Construction and Operation of Mini-CAPTAIN LArTPC

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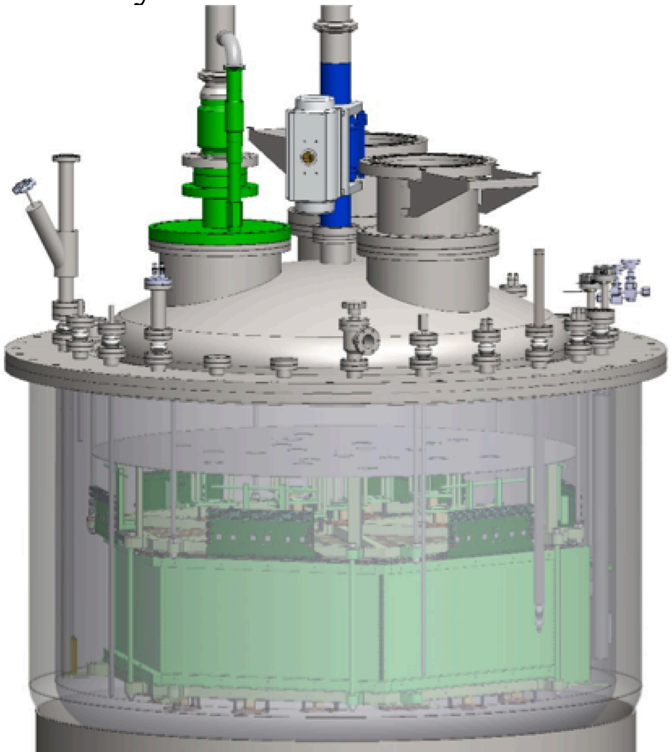
CPAD Instrumentation Frontier 2016, Caltech

Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos - CAPTAIN

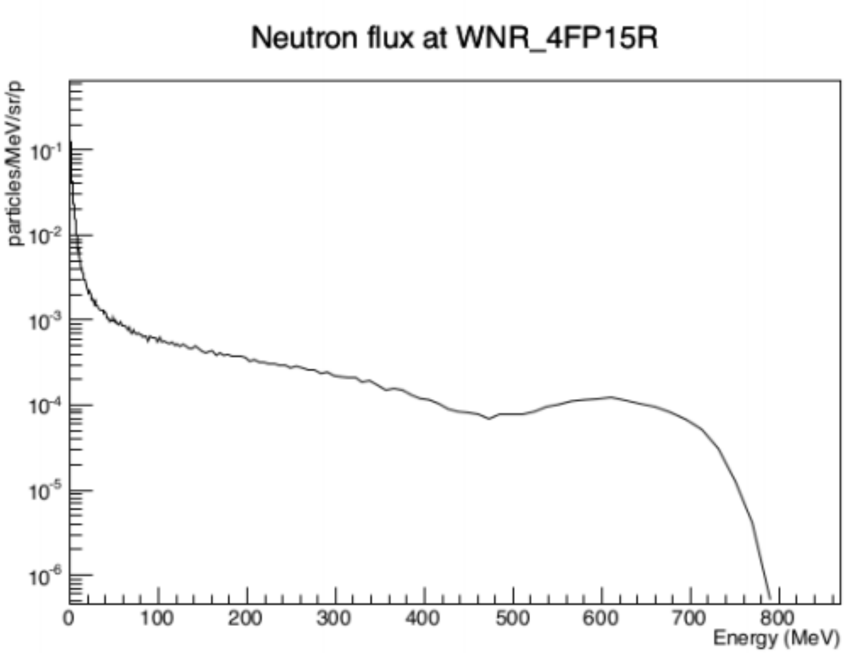
Mini-CAPTAIN
- A Cryostat – 1700 L of liquid argon.
- TPC: 1000 sense wires in 3 planes, drift length of 32 cm
- 16-1'' PMTs facing the TPC volume
- Laser System
- Muon telescope
- Purity monitor



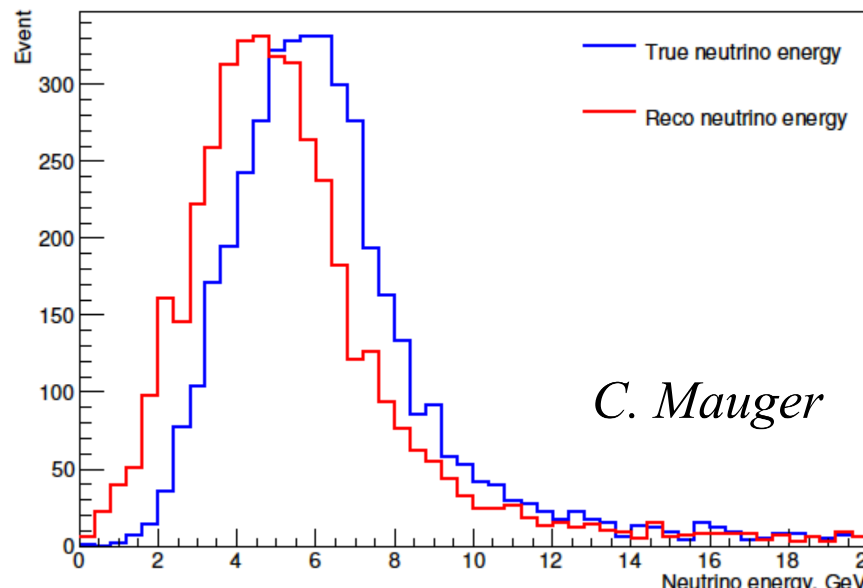
- CAPTAIN project originally supported by Los Alamos National Laboratory (LANL), evolved into a multi-institutional collaboration
- Study neutron and low energy neutrino in LArTPC with neutron and neutrino sources
- Two detectors: CAPTAIN and Mini-CAPTAIN

Run Mini-CAPTAIN at the Weapon Neutron Research Facility (WNR), Los Alamos

- Study neutron interaction for high energy neutrons for DUNE
- Study low energy nAr→nAr interaction for NC from supernovae neutrinos
- Mini-CAPTAIN has been run in the WNR neutron beam at Los Alamos Neutron Science Center (LANSCE)
- WNR provides a high flux neutron beam with a broad energy spectrum



Simulated NuMI beam neutrinos

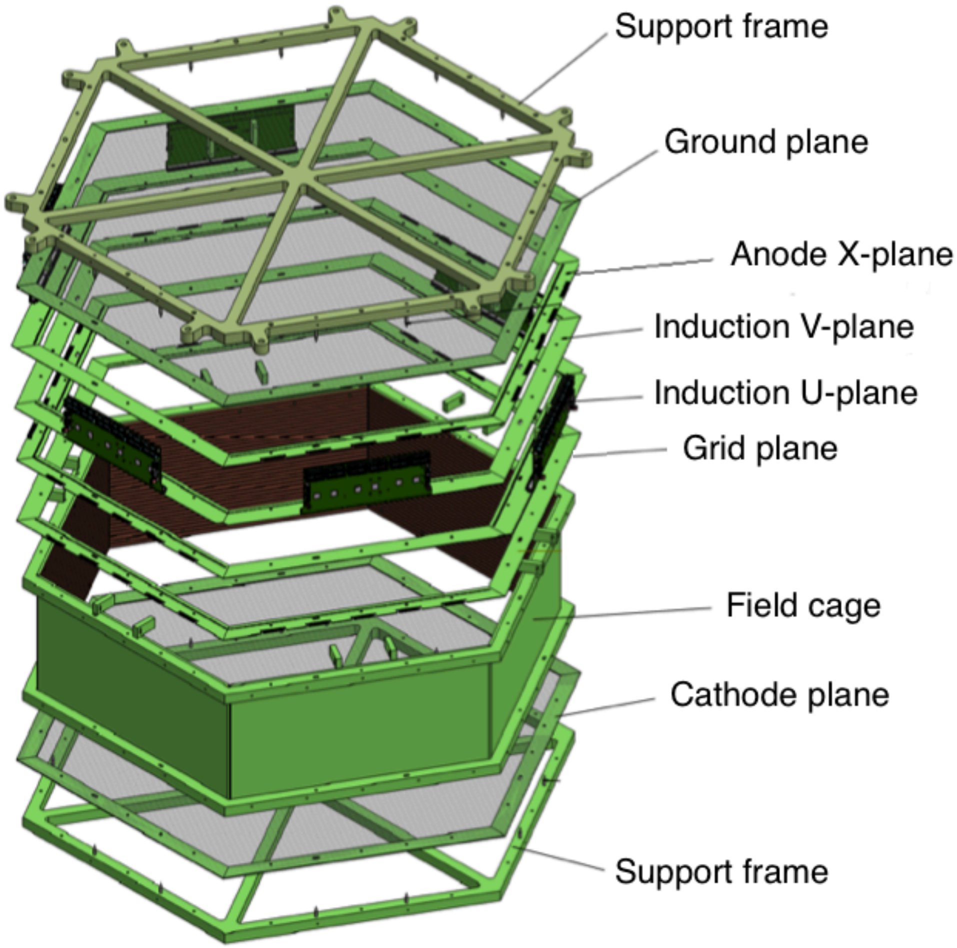


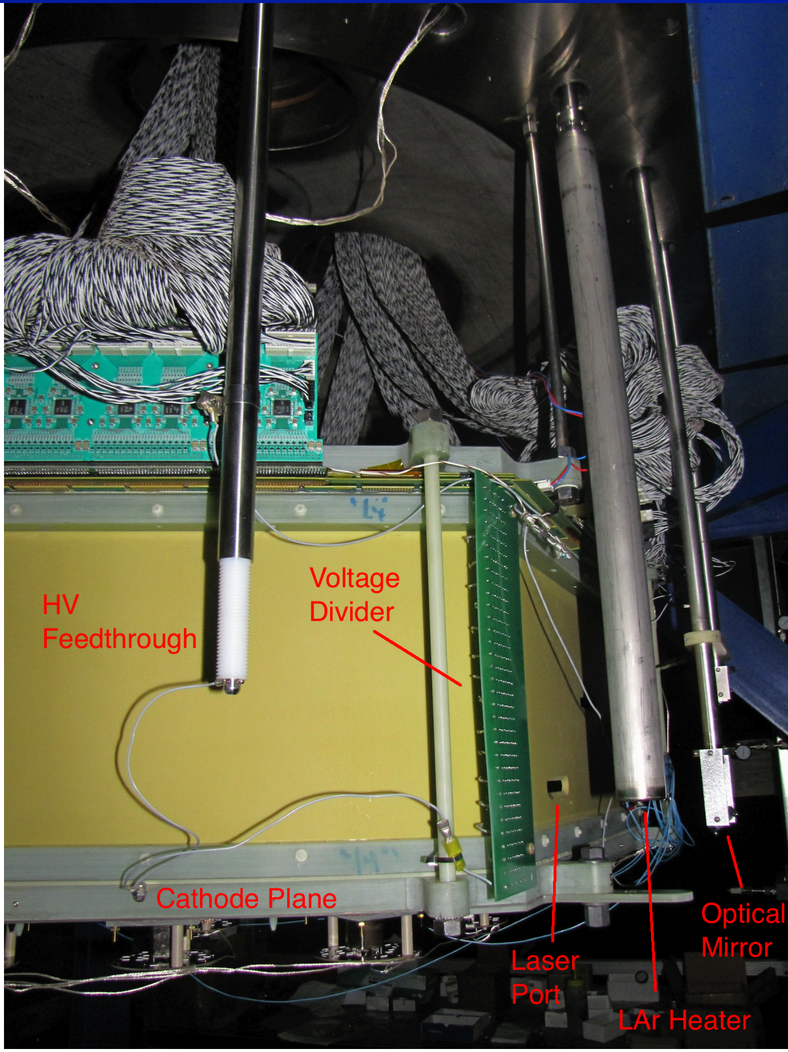
Neutron energy has a large impact on neutrino energy

Timeline

- Liquid nitrogen fill in Summer 2014: test electronics and TPC, test heat load
- 1st LAr engineering run in Fall 2014: development of filling procedure, test cryogenic and purification system, DAQ development, laser system testing
- 2nd LAr engineering run in March 2015: further development of above items plus installation of gas recirculation system, integration with muon system
- Commissioning run in Summer 2015: more development of electronics and recirculation system–achieved sufficient purity to see tracks
- 1st mini-CAPTAIN Neutron Run at WNR: 23–28 February 2016

TPC

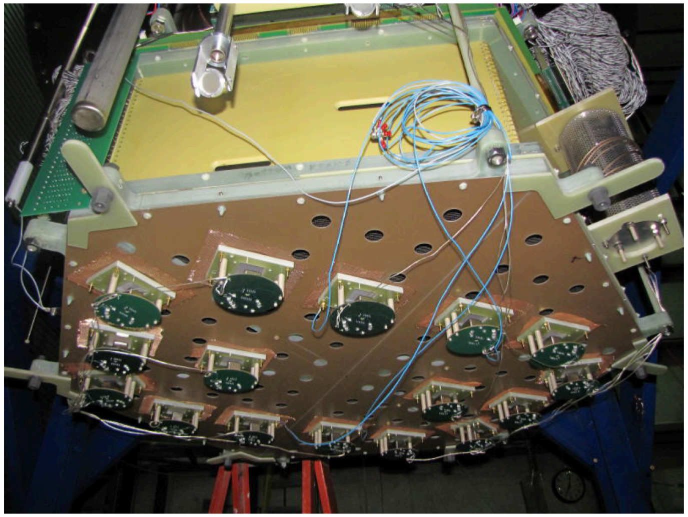




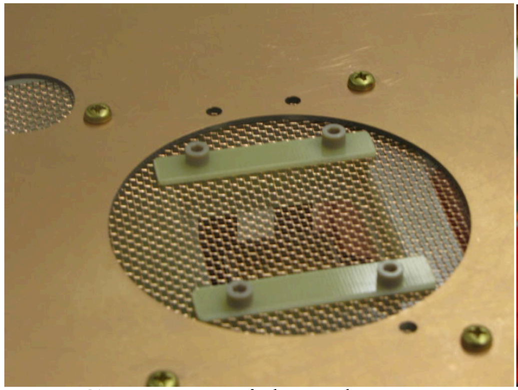
- Drift length 32 cm, apothem 50 cm
- 5 wire planes: each consists of 332 wires, pitch 3 mm
- 3 sense planes: X (collection, 0^o) U ($+60^o$) and V (-60^o)
- 500 V/cm drift field
- BNL Front-End Motherboard in LAr
- Service board/intermediate amplifier on feedthrough board

View of the field cage assembly
Cathode HV: -16 kV

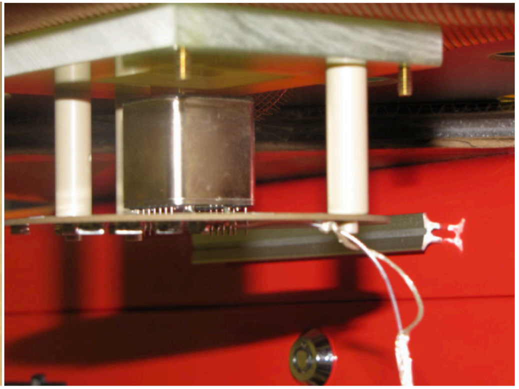
Photon Detection System (PDS)



PMT with their bases were mounted on the bottom of a copper plate

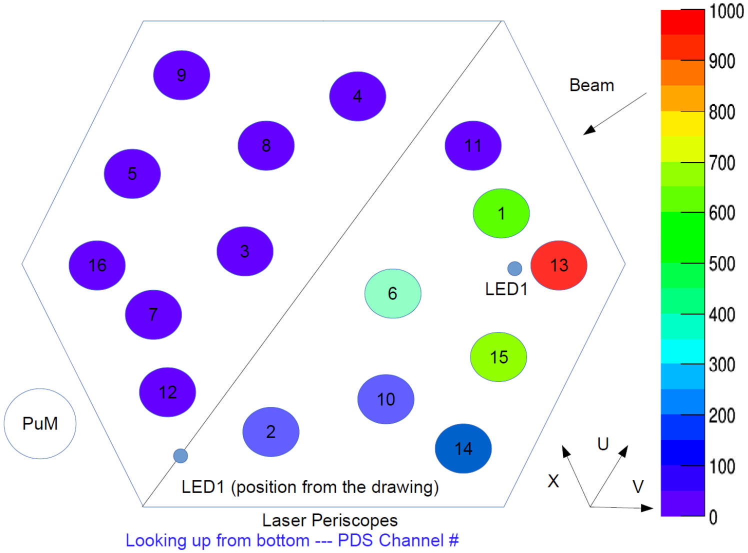


Copper grid and TPB coated window



PMT base

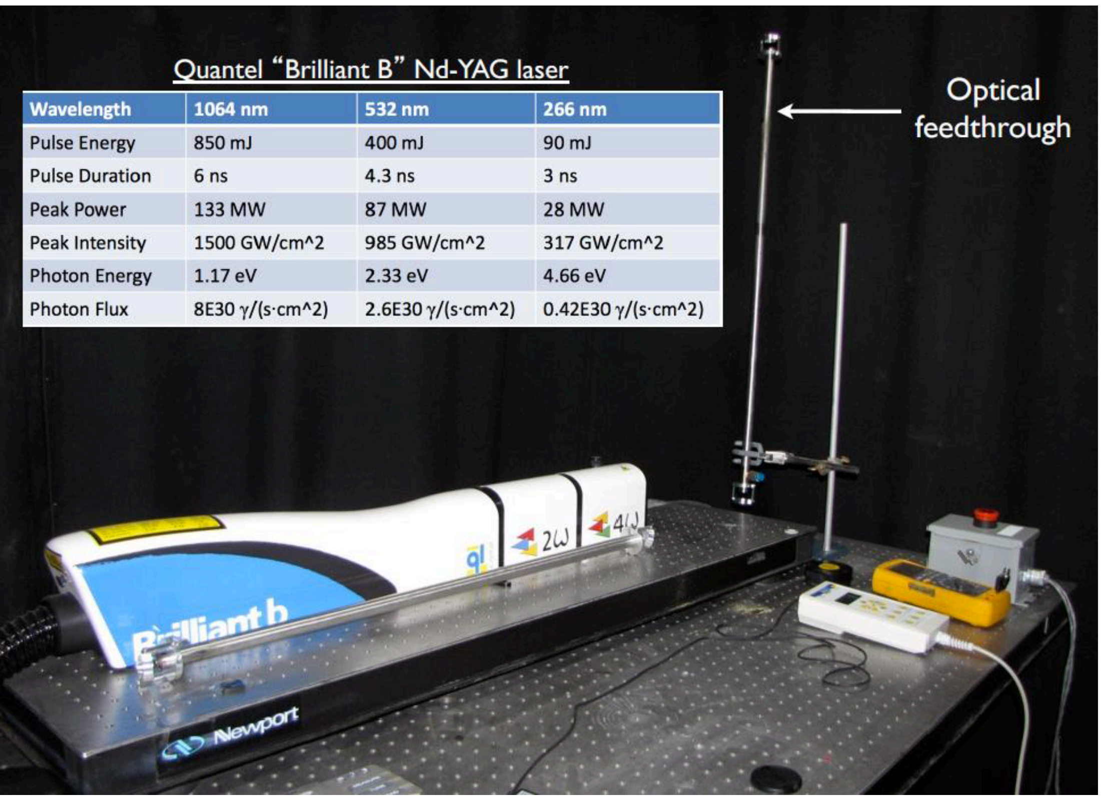
- 16 Hamamatsu R8520-500 PMT (1”x1”x1”)
- Fix behind TPC cathode plane on a copper plate
- 25% quantum efficiency at 340 nm
- Copper grid and TPB coated window



PMT configuration and LED tests

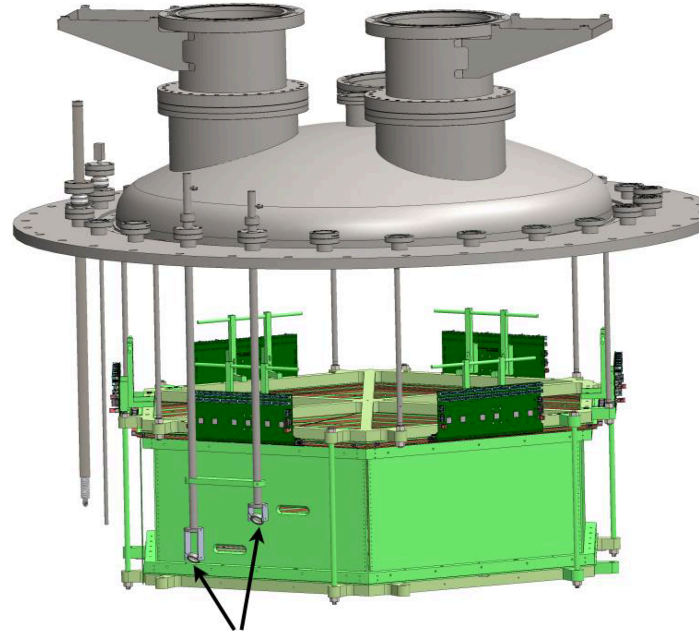
Laser System

- Use frequency quadrupled Nd-YAG laser to generate 266 nm light for calibration
- Light deflected by mirrors into the desired path

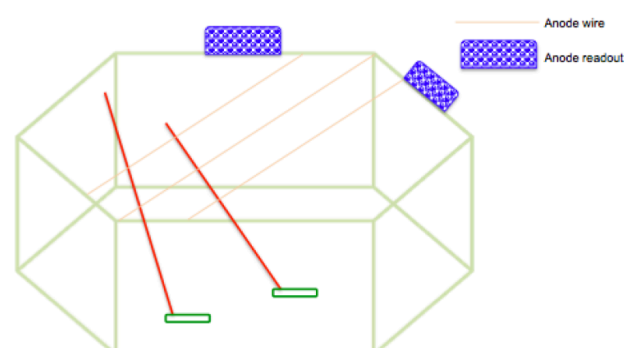


Quantel "Brilliant B" Nd-YAG laser

Wavelength	1064 nm	532 nm	266 nm
Pulse Energy	850 mJ	400 mJ	90 mJ
Pulse Duration	6 ns	4.3 ns	3 ns
Peak Power	133 MW	87 MW	28 MW
Peak Intensity	1500 GW/cm^2	985 GW/cm^2	317 GW/cm^2
Photon Energy	1.17 eV	2.33 eV	4.66 eV
Photon Flux	8E30 γ/(s·cm^2)	2.6E30 γ/(s·cm^2)	0.42E30 γ/(s·cm^2)



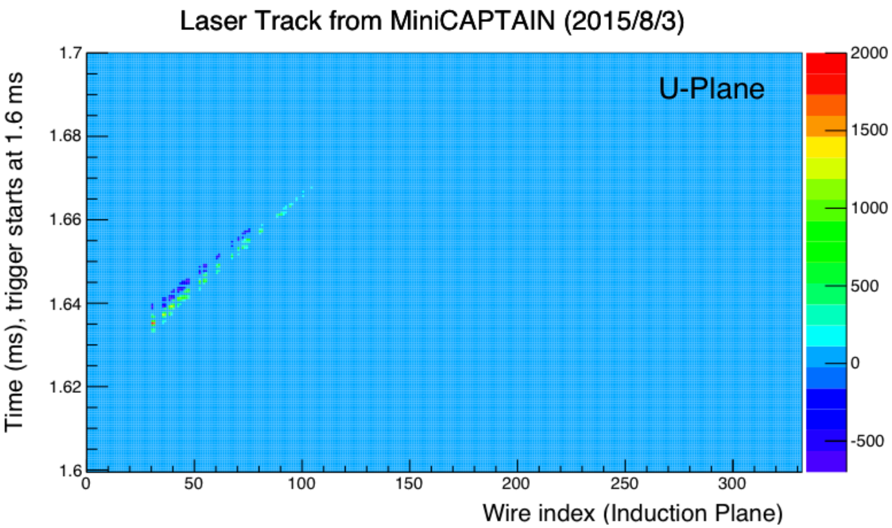
optical feedthroughs

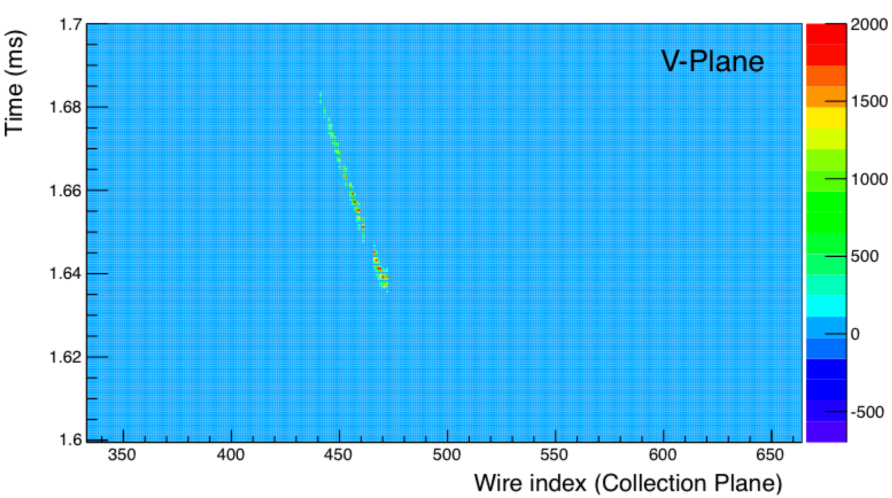


Laser path setup

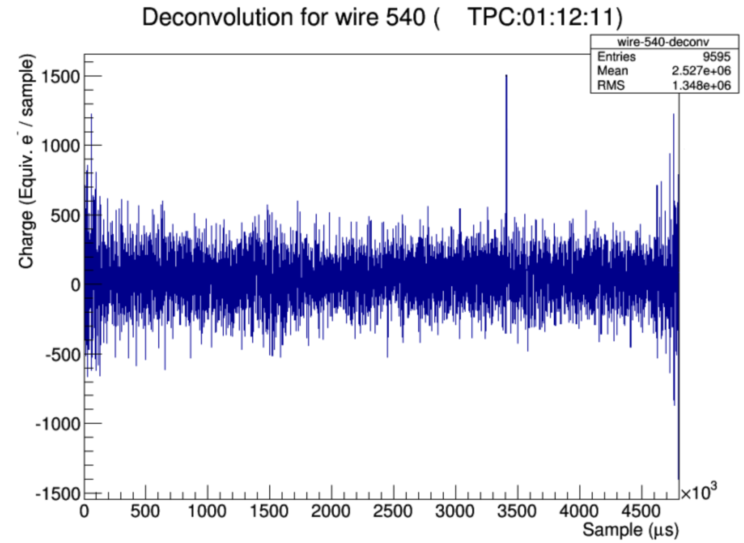
Laser Data from the Commissioning Run

First confirmed laser track found during the commissioning of mini-CAPTAIN.

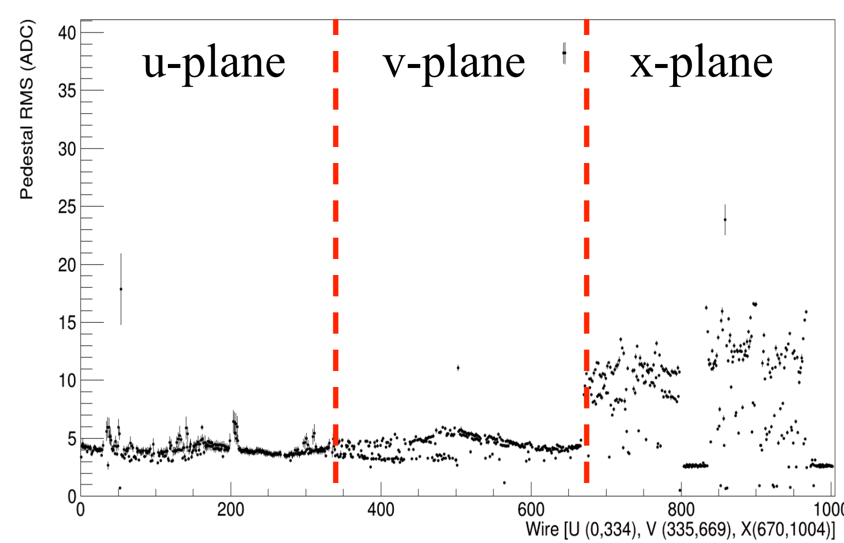




Signal on a v-plane wire after Wiener filtering

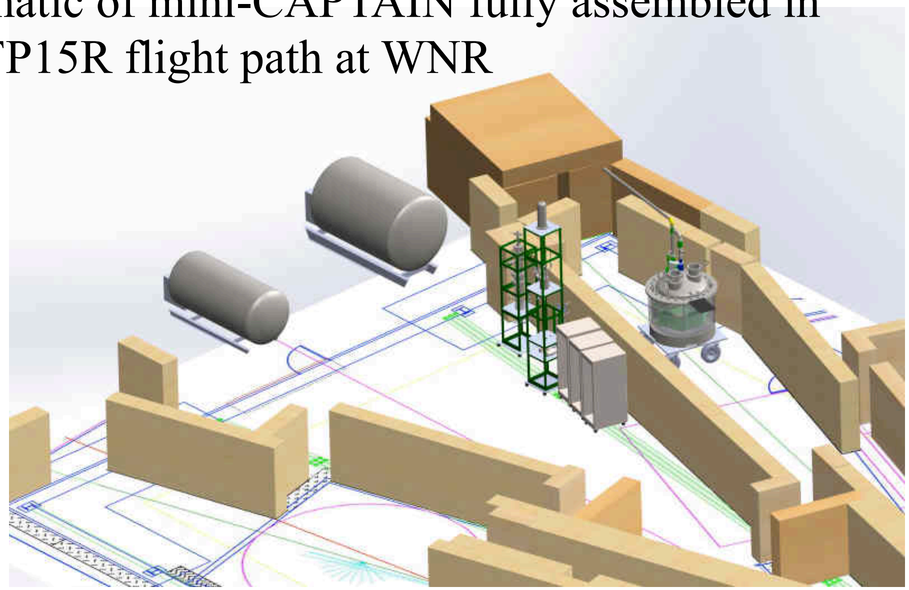


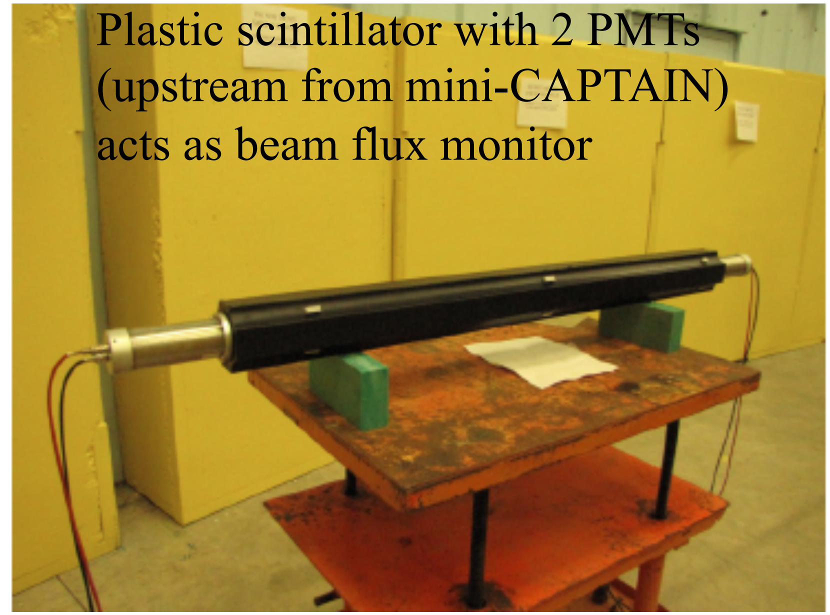
Final Noise Levels



First Mini-CAPTAIN Neutron Run

Schematic of mini-CAPTAIN fully assembled in the 4FP15R flight path at WNR



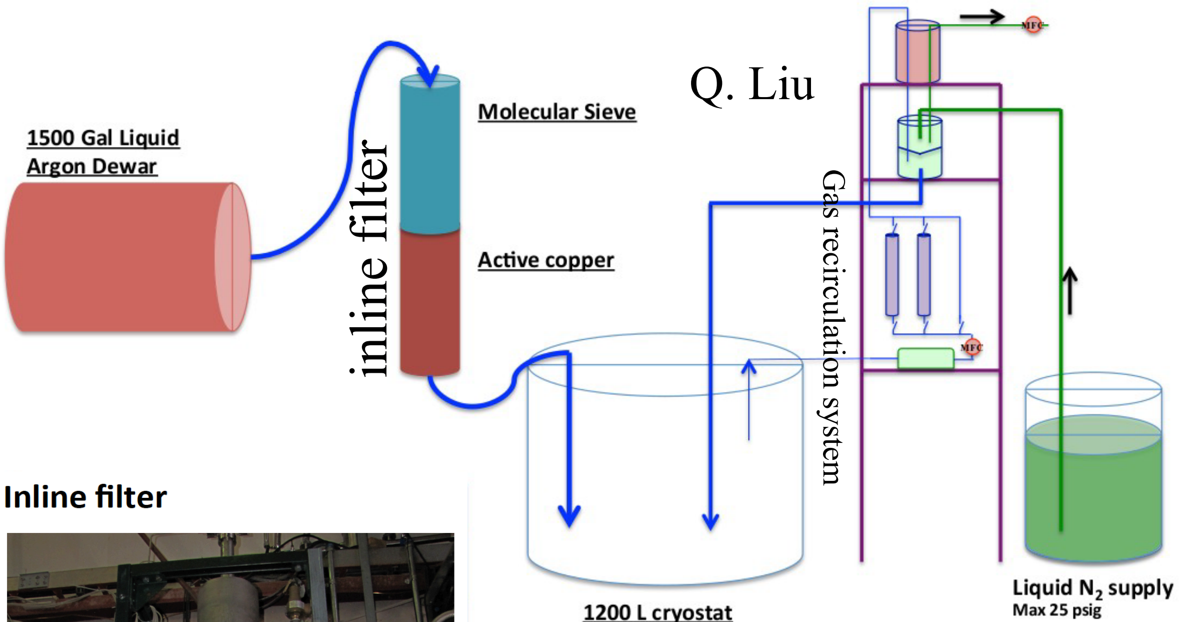


Plastic scintillator with 2 PMTs (upstream from mini-CAPTAIN) acts as beam flux monitor

Purification

MiniCAPTAIN Cryogenics and Purification system consists of:

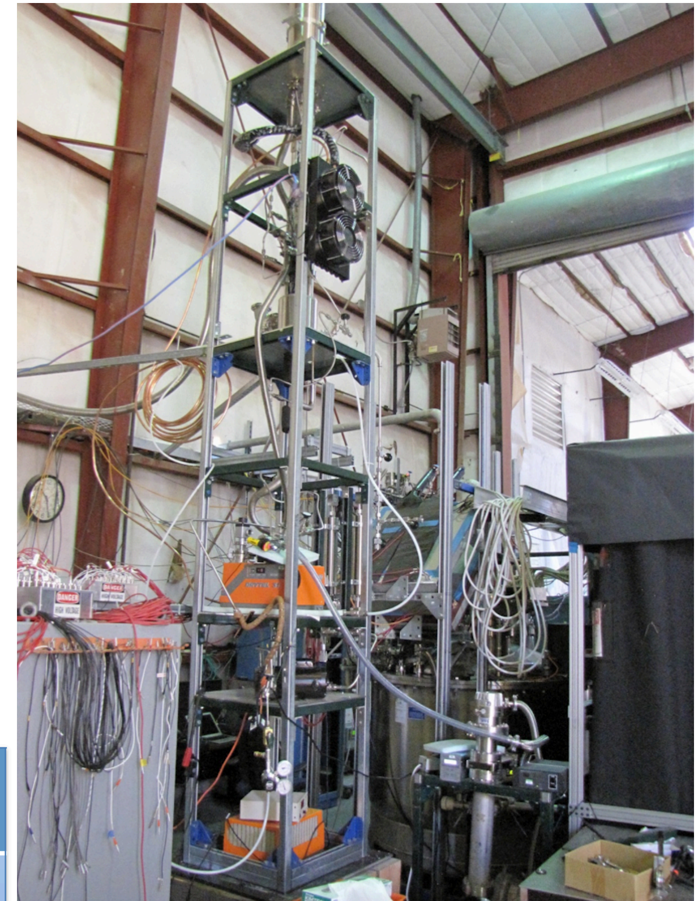
1) An inline **liquid argon filter**
2) A **gas recirculation system** including a condenser and filters



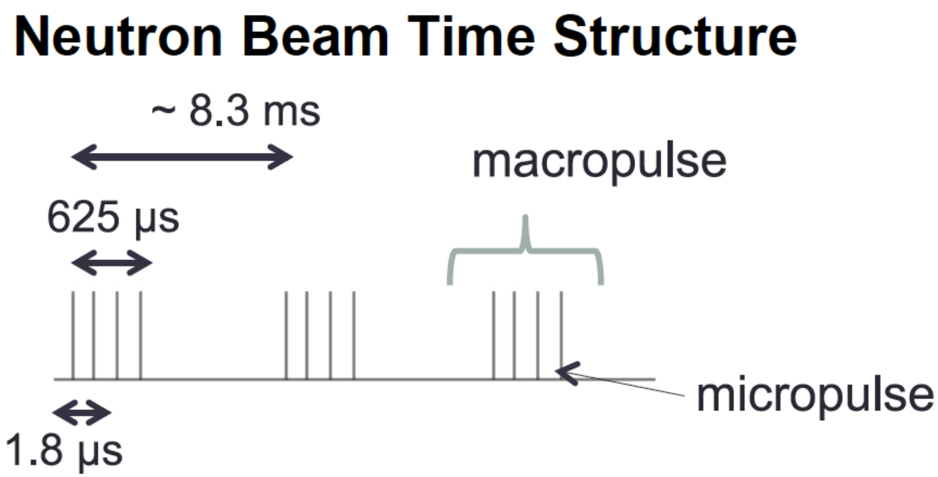
Inline filter

Electron drift distance	Electron Lifetime	O2 concentration	H2O concentration
32 cm	0.2 ms	1.5 ppb	0.3ppb
1 cm	0.006 ms	50 ppb	10 ppb

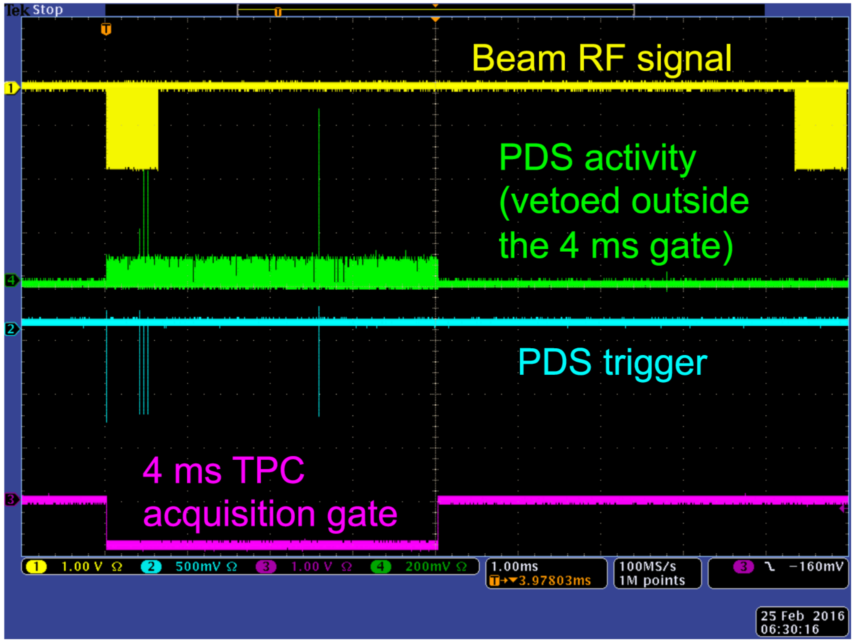
- After initial fill O_2 2.7 ppm→800 ppb, copper show inefficiency in LAr temperature
- Air backflowed into the cryostat when continued recirculation
- O_2 concentration 23 ppb when started neutron run Feb 23
- O_2 1.5 ppb on April 7, after neutron run



Trigger



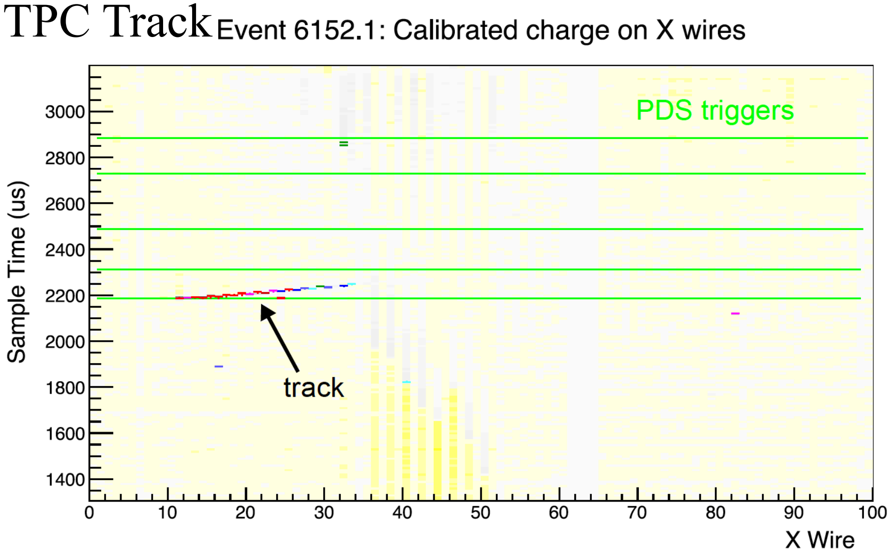
Oscilloscope trace taken during running



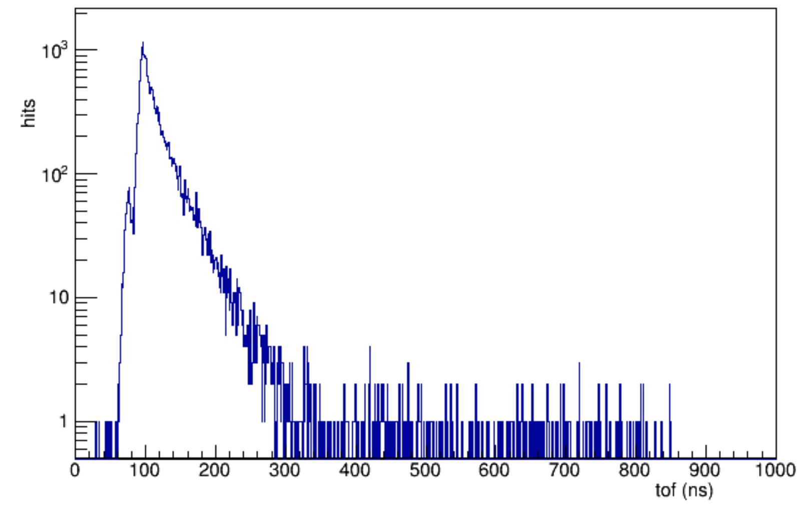
- First micropulse in each macropulse triggers TPC
- TPC Trigger window: 4 ms
- First PDS trigger also sent by beam, then PDS triggered on its own light within the 4ms TPC trigger window
- PDS Trigger window: 8.192 µs
- PDS triggered for 2+coincident PMTs, threshold: 2.5mV (~4 P.E.)
- TPC trigger rate limited to 0.5 Hz for stability

Neutron Data

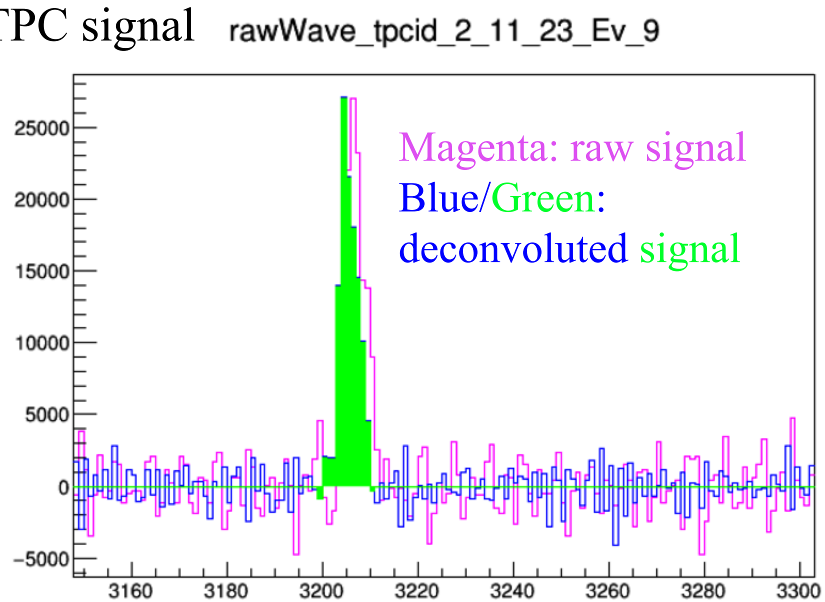
TPC Track



Neutron time-of-flight spectrum from PDS data



TPC signal



- Tracks are clear
- TPC noise is low
- PMTs performed well
- Missed GPS timestamps for many PDS events, trouble for PMT-TPC matching
- Neutron time-of-flight analysis underway (for incident neutron energy)

More Lessons - Noise

From CAPTAIN Electronics Technical Report, C. Taylor et. al.

Power Supply Noise

Most of the power supplies used in mini-CAPTAIN were linear. **However, Sorensen 30-20 switching power supply was used for the FEM boards.** This induced problems in both the quality of the data and the stability of the DAQ. With the scopes Fast Fourier Transform (FFT) function, several key frequencies were identified. **While there were many frequencies found over 100 MHz, the most concerning frequencies were around 35 kHz and 90 MHz. The DAQ is not very sensitive to frequencies over 100 MHz, so capacitors and inductors were chosen with focus on the lower frequencies.**

Pump Noise

With careful grounding of the pump specifically, no electronic noise was observed from the pump.

More Lessons - Noise

Noise from building sources and power supplies

It was observed that there were several key areas which could introduce RF signal on mini-CAPTAIN. These were easily identified with observation of the line driver signals on the oscilloscope while moving grounds around. **The Faraday Box on top of the FEE feedthrough proved to be the most significant reduction to RF. For best results, it was necessary to properly ground it with the top-head flange**. More careful grounding practices were necessary with the decision to ground most of the front-end to the cryostat.

Sweep signal (chirping)

A sweep signal (chirping) effect was commonly seen from RF frequency pickup. Instead of a the constant frequency (or superposition of frequencies) seen from a power noise source, a signal is observed in which the frequency increases (up-chirp) or decreases (down-chirp) with time. The chirping effect could easily be reproduce by tapping on the cryostat or cable trays. **Three inch thick copper braids were used on most large bodies of metal around mini-CAPTAIN to significantly reduce this effects.** By the time the grounding was completed at WNR, no signal was observed from physical activities around the detector.

More Lessons – Test/Grounding

Analogue Signal Test Point

The large majority of troubleshooting on mini-CAPTAIN was performed on the analogue output, particularly from the intermediate amplifiers in the Faraday box.It allowed for a quick interpretation of signal response to changes in the system's configuration. **Suggest that systems with cold digitization electronics have at least 1 in 100 channels with an analogue trace to the outside.**

DMV Checks for Grounding

Grounding can prove challenging with any new system. A new ground loop or RF antenna can easily be introduced with any changes to an otherwise stable detector. Also two systems referenced to the same grounding bus bar can have components with a voltage potential. **We found it necessary to use a digital volt meter to locate and remove these variances.**

Breaking Grounds

Even a well thought out system might need to break in its grounds for testing purposes. It would be best for the internal components to have grounds separate from they cryostat and other subsystems. If necessary, these points can be then be tied or broken externally. Each ground point can be used to look for shorts between the subsystems. It also allows for quick measurement of the voltage potential differences between them.

More Lessons – Risk Control

Channel Isolation
To prevent HV Breakdown/wire shorts damaging down-stream motherboards in the chain, it would prove advantageous to install switches to break the trace to each wire or set of wires.

Limit on Injected Calibration Pulse
Some motherboards were damaged during the initial two testing phases of mini-CAPTAIN with 0.4 to 0.7 V calibration pulse. No more motherboards were lost after limiting the injected pulses to 0.25 V. The large majority of test pulses used in mini-CAPTAIN during the last three phases were set to 0.08 V.

Chaining Motherboards
Each time we lost a motherboard, the motherboard down stream was no longer configurable. This problem is amplified with more motherboards in a chain. Realistically most large detectors would need to chain their motherboards to reduce cables and feedthrough points. However where possible, reducing the number of motherboards in a chain reduces the risk of losing large sections of wire outputs.

Future Plan for mini-CAPTAIN

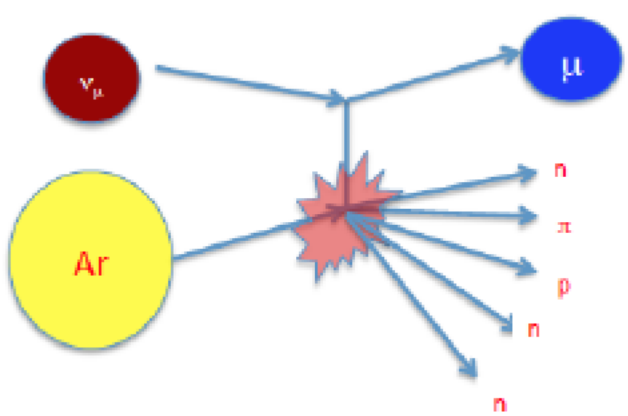
- Mini-CAPTAIN has taken 1st neutron data
- Analyze the first neutron data
  - Vertex reconstruction
  - track reconstruction
  - particle ID
  - reaction rates and cross sections
- Planning 2nd neutron running in WNR in summer, 2017

Backup

Long-Baseline Neutrino Event Reconstruction

At 1300 km, DUNE will measure neutrino interactions between 1.5 – 5 GeV (near first oscillation maximum), where neutrino-nucleus interactions are poorly understood:

- **ArgoNEUT** has the first and only inclusive cross-section measurement at these energies **(~3200 ν and anti-ν events) from NuMI beam**
- In the 1.5 – 5 GeV energy window, rich and complex neutrino-nuclei interactions will take place - **more than half of neutrino interaction events will occur in the baryon resonance channel**
- **Neutrons produced in neutrino interactions will complicate energy reconstruction of incoming neutrinos (missing energy = uncertainty in L/E)**



Understand neutrons better to improve neutrino Energy reconstruction.

Supernova Neutrino Event Reconstruction

A supernova burst will result in a continuous spectrum of neutrino energies < 100 MeV. Neutrinos in this energy regime have **NEVER** been detected in a liquid argon TPC.

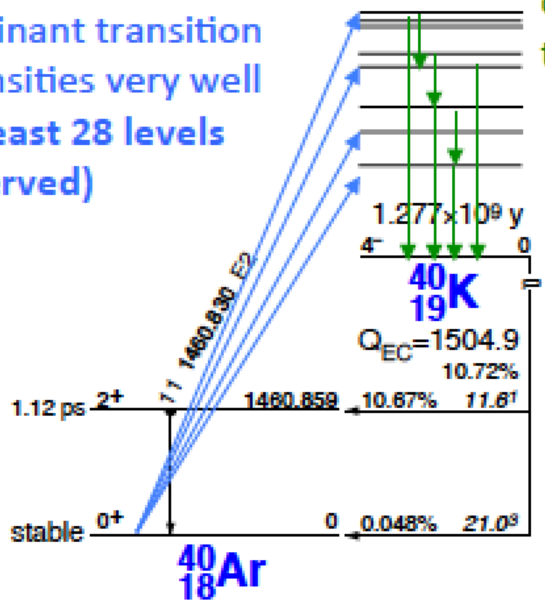
Extracting physics from supernova neutrinos requires reconstructing true neutrino energy.

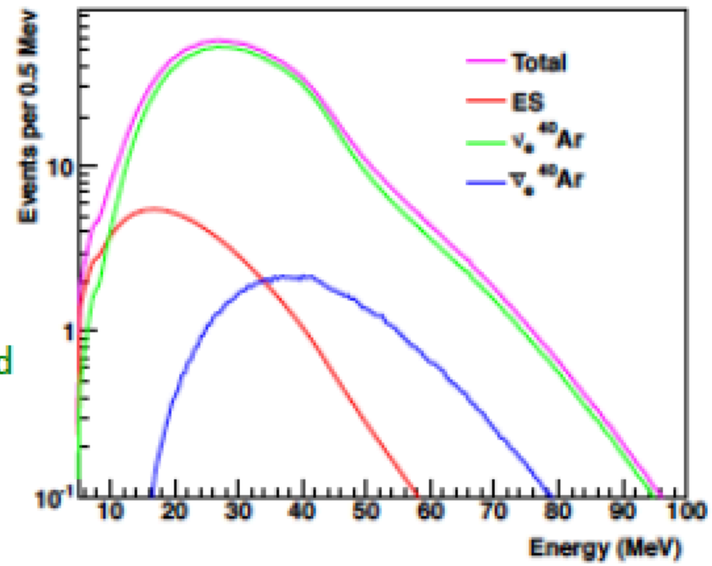
Neutrino Energy | Outgoing Electron Energy | Q-value of Transition | Recoil Energy of Nucleus

CC reaction: $E_\nu = E_e + Q + K_{\text{recoil}}$

We need to know dominant transition intensities very well **(at least 28 levels observed)**

Also need to know all the de-excitation gammas and their branching fractions





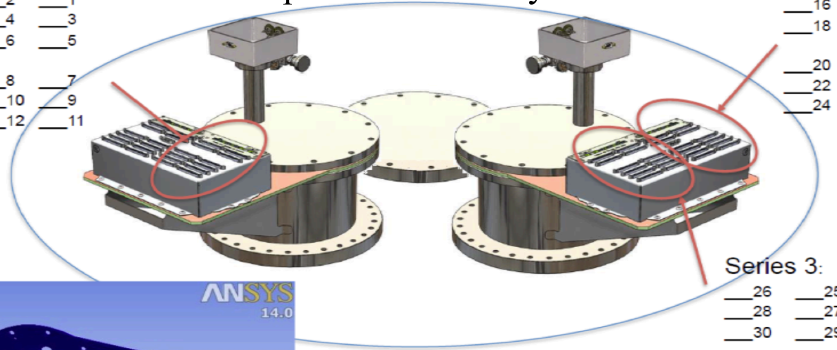
[1] K. Scholberg
[2] A. Hayes

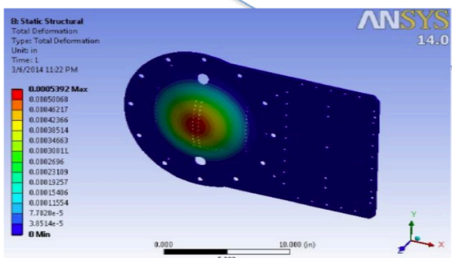
Reaction Type	Events / 10 kt
(CC) $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	~700 [1]
(CC) $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	~60 [1]
(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$	~85 [1]
(NC) $\nu_x + {}^{40}\mathrm{Ar} \rightarrow \nu_x + {}^{40}\mathrm{Ar}^*$	~90 [2]

(SN at 10 kpc)

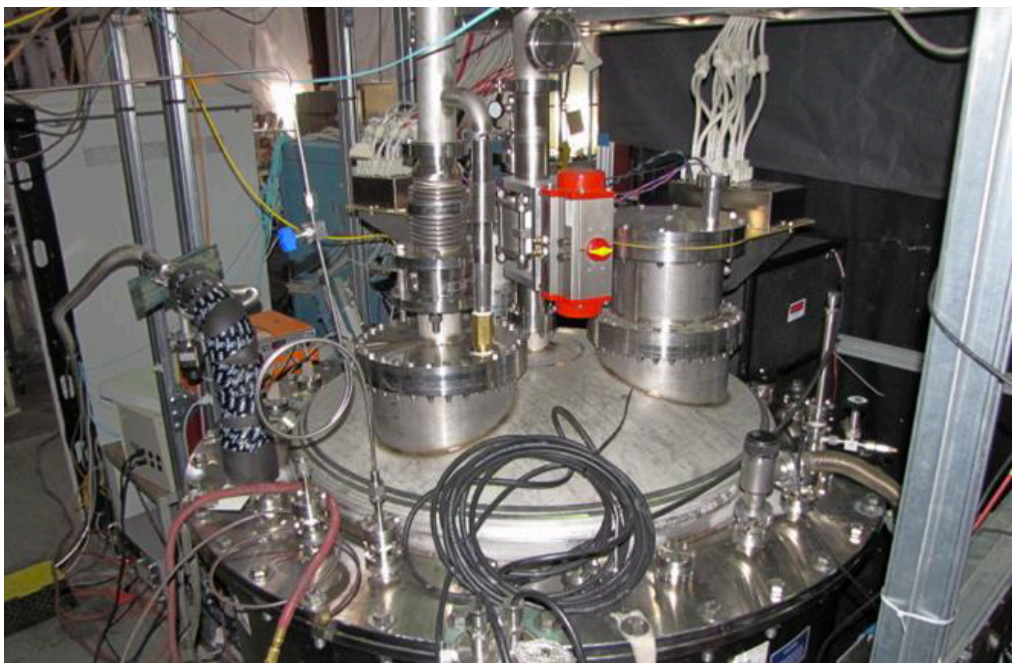
Feedthroughs

Service/intermediate amplifier and 4 bias of planes in Faraday Boxs

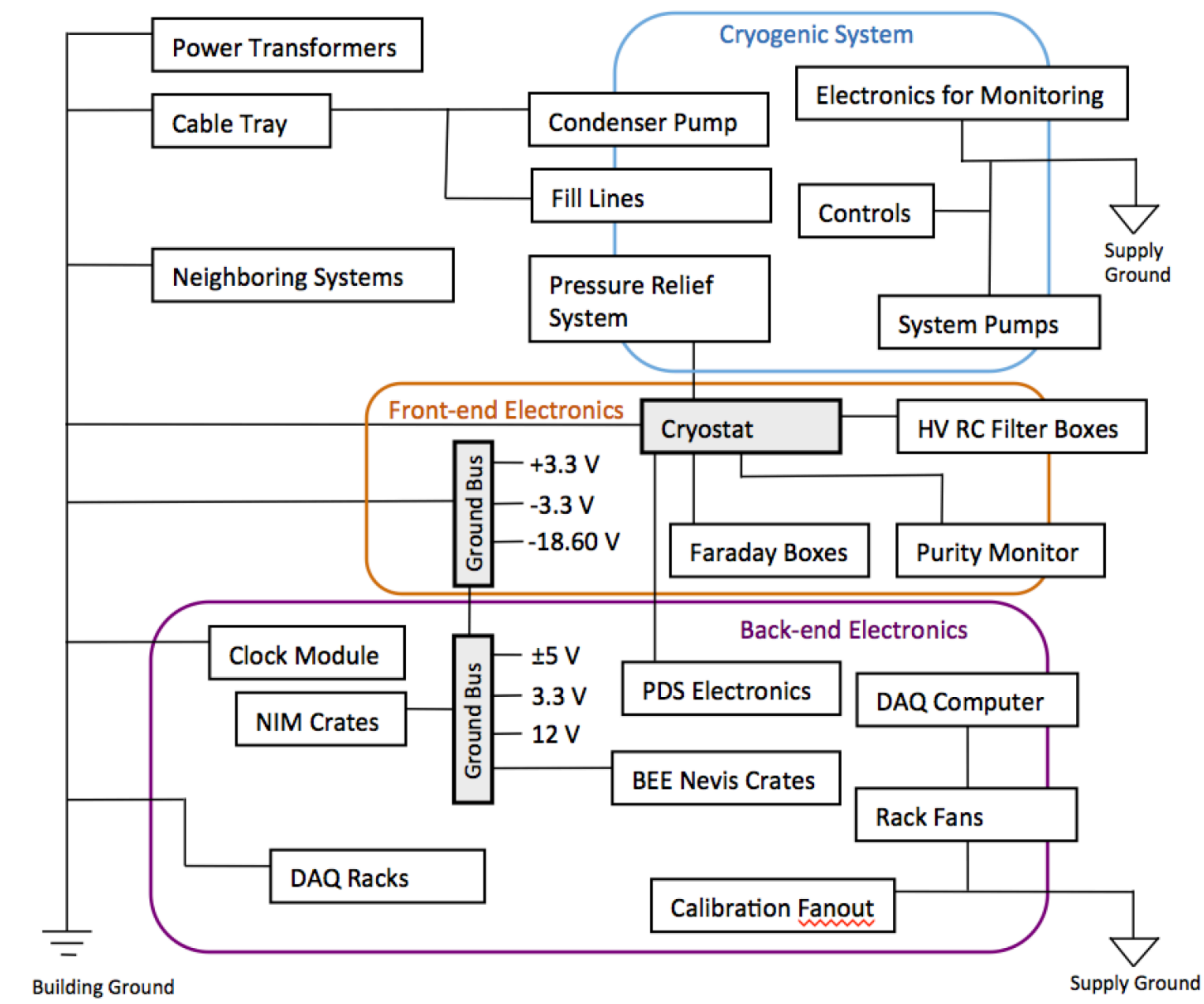




Calculations showed the feed-thru boards could support the weight of the cables



Grounding Layout



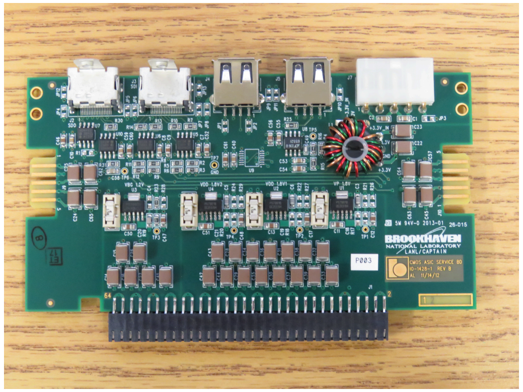
The layout of the grounds for mini-CAPTAIN at the WNR facility at LANSCE. Initially in the commissioning, the larger components attached to the cryostat were isolated. However after time we found that such components needed to be ground with the cryostat. We also found that there had to be a consistent chain of grounds on the back-end electronics to keep the DAQ from crashing.

Voltage requirements of TPC

TPC High Voltage Requirements		
Parameter	Value	Comments
Nominal Cathode Voltage	-16 kV	A field with 500 V/cm was chosen for the ideal 1.6 mm/us electron drift velocity
Ripple	<2 mV @ 0.020 mA	Low voltage fluctuation was ideal for reduced variation for the estimation drift velocity
Resistors in Divider Chain	Four 25 MΩ resistors per 1 cm spacing	Maintain 20 uA to insure an electric field of 500 V/cm
Wire Plane Voltage Requirements		
Grid-Plane	-430 V	The grid plane is used for shapping the u-plane's signal shape. it should have not draw current.
U-Plane	-230 V	First induction plane. Usually no visible current is seen.
V-Plane	0 V	Second induction plane. Usually has a current of 0.5 μA.
X-Plane	230 V	The collection anode plane. Usually has a current of 1 μA.

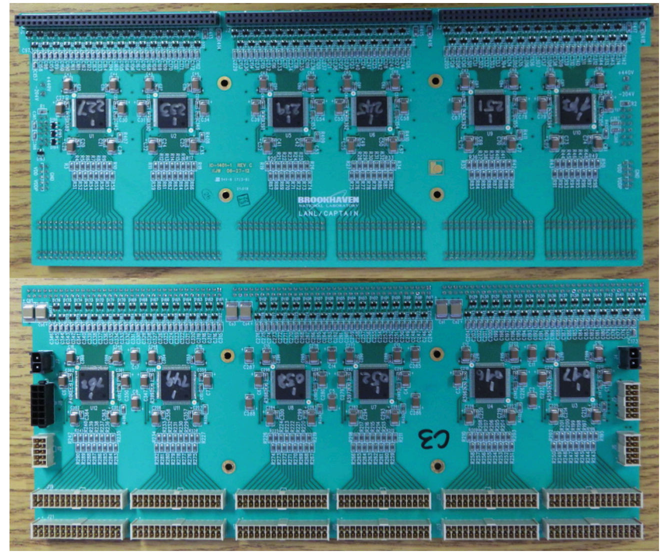
Front-End Electronics

Service board



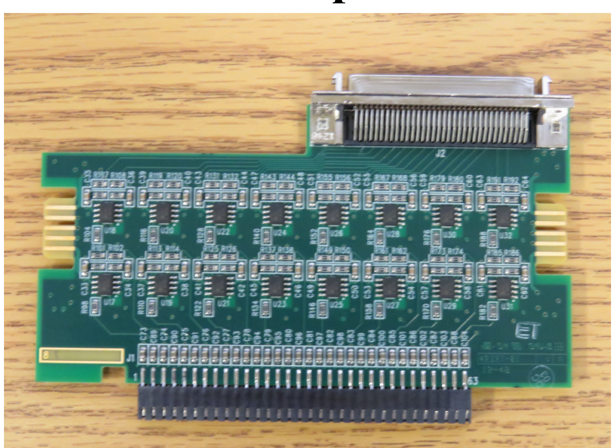
The service board supplies the power to the motherboard and line drivers and sends commands to the ASIC chips on the motherboards. It can also pass injected pulses to the ASIC.

Motherboard (CMOS ASIC preamplifier)



The Brookhaven National Laboratory motherboards, which connect directly to the wire planes. The motherboards have the CMOS ASIC chips made for operation in liquid argon. The ASIC chips amplify and shape the signal from the wires.

Intermediate amplifier



The intermediate amplifier takes the signals from the motherboards and splits them differentially before applying a 12 dB gain. This helps the signal reach the ADD boards 10 meters away.