8th High Power Targetry Workshop
November 6-10, 2023

Target and cooling system for the high intensity neutrino beams at J-PARC

10 November 2023

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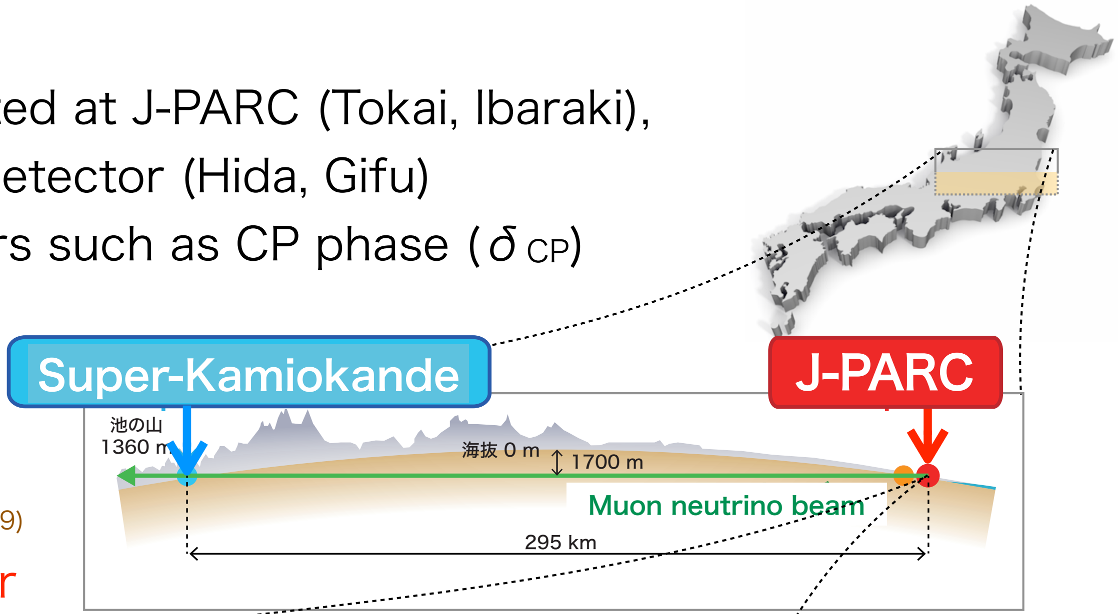
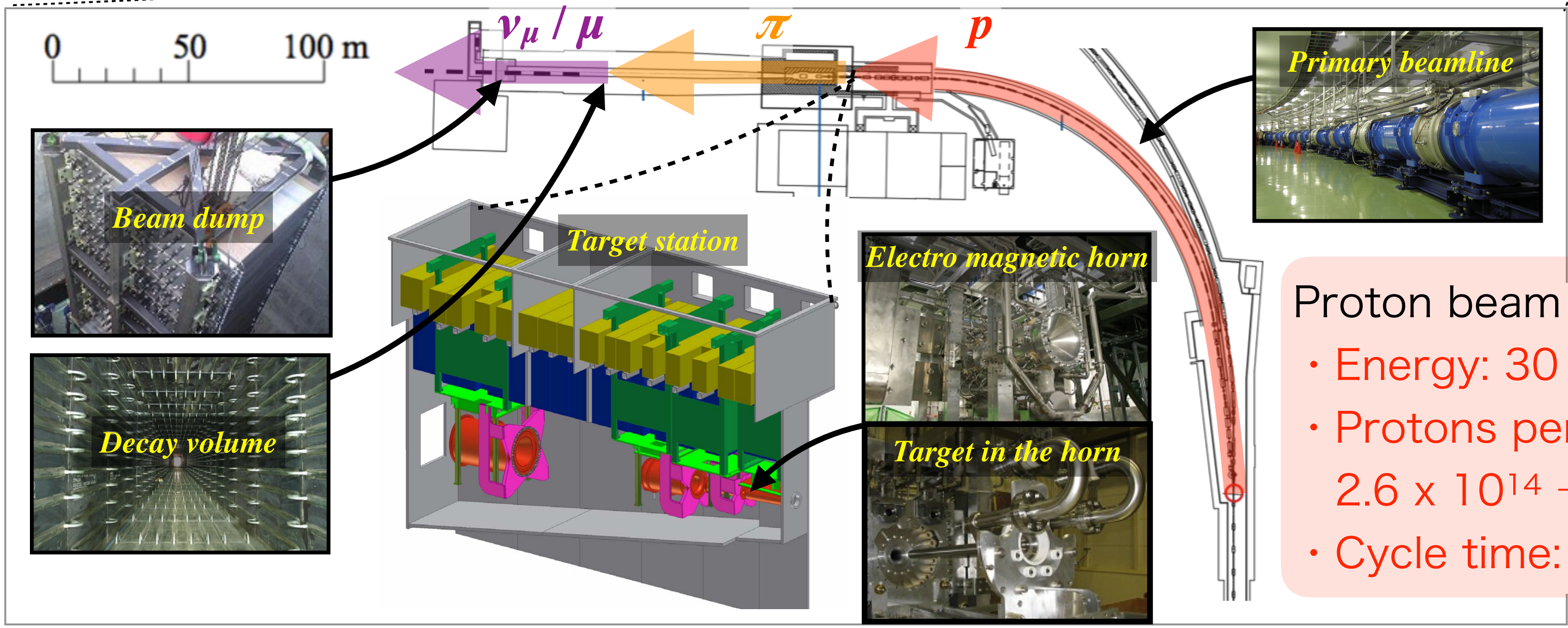
T2K experiment & ν beamline at J-PARC

High-intensity $\nu_\mu/\overline{\nu}_\mu$ beams are generated at J-PARC (Tokai, Ibaraki),
and observed at the Super-Kamiokande detector (Hida, Gifu)
to measure neutrino oscillation parameters such as CP phase (δ_{CP})

Showing the strongest δ_{CP} constraint
w/ a hint of CP violation at ~90% C.L.
using ~500 kW beam power (Nature **580** (2020) 339)
→ More statistics w/ 1.3 MW beam power

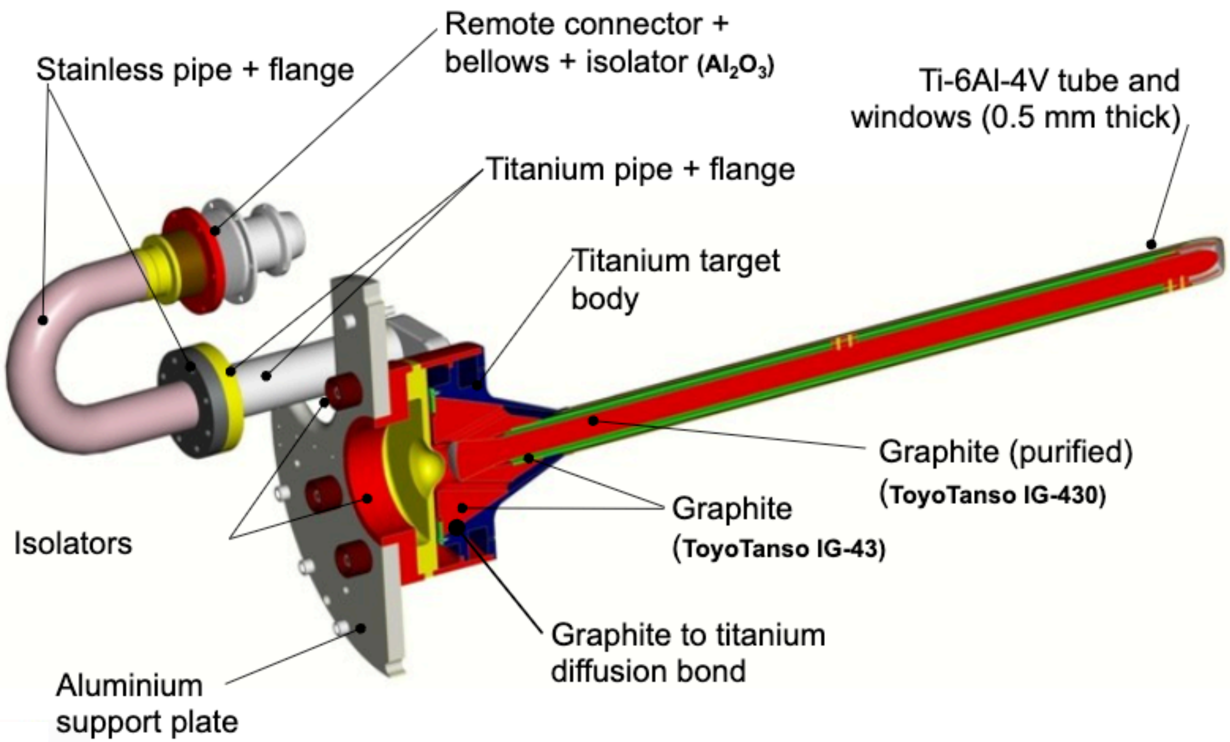


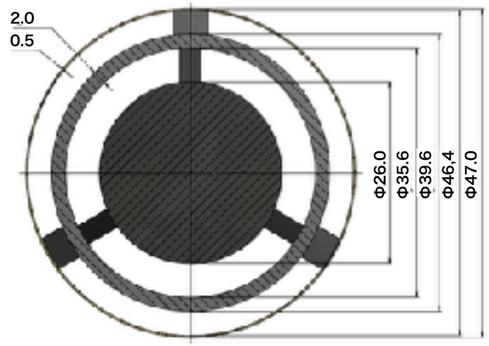


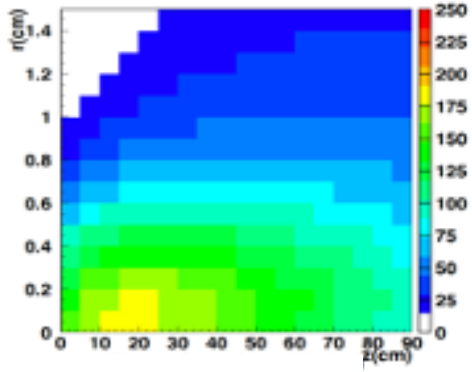
Proton beam toward 1.3 MW

- Energy: 30 GeV
- Protons per pulse: $2.6 \times 10^{14} \rightarrow 3.2 \times 10^{14}$
- Cycle time: 2.48 s → 1.16 s

T2K Target - design concept





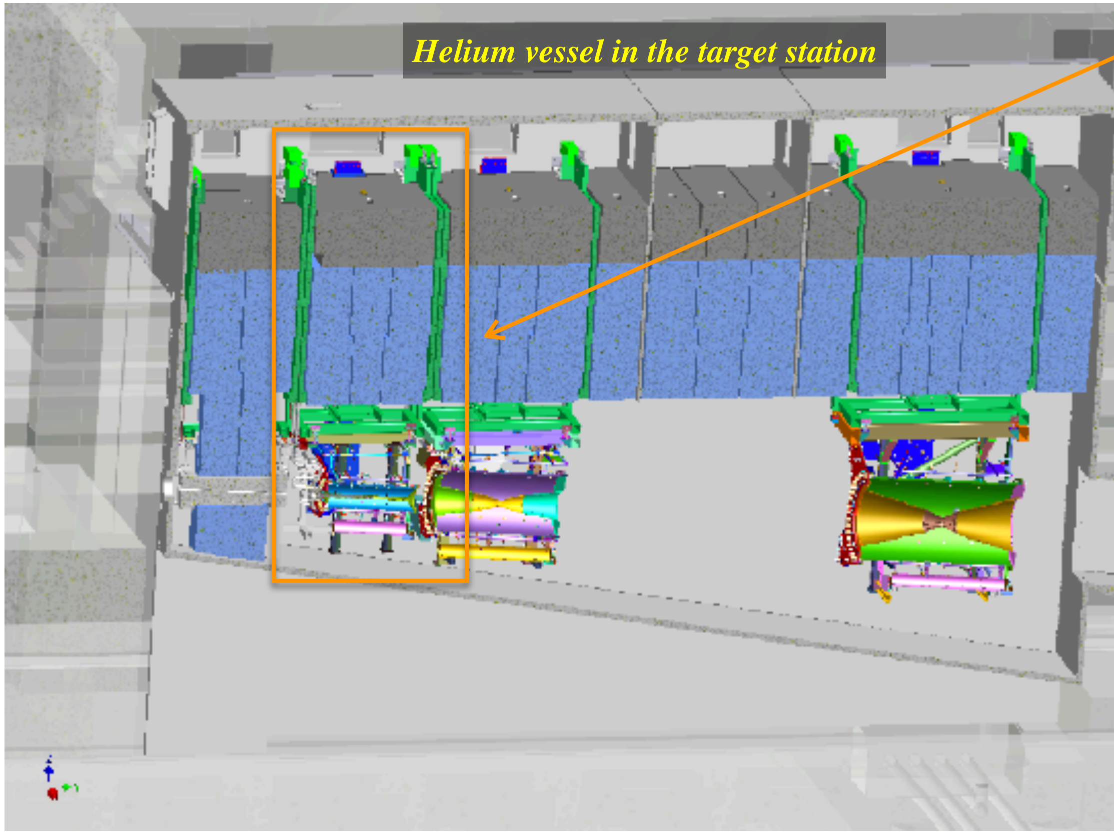


Simulated energy deposition (J/g/pulse)
for proton beam (3.3 x 10^{14} ppp)

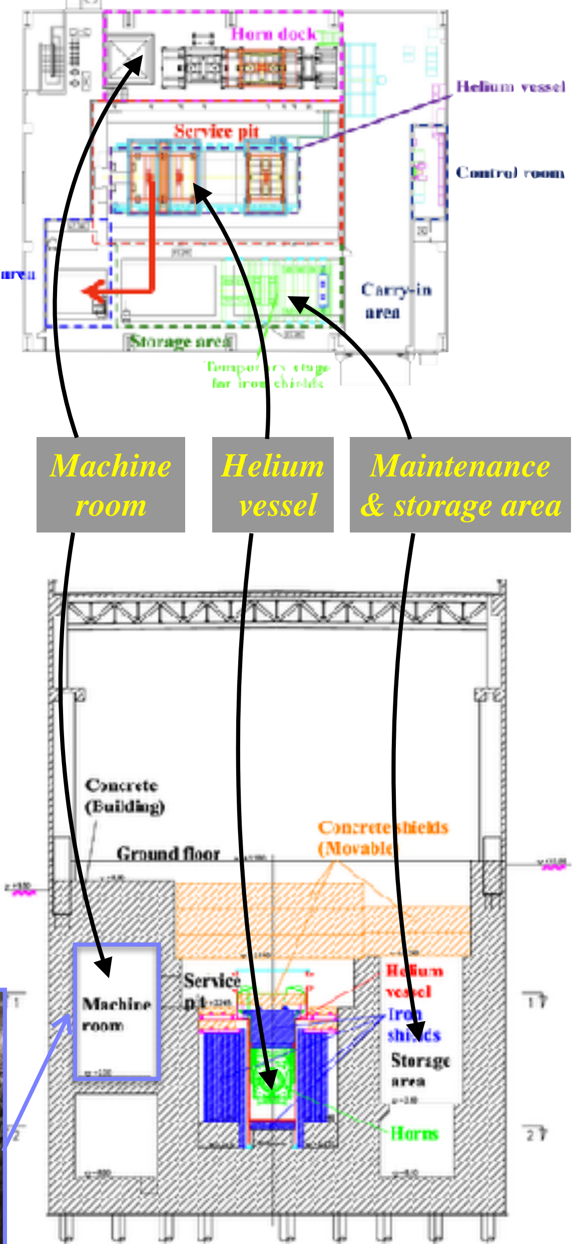
- Isotropic graphite
  → Low density for low heat generation density. Thermal shock tolerance. Radiation hardness
- ~90 cm long (~2 X_0) & 26 mmΦ (σ_{beam} = ~4.2 mm) → Maximizing pion yield
- Cantilever → To accept graphite shrinkage
- Co-axial two pipes, Ti-alloy (Ti-6Al-4V) container, up/downstream window
  → For single side Helium gas cooling from upstream
- He cooled
  → To minimize pion absorption. To avoid heat generation of refrigerant.
  → To all higher operating temperature (above 400℃ to reduce radiation damage in graphite)

Layout of the target & cooling system

- Target installed inside Horn-1 in the Helium vessel
- Helium compressor for cooling is located at the machine room
- Remote exchange is conducted in the maintenance area



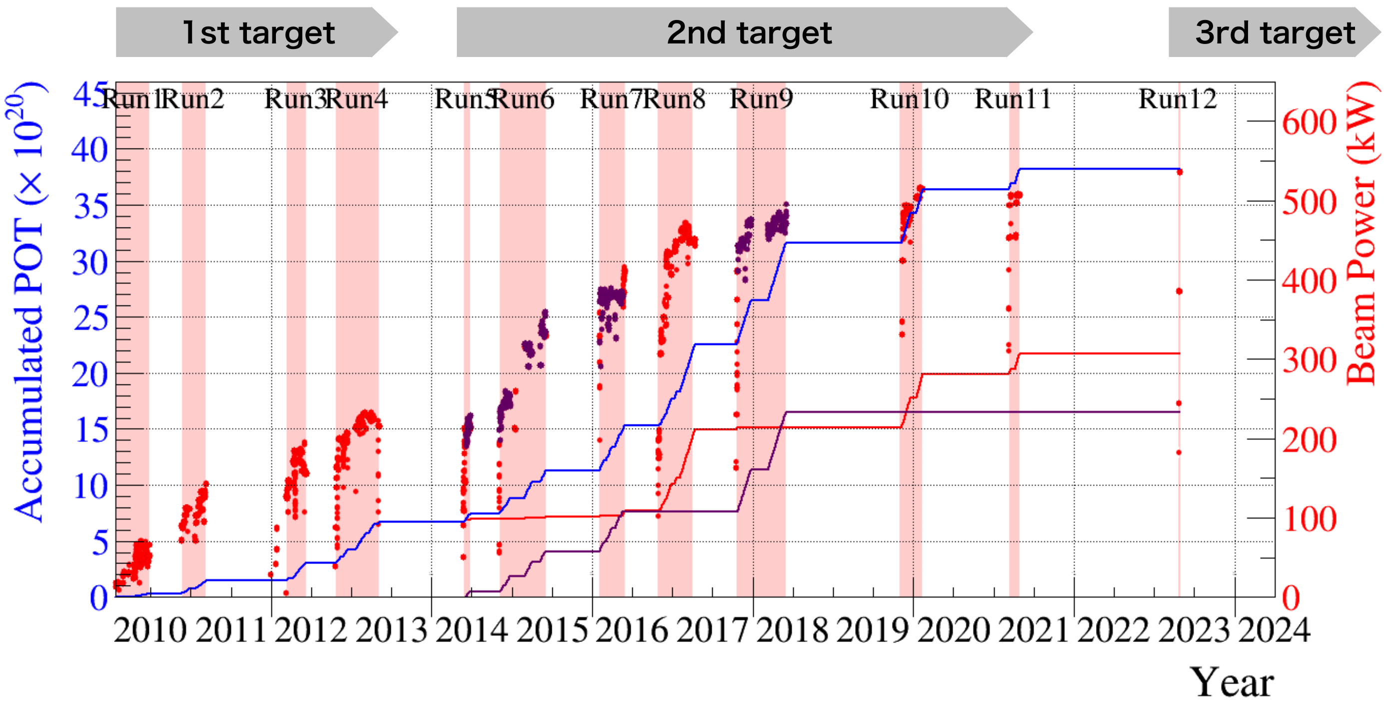
Target station (Top view)

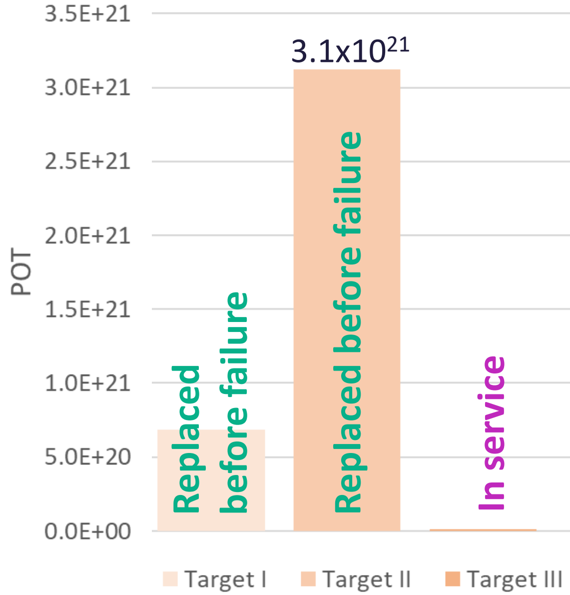


Target station (Side view)

Operation history and future

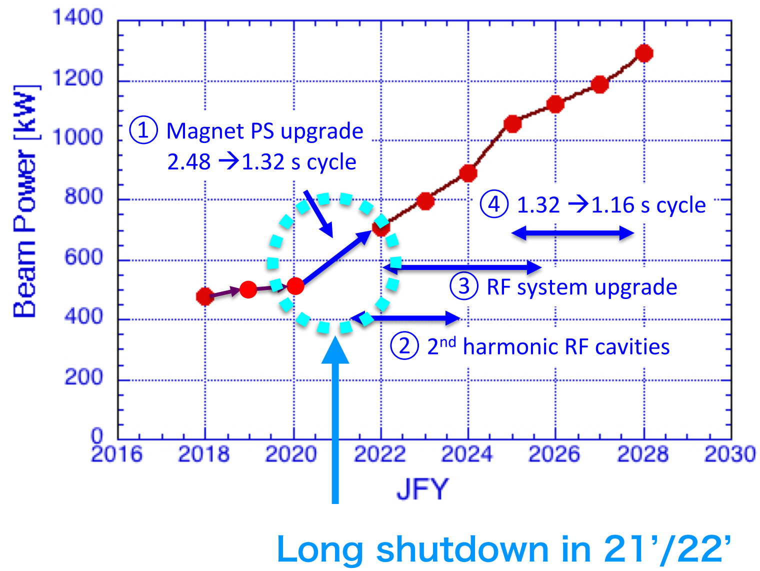
(*) POT: Proton on target





Exposed POT for each target

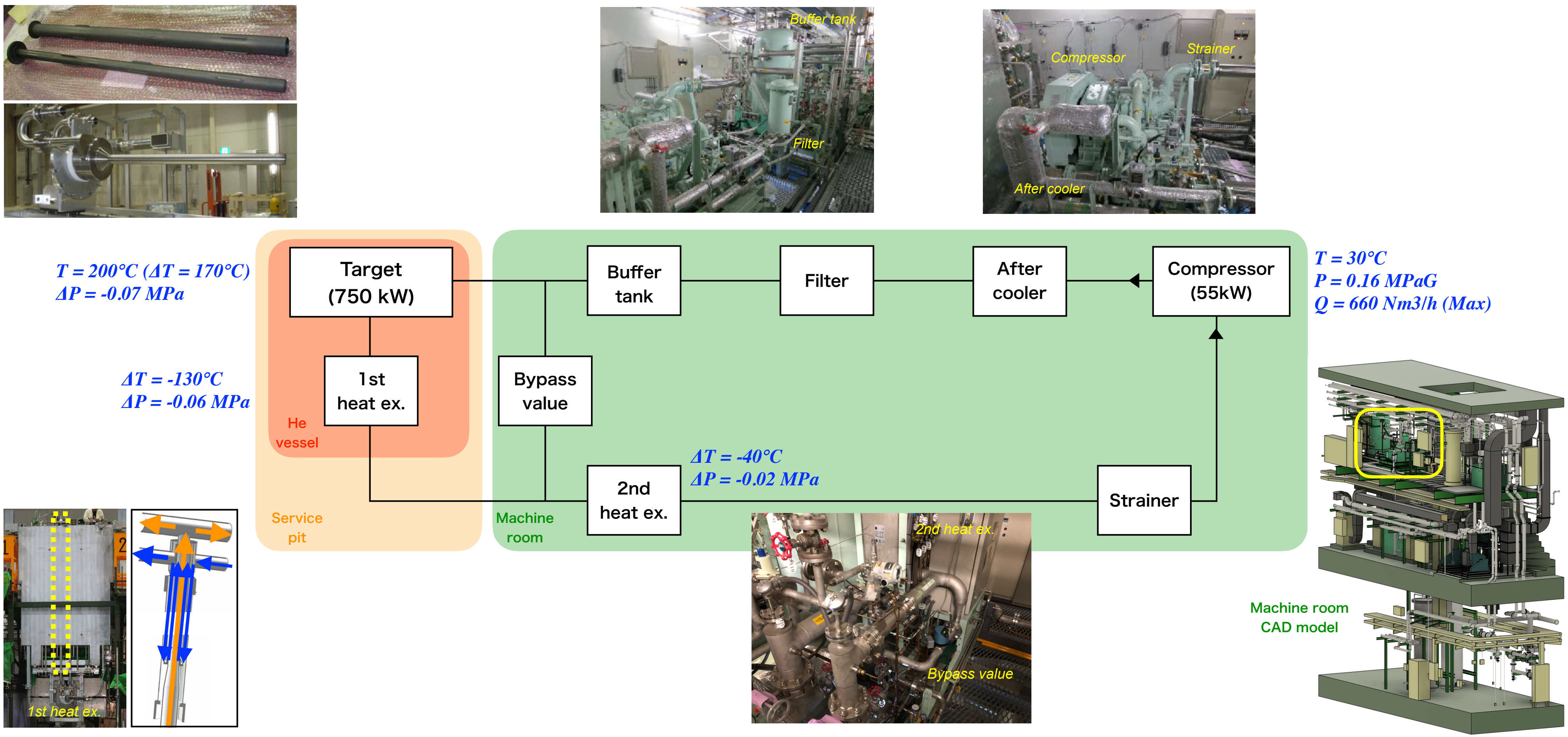
	1st target	2nd target	3rd target
Period	09' Apr. ~ 13' May	14' Nov. ~ 21' Apr.	22 Apr. ~
POT	0.7×10^{21}	3.1×10^{21}	0.01×10^{21}
Max. beam power	~230 kW	~490 kW	~540 kW
Comment	· No significant trouble · Replaced with horn-1	· He leak at ceramic part and fixed in 15' · Replaced with horn-1	· To be remotely exchanged in 25' for 1.3 MW



Neutrino event rate (POT normalized) monitored by T2K near detector is stable so far → Target is fine

Current Helium gas cooling system

Current target cooling capacity : 750kW + 20% margin = 900 kW (Beamline upgrade TDR: arXiv:1908.05141)

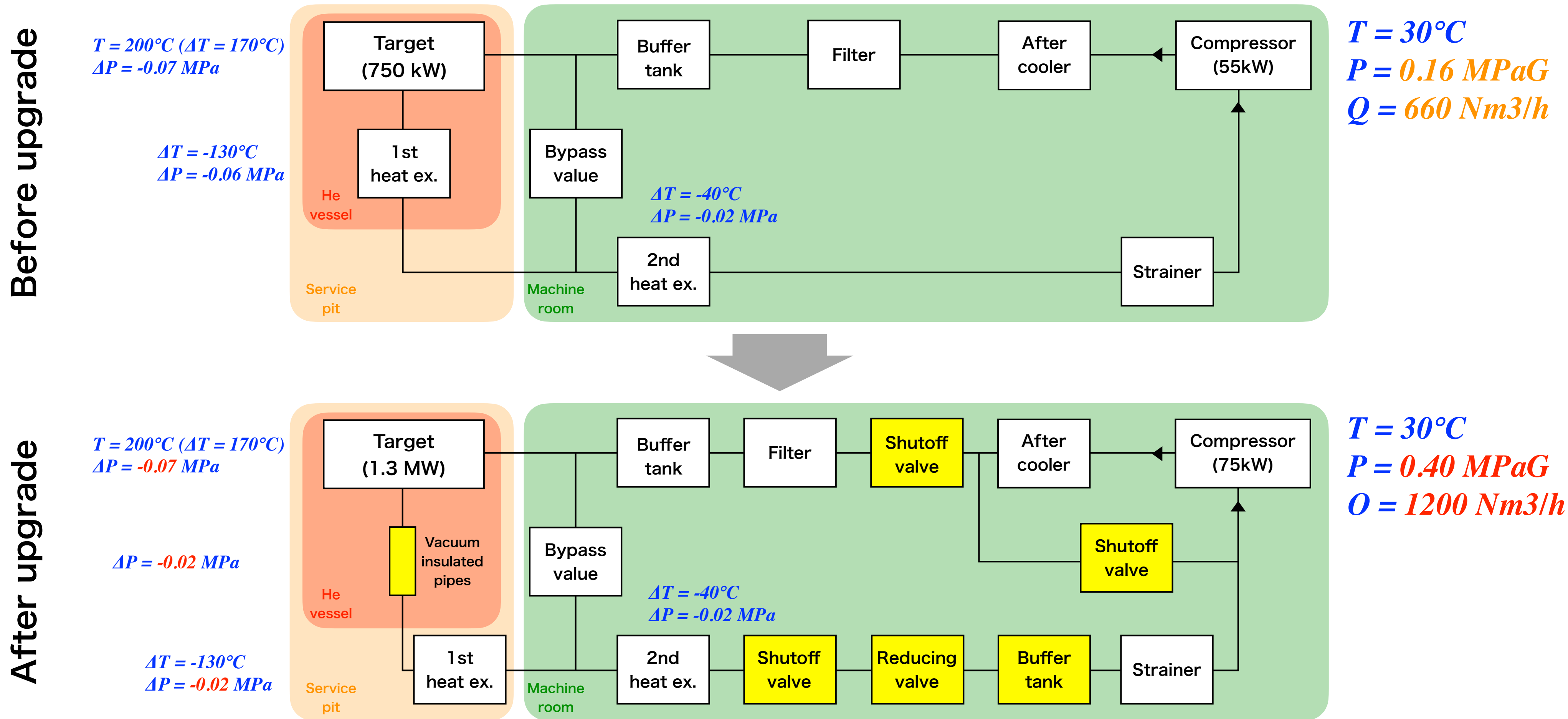


- Need to have doubled mass flow rate, i.e. 32 g/s (660 Nm3/h) → 60 g/s (1200 Nm3/h), but we can not just increase flow rate due to pressure drop and Helium velocity
  → Increase operating pressure

Upgrade to increase operating pressure

- All components to be renewed for the high pressure tolerance/operation by 2025

e.g. 1st heat exchanger pipe was exchanged to vacuum insulated pipes + heat exchanger

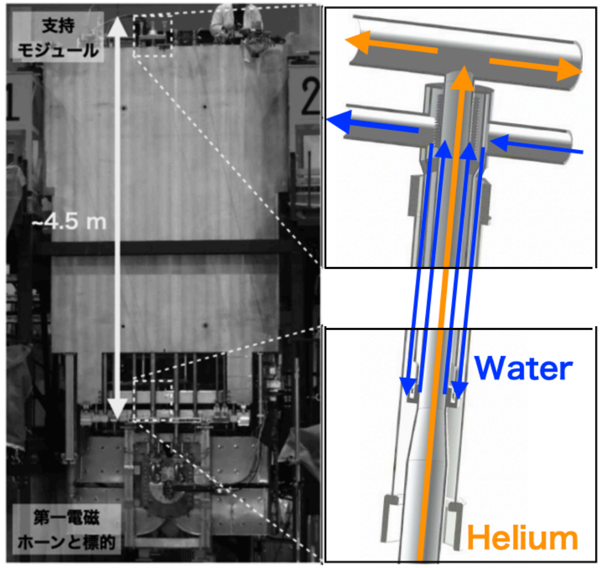


New components in the machine room to be installed in 25'

- Shut off vales : For star-delta starter (reduced current but no load operation required)
- Reducing valve : Required to protect compressor inlet (< 0.4 MPaG)
- Buffer tank : Required to have reduced filling pressure (~0.3 MPaG)

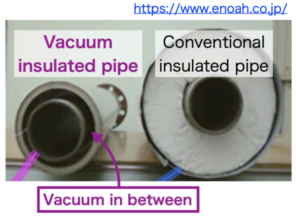
Challenges to exchange the 1st heat exchanger

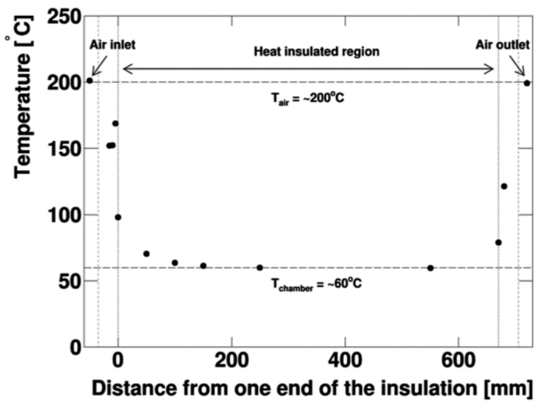
- The original first heat exchanger in the support module
  - Pipes & bellows rated up to 0.2 MPaG operation
    → Need to replace
  - Water cooled with cylindrical structure (gas, water, water, wrench)
    → Large pressure drop due to small inner diameter (ϕ23.9)
  - ϕ65 outer diameter in ϕ70 hole in the radioactive steel plate
    → Constraint of mechanics & radiation
  - Located in the Helium vessel
    → Difficult to maintain. Tritium production in water



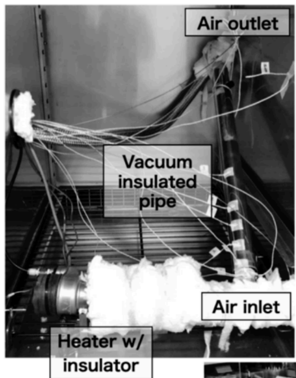
- Developed new scheme w/ vacuum insulated pipe
  - Higher pressure tolerance
  - Enlarged diameter (ϕ23.9 → ϕ30.7) for low ΔP
  - New heat ex. at outside Helium vessel

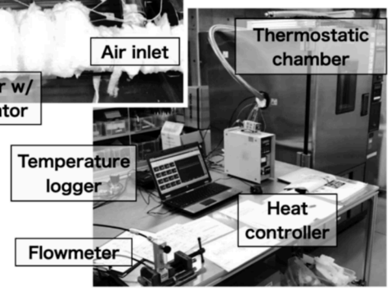
https://www.enoah.co.jp/





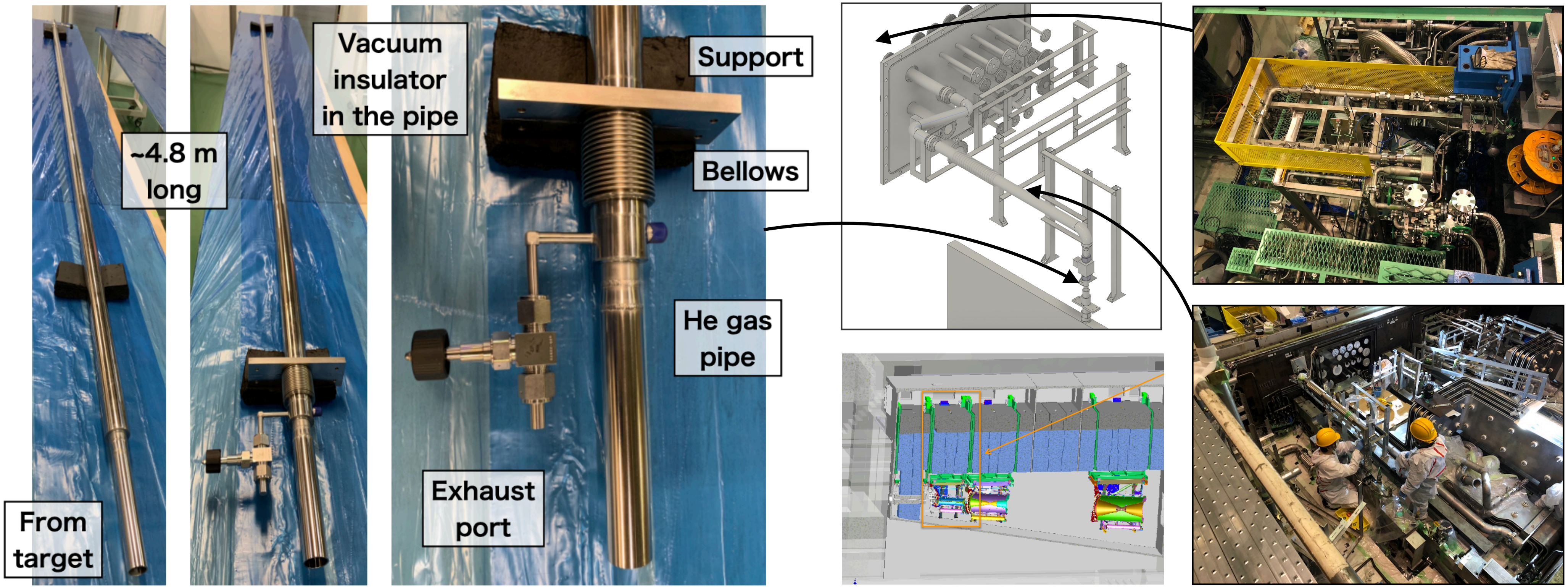
- Produced small prototype
  - Tested with a air with heater in a chamber
  - Showed an excellent insulation performance





Upgrade work in the last long shutdown

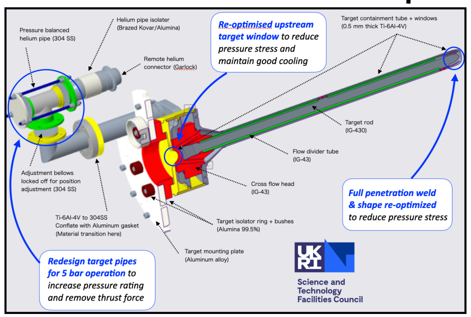
- Produced new insulated pipe with 4.8 m long & other 3 pipes in the Helium vessel
- Dismantled the old 1st heat exchanger by cutting top part (less radiated)
- Install new pipes with other upgrade works like horn and target replacement
- Installed new heat exchanger outside Helium vessel

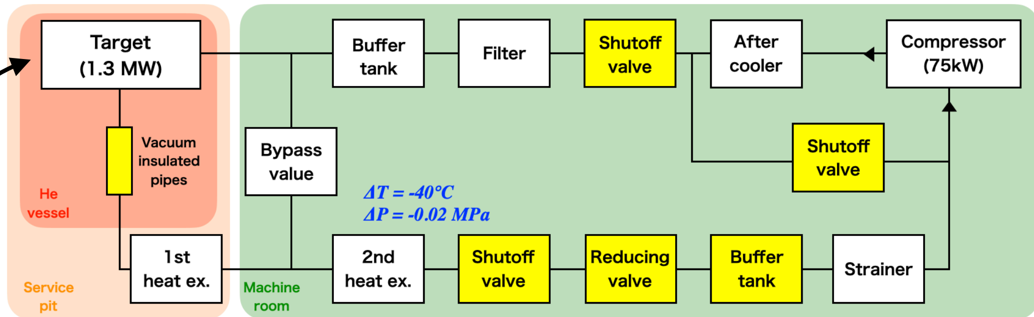


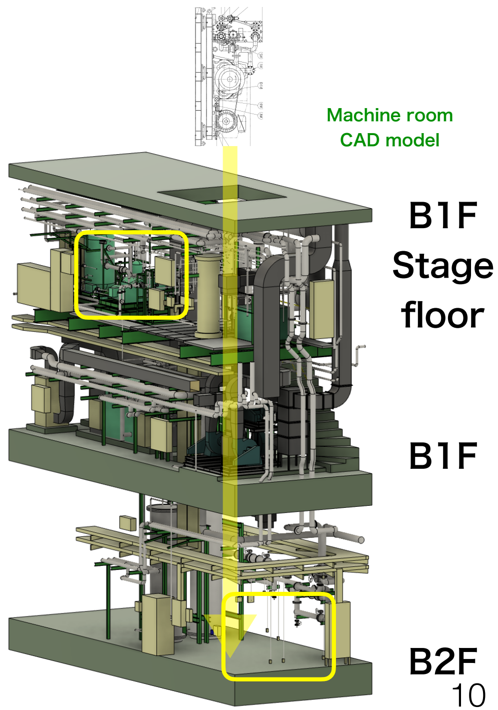
- Already confirmed insulation performance in the beam operation this year up to 540 kW

Plan to complete upgrade in 2025

- 1.3 MW target production well in progress (as presented by Mike on Tuesday)
- New compressor and filter unit for high outlet pressure (0.4 MPaG) was delivered
- Now developing the new circulation system to have commissioning work in 2024
- Making installation plan carefully to fit existing facility







Estimate of target oxidation by the He cooling gas

Question: How much carbon consumed by oxidation?

- Allowed target loss reduction by design is 2%, i.e. ~17 g out of 869 g (target-rod mass)

Gas impurity measurement of O_2, CO, CO_2 H_2, CH_4, N_2 by a gas chromatography system in the Target station

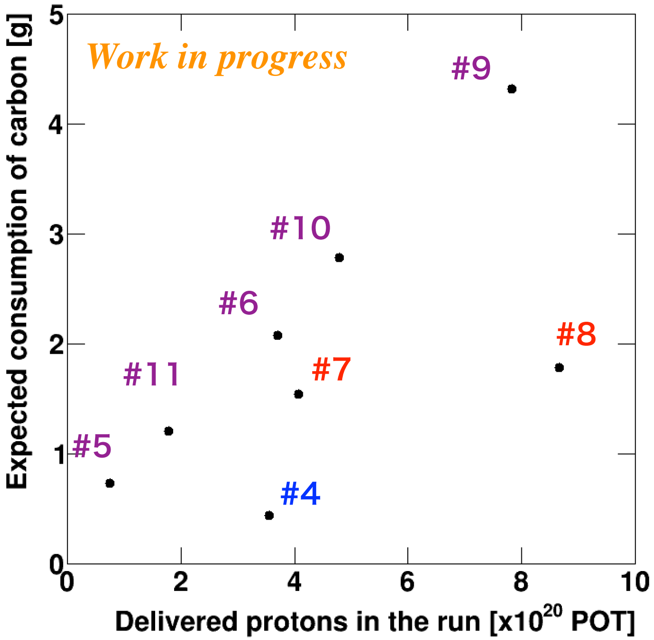
- System based on GC2014 (SHIMAZU CORPORATION)
- Operating since 2013 (in the middle of Run #4)
- Before beam operation, high purity He gas is filled, targeting to control O_2 contamination with ~1 ppm

Oxidation is estimated from CH_4, CO, CO_2 contamination after the beam operation

→ ~2% loss after ~3 x 10^{21} POT (equal to 1.3 MW x 6 months operation) if we ignore outliers and assume naive extrapolation

→ Overestimating? Carbon may comes from other parts like a slider of the compressor.

To be checked with more data with a high repetition rate



Summary

- Target and cooling system for the T2K experiment is in operation since 2009, accumulating experiences for the high intensity neutrino beams at J-PARC
- Beam power upgrades beyond original design requires replacement of the target and cooling system to increase operating pressure of He cooling gas
- Upgrades of cooling system in progress. Vacuum insulated pipes were adopted to realize the high pressure tolerance and low pressure drop in a confined space
- Completion of the upgrade foreseen in 2025 after commissioning and installation of the new circulation system in the machine room
- Estimation of target oxidation from impurities in the He gas was performed. To be evaluated more in the future operation with the higher beam power

Backup

He gas measurement so far

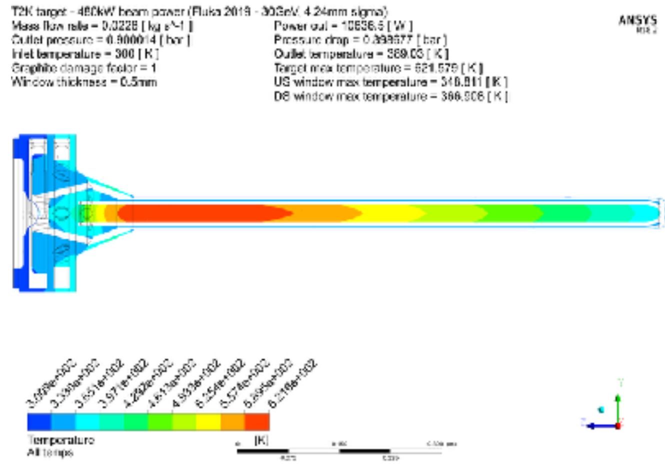
- He gas temperature is measured during beam operation
  - 490 kW beam, He flow ~ 25 g/s → ΔT_{Helium} ~ 72K
- Latest simulation with FLUKA (2019) & ANSYS
  - 480 kW beam, He flow 23 g/s → ΔT_{Helium} ~ 89K

  (*) Simulated ~145K with MARS (2006)

→ No significant discrepancy

NOTE: Naive explanation based on the latest measurement shows that we can increase the power beyond 900 kW before 25'. But we have to check it with larger power in the Nov./Dec. run. Some margin by He flow rate (550 Nm^3/h), filling pressure (~0.17 MPaG).

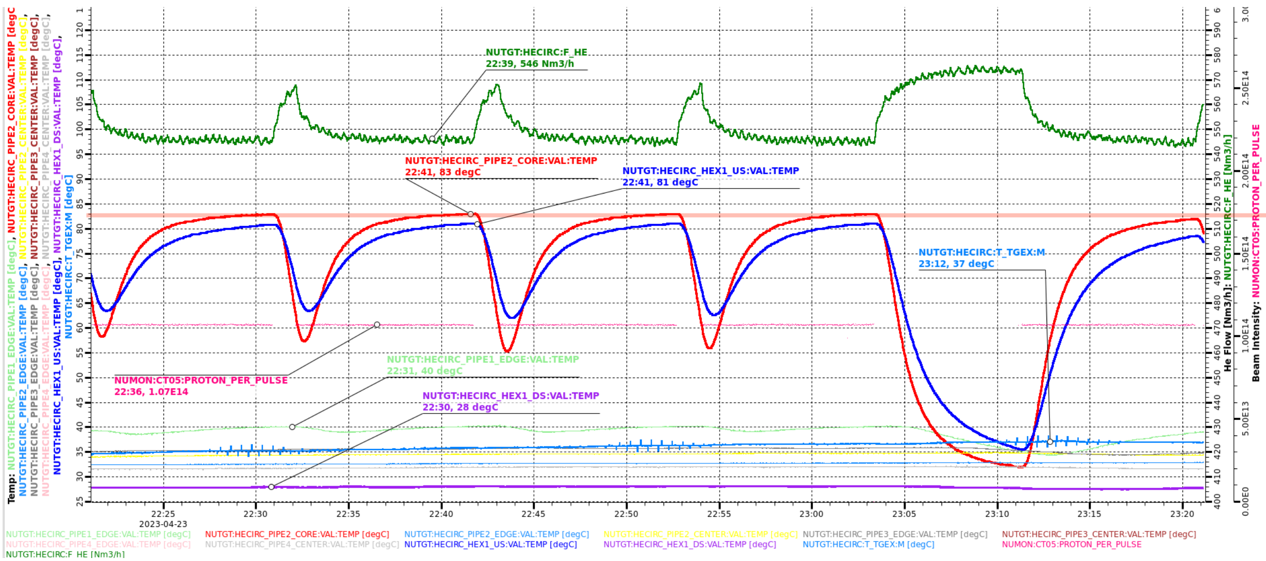
FEM



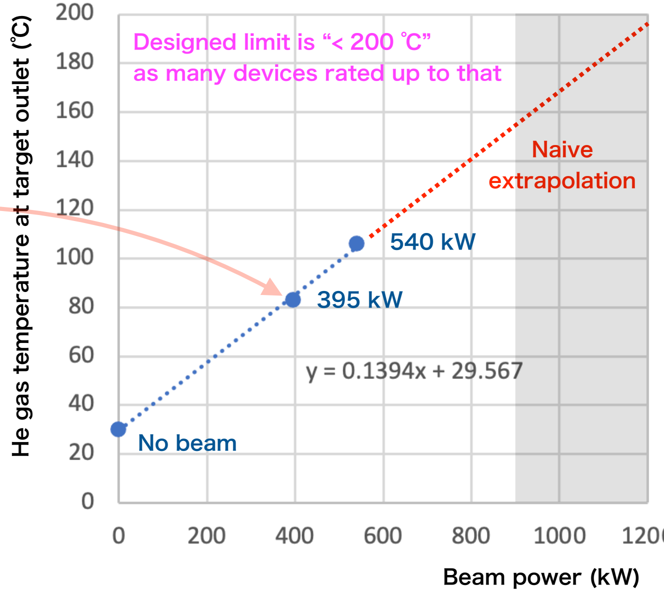
480kW 22.8[g/s] No. Rad. damage

He: 300K→ 389K

Graphite: 622K max.



An example of the latest monitor during 395 kW operation in 23' April (After replacement of the 1st heat exchanger)

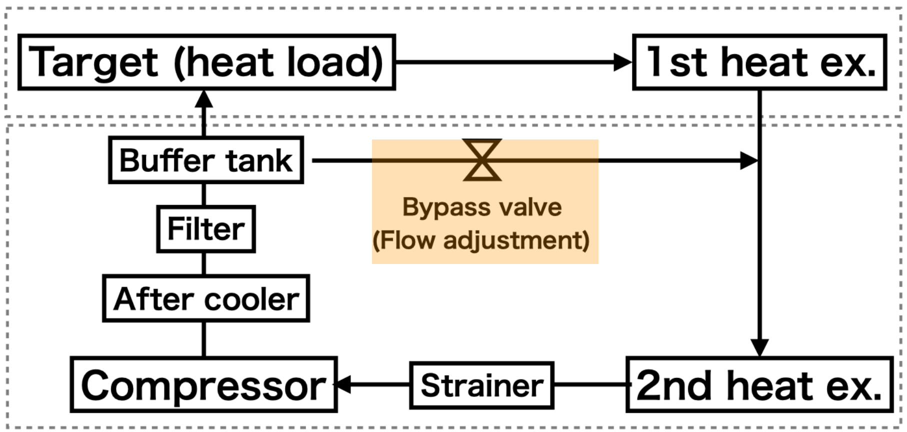


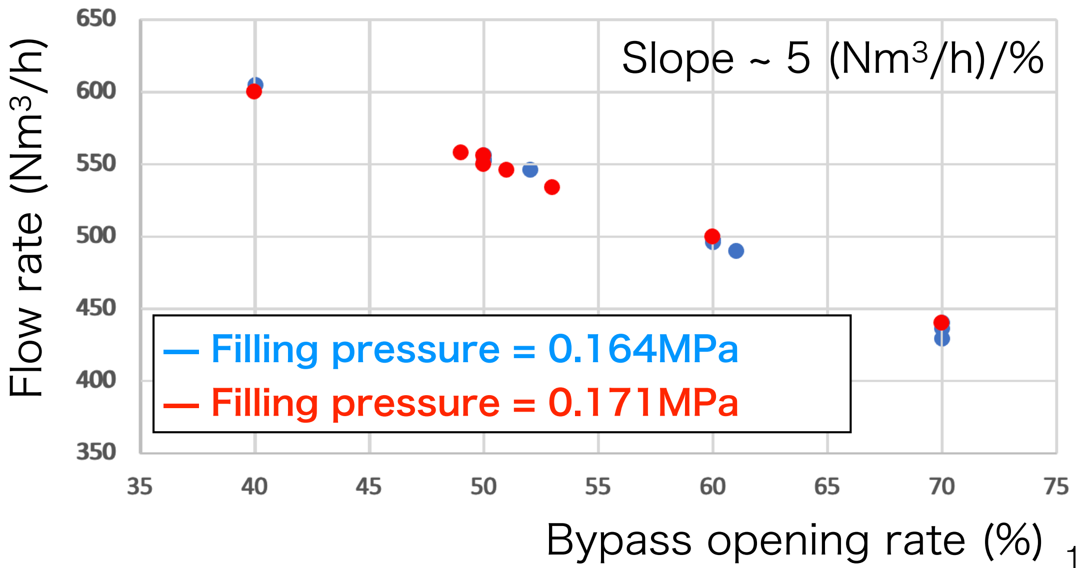
Flow rate setting (discharge pressure, bypass opening rate & fill pressure)

How to adjust the flow rate in the current circulation system:

1) Set discharge pressure (e.g. 0.165 MPaG) of the Helium compressor
2) Bypass opening rate is changed (Automatic mode in [0, 100]%)
3) Flow rate changes accordingly

Checked flow rate varying bypass opening rate to know the optimal setting
→ Linear correlation between between those
→ Not affected by filling pressure (unless it has sufficient pressure for discharge)
→ Decided appropriate settings to provide flow rate of 560 Nm^3/h for 750kW

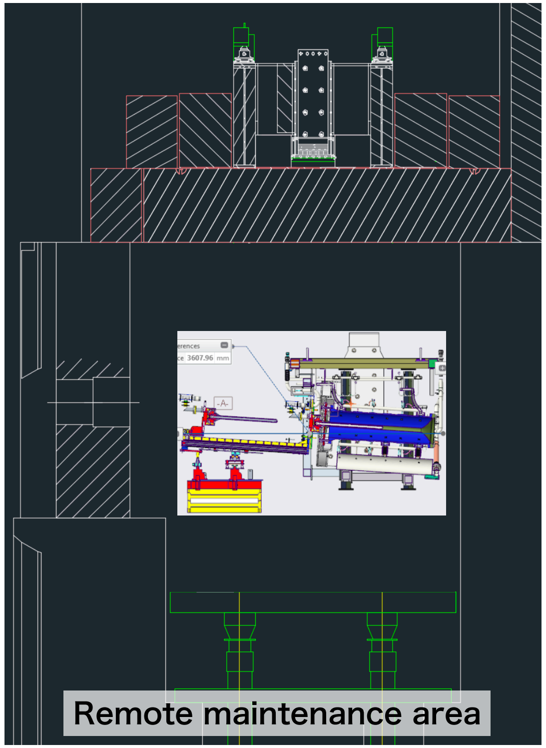


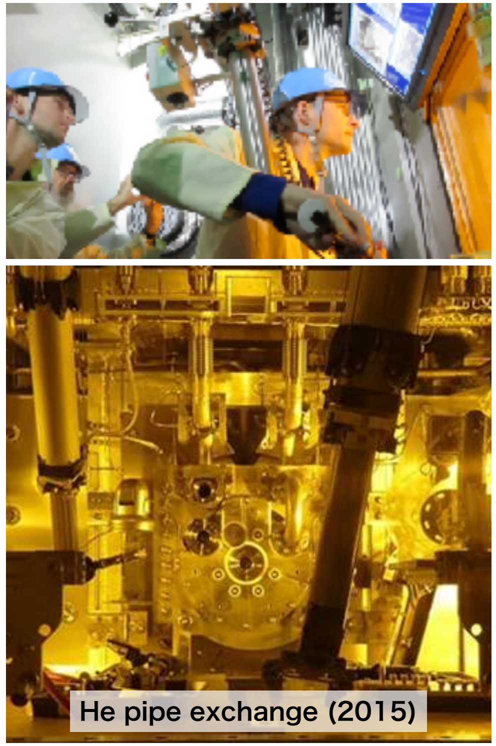


Target remote exchange

We will have to remove/install the targets remotely to the highly radioactive horn
→ This allows the large and expensive magnetic horn in which the target is installed to be reused, saving money and reducing radioactive waste.


Exchanger commissioning (2009)


Remote maintenance area

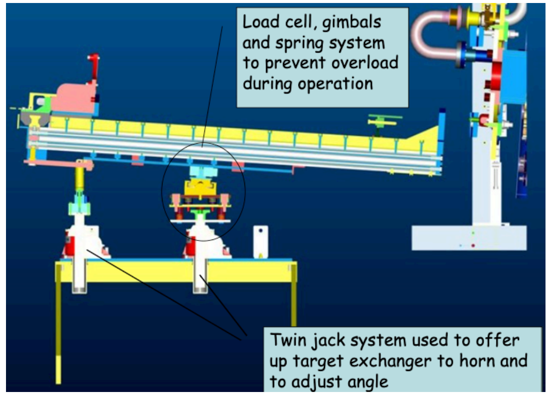

He pipe exchange (2015)

Challenges to exchange targets :

- The clearance between the target and horn bore is only 3 mm
- Target is ~1 m long and contains delicate graphite components

→ Designed/developed a "remote exchange system" which permits targets to be safely and quickly replaced using master-slave manipulators in a remote maintenance area

Target exchanger



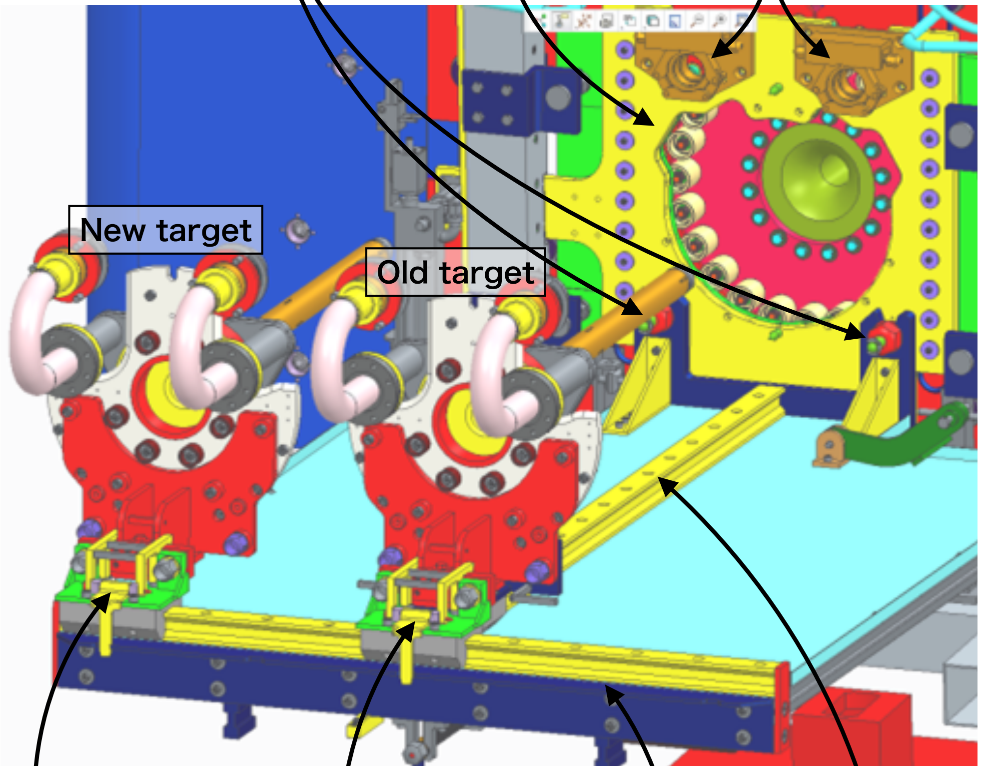
Two taper nuts

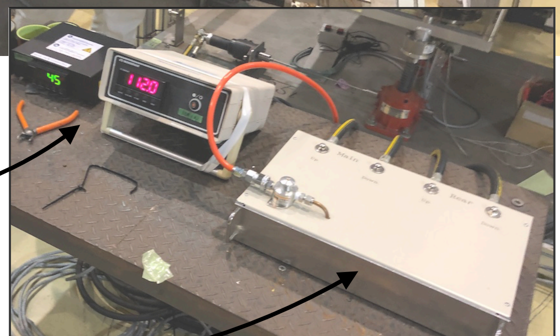
Target plate

Clamp bolts

Power jacks (central/rear)

Target-horn touch wire





Carriage (LH)

Carriage (RH)

X-axis rail

Z-axis rail

Load cell and monitors

Lift table controller