Accelerator and Beamline for Neutrino Long-Baseline Experiments

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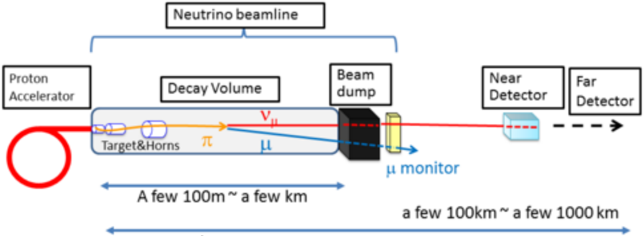
Outline

- How to make a neutrino beam for long-baseline neutrino experiments
- Accelerators for neutrino beamlines
- Neutrino beamline components
- Neutrino fluxes
- Errors on neutrino fluxes

- Using the J-PARC neutrino facility as an example
  $\rightarrow$ Neutrino source for current T2K and future Hyper-K experiments in Japan

Producing A Neutrino Beam

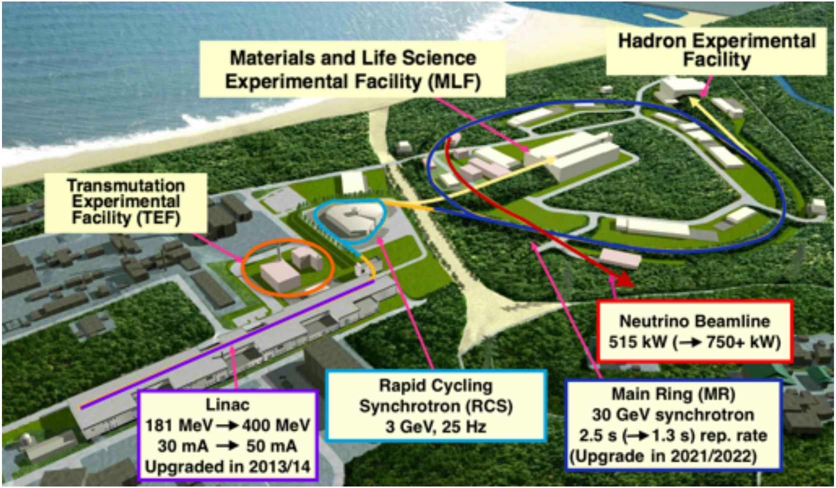


- High energy protons from an accelerator hit a production target and produce hadrons
- Outgoing hadrons are sign selected + focused in electro-magnetic focusing horns
  - Change polarity of horn field to switch between focusing positive or negative hadrons
- Allow hadrons to decay in long decay volume: $\pi^+ \to \mu^+ + \nu_\mu$, ..
- Monitor hadrons in hadron monitor at downstream of decay volume, or muons in muon monitor installed in shielding/beam dump
- Stop protons, hadrons, muons, in beam dump or ground, while neutrinos continue on to near and far detectors

Increasing the Neutrino Flux

- Neutrinos are very weakly interacting – want to increase the neutrino flux as much as possible
- How do we increase the number of neutrinos?
  $\rightarrow$ First step is to increase the number of protons
- Two ways to increase the proton beam power:
  1. Increase the frequency, number of beam spills
     - Increase beam repetition rate
     - (Maximize beam operation time..)
  2. Increase the number of protons per spill
     - Reduce beam instabilities and beam losses
  - Of course, after increasing the proton beam power, all components in the neutrino extraction beamline must be able to handle the increased power
- – And – there are ways to increase the *effective* number of protons
  - i.e. improve the target to increase right-sign hadrons, increase/tune the horn current for better right-sign hadron focusing
- Also important to run the neutrino experiment as much as possible !

High-Power Proton Source – J-PARC



- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) → 3 GeV RCS (Rapid Cycling Synchrotron) → 30 GeV MR (Main Ring Synchrotron)

Ion Source

- Accelerator chain begins with an ion source
  - Radio-Frequency (RF) driven plasma discharge
- Produces H^- ions (proton with 2 electrons)
- Why use an H^- source, rather than proton ?
  - H^- easier to handle at ion source
  - After acceleration in Linac, stripping charge to convert to protons allows for easy separation between particles (opposite forces in applied field)

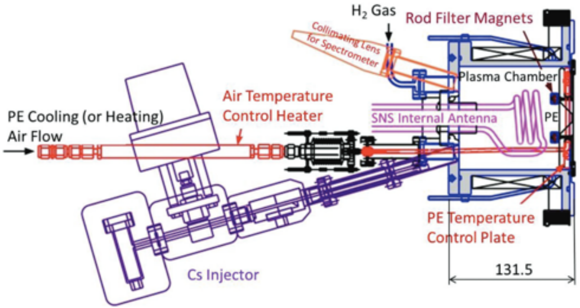


Figure from https://doi.org/10.1063/1.4995773

Radio-Frequency (RF) Cavities

- Radio-frequency cavities are the building block of any accelerator
  - High-frequency, high-power electromagnetic cavities
- Charged particles traveling through the cavity at the correct timing and energy are accelerated
  - By an electrical impulse from the field produced by the RF cavity

Beam Transport

- Particle beams are transported through beam ducts
  - Beam ducts and accelerating cavities where the particles travel must be kept at high vacuum
    - To prevent collision of the particles accelerated inside the beam ducts with gas molecules in the beam pipe
  - Charged particles of the same charge sign repel each other (space-charge effects from the Coulomb force)
    - Must prevent beam size blow-up by focusing the particle beam
    - Use focusing magnets (quadrupole magnets) with some periodicity to focus the particle beam as it propagates

Figure from
https://j-parc.jp/c/facilities/accelerators/index.html

Linear Accelerator (LINAC)

- Accelerates 50keV H^- ions from the ion source to 400MeV by four stages of DC linear accelerators:
  - Radio Frequency Quadrupole Linac – 50keV $\to$ 3MeV
  - Drift Tube Linac – 3MeV $\to$ 50MeV
  - Separated-type Drift Tube Linac – 50MeV $\to$ 191MeV
  - Annular-ring Coupled Structure linac – 191MeV $\to$ 400MeV

Ion Source

RFQ outsite

RFQ inside

DTL inside

Figures from
`https://j-parc.jp/c/facilities/accelerators/index.html`

H^- Stripping

- H^- ions are stripped of two electrons (converted to protons) after acceleration in the linac, as they are being injected into the next accelerator (RCS)
  - This conversion means that the particles move opposite directions in the applied magnetic field
- Use a very thin charge-stripping foil (carbon)
  - More advanced techniques – laser stripping – under development
- At injection point (bunching), again need to worry about beam blow up by space-charge effects

- RCS injection point:
- Particles come from the linac (right) and enter the RCS (left)

https://j-parc.jp/c/facilities/accelerators/index.html

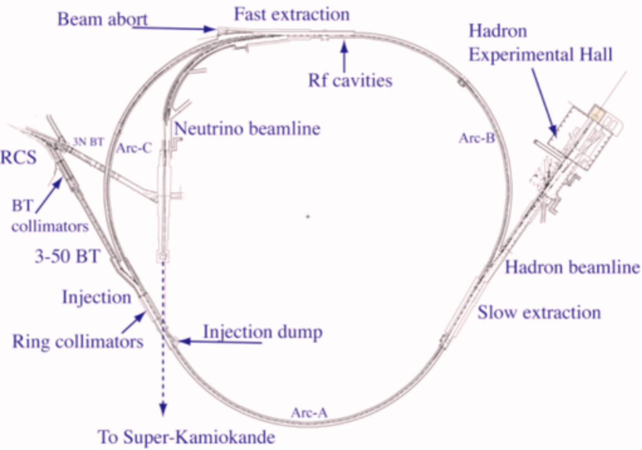
Rapid Cycling Synchrotron (RCS)

- In a linear accelerator, each particle only passes through each RF cavity a single time
- In a circular accelerator, the beam is recirculated >10,000 times, passing each accelerating cavity each time
- In a Synchrotron, the fields which bend the particle around the fixed orbit increase “synchronized” with the increasing particle energy

- J-PARC RCS:
  - ∼350m circumference
  - Accelerates protons 400MeV → 3GeV in ∼20ms
  - Operation cycle of 25Hz
    - Injection, acceleration, extraction, field decrease happen in 40ms

https://j-parc.jp/c/facilities/accelerators/index.html

Main Ring Synchrotron (MR)

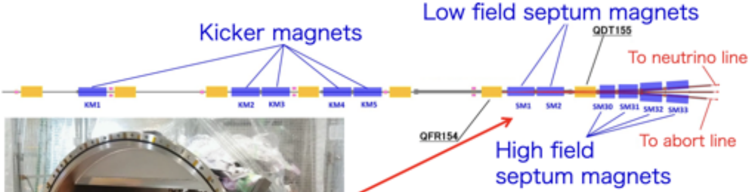


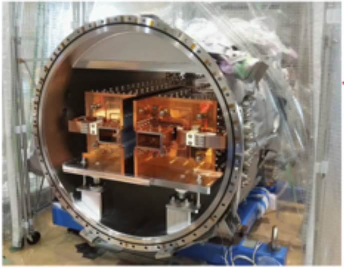
- J-PARC Main Ring Synchrotron
- Accelerates protons 3GeV $\rightarrow$ 30GeV
- 3-fold symmetric straight and bending sections
- 1568-m circumference
- 8-bunch beam structure

- 3 116-m-long straight sections dedicated to:
  - Injection and beam collimators
  - Slow extraction
  - Fast extraction and RF system
    $\rightarrow$ Fast extraction to neutrino target

Fast Extraction System

- Beam is extracted from the MR by kicker and septum magnets
  - Kicker magnet applies a time-dependent magnetic field
    - Fast, precise timing is necessary
  - Septum magnet applies a space-dependent magnetic field
    - Field localization is important – high field at extraction line must drop to 0 at recirculating line



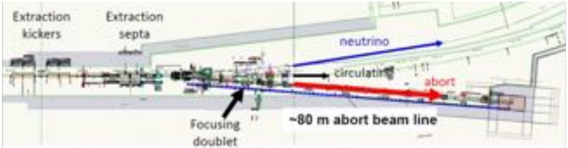

New eddy current septum magnet

Low field septum magnets were replaced by eddy current magnets.

Leakage field was reduced

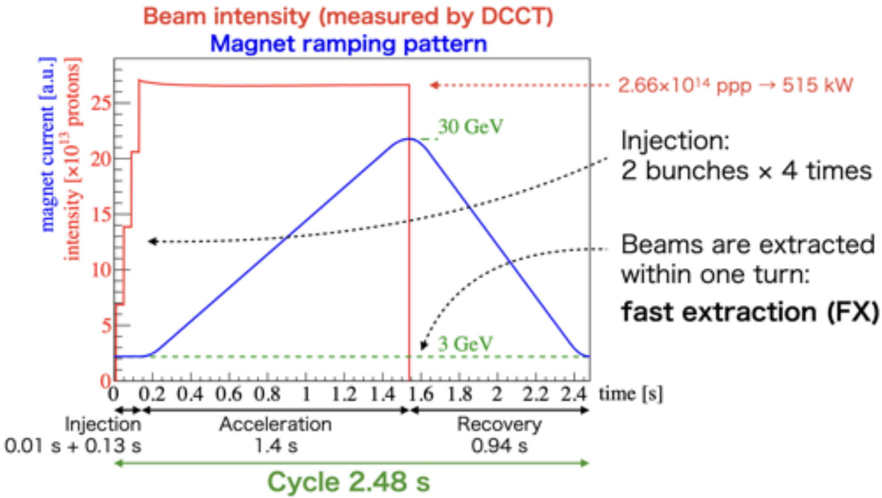
Beam Dump

- The beam dump is another component that can limit the operation of the accelerator
- During MR beam study/tuning, or when the beam is aborted, the beam is kicked to a beam dump
- The current J-PARC MR beam dump is passively cooled iron blocks in concrete
    - Operational capacity of only ∼18 shots per hour at full beam power – significantly limits time which can be spent on accelerator tuning, especially as beam intensity is increased
- Now considering upgrades to increase capacity 3∼4×



C. Densham, NBI2022

Typical MR FX Operation

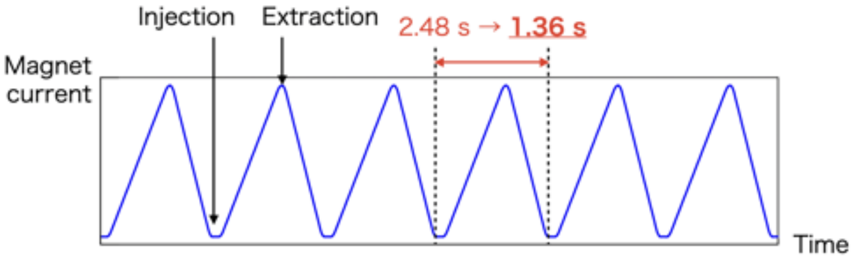


T. Yasui, NuFact2022

MR Upgrade Operation

Power = Energy × Number of protons / Cycle time
30 GeV

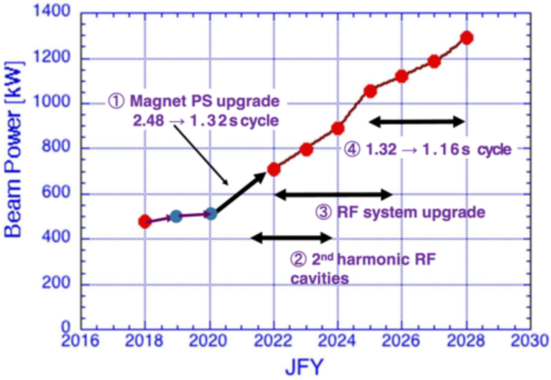
JFY2021	515 kW	2.66×10^{14} ppp	2.48 s
JFY2023	750 kW	2.1×10^{14} ppp	1.36 s
Future	1300 kW	3.3×10^{14} ppp	1.16 s



T. Yasui, NuFact2022

Increasing the MR Proton Beam Power

- In 2020, J-PARC MR accelerator delivered $\sim 2.65 \times 10^{14}$ protons every 2.48 seconds = 515 kW
- Now increasing the beam power in 2 ways:
  - Upgrade PSs + RF to reduce the time between beam spills from 1 spill every 2.48s → 1.36s → 1.16s
  - Improve stability to increase the number of protons per spill from $\sim 2.65 \times 10^{14} \rightarrow 3.2 \times 10^{14}$ 515 kW → >700 kW → 1.3 MW



	Achieved		Target
Beam power [MW]	0.5	~x3	1.3
# of protons per pulse	2.6 x 10^{14}	+30%	3.2 x 10^{14}
Rep. Time [sec]	2.48	~1/2	1.16

MR Upgrades Towards 1.3MW

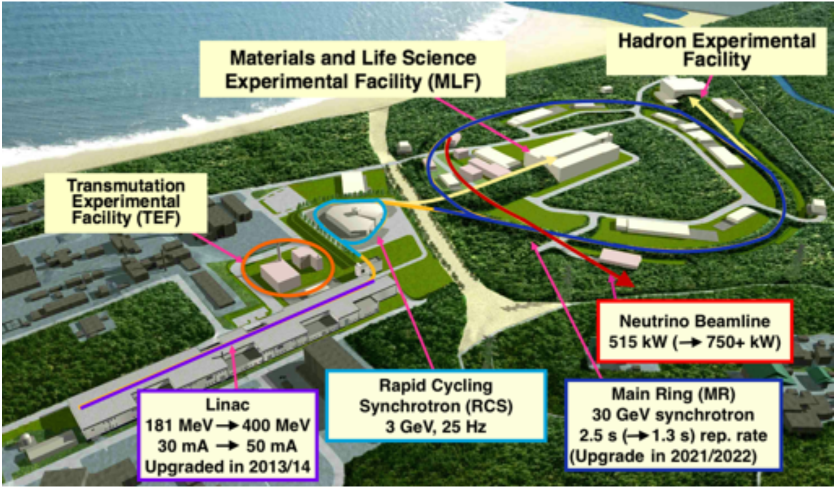
JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		Long Shutdown							
FX power [kW]	515	-	>700	800	900	>1000	>1100	>1200	1300
SX power [kW]	55	60–70	>80	>80	>80	>80	~100	~100	~100
Cycle time for Fast Extraction	2.48s		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
New Magnet PS	Mass Production Installation/Test								
RF system upgrade									
2nd RF system upgrade									
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement Septa manufacture Test								
Beam Monitors (BPM circuits)									
SX: Diffuser/Bent crystal/VHF Local shield									

Prog. Theor. Exp. Phys. 2021, 033G01

MR Power Supply Upgrade

- New MR magnet power supplies with energy recovery with capacitor banks developed
  - Allow for 1.36s repetition rate
- Installed in 2021
- Power supplies tested in-situ in April and May 2022
- Took first neutrino beam with 30GeV, 1.36s cycle repetition protons from the J-PARC MR in April 2023 → Achieved record 540kW!

High-Power Proton Source – J-PARC



- Accelerates proton beam to 30 GeV by:
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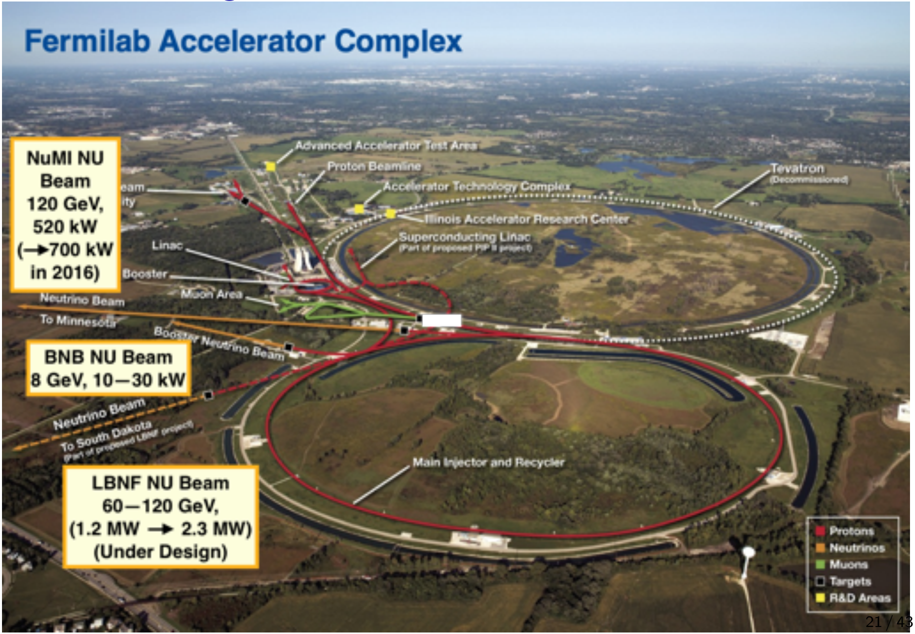
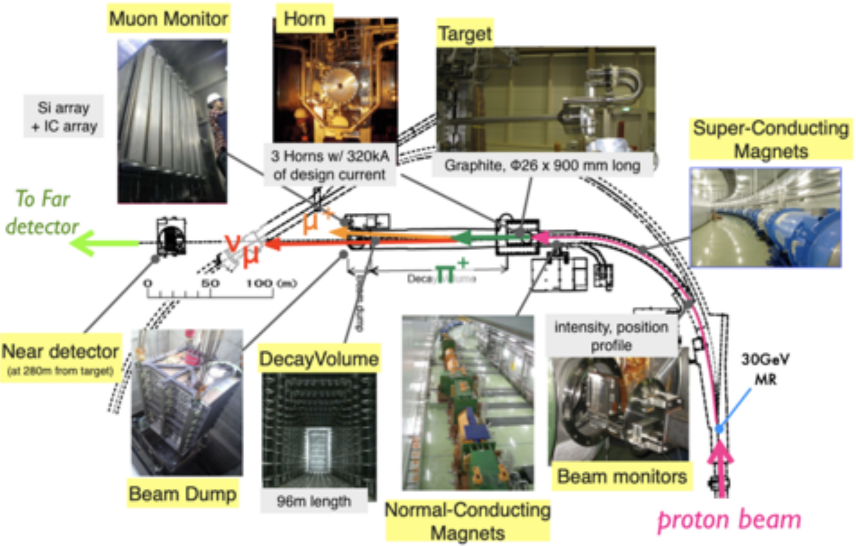
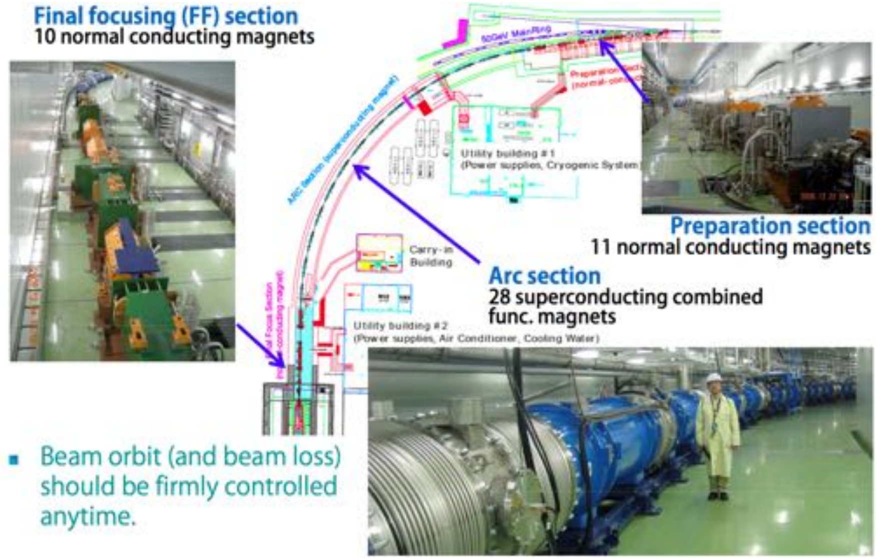
High-Power Proton Source – Fermilab



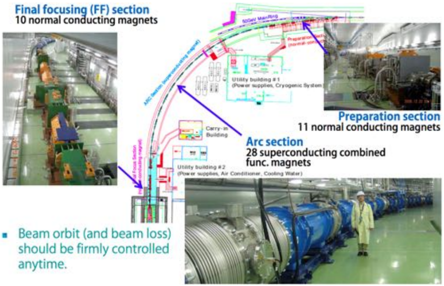
J-PARC Neutrino Beamline



J-PARC Neutrino Primary Beamline



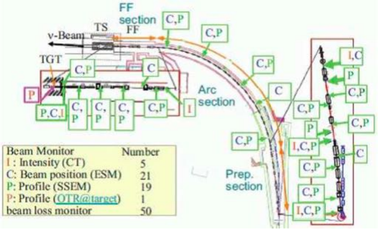
J-PARC Neutrino Primary Beamline



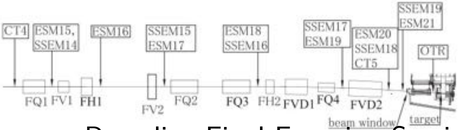
- Arc section : superconducting combined-function magnets
  - Used to sharply bend the beam towards the Super Kamiokande direction

- Preparation section : normal conducting dipole and quadrupole magnets
  - Used to bend and focus the proton beam extracted from the MR accelerator
  - Prepare the beam to be safely transported through the superconducting Arc section
- Final Focusing section : normal conducting dipole and quadrupole magnets
  - Used to bend and focus the proton beam correctly onto the neutrino production target
  - Proton beam position, angle, size at the target must be carefully controlled

Beam Monitoring



Beam Direction ⟶

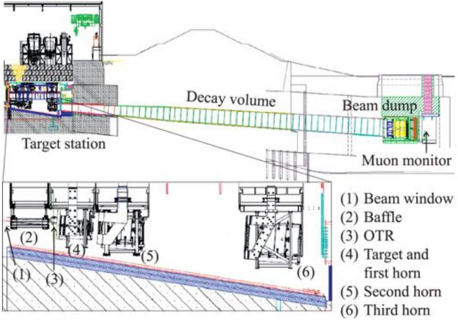


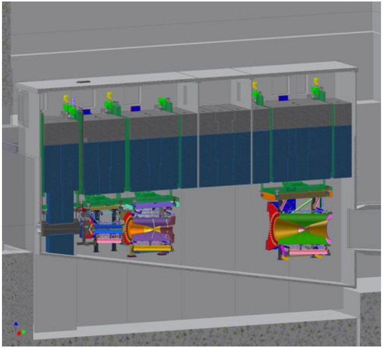
Beamline Final Focusing Section

- Beam monitors are essential for protecting beamline equipment and understanding proton beam parameters for flux simulation
- At J-PARC neutrino beamline, various monitors are installed along the beamline:
  - Current Transformers – monitor beam intensity
  - Beam Loss Monitors
  - Electrostatic Monitors – monitor beam position
  - Segmented/Wire Secondary Emission Monitors – non-continuously monitor beam profile
  - Optical Transition Radiation Monitor – continuously monitors beam at target
  - Muon Monitor – monitors tertiary muon beam profile

Neutrino Secondary Beamline

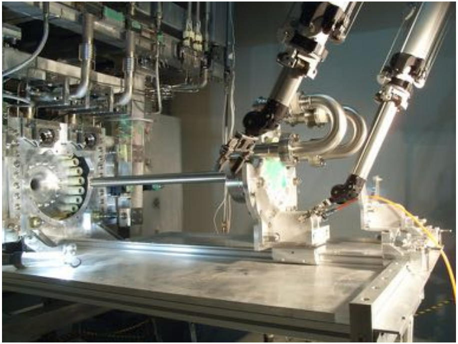
- Neutrino production target and focusing horns for J-PARC neutrino beamline are kept in a gigantic He vessel
  - $\sim$1500 m^3 He vessel (world's largest?)
  - He-filled to minimize production of tritium and NOx by interaction of high-energy hadrons with air





Neutrino Production Target

- Goal for target – increase the number of proton interactions as much as possible to maximize the number of neutrinos produced
  - Another important part – Don't degrade ! Don't break !
- J-PARC neutrino production target consists of a long, monolithic carbon target
  - 91.4cm long (1.9 interaction length), cooled by He gas
- Other world-wide targets have different configurations (ie array of fins, different materials, water cooling, etc)

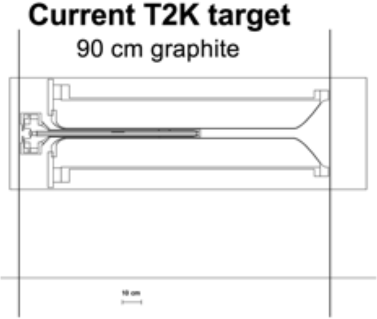


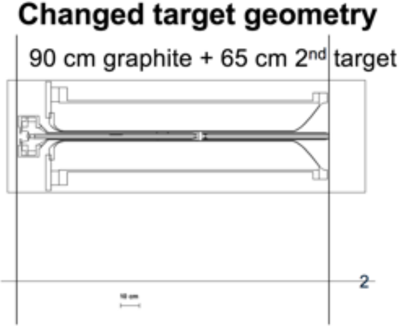
- R&D to establish new target types to further maximize number of produced neutrinos is ongoing
- Higher-density and/or hybrid materials, longer targets

Neutrino Production Target Upgrade Ideas

- Longer term studies to establish new target types to further maximize number of produced neutrinos are also ongoing
  - Possible to increase pion yield and decrease forward-going (non-horn-focused) wrong-sign component by new target design
  - Higher-density and/or hybrid materials, longer targets

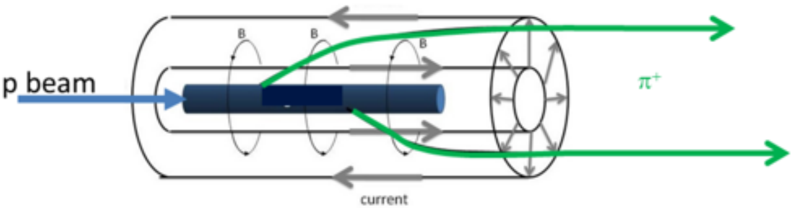
One example new target idea – insert 2nd (higher density?) target into downstream end of Horn 1:





University of Glasgow, RAL

Electromagnetic Focusing Horns



- Electromagnetic focusing horn consists of inner and outer conductor
  - Large magnetic field between conductors achieved by flowing high current down one conductor and back along the other
    - Generally 100–300 kA – T2K used 250kA, now upgraded to 320kA
- Pions of the correct sign traveling between two conductors are focused
  - Sign of focused pions chosen based on direction of flowed current
- Generally cooled by water spray between 2 conductors
- J-PARC has 3 horn configuration (other beamlines in the world have 1∼3 horns)
  - Horn 1 over-focuses some outgoing particles, Horns 2 and 3 correct path of focused and over-focused particles

J-PARC Horns

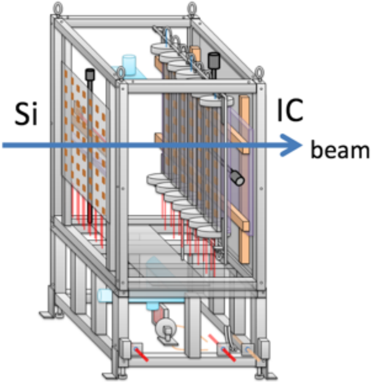
- Horn 1 (bottom) and Horn 3 (right)
- Horns held in place from above by support modules mounted to ceiling of He vessel

Decay Volume and Beam Dump

- Decay volume is just a big empty space where particles produced in the target can propagate and decay
- J-PARC neutrino beamline has 96m-long decay volume (similar at facilities around the world)
- J-PARC neutrino beamline decay volume is connected to He vessel – also He-filled to minimize production of tritium and NOx by interaction of high-energy hadrons with air
- Beam dump is graphite + iron blocks ($\sim$5m) to stop hadrons
- Water-cooled by coils

Hadron/Muon Monitor

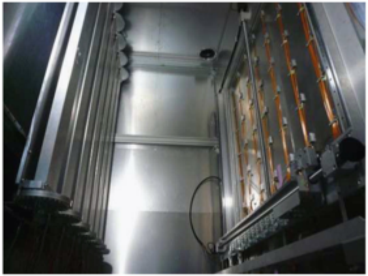
- Detect hadrons or muons after decay volume to understand hadron/muon (+ neutrino) beam direction, profile
  - Upstream (hadron monitor) or inside (muon monitor) of the beam dump
- Use large array of radiation-tolerant detectors to reconstruct the hadron/muon beam profile

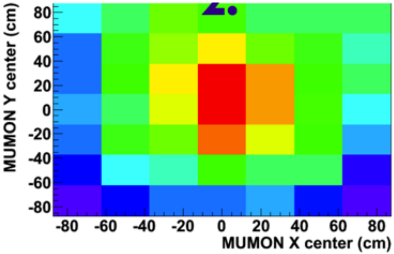


T2K Muon Monitors

MUMON (Muon Monitor)

- Continuously monitors muon beam profile downstream of the decay volume, beam dump (>∼5 GeV muons)
  - Ensure alignment, healthiness of target, horns; proton beam position, angle at target; etc
- 2 redundant measurements of the muon beam profile, position using 7x7 arrays of sensors
  - Ionization chambers (IC) w/ Ar or He gas
  - Silicon photodiode sensors (Si)
- Same IC design used at Fermilab NUMI beamline
- Now developing upgraded sensors; Electron Multiplier Tube (EMT) under testing



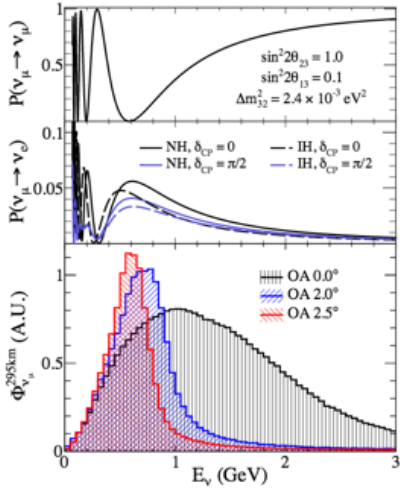


Controlling the Flux – Off-Axis Beam

- "Off-axis" beam concept :
  - Due to pion decay kinematics, the neutrino energy depends on the outgoing neutrino angle:

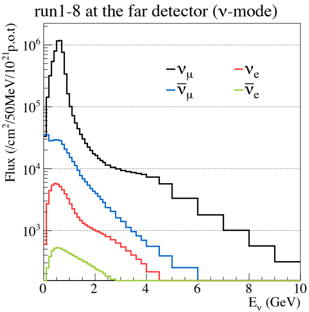
    $E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$
  - So, an "off-axis" beam gives a smaller range of neutrino energies
- Many experiments use an off-axis beam to select a neutrino flux with a peak energy near the oscillation maximum

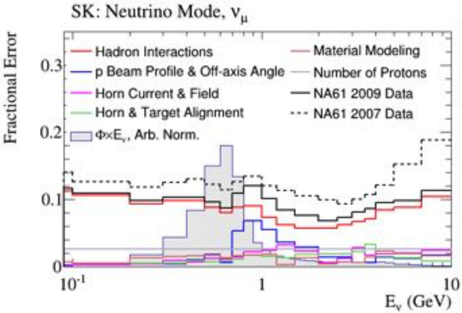
Flux + Osc. Prob. at T2K



- Install detectors off-axis from the center of the neutrino beam to select the energy
- Precise understanding of the neutrino beam direction essential

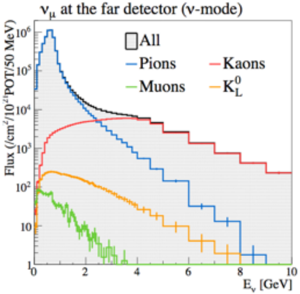
Flux Prediction

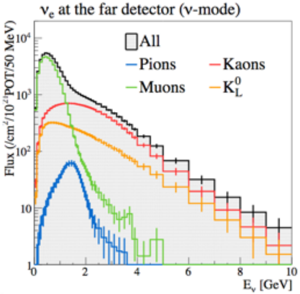




- It is essential to not just produce a world-class neutrino beam, but also to understand the energy spectrum and number of produced neutrinos
- The ν flux is predicted by simulations which take into account
  - Hadron interactions inside + outside the production target
  - Measured proton beam current, position, angle, profile
  - Measured neutrino beam angle
  - Measured Horn field, alignment
  - etc..

Neutrino Parent Particles





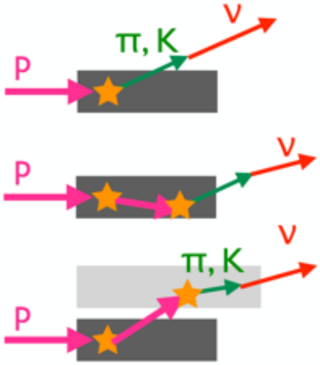
- ν_μ parent particle is mostly pions, which decay into $\mu + \nu_\mu$ 99.9% of the time
- However, kaons and other particles also contribute, especially at higher energies – produce some ν_e's, as well as muons
- Muons also decay, always produce $\nu_\mu + \nu_e$
- Need to understand neutrino parent particles produced inside and outside of the target
  $\rightarrow$ External hadron production experiments

		channel	BR [%]
π	$\rightarrow$	$\mu\ \nu_\mu$	99.9
	$\rightarrow$	e ν_e	10^{-4}
K	$\rightarrow$	$\mu\ \nu_\mu$	63.5
	$\rightarrow$	π^0 e ν_e	5.1
	$\rightarrow$	$\pi^0\ \mu\ \nu_\mu$	3.3
K_L^0	$\rightarrow$	π e ν_e	40.5
	$\rightarrow$	$\pi\ \mu\ \nu_\mu$	27.0
μ	$\rightarrow$	e $\nu_e\ \nu_\mu$	100

Neutrino Parent Interactions

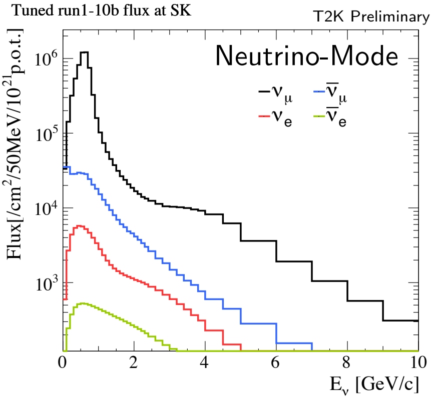
Percentage of neutrino-mode T2K far detector flux from in-target or out-of-target interactions :

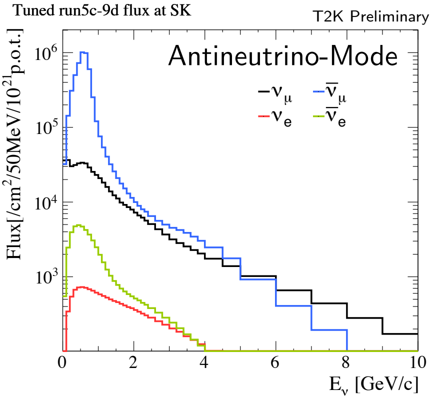
	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)



- In-target primary interactions are the main contribution
- However, there is a significant contribution from secondary+tertiary and/or out of target interactions, especially for the wrong sign flux

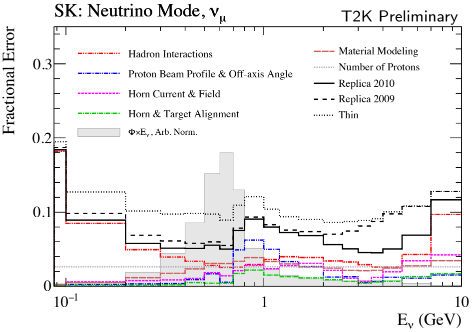
T2K Neutrino Fluxes





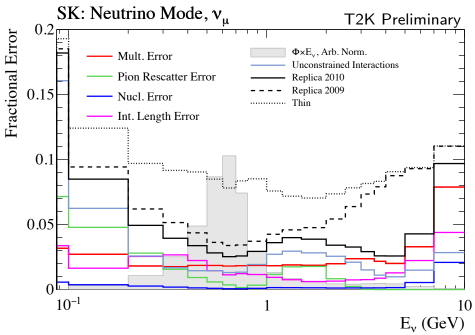
- Accelerators can produce a relatively pure beam of right-sign muon neutrinos (ie ν_μ's in neutrino-mode and $\bar{\nu}_\mu$'s in antineutrino-mode)
- At J-PARC:
  - $\sim$3% contamination of beam wrong-sign ν_μ at flux peak
  - $<$1% contamination of beam ν_e at flux peak

Systematic Errors on the Neutrino Flux



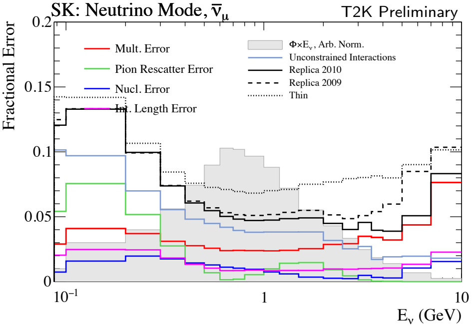
- Total current flux errors are around ∼5∼10% near the flux peak for various experiments
  - Can be (significantly) higher at low and high energies
- Significant contribution from hadron production uncertainties
- As hadron production errors are reduced by external measurements, errors related to beamline hardware are becoming important

Hadron Production Errors on the Neutrino Flux



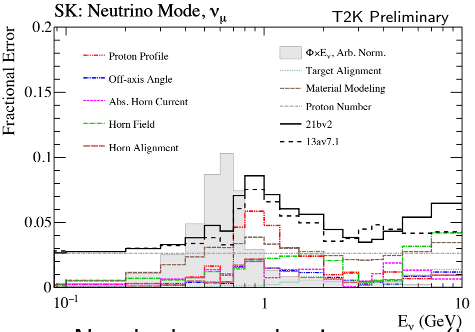
- Hadron production errors are coming from numerous relatively small sources – non-trivial to reduce (although we're working on it!)
- Especially, interactions not constrained by external measurements – "Unconstrained interactions" – are becoming important
  - Try to constrain by additional data from dedicated hadron production measurements: NA61 @CERN, EMPHATIC @FNAL

Hadron Production Errors on the Neutrino Flux



- These unconstrained and out-of-target secondary interactions are even more of an issue for the wrong-sign neutrino flux and beam intrinsic electron neutrino flux

Non-Hadron Production Errors on the Neutrino Flux



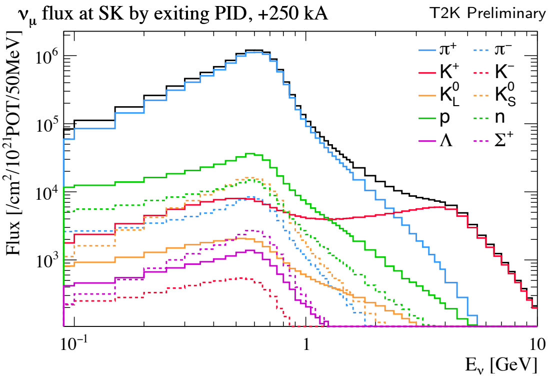
- Non-hadron production errors (beamline hardware related errors) can also have ∼5% energy-dependent contribution
- Becoming more important as hadron production errors are reduced
- These errors are related to beamline hardware, so can be time-dependent – need to worry about correlations between different run periods, etc

Conclusion

- Many components required to produce a high-intensity neutrino beam:
  - Proton source
  - Proton beam transport to the production target
  - Proper beam monitoring
  - Production target
  - Focusing horns
  - Decay volume/beam dump
  - Tertiary beam monitoring
- Essential to have a stable, high-intensity proton source
- Essential to have neutrino beamline components robust to beam heating, radiation damage, ...
- Essential to have a well-understood beamline in order to have a well-understood/well-constrained neutrino flux

Backup Slides

Neutrino Parent Particles



Neutrino parent particles are mostly pions, kaons produced in the target

$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=99.99%) (right-sign low-E ν_μ's)

$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ (BR=63.6%) (right-sign high-E ν_μ's)

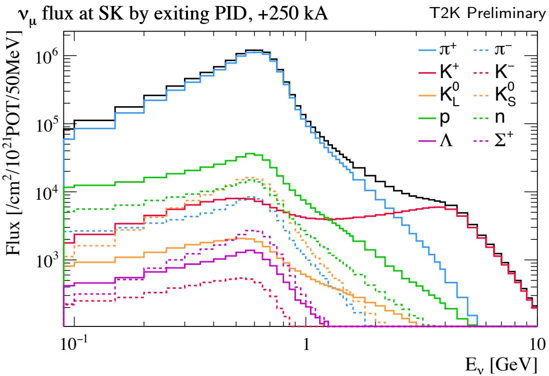
↳ $\mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ (BR=100%) (right-sign ν_e's)

$K_L \to \pi^\pm + \mu^\mp + \bar{\nu}_\mu(\nu_\mu)$ (BR=27.0%) (right- and wrong-sign ν_μ's)

$K_L \to \pi^\pm + e^\mp + \bar{\nu}_e(\nu_e)$ (BR=40.6%) (right- and wrong-sign ν_e's)

....

Neutrino Parent Particles



Neutrino parent particles are mostly pions and kaons produced in the target, but can also be from particles produced by secondary interactions of protons and neutrons (+ pions, kaons, ...) in other materials around the beamline

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$ (BR=99.99%) (right-sign low-E ν_μ's)

$K^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$ (BR=63.6%) (right-sign high-E ν_μ's)

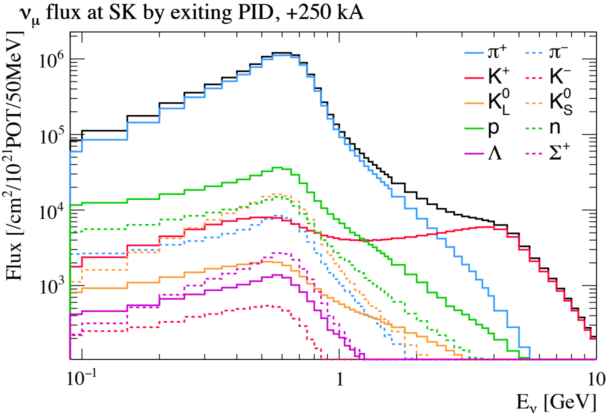
$\quad \hookrightarrow \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ (BR=100%) (right-sign ν_e's)

$K_L \rightarrow \pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu)$ (BR=27.0%) (right- and wrong-sign ν_μ's)

$K_L \rightarrow \pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e)$ (BR=40.6%) (right- and wrong-sign ν_e's)

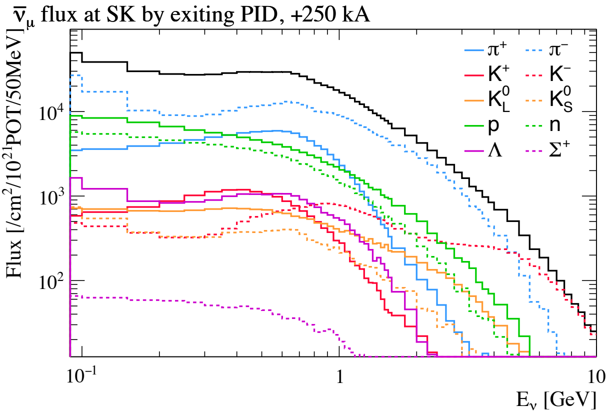
....

Neutrino Parent Particles



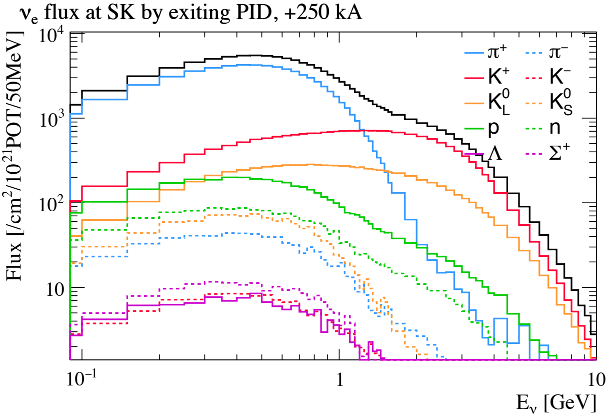
- Main contribution of right-sign flux from right-sign pions near flux peak, right-sign kaons at higher energies
- Then hadrons produced by proton interactions with materials outside of the target, then others..

Neutrino Parent Particles



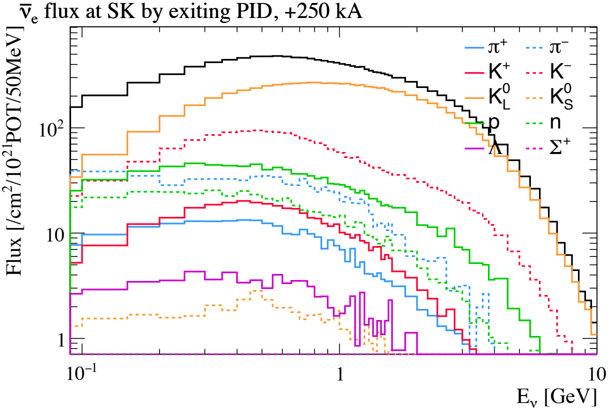
- Main contribution of wrong-sign flux from wrong-sign pions, muons from right-sign pion decay
- Then hadrons produced by proton/neutron interactions with materials outside of the target

Neutrino Parent Particles



- Main contribution of ν_e flux from muon decay from right-sign pions and kaons
- Then K^0, hadrons produced by proton/neutron interactions with materials outside of the target, ...

Neutrino Parent Particles



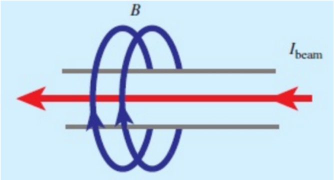
- Main contribution of $\bar{\nu}_e$ flux from K^0_L, then muon decay from wrong-sign kaons
- Then hadrons produced by proton/neutron interactions with materials outside of the target, muon decay from wrong-sign pions, ...

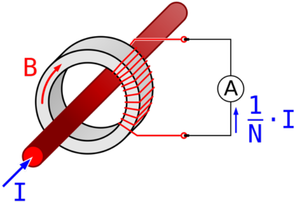
Beam Monitoring

Beam Intensity Monitoring

Current Transformer Concept

- A proton beam with current I_{beam} generates a magnetic field, **B**, as it travels
  - Exactly like a wire carrying a current
- The magnetic field is felt by a transformer core around the beamline

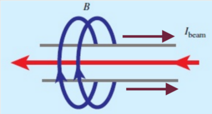




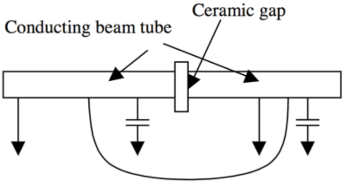
- Magnetic field in core induces a secondary current, I_{sec} on a wire coiled around the core
- The beam acts as primary winding with $N_{beam} = 1$, so :
  - $I_{beam}/I_{sec} = N_{torus}/N_{beam} \quad \rightarrow \quad I_{sec} = I_{beam}/N_{torus}$
- Can measure beam current by adding a resistor and using Ohm's Law : $V = R \times I_{sec} \quad \rightarrow \quad I_{sec} = V/R$
- So : $I_{beam} = N_{torus} \times V/R$

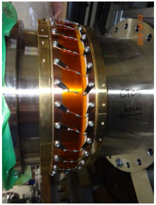
Current Transformer Concept

- When the proton beam travels along the beamline, a ∼equal but opposite "image charge" is induced on the (conducting) beampipe
- This image charge basically cancels the beam current, making monitoring through the beam pipe impossible !



- Must put a non-conducting "break" in the beamline to see the beam (ceramic works well)
  - High-frequency component of the image charge goes through series of resistors over the gap (so, not seen by the CT)
  - Conducting shell around the CT should allow the low-frequency component of the image charge to pass

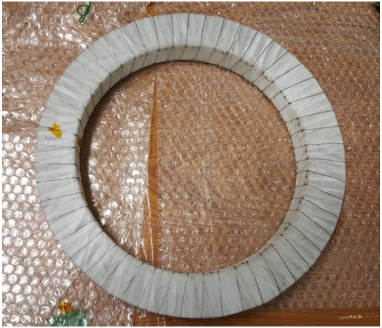




T2K Current Transformers

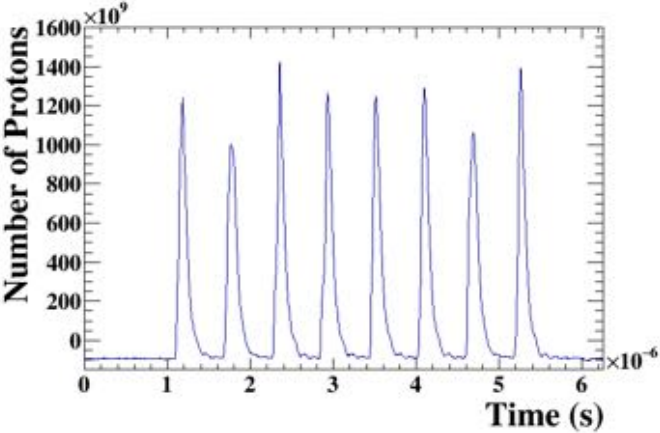
5 CTs (Current Transformers) + 2 R&D PPS-CTs

- Monitor proton beam intensity
- Cylindrical ferromagnetic core made of FINEMET® (nanocrystalline Fe-based soft magnetic material) from Hitahi Metals
- 50-turn toroidal coil
- Stainless steel + iron outer casing



Signal From Current Transformers

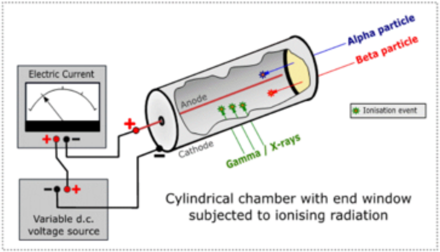
- CT is read out/digitized by 160MHz ADC
  - Integrate total charge seen by CT, then convert to # of protons (1 proton $= 1.602 \times 10^{-19}$ C)
  - Very clearly see the time structure of the J-PARC proton beam



Beam Loss Monitor

Beam Loss Monitor

- Wire proportional counter filled with a mixture of ∼90% inert gas + ∼10% quench gas
- Ionizing particle produced by beam loss travels through the chamber, ionizes inert gas in the chamber, produces e^{-} – ion^{+} pairs
  - Number of pairs proportional to the energy of the particle
- An electric field in the chamber causes positive ions to drift towards the cathode and electrons towards the anode
- Near the anode wire, the field strength is large enough to produce an avalanche to multiply the electron signal for readout
  - Should only produce one avalanche per electron-ion pair for linear response



T2K Beam Loss Monitors

50 BLMs (Beam Loss Monitors)

- Continuously monitor beam loss
- Wire proportional counter filled with an Ar-CO_2 mixture
- Ionizing particles produced by beam loss ionize gas in chamber $\sim$proportional to amount of beam loss
  - Actually, some BLM response function needed..
  - Down to very low levels of loss
- The BLM signal is integrated during each beam spill, and if it exceeds a set threshold a beam abort interlock signal is fired

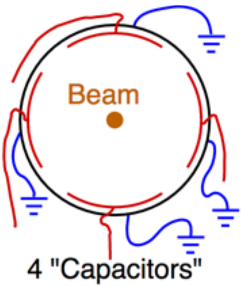
$\rightarrow$ Extremely important for protecting beamline equipment and understanding residual radiation of beamline components

- R&D for new BLM types (optical fiber, etc) is also underway at T2K

Beam Position Monitoring

Beam Position Monitor

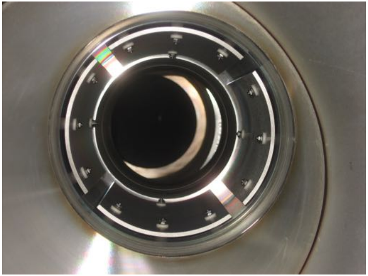
- Standard beam position monitor uses 4 segmented cylindrical electrodes surrounding the proton beam orbit
  - Beam passage induces charge on electrodes proportional to distance from that electrode
- Asymmetry between signal from opposite electrodes gives beam position inside the beampipe :
  - $\frac{C_R - C_L}{C_R + C_L}$ gives beam X position
  - $\frac{C_U - C_D}{C_U + C_D}$ gives beam Y position



T2K Beam Position Monitors

21 ESMs (Electrostatic Monitor) used in T2K extraction beamline

- Non-destructively, continuously monitor the proton beam position
  - Uses 4 simple, curved electrodes
  - Can be non-linearites, second order effects, especially away from monitor center
  - Can be effect due to scattered particles from other beam monitors
    - Improved designs, beyond simple 4-electrode one, also in use at different facilities

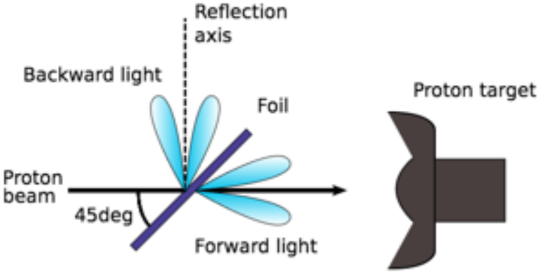


Beam Profile Monitoring

- Beam profile $=$ beam position $+$ beam width

Optical Transition Radiation Monitor (OTR)

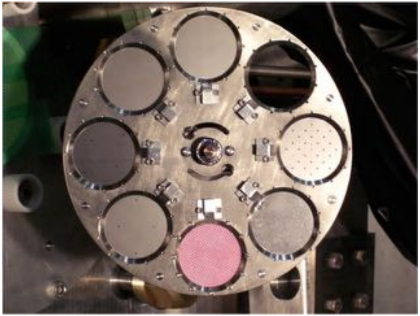
- Optical Transition Radiation is produced when a charged particle travels between two materials with different dielectric constants
  - Light profile is proportional to charged particle beam profile
- If the material (foil) is placed at 45° with respect to the beam, can measure backwards-going OTR light at 90° from the beam direction



T2K Optical Transition Radiation Monitor

1 OTR (Optical Transition Radiation Monitor)

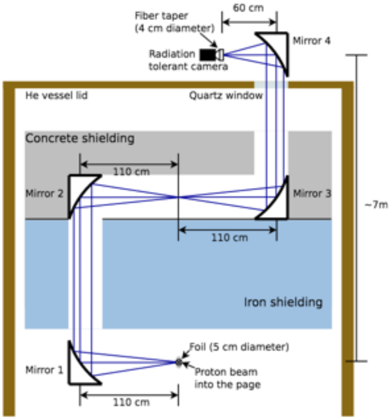
- Continuously monitors beam profile directly upstream of the target
- Rotatable disk with 8 foil positions allows for many OTR target types
  - 50-μm-thick Ti foil designed for standard data-taking
  - Ceramic foil (which produces fluorescent light) used for very low intensity beam
  - Ti foils with holes used for optical system calibration by back-lighting



T2K Optical Transition Radiation Monitor

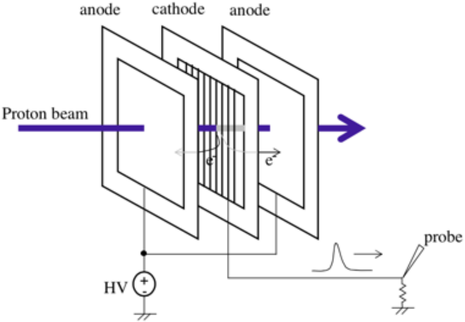
1 OTR (Optical Transition Radiation Monitor)

- Continuously monitors beam profile directly upstream of the target
- T2K OTR monitors backwards-going light from foil
  - Light is directed to TS ground floor by a series of 4 mirrors and then monitored by a radiation-hard camera



Secondary Emission Monitor

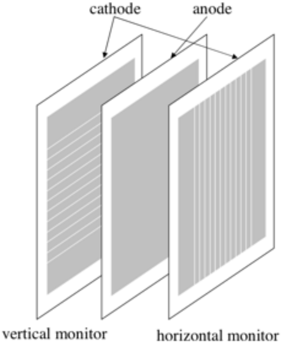
Secondary Emission Profile Monitor Principle



- Protons interact with foils inserted into the beam
- Secondary electrons are emitted from segmented cathode plane and collected on anode planes
  - Proportional to proton beam profile
- Compensating charge in each cathode strip is read out as positive polarity signal

T2K Secondary Emission Monitor

T2K Profile Monitor : Segmented Secondary Emission Monitor (SSEM)

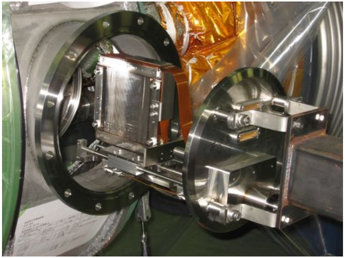


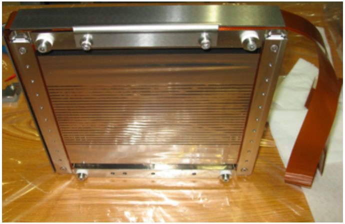
- Same principle, but single anode plane between two stripped cathode planes used to collect electrons
  - 1 stripped plane for X, 1 for Y
- 5 μm thick Ti foils

T2K SSEMs

19 SSEMs (Segmented Secondary Emission Monitor)

- Measure beam profile during tuning
  - 1 SSEM causes 0.005% beam loss
    $\rightarrow$ Only most downstream SSEM (SSEM19) can be used continuously
- Two 5-μm-thick titanium foils stripped horizontally and vertically, with a 5-μm-thick anode HV foil between them
  - Strip width ranges from 2 to 5 mm, optimized according to the expected beam size
  - Remotely move into and out of the beamline
- SSEM19 is used for beam interlock – if beam profile at the target is outside of the allowed range, beam abort interlock signal is fired



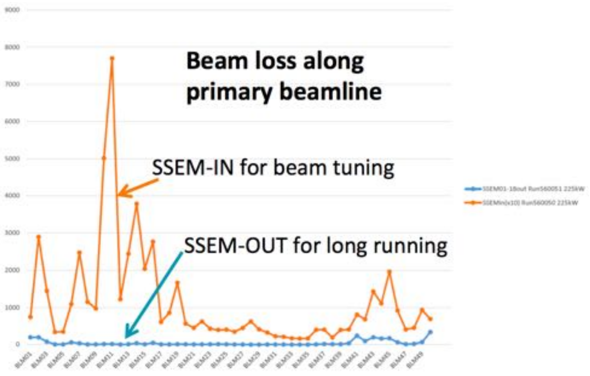


T2K Proton Beam Profile Monitor R&D

Why Is Non-Destructive (+ Minimally-Destructive) Proton Beam Monitoring Important?

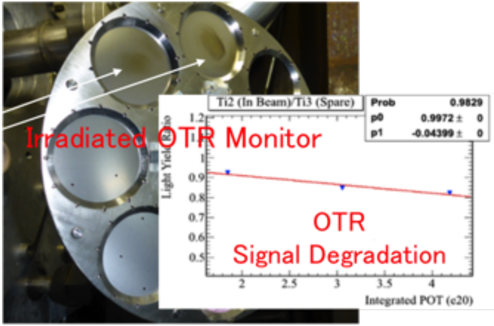
- Standard monitors measure the beam profile by intercepting the beam – they are *destructive* and cause *beam loss*
  - Absolute amount of beam loss is proportional to beam power and volume of material in the beam
- Beam loss can cause :
  - Irradiation of and damage to beamline equipment
  - Increased residual radiation levels in the beamline tunnel
- Foils in the beam may degrade
  - Rate of degradation will increase as the beam power increases
- The beam profile must be monitored continuously
  - So, R&D for J-PARC proton beam profile monitors that work well at high beam power is ongoing
    - Goal : reduce or eliminate beam loss due to profile monitor
    - Goal : work well for a long time, even at high beam power

Measured Beam Loss Due to SSEMs



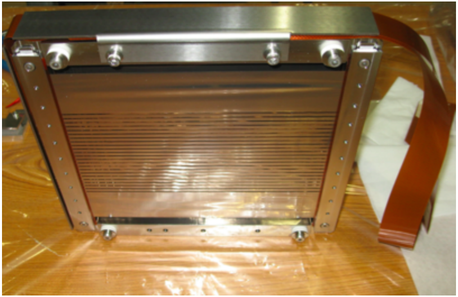
- Beam loss when SSEMs are IN is quite high
  - $\sim$0.005% beam loss at each SSEM
- Can cause radiation damage, activation of beamline equipment
  - SSEMs upstream of the neutrino target station cannot be used continuously

Observed Degradation



WSEM Beam Profile Monitor

- Wire Secondary Emission Monitor (WSEM) designed to measure proton beam profile in the T2K beamline (same design used at Fermilab)
- Monitor beam profile using twinned 25 μm Ti wires
  - Exact same principle as SSEMs but with reduced material in the beam $\rightarrow$ beam loss reduced by factor of 1/10
  - C-shape allows monitor to be moved into and out of the beam wile the beam is running
    - Wires mounted at 45° so they can measure X and Y



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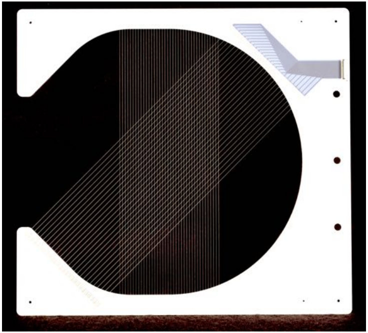
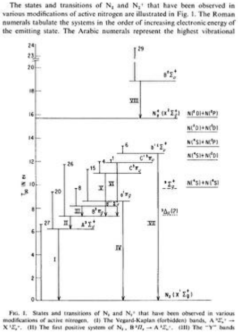
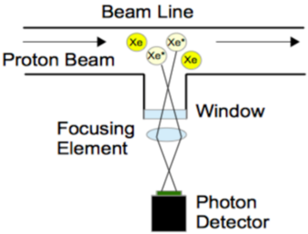


Beam Induced Fluorescence Monitor (BIF)

- Protons hit gas (i.e. N_2, Xe) inside the beam pipe
- Gas molecules are excited by the interaction with the protons
  - Electrons in the gas promoted to excited (rotational, vibrational, etc) states
  - Gas may or may not be ionized (electrons ripped off)
- When electrons fall to a lower energy orbit, photons are emitted
  - Fluorescence of the gas
- Pattern of fluorescence light should be proportional to the proton beam profile that excited the gas



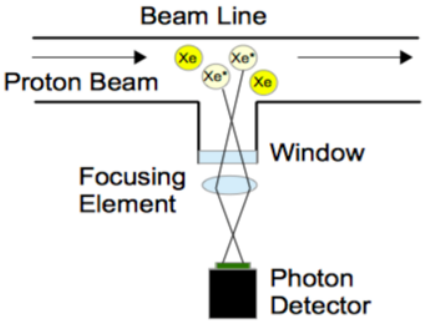


Beam Induced Fluorescence Monitor Merit

- Measure beam profile by fluorescence induced by proton beam interactions with gas in the beamline
- Need ∼1000km of gas @1×10^{-3} Pa to equal beam loss from 1 SSEM

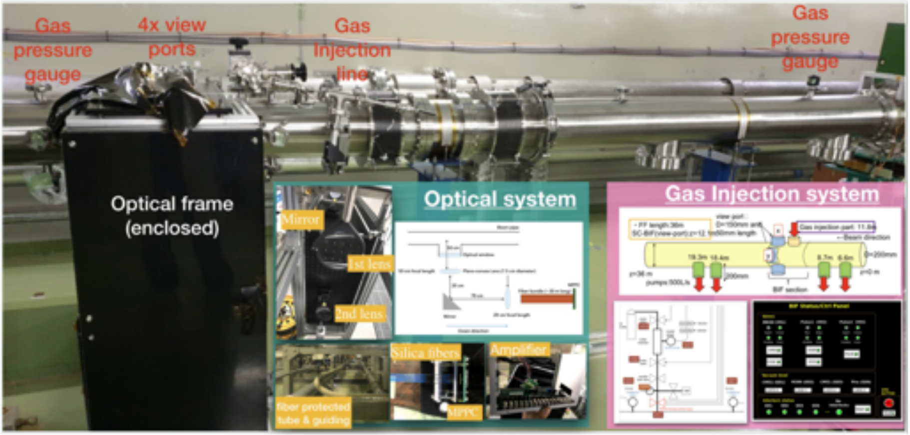
    → Basically totally non-destructive (in T2K extraction line)

→ Can be used to continuously and non-destructively monitor proton beam profile even at very high beam power !



T2K Beam Induced Fluorescence Monitor

- Installed various components for full prototype monitor in neutrino primary beamline in 2019
  - Pulsed gas injection system
  - 2 systems for optical focusing, transport, light detection (1 horizontal, 1 vertical)



Working Prototype BIF Monitor @T2K (!)

- Injected N_2 gas into J-PARC neutrino primary beamline at the same timing as the proton beam
- Installed 2 different sensor arrays to observe produced BIF light from proton interactions with injected gas
- Made first observation of BIF light at J-PARC neutrino beamline last January (!)