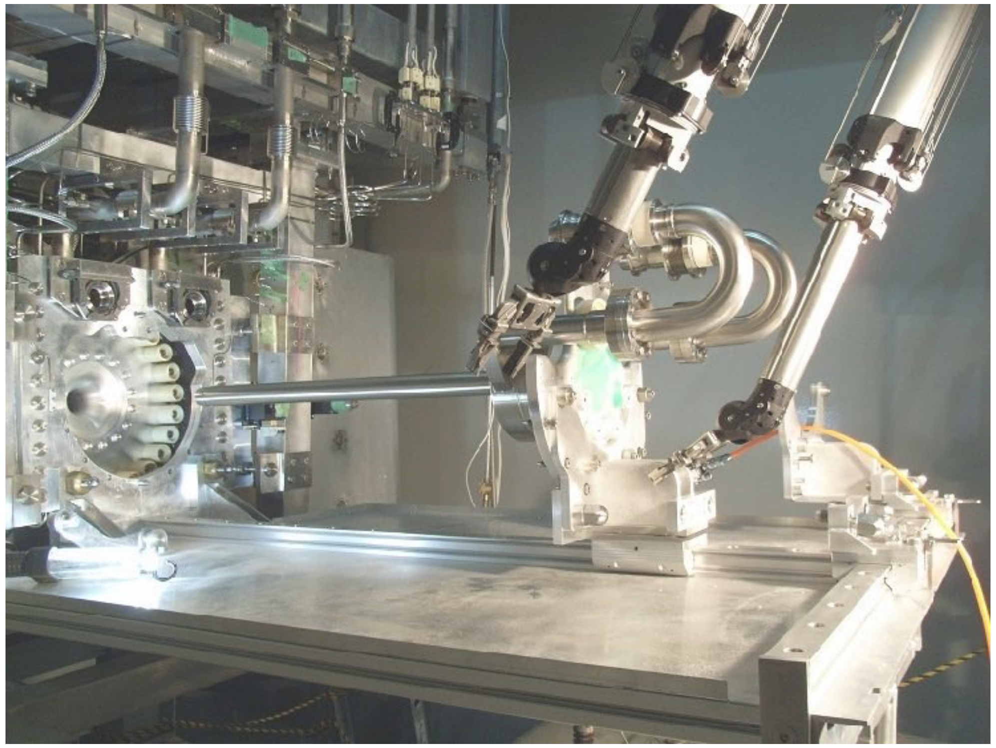
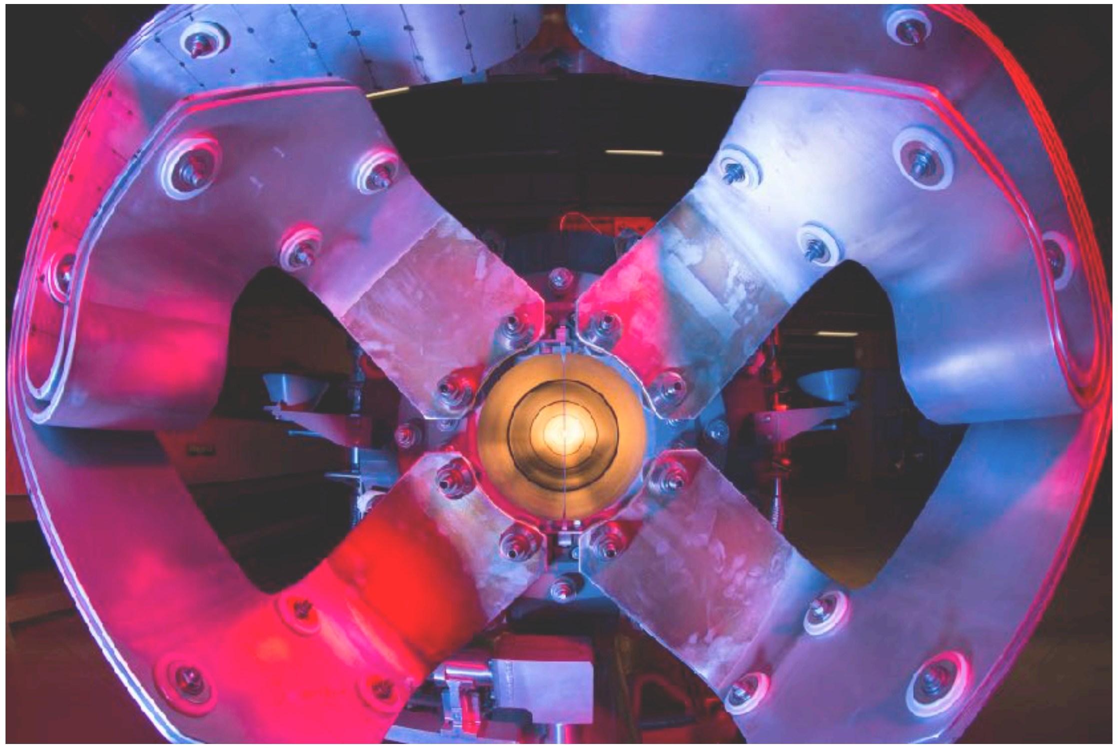
Future of Neutrino Beam Facilities

Tetsuro Sekiguchi (KEK, IPNS)

August 10, 2019





29th International Symposium on
Lepton Photon Interactions at High Energies (Lepton Photon 2019)

Westin Harbour Castle, Toronto

Outline

- Overview of neutrino beam facilities
- Planned future facilities
- International cooperation on high power neutrino beam
- Summary

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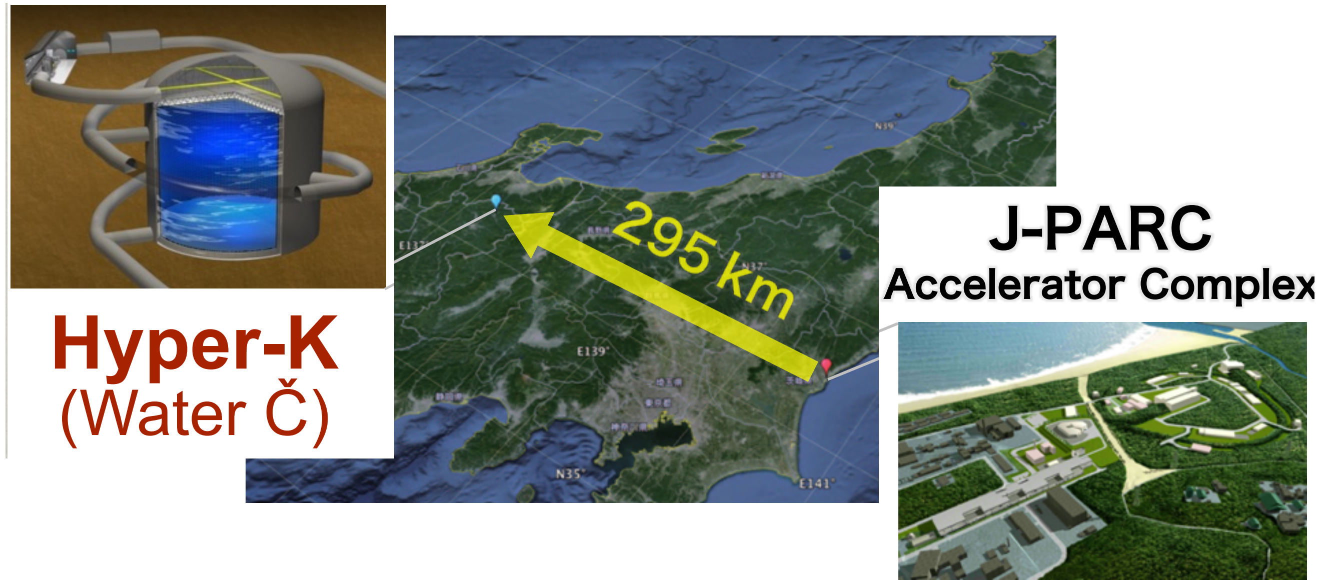
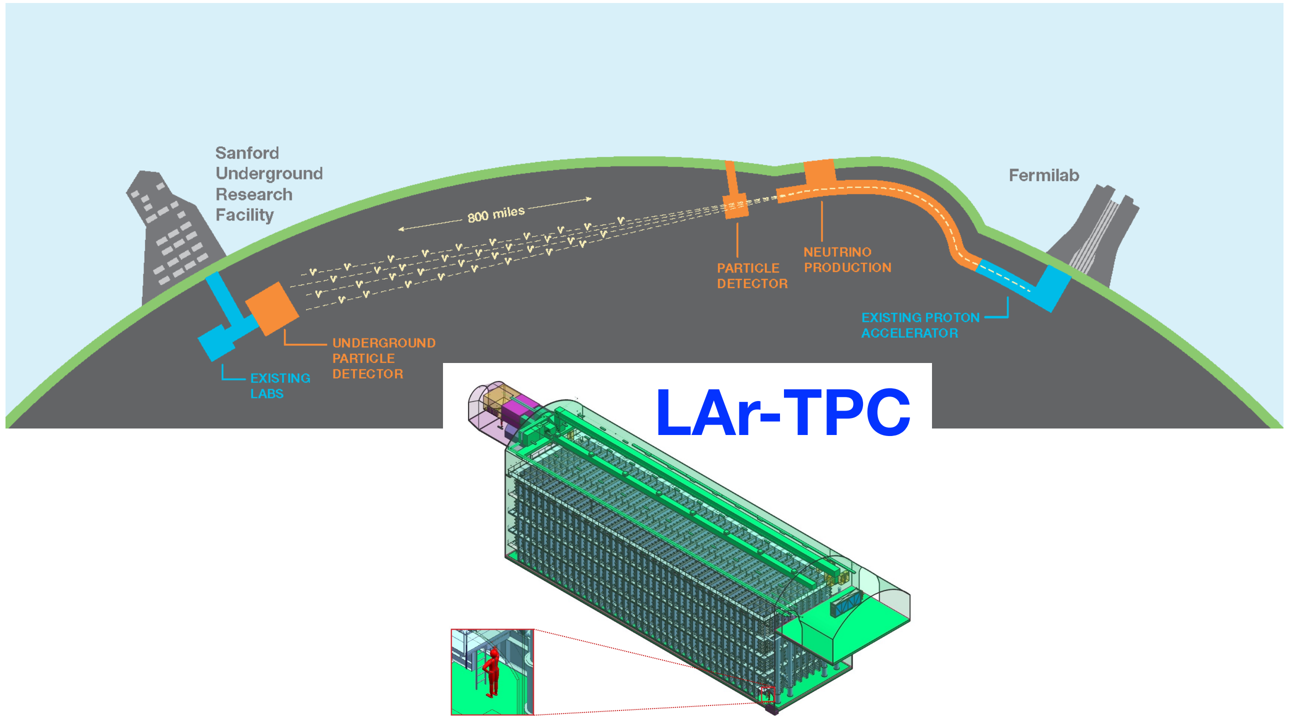
Overview

J-PARC / Hyper-Kamiokande



LBNF / DUNE

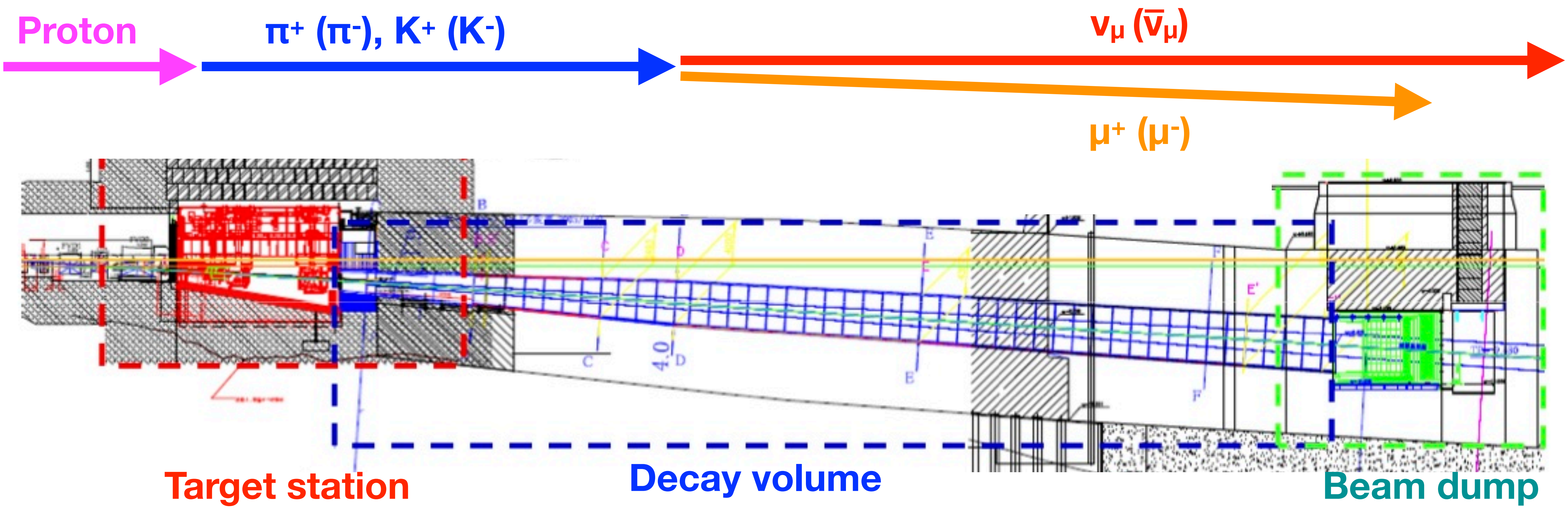


- **Next generation experiments are aiming to reveal full picture of neutrino oscillation with precise measurements of CP and mixing parameters**
  - Sensitivity for CP violation ~2σ (current) → **>5σ** (future)
  - > 10 times statistics needed
- To achieve it,
  - **~10 x larger new detectors**
  - **>1MW-class beam power needed**

$$N_\nu \propto \underset{\substack{\Downarrow \\ \text{Beam power}}}{\boxed{\Phi_\nu(E)}}\ \mathrm{x}\ \sigma_\nu(E)\ \mathrm{x}\ \underset{\substack{\Downarrow \\ \text{Detector volume}}}{\boxed{\text{target}}}$$

How To Produce Neutrino Beam?

Conventional neutrino beam from pion decay (since 1960's)



- High intensity proton beam hit a graphite target
- Secondary π/K's focused by magnetic horns and decay to neutrinos
  - Neutrino beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Antineutrino beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - Changing neutrino beam mode by flipping the horn polarity
- All hadrons absorbed by beam dump
- High energy muons penetrating beam dump measured by muon monitors

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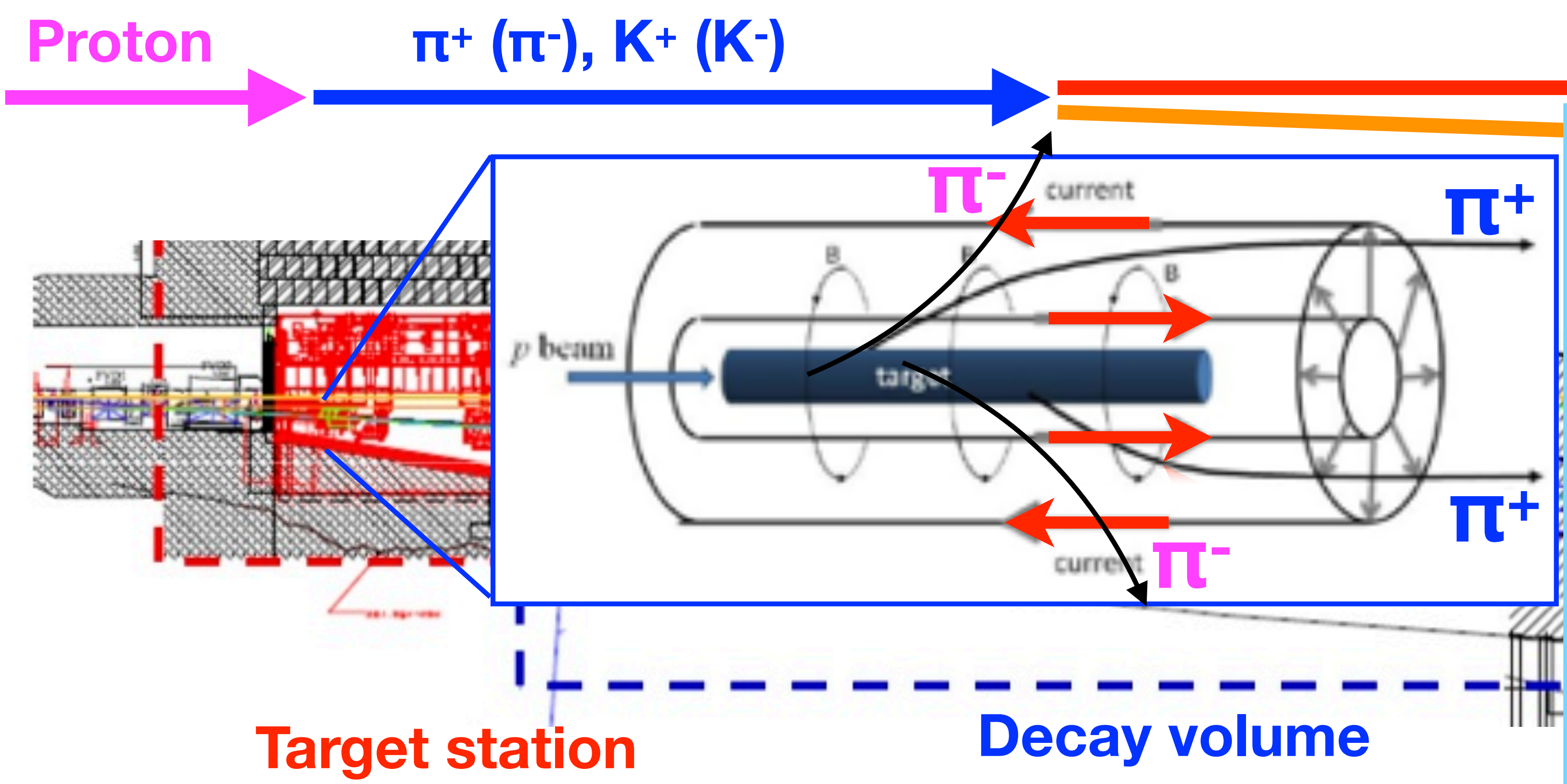

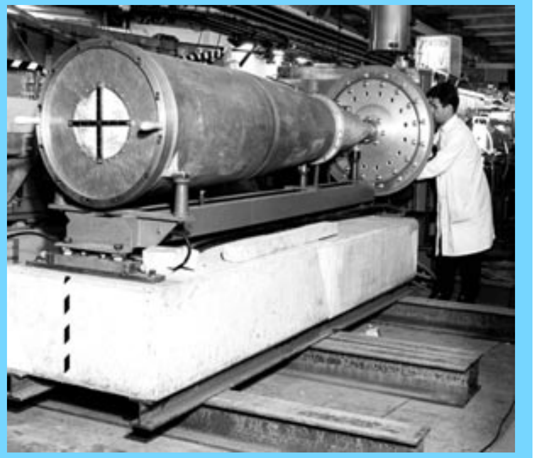

The 1st Neutrino Horn – Van den Meer, CERN, 1961

Horn-focused beam developed at CERN by Simon van der Meer (1984 Novel Prize)

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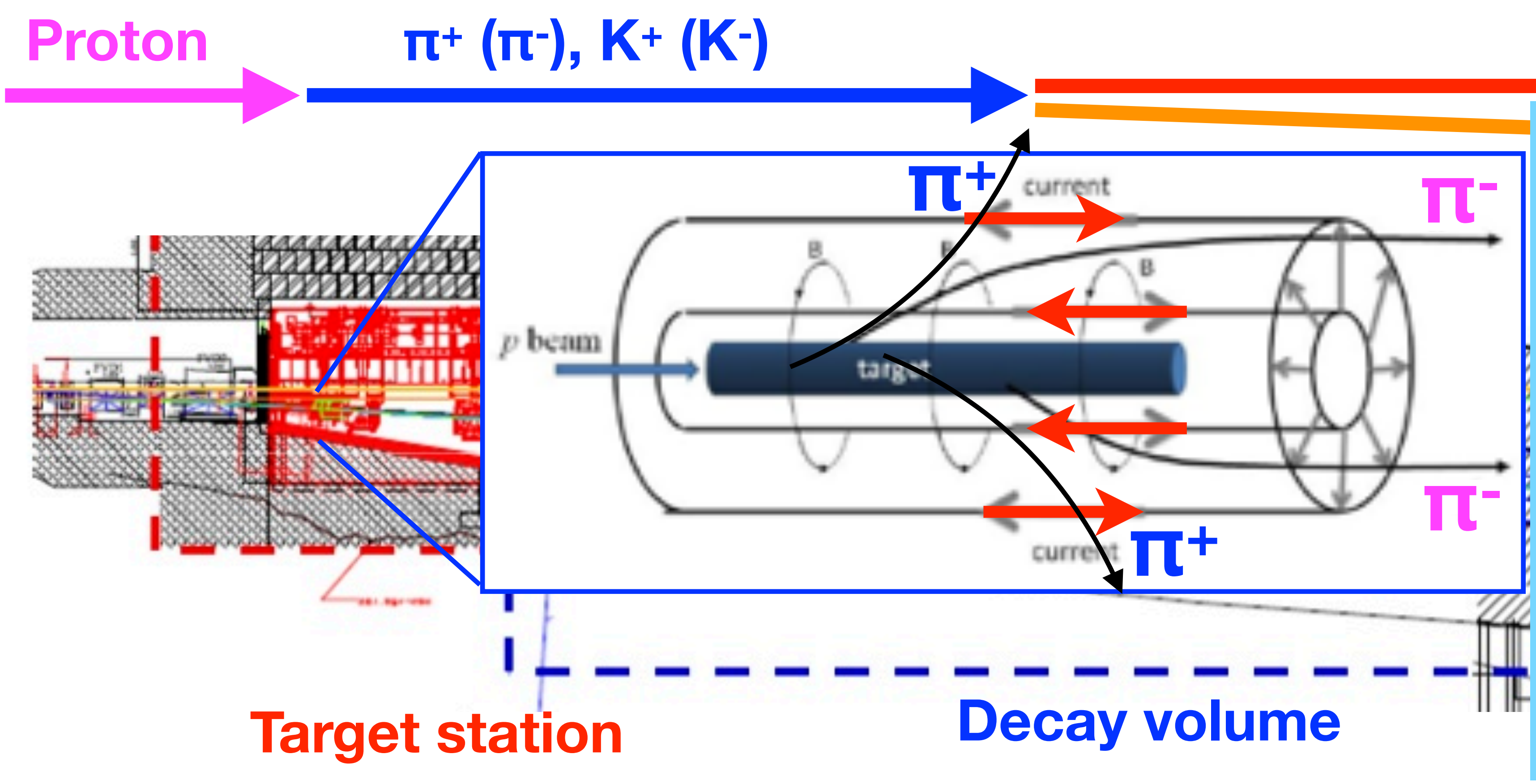

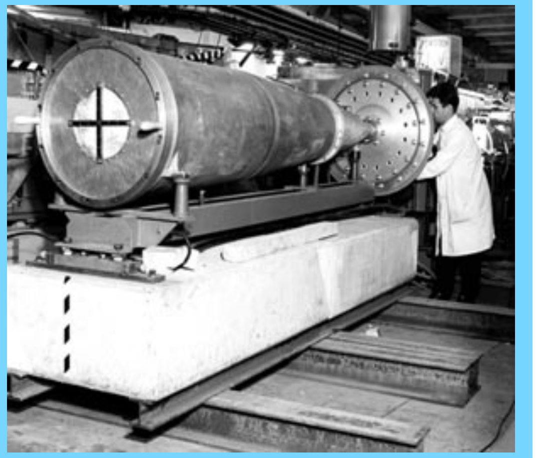

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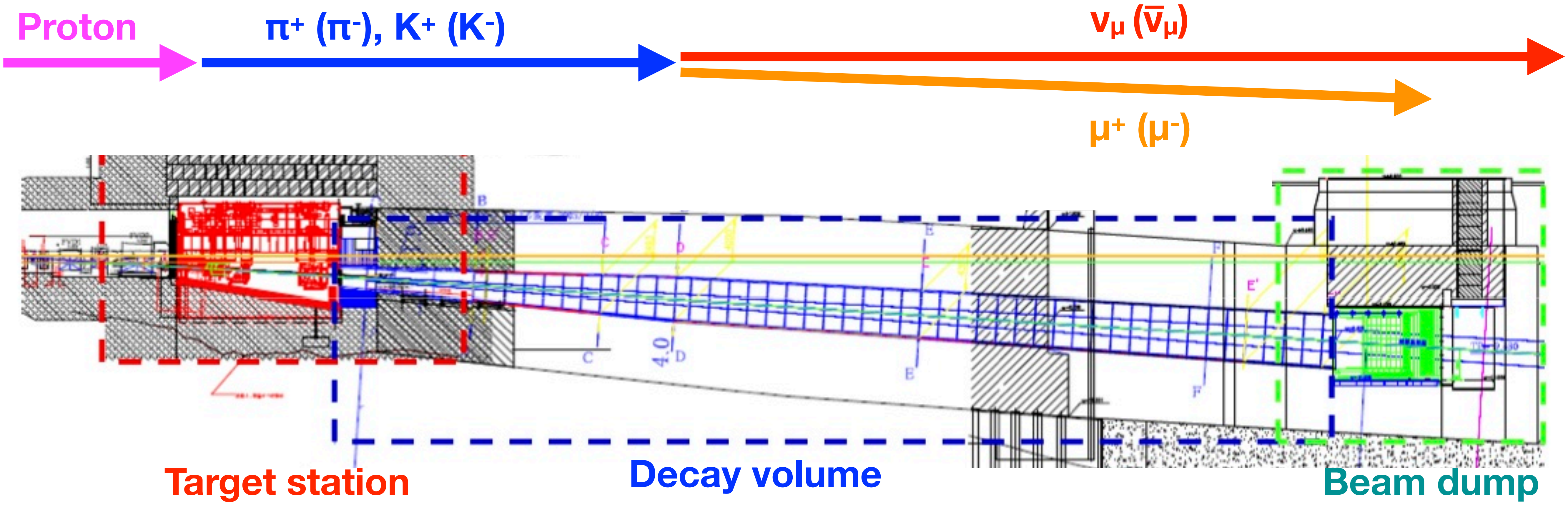

Proton

π^+ (π^-), K^+ (K^-)

ν_μ ($\bar{\nu}_\mu$)

μ^+ (μ^-)

Target station

Decay volume

Beam dump

- High intensity proton beam hit a graphite target
- Secondary π/K's focused by magnetic horns and decay to neutrinos
  - Neutrino beam from $\pi^+ \to \mu^+ + \nu_\mu$
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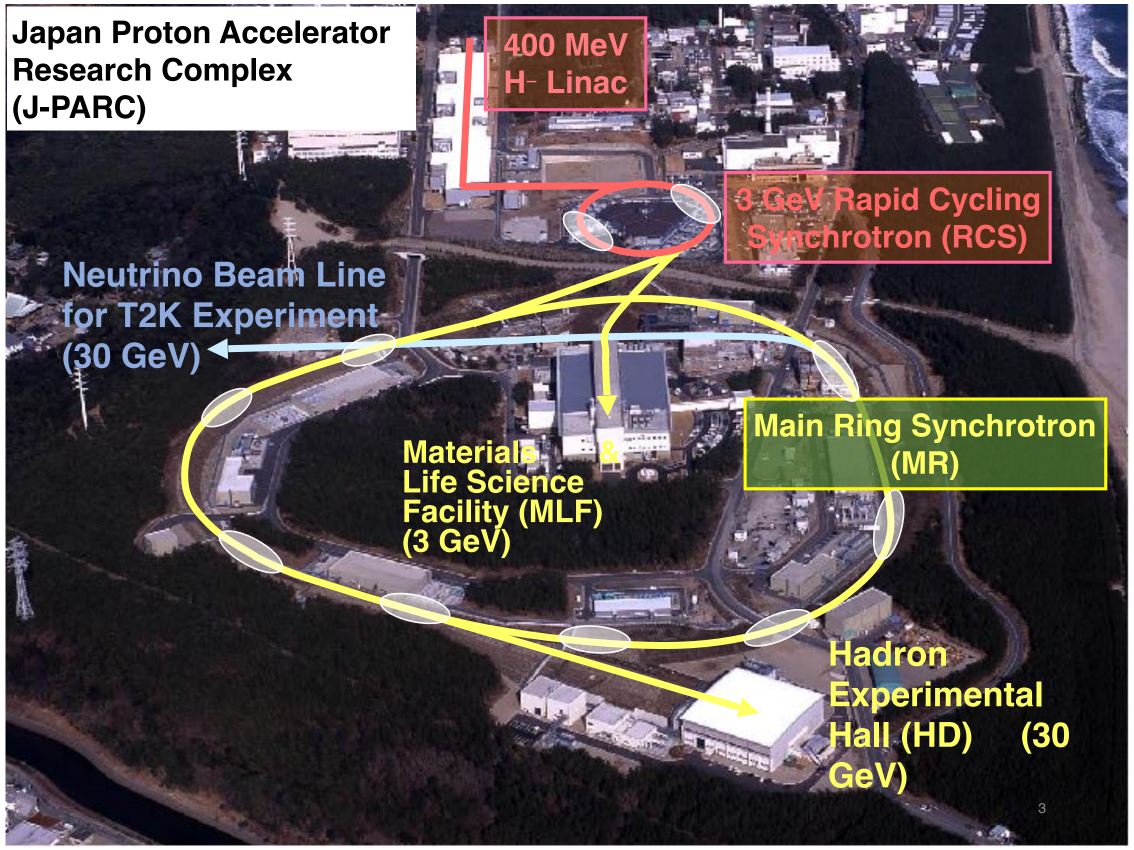
Operating Facilities

J-PARC



- 400 MeV Linac
- 3 GeV Rapid Cycling Synchrotron (RCS)
  - Material and life science, muon science
- 30 GeV Main Ring Synchrotron
  - Neutrino experiment (T2K)
  - Nuclear and particle experiments

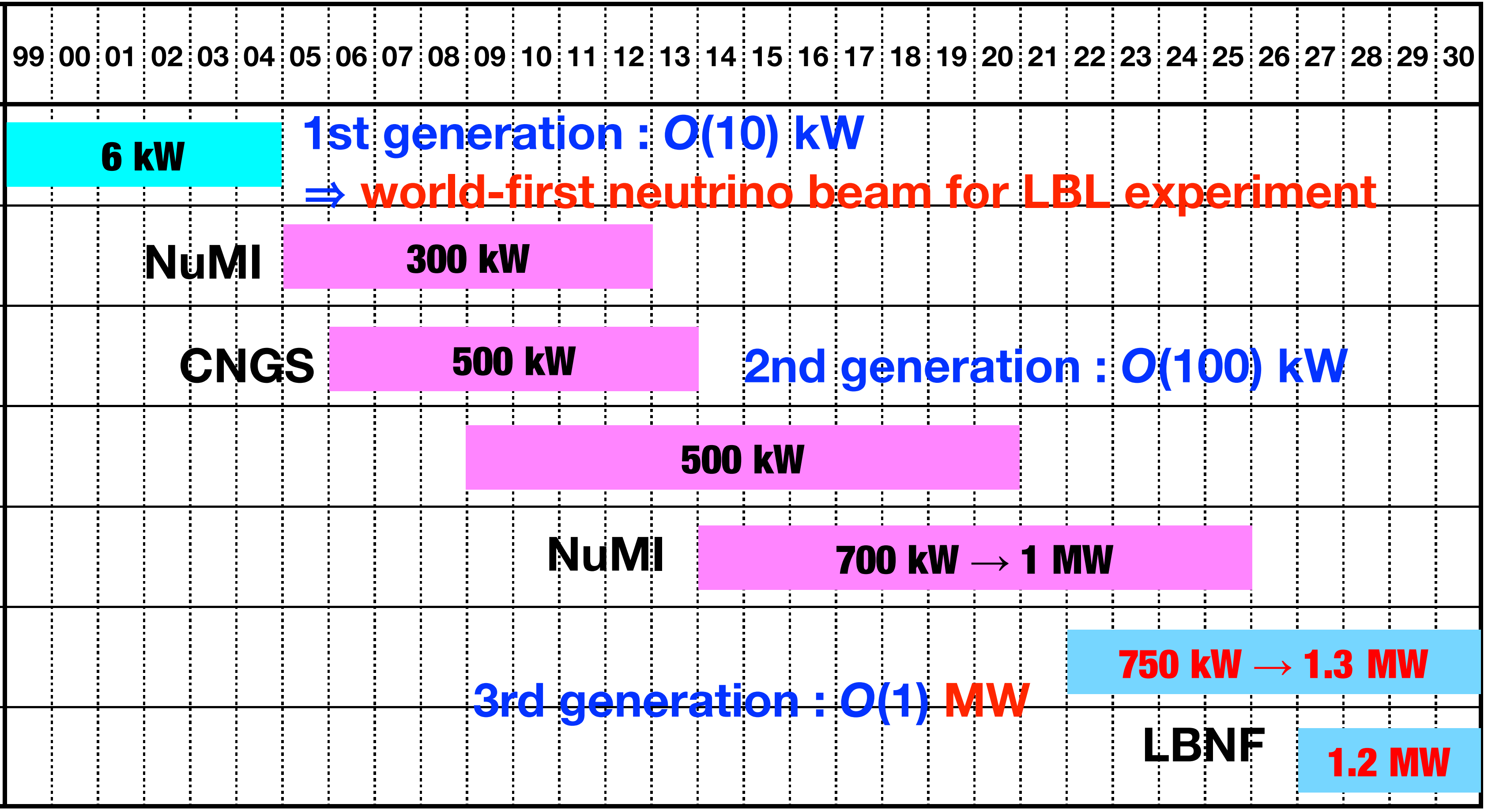
Fermilab

- 400 MeV Linac
- 8 GeV Booster
  - Short baseline neutrino experiments
- 120 GeV Main Injector
  - Neutrino experiments (NOvA, etc)
  - Muon experiments

Progress on High Power Neutrino Beam

Neutrino beam facilities for long baseline experiments

Facility	Accelerator	Energy [GeV]	Current [μA]	Experiment
KEK	PS	12	0.5	K2K
Fermilab	Main Injector	120	2.5	MINOS
CERN	SPS	450	1.1	OPERA
J-PARC	Main Ring	30	16.7	T2K
Fermilab	Main Injector	120	5.8-8.3	NOvA
J-PARC	Main Ring	30	25-43	T2K-II → HK
Fermilab	Main Injector	60-120	10	DUNE



1st generation : *O*(10) kW

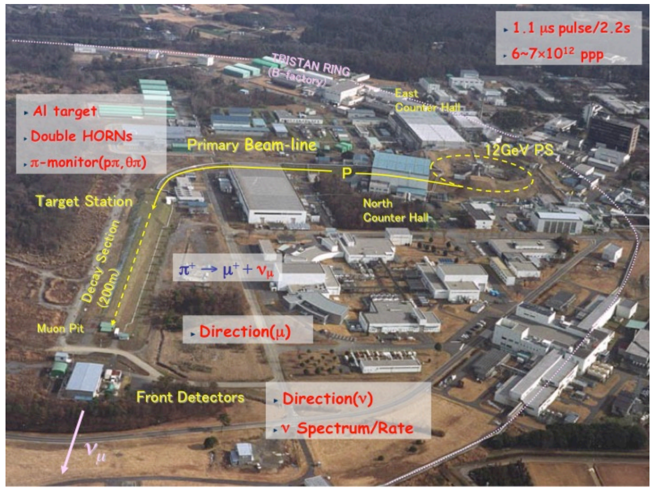
⇒ world-first neutrino beam for LBL experiment

2nd generation : *O*(100) kW

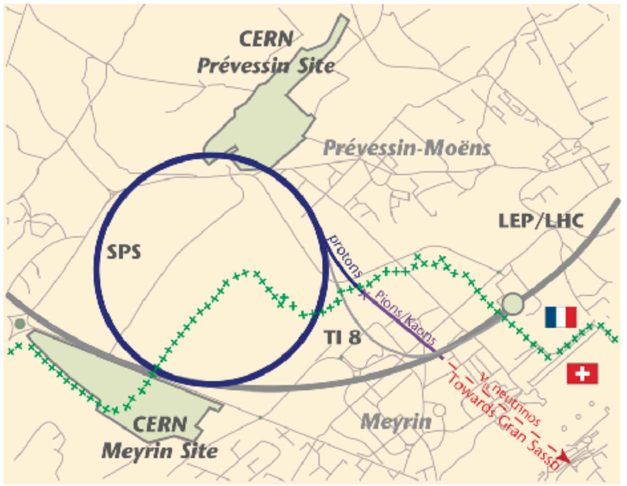
3rd generation : *O*(1) MW

Note: Beam power (kW) = Beam energy (GeV) x Current (μA)

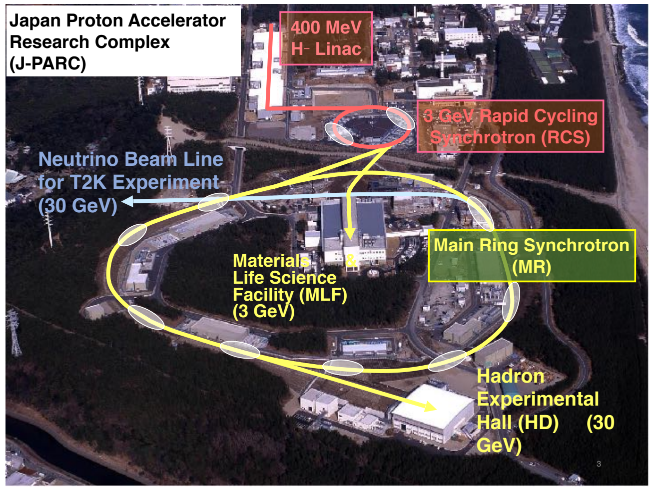
KEK 12GeV-PS (1999-2004)



CERN CNGS (2006-2012)

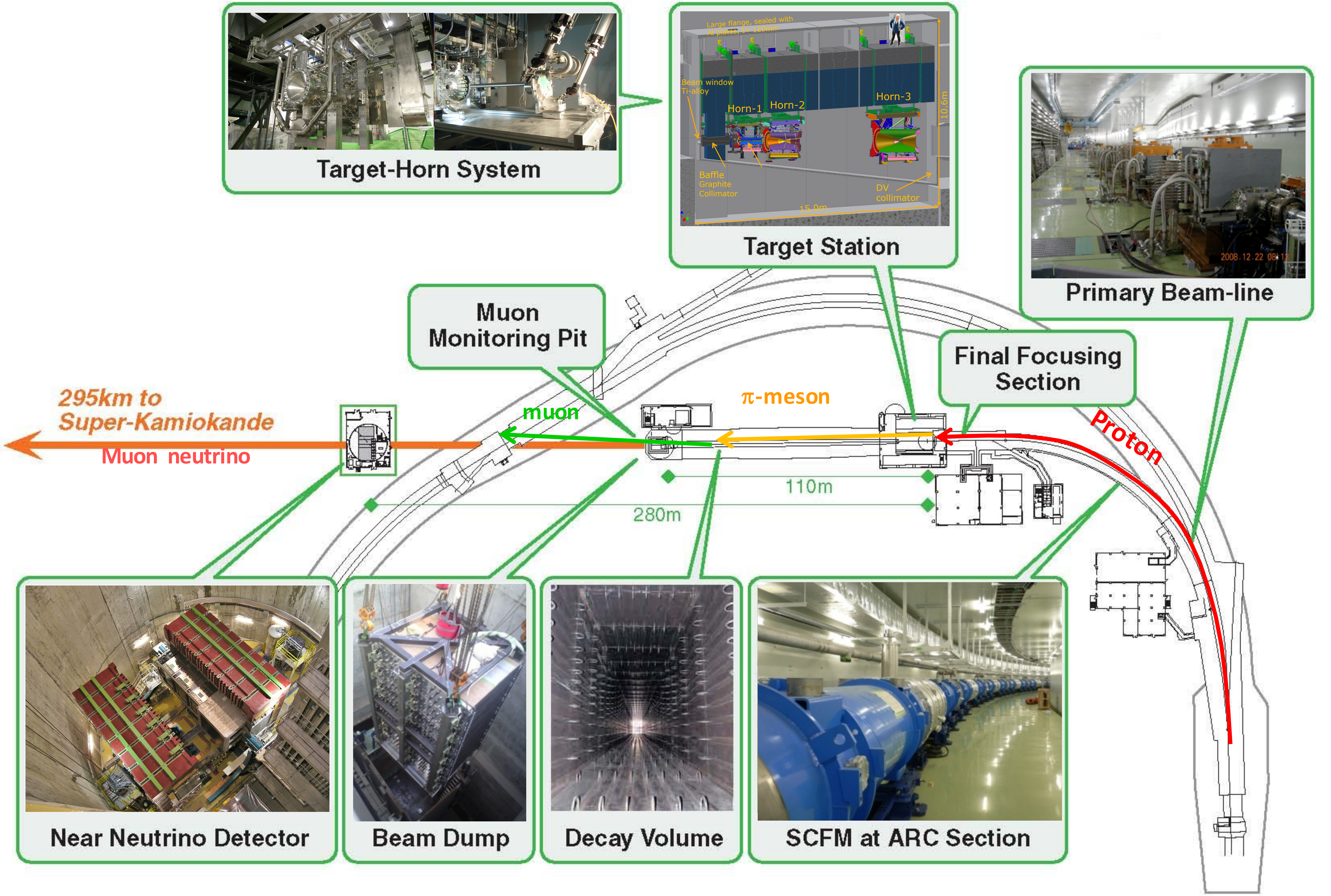


J-PARC (2009-)



Fermilab NuMI (2006-)

Neutrino Beamline



Target-Horn System

Target Station

Primary Beam-line

Muon Monitoring Pit

Final Focusing Section

295km to Super-Kamiokande

Muon neutrino

muon

π-meson

Proton

110m

280m

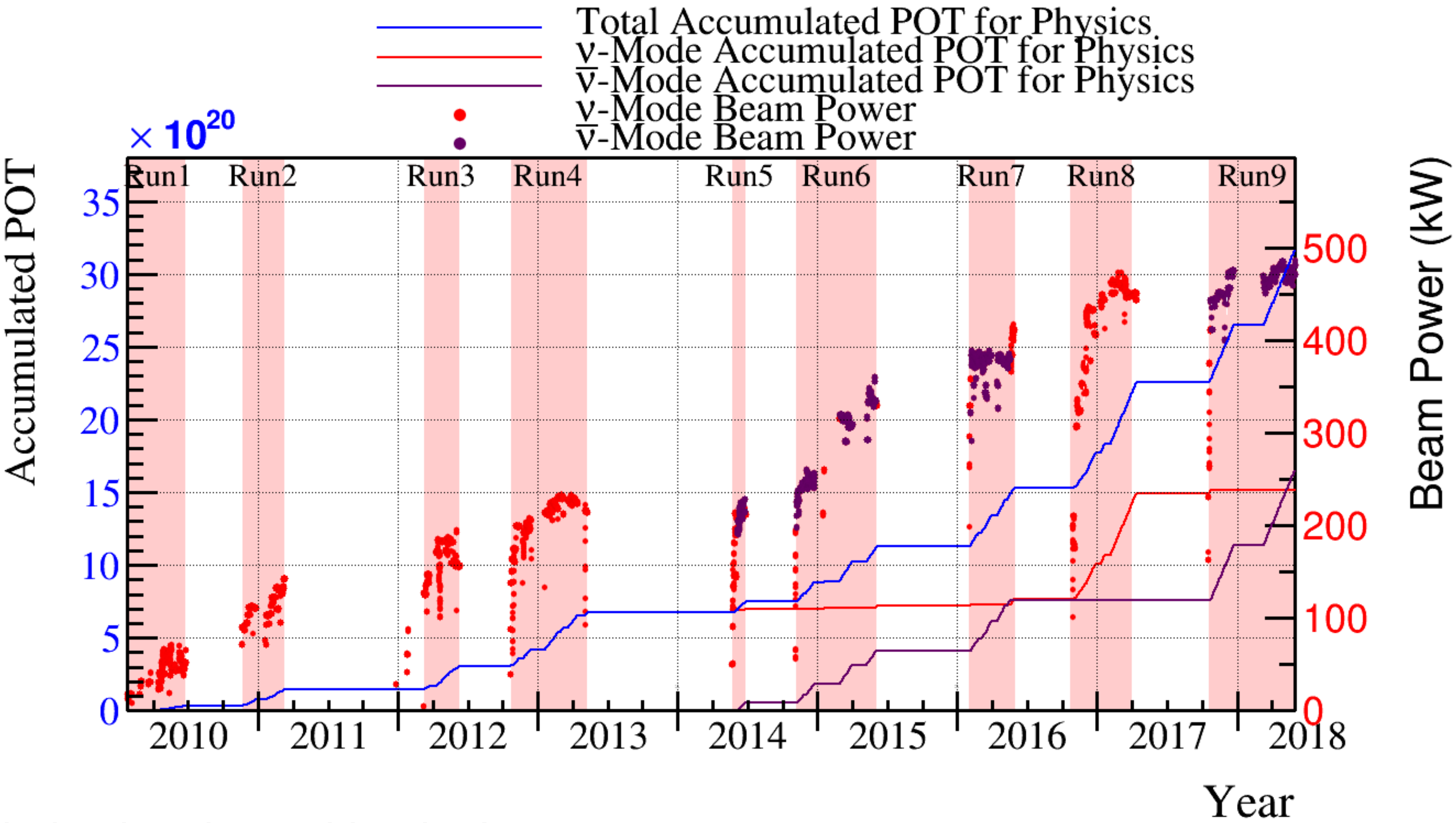
Near Neutrino Detector

Beam Dump

Decay Volume

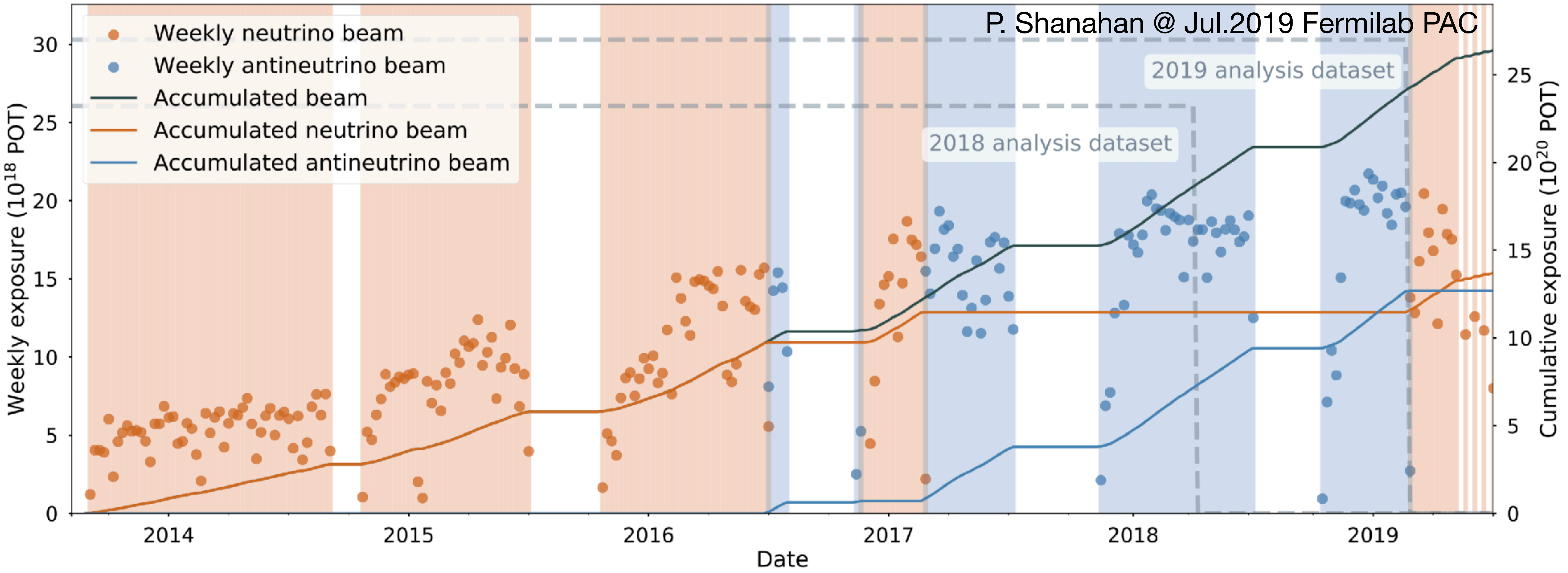
SCFM at ARC Section

Status of J-PARC Neutrino Beam



- Started physics data taking in January 2010
- **~500 kW** stable operation : **2.5x10^{14}** ppp ⇒ world-highest intensity in fast-extracted beam from proton synchrotron
    - Beam power limited by space charge effect, beam instability due to insufficient RF voltage
- Provide **3.16x10^{21}** protons on target (POT) to T2K
    - ν mode POT : 1.51x10^{21}, anti-ν mode POT : 1.65x10^{21} POT

Status of Fermilab Beam



- NuMI operation for NOvA started in 2014
- **~700 kW** stable operation : **756 kW** hourly beam power recorded
- **2.38x10^{21}** POT (14kt-equivalent) in total since 2014
  - ν-mode POT : 1.11x10^{21} POT (14kt-equivalent), anti-ν mode POT: 1.27x10^{21} POT
- NuMI upgrade to ~1 MW (PIP-I+)
  - 1 MW-capable target scheduled to be installed during this summer shutdown
  - Booster improvements for PIP-II by 2023 will allow **900 kW**
- NuMI operation until start of long LBNF shutdown in 2025

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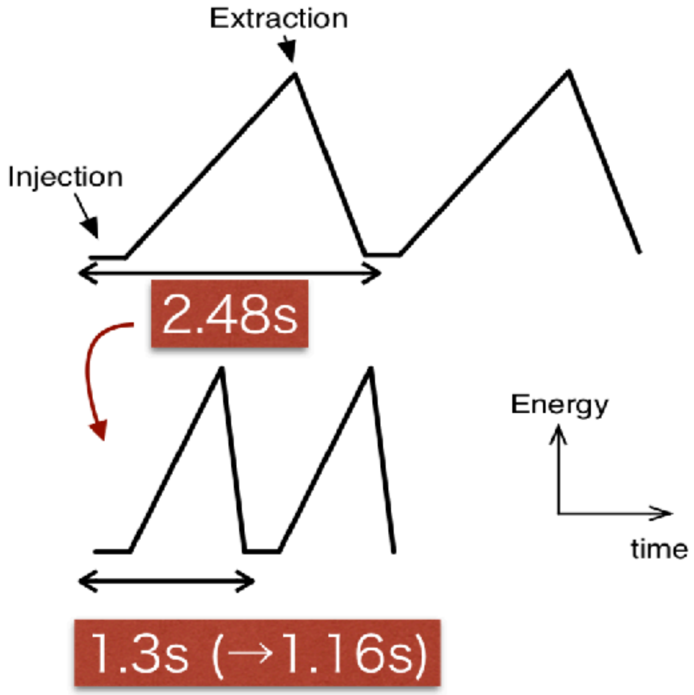
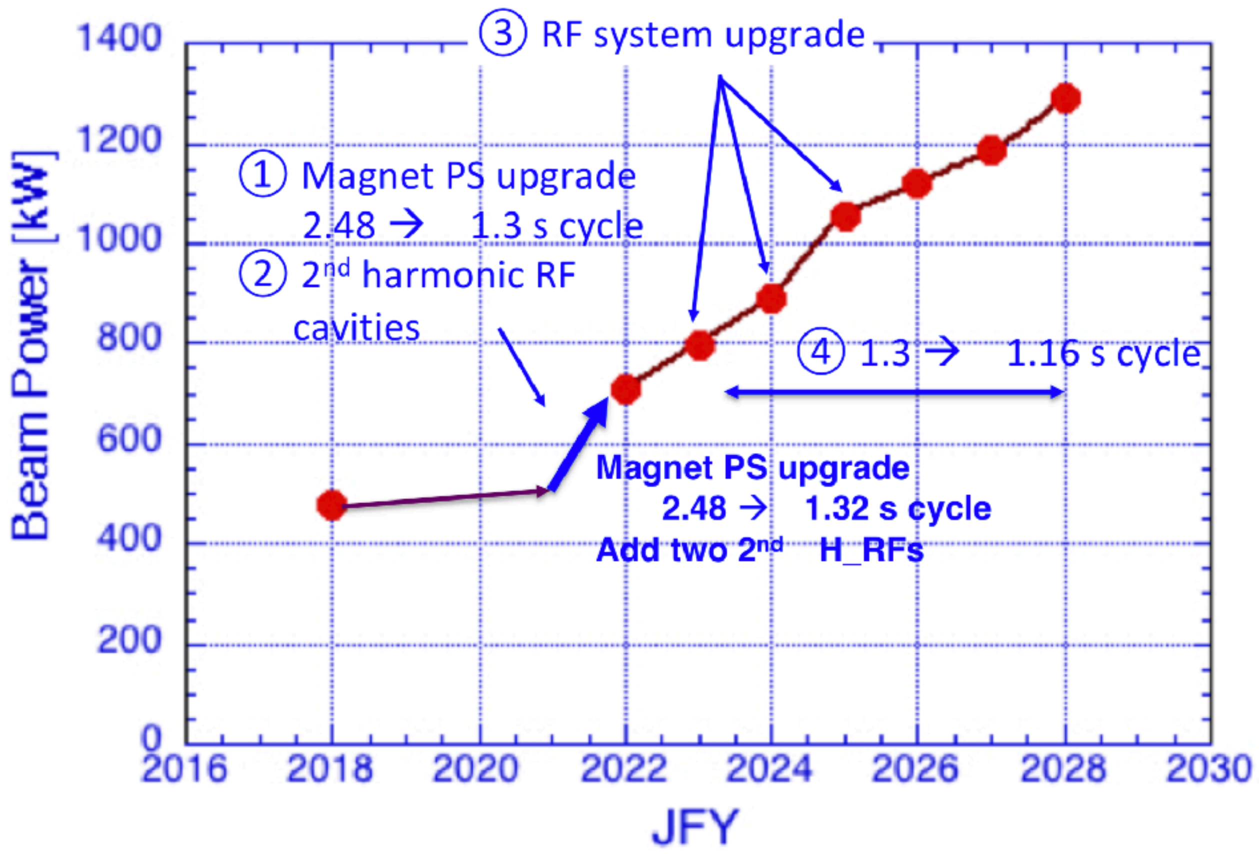
J-PARC Upgrade Toward 1.3 MW

Power ∝ E_{beam} x Intensity x 1/cycle

- **Staged accelerator upgrade toward 1.3 MW**
  - **Shorter cycle** (2.48s→1.32s) for >750 kW (FY2021)
    - MR PS upgrade
    - 2nd harmonic RF cavities
  - **Higher beam intensity** for 1.3 MW (~FY2027)
    - Increase # of RF cavities (9 → 11)
    - RF anode PS upgrade
- **Upgrade of neutrino beamline is also needed**

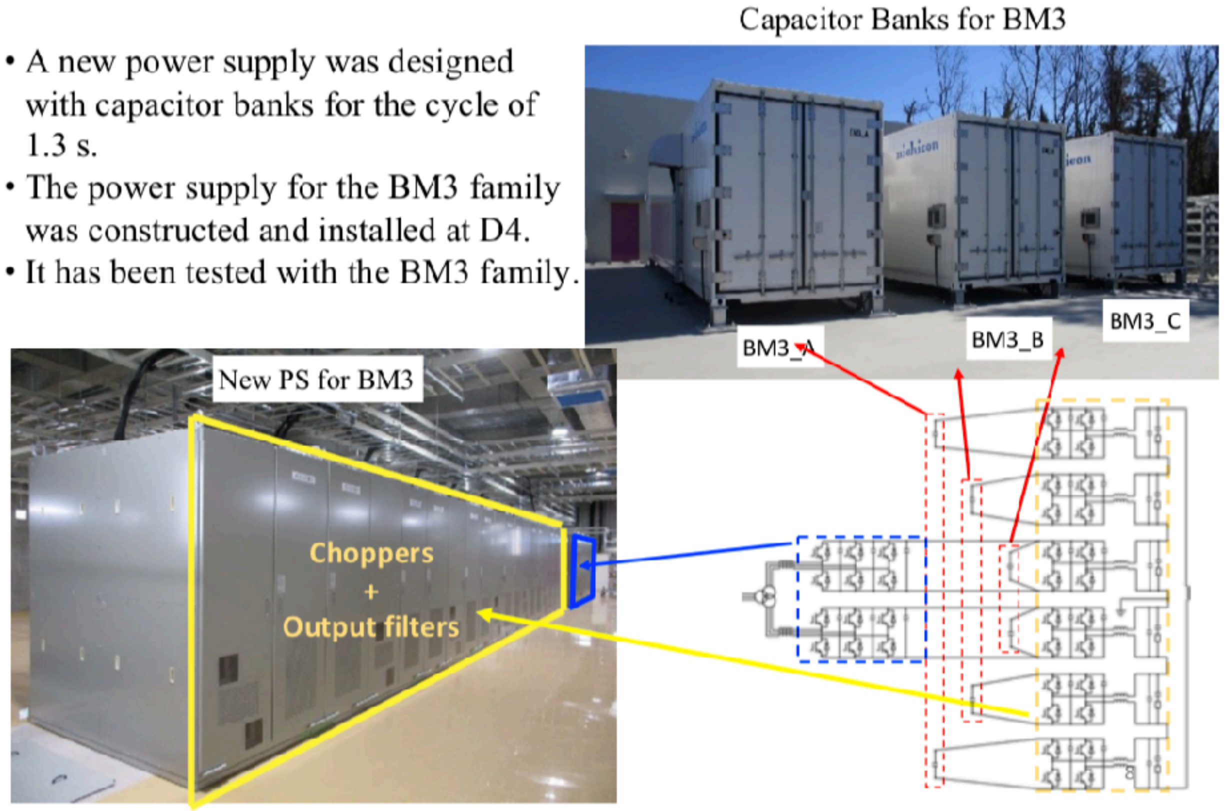


	Current	Upgrade
Beam power [MW]	0.5	1.3
Proton intensity [10^{14} / pulse]	2.5	3.2
Cycle [s]	2.48	1.16

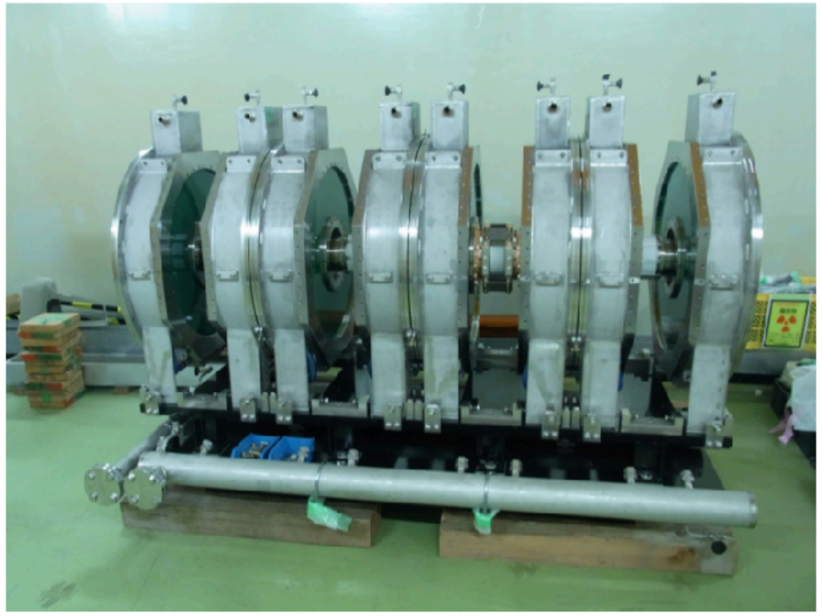


MR Upgrade Status

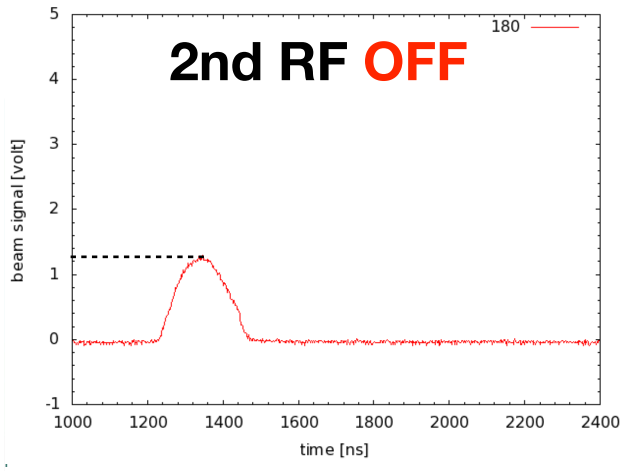
- **New power supply**
  - Commissioning with actual bending magnet (BM3) was successfully performed
    - More than 2-hour continuous operation with 1.32 s cycle was confirmed
- **RF upgrade**
  - New 2nd harmonic RF system for 1.32 s operation was assembled

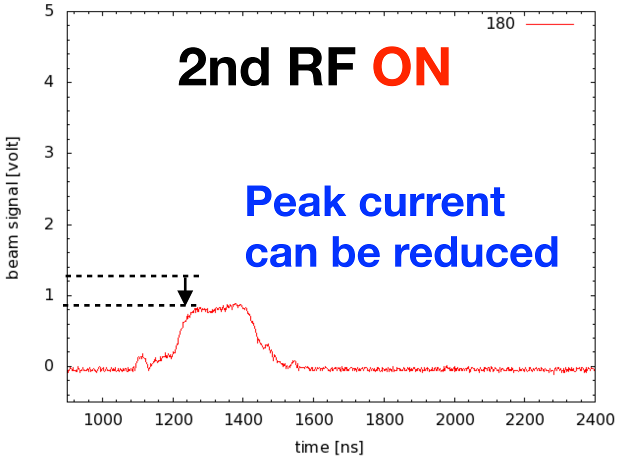


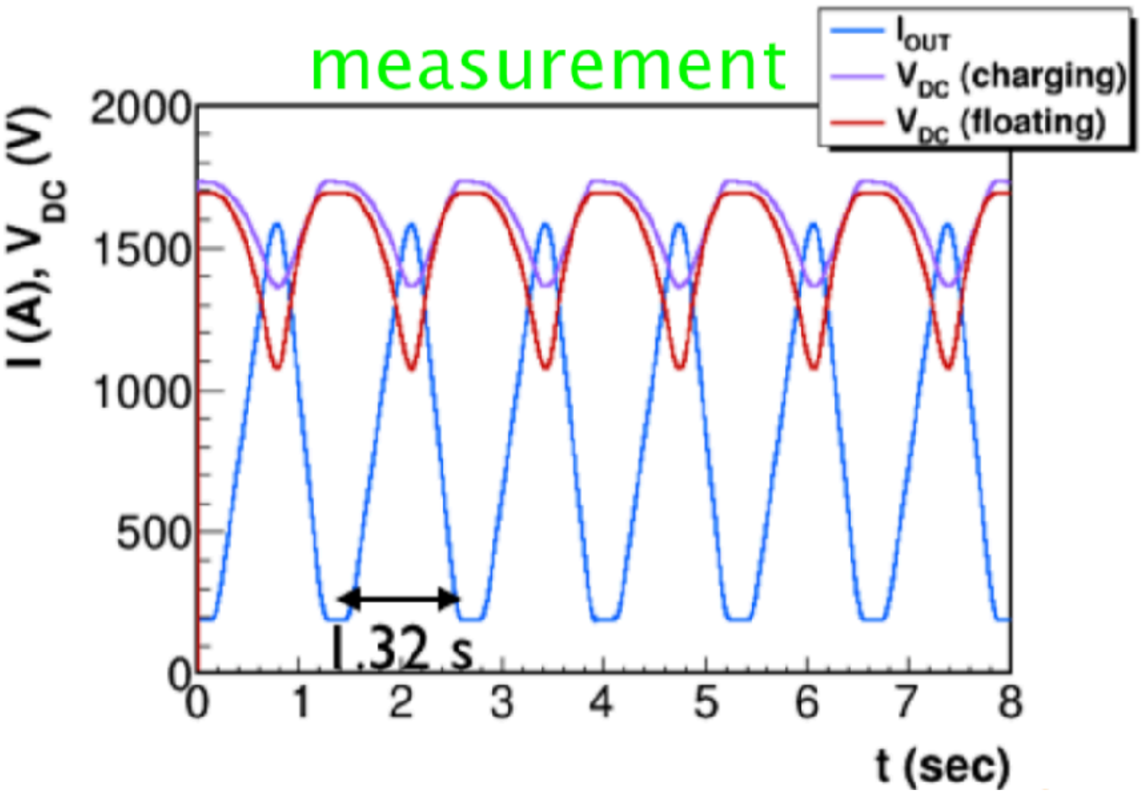
- A new power supply was designed with capacitor banks for the cycle of 1.3 s.
- The power supply for the BM3 family was constructed and installed at D4.
- It has been tested with the BM3 family.



- New 2nd harmonic cavity with 4 accelerating gaps







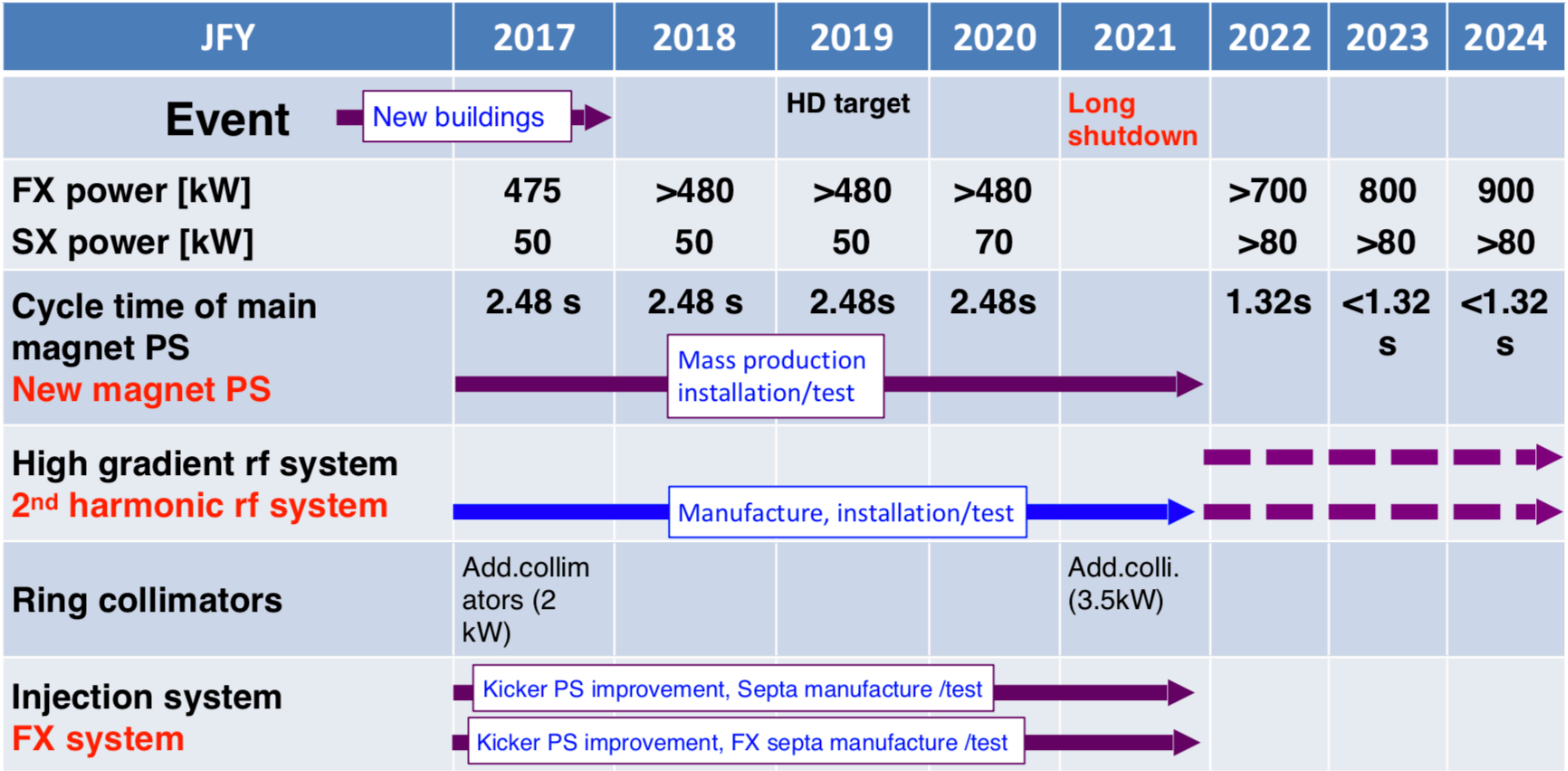
Small current ripple @ 1580A also confirmed

J-PARC Accelerator Upgrade

F. Naito @ Jul.2019 J-PARC PAC

FX: The higher repetition rate scheme : Period 2.48 s —> 1.3 s for 750 kW.
(= shorter repetition period) —> 1.16 s for 1.3 MW

SX: Mitigation of the residual activity for 100kW



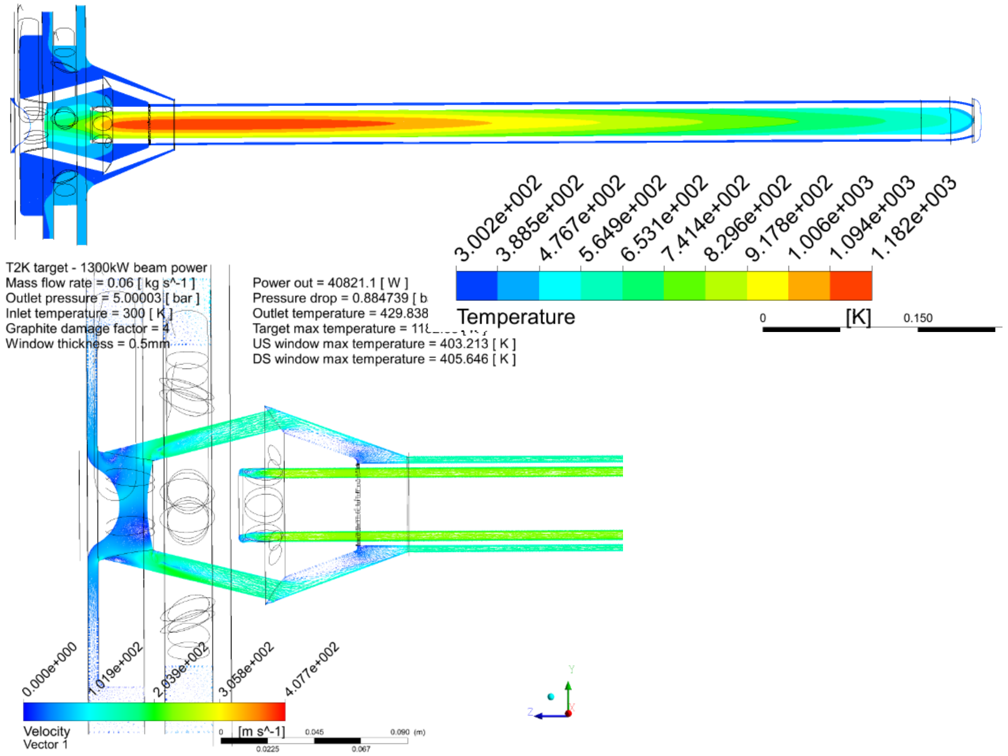
JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW]	475	>480	>480	>480		>700	800	900
SX power [kW]	50	50	50	70		>80	>80	>80
Cycle time of main magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32s	<1.32 s	<1.32 s
New magnet PS		Mass production installation/test						
High gradient rf system								
2nd harmonic rf system			Manufacture, installation/test					
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system	Kicker PS improvement, Septa manufacture /test							
FX system	Kicker PS improvement, FX septa manufacture /test							

J-PARC Neutrino Beamline Upgrade

- **Baseline design**
  - Beamline components designed to accept **$3.3\text{x}10^{14}$** ppp
  - Replaceable components designed for **750 kW** (can be upgraded later)
  - Non-replaceable components (HV, DV, BD) designed for **3-4 MW**
- **Necessary upgrade toward 1.3 MW**
  - Improve cooling capacity to remove larger heat generated by higher power beam
    - **Target He cooling, water cooling for horn, He vessel etc**
  - Accommodate shorter cycle operation
    - **Horn operation, DAQ**
  - Accommodate larger amount of radioactivity produced by higher power beam
    - **Upgrade radioactive waste disposal facility**
  - Safe and reliable control of higher power beam
    - **Improved control system and beam monitors**

Target Upgrade

- **Original target design**
  - To survive thermal shock by **3.3x10¹⁴** ppp beam ⇒ **3.2x10¹⁴ ppp should be OK**
  - Cooling capacity only **900 kW**
- **Improvement**
  - Higher He flow rate needed to improve cooling performance
    - 0.5 MPa pressure needed ⇒ high pressure tolerance
    - He compressor upgrade
  - Thermal analysis for 1.3 MW ⇒ max temp. **~900°C** expected
    - Further optimization to be done
  - New target production with high pressure tolerance ⇒ to be installed in **FY2021**
  - He circulation system upgrade scheduled in **FY2023**



T2K target - 1300kW beam power
Mass flow rate = 0.06 [kg s^-1]
Outlet pressure = 5.00003 [bar]
Inlet temperature = 300 [K]
Graphite damage factor = 4
Window thickness = 0.5mm

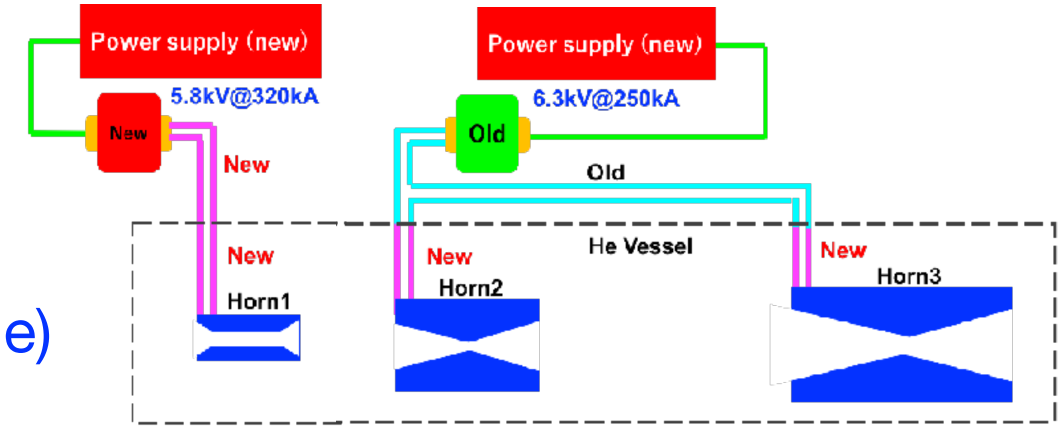
Power out = 40821.1 [W]
Pressure drop = 0.884739 [b
Outlet temperature = 429.838
Target max temperature = 11
US window max temperature = 403.213 [K]
DS window max temperature = 405.646 [K]

	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 ℃

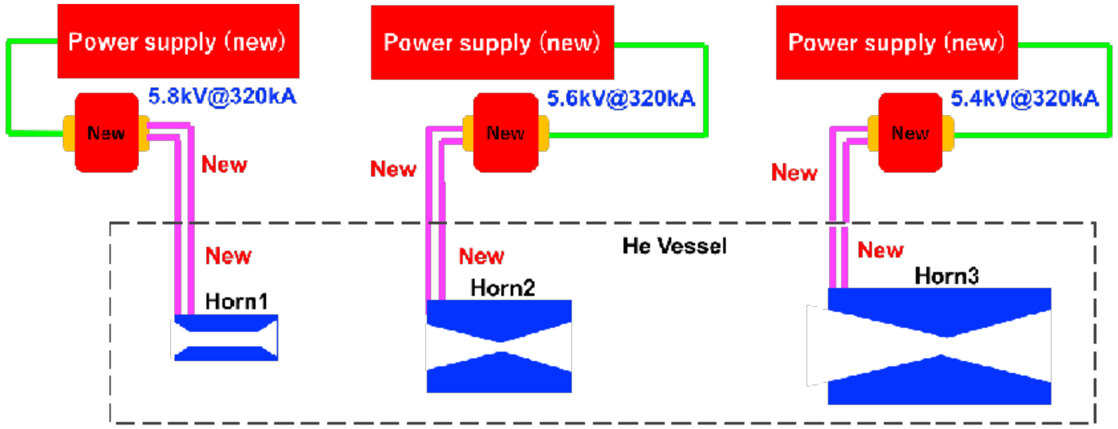
Horn Upgrade

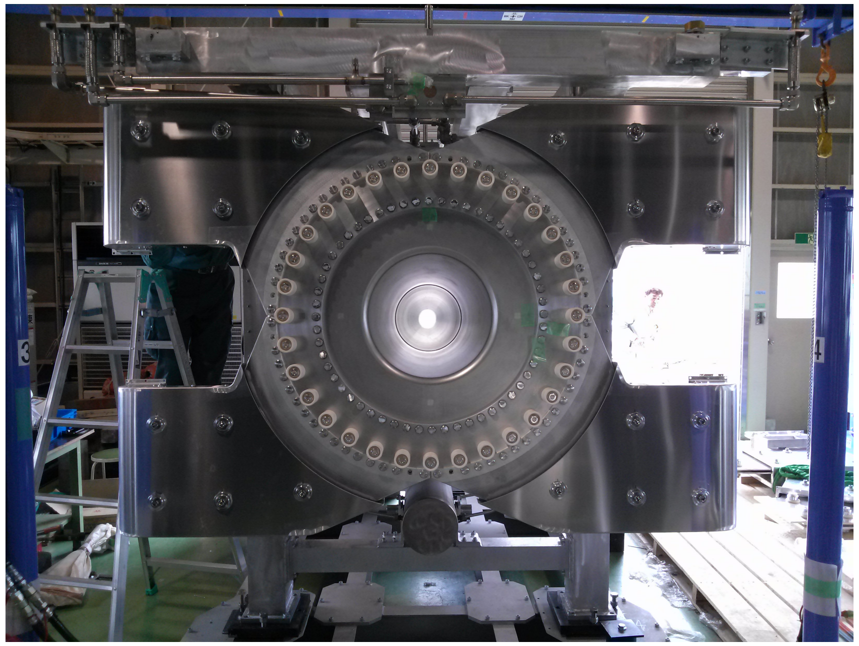
- **Horn electrical system upgrade for 320 kA at 1 Hz**
  - Horn current 250 kA → 320 kA (design)
    - ~10% flux gain for right-sign neutrinos
    - 5~10% flux reduction for wrong-sign neutrinos
  - Three power supplies to drive three horns (one-by-one)
    - New electrical system (PS, transformer, striplines) developed
  - Staged upgrade
    - 1 Hz (@250kA) operation achieved by two PS configuration (FY2021)
    - 320 kA to be achieved with third PS and transformer (FY2023)
- **Stripline cooling improvement (for Horn2)**
  - Current He flow cooling not enough for 1.3 MW
  - Water-cooled striplines under development
    - R&D indicates proven results ⇒ to be installed in FY2021

Current config.

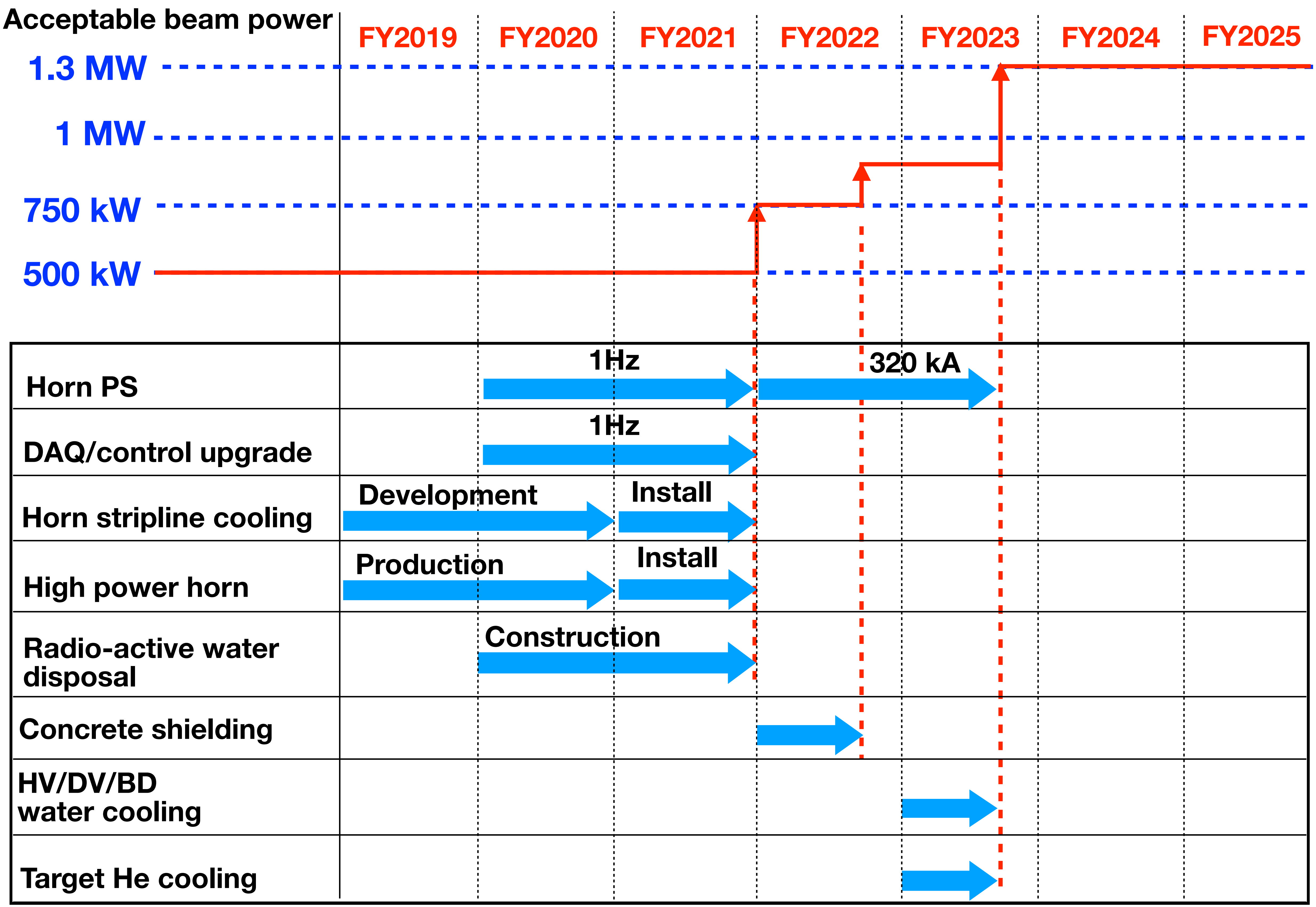


Proposed config.

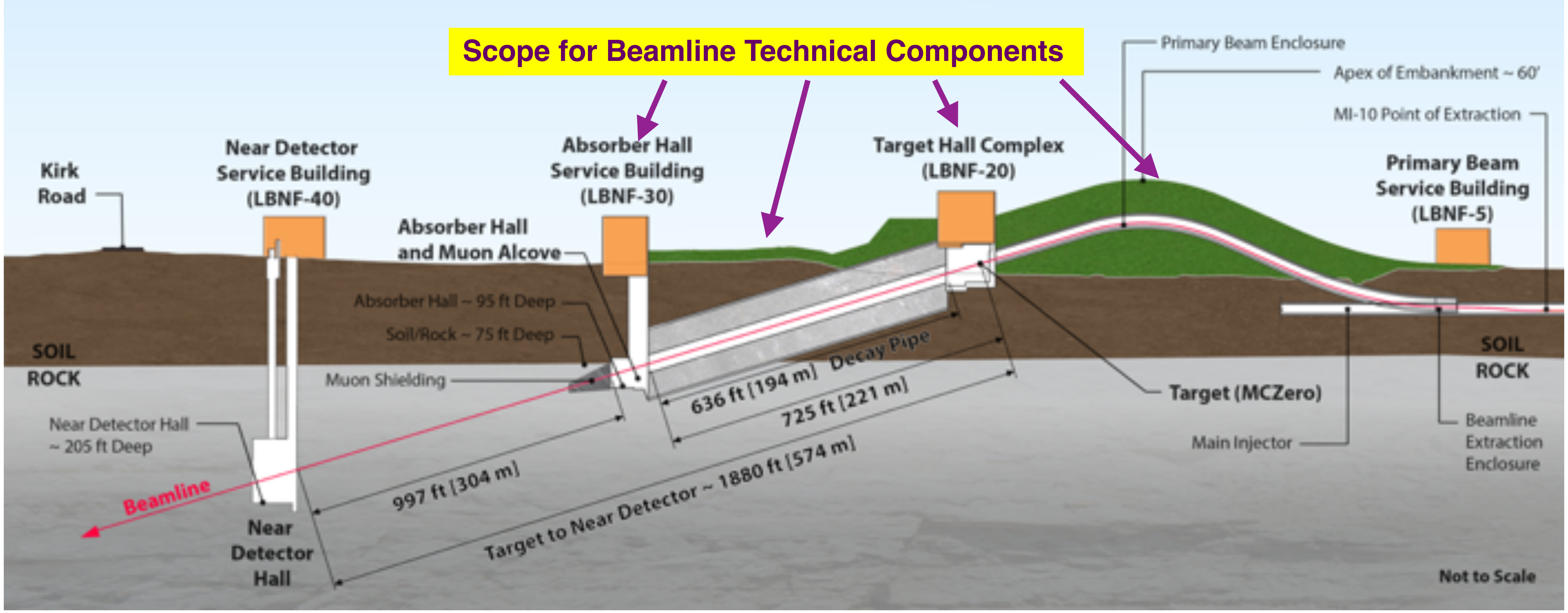




Timeline


Acceptable beam power
FY2019
FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
1.3 MW
1 MW
750 kW
500 kW
Horn PS
1Hz
320 kA
DAQ/control upgrade
1Hz
Horn stripline cooling
Development
Install
High power horn
Production
Install
Radio-active water disposal
Construction
Concrete shielding
HV/DV/BD water cooling
Target He cooling

Long Baseline Neutrino Facility (LBNF)

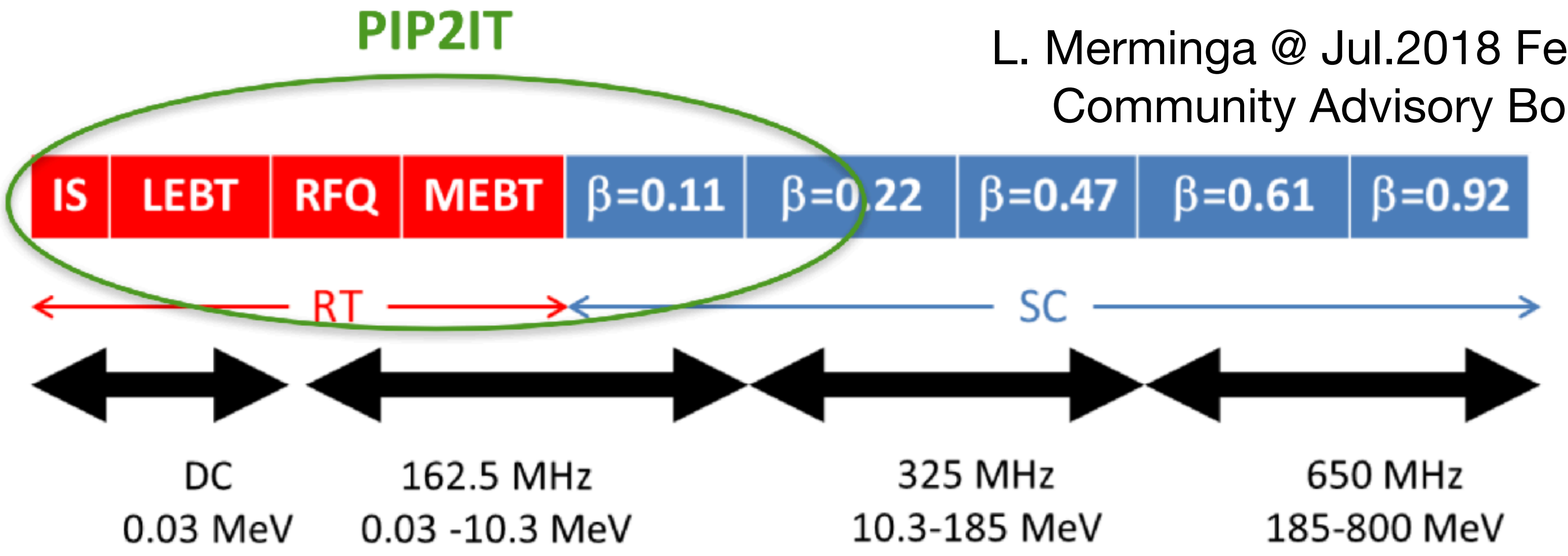


- New neutrino beamline for DUNE
- Primary protons in energy range of 60-120 GeV to LBNF target
- All systems designed for 1.2 MW initial proton beam power. Facility upgradable to 2.4 MW proton beam power.
- Aim to start operation from FY2027

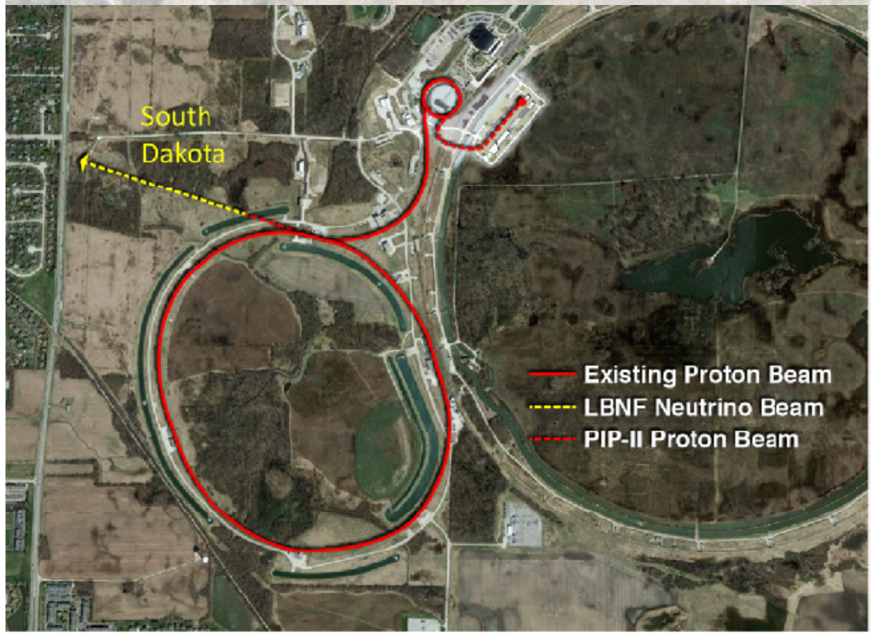
Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

Fermilab Accelerator Upgrade: PIP-II

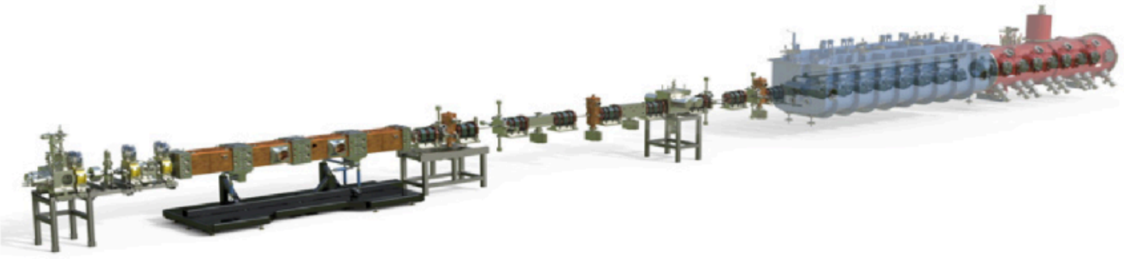
- **PIP-II**
  - **800 MeV superconducting linac** to inject higher intensity proton beam to Booster
    - Higher energy will help to reduce space-charge effect
  - International contribution from many countries
- Status
  - PIP2IT for Front End components to be completed in FY2021
  - Facility construction started in 2019

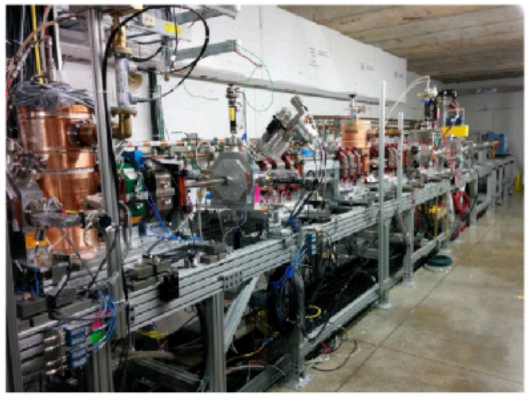


L. Merminga @ Jul.2018 Fermilab Community Advisory Board



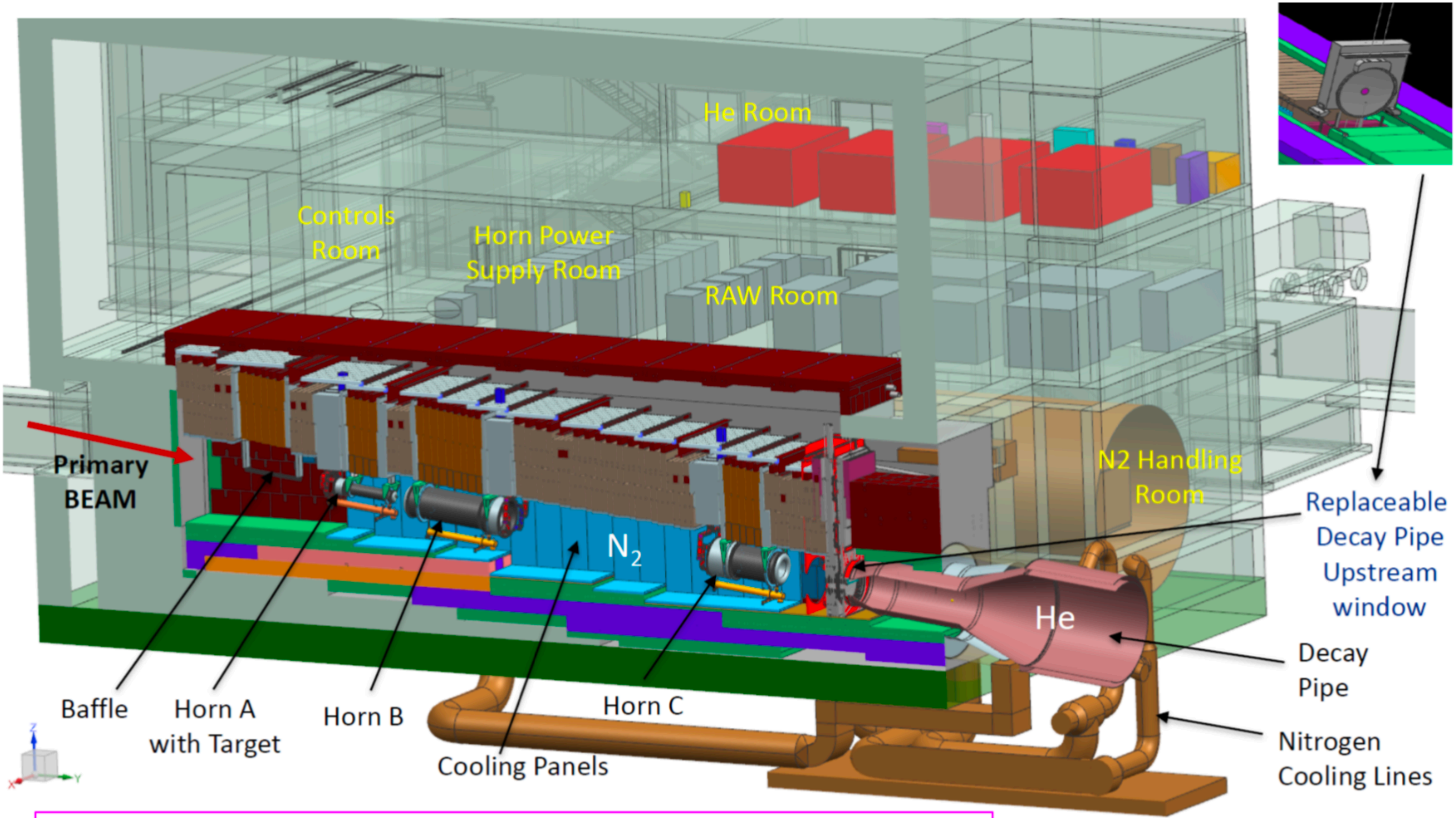
PIP2IT is a complete systems-integration of the PIP-II Front End - coming to completion in FY21





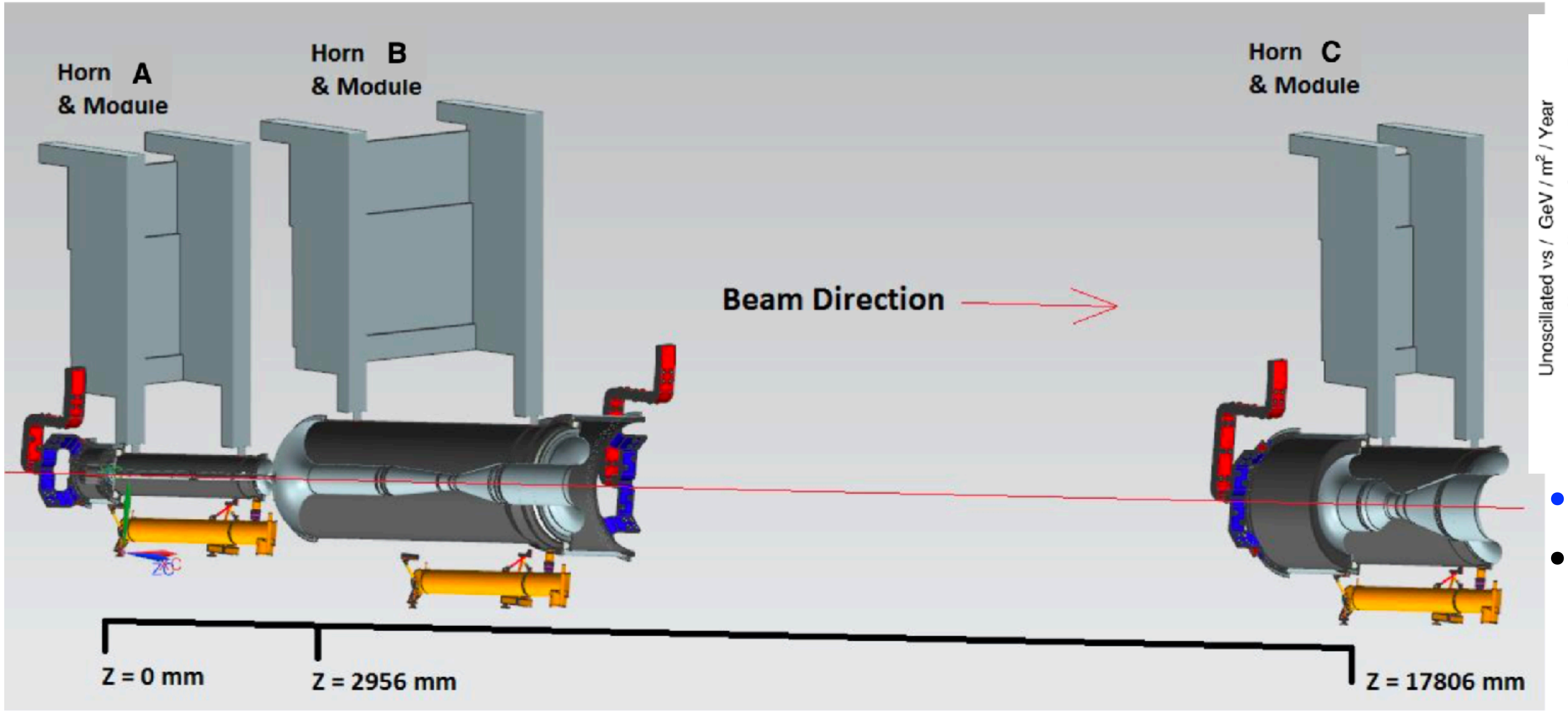
LBNF Target Hall Design

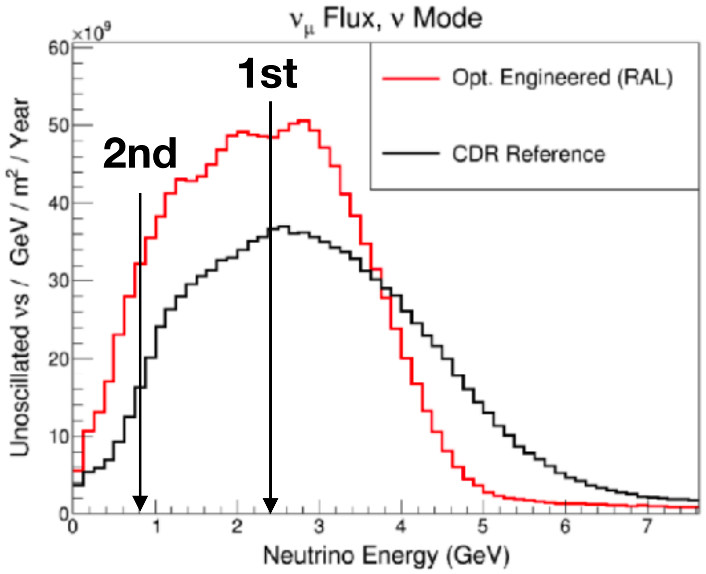
Air-filled target chase (NuMI) ⇒ N_2-filled hermetic vessel + He-filled Decay pipe



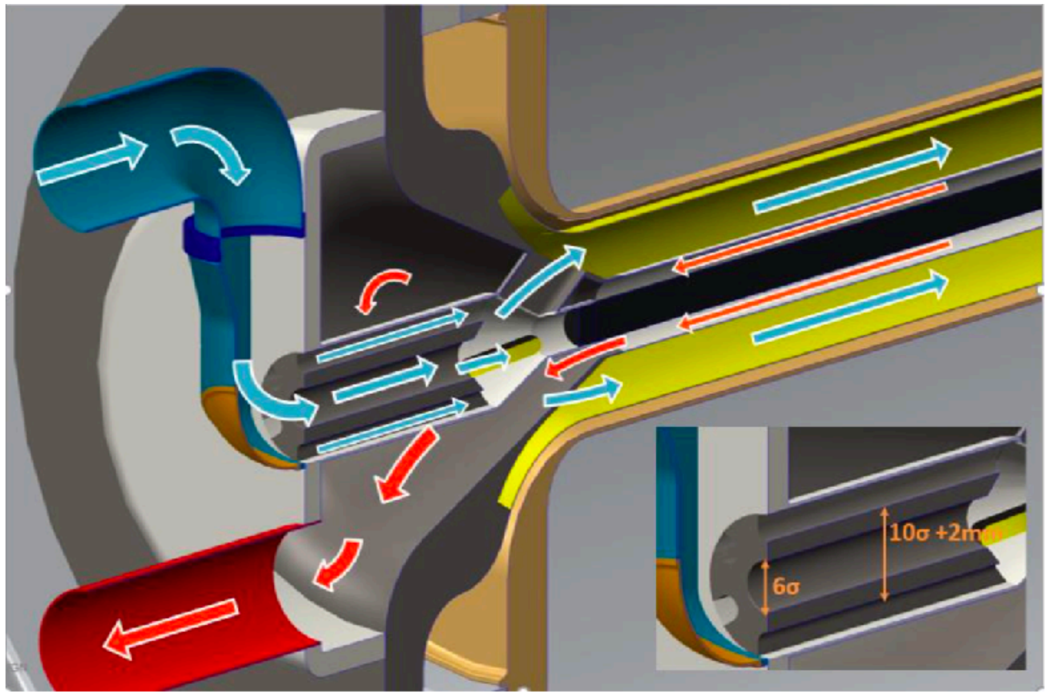
Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (replaceable cooling panels).

Target and Horns





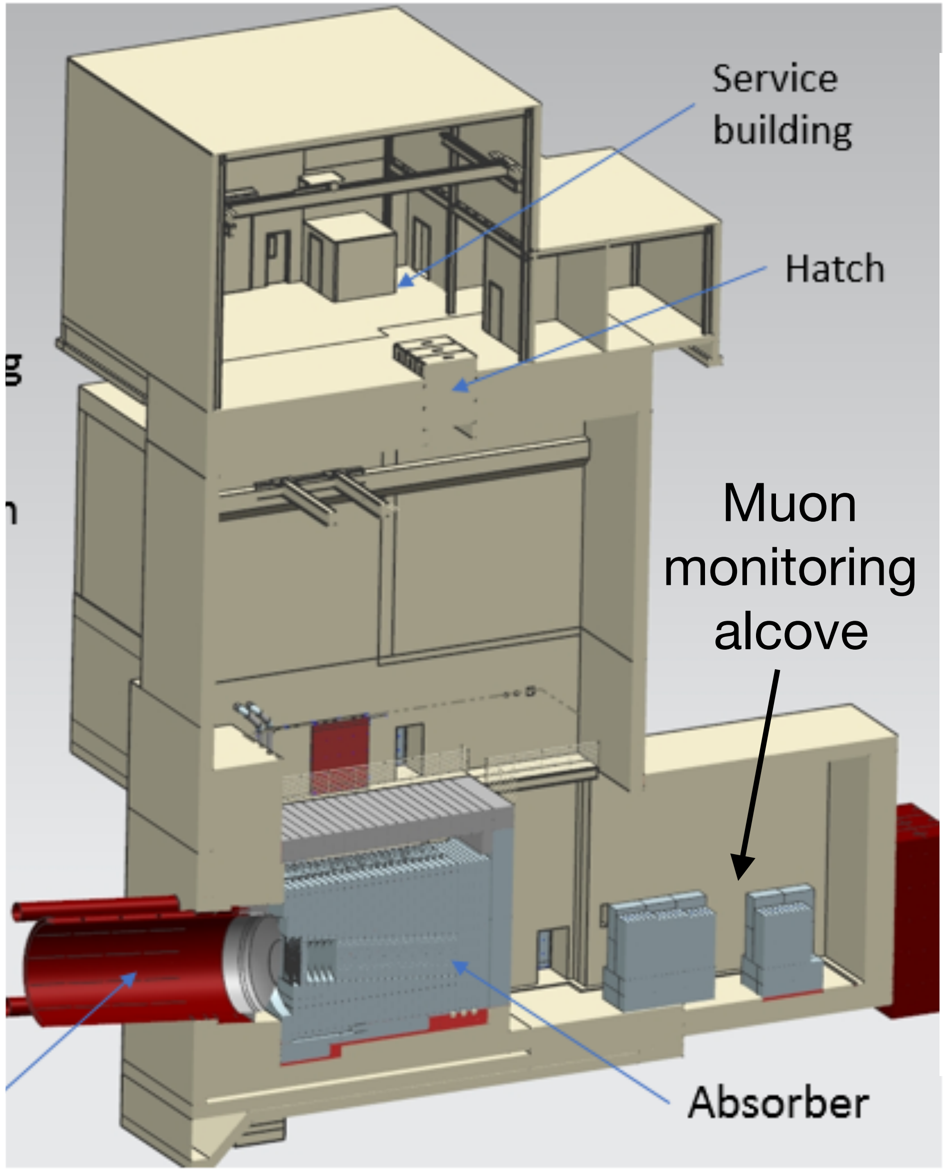
- Significant increase in flux
- Covers 1st (2.4GeV) and 2nd (0.8 GeV) osc. max.



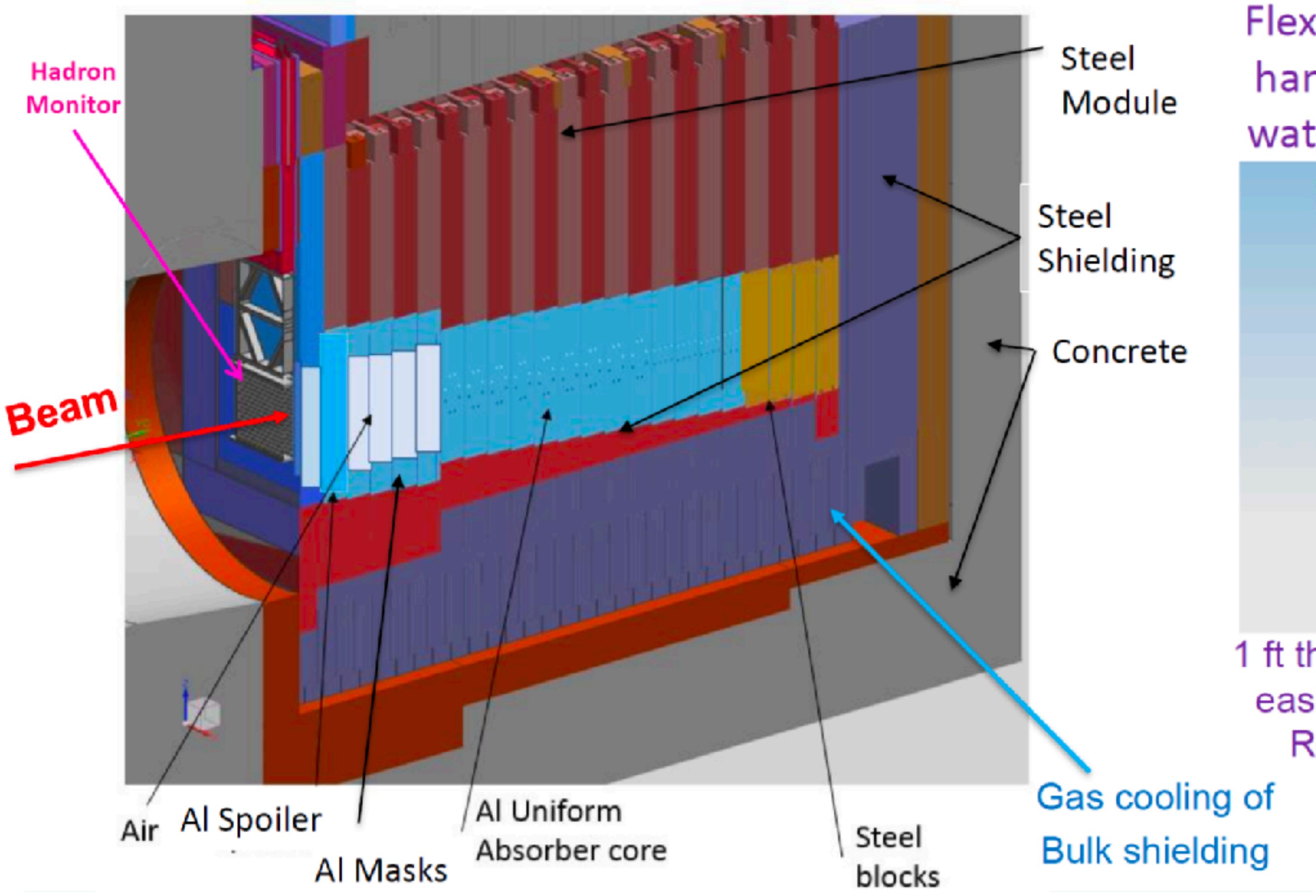
- **1.2 MW optimized three horn design**
  - 300 kA horn current
  - Heat deposit calculation and FEA analysis completed. Results look satisfactory.
- **1.5-2m long He-cooled graphite target (by RAL-UK)**
  - Graphite cylindrical segments centered in coaxial Titanium tubes carrying He gas
  - Graphite at higher temperature ⇒ can reduce radiation damage

Hadron Absorber Design

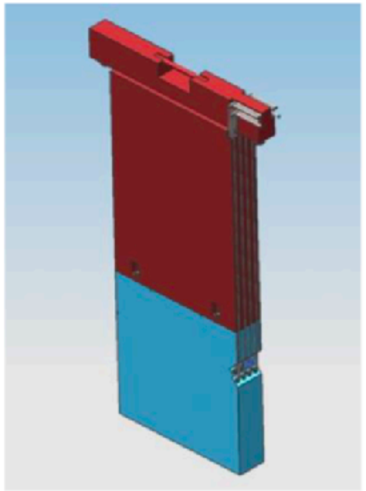
Hadron Absorber complex



Large diameter core with uniform density to enable good muon monitoring



Flexible, modular hanger design of water cooled core



1 ft thick core blocks are easily replaceable via Remote Handling

- Al water-cooled core blocks : 1 ft thick modular hanger ⇒ replaceable via remote handling
- Surrounding iron blocks : air cooling
- Hadron monitor in front of the absorber
- Muon monitors behind the absorber : ionization detectors

Outline

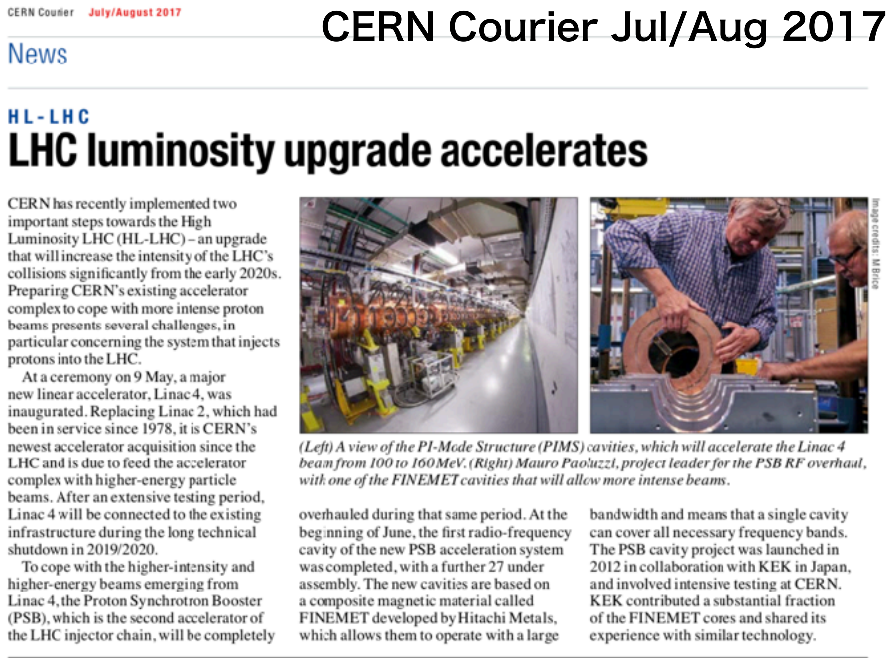
- Overview of neutrino beam facilities
- Planned future facilities
- International cooperation on high power neutrino beam
- Summary

International Cooperation on High Power Neutrino Beam

- **Good relationship among KEK, Fermilab, CERN experts since 1999** (including participation from many other institutes)
  - Detailed discussions and information exchange in Neutrino Beam and Instrumentation (NBI) workshop series
    - **Many lessons learned from other facilities**
  - NBI2019 at Fermilab (Oct. 22-25) : 20th anniversary !
    - https://indico.fnal.gov/event/21143/
- **US-Japan Cooperative Programs in High Energy Physics**
  - Accelerator and beamline R&D for high power neutrino beam since 2014
    - KEK-Fermilab collaboration in accelerator and neutrino beamline development
  - LBNF-specific program launched since 2018
    - KEK-Fermilab collaboration for LBNF
- **CERN-KEK cooperation for accelerator and beamline technology**
  - Accelerator technology (RF, beam monitors, etc)
  - Expanding to other fields (radiation damage, beamlines)

KEK contribution to LHC upgrade on RF

CERN Courier Jul/Aug 2017



CERN Courier **July/August 2017**

News

HL-LHC

LHC luminosity upgrade accelerates

CERN has recently implemented two important steps towards the High Luminosity LHC (HL-LHC) – an upgrade that will increase the intensity of the LHC's collisions significantly from the early 2020s. Preparing CERN's existing accelerator complex to cope with more intense proton beams presents several challenges, in particular concerning the system that injects protons into the LHC.

At a ceremony on 9 May, a major new linear accelerator, Linac 4, was inaugurated. Replacing Linac 2, which had been in service since 1978, it is CERN's newest accelerator acquisition since the LHC and is due to feed the accelerator complex with higher-energy particle beams. After an extensive testing period, Linac 4 will be connected to the existing infrastructure during the long technical shutdown in 2019/2020.

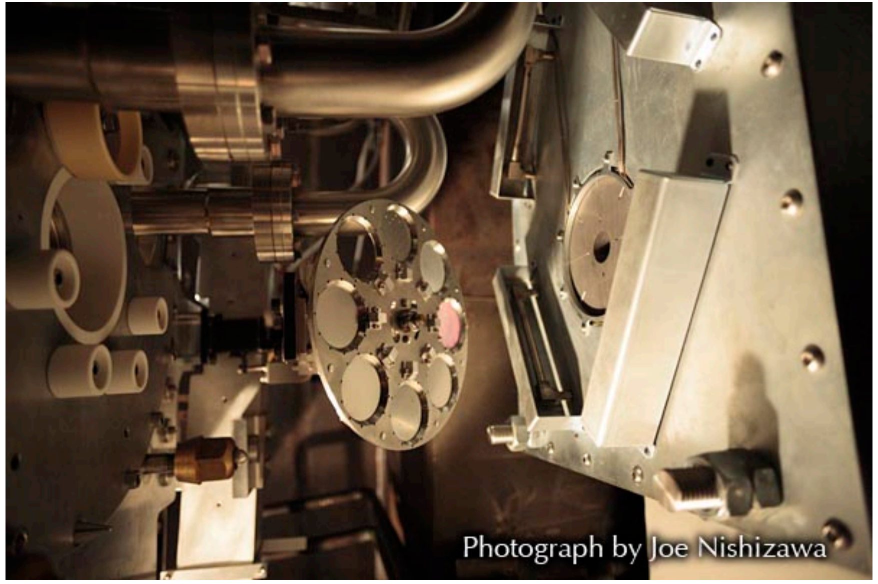
To cope with the higher-intensity and higher-energy beams emerging from Linac 4, the Proton Synchrotron Booster (PSB), which is the second accelerator of the LHC injector chain, will be completely overhauled during that same period. At the beginning of June, the first radio-frequency cavity of the new PSB acceleration system was completed, with a further 27 under assembly. The new cavities are based on a composite magnetic material called FINEMET developed by Hitachi Metals, which allows them to operate with a large bandwidth and means that a single cavity can cover all necessary frequency bands. The PSB cavity project was launched in 2012 in collaboration with KEK in Japan, and involved intensive testing at CERN. KEK contributed a substantial fraction of the FINEMET cores and shared its experience with similar technology.

(Left) A view of the PI-Mode Structure (PIMS) cavities, which will accelerate the Linac 4 beam from 100 to 160 MeV. (Right) Mauro Paoluzzi, project leader for the PSB RF overhaul, with one of the FINEMET cavities that will allow more intense beams.

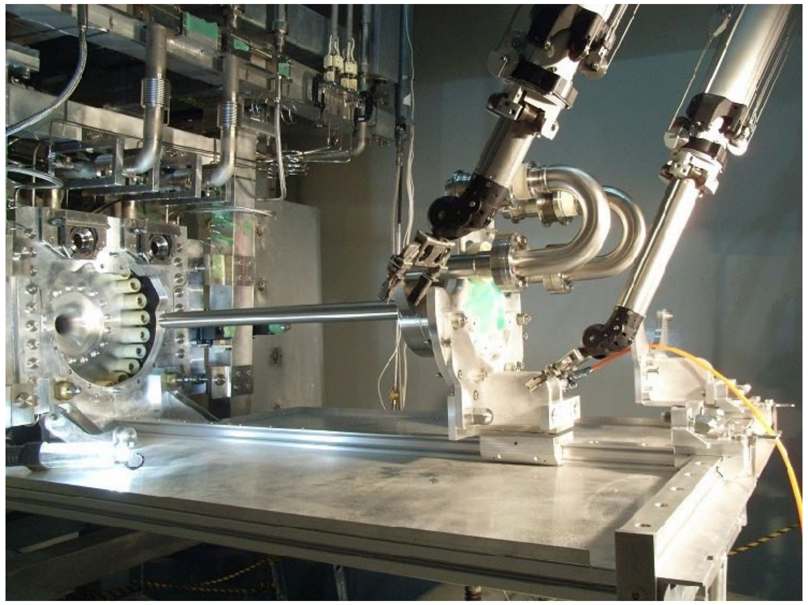
Image credits: M Brice

Canadian Efforts on J-PARC Neutrino Beam

- **Optical Transition Radiation (OTR) monitor in front of target**
    - Lead by **York U**, **U of Toronto**
    - Long-standing effort over 10 years
    - Significant contribution to beamline operation and analysis
- **Remote handling system in Target Station**
    - Lead by **TRIUMF**
    - Remote manipulator and lead glass window produced and installed in 2008
    - TRIUMF experts contributed to actual remote maintenance work for target



Photograph by Joe Nishizawa



Summary

- High power neutrino beam is key for future neutrino programs
- Ongoing facilities
  - J-PARC : ~500 kW
  - Fermilab NuMI : ~750 kW
- Future facilities
  - J-PARC 1.3 MW upgrade ($3.2\text{x}10^{14}$ ppp and 1.16 s cycle)
    - PS and RF upgrade to 750 kW scheduled in FY2021
    - Further RF upgrade thereafter
    - Neutrino beamline upgrade
  - LBNF : facility for DUNE (1.2 MW → 2.4 MW)
    - Accelerator upgrade (PIP-II) : building new 800 MeV SC Linac
    - New neutrino beamline :
      - Three horn + 1.5~2m target optimized for 1.2 MW
      - Upgradable to 2.4 MW
- International cooperation to realize high power neutrino beam facility