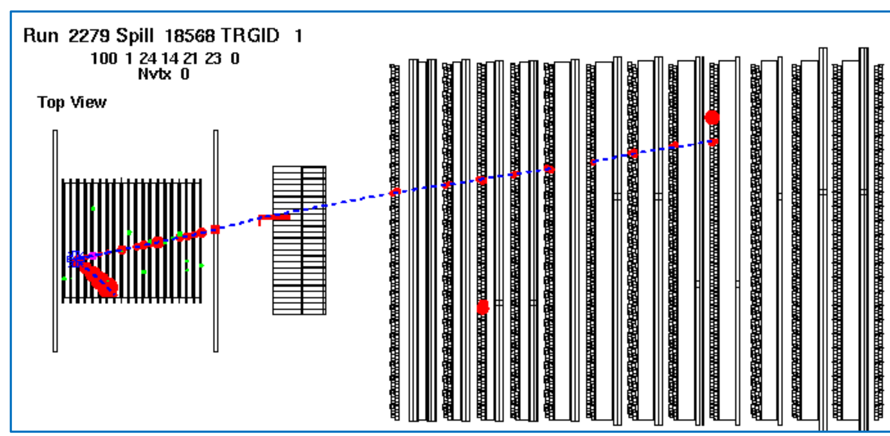


Neutrino energy spectrum at production

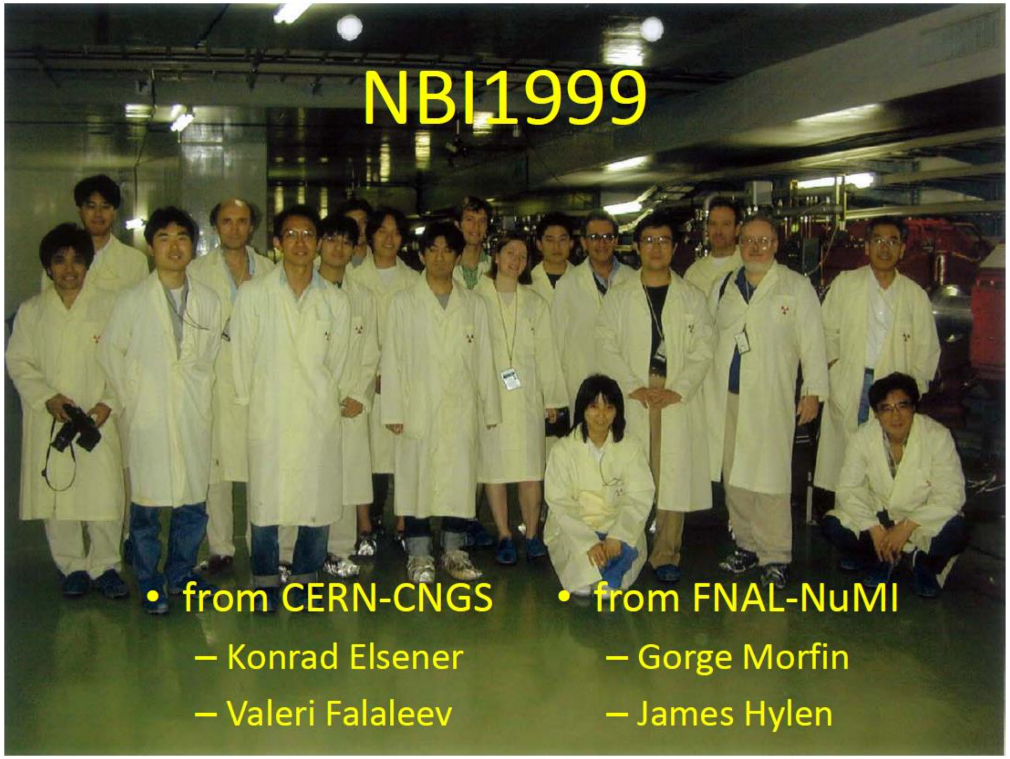
Charged Current
Quasi-Elastic

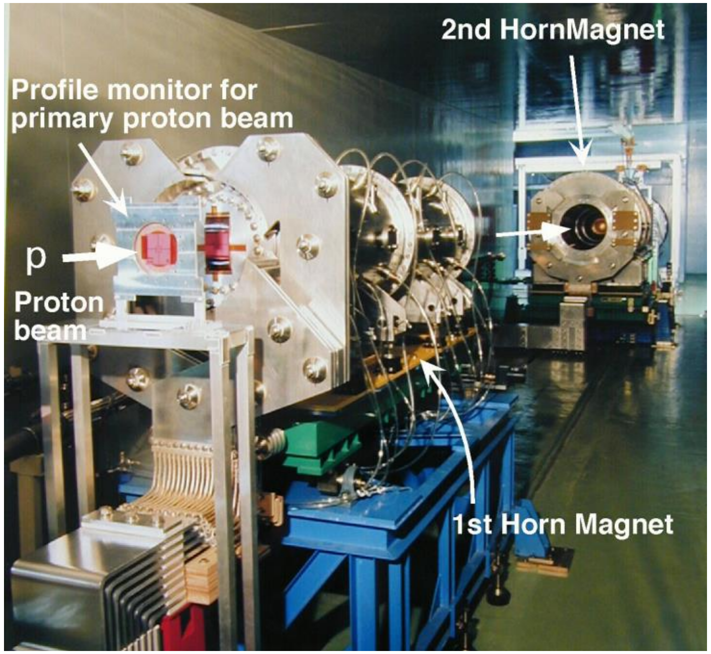
$$\nu_\mu + n \rightarrow \mu^- + p$$

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



NBI : WS on Neutrino Beams and Instrumentation



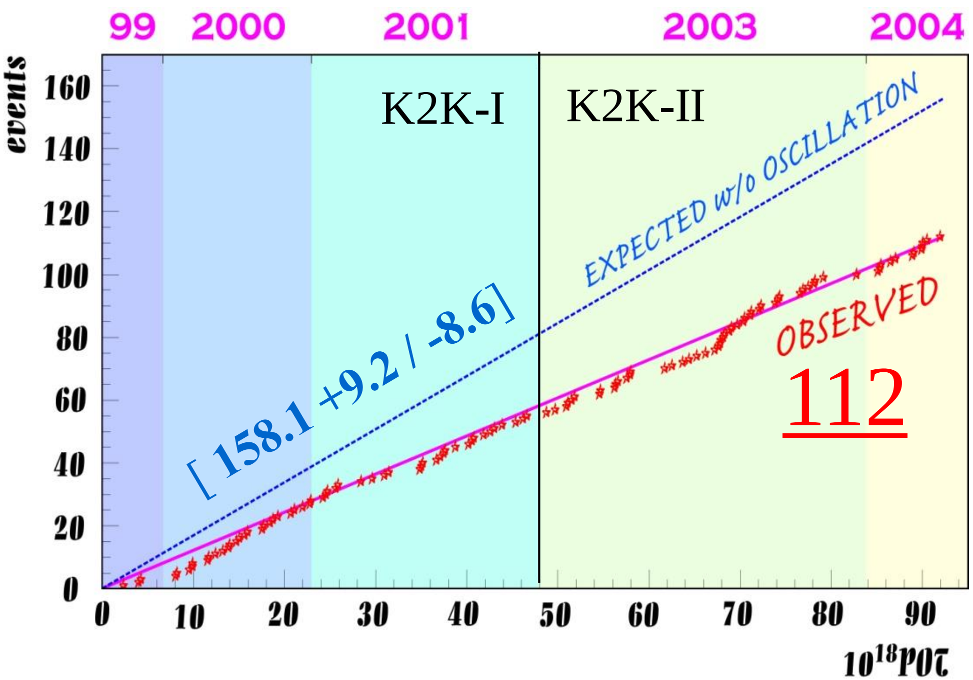


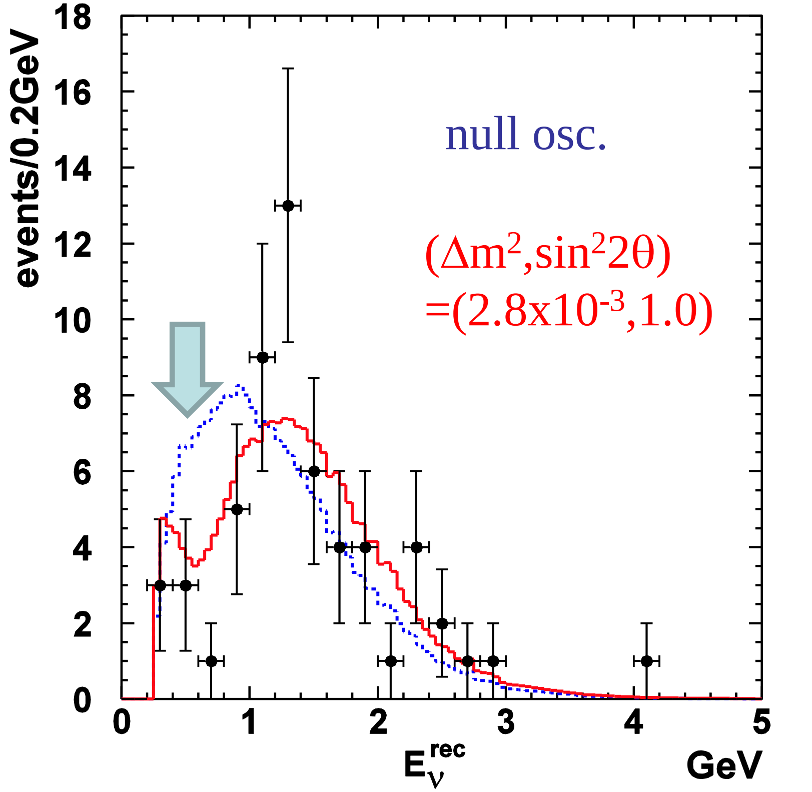
1st Horn Target Rod (20mmΦ) Break
(1.9×10^6 excitations)

- Neutrino beam-line experts (physicists / engineers) come together to openly discuss failure to be learned by others.
- Initiated at KEK in 1999 : K.Tanaka(KEK)/J.Hylen(FNAL)/K.Elsener(CERN)
- Once per every two years, organized by FNAL(NuMI)/CERN(CNGS)/KEK(J-PARC)
  - 10th was at J-PARC in Sep. 2017, 11th in Europe

K2K's Result

Total : *9.22 x 10^{19} p.o.t.*





Null Oscillation Probability

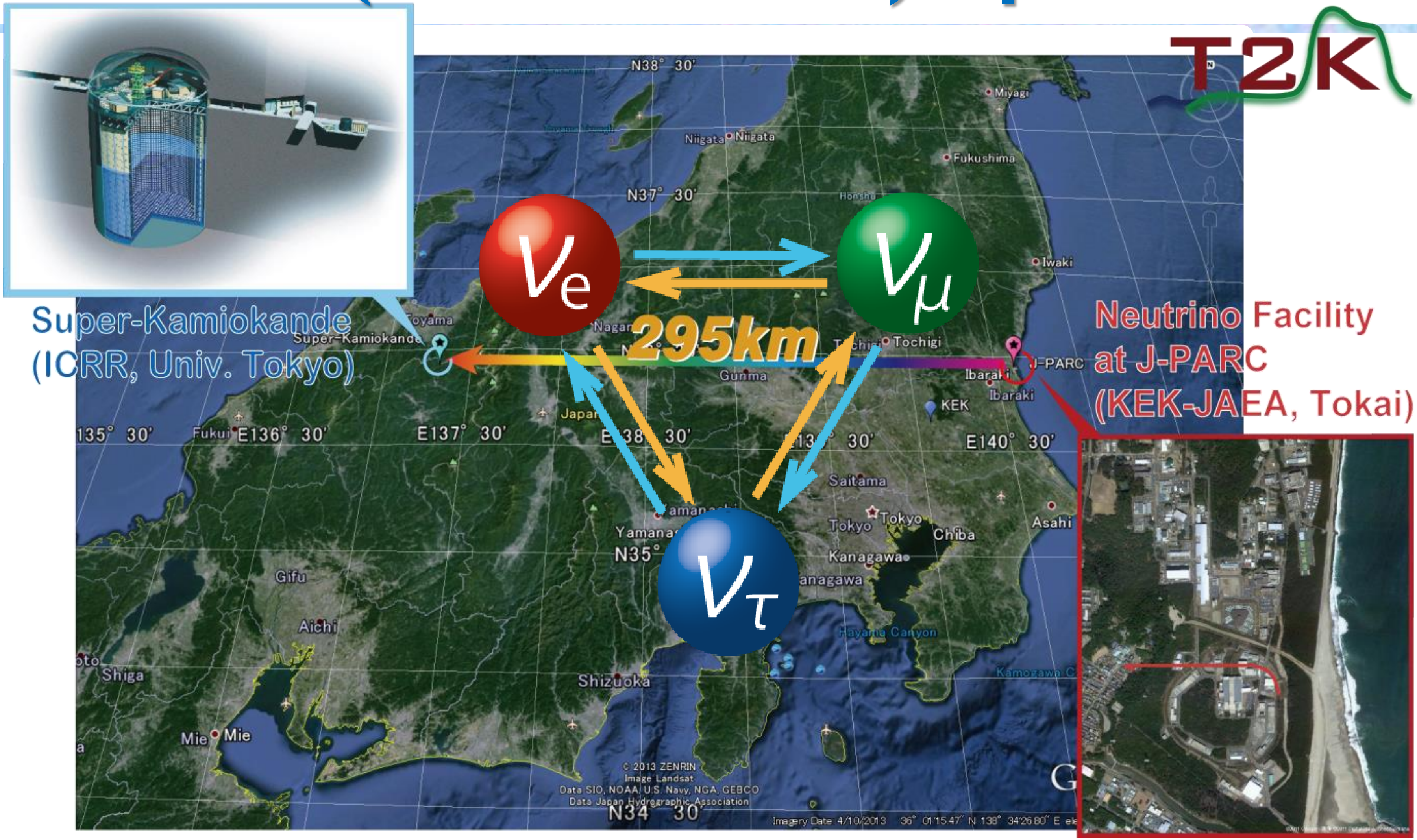
①# events 0.06% (3.4σ)
②spectrum 0.42% (2.9σ)
③combination 0.0015% (4.3σ)

Reconstructed Neutrino Energy
（1 ring, μ-like 58 events）

Validate Super-K's atmospheric neutrino anormaly by accelerator LBL

PRD 74, 072003 (2006)

The T2K (Tokai-to-Kamioka) Experiment



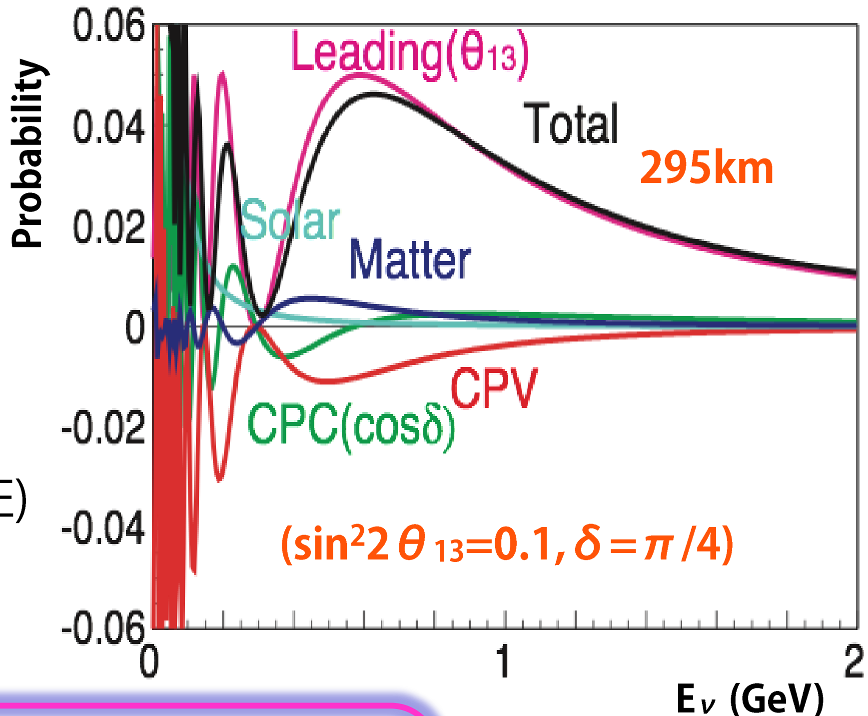
- KEK Proton Sync. 5kW → **J-PARC Main Ring Synchrotron 750kW**
- Wide-band beam → **Off-Axis low-energy semi-monochromatic beam**

Motivation

- **Discovery of $\nu_\mu \to \nu_e$**
  - 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)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$

$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$



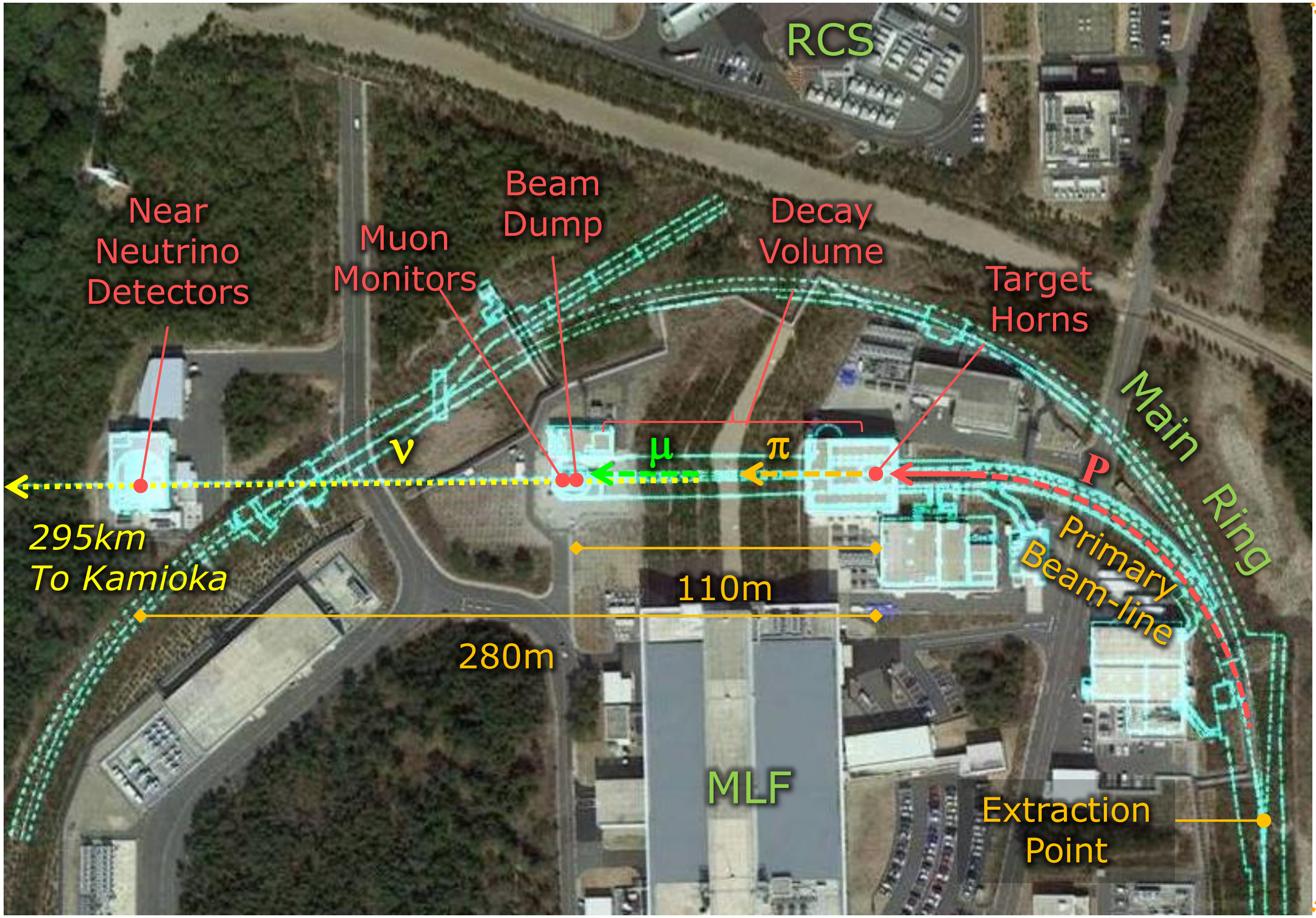
CPV ∝

$$\sin\theta_{12} \times \sin\theta_{13} \times \sin\theta_{23} \times \sin\delta$$

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
Neutrino
Experimental
Facility (ν)
3GeV Rapid Cycling
Synchrotron (RCS)
25Hz, 1MW
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]

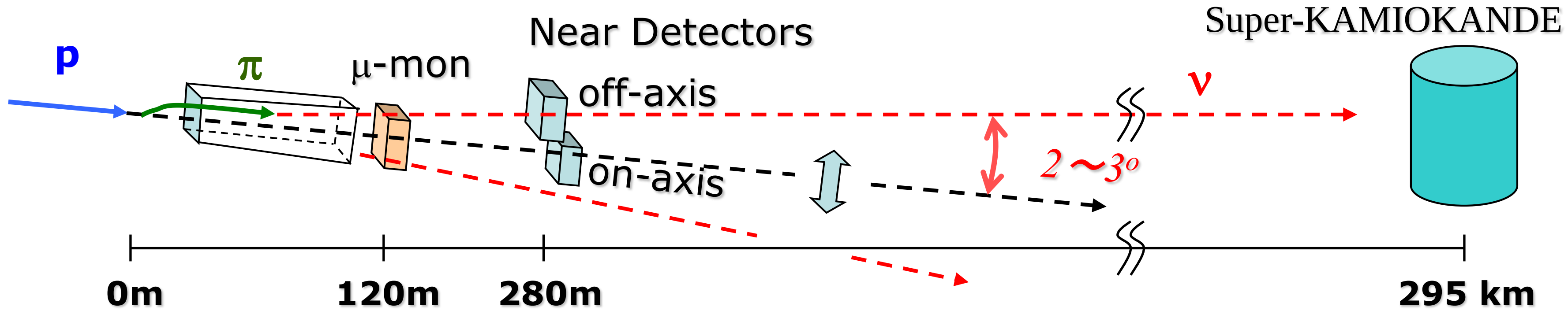
2. Facility Overview, Operational Status & T2K Achievements



J-PARC, Tokai

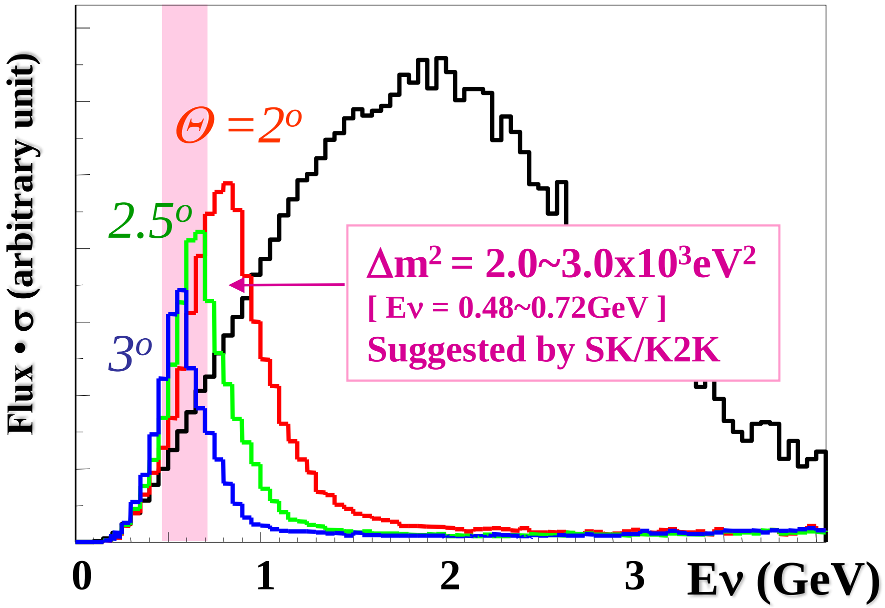
- Conventional neutrino beam-line, accept beam from H.I. proton driver
- Lots of inputs from NBI community (CNGS team / BNB, NuMI team)
- Construction completed in JFY2008, commissioning started from Apr. 2009

Off-Axis Beam with Variable Angle



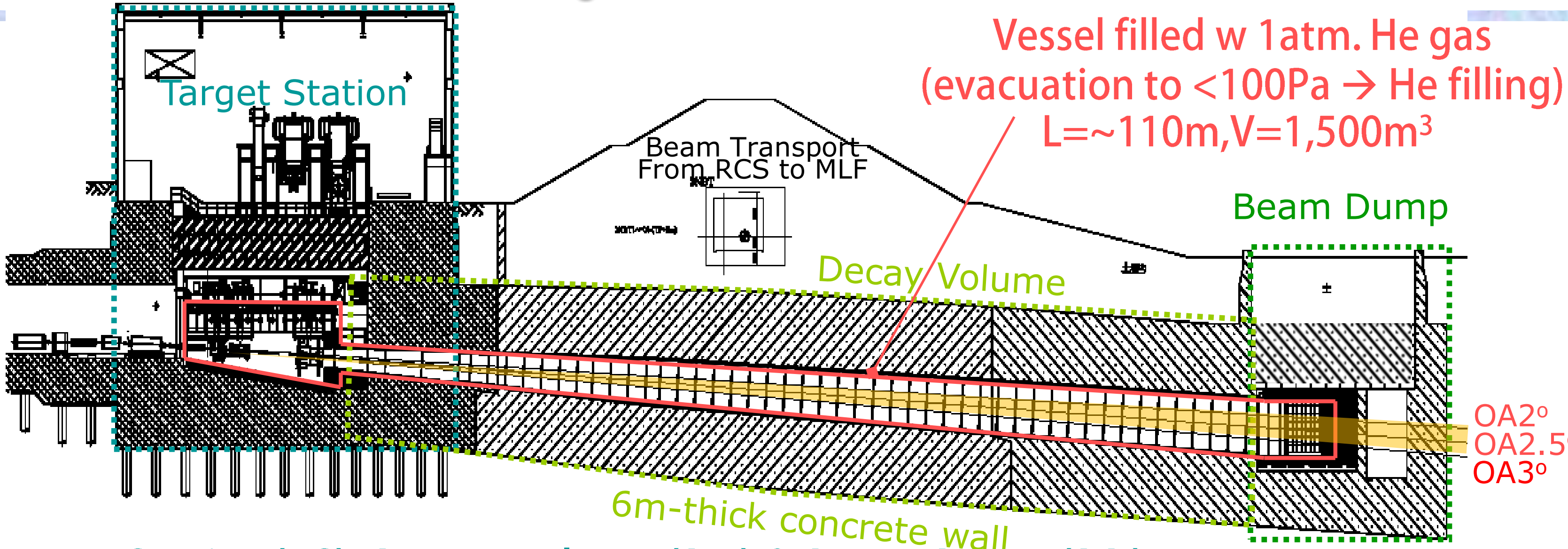
＊ Idea of OAB: D. Beavis, A. Carroll, I. Chiang, et al., Proposal of BNL AGS E-889 (1995).

- Beam axis tilted a few degrees wrt. far detector direction
  - High energy pion in forward direction
  - Low energy pion with finite angle
  - The neutrinos produced by pion decay: high-erergy in forward direction, low energy in finite angle
- As a result, neutrino in a certain finite off-axis angle shows spectrum with lower energy / narrower width
- Variable off-axis angle: to cover ambiguity of the oscillation maximum at that time



Quasi Elastic Interaction Dominant

The Secondary Beam-line



- Target Station(TS), Decay Volume(DV) & Beam Dump(BD)
  - TS: target, 3 magnetic horns, remote maintenance
  - DV: 94m-long tunnel with rectangular cross section, tunable OA angle
  - BD: hadron absorber + iron shields
- Enclosed in a gigantic helium vessel, made of carbon steel plates
  - He atmosphere prevents nitrogen oxide (NO_x) production / oxidization of apparatus
  - Absorber also in the vessel: no need to develop large beam window at upstream of BD
  - To withstand evacuation: 100~200mm thick steel plates at TS/BD (*recycled ones from K2K near muon range detector)
- Cooling by water circuits (plate coils)
  - Maintenance / upgrade is not possible after beam operation due to irradiation.
  - Radiation shielding / cooling capacity to accept up to future ~4MW beam.

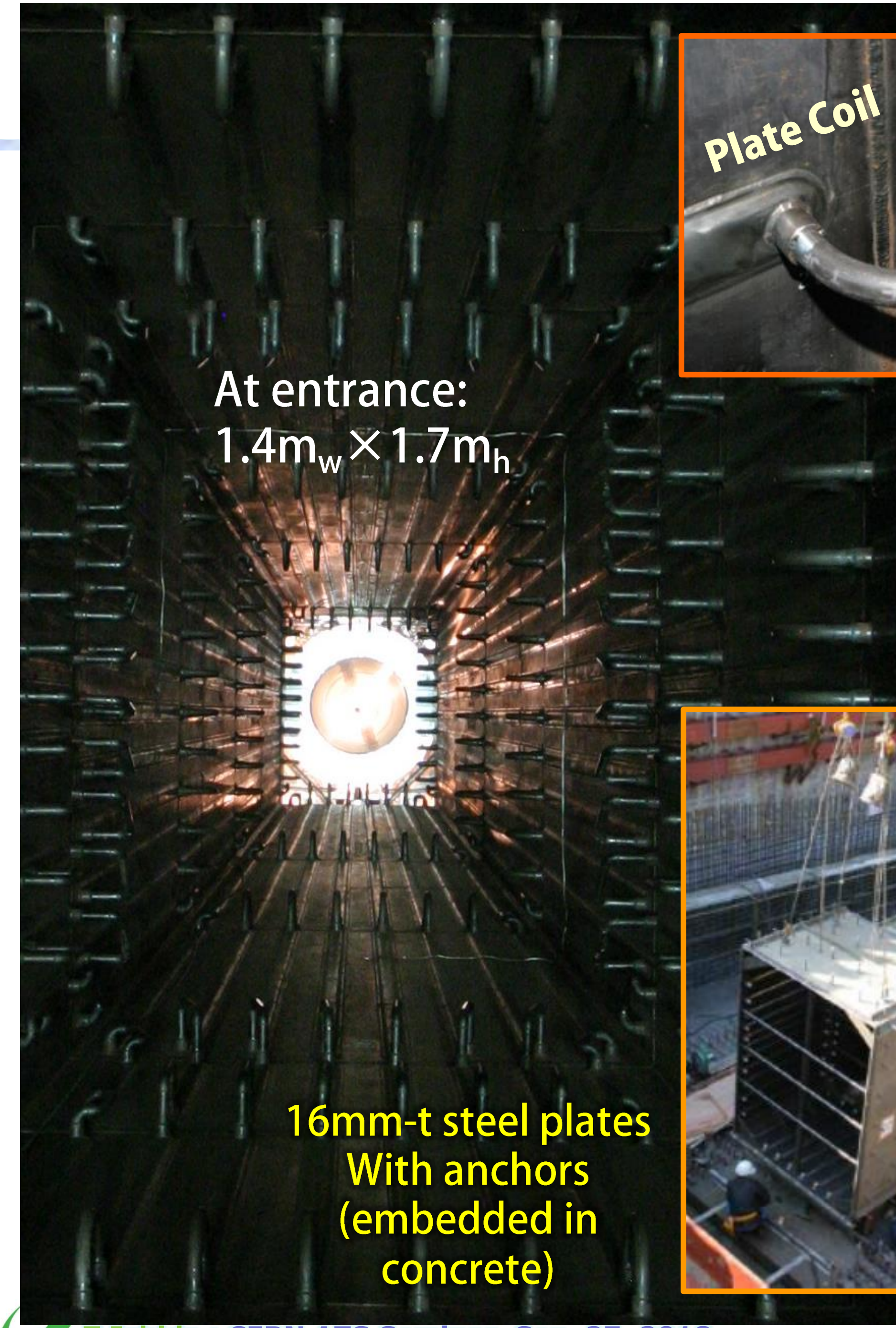
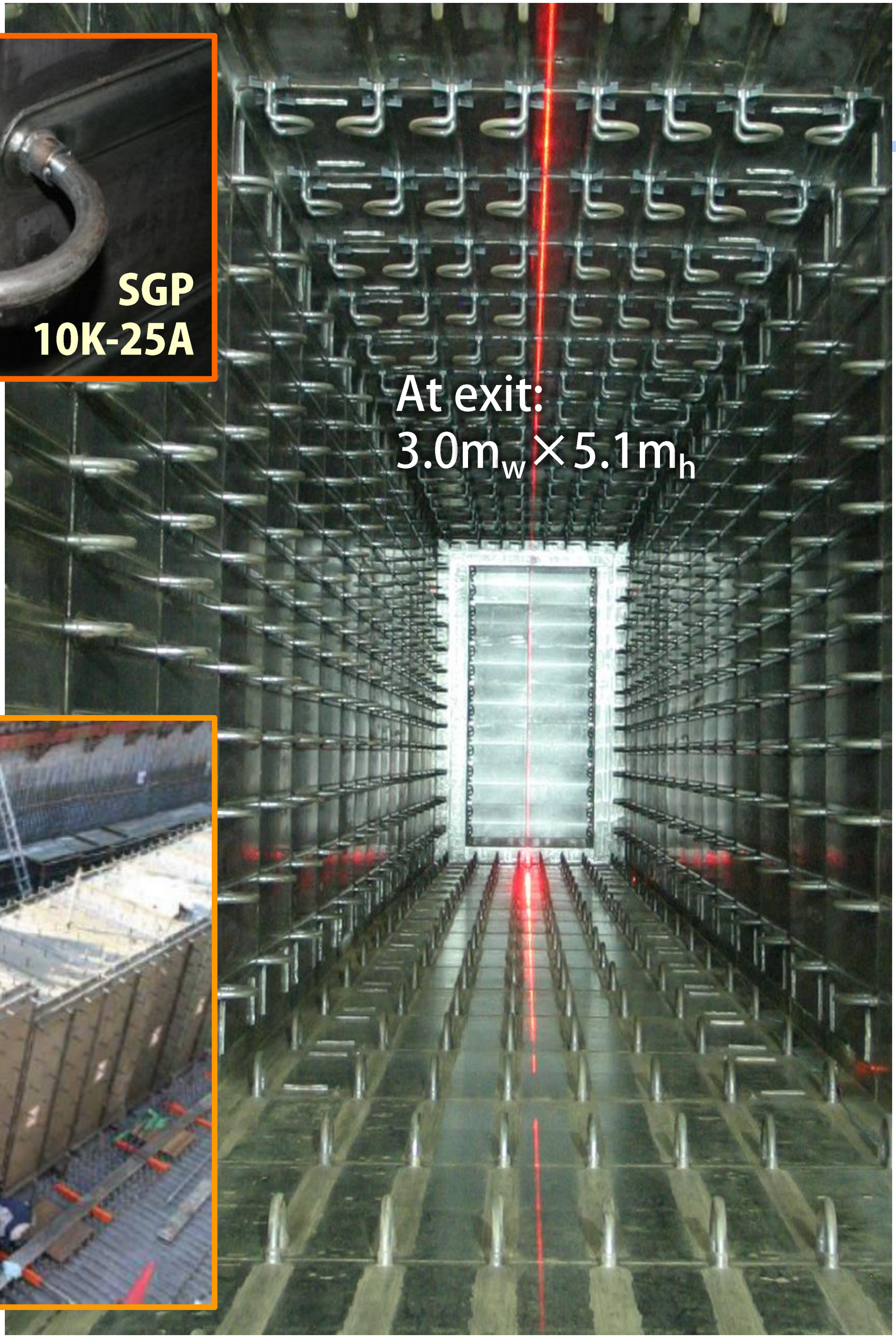
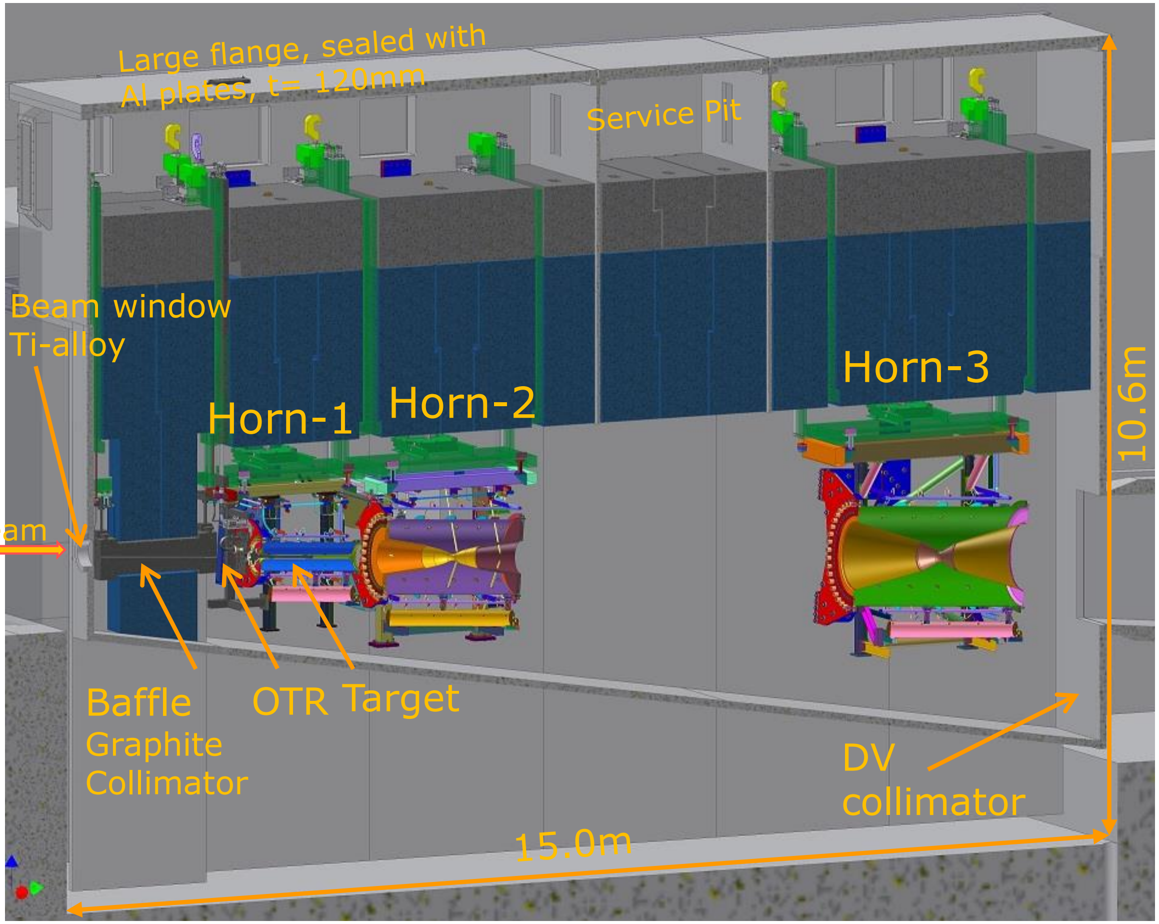

At entrance:
1.4m$_w$×1.7m$_h$
16mm-t steel plates
With anchors
(embedded in
concrete)

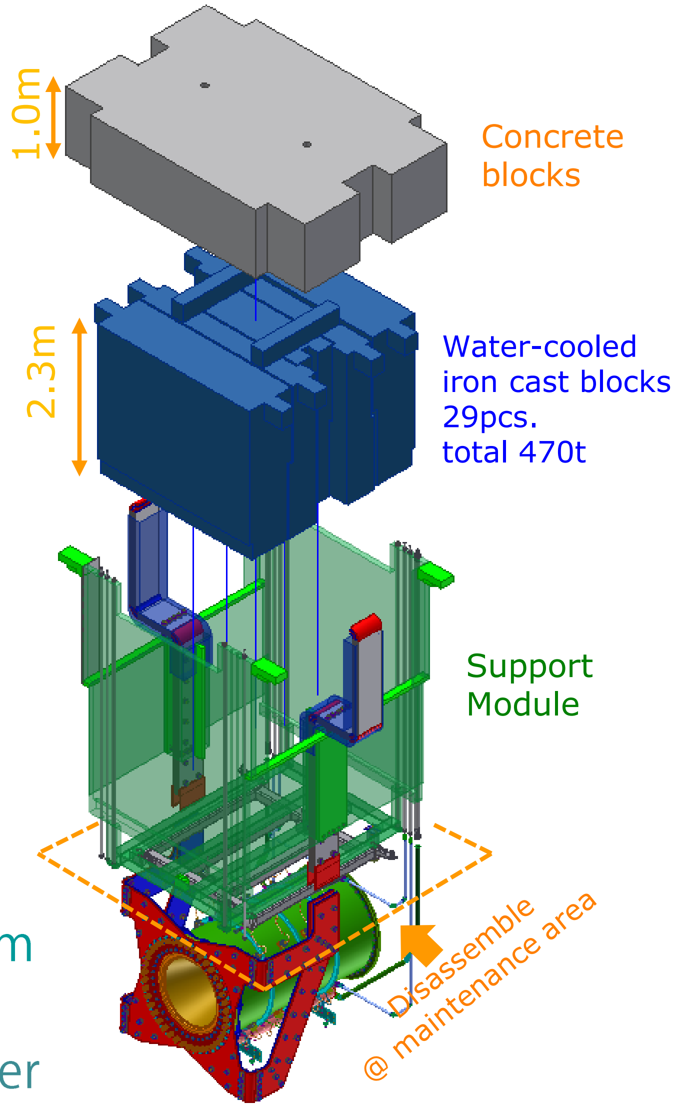

Plate Coil
SGP
10K-25A


At exit:
3.0m$_w$×5.1m$_h$

Target Station (TS)

Support module / shield design refers to NuMI



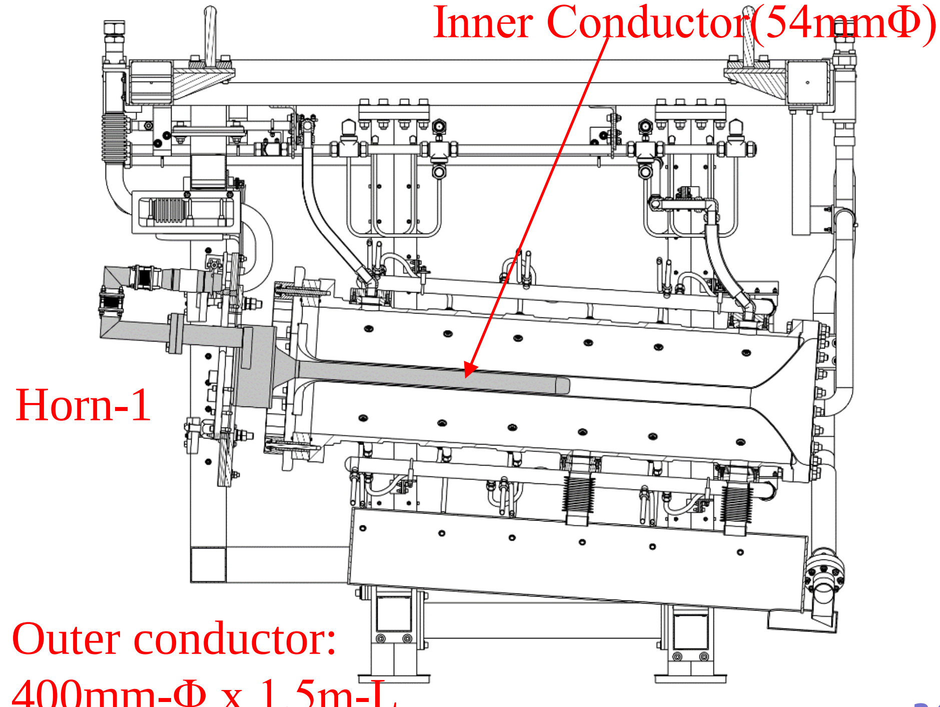


- 3 electromagnetic horns / a baffle are supported from the wall of vessel by support modules.
- Apparatus on the beam-line are highly irradiated after beam. Remote maintenance is the key issue.

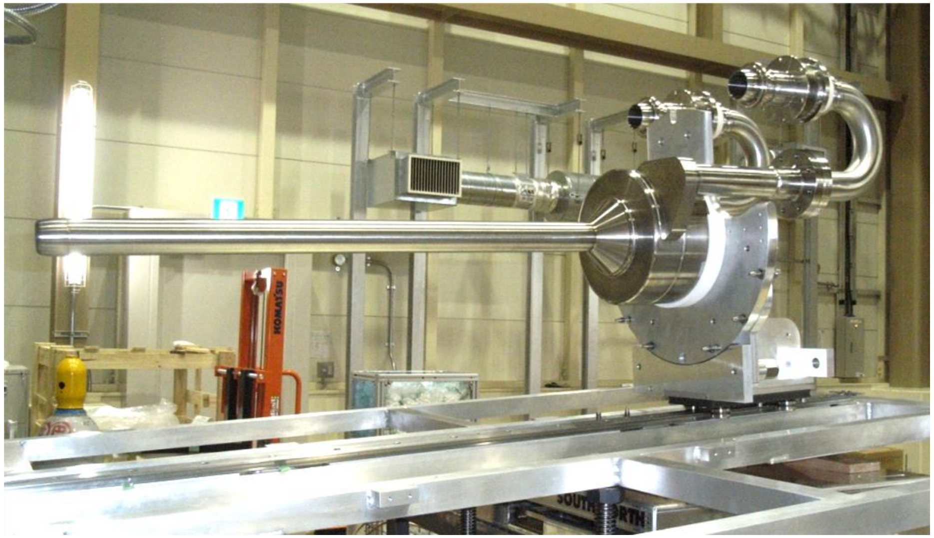
Electromagnetic Horns

BARTOSZEK ENGINEERING

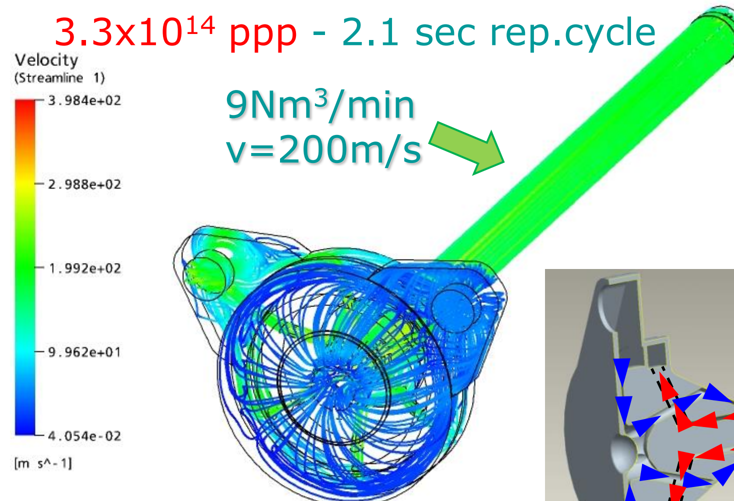
- Aluminum alloy A6061-T6
  - Inner conductor: 3mm-t, outer: t10mm.
- 320kA pulsed current (250kA in use so far)
  - Max field: ~2.1T, pulse width: 2~3ms
  - Operation cycle: 2.48 s → 1.1 s
- Spraying water to inner conductor
  - 15kJ (beam) + 10kJ (Joule)=25kJ
  - Keep <80℃

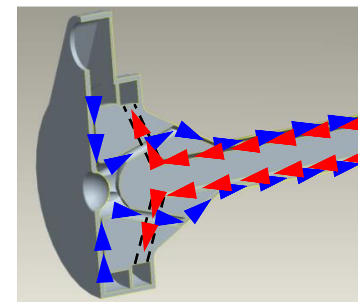


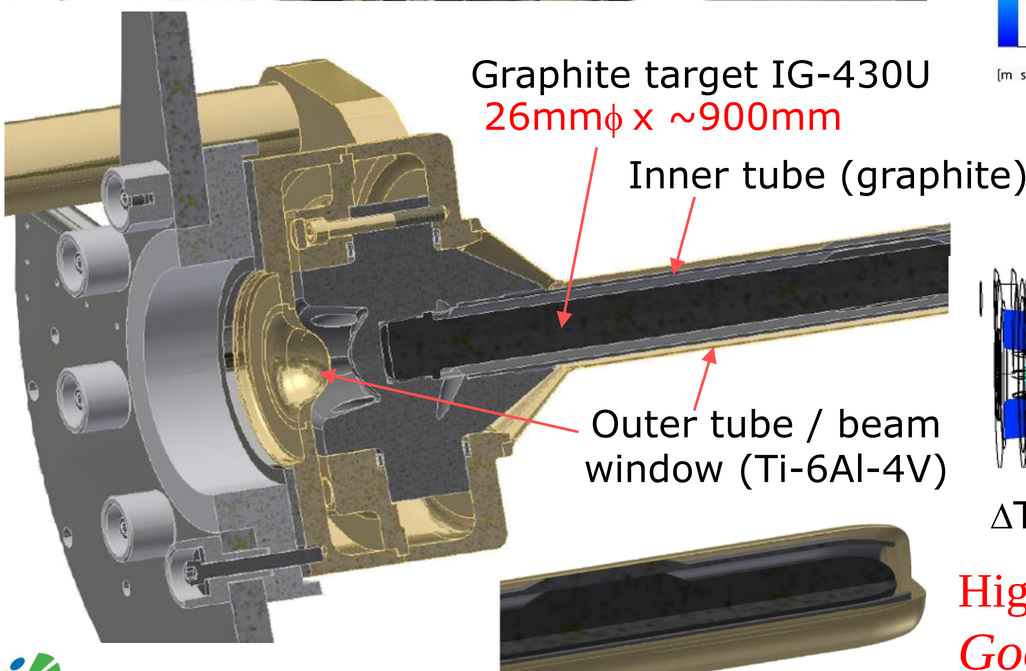
Target



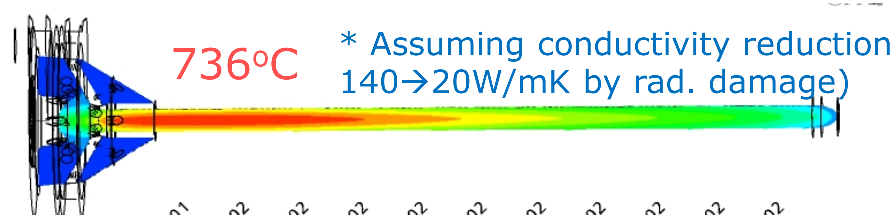
- He-gas cooled isotropic graphite
- Proton beam : 30GeV, 4.2mm sigma
- Design beam power: 750kW
- 3.3×10^{14} ppp - 2.1 sec rep.cycle







Energy deposit 41kJ/spill (19.6kW)

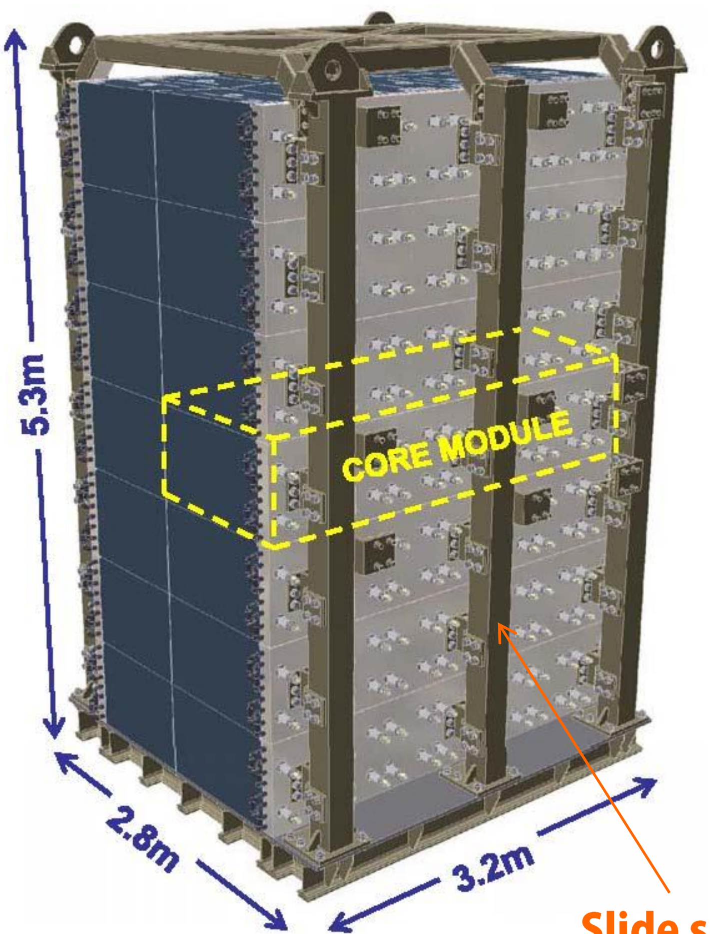


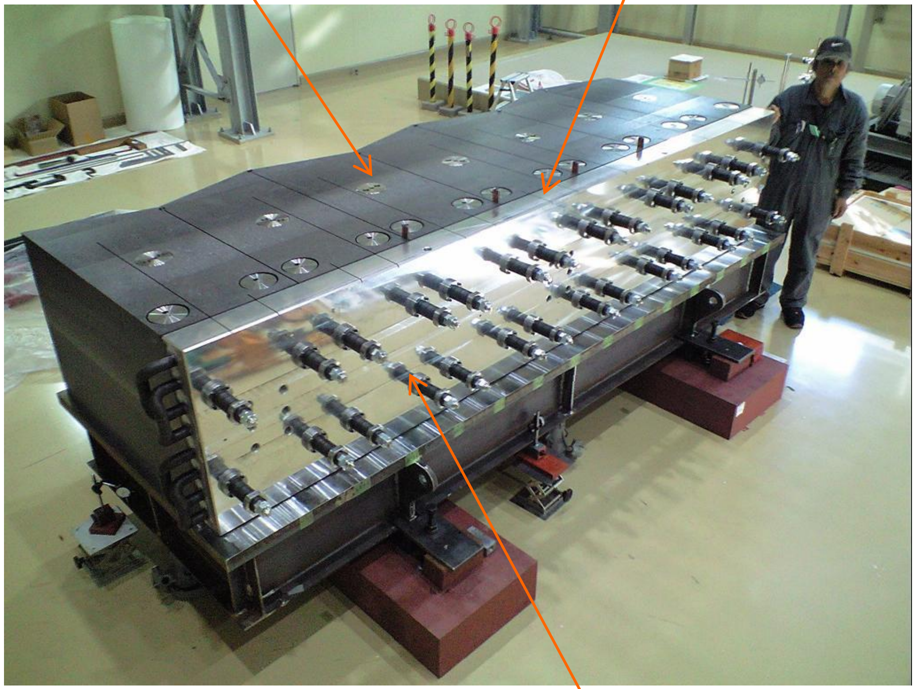
ΔT=200K, 7.2MPa (Tensile strength 37.2MPa)

High Temp:

Good to mitigate radiation damage effect

Hadron Absorber





7 extruded large graphite blocks

Aluminum cast water cooling plate

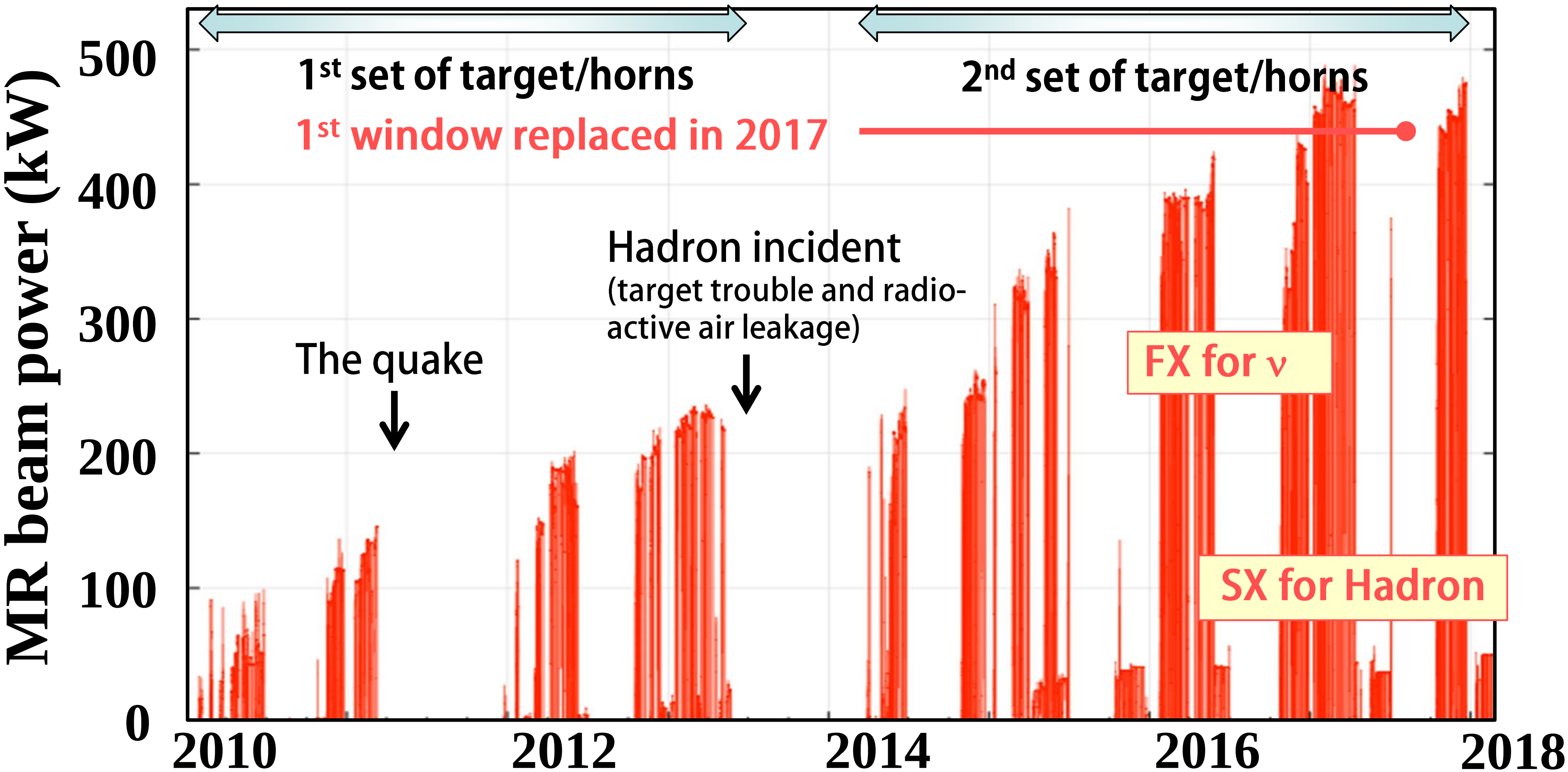
Slide support frame

Fastening with multi disk washers

- Material choice: large extruded graphite blocks +cast aluminum cooling plate, from CNGS design

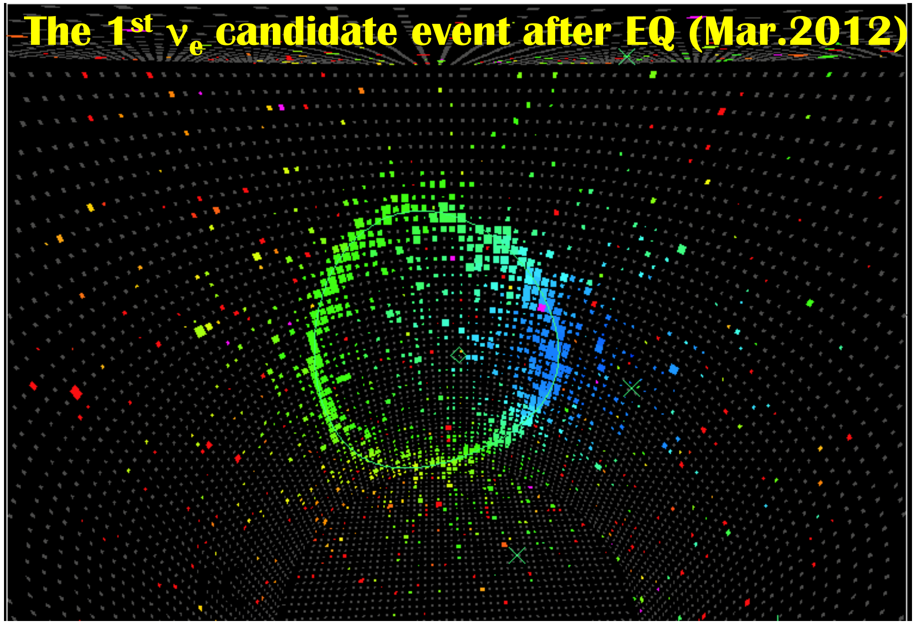
Thanks go to A.Pardons

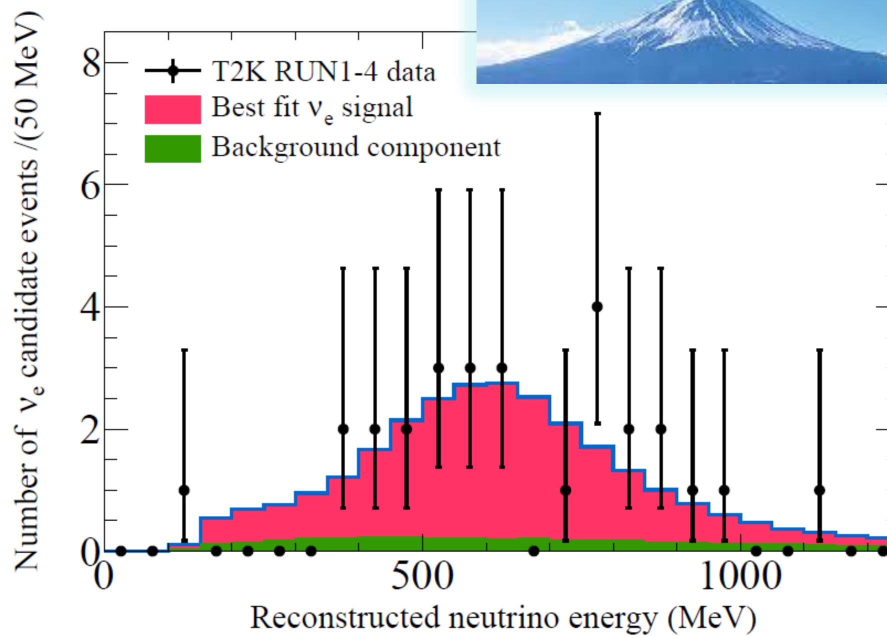
Operational Status of Main Ring



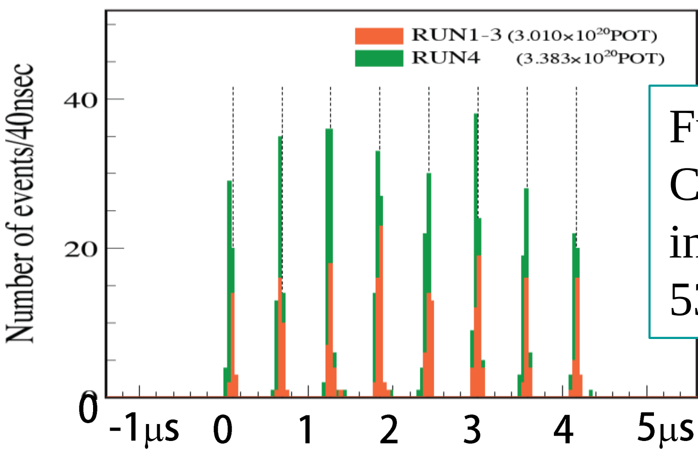
- Max. delivered power: World record of FX'd # of protons from synchrotron
  - Fast eXtraction to Neutrino 485kW (2.5×10^{14}ppp / 2.48s)
  - Slow eXtraction to Hadron 50kW (5.8×10^{13}ppp / 5.52s)

T2K ν_e appearance (Jul.2013)





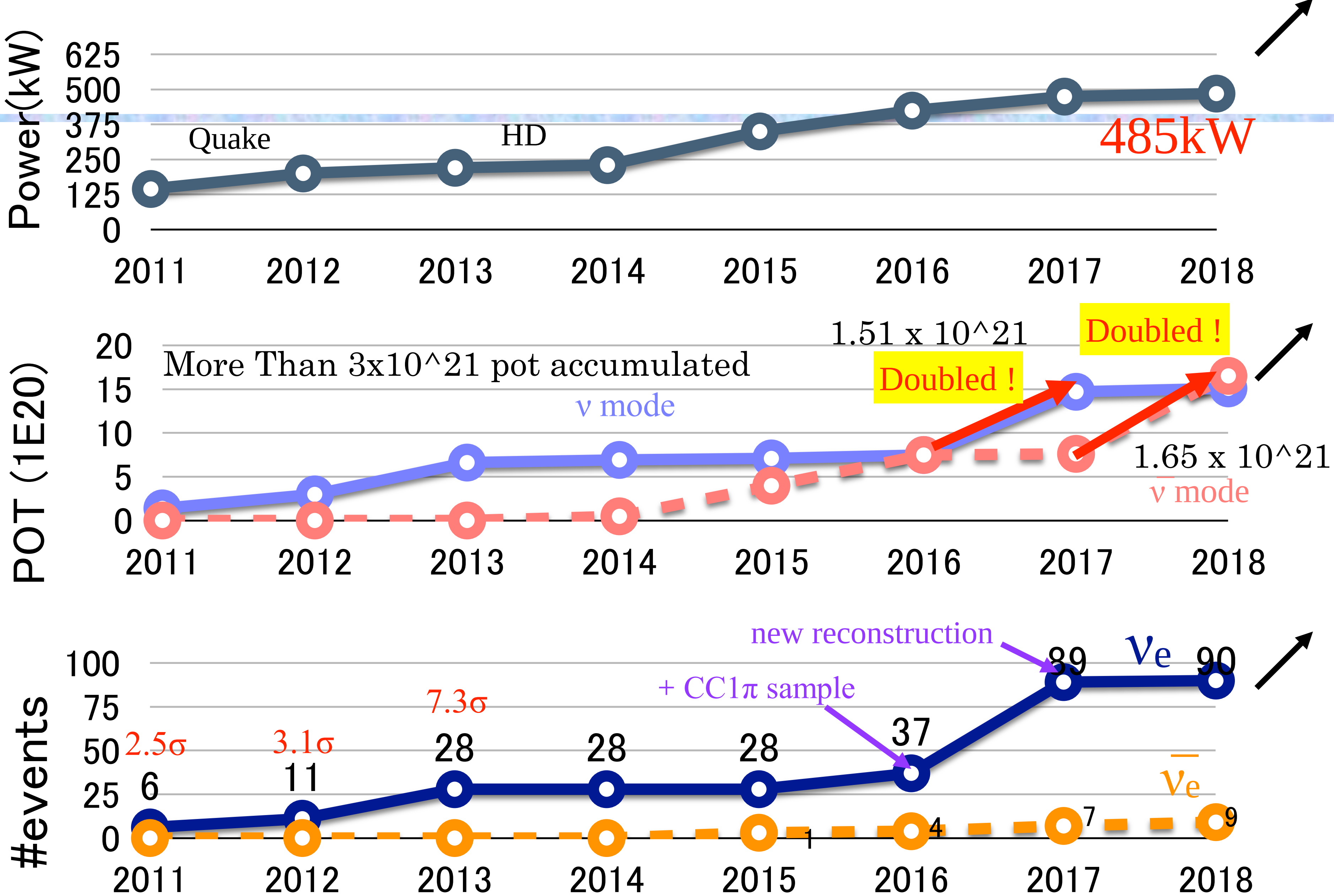
$\Delta T_0 = T_{SK} - T_{J\text{-}PARC} - TOF$



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

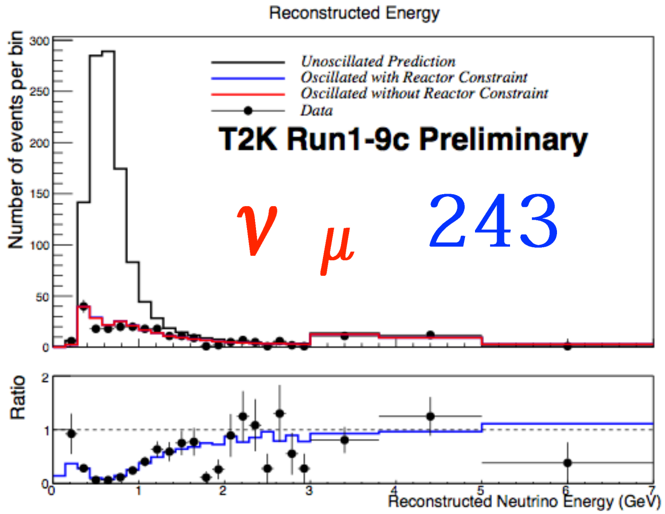
http://jnusrv01.kek.jp/public/t2k/sites/default/files/130719-KEK-seminar.pdf

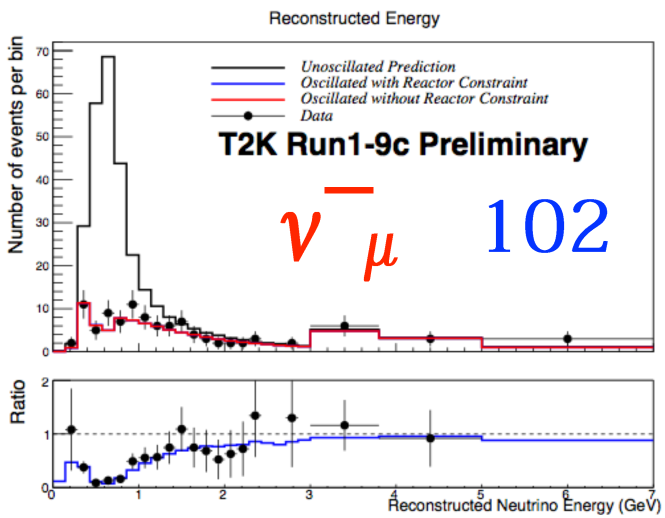


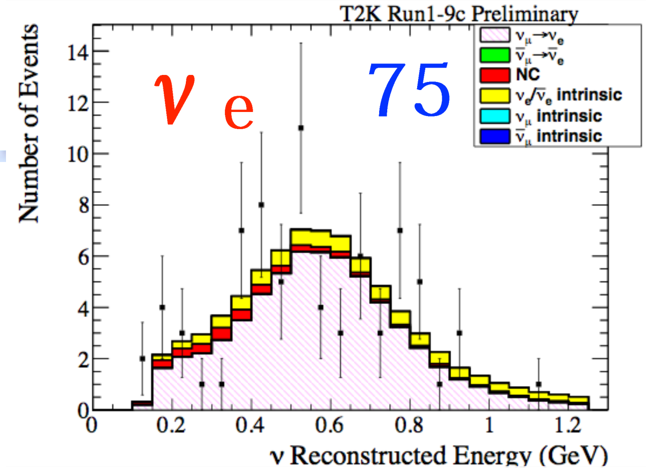
原子炉と合わせて
初のCP制限

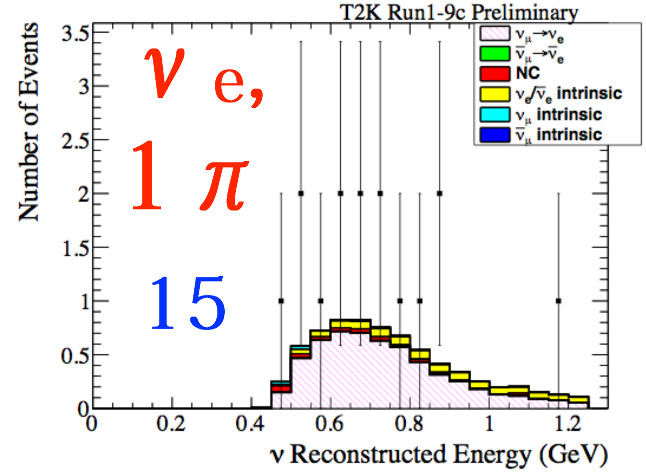
CPV 90%CL CPV 2σ

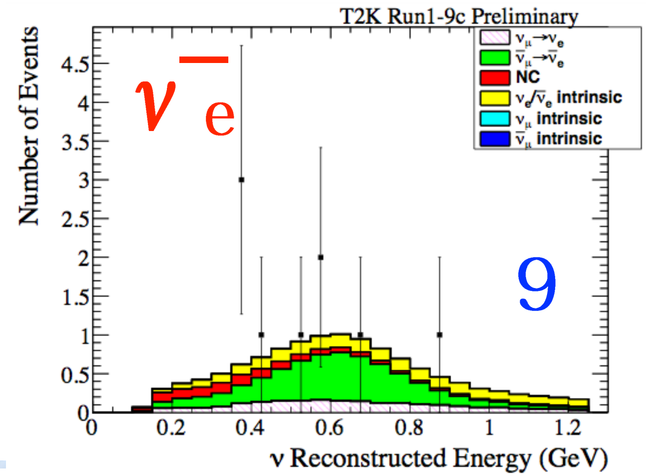
T2K SK events











Analyzed: ν: 1.49×10^{21} POT
$\bar{\nu}$: 1.12×10^{21} POT

Neutrino Conference 2018

T2K $\nu\&\bar{\nu}$ oscillation analyses

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

Oscillation Probability — *Constrained by near detector fit*

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

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
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

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

3. Hyper-Kamiokande Project and Facility Upgrade to > Mega-Watt Beam Power

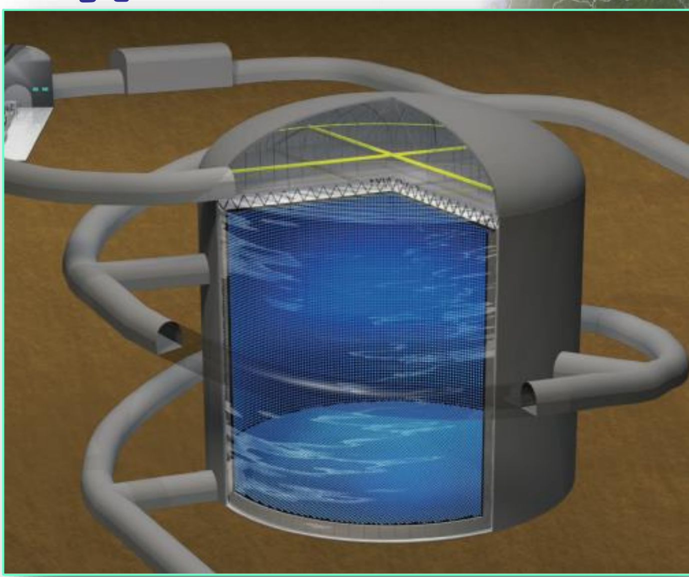
39mϕ x 41mH
Total[Fiducial] Volume
= 50[22.5]kt

750kW upgrade to 1.3 MW

Neutrino Facility at J-PARC

x ~10 of Super-K

Hyper-Kamiokande

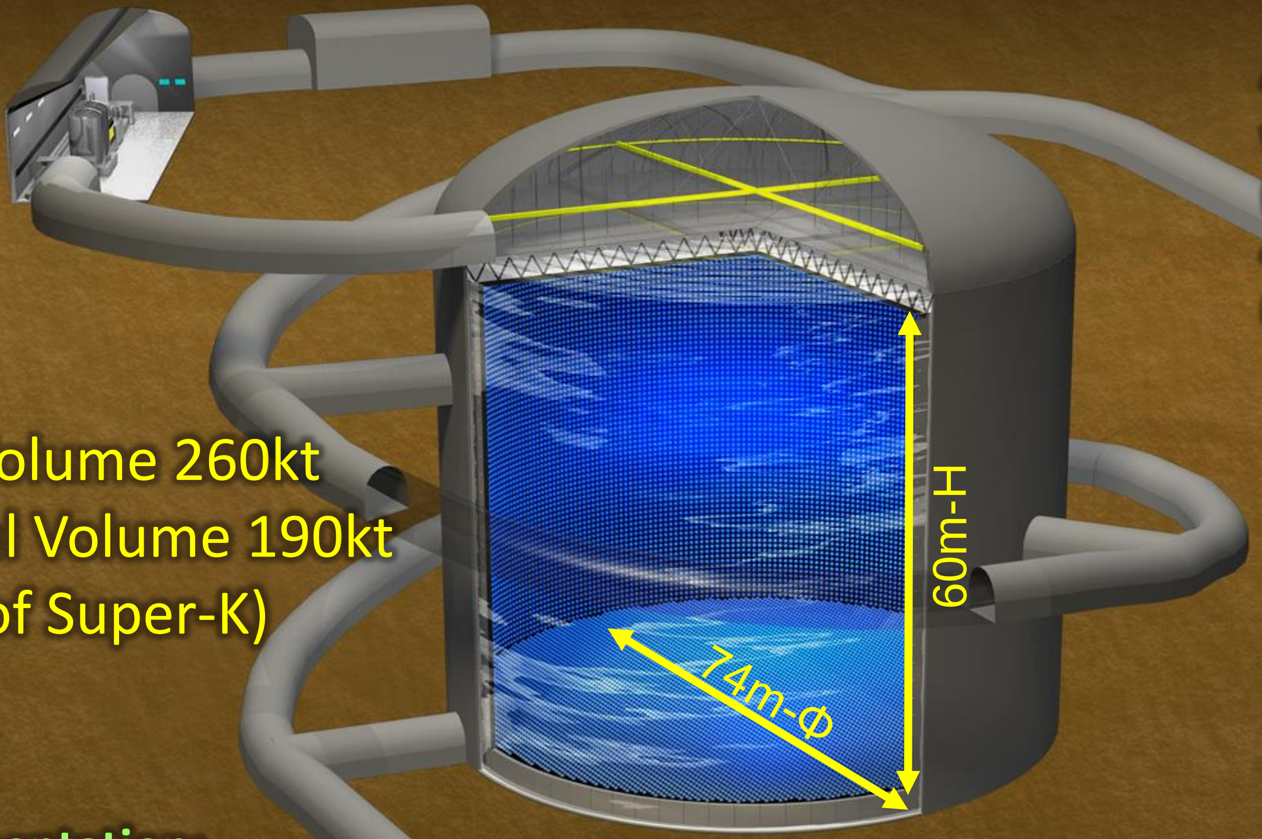


74mϕ x 60mH = 258[187]kt

Exploring CPV in Lepton Sector

Hyper-Kamiokande Detector

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



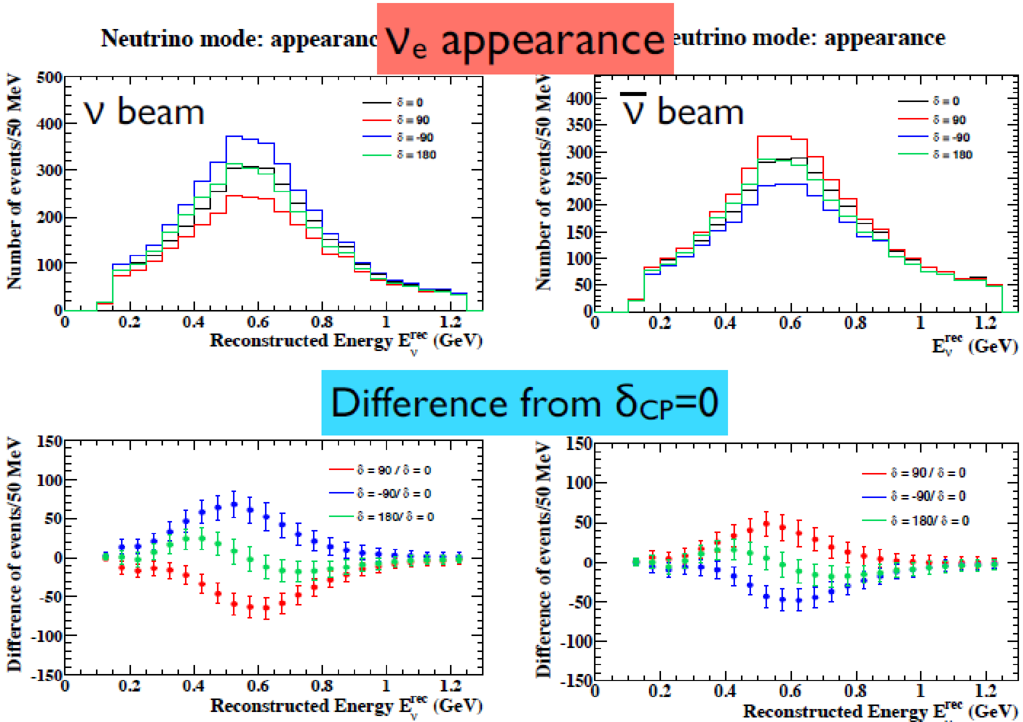
Total Volume 260kt
Fiducial Volume 190kt
(~x10 of Super-K)

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

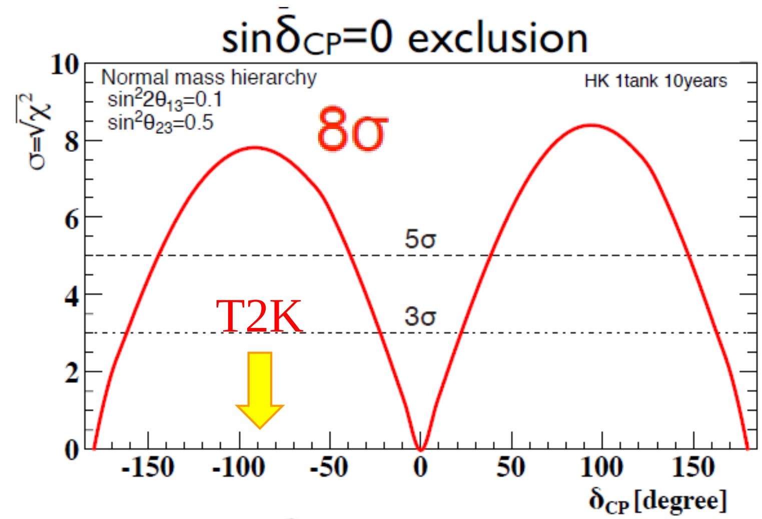
Documentation:
Letter Of Intent https://arxiv.org/abs/1412.4673
HK Design Report https://arxiv.org/abs/1805.04163
Construction: 2019 ~ to start experiment from 2026

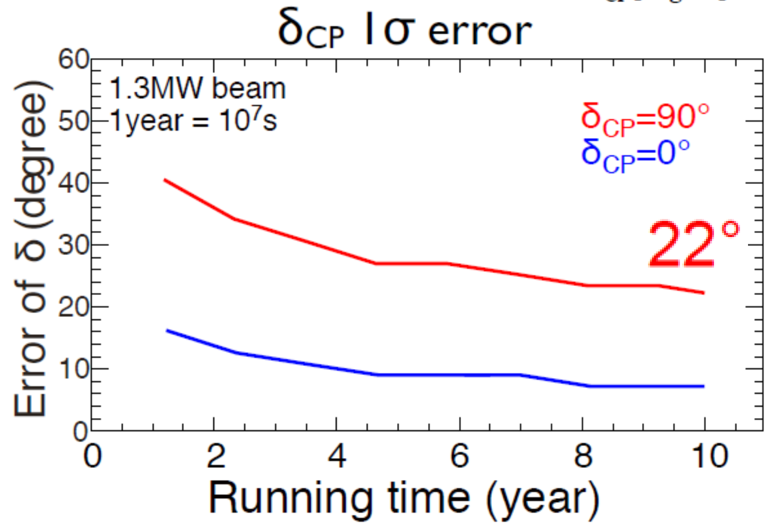
Expected events / CP sensitivity

- 10 years (13MW x 10^7sec)



for δ=0	Signal (νμ→νe CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

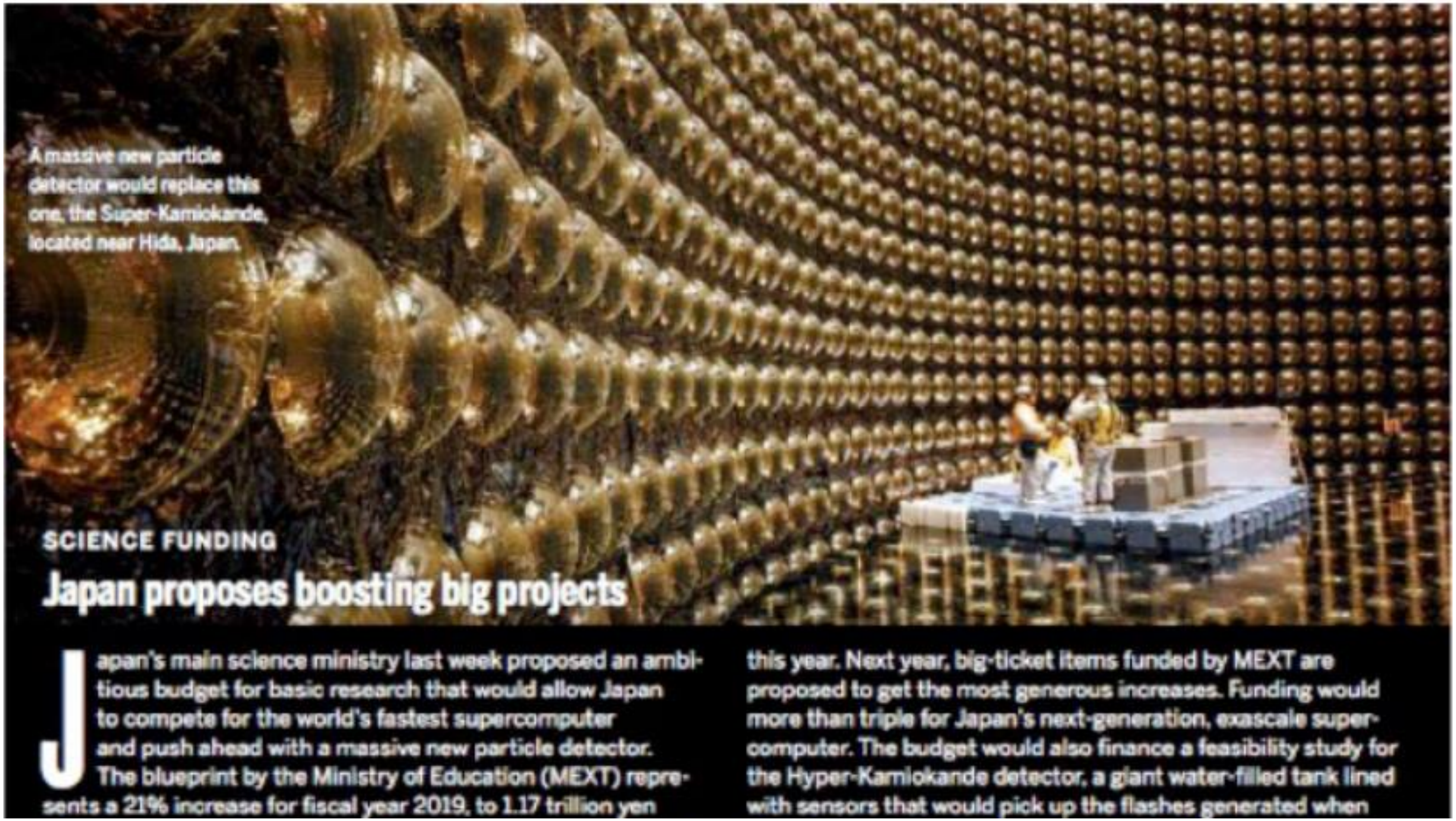




“Japan proposes boosting big projects”

- SCIENCE 7 SEPTEMBER 2018 • VOL 361 ISSUE 6406 pp. 954-955
DOI: 10.1126/science.361.6406.954

“Japan’s main science ministry last week proposed an ambitious budget for basic research that would… push ahead with a massive new particle detector.”



A massive new particle detector would replace this one, the Super-Kamiokande, located near Hida, Japan.

SCIENCE FUNDING

Japan proposes boosting big projects

Japan's main science ministry last week proposed an ambitious budget for basic research that would allow Japan to compete for the world's fastest supercomputer and push ahead with a massive new particle detector. The blueprint by the Ministry of Education (MEXT) represents a 21% increase for fiscal year 2019, to 1.17 trillion yen this year. Next year, big-ticket items funded by MEXT are proposed to get the most generous increases. Funding would more than triple for Japan's next-generation, exascale supercomputer. The budget would also finance a feasibility study for the Hyper-Kamiokande detector, a giant water-filled tank lined with sensors that would pick up the flashes generated when

Decision by Univ. of Tokyo President (Sep.12)

Concerning the Start of Hyper-Kamiokande

2018年9月12日

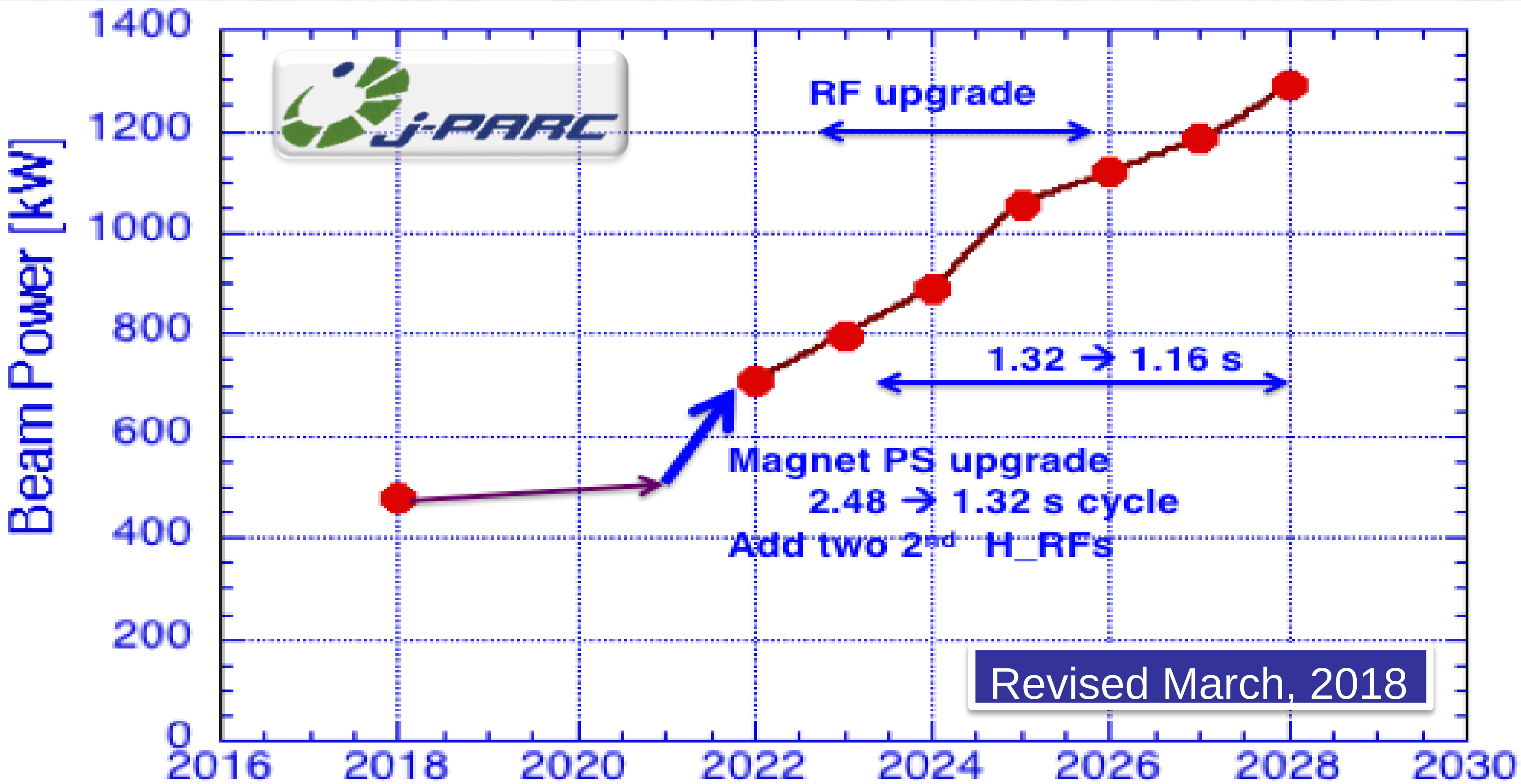
Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

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.

Makoto Gonokami
President, The University of Tokyo

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

J-PARC Main Ring operates beyond 1 MW



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

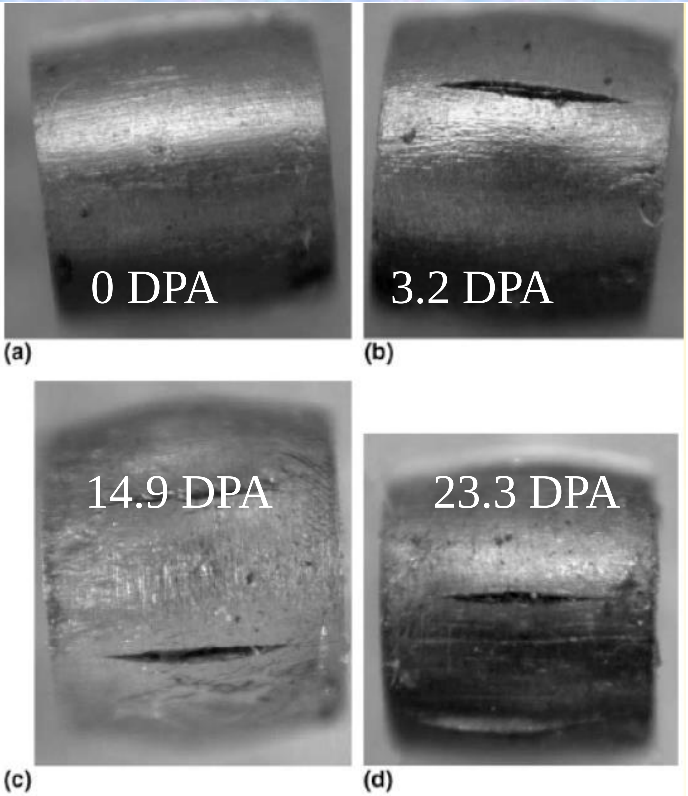
Neutrino Beam-line Upgrade

- Primary beamline
  - Beam monitor upgrade
  - Remote maintenance scheme in FF section
  - Larger aperture magnets and/or upgraded collimators (may be needed)
- 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
- Radiation damage studies / develop radiation-thermal shock tolerant materials for beam intercepting devices (target /beam window…)

Very active collaboration item with CERN

Radiation Damage Effects

- **Displacements in crystal lattice, expressed as Displacements Per Atom (DPA)**
  - Embrittlement / Creep / Swelling
  - Fracture toughness reduction
  - Thermal/electrical conductivity reduction
  - Change of thermal expansion coefficient / modulus of elasticity
  - Fatigue response
  - Accelerated corrosion
  - Void formation/ embrittlement caused by Hydrogen/Helium gas production (expressed as atomic parts per million per DPA, appm/DPA)
- **Recent high-intensity proton target facilities meet irradiation with a few to several DPA**
  - Effects from low energy neutron irradiations (as fusion/fission reactor materials) do not equal effects from high energy proton irradiations

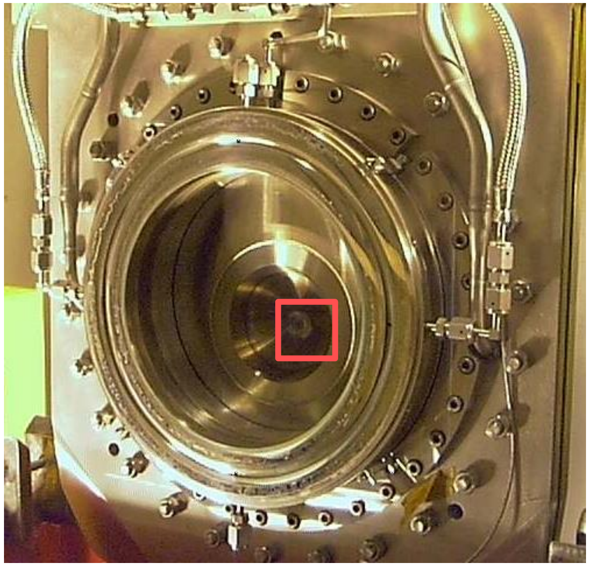


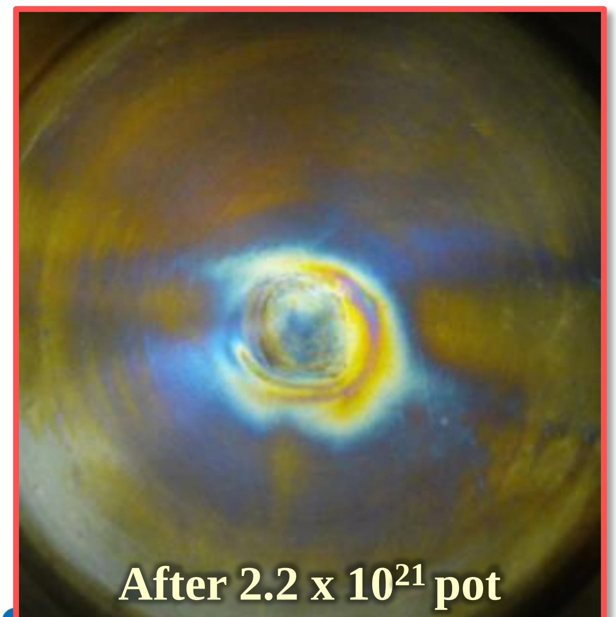
Tungsten, 800MeV proton irradiation at LANSE

after compression to ~20% strain at room temperature

S. A. Maloy, et al., Journal of Nuclear Materials 343 (2005) 219-226.

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 0.1~0.3DPA (*no higher DPA data exists*)
- No known data exists on high cycle fatigue (>10^3 cycles) of irradiated titanium alloys

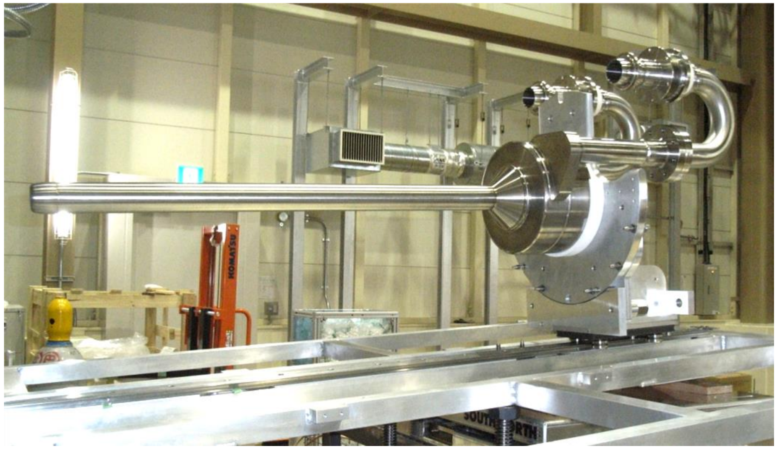
Beam Power	PPP	Rep. cycle	POT / 100 days
485kW (achieved)	2.5×10^{14}	2.48 sec	0.9×10^{21}
750kW (proposed)	2.0×10^{14}	1.3 sec	1.3×10^{21}
750kW [original plan]	3.3×10^{14}	2.1 sec	1.3×10^{21}
1.3 MW (proposed)	3.2×10^{14}	1.16 sec	2.4×10^{21}

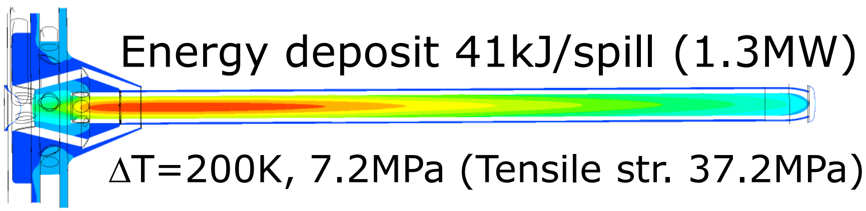
designed

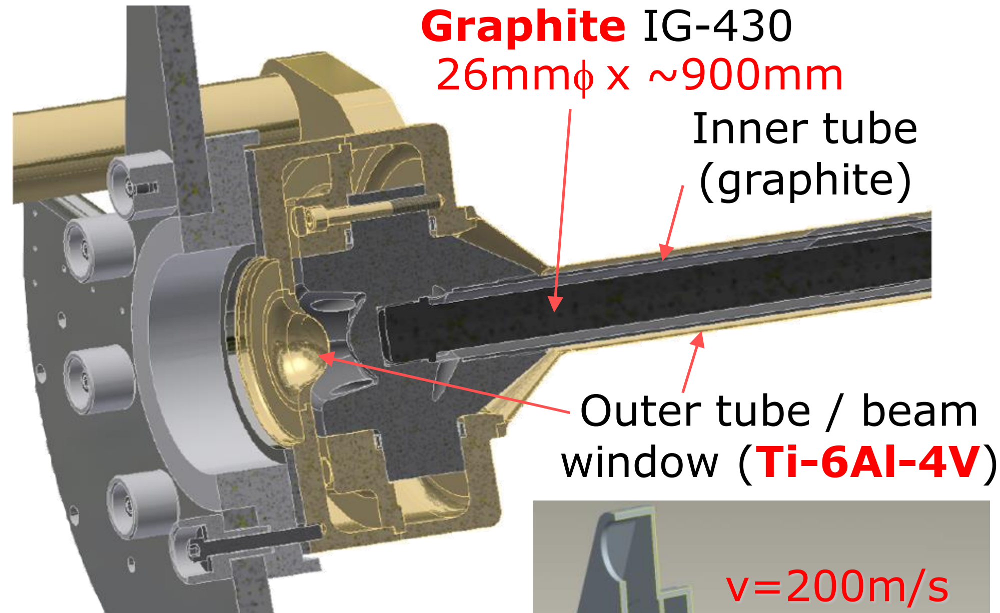
~8M pulses/yr

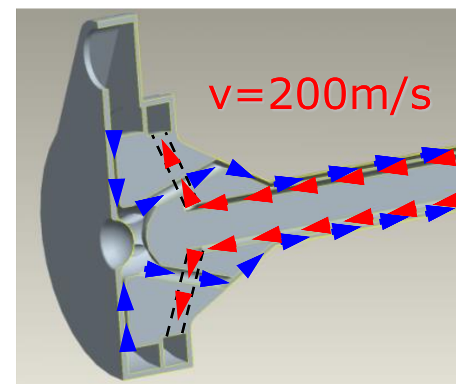
~1DPA/yr

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
- Radiation damage on Ti beam window: under much higher pressure ?

RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

- Founded in 2012 by 5 institutions led by FNAL and STFC to bring together the HEP/BES accelerator target and nuclear fusion/fission materials communities

In 2017, 2nd MoU revision has counted J-PARC (KEK+JAEA) & CERN as official participants
Collaboration has now grown to
13(14) Institutions, 70 members
Program manager: Patrick G.Hurh(FNAL)

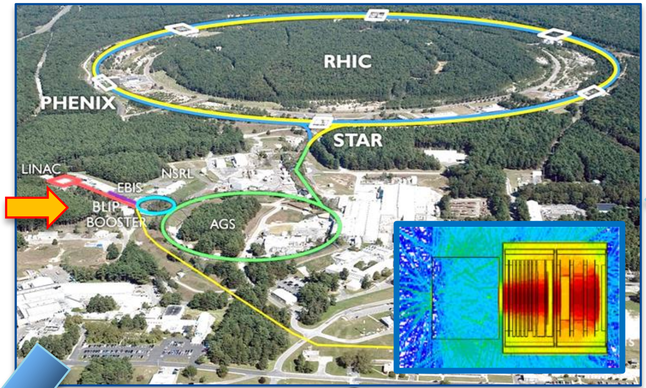
Fermilab, University of Oxford, Argonne National Laboratory, Science & Technology Facilities Council, Brookhaven National Laboratory, Pacific Northwest National Laboratory, Los Alamos National Laboratory EST. 1943, CERN, FRIB, European Spallation Source, Oak Ridge National Laboratory, Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

http://radiate.fnal.gov

RaDIATE Program Overview

High Power Proton Beam Irradiation at BLIP

Brookhaven
Linac
Isotope
Producer

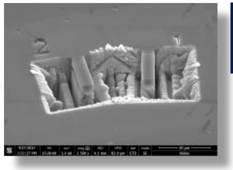


BROOKHAVEN NATIONAL LABORATORY

Specimen Preparation

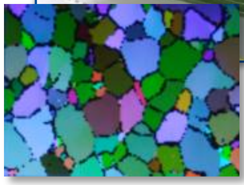
Fermilab
EUROPEAN SPALLATION SOURCE
CERN
FRIB
Science & Technology Facilities Council
UNIVERSITY OF OXFORD

PIE



UNIVERSITY OF OXFORD
(CCFE)

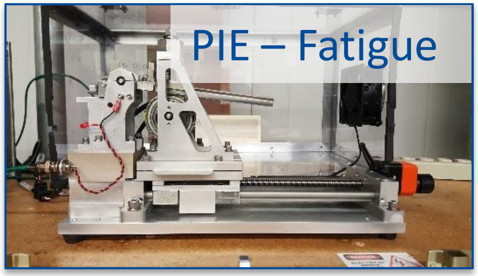
Unloading / PIE



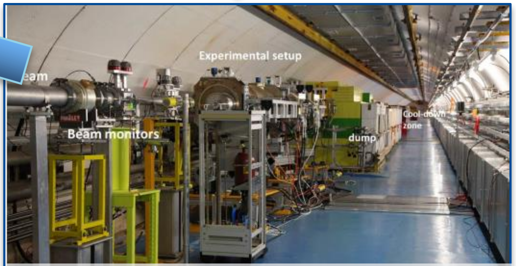
Pacific Northwest NATIONAL LABORATORY

Fermilab

PIE – Fatigue



In-beam Thermal Shock

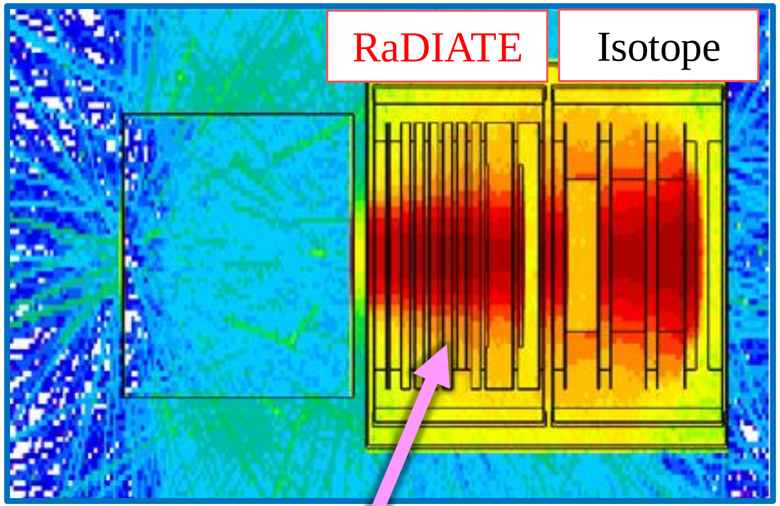


HiRadMat
High-Radiation to Materials
CERN

High Power Proton Irradiation at BLIP

- Brookhaven Linac Isotope Producer (BLIP) facility to produce medical isotope w 116 MeV primary proton beams
- Linac capable to deliver protons up to 200 MeV → operate at higher energies in tandem with RaDIATE material targets upstream
- 1st phase irradiation (2017)
  - 1.76 x 10^{21} POT in 22d@146μA average
- 2nd phase irradiation(Jan-Mar 2018)
  - 2.81 x 10^{21} POT in 33d@158uA average

181MeV rastered beam with 165uA peak current 7×10^{13} p/cm^2·s (3 cm dia. footprint) 8weeks



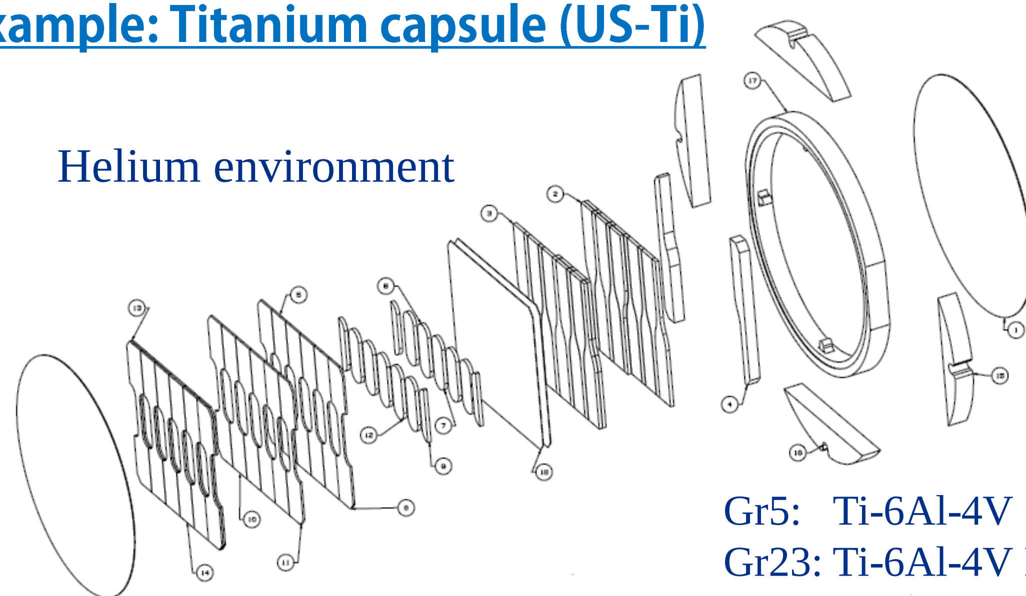
Example: Accumulated Damage on Titanium:
1.5 DPA at peak (MARS-NRT)
Much more than existing data (~0.3DPA)
Close to that for future MW facility op.yr.

Specimens and Capsules Assembly

Over 200 specimens
from 6 RaDIATE institutions

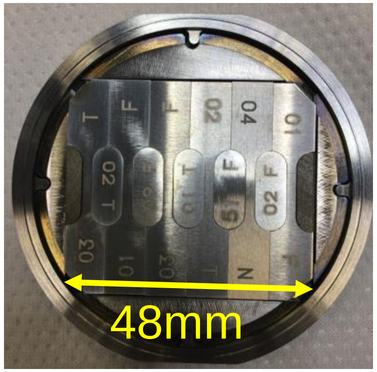
1. Beryllium in Ar [FNAL]
2. Graphite in vacuum
   IG-430 /ZXF-5Q/GC20 [FNAL]
3/8. Silicon in vac.
   Si / Expanded graphite [CERN]
   SiC-Coated Graphite [J-PARC]
4. Aluminum in He [ESS]
5/7/9. Titanium in He
   Several Grades [J-PARC]
   3 microstructures [FRIB]
   Meso-scale fatigue foil [Oxford]
6. Heavy materials in vac.
   TZM, Iridium, CuCrZr [CERN]

Example: Titanium capsule (US-Ti)

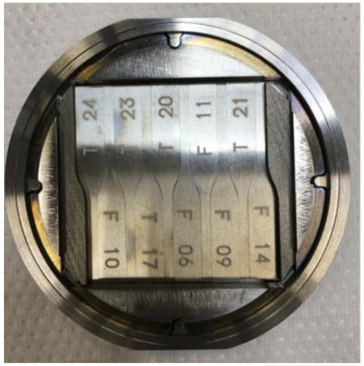


Gr5: Ti-6Al-4V
Gr23: Ti-6Al-4V ELI
Gr9: Ti-3Al-2.5V

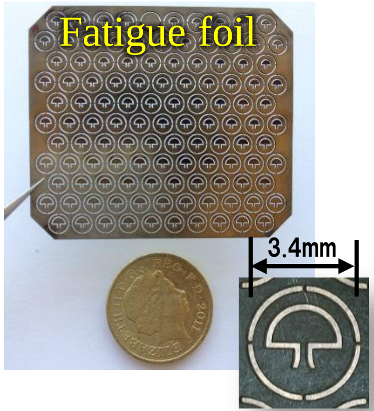
Tensile+Micro



Bend-fatigue



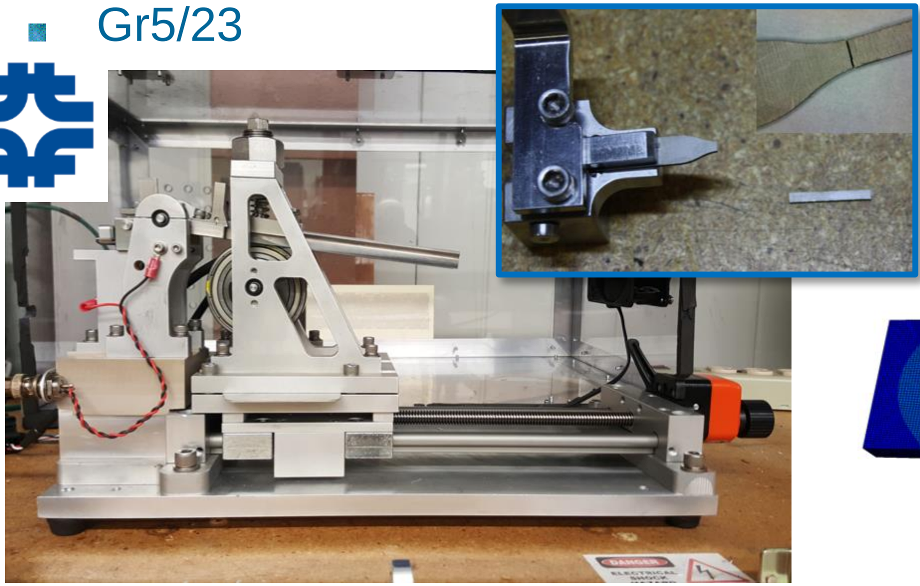
Mesoscale



Fatigue Testing at Fermilab & at UK

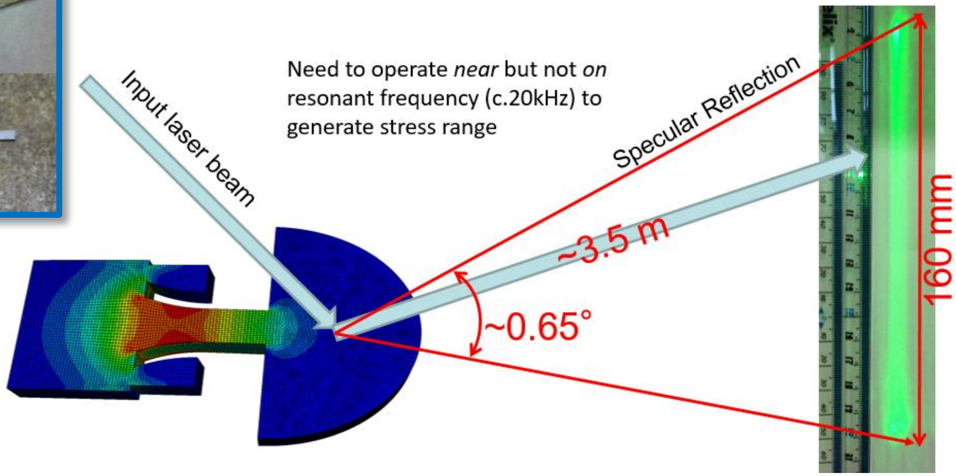
Macro-scale Fatigue Testing

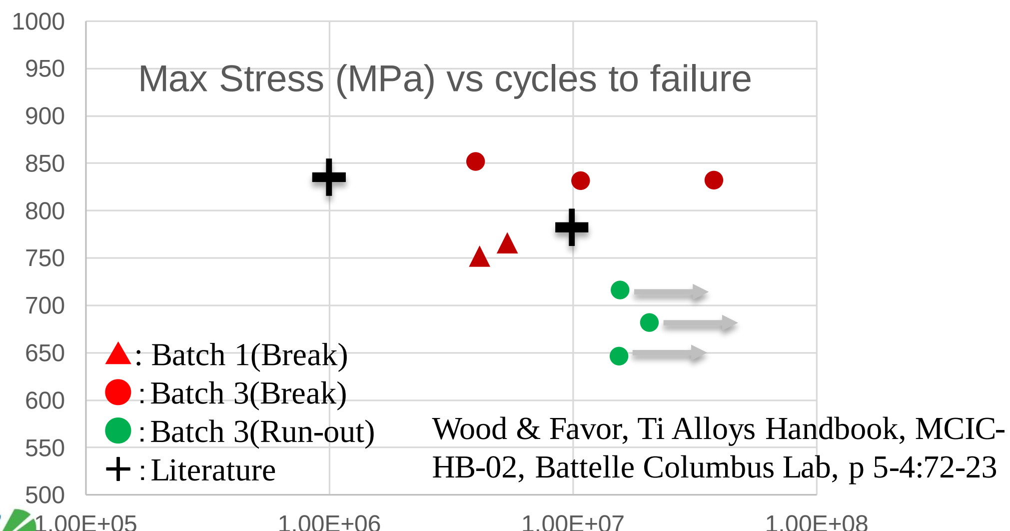
- Gr5/23

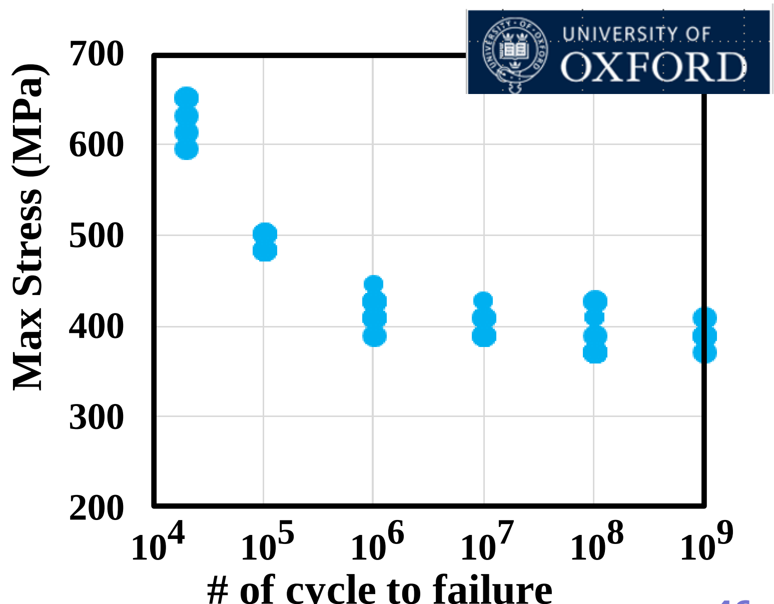


Meso-scale Fatigue Testing

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



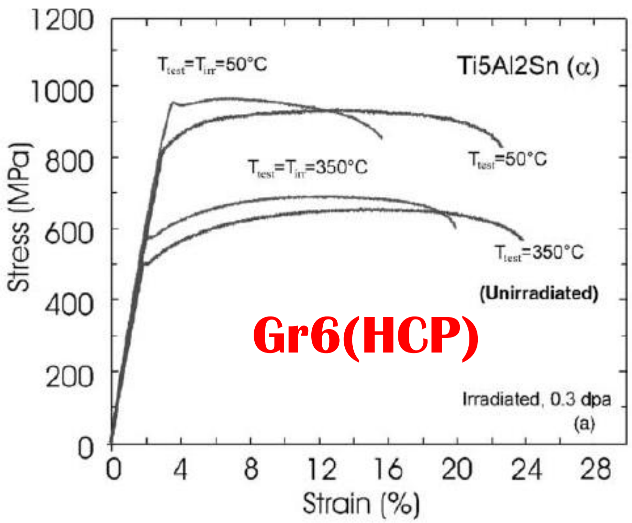




Damage-tolerant Ti-alloy Candidates

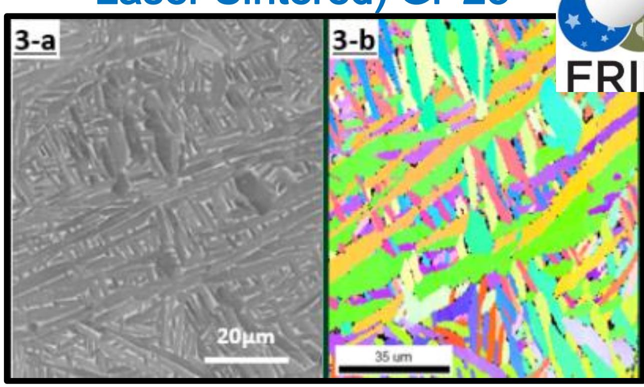
HCP α alloy Gr6

Better ductility (n 0.3DPA)



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

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

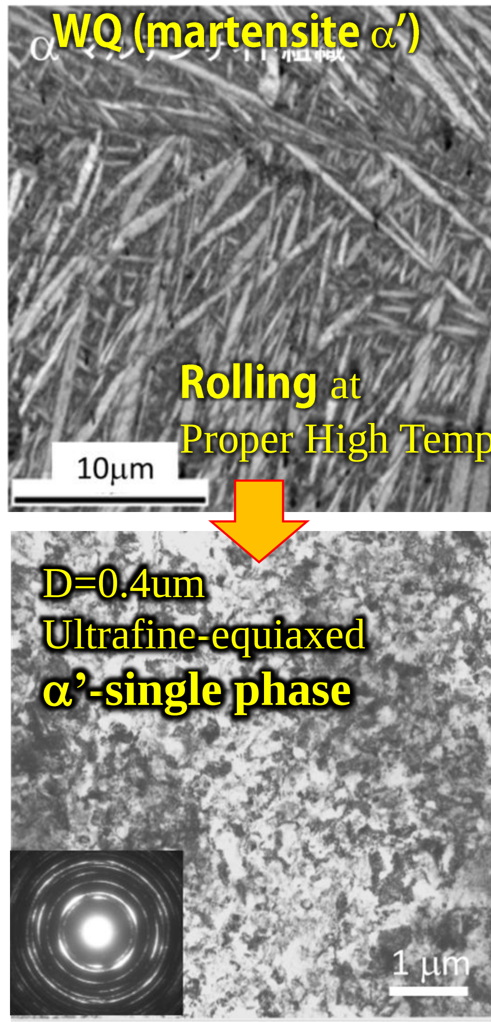


FRIB

F.Pellemoine, NBI2017+RaDIATE

64Ti α'-Ultra FineGrain

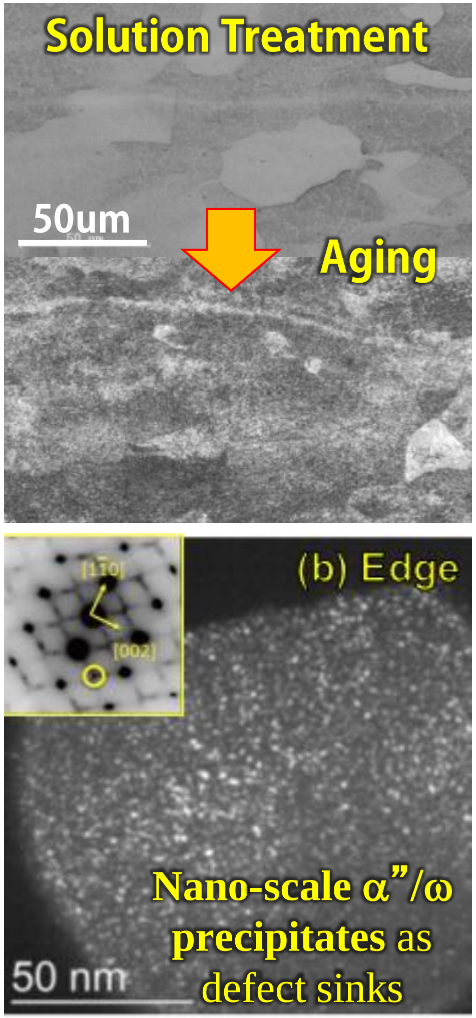
Rich grain boundaries



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

Metastable β 15-3Ti

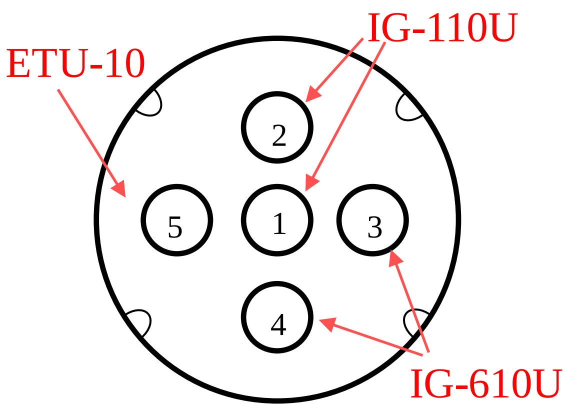
Nanoscale precipitates

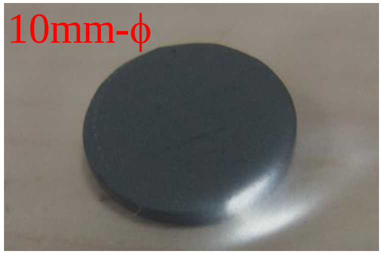


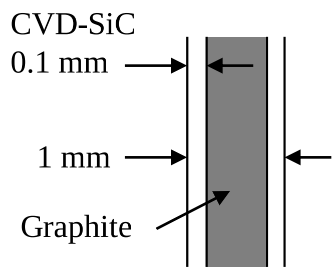
T.Ishida et al, Nucl.Mat En.15(2018)169

SiC-coated Graphite

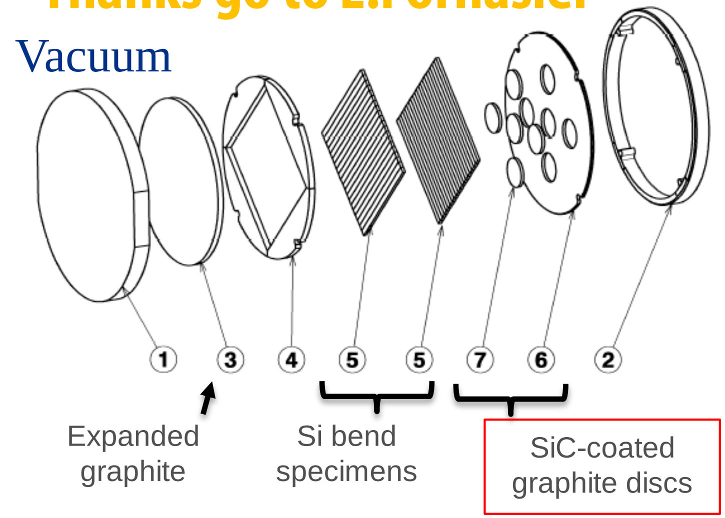
CVD-SiC-coated graphite in Silicon capsule





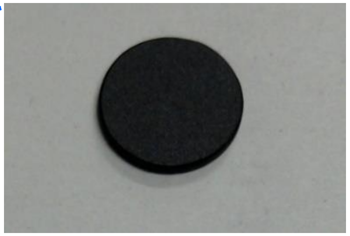


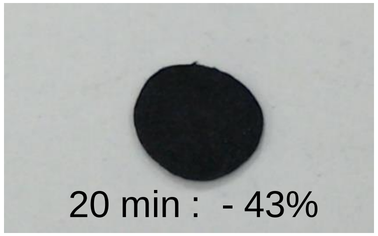
Thanks go to E.Fornasier



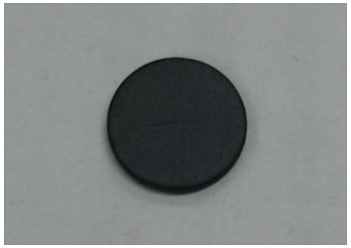
- 800 deg C
- Air 200 cc/min.

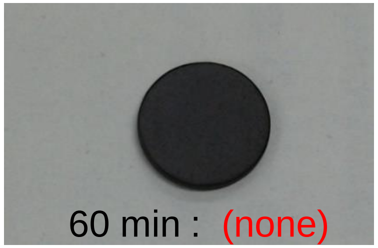
IG-430U

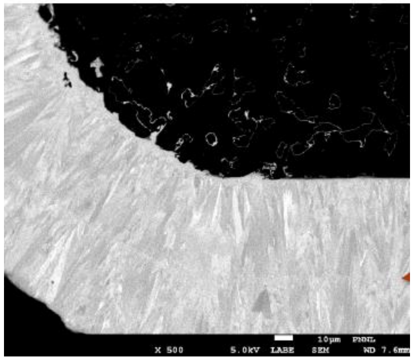




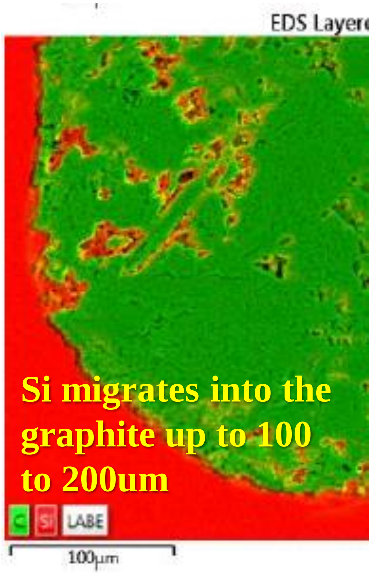
SiC-coated graphite (IG-610U)







Intact coating grain perpendicular to graphite surface



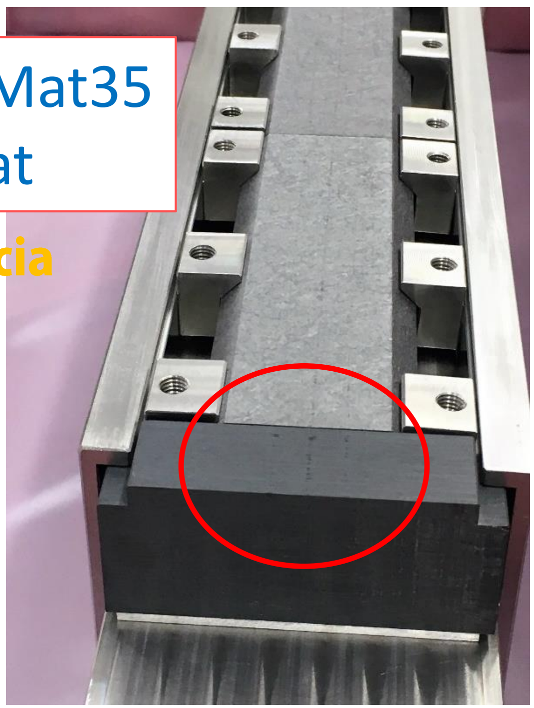
BLIP Irradiated specimen (64Ti/SiC-G) to be studied at HiRadMat

Target Materials to be tested at HiRadMat

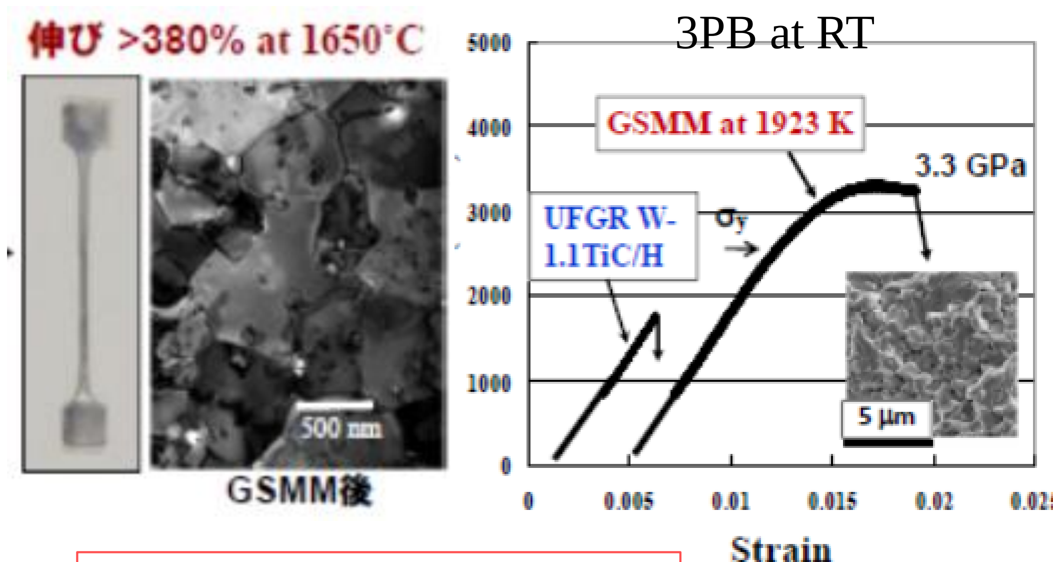
- NITE-SiC/SiC
  - Density 3.2 g/cc (SiC) → more secondary emission than graphite
  - SiC fibers + matrix, control mechanical properties / to replicate ductility

HiRadMat35
TDICoat

I.L. Garcia



- 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

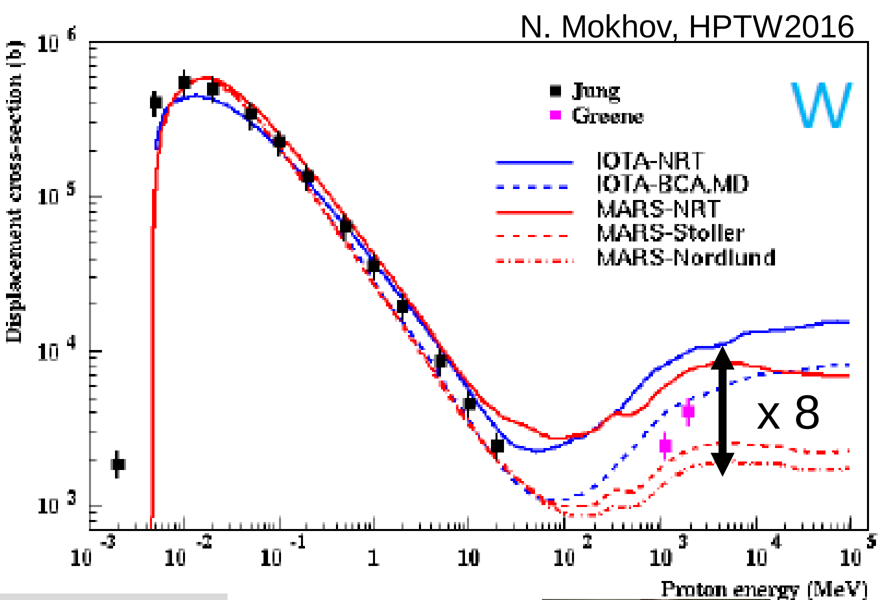


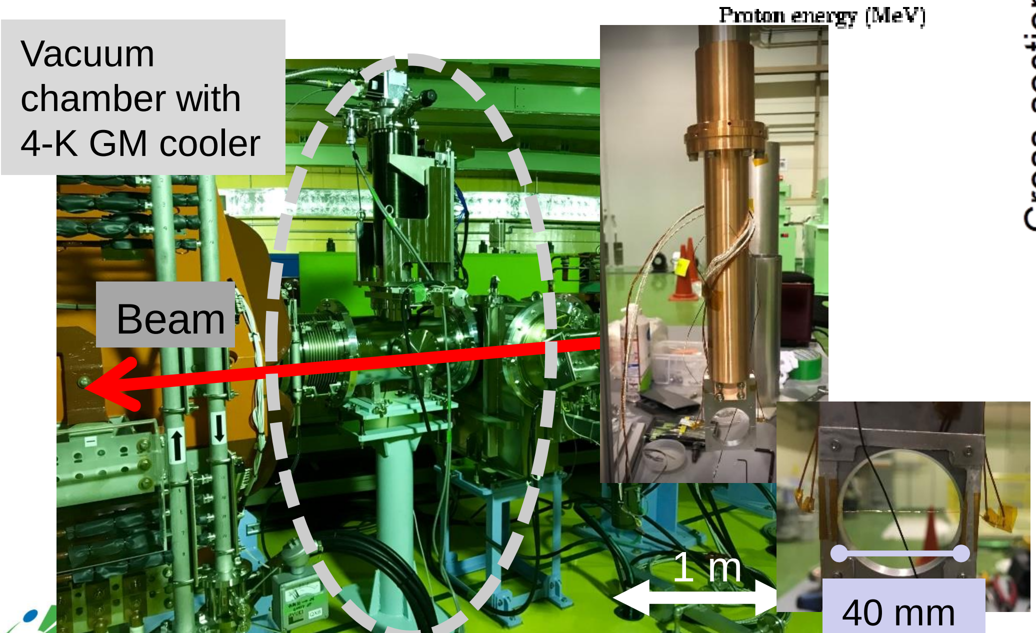
HiRadMat48 PROTAD

C. Torregrosa

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

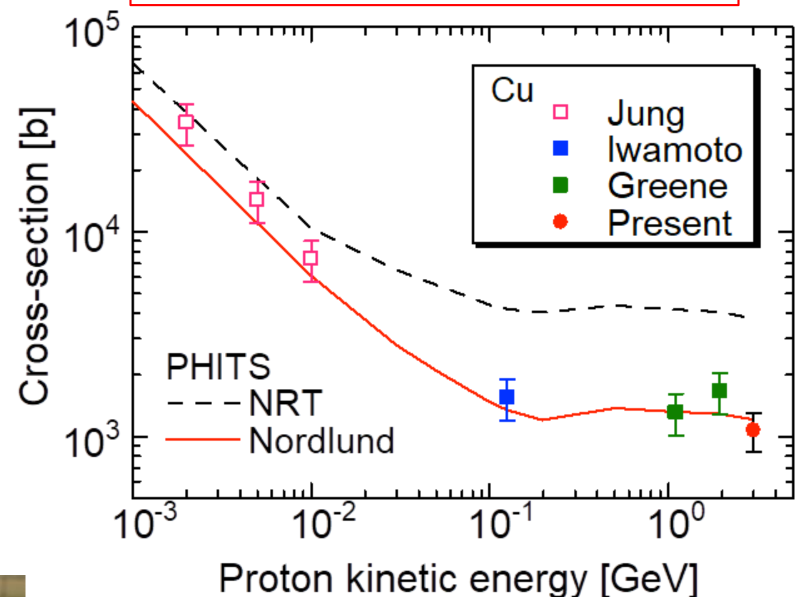
S.Meigo et al., IPAC2018, MOPML045





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

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



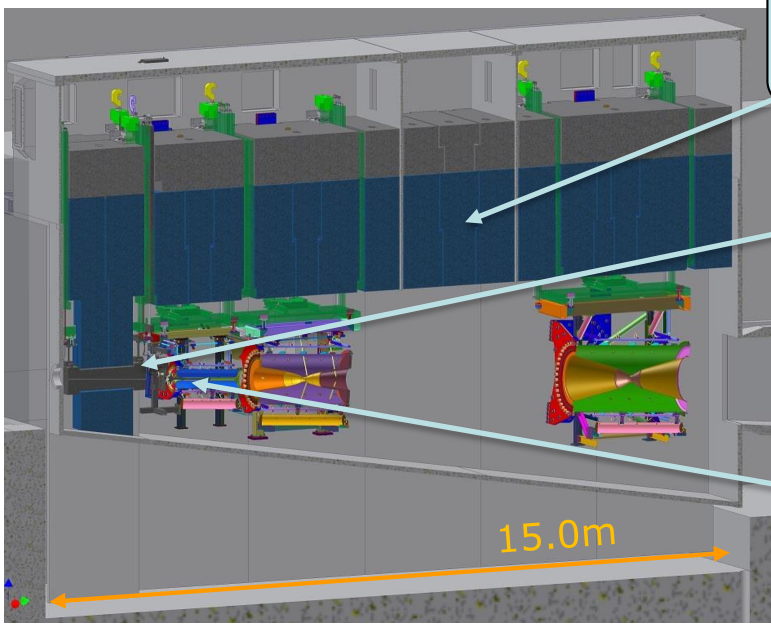
NRT overestimates about 4 times of the present data, while Nordlund model drastically improves.

Collaboration On High-Power Target Facilities

J-PARC Neutrino Facility Target Station

Remote maintenance

CERN Beam Dump Facility Target Station Design

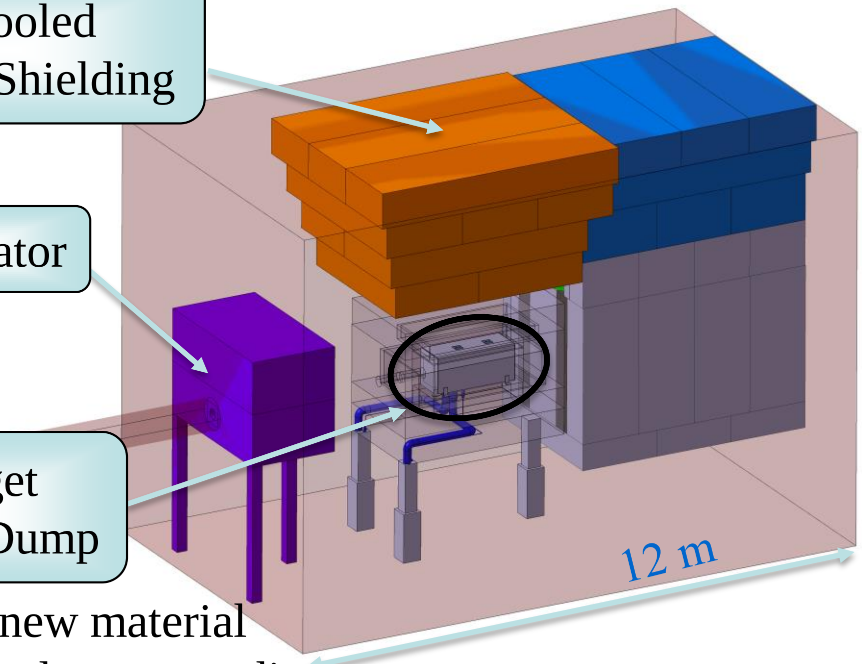


Water-cooled Mobile Shielding

Collimator

Target
Beam Dump

Targety: new material
Radiation damage studies



Helium Vessel Enclosure

Design
Vessel lid, Feedthrough,
He circulation /
purification,….

Radiation Safety Protection

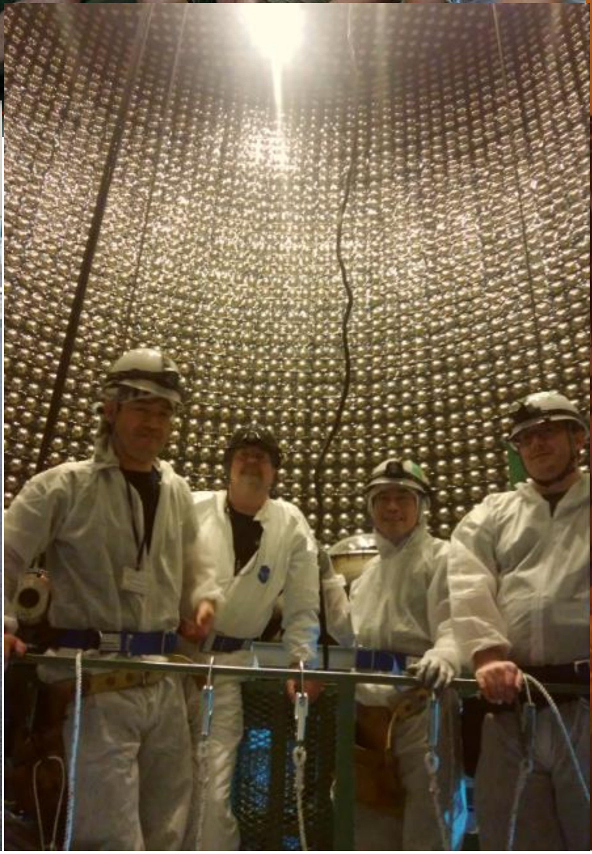
Tritium handling in the cooling water
radioactive air ventilation/exhaust

Collaboration on the items is quite beneficial for both institutions

4. Summary

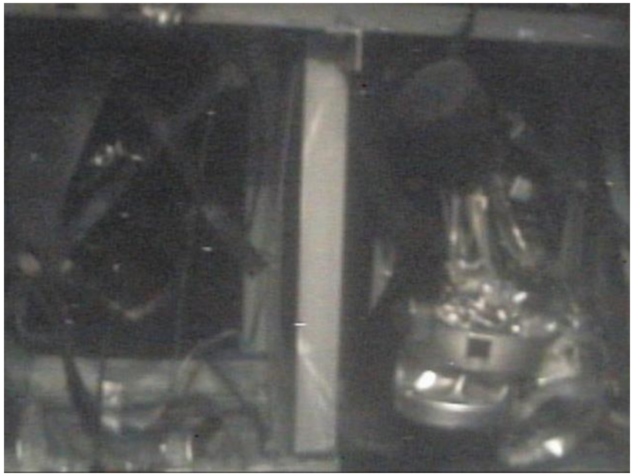
- J-PARC Neutrino Experimental Facility accepts world's most intense fast-extracted proton beam pulse from synchrotron (2.5×10^{14} ppp) for T2K experiment.
- T2K accumulates > 3×10^{21} pot with about even amounts of neutrino and anti-neutrino mode data. The analysis clearly indicates the possibility that the CP symmetry in the lepton sector can be maximally broken.
- (Situation looks quite similar to that atmospheric anomaly was indicated by Kamiokande in 1980-90s.)
- To confirm this, construction of Hyper-Kamiokande and power upgrade of J-PARC are both urgency.
- For HK, seed funding is going to be allocated from JFY2019 by government, and U-Tokyo pledges to start construction from JFY2020 as scheduled.
- The J-PARC power upgrade (Accelerator/Beamline) to ~1.3 MW will synchronize. So far no show-stoppers emerge.
- Radiation Damage / Thermal Shock studies of beam intercepting devices are critical to maximize the benefit of the high power accelerators
- Collaboration between J-PARC and CERN is beneficial for the challenges to be addressed in time, to provide critical input to multi-MW target facility design, construction and operation.

Thank you for your attention

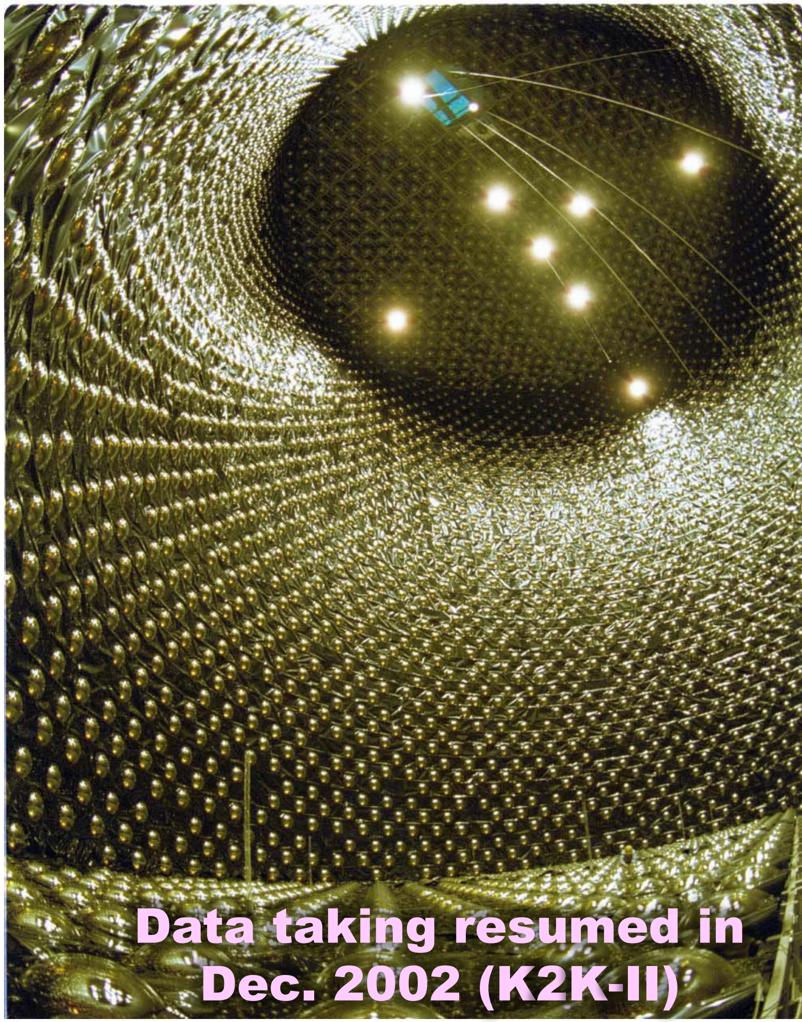


Super-K accident (Nov 2001)

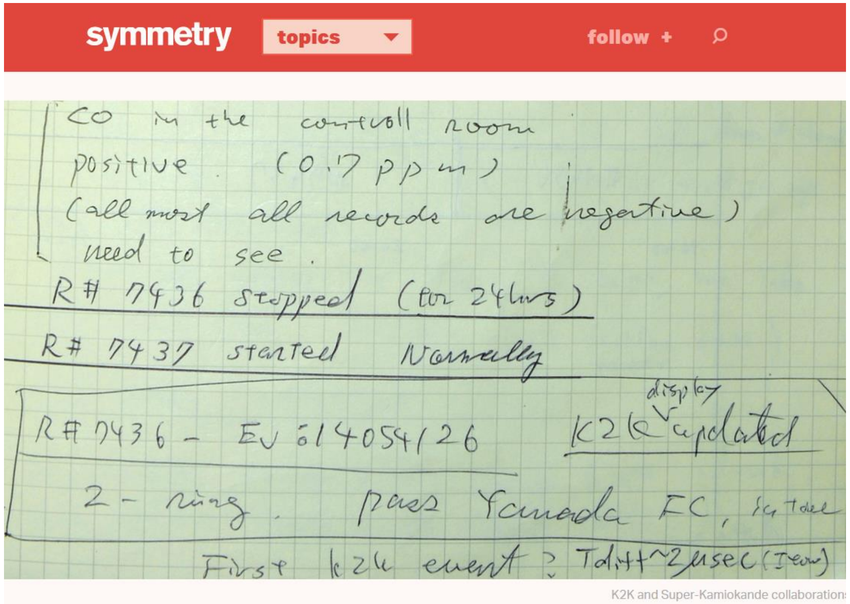
- reduce the number density of the photomultiplier tubes by about a half



Acrylic + FRP vessel cover

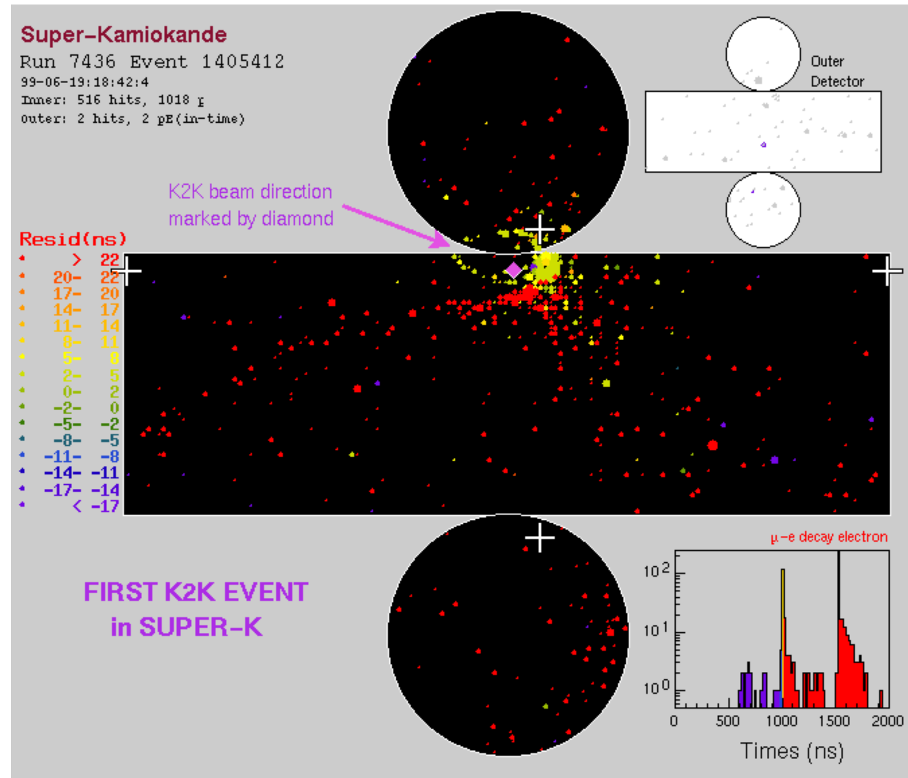


K2Ks First Neutrino Event



http://www.symmetrymagazine.org/article/may-2006/k2ks-first-neutrinos

detector site 250 kilometers from KEK in Tsukuba. Taku Ishida and Todd Haines were sitting in the control room of Super-K on the evening of Saturday, June 19, 1999. Taku saw a particle event displayed after it registered in the detector, and he entered his observations in the logbook. The event was also circulated with an automatic email alert,



T2K Proposal (2001)

Cornell University Library

arXiv.org > hep-ex > arXiv:hep-ex/0106019

Search or Article-id

High Energy Physics - Experiment

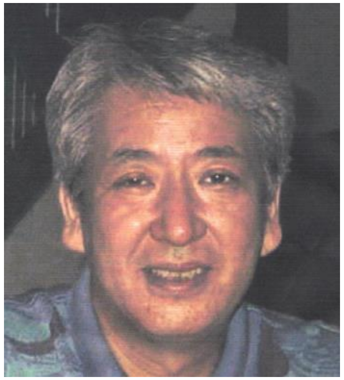
The JHF-Kamioka neutrino project

Y.Itow, T.Kajita, K.Kaneyuki, M.Shiozawa, Y.Totsuka, Y.Hayato, T.Ishida, T.Ishii, T.Kobayashi, T.Maruyama, K.Nakamura, Y.Obayashi, Y.Oyama, M.Sakuda, M.Yoshida, S.Aoki, T.Hara, A.Suzuki, A.Ichikawa, T.Nakaya, K.Nishikawa, T.Hasegawa, K.Ishihara, A.Suzuki, A.Konaka

(Submitted on 5 Jun 2001)

The JHF-Kamioka neutrino project is a second generation long base line neutrino oscillation experiment that probes physics beyond the Standard Model by high precision measurements of the neutrino masses and mixing. A high intensity narrow band neutrino beam is produced by secondary pions created by a high intensity proton synchrotron at JHF (JAERI). The neutrino energy is tuned to the oscillation maximum at ~1 GeV for a baseline length of 295 km towards the world largest water Cerenkov detector, Super-Kamiokande. Its excellent energy resolution and particle identification enable the reconstruction of the initial neutrino energy, which is compared with the narrow band neutrino energy, through the quasi-elastic interaction. The physics goal of the first phase

Y.Totsuka



K.Nishikawa

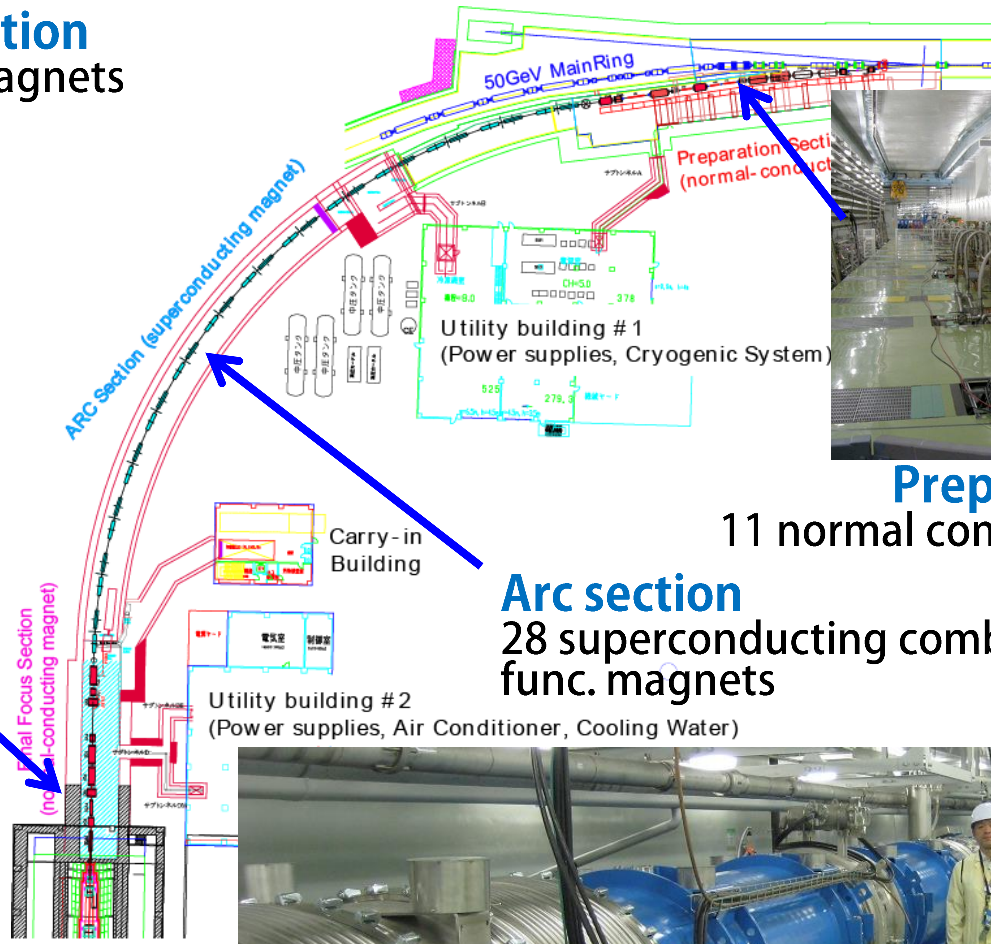
- "CPV by J-PARC upgrade and 1Mt detector"

http://arxiv.org/abs/hep-ex/0106019

$\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events. In the second phase, an upgrade of the accelerator from 0.75 MW to 4 MW in beam power and the construction of 1 Mt Hyper-Kamiokande detector at Kamioka site are envisaged. Another order of magnitude improvement in the $\nu_\mu \to \nu_e$ oscillation sensitivity, a sensitive search of the CP violation in the lepton sector (CP phase δ down to $10^\circ - 20^\circ$), and an order of magnitude improvement in the proton decay sensitivity is also expected.

Primary beam-line

Final focusing (FF) section
10 normal conducting magnets



Preparation section
11 normal conducting magnets

Arc section
28 superconducting combined func. magnets

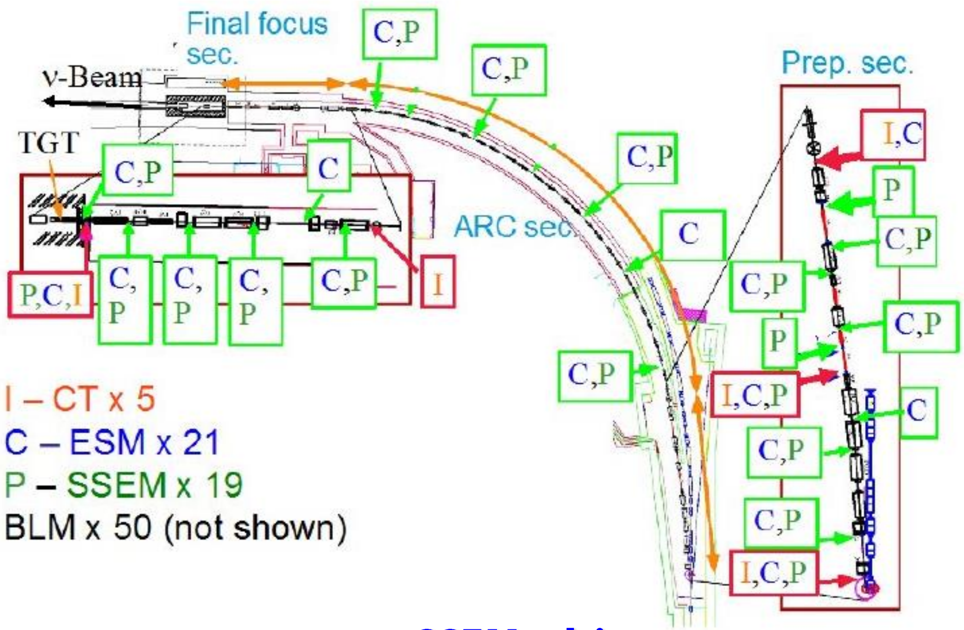
- Beam orbit and beam loss should be firmly controlled anytime.

Beam monitors

- Intensity: Current Transformer (CT)
- Center: Electro-Static Monitor (ESM)
- Profile: Segmented Secondary Emission Monitor (SSEM)
- Beam Loss: Ionization chambers
- Readout by COPPER/UW-FADC

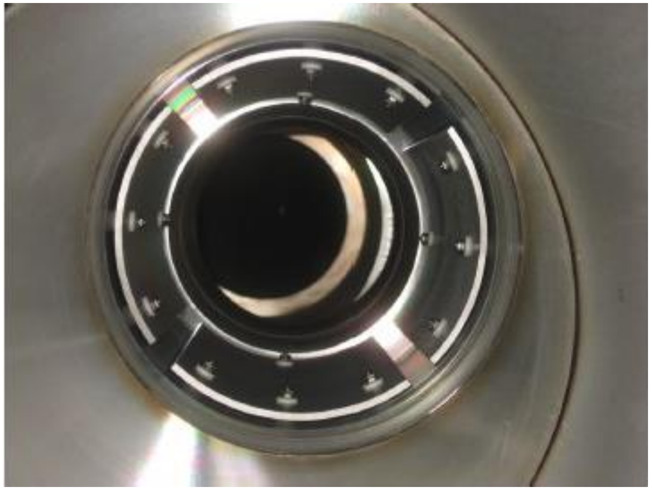
- Monitor stack (C,P) at upstream of TS
- An OTR upstream of target

Need to control beam on target within 1mm precision



CT

ESM

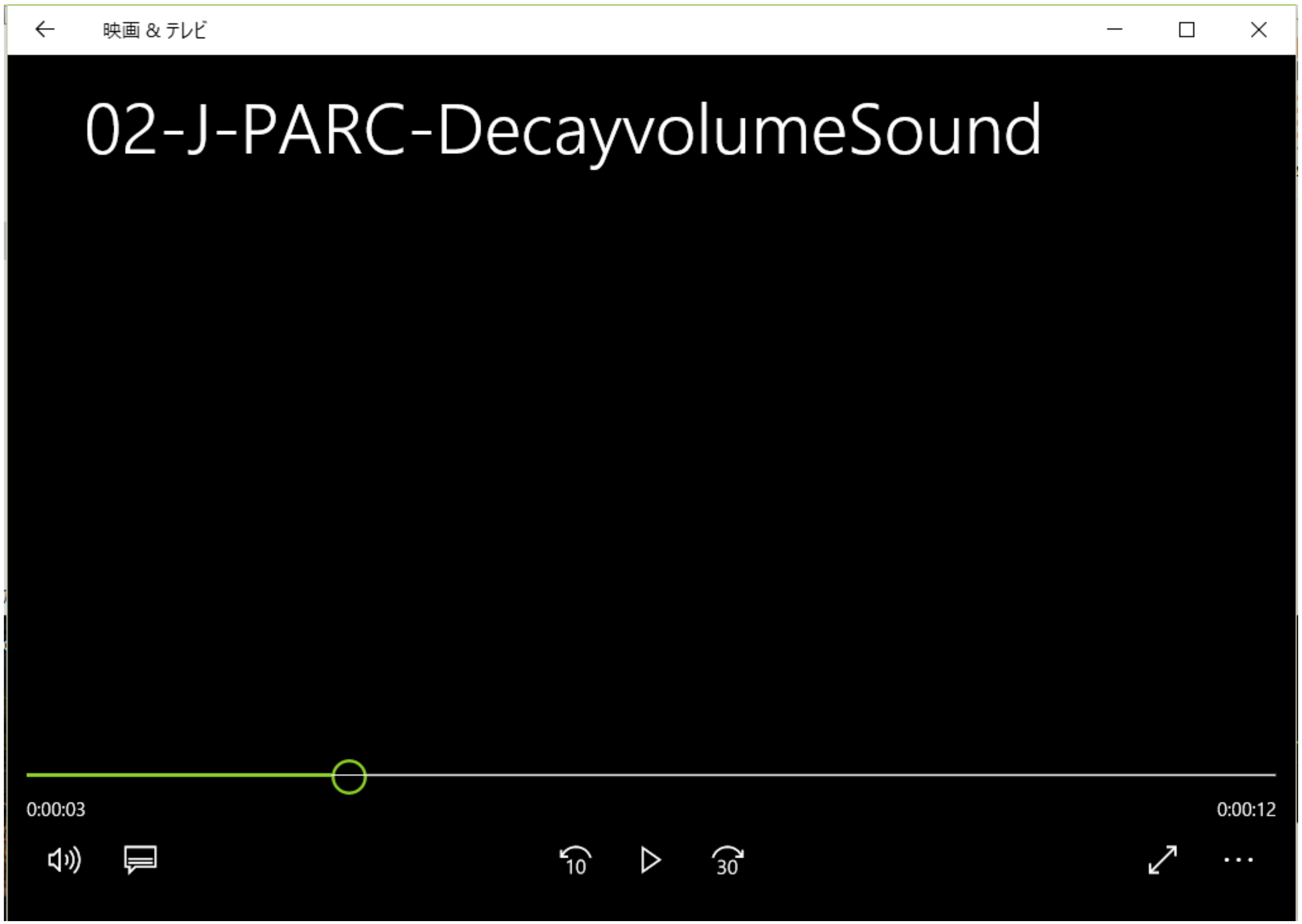


SSEM+driver

Horn in Operation

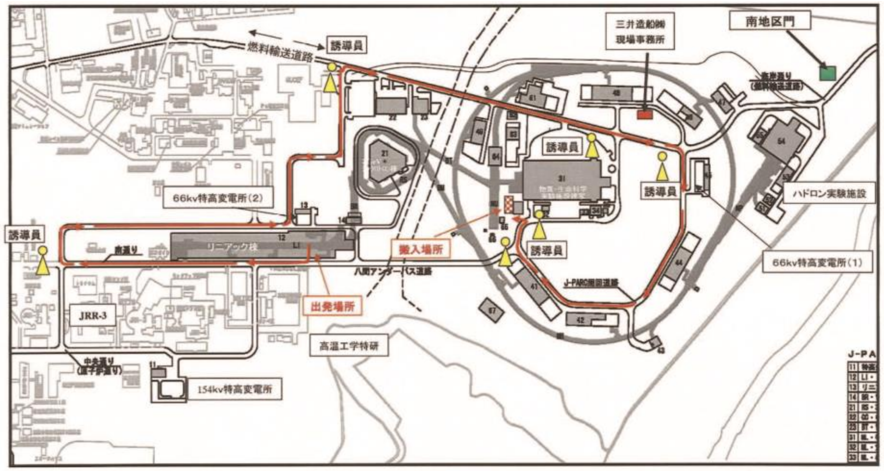
https://www.facebook.com/ishi.tataku/videos/535783663209113/

Decay Volume...



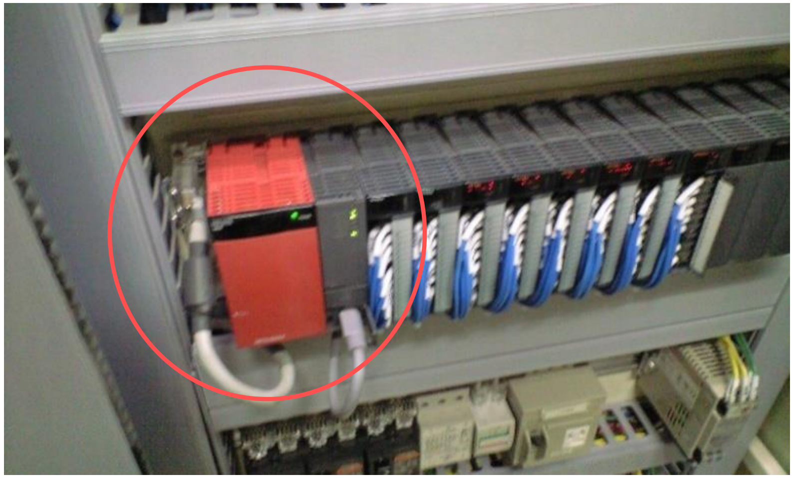
https://www.facebook.com/ishi.tataku/videos/948369681950507/

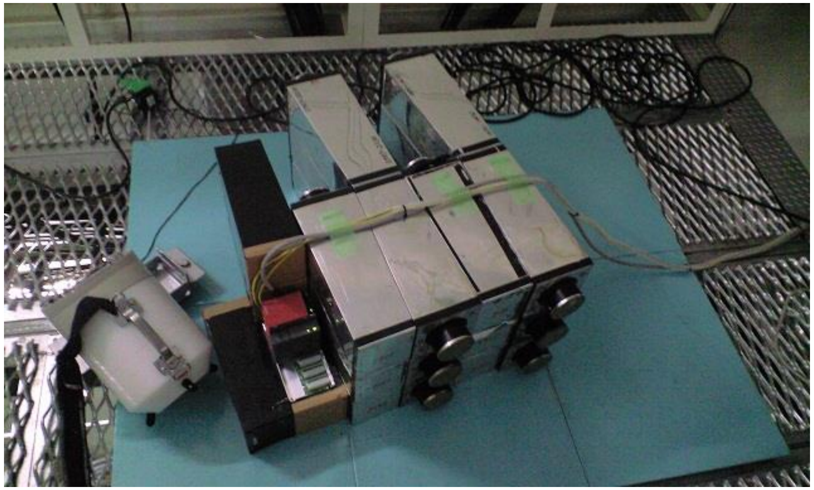
Oct.18, 2008



http://www.youtube.com/watch?v=XKwISDTMbRQ

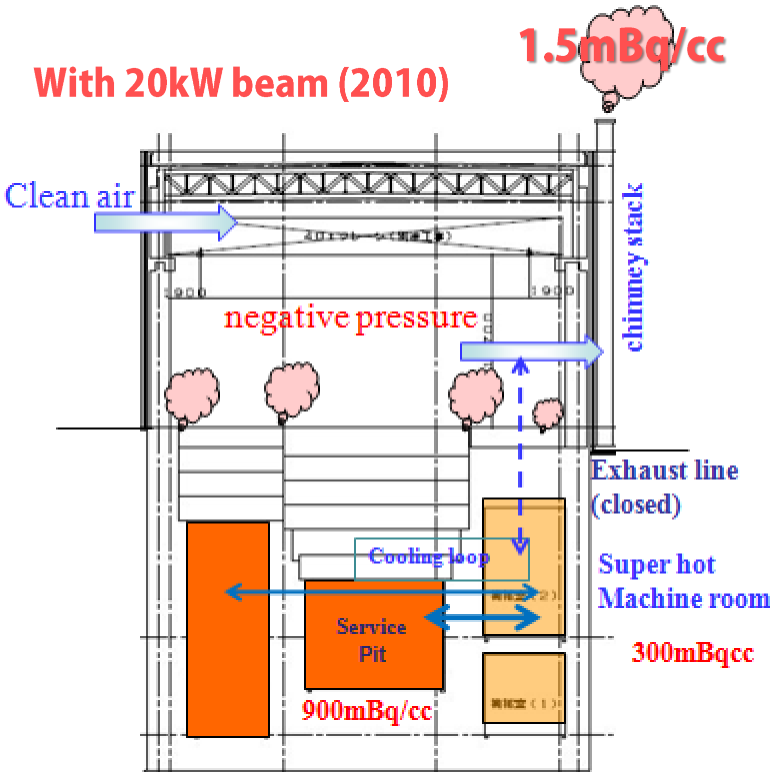
Sudden Stop of TS Ventilation System (2009)





- The control panel was located in B1F machine room, since limitation of 1F floor space.
- Later we noticed it was around the level of target..
- Single event upset on a CPU unit of the PLC by beam-induced fast neutrons → system malfunctioned, but air flushing (to go into B1) was not possible… ☹☹☹
- As temporary fix, relocate CPU unit by 10m to area with less neutrons, covered with LG blocks.
- Whole control panels of air-conditioning/cooling water at TS had to moved to the ground floor.

Exhaust Air at Target Station / NU3 (2010)



TS

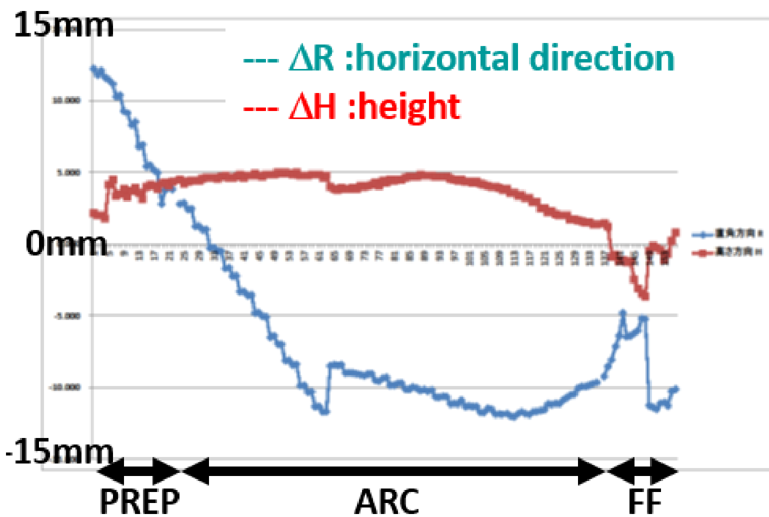
Regulation: < 0.5 mBq/cc (3 month average)

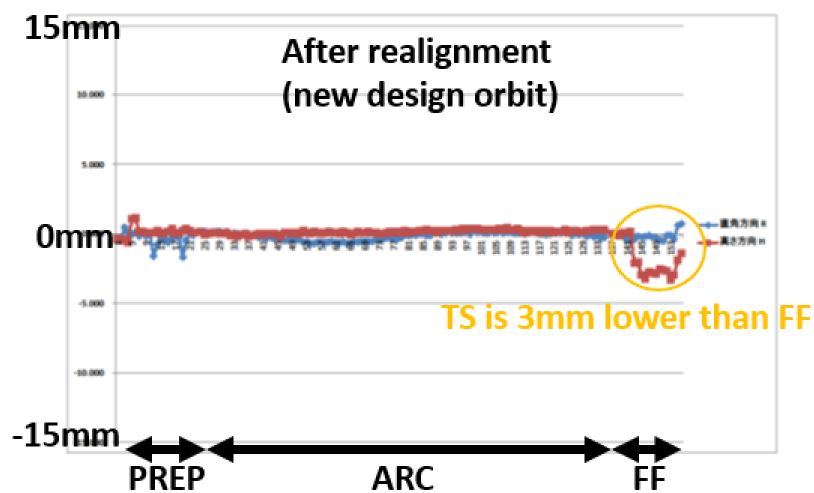
- Radiation in exhaust air was being the bottleneck of beam power.
- At the start of the physics run in early 2010 with only 20kW beam, the operation was limited to <30 min ☹☹☹
- By improving air-tightness of floor / through-going ducts / reinforce air ventilation system, acceptable beam is improved by 2 order

Recovery from the Great East-Japan Quake (2011-12)

- Subsidence around beam-dump pit / NU3
- Distorted expansion joints

Primary line magnets

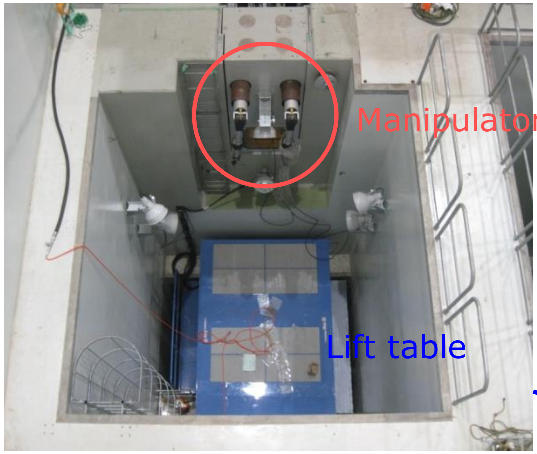


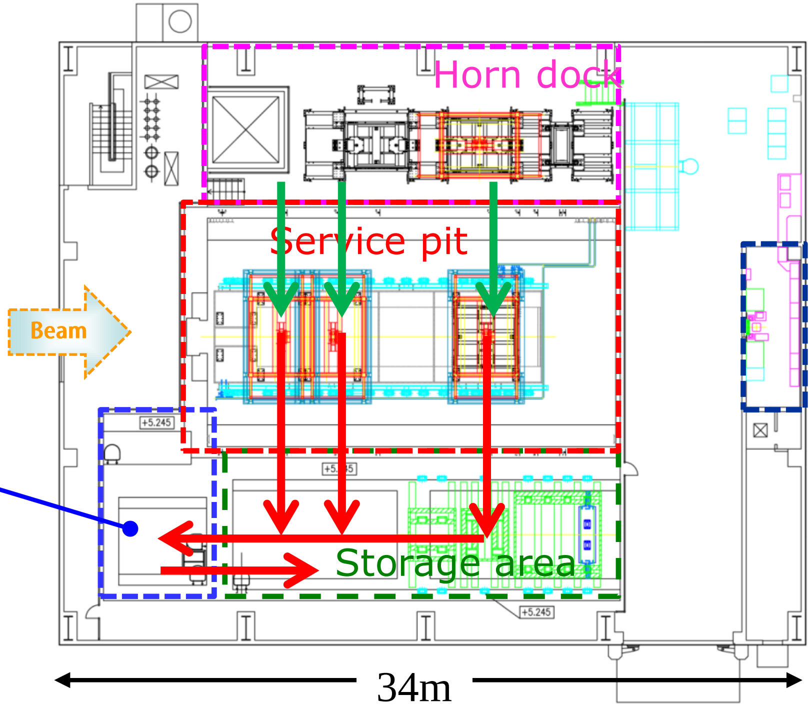


Replacement of Horns / Target (2013-14)

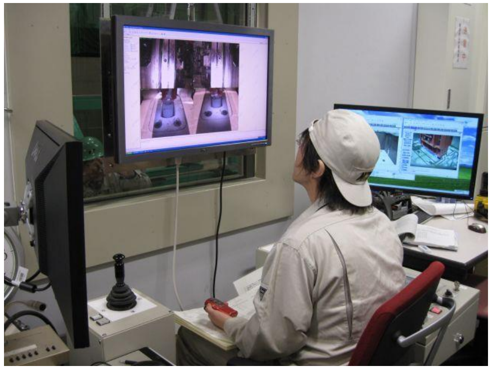
- H_2 production by radiolysis from horn conductor-cooling water
  - H_2 after 1 week of 220kW beam: 1.6% (⇔explosion limit >4%)
  - Only one port available for cover gas helium. We were forced to flush/replace helium using water ports in every maintenance day
  - This limits maximum acceptable beam power to ~300kW
  - Limitation also exists for the stripline cooling (up to 400kW)
- Replace all horns to improved spares for higher power operation

Maintenance area





Control room



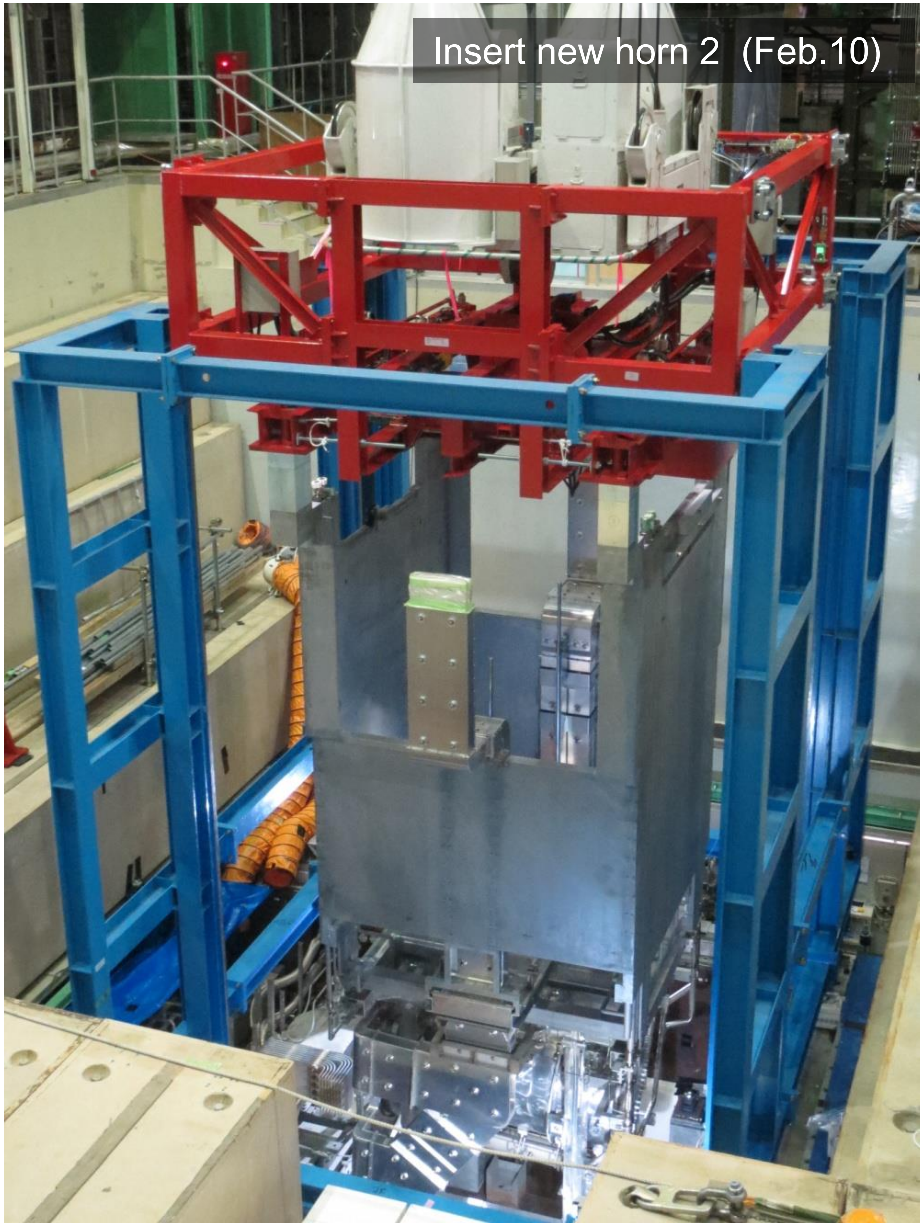
Every process managed remotely at control room

Horn Remote Maintenance

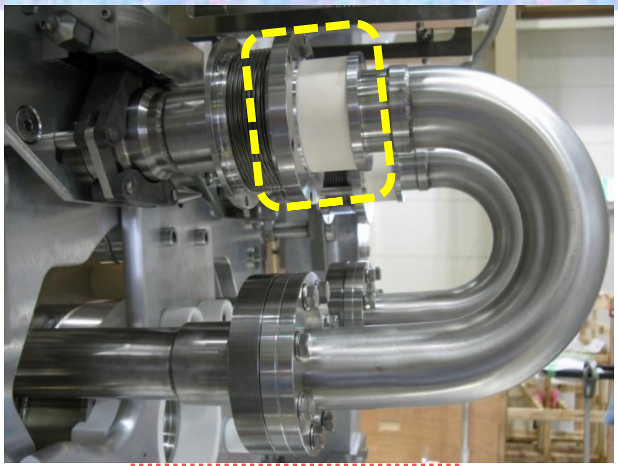
http://www.youtube.com/watch?v=E6QdUwsdClk

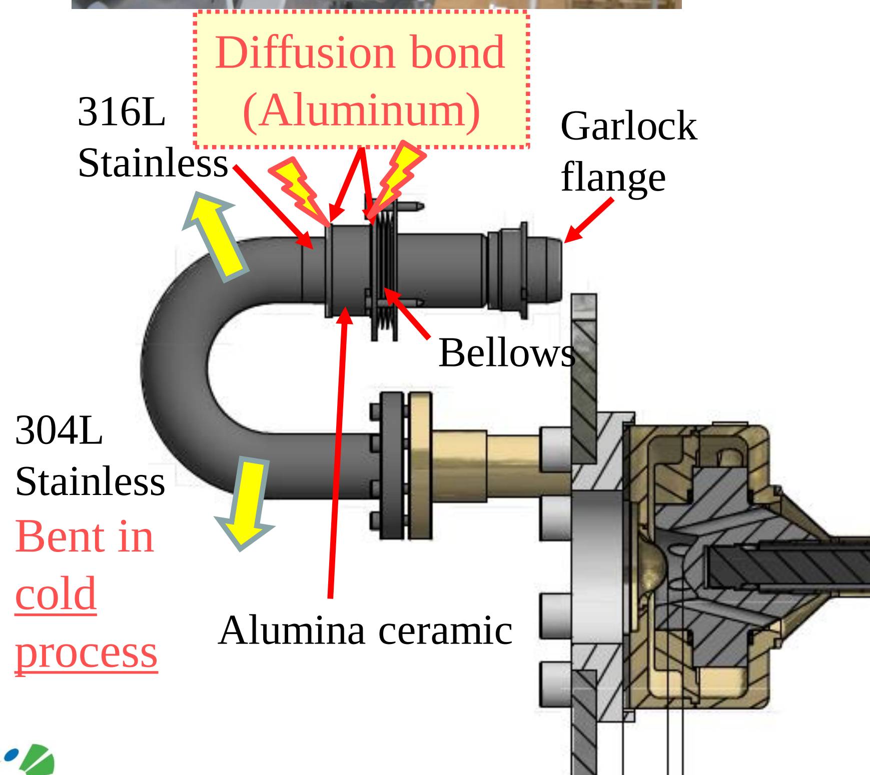
- Remote exchange scheme worked in perfect manner
- Radiation level at border of control area was monitored
  - ~2.5 μSv, (4 μSv/h max) [Horn-2]
  - Well under control (<20 μSv in a week)
  - Good agreement to the MCNP simulations
- Works completed Sep.2013~Apr.2014

  → *anti-ν mode operation started*



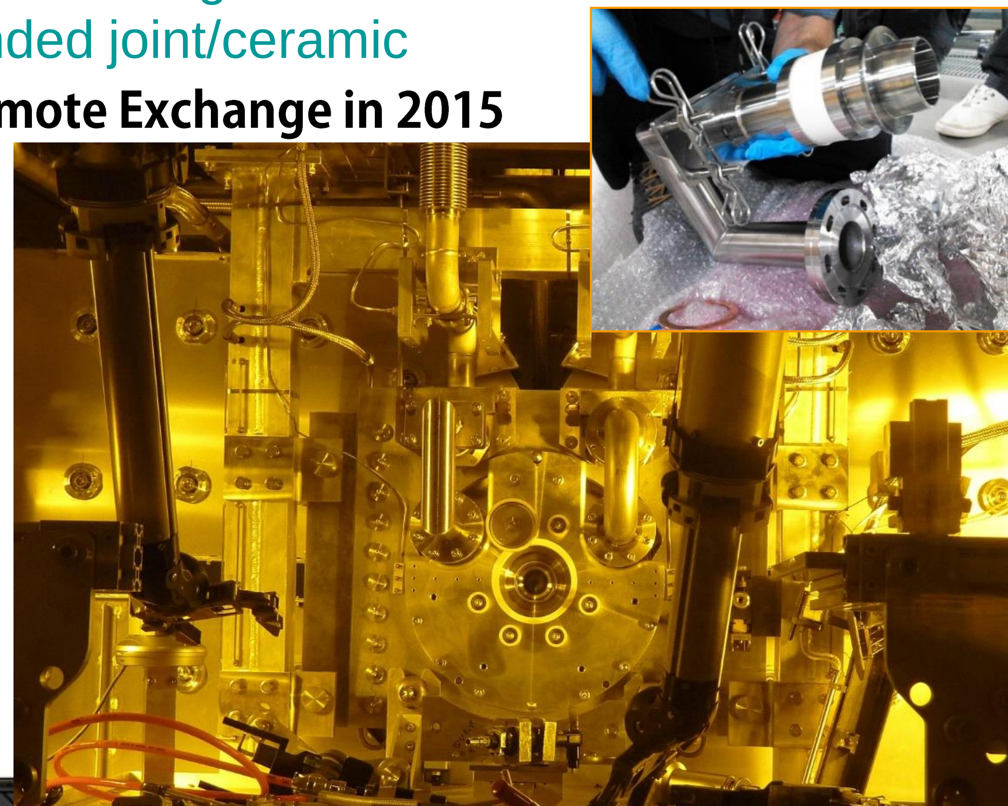
Leak at Target Helium Outlet Pipe (2015)





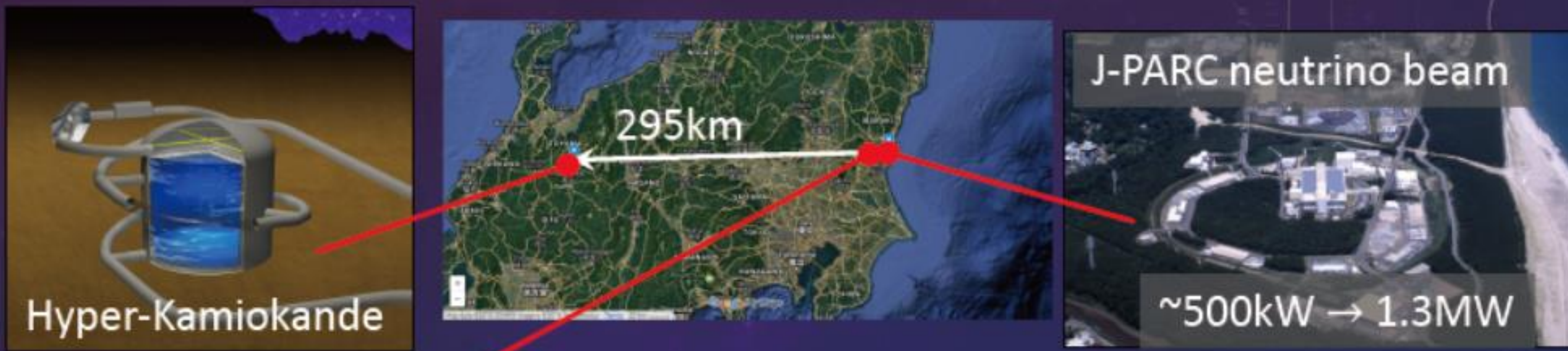
- Failure of joint/ceramic from movement of stainless pipes (stress relieving)
- Thermal fatigue failure of the diffusion bonded joint/ceramic

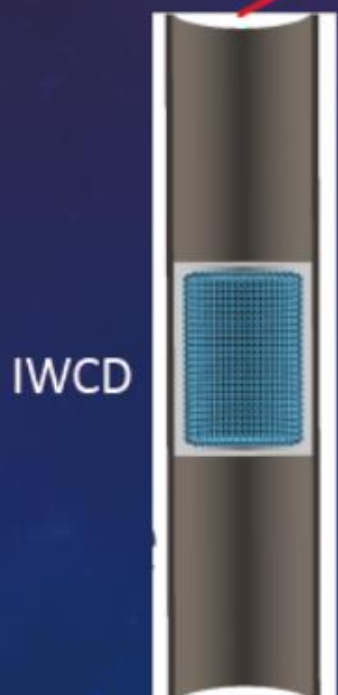
Remote Exchange in 2015



https://www.facebook.com/ishi.tataku/videos/948622585258550/?t=1
https://www.facebook.com/ishi.tataku/videos/948623391925136/?t=14

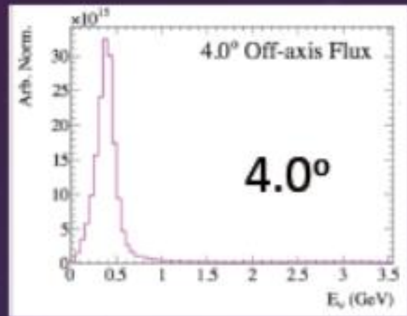
INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)

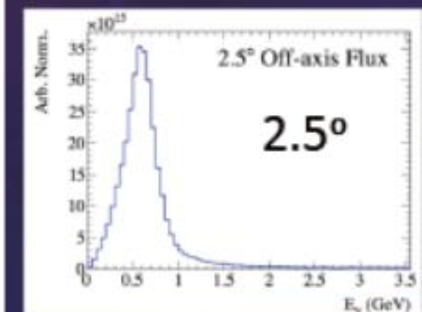


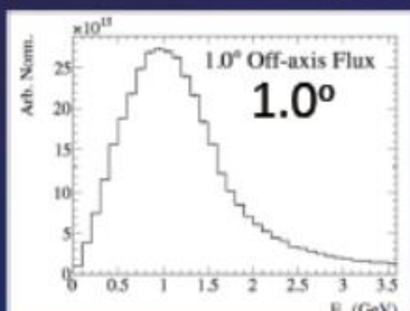


- Measures J-PARC neutrino beam with intermediate water Cherenkov detector
  - Suppress systematic uncertainties on neutrino interactions with same water target and same detection method
  - Measures neutron multiplicity with Gd-loading
  - Test of sterile neutrino

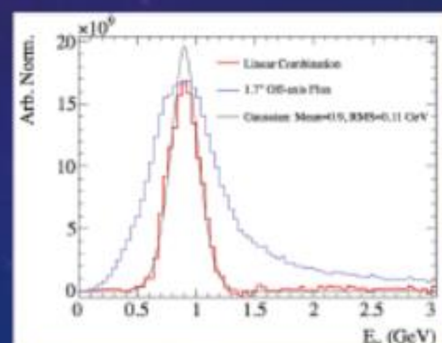
MOTIVATION OF IWCD AND OFF-AXIS SPANNING



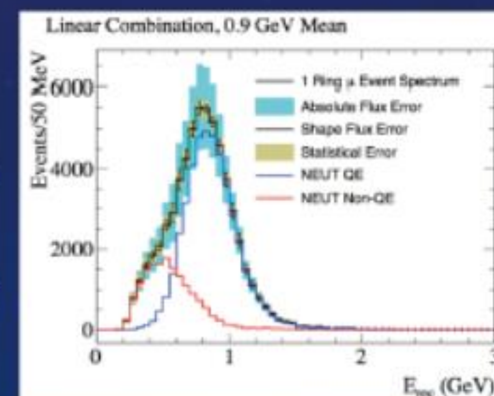




- $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross-section ratio
  $\Leftarrow$ Larger ν_e contribution at OAA > 2.5°
- Intrinsic ν_e and NC contamination
  $\Leftarrow$ Same (unoscillated) beam flux at OAA=2.5°
- Resolve $(p_l, \theta_l) \leftrightarrow E_\nu$ relation
  $\Leftarrow$ Combination of different OAA measurements (down to 1° to measure high energy tail)



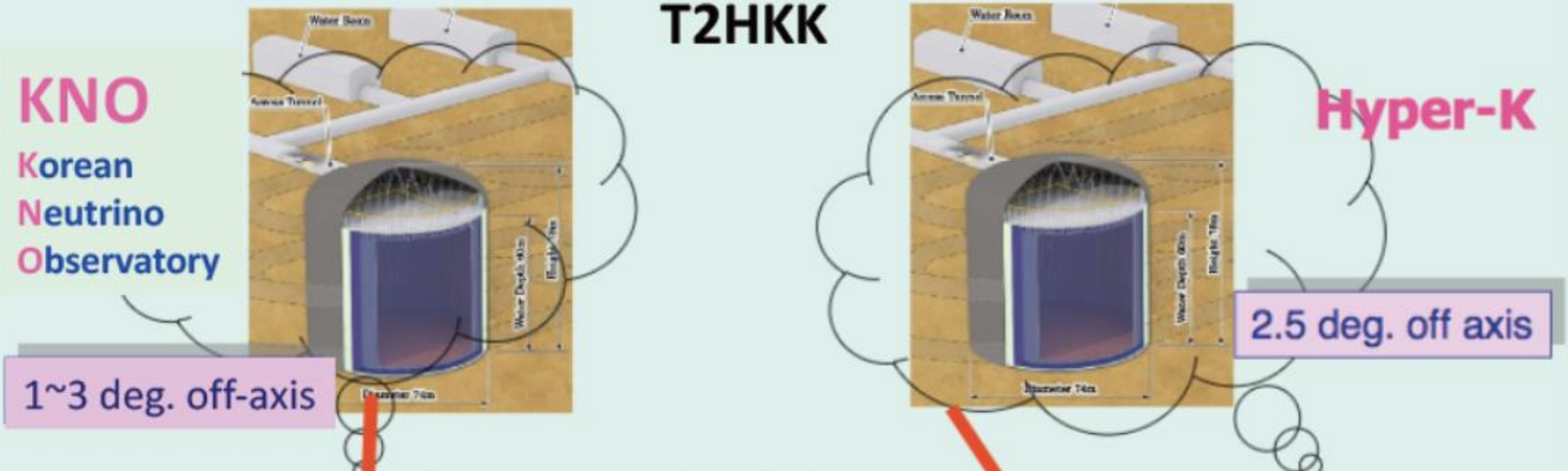
Reco.



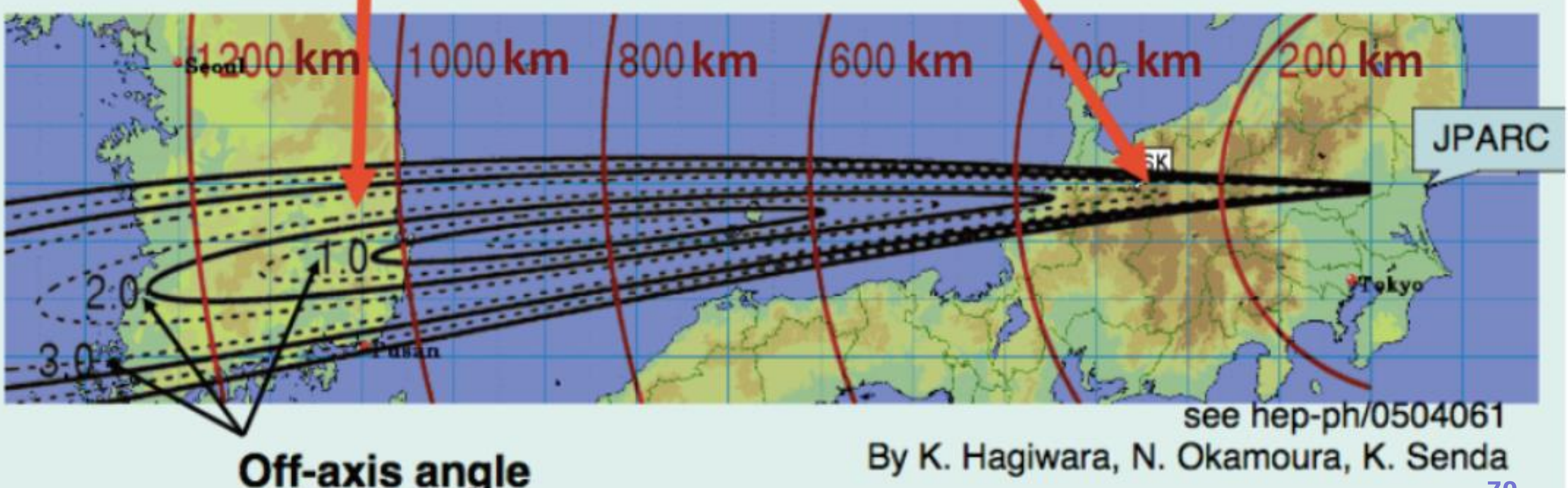
Note: energy from (p_l, θ_l) biased due to non-QE, 2p2h, nuclear effects and inefficiency of 2nd ring
→ Uncertainties on θ_{23}, Δm^2_{32} and δ_{CP} (shape information will be more important for precision measurements with high statistics)

2nd Hyper-K Detector in Korea

T2HKK



The J-PARC ν beam comes to Korea.



see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Energy vs. Baseline