T2K Primary Beam Monitor Status and Upgrade

For the 2014 NBI Workshop at Fermilab

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KEK

September 24, 2014

Outline

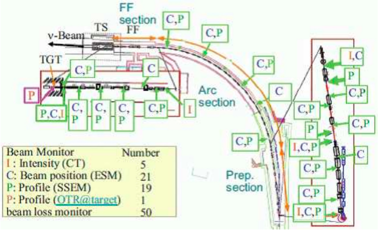
- Motivation and T2K Primary Beam Monitor Overview
- ESMs
- SSEMs
  - Recent Work on SSEMs in SC section
- BLMs
- CTs
  - Recent Absolute Calibration Work
- Future Beam Monitor Ideas
  - Beam Induced Fluorescence Monitor

Why Are the T2K Proton Beam Monitors Important?

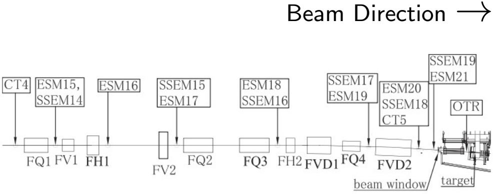
- Required to correctly steer the proton beam/protect beamline equipment
- Information from proton beam monitors is used as input into the T2K neutrino flux prediction simulation

T2K Primary Beam Monitors

Primary Beamline Monitors



Final Focusing Section
(these are used for flux simulation inputs)

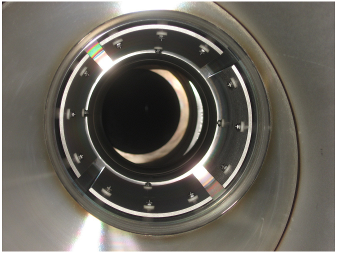


- 21 ESMs (Electrostatic Monitors)
- 19 SSEMs (Segmented Secondary Emission Monitors)
- 50 BLMs (Beam Loss Monitors)
- 5 CTs (Current Transformers)
- 1 OTR (Optical Transition Radiation) Monitor
  - See next talk by M. Hartz
- MUMON (Muon Monitor)
  - See talk on Friday by T. Hiraki

ESMs

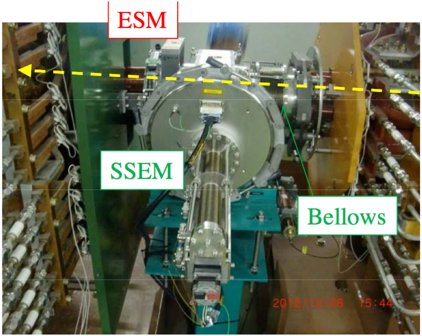
21 ESMs (Electrostatic Monitor)

- Four segmented cylindrical electrodes surrounding the proton beam orbit (80°coverage)



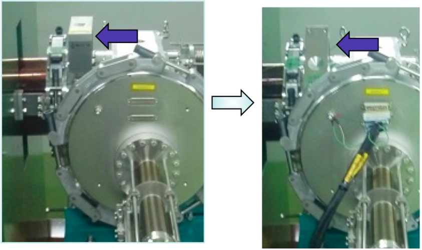
- Non-destructively, continuously monitor the proton beam position using a top-bottom and left-right asymmetry of the beam-induced current on each electrode
  - 4 ESMs were rotated by 45° last year
- Precision on the beam position is better than 450 μm
- However, ESMs are used for monitoring stability of beam position, rather than for calculating absolute beam position
  - ESM19, 20, 21 monitor the beam position nearest the target and are used in determining the proton beam parameters for the flux prediction (when SSEMs are OUT)

ESM Beam Hit in 2012 and ESM Rotation in 2013



- Accidental beam hit of ESM (due to magnet tripping off) caused vacuum leak at ESM feedthrough

- 4 ESMs (those placed after bending magnets) were rotated by 45°
- In order to prevent damage due to a beam hit if a magnet accidentally trips off

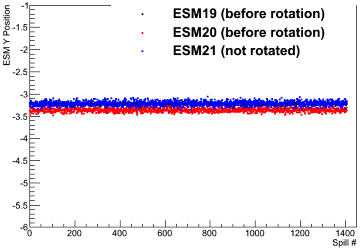


ESM Data: Performance of Rotated ESMs

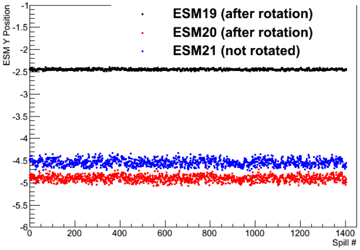
- 4 ESMs were rotated by 45°
  - Including ESM19 and ESM20, which are used to determine the beam position at the target spill-by-spill
- Required updated analysis to calculate positions in X and Y
- Performance (stability) of rotated ESMs looks reasonable

ESM19, 20, 21 stability before and after ESM19, 20 rotation

ESM data pre-rotation



ESM data post-rotation

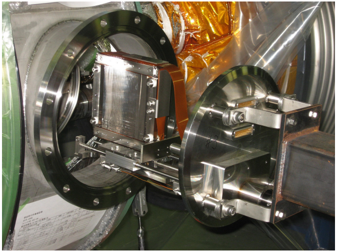


(note: there are magnets between ESMs – beam position shouldn't be the same at each ESM)

SSEMs

19 SSEMs (Segmented Secondary Emission Monitor)

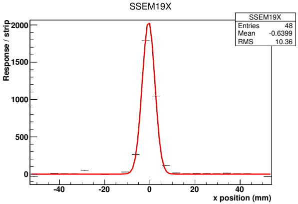
- Two 5-μm-thick titanium foils stripped horizontally and vertically, with a 5-μm-thick anode HV foil between them
  - Strip width ranges from 2 to 5 mm, optimized according to the expected beam size

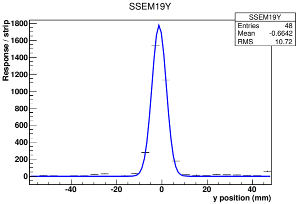


- Monitor proton beam profile during beam tuning
  - All SSEMs except SSEM19 are extracted during standard beam running since SSEMs cause ($\sim$0.005%) beam loss
  - SSEMs move on a stage connected to a traveling nut moving along a screw which is turned by a remotely controlled motor
- Precision on the beam width measurement is 200 μm
- Recently, degradation of Oiles washers used in superconducting magnet section required work on two SSEMs (see later slide)

SSEM Data

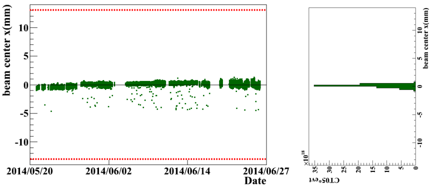
Signal in SSEM19 from a single beam bunch:



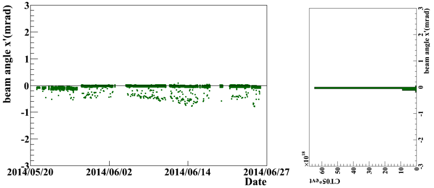


Fit data from:
SSEM19 + OTR + SSEM1-18 (if SSEMs IN) -or- ESMs (if SSEMs OUT) to calculate beam position, angle, width, etc at the baffle (upstream of the target) and target

X Position at Target



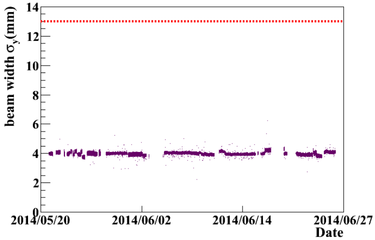
X Angle at Target



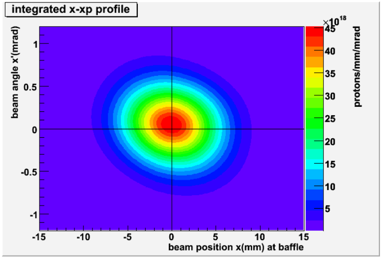
T2K Proton Beam Parameters

Use information from beam position and profile monitors to calculate the beam profile at the baffle (upstream of the target) → input into flux MC

Y Width at Target vs. Time



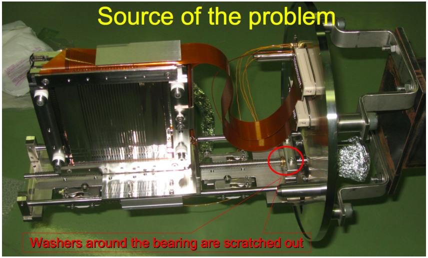
Integrated X Profile at Baffle

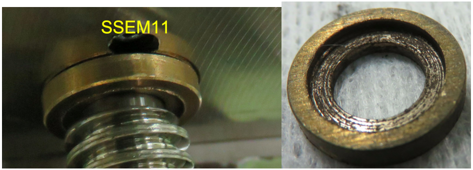


T2K Run 4	X Profile		Y Profile	
Parameter	Central value	Error	Central value	Error
X, Y (mm)	0.03	0.34	-0.87	0.58
X', Y' (mrad)	0.04	0.07	0.18	0.28
σ (mm)	3.76	0.13	4.15	0.15
ϵ (π mm mrad)	5.00	0.49	6.14	2.88
Twiss α	0.15	0.10	0.19	0.35

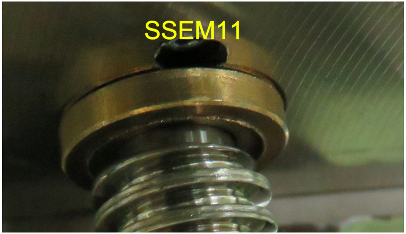
Recent SSEM Work

- 4 / 19 SSEMs are in the superconducting section of the T2K primary beamline
- Require use of Oiles washers and traveling nut for motion into and out of the beamline because of low temperature (other 15 SSEMs use standard pieces + grease)
- Problem with some Oiles washers being scraped by screw – was causing considerable backlash in motion of 2 SSEMs
  - The SSEM position/beam position measurement is fine
  - But, would be a major problem if an SSEM got stuck while being extracted/inserted





Recent SSEM Work



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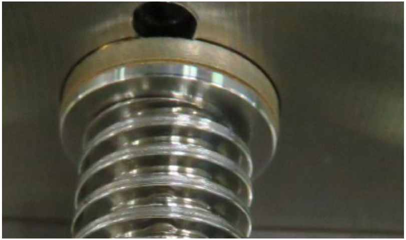
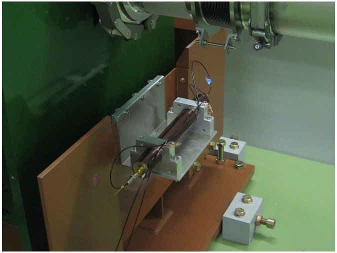


- Replaced damaged washers with a thinner Oiles washer paired with a protective stainless steel washer
- Stainless steel washers shouldn't be scratched by the rotating screw, but Oiles washers should still allow motion
- This solution hasn't been tested, so we hope it's an okay solution

BLMs

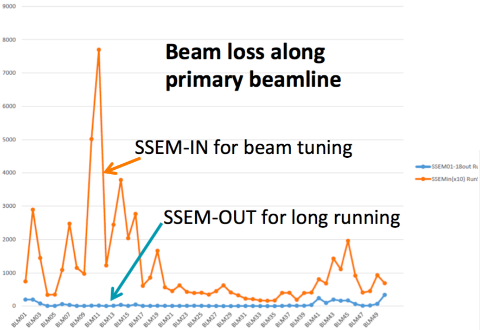
50 BLMs (Beam Loss Monitors)

- Wire proportional counter filled with an Ar-CO_2 mixture

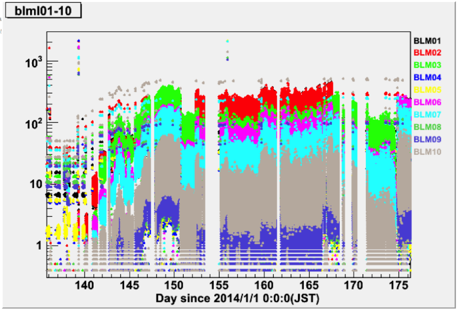


- The BLM signal is integrated during each beam spill, and if it exceeds a threshold a beam abort interlock signal is fired
- BLMs have a sensitivity down to a 20 mW beam loss
- Other than some power supply work, BLMs have been working stably

BLM Data



Beam-loss history plot from 2014 May-June Run



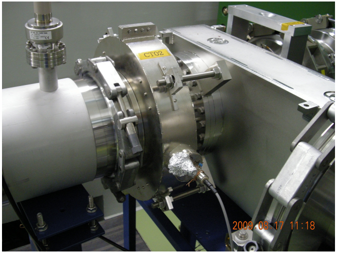
- Beam loss is monitored spill-by-spill
- If the beam loss exceeds a predetermined limit, an alarm is issued and the beam is stopped

- Gradual increase in beam loss tracks gradual increase in beam power during the start of the run

CTs

5 CTs (Current Transformers)

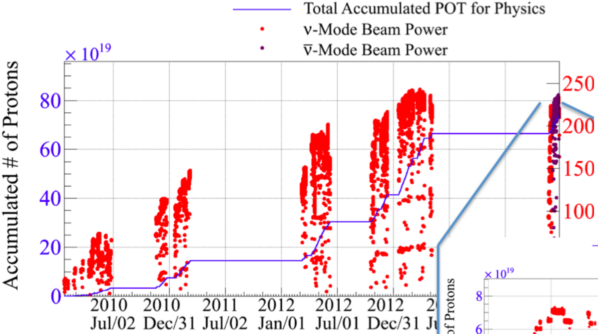
- 50-turn toroidal coil around a cylindrical ferromagnetic core
- Monitor proton beam intensity

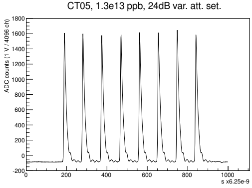


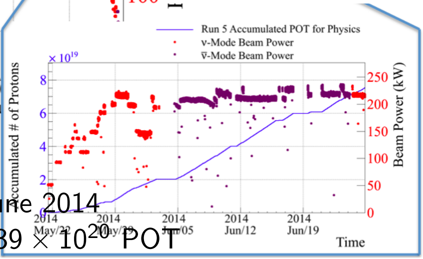
- Currently assigned a 2.7% systematic error on the absolute number of protons on target
  - CT absolute calibration error doesn't affect T2K oscillation measurement, since the near/far detector normalization cancels
  - Is an issue for cross section measurements, sterile neutrino searches, etc.
- Have had some trouble with CT stability over time
- We are now doing CT calibration work (see next slides)
  - Calibration is more difficult than expected due to possible CT response frequency dependence

CT Data: T2K Protons on Target

Use information from CTs to calculate number of protons on target



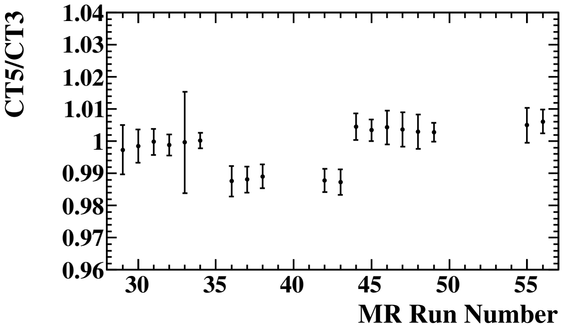




- Began taking $\bar{\nu}$-mode data in June 2014
- Integrated for Physics so far: 7.39×10^{20} POT
- Integrated ν-Mode for Physics so far: 6.88×10^{20} POT
- Integrated $\bar{\nu}$-Mode for Physics so far: 0.51×10^{20} POT

$\rightarrow$ $\sim$9.5% of T2K approved full statistics (7.8×10^{21} POT)

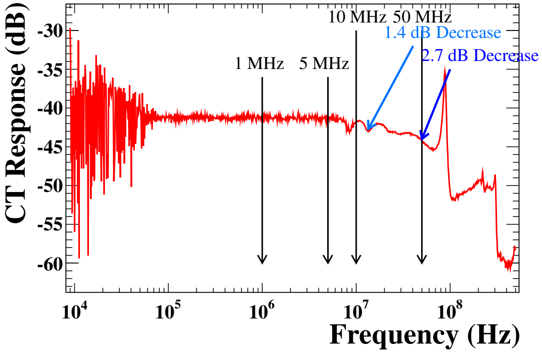
CT Stability



- CTs have drifted by ~2% with respect to one another over the full T2K run
- Regular calibration of the attenuators (used to attenuate the CT signal read out by the DAQ) is required
- Absolute calibration hasn't been done since the CTs were installed
    - Now working on doing this absolute calibration

CT Frequency Dependence

- To do absolute calibration, you must:
  1. Input some pulse (from a signal generator) and precisely measure the input pulse integral
  2. Calculate output integral in DAQ
  3. Correctly evaluate errors
- Issue if the CT output signal size changes depending on the frequency of the input signal

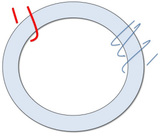


CT Frequency Dependence

Two ways to input a signal into a CT:

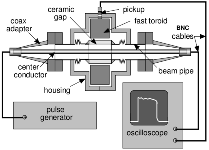
Single turn coil test input port:

- On all installed CTs, can be used easily

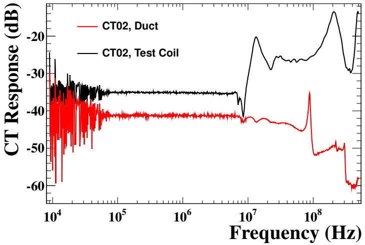


Special test duct:

- To use on installed CTs, must break vacuum, uninstall CT



Frequency dependence of CT response for two input methods is different:



- Understanding the frequency structure of the beam pulse is very important for calibration!

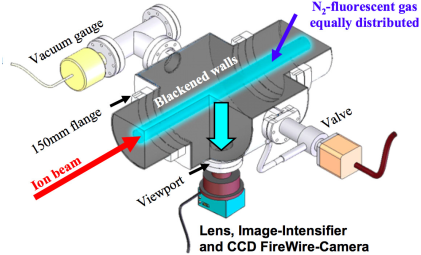
Future Beam Monitor Plans

- SSEMs are *destructive* and cause *beam loss*
- Only the most downstream SSEM (SSEM19) can be used continuously
  - All other SSEMs are only used during beam tuning and are removed from the beamline during normal data-taking
  - Actually, according to the T2K LOI, SSEM19 has already been exposed to a larger POT than it was designed to withstand
    - Although we haven't seen any evidence of SSEM19 signal degradation, it won't necessarily be usable for a long period of time at high beam power
- OTR is also used to monitor the beam position directly upstream of the target
  - This is also a destructive monitor
  - Degradation of the OTR foils has been observed
- The beam profile must be monitored continuously, so we need to start working on something for use at high beam power

Beam Induced Fluorescence Monitor Concept

- Beam Induced Fluorescence (BIF) monitors or Ionization Profile Monitors (IPM) use fluorescence or ions induced by proton beam interactions with gas in the beamline
  - Either residual gas or gas injected into the beamline
    - Probably the residual gas level (3e-6 Pa) is too low in the J-PARC neutrino beamline – will need to inject gas to ∼1e-4–1e-3 Pa
  - An IPM drifts ions to a multi-channel plate
    - The large field from the beam protons make this type of monitor impractical for the J-PARC neutrino beamline
    - In use here, J-PARC RCS; has been designed for the J-PARC MR

- BIF monitor detects the fluorescence of gas in the beamline
- Have been used in CERN SPS, etc.



Considerations on Gas Type for BIF

Choice of gas is important – light level is very low

- 2 (of many) possibilities are N_2 and Xe
- Interaction cross section and fluorescence spectrum/lifetime must be considered:
    - Cross section is $3.3\times$ higher for N_2
    - N_2 fluorescence has lifetime of 58 ns
    - Xe has two components, 6 and 52 ns – may require fast readout to see full spectrum details
    - Significant light is produced in the visible region, although the Xe spectrum may also extend into the near UV
- Studies shown in NIMA 492 (2002) 7490

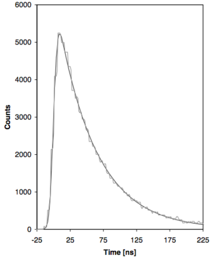


Fig. 7. N_2 lifetime, no optical filter. The solid curve is a fit to the data giving a bunch length of 5.4 ± 0.2 ns and a decay time of 57.7 ± 0.2 ns. Gas pressure $=1.0\times10^{-6}$ Torr. Beam momentum $=26$ GeV/c.

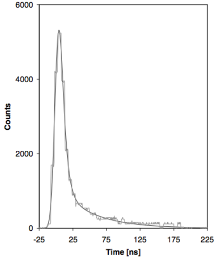


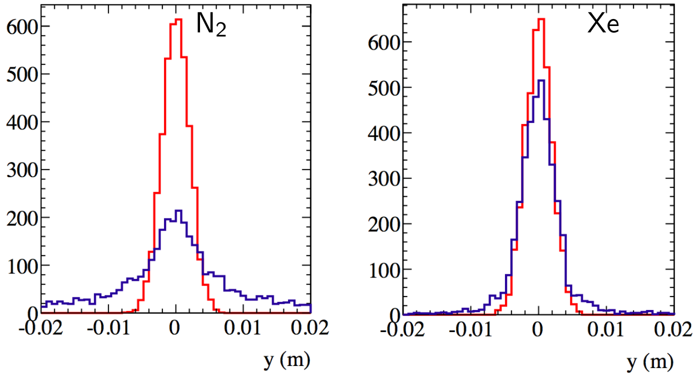
Fig. 9. Xe lifetime measurement, no optical filter. The solid curve is a fit to the data giving a bunch length of 5.09 ± 0.05 ns and decay times of 6.0 ± 0.1 and 51.5 ± 0.9 ns. Gas pressure $=1.3\times10^{-6}$ Torr. Beam momentum $=26$ GeV/c.

Considerations of Space Charge Effects

- The J-PARC neutrino beam has the highest protons per pulse in the world
  - Electric field from space charge is as large as 4e6 V/m
- Large space charge effects $\rightarrow$ must use fluorescence (BIF) rather than ionization (IPM)
- Issue with ionized particles drifting in the beam field before producing light and distorting beam profile measurement
- Some ideas to mitigate space charge effects:
  - Fast readout with PMT or MPPC (instead of slower readout with CCD)
  - Possible beam test including check of amount of ionized (vs. non-ionized) particles which contribute to the fluorescence signal
  - Using Xe may be help reduce issues due to drift in high field
    - Larger molecular mass reduces ion velocity
    - $\sim$1/2 of the light has 6 ns lifetime - less time to drift before the light is produced

Considerations of Space Charge Effects

- May be possible to mitigate beam space charge effects by using Xe
  - Because Xe is heavier/has a shorter fluorescence lifetime, ions don't move in the beam field as much
- Red: simulated fluorescence profile before drift in beam field
  Blue: simulated fluorescence profile after drift in beam field



Other Considerations for BIF Design

- Residual gas levels are probably too low in the T2K beamline
  - Need to design gas injection/vacuum system
  - Running gas flow simulations using COMSOL software now
- Need to design optical system
  - Need to consider noise due to the proton beam since optical components must be placed relatively near the beamline
    - Shielding may be required
    - Optical elements (such as mirrors or lenses) may also be needed so that PMTs/MPPCs may be placed as far away from the beam as possible
    - Number/size of "pixels" must also be chosen
- Need to design readout system
  - Considering if fast (500 MHz) readout is required due to fluorescence lifetime – may depend on gas choice
  - Many channels may be required depending on the number of PMTs/MPPCs used
- Cost – we'd like this monitor to be *as cheap as possible*

Plans for BIF

- Now/soon:
  - Using COMSOL software to run simulations to help design gas valve and vacuum system
  - Testing PMT/MPPC options
    - Will install some MPPCs in the beamline during the next T2K run to check noise/background levels
- Would like to do a beam test at RCNP to help choose gas type/measure amount of ionized vs. non-ionized particles
  - Will need to submit a proposal to the RCNP facility to get beamtime
- Would eventually like to install monitor in the T2K neutrino beamline final focusing section
  - (When T2K beamtime allows – 750 kW beam power upgrade will maybe take place in 2018/2019 – may be a good time to install a new monitor if it is ready)

Conclusion

- T2K beam monitors are working well
  - Have done recent repair work on two SSEMs which use Oiles parts
  - Currently working on re-doing an absolute CT calibration
    - CT output dependence on frequency of input signal may be an issue
- Future beam monitor plans
  - Beam Induced Fluorescence non-destructive profile monitor