Upgrade of J-PARC Accelerator and Neutrino Beamline toward 1.3MW

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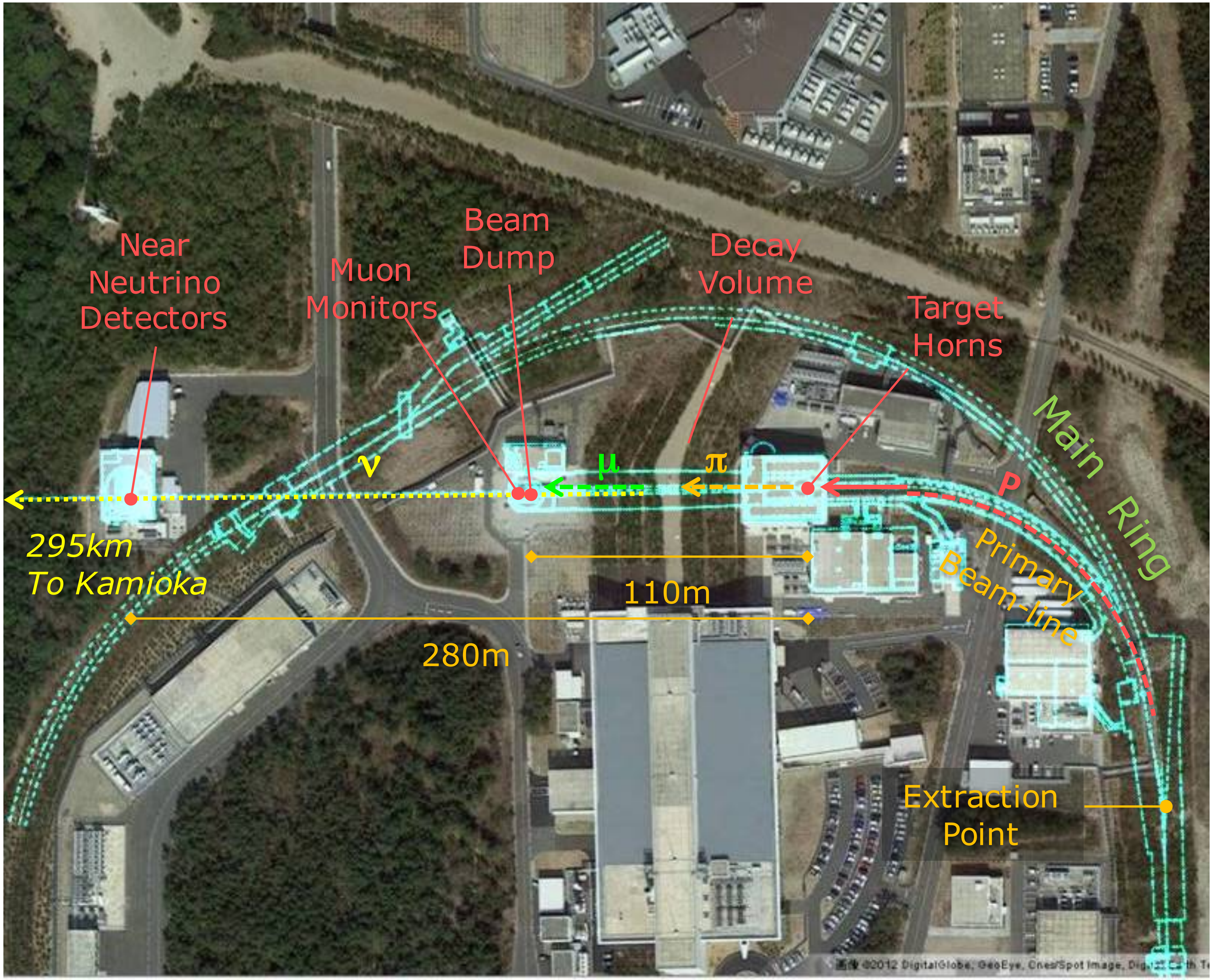
on behalf of
J-PARC Accelerator team and Neutrino Group

2017.09.25

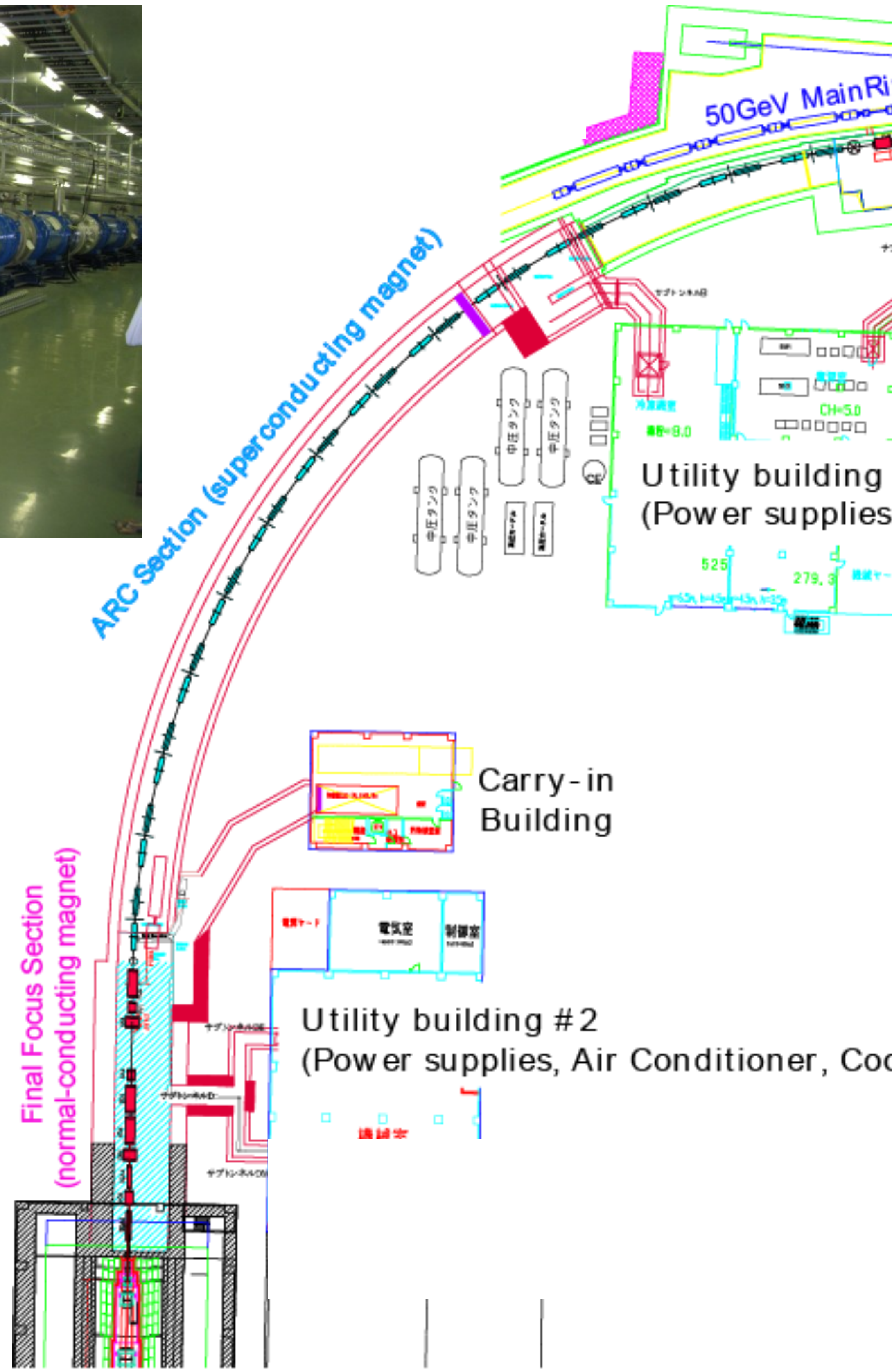
19th International Workshop on Neutrinos from Accelerators (NUFACT2017)

Contents

J-PARC Neutrino Facility

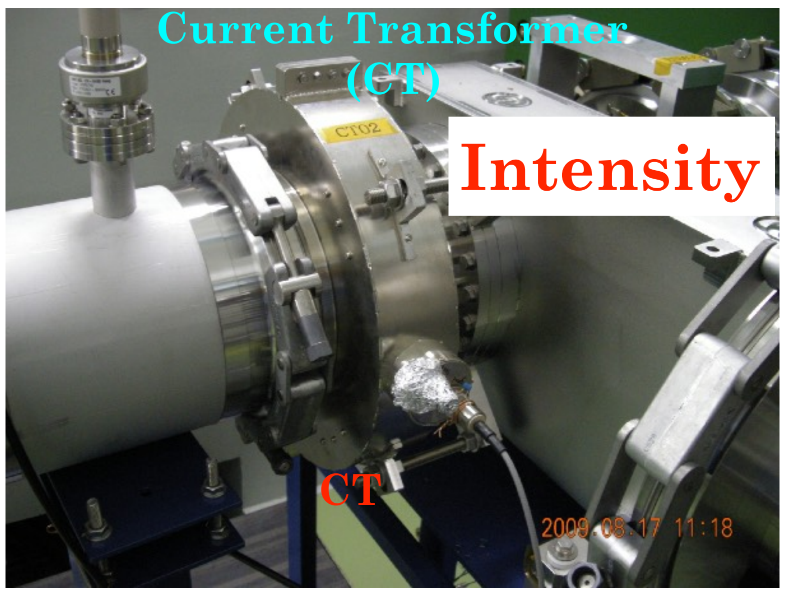


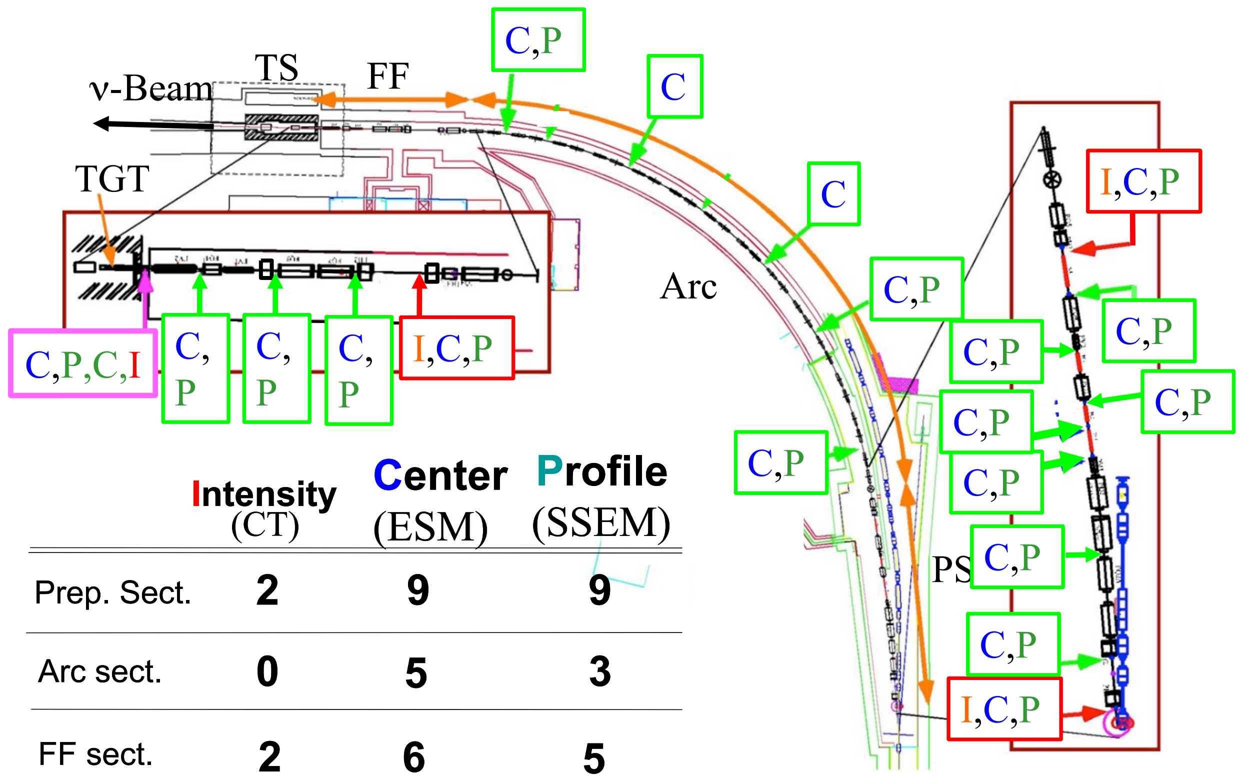
Primary Beamline



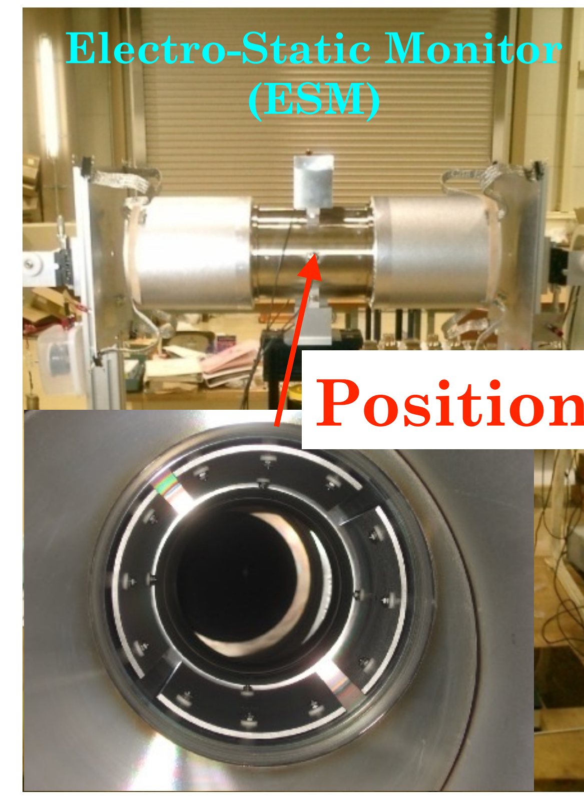
Beam Monitors

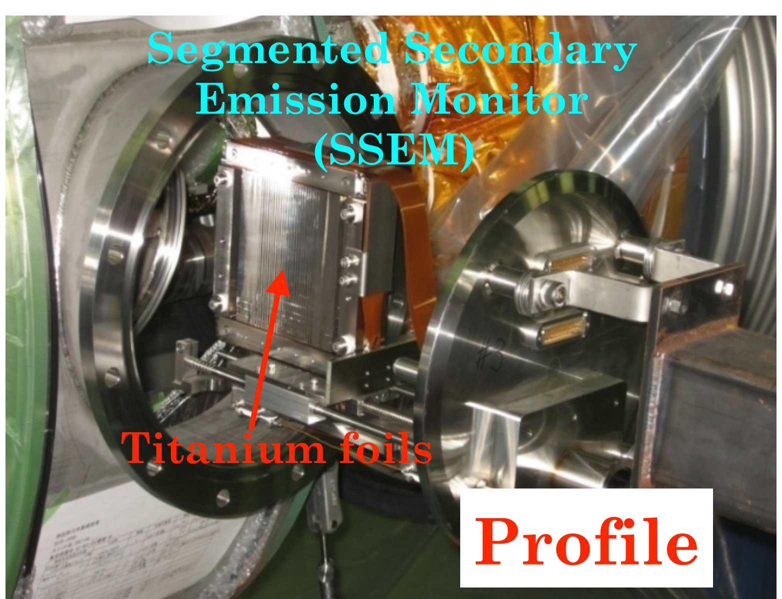
- Proton beam measurements and control
  - Precise beam control is crucial for high intensity beam

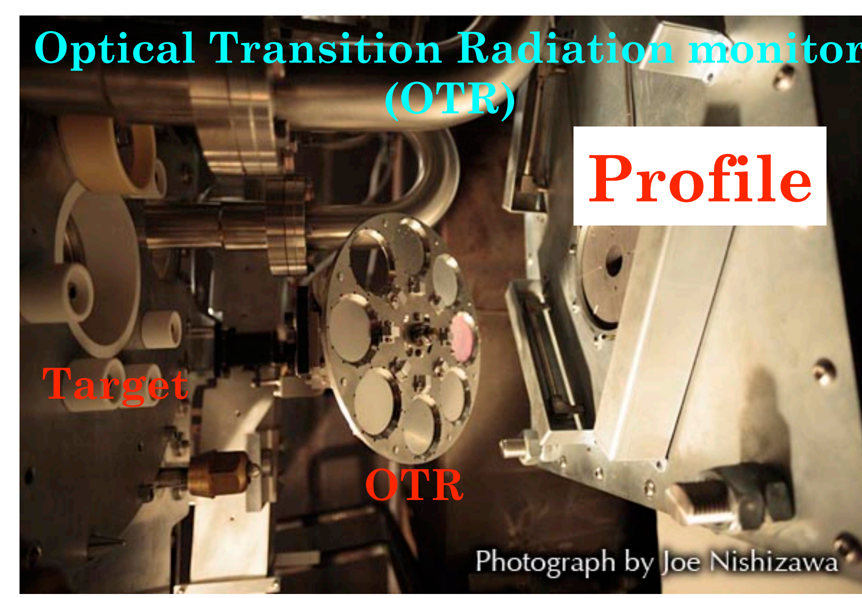




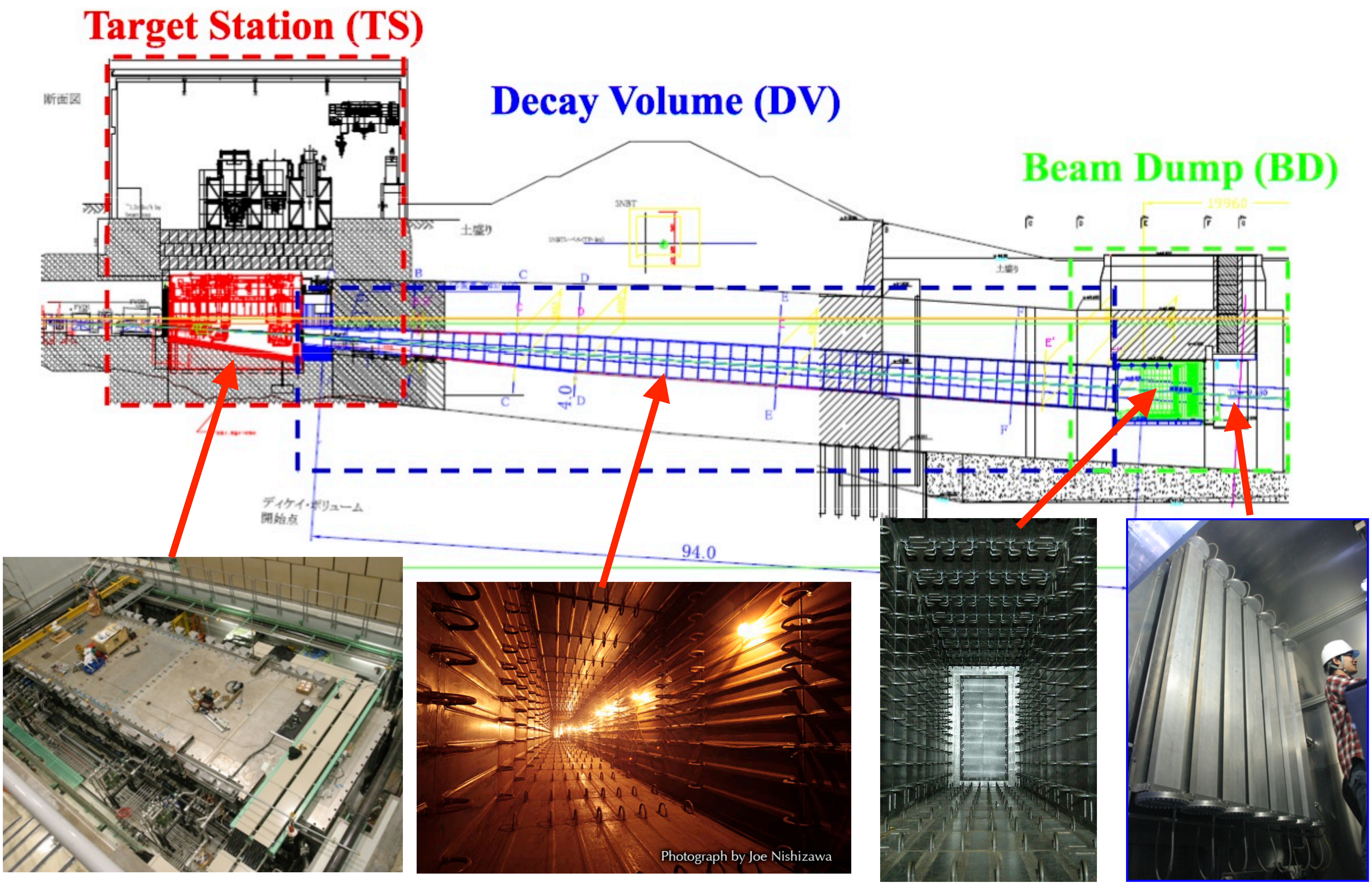
	Intensity (CT)	Center (ESM)	Profile (SSEM)
Prep. Sect.	2	9	9
Arc sect.	0	5	3
FF sect.	2	6	5





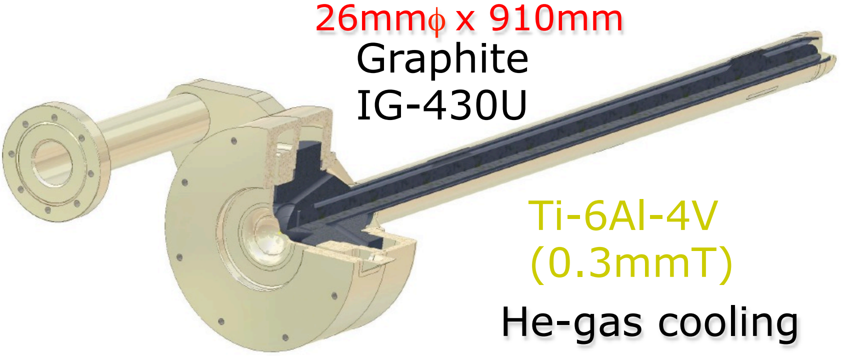


Secondary Beamline

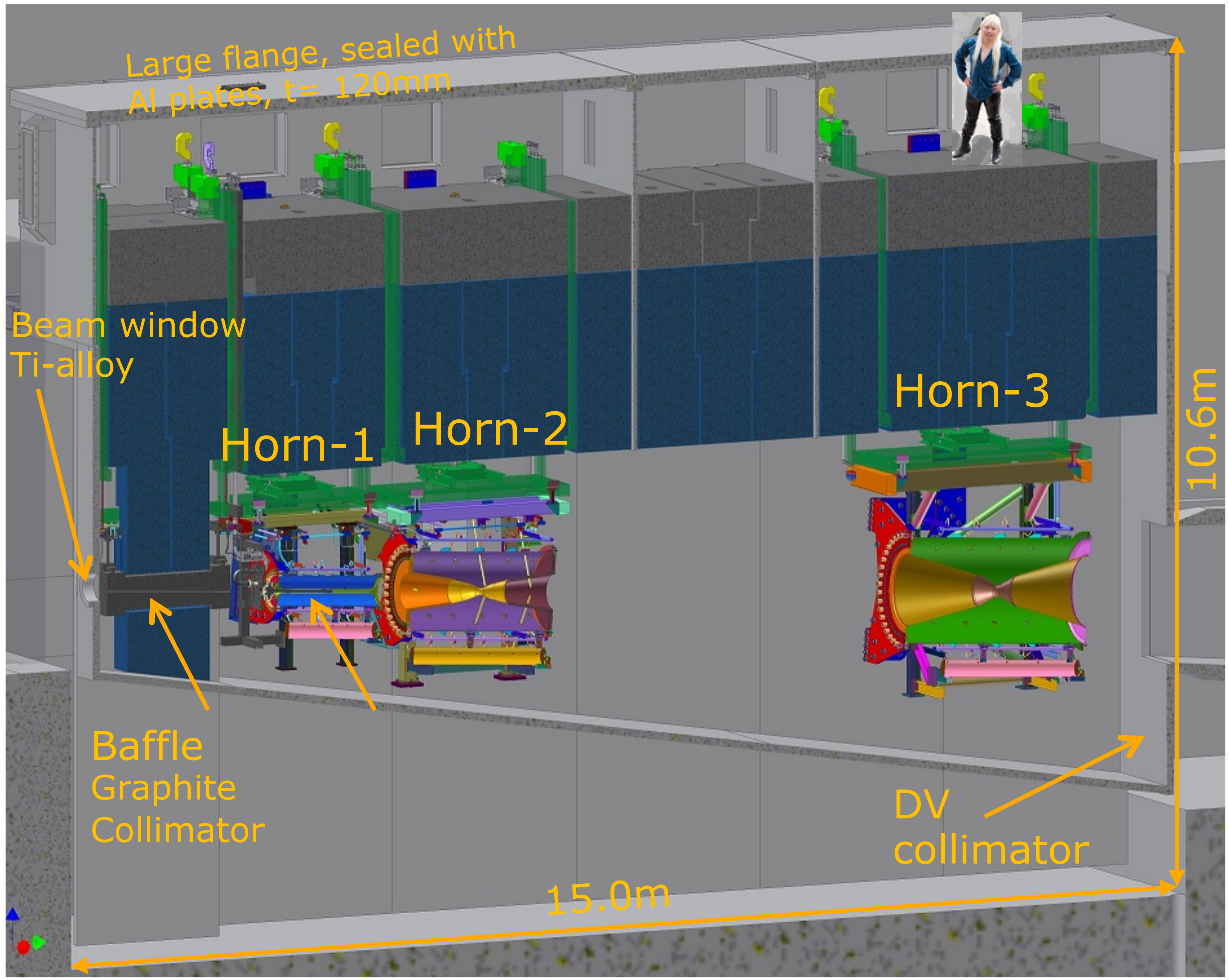


Target Station

Horn1



Target



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1. Introduction
2. Accelerator Upgrade
3. Neutrino Beamline Upgrade
4. Summary

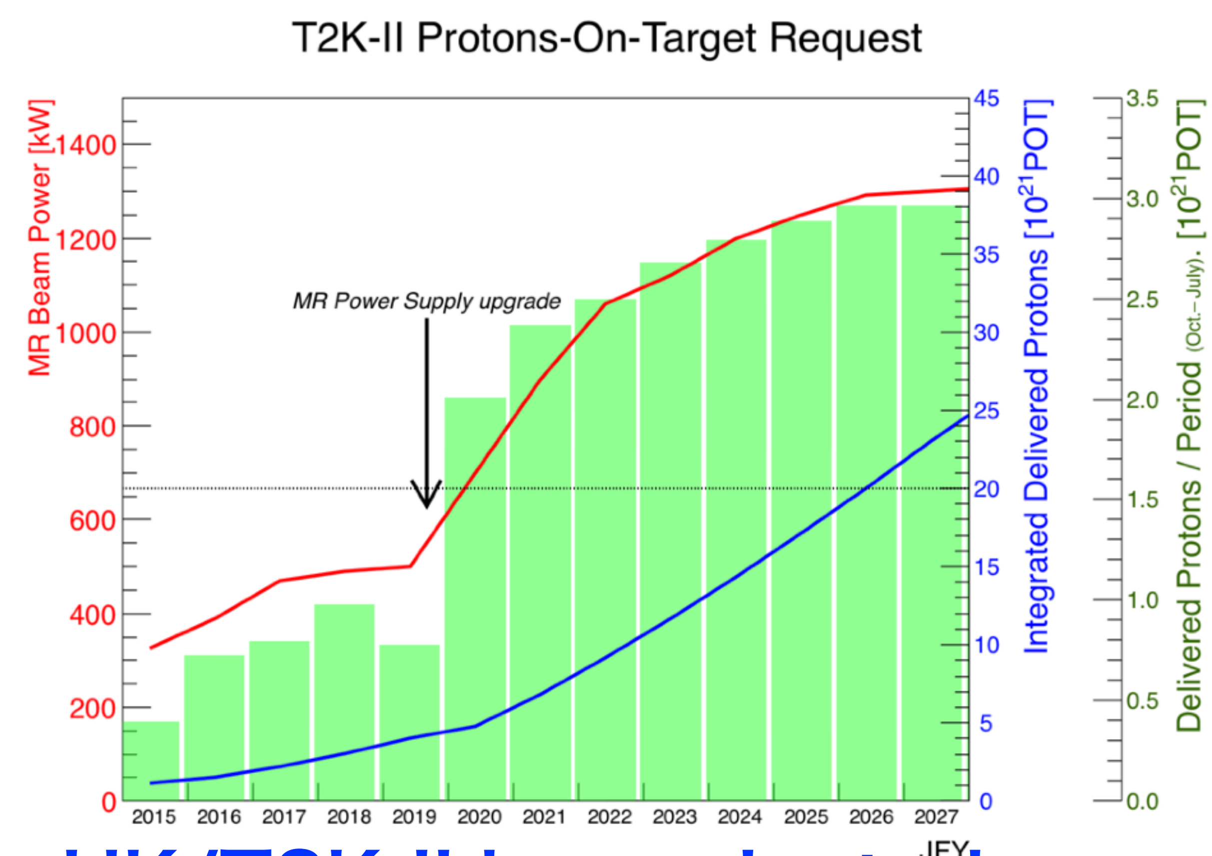
MR Beam Power Upgrade Plan

Beam Power	470 (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.6×10^{14}	3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

+25% +18%

Method

- Increase repetition rate for 750kW
- Increase beam intensity for >1.3MW

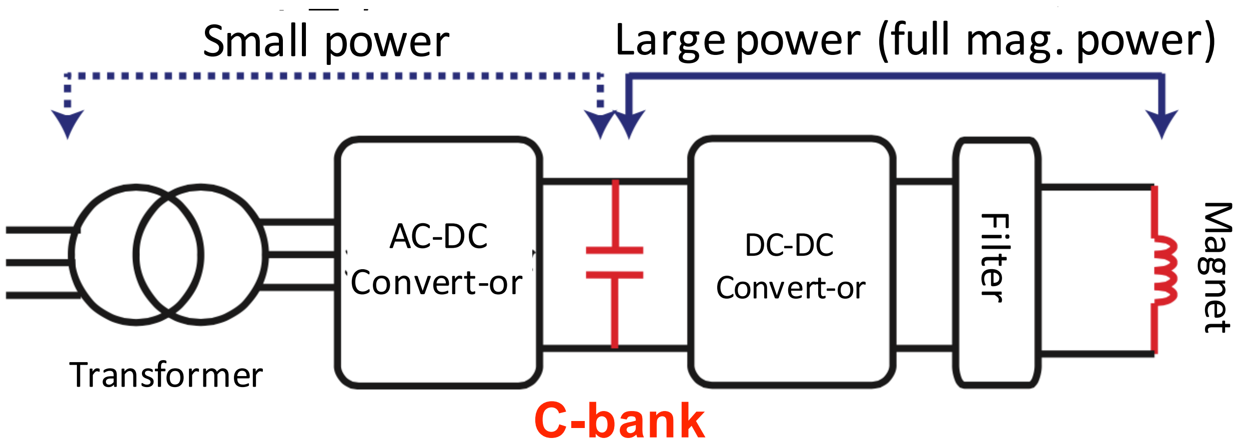


- Accelerator/beamline upgrade for HK/T2K-II has selected as the highest priority project in KEK PIP

New PS for High Rep. Rate Operation

Courtesy of T. Koseki

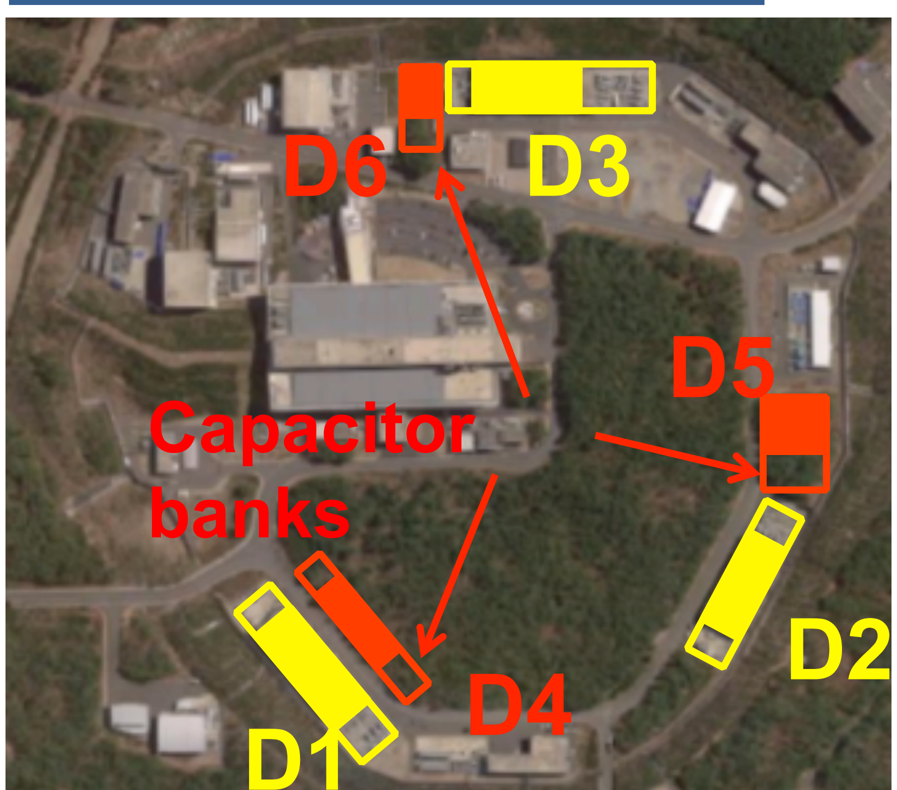
Large scale PS for bending magnets and quad. magnets in arc setions



Two large converters and large capacitance for energy recovery, symmetric power module circuit

Budget for three buildings of the magnet PS's and starting mass production of the PS's have been approved by the government in JFY2016.

D1-3: existing buildings
D4-6: New buildings

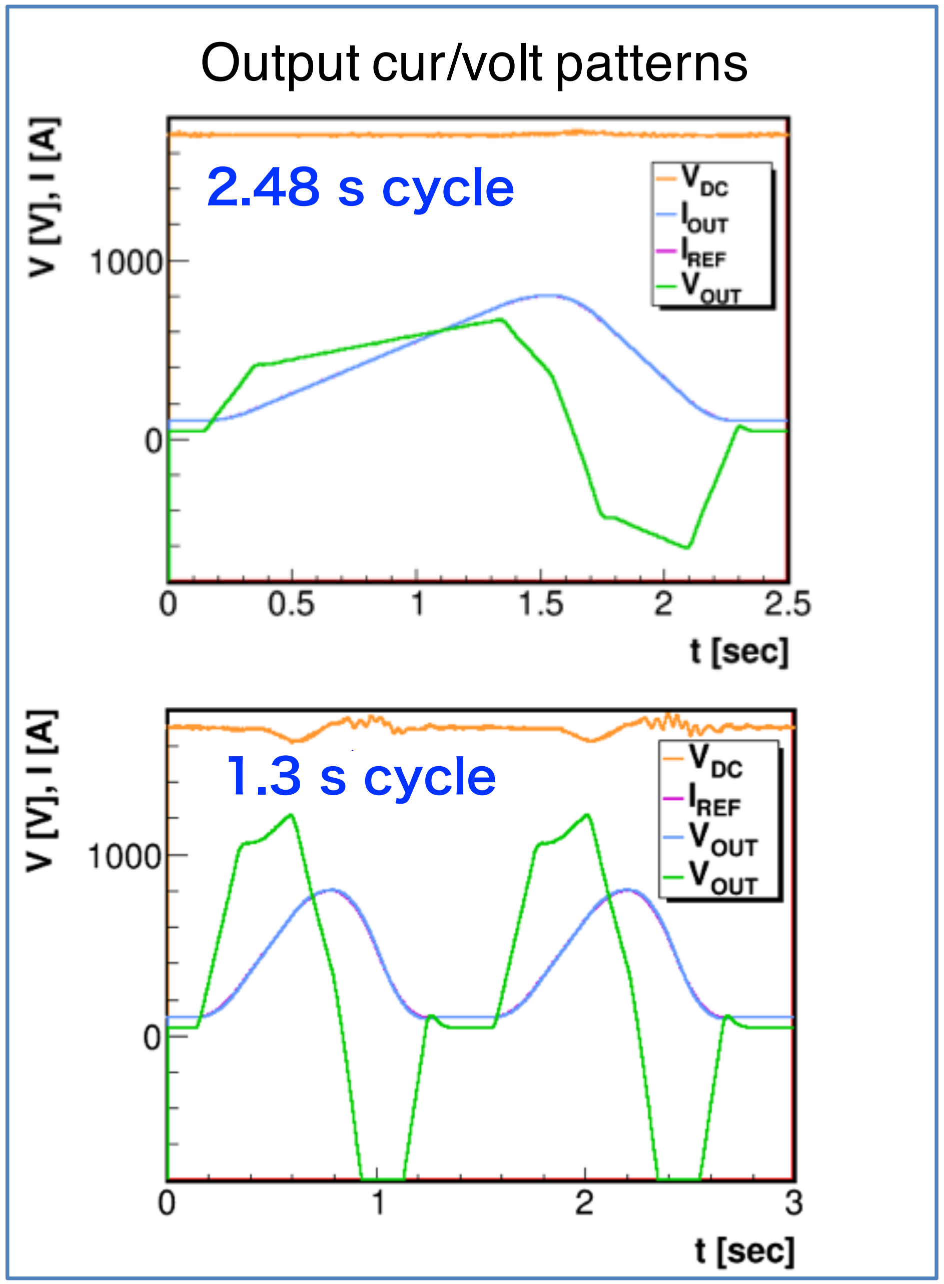


Construction will be finished in 2017.

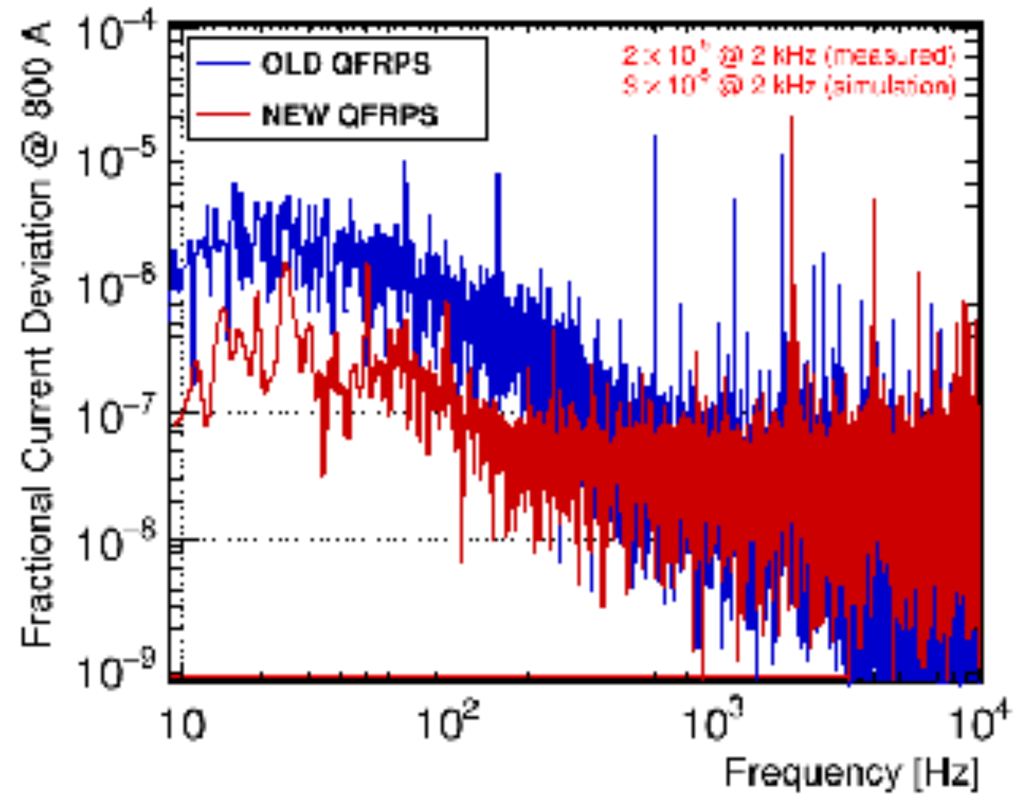
First New PS for Q-magnet

Courtesy of Accelerator group

Middle scale PS for quad. magnets in straight section



Output current ripple



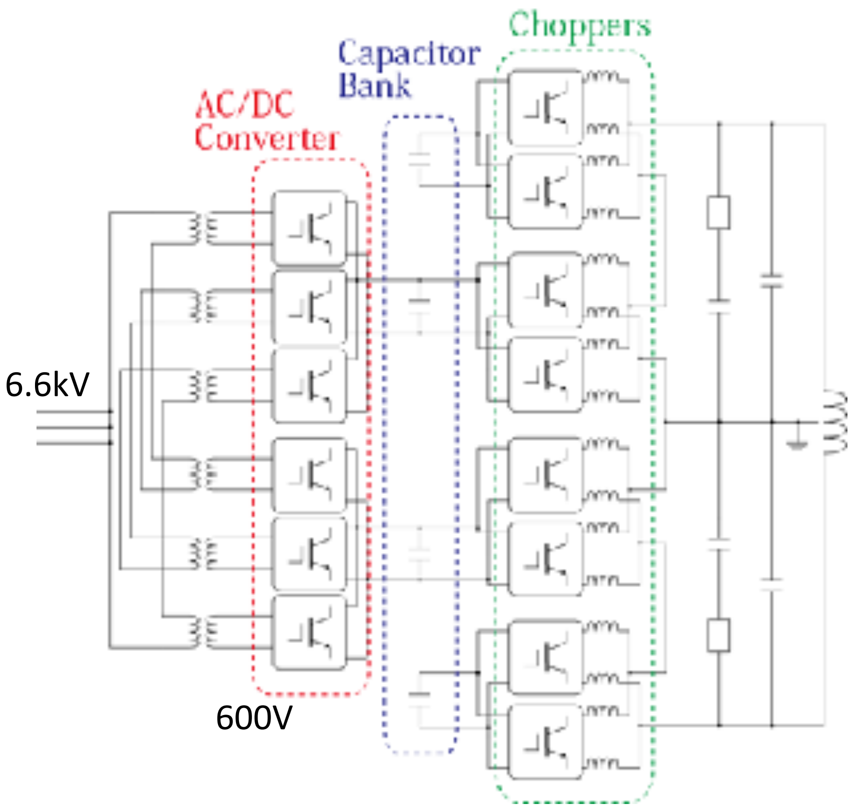
Operated stably in user operation since the end of October 2016.

New PS for B-magnet

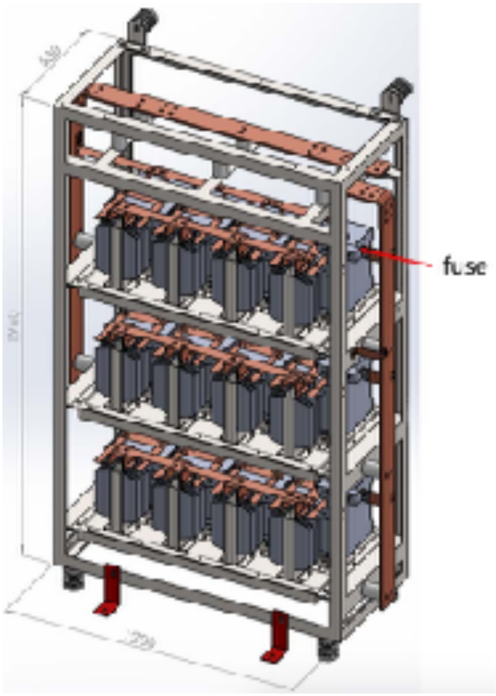
From Jul. 2017 PAC slides by F. Naito

- **First new PS will be tested in the new building in this winter**

Scheme of BM PS



1 unit of C-bank



1 container has 16 units.
1 power supply has 3 containers.

Containers for capacitor bank

Inside containers

Toward Beam Power > 1MW

Courtesy of T. Koseki

Beam Power (kW)	460 (Achieved)	864	1049	1326
#ppp(10^{14})	2.4	2.4	2.9	3.2
Rep T (s)	2.48	1.32	1.32	1.16

(1) To achieve 750 kW:

- **New power supplies**
- **2nd harmonic rf system**
  2 harmonic cavities

(2) Toward > 1 MW

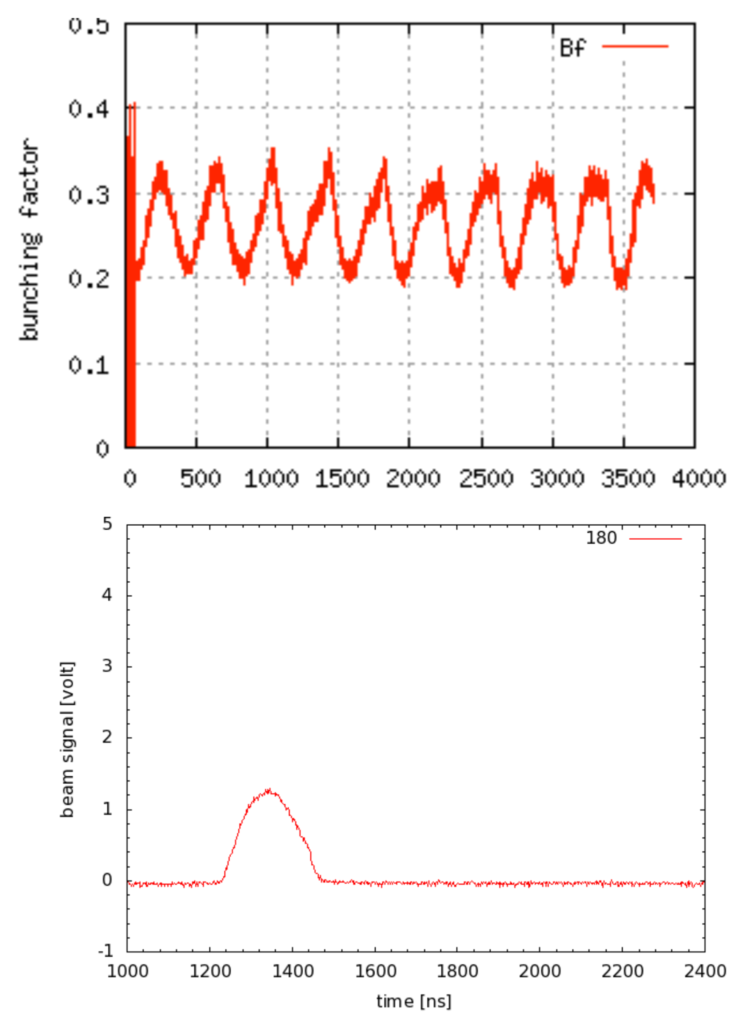
- **Higher rf voltage and more margin**
  11 fundamental cavities

In addition:

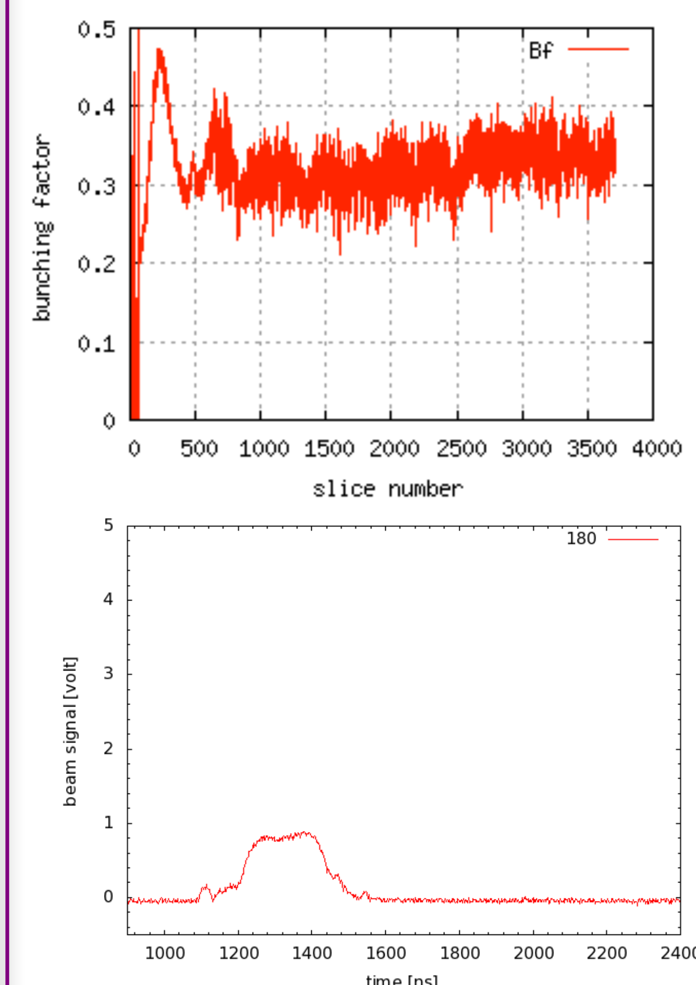
- VHF rf system
- BPM upgrade
- FX kicker upgrade

Bunching factor and longitudinal distribution
3.2×10^{13} ppb (~1 MW for 1.3 s cycle)

Without 2nd harmonics

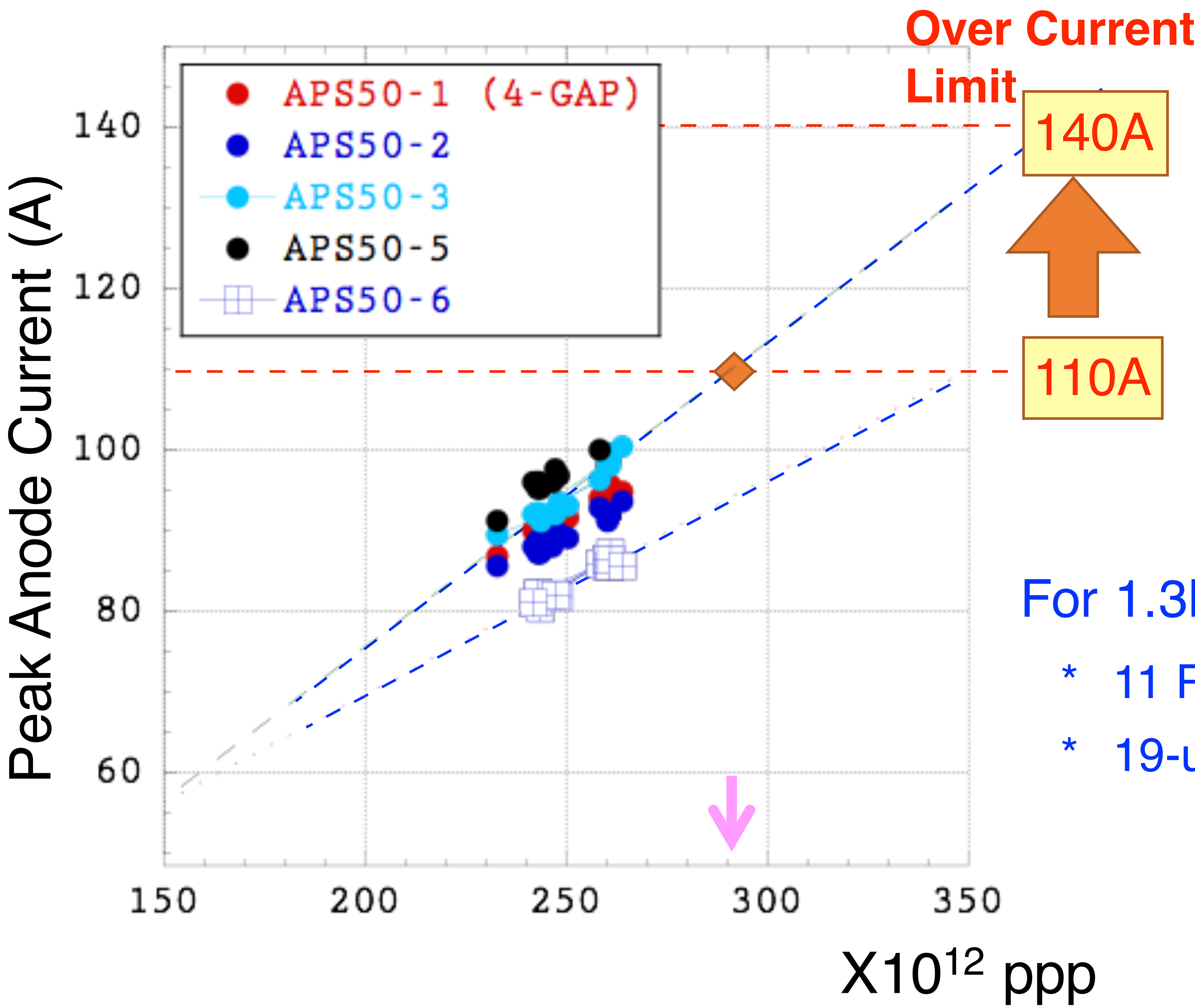


With 2nd harmonics



Peak Anode Current vs Circulating Protons/pulse

Courtesy of T. Koseki



19-inverter-units (RCS modification)

* Original Anode PS consists of 15-inverter units

For 1.3MW,

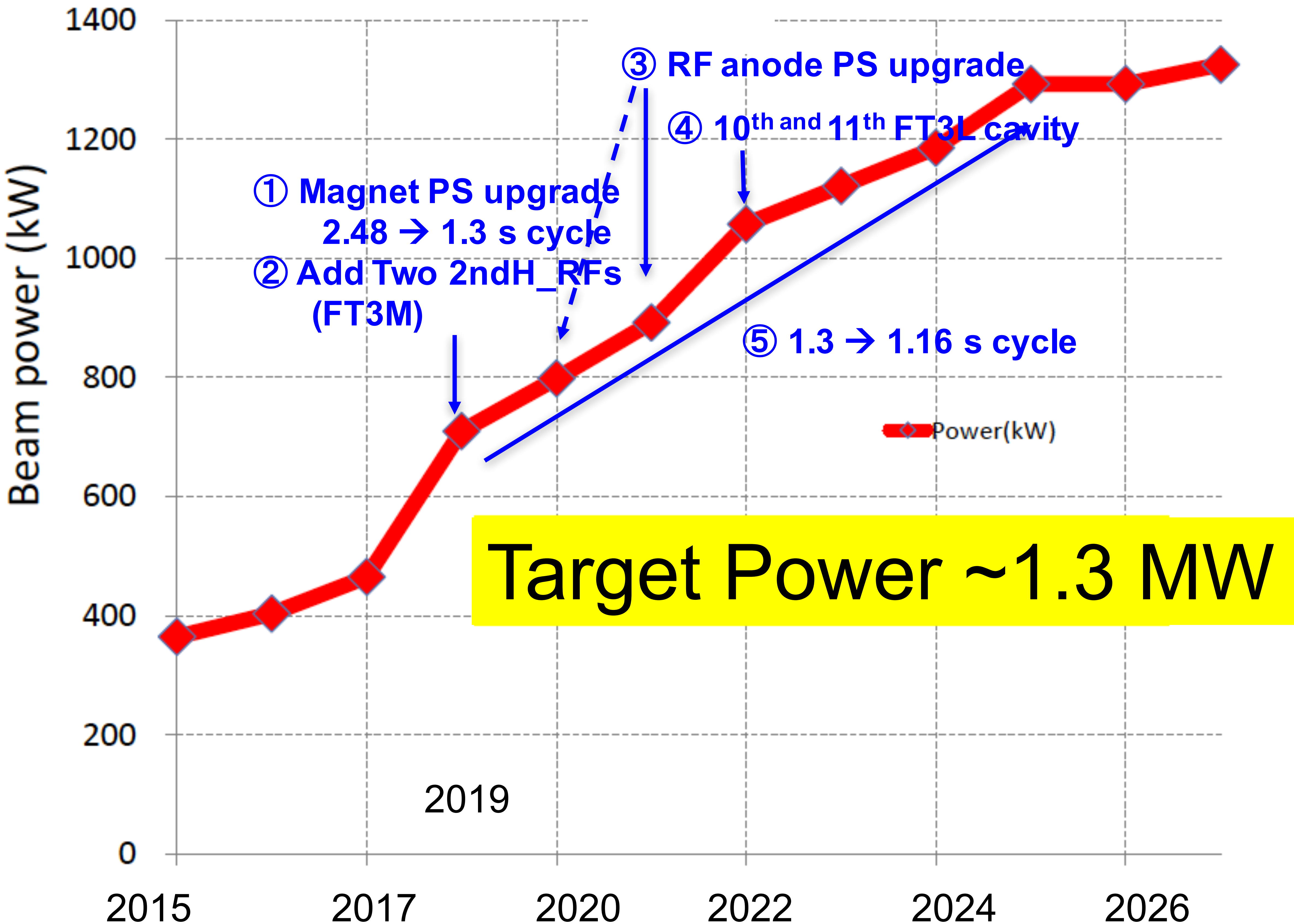
* 11 RF system in total &
* 19-unit modification

are necessary.

ppp ($\times 10^{12}$)	200	240	300	330	#of AccRF	VRF(h=9)	#of 2ndRF	VRF(h=18)
2.48s	390kW	465kW	580kW	640kW	7	280kV	2	110kV
1.28s	750kW	900kW	1100kW		9	510kV	2	110kV
1.16s	830kW	1000kW	1.2MW	1.3MW	11	600kV	2	110kV

Beam Power Upgrade

Courtesy of T. Koseki



Contents

Neutrino Beamline Upgrade

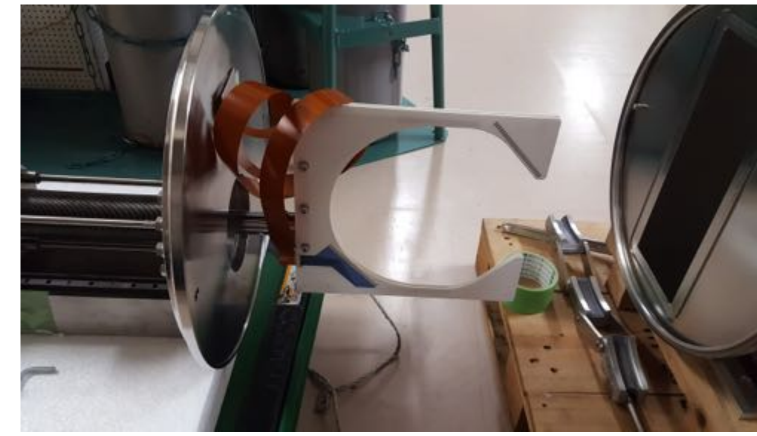
- **Basic philosophy for beamline design**
  - Most of components were designed to accept **3.3×10^{14} ppp**
  - Replaceable components designed for **750kW** (can be upgraded later)
  - Non-replaceable components (HV, DV, BD) designed for **3~4MW**
- **Necessary upgrade toward >1.3MW**
  - **Primary beamline**
    - Upgrade beam monitors
  - **DAQ**
    - Upgrade DAQ/control system for higher rep. rate and safety operation
  - **Secondary beamline**
    - **Higher current** horn operation (250kA → **320kA**)
    - **Cooling capacity** upgrade
    - Upgrade for **radioactive water disposal**
    - **Radiation damage studies** and develop more radiation-resistant beamline components (target/beam window, etc)

Current Acceptable Beam Power

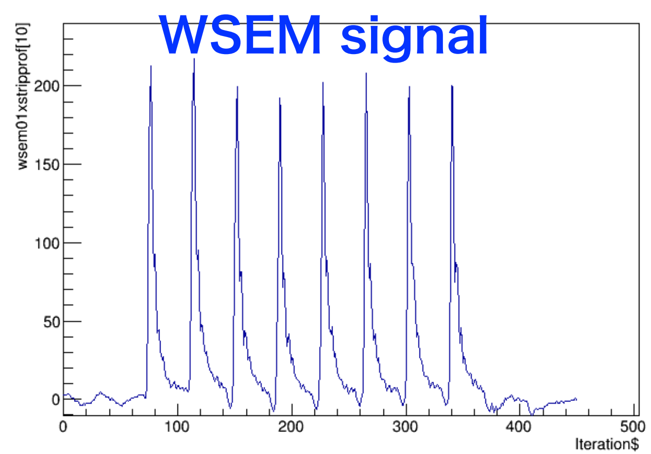
Component	Limiting factor	Current acceptable value	
Target/ Beam window	Thermal shock	3.3×10^{14} ppp	
	Cooling capacity	0.9MW	
Horn	Conductor cooling	2MW	
	Stripline cooling	0.75MW	
	Hydrogen production	1MW	
	Operation	250kA, 2.48s	
He Vessel	Thermal stress	4MW	
	Cooling capacity	0.75MW	
Decay Volume	Thermal stress	4MW	
	Cooling capacity	0.75MW	
Beam Dump	Oxidization	3MW	
	Cooling capacity	0.75MW	
Radiation disposal	Radioactive air	>2MW	
	Radioactive water	0.4MW	

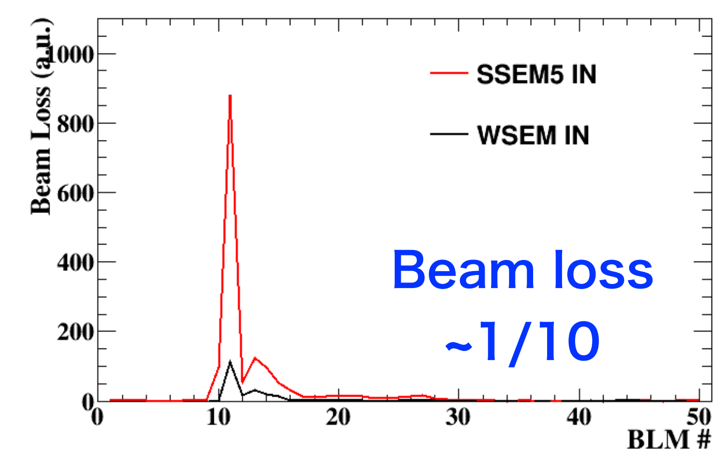
Beam Monitor Upgrade

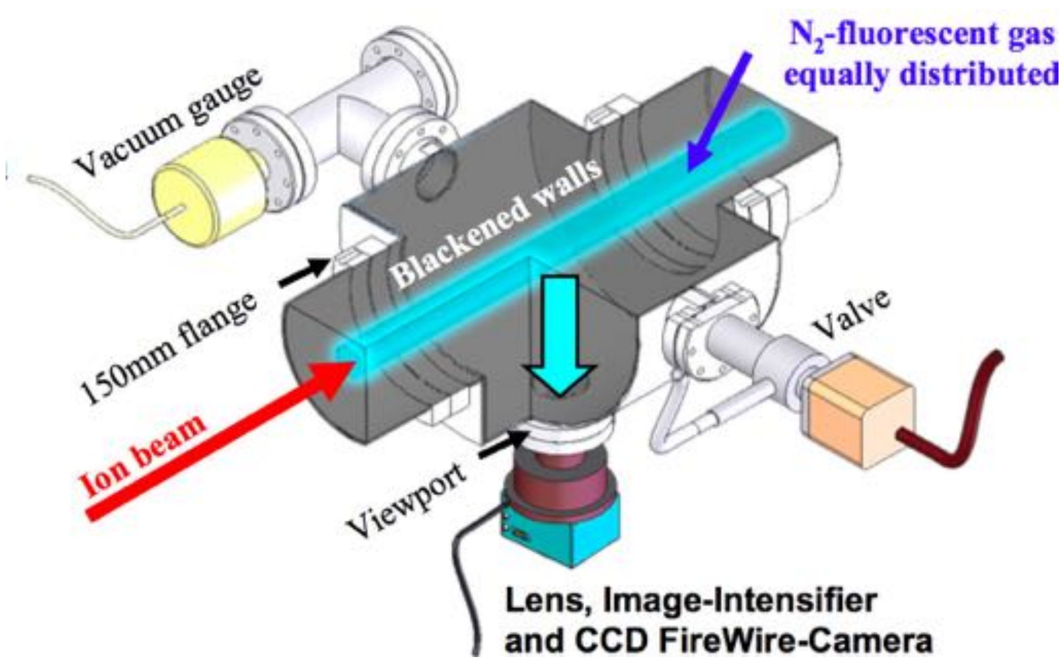
- **Wire Secondary Emission Monitor (WSEM)**
  - First prototype installed ⇒ worked well as expected
  - Beam loss reduced by 1/10 of current SSEM
- **Beam Induced Fluorescent Monitor (BIF)**
  - Light emission from beam-gas interaction
  - Various component tests ongoing
- **Schedule**
  - Aim to install
    - WSEM in ~2018
    - BIF in ~2020



WSEM Mounted on Mover 13 /

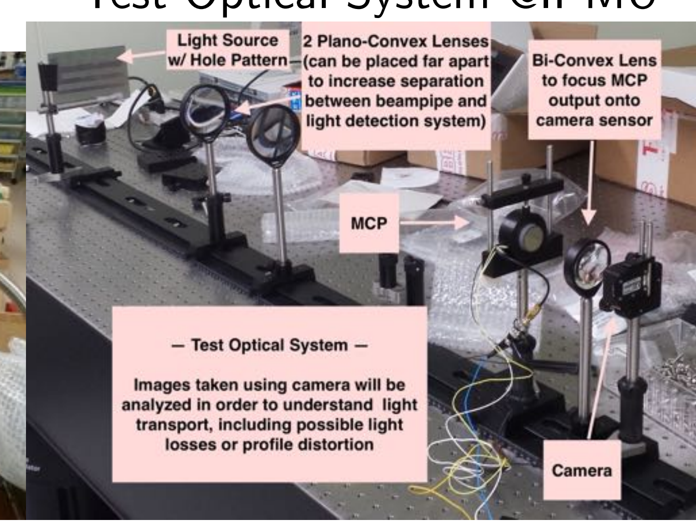






Test Vacuum Vessel @Tokai

Test Optical System @IPMU



Other Monitors

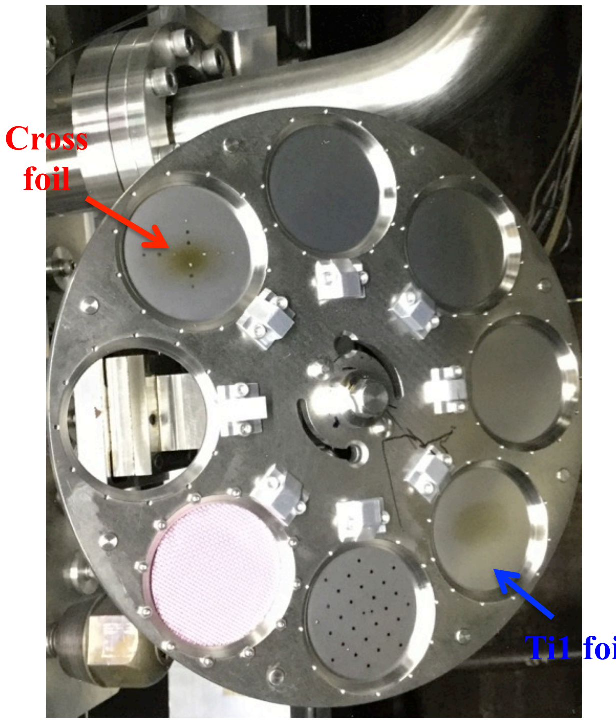
Muon monitor upgrade

- Si detectors and Ion Chambers ⇒ **Si degradation** at high beam power
- Developing new type of muon monitors (**electron multiplier tube**, EMT)

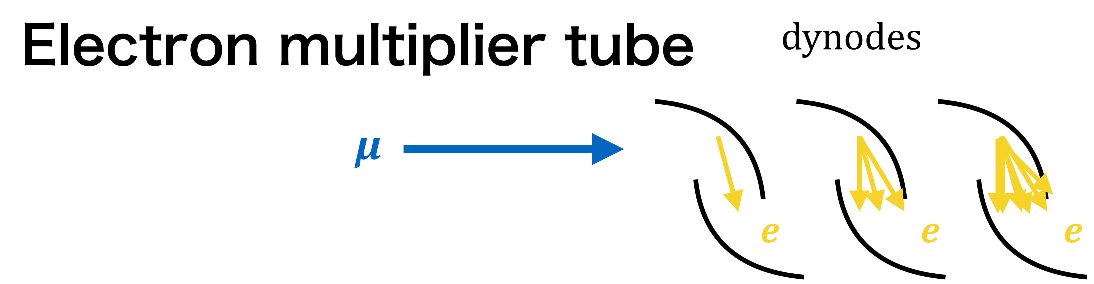
OTR upgrade

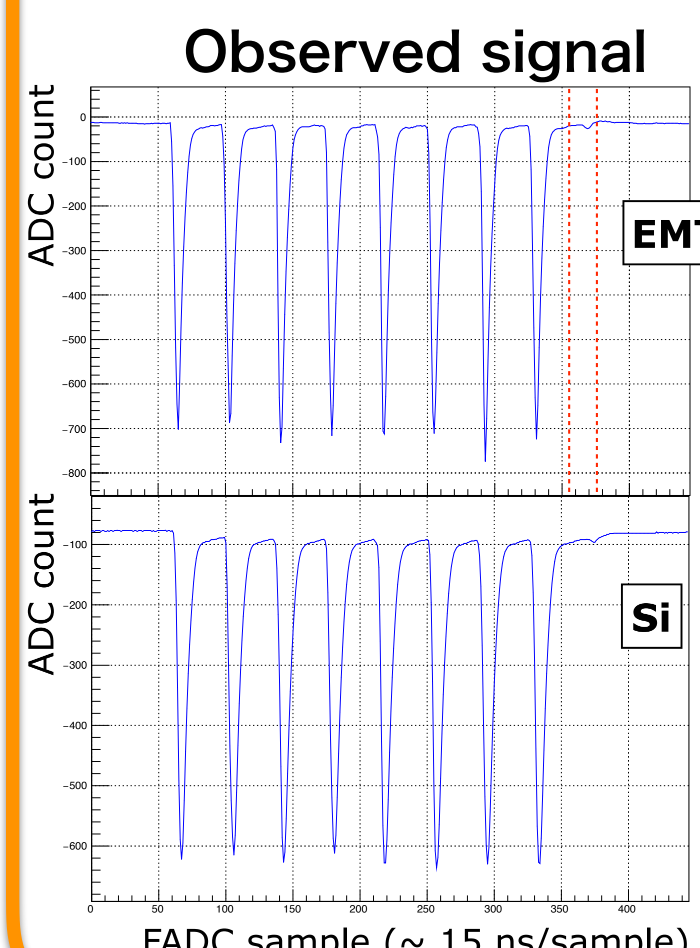
- Problem on rotation system
  - Develop more redundant system
- Radiation damage is an issue
  - New Ti material to be used
  - Other material (e.g., graphite)

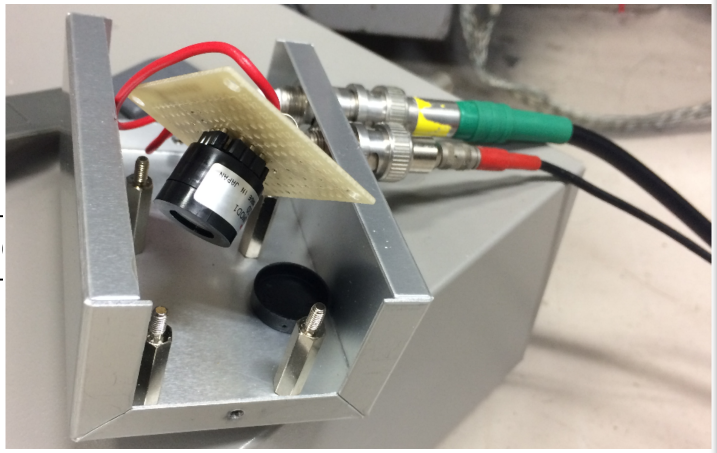
OTR

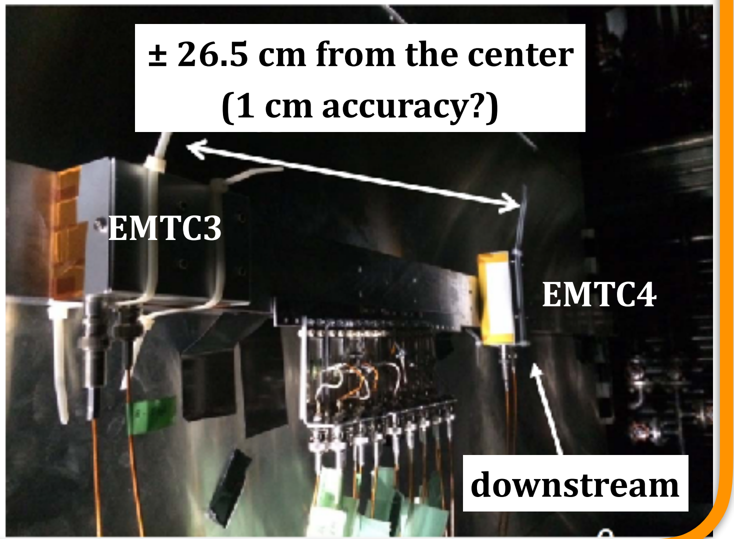


Muon monitor





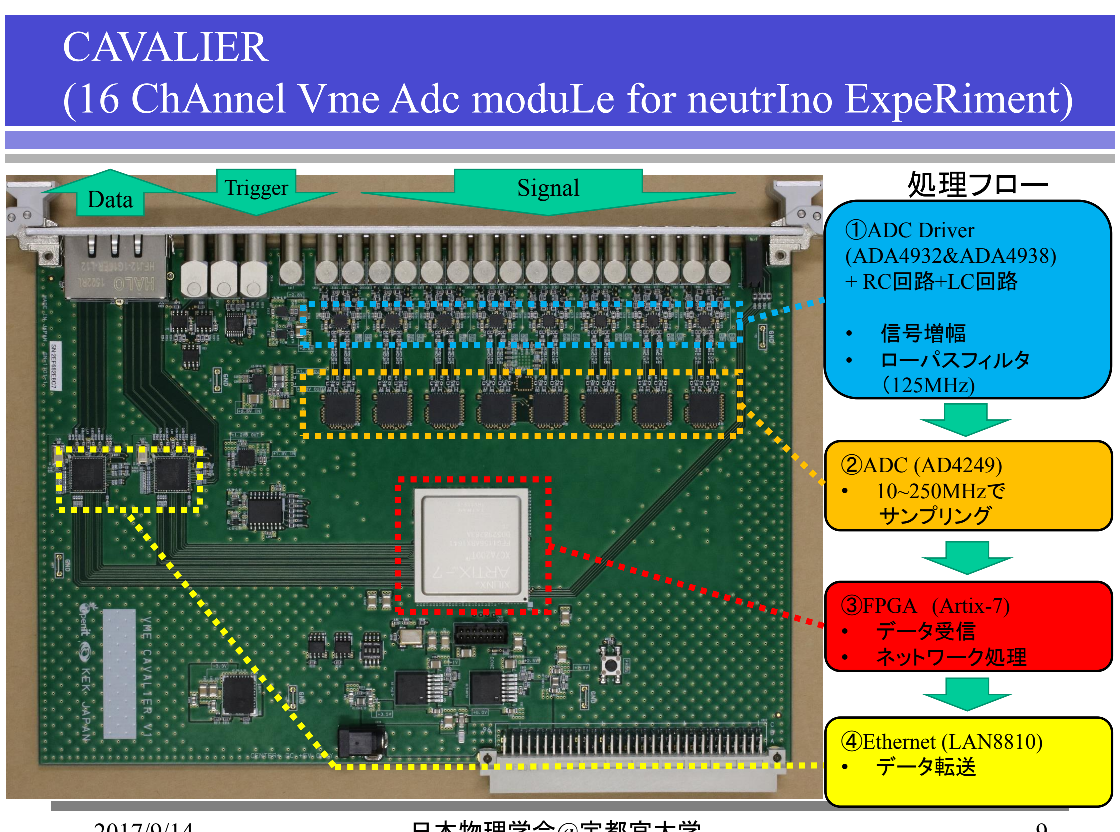




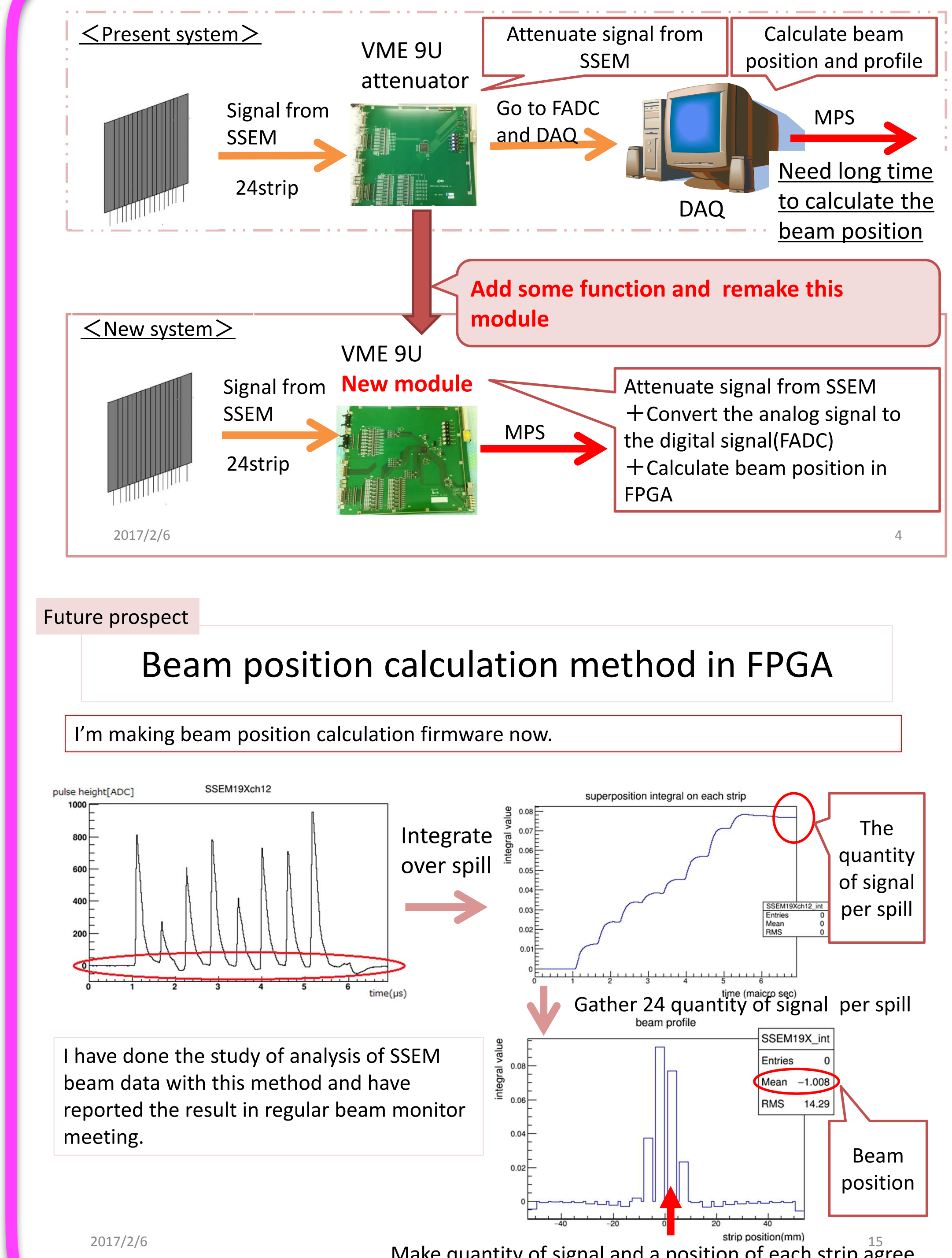
Control/DAQ Upgrade for 1Hz Operation

- Faster DAQ for high rep. rate ⇒ New FADC (by Hamada@KEK)
- New hardware interlock for safe beam operation ⇒ New interlock module (by Yamasu@Okayama U)
- Prototype boards under development
- Aim to implement in FY2019 or earlier

New FADC



New hardware interlock



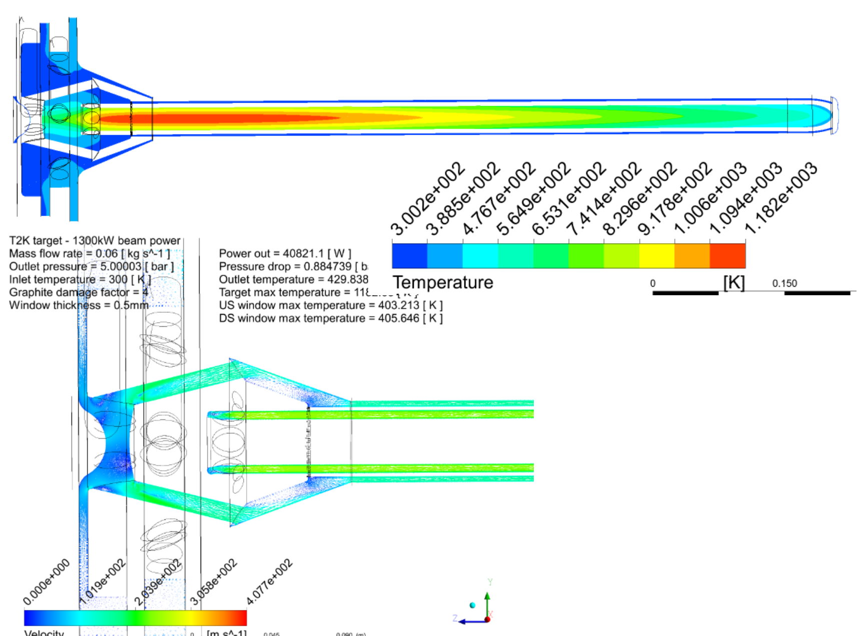
Target Upgrade

Original target design

- Design intensity = 3.3×10^{14} ppp → **3.2×10^{14} ppp** should be no problem
  - Understanding radiation damage is crucial
- Cooling capacity: **900kW**

Improvement

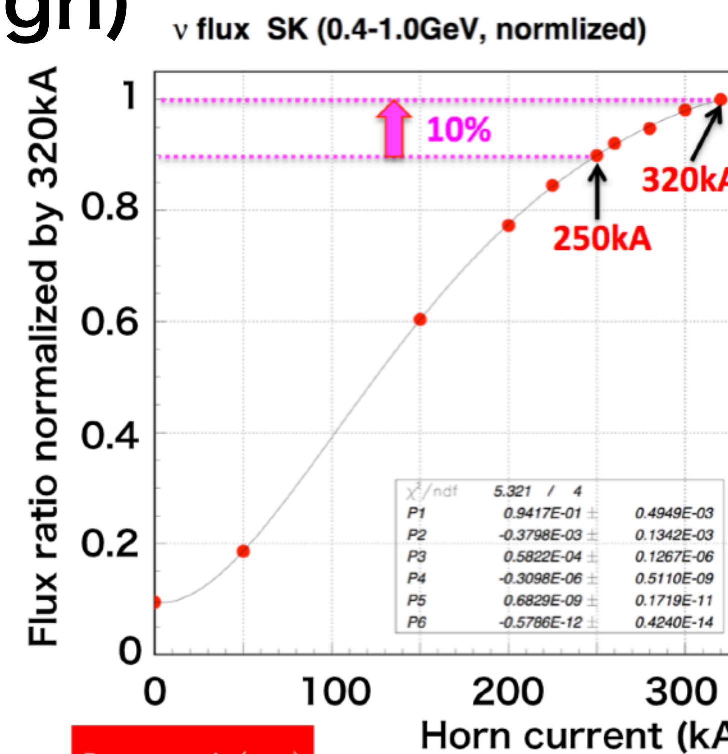
- **Higher flow rate** needed → higher pressure tolerance
  - **Upgrade of He compressor** is needed to increase flow rate
- FEM simulation for 1.3 MW ⇒ max temp. = 909℃ (should be reduced)
  - Further study is ongoing

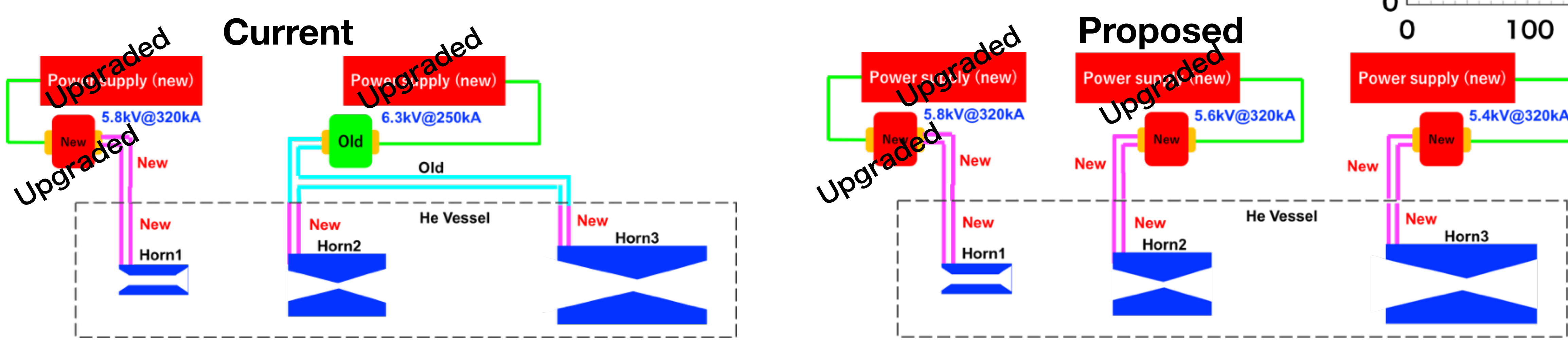


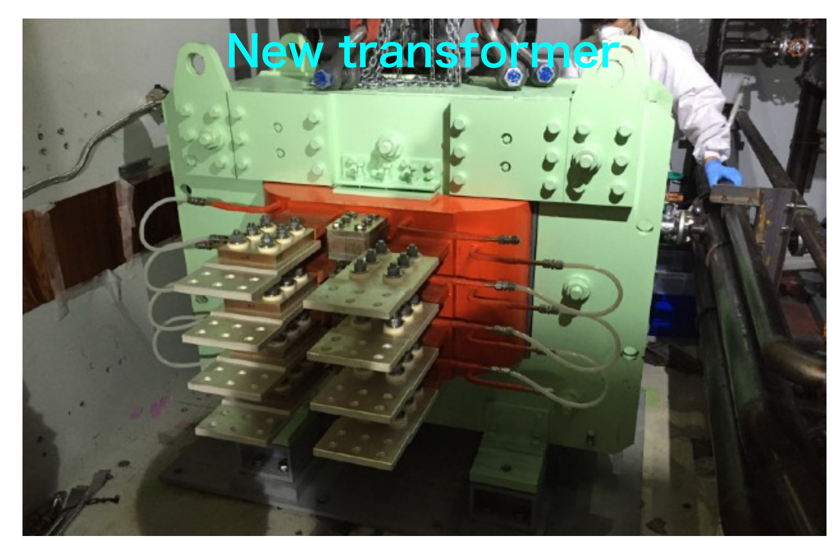
	0.75 MW	1.3 MW
Helium pressure	1.6 bar	5 bar
Pressure drop	0.83 bar	0.88 bar
Helium mass flow	32 g/s	60 g/s
Heat load	23.5 kW	40.8 kW
US window temp	105 ° C	157 ° C
DS window temp	120° C	130° C
Targe core temp	736 ℃	909 ℃

Horn System Upgrade

- **Horn current increase**: 250 kA → **320 kA** (design)
  - **~10% flux gain** for right-sign neutrinos
  - **5~10% flux reduction** for wrong-sign neutrinos
  - **3 power supply** system is adopted
    - New PS, new transformer, new striplines developed
    - Further 1PS, 2trans., striplines needed



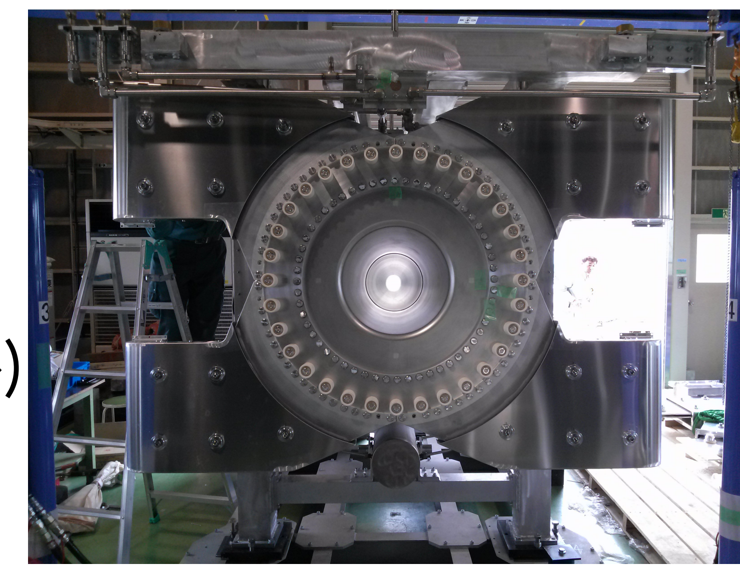


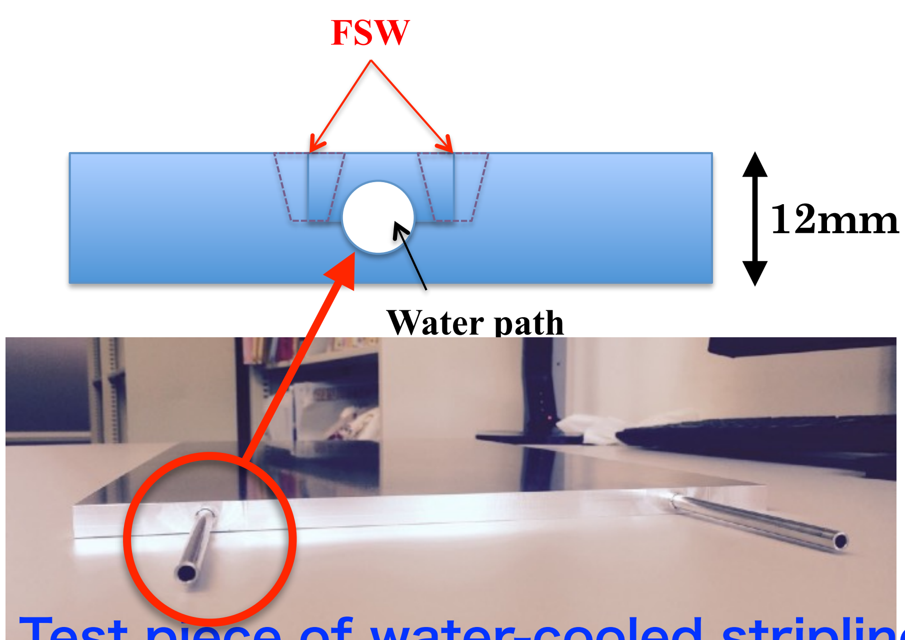


Horn System Upgrade

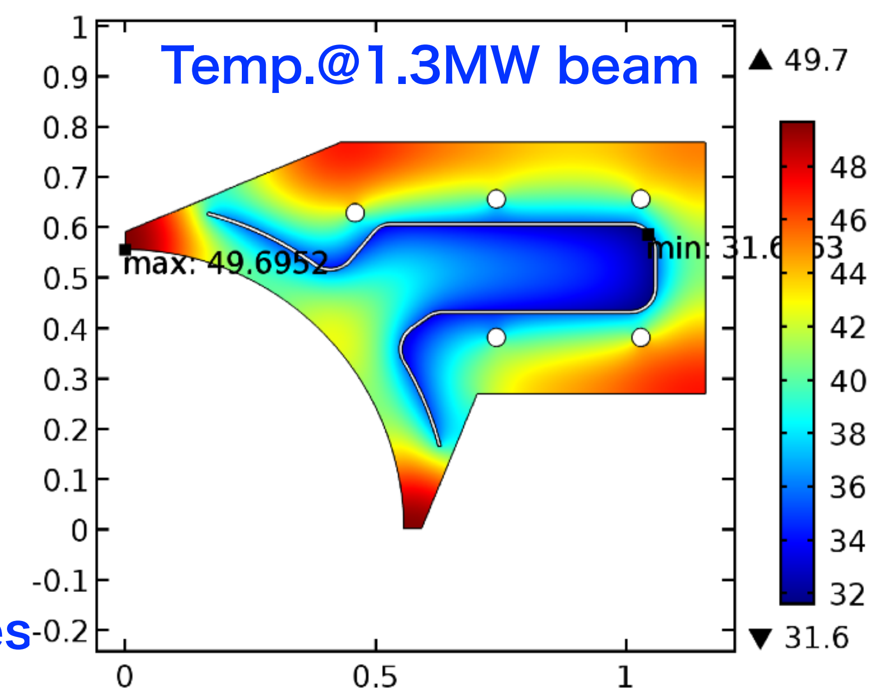
Stripline cooling improvement

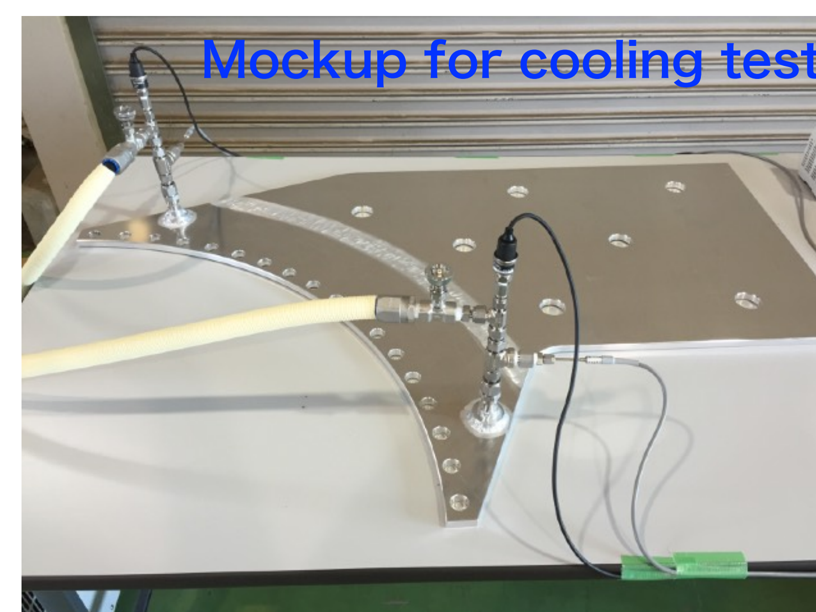
- Heat deposit by defocused particles ⇒ Cooling w/ forced He flow (**750kW**)
- Staged upgrade toward 1.3MW
  - **Higher He flow rate** w/ He compressor upgrade ⇒ **~1MW**
  - **Water-cooled striplines** for **>1.3MW**
    - Water-tube embedded in Al plates using FSW
      - **Can be acceptable >3MW**
    - R&D plan :
      - Cooling test (~FY2017) ⇒ current test (FY2018~)
    - To be installed to horn in FY2021





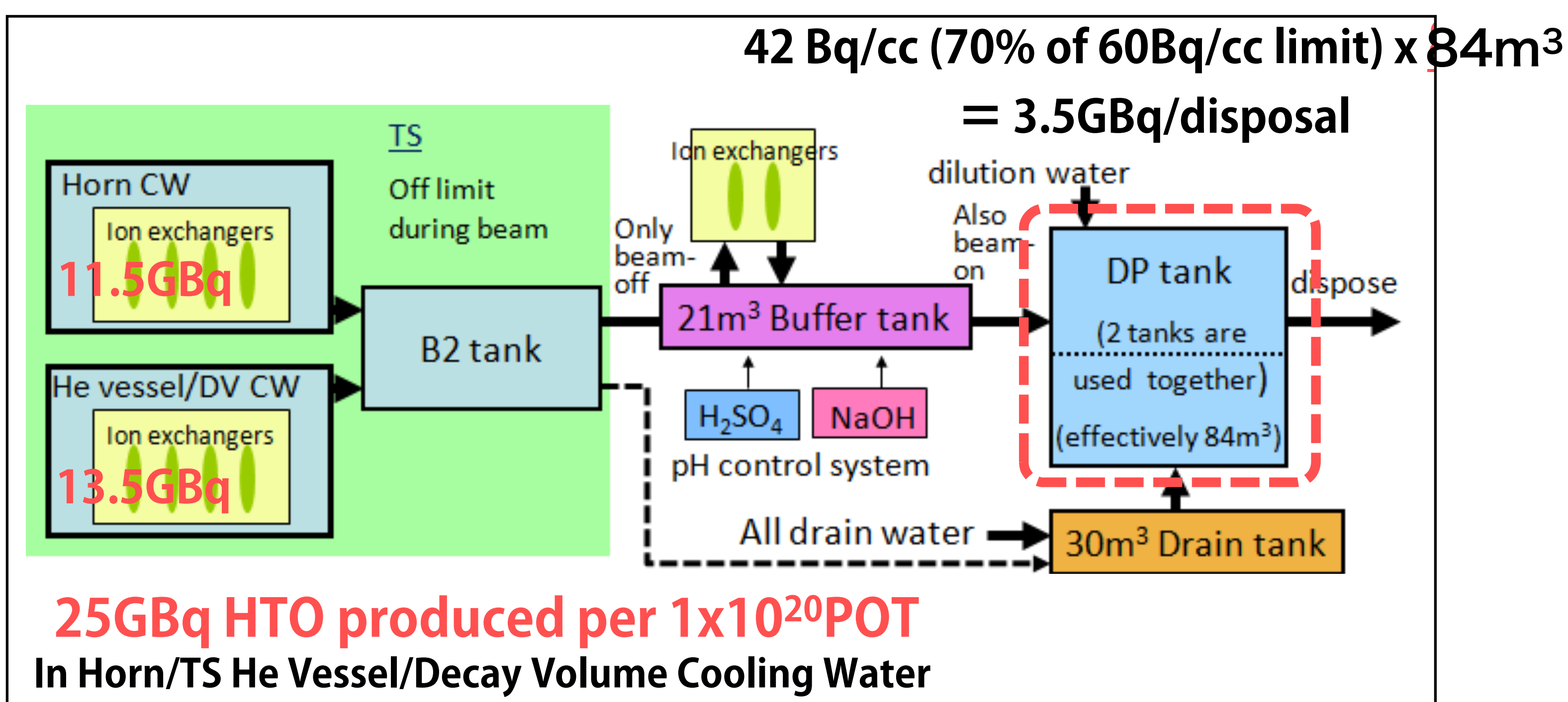
Test piece of water-cooled striplines




Mockup for cooling test

Radioactive Water Disposal

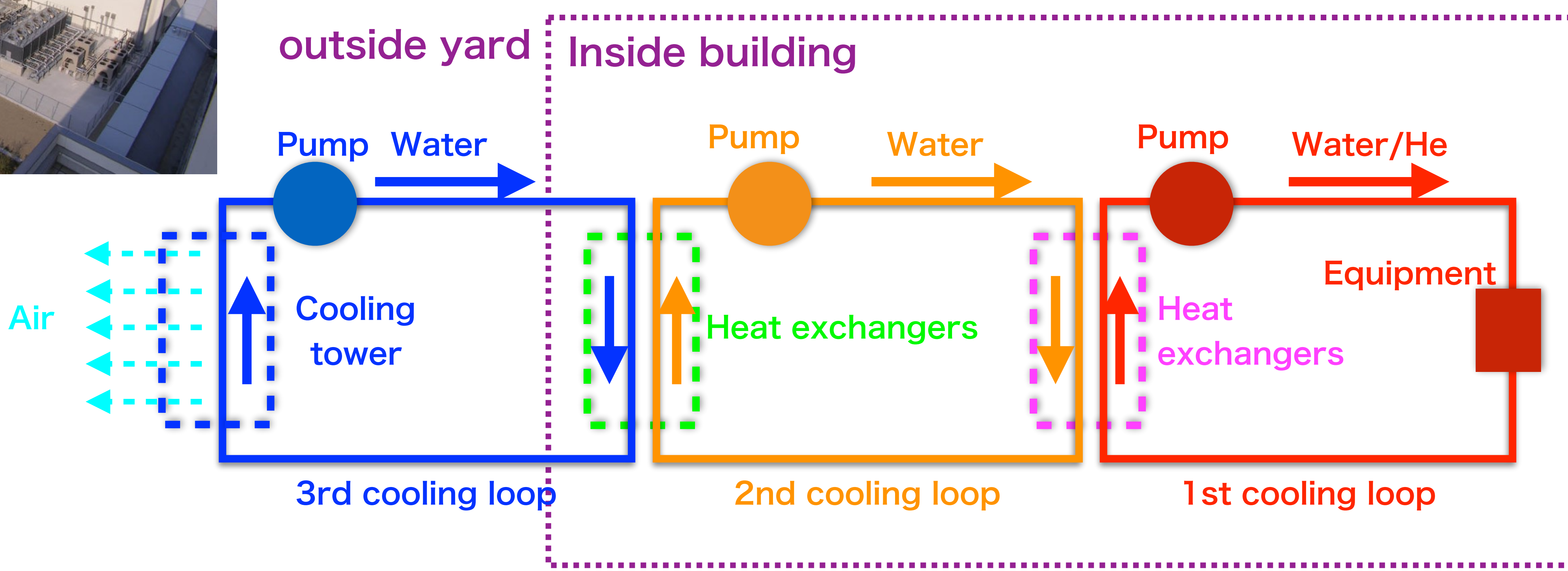
- Radioactive water disposal
  - ^{3}H (Tritium) → **dilution**, ^{7}Be → 99.9% removed by ion-exchange
- HTO disposal by dilution
  - Current dilution tanks (84m³) : **400kW** (8.4x10²⁰ POT/year) acceptable
  - Toward >1.3MW, following will be adopted step by step
    - **Increase disposal cycle** ⇒ needs some technical improvements
    - A portion of radioactive water is taken by **tanker truck**
    - Construct an **additional dilution tank** with O(200)m³, entailing construction of new dedicated building



Cooling Capacity Improvement

- Secondary beamline
  - Designed for 750kW → higher capacity needed for > 1.3MW
- Improvement
  - Higher flow rate → replace with larger pumps
  - Higher cooling capacity → larger heat exchangers/cooling tower

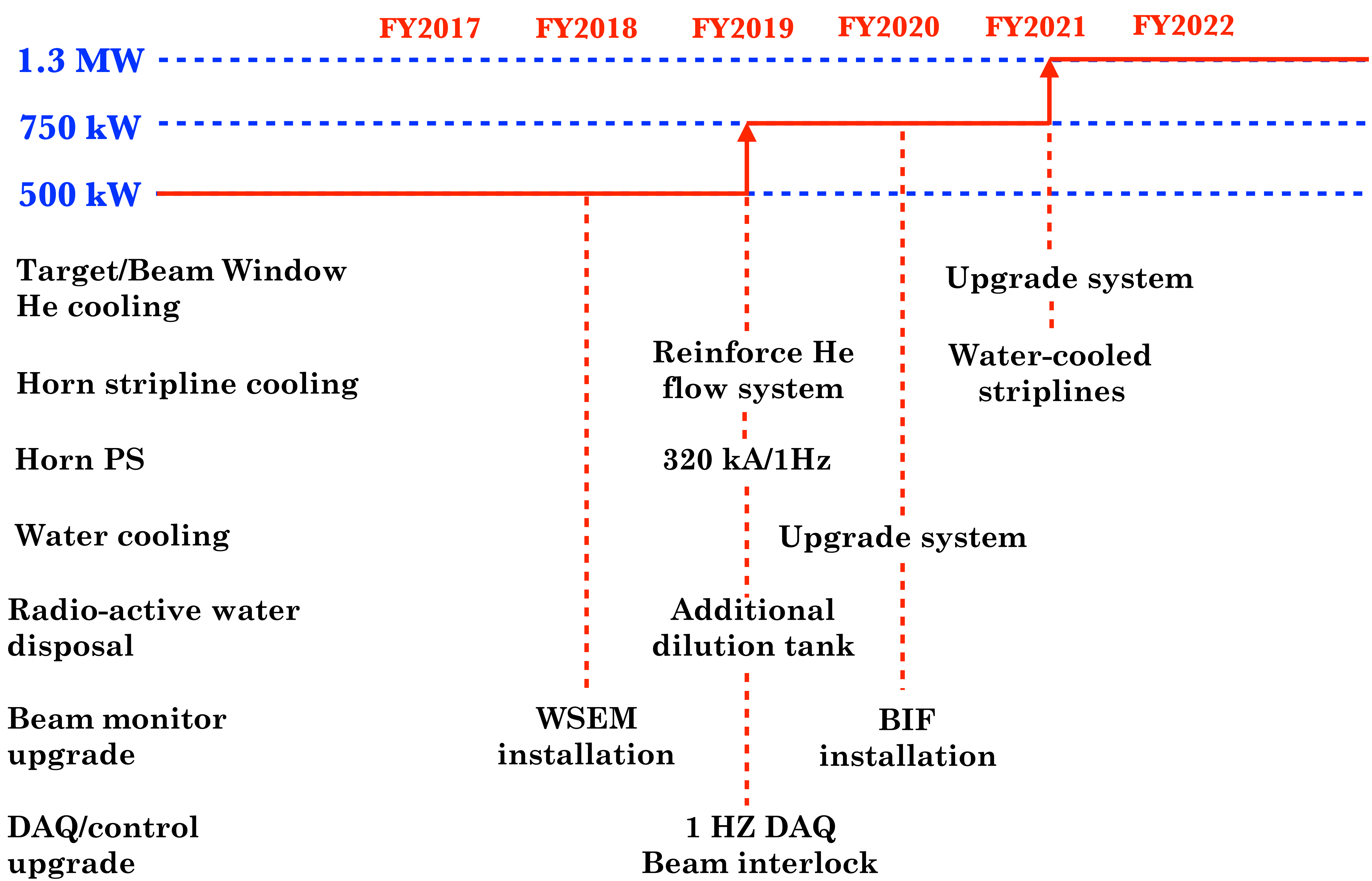
Detailed design is needed soon



Acceptable Beam Power

Component	Limiting factor	Current acceptable value	Upgraded acceptable value
Target/ Beam window	Thermal shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling capacity	0.9MW	>1.5MW
Horn	Conductor cooling	2MW	2MW
	Stripline cooling	0.75MW	>3MW
	Hydrogen production	1MW	>1.5MW
	Operation	250kA, 2.48s	320kA, 1s
He Vessel	Thermal stress	4MW	4MW
	Cooling capacity	0.75MW	>1.5MW
Decay Volume	Thermal stress	4MW	4MW
	Cooling capacity	0.75MW	>1.5MW
Beam Dump	Oxidization	3MW	3MW
	Cooling capacity	0.75MW	>1.5MW
Radiation disposal	Radioactive air	>2MW	>2MW
	Radioactive water	0.4MW	>1.5MW

Timeline


FY2017
FY2018
FY2019
FY2020
FY2021
FY2022
1.3 MW
750 kW
500 kW
Target/Beam Window
He cooling
Horn stripline cooling
Horn PS
Water cooling
Radio-active water
disposal
Beam monitor
upgrade
DAQ/control
upgrade
Upgrade system
Reinforce He
flow system
Water-cooled
striplines
320 kA/1Hz
Upgrade system
Additional
dilution tank
WSEM
installation
BIF
installation
1 HZ DAQ
Beam interlock

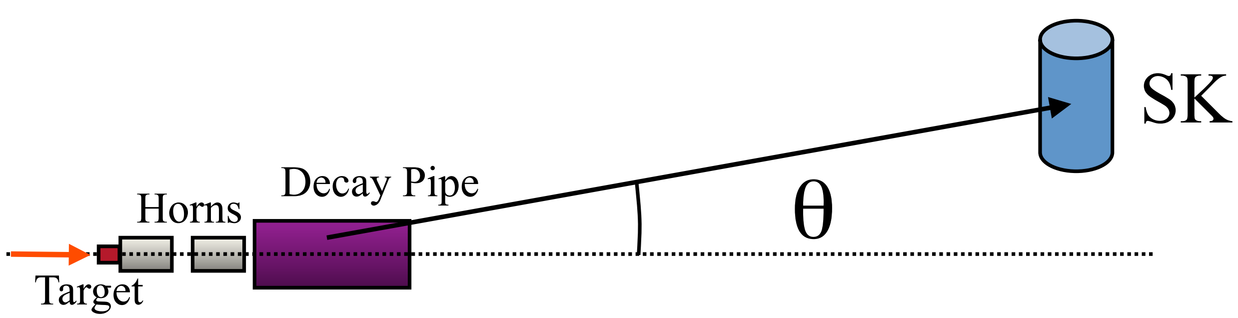
Summary

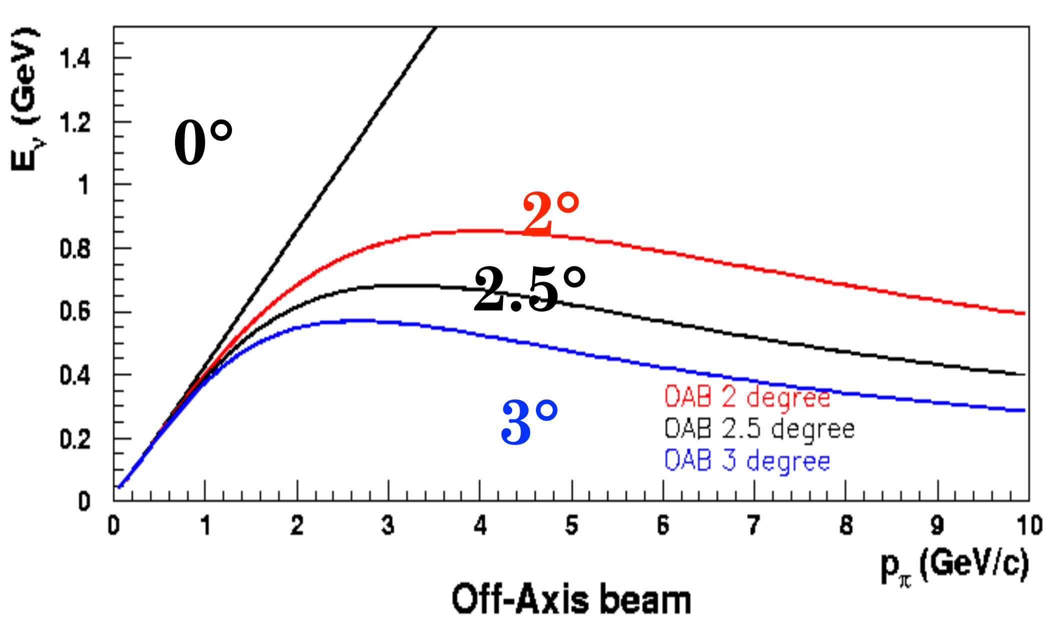
- **Upgrade toward 1.3 MW**
  - **Accelerator upgrade**
    - Higher rep. rate (2.48 s → 1.3 s → **1.16 s**) : PS upgrade, RF upgrade
    - Higher intensity (2.4×10^{14} ppp → $\mathbf{3.2 \times 10^{14}}$ ppp) : RF upgrade
  - **Beamline upgrades**
    - Beam monitor upgrade
    - Control/DAQ upgrade for high rep. rate operation
    - Target upgrade
    - Horn current upgrade to 320kA
    - Upgrade of radioactive water disposal
    - Higher cooling capacity for secondary beamline

Backup

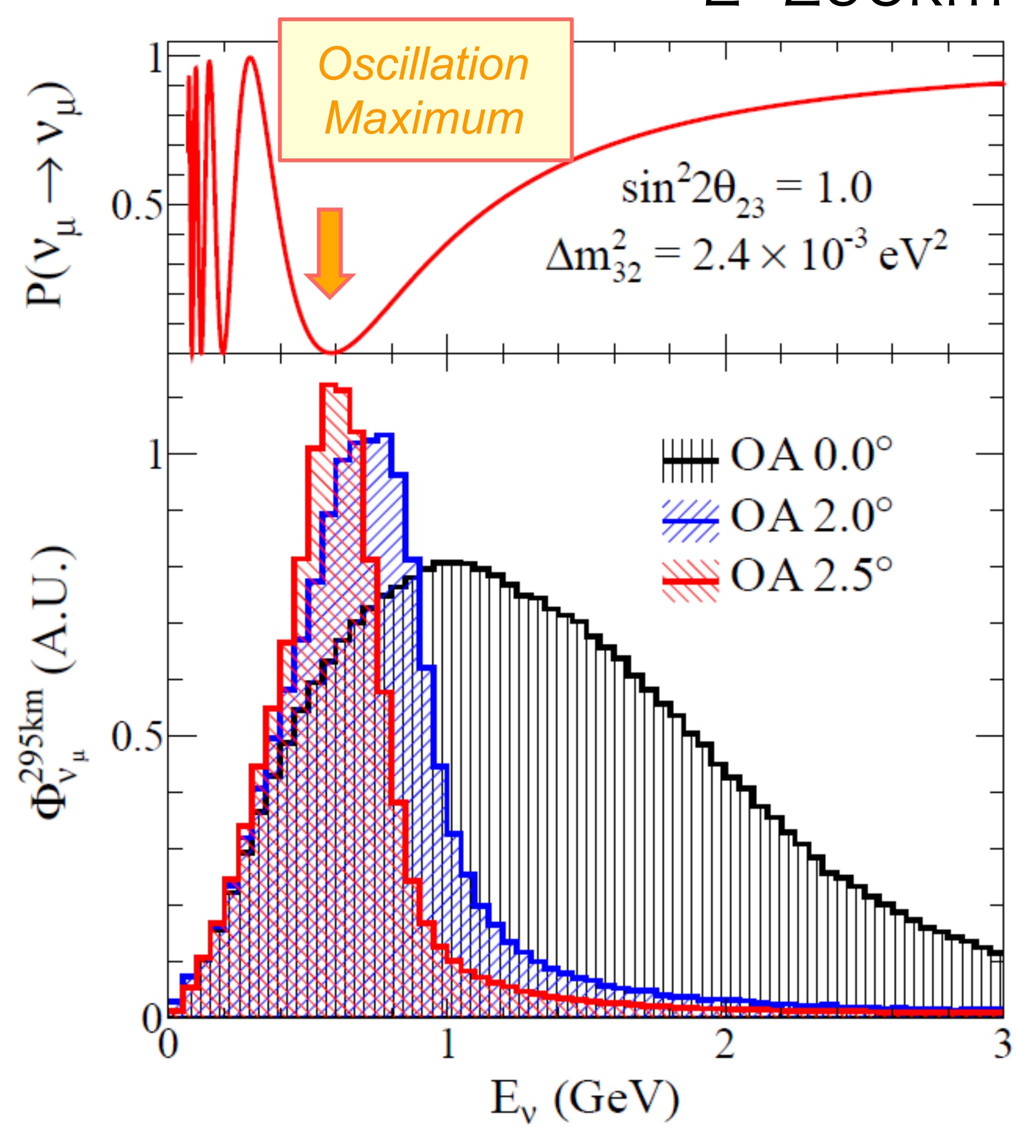
J-PARC Neutrino Beam

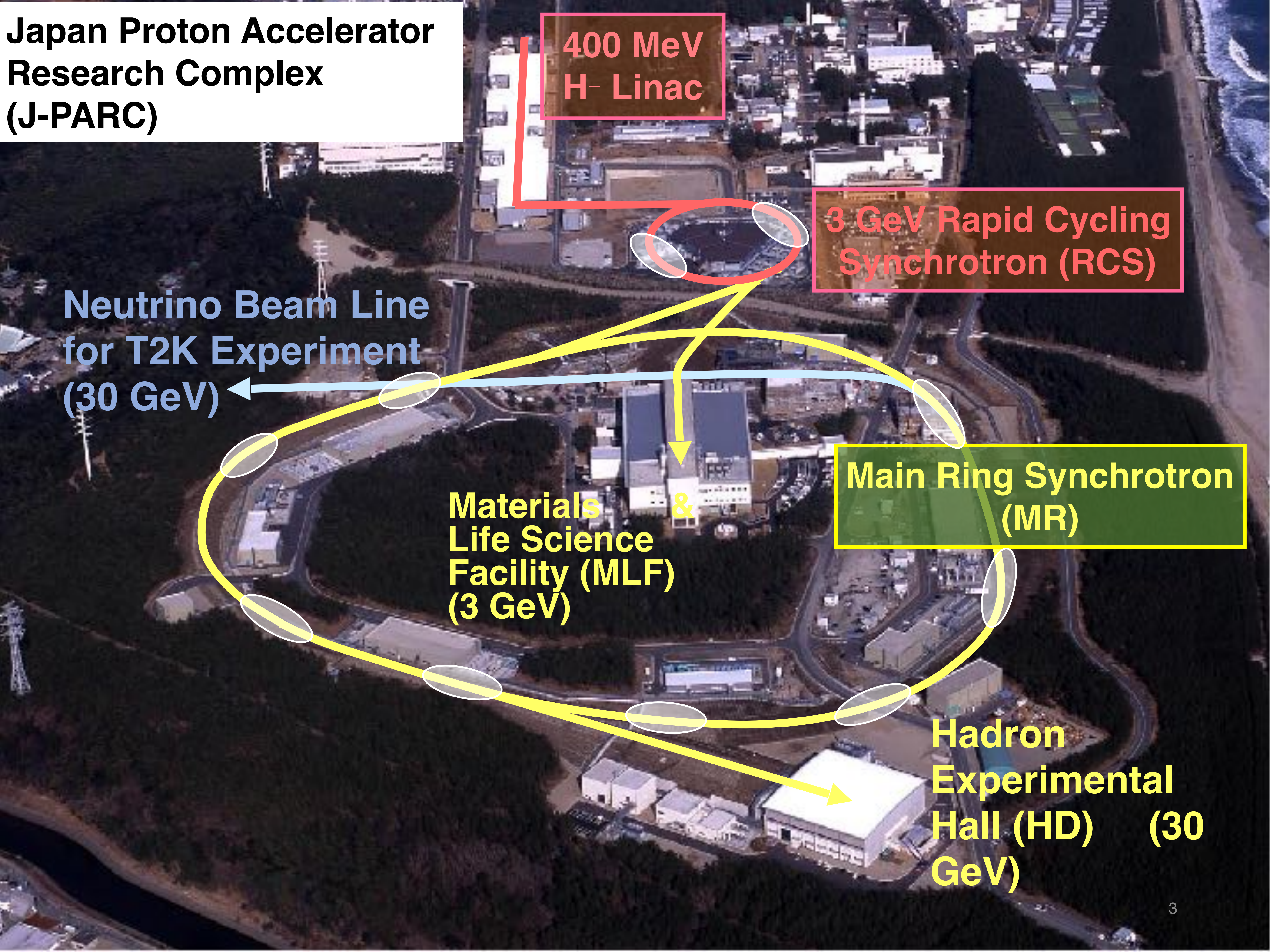
- **High intensity beam**
  - 750 kW proton beam (design: 30 GeV, 3.3x10[14] ppp, 2.1 s cycle)
- **Off-axis neutrino beam (2~2.5°)**
  - Narrow band beam ~ 0.6 GeV
    - Suppress high E background
  - 99% pure ν_μ beam (1% ν_e contamination)





L=295km

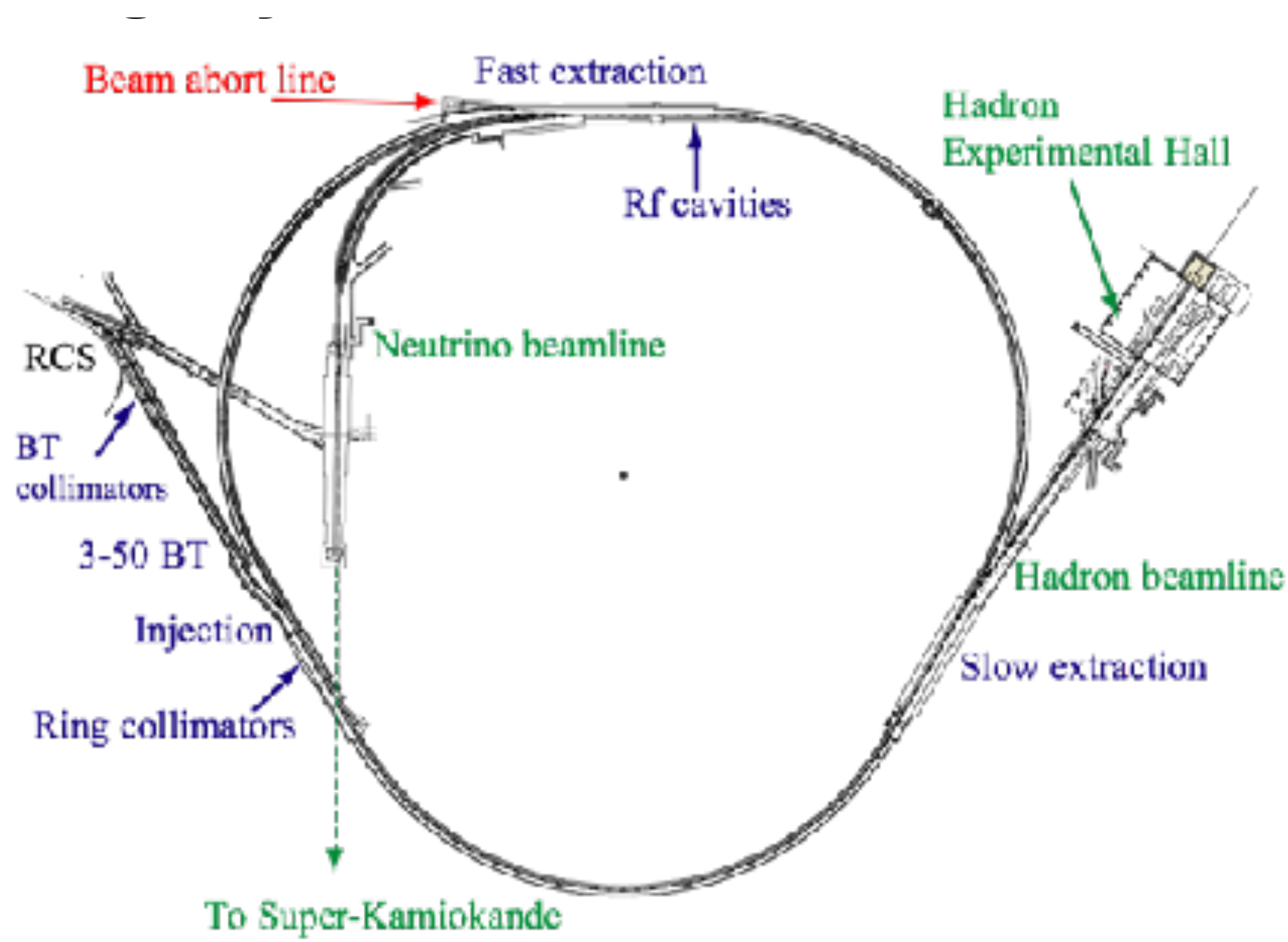



Japan Proton Accelerator Research Complex (J-PARC)
400 MeV H⁻ Linac
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino Beam Line for T2K Experiment (30 GeV)
Main Ring Synchrotron (MR)
Materials & Life Science Facility (MLF) (3 GeV)
Hadron Experimental Hall (HD) (30 GeV)

30GeV Main Ring Synchrotron (MR)

Main parameters

Circumference	1567.5 m
Injection energy	3 GeV
Extraction energy	30 GeV
Super-periodicity	3
harmonic	9
Number of bunches	8
Rf frequency	1.67 - 1.72 MHz
Transition γ	j 31.7 (typical)
Physical Aperture	
3-50 BT Collimator	54-65 π.mm.mrad
3-50 BT physical ap.	> 120 π.mm.mrad
Ring Collimator	54-70 π.mm.mrad
Ring physical ap.	> 81 π.mm.mrad

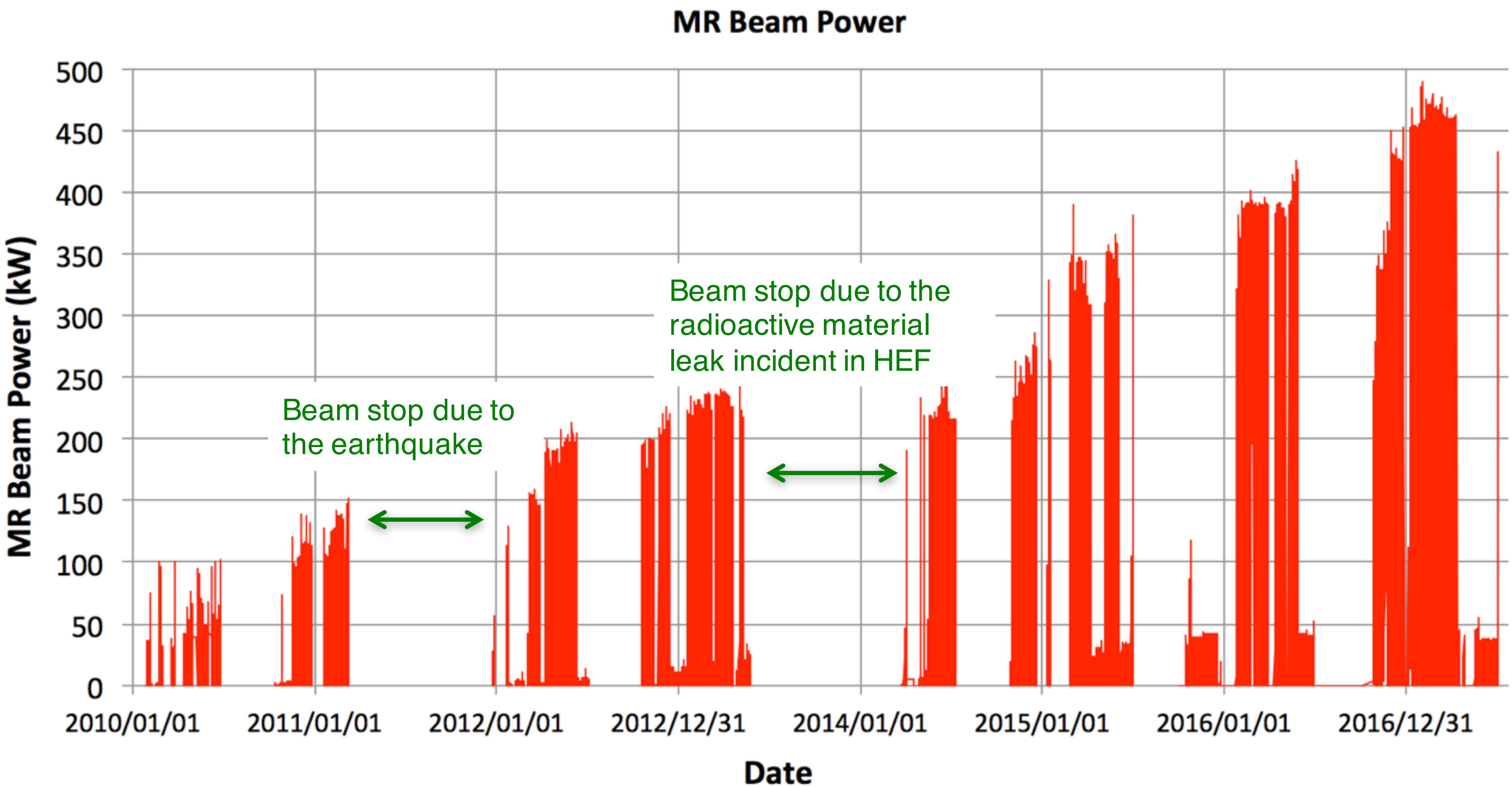


Three dispersion free straight sections of 116-m long:
- Injection and collimator systems
- Slow extraction （SX）

  to Hadron experimental Hall
- RF cavities and Fast extraction(FX) (beam is extracted inside/outside of the ring)
  outside: Beam abort line
  inside: Neutrino beamline (intense ν beam is send to SK)

Operation History

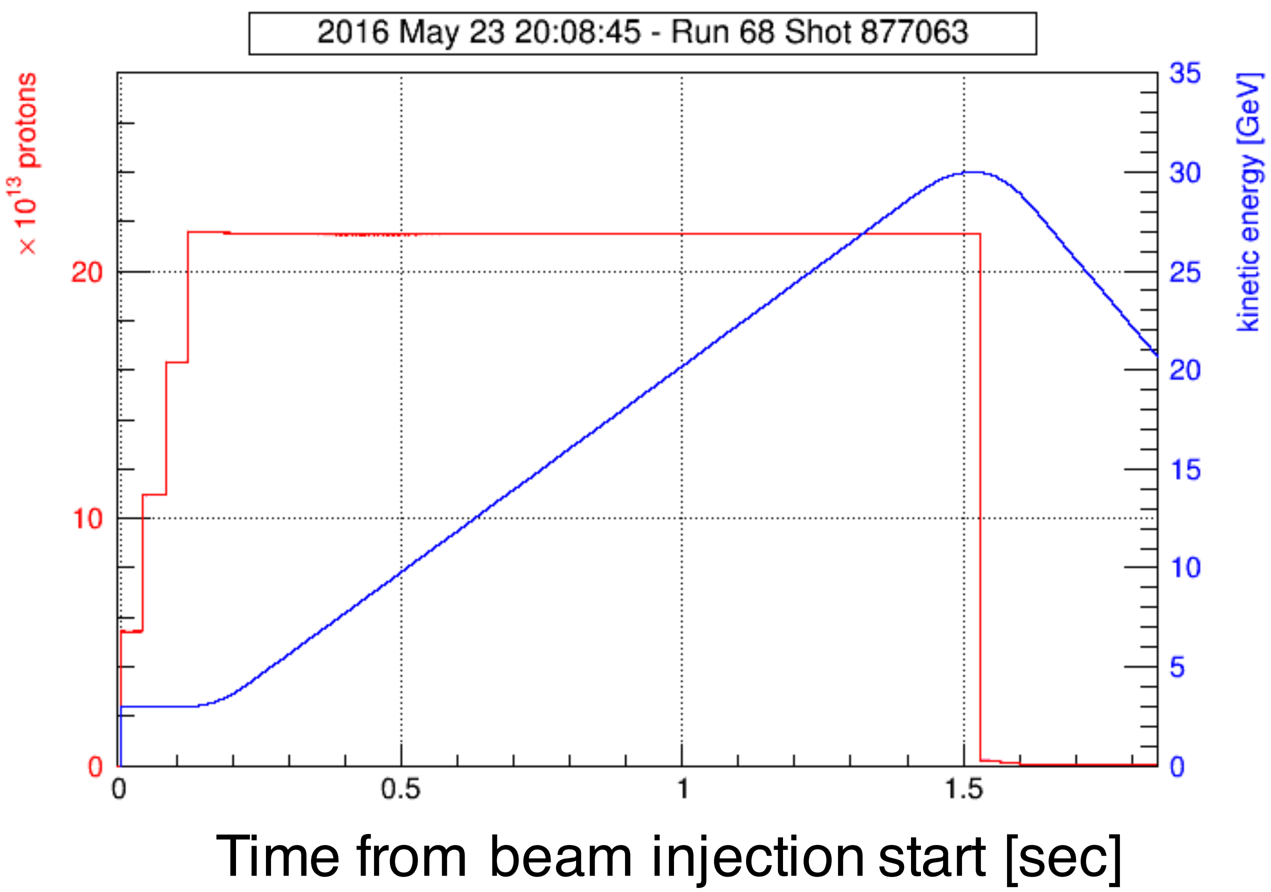
Courtesy of T. Koseki

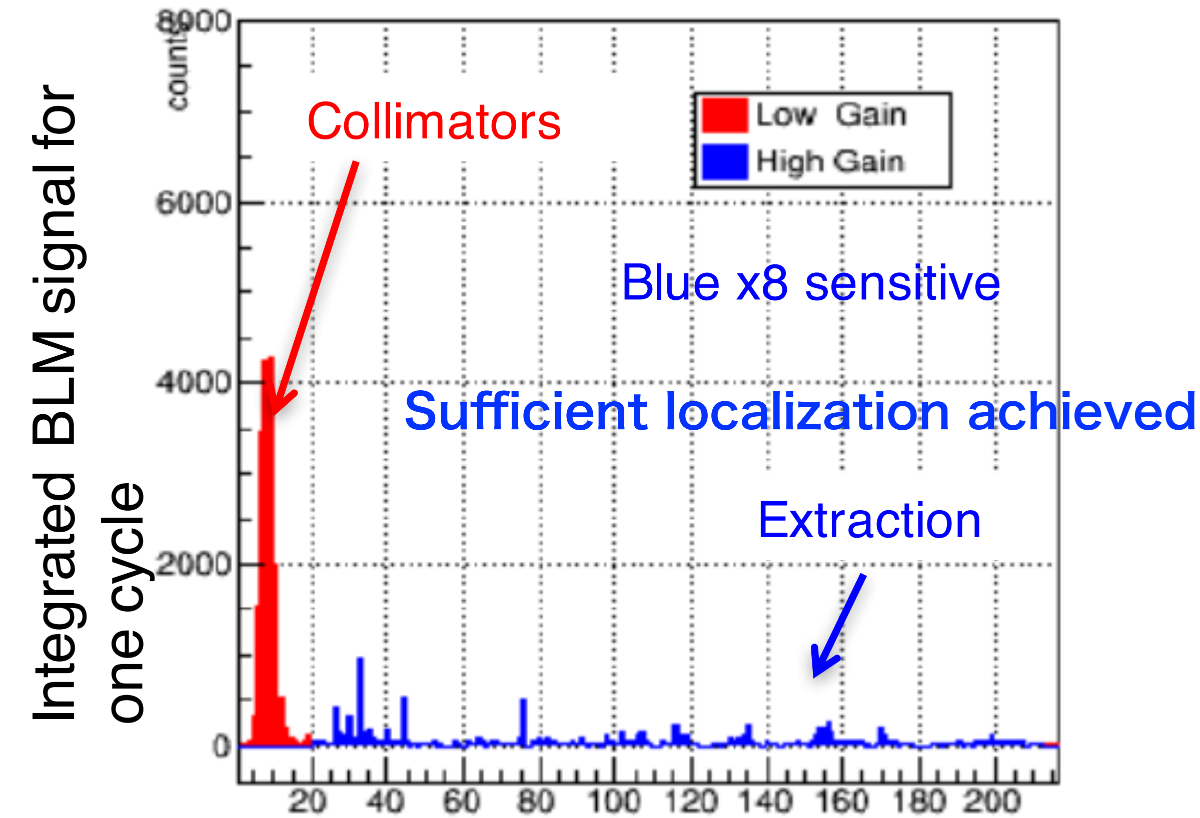


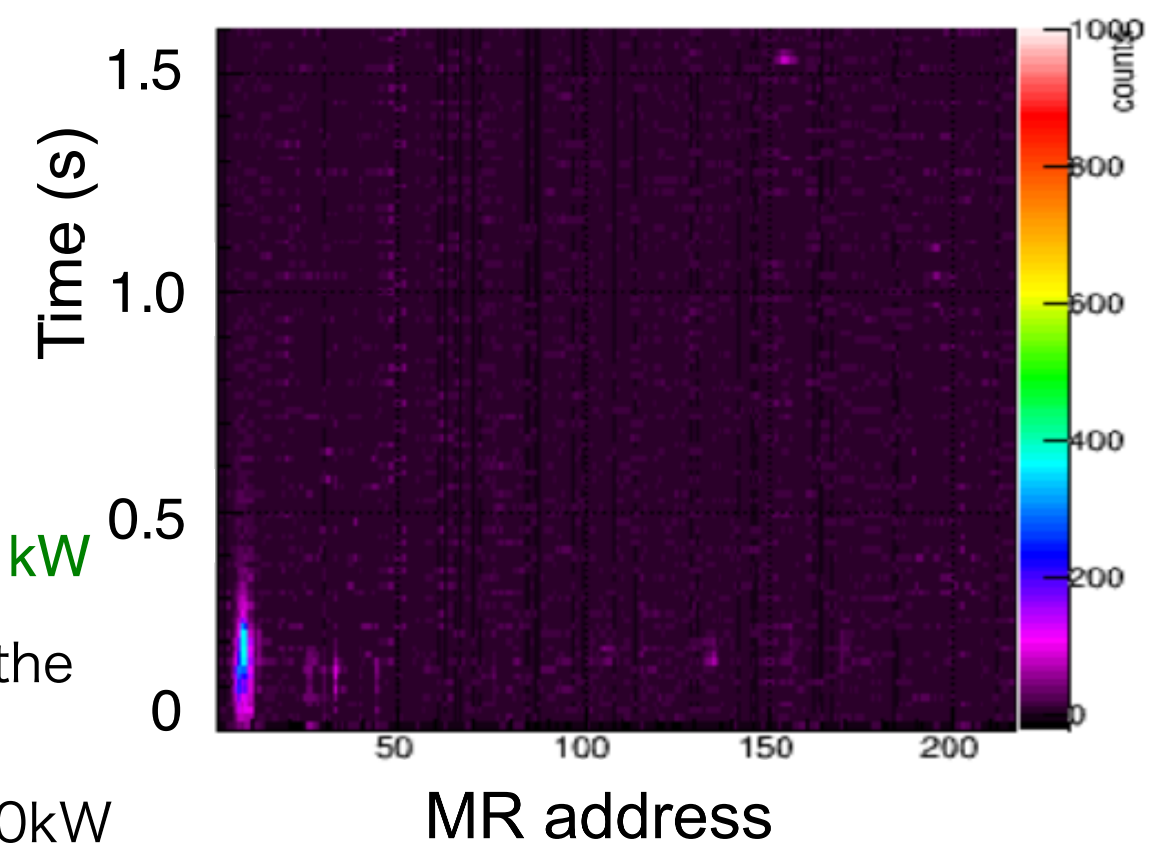
Achieved beam power:
Fast extraction ~ 470 kW (2.4 x10^{14} ppp) for users, 516 kW for demonstration.
Slow extraction ~ 44 kW (5.1 x10^{13} ppp) for users , 50 kW for demonstration.

470kW User Operation

Courtesy of T. Koseki







Power : 473 kW @ 2.48 sec
2.44e14 ppp
3.05e13 ppb

Loss at MR ~ 800 W < MR collimator limit of 2 kW .
Loss at 3-50BT <100 W < 3-50BT collimator limit of 2 kW

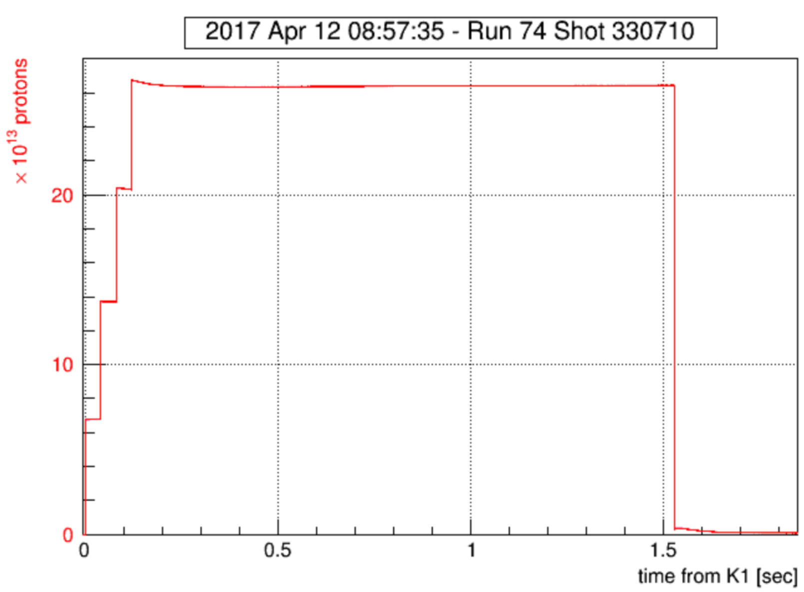
- **RF anode power supply tripped** several times by the current limit. **It limited the beam power**.
- **Longitudinal instability happened** frequently > 480kW

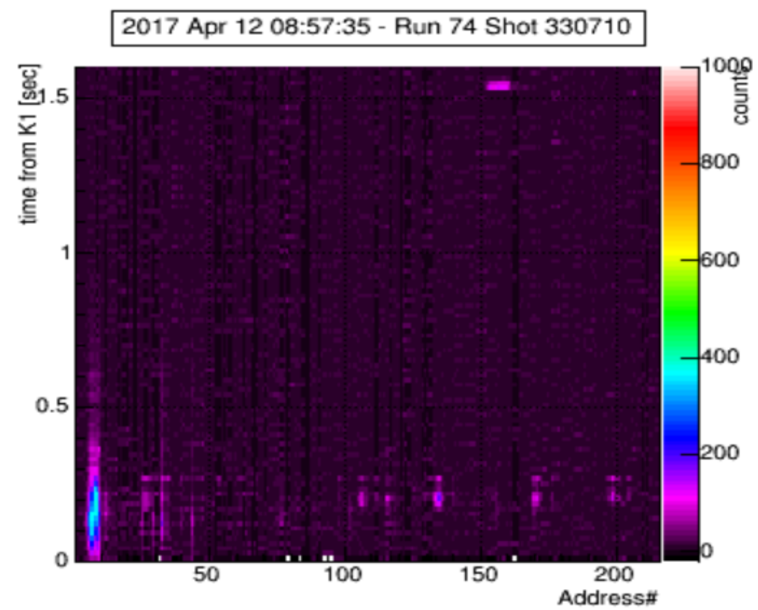
510kW Trial

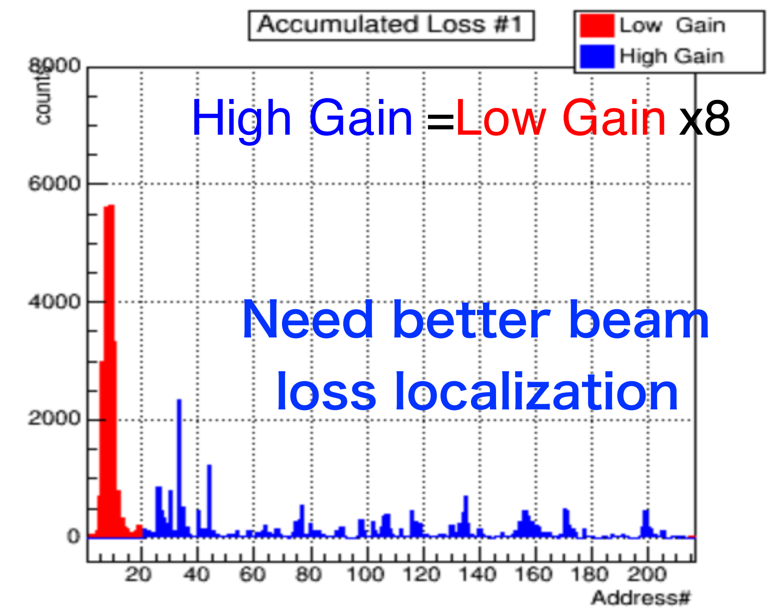
Courtesy of T. Koseki

- at the new betatron tune (21.35, 21.45) -

High power trial (2^{nd} rf voltage was adopted)







Extracted beam : 2.64 e14 ppp

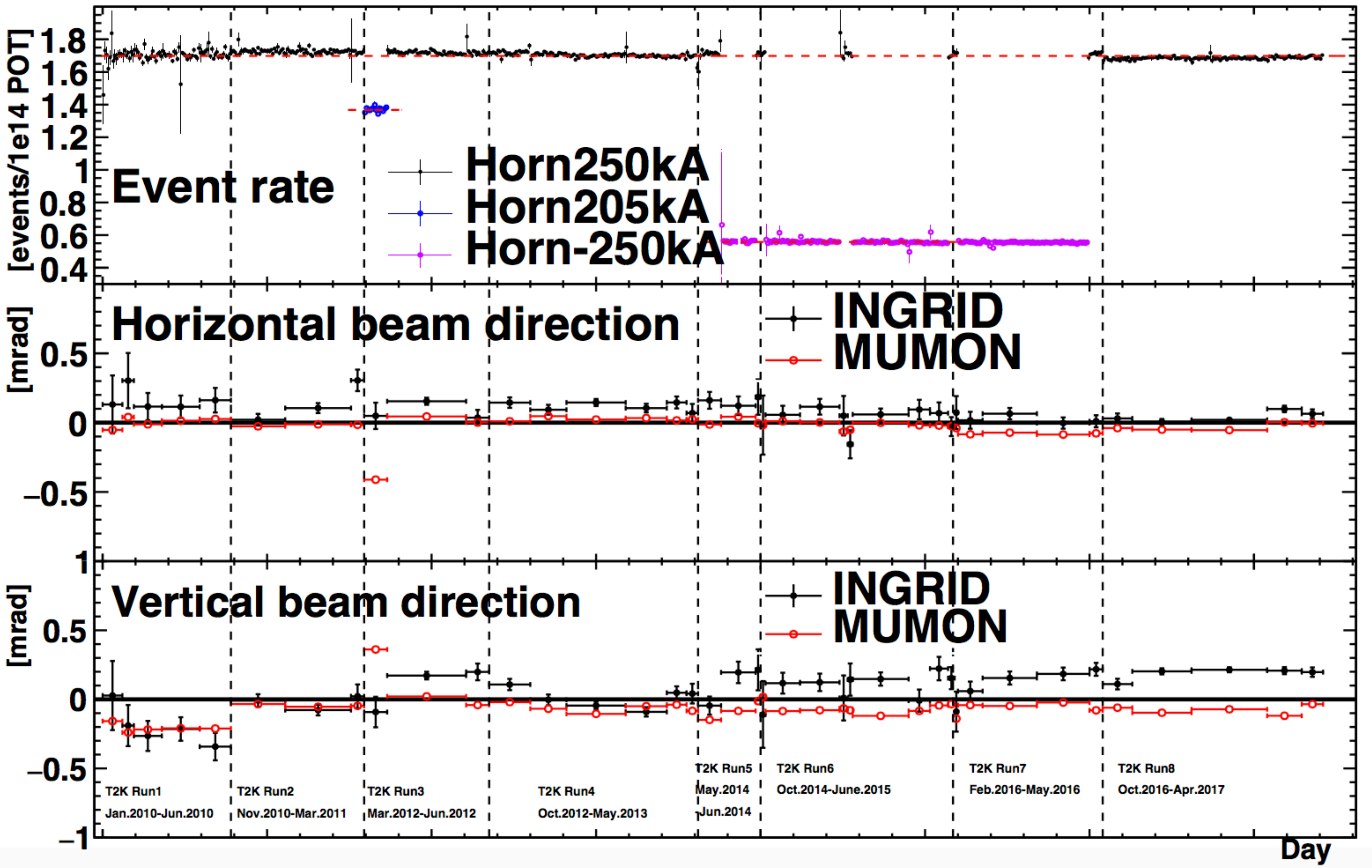
Total beam loss ~ 1.7 kW

	Number of ppp	Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2.64e14	8	2.48	511	1.7	measurement
2	2.64e14	8	1.28	991	3.3	estimation

The MR has capability to achieve >1MW with the high repetition rate operation.

Neutrino Beam Stability

Courtesy of T2K Collaboration



- Event rate was very stable within 1%
- Beam direction was also stable within 1 mrad.

KEK Project Implementation Plan (KEK-PIP)

- Prioritization of projects which require new funding requests
- External review (May 22,23, 2016)
  - Recommendations
  - https://www.kek.jp/ja/About/OrganizationOverview/Assessment/Roadmap/KEK-PIP_Evaluation.pdf
- KEK-PIP taking into account the recommendations
  - https://www.kek.jp/ja/About/OrganizationOverview/Assessment/Roadmap/KEK-PIP.pdf

Project to be prioritized:
- COMET II
- J-PARC upgrade for Hyper Kamiokande
- Hadron Hall Extension
- H-line and g-2/EDM
- LHC and ATLAS
- Super Computer
- RNB

Separate prioritization
- Light Source

Upgrade of J-PARC for Hyper-K/T2K-II is highest priority

MR Upgrade Plan

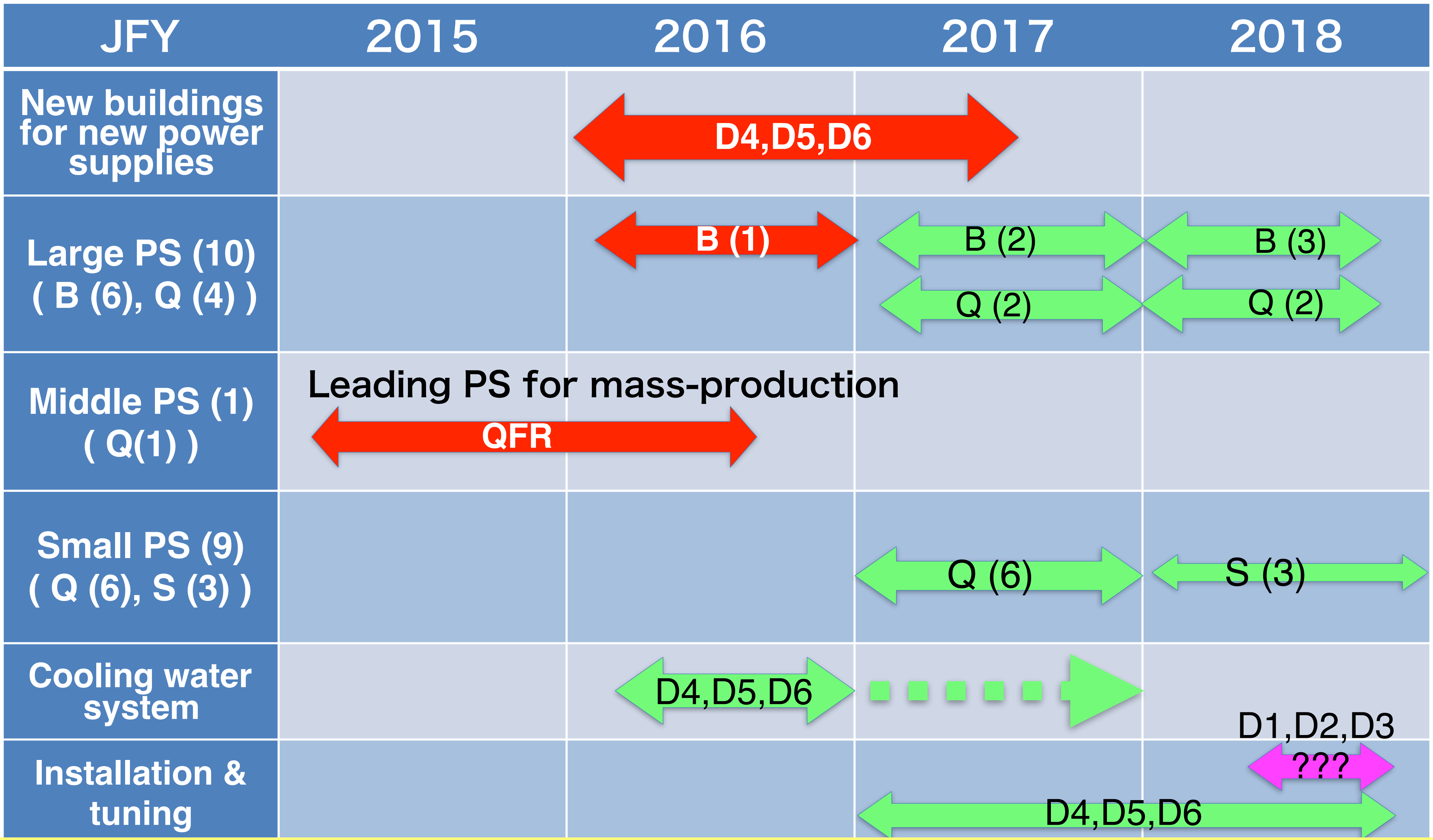
Courtesy of T. Koseki

Revised in Jan. 2017

JFY	2015	2016	2017	2018	2019	2020	2021	2022
		New buildings			Long shutdown			
FX power [kW]	390	470	480-500	> 500	700	800	900	1060
SX power [kW]	42	42	50	50-60	60-80	80	80-100	100
Cycle time of main magnet PS New magnet PS	2.48 s		Mass production installation/test	2.48 s	1.3 s	1.3 s	1.3 s	1.3 s
High gradient rf system 2^{nd} harmonic rf system	Installation		Manufacture, installation/test					
Ring collimators	Add.coll imators (2 kW)				Add.colli. (3.5kW)		Upgrade for 1.3MW	
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields						Local shields		
Ti ducts and SX devices with Ti chamber			ESS					

MR PS Upgrade

Original Plan of the PS development

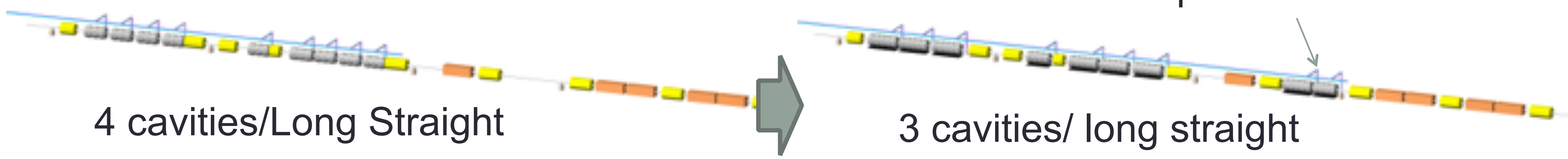


The KEK budget of JFY2017 is too low to produce 4 large power supplies. (However we want to make two PSs at least if it is possible.) —> It is hard to complete the mass-production of the magnet until JFY2018. So we are discussing the postponement of the schedule for a year.

PAC July/27/2016

J-PARC

MR: RF voltage upgrade



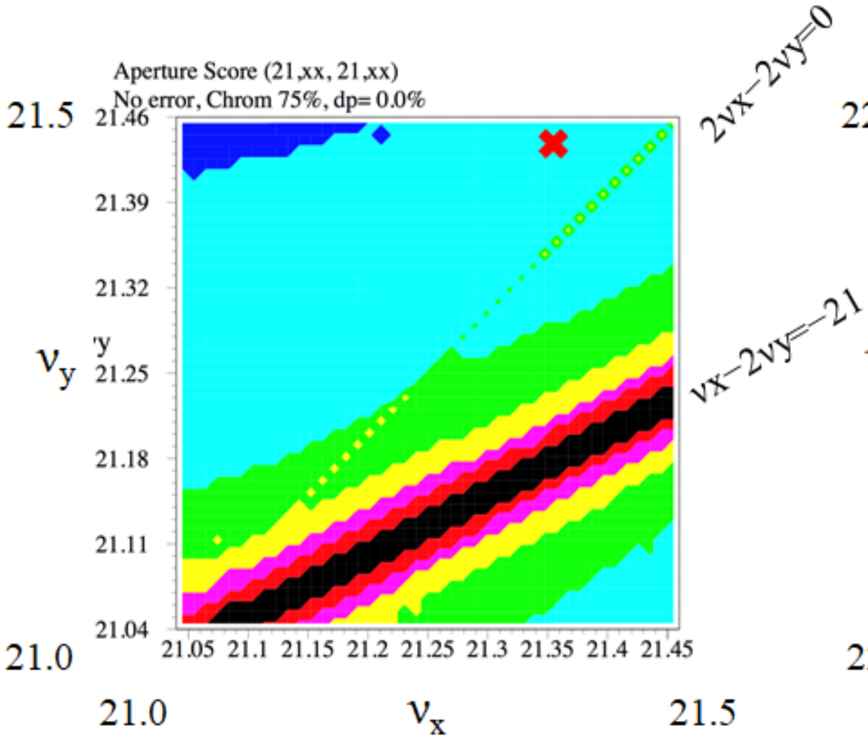
	2013	2014	2015	2016	2017	2018
Events	*Li 400 MeV*	*Li 50mA*				*MR 1.3-sec operation*
Present FT3M cavities	*9*	*8*	*4*	*0*	*0*	*0*
New FT3L Cavities	*0*	*1*	*5*	*9*	*9*	*9*
2nd harmonic cavity	*0*	*0*	*0*	*0*	*2*	*2*
Available voltage	*315 kV*	*355 kV*	*485 kV*	*602 kV*	*602 kV*	*602 kV*
(2nd Harmonic)	*(35 kV)*	*(70 kV)*	*(70 kV)*	*(70 kV)*	*(70 kV)*	*80 kV*
Number of cavity cells	*27*	*29*	*36*	*43*	*43*	*43+8(2nd)*

Power modules are also added to the anode power supply of the RF cavity in this summer for the beam power increment.

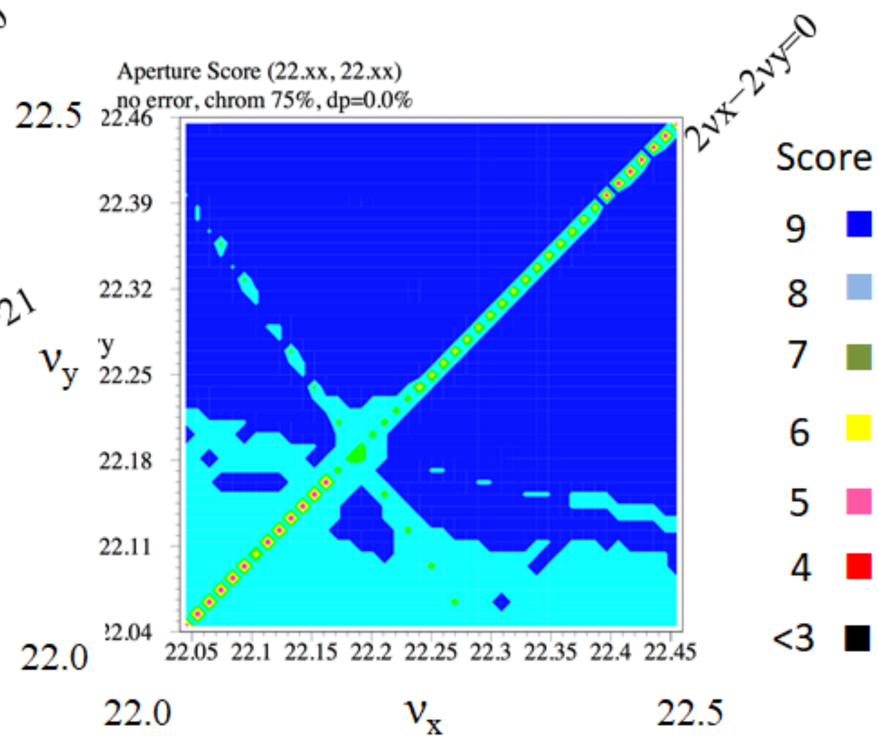
Simulation Studies on Dynamic Aperture at (21.x, 21.x) and (22.x, 22.x)

Courtesy of T. Koseki

Dynamic aperture survey
(No magnetic error/no space charge)

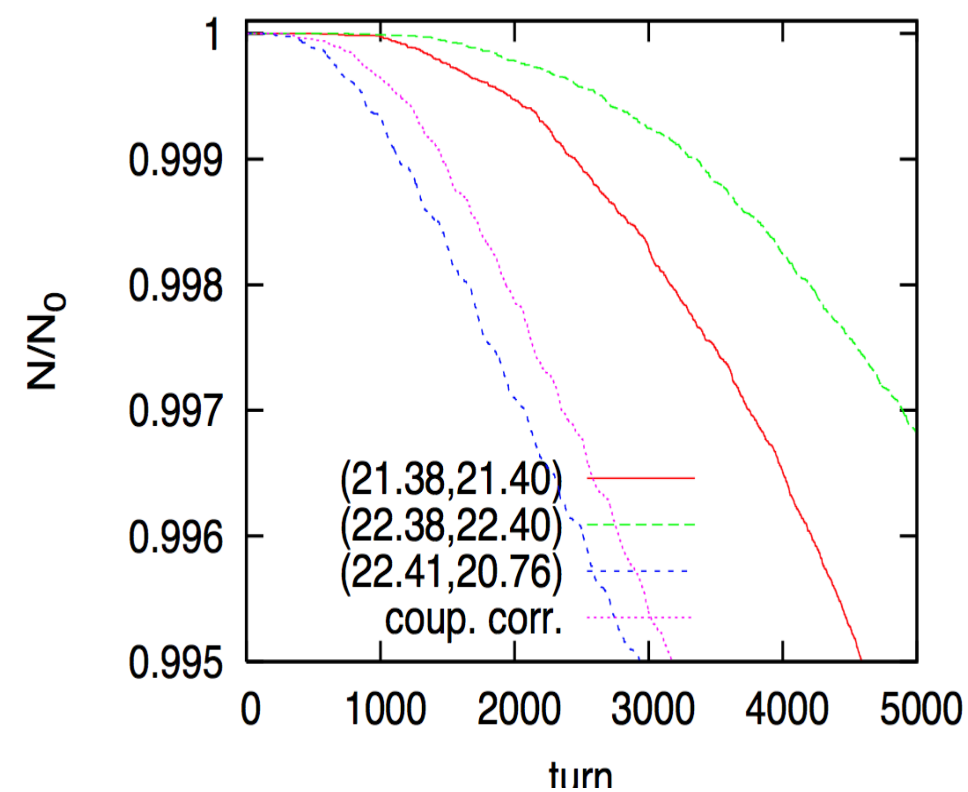


(21.*, 21.*)



(22.*, 22.*)

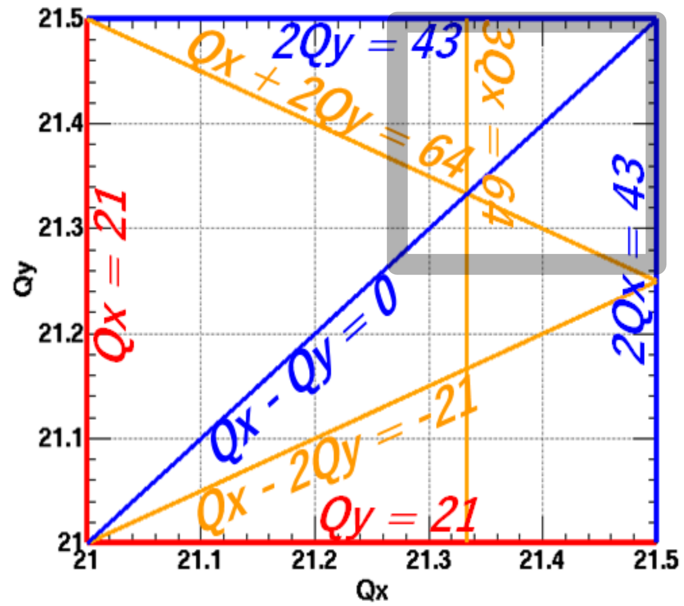
Survival ratio by space charge PIC simulation



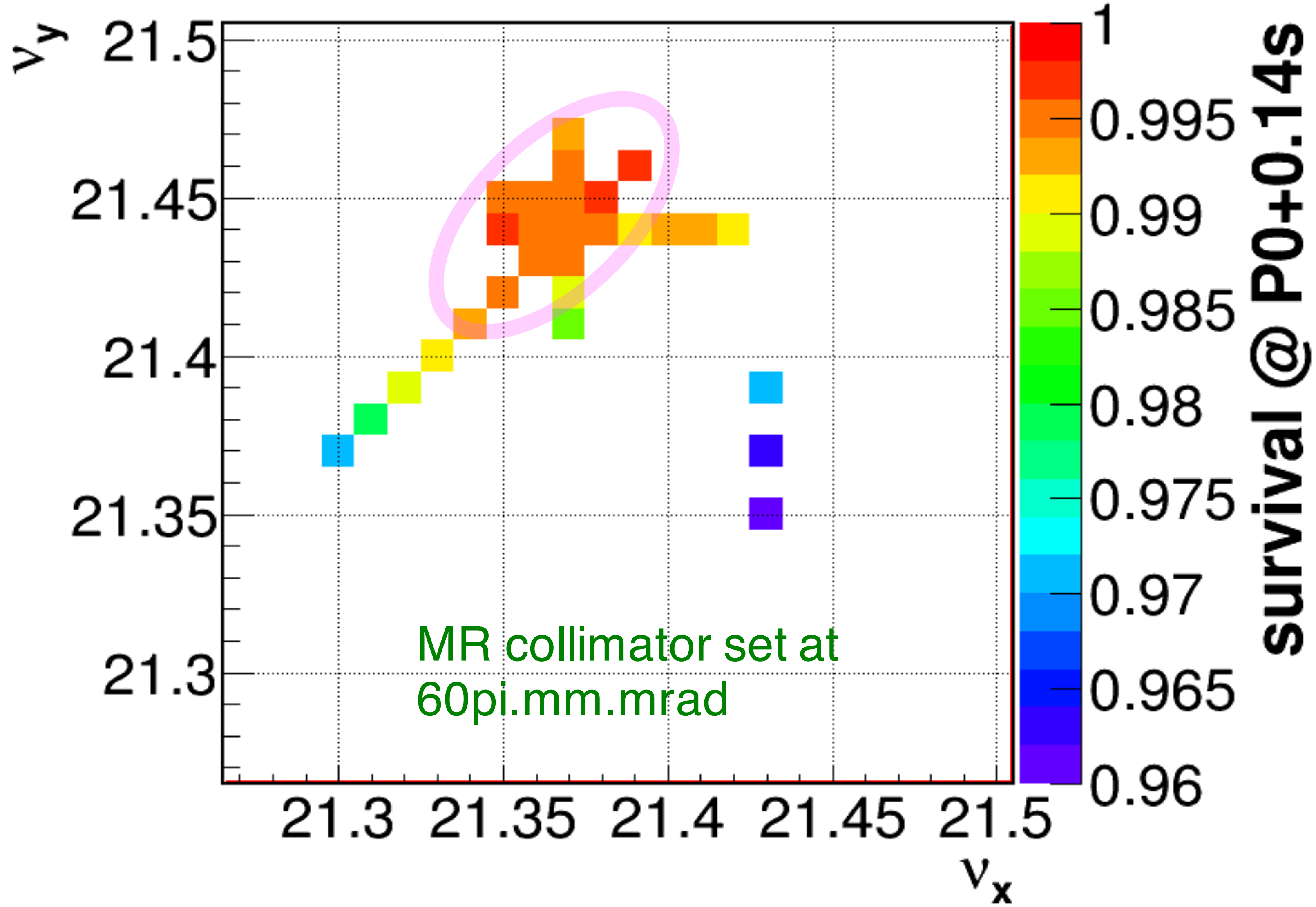
Dynamic aperture at the current operation tune of (21.35, 21.45) is affected by the structure resonance of vx–2vy = –21. Operation at the tune of (22.*, 22.*) has better beam survive ratio than (21.*, 21.*)
For the area (22.*, 22.*) , new magnet power supplies are needed in our operation.

Tune survey around the present operating point

Courtesy of T. Koseki



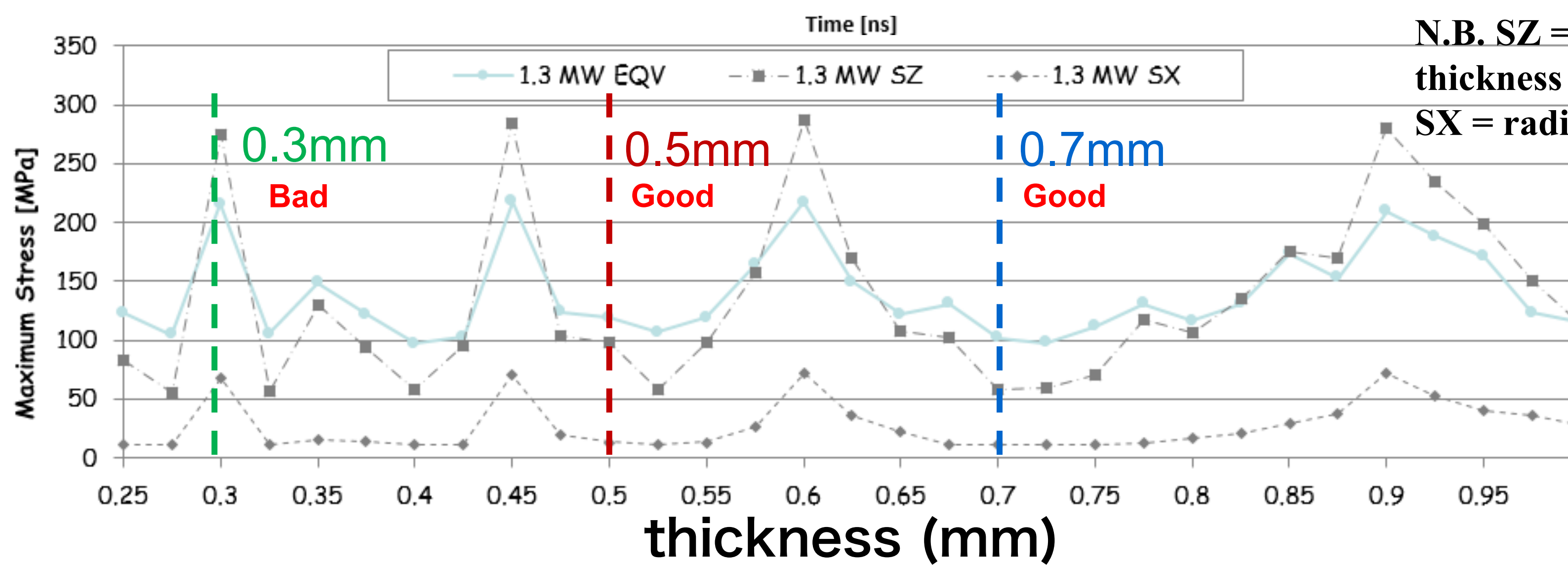
Survival ratio during beam injection for
beam intensity of 2.9e13 ppb



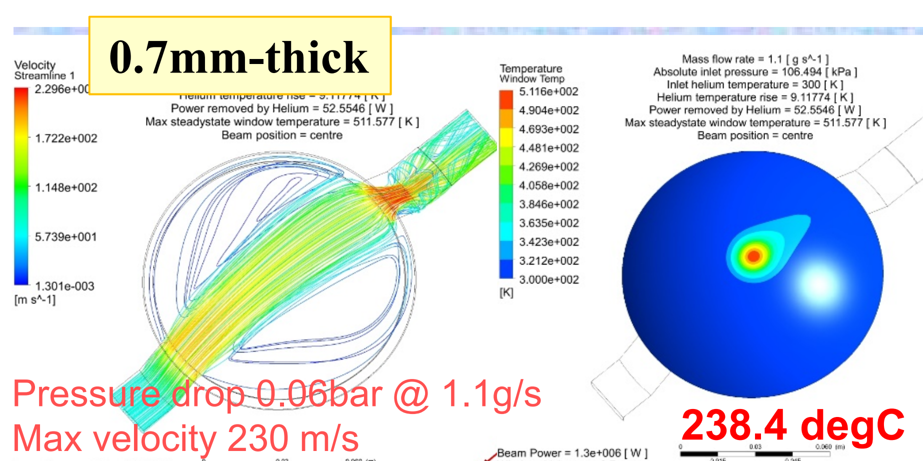
Tune scan for 2.9 e13 ppb (450 kW equivalent for 2.48 s cycle) provided reasonable beam survival between (21.35, 21.42) and (21.39, 21.46). Present 470 kW user operation is at (21.35, 21.45).

Beam Window Upgrade

- Design change considered
  - FEM simulation for 1.3 MW with expected beam parameters
  - Various thickness considered
    - Current 0.3mm is not good → 0.5mm or 0.7 mm is much better
    - Transient analyses say 0.5mm is optimum.



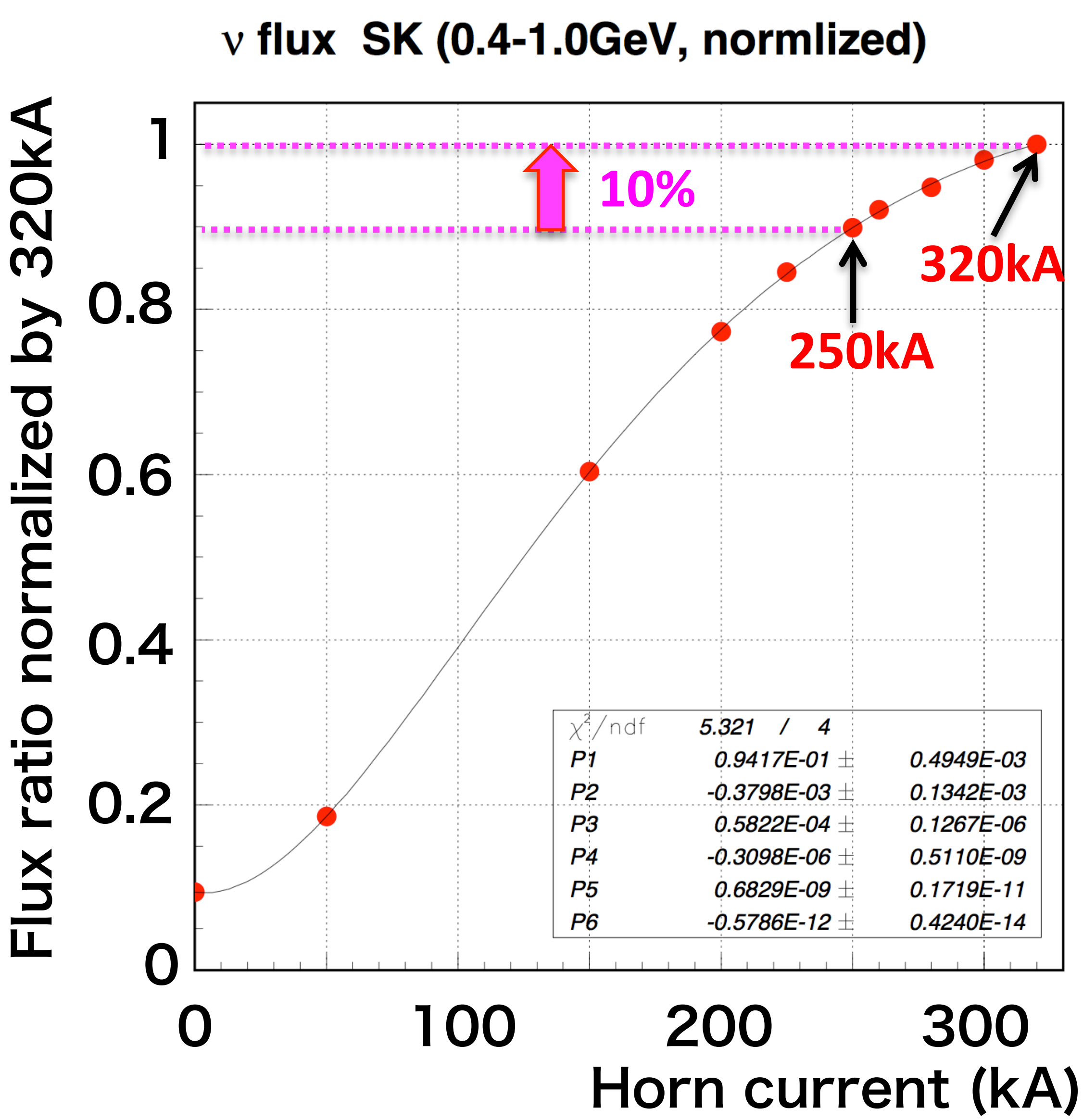
N.B. SZ = through thickness stress, SX = radial stress

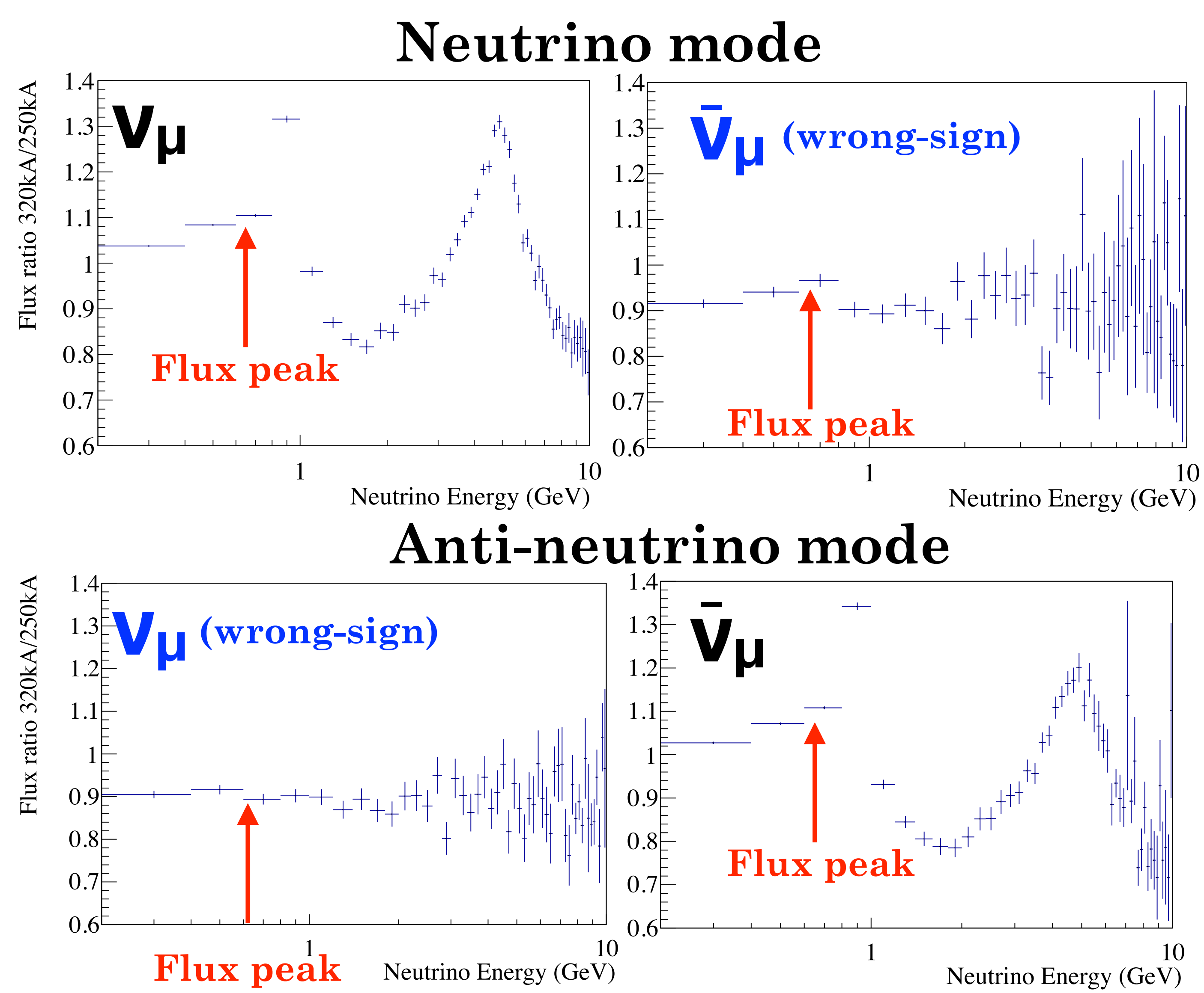


Thickness [mm]	Peak temp [K]	Maximum stress [MPa]	Maximum stress with 1 bar helium [MPa]
0.3	490.7	93.9	
0.5	529.0	132.3	126.5
0.7	565.0	164.0	

Horn Current Increase

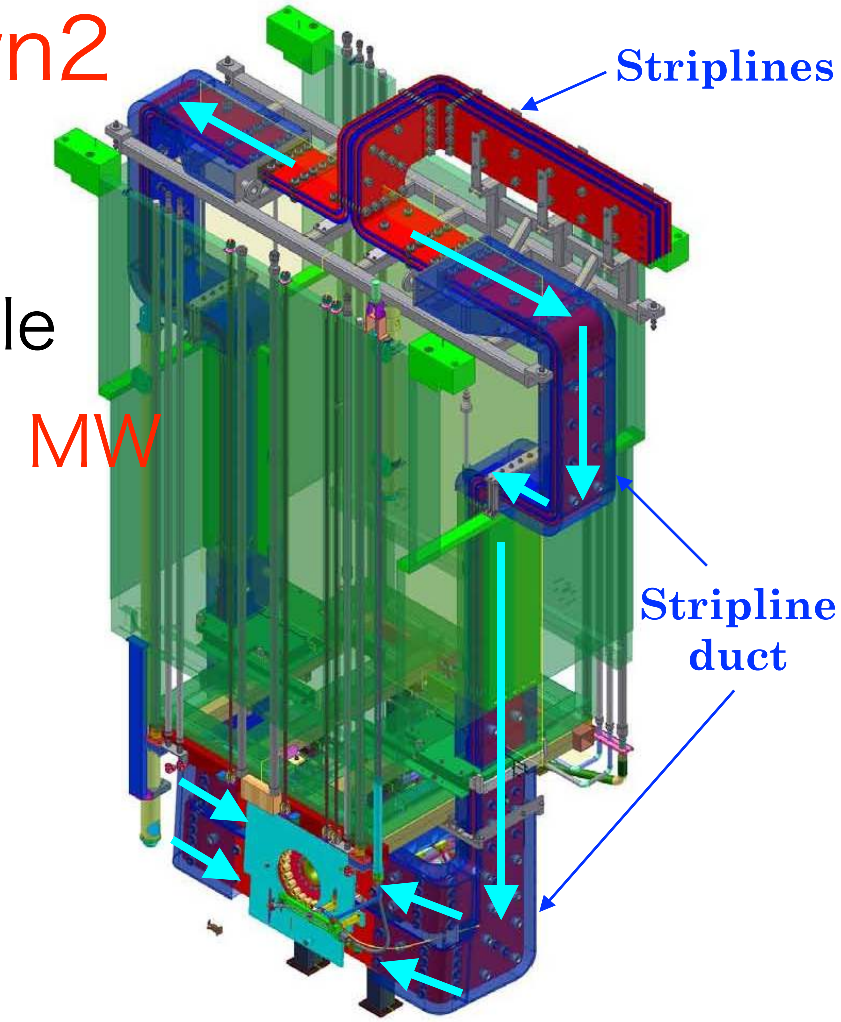
- Horn current increase: 250 kA → 320 kA (design)
  - **~10% flux improvement** for right-sign neutrinos
  - **5~10% flux reduction** for wrong-sign neutrinos



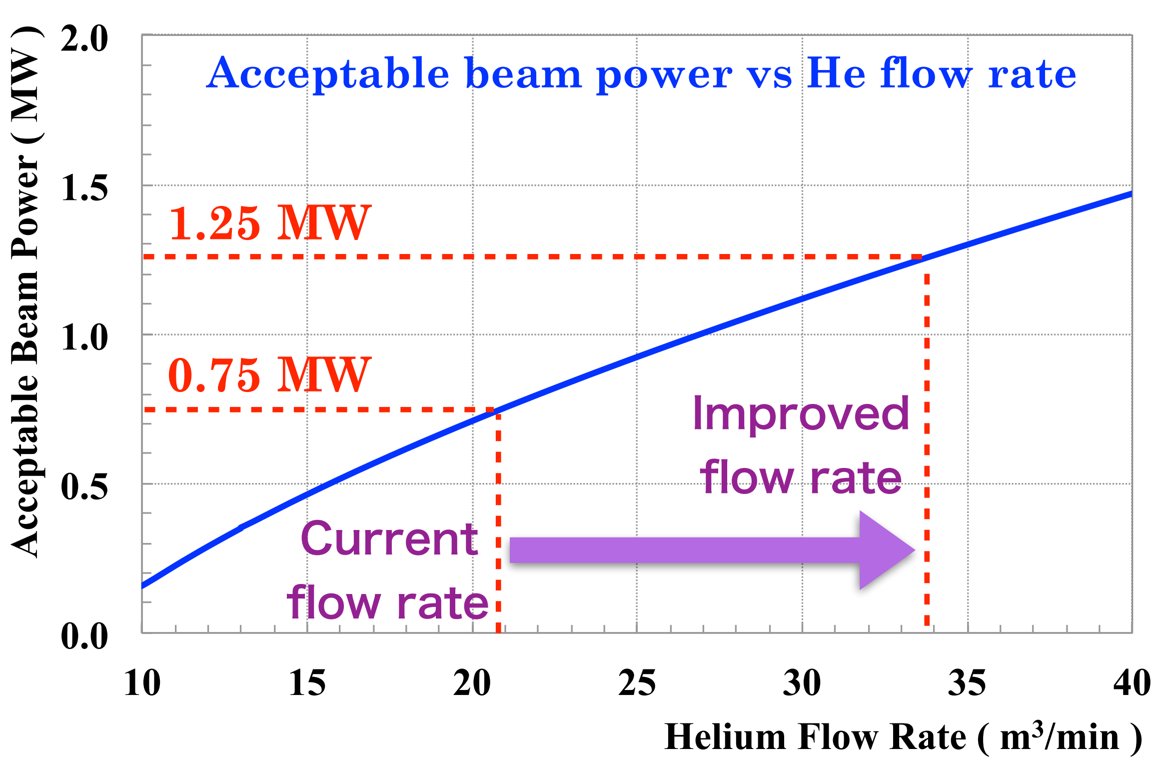


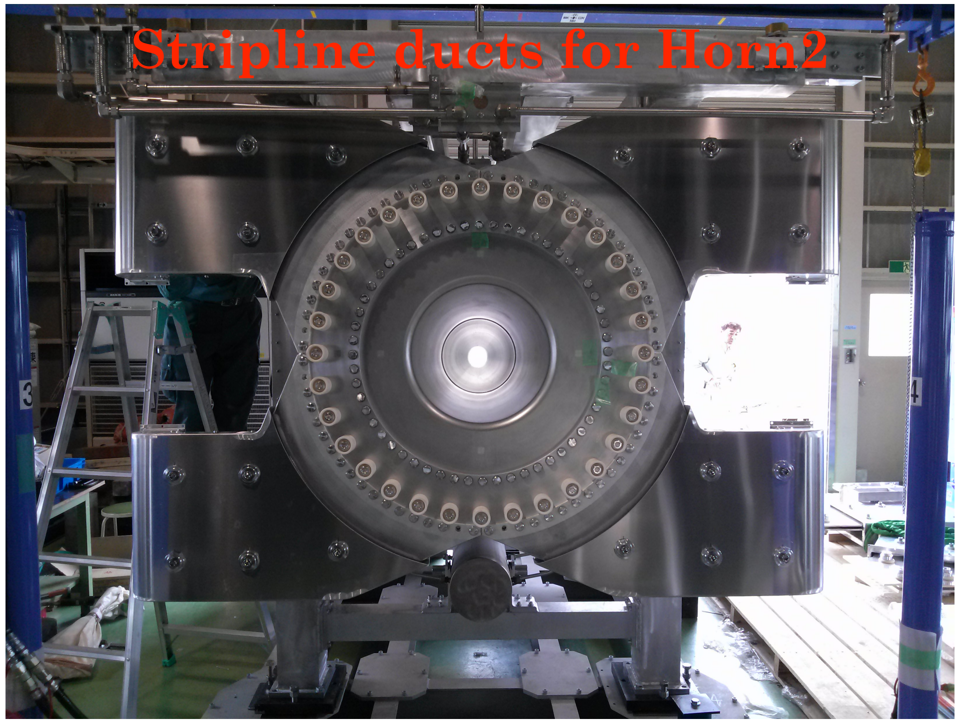
Stripline Cooling

- Heat deposit at striplines → largest at horn2
- Forced He flow inside stripline ducts
  - Current flow rate for Horn2 → 750 kW acceptable
  - Increase flow rate with dual compressors → 1.25 MW



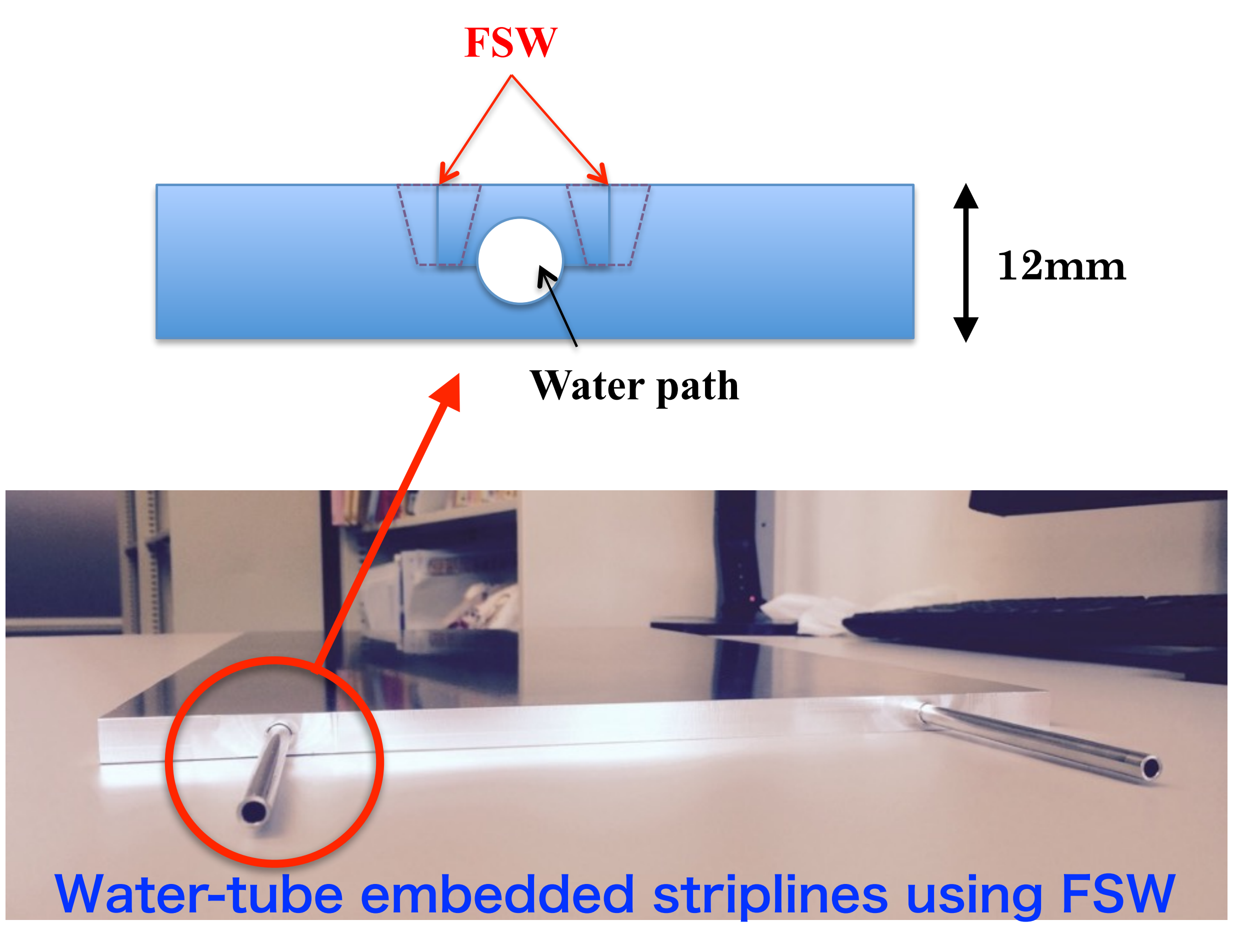
	Horn1	Horn2	Horn3
Heat flux per stripline plate (J/m²) @ 1.3 MW			
Total (Beam + Joule)	214	1066	141
Acceptable beam power (MW)			
Current flow rate	2.10	0.75	2.04
Improved flow rate	-	1.25	-

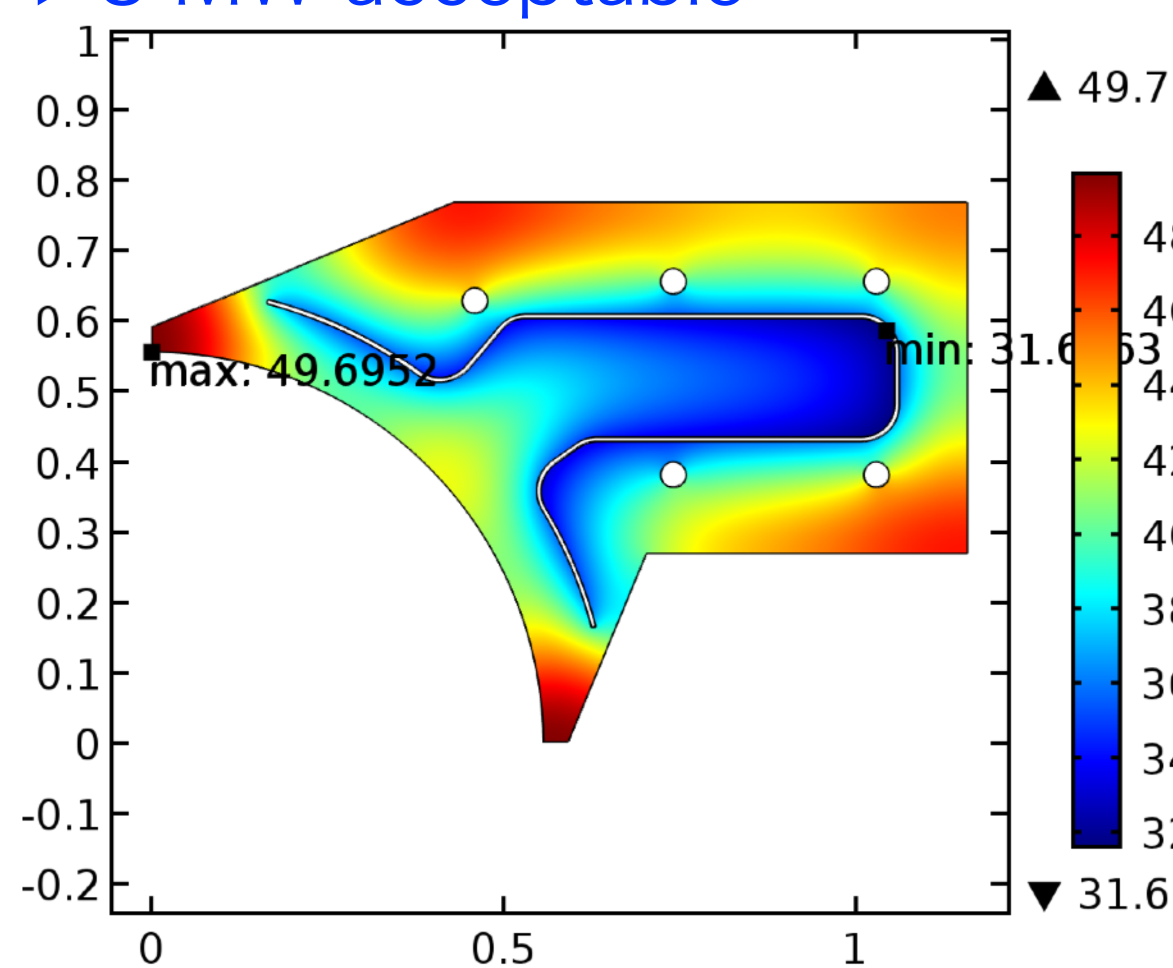




Stripline Water Cooling

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





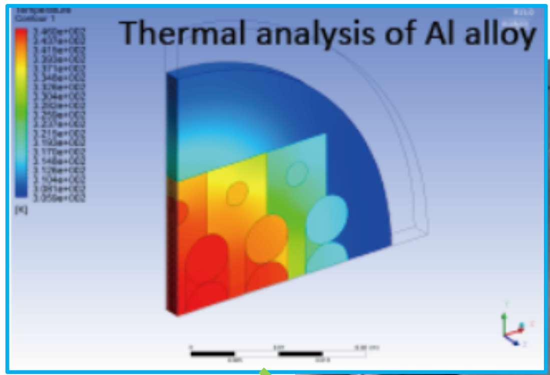
RaDIATE

Radiation Damage In Accelerator Target Environments

radiate.fnal.gov

- To solve a world's common problem to understand the effect of radiation damage on target/window materials, accelerator & fission/fussion communities' researchers & engineers work together.
- J-PARC neutrino was an active partner since 2014
- From JFY2016 J-PARC plan to join officially

Neutrino Beam Window
Ti Alloy ~1x10^{21} pot
~1 Displacement Per Atom
(Existing data up to ~0.3DPA)



Fermilab
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Science & Technology Facilities Council
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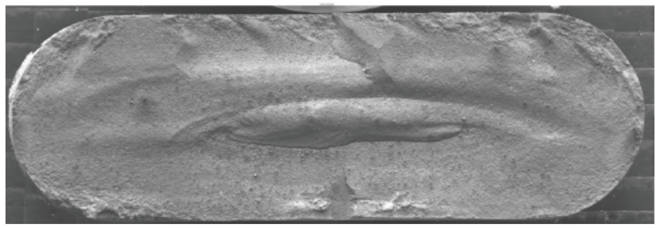

NuMI graphite broken target
Post-Irradiation Examination (PIE)
at PNNL: Swelling effect observed

New Irradiation Run at
BNL (2017 February ~)