Neutrino Flux Predictions
Day 1 – Neutrino Beam Production

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Outline

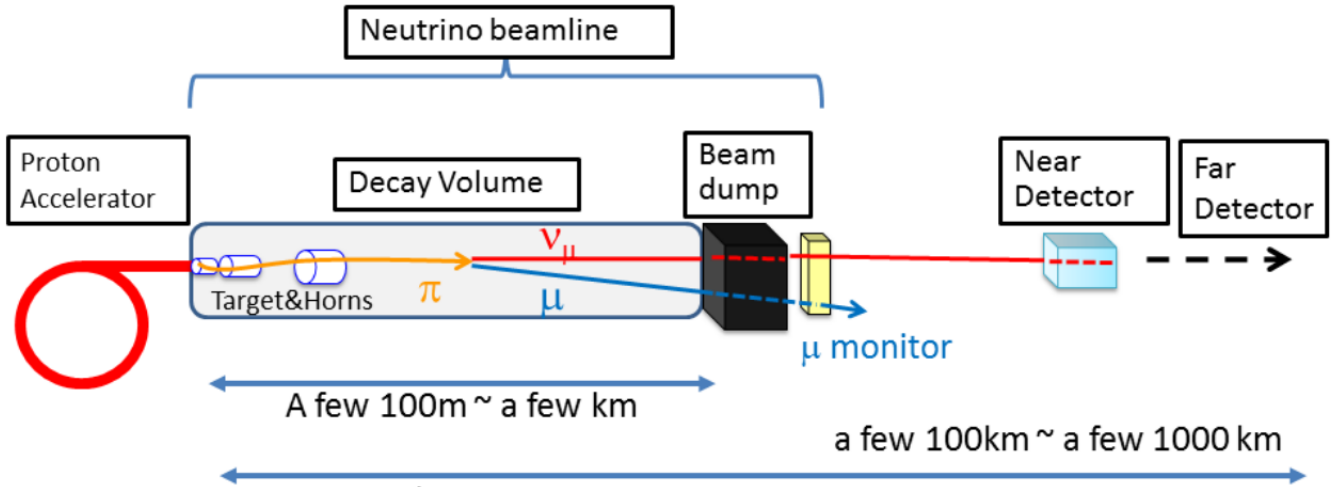
- Today :
  - How to make a neutrino beam
  - Accelerators for neutrino beamlines
  - Neutrino beamline components
- Tomorrow :
  - Predicting neutrino fluxes
  - Calculating systematic errors on neutrino fluxes

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

Conventional Neutrino Beams

- Conventional neutrino beams are currently the best way are able to produce a **well-known** flux of neutrinos – concentrate on conventional beams here
- Various facilities for producing conventional neutrino exist or are planned around the world – focus today on current and near-future facilities
  - Neutrino beamline at J-PARC
  - Neutrino beamlines at FNAL

Producing A Conventional 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

Neutrino Parent Particles

- Main neutrino parent particles are pions and kaons produced in the target
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - $K^+ \rightarrow \mu^+ + \nu_\mu$
  - $K^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - ($+$ $\mu^\pm$ decays..)
- Focus right-sign hadrons and defocus wrong-sign hadrons using focusing horns

Proton Beam Considerations

- Neutrinos are very weakly interacting – often want to increase the neutrino flux as much as possible to increase the possible number of neutrino interactions
- Proton beam power:
  - Power [W] = Number of Protons / time [s] $\times$ Energy [eV] $\times$ e
    - e = 1.602E-19 C
- Note that we use a pulsed proton beam for various reasons:
  - Horn electromagnets need to be pulsed
  - Non-beam backgrounds can be eliminated by beam timing
  - Proton accelerator design for pulsed beam
  - etc..
- Increase the beam power by:
  - Increasing the number of protons per pulse
    – Or –
  - Decreasing the amount of time between pulses
    – Or –
  - Increasing the beam energy (doesn't increase the number of protons)

Secondary Beam Considerations

- Cannot directly steer/focus/control the neutrino beam, but can use some tools to control it
  - Horn focusing to increase the number of charged parent particles traveling in the correct direction
  - Off-axis beam to control the neutrino beam energy : $E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$
  - Tune decay volume length to select energy of decaying pions

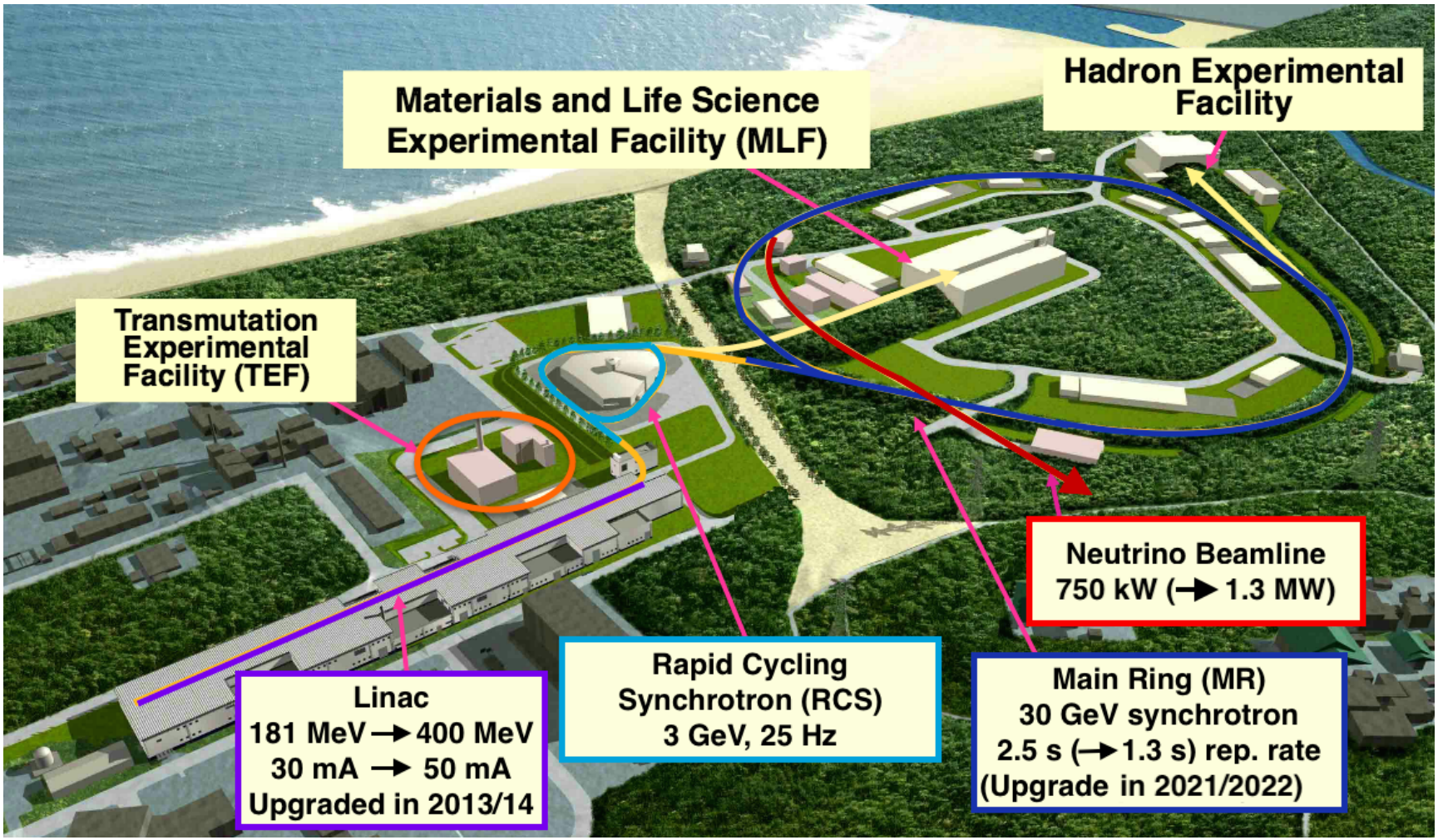
- Also very important to maintain stable, well-understood primary proton and secondary beams in order to have a stable, well-understood neutrino beam
  - i.e. control systematic errors on the neutrino flux

Increasing the Neutrino Flux

- 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 beamline must be able to handle the increased power

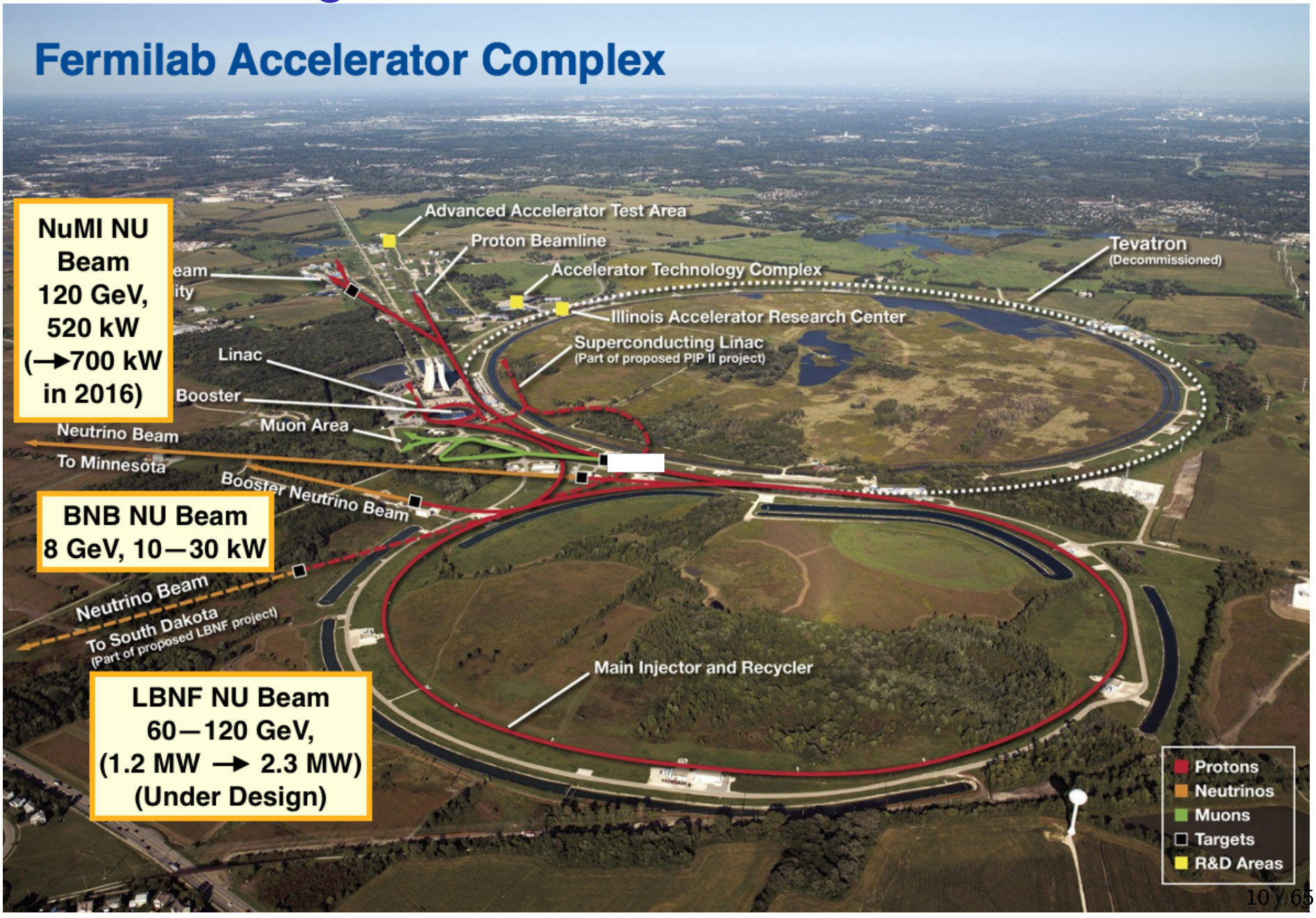
  – And –
- There are ways to increase the *effective* number of protons, e.g.:
  - Improve the target to increase right-sign hadrons
  - Increase/tune the horn current for better right-sign hadron focusing
- Important to run the neutrino beam and neutrino experiment as much as possible !

High-Power Proton Source – J-PARC



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

High-Power Proton Source – Fermilab



Proton Beams for Neutrino Experiments

J-PARC neutrino beamline

- Beam Energy: 30 GeV
- Beam Power: 500 kW $\rightarrow$1.3 MW
- Beam Intensity: 2.4E14 ppp $\rightarrow$ 3.2E14 ppp
- Beam Bunches: 8
- Pulse Length: 4.2 μs
- Duty cycle: 2.48 s $\rightarrow$ 1.16 s
- Beam spot size at target: 4 mm
- Running since: 2009

NUMI neutrino beamline at FNAL

- Beam Energy: 120 GeV
- Beam Power: 700-750 kW $\rightarrow$ 1 MW
- Beam Intensity: 5.4E13 ppp $\rightarrow$ 6.5E13 ppp
- Beam Bunches: 588
- Pulse Length: 11 μs
- Duty cycle: 1.333 s $\rightarrow$ 1.2 s
- Beam spot size at target: 1.3 mm $\rightarrow$ 1.5 mm
- Running since: 2005

Proton Beams for Neutrino Experiments

BNB neutrino beamline at FNAL

- Beam Energy: 8 GeV
- Beam Power: 35 kW
  $\rightarrow$115 kW ?
- Beam Intensity: 4$\sim$5E12 ppp
- Running since: 2002

LBNF neutrino beamline at FNAL

- Beam Energy: 60-120 GeV
- Beam Power: 1.2 MW
  $\rightarrow$ 2.4 MW

Under Design

Accelerator – 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)

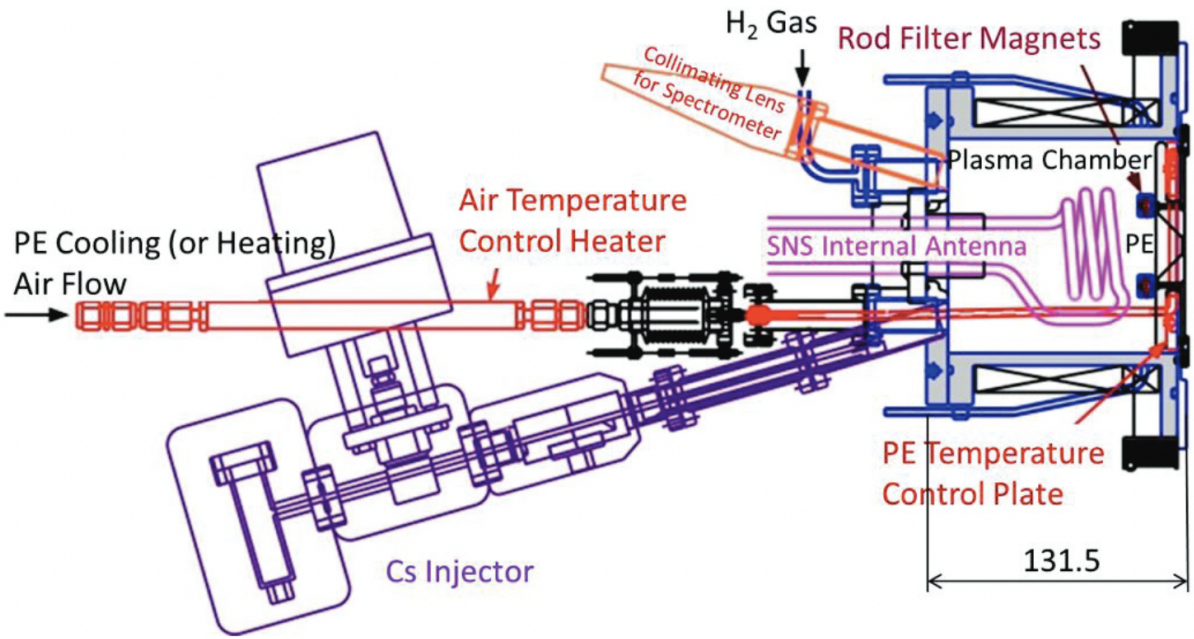
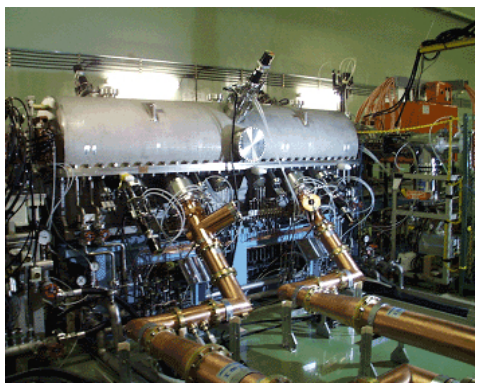


Figure from `https://doi.org/10.1063/1.4995773`

Accelerator – 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



Accelerator 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

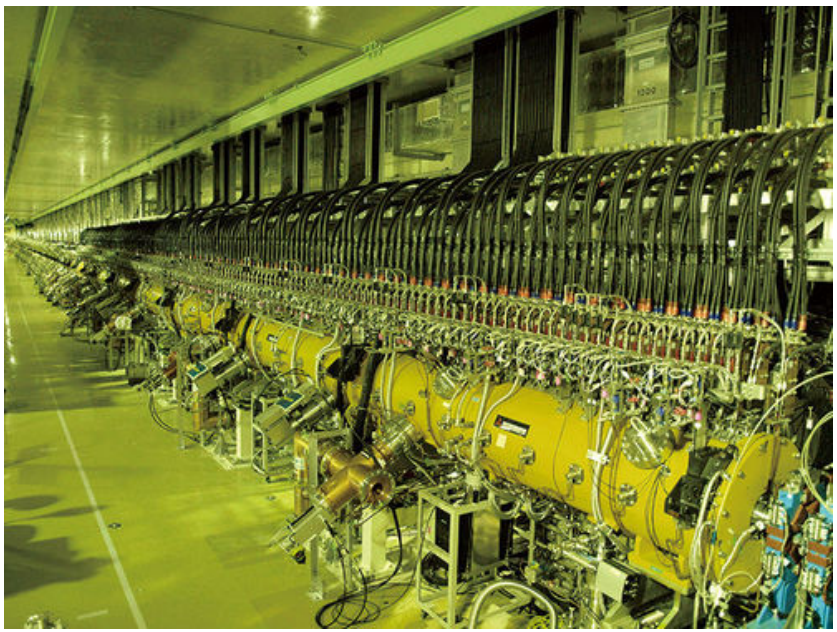
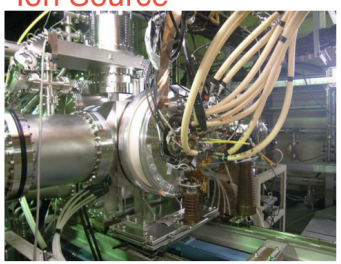


Figure from https://j-parc.jp/c/facilities/accelerators/index.html

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 $\rightarrow$ 3MeV
  - Drift Tube Linac – 3MeV $\rightarrow$ 50MeV
  - Separated-type Drift Tube Linac – 50MeV $\rightarrow$ 191MeV
  - Annular-ring Coupled Structure linac – 191MeV $\rightarrow$ 400MeV

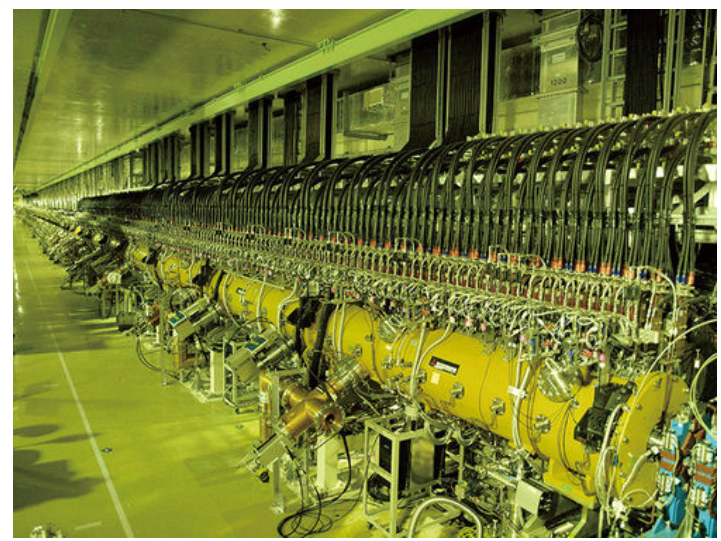
Ion Source



RFQ outsite

RFQ inside

DTL inside

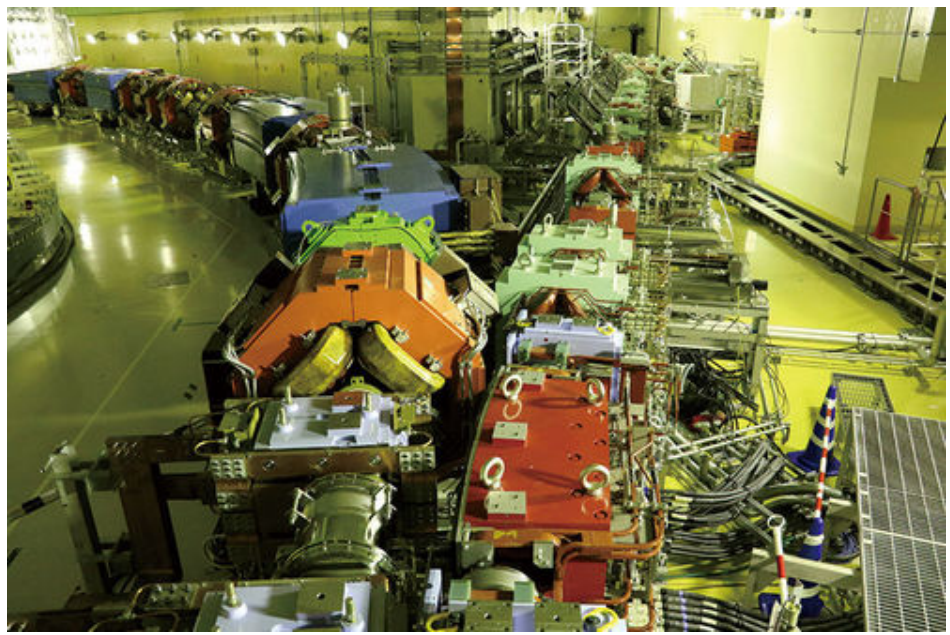


Figures from
`https://j-parc.jp/c/facilities/accelerators/index.html`

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
  - 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

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

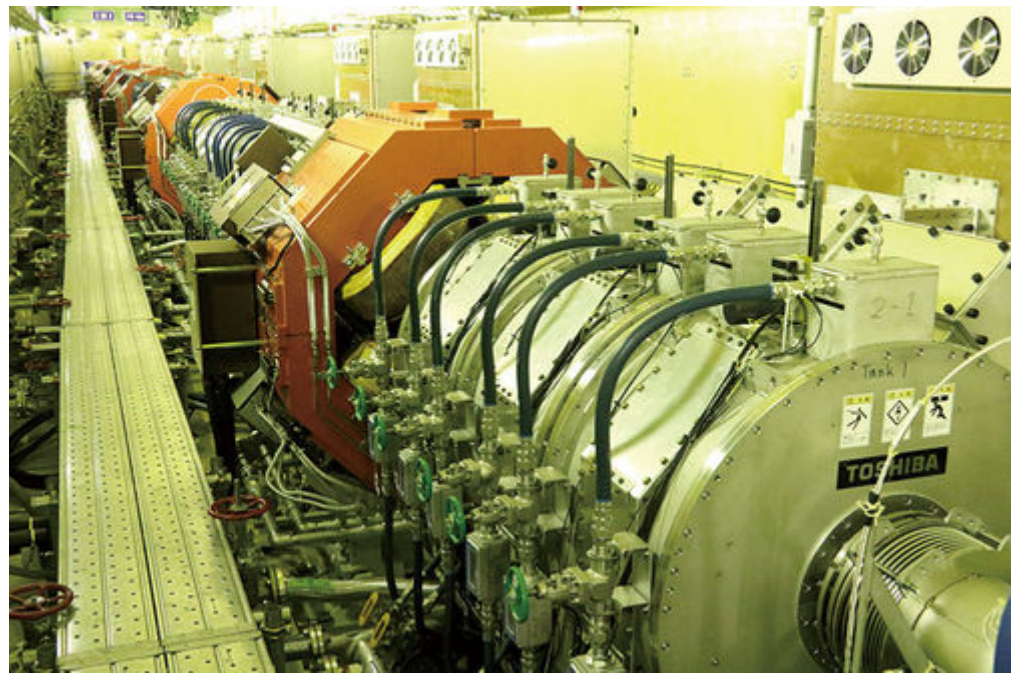


https://j-parc.jp/c/facilities/accelerators/index.html

Rapid Cycling Synchrotron (RCS)

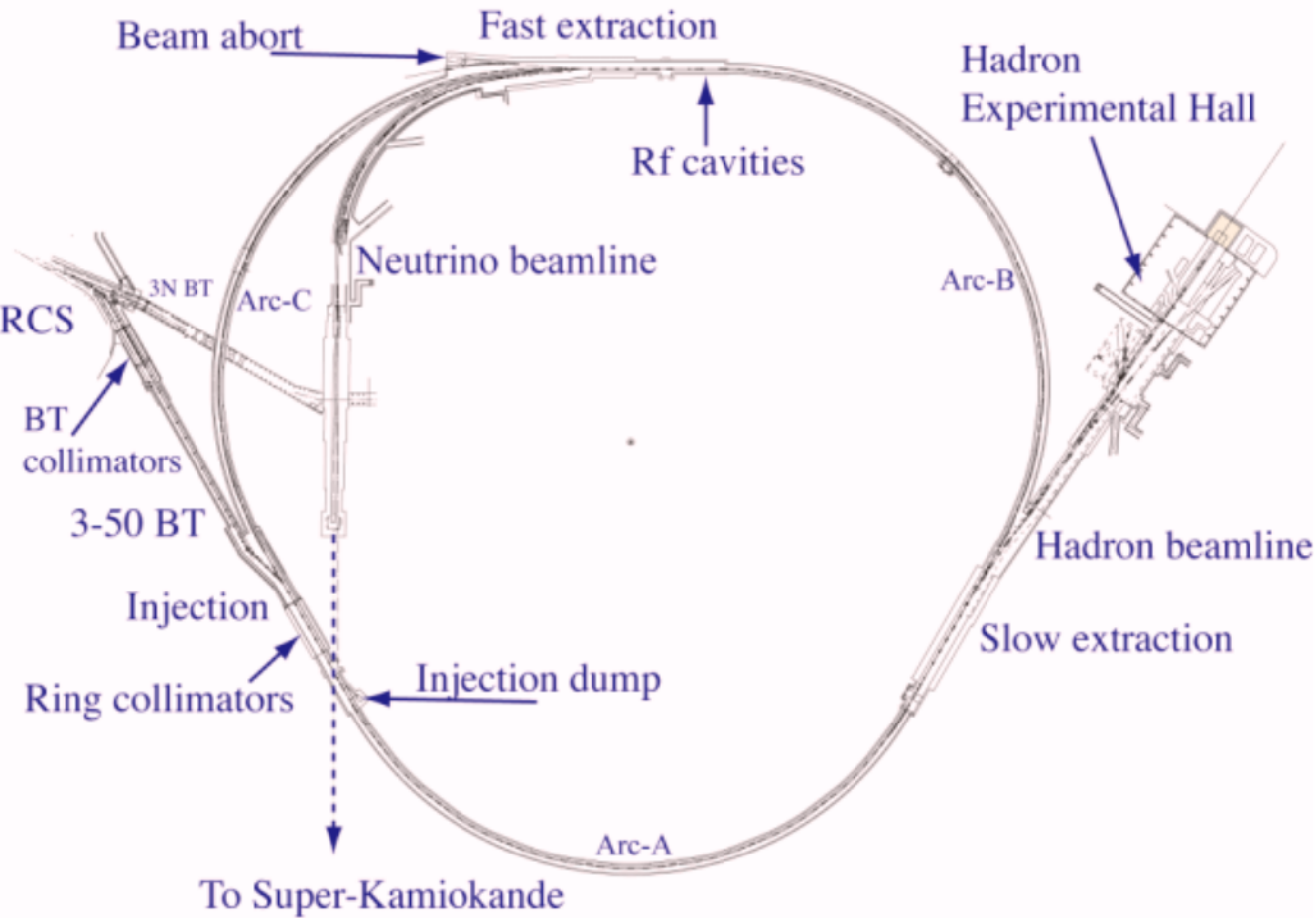
- In a linear accelerator, each particle only passes through each RF cavity a single time
- In a circular accelerator, the beam is recirculated >10,000 times, passing each accelerating cavity each time
- In a Synchrotron, the fields which bend the particle around the fixed orbit increase "synchronized"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

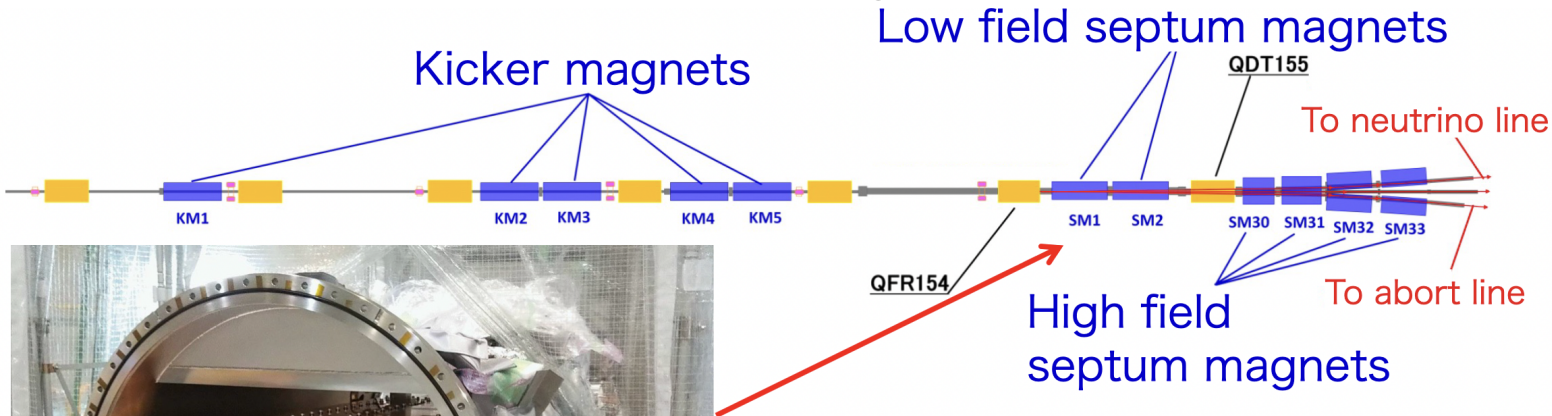


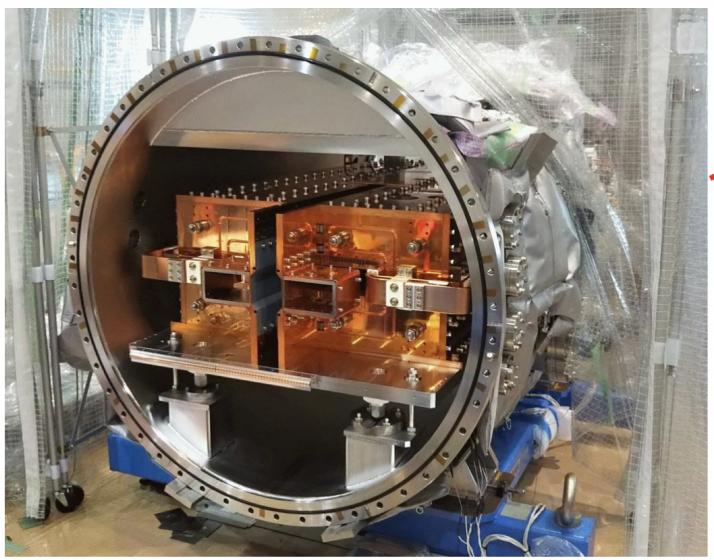
- 3 116-m-long straight sections dedicated to:
  - Injection and beam collimators
  - Slow extraction
  - Fast extraction and RF system
    $\rightarrow$ Fast extraction to neutrino target

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

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



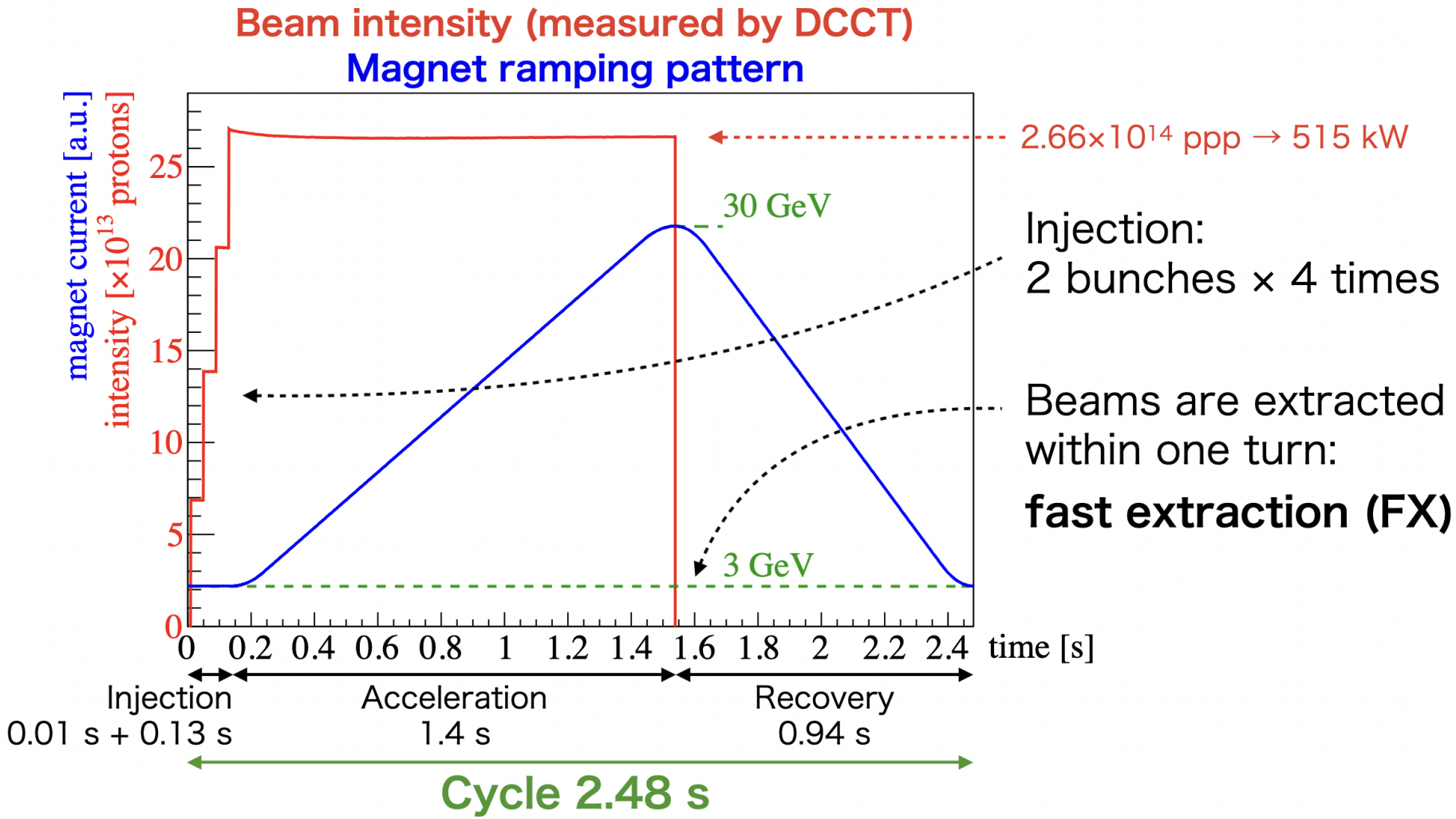


New eddy current septum magnet

Low field septum magnets were replaced by eddy current magnets.

Leakage field was reduced

Typical J-PARC MR FX Operation



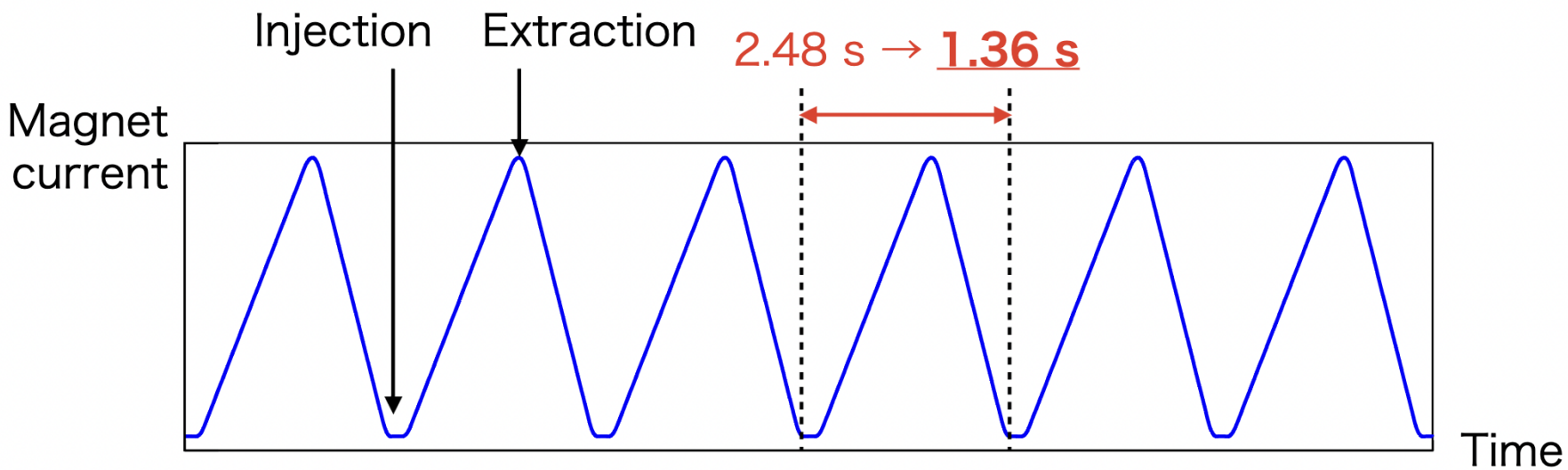
T. Yasui, NuFact2022

J-PARC MR Upgrade Operation

Power = Energy × **Number of protons** / **Cycle time**

Energy: 30 GeV

JFY2021	**515 kW**	**2.66×10¹⁴ ppp**	**2.48 s**
JFY2023	**750 kW**	**2.1×10¹⁴ ppp**	**1.36 s**
Future	**1300 kW**	**3.3×10¹⁴ ppp**	**1.16 s**



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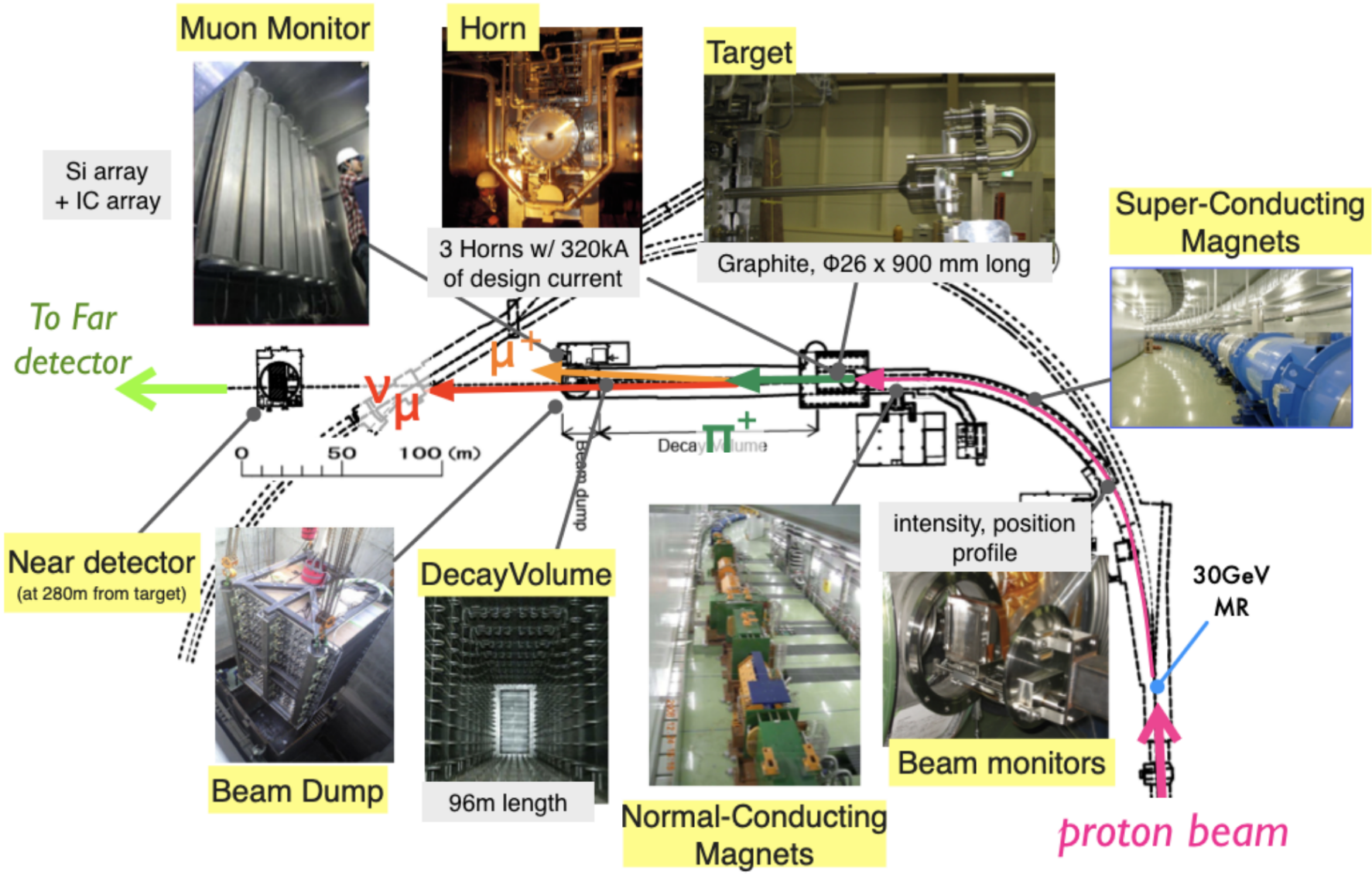
J-PARC MR Upgrades Towards 1.3MW

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	Kicker PS improvement Septa manufacture Test ▶								
FX system									
Beam Monitors (BPM circuits)	⟷	⟷	⟷	⟷	⟷				
SX: Diffuser/Bent crystal/VHF		⟷	⟷	⟷	⟷	⟷			
Local shield									

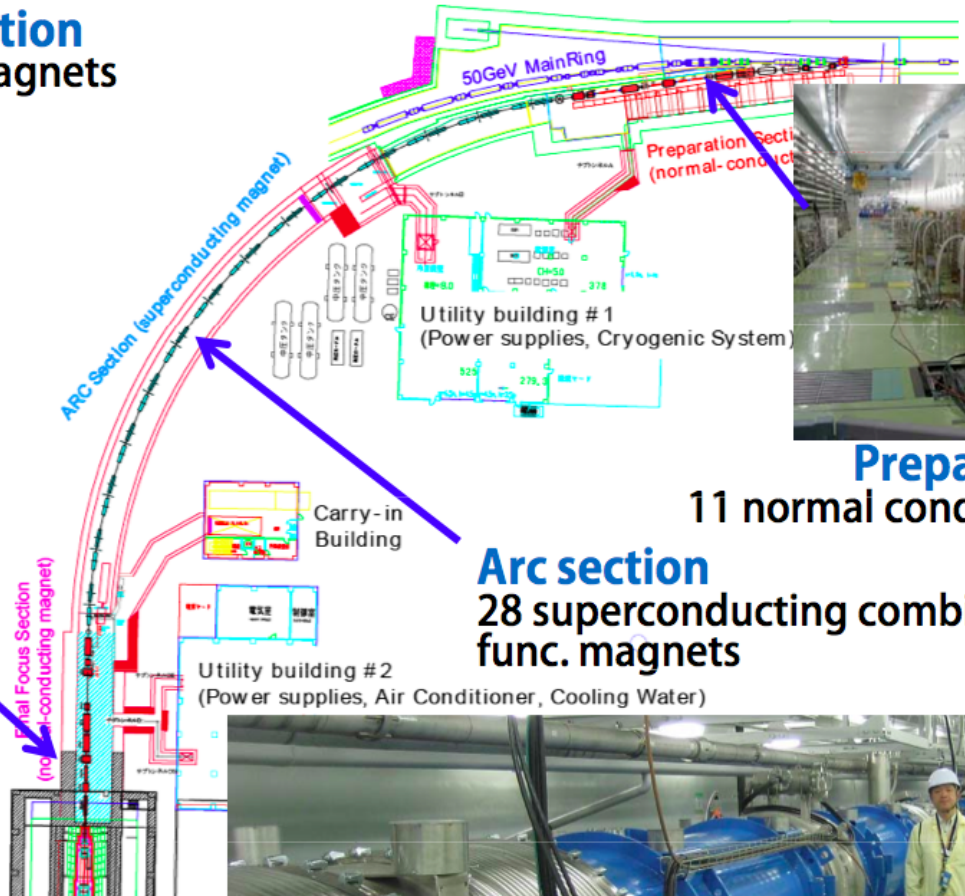
Prog. Theor. Exp. Phys. 2021, 033G01

J-PARC Neutrino Beamline



J-PARC Neutrino Primary Beamline

Final focusing (FF) section
10 normal conducting magnets

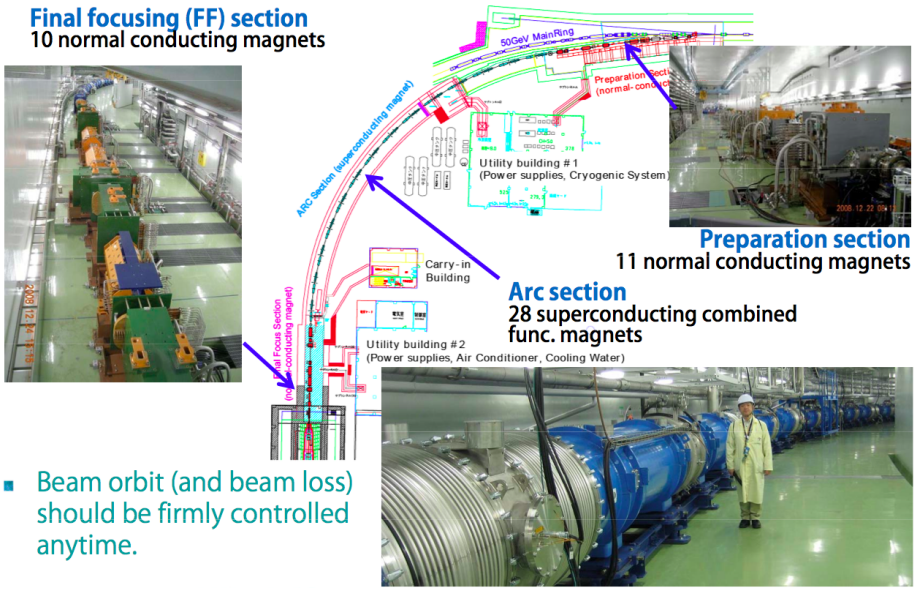


Preparation section
11 normal conducting magnets

Arc section
28 superconducting combined func. magnets

- Beam orbit (and beam loss) should be firmly controlled anytime.

J-PARC Neutrino Primary Beamline

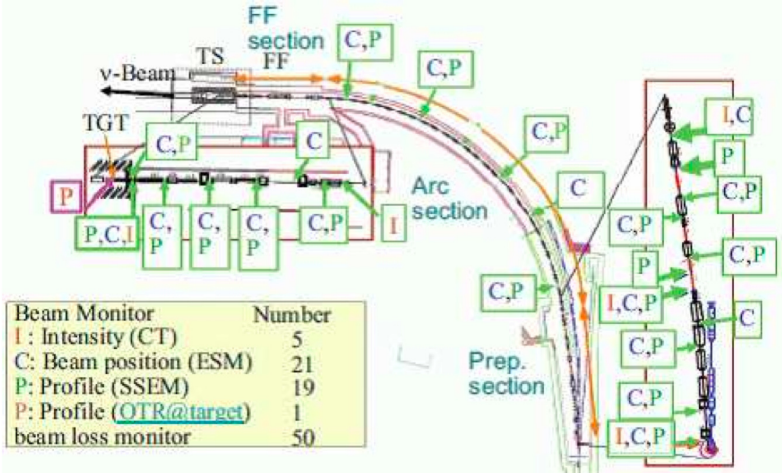


- Beam orbit (and beam loss) should be firmly controlled anytime.

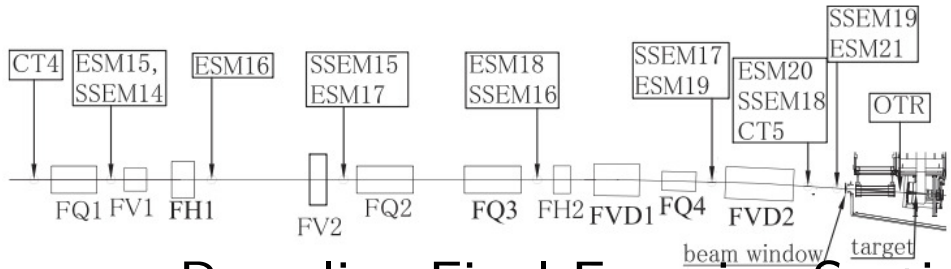
- Arc section : superconducting combined-function magnets
  - Used to sharply bend the beam towards the Super-Kamiokande direction

- 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 $\longrightarrow$

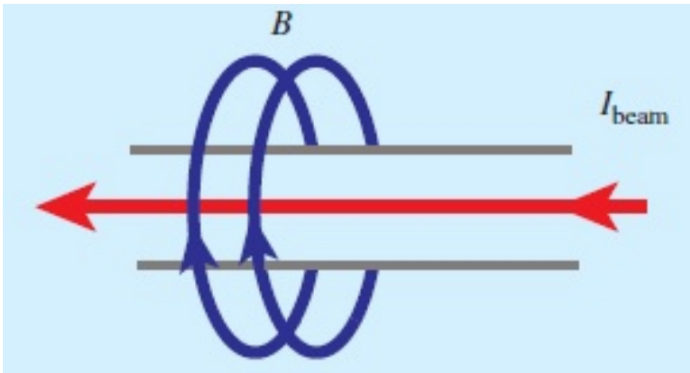


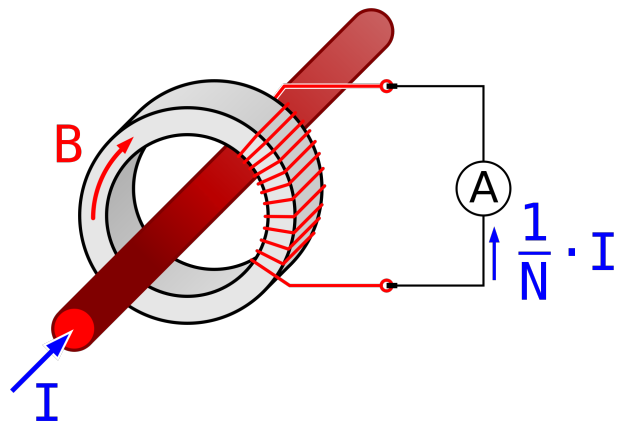
Beamline Final Focusing Section

- 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

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

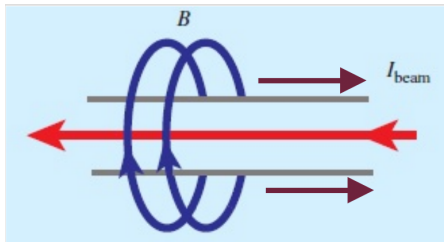




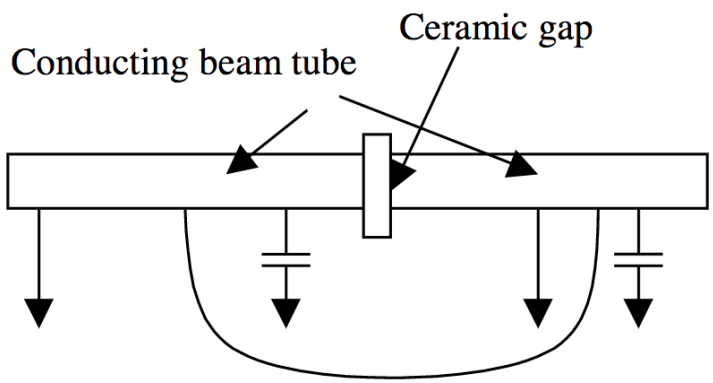
- Magnetic field in core induces a secondary current, I_{sec} on a wire coiled around the core
- The beam acts as primary winding with $N_{beam} = 1$, so :
  - $I_{beam}/I_{sec} = N_{torus}/N_{beam} \quad \rightarrow \quad I_{sec} = I_{beam}/N_{torus}$
- Can measure beam current by adding a resistor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

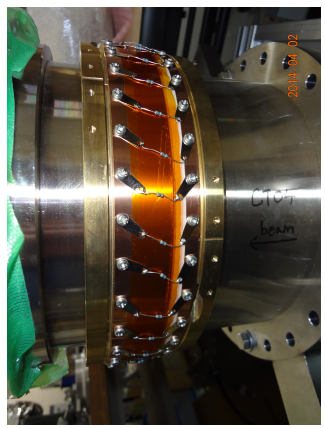
Current Transformer Concept

- 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

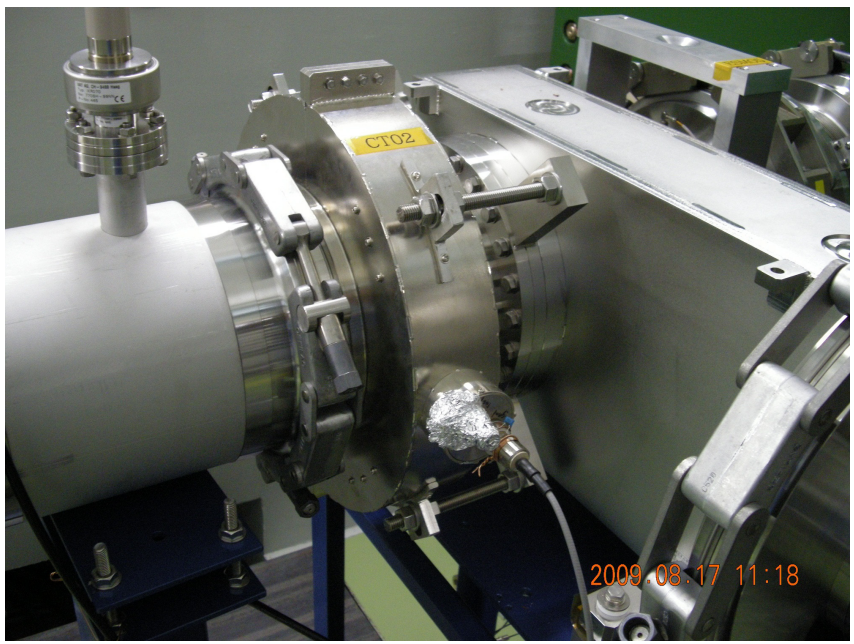


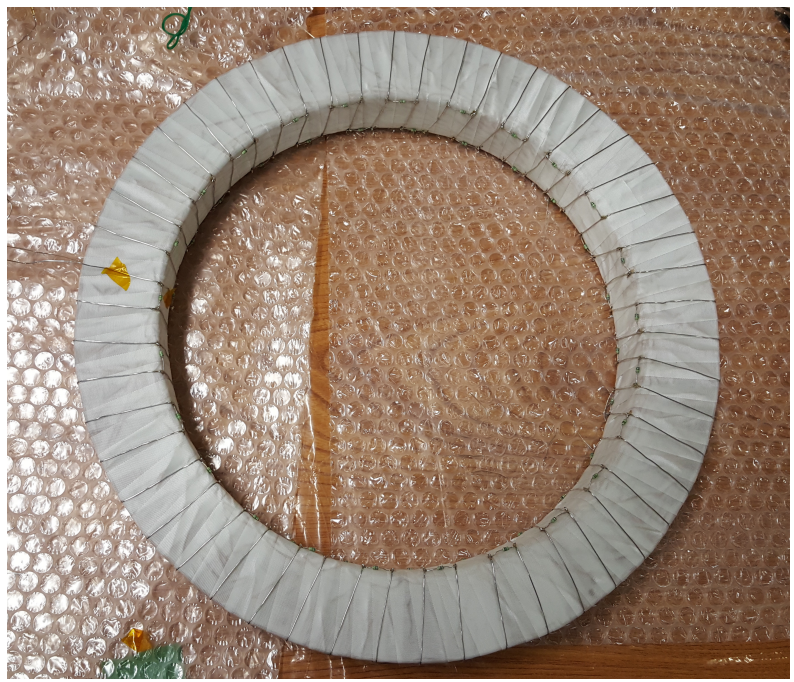


J-PARC Current Transformers

5 CTs (Current Transformers)

- 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

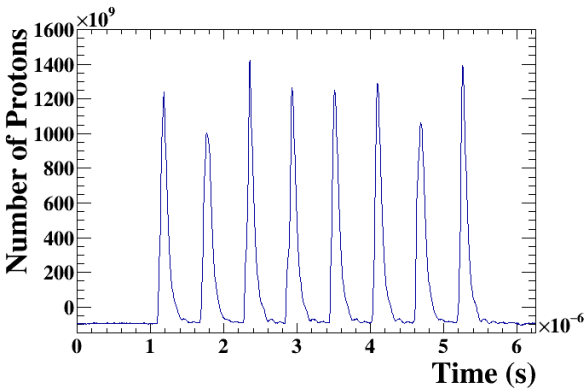




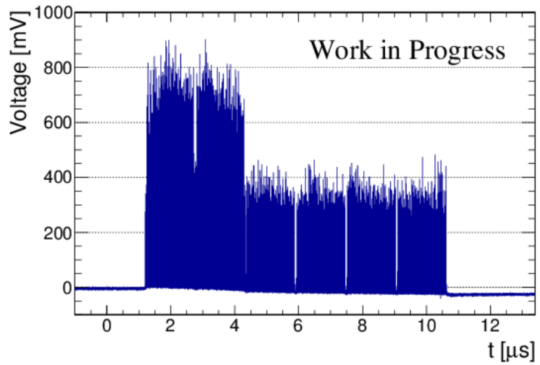
Signal From Current Transformers

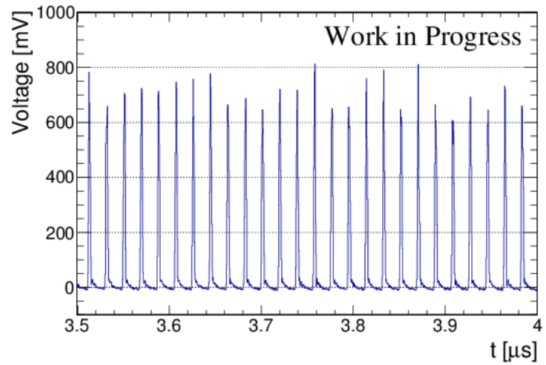
- J-PARC CT is read out/digitized by 160MHz ADC
  - Integrate total charge seen by CT, then convert to # of protons (1 proton $= 1.602 \times 10^{-19}$ C)
  - This measured number of protons is directly used in physics analyses $\rightarrow$ Very important to get this right, especially for cross-section measurements
  - Clearly observe the time structure of the proton beam
    - Unfortunately, can be some smearing in the time signal due to electronics shaping circuit – cannot be used for precise bunch shape measurement

J-PARC proton structure



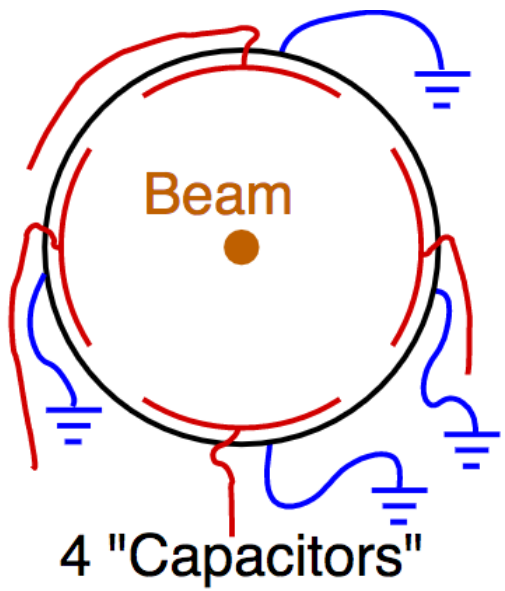
NUMI proton structure





Beam Position Monitor

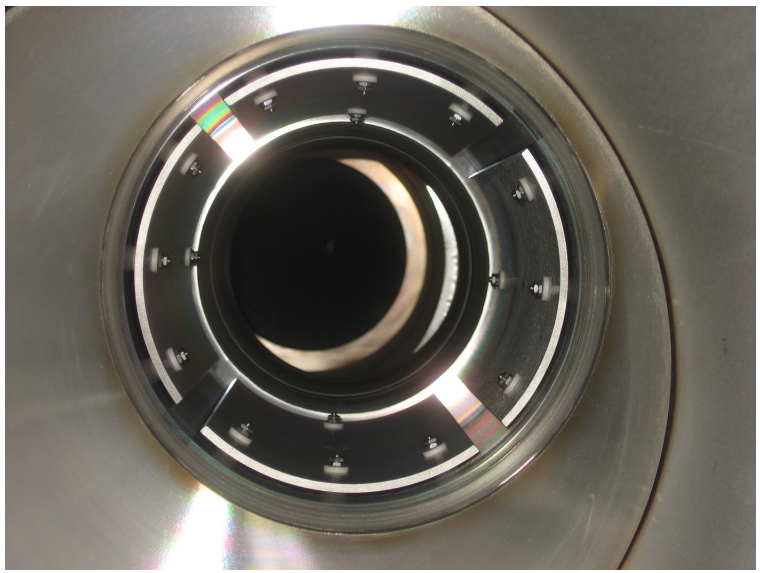
- Standard beam position monitor uses 4 segmented cylindrical electrodes surrounding the proton beam orbit
  - Beam passage induces charge on electrodes proportional to distance from that electrode
- Asymmetry between signal from opposite electrodes gives beam position inside the beampipe :
  - $\frac{C_R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



J-PARC Beam Position Monitors

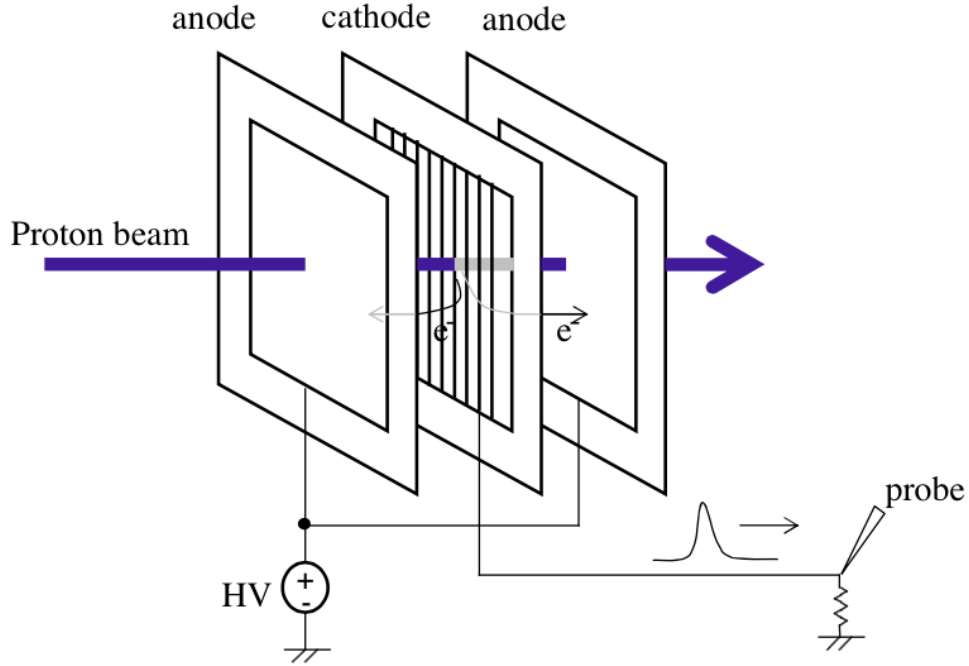
21 ESMs (Electrostatic Monitor) used in J-PARC neutrino extraction beamline

- 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
      $\rightarrow$ Optimized electrode shape, additional electrodes, etc..



Secondary Emission Monitor

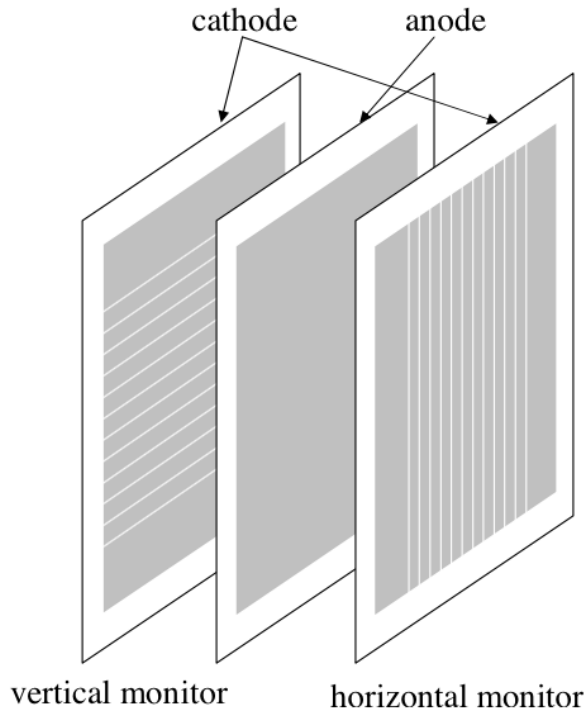
Secondary Emission Profile Monitor Principle



- 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

J-PARC Secondary Emission Monitor

J-PARC neutrino beamline Profile Monitor : Segmented Secondary Emission Monitor (SSEM)

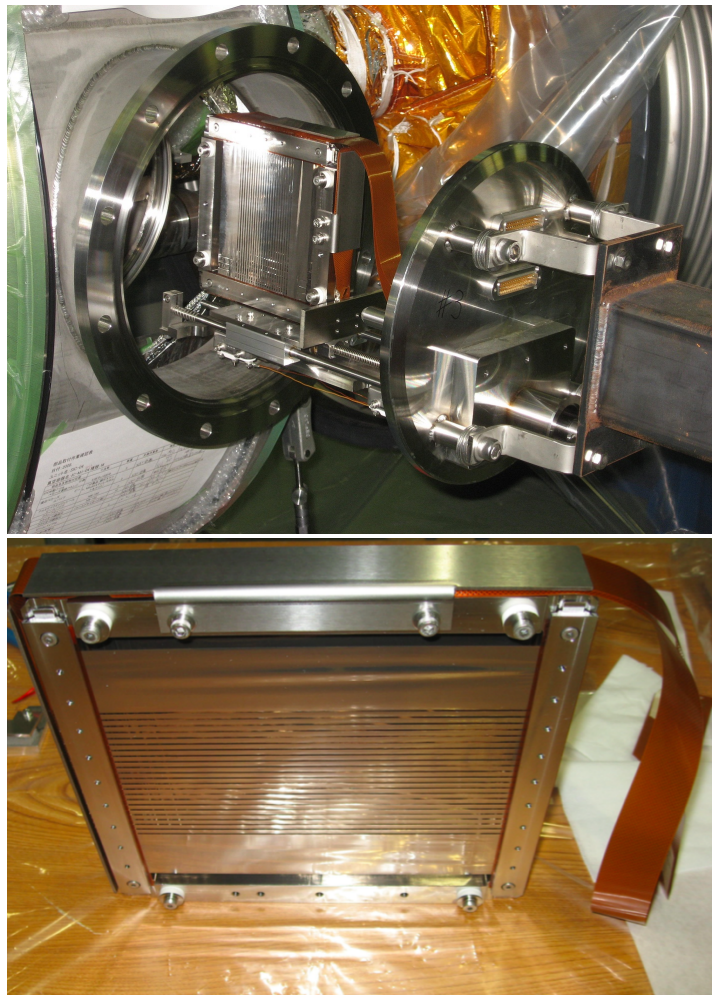


- Same principle, but single anode plane between two stripped cathode planes used to collect electrons
  - 1 stripped plane for X, 1 for Y
- 5 μm thick Ti foils

J-PARC SSEMs

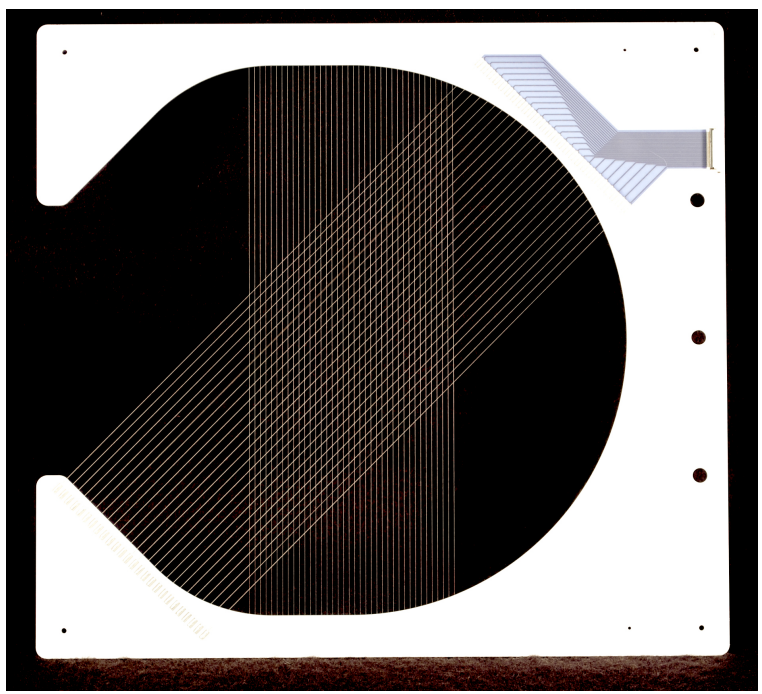
19 SSEMs (Segmented Secondary Emission Monitor)

- 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



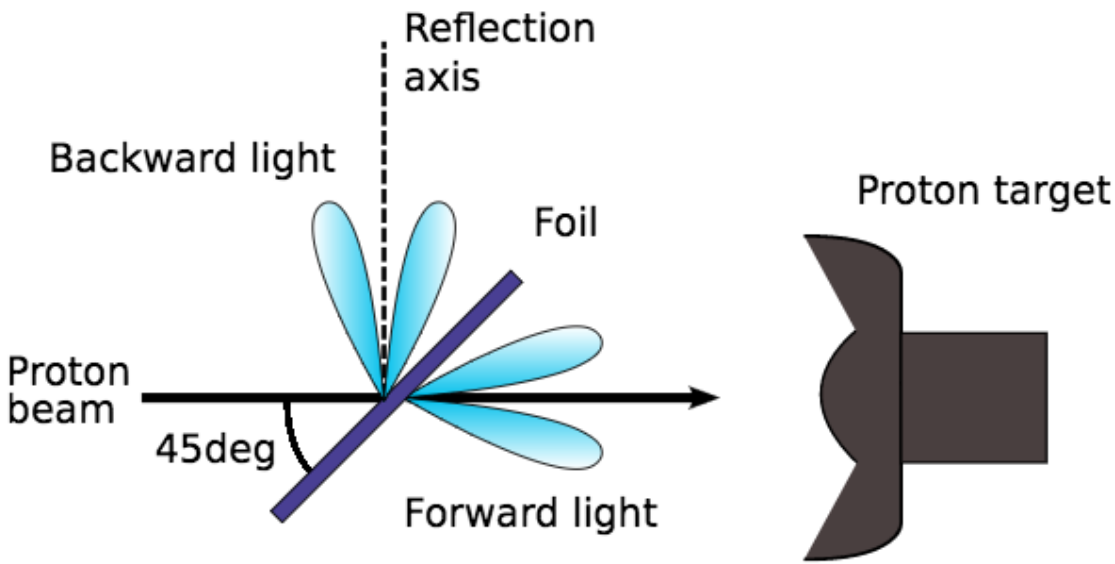
FNAL SEMs

- At FNAL, SEMs or Wire Secondary Emission Monitors (WSEMs) are used, rather than SSEMs
- Monitor beam profile using wire (e.g. 25 μm Ti x2)
  - 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



Optical Transition Radiation Monitor (OTR)

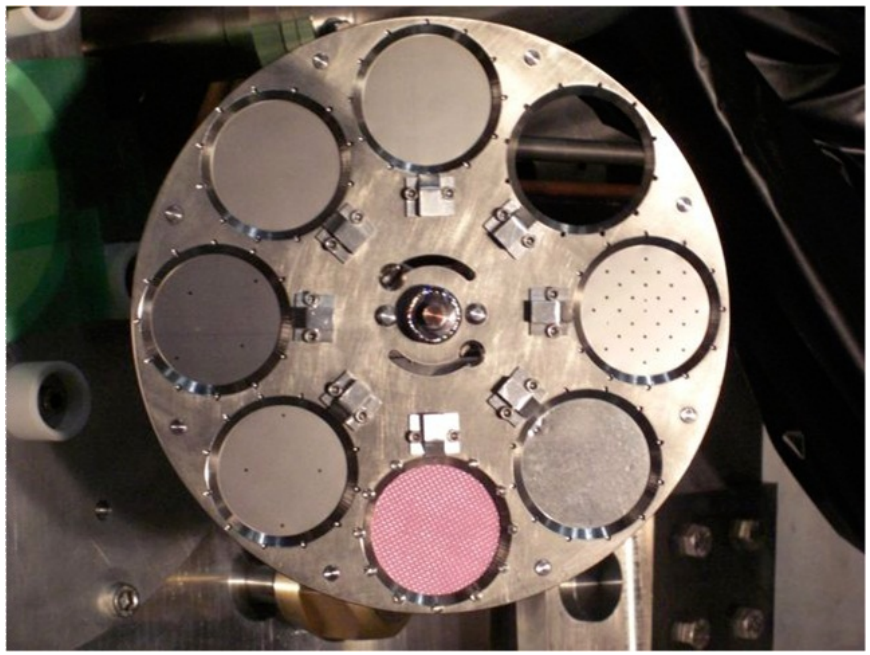
- Optical Transition Radiation is produced when a charged particle travels between two materials with different dielectric constants
  - Light profile is proportional to charged particle beam profile
- If the material (foil) is placed at 45° with respect to the beam, can measure backwards-going OTR light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



J-PARC Optical Transition Radiation Monitor

1 OTR (Optical Transition Radiation Monitor)

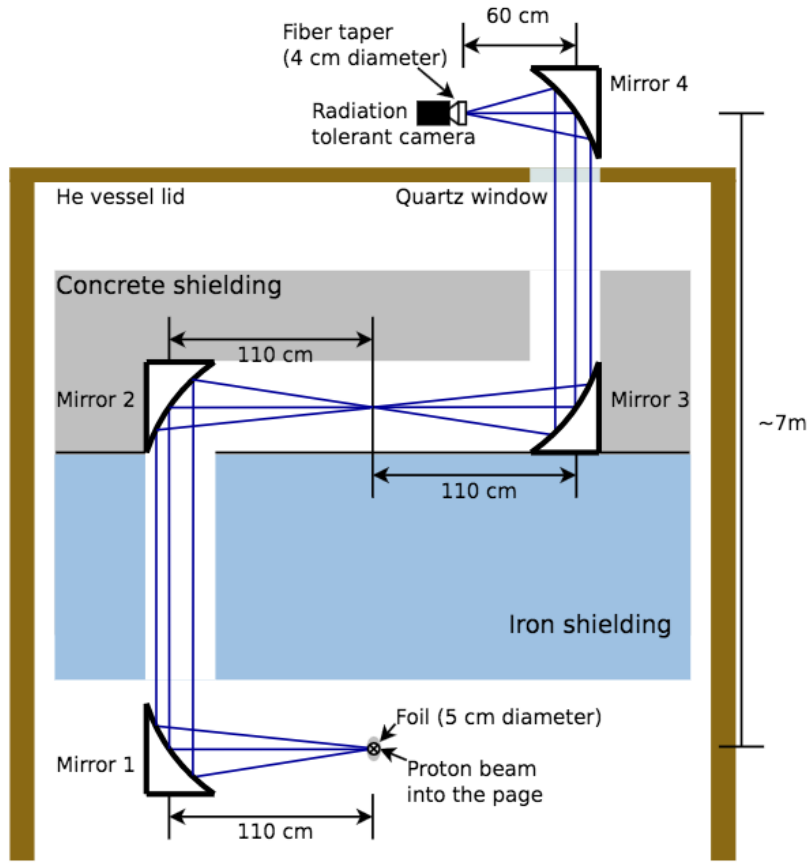
- Continuously monitors beam profile directly upstream of the target
- Rotatable disk with 8 foil positions allows for many OTR target types
  - 50-μm-thick Ti foil designed for standard data-taking
  - Ceramic foil (which produces fluorescent light) used for very low intensity beam
  - Ti foils with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



J-PARC Optical Transition Radiation Monitor

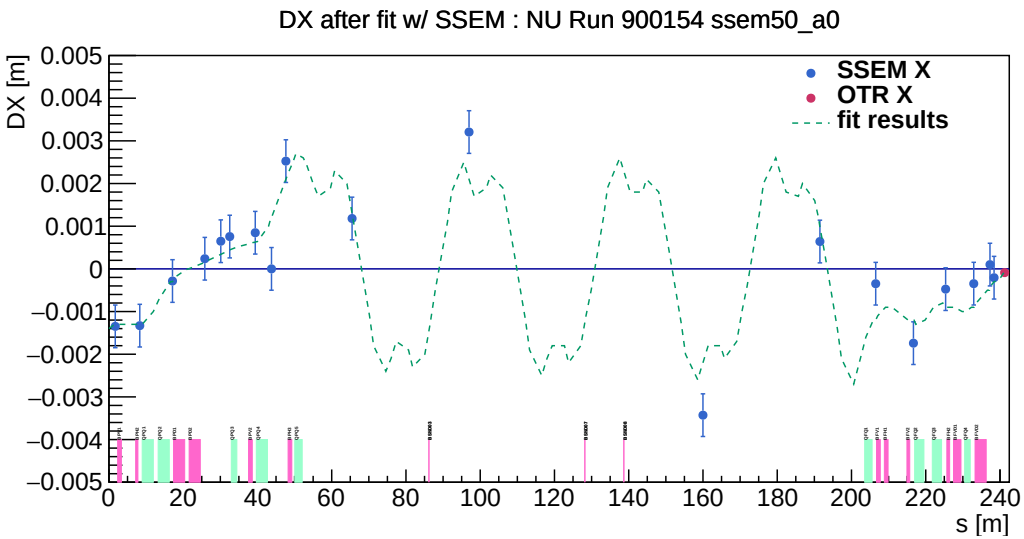
1 OTR (Optical Transition Radiation Monitor)

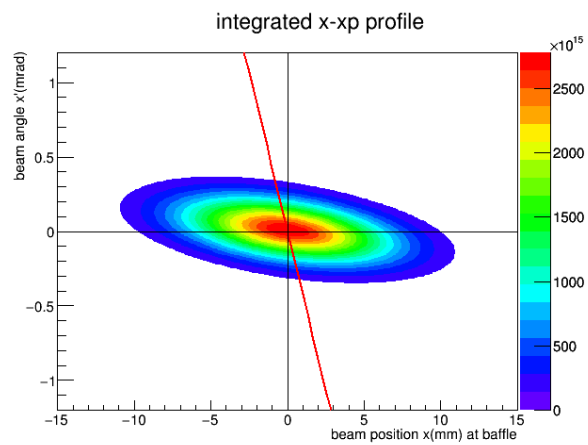
- Continuously monitors beam profile directly upstream of the target
- J-PARC neutrino beamline OTR monitors backwards-going light from foil
  - Light is directed to TS ground floor by a series of 4 mirrors and then monitored by a radiation-hard camera



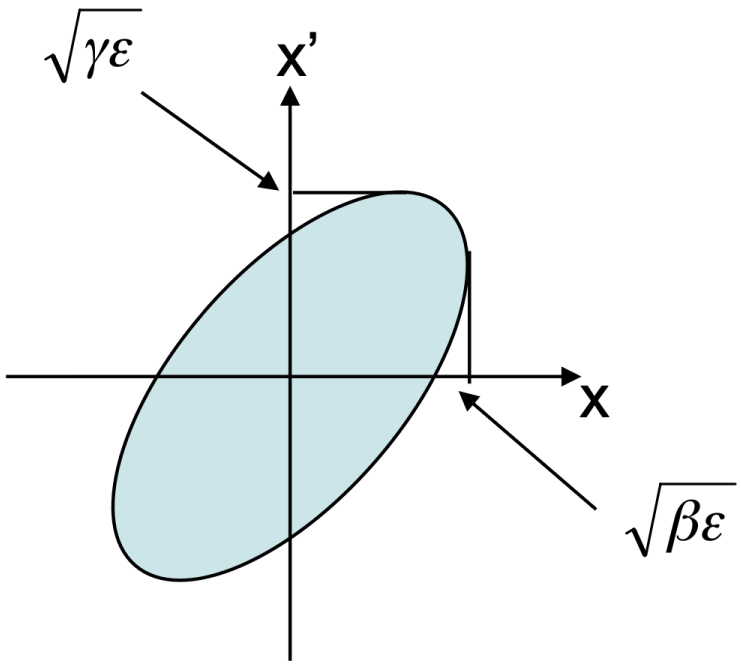
Beam Orbit and Optics

- Measure proton beam orbit (position) and optics (width) along the beamline
  - Orbit is measured continuously using BPMs
  - Optics are measured only during beam tuning/checking, otherwise only use most downstream monitors (SSEM19, OTR at J-PARC)
- Calculate beam parameters at the target (or.. upstream end of the beam flux simulation) based on measurements along the beamline
  - Position, angle, width, emittance, twiss α used for J-PARC simulation





Beam Orbit and Optics



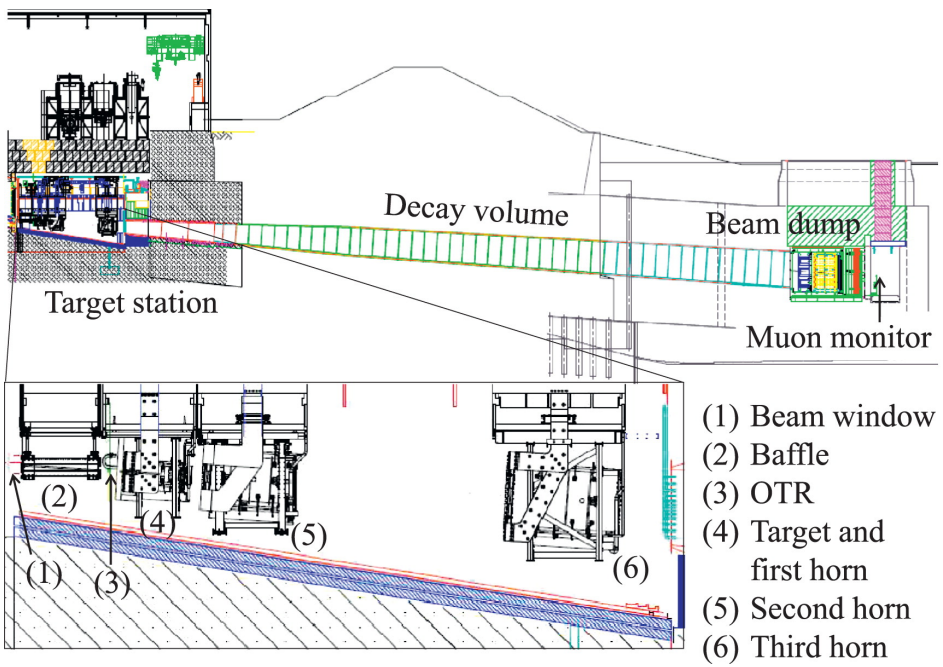
(α define the tilt of ellipse)

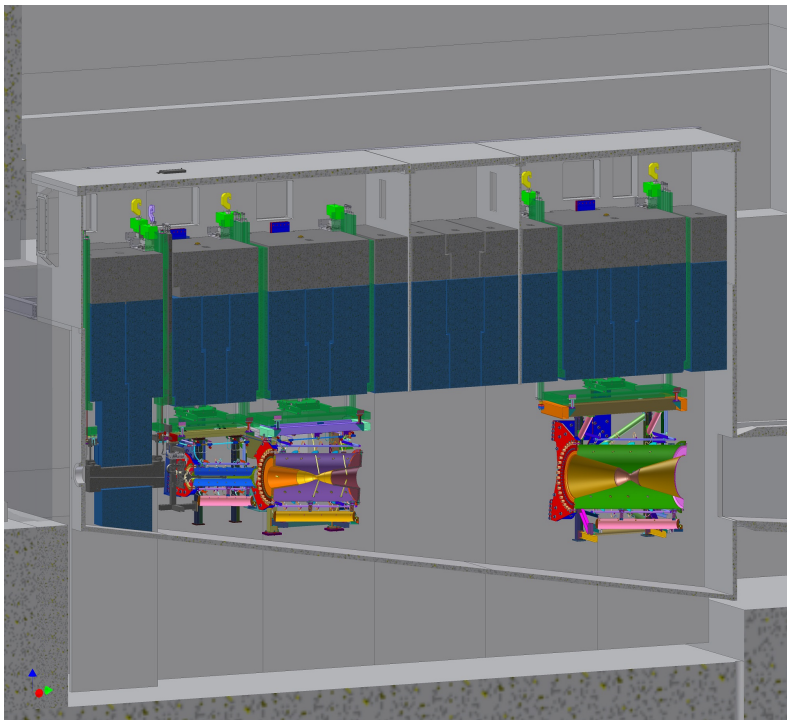
- Protons fill up a phase space ie ellipsoid in x,x'
- Area of phase space is unchanged as particles propagate – area is Emittance ϵ/π
- Ellipse can be represented by the formula $\gamma x^2 + 2\alpha x x' + \beta x'^2 = a^2$, where $\epsilon = \pi a^2$
  - (γ is not independent and can be defined as $\gamma = \frac{1+\alpha^2}{\beta}$)

$\rightarrow$ Use these measured parameters directly as input to flux simulation

Neutrino Secondary Beamline

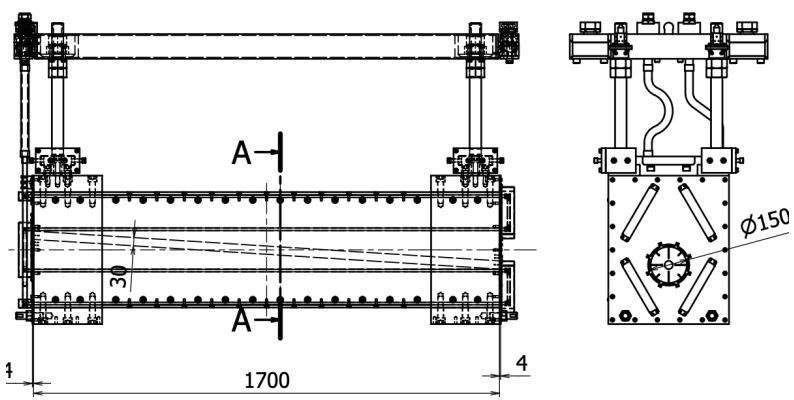
- Neutrino production target and focusing horns for J-PARC neutrino beamline are kept in a gigantic He vessel
  - $\sim$1500 m^3 He vessel (world's largest?)
  - He-filled to minimize production of tritium and NOx by interaction of high-energy hadrons with air





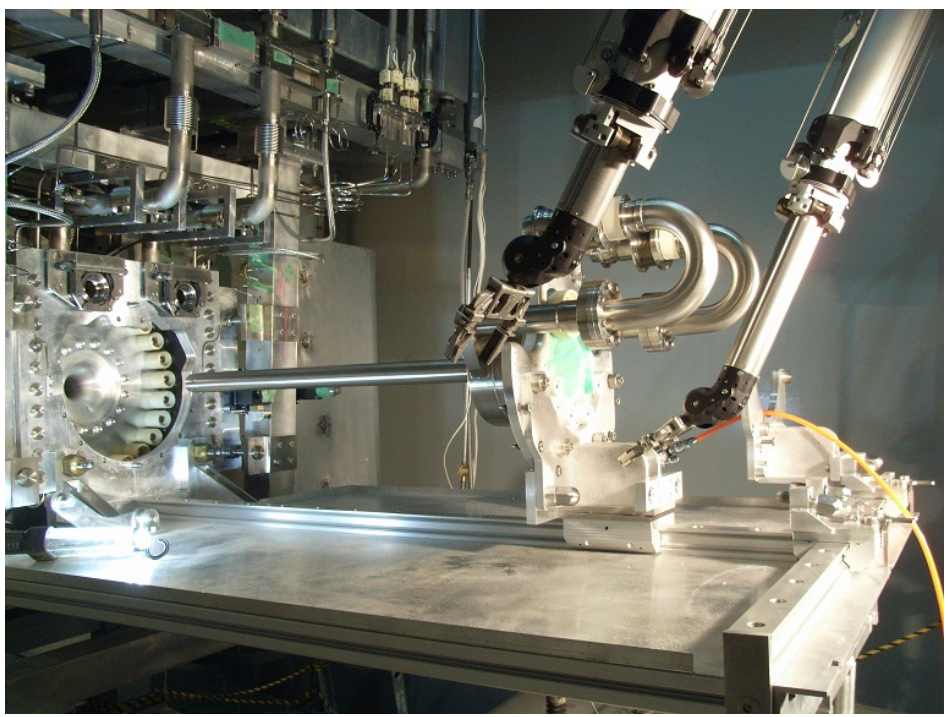
Baffle/Collimator

- Baffle/collimator sits upstream of the neutrino production target and first horn
  - In order to protect delicate equipment from mis-steered proton beam
- Thick (graphite) block with a hole concentric with the intended beam orbit
  - At J-PARC, baffle hole is 30mm in diameter, target is 26mm in diameter, horn inner conductor is 54mm
  - Intended proton beam width is $\sim$4.2 mm (Gaussian, 1σ
    $\rightarrow$ Removes beam tails, especially in the case of wide or mis-steered beam
  - $\sim$0.7% of beam tail is lost in the baffle, in the case of intended beam orbit, optics

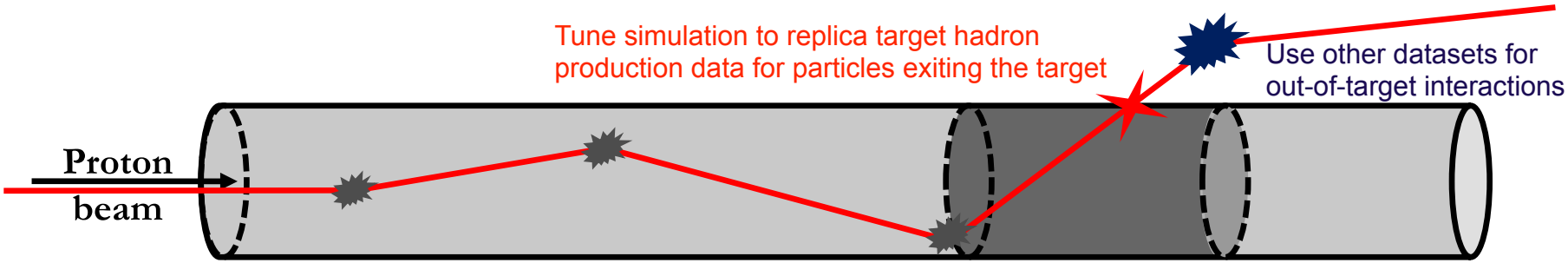


Neutrino Production Target

- 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)

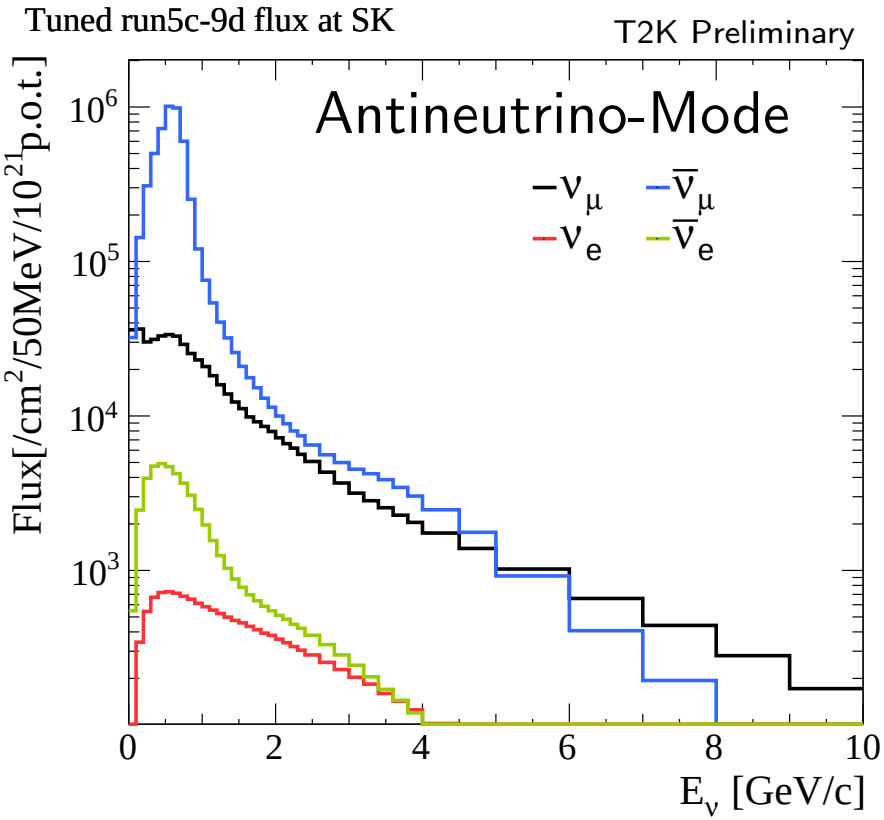


Particle Production in the Target



- Will discuss in much further detail tomorrow, but..
  - Process of particle production in the target is complicated..
  - Lower momentum particles tend to leave the target earlier, have higher outgoing angles
  - Higher momentum particles tend to be more forward – less likely to be focused by horns
- Possible to increase the right-sign neutrino flux and decrease the wrong-sign neutrino flux by optimizing the target density, geometry

Minimizing the Wrong-Sign Component



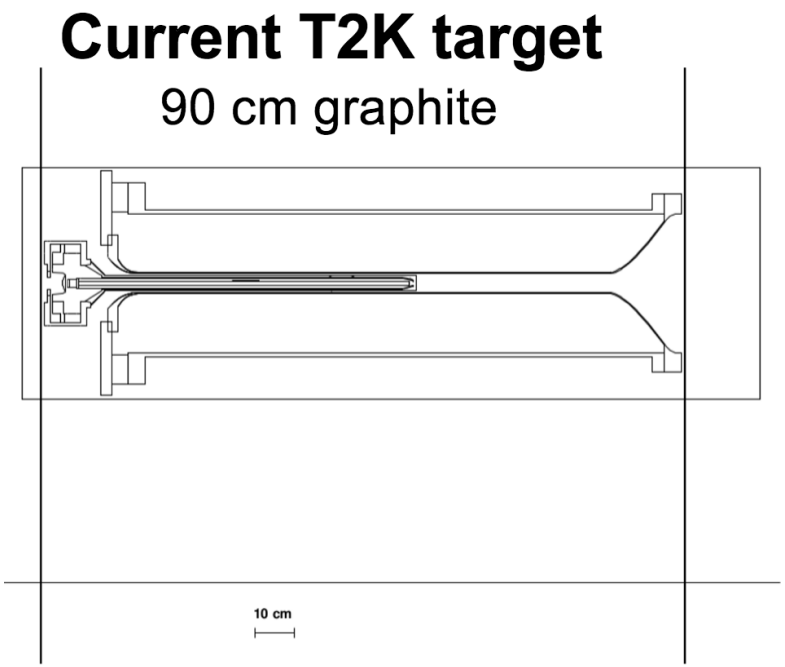
- For future accelerator neutrino beams – is it possible to further reduce the wrong-sign component by adjusting the target design?
- Simply using a **longer target** could help by absorbing forward going (non-horn-focused) hadrons, but:
  - Technically (mechanically) difficult
  - Don't want to absorb too many right-sign hadrons

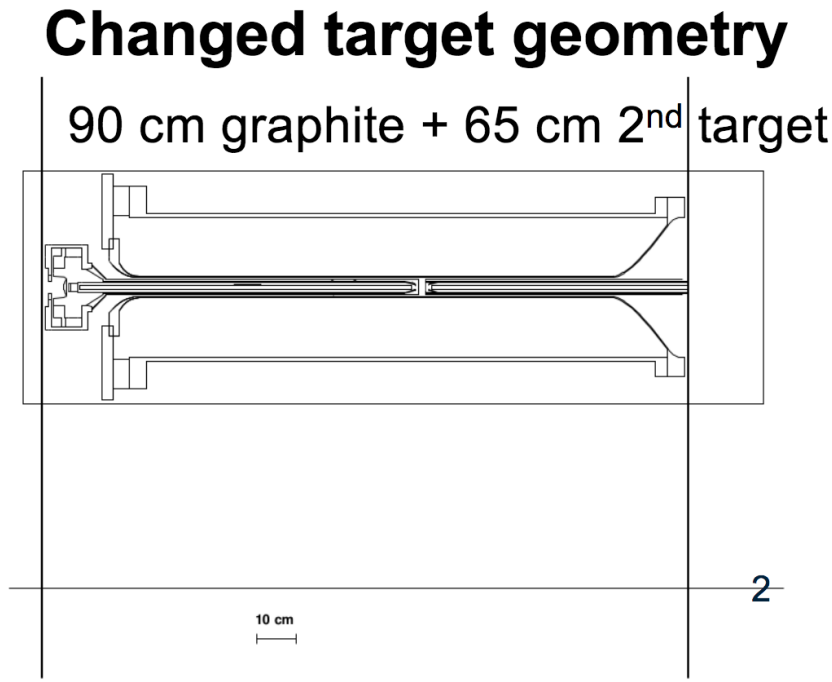
- Installing a second target (or "beam plug") at the downstream end of the first horn
  - Mechanically simpler than a single long target
- Different materials could help to optimize the effect

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

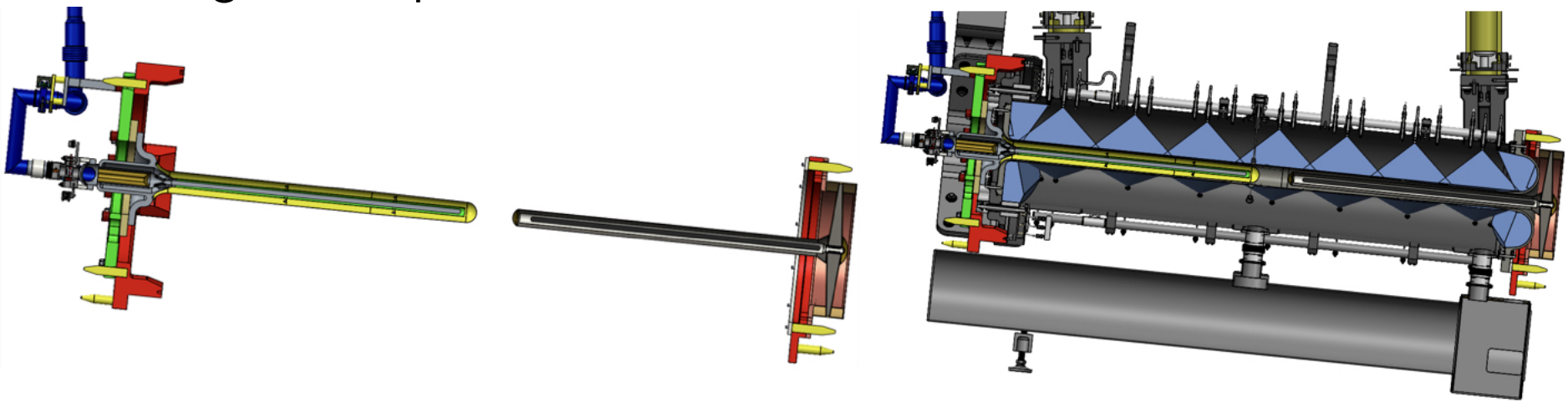
One example new target idea – insert 2nd (higher density?) target into downstream end of Horn 1:





Minimizing the Wrong-Sign Component

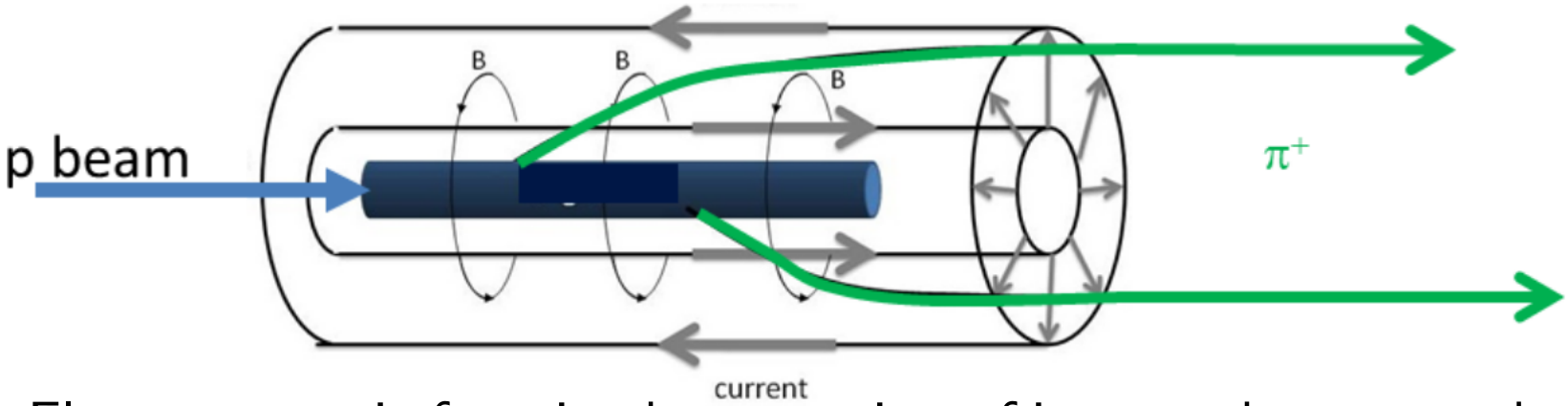
DUNE target concept:



C. Densham, NuFACT2019

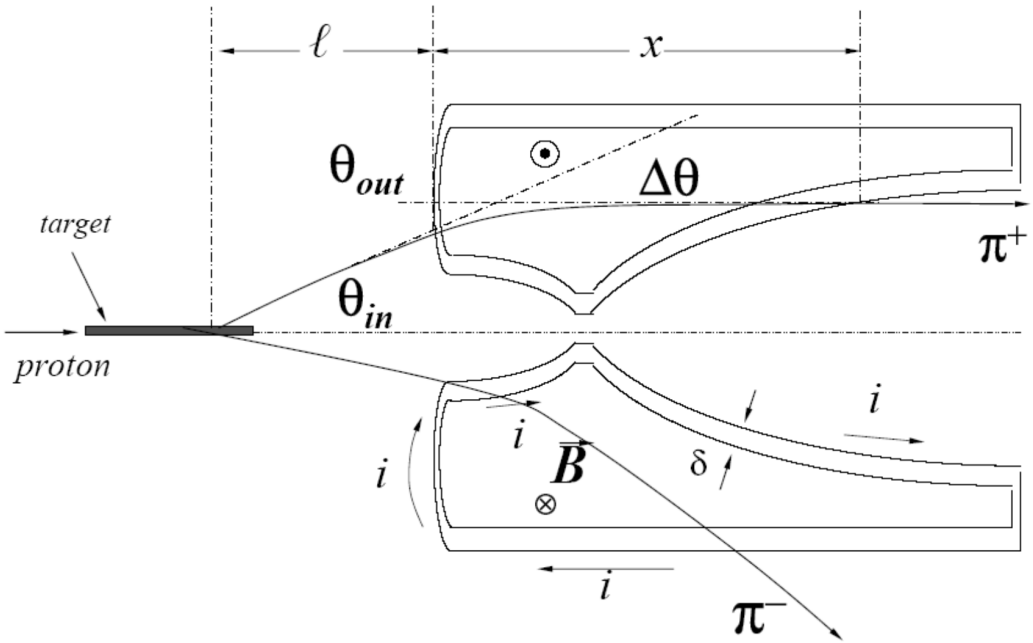
- Installing a second target (or "beam plug") at the downstream end of the first horn
  - Mechanically simpler than a single long target
- Different materials could help to optimize the effect
  - Can tune/optimize material of downstream target
  - "Hybrid" target with higher density core, lower density sheath could be anther option (also maybe mechanically difficult?)

Electromagnetic Focusing Horns



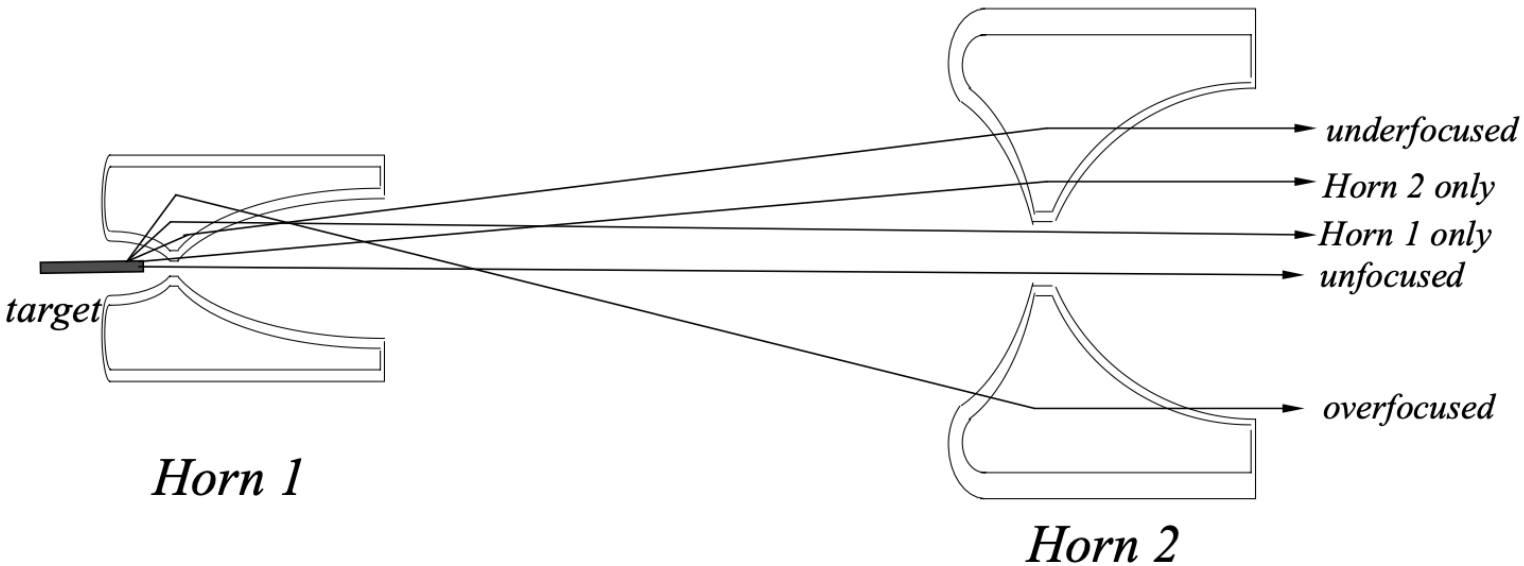
- Electromagnetic focusing horn consists of inner and outer conductor
  - Large magnetic field between conductors achieved by flowing high pulsed current down one conductor and back along the other
    - Generally 100–300 kA – at J-PARC, used 250kA, now upgraded to 320kA
- Pions of the correct sign traveling 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$\sim$3 horns)
  - Horn 1 over-focuses some outgoing particles, Horns 2 and 3 correct path of focused and over-focused particles

Horn Focusing



- Parabolic horn curve $z = ar^2$, with parabolic parameter a
- $\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$, $x = 2\pi r$ is the path-length through the horn
- Focal length $f = \frac{\pi}{\mu_0 a I} p \rightarrow$ focal length depends on momentum p
- Parabolic horn works for all angles
- Quality of the focus is independent of the momentum, and improves with:
  - Larger horn current, thinner conductors, lighter-weight materials with longer radiation lengths, longer horns with larger parameter a

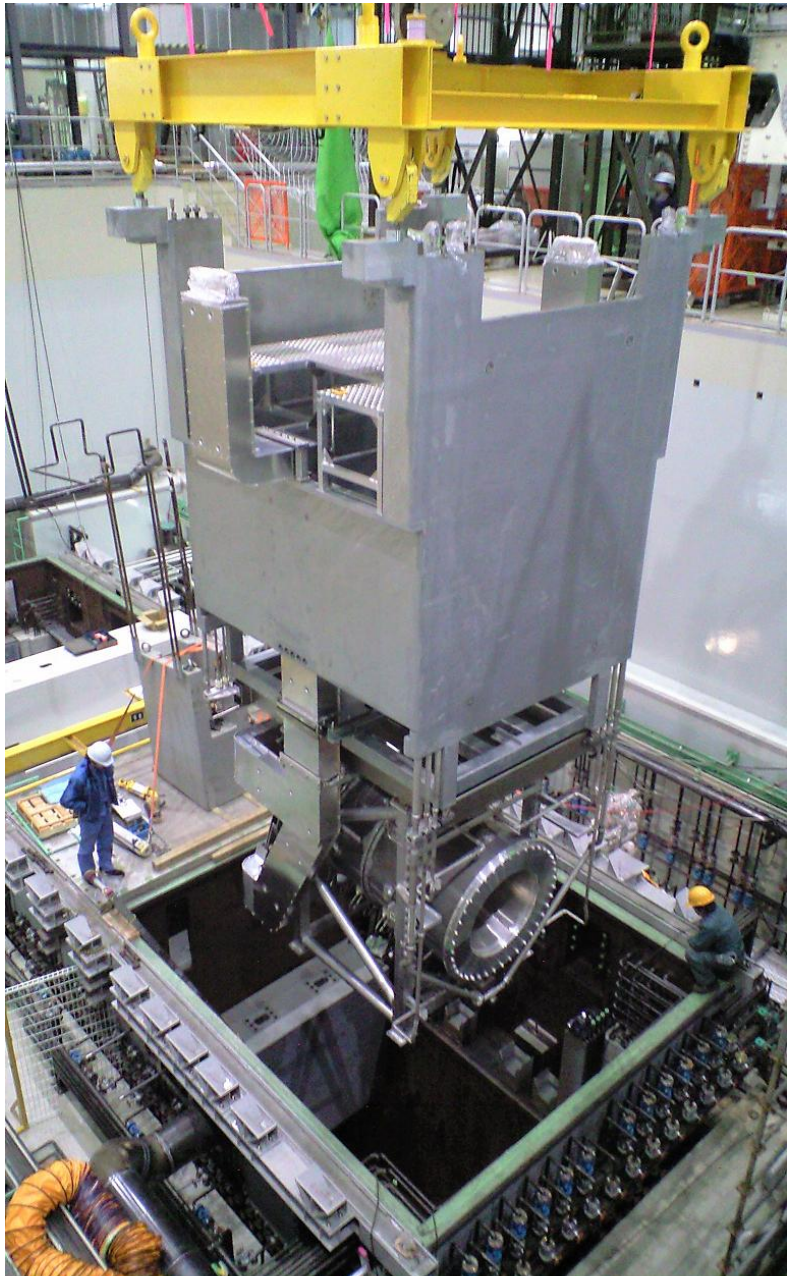
Horn Focusing



- Multiple horn configuration can be used to correct trajectory of right-sign particles which are overfocused or unfocused by Horn 1

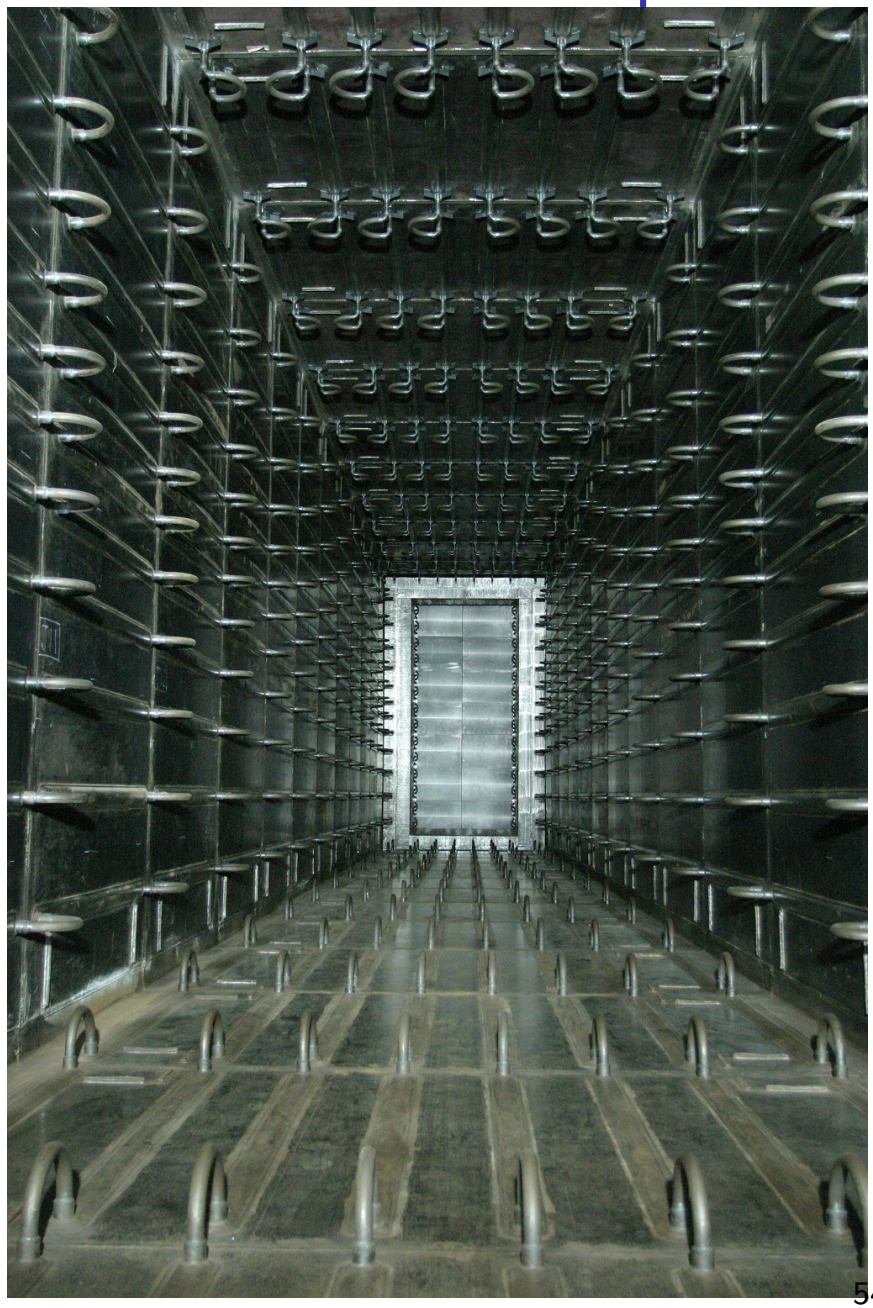
J-PARC Horn Photos

- 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

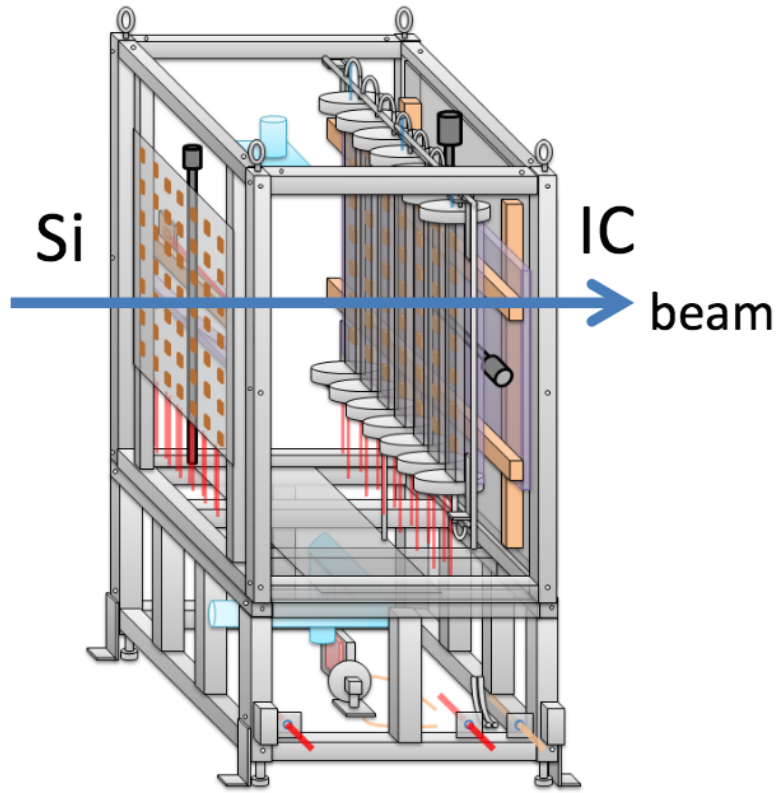


Decay Volume Considerations

- Tune the decay volume length based on the pion energy and decay lifetime
  - For 5 GeV pion, $\gamma \simeq 35$, $\gamma\beta c\tau_\pi \simeq 280$ m
- Particle collisions with air matter (!) – better to evacuate (at J-PARC, decay volume is He-filled)
- Should be as wide as practical for efficient low neutrino energy beams:
  - In general, low-energy pions are not focused so well – divergence will send them into the decay volume walls before decaying
- Also need to consider the effect of the Earth's magnetic field in the decay volume

Hadron/Muon Monitor

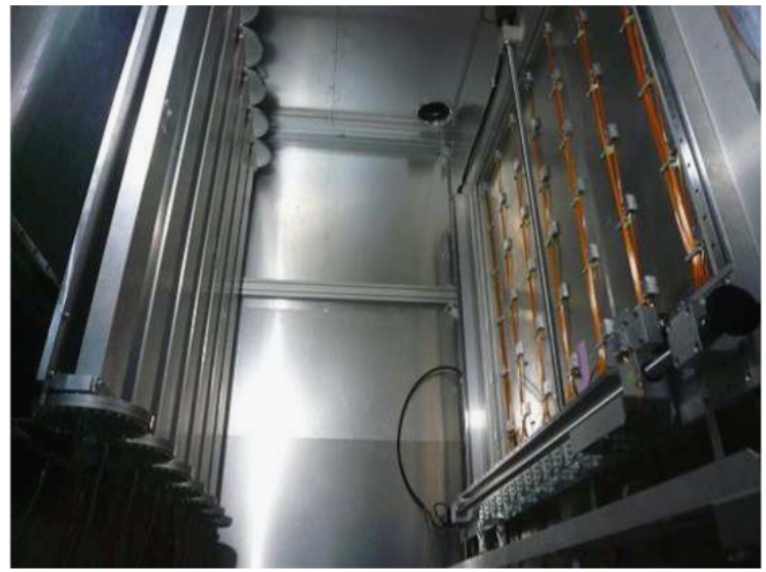
- Detect hadrons or muons after decay volume to understand hadron/muon (+ neutrino) beam direction, profile
  - Upstream (hadron monitor) or inside (muon monitor) of the beam dump
- Use large array of radiation-tolerant detectors to reconstruct the hadron/muon beam profile

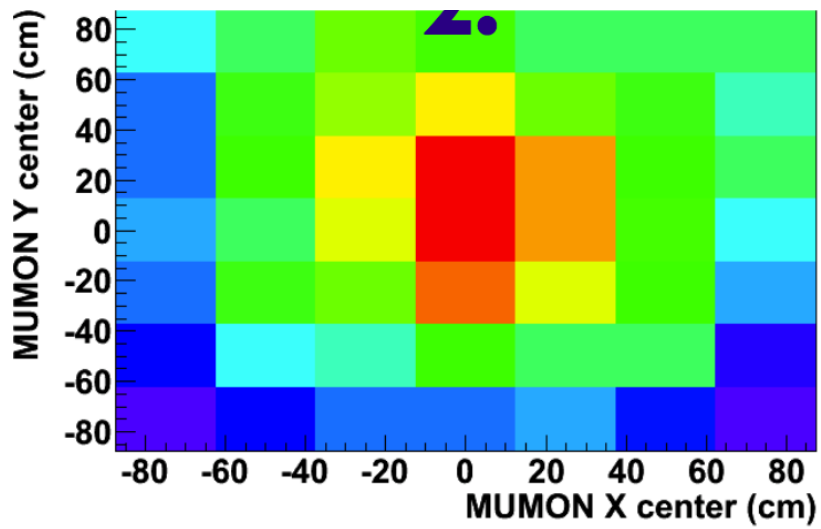


T2K Muon Monitors

MUMON (Muon Monitor)

- Continuously monitors muon beam profile downstream of the decay volume, beam dump ($>\sim$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



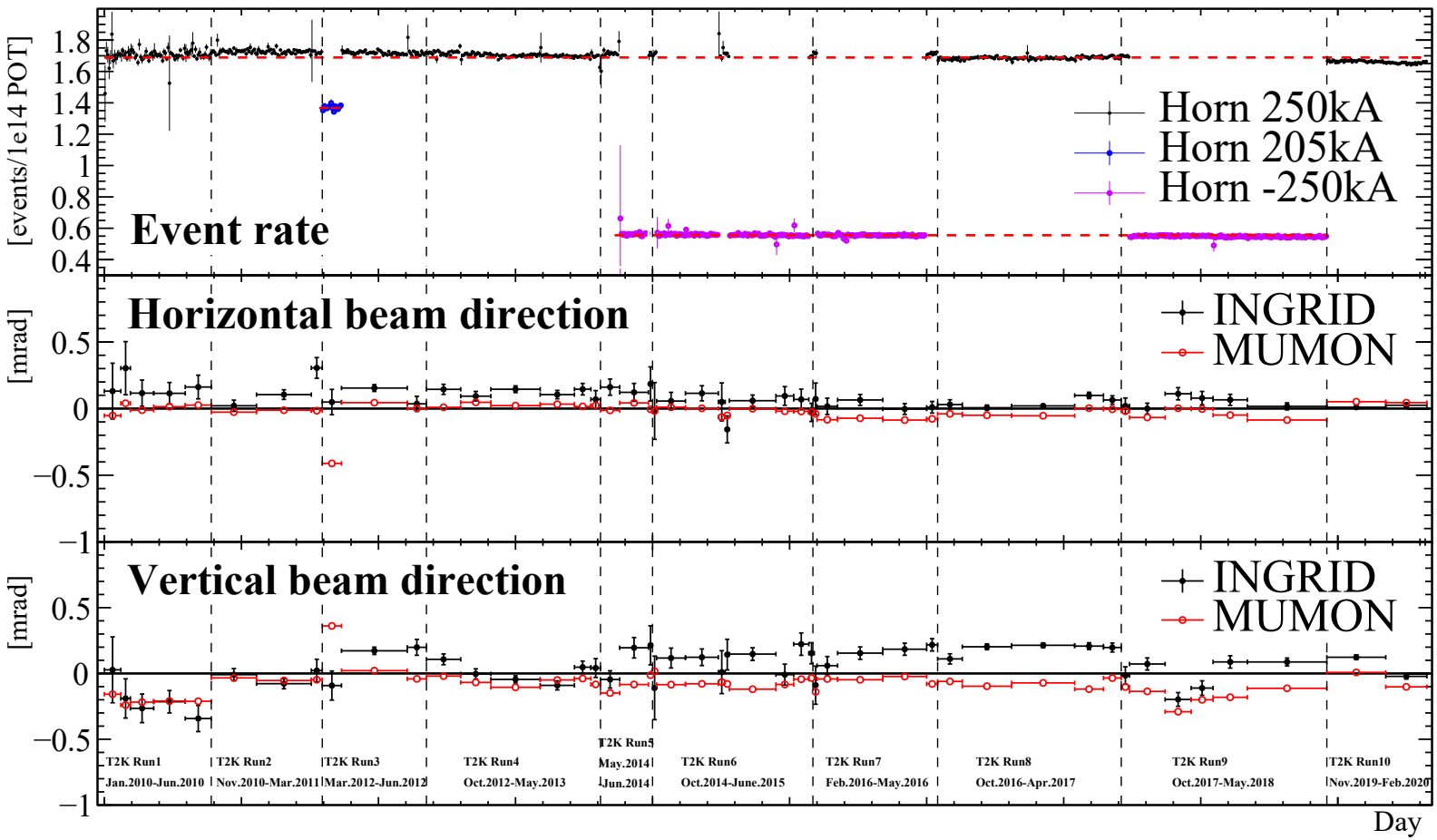


Beamline Component Alignment

- Need to be careful about the alignment of each beamline component
  - With respect to each other
  - With respect to the neutrino detectors
- Impossible to control a beam if the relative alignment between components is not know
  - e.g. cannot guarantee that the proton beam is precisely centered on the target
- Mis-alignment of the beamline with respect to the detectors can be a direct systematic error on the neutrino flux
- Need to be careful during initial design/installation
- Various ways in which the component alignment can change over time
  - Uninstallation/reinstallation for repair/replacement
  - Earthquakes (!?!)
    $\rightarrow$ Frequent component surveys are important

Neutrino Beam Monitoring

- Also important to continuously monitor neutrino beam stability
  - Neutrino beam interaction cross section is very low, so takes order days∼weeks to get sufficient statistical errors
    - But, at J-PARC we actually tune the proton beam to the on-axis neutrino detector measurement (∼once per week)
  - J-PARC on-axis neutrino beam measurement:



Neutrino Beam Monitoring

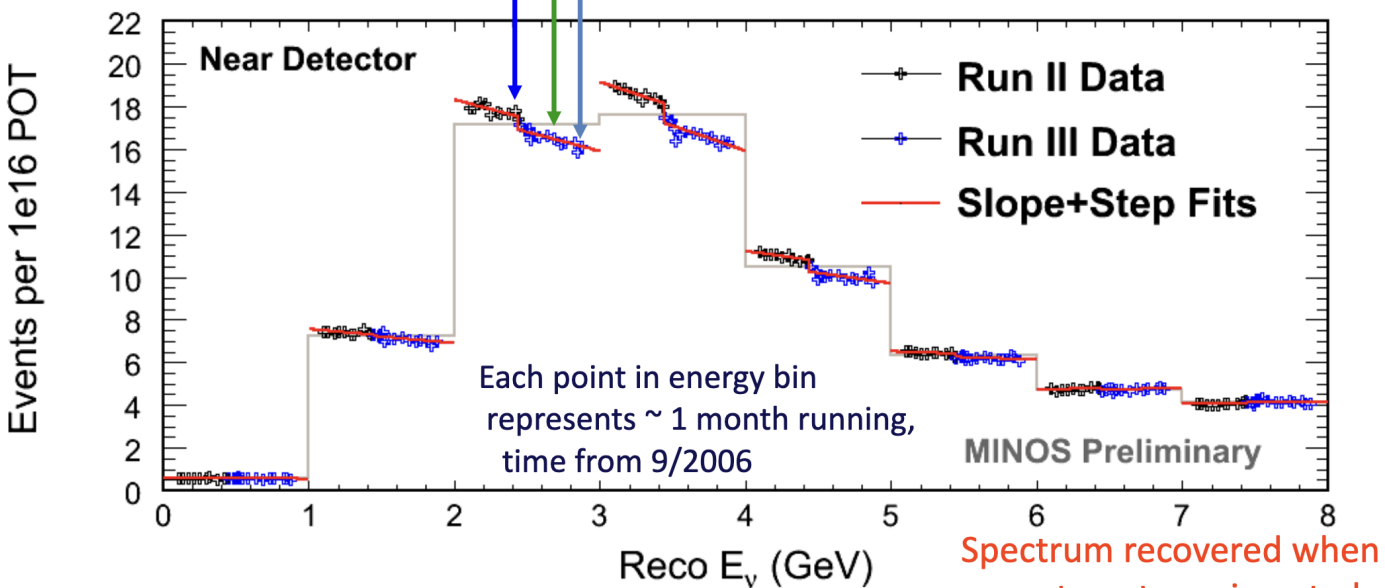
- Can be used to diagnose major issue with production target
- NuMI Target degradation observed at neutrino near detector:

Gradual decrease in neutrino rate attributed to target radiation damage

Decrease as expected when decay pipe changed from vacuum to helium fill

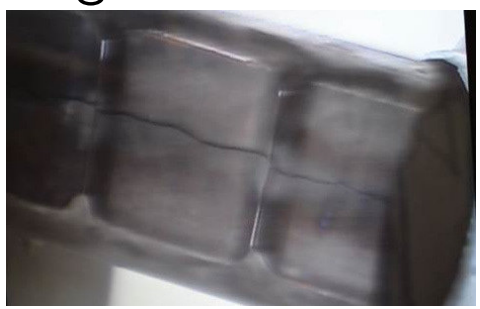
No change when horn 1 was replaced

No change when horn 2 was replaced

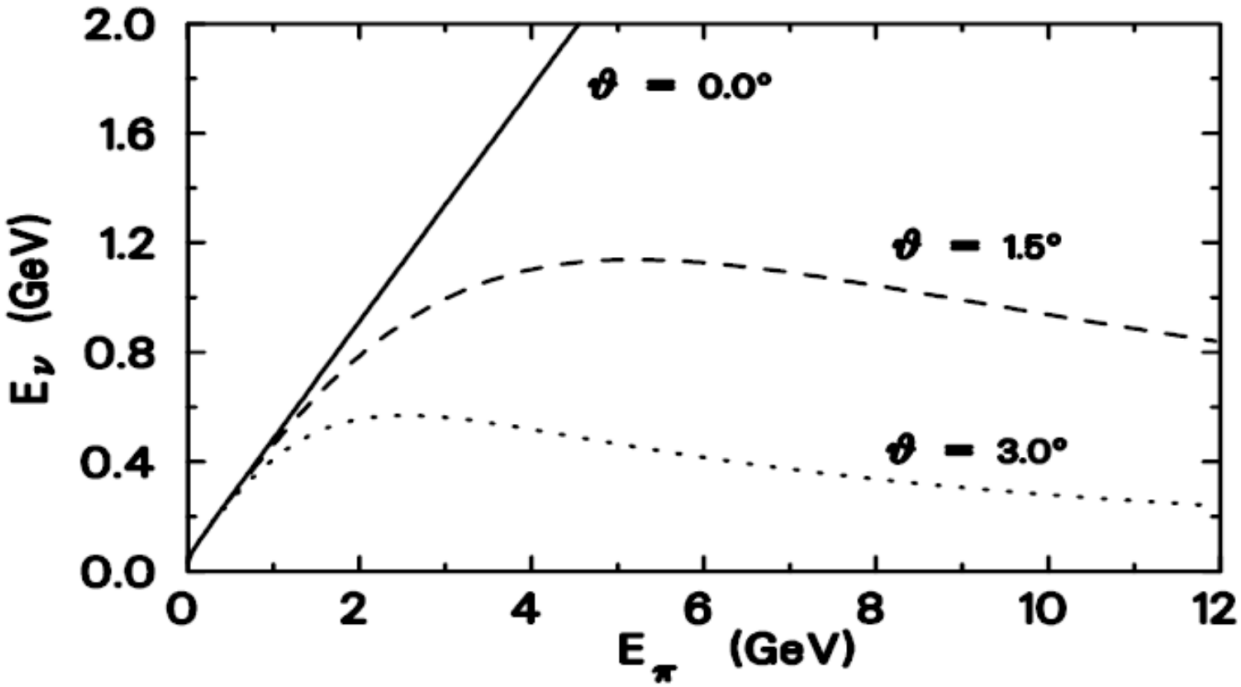


Spectrum recovered when new target was inserted

Degraded NT02 target:



Controlling the Flux – Off-Axis Beam



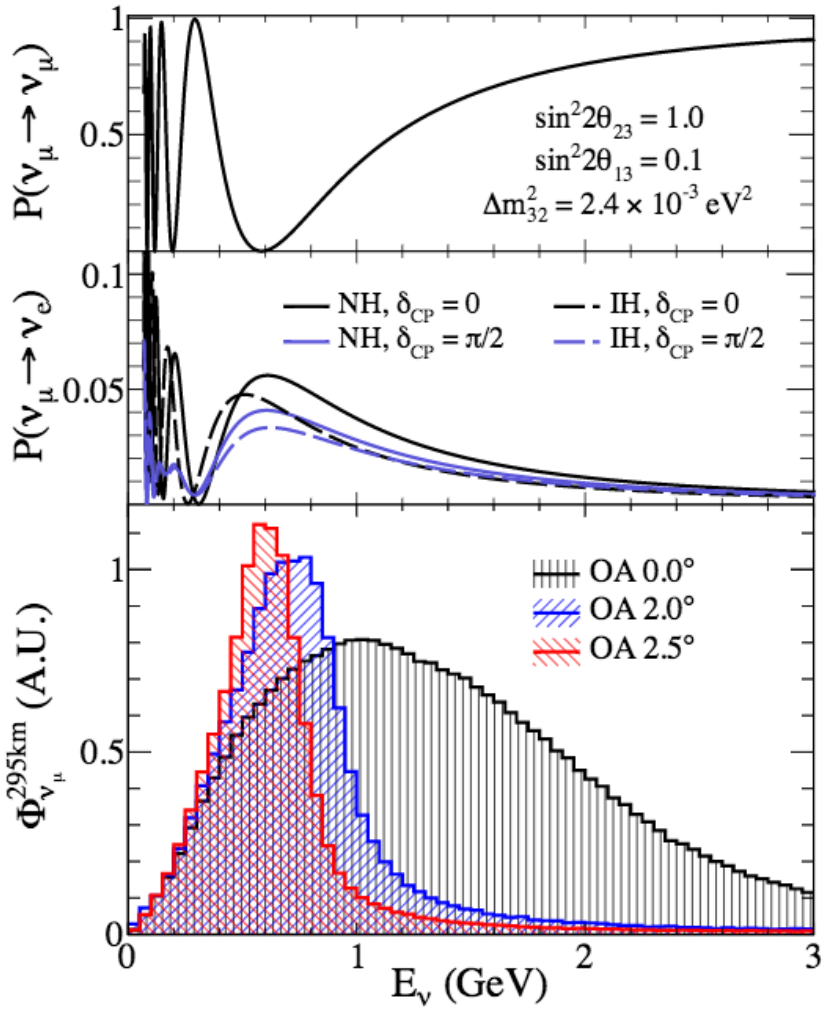
- "Off-axis" beam concept :
  - Due to pion decay kinematics, the neutrino energy depends on the outgoing neutrino angle:

    $E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2}$
  - So, an "off-axis" beam gives a smaller range of neutrino energies

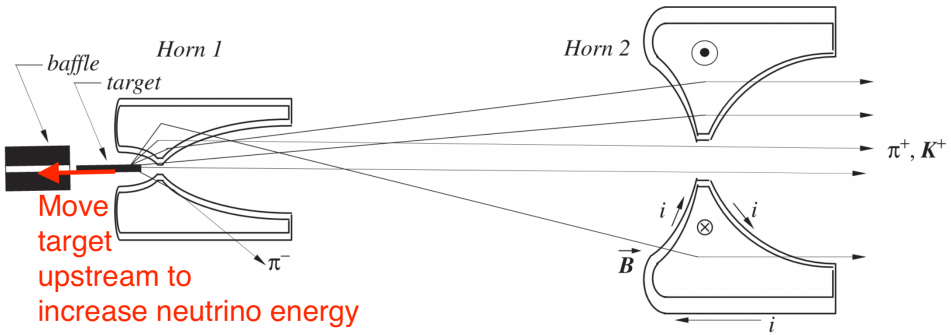
Controlling the Flux – Off-Axis Beam

- Use an off-axis beam to select a neutrino flux with a peak energy near the oscillation maximum
- Install detectors off-axis from the center of the neutrino beam to select the energy
- Precise understanding of the neutrino beam direction essential

Flux + Osc. Prob. at T2K

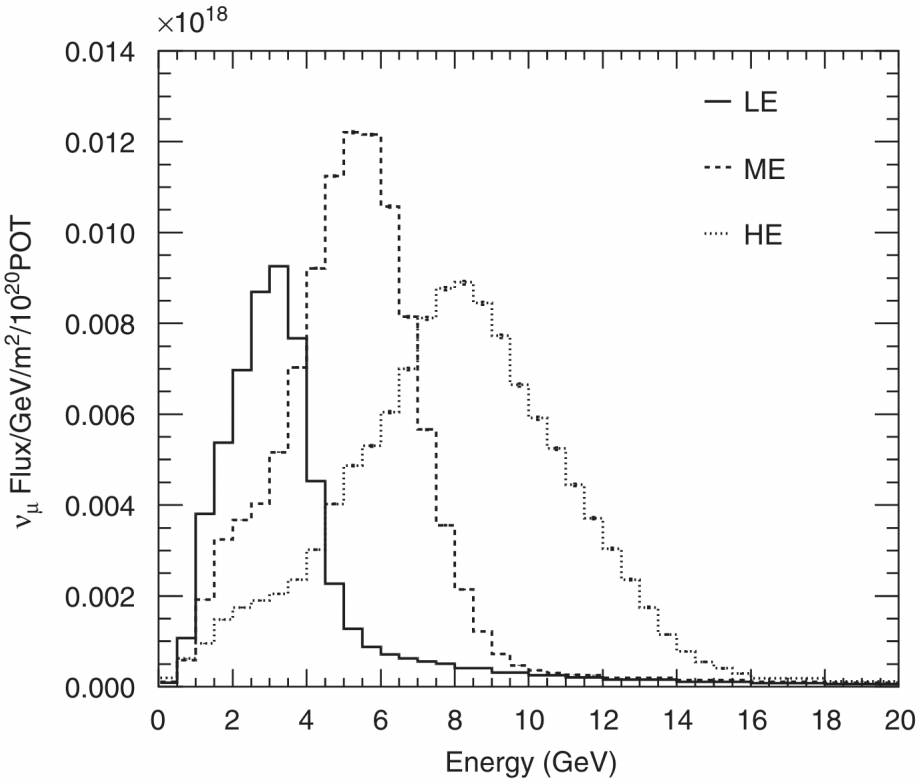


Controlling the Flux – Adjusting the Beamline Configuration



- A movable target in the NUMI beamline allows for control of the neutrino flux distribution
- Moving the target upstream directs smaller-angle, higher-momentum particles into the horn field, resulting in a higher energy neutrino beam

Flux at NuMI Near Detector

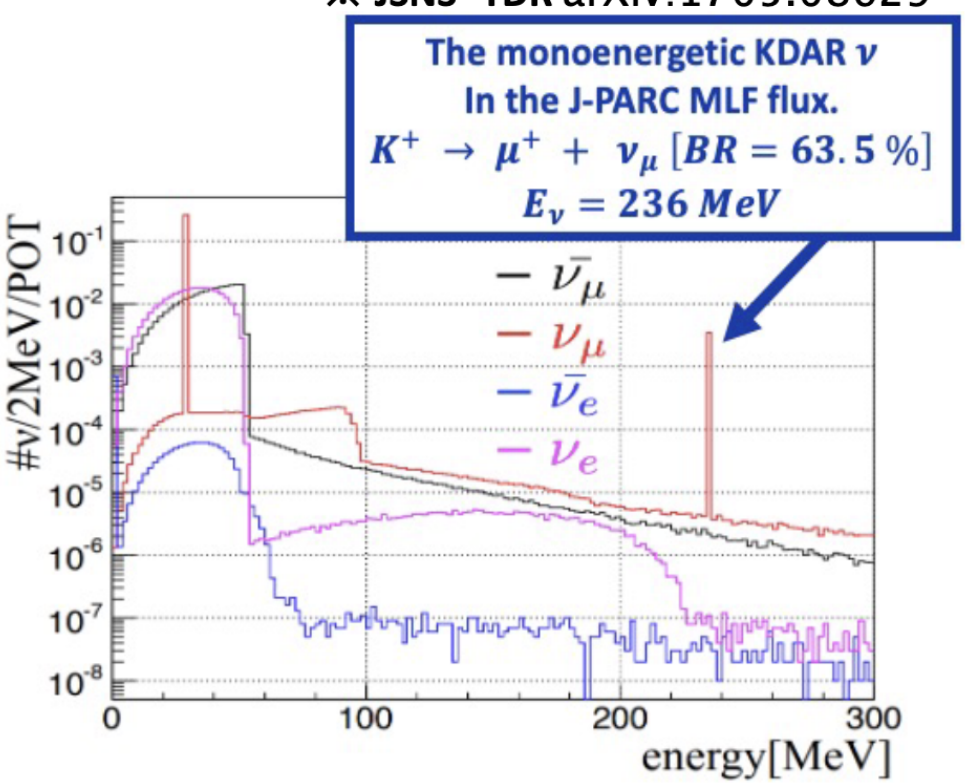


Nucl. Instrum. Meth. A 568 (2006)

Non-Conventional Neutrino Beam – Kaon Decay at Rest

- Kaon Decay at Rest (KDAR) beam is made using kaons (from some accelerator source) which decay at rest in a beam dump
- When charged kaons decay at rest, they can produce mono-energetic neutrinos from the two-body decay : $K^+ \rightarrow \mu^+ + \nu_\mu$ [BR = 63.5 %]
- The emitted muon neutrino is mono-energetic: $E_\nu = 236 MeV$

※ **JSNS² TDR** arXiv:1705.08629



Conclusion

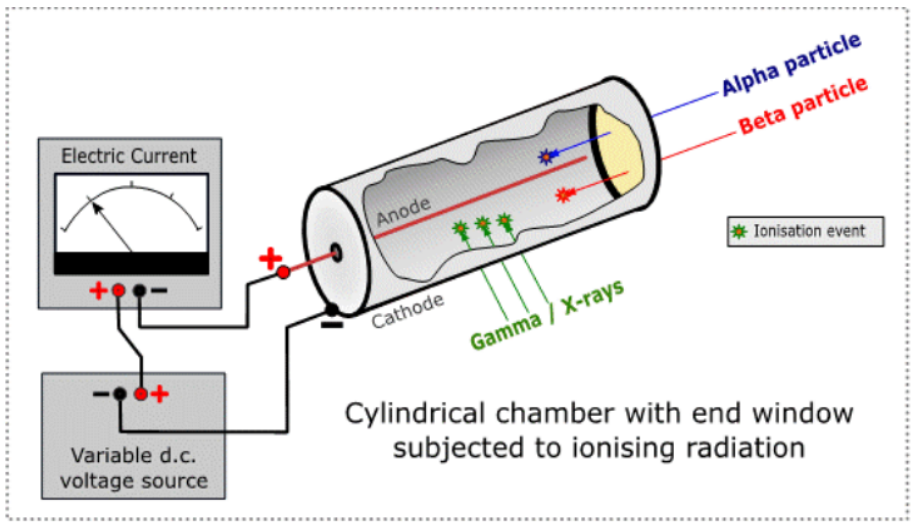
- Many components required to produce a high-intensity neutrino beam:
  - Proton source
  - Proton beam transport to the production target
  - Proper primary proton beam monitoring
  - Production target
  - Focusing horns
  - Decay volume/beam dump
  - Tertiary/neutrino beam monitoring
- Essential to 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

Further reading: "Accelerator Neutrino Beams" by S. Kopp

Backup Slides

Beam Loss Monitor

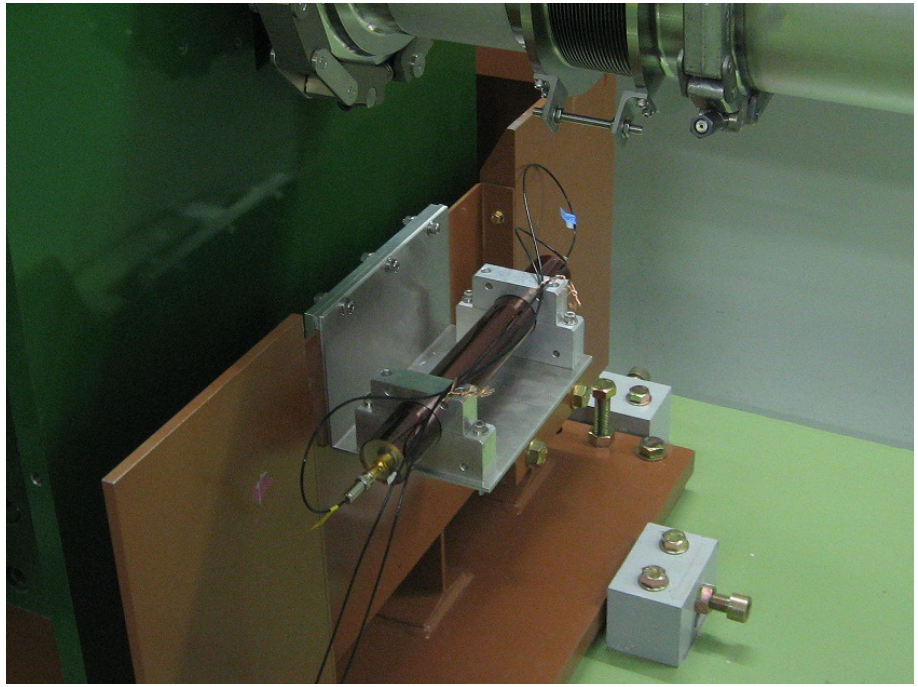
- Wire proportional counter filled with a mixture of $\sim$90% inert gas + $\sim$10% quench gas
- Ionizing particle produced by beam loss travels through the chamber, ionizes inert gas in the chamber, produces e^- – ion^+ pairs
  - Number of pairs proportional to the energy of the particle
- An electric 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



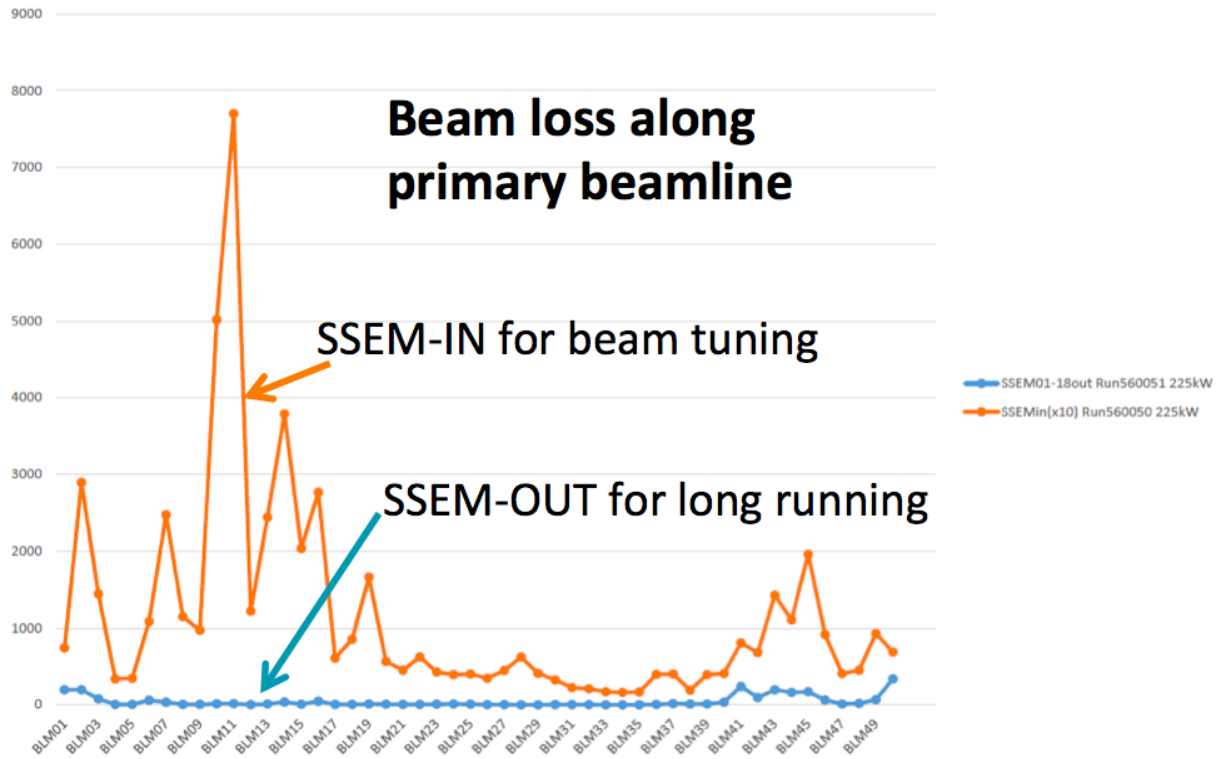
$\rightarrow$ Extremely important for protecting beamline equipment and understanding residual radiation of beamline components

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

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

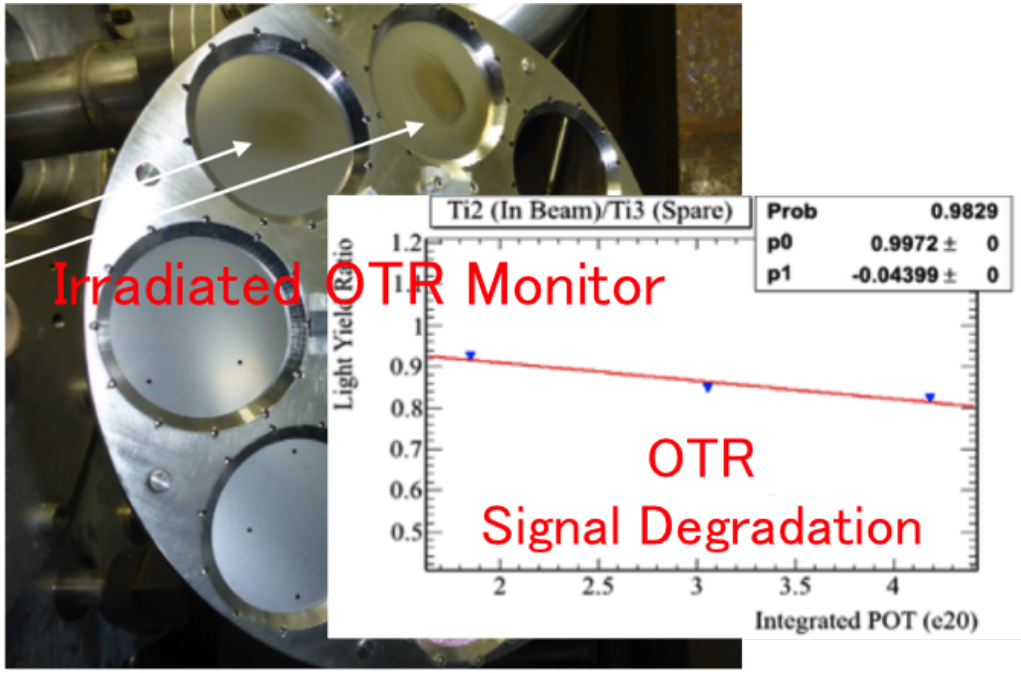
- Standard monitors measure the beam profile by intercepting the beam – they are *destructive* and cause *beam loss*
  - Absolute amount of beam loss is proportional to beam power and volume of material in the beam
- Beam loss can cause :
  - Irradiation of and damage to beamline equipment
  - Increased 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

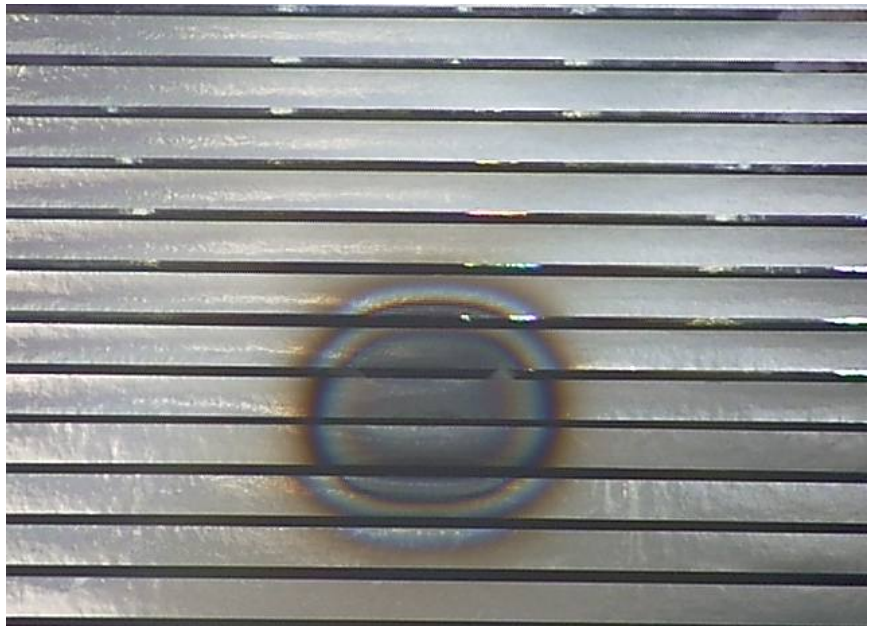
Measured Beam Loss Due to SSEMs



- 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

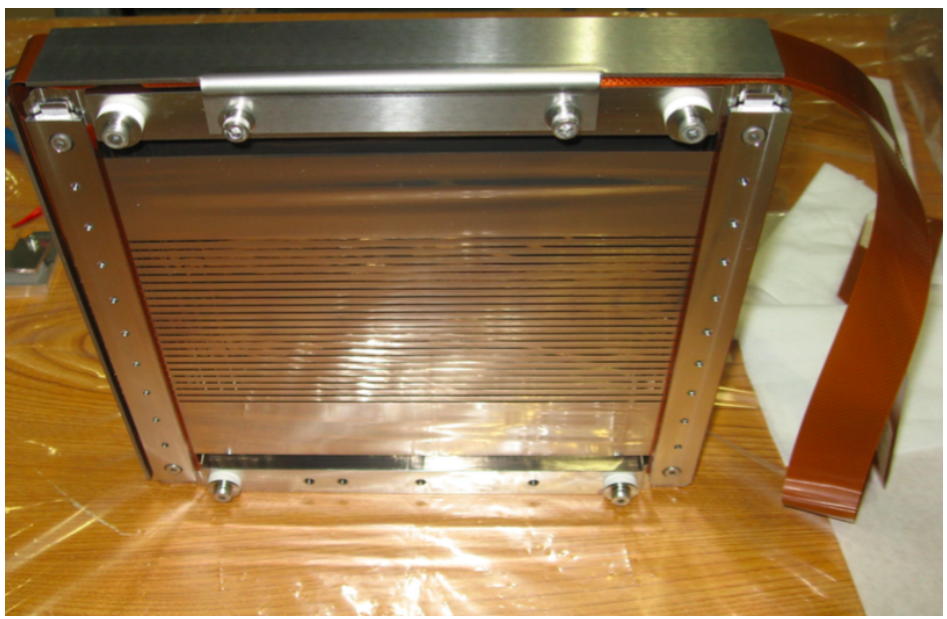
Observed Degradation





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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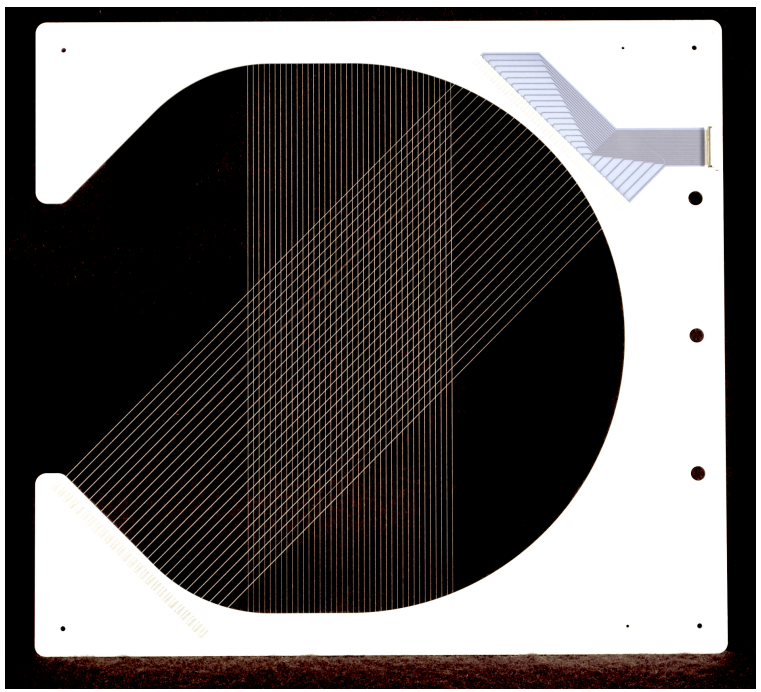
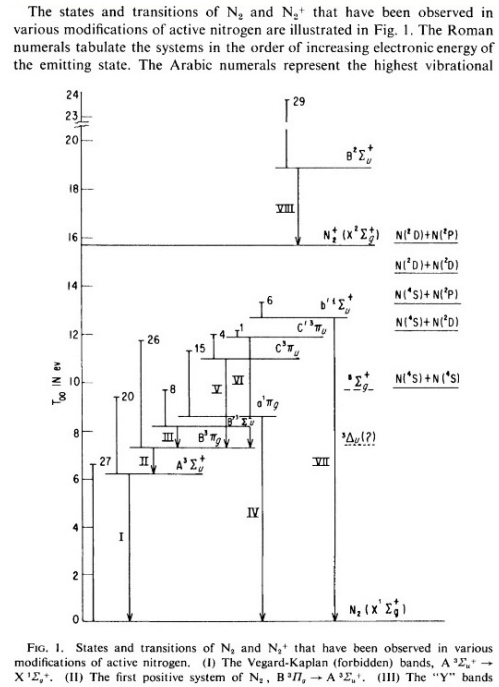


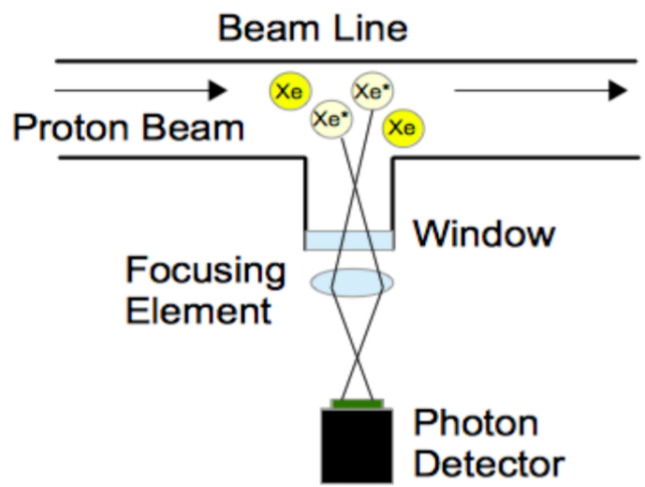
Beam Induced Fluorescence Monitor (BIF)

- 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



The states and transitions of N_2 and N_2^+ that have been observed in various modifications of active nitrogen are illustrated in Fig. 1. The Roman numerals tabulate the systems in the order of increasing electronic energy of the emitting state. The Arabic numerals represent the highest vibrational

FIG. 1. States and transitions of N_2 and N_2^+ that have been observed in various modifications of active nitrogen. (I) The Vegard-Kaplan (forbidden) bands, $A\,^3\Sigma_u^+ \rightarrow X\,^1\Sigma_g^+$. (II) The first positive system of N_2, $B\,^3\Pi_g \rightarrow A\,^3\Sigma_u^+$. (III) The "Y" bands

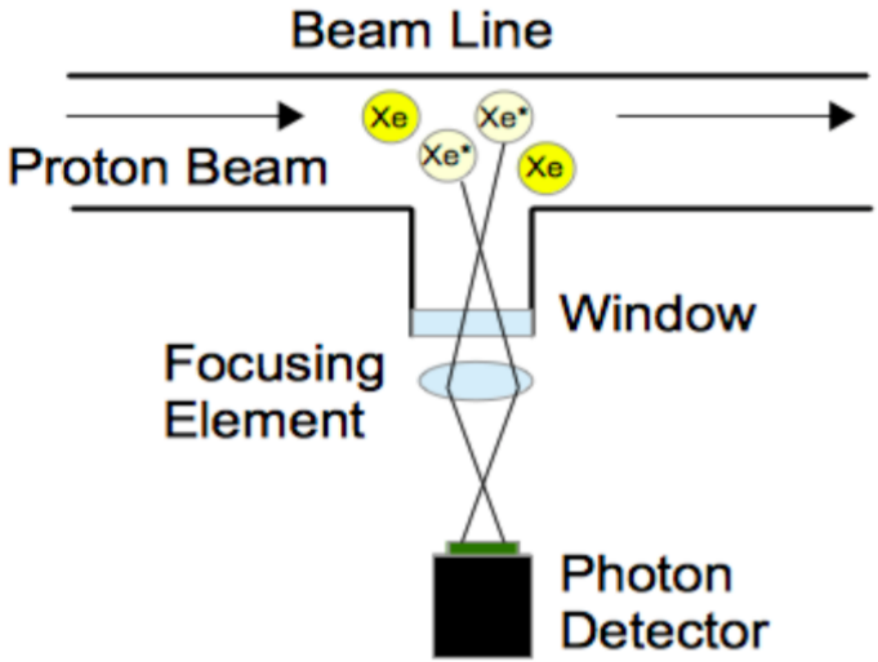


Beam Induced Fluorescence Monitor Merit

- 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

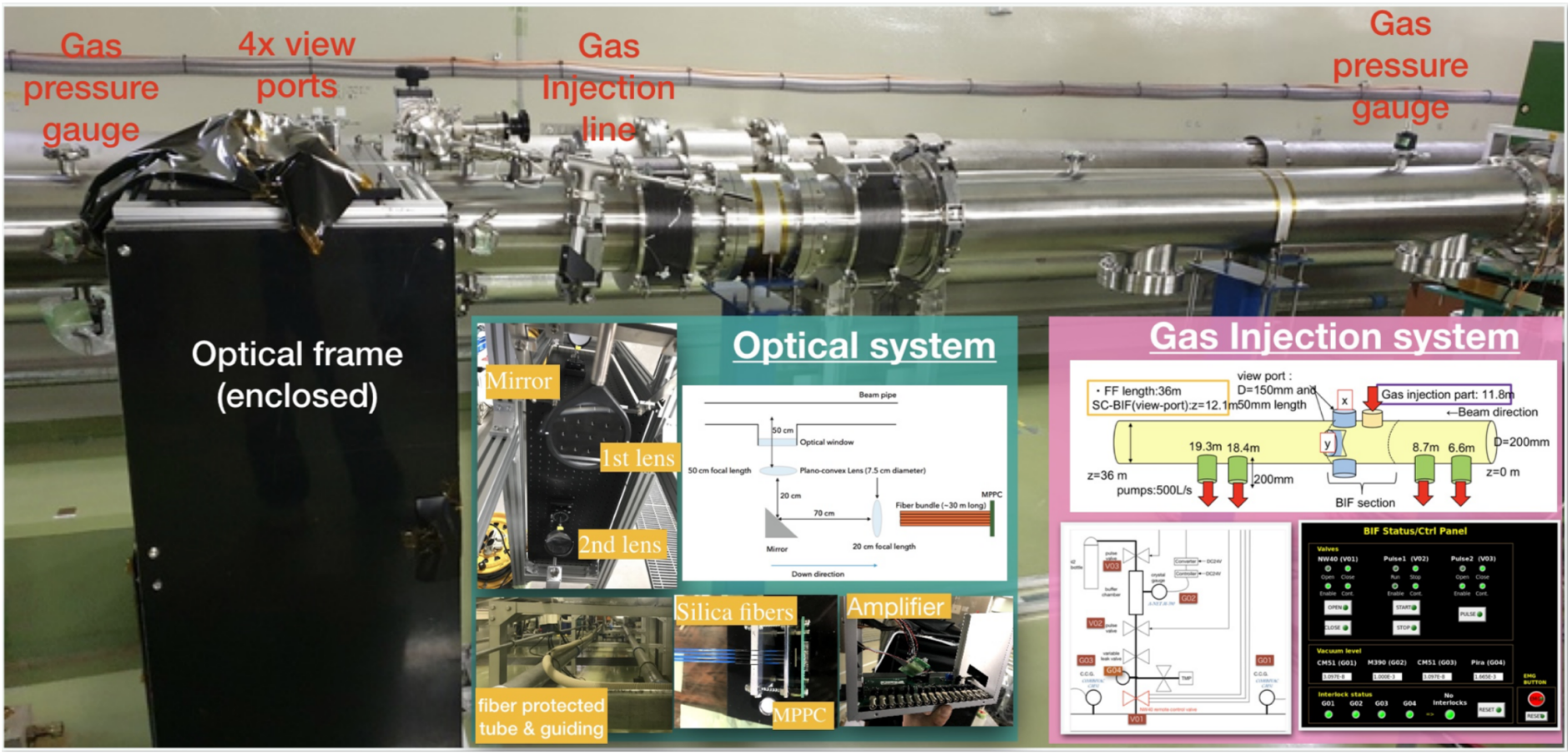
  → Basically totally non-destructive (in T2K extraction line)

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



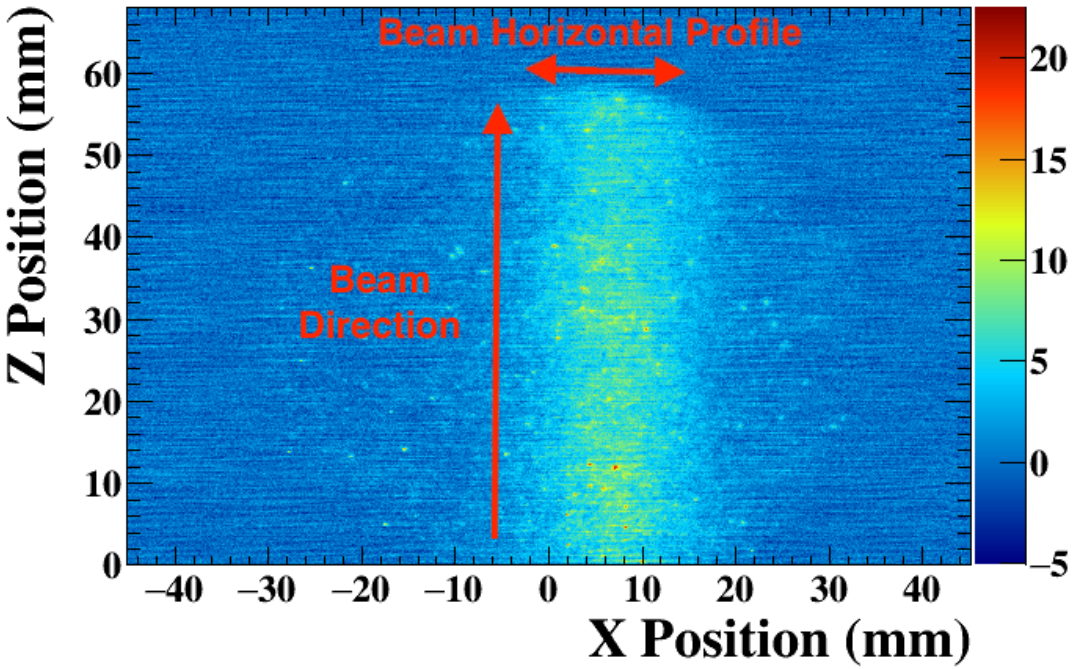
T2K Beam Induced Fluorescence Monitor

- 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)



J-PARC Prototype BIF Results

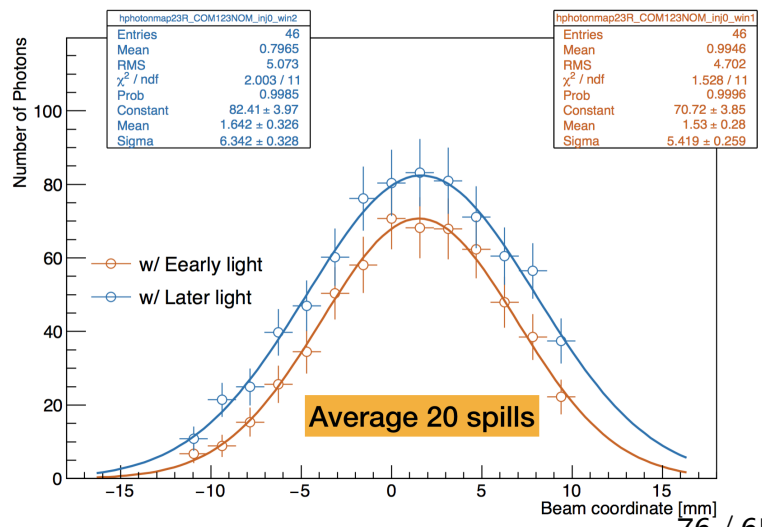
Beam image at camera (1 spill):



- Clear beam signal across camera sensor
- Gaussian fit to extract beam position + profile

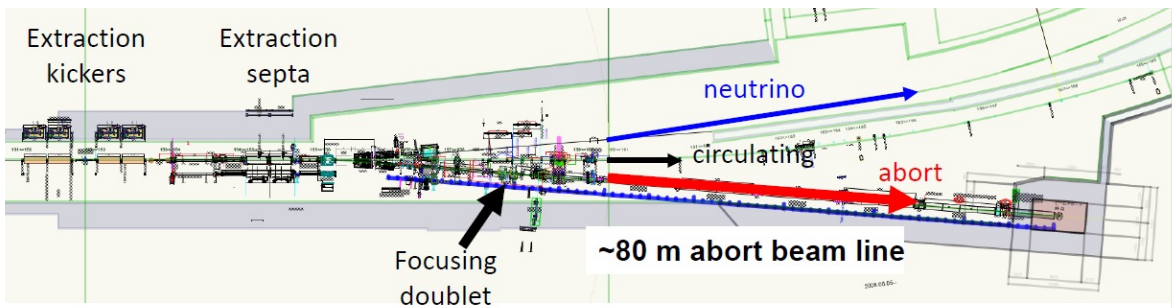
- ∼4e6 V/m beam-induced space-charge field at J-PARC
- Concern that ionized particles would drift in beam space-charge field
  → Measure time dependence of BIF profile using fast readout

Profile with optical fibers:



Beam Dump

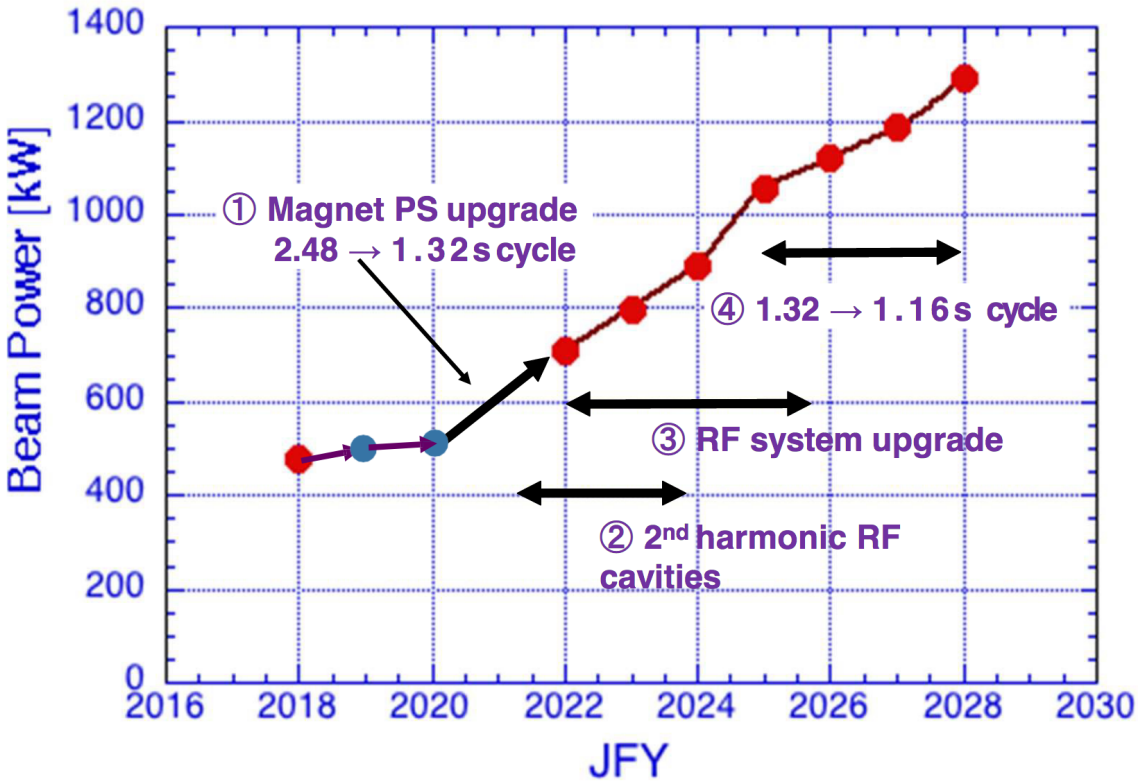
- The beam dump is another component that can limit the operation of the accelerator
- During MR beam study/tuning, or when the beam is aborted, the beam is kicked to a beam dump
- The current J-PARC MR beam dump is passively cooled iron blocks in concrete
  - Operational capacity of only $\sim$18 shots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



C. Densham, NBI2022

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 $\rightarrow$ 1.36s $\rightarrow$ 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 $\rightarrow$ >700 kW $\rightarrow$ 1.3 MW



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

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 $\rightarrow$ Achieved record 540kW!

Capacitor Banks for BM3