How to Make and Monitor an Accelerator-Based Neutrino Beam

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Outline

• How to make a neutrino beam
  • Components of a neutrino beamline
• How to monitor a neutrino beam
  • Near detectors ! → Discussed by Matsubara-san last week
  • → How to monitor neutrino beam production

• Note: I work at the J-PARC neutrino beamline, so will focus on components there
  • However, the configuration of other neutrino beamlines around the world is quite similar
How to Make a Neutrino Beam
How to Make a Neutrino Beam

- High energy protons from an accelerator hit a long carbon target and produce (mostly) $\pi$’s
  - Understanding + controlling this proton beam is very important
- $\pi$’s are focused in electro-magnetic horns
  - + horn polarity focuses $\pi^+$’s, which mostly decay into $\mu^+$ and $\nu_\mu$ in long decay volume
  - – horn polarity focuses $\pi^-$’s, which mostly decay into $\mu^-$ and $\bar{\nu}_\mu$
- The decay $\mu$’s are monitored using a muon monitor and stop in shielding, while the $\nu$’s continue on to a near and far detector
- The neutrino flux is directly proportional to the proton beam power
Proton Source
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)
J-PARC High Power Proton Accelerator

- 30 GeV proton beam from J-PARC MR to J-PARC neutrino beamline for T2K (and future Hyper-K) experiments
- Delivers \( \sim 2.65 \times 10^{14} \) protons every 2.48 seconds
  - Power = Number of Protons/Second \( \times \) Energy \( \rightarrow \) \( \sim 515 \) kW
  - MR design beam power: 750 kW
    - Plan to upgrade beamline to deliver \( \sim 3.2 \times 10^{14} \) protons per 1.16 seconds (\( \sim 1.3 \) MW)
- One of the world’s highest intensity proton beams!
High-Power Proton Source – Fermilab

Fermilab Accelerator Complex

NuMI NU Beam
120 GeV, 520 kW
(→700 kW in 2016)

BNB NU Beam
8 GeV, 10–30 kW

LBNF NU Beam
60–120 GeV,
(1.2 MW → 2.3 MW)
(Under Design)
**Increasing the Proton Beam Power**

- Want to increase the number of protons hitting your target as much as possible
  - Since number of neutrinos produced is proportional to number of incident protons

- At J-PARC, plan to do this in 2 ways:
  - Reduce the time between beam spills from 1 spill every 2.48s → 1.3s → 1.16s
  - Increase the number of protons per spill from \( \sim 2.65 \times 10^{14} \rightarrow 3.2 \times 10^{14} \)

- Also important to run the neutrino experiment as much as possible!
Neutrino Beamline Overview
J-PARC Neutrino Beamline

- Muon Monitor
- Horn
- Target
- 3 Horns w/ 320kA of design current
- Graphite, Φ26 × 900 mm long
- Super-Conducting Magnets
- Near detector (at 280m from target)
- Beam Dump
- DecayVolume (96m length)
- Normal-Conducting Magnets
- Beam monitors
- intensity, position profile
- proton beam
J-PARC Neutrino Primary Beamline

Final focusing (FF) section
10 normal conducting magnets

Arc section
28 superconducting combined func. magnets

Preparation section
11 normal conducting magnets

Beam orbit (and beam loss) should be firmly controlled anytime.
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 orbit (and beam loss) should be firmly controlled anytime.
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
- Other beamlines (ie NUMI at Fermilab) are air-filled
- Future LBNF beamline at Fermilab will be N$_2$/He-filled
Neutrino Secondary Beamline Components
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
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 uses 250kA to be 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 (≈5m) to stop hadrons
- Water-cooled by coils
Off-Axis Beam Concept + Flux Prediction
Off-Axis Beam Concept

- T2K at J-PARC was the first neutrino experiment to use an “off-axis” beam:
  - The T2K far detector is not sitting at the center of the neutrino beam – instead it is 2.5° off-axis
- The “off-axis” beam concept gives a smaller range of neutrino energies
- Precise measurement of the beam angle is very important
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 T2K $\nu$ 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

- $\nu_\mu$ 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 $\nu_e$'s, as well as muons.
- Muons also decay, always produce $\nu_\mu + \nu_e$.
- Need to understand neutrino parent particles produced in the target $\rightarrow$ external hadron production experiments.
  - ie NA61/SHINE experiment @CERN

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Beam Monitoring
Beam Monitors @J-PARC NU Beamline

Beam Direction →

Beamline Final Focusing Section

• Beam monitors are essential for protecting beamline equipment and understanding proton beam parameters for flux simulation

• 5 CTs (Current Transformers) – monitor beam intensity
• 50 BLMs (Beam Loss Monitors)
• 21 ESMs (Electrostatic Monitors) – monitor beam position
• 20 SSEMs + WSEMs (Segmented/Wire Secondary Emission Monitors) – non-continuously monitor beam profile
• 1 OTR (Optical Transition Radiation) Monitor – continuously monitors beam at target
• 1 MUMON (Muon Monitor) – monitors secondary muon beam profile
Beam Intensity Monitoring
Current Transformer Concept

- A proton beam with current $I_{\text{beam}}$ 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, $I_{\text{sec}}$ on a wire coiled around the core

The beam acts as primary winding with $N_{\text{beam}} = 1$, so :
- $I_{\text{beam}}/I_{\text{sec}} = N_{\text{torus}}/N_{\text{beam}}$ \implies $I_{\text{sec}} = I_{\text{beam}}/N_{\text{torus}}$
- Can measure beam current by adding a resistor and using Ohm’s Law : $V = R \times I_{\text{sec}}$ \implies $I_{\text{sec}} = V/R$
- So : $I_{\text{beam}} = N_{\text{torus}} \times V/R$
Current Transformer Concept

- When the proton beam travels along the beamline, a \( \sim \) 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 Hitachi 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
    \[ 1 \text{ proton} = 1.602 \times 10^{-19} \text{ C} \]
  - 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 \( \sim 90\% \) inert gas + \( \sim 10\% \) quench gas
- Ionizing particle produced by beam loss travels through the chamber, ionizes inert gas in the chamber, produces \( \text{e}^- - \text{ion}^+ \) 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
50 BLMs (Beam Loss Monitors)

- Continuously monitor beam loss
- Wire proportional counter filled with an Ar-CO₂ mixture
- Ionizing particles produced by beam loss ionize gas in chamber ~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 → 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 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
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-linearities, 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
19 SSEMs (Segmented Secondary Emission Monitor)

- **Measure beam profile** during tuning
  - 1 SSEM causes 0.005% beam loss
  - 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

- T2K OTR generally working well, but ...
- Gradual decrease in OTR signal size with integrated incident POT has been observed (left)
- Foil darkening where the beam hits also observed
  - Materials properties study of previously used OTR foils ongoing
  - Foil darkening also seen for SSEM19 (right)
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 → beam loss reduced by factor of 1/10
  - C-shape allows monitor to be moved into and out of the beam while the beam is running
    - Wires mounted at 45° so they can measure X and Y
Beam Induced Fluorescence Monitor (BIF)

- Protons hit gas (i.e. N\textsubscript{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 $\sim 1000\text{km}$ of gas @1 $\times 10^{-3}$ 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 (!)
Secondary Beam Monitoring
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
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
Conclusion

- Many components required to produce a high-intensity neutrino beam!
- Careful monitoring required to maintain a stable and high-quality neutrino beam!