Development and Operational Experience of T2K Magnetic Horn for over-MW Beam

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NuFact 2018, 20th workshop on neutrinos from accelerators, Virginia tech

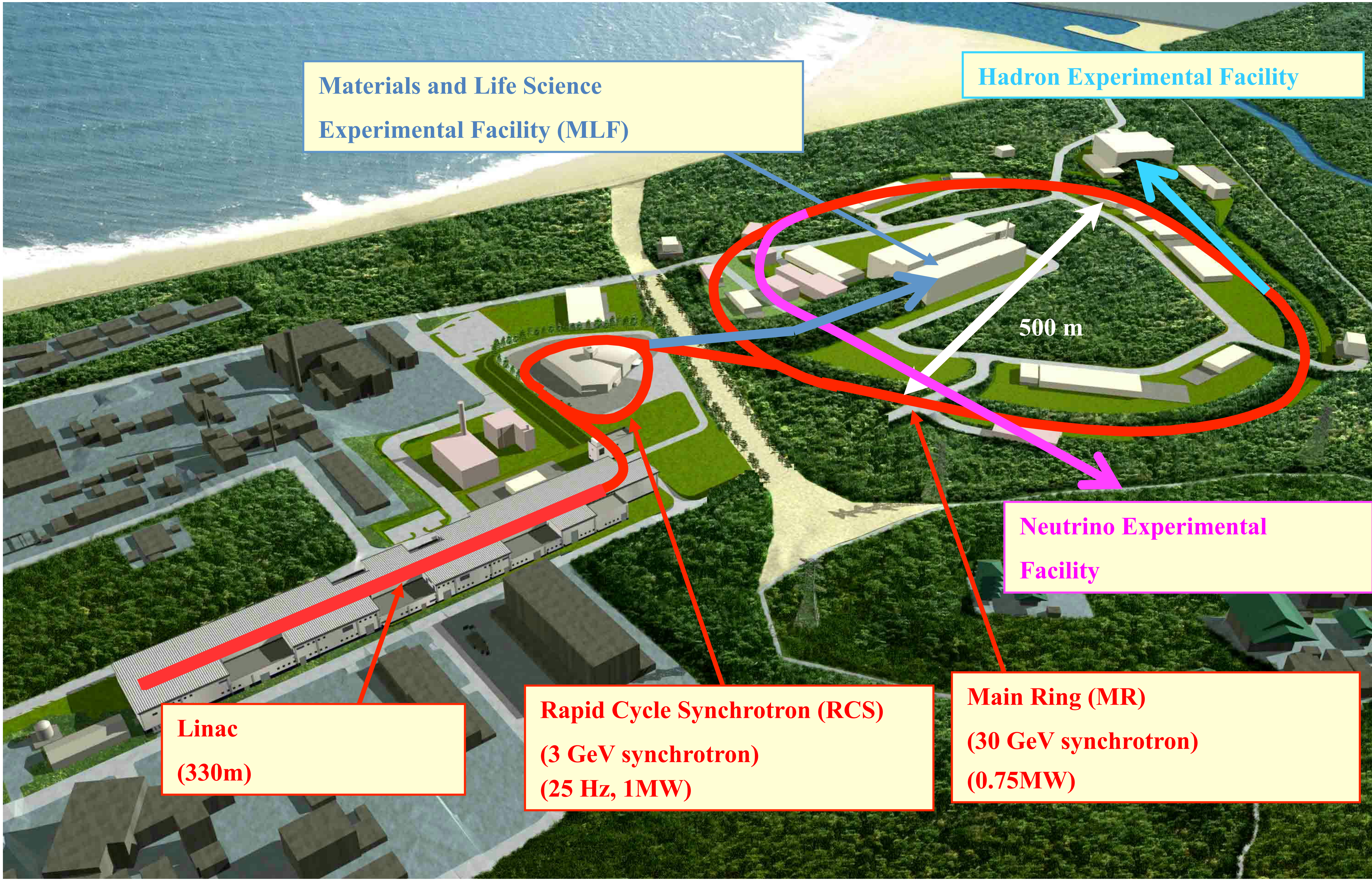
Contents

Introduction

T2K Experiment

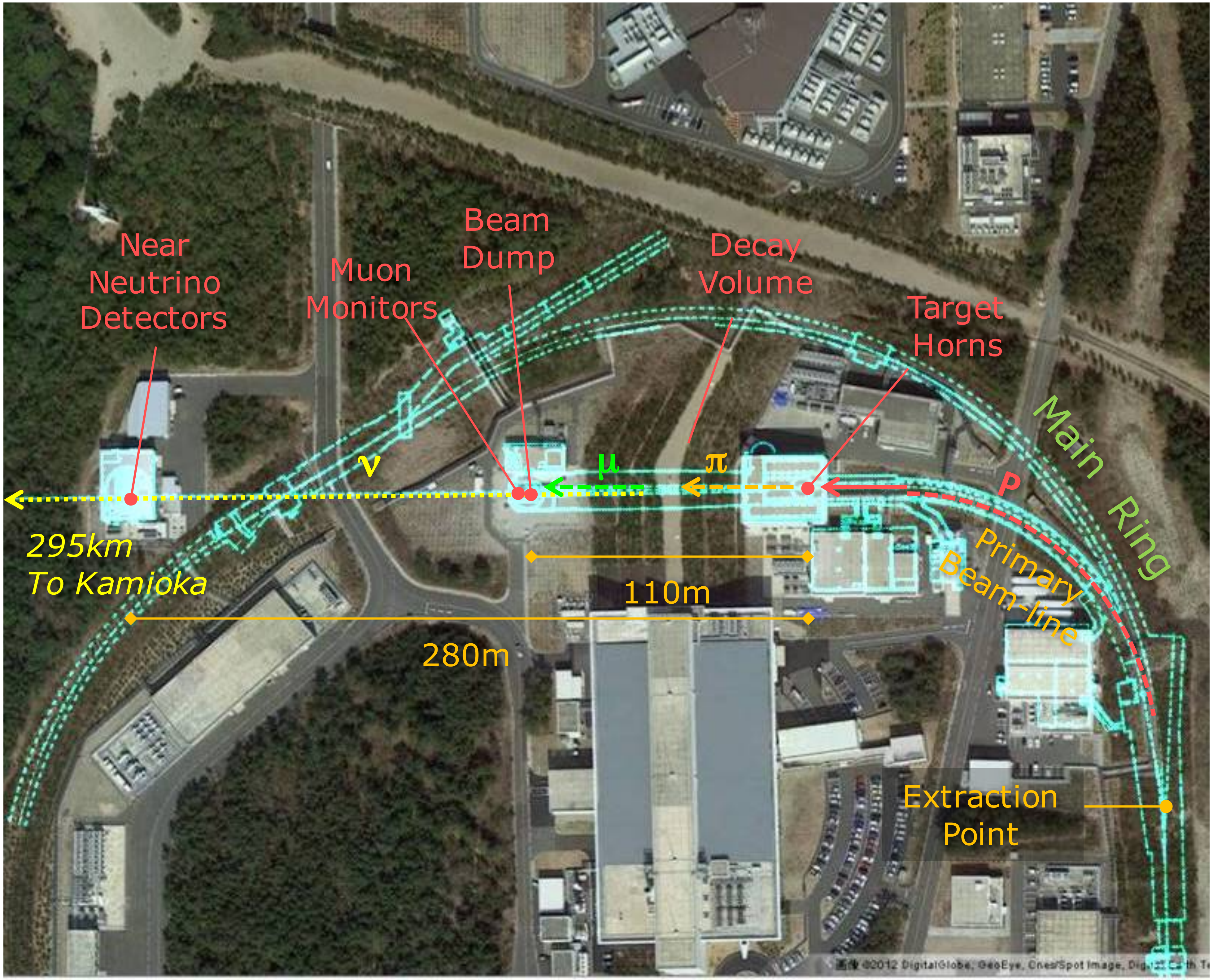
- **Physics motivation**
  - **Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance) → done in 2013**
  - **Precise measurement of θ_{23} and Δm^2_{23} → now in progress**
  - **Search for CP violation in neutrino sector → now in progress**

J-PARC



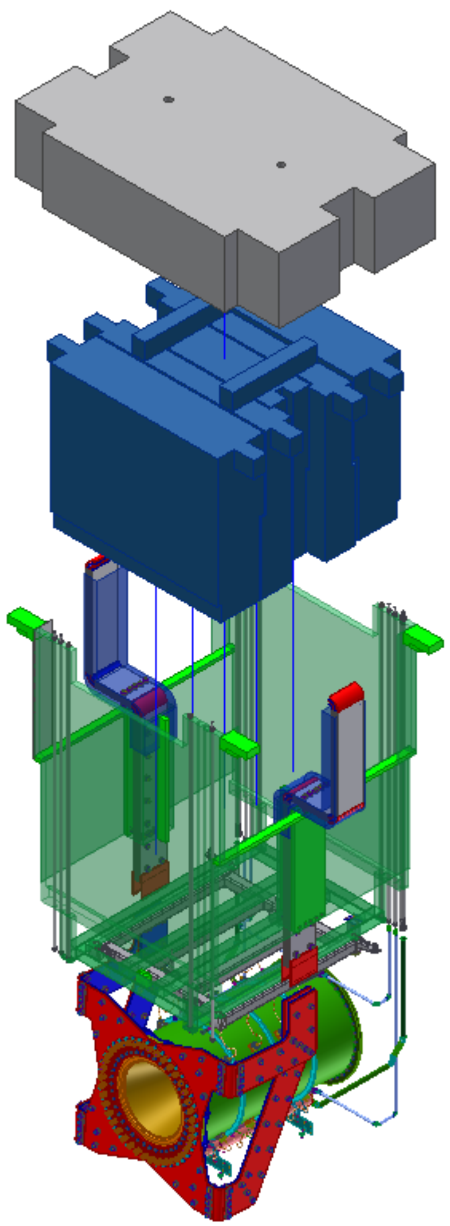
Materials and Life Science
Experimental Facility (MLF)
Hadron Experimental Facility
500 m
Neutrino Experimental
Facility
Linac
(330m)
Rapid Cycle Synchrotron (RCS)
(3 GeV synchrotron)
(25 Hz, 1MW)
Main Ring (MR)
(30 GeV synchrotron)
(0.75MW)

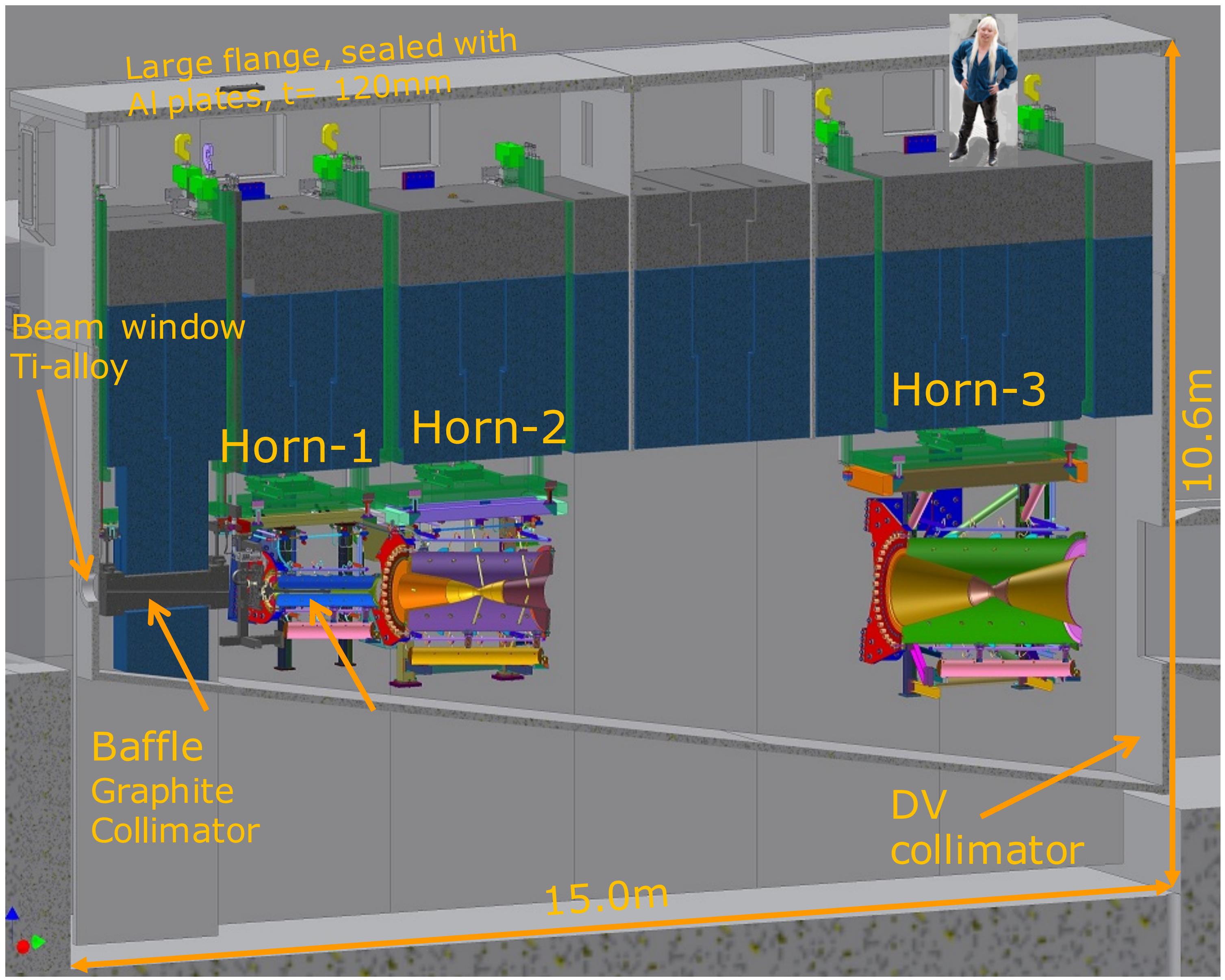
J-PARC Neutrino Facility



Target Station

All equipments inside Helium Vessel can be replaceable

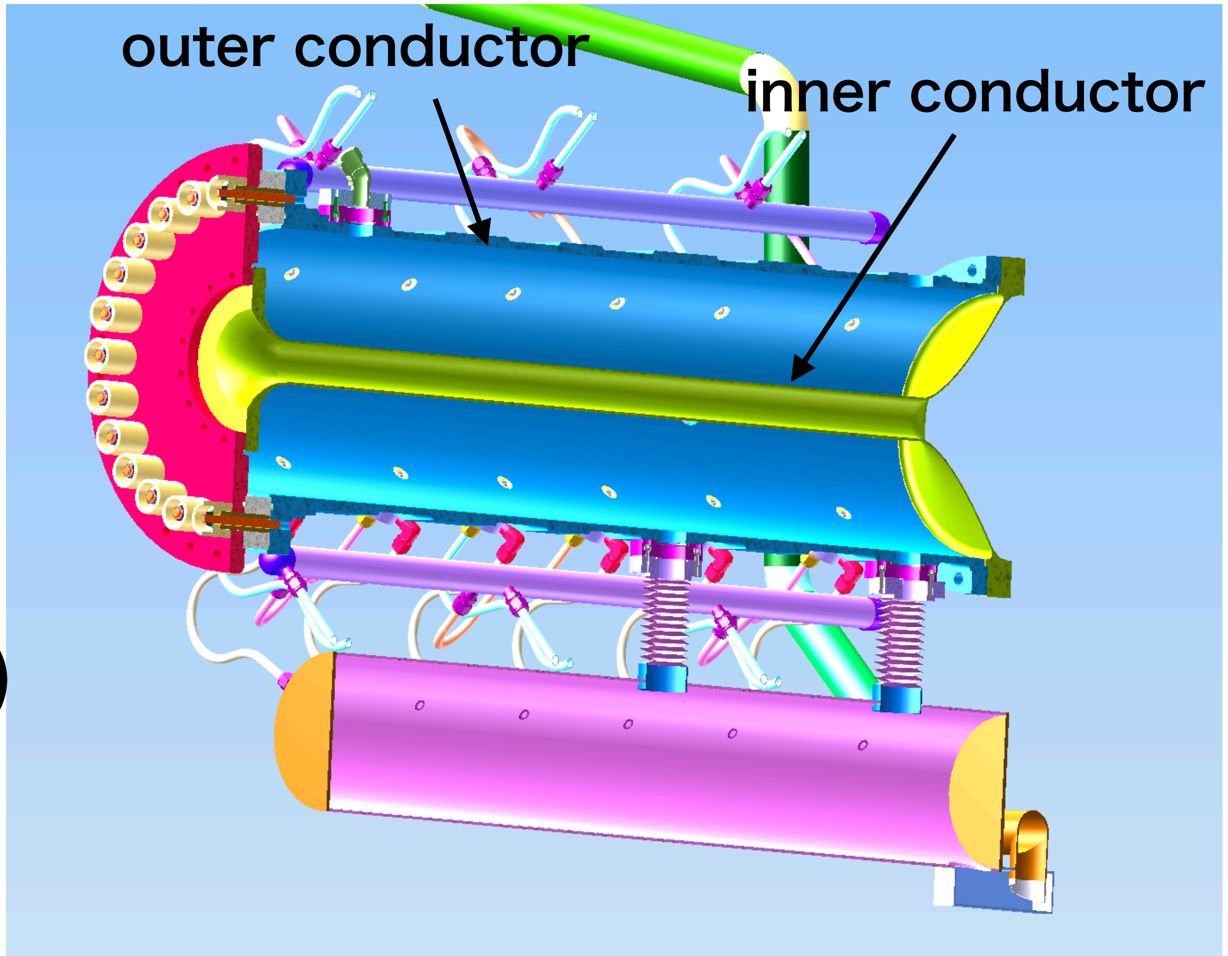




- **All beamline equipments are highly irradiated at *O*(10) Sv/h**
- **Exchangeable with remote handling.**
- **Guide system for precision alignment during movement.**

T2K Magnetic Horn

- **Aluminum coaxial conductor by A6061-T6**
  - **3mm(10mm)-thick inner (outer) conductor**
  - **Fatigue: 310 MPa → 68.9 MPa after 2x10^{8} cycle at 97.5% C.L.**
  - **Corrosion: Strength reduction x ~0.43**
  - **Allowable stress: 29.6 MPa**
- **320kA pulsed current (design)**
  - **Toroidal magnetic field: 2.1 T (max.)**
  - **Pulse width: 2~3 ms**
  - **Cycle: 2.48 s → 1.3 s → 1.16 s**
- **Water cooling**
  - **Heat deposit: 32.8 kJ/pulse (1.3 MW)**
  - **Spray water onto inner conductor**



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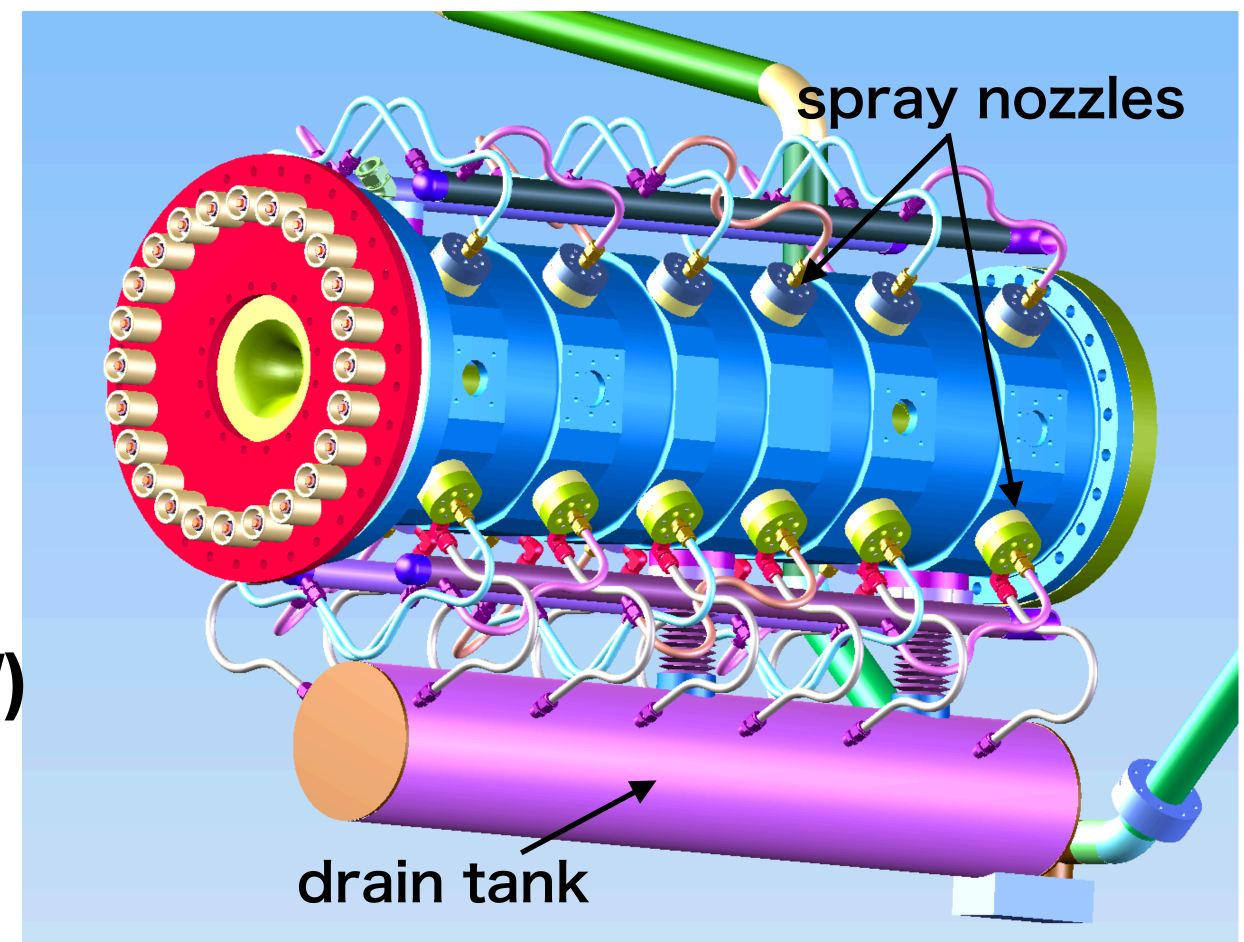
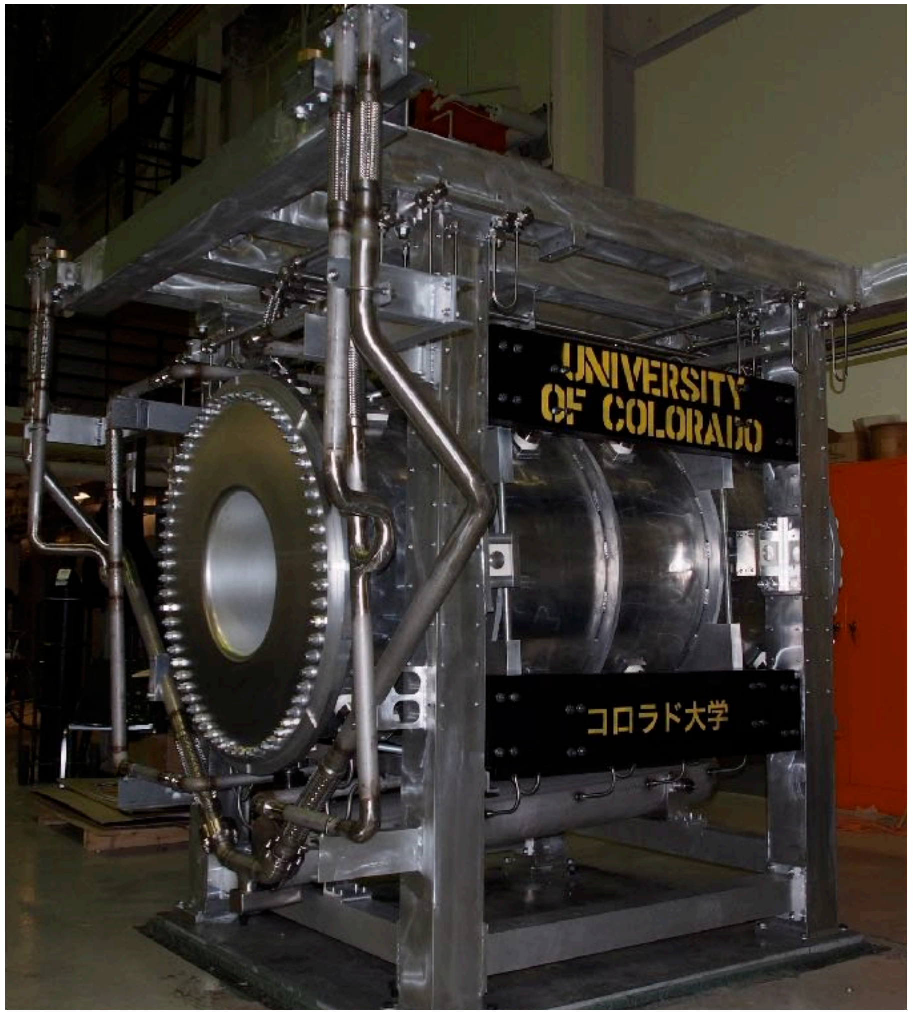


T2K Magnetic Horn

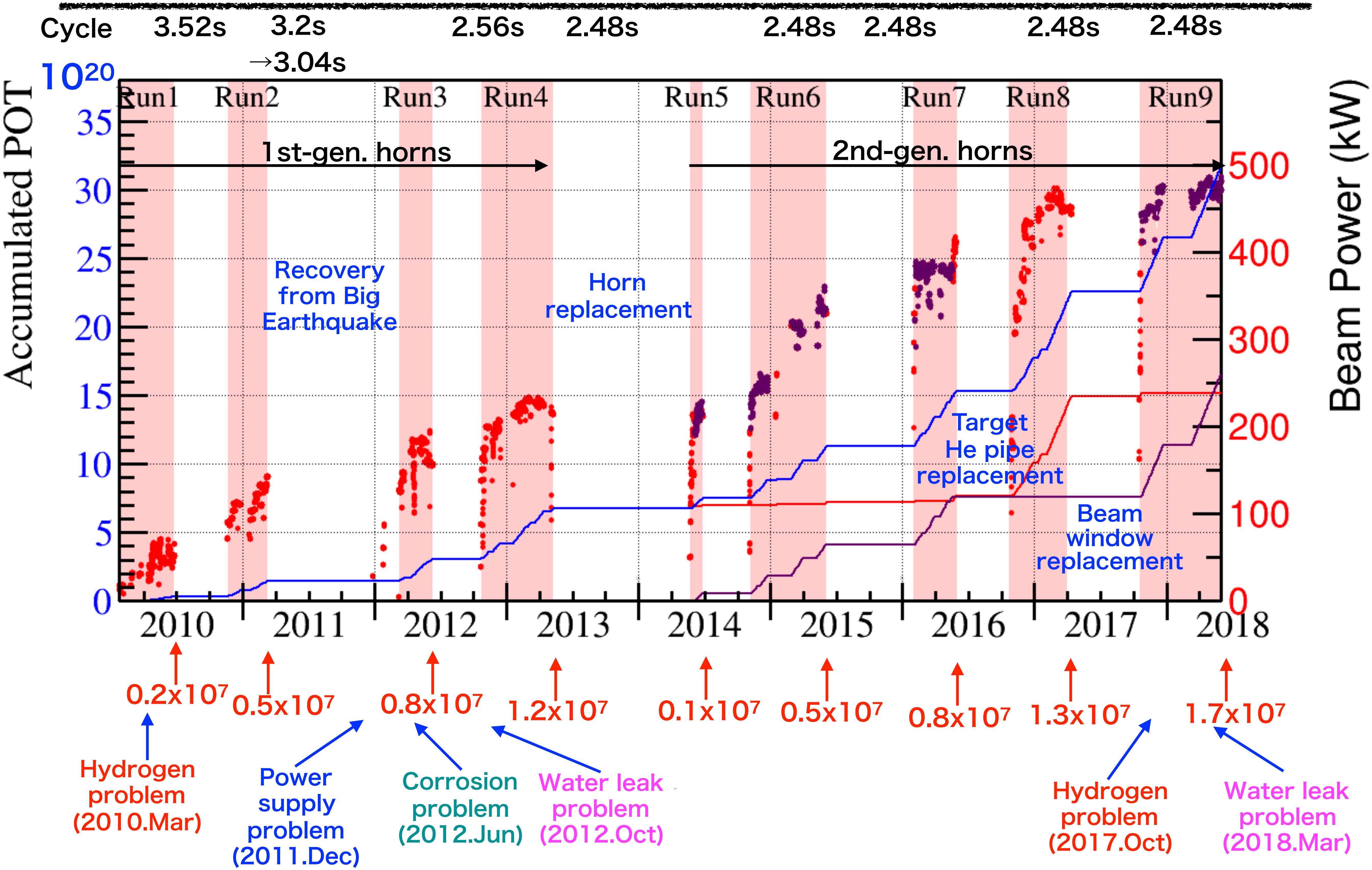
Horn1

Horn2



Horn3

Horn Operation History



Beam Power Upgrade Plan

- **Design beam power = 750 kW**
  - Proton intensity = 2.0×10^{14} ppp → already achieved!
  - 1.3 s cycle with new MR power supplies → to be achieved by 2021
- **Aiming for 1.3 MW beam by 2026**
  - Proton intensity = 3.2×10^{14} ppp
  - Operation cycle = 1.16 s
- **Horn upgrade for 1.3 MW**
  - 320 kA & 1 Hz operation
  - Cooling upgrade

Beam Power	Proton intensity	Ope. cycle
485 kW (achieved)	2.5×10^{14} ppp	2.48 s
750 kW (proposed) [original plan]	2.0×10^{14} ppp [3.3×10^{14} ppp]	1.32 s [2.1 s]
1.3 MW (proposed)	3.2×10^{14} ppp	1.16 s

What are Issues for High Power Beam?

T. Sekiguchi @ NuFact 2013

Problem/Limitation

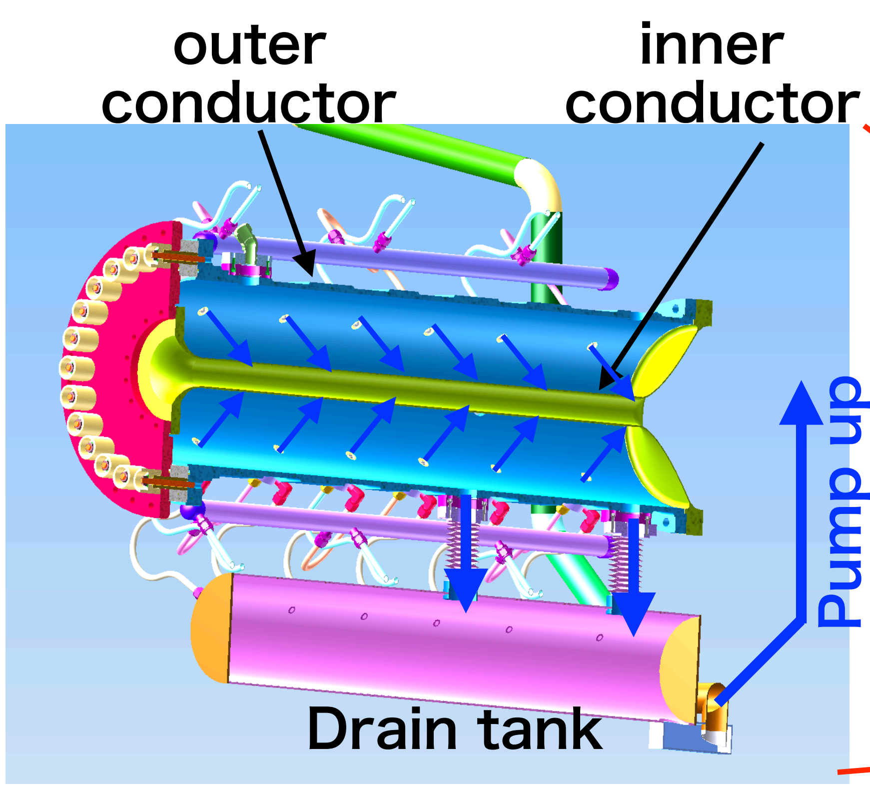
- **What are real problems for horns in a high power beam?**
  - One tends to consider about these things for a high power beam.
    - Cooling to survive a large heat deposit.
    - Mechanical strength for a high current (~300kA)
    - Fatigue due to a repetitive stress of $O(10^8)$.
  - These issues are actually major consideration, but…
  - **Real problems in a high power beam do happen due to**
    - Radio-activation:
      - A treatment of radioactive waste (tritium and ^{7}Be, etc).
      - No more manual maintenance → **Remote maintenance needed**.
    - **Hydrogen production by a water radiolysis.**
    - NO_x production in case of air environment.
      - Acidification of water.

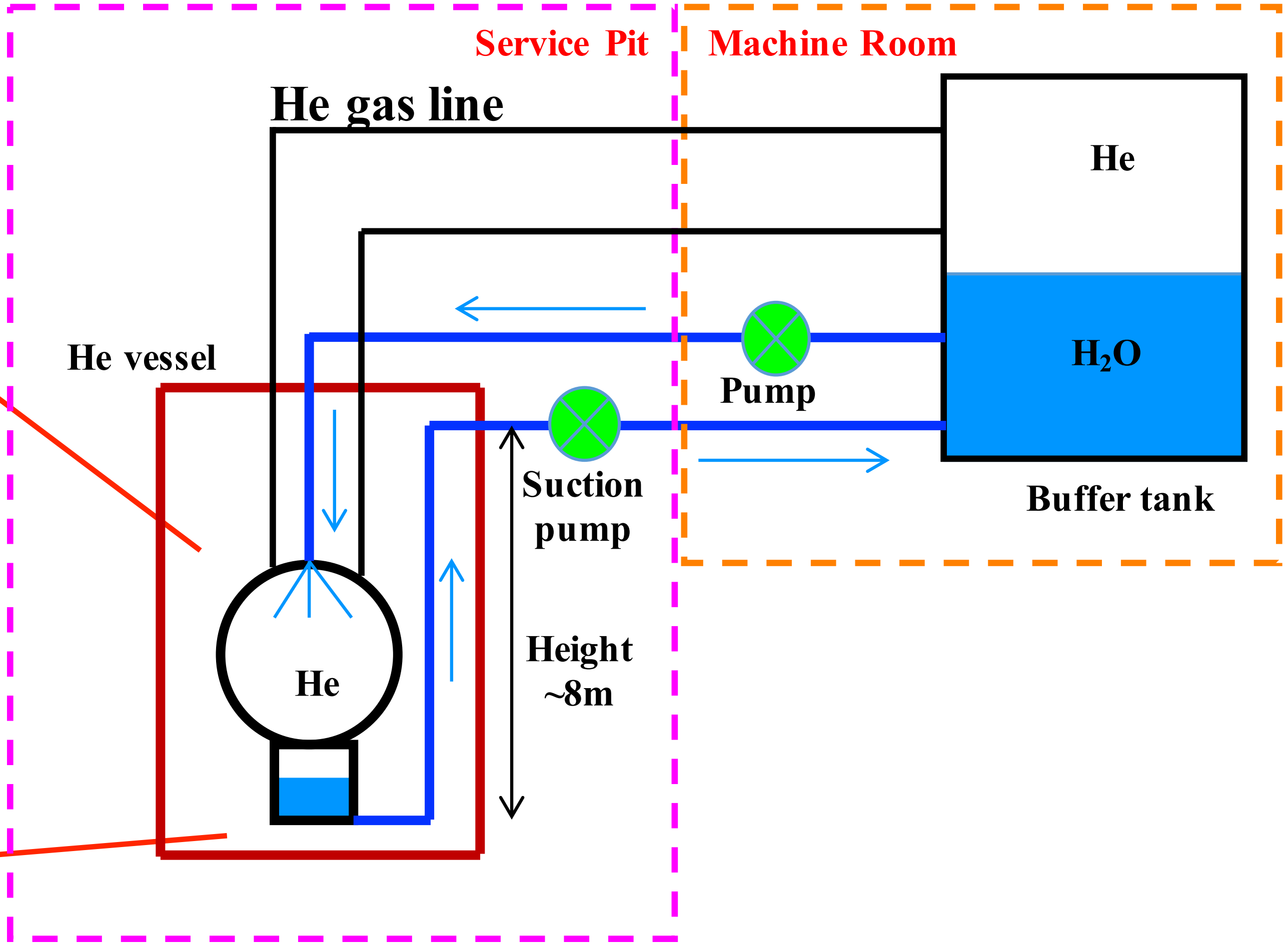
August 20th, 2013 *NuFact2013 @ IHEP, Beijing* *12*

Hydrogen Problem

Horn Cooling Water System

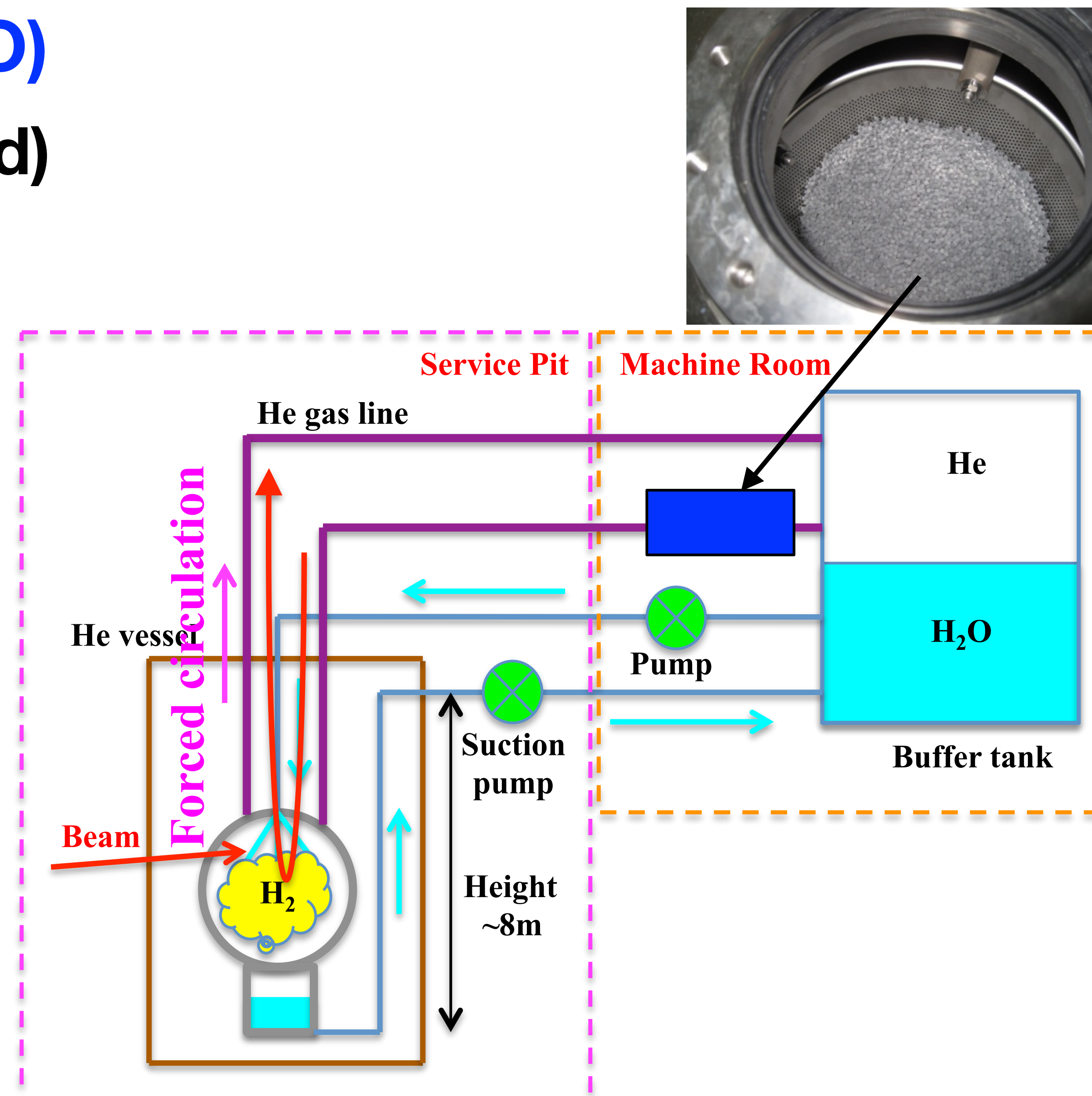
- **Water cooling of horn conductors**
  - Water spray onto IC ⇒ collected in drain tank ⇒ pump up
- **Two independent pumps for water circulation**
  - Water supply pump
  - Water suction pump @ 7~8 m above horns
  - Supply and suction flow rates are balanced manually



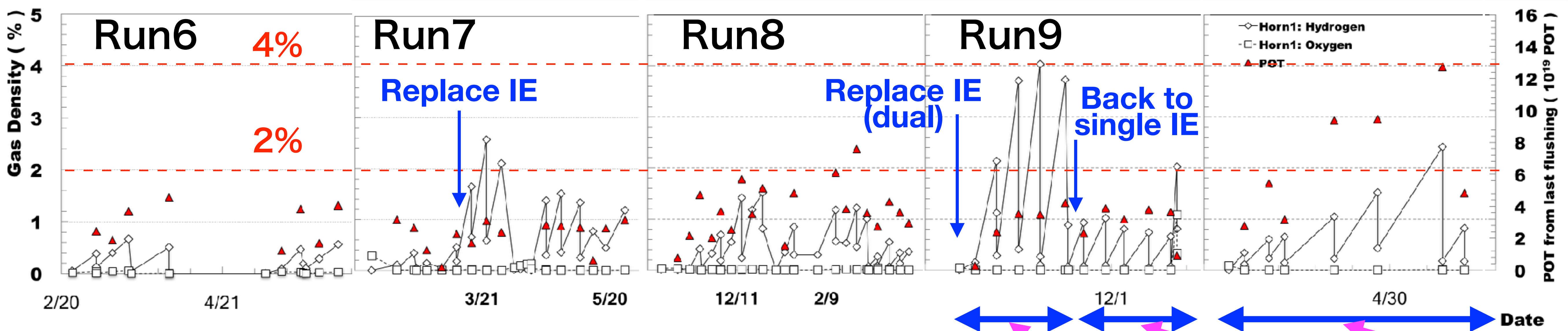


Hydrogen Production Issue

- H_2 production by water radiolysis ($2H_2O \rightarrow 2H_2 + O_2$)
  - Expected production rate @ 750 kW
    - 40 L/day (from K2K experience)
    - 400 L/day (MARS calculation assuming 1mm-thick water layer)
- H_2 recombination ($2H_2 + O_2 \rightarrow 2H_2O$)
  - Catalyst (alumina pellet w/ 0.5% Pd)
  - Forced He flow inside the horns
- Operation criteria
  - Keep H_2 concentration below 3%
    - H_2 explosion limit in air = 4%
  - Weekly He flushing to remove H_2



Issues on Hydrogen Recombination



Run period	Run6	Run7	Run8	Run9-1	Run9-2	Run9-3
Configuration	Single (old)	Single (new)	Single (old)	Dual (new)	Single (new)	Single (new)
Beam power (kW)	330	390	470	450	475	485
H_2 concentration (%)	0.4	2.5	1.5	4.0	1.0	2.4
Production rate (% / 10^{19} POT)	0.094	0.482	0.117	0.741	0.191	0.106

- **Remarks**
  - Oxygen concentration was very low ⇒ recombination not efficient
  - H_2 production rate = <1%/week@485 kW ⇒ < 3%/week@1.3 MW
  - Large production rate with new ion exchangers (IE) ⇒ must be solved

Water Radiolysis

- Ionization and excitation of H_2O molecule primarily occur by radiation exposure
  - Primary products are : e^-_{aq}, OH, H, H_2, H_2O_2
  - Final products are : H_2, O_2, H_2O_2
  - Production rate (G-value) by simulation
    - Oxygen production rate is very small !!

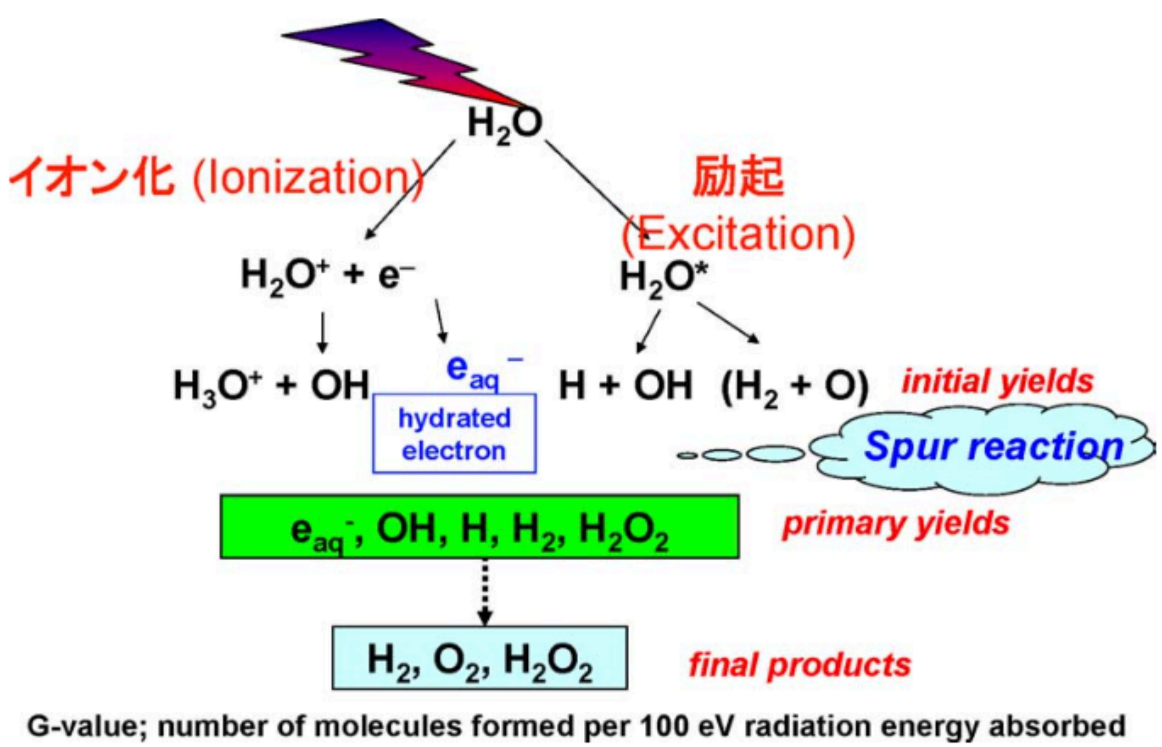
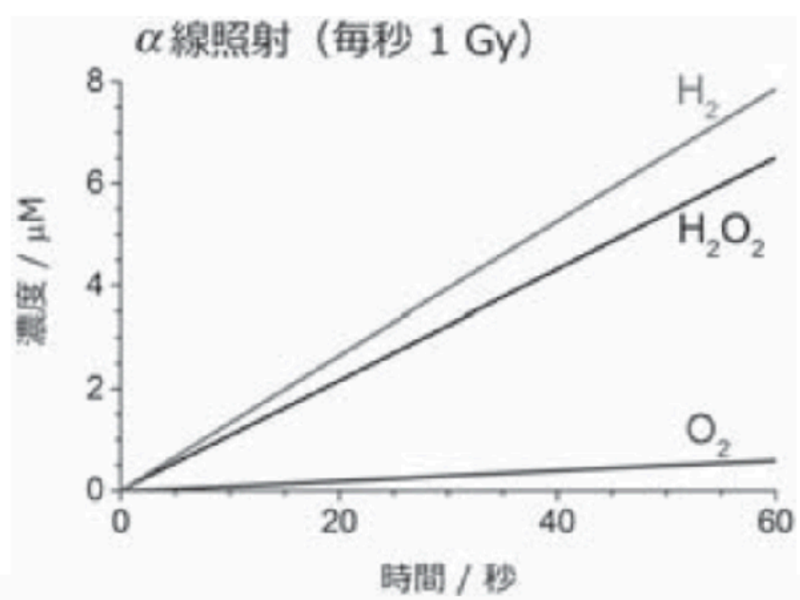


図 2　水の放射線分解スキーム

Y. Katsumura, Radiation Chemistry, No.81, 2-7 (2006)

表 1　γ(X)線と α 線照射時の水の放射線分解で生じる化学種の G 値（個/100 eV）[2, 3]

G-values	$-H_2O$	e^-_{aq}	OH	H	H_2O_2	H_2	HO_2
γ(X)-ray	4.11	2.64	2.82	0.57	0.645	0.45	—
α-ray	2.65	0.06	0.24	0.21	0.985	1.3	0.22



Y. Katsumura, Isotope News, No.746, 48-49 (2016)

H_2O_2 Issue

- **Hydrogen peroxide (H_2O_2)**
  source for recombination
  - Naturally decompose : $2H_2O_2 \Rightarrow 2H_2O + O_2$
  - Can corrode ion-exchange resins

    $\Rightarrow$ degradation of ion-exchangers (currently < 1 year)
  - Measured H_2O_2 concentration : ~10mg/L @ 4×10^{20} POT (exp.~500mg/L)
- **Countermeasures**
  - H_2O_2 must be removed for safe/stable operation at higher beam power
  - A company developed a H_2O_2 resistant IE
    - Pd-doped resins work as a catalyst for H_2O_2 decomposition
  - This new resins will be overlaid to the existing IE resins
    - To be used from next beam time

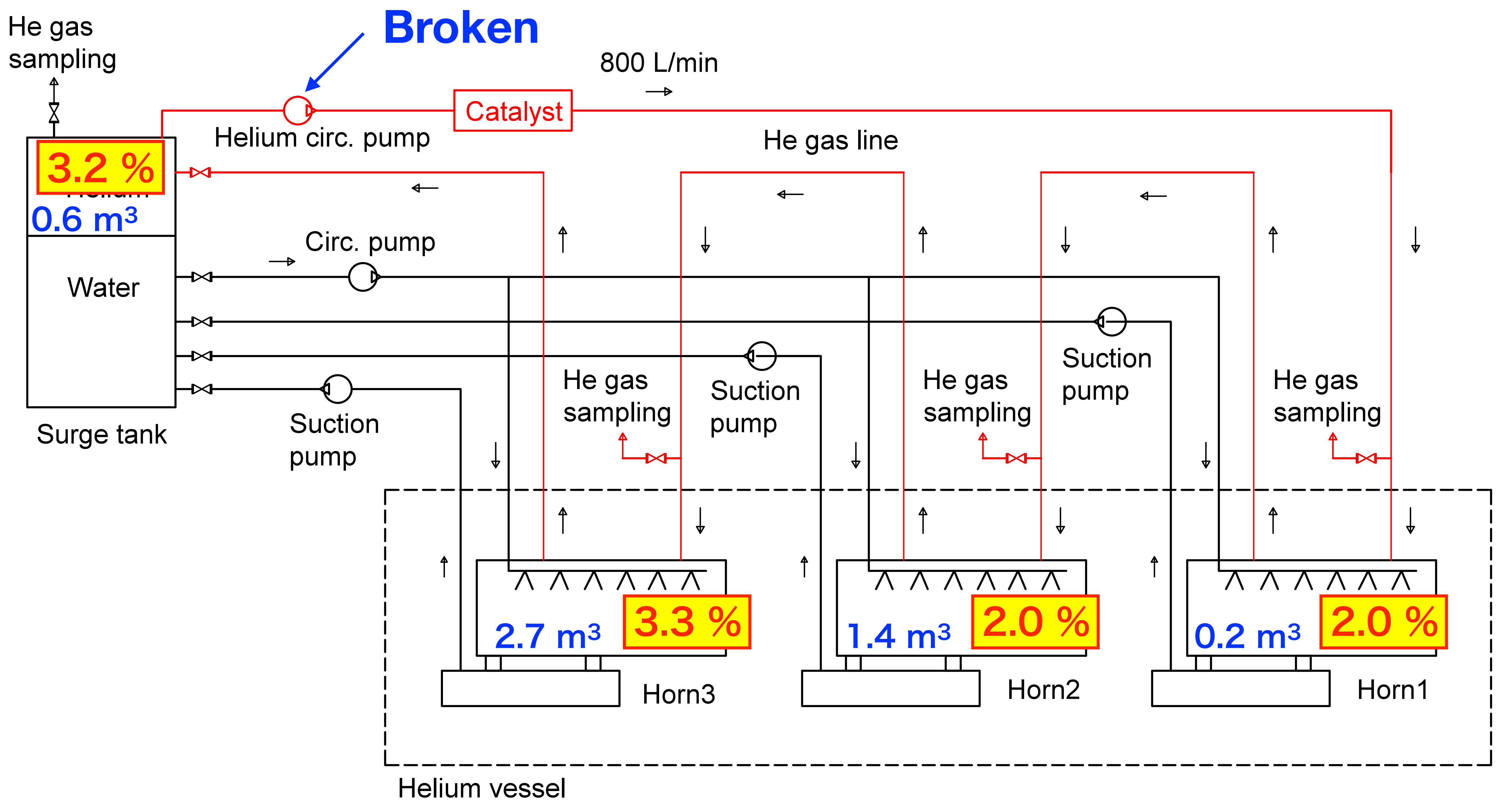
      $\Rightarrow$ see if the problem is solved or not

He Blower Problem

- He blower was broken in Run9
  - Took beam WITHOUT H_2 recombination system for 18 hours !
- H_2 and O_2 concentration measured ⇒ real production rate
  - H_2 : ~2.9 %, O_2 : ~1.3 %
  - H_2/O_2 ratio is close to 2 ⇒ most of H_2O_2 decomposed naturally
- Production rate : ~260 L / 10^{19} POT
  - Quite different from the estimation : ~30 L / 10^{19} POT
- H_2 recombination absolutely needed during beam !
  - He circulation interlock included in beam operation

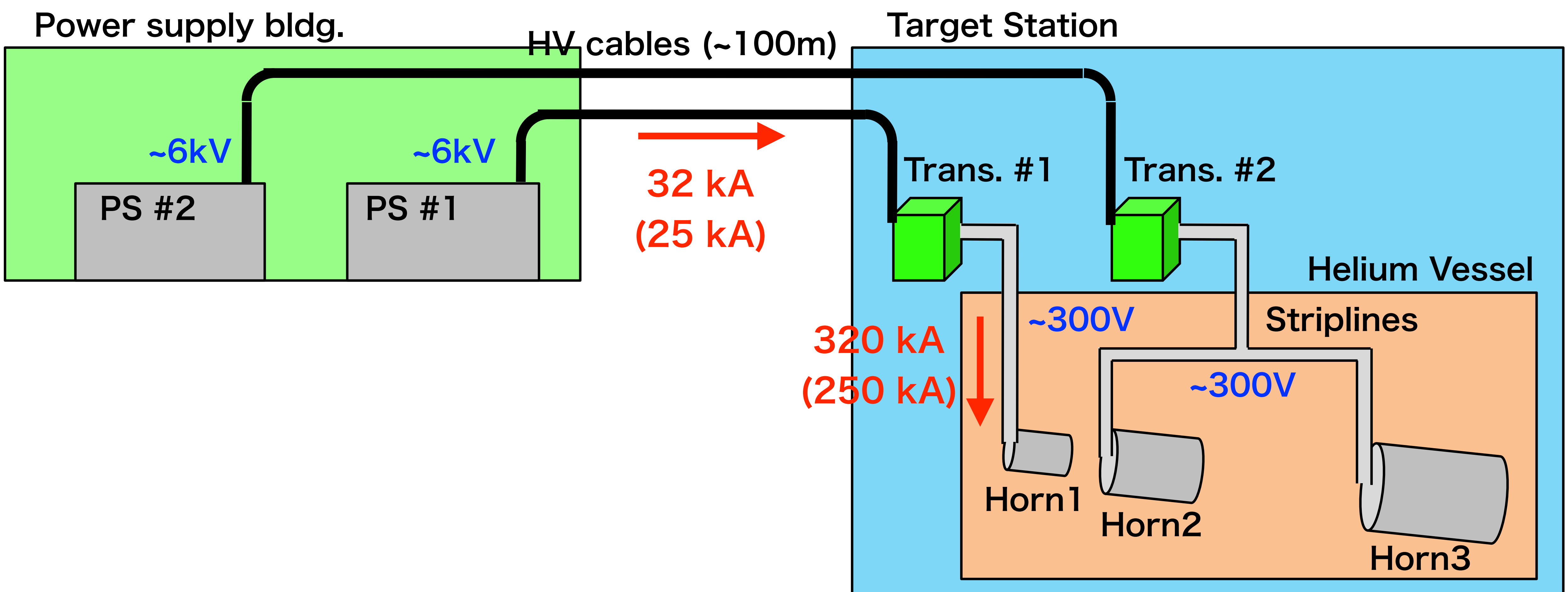
	Horn1	Horn2	Horn3	Tank	Average	Prod. rate
Volume	0.2 m^3	1.4 m^3	2.7 m^3	0.6 m^3	-	-
H_2 concentration	2.02%	2.01%	3.31%	3.19%	2.87%	257 L / 10^{19} POT
O_2 concentration	1.08%	1.02%	1.41%	1.38%	1.28%	115 L / 10^{19} POT

He Circulation Diagram



Horn Power Supply Issues and Upgrade

Horn Electrical System



- **Current flow**
  - **Power supply $\xrightarrow{\text{32 kA}}$ Transformer $\xrightarrow{\text{320 kA}}$ Horn**
- **250 kA operation since beginning of T2K physics run**
  - **K2K PS (250 kA rated) reused for T2K at day1**
  - **Several PS-related problems limited horn current to 250 kA**
  - **New power supplies were developed for 1 Hz operation**

Horn PS History

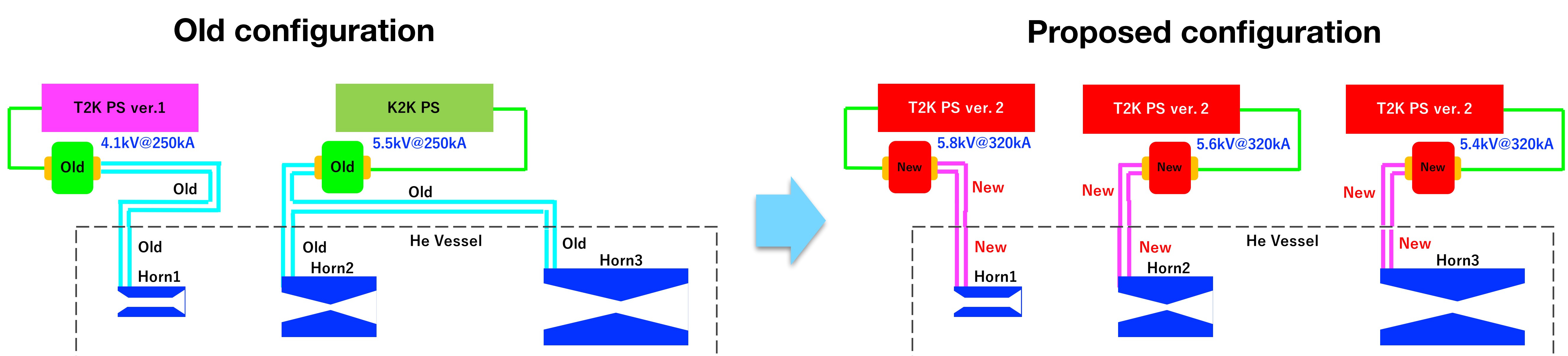
Period	Configuration		Current (kA)	Voltage (kV)		Width (ms)	
	Horn1	Horn2&3		Horn1	Horn2&3	Horn1	Horn2&3
Run1	K2K	K2K	250	4.5	5.4	2.4	3.6
Run2	T2K ver.1		250	6.2		4.6	
Run3	K2K		200	5.4		4.3	
	K2K		250	6.7		4.3	
Run4	K2K		250	6.7		4.3	
	T2K ver.1	K2K	250	4.1	5.4	3.1	3.6
Run5	T2K ver.2	K2K	250	5.3	4.5	2.2	3.4
Run6	T2K ver.2	K2K	250	5.3	4.5	2.2	3.4
Run7	T2K ver.2	T2K ver.2	250	5.3	6.3	2.2	2.8
Run8	T2K ver.2	T2K ver.2	250	5.3	6.4	2.2	2.7
Run9	T2K ver.2	T2K ver.2	250	4.8	6.5	2.0	2.7

1st gen.

2nd gen.

Horn Operation Improvement

- Aiming to achieve 320 kA and 1 Hz
  - 10% neutrino flux gain and 5~10% reduction of wrong-sign neutrinos
- Requirements
  - Lower voltage operation to reduce a risk of failure ⇒ lower input load
  - Shorter charging time ⇒ Need energy recovery and low Joule loss
- Solution = One-by-one operation (one PS ⇔ one horn)
  - Need three power supplies and transformers



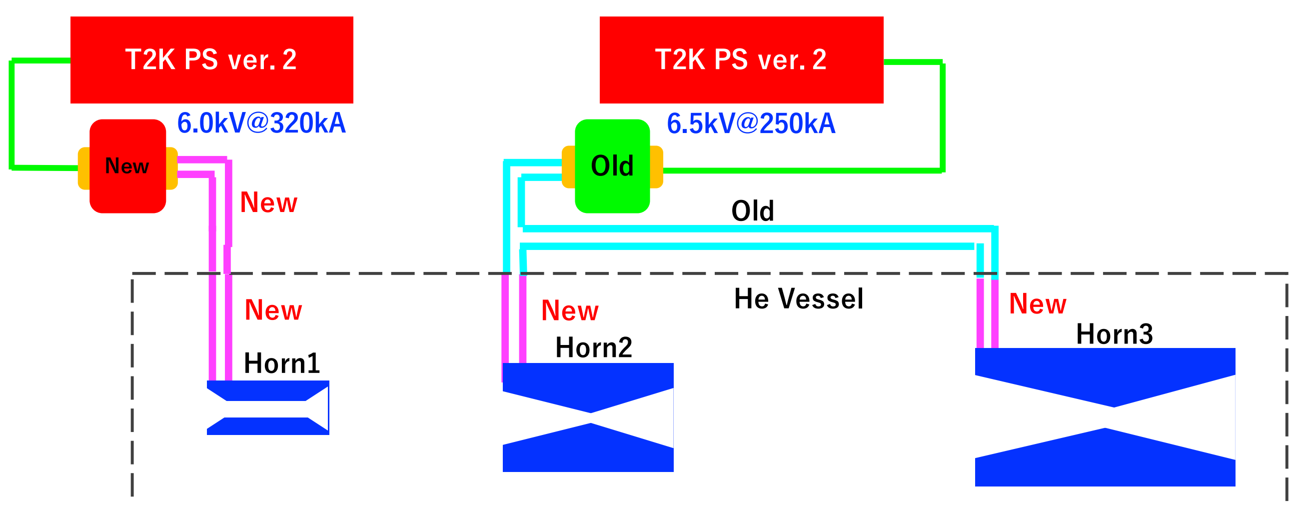
New Electrical System

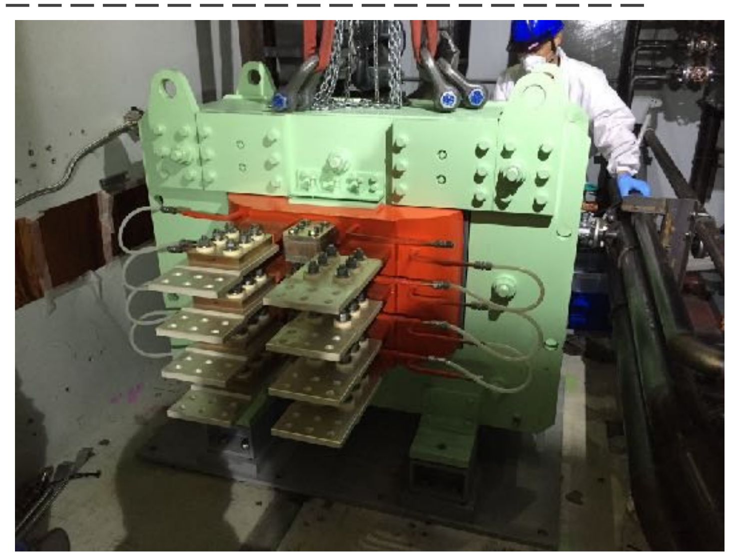
- **Upgrade**
  - **New power supplies with energy recovery**
    - **Operation voltage < 6 kV at 320 kA**
    - **Charging time < 1 sec**
  - **New low impedance striplines**
  - **New transformers for 320 kA operation**
- **Status**
  - **Two PS installed ⇒ very stable operation**
  - **Horn1 setup already completed**
    - **Need spare horn1 to start 320 kA**
  - **One PS, two transformers needed**

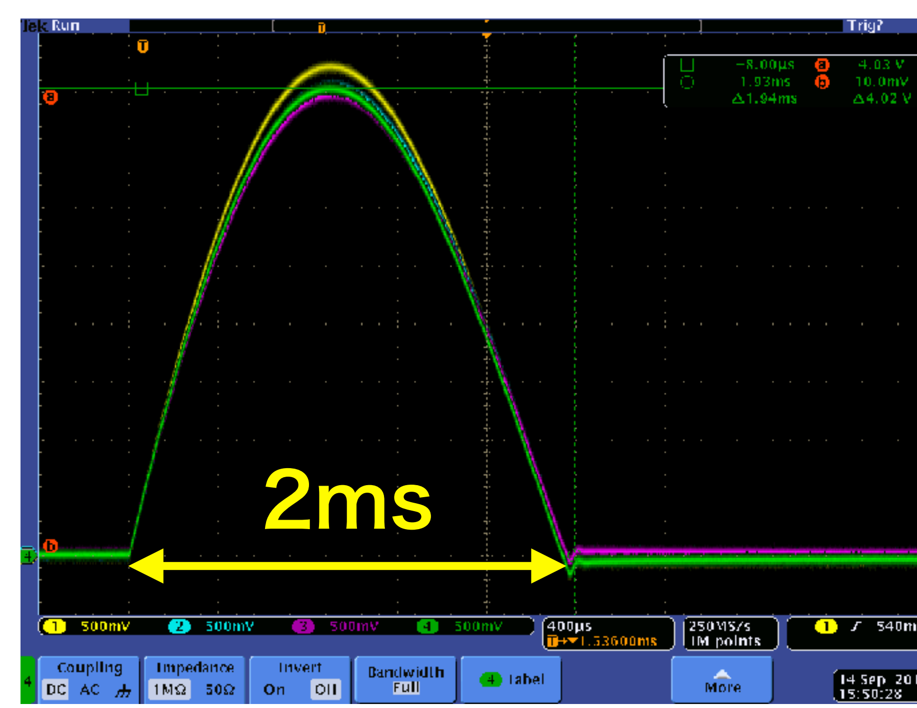
Parameter	horn1	horn2	horn3
Operation current	323 kA	323 kA	323 kA
Operation voltage	5.85 kV	5.72 kV	5.91 kV
Returned voltage	4.60 kV	4.78 kV	5.00 kV
Voltage recovery rate	78.6 %	83.6 %	84.6 %
Pulse width	2.00 ms	2.01 ms	2.08 ms
Charging time	0.71 s	0.54 s	0.52 s

Upgrade for Horn1

- For horn1, all upgrade were completed
- 320kA test operation performed
  - Charging voltage : 6.05 kV as expected (⇔ 5.8 kV, rated 7kV)
  - Pulse width : 1.98 ms as expected (⇔ 2 ms)
  - Short-term (24 hours) continuous operation performed
  - No problem observed ⇒ ready for 320 kA





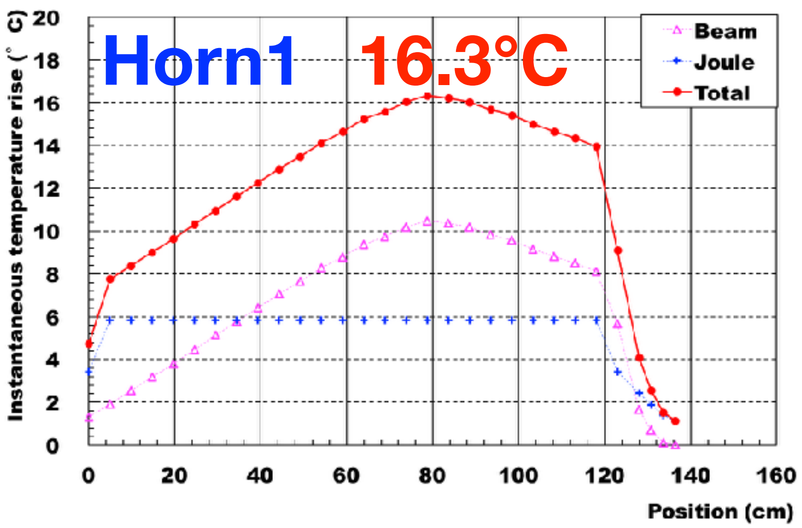


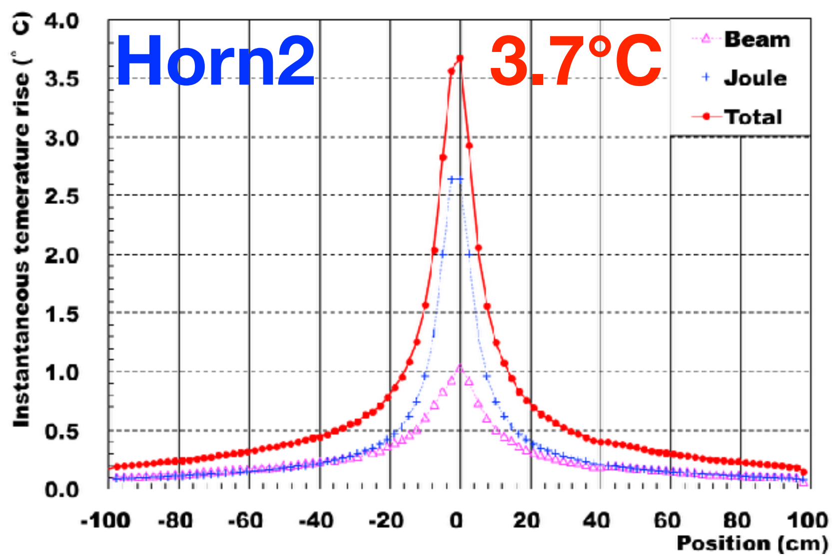
Horn PS Capacitor Problem

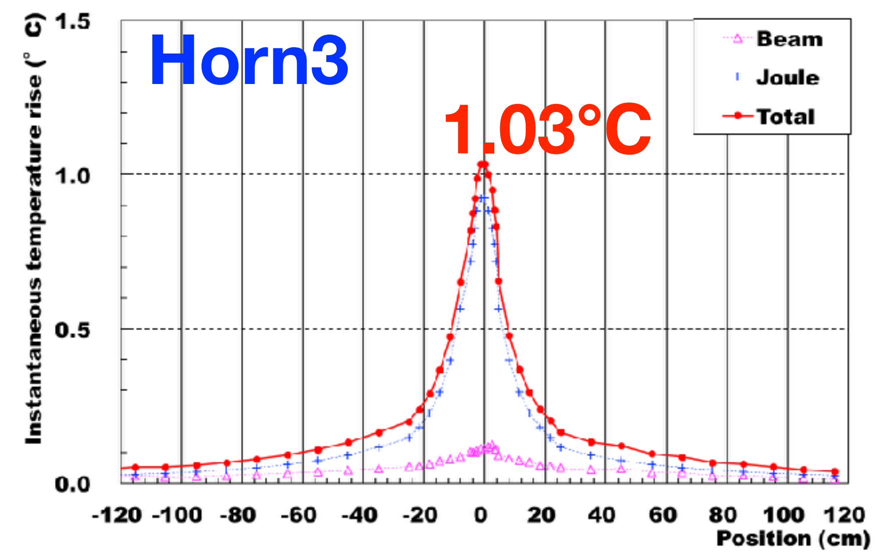
- Horn current and pulse width reduced during Run8
- Capacitance measurement
  - Decrease by 5~10%@1.3x10^7 ⇔ Spec : $\Delta C/C < 5\%$ @ 2x10^8 pulses
- Inspection by manufacturing company
  - Electro-corrosion on Al metallized electrode
    - Resulting in capacitance drop
    - Caused by 100% alternating voltage operation
- Measures
  - Same phenomenon at CERN Booster magnet PS
  - CERN already has a solution for this problem
    - Al+Zn metallization ⇒ no electro-corrosion
    - rf. https://doi.org/10.1109/EPE.2015.7309424
  - All capacitors to be replaced with modified ones

Cooling upgrade

Horn Conductor Cooling @ 1.3 MW





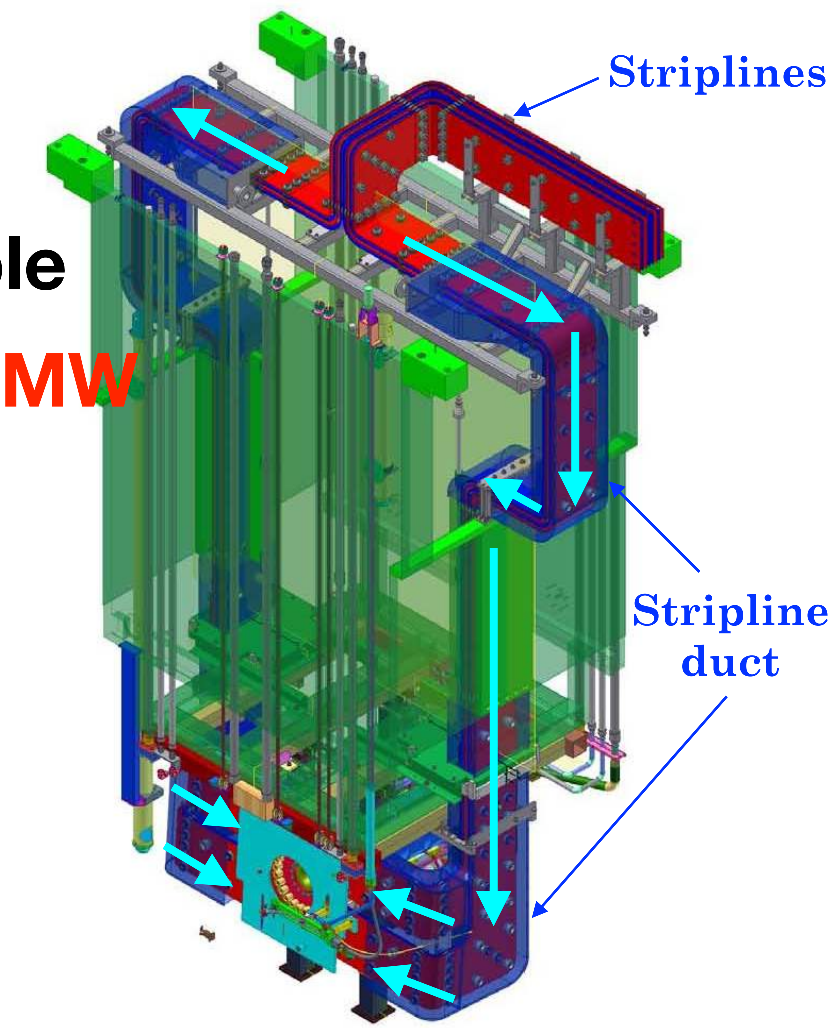


Item	Horn1	Horn2	Horn3
Instantaneous temp. rise (°C)	16.3	3.6	1.0
Steady state temp. rise (°C)	19.1	22.1	5.8
Coolant water temp. (°C)	25.0	25.0	25.0
Max. temp. (°C)	60.4	55.3	31.8

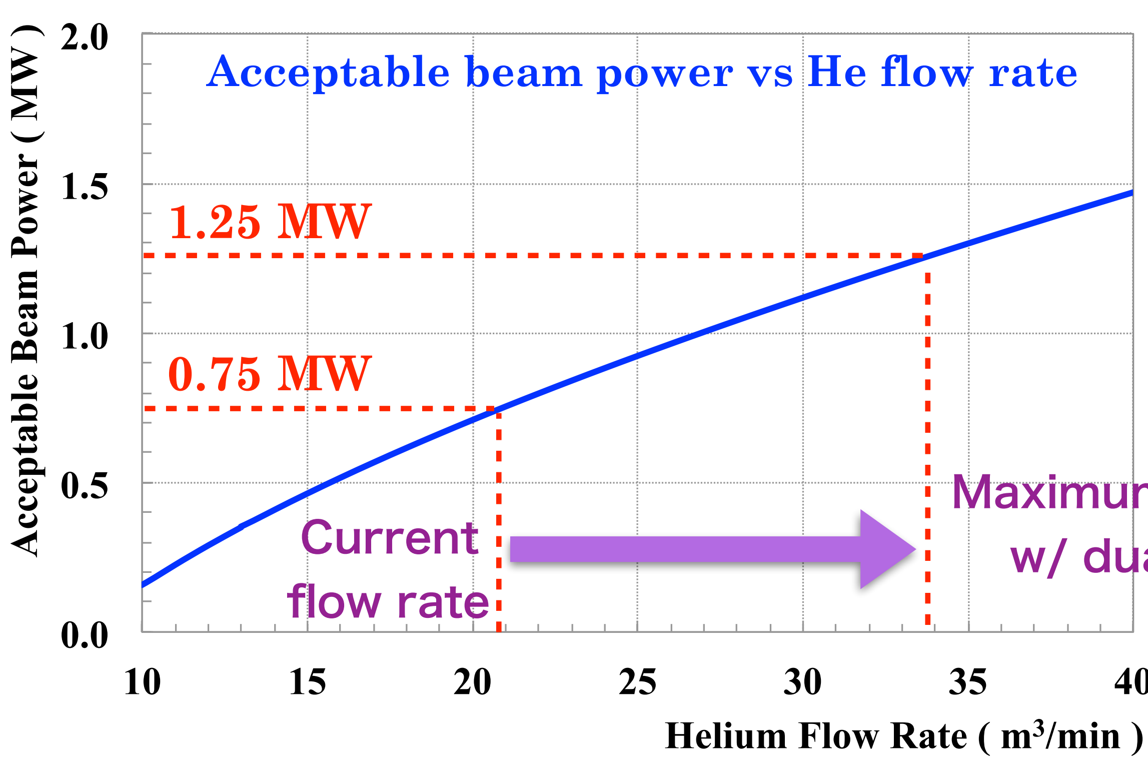
- Expected max temperature ~ 60.4°C < allowable temperature 80 °C
  - Cooling performance is sufficient for 1.3 MW
  - Monitor temperature at several non-energized parts (water, frames, etc)
- Cooling capacity
  - Currently ~1 MW acceptable ⇒ cooling capacity improvement
    - Pump and heat exchangers at 2nd/3rd cooling circuits needed

Stripline Cooling

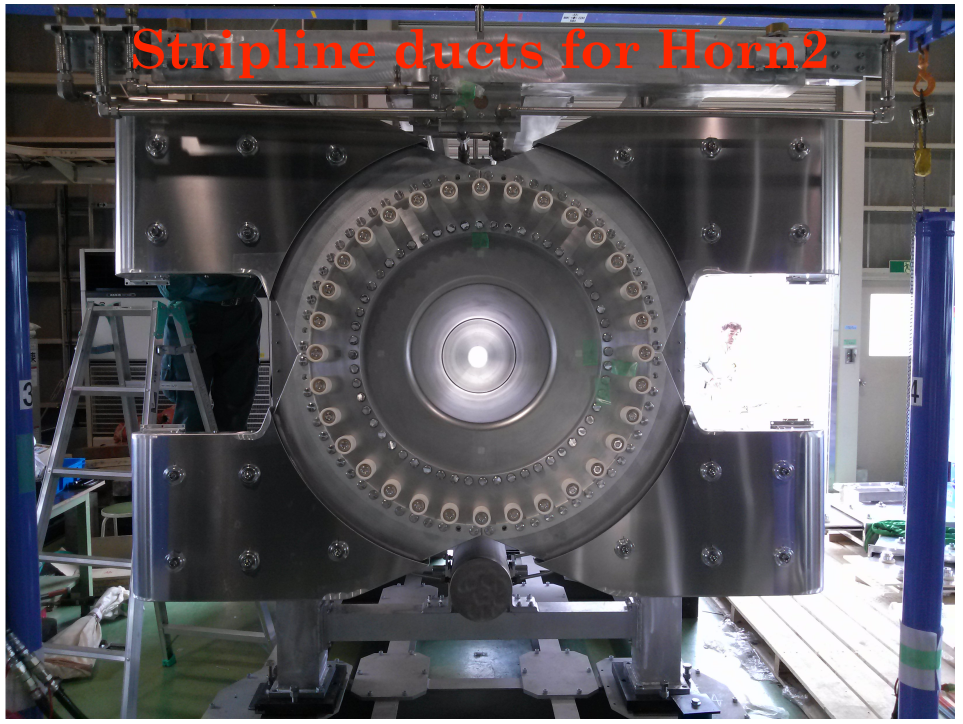
- Heat deposit at striplines → largest at horn2
- Forced He flow inside stripline ducts
  - Current flow rate for Horn2 → 750 kW acceptable
  - Higher flow rate with dual compressors → 1.25 MW
    - Not enough for 1.3 MW operation



	Horn1	Horn2	Horn3
Heat flux per stripline plate (J/m²) @ 1.3 MW			
Total (Beam + Joule)	214	1066	141
Acceptable beam power (MW)			
Current flow rate	2.10	0.75	2.04
Improved flow rate	-	1.25	-

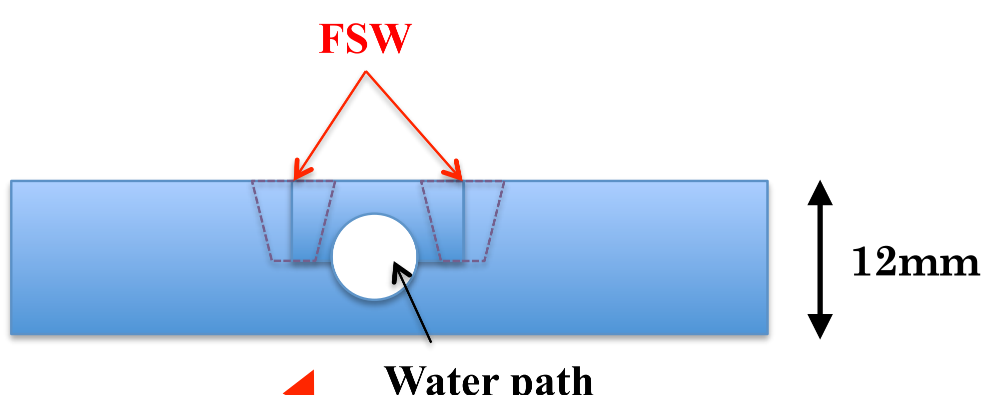


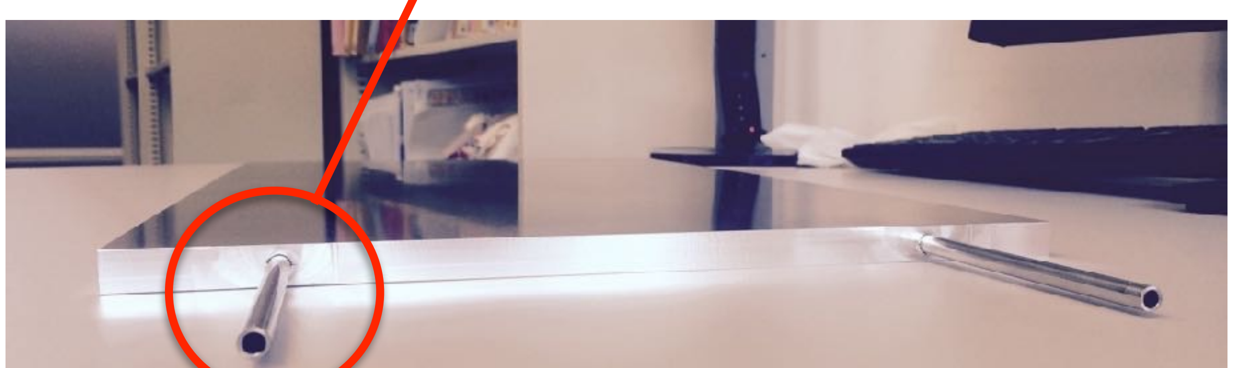
Virginia Tech



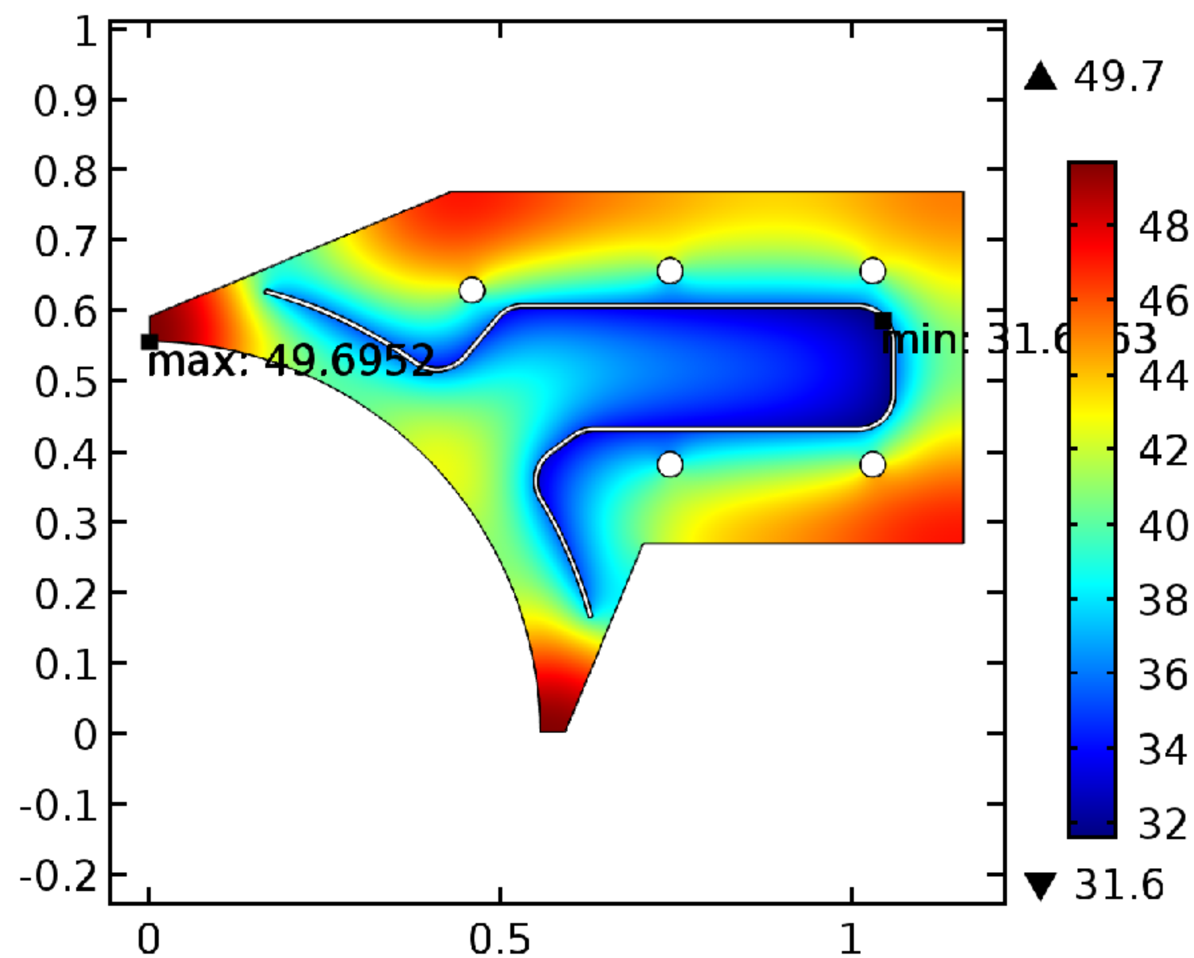
Stripline Water Cooling

- Water cooled striplines
  - Stainless pipe embedded in 12mm-thick plate by FSW technique
    - Well-established technique used for striplines and horn inner conductors
  - Cooling test with small test piece → > 3 kW/m²/K achieved.
  - Max temp. @ 1.3 MW = ~50°C (< allowable temp. 80°C)
    - 1.25 MW (by He cooling) → > 3 MW acceptable



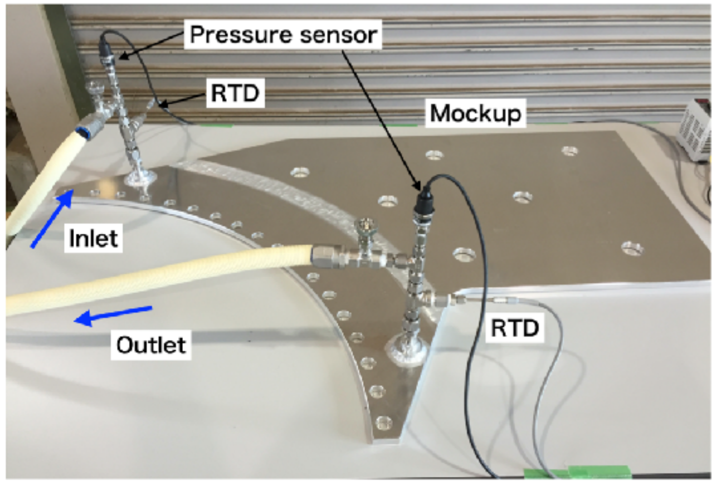


Water-tube embedded striplines using FSW



Stripline Water Cooling

- Mockup production in FY2016
  - Producibility for real size was checked
    - Some minor modification to avoid deformation
  - Water circulation test performed
    - Large pressure drop ⇒ pipe diameter increased
- Further development
  - Current test with mockup in FY2019 (with spare horn1)
    - Water plumbing to be designed
    - Vibration tolerance to be considered
  - Real production in FY2021
  - Installation to Horn2 in FY2021



Summary

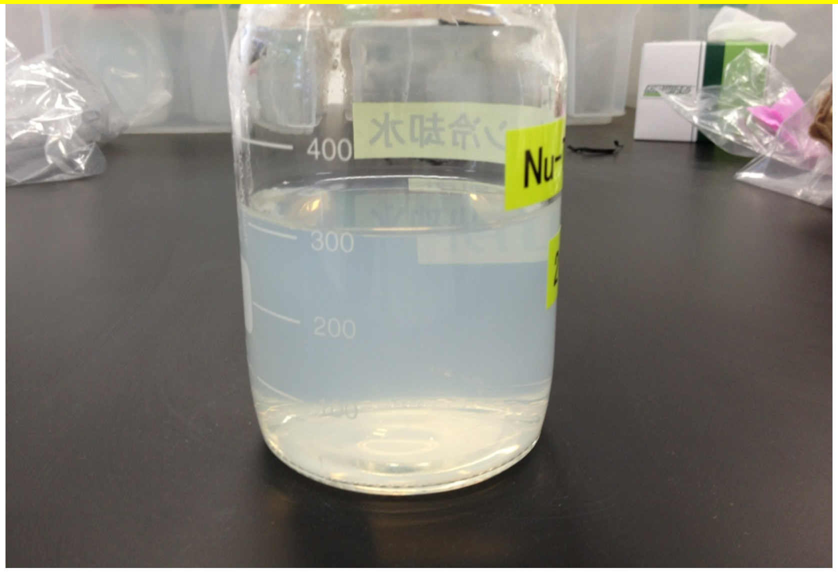
- T2K magnetic horns
  - Designed for 320 kA & 750 kW operation
  - To be upgraded for 1.3 MW with 320 kA at 1 Hz
  - 2nd-generation horns in service. Operated over 1.7×10^7 pulses
- Problems, measures, and upgrades for 1.3 MW
  - Hydrogen production ⇒ 1.3 MW accepted with current scheme
    - Treatment of H_2O_2 is key for higher beam power
  - Electrical system upgrade for 320 kA & 1 Hz operation
    - Capacitors must be replaced with new production method
  - Cooling upgrade
    - Horn conductor cooling performance sufficient for 1.3 MW
    - Cooling capacity improvement for 1.3 MW
    - Development of water-cooled striplines for high power > 1.3 MW

Backup

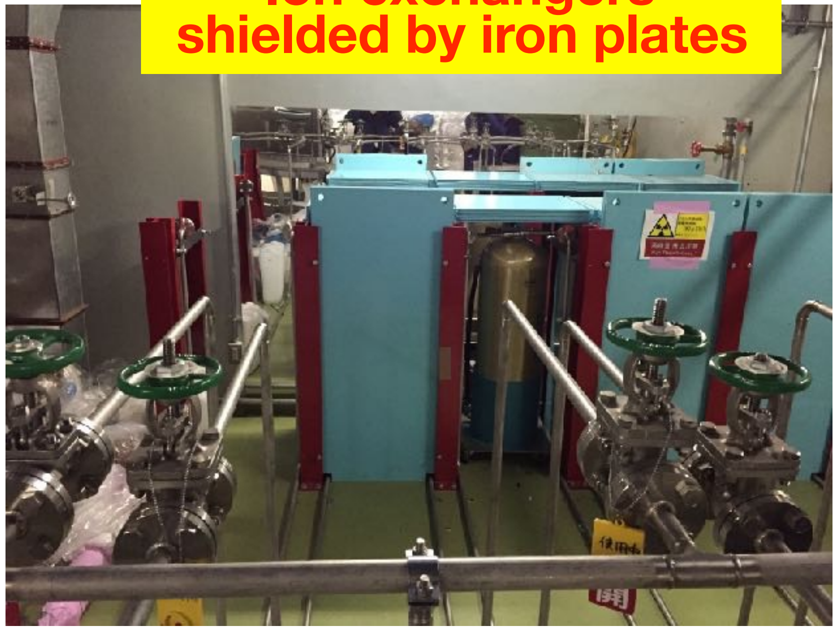
Corrosion of Aluminum Conductor

- Horn inner volume filled with He gas
- Large air contamination happened (spring 2012)
  - NOx production ⇒ dissolved in water ⇒ water acidification by HNO_3 (pH=3.8) ⇒ Aluminum conductors corroded ⇒ water leak at horn1
- Measures
  - Ion exchanger operation during beam to remove nitric acid (NO_3^-)
  - Monitor pH and conductivity of cooling water

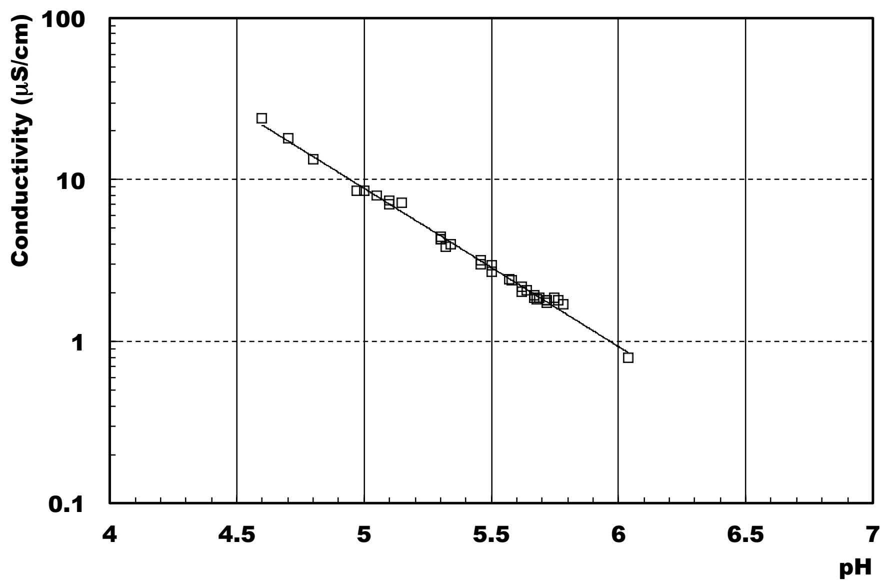
Observed whitened horn cooling water due to aluminum corrosion



Ion exchangers shielded by iron plates

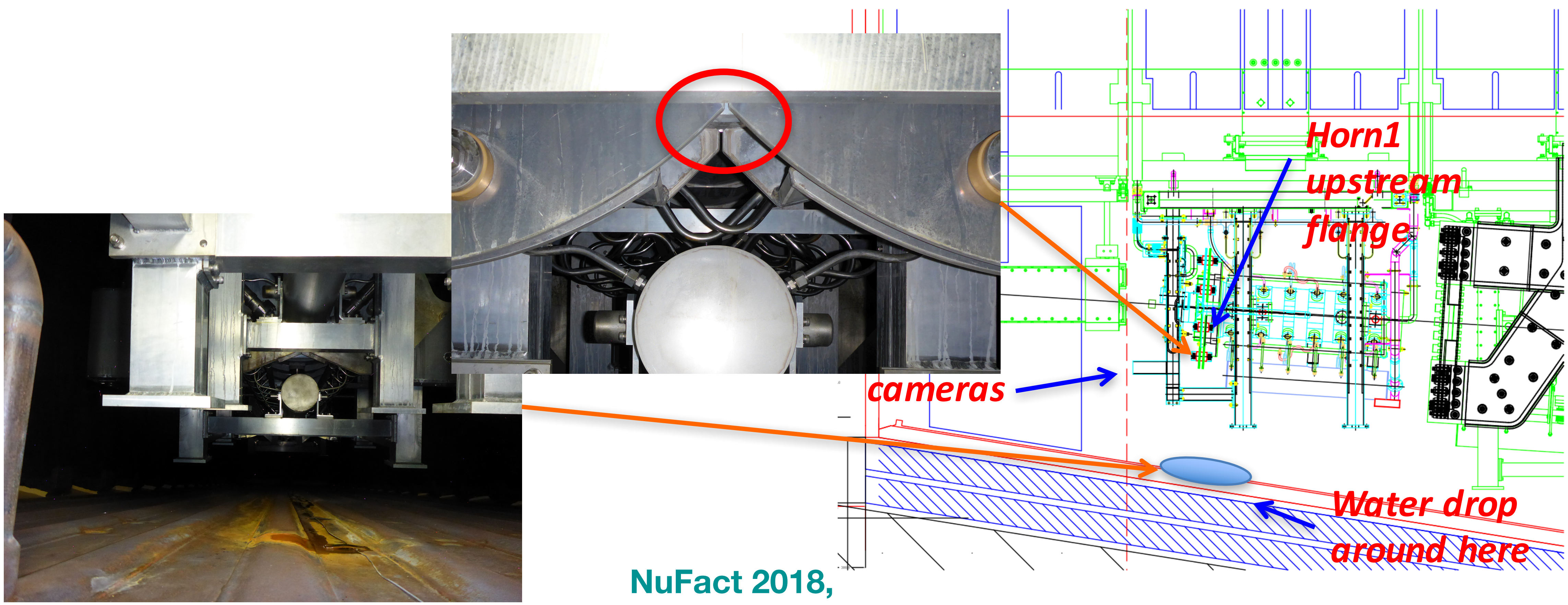


Measured relation between pH and conductivity



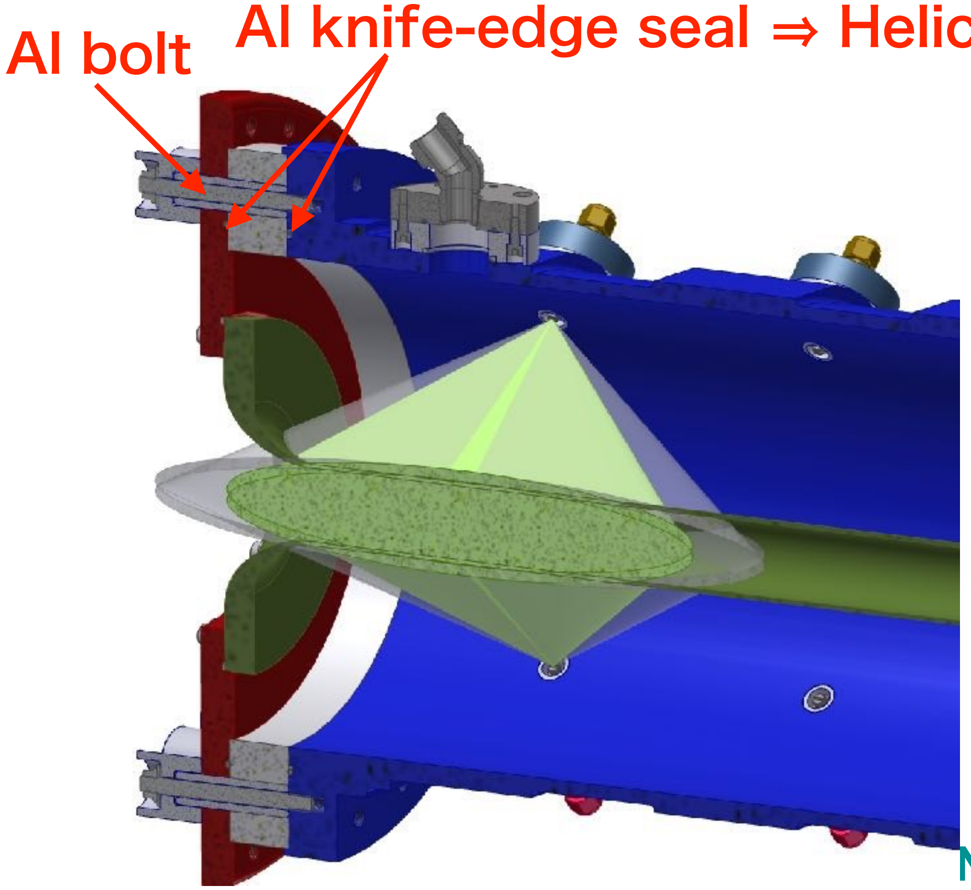
Water Leak in Horn

- Water leak in Horn1 from upstream flange (winter 2012)
  - Leak from Aluminum knife-edge seal
    - Mainly due to corrosion by acidic water
    - Leak rate increased by beam exposure (more later)
- Water leak occurred again (spring 2018)
  - Leak point not identified yet, but horn1 is a suspect
    - Leak rate increased by beam exposure

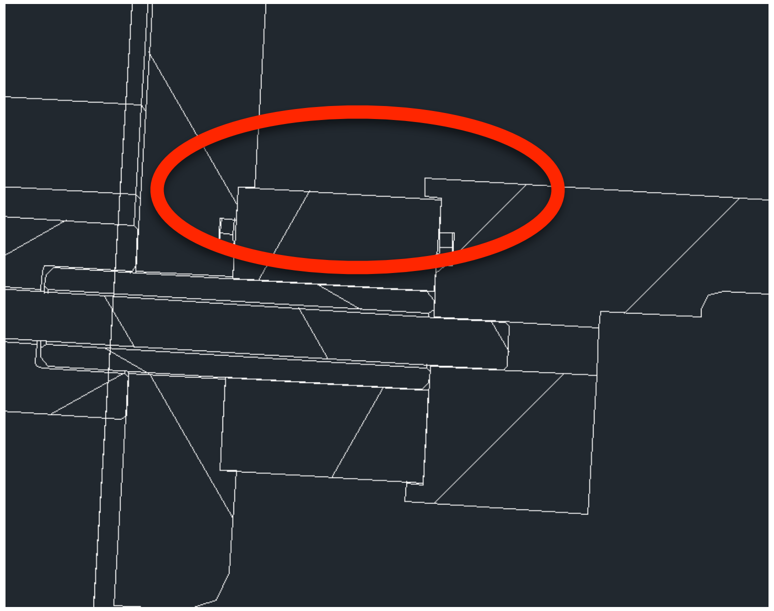


Horn1 Sealing Improvement

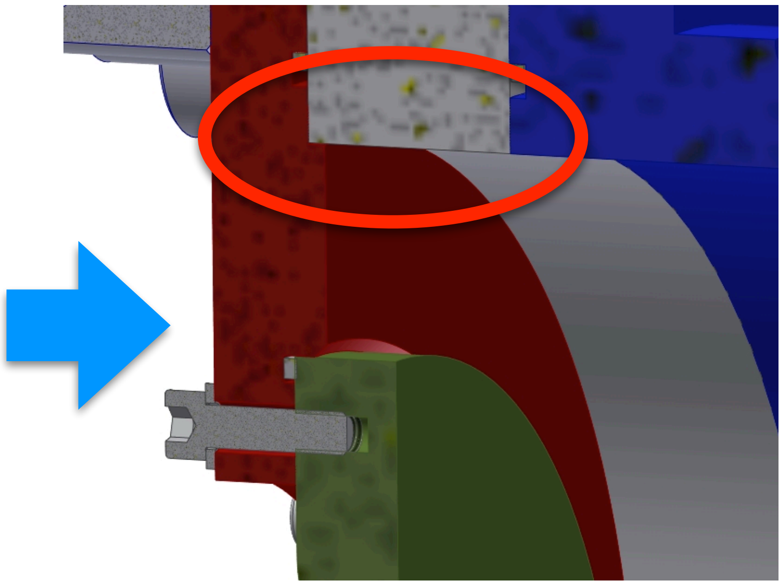
- **For 3rd-generation horn1**
  - **Aluminum knife-edge seal + long aluminum bolts**
    - **Not good against thermal expansion**
  - **Replace with Helicoflex seal ⇒ good elasticity for thermal expansion**
  - **Upstream structure changed to remove a step ← potential source of water leak**
- **These already applied for 1st and 2nd gen. Horn2 and horn3**



1st, 2nd gen. horn1

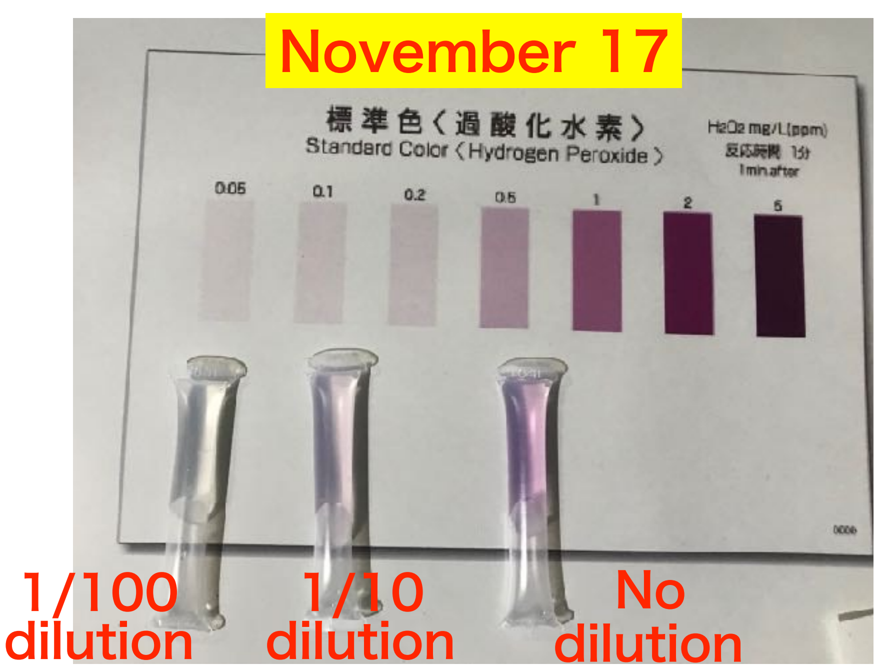


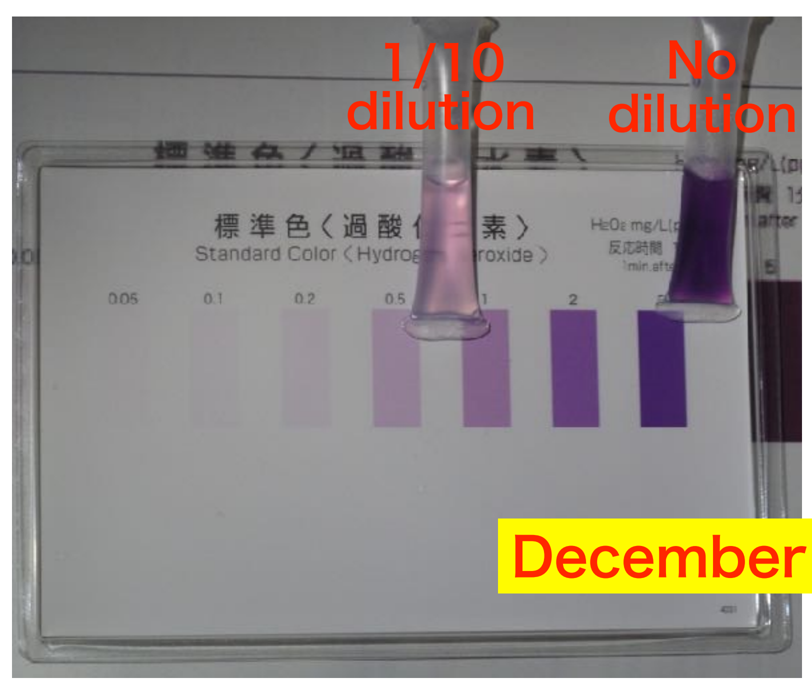
3rd gen. horn1



H_2O_2 Concentration

- **Measurement of H_2O_2 concentration**
  - **A simple measurement (PACKTEST)**
    - **http://kyoritsu-lab.co.jp/english/seihin/list/packtest/h2o2.html**
  - **Measured :**
    - **0.5~1mg/L ⇔ estimated : ~220mg/L @ 1.7×10^{20} POT (on Nov. 17)**
    - **~10 mg/L ⇔ estimated : ~500 mg/L @ 3.9×10^{20} POT (on Dec. 22)**
    - **Significantly smaller concentration observed**
    - **Due to decomposition of hydrogen peroxide? (it's unstable)**





H_2O_2 Resistant Ion Exchanger

- **H_2O_2 is problematic for nuclear reactor business**
  - **H_2O_2 resistant ion exchanger developed for reactor**
  - **Pd-doped ion exchanger can decompose H_2O_2 and therefore can extend lifetime of ion exchanger**

Development of Decomposition Method of Hydrogen Peroxide in Spent Fuel Pool

by Takeshi IZUMI, Makoto KOMATSU, Tatsuya DEGUCHI, Daisuke AKUTAGAWA, Takeshi MANABE, & Yusuke NAKANO

From the viewpoint of the minimizing the corrosion of the spent fuel rods and structural material in the spent fuel pool, the ion exchange resins are generally used as one of purification system in order to keep water quality clean.

Hydrogen peroxide generated by the radiolysis of water exists in the pool water and it accelerates the oxidation decomposition of the ion exchange resins and finally, it becomes the cause to shorten the resin life.

To solve this problem, the application of Pd doped resins which can decompose hydrogen peroxide catalytically at the surface has been considered. It was confirmed by the cold test that Pd doped resins overlaid on the ion exchange resins decomposed hydrogen peroxide contained in the pool water and inhibited the oxidative degradation of the ion exchange resins.

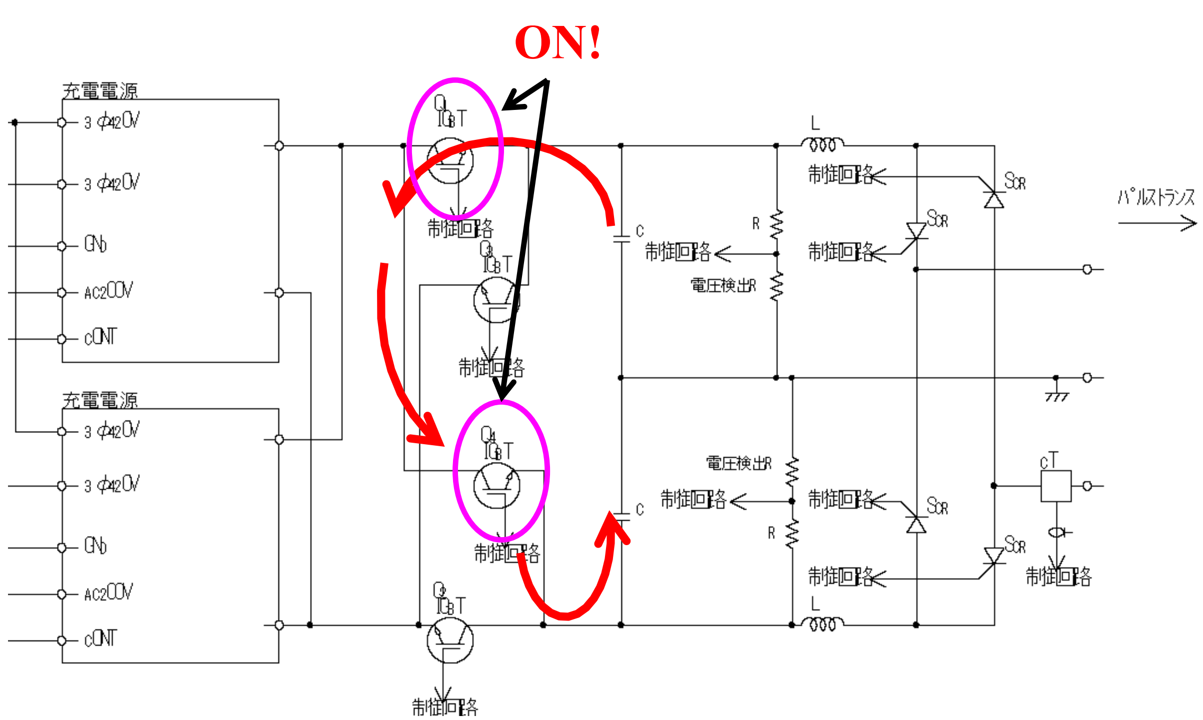
Based on the results, hot examination tests by using actual pool water in Tsuruga-2 were carried out from Jan. 2014 to Mar. 2014. We report the results of these tests.

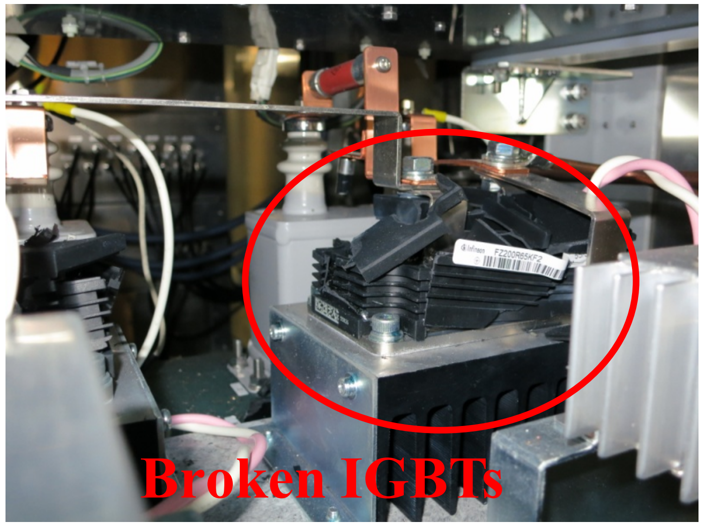
Keywords: Pd doped resins, Hydrogen peroxide, Ion exchange resins, Spent fuel pool, Nuclear power plants

T. Izumi et al, Ebara Jiho, No. 247, p.3-8 (2015)

T2K PS ver. 1

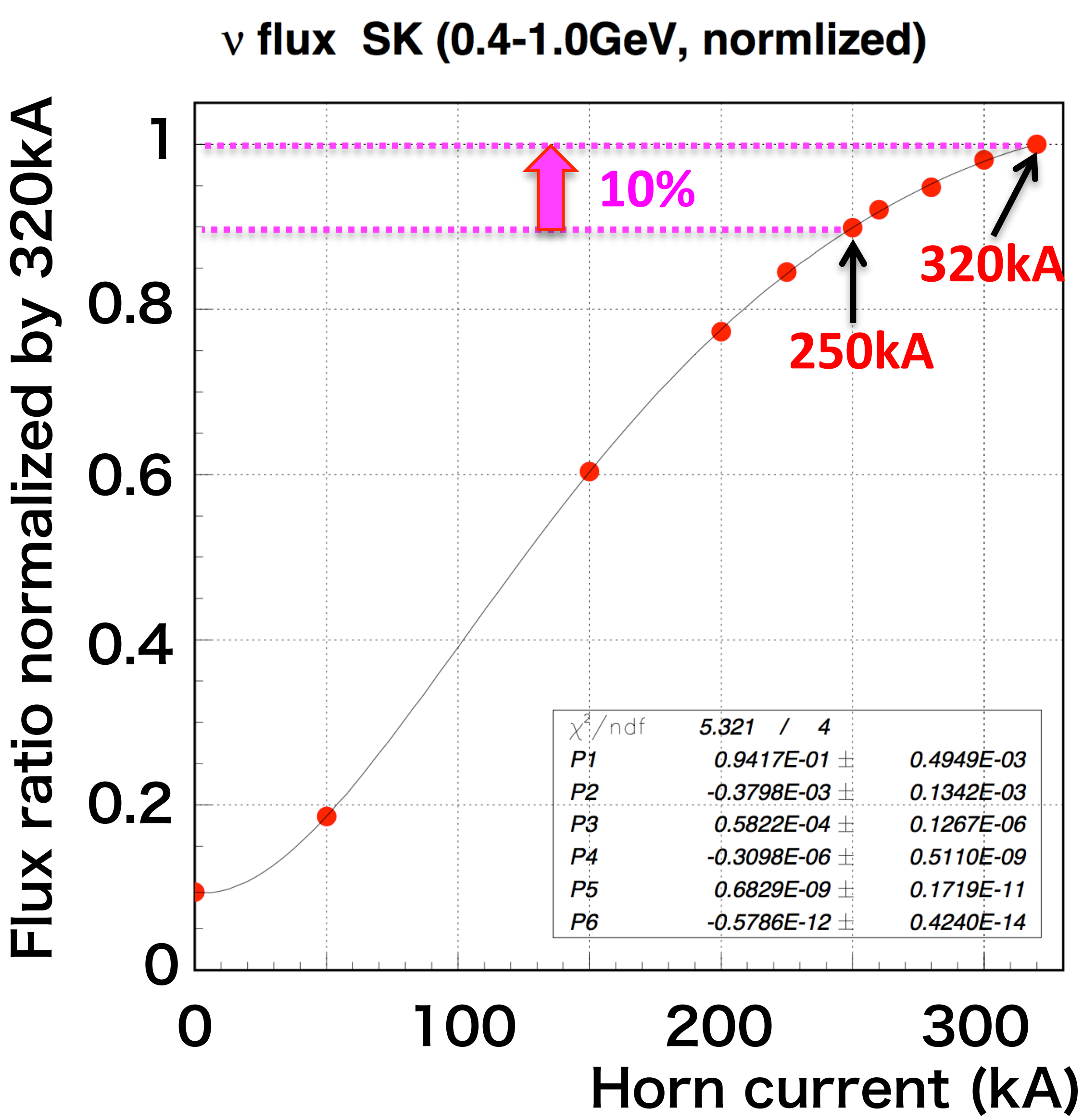
- Produced for three-horn series operation by one PS
  - Energy recovery ⇒ alternating voltage operation (+ → - → + …)
  - Spec : 35 kA, 10 kV (±5 kV)
- Serious trouble in December 2011
  - IGBTs were broken due to malfunction
    - High voltage operation can potentially cause a large inrush noise
  - It took whole a year to recover (but, finally out of service now)
  - K2K PS recycled again for three-horn configuration ⇒ struggled with high voltage operation at 6.7 kV ⇒ achieved with several measures

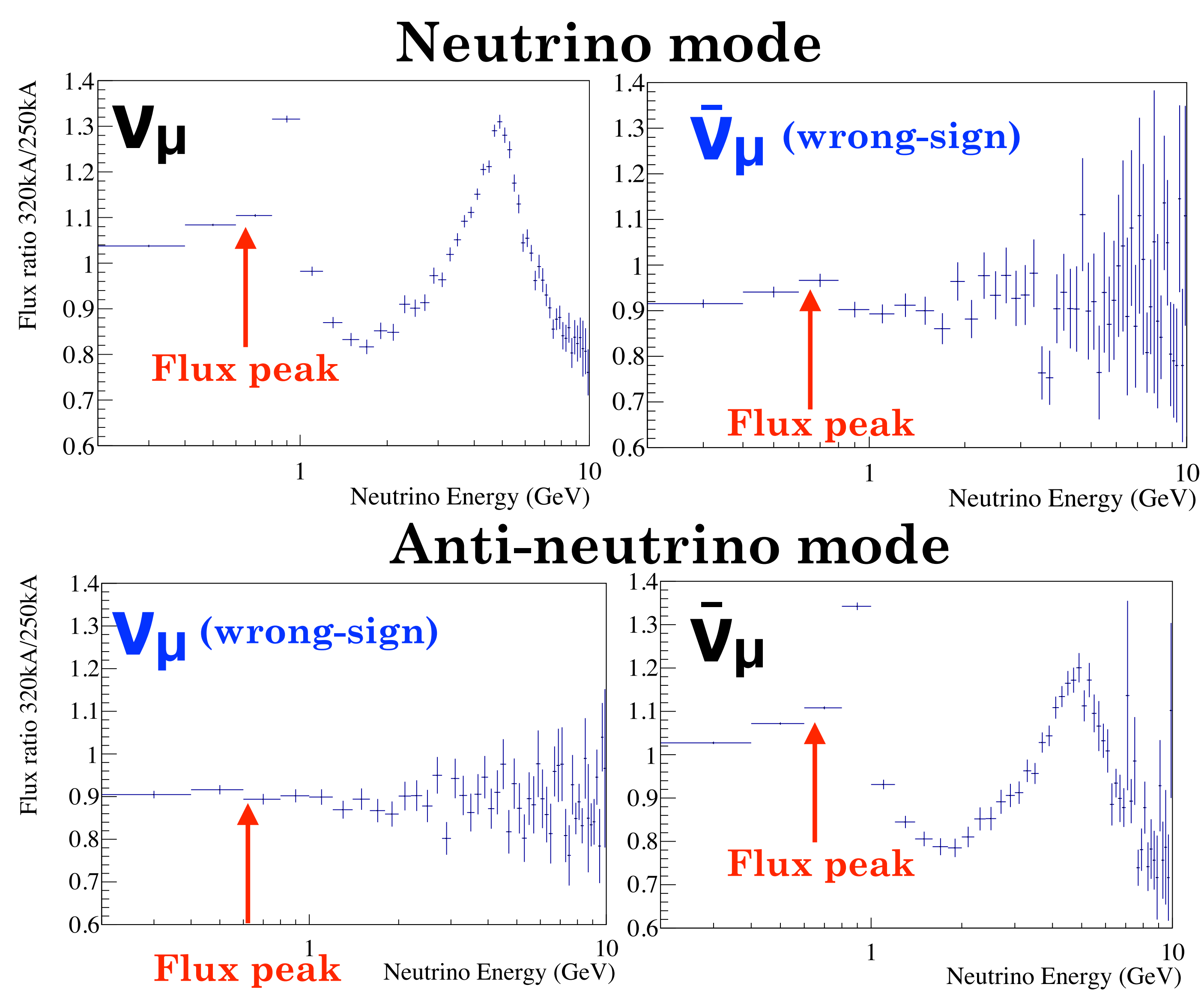




Horn Current Increase

- **Horn current increase: 250 kA → 320 kA (design)**
  - **~10% flux improvement for normal sign neutrinos**
  - **5~10% flux reduction for wrong-sign neutrinos**





Development of New PS

- **Parameters of new PS**
  - **32 kA rated current, 7 kV rated voltage**
  - **4mF capacitance ⇒ 2 ms pulse width**

- **Features**
  - **Energy recovery system (alternating voltage operation)**
  - **Lower voltage operation < 6 kV**
  - **Noise-tolerance improved for control circuit**
  - **Current limiter (LR circuit) to avoid large current flow to IGBTs**

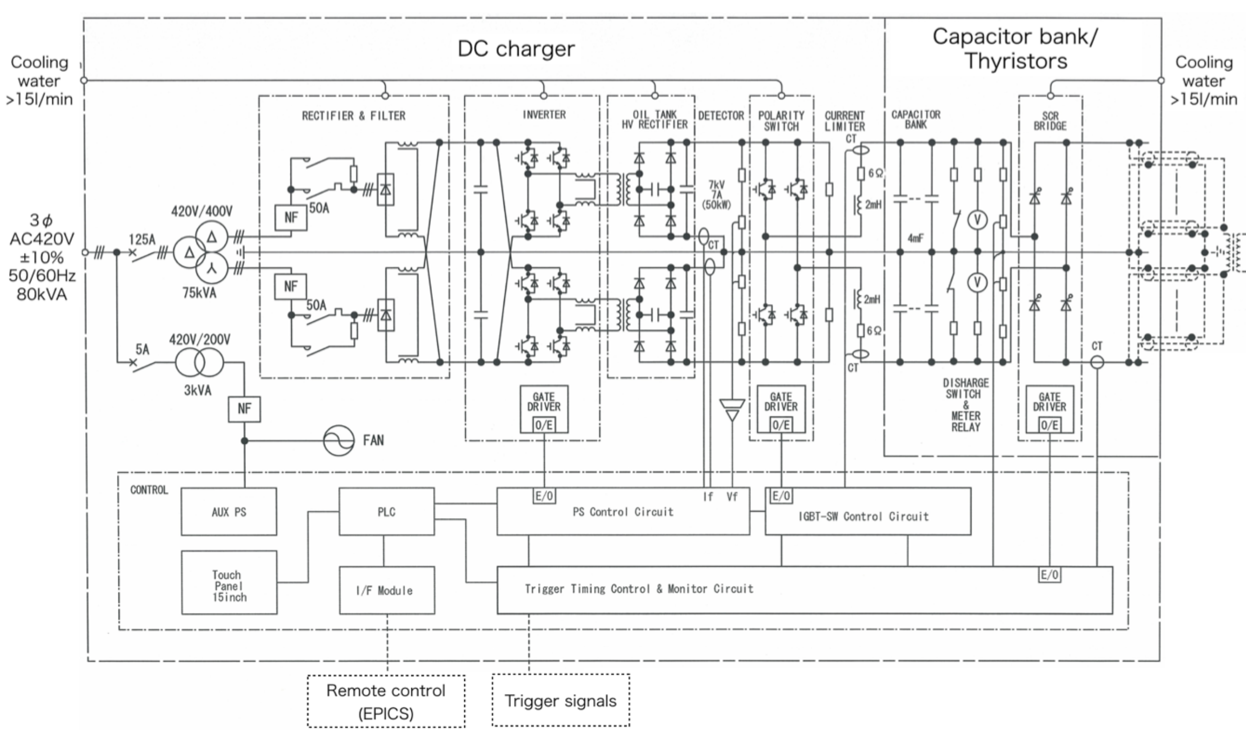


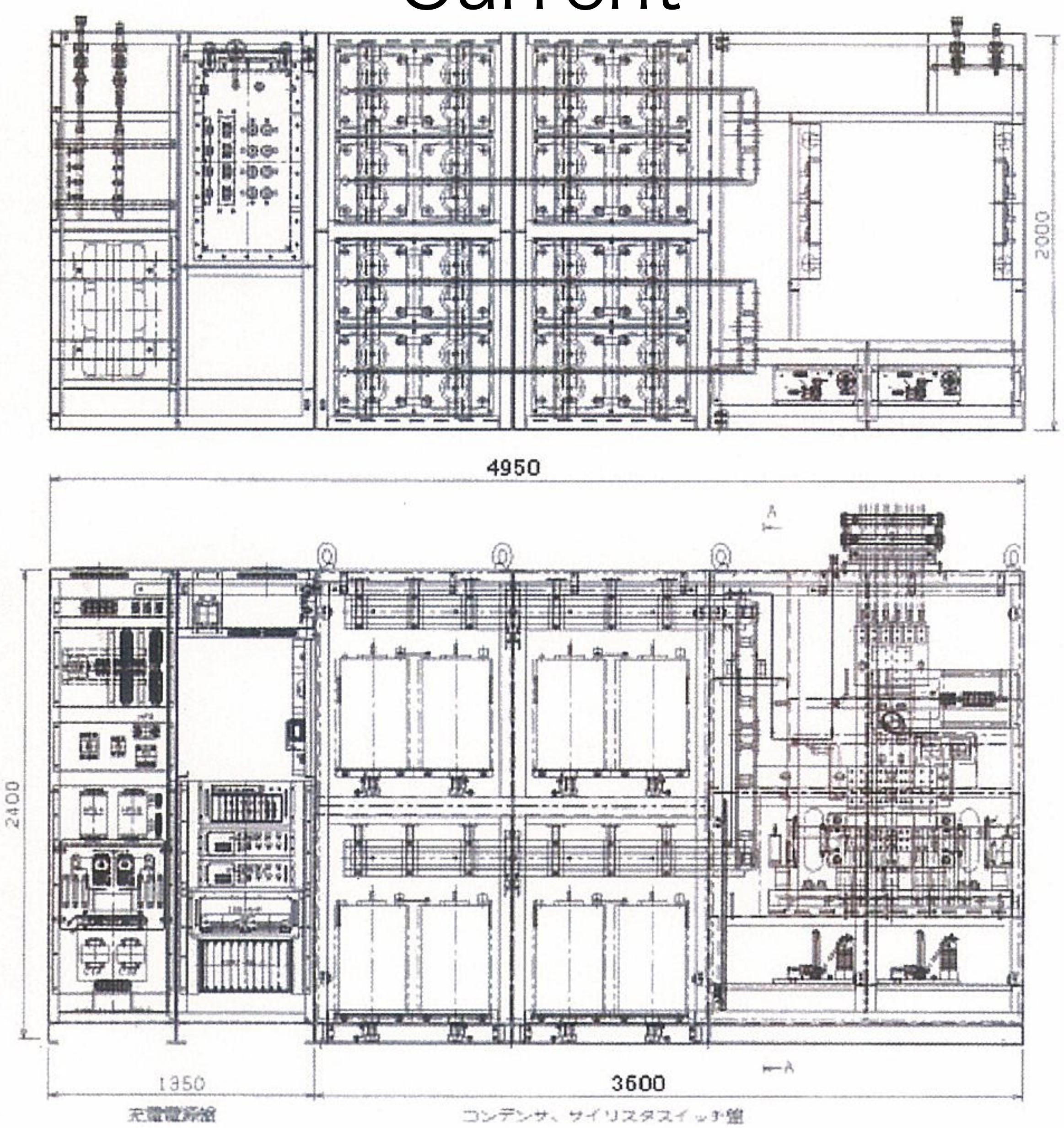
Table 20: Summary of specification of the new power supply.

Item	Value
Rated operation voltage	7 kV
Rated charging current	7 A
Charging unit	50 kW
Rated operation cycle	1 Hz
Total capacitance	4 mF
Capacitor bank configuration	
(original design)	2S16P (0.5 mF×32)
(modified)	2S24P (0.335 mF×48)
Pulse width	2 ms
Rated output current	32 kA
Stored energy	98 kJ

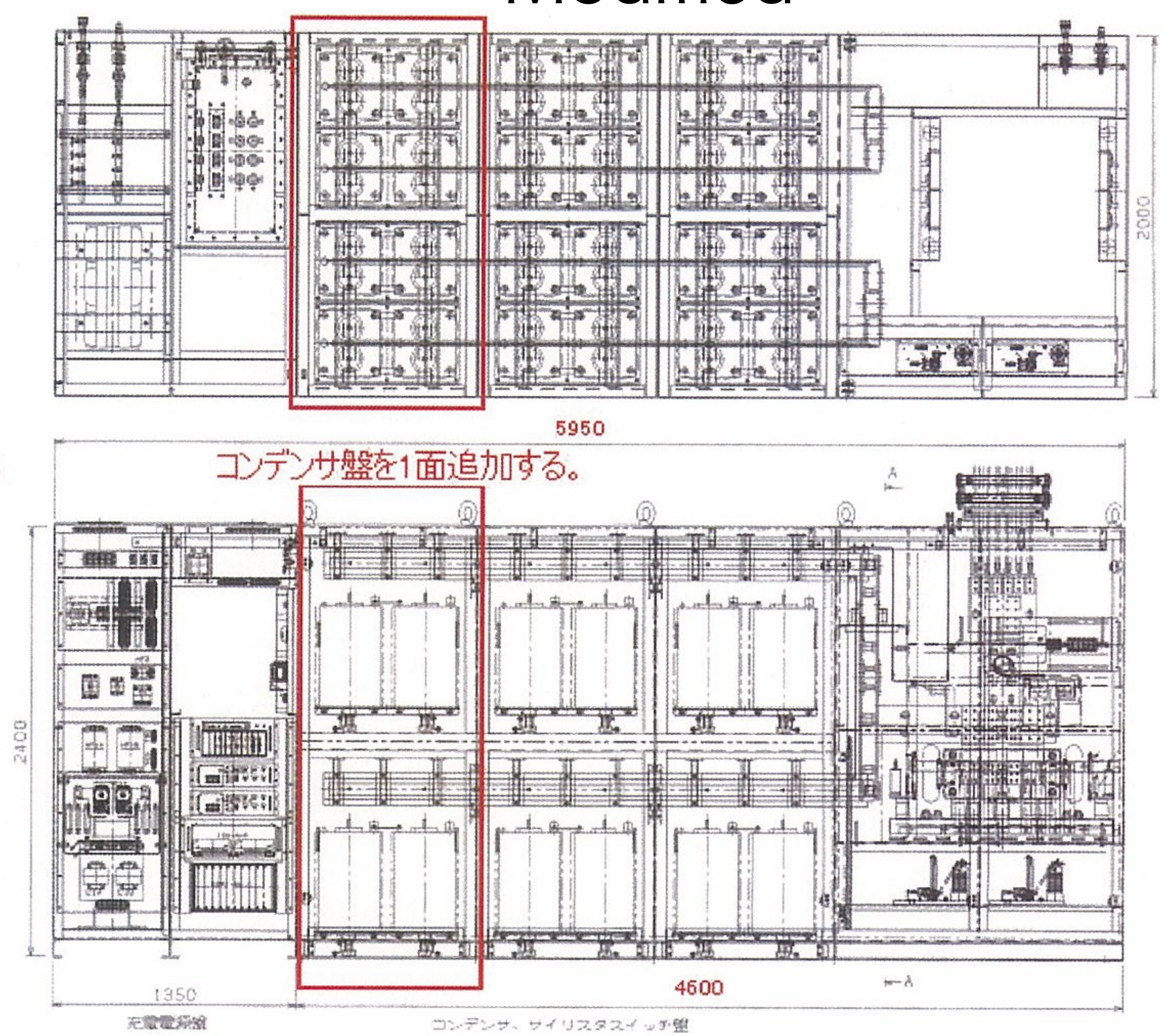
PS Modification

- Modification plan
  - Add capacitor bank

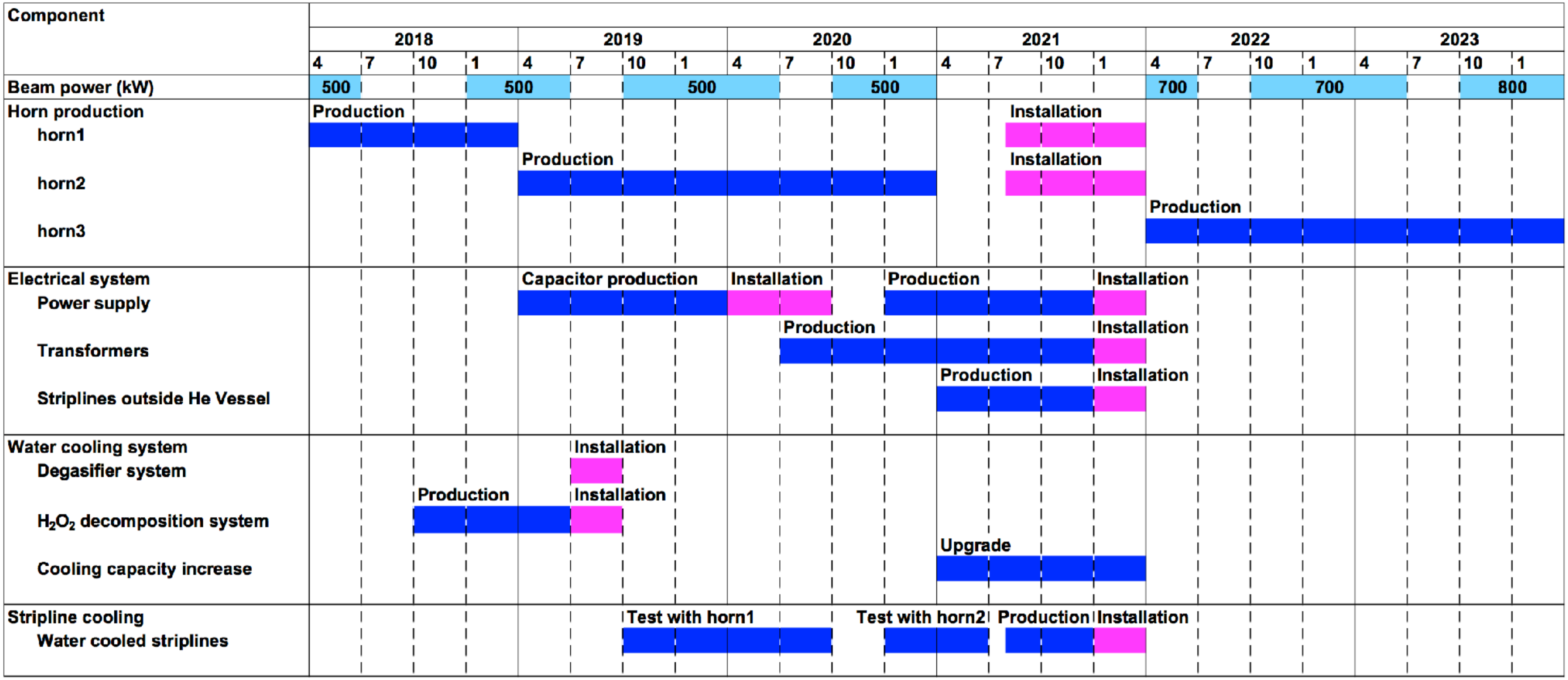
Current



Modified



Schedule



- **Aiming to complete all the upgrades by FY2021**