T2K Primary Beamline – Beam Induced Fluorescence Monitor

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- New Non-Destructive Beam Monitor for J-PARC NU Beamline
- Collaborative Work Between KEK NU Group and University of Tokyo, IPMU T2K Group

Outline

- Beam Induced Fluorescence (BIF) Monitor Concept
- Considerations for BIF
  - Gas Type
  - Space Charge Effects
  - Beamline Configuration
  - Gas Injection
  - Optical System (see next talk)
  - Readout
- Some Studies in Progress
  - Gas Flow Simulation
  - DAQ Pulse Shape Simulation
  - MPPC Tests (see next talk)

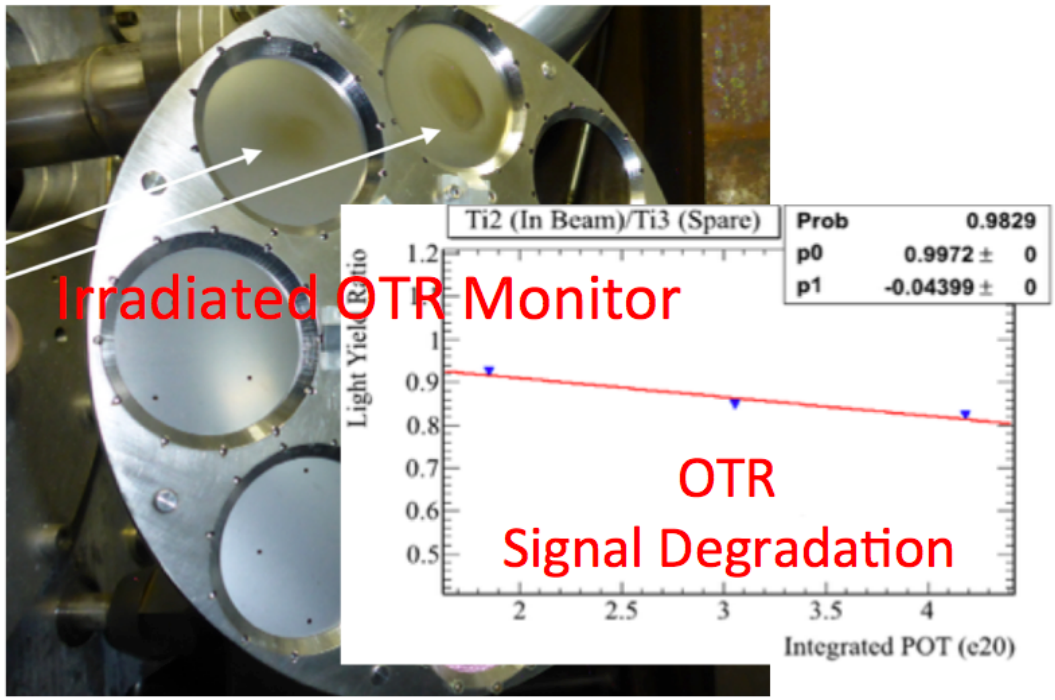
Why are Beam Monitors Important?

- Beam monitors are required to correctly steer the J-PARC proton beam/protect beamline equipment
  - Because the J-PARC beam power (number of protons per pulse) is very high, mis-steering the beam can cause serious damage to equipment
    - At 750 kW (1 Hz, 30 GeV) – $\sim 1.6 \times 10^{14}$ PPP ($\sim 2 \times 10^{13}$ ppb)
  - Monitoring must be done continuously, shot-by-shot
- Information from beam monitors is also used to determine the T2K neutrino flux – proton beam parameters are used as inputs into the neutrino flux simulation

Why is a Non-Destructive Beam Profile Monitor Important?

- Currently, the proton beam profile is monitored by a set of 19 Segmented Secondary Emission Monitors (SSEMs)
  - These are *destructive* and cause *beam loss*
  - Only the most downstream SSEM (SSEM19) can be used continuously (because it is just upstream of the target, the beam loss is okay)
    - All other SSEMs are only used during beam tuning and are removed from the beamline during normal data-taking
  - Actually, according to the TDR, SSEM19 has already been exposed to a larger POT than it was designed to withstand
    - Although we haven't seen clear SSEM19 degradation, it won't necessarily be usable for a long period of time at high beam power

Why is a Non-Destructive Beam Profile Monitor Important?

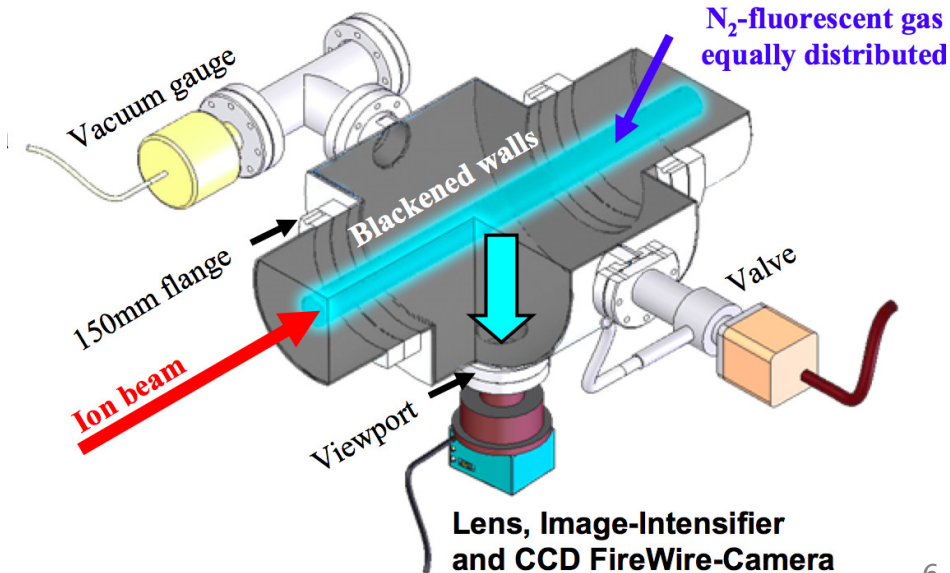


- An Optical Transition Radiation (OTR) monitor is also used to monitor the beam position directly upstream of the target
  - This is also a destructive monitor
  - Degradation of the OTR foils has been observed
- The beam profile must be monitored continuously, so we need to start working on something for use at high beam power

Beam Induced Fluorescence Monitor Concept

- Beam Induced Fluorescence (BIF) monitors detect fluorescence light induced by proton beam interactions with gas in the beamline
  - Non-destructive, so it can continuously monitor the proton beam profile in the primary beamline
  - Either residual gas or gas injected into the beamline
    - Residual gas level is the J-PARC neutrino beamline is $\sim 3 \times 10^{-6}$ Pa
    - Require $\sim 10^{-4}$ Pa $\rightarrow$ will need to inject gas

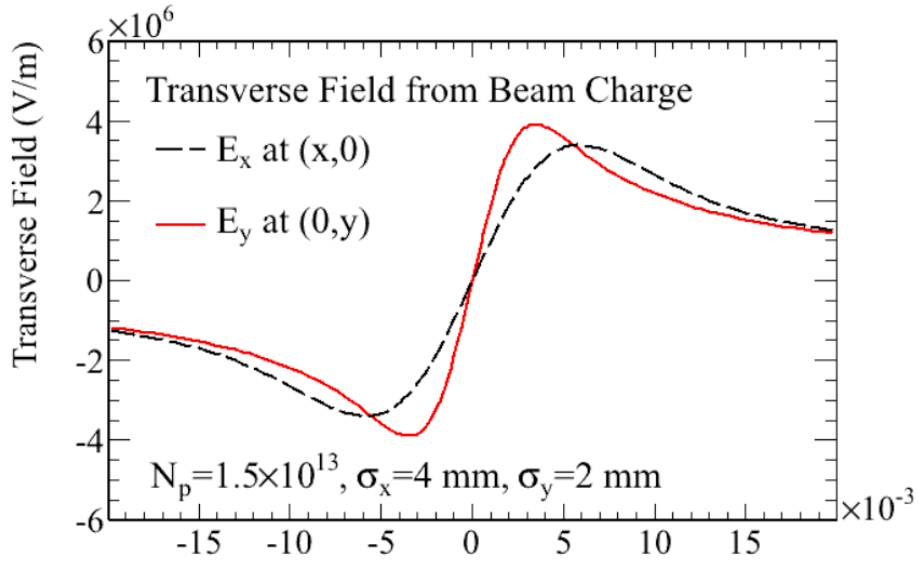
- These monitors have been used in/developed for a number of beamlines, including CERN SPS (NIMA 492 (2002) 7490)



Ionization Profile Monitor Concept

- Ionization Profile Monitors (IPM) detect ionized particles, with ionization induced by proton beam interactions with gas in the beamline
  - Ions are then drifted to a multi-channel plate in an external field
  - Used at J-PARC and FNAL

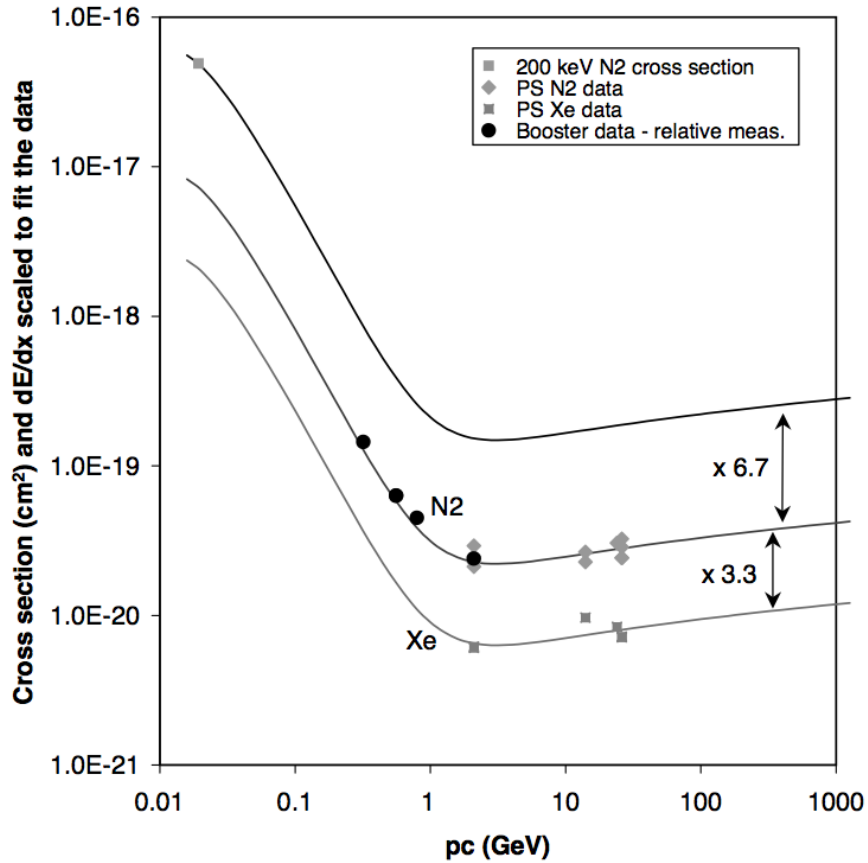
- The large field from the beam protons make this type of monitor impractical for the J-PARC NU beamline
  - 30 GeV, $\sim$4 mm σ spot size
  - Field from space charge in NU beamline is as large as 4000 kV/m



Considerations on Gas Type

Choice of gas is important (Studies shown in NIMA 492 (2002) 7490)

- Light level is very low for this monitor
  - Interaction cross section must be considered
  - Two possibilities are N_2 and Xe, although there are also other possibilities
    - Cross section is 3.3× higher for N_2
    - Cross section is approximately flat above 1 GeV
  - Energy loss per visible photon created:
    - N_2 – 3.6 keV per photon
    - Xe – 46 keV per photon



Considerations on Gas Type

(Studies shown in NIMA 492 (2002) 7490)

- Fluorescence lifetime must be considered
  - 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

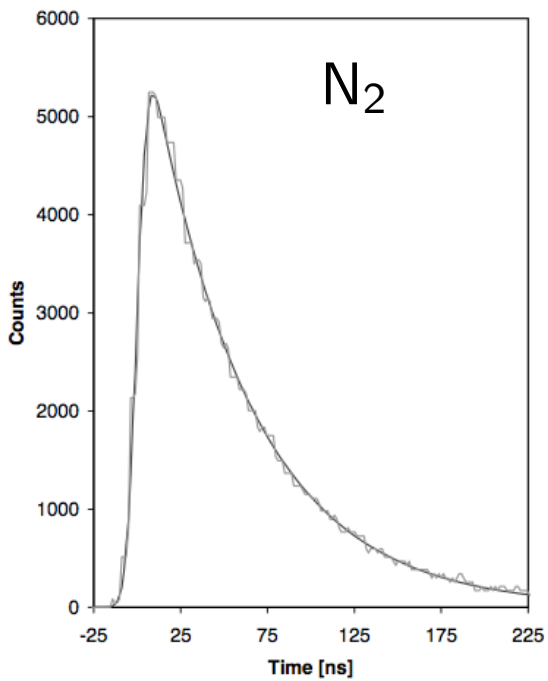


Fig. 7. N_2 lifetime, no optical filter. The solid curve is a fit to the data giving a bunch length of 5.4 ± 0.2 ns and a decay time of 57.7 ± 0.2 ns. Gas pressure $= 1.0 \times 10^{-6}$ Torr. Beam momentum $= 26$ GeV/c.

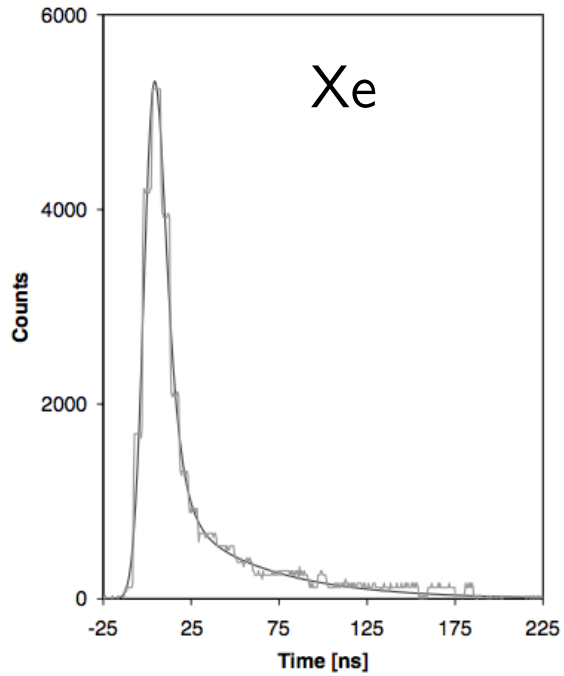
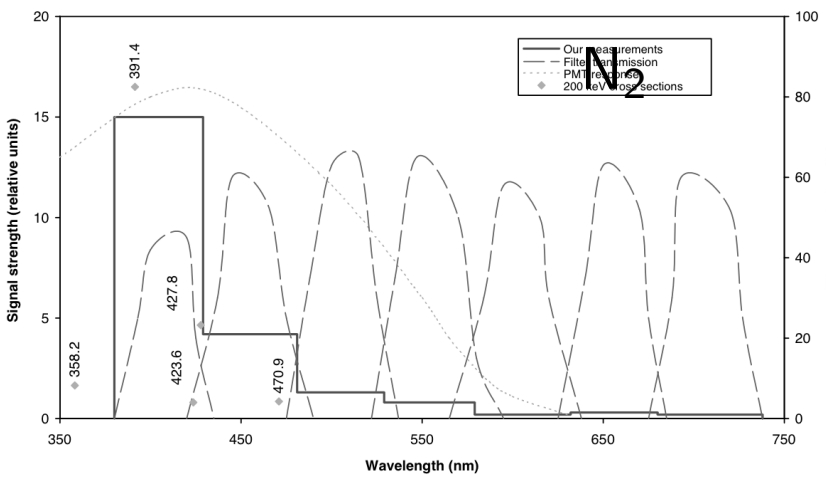


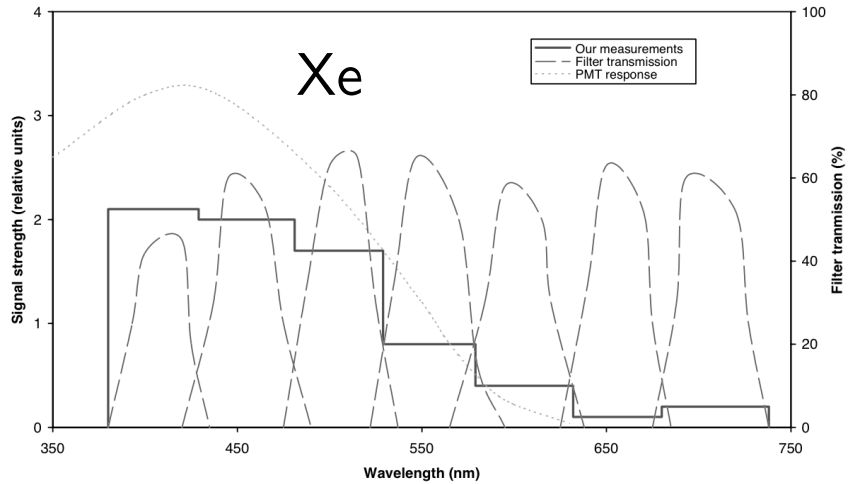
Fig. 9. Xe lifetime measurement, no optical filter. The solid curve is a fit to the data giving a bunch length of 5.09 ± 0.05 ns and decay times of 6.0 ± 0.1 and 51.5 ± 0.9 ns. Gas pressure $= 1.3 \times 10^{-6}$ Torr. Beam momentum $= 26$ GeV/c.

Considerations on Gas Type

(Studies shown in NIMA 492 (2002) 7490)

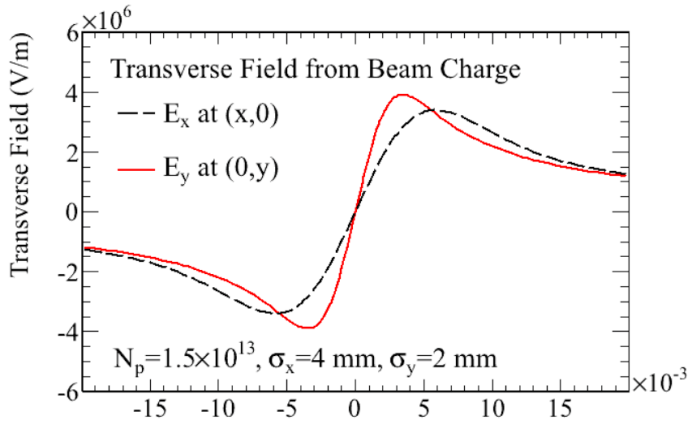
- Fluorescence spectrum must be considered
  - Significant light is produced in the visible region, although the Xe spectrum may also extend into the near UV





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 in NU line

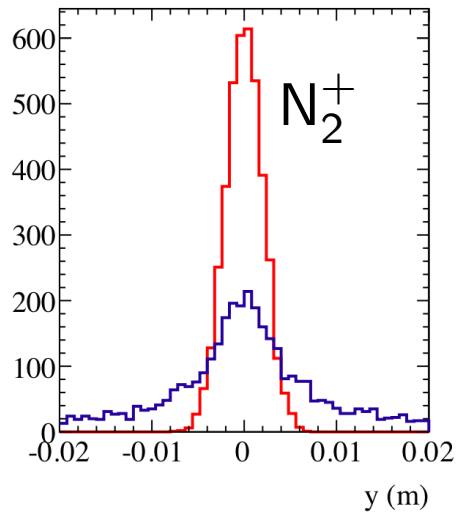


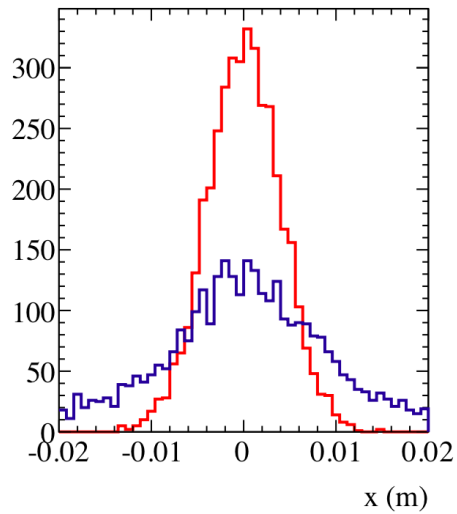
- Issue with ionized particles drifting in the beam field before producing light and distorting beam profile measurement
- Some ideas to mitigate space charge effects:
  - Fast readout with PMT or MPPC (instead of slower readout with CCD)
  - Possible beam test including check of amount of ionized (vs. 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
    - ∼1/2 of the light has 6 ns lifetime - less time to drift before the light is produced

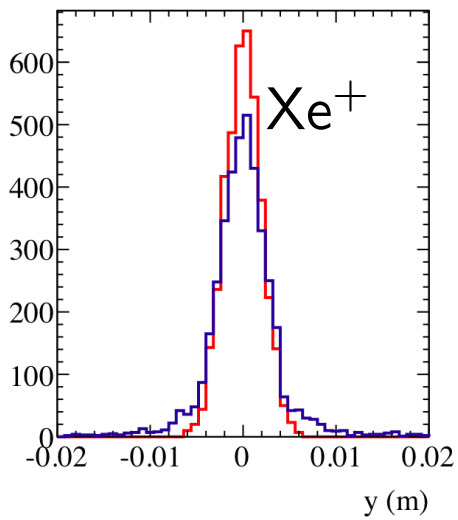
Simulated Drift of Ions in Beam Field

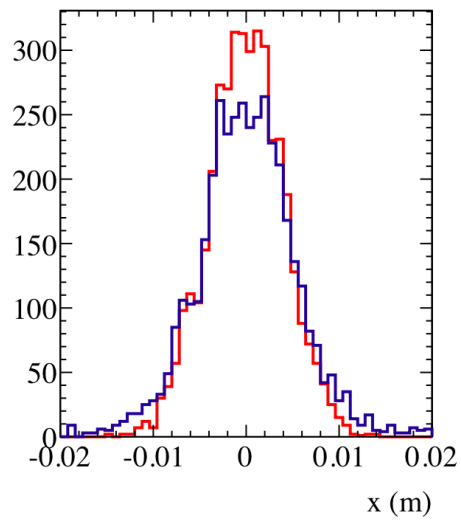
- Beam field is calculated and trajectory of the ions in the lab frame is simulated
- Since the ions' velocities are $<0.1c$, simulation is non-relativistic and the magnetic field is neglected
  - Want to update simulation using relativistic effects, decay timing information
- Assuming 3e13 ppb, $\sigma_x = 4$ mm, $\sigma_y = 2$ mm
- Drift of Xe ions due beam space charge is much smaller than N_2

Ion profile before (red) and after (blue) drift in the beam field:









J-PARC Beamline

- Plan to install monitor in NU final focusing section
- We have a ∼3-m-long, 190 mm inner diameter empty section of beampipe in the NU final focusing section
  - Otherwise, J-PARC beamline is very crowded
- Would also like to install a new SSEM in same section of beamline as a cross-check

Other Considerations for Apparatus Design

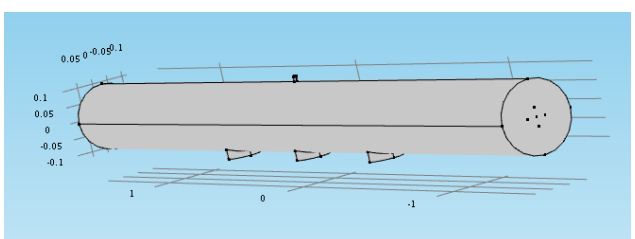
- Residual gas levels are too low in the T2K beamline
  - Need to design gas injection/vacuum system
    - Pumping noble gas (Xe) safely may be much more difficult (expensive)
    - Running gas flow simulations using COMSOL software now
- Need to design optical system (see next talk)
  - Need to consider 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

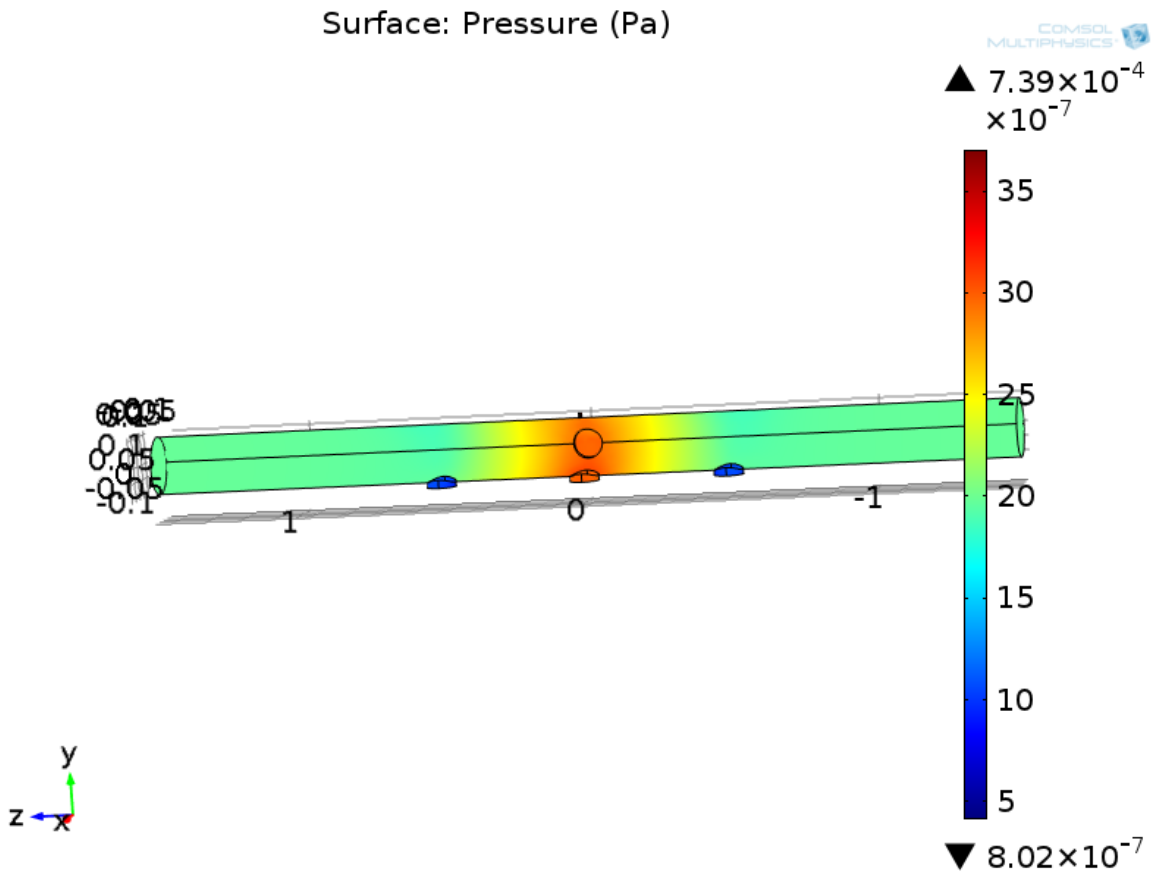
Preliminary Checks of Beamline Pressure with COMSOL Multiphysics Modeling Software

- Using COMSOL Multiphysics Modeling Software v4.4 to simulate gas valve and vacuum system
  - Will switch to COMSOL v5.0 soon
- Simulate pressure in vacuum vessel assuming an inlet port and vacuum system
  - Inlet port with constant pressure
    - Eventually may be interested in inlet port with pulsed gas release (gas released each beam spill)
  - Differential pumping by two vacuum pumps on either side of inlet
  - Beampipe with 100 mm radius ($\sim$same as FF section beampipe)
- Results are preliminary – still doing cross checks to make sure we understand the simulation software

Pressure on Beampipe Walls

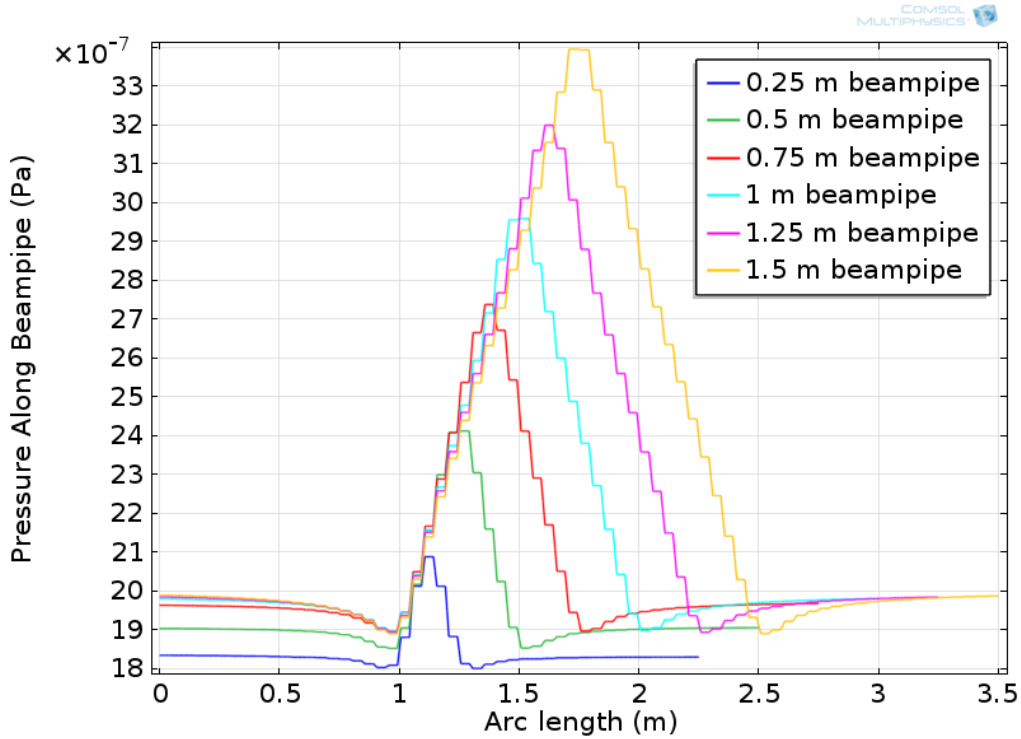
- Pressure on beampipe walls in color scale
- Inlet port (top, dark red region) with constant pressure of 1×10^{-3} Pa
- Differential pumping with two 5000 L/s vacuum pumps (dark blue regions)





Pressure Along Beampipe Wall for Different Lengths

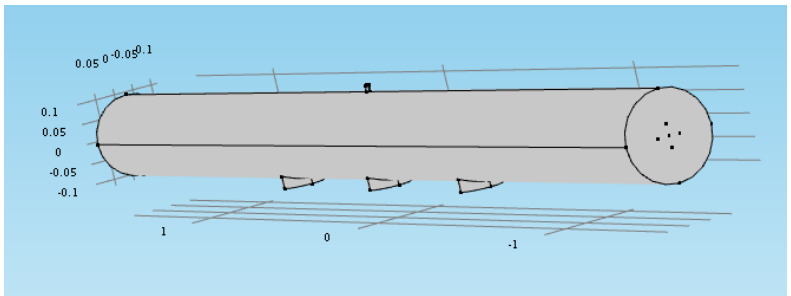
- Inlet port has constant pressure of 1×10^{-3} Pa
- Differential pumping with two 5000 L/s vacuum pumps
- Pressure at center is $\sim 3 \times 10^{-6}$ Pa
- Pressure in beamline (outside of monitor region) is $\sim 2 \times 10^{-6}$ Pa
- Residual gas level is the J-PARC neutrino beamline is $\sim 3 \times 10^{-6}$ Pa – so vacuum level seems acceptable
- However, need $\sim 10^{-4}$ Pa in monitor region

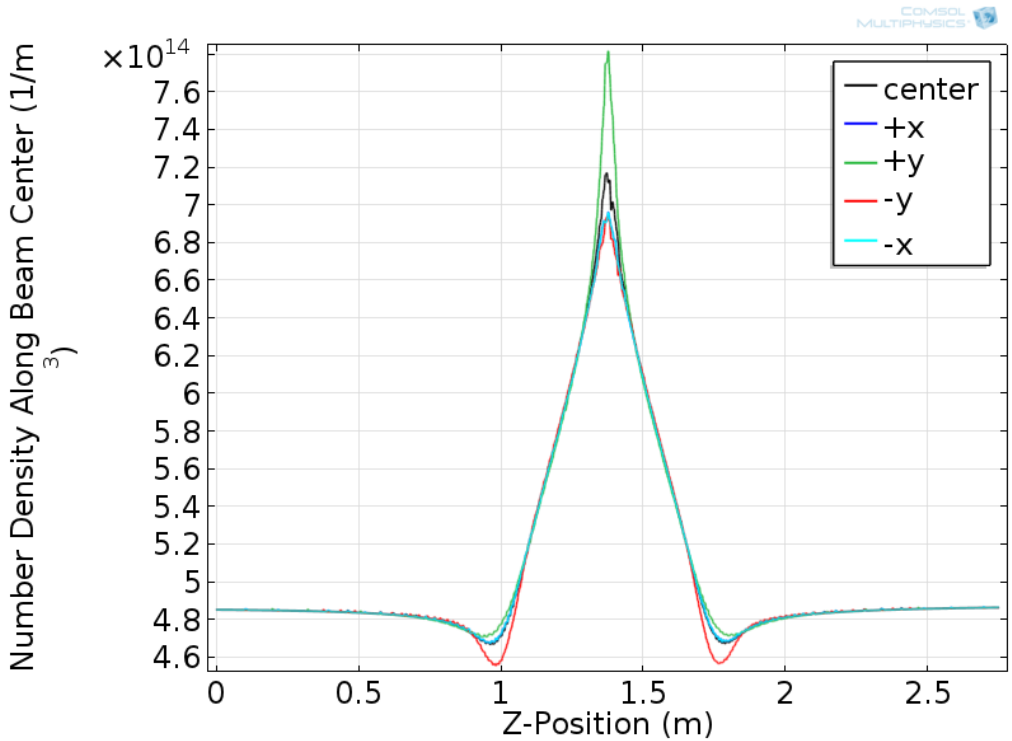


Arc-length is position along beampipe, with inlet port at highest pressure point in center of each curve

Number Density Inside Beampipe

- For 0.75-m-long beampipe
- Number density along different positions inside beampipe – offset from beamline center by 2.5 cm (see top figure)
- Inlet port has constant pressure of 1×10^{-3} Pa
- Differential pumping with two 5000 L/s vacuum pumps
- Gas density is more uniform a few cm upstream or downstream of the inlet port



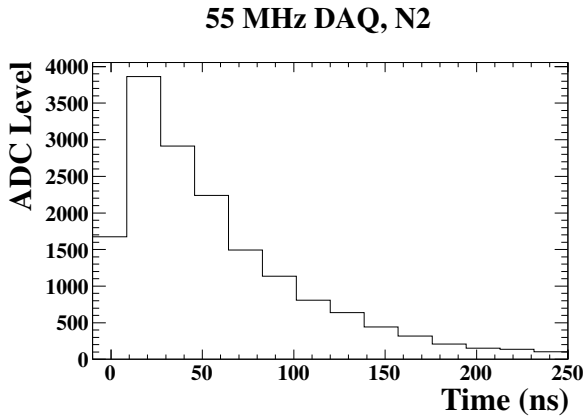


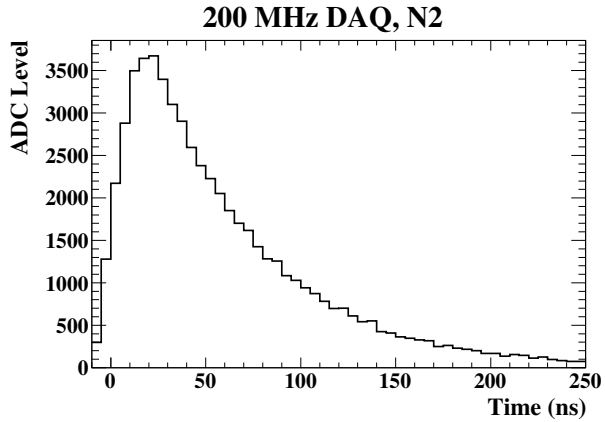
Test Vacuum Chamber

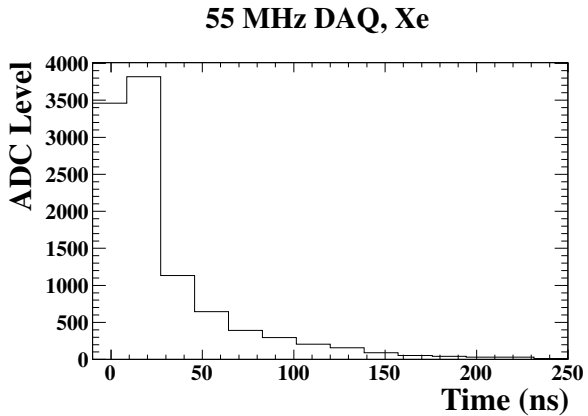
- Bought parts to build test vacuum chamber
- Want to test:
  - Different options for gas injection, pumping
  - Different gas types
  - Gas uniformity
    - Idea – excite gas using laser and then look at uniformity of signal from fluorescing gas to measure gas uniformity
    - However, this might be difficult/expensive
    - Other ideas for checking uniformity?
- Parts for test chamber have been delivered – plan to fabricate and start tests soon

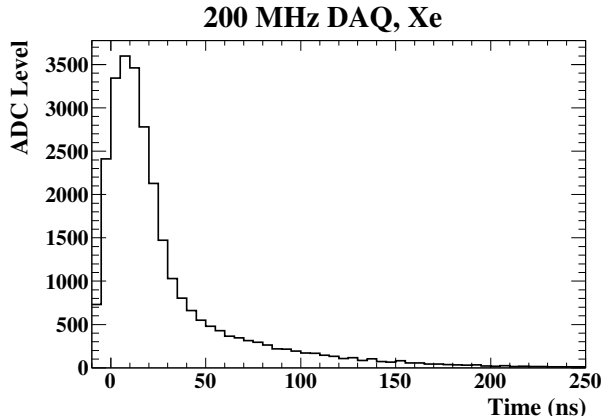
Preliminary DAQ Simulation

- Simulation of detected BIF signal in FADC
- Using decay times from NIMA 492 (2002) 7490
  - Assuming 11 ns width Gaussian beam pulse
    - Plan to add real proton beam pulse shape, PMT/MPPC response into simulation
- DAQ requirements depend on gas type
- Maybe need $\geq$200 MHz FADC for clear measurement









Summary

Now:

- Considering gas types
  - Xe has lower cross section and is harder to pump, but is less susceptible to space charge effect
- Doing simulations to help design gas valve and vacuum system
  - Bought parts to build test vacuum chamber – will assemble and start tests of gas uniformity, pumping, etc soon
- Testing light detection options (MPPCs, rad-hard fibers, etc)
  - See next talk from Christophe

Plans

Plans:

- Possible beam test (at RCNP? J-PARC beam dump?) to help choose gas type/measure amount of ionized vs. non-ionized particles
- Would eventually like to install monitor in T2K NU beamline final focusing section
  - Would like to install it with new SSEM to have redundant check of beam profile
  - When J-PARC 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