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

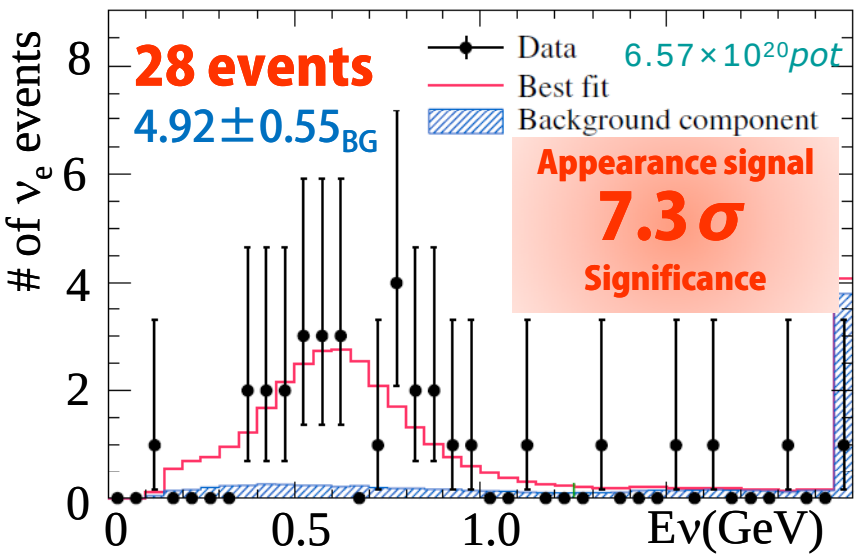
T. Ishida

Neutrino Section, J-PARC Center, KEK

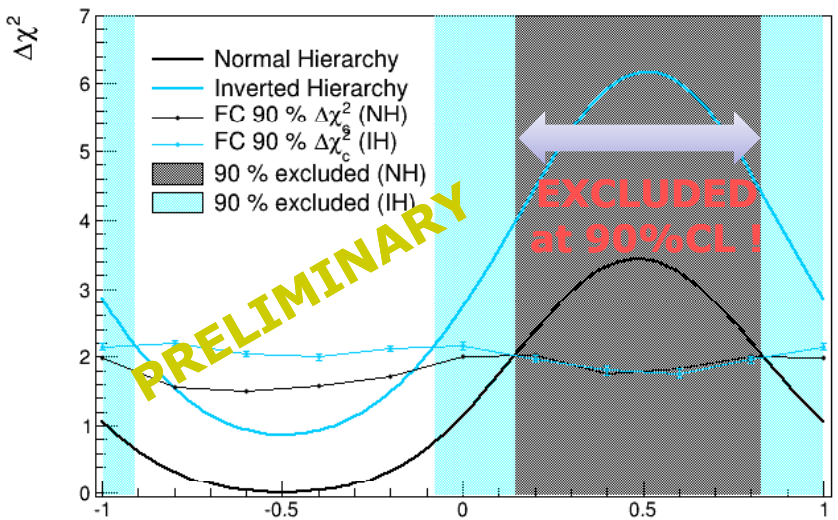
on behalf of the neutrino beam group

T2K ν_e appearance observation

- Definitive observation on ν_μ turning to ν_e (July 19, 2013, 6.6×10^{20}pot)
  - *Neutrino experiments come closer to see CPV in lepton sector !*
  - With 10 times more data (7.8×10^{21} *p.o.t.*), T2K has the opportunity to establish *evidence* (~3σ) of CPV. ⇒ M. Friend
- A prompt realization of the design beam power of 750 kW is highly desired to the J-PARC Main Ring and the neutrino experimental facility
- A power upgrade to Mega-Watt class beam will directly enhance reach of the future project: LBL from J-PARC to Hyper-Kamiokande ⇒ Y. Koshio



⇒ Phys. Rev. Lett. 112, 061802 (2014)



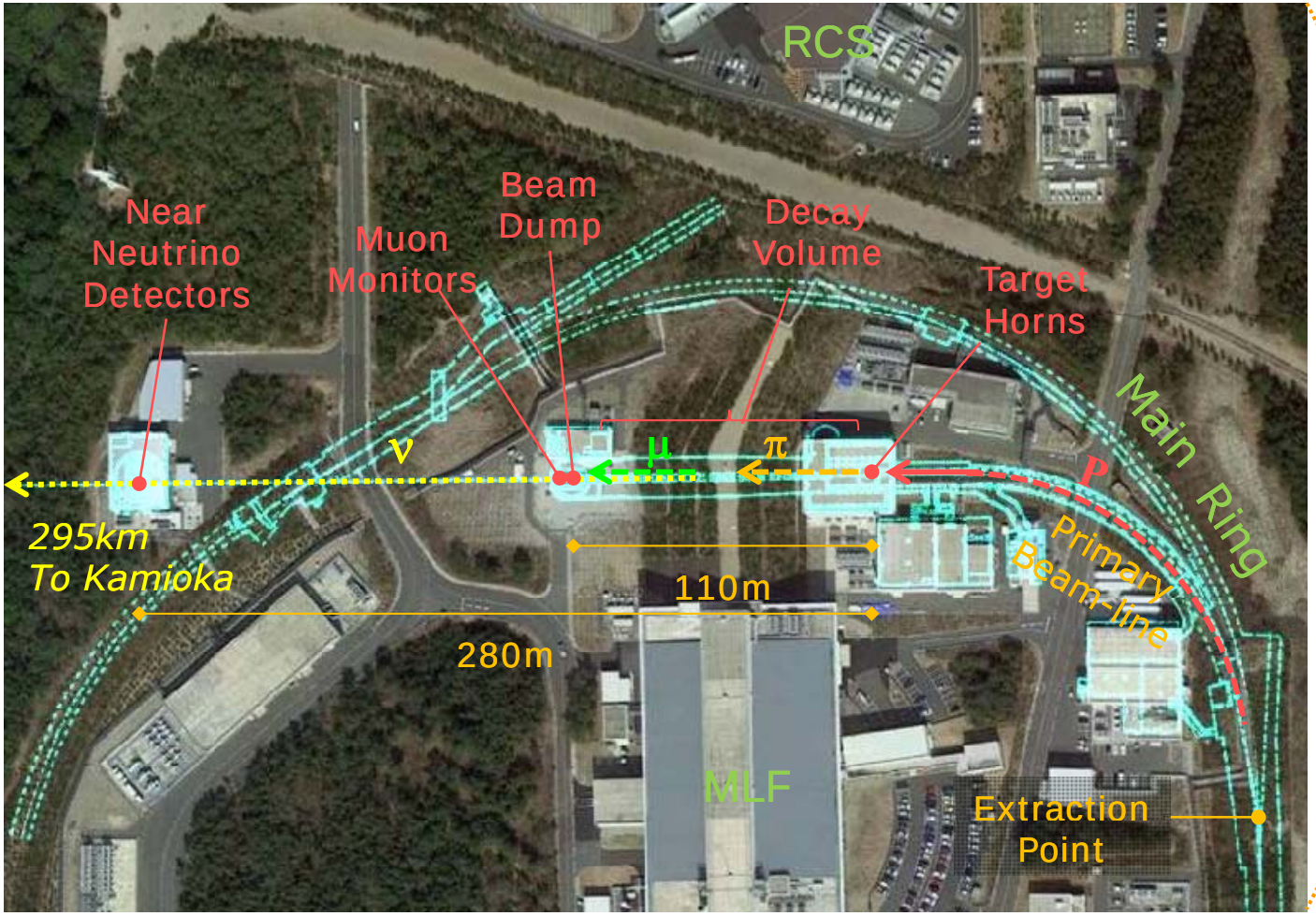
Joint ν_μ + ν_e *Analysis*

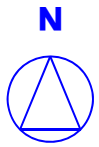
⇒http://moriond.in2p3.fr/

Contents

1. Neutrino experimental facility at J-PARC
2. Operational status of the neutrino beam-line
3. Prospects for power upgrade
4. Summary

1. Neutrino experimental facility at J-PARC



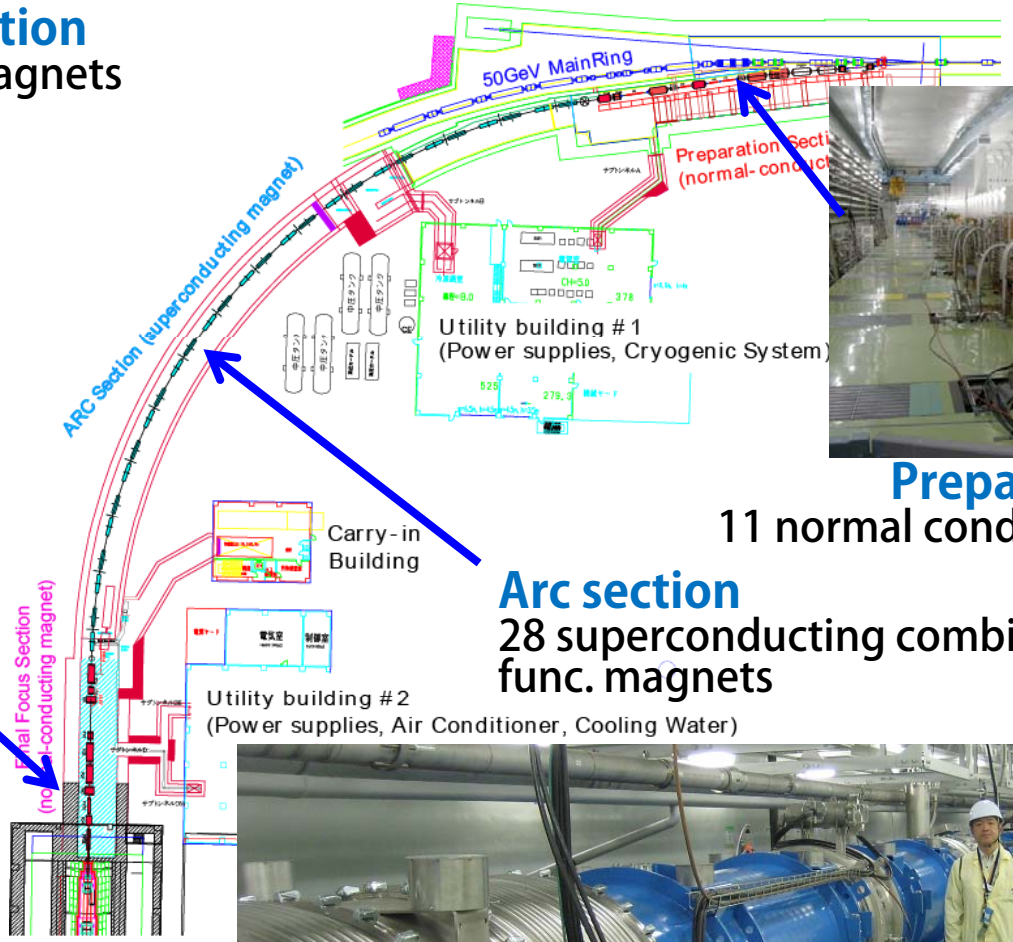


J-PARC, Tokai

- Conventional (horn-focused) beam-line, designed/constructed for T2K long base-line neutrino oscillation experiment & for its future upgrade
- Off-axis beam configuration with variable off-axis angle 2.0°~2.5°

Primary beam-line

Final focusing (FF) section
10 normal conducting magnets



Preparation section
11 normal conducting magnets

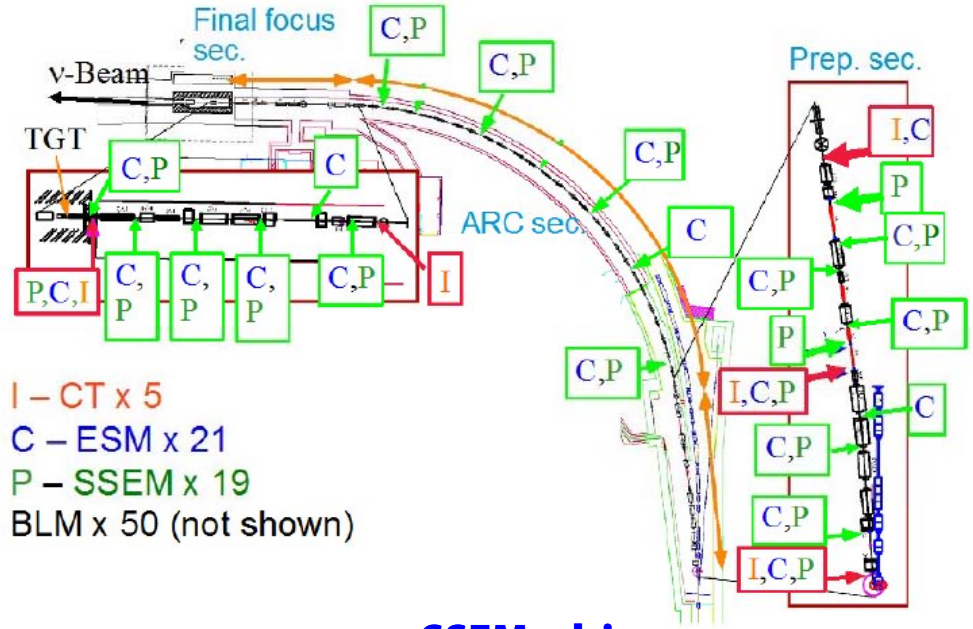
Arc section
28 superconducting combined func. magnets

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

Beam monitors

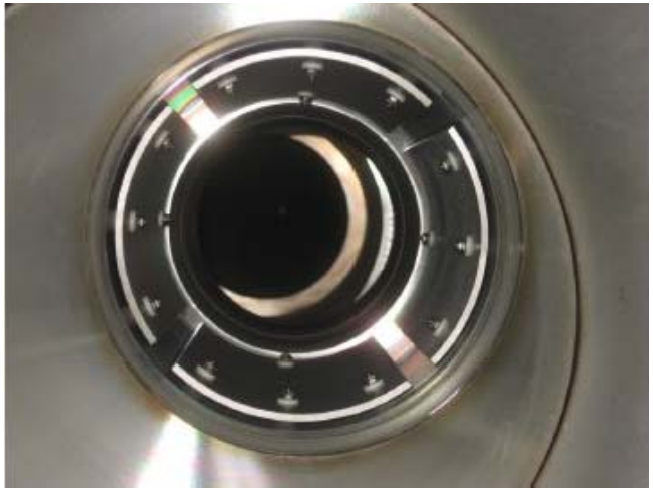
- Intensity: Current Transformer (CT)
- Center: Electro-Static Monitor (ESM)
- Profile: Segmented Secondary Emission Monitor (SSEM)
- Beam Loss: Ionization chambers
- Readout by COPPER/UW-FADC

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



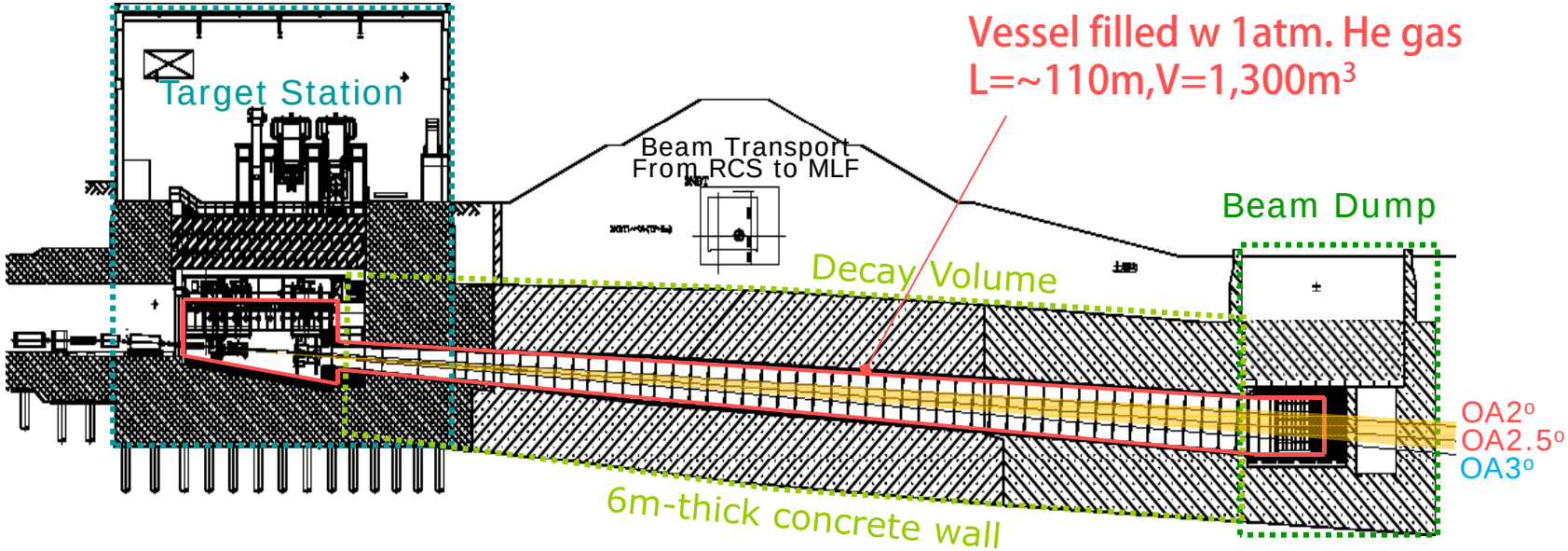
CT

ESM



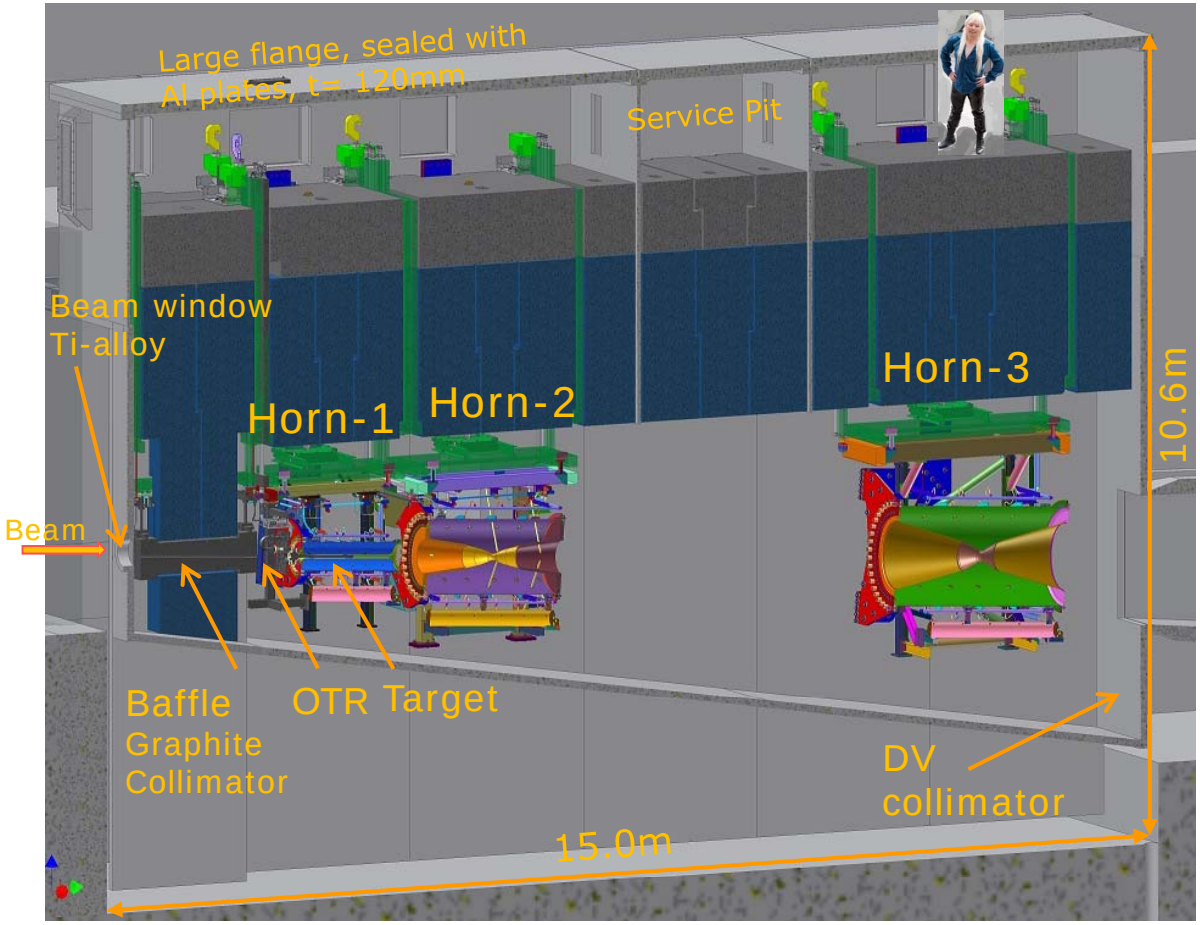
SSEM+driver

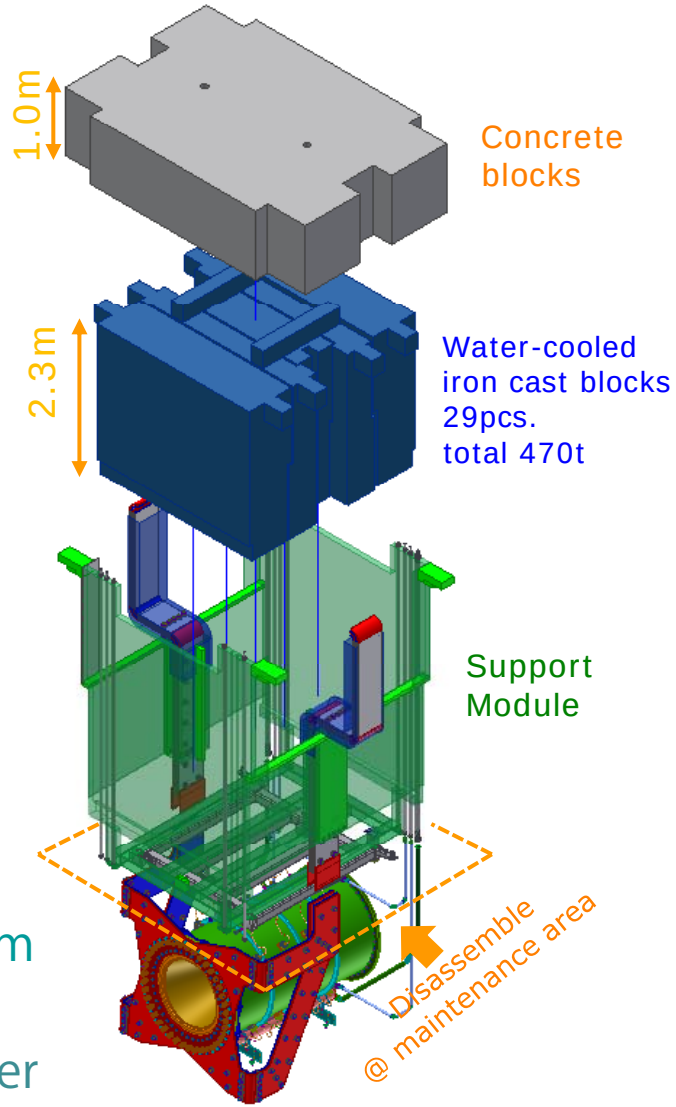
Secondary Beam-line



- Target Station(TS), Decay Volume(DV), & Beam Dump(BD)
  - TS: He-cooled graphite target, 3 magnetic horns, remote maintenance
  - DV: 94m-long tunnel with rectangular cross section ($1.4m_w \times 1.7m_h \rightarrow 3.0m_w \times 5.1m_h$)
  - BD: hadron absorber made of large graphite blocks, surrounding iron shields
- Enclosed in a gigantic helium vessel, made of carbon steel plates.
  - He atmosphere prevents nitrogen oxide (NO_x) production / oxidization of apparatus.
- Iron plates of the vessel are cooled by water circuits.
  - Maintenance is not possible after beam operation due to irradiation.
  - Radiation shielding / cooling capacity were designed to accept up to ~4MW beam.

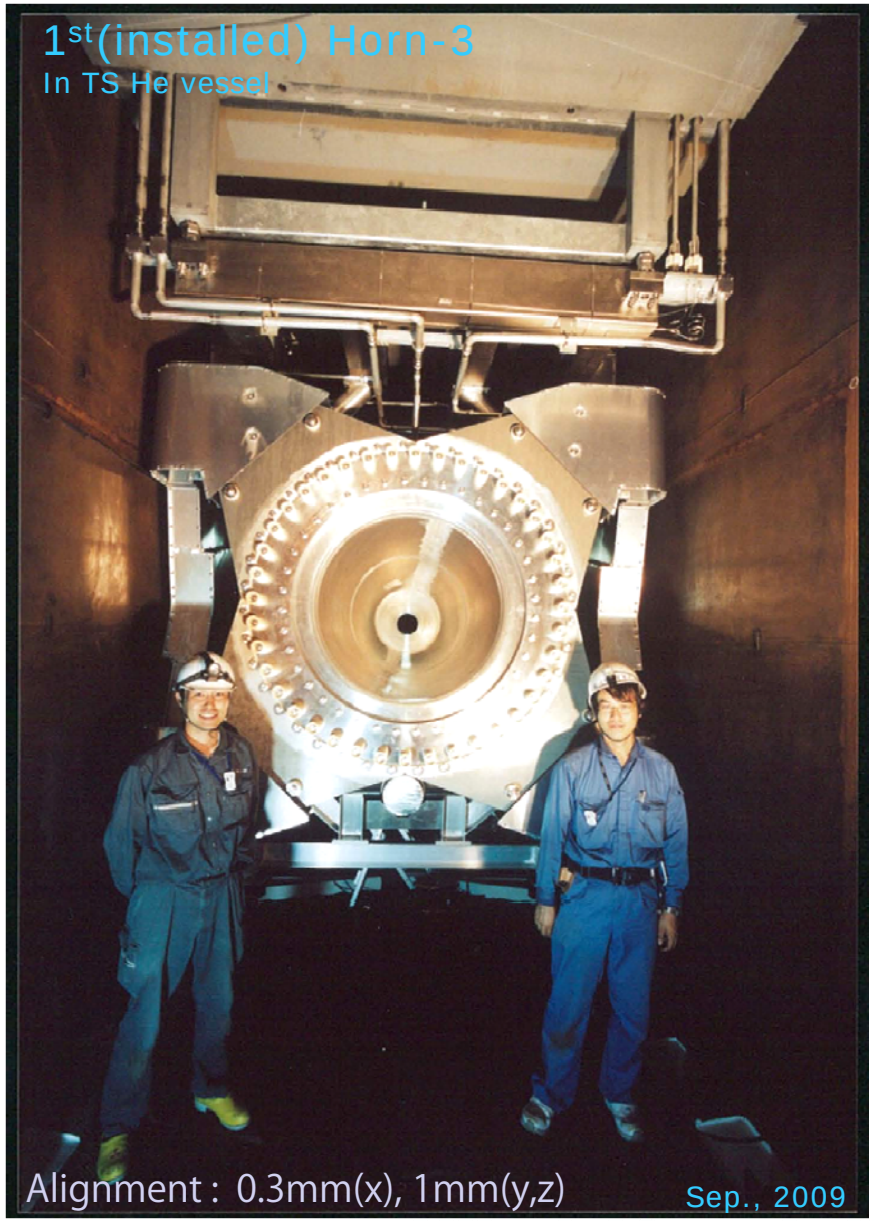
Target Station (TS)



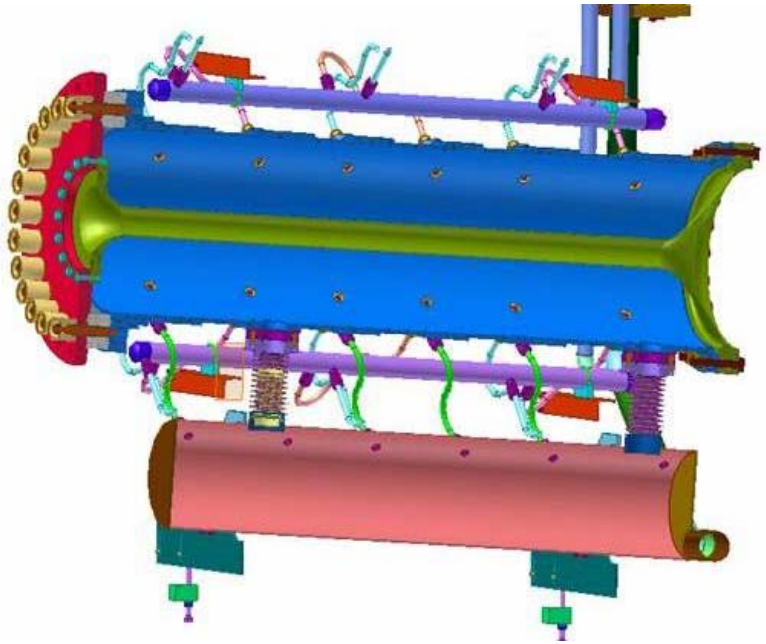


- 3 electromagnetic horns / a baffle are supported from the wall of vessel by support modules.
- Apparatus on the beam-line are highly irradiated after beam. Remote maintenance is the key issue.

Electromagnetic horns

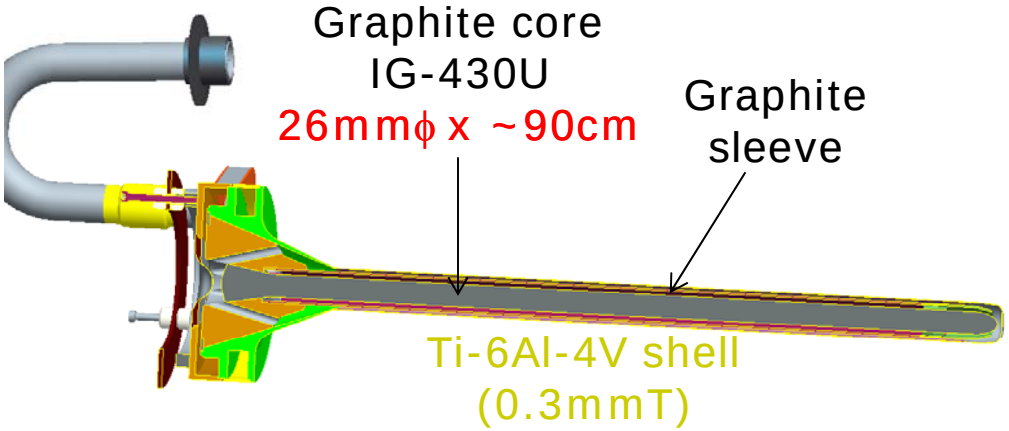


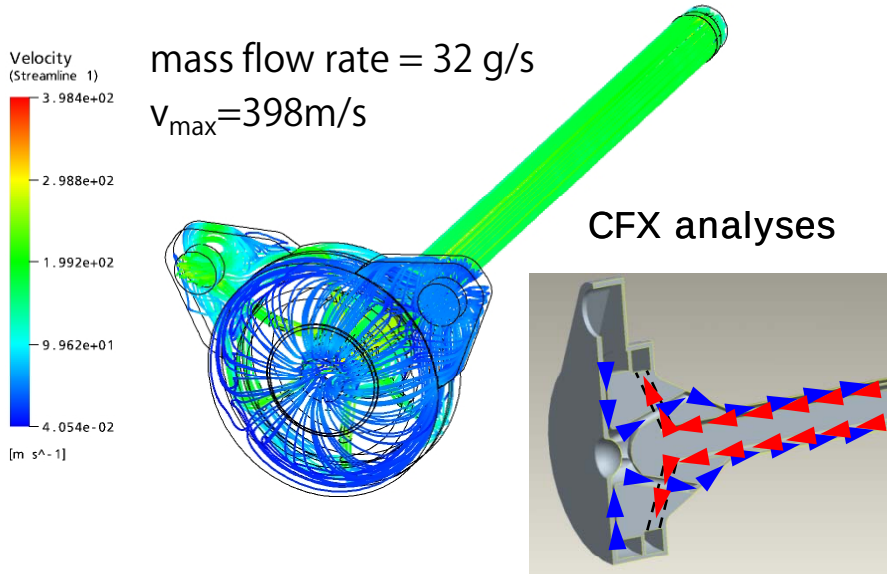
- Aluminum alloy A6061-T6
  - Inner conductor: t3mm, outer: t10mm.
- 320kA pulsed current (250kA in use so far)
  - Max field: ~2.1T, pulse width: 2~3ms
  - Operation cycle: 2.48 s → 1.3 s
- Spraying water to inner conductor
  - 15kJ (beam) + 10kJ (Joule)=25kJ
  - Keep <80℃ : cooling capacity ~2MW

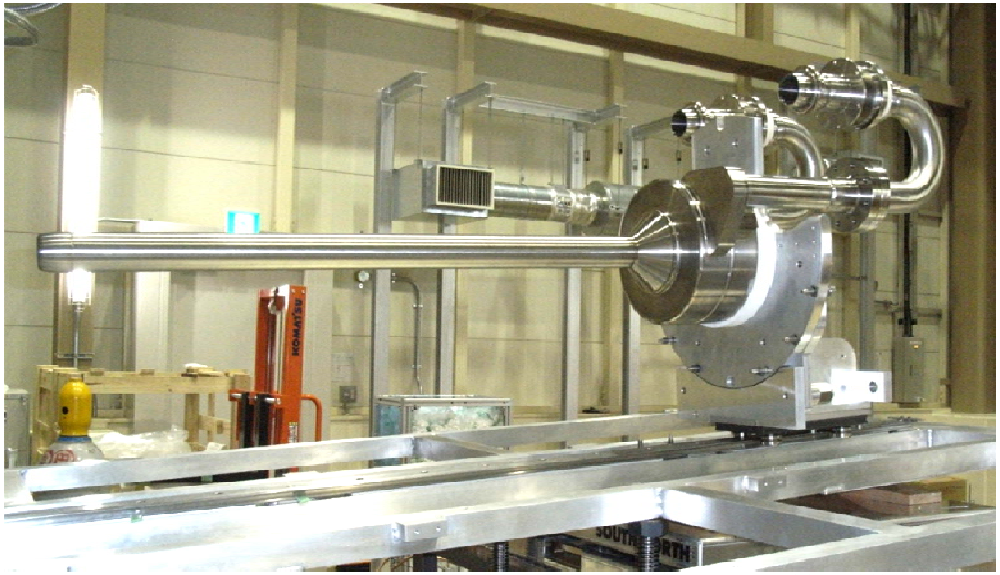


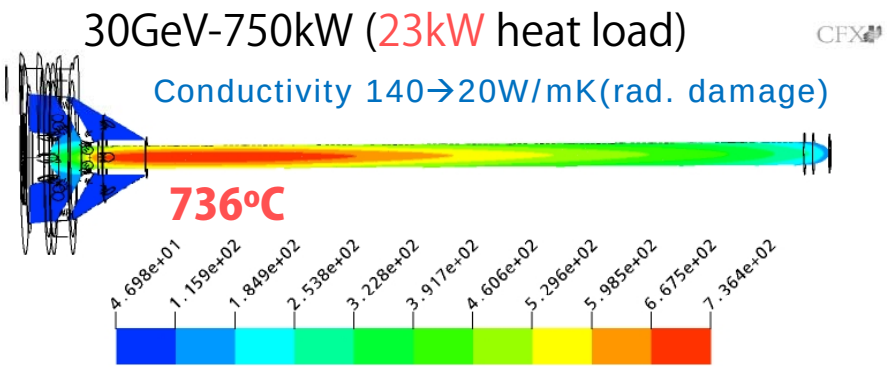
Production target

- Helium gas cooling to keep temperature of graphite around 400~800℃
  - Slow down degradation of conductivity/dimensional change by rad. damage (0.25DPA/yr)

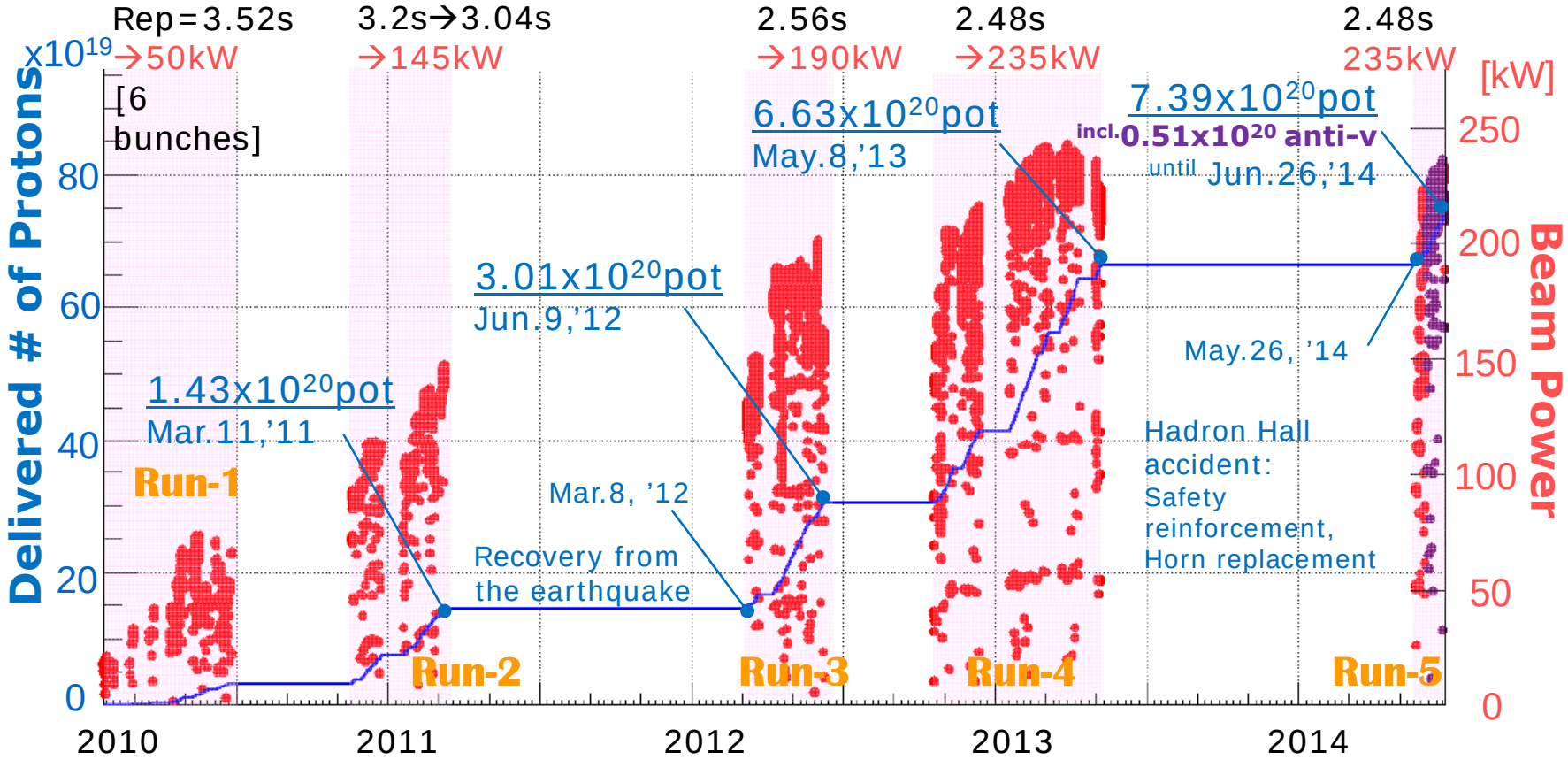








2. Operational status of the neutrino beam-line

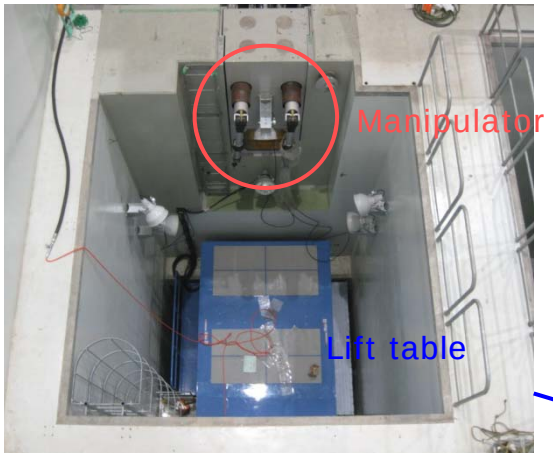


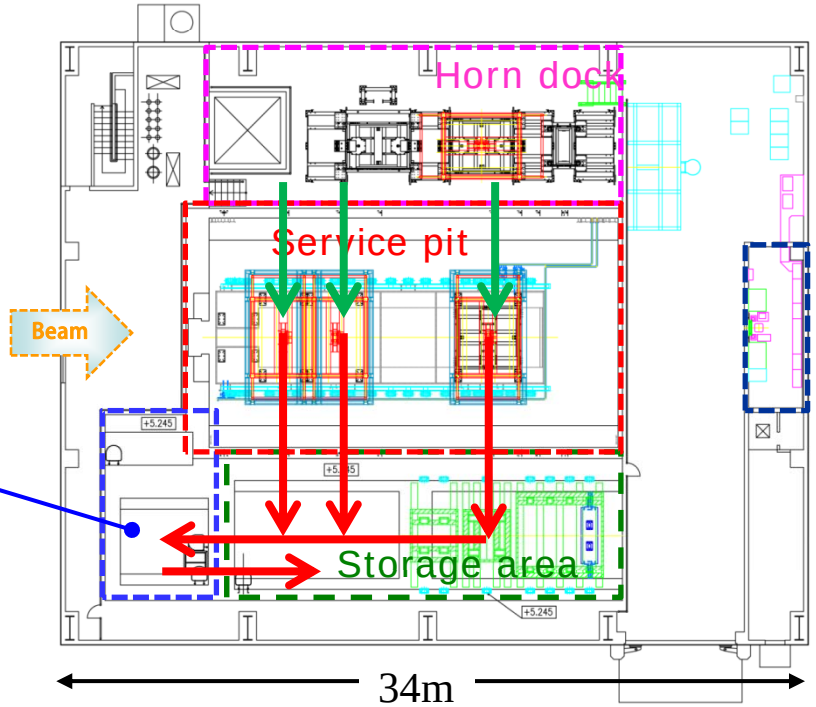
- Stable operation at ~230kW
  - >1.2x10^{14}ppp is the world record of extracted protons per pulse for synchrotrons.
- Accumulated *pot*: 7.39x10^{20}, including **0.51x10^{20} of anti-ν mode operation**.
- Accumulated # pulses for the 1st set of horns and the target : 1.2x10^{7} [until Run-4]
  - No serious troubles.

Replacement of horns

- 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 (Run-4)
  - This limits maximum acceptable beam power to ~300kW
  - Problem also exists for the stripline cooling (up to 400kW)
- We decided to replace all horns to improved spares for higher power operation

Maintenance area

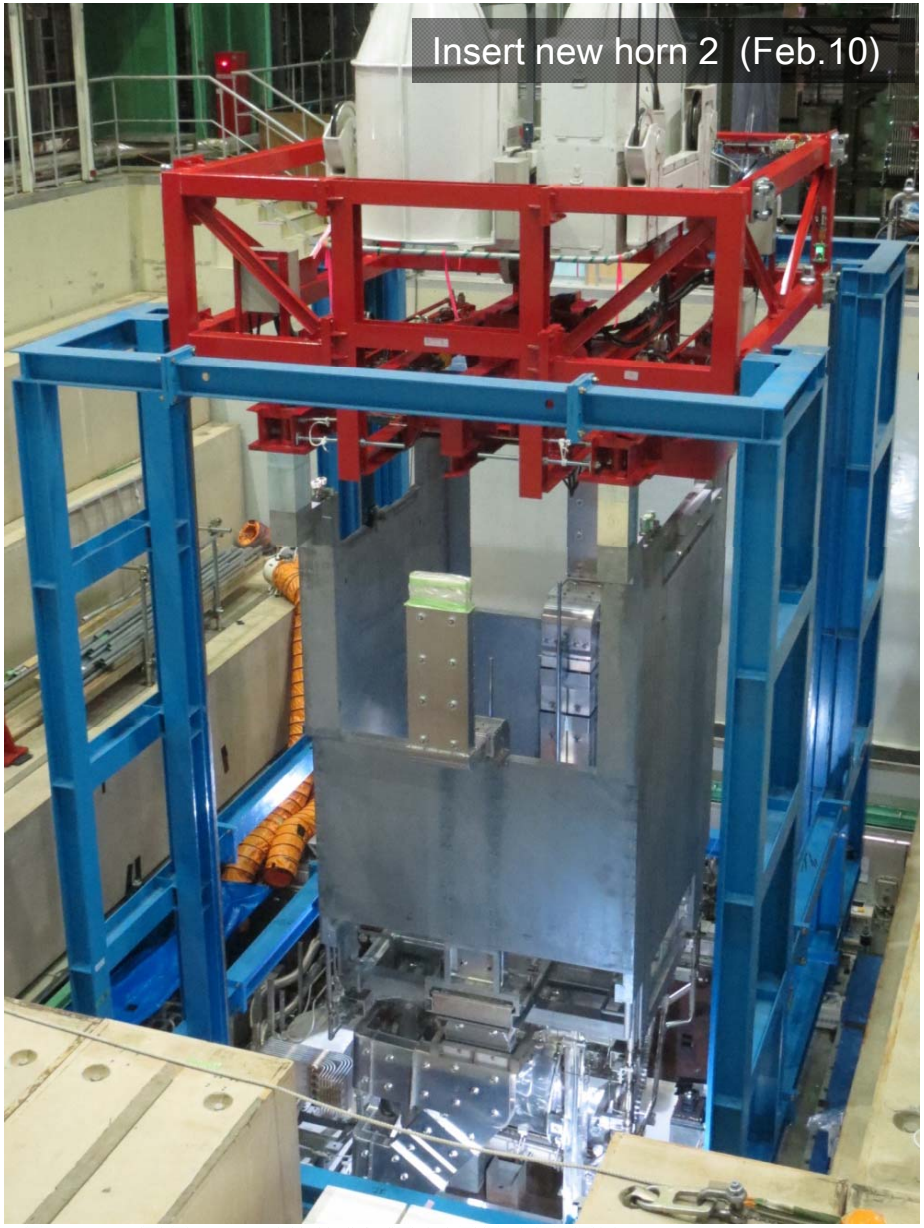




Control room

Every process managed remotely at control room

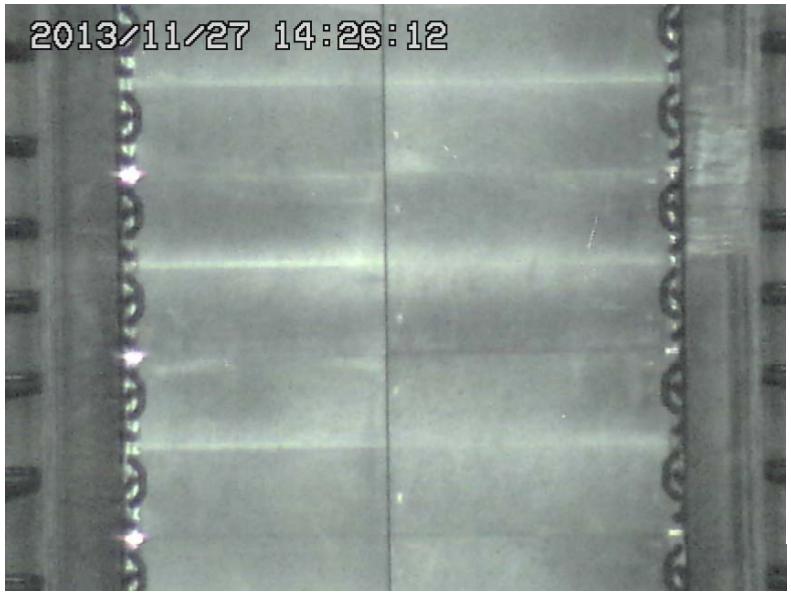
Replacement of horns (cont.)



- Remote exchange scheme worked in perfect manner
  - It only took ~1.5 hours to take out each old horn to maintenance area
- 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

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

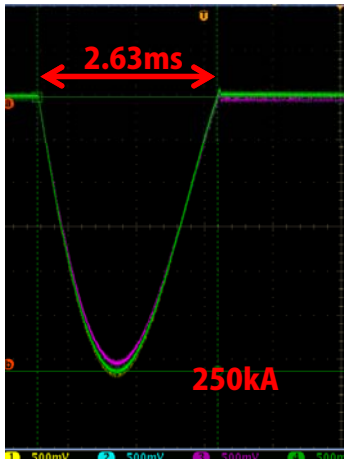
Helium vessel inspection

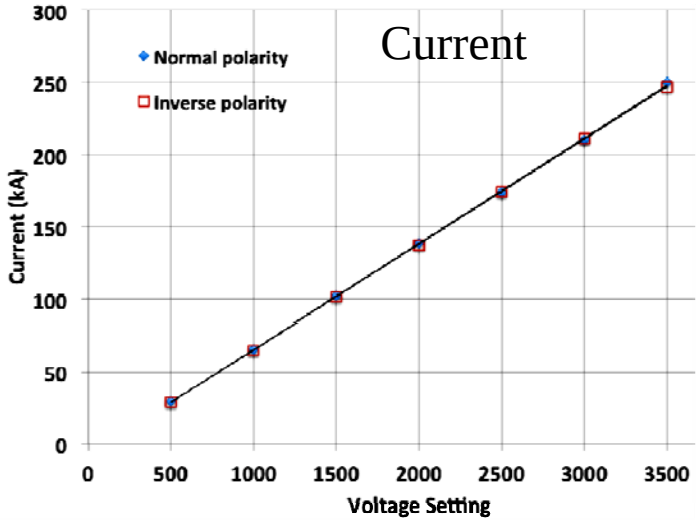


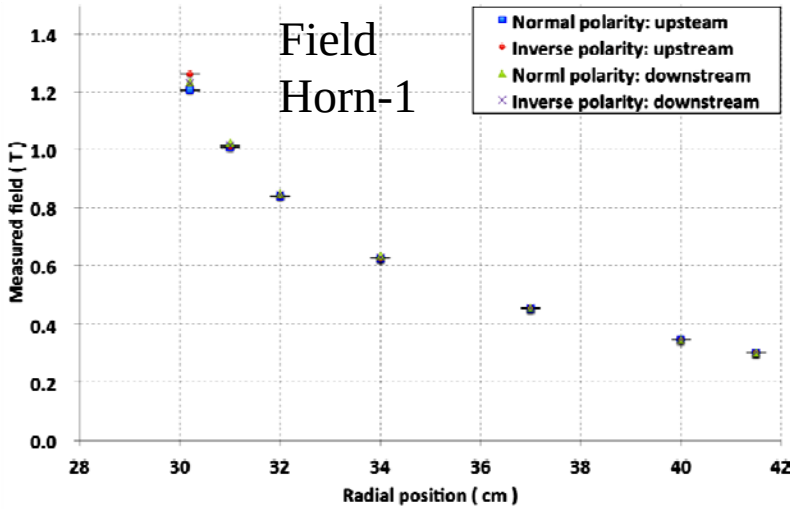
- Residual dose in the TS vessel was reached to ~100mSv/h
  - Maintenance is already impossible.
- Web-camera inserted to the gap after old horn-3 was taken out
- No damage was seen on the decay volume / hadron absorber.
  - Pure Helium atmosphere seems to be quite effective to keep good condition.

Horn operation with inverse polarity

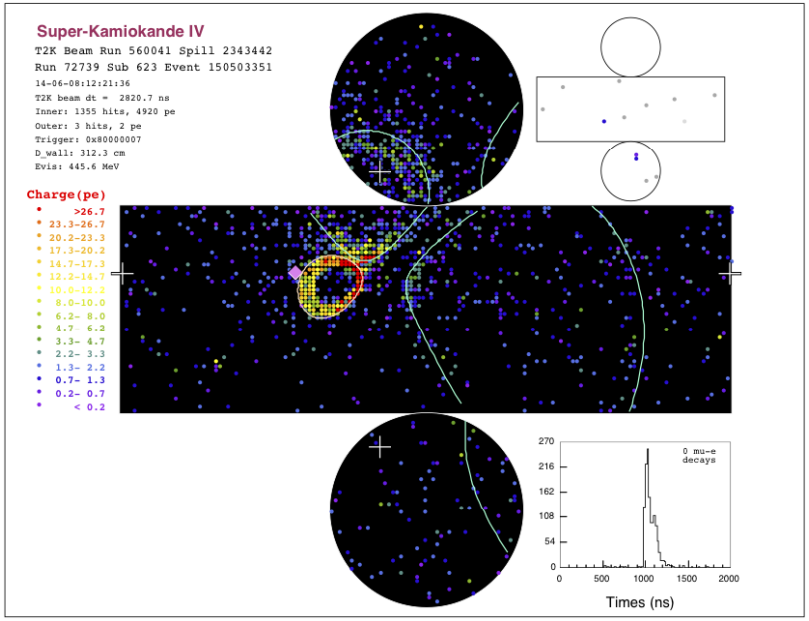
[anti-neutrino mode running]







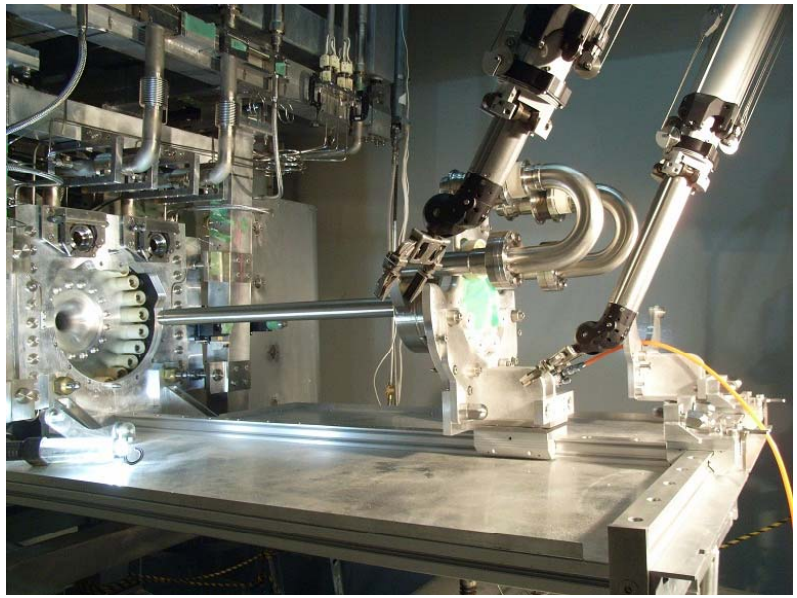
- Inverse polarity operation
  - 250kA operation succeeded
  - Good linearity
  - Good current balance (a few %)
- Measured azimuthal fields were consistent within measurement errors
- Physics run with anti-neutrino mode operation was started on June 4
  - On June 8, 1st beam-induced candidate event was observed at Super-Kamiokande



3. Prospect for power upgrade

Secondary beam component limitations

- Target
  - Radiation damage of graphite
    - Reduction in thermal conductivity, swelling etc
  - Structural integrity & dimensional stability
  - Heat transfer
  - High helium volumetric flow rate (and high pressure or high pressure drops)
- Beam windows (target station and target)
  - Radiation damage and embrittlement of Ti6Al4V alloy
  - Stress waves from bunch structure
- Magnetic Horns and power supplies
- OTR, beam monitors
- Target station emission limitations



Parameters of Main Ring operation

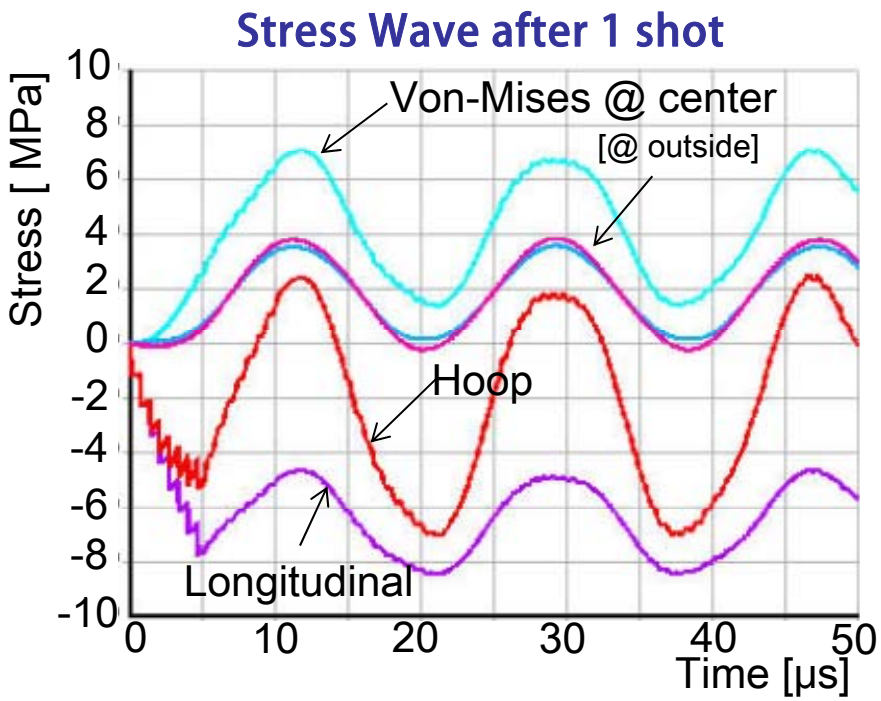
Parameter	Original	Achieved	Doubled rep rate		8GeV Booster Ring	
circumference	1567.5m					
beam kinetic energy	30 GeV					
beam intensity	3.3×10^{14}ppp	1.24×10^{14}ppp	2.0×10^{14}ppp	2.3×10^{14}ppp	6.6×10^{14}	1.3×10^{15}
	4.1×10^{13}ppb	1.57×10^{13}ppb	2.5×10^{13}ppb	2.9×10^{13}ppb	8.2×10^{13}ppb	
[RCS equivalent power]	[1MW]	[377kW]	[610kW]	[700kW]	[2MW]	
RF frequency	1.67-1.72MHz					
harmonic number	9				9	18
number of bunches	8 / spill				8	16
spill width	~5us					
bunch full width (at injection)		~160ns	150 - ~400ns			
at extraction	~50ns					
maximum RF voltage		280kV	560kV			
repetition period	2.1sec	2.48 sec	1.3sec		1.0sec	1.16sec
		0.14+1.4+0.94	0.12+0.5+0.68			
beam power	750kW	240kW	750kW	870kW	3.2MW	5.5MW
beam size at target(1σ)	4.24mm		?	?	?	?

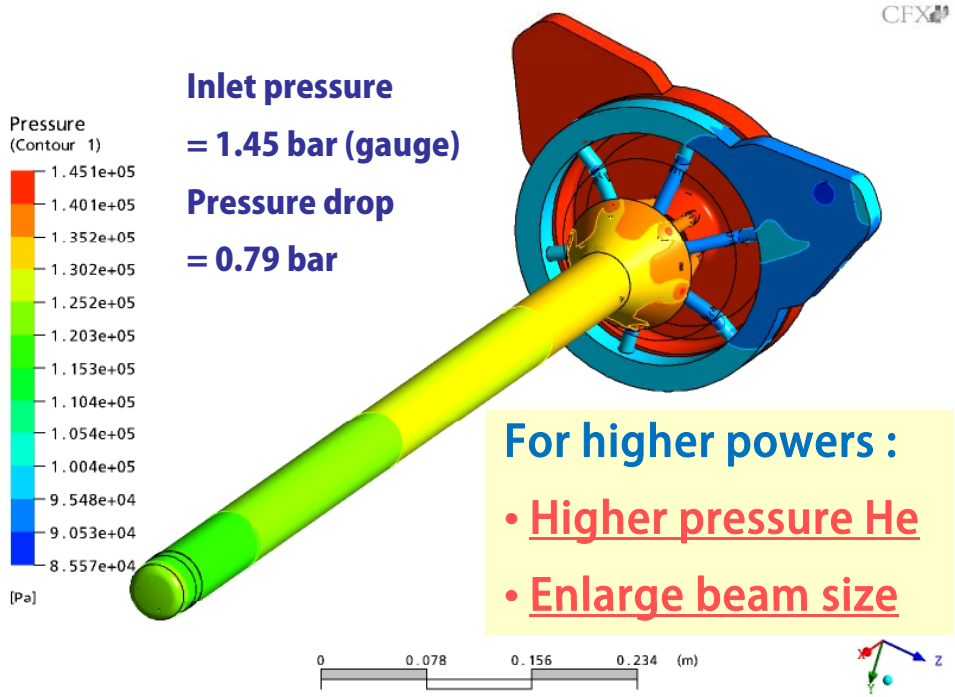
⇒ T. Koseki
S. Igarashi

- Original (old) planed parameters for 750kW was MR cycle: 2.1s, PPP: 3.3×10^{14}
  - Components of the neutrino facility (target/beam window) were designed
- Present expected parameters: Doubled rep-rate, MR cycle: 1.3 s, PPP: 2.0×10^{14}
  - Instantaneous temperature rise / pulse (thermal shock) will be reduced by 60%

Production Target

- Instantaneous heat deposit / thermal shock with original (old) 750kW scenario
  - 30GeV,3.3×10^{14}ppp: $\Delta T = 200$K/spill, σ_{eq}=7.4MPa
  - Safety factor = Strength(37MPa) / Stress x fatigue(0.9) = ~3.5 ($\propto$ 1/ppp)
- Oxidization due to contamination in He gas reduces graphite strength
  - Assuming O_2=100ppm and temperature =700°C, safety factor >2 for **5 yrs**.
- Simulation studies: To what protons-per-pulse can current design work ?
  - Close cooperation with STFC Rutherford Appleton Lab.



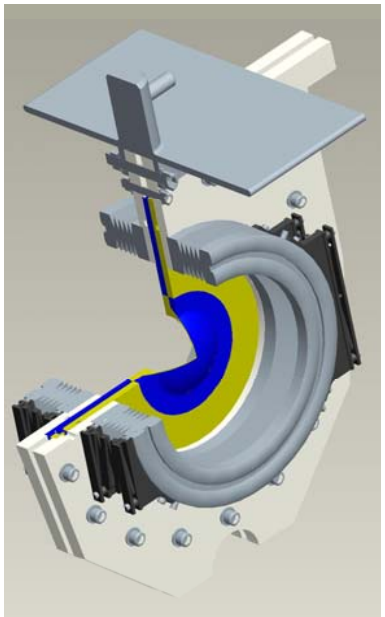


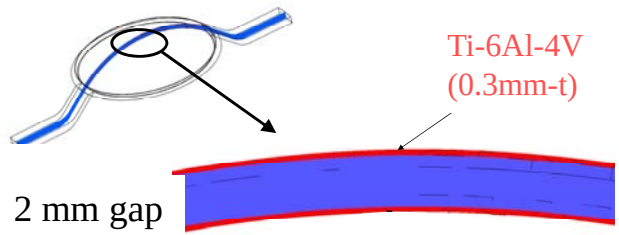
For higher powers :

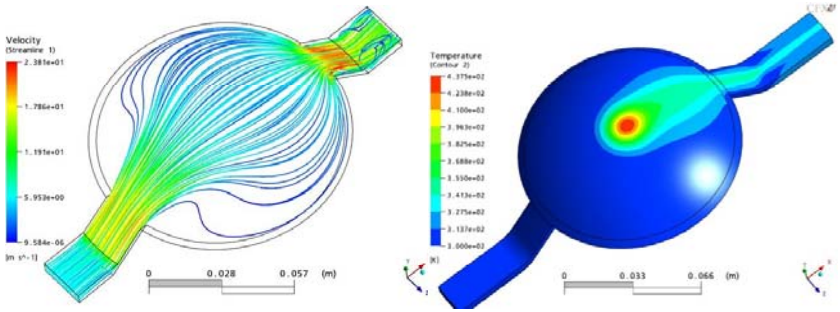
- **Higher pressure He**
- **Enlarge beam size**

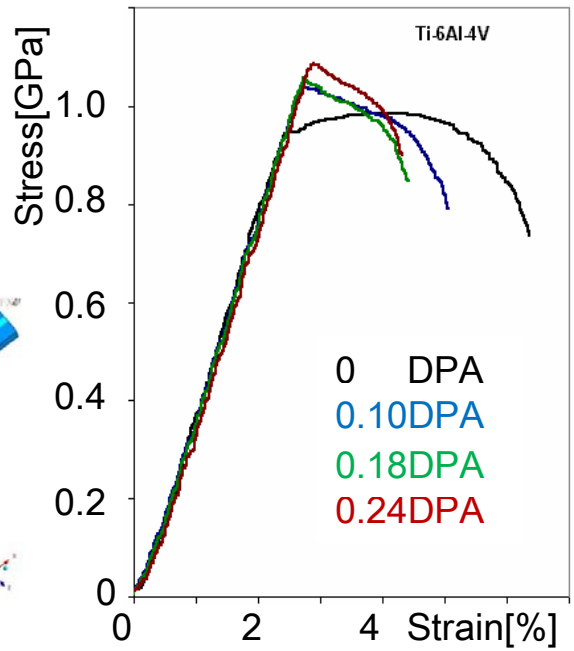
Beam window

- Separates He vessel from vacuum in primary line with pillow seals
- Double skin of 0.3mm thick Ti-6Al-4V, cooled by He gas (0.8g/s)
- For 3.3×10^{14}ppp, +150°C (160MPa)/ pulse, reach to 300°C (200MPa).
  - Safety factor 2.5 (tensile strength 1GPa⇒ 750MPa at 300℃⇒500MPa by cyclic fatigue), safer for 2.0×10^{14}ppp
- Reduction of Ductility reported with 0.24DPA
  - 6×10^{20}pot≈1DPA (?) Replacement cycle should be considered.



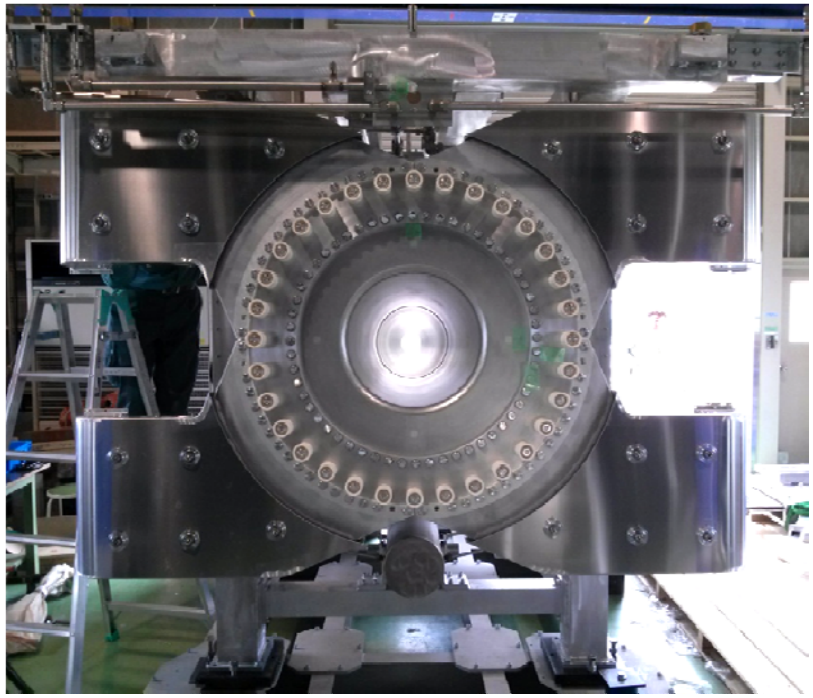




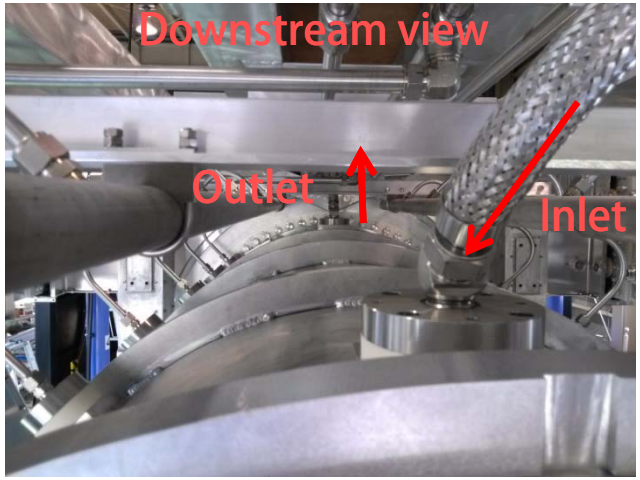


New electromagnetic horns

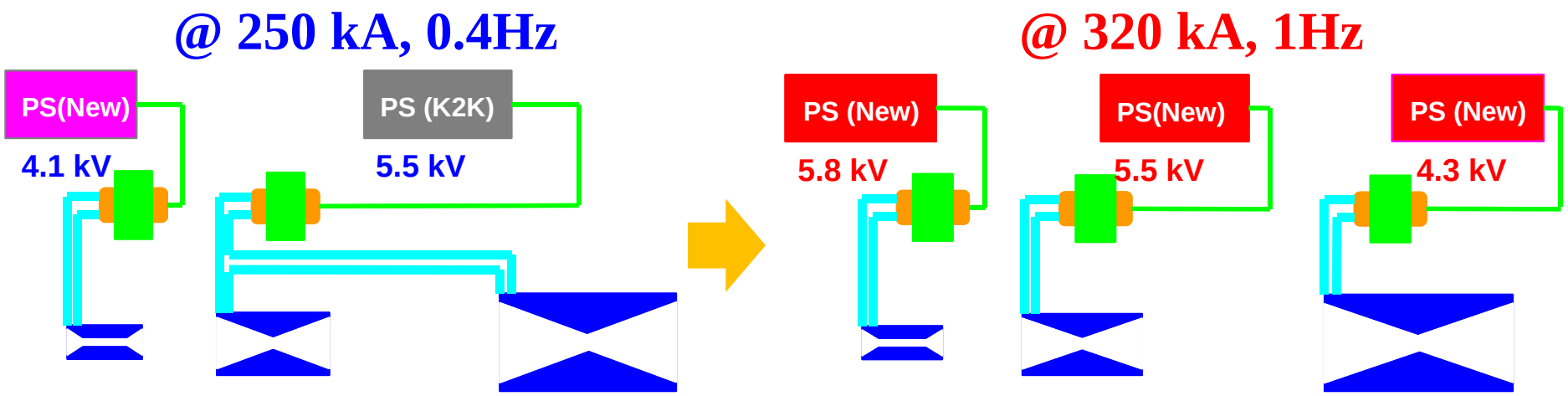
- Hydrogen problem
  - Two ports on outer conductor to circulate He
- Strip-line cooling
  - New strip-line ducts to achieve even He flow at each gap, no leakage at remote connection
  - ~1MW acceptable with doubled flow rate (reinforcement of compressor is necessary)
- Low impedance strip-line for 1Hz operation
  - Wider: 400mm → 600mm (or 500mm)
  - Narrow gap: 20mm → 15mm
  - 40% reduction in L and 30% reduction in R at whole strip-lines.



Spare Horn-2 produced at Univ. Colorado at Boulder



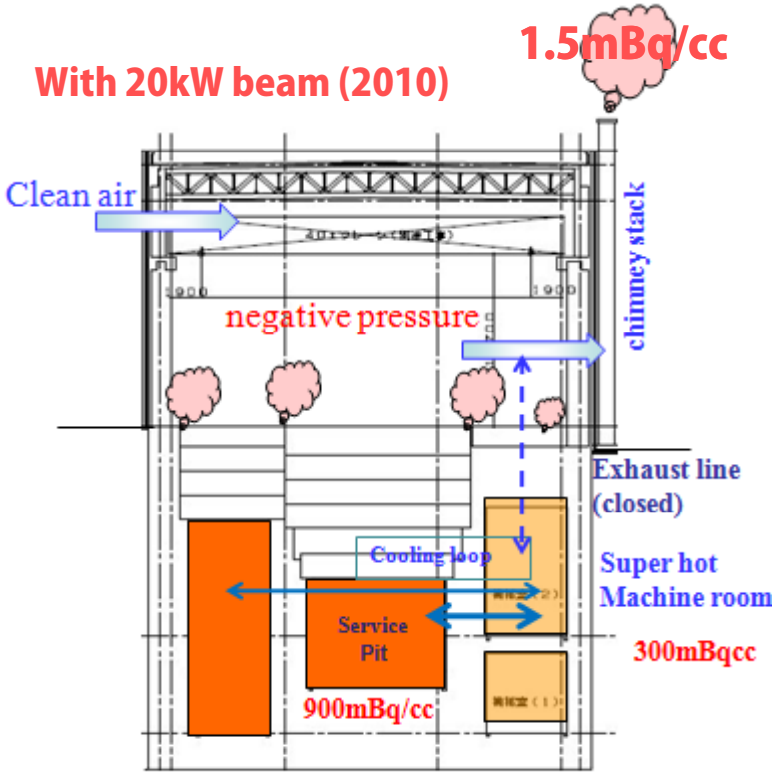
Upgrade of horn power supplies



- New power supply production for 1Hz operation
  - Designed for 320kA operation
  - Energy recovery (~50% of stored energy recycled)
  - Low input load
    - Each horn operated with individual PS
    - Low impedance strip-lines
- Production completed, operation scheduled in fall 2014
  - To be postponed due to tight budget situation

A New PS set up at NU2

Exhaust air at Target Station



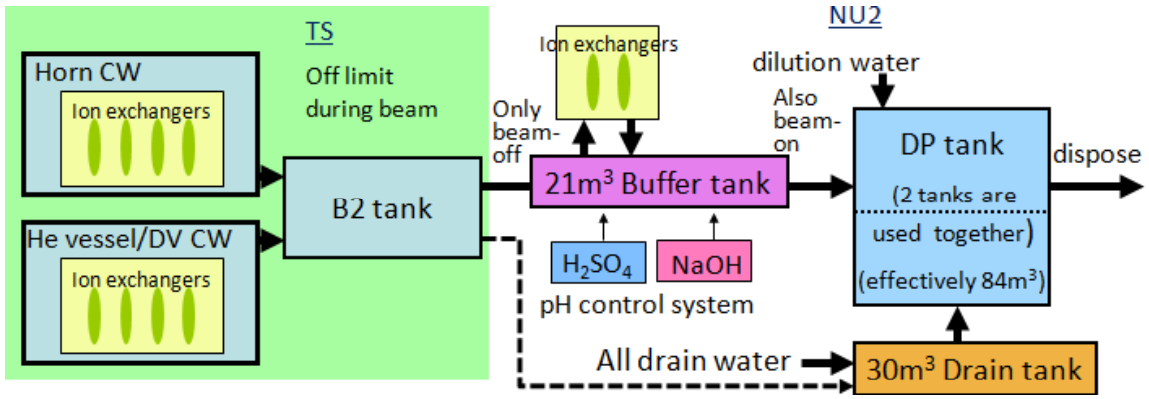
< 0.5 mBq/cc for 3 month average

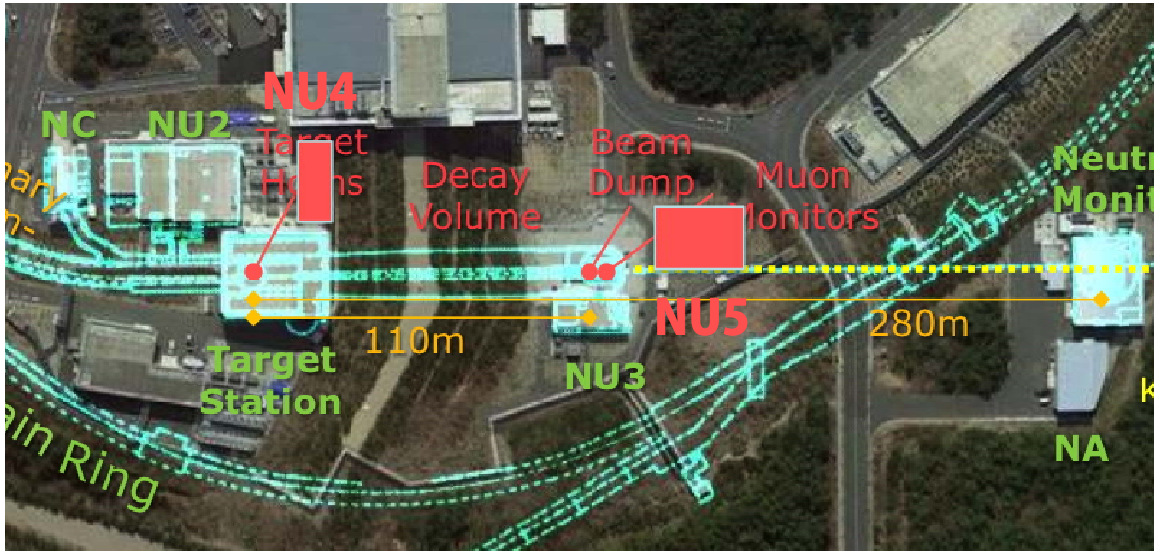
- Radiation in exhaust air of TS was being the bottleneck of beam power.
- By improving air-tightness of floor / through-going ducts / reinforce air ventilation system, acceptable beam is being improved by 2 order, now 500kW~1MW .

Cooling water dilution/drainage

- Disposal of radioactive cooling water
  - 400GBq ^{3}H produced for 750kW×120d
  - Dilution to 60(42)Bq/cc
  - FY2013: 73.2GBq (106kW×10^{7} sec eqv.)
  - Drainage from NU2(TS) =20 times, NU3=23 times, 3days each
  - Current capacity = ~600kW×100days
- Reinforce capacity of cooling power and irradiated water treatment
  - New facility buildings with large DP tanks are necessary

Effective removal of ^{7}Be by 99.99%





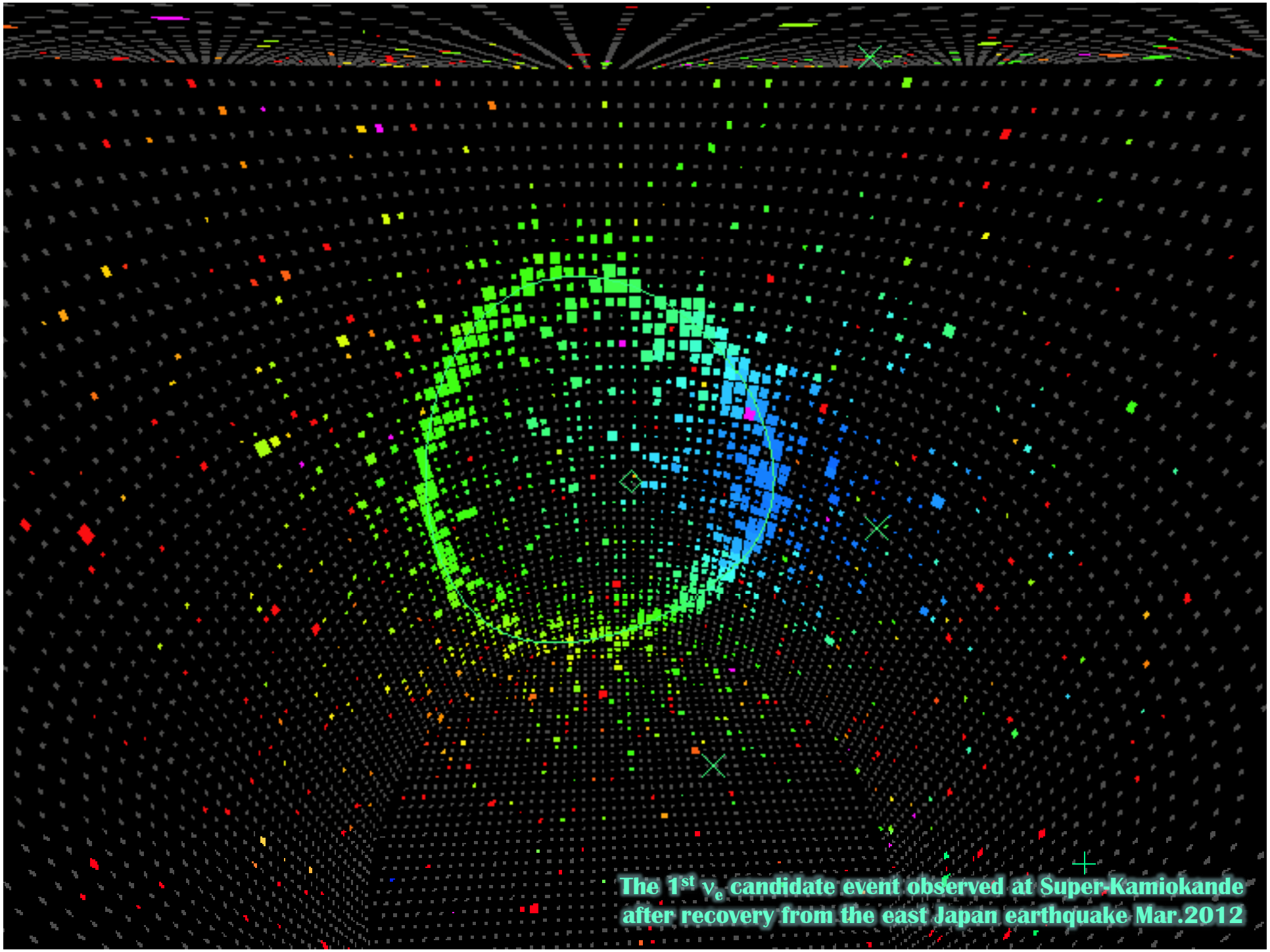
Present limit and prospect for upgrade

Component	beam power / parameter limitation	upgrade
target	3.3×10^{14}ppp	
beam window	3.3×10^{14}ppp	
horn		
cooling for conductors	2MW	
stripline cooling	400kW	1~2MW
hydrogen production	300kW	1~2MW
horn current	250kA	320kA
PS repetition	0.4Hz	1Hz
decay colume	4MW	
hadron absorber / beam dump	3MW	
water cooling facilities	750kW	~2MW
radiation shielding	750kW	4MW
radioactive air leakage to the TS ground floor	500kW	~2MW
radioactive cooling water drainage	600kW	~2MW

- Based on ~5yrs of operation experience, facility is ready to accept 750kW beam.
  - Doubled rep-rate scenario may allow us to go beyond 750kW !
- Facilities for radioactive waste treatment (drainage, exhaust) and cooling are the bottleneck.
  - Timely upgrade of the facilities is desirable.
- Apparatus which are inaccessible after beam irradiation (decay volume/beam dump, radiation shield) were designed to accept 3~4MW beam and working nicely.
- Upgrades of core apparatus (target/window/horn) may become necessary for multi-MW.

4. Summary

- Operational status of the neutrino experimental facility:
  - 230kW beam operation for the T2K experiment.
  - No essential troubles for critical components so far until Run-4 (May 2013)
  - Works to replace all 3 horns/target were completed in perfect manner.
  - Anti-neutrino mode running started since June 2014.
  - Accumulated *pot* : 7.39×10^{20}, including 0.51×10^{20} of anti-ν mode operation
- Based on ~5yrs of experience, facility is ready to accept 750kW beam.
- We think current design/technology of the facility is feasible for ~2MW:
  - Target / beam-window designed for RCS-1MW equivalent beam.
    - Doubled rep-rate: less thermal shock.
    - Study going on to what *ppp*/beam power current design can work.
    - Radiation damage on Ti-alloy may be the key for lifetime of beam windows.
  - Horns: many improvements, triple PS operation will be realized soon for 1Hz - 320kA operation. Better performance may be required for strip-line cooling.
  - New facility buildings with larger DP tanks for radioactive water drainage and higher cooling power are necessary.
- We have started international collaboration to realize multi-MW facility
  - SFTC RAL (target/window) / U.Colorado (horn) / FNAL(radiation damage)…


The 1st ν_e candidate event observed at Super-Kamiokande
after recovery from the east Japan earthquake Mar.2012