J-PARC Neutrino Primary Beamline, Beam Monitors & Upgrade

Megan Friend
For the J-PARC Neutrino Beam Group

KEK

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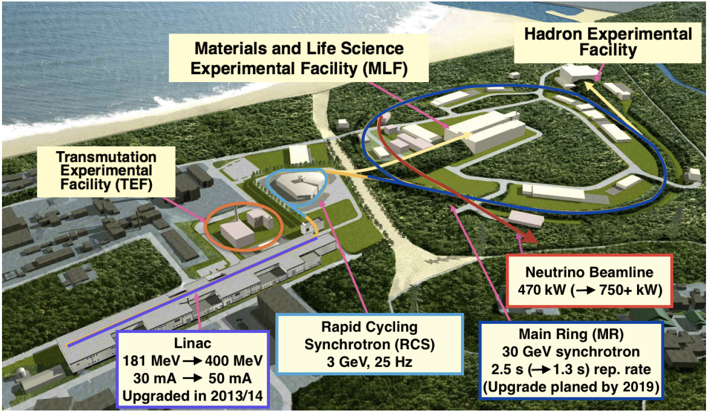
Outline

- Neutrino Primary Beamline
  - Overview
  - Upgrades
- Neutrino Primary Proton Beam Monitors
  - Overview
  - Upgrades

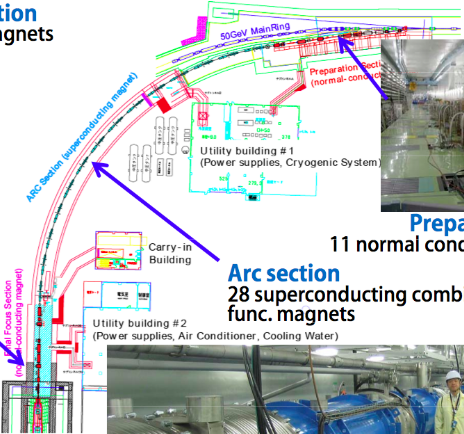
J-PARC Accelerator



- J-PARC MR 30 GeV proton beam extracted into the neutrino primary proton beamline by a fast extraction scheme
- MR design beam power: 750 kW (currently ∼470 kW)
  - Delivers $\sim 2.3 \times 10^{14}$ protons per 2.48 s
  - Plan to upgrade beamline to deliver $\sim 2.0 - 3.3 \times 10^{14}$ protons per 1.3 s (∼750 kW) → 1.13 s (∼1.3 MW)

Primary Proton Beamline

Final focusing (FF) section
10 normal conducting magnets

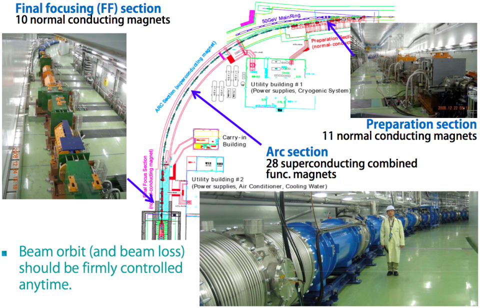


Preparation section
11 normal conducting magnets

Arc section
28 superconducting combined func. magnets

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

Primary Proton Beamline



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

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

See talk by Y. Fujii

Primary Beamline Upgrades to 750 kW

	2017	2018	2019	2020
	No Budget	MR=750kW？ →	MR=750kW？	
0. New tune study	optics measurement and calculation			
1a. Normal-conducting magnets : New tune study so far suggests **no upgrade necessary.**				
1b. N.C. power supplies : New tune study so far suggests **no upgrade necessary.**				
2. Super-conducting magnets, cryogenic system, and power supplies ; Basically OK.				
3. Vacuum System				
+ Replace stainless-steel ducts with Ti ducts		Fabrication	Installation	- - - →
+ More vacuum pumps with RF shields		Fabrication	Installation	- - - →
4a. Beam Plugs				
+ New beam plugs (just bellows aged)	Design		Fabrication	Installation
4b. Collimator				
+ PC1, PC4 be water-cooled.	Design	Fabrication	Installation	- - - →
5. Infrastructures, etc.				
+ Remote handling for the most-downstream FF	Discussion	Design Fabrication	Installation	

To Do list may just slip one year. No hardware progress this year.

Residual Radiation at Final Focusing Section

- Periodically inspect residual radiation level each week during beam running
- Generally residual dose is relatively low, even at 470kW ($\sim 10\mu$Sv/h)
- Modest residual dose at most upstream part (near extraction kicker) ($\sim 100\mu$Sv/h)

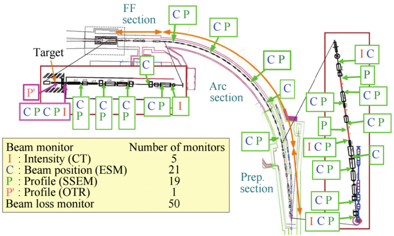
- High residual dose at most downstream part of final focusing section (~ 4.5mSv/h)
  - Need remote maintenance scheme in case maintenance work is required directly after beam running
    - Without remote maintenance scheme, may need months cooldown time for hands-on work at 750kW
    - Especially since residual dose is correlated with beam power
    - Suspected source : back scattering from the collimator, beam window, or target

Primary Beamline Upgrades Beyond 1MW

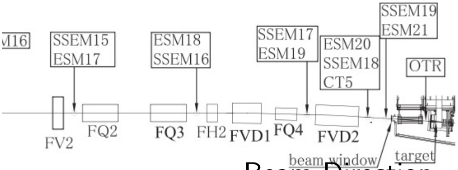
- 750kW → 1MW can be achieved simply by quicker repetition 1.3sec → 1.1sec.
- Beyond 1MW needs more protons in a bunch → larger ε, halo, direct-hit damage

1. Normal-conducting magnets and their power supplies
   - ✓ MR Fx aperture enlargement (10π/54π → 80π) may force us to enlarge our upstream magnet aperture, and hence more powerful power supply.
2. Super-conducting magnets, cryogenic system, and power supplies
   - ✓ May need more collimators and/or movable collimators for S.C. protection/ halo scraping.
3. Vacuum System
   - ✓ May need more vacuum pumps for more out-gas.
4. Beam Plugs, Collimators, etc. ; New collimator at very upstream.
5. Infrastructure ; Radiation shield/air-tightness improvement.

Neutrino Primary Proton Beam Monitors



Beamline Final Focusing Section



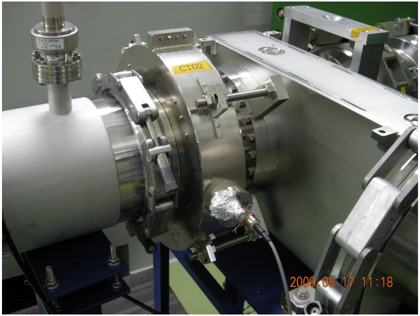
Beam Direction $\longrightarrow$

- Beam monitors are essential for protecting beamline equipment and understanding proton beam parameters for neutrino flux MC
- 5 CTs (Current Transformers) – monitor beam intensity
- 50 BLMs (Beam Loss Monitors)
- 21 ESMs (Electrostatic Monitors) – monitor beam position
- 19 SSEMs (Segmented Secondary Emission Monitors) – non-continuously monitor beam profile
- 1 OTR (Optical Transition Radiation) Monitor – continuously monitors beam at target $\rightarrow$ See talk by M. Yu
- MUMON (Muon Monitor) – continuously monitors secondary muon beam position and profile $\rightarrow$ See talk by Y. Ashida

CTs

5 CTs (Current Transformers)

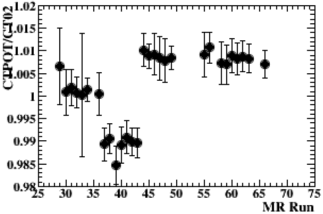
- Monitor proton beam intensity
  - Ferromagnetic core made of FINEMET® from Hitahi Metals
  - 50-turn toroidal coil
- Biggest issue : calibration !
  - CT's calibrations have drifted by ~2% with respect to one another over the full T2K run
  - Direct systematic error on cross section measurements
    - Cancels in near/far fit for neutrino oscillation analysis



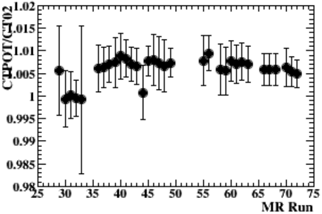
- Two types of calibration:
  - Regular calibration of CT attenuators (used to attenuate the CT signal read out by the DAQ) is required
  - Absolute calibration
    - Absolute calibration + analysis method update was done in 2014
    - Absolute CT error still being finalized, but error reduced 2.7%→~2% after re-calibration campaign

CT Calibration Result and Errors

CT5/CT2 Before Re-Calibration



CT5/CT2 After Re-Calibration



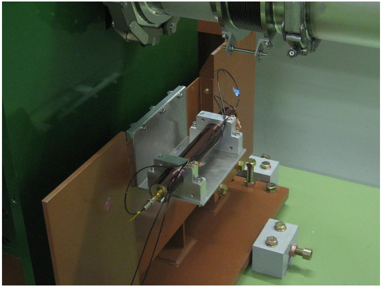
CT Calibration Error Source	% Error
Scope Input Impedance	1%
Scope DC Gain Accuracy	0.4%
Frequency Dependence	0.1%?
DAQ Noise?	–
Attenuator Calibration	1%?
Reproducibility/Measurement Statistical Error	0.3%
Analysis (Integration Window)	1.7% → 0%
Propagation from CT02 to CT05, etc.	→ 0.5%
Total	1.6%
Previous Total	2.6%

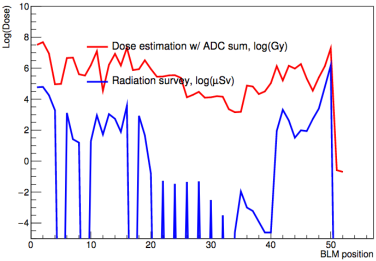
Work in Progress

BLMs

50 BLMs (Beam Loss Monitors)

- Wire proportional counter filled with an Ar-CO_2 mixture
- Continuously monitor beam loss
- The BLM signal is integrated during each beam spill, and if it exceeds a threshold a beam abort interlock signal is fired
- BLMs have been working stably
- Now working on :
    - Testing/implementing Si sensors as new, (more robust/linear ? portable) BLM
    - Predicting primary beamline residual radiation level using BLM measurement

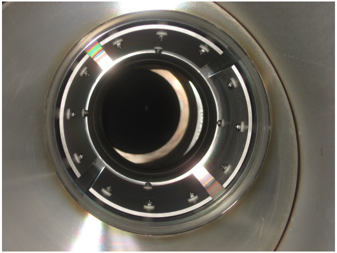




ESMs

21 ESMs (Electrostatic Monitor)

- Four segmented cylindrical electrodes surrounding the proton beam orbit
- Non-destructively, continuously monitor the proton beam position

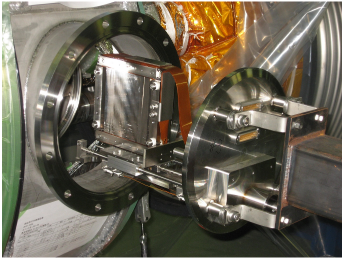


- Recently : ADC for ESM readout sometimes saturating at high beam power
  - Reduced signal size by increasing automatic attenuator settings
- Precision on the beam position measurement is better than 450 μm
  - Including resolution + alignment
  - However, ESMs are currently mainly used for monitoring stability of beam position, rather than for calculating absolute beam position
- Now thinking of ways to improve the ESM measurement precision
  - Re-calibration needed ?
  - Preliminary check of ESM precision, stability done
  - Idea for additional noise filtering circuit before readout of most downstream ESMs

SSEMs

19 SSEMs (Segmented Secondary Emission Monitor)

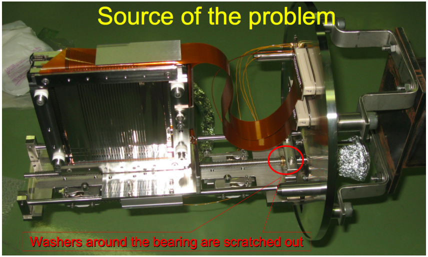
- Measure beam profile during beam tuning by secondary emission from Ti foil strips
- Two 5-μm-thick titanium foils stripped horizontally and vertically, with a 5-μm-thick anode HV foil between them
    - Strip width : 2$\sim$5 mm, optimized according to expected beam size



- 1 SSEM causes 0.005% beam loss $\rightarrow$ Only most downstream SSEM (SSEM19) can be used continuously
    - Others remotely move into and out of the beamline
    - SSEM19 used continuously $\rightarrow$ Need to carefully check any possible degradation as integrated POT on monitor increases
- Recent issues :
    - Superconducting section SSEM (SSEM10,11,12,13) mover issue
    - SSEM19 inspected during TS window replacement work this summer

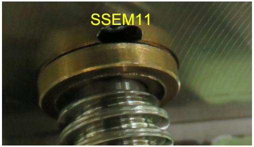
2014 SC SSEM Mover Repair

- SC section SSEMs require use of Oiles washers and traveling nut for motion into and out of the beamline because of low temperature (NC 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 fine
  - But, would be a major problem if an SSEM got stuck while moving
- 2014 fix : replaced SSEM11 and SSEM12 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



Scratched washer →

Attempted fix ↓



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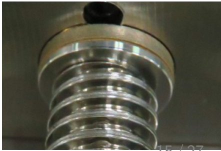
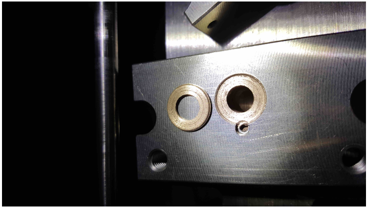
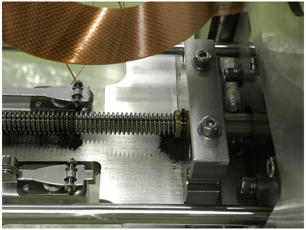
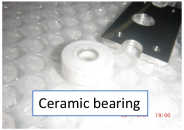


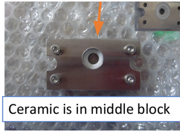
2017 SC SSEM Mover Repair

- Found that SSEM11 motion was becoming unstable again, despite 2014 fix (SSEM12 was OK) →
  - Bearing block scratching Oiles washer, Oiles washer scratching Oiles bearing
- SSEM13 motion also became bad – checked and found same problem as for SSEM11,12 in 2014 →
  - Oiles washer scratched by screw causing ∼1mm gap near bearing, backlash
- Replaced Oiles bearing w/ ceramic bearing, Oiles washers w/ Al washers for SSEM11,13 →
  - After extensive cryo-test
  - Keep watching and do same work on SSEM10,12 next summer (?)



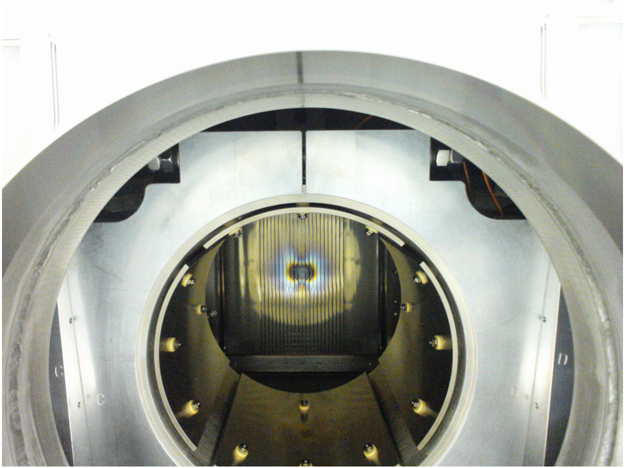




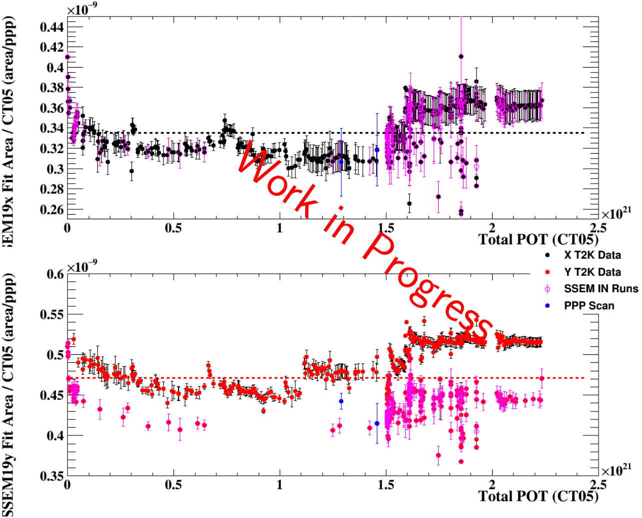


SSEM19 Inspection

- SSEM19 inspection done during beam window replacement work this summer
  - Discoloration of SSEM19 foil after $\sim 2.3 \times 10^{21}$ incident protons
  - No noticeable signal degradation, but may replace monitor next summer



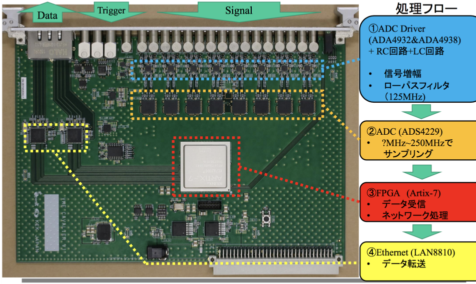
SSEM19 Secondary Emission Stability



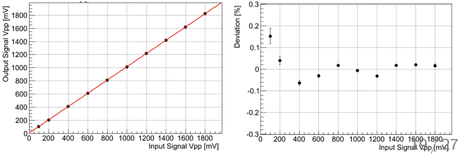
- SSEM19 secondary emission generally stable
- Increase correlated with beam power – doesn't seem to be degrading

Monitor Readout FADC Upgrade

- DAQ for neutrino beamline monitor readout works very stably
- Improvement of DAQ latency, which is limited by readout FADC module for CTs, ESMs is required for high (1Hz) repetition rate
  - Development of new FADC (∼250MHz) with shorter readout speed is underway
- New prototype FADC board was developed in JFY2016 by KEK E-sys group
- First prototype board is now under evaluation
  - Checked gain, linearity, channel-by-channel cross-talk, latency, frequency cutoff, etc. during this summer : no issue
  - Plan (1) : feedback on design
  - Plan (2) : install new boards in neutrino beamline DAQ, test during summer 2018



Measured Non-Linearity (<0.5%) :



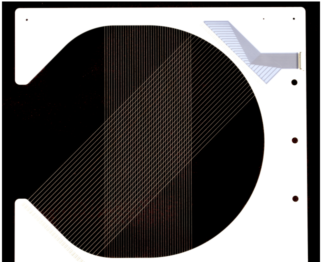
Non-Destructive + Minimally-Destructive Proton Beam Monitor Upgrades

- 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 : monitor should work well for a long time, even at high beam power
- R&D for 2 minimally-/non-destructive profile monitors underway :
  - Wire Secondary Emission Monitor (WSEM)
  - Beam Induced Fluorescence Monitor (BIF)

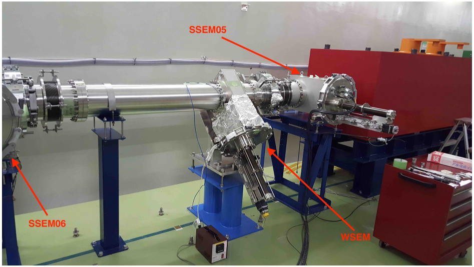
New WSEM Prototype

- 1 Prototype WSEM (Wire Secondary Emission Monitor)
  - Like SSEM, but WSEM uses 25μm twined wires to make beam profile measurement $\rightarrow$ reduction of beam loss compared to SSEM
- Design, fabrication done jointly with FNAL profile monitor experts, supported as a US/Japan collaboration project :
  - Prototype monitor designed, fabricated during JFY2015
  - Prototype WSEM installed in J-PARC beamline in summer 2016
  - Working on design of improved mover during JFY2017
- Aim to replace SSEM18 w/ WSEM (in summer 2018 ?)
  - Then, could use SSEM18 continuously in case of SSEM19 failure

WSEM Plane

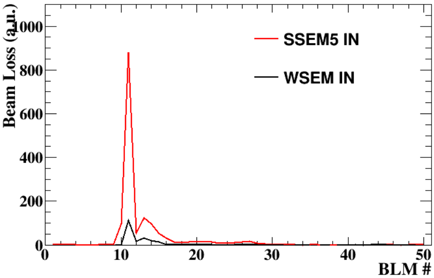


WSEM Installed in Beamline



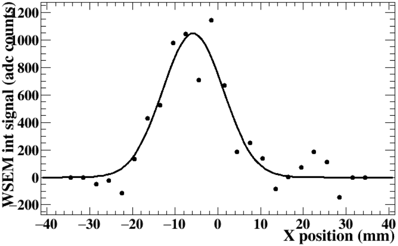
WSEM Beam Loss, Signal Check

- Checked beam loss, measured profile during WSEM beam test
- Compared loss due to WSEM to that due to neighboring SSEM
  - Note: BLM acceptance is different for SSEM vs WSEM – BLM10 is closer to WSEM
  - Beam loss by WSEM lower than SSEM by factor of ∼10

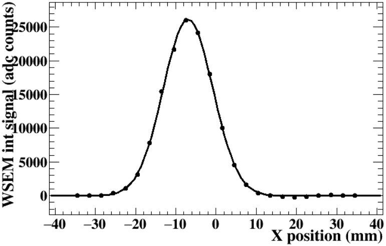


- Reasonable profile measurement even at very low beam power :

Measured Profile @ ∼10kW

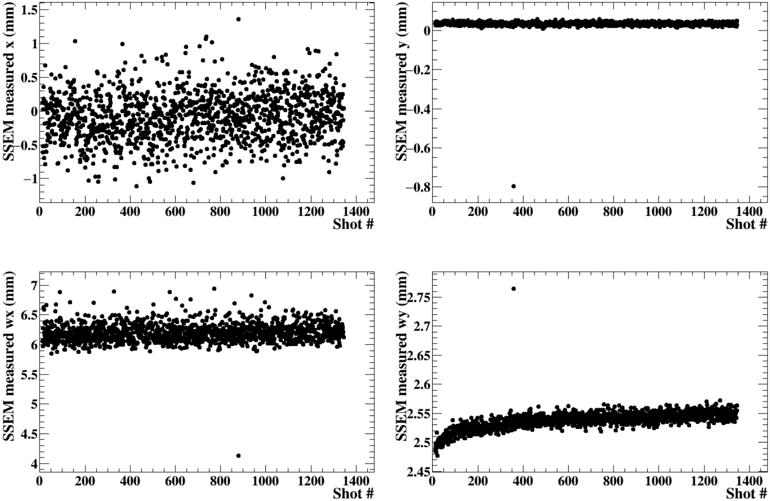


Measured Profile @ ∼460kW



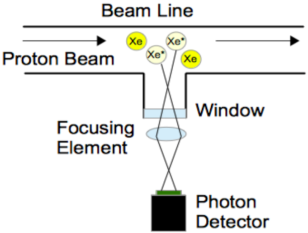
WSEM Long-Term Check

- Ran with WSEM IN for 2 hours at high beam power (∼465 kW)
  - Stability is pretty good ! (some bake-in expected..)
  - Still investigating 2 strange shots



Beam Induced Fluorescence (BIF) Monitor

- Uses fluorescence induced by proton beam interactions with gas injected into the beamline
  - Protons hit gas (i.e. N_2, Xe) inside the beam pipe
  - Gas molecules are excited or ionized by interaction with protons, then fluoresce during de-excitation
  - Continuously and non-destructively monitor proton beam profile



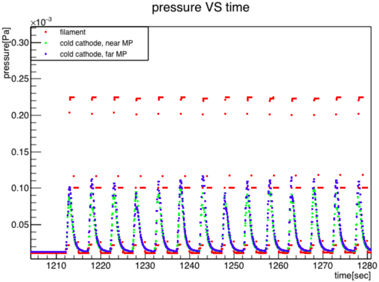
- Now doing R&D for various components :
  - Gas injection :
    - For $\sim$1000 photons/spill, need to locally degrade vacuum level from $\sim 10^{-5}$Pa $\rightarrow \sim 10^{-3}$Pa while maintaining average vacuum level of $\sim 10^{-4}$Pa at ion pumps and $\sim 10^{-6}$Pa at SC section
  - Light transport and focusing : Must be radiation hard
  - Light detection :
    - Must work in/near radiation environment
    - Must work down to very low light levels
    - Must be fast to compensate for drift of any ions in proton beam space charge field

BIF Monitor Gas System Tests

- Plan to use pulsed gas injection (inject gas pulse right before each beam spill) to achieve lower average vacuum level
- Testing pulsed gas injection with test vacuum chamber
- Compare test chamber result to expected gas distribution by hand calculation, COMSOL simulation
  - Local gas pressure, diffusion/pumping speed, transverse uniformity all very important

Test Vacuum Chamber

Pulsed Gas Injection Result

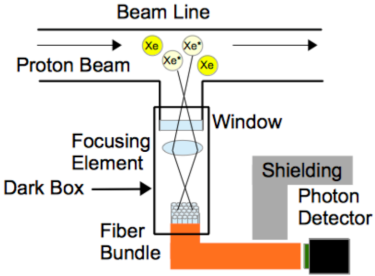


ON:300μs OFF:5s

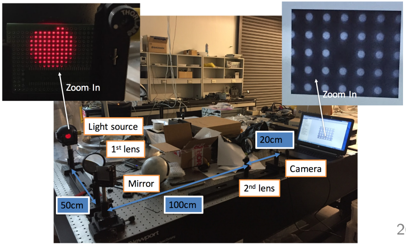
BIF Monitor Optical System

- Set up prototype optical system to understand alignment procedure, light transport efficiency, acceptance, etc
  - Compare to GEANT4 optical simulation result
  - Plan to install prototype optical system in beamline soon
- Now also testing radiation hardness of various optical components
- Plan to develop 2 optical systems in parallel (1 for x, 1 for y) :
  1. Light transport by optical fibers to MPPCs in beamline subtunnel
     - Faster readout, cheaper (?)
  2. Light focused onto MCP+rad-hard CID camera near beamline
     - Higher resolution, more rad-hard (?), simpler readout (?)

Light Transport Scenario



Optical System Test Setup



Conclusion

- Neutrino primary proton beam beamline components generally working well
  - Current biggest issue : remote maintenance scenario for most downstream components (high residual radiation level at high beam power)
- Neutrino primary proton beam monitors also working well
  - Current biggest issue : non-destructive profile monitoring at high beam power
    - R&D for new profile monitors ongoing