J-PARC Horn Operational Status and Upgrade Plan

T. Sekiguchi

2019. 10. 22

Contents

- Introduction
- Operational experience
- Horn upgrade
  - Electrical system upgrade
  - Cooling upgrade
- Summary

Contents

- Introduction
- Operational experience
- Horn upgrade
  - Electrical system upgrade
  - Cooling upgrade
- Summary

Secondary Beamline

Proton

π , K

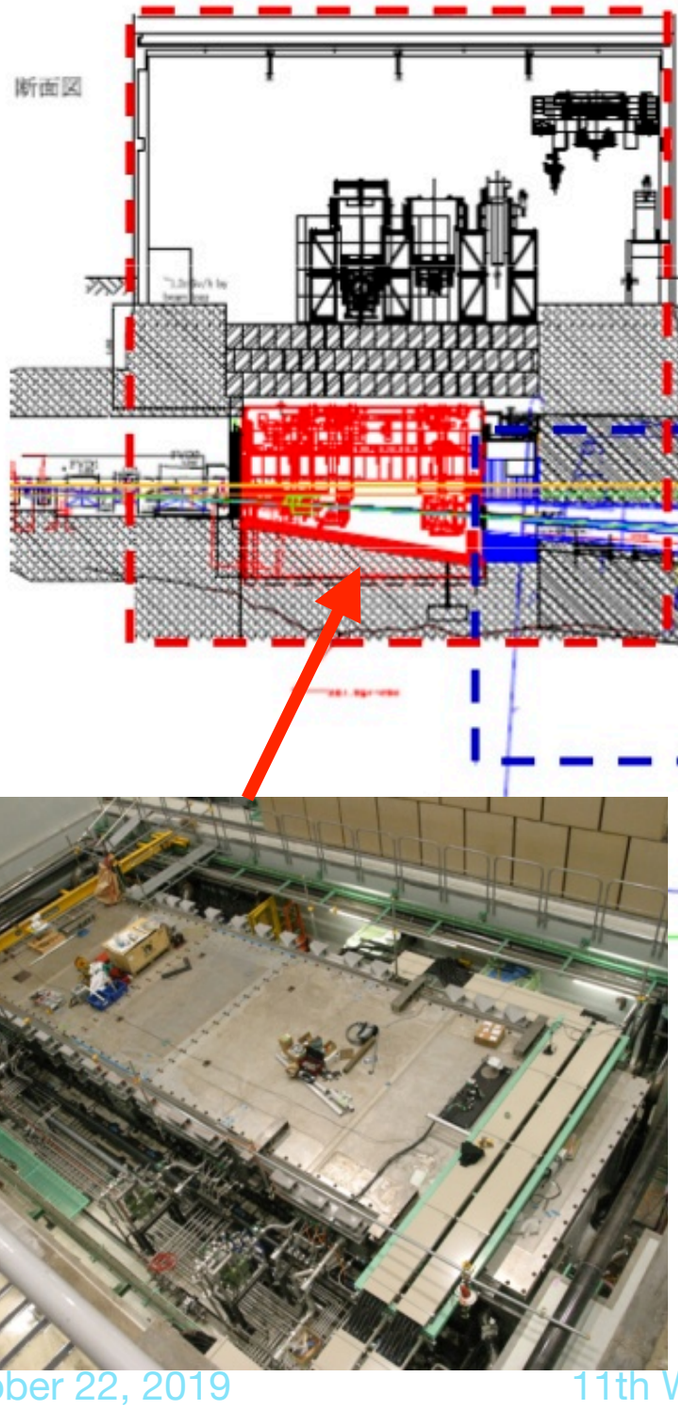
ν_μ

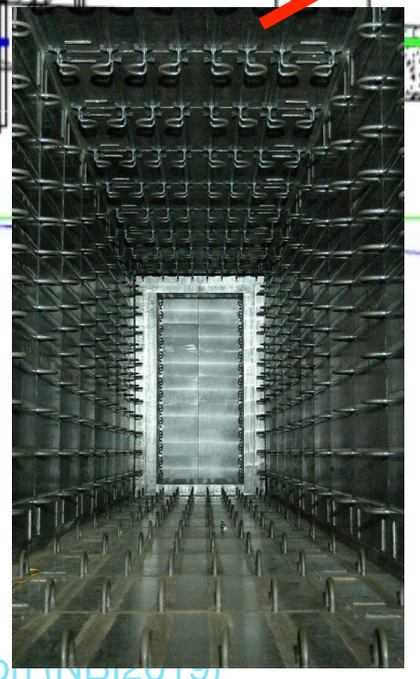
μ

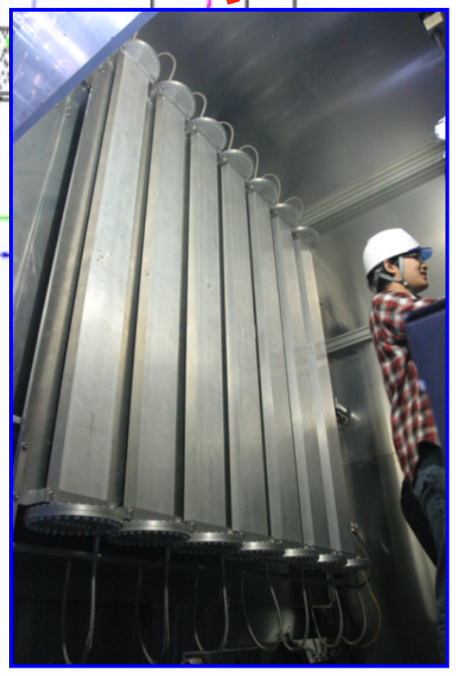
Target Station (TS)

Decay Volume (DV)

Beam Dump (BD)



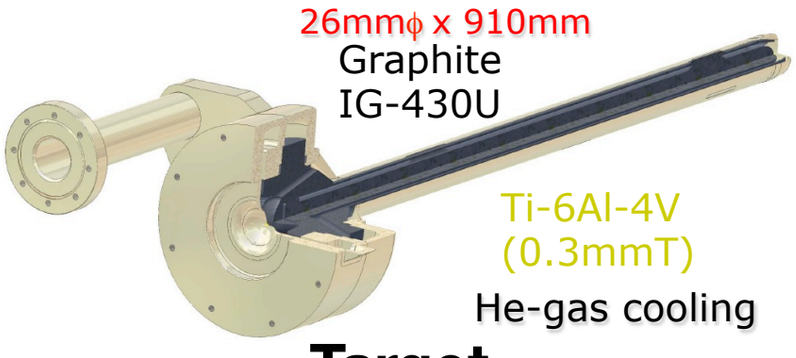




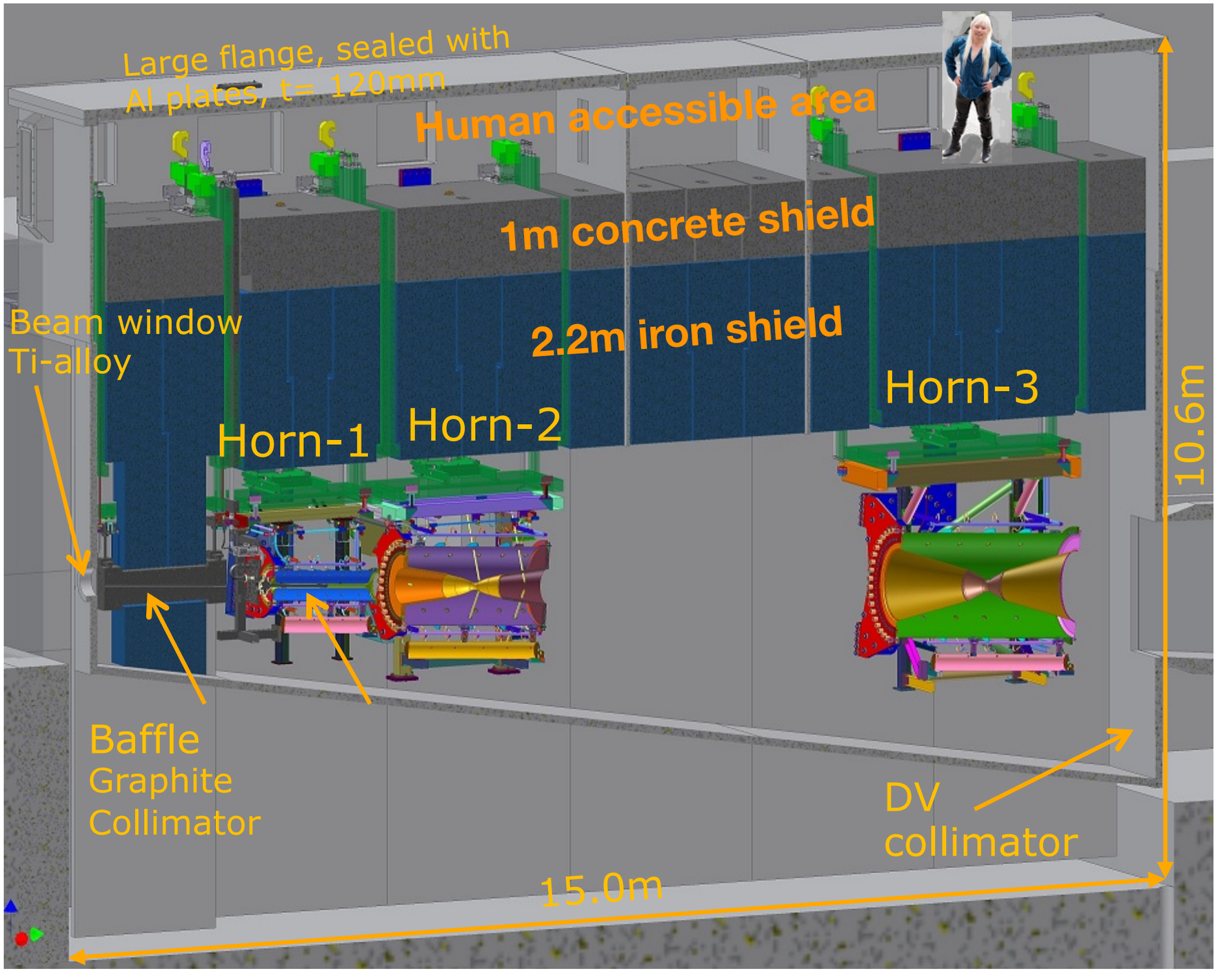
Target Station

Target and magnetic horns are located inside He vessel at Target Station

Horn1

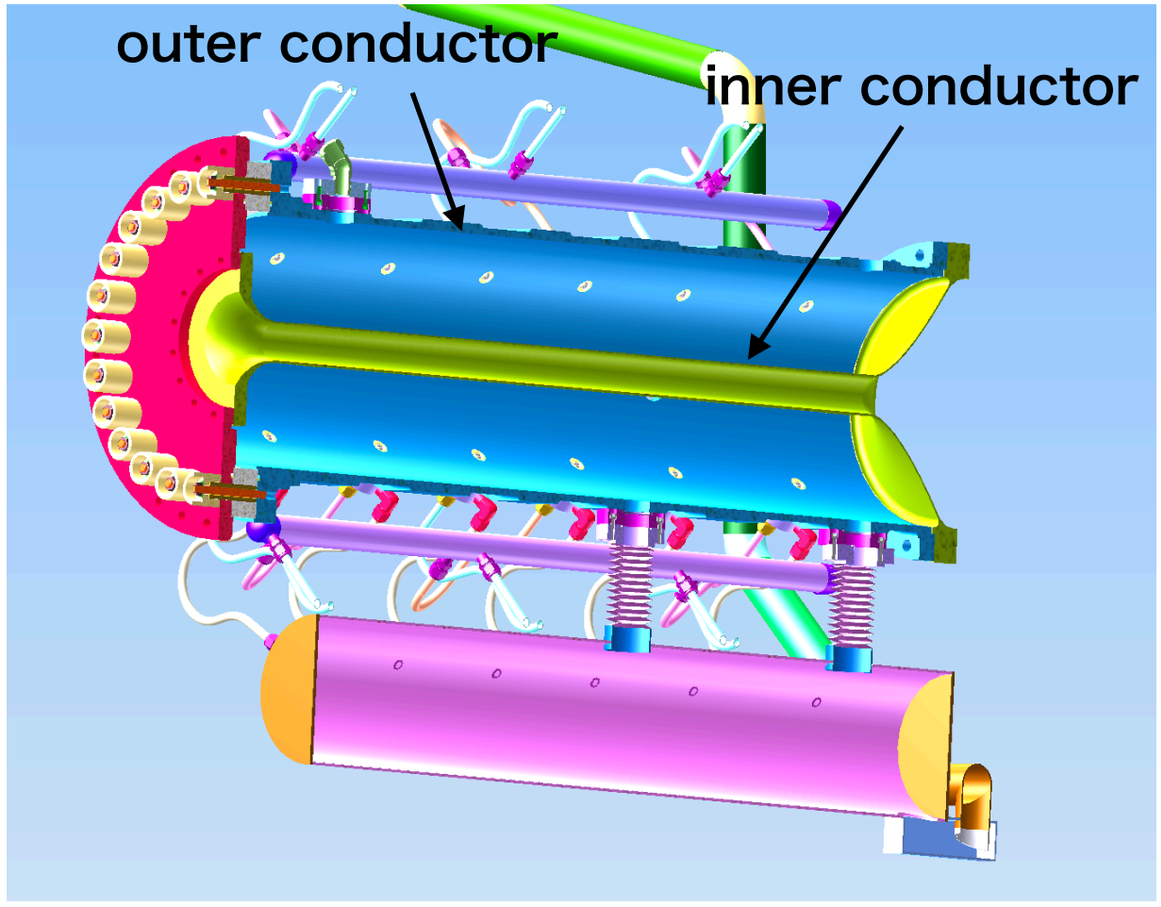


Target



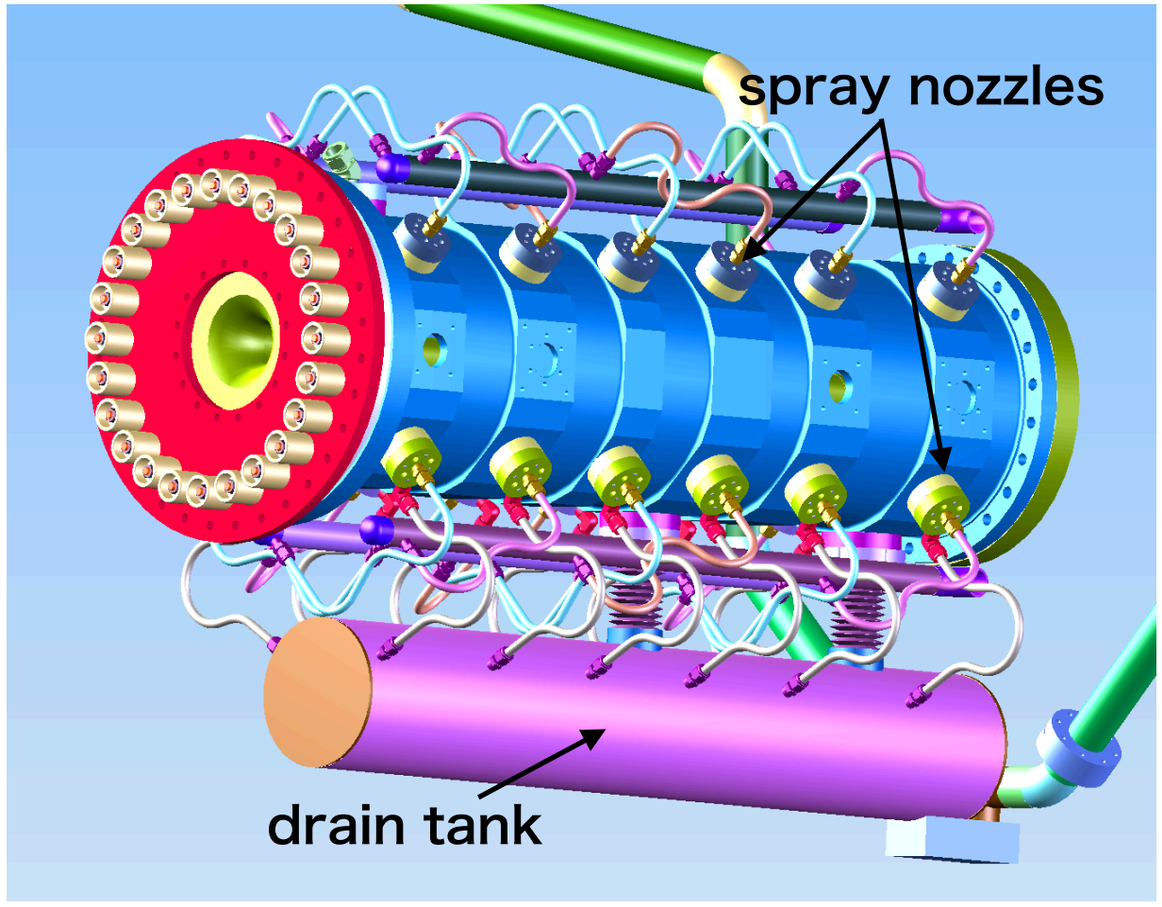
T2K Magnetic Horn

- **Aluminum coaxial conductor by A6061-T6**
  - 3mm(10mm)-thick inner (outer) conductor
  - Fatigue: 310 MPa → 68.9 MPa after 2×10^8 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



T2K Magnetic Horn

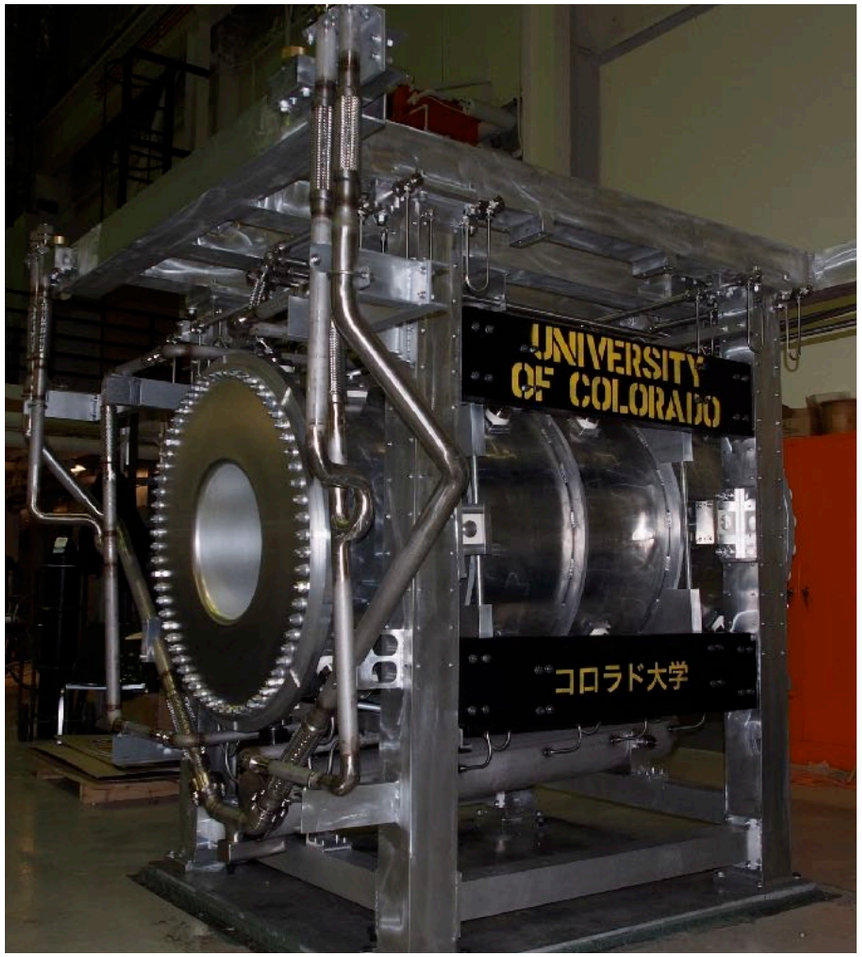
- **Aluminum coaxial conductor by A6061-T6**
  - 3mm(10mm)-thick inner (outer) conductor
  - Fatigue: 310 MPa → 68.9 MPa after 2×10^8 cycle at 97.5% C.L.
  - Corrosion: Strength reduction x ~0.43
  - Allowable stress: 29.6 MPa
- **320kA pulsed current (design)**
  - Toroidal magnetic field: 2.1 T (max.)
  - 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



T2K Magnetic Horn

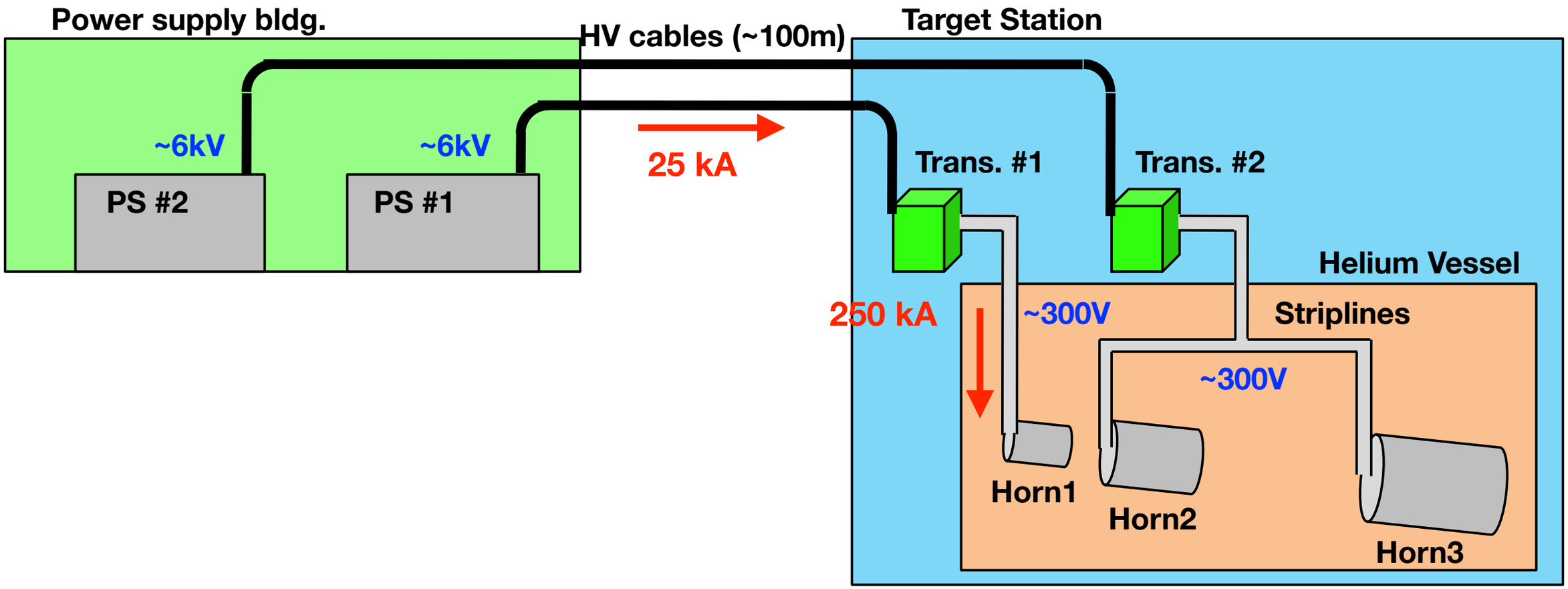
Horn1

Horn2



Horn3

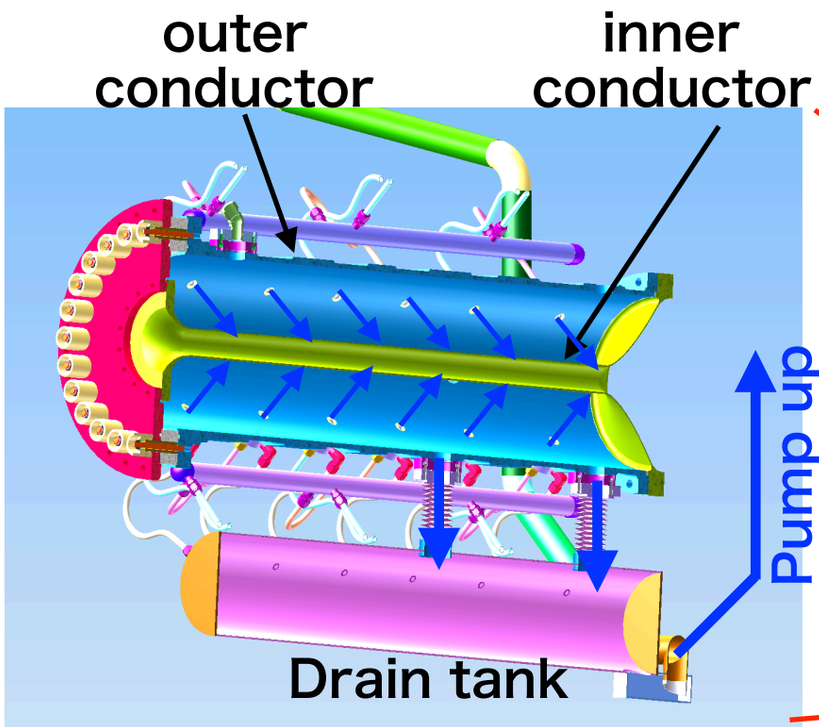
Horn Electrical System

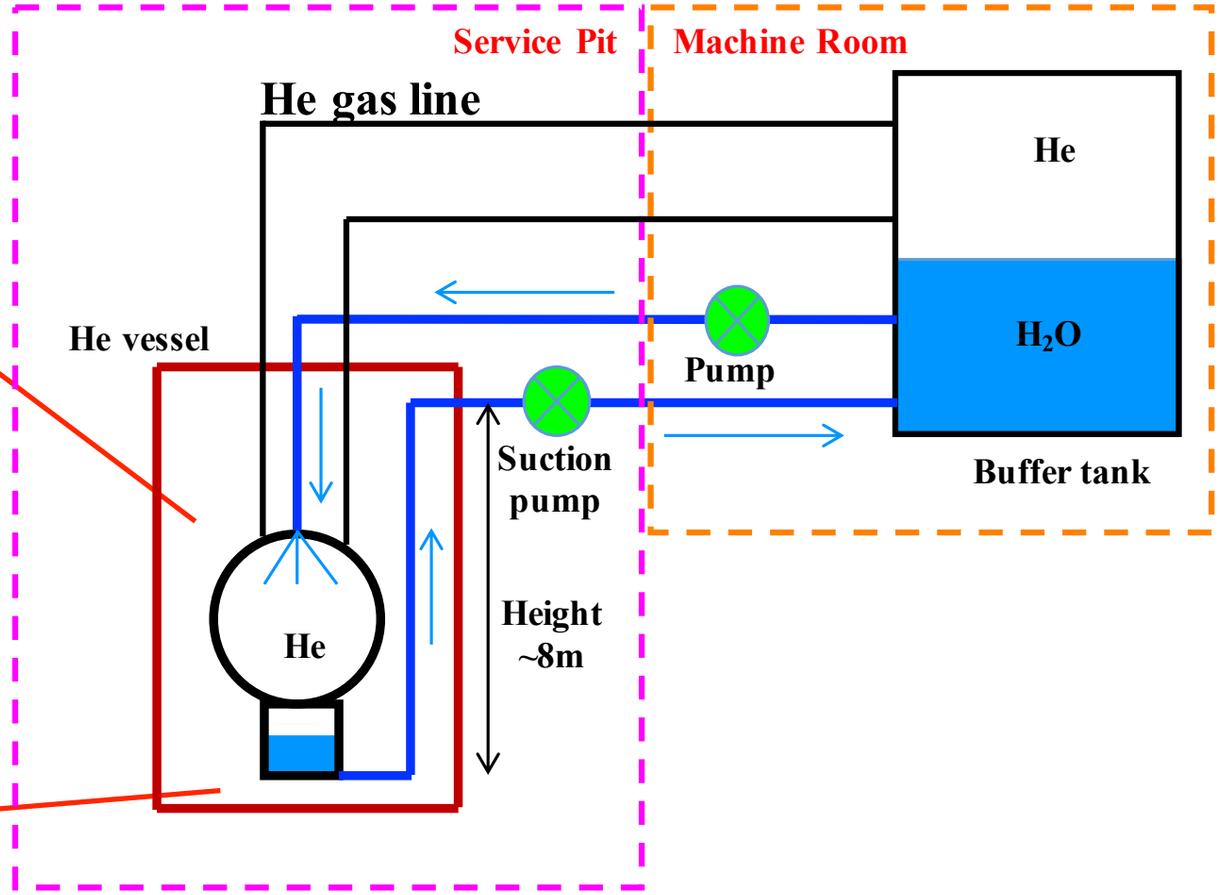


- Current flow
  - Power supply $\xrightarrow{25\ \text{kA}}$ Transformer $\xrightarrow{250\ \text{kA}}$ Horn
- 250 kA operation since beginning of T2K physics run
  - K2K PS (250 kA rated) reused for T2K at day1
  - Several PS-related problems limited horn current to 250 kA

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**





Contents

- Introduction
- Operational experience
- Horn upgrade
  - Electrical system upgrade
  - Cooling upgrade
- Summary

Horn Operation History

Cycle 3.52s | 3.2s →3.04s | 2.56s | 2.48s | 2.48s | 2.48s | 2.48s | 2.48s | 2.48s

Accumulated POT (10^{20}) / Beam Power (kW)

Run1 Run2 Run3 Run4 Run5 Run6 Run7 Run8 Run9

1st-gen. horns

2nd-gen. horns

Recovery from Big Earthquake

Horn replacement

Target He pipe replacement

2010 2011 2012 2013 2014 2015 2016 2017 2018

horn pulse

0.2x10⁷ Hydrogen problem (2010.Mar)

0.5x10⁷ Power supply problem (2011.Dec)

0.8x10⁷ Corrosion problem (2012.Jun)

1.2x10⁷ Water drop problem (2012.Oct)

0.1x10⁷ Neutral grounding problem (2014.Oct)

0.5x10⁷

0.8x10⁷ Neutral grounding problem (2016.Feb.&Apr.)

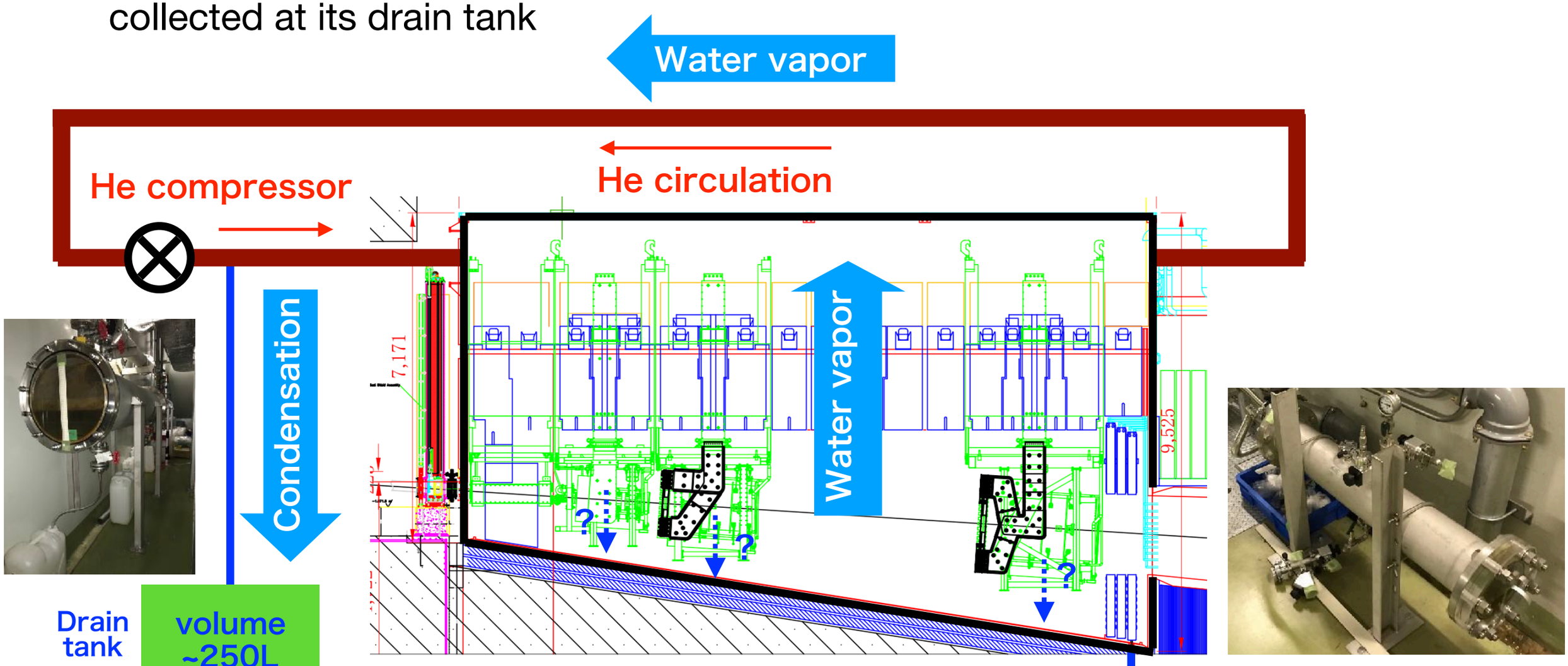
1.3x10⁷ Capacitor problem (2017.Mar)

1.7x10⁷ Hydrogen problem (2017.Oct)

Water drop problem (2018.Mar)

Water drop from Horn

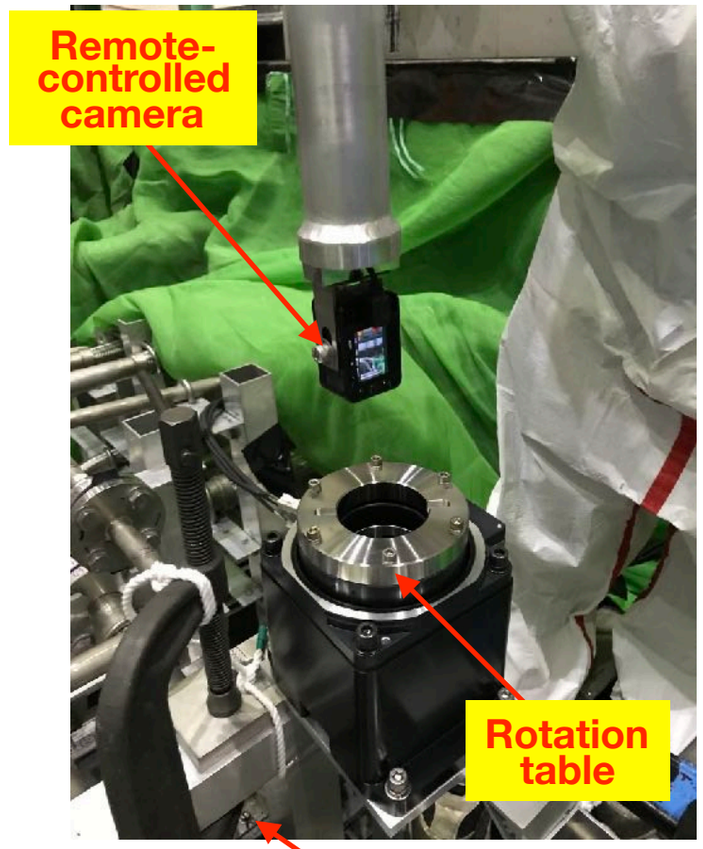
- **Water level decreased during beam operation since March 2018**
  - **~5 L/day** (⇔ 10 L/day in 2012)
  - Dropped water immediately evaporated and condensed after He compressor, then collected at its drain tank

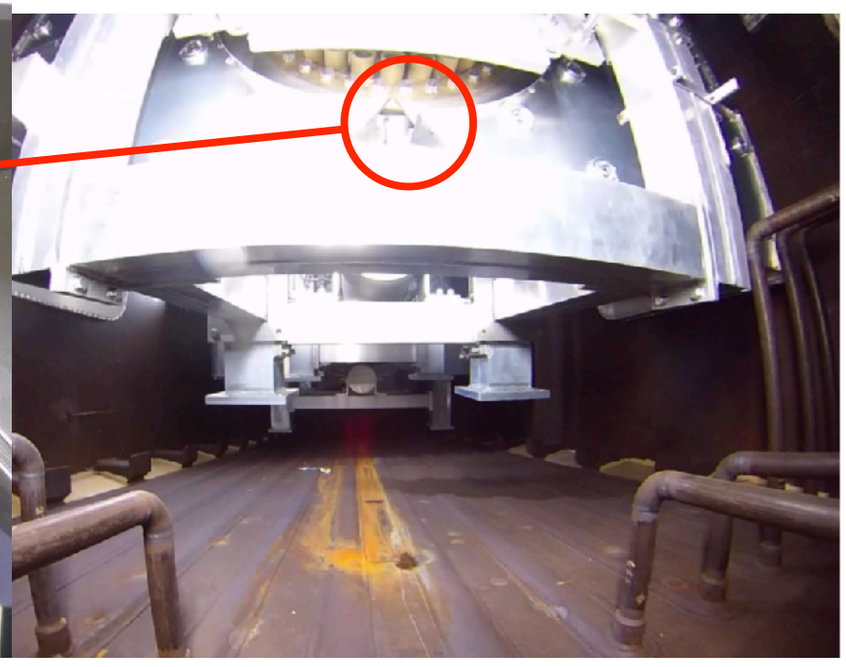


Almost no water stayed at the bottom of He vessel
→ no further corrosion of iron vessel

Water Drop Investigation

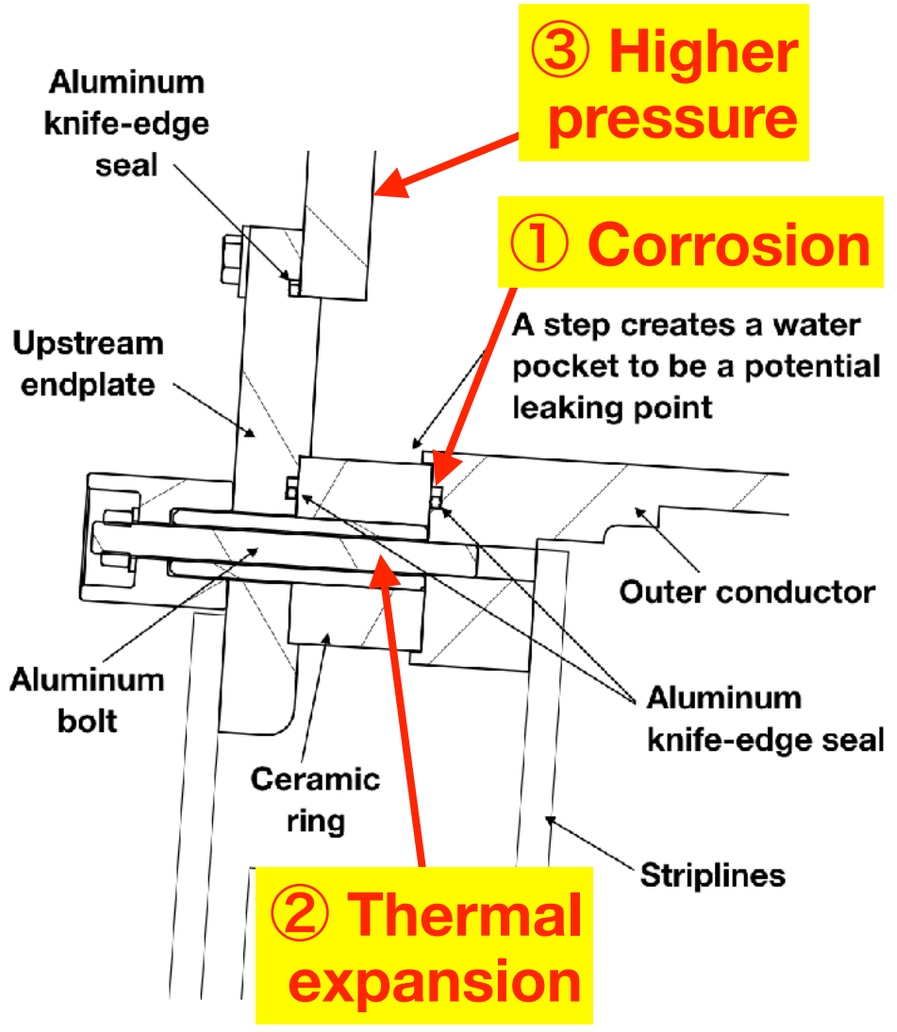
- **Investigation performed after beam operation**
  - **Before opening He vessel**
    - One-by-one horn operation and water circulation
      - Check water level → **Horn1 caused water drop**
  - **In-situ investigation after He vessel opened**
    - Remote camera inspection during horn operation
      - Special visual inspection tool lowered through ϕ65mm through-hole
  - **Observed actual water drop from upstream of horn1**





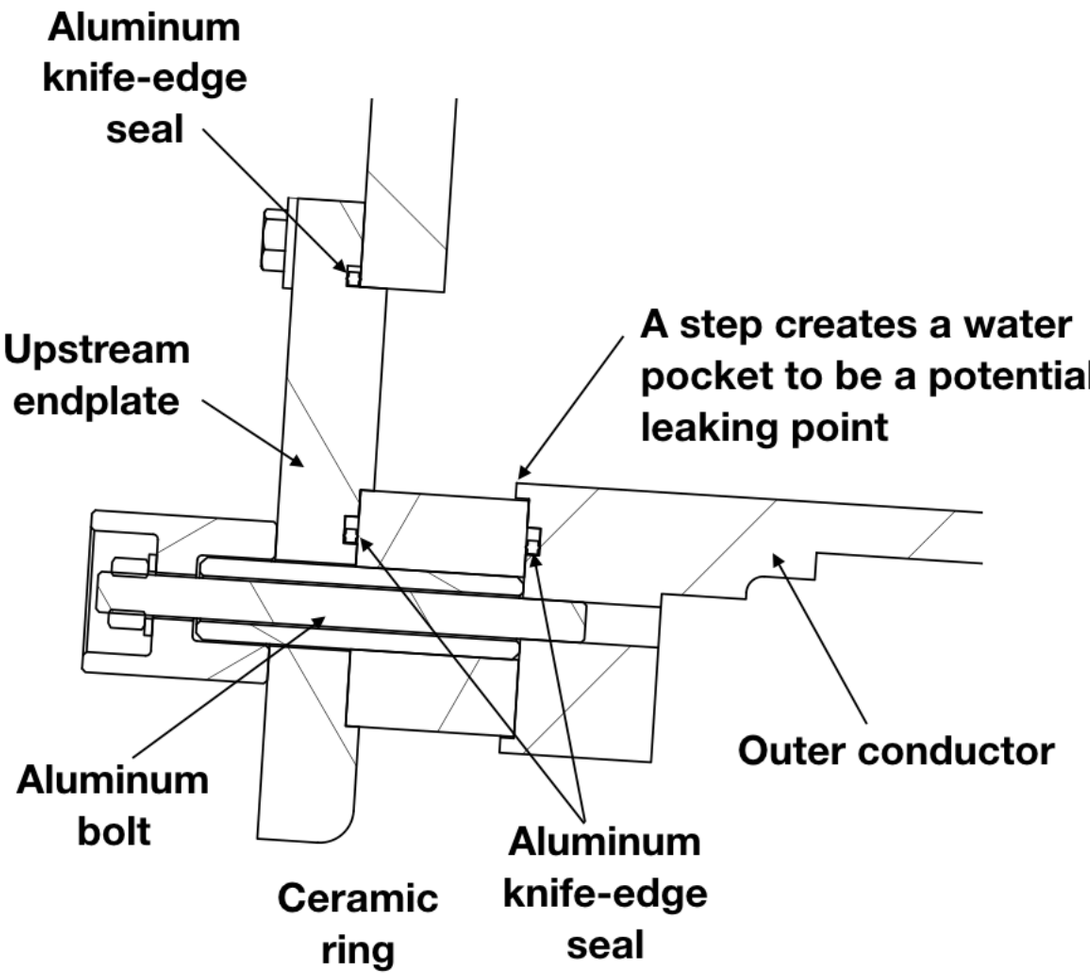
Reason of Water Drop and Countermeasures

- **Expected reasons of the drop**
  - ① **Corrosion at the upstream seal**
    - A step structure at the upstream flange created a water pocket
    - If water stays at a tiny gap, a gap corrosion occurs
  - ② **Beam heating caused thermal expansion of bolts**
    - Contact pressure at seal reduced
  - ③ **Higher pressure inside horn than before**
    - Outlet pressure of new He blower is higher by ~4 kPa than before (~115kPa@Horn1)
- **Countermeasures**
  - Don't stop water circulation during long shutdowns
  - Change He flow direction to reduce He pressure
    - Horn1(**115kPa**)→Horn2(105kPa)→Horn3(101kPa)
    - Horn3(115kPa)→Horn2(105kPa)→Horn1(**101kPa**)
  - Larger drain tank for He vessel drain (30L→250L)
- **Current horn1 will be replaced in FY2021**

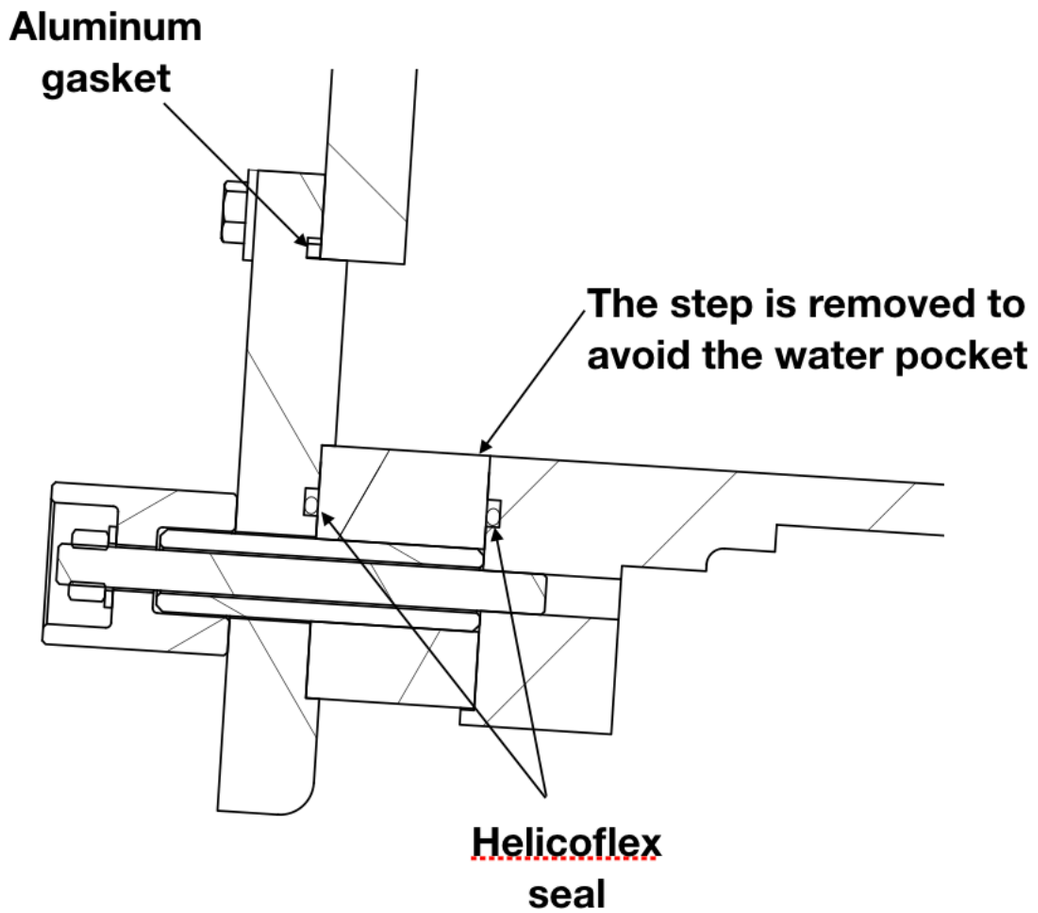


Modification At Next Horn1

1st/2nd generation horn1



3rd generation horn1



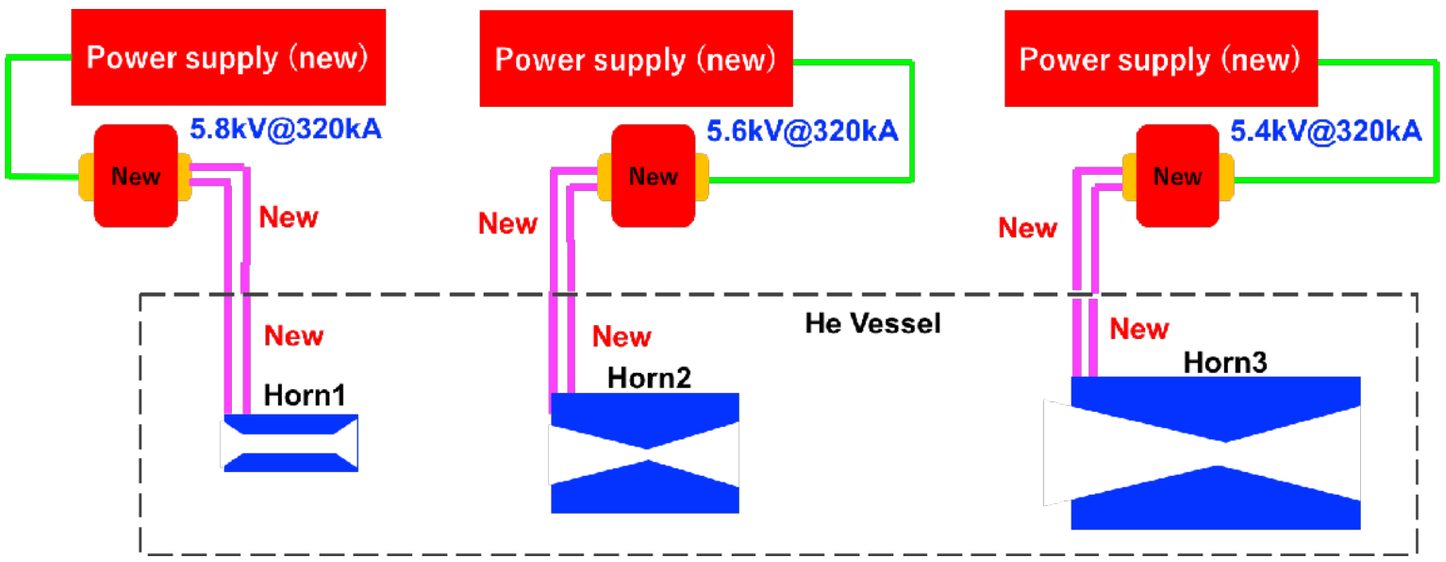
- Al knife-edge seal → Helicoflex seal ⇒ Countermeasure for thermal expansion
- Remove step structure ⇒ Avoid corrosion
- Al bolts ⇒ Ti bolts ⇒ Countermeasure for thermal expansion

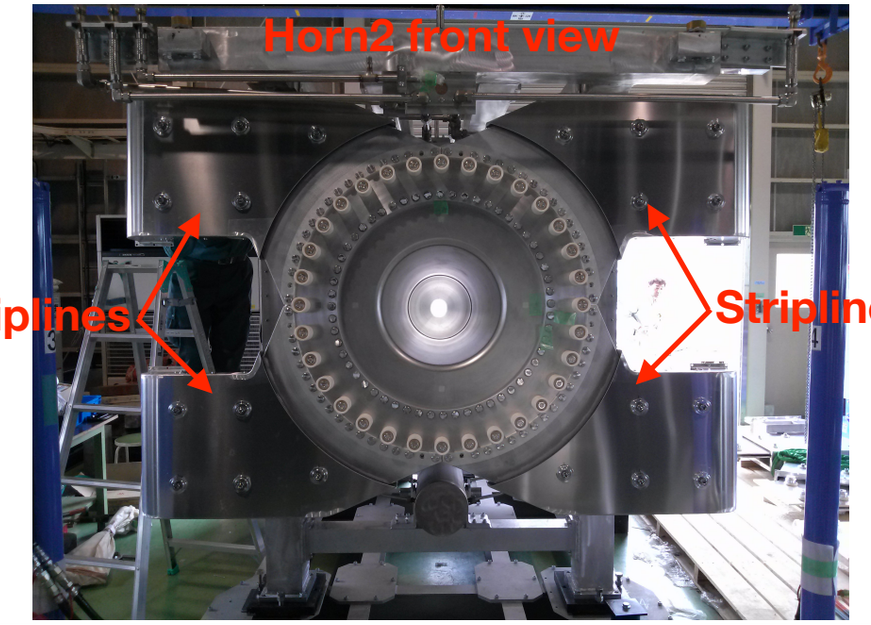
Contents

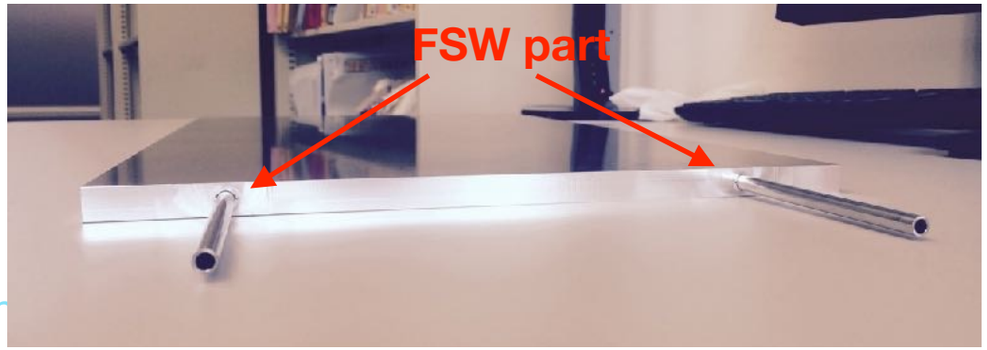
- Introduction
- Operational experience
- Horn upgrade
  - Electrical system upgrade
  - Cooling upgrade
- Summary

Horn Upgrade Plan

- **320 kA & 1 Hz operation ⇒ 10% neutrino flux gain**
  - 3 power supply configuration
  - Need new PS, Transformer, striplines
- **Cooling improvement**
  - Horn2 stripline cooling : He gas cooling (~750 kW) ⇒ water cooling (1.3 MW)
    - Development of water-pipe embedded striplines (only for Horn2)
  - Additional cooling for upstream part of Horn2 outer conductor
  - Cooling capacity improvement
  - H_2 removal system for safe operation







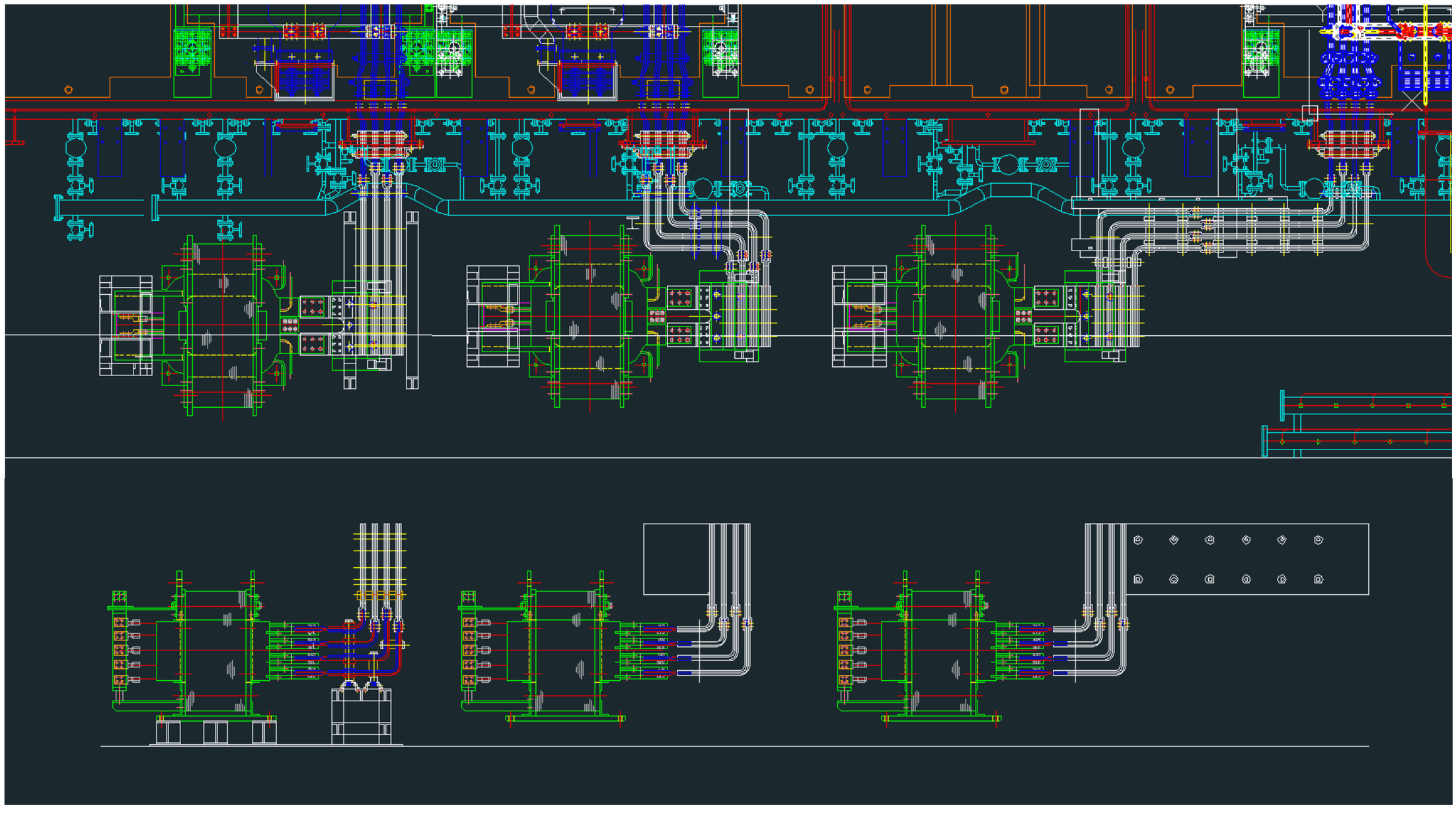
Electrical System Upgrade

- **New power supplies with energy recovery**
  - Operation voltage < 6 kV at 320 kA
  - Charging time < 1 sec
- **New low impedance striplines**
  - L ~ -40%, R ~ -30%
  - Wider and thicker stripline plates
    - Stronger against Lorentz force
- **New transformers for 320 kA operation**
  - High mechanical strength
  - High magnetic field tolerance
  - High cooling performance

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

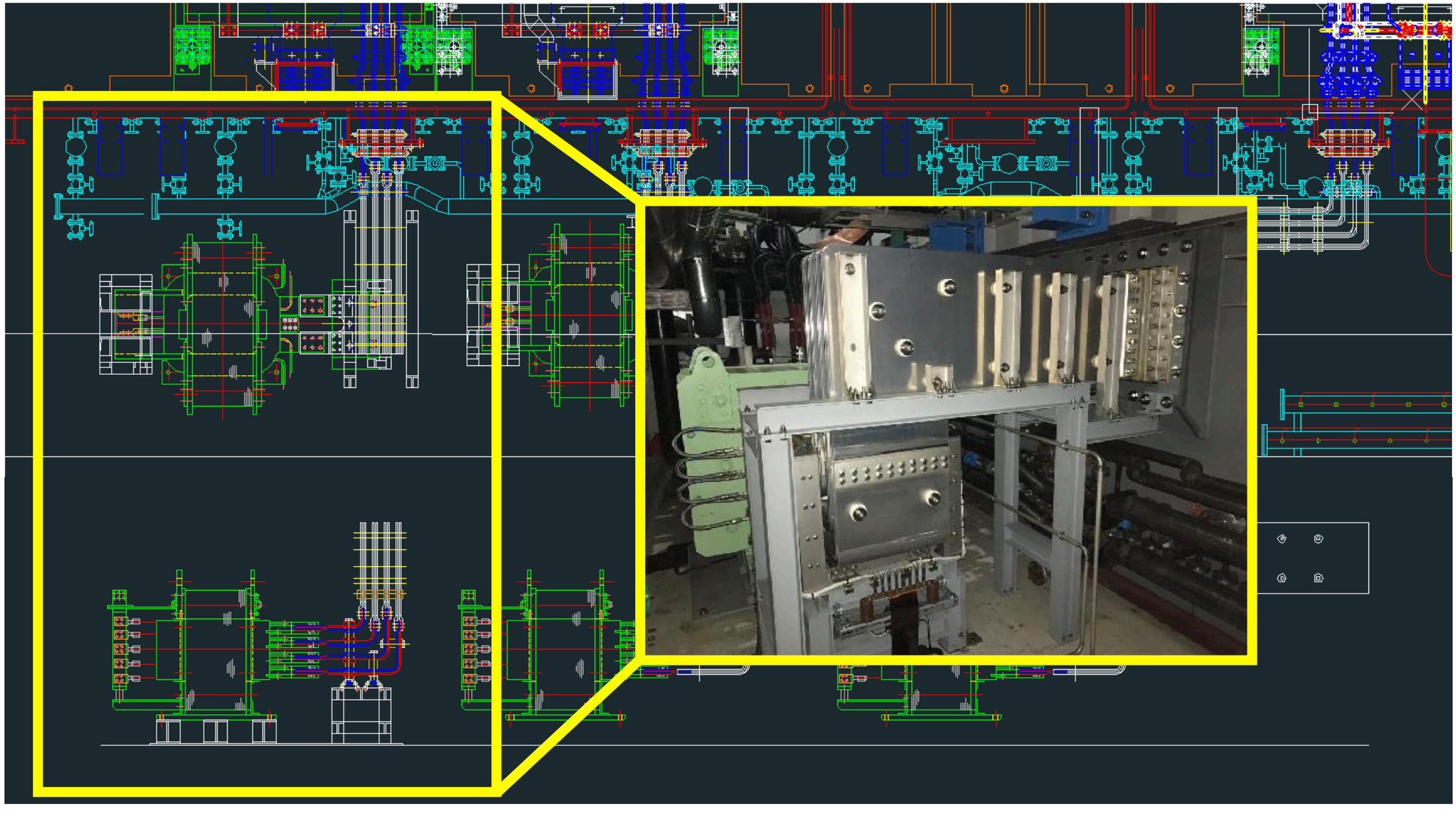
Transformers and Striplines Layout

- **Three transformers should be placed in the existing space**
  - **Available space for transformers is very limited ⇒ compact design needed**



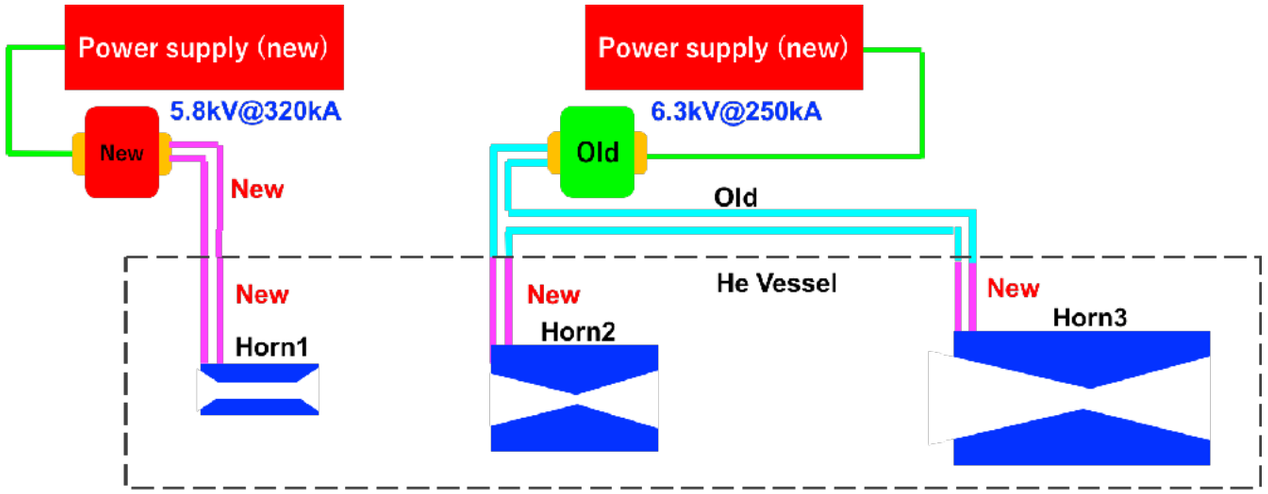
Transformers and Striplines Layout

- **Three transformers should be placed in the existing space**
  - **Available space for transformers is very limited ⇒ compact design needed**



Staged Upgrade Scenario

Current

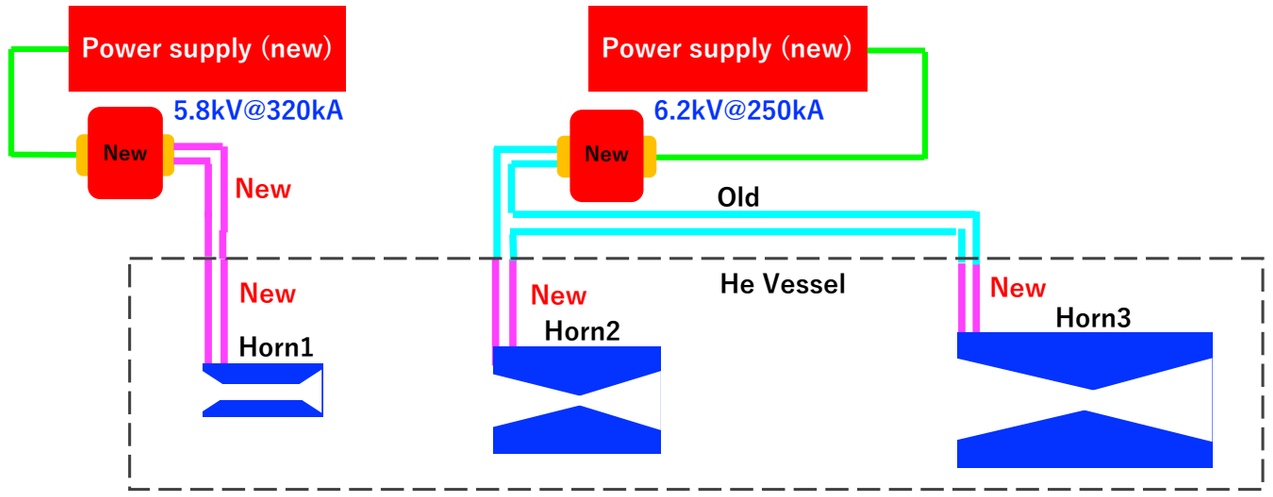


1st upgrade in FY2021

for 1Hz operation @ 250 kA

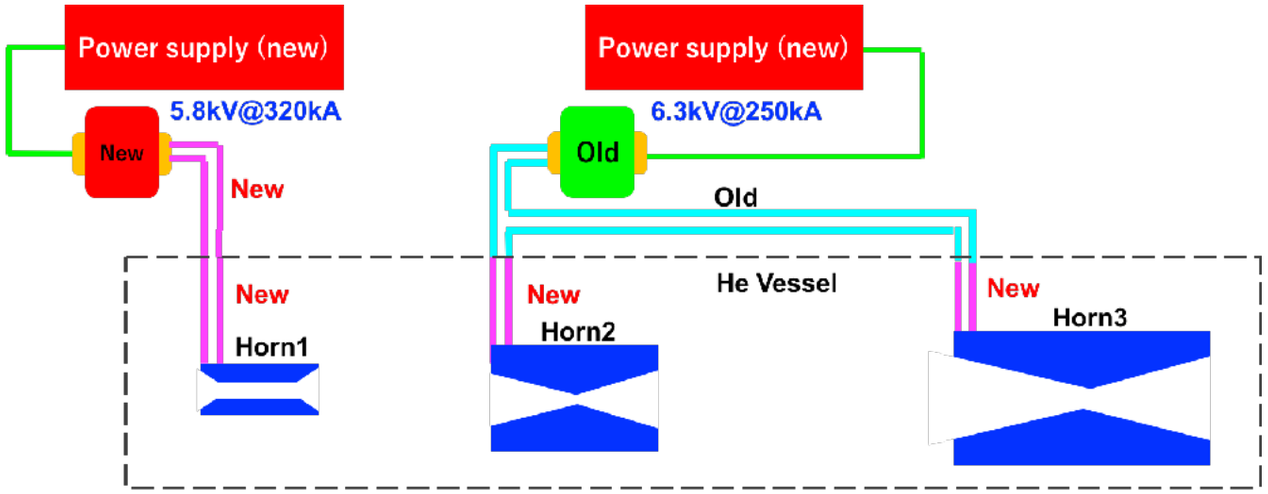
- New transformer
- Capacitor upgrade

After FY2021



Staged Upgrade Scenario

Current

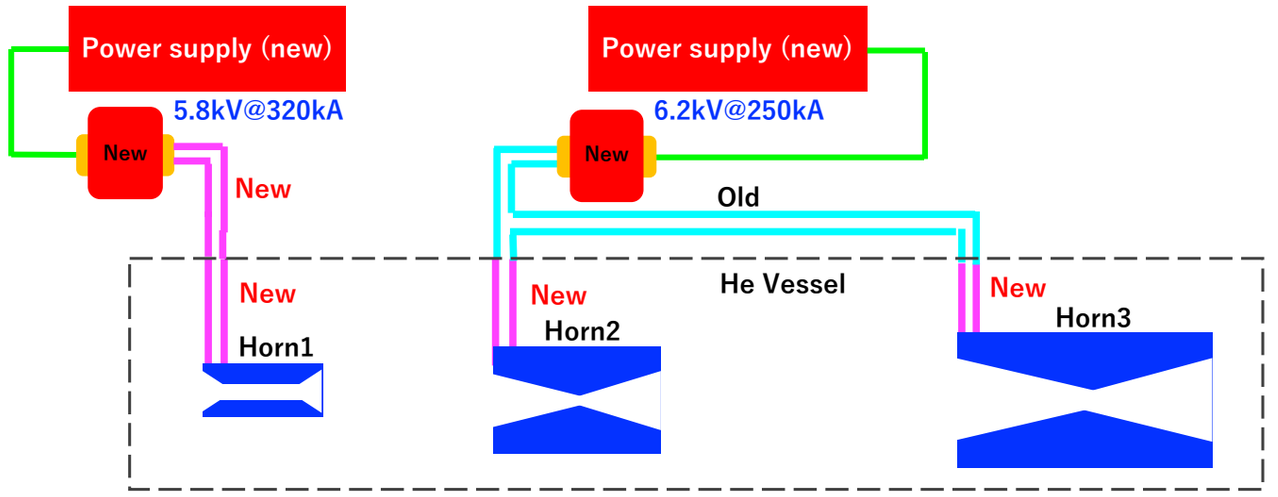


1st upgrade in FY2021

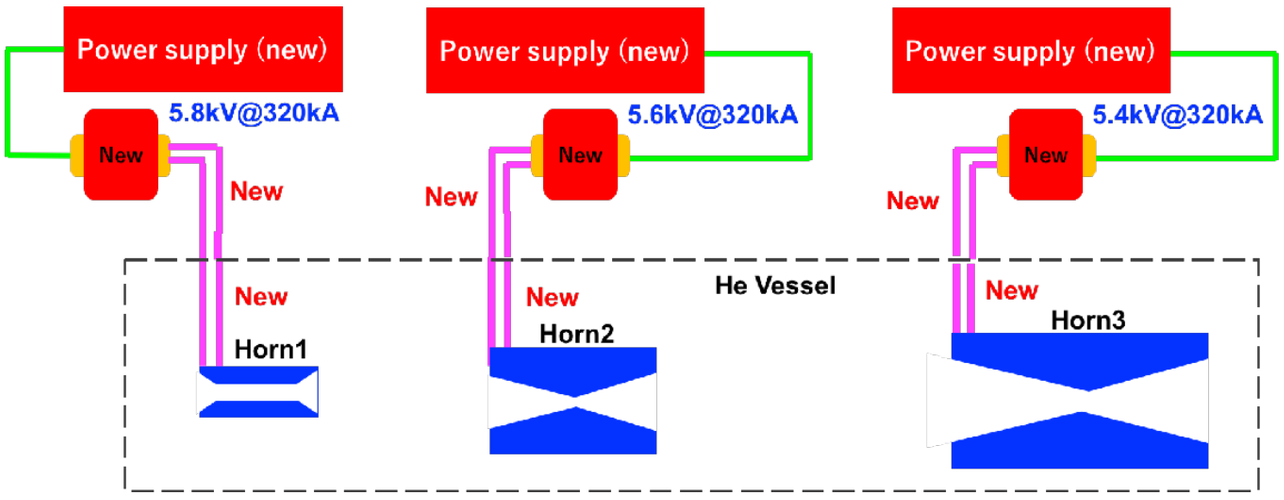
for 1Hz operation @ 250 kA

- New transformer
- Capacitor upgrade

After FY2021



After FY2023

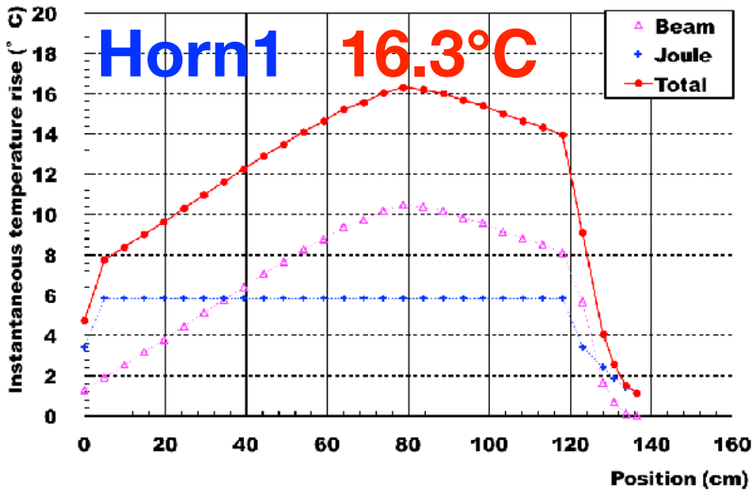


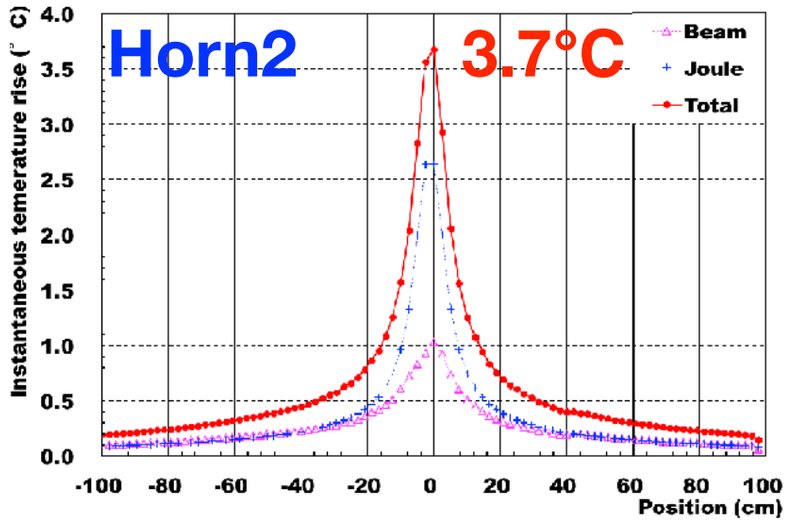
2nd upgrade in FY2021

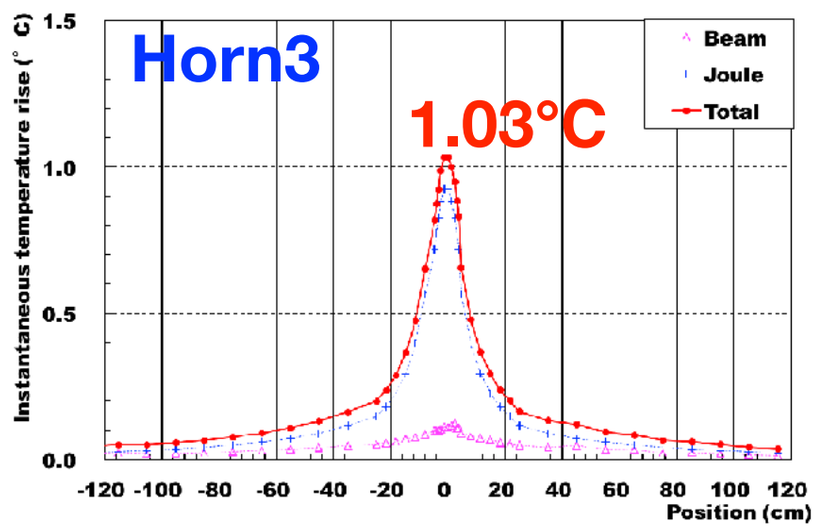
for 320 kA operation

- New power supply
- New transformer
- Striplines outside He vessel

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 < 80 °C (allowable temp.)**
  - 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
    - Replacing pump and heat exchangers needed

Horn Upgrade

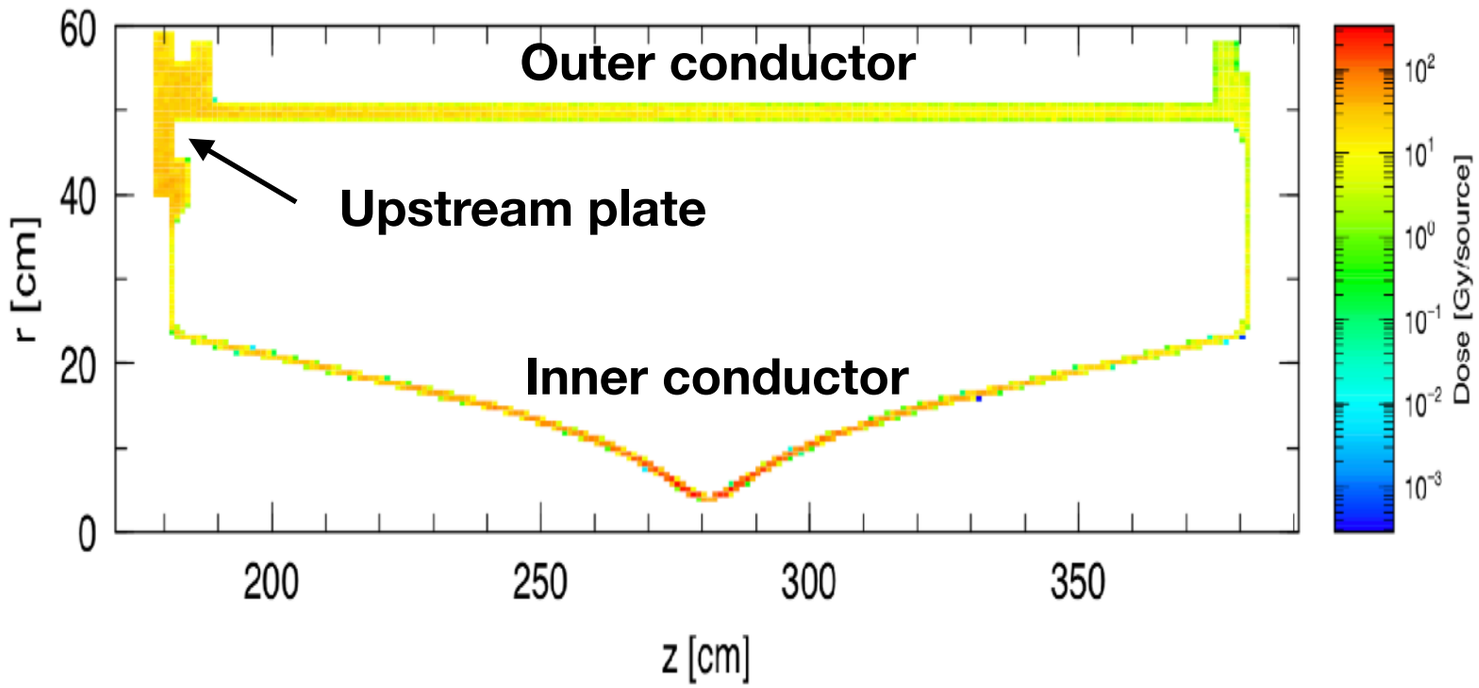
Summary of upgrade from ver.2 to ver.3

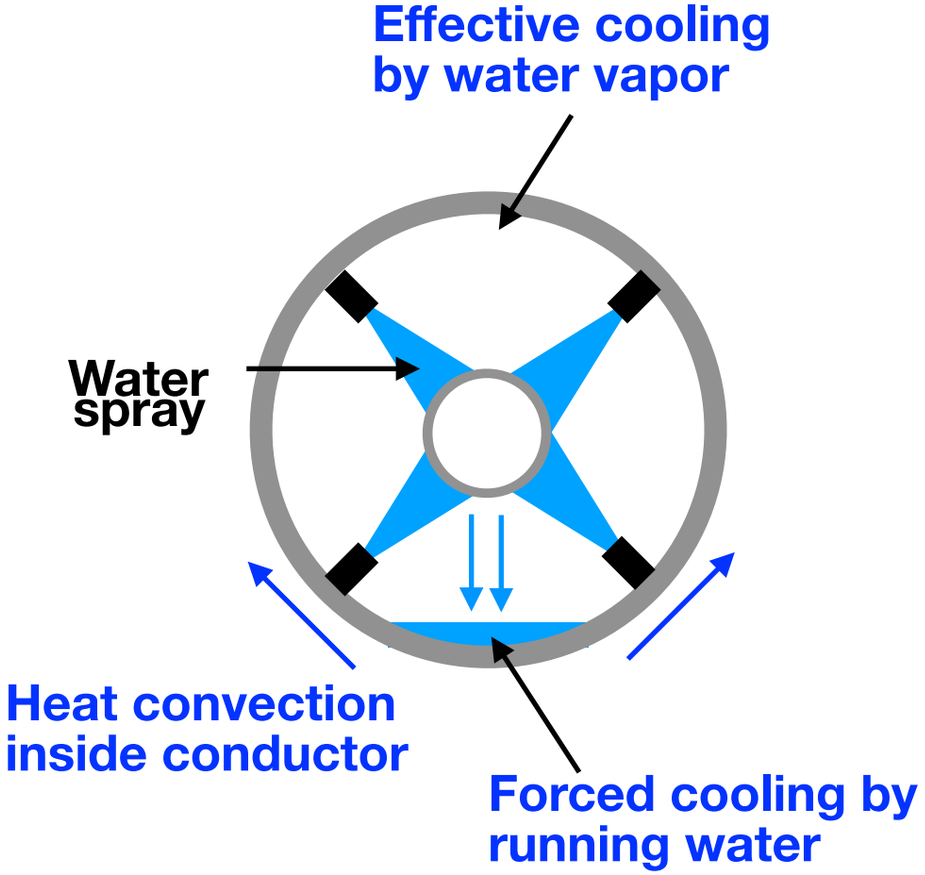
Item	Horn1	Horn2	Horn3
Conductors	Improved upstream sealing	Improved inner conductor	No change
Cooling	No change	Forced cooling of upstream plate and flange	No change
Striplines	No change	Water-cooled striplines	No change

Horn2 Outer Conductor Cooling

- **Heat deposit at Horn2**
  - Heat deposit by single shot 3.2x10^{14} ppp beam
    - Higher heat deposit at upstream thick plate and flange
- **Horn2 OC cooling**
  - No forced cooling, but bottom running water has cooling effect
  - Water vapor inside the horn conductors can help for cooling

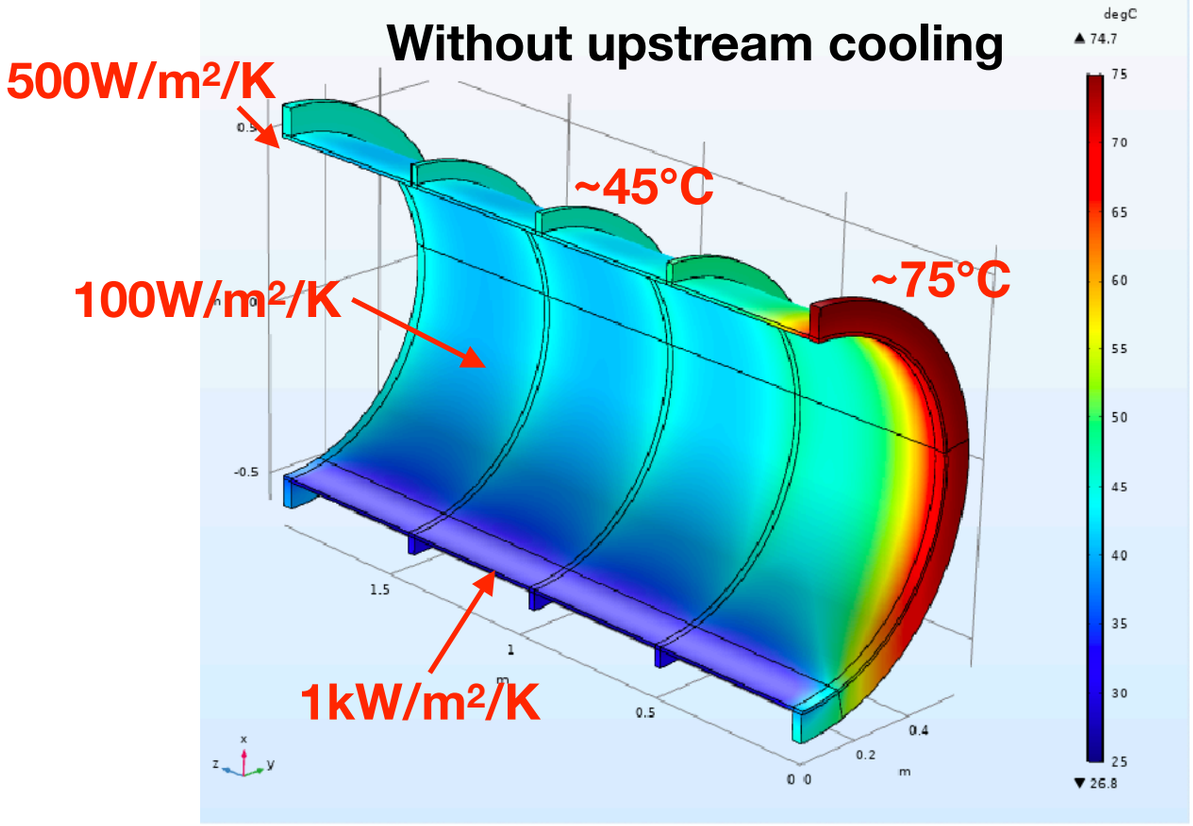
Heat deposit at Horn2 by PHITS 3.11 (in unit of Gy)

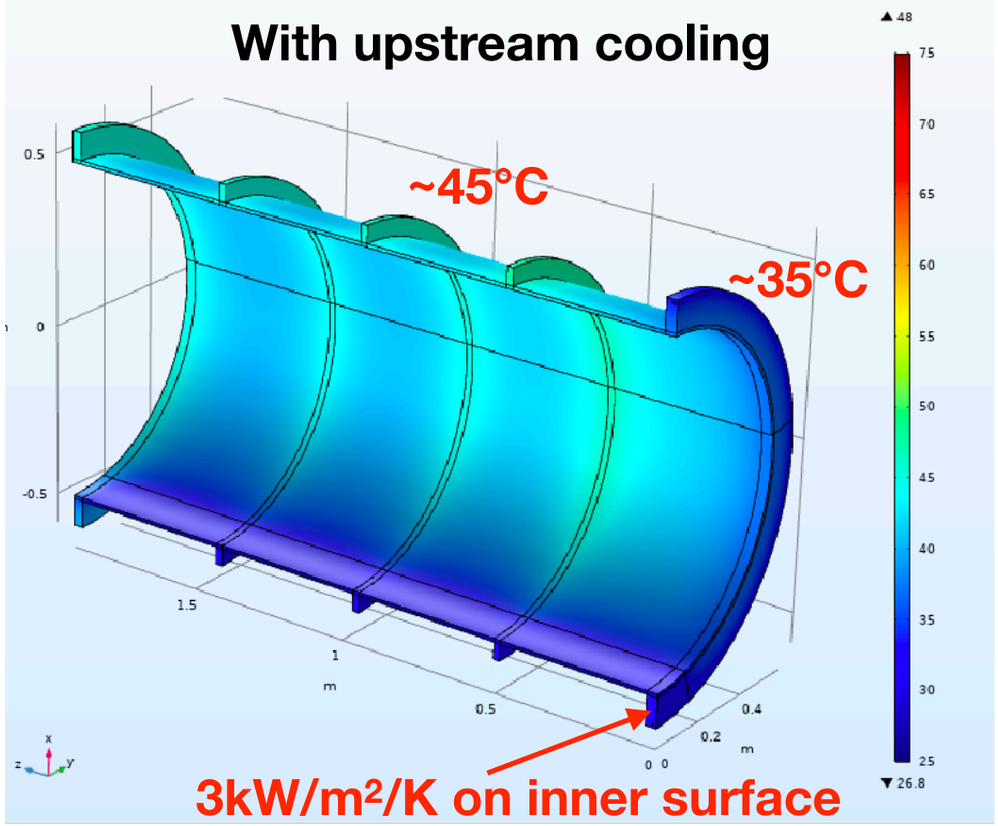




Horn2 Outer Conductor Cooling

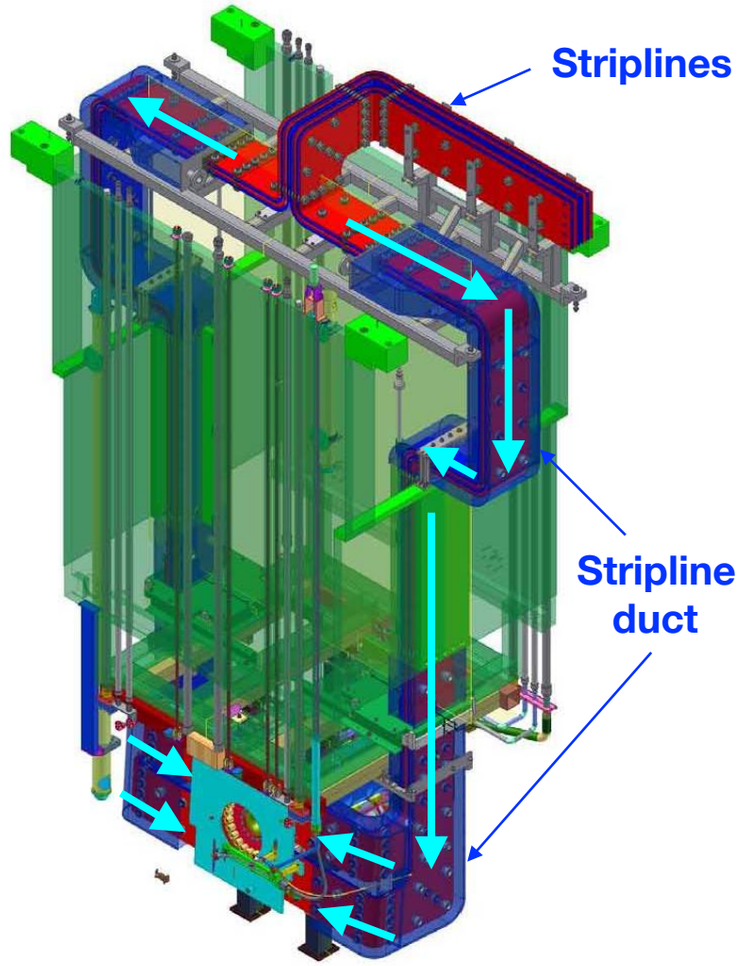
- **Cooling simulation**
  - 1 kW/m²/K (bottom) and 100 W/m²/K (others) assumed
  - Expected temperature to be **45°C** (barrel) and **75°C** (upstream flange)
    - High temperature causes **1mm deformation**
  - **Water cooling for upstream parts**
    - Water-pipe embedded as same as water-cooled striplines
    - **Upstream part successfully cooled down to 35°C**





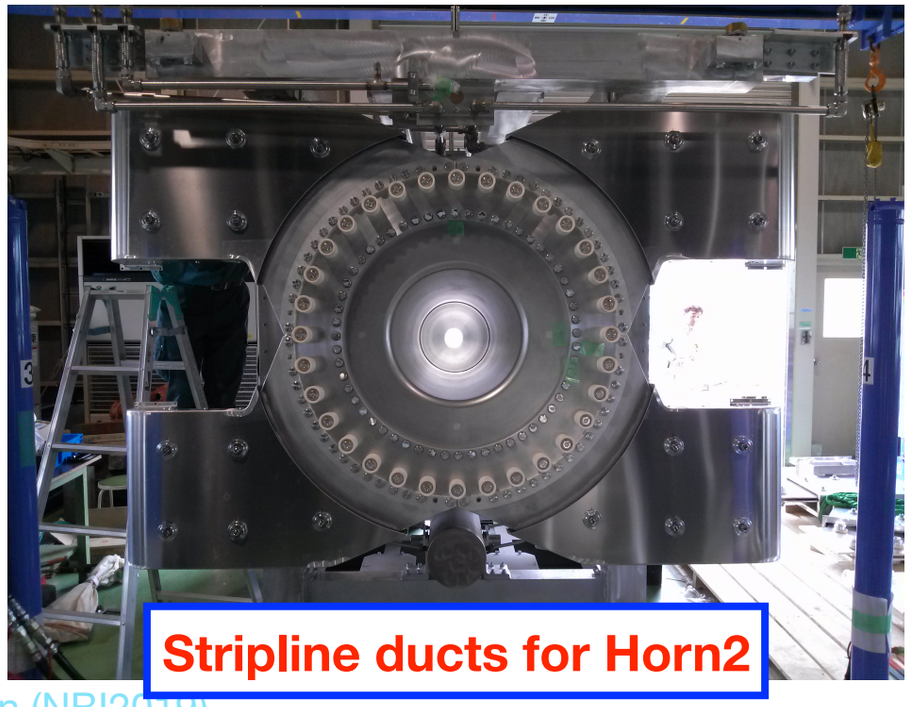
Stripline Cooling

- **Heat deposit at striplines**
  - Largest at horn2 due to defocused particles
- **Forced He flow inside stripline ducts**
  - Current flow rate for Horn2 → 750 kW acceptable
- **Water-cooled striplines development for 1.3 MW**



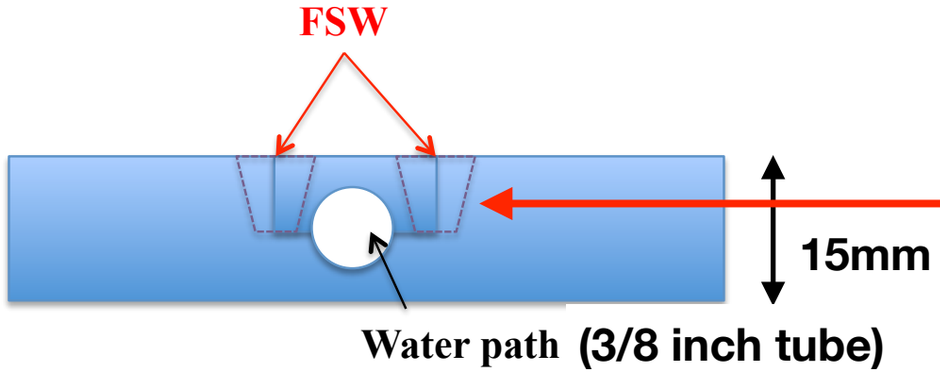
Heat flux per stripline plate (J/m²) @ 1.3 MW

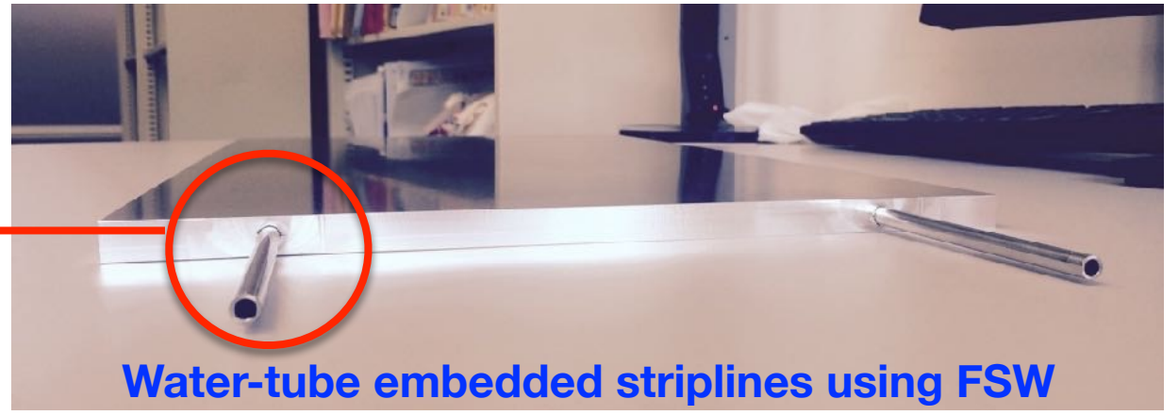
	Horn1	Horn2	Horn3
Total (Beam + Joule)	214	1066	141
Acceptable beam power (MW)	2.10	0.75	2.04

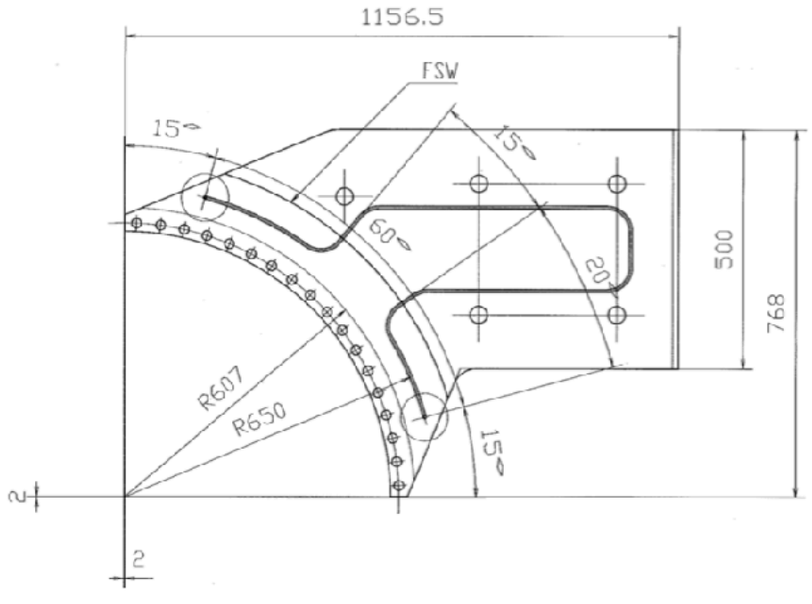

Stripline ducts for Horn2

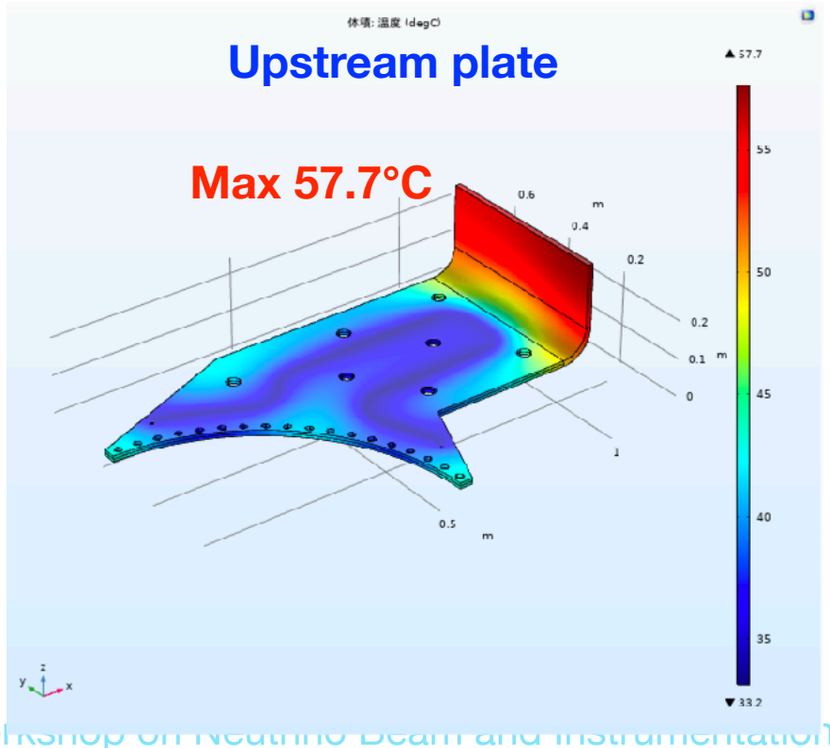
Stripline Water Cooling

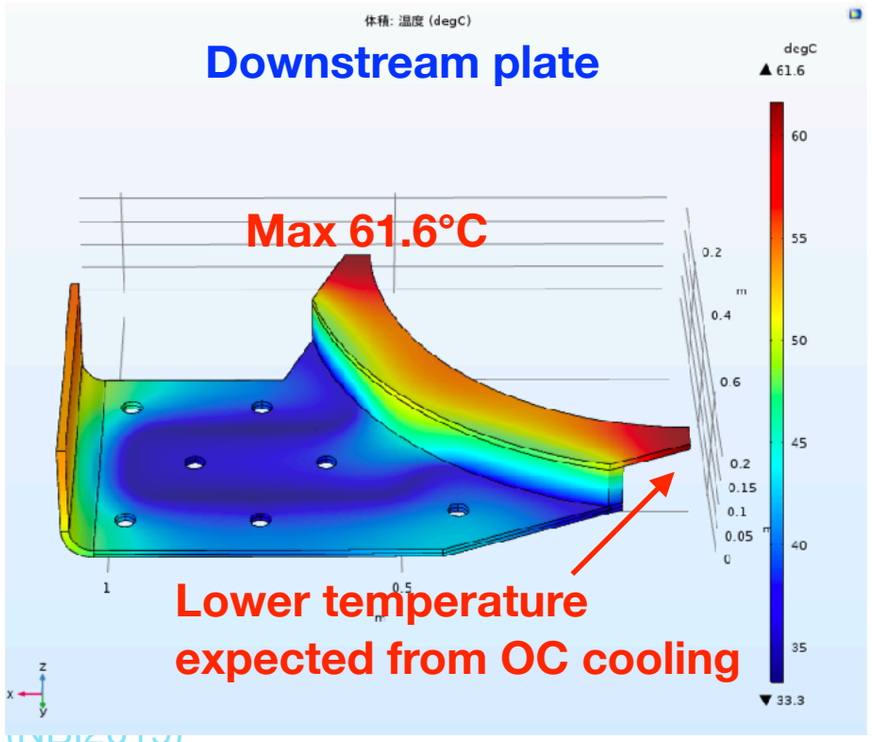
- **Water cooled striplines**
  - **Stainless pipe embedded** in 15mm-thick plate by **Friction Stir Wending (FSW)**
  - Cooling test with small test piece → > 3 kW/m²/K achieved.
  - **Max temp. @ 1.3 MW = 61.6°C (< allowable temp. 80°C)**
    - 0.75 MW (by He cooling) → **2.1 MW acceptable**





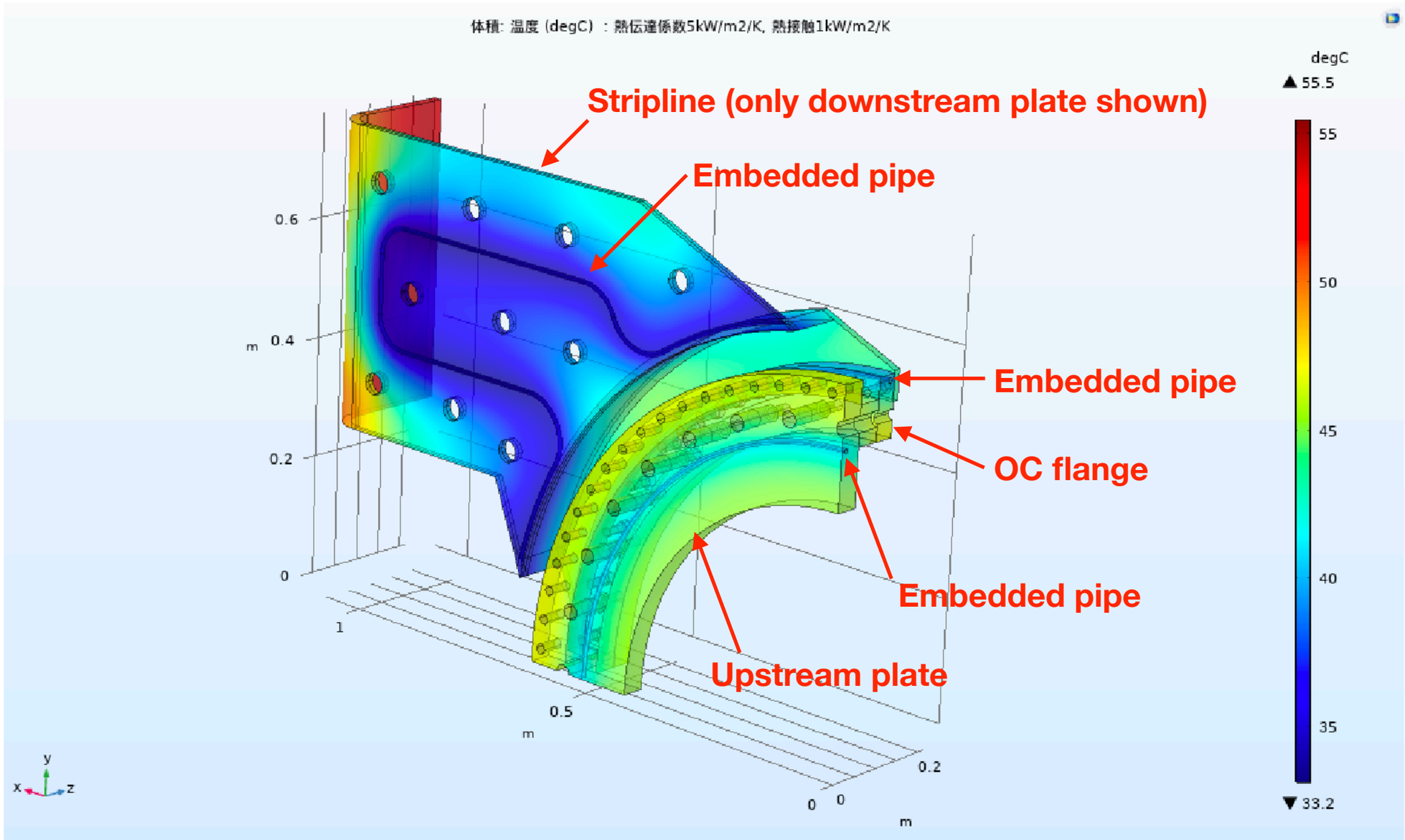






Stripline Water Cooling

- **With water-cooled OC flange**
  - 3/8 inch stainless pipe embedded
  - Effective heat transfer coefficient = 5 kW/m²/K
  - Heat transfer coefficient of 1kW/m²/K at stripline connection
  - Max temp. @ connection can be reduced to ~ 45°C

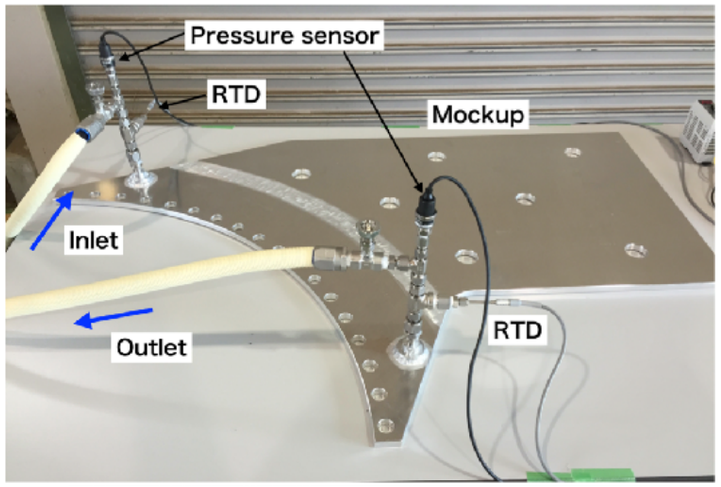


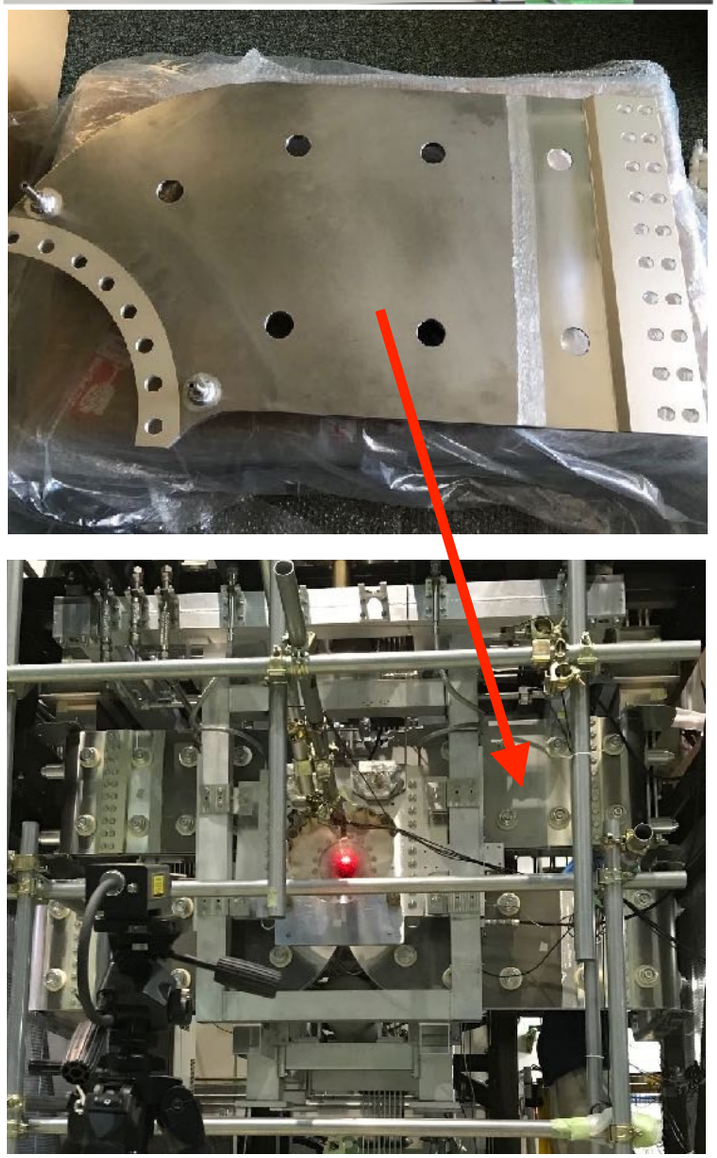
Mockup Production

- **First mockup produced in FY2016**
  - Producibility check for real size
  - Water circulation test
- **Further mockup tests**
  - **Current test** with spare horn1 (ongoing now)
    - Vibration measurement

      ⇒ No difference compared to normal one

    - **Check vibration tolerance** of water inlet/outlet
  - **Current test** in FY2020
    - Final mockup to be tested
    - Spare horn2 not ready, test with striplines only
    - The final mockup can be installed if no further modification needed
- **Installation** to Horn2 in FY2021





Upgrade Schedule

Item	FY2019	FY2020	FY2021	FY2022	FY2023
Power supply (existing)			Install		
Capacitor		Production			
Transformer #2		Production	Install		
Power supply (new)				Production	Install
Transformer #3				Production	Install
Horn operation		Horn1 320 kA?		1.3 s	All horn 320 kA
Horn1 ver.3			Install	Horn1 320 kA	
Horn2 ver.3	Production		Test Install		
Water-cooled stripline	Production	Test			

Summary

- **Magnetic horns to focus secondary pions**
  - Currently 250kA @ 2.5 s
  - Water-cooled horn conductors
- **Operation status**
  - Operating second-generation horns since 2014 ⇒ 17 million pulses
  - Water drop problem at horn1
- **Upgrade for 1.3 MW beam**
  - Horn current increase to 320 kA @ 1Hz
    - New PS, transformer, striplines developed
    - Staged upgrade
      - For 1Hz operation in FY2021
      - For 320 kA operation in FY2023
  - Cooling improvement
    - Horn2 upstream cooling
    - Horn2 striplines with water cooling

Backup

Past (2012-13) vs Current (2018)

January 2014

- Drop rate : >10 L/day
- Dropped water ran the bottom
- Significant corrosion of iron surface
- Condensation at horn surface

December 2018

- Drop rate : ~5 L/day
- Dropped water was evaporated
- No additional significant corrosion
- Horn surface is still clean (shinny)

Requirements

- **Power supply**
  - 1 Hz operation cycle ⇒ charging time < 1 sec.
  - Rated peak current : 32 kA at PS output
  - 2 ms pulse width ⇐ can be widened up to 3ms since lower heat load at Horn3
  - Design lifetime > 2×10^8 pulses ($\Delta C/C < 5\%$ at 2×10^8 pulses)
  - Remote control from external system (via EPICS)
- **Transformer**
  - Turn ratio = 10 : 1 (32 kA → 320 kA)
  - Rated peak current : 320 kA
  - Compact size
  - Water cooled

Electrical Parameters

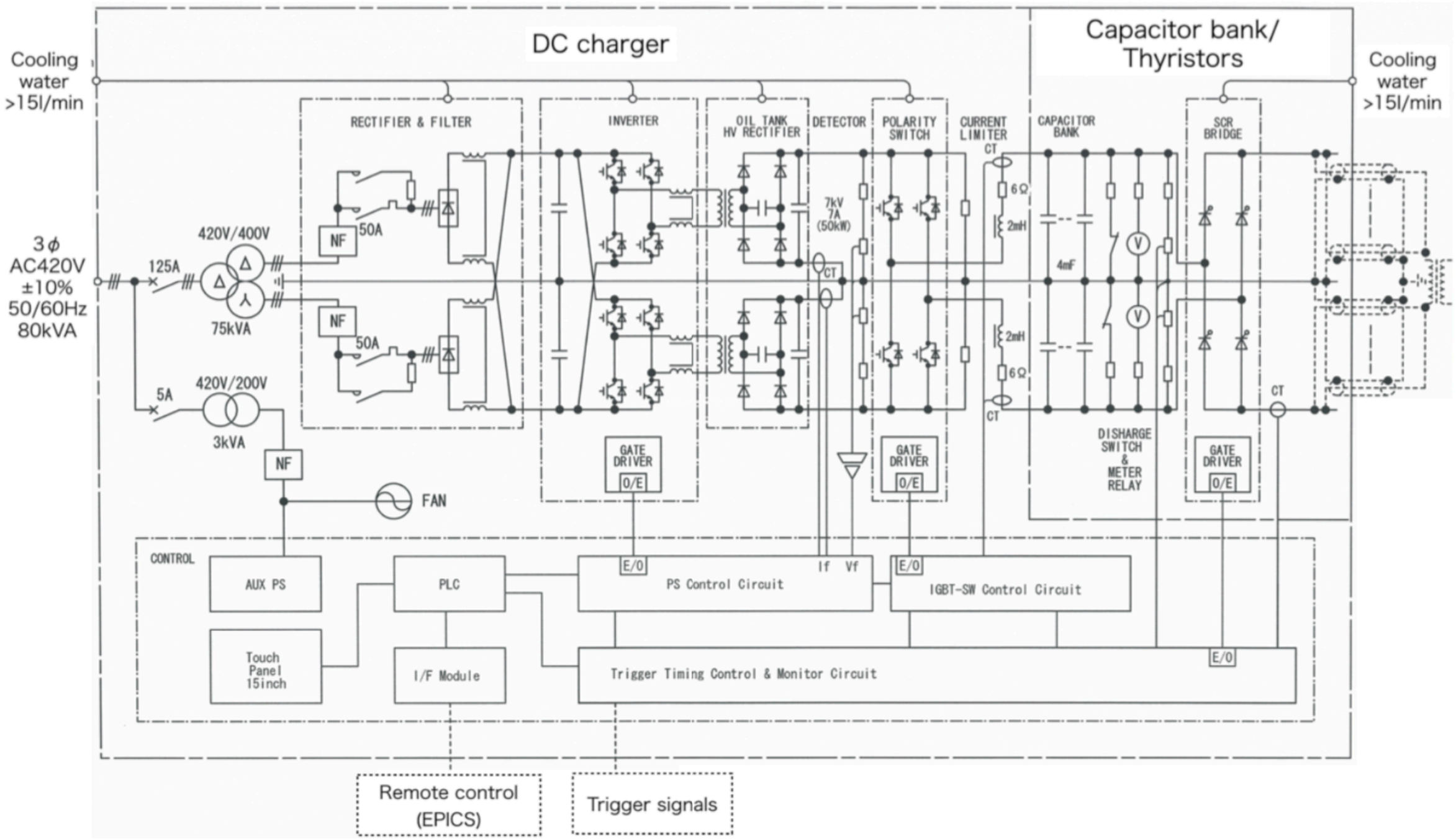
Inductance and resistance

Components	New configuration					
	horn1		horn2		horn3	
	L (μH)	R (mΩ)	L (μH)	R (mΩ)	L (μH)	R (mΩ)
Horn	0.47	0.100	0.46	0.035	0.53	0.023
Striplines	0.15	0.056	0.17	0.060	0.18	0.065
Transformer	0.25	0.025	0.25	0.025	0.25	0.025
Total	0.87	0.181	0.88	0.120	0.96	0.113

PS circuit parameters

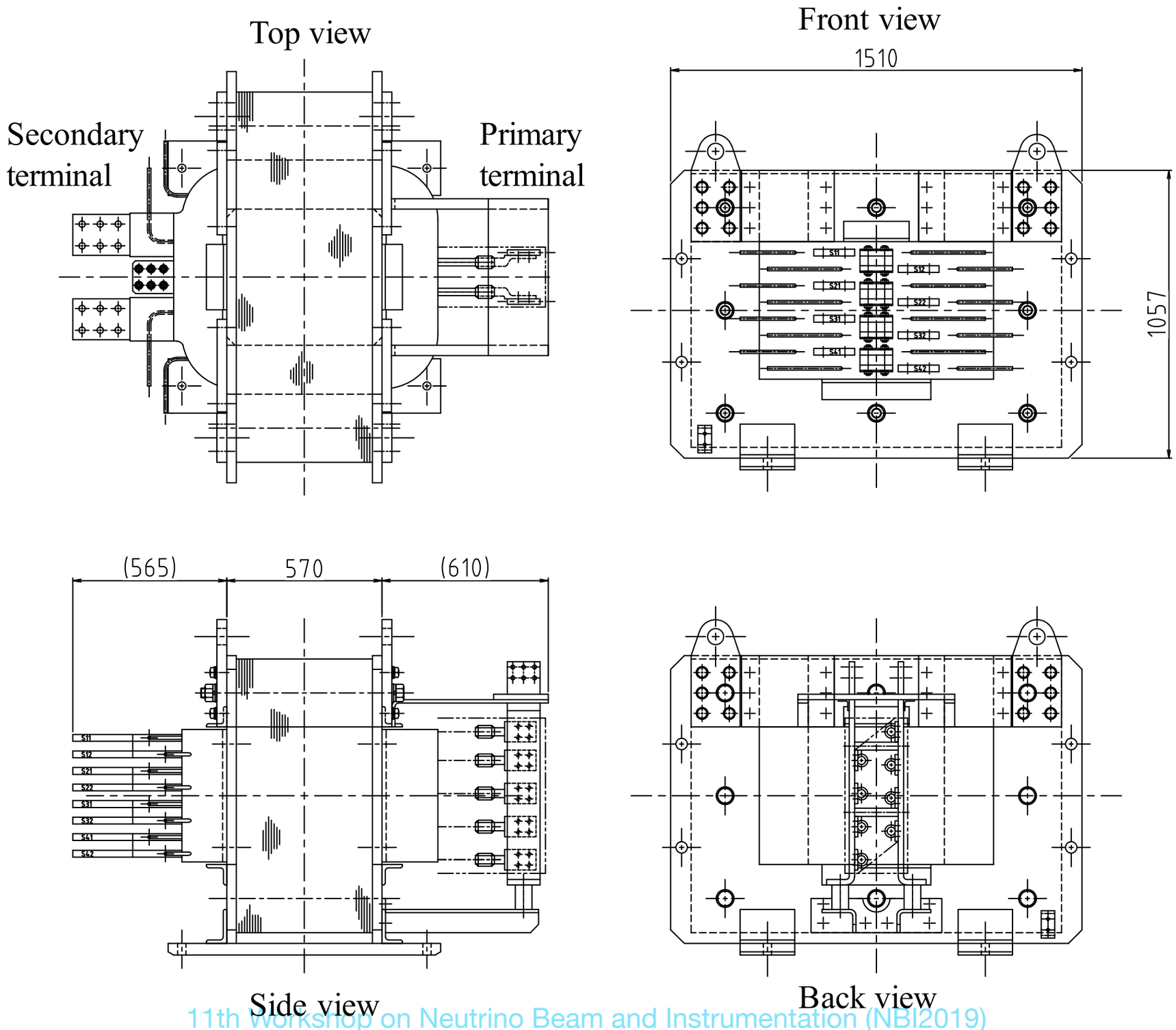
Item	Value
Rated operation voltage	7 kV
Rated charging current	7 A
Charging unit	50 kW
Rated operation cycle	1 Hz
Total capacitance	4 mF
Capacitor bank configuration	
(original design)	2S16P (0.5 mF$\times$32)
(modified)	2S24P (0.335 mF$\times$48)
Pulse width	2 ms
Rated output current	32 kA
Stored energy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

PS Circuit Diagram



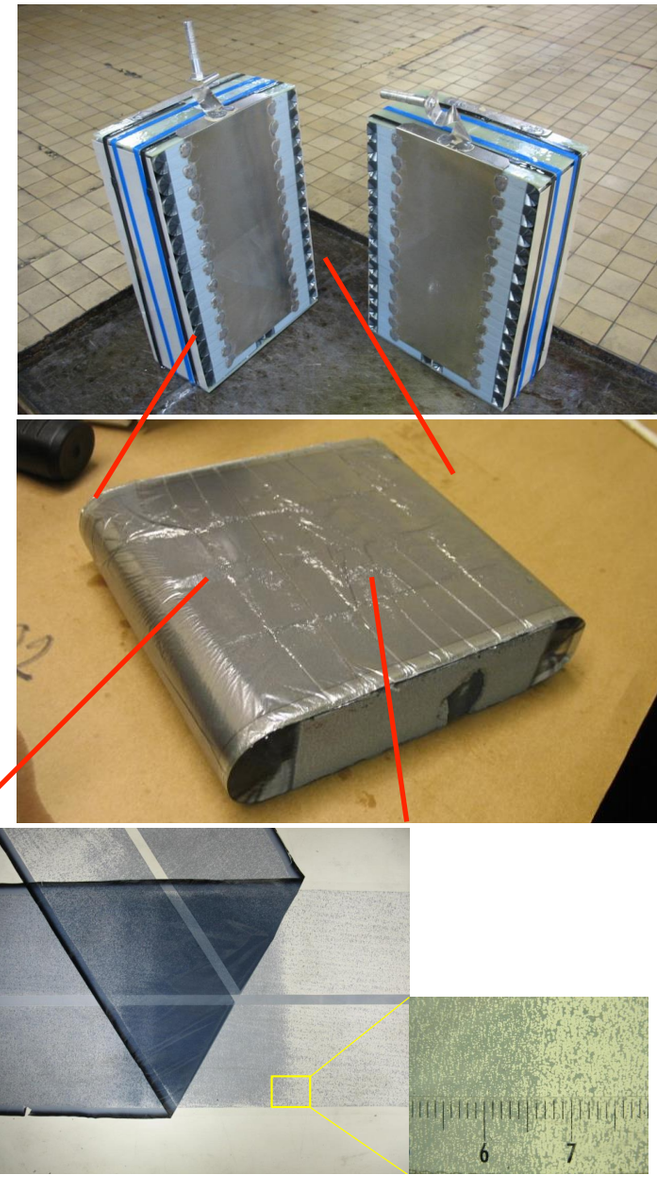
Transformer Drawing

Iron core cross section : 0.5m x 0.5m = 0.25m²



Horn PS Capacitor Problem

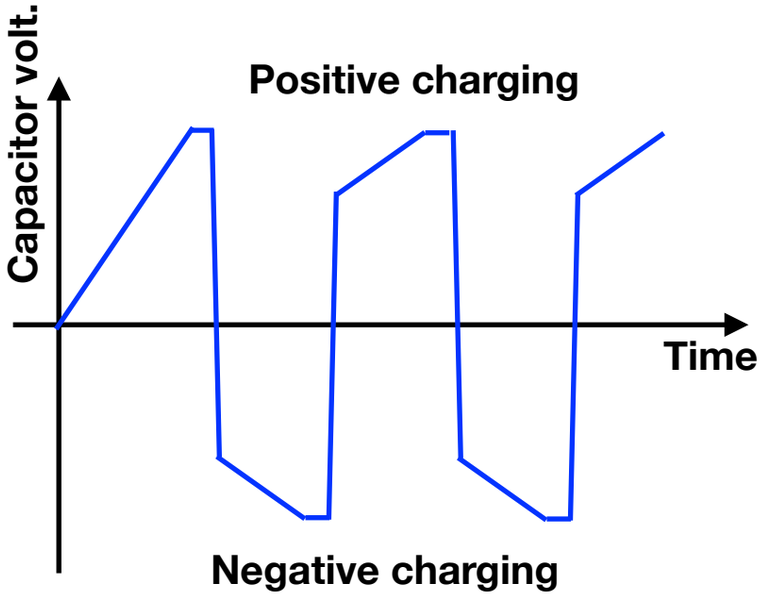
- **Horn current and pulse width reduced during Run8**
- **Capacitance measurement**
  - Decrease by **5~10%@1.3x10^7** ⇔ Spec : ΔC/C < 5% @ 2x10^8 pulses
- **Inspection by manufacturing company**
  - Electro-corrosion on Al metallized electrode
    - Resulting in capacitance drop
    - Caused by 100% 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



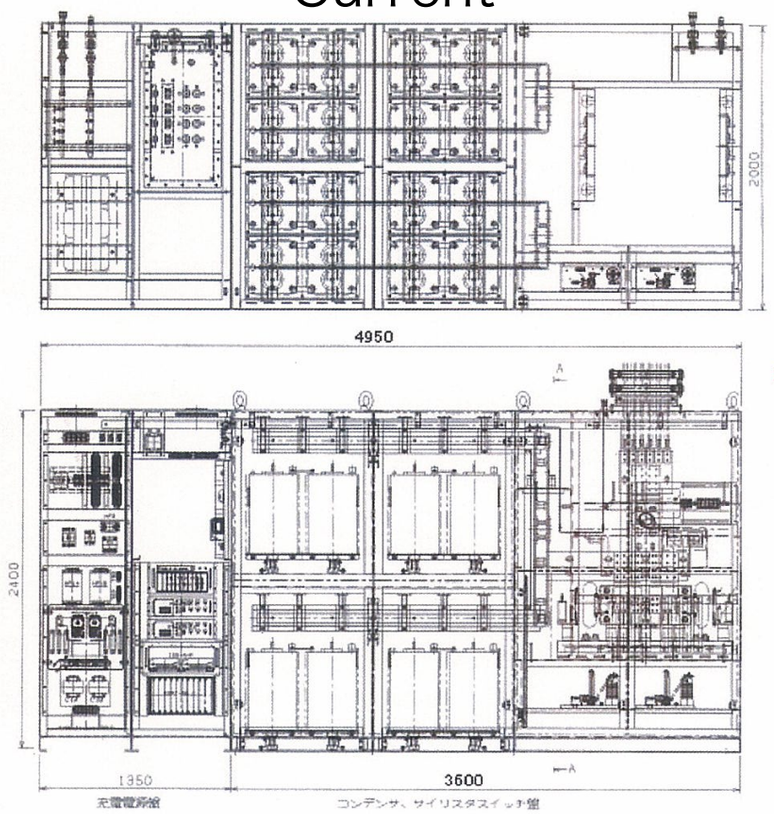
Capacitor Upgrade

- **New PS developed for 320kA&1Hz operation**
  - Two PSs in service since 2014 (~1.75x10^7 pulses) ⇒ **5~10% capacitance drop** observed
    - Found that alternating voltage usage caused electro-corrosion
- **New capacitors with countermeasures already developed**
  - **Replacement of all capacitors needed**
  - New capacitors have 50% larger in volume with same capacitance (0.5mF)
  - To keep the size, capacitance 0.5→0.335mF(x2/3) and # of capacitors increased (x3/2)
  - **Additional PS chassis is needed**

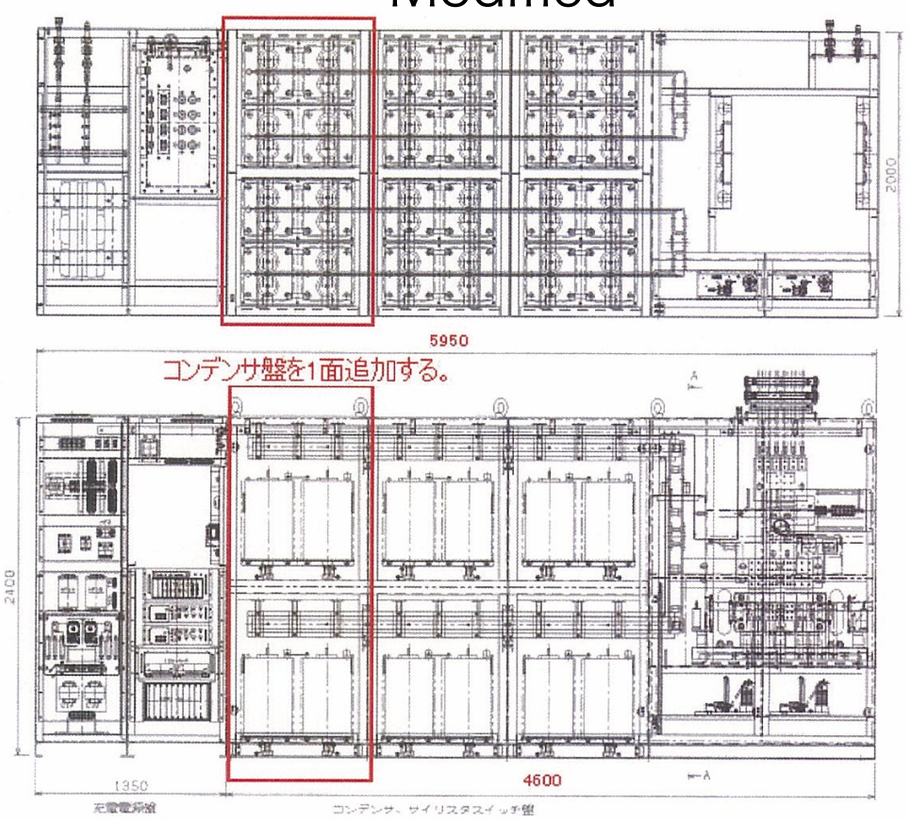
Energy recovery with alternating voltage



Current

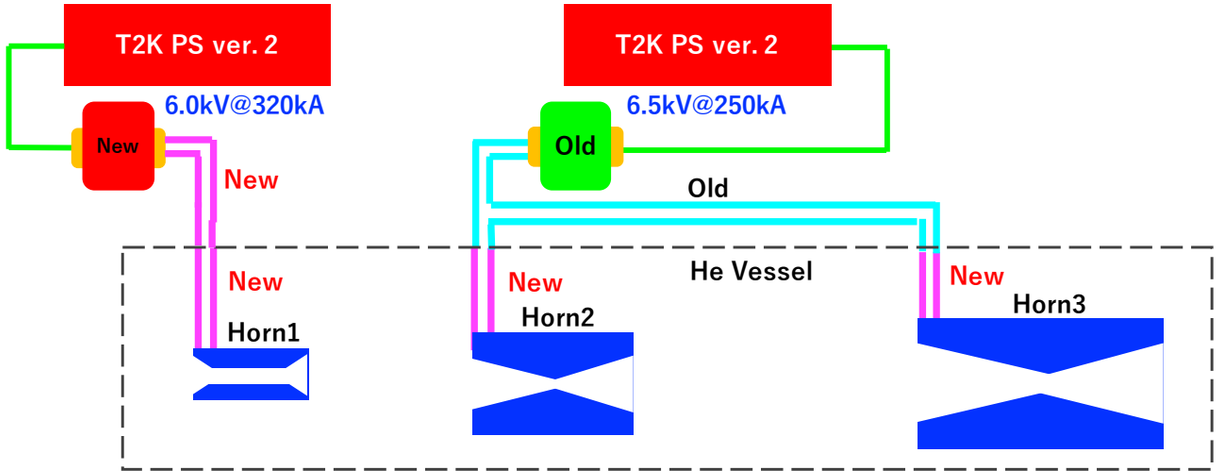


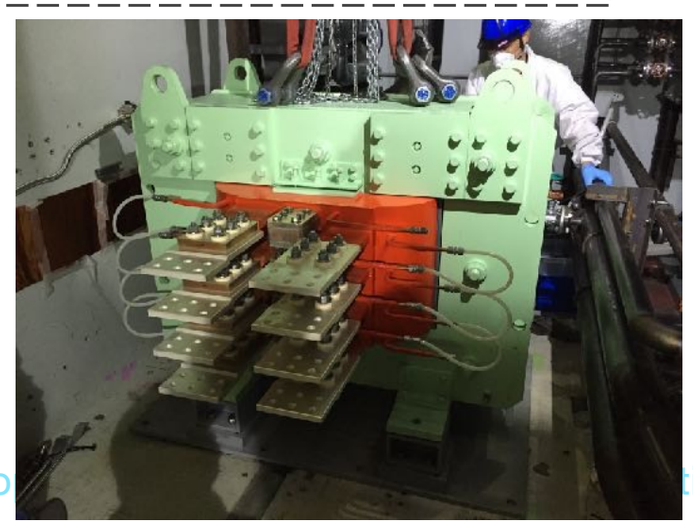
Modified

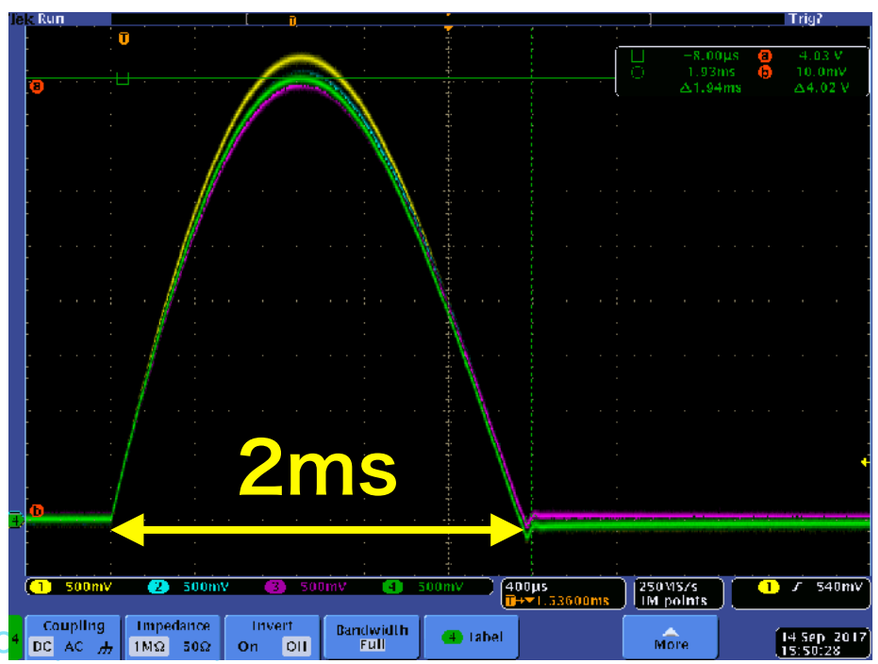


Upgrade for Horn1

- **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

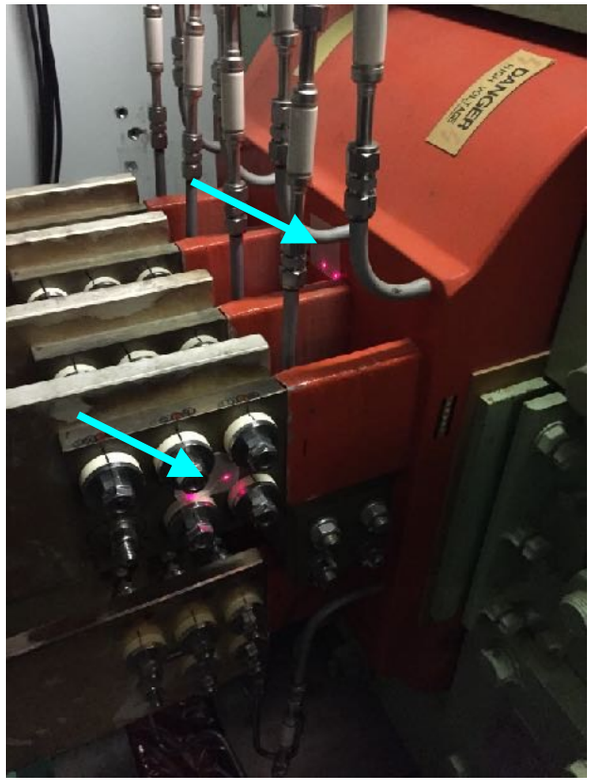




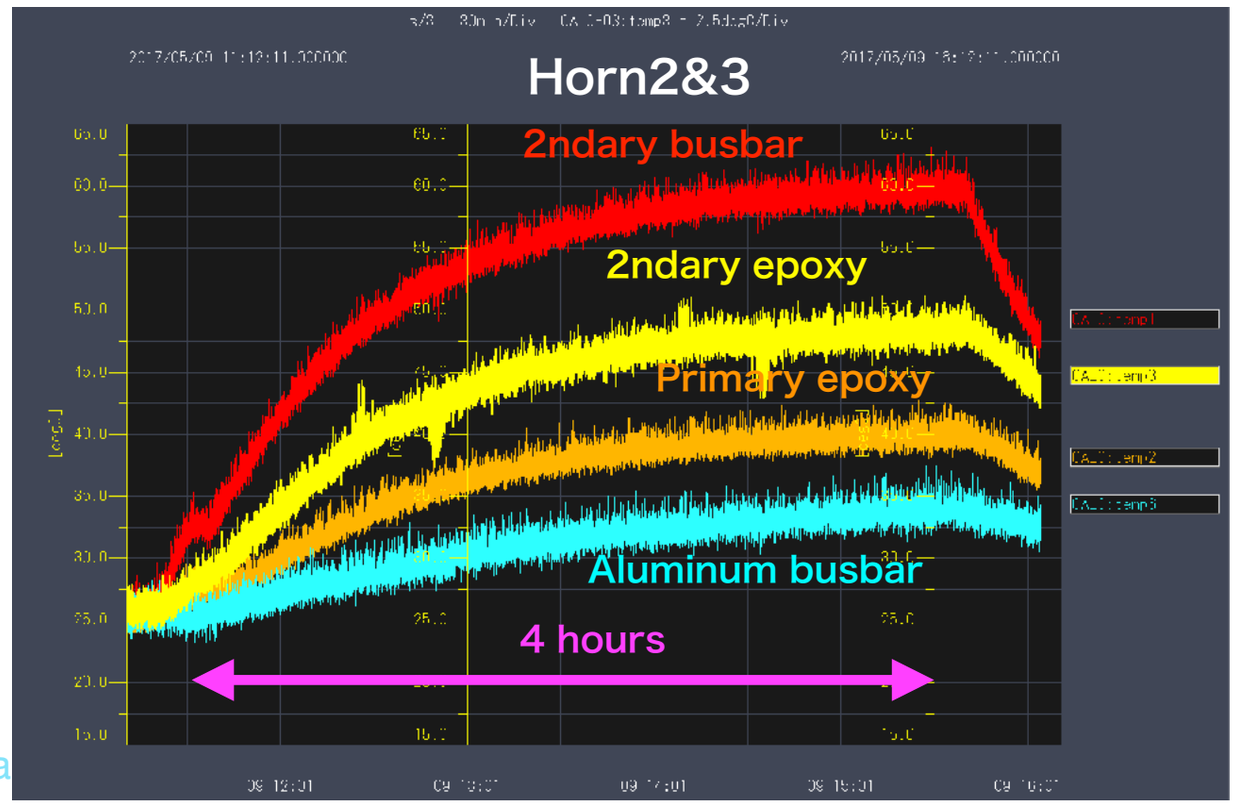


Operation Test at 1.3 Cycle

- **1.3s operation w/ current setup**
  - If no budget, we must use current setup for high rep. rate operation ==> Is it feasible or not?
  - A concern on temperature at epoxy insulator < ~60°C
  - 4 hour operation at 1.3 s cycle
  - Measured temp. at various points
    - ~60°C @ copper busbar
    - ~50°C @ nearby epoxy insulator
  - 1.3 s cycle operation is feasible but new transformer should be prepared for a safe and stable operation



	Horn1	Horn2&3
Primary busbar	<50℃	<50℃
Primary epoxy	<50℃	40℃
Secondary busbar	48 ℃	60 ℃
Secondary epoxy	38℃	48℃
Iron core	<50℃	<50℃
Aluminum busbar	35℃	34℃

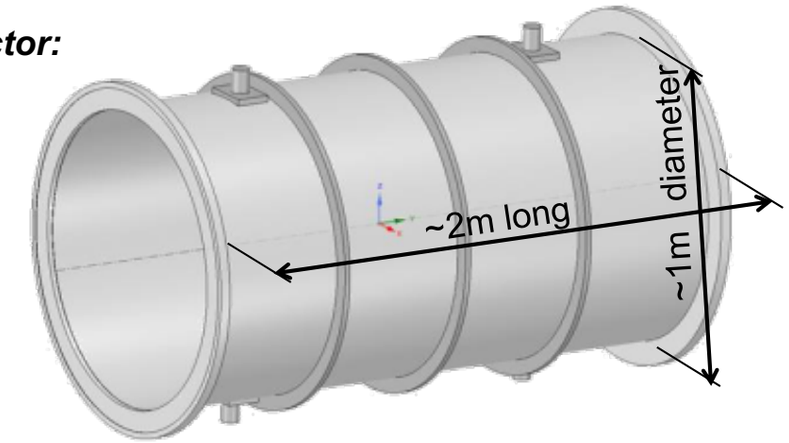


Horn Conductor Improvement

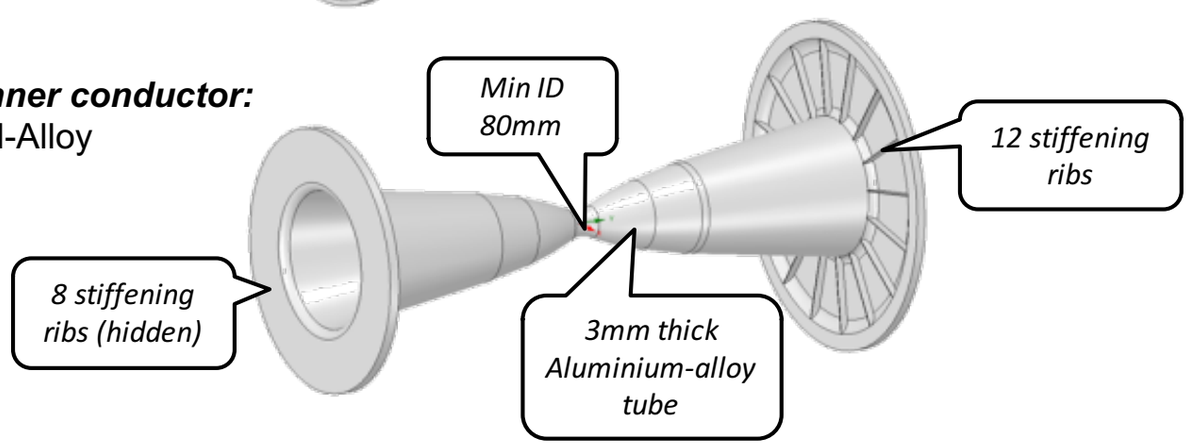
- **Large displacement@Horn2 ⇒ ~1mm@320 kA**
  - Inner conductor was modified to reduce displacement.
    - Adding ribs on both upstream and downstream ends
  - Transient stress analysis for Lorentz force and Joule heating
    - Done by RAL team (P. Loveridge)

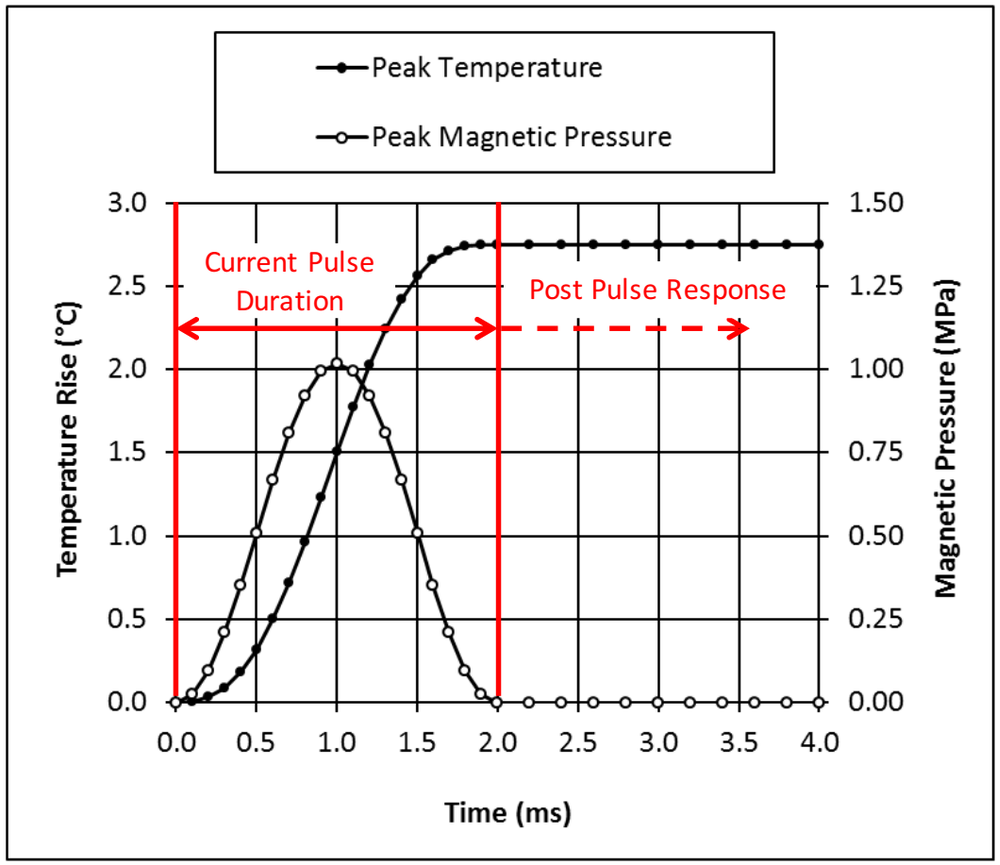
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Outer conductor:
Al-Alloy



Inner conductor:
Al-Alloy



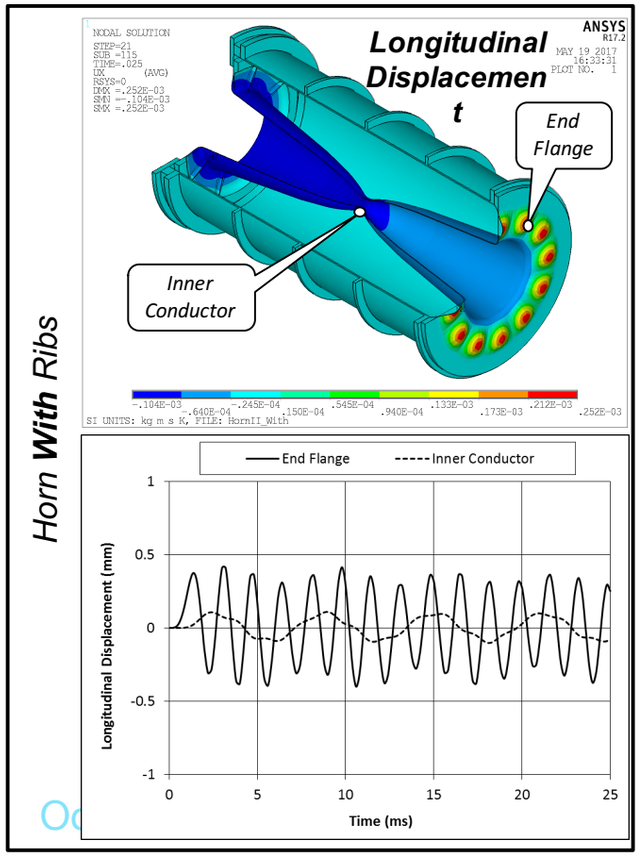


Time-history for Joule Loss and Magnetic Pressure loads corresponding to I_{max}=320kA

Horn Conductor Improvement

- **FEM results**
  - Displacement reduced from 0.93mm to **0.25mm**
  - Stress at endplate also reduced from 45MPa to **24MPa**
- **Design modification and outer conductor production to be done**

Transient Analysis: Displacement Results (320 kA)



Transient Analysis: Stress Results (320 kA)