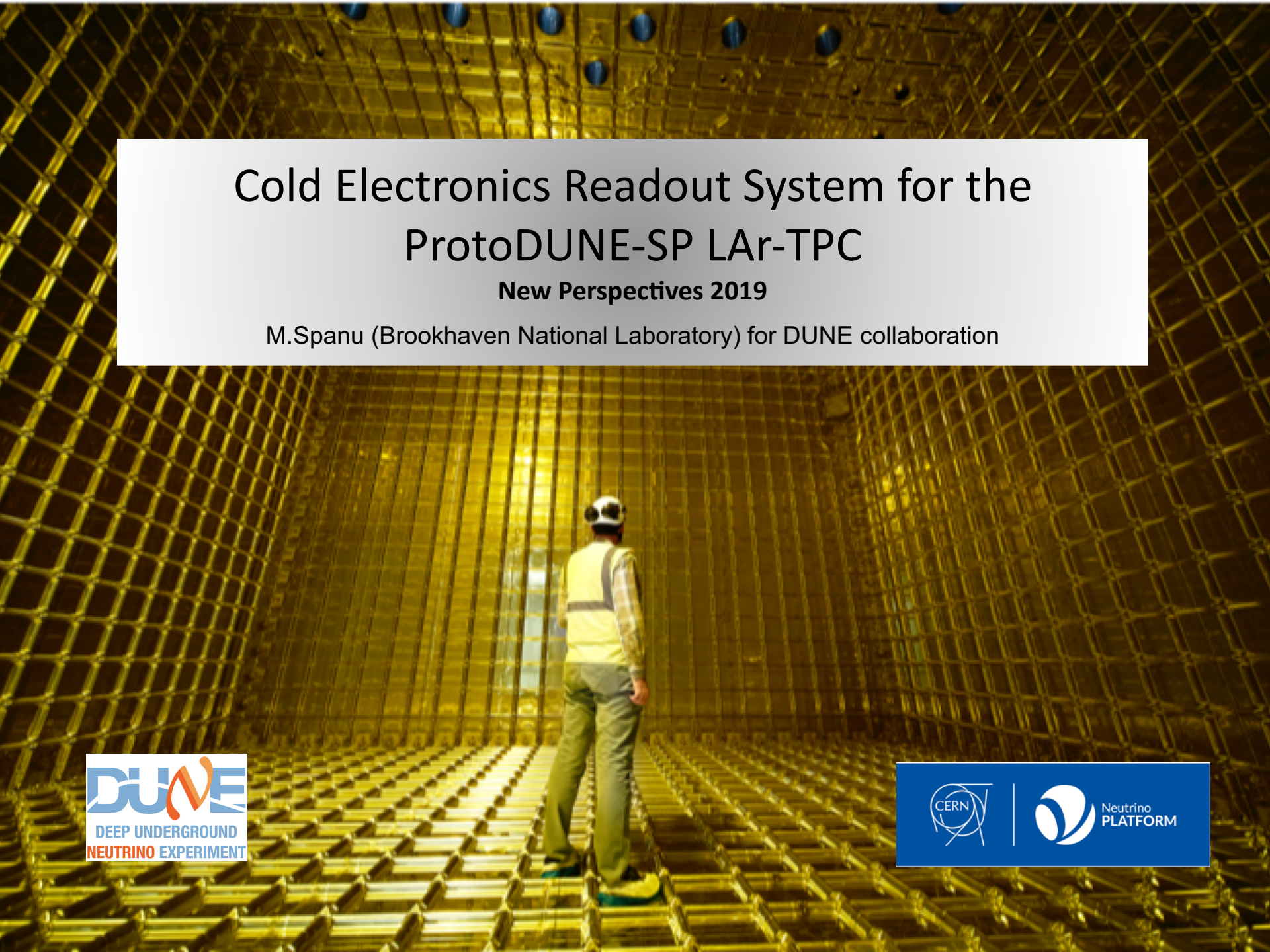
Cold Electronics Readout System for the ProtoDUNE-SP LAr-TPC

New Perspectives 2019

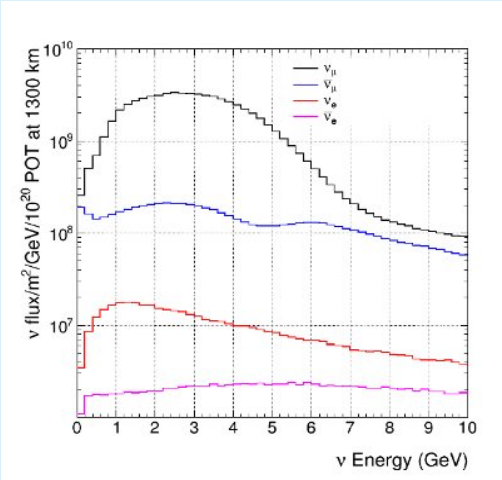
M.Spanu (Brookhaven National Laboratory) for DUNE collaboration



Deep Underground Neutrino Experiment (DUNE)

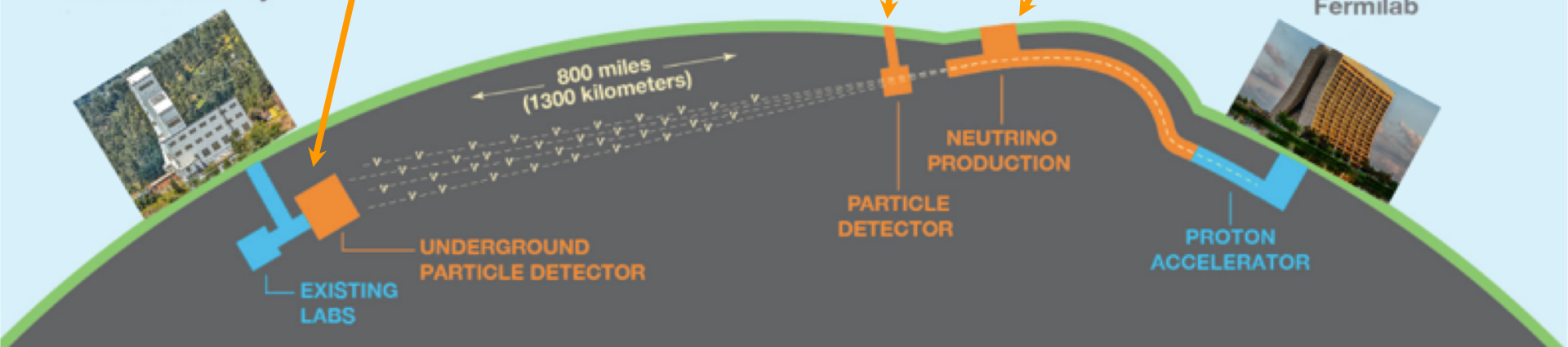
1100+ collaborators from 178+ institutions in 32+ countries

$\nu_\mu / \bar{\nu}_\mu$ Beam
1300 km baseline, from Fermilab to SURF
1.2 MW power (2026), up to 2.4 MW (II phase, 2032)



Far Detector (FD)
Hosted at SURF, South Dakota
New hall, 1.5 km depth
4 LAr-TPC, 40ktons fid. vol. (70 ktons in total)
Two variants of LAr-TPC technology (Single and Dual Phase)
First module operational in mid 2020s

Near Detector (ND)
Hosted at Fermilab

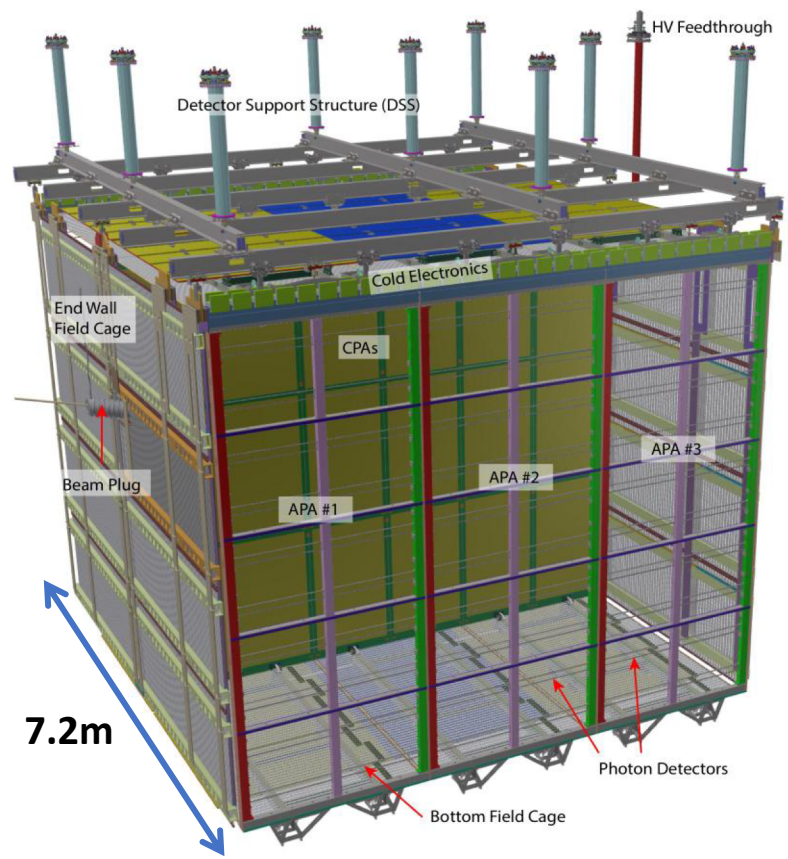


A huge, small prototype: ProtoDUNE Single Phase

- **Big!** A 12m x 12m x 11m cryostat holding 720 ton of LAr (411 active volume). Detector is made with full scale elements designed for DUNE FD → test of FD engineering solutions and installation procedures
- **Small!** The detector is 1/20 of one FD module, ~ 1% of DUNE! → optimal size for effective tests within the DUNE timeline
- **Beamy** ProtoDUNE-SP has been exposed to a dedicated low energy beam lines → characterization of LArTPC response to charged particles in the same energy range (1 – few GeV) of neutrino interactions in DUNE
- **International!** Strong collaboration between the involved countries → building the community and forming the expertise for DUNE

ProtoDUNE SP Overview

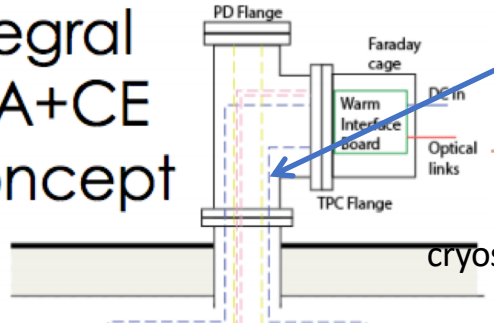
- **6 Anode Plane Assemblies (APAs)**
  - Full-size APAs (6x2.5 m^2)
  - Total of **15,360** TPC sense wires and electronic channels
- **3 Cathode Plane Assemblies (CPA)**
  - Resistive Kapton laminated on dielectric panels
  - 180 kV nominal (2 x 3.6 m drift @ 500 V/cm)
- **16 Field Cage profiles**
  - Aluminum profiles on dielectric frame, provides constant 500 V/ cm electric field
  - Top and bottom elements equipped with perforated SS ground planes to ensure no field outside the active volume



- ***60 Photon Detectors***
  - Light collecting bars read out by SiPMs installed in the APA frame (10 detectors/APA)
  - high coverage with small number of channels, no HV needed
  - 3 distinct versions installed → testing solutions for DUNE

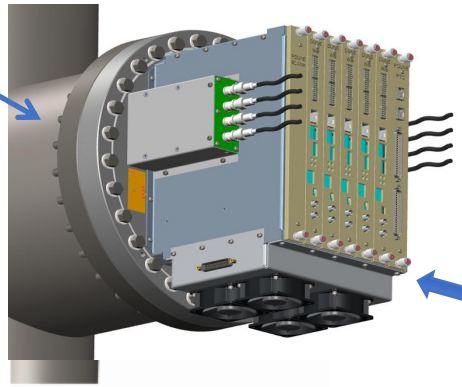
Integrated LAr-TPC Readout

Integral APA+CE Concept



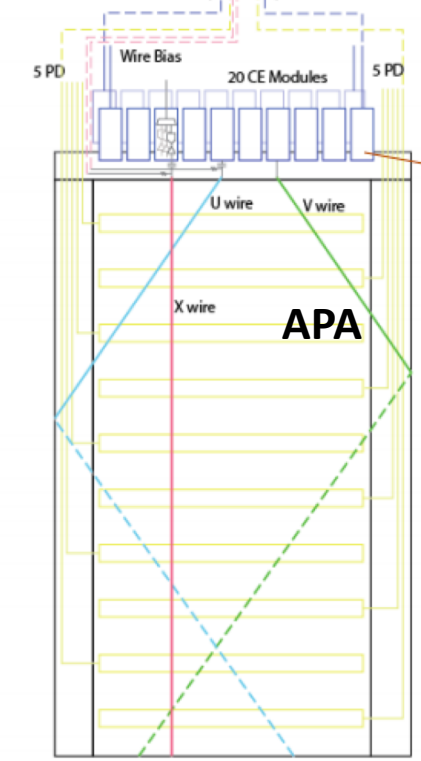
Feedthrough

cryostat



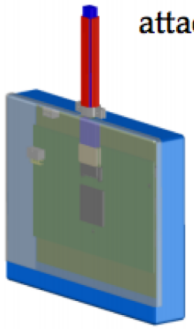
Each APA is isolated inside the cryostat and only connected to the cryostat through the CE at its own CE flange.

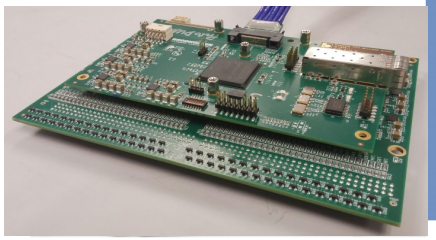
Warm Interface
Electronics: from CE to DAQ with shielding and local real-time diagnostics.

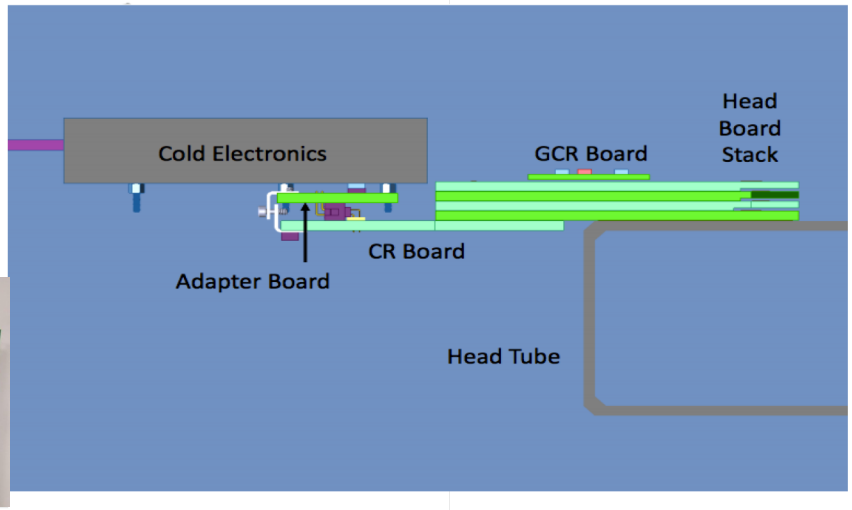


ProtoDUNE-SP

Cold electronics module and its attachment to the APA frame

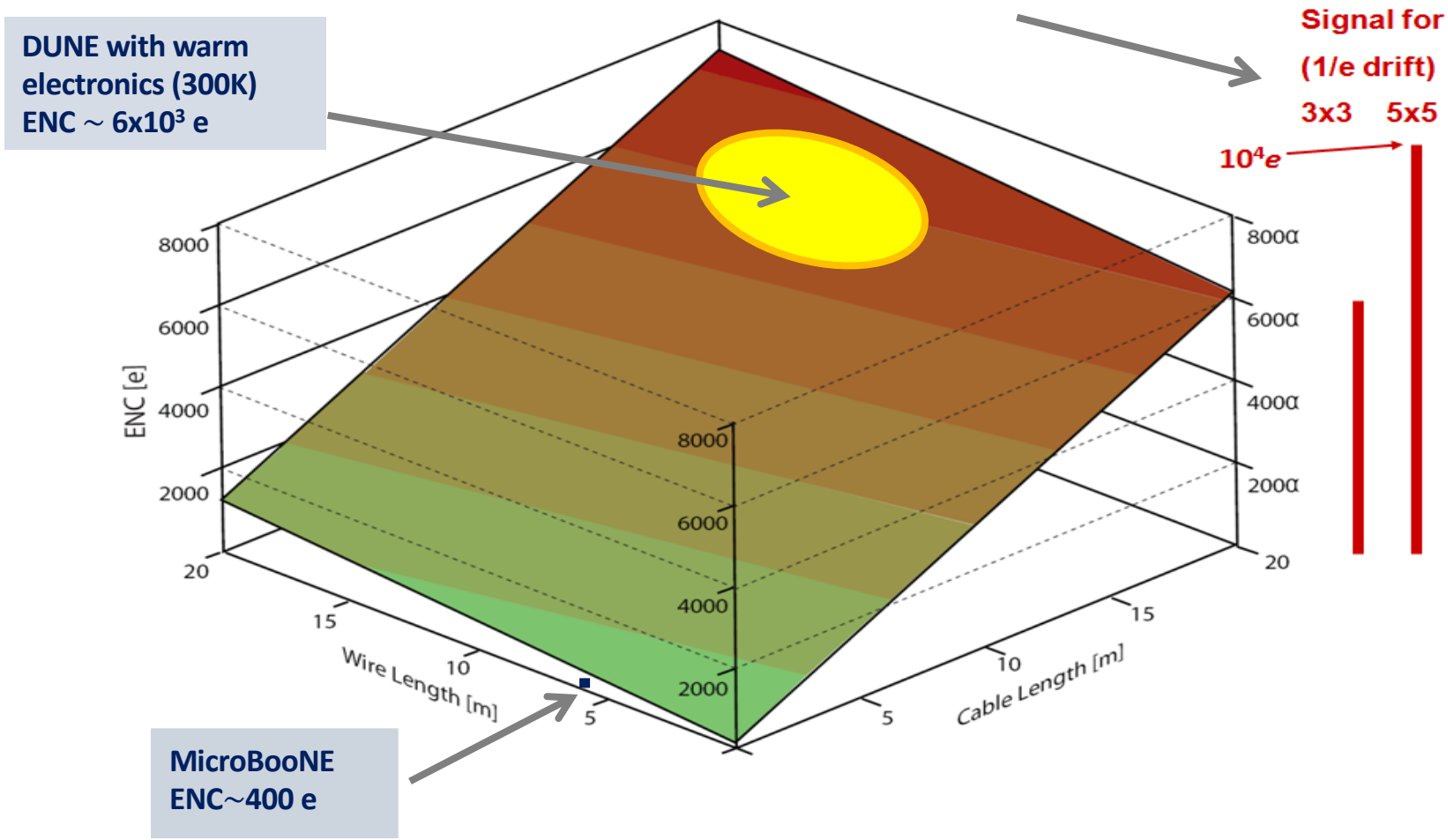




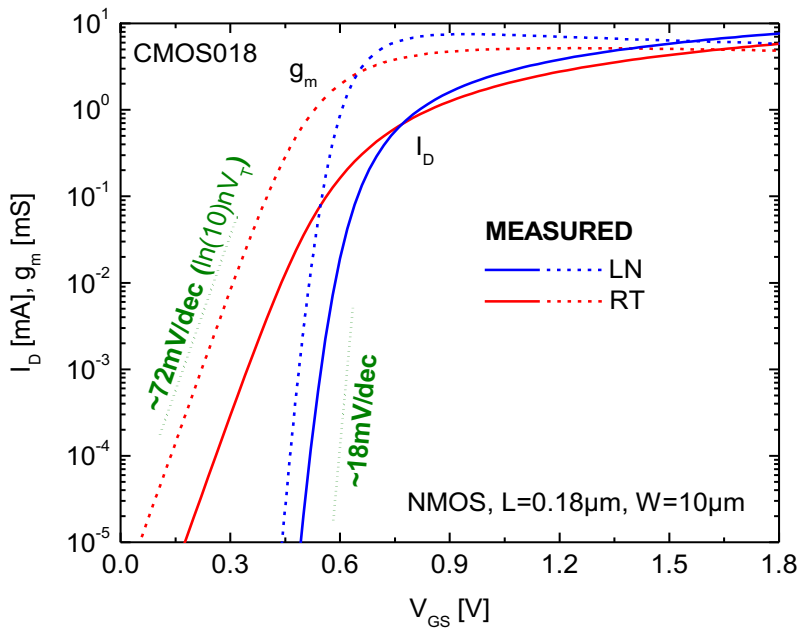


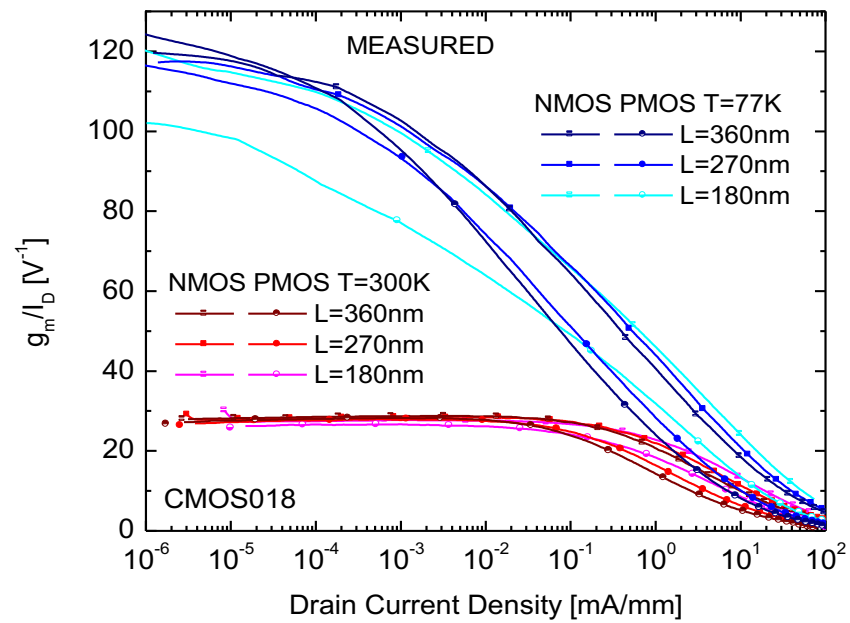
Noise (ENC) vs TPC Sense Wire and Signal Cable Length for CMOS at 300K and 89K

MIP Signal for 3x3 and 5x5 mm Sense Wire Spacing



Cold vs. Warm CMOS: static characteristics vs. T





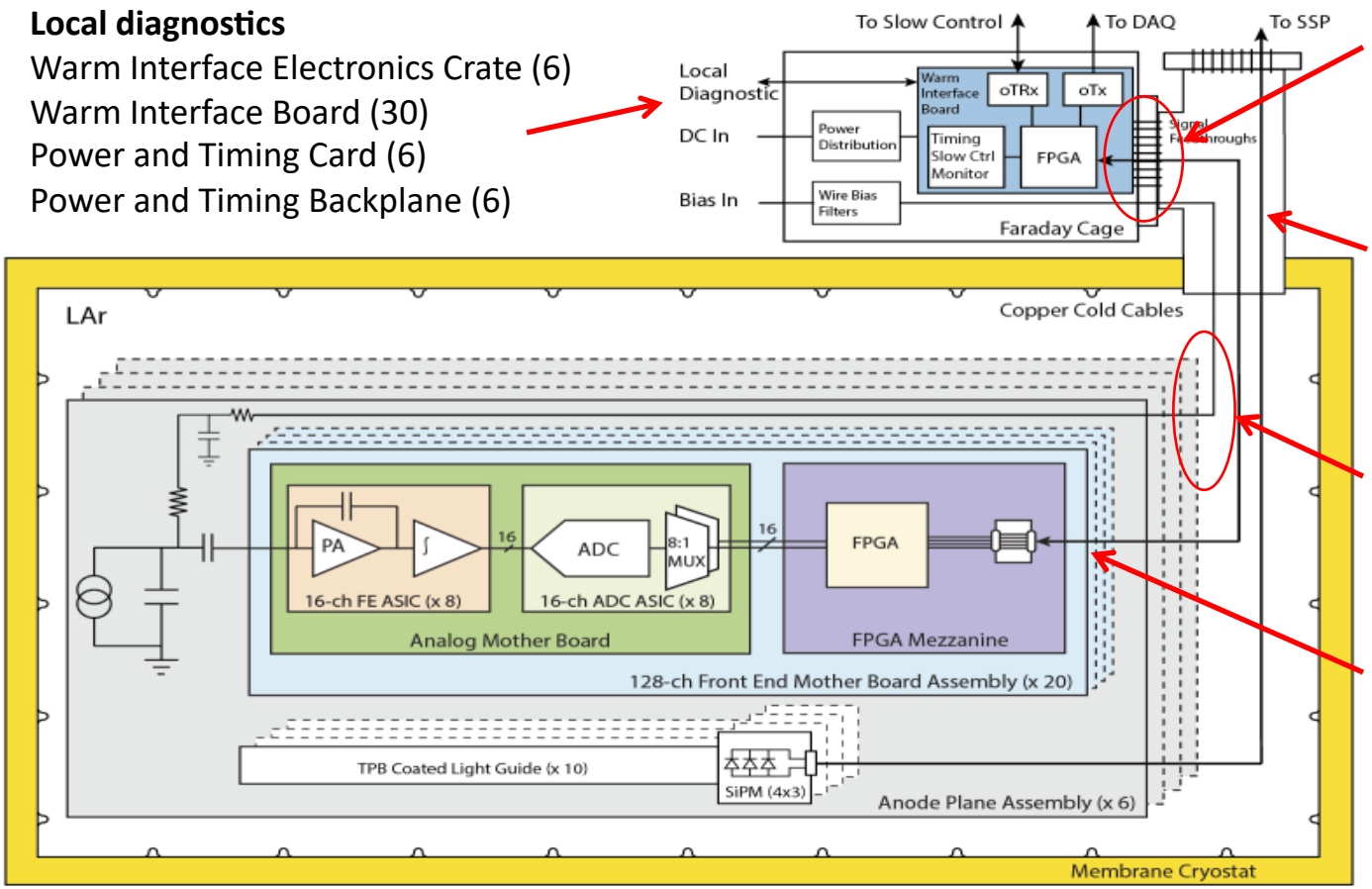
Transconductance / drain current

$$\frac{g_m}{I_D} \rightarrow \frac{q}{nk_BT} = \begin{cases} \sim 30 \;\; at \;\; T = 300K \\ \sim 116 \;\; at \;\; T = 77K \end{cases}$$

At 77-89K, charge carrier ***mobility*** in silicon *increases*, ***thermal fluctuations*** *decrease* with ***kT/e***, resulting in a ***higher gain, higher g_m /I, higher speed*** and ***lower noise***.

ProtoDUNE-SP Cold Electronics

Warm electronics
Local diagnostics
Warm Interface Electronics Crate (6)
Warm Interface Board (30)
Power and Timing Card (6)
Power and Timing Backplane (6)



CE flange
Flange assembly with cable strain relief and flange PCB for cable/WIB connection (6)

Signal feed-through
Tee pipe with 14” Conflat flanges and crossing tube cable (CTC) support (6)

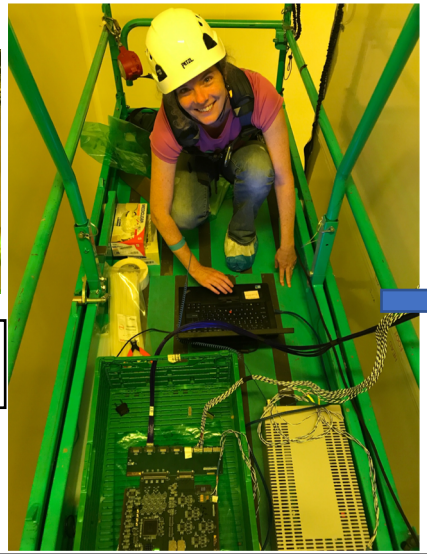
Cold cable
LV and data cable (120+120) to FEMB and APA wire-bias SHV cable (48)

Front End Motherboard
(FEMB) 128 channels of digitized wire readout enclosed in CE Box (120)

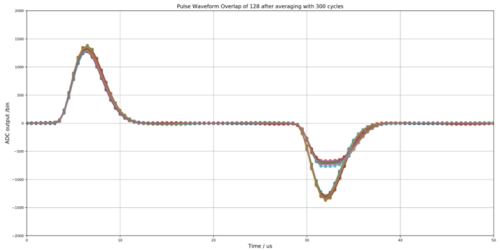
CE Installation at CERN

1. CE boxes installation on APA

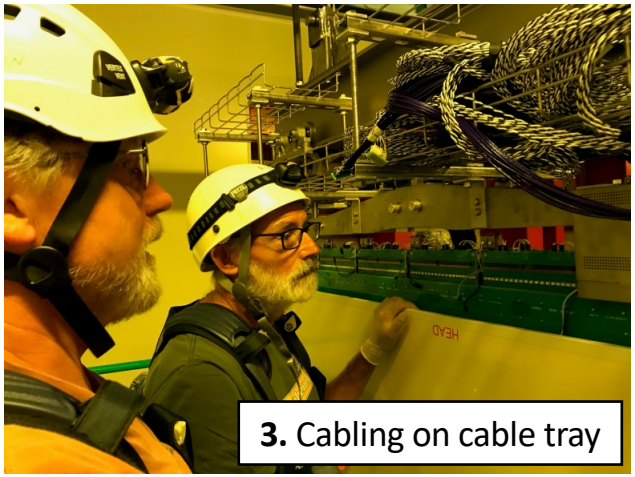
Installed CE boxes on one APA side



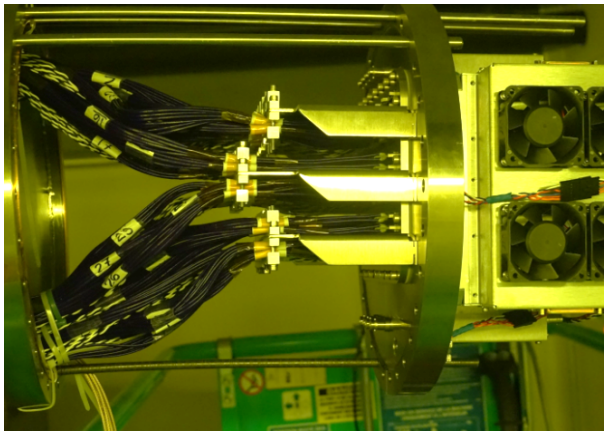
2. CE boxes test after installation on APA



Pulse Waveform



3. Cabling on cable tray

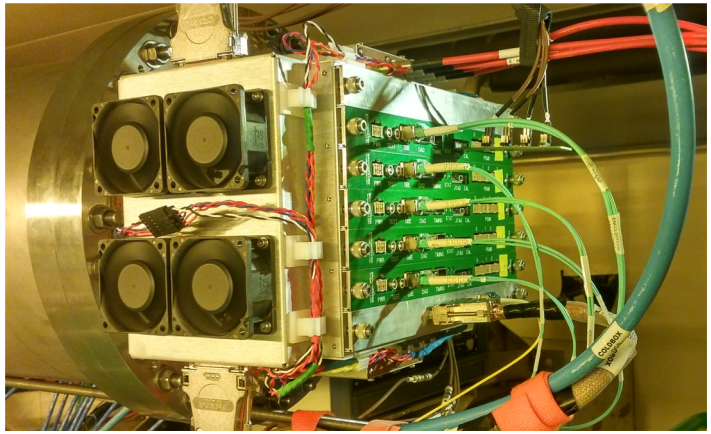


4. Cable hook up to feed-through

APA Cold Test at CERN Cold Box facility

A Cold Box was built at CERN for cold integration test:

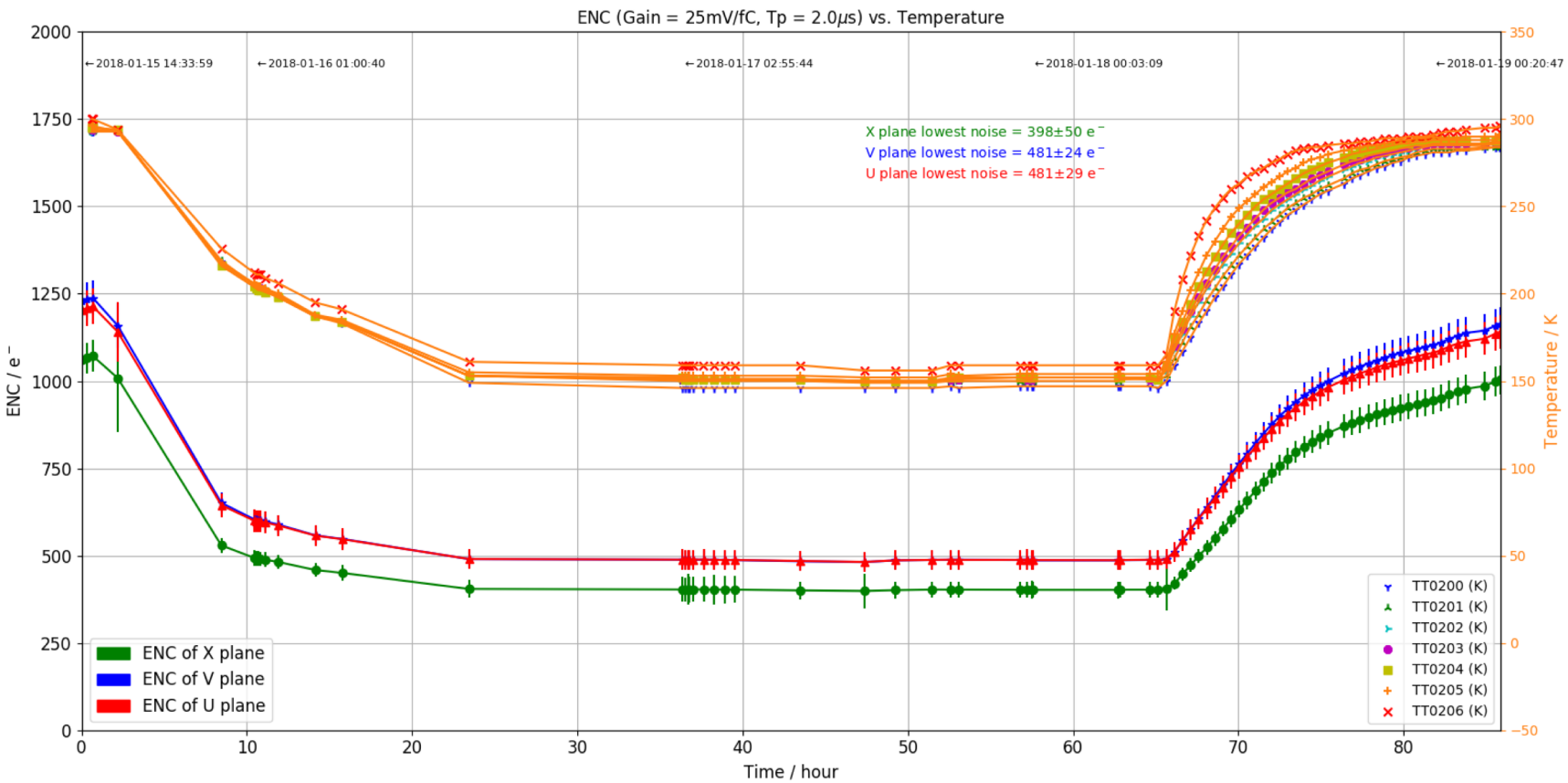
- Allows integral test of electronics and photodetectors on production APAs
- Follows the same power and grounding rules for the detector electronics
- Incorporates a full scale warm feed-through and use cables and readout identical to the production system
- FEMB readout through optical links from WIB on top of the signal feed-through allows a real time study of detector performance in the cold box integration test.



Noise vs Temperature – Cold Box Cooldown

APA2 (January 2018)

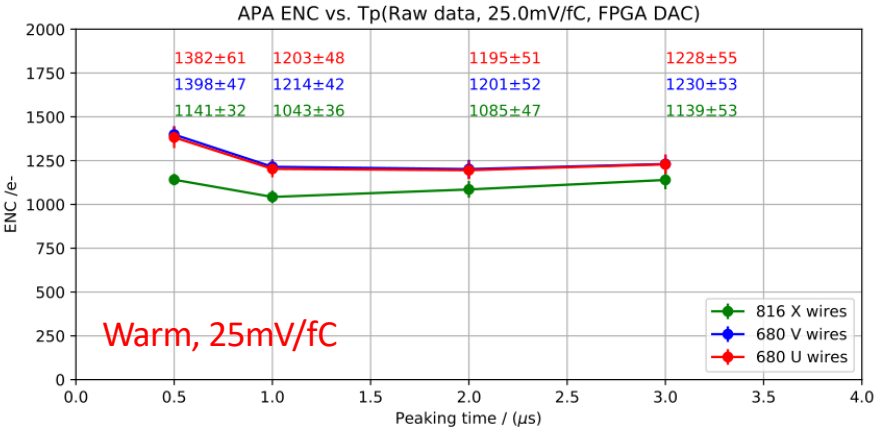
Lowest reached temperature ~ 159K

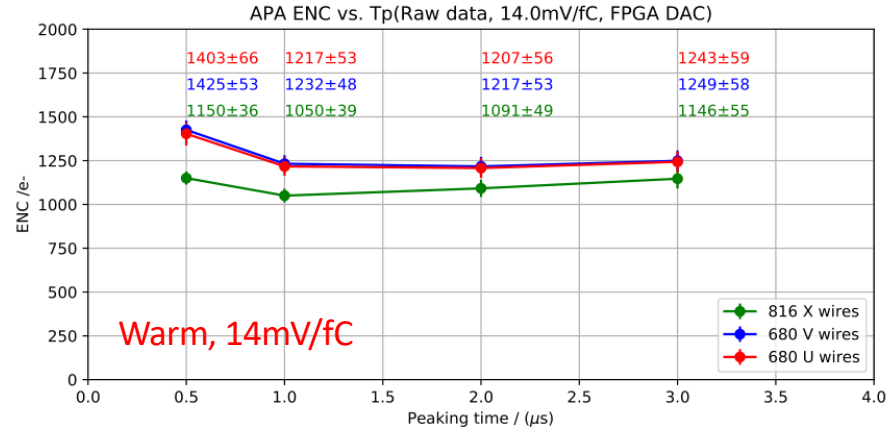


Overall ENC Performance- Warm vs. Cold

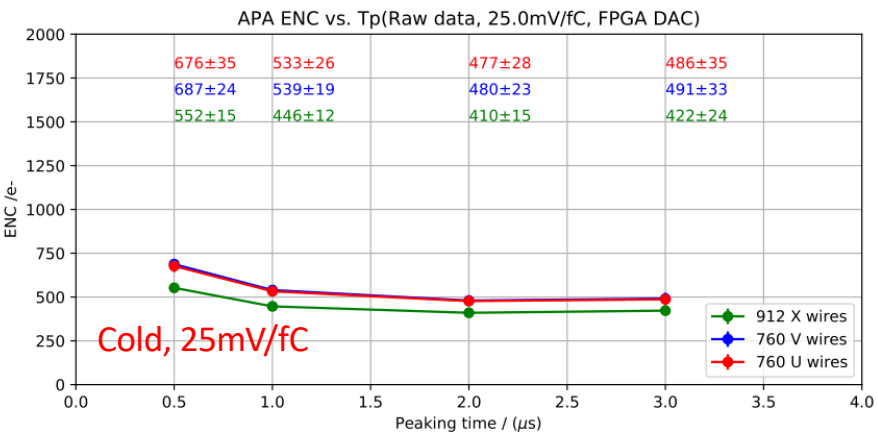
APA4 (2018-03)

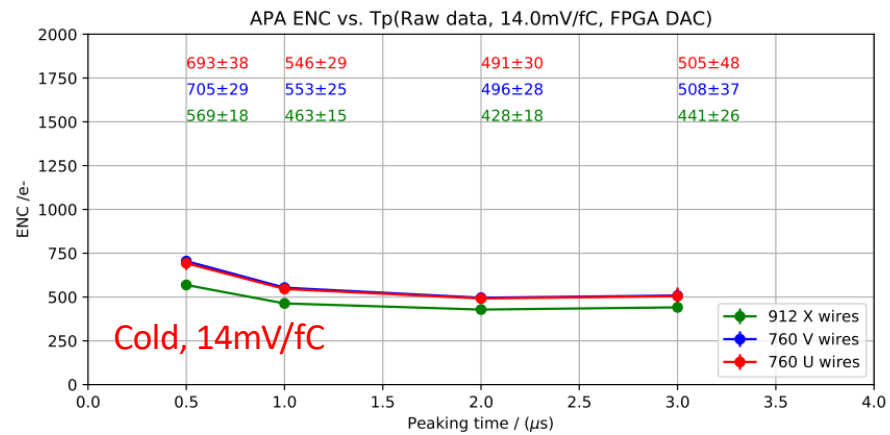
Noise Measurement





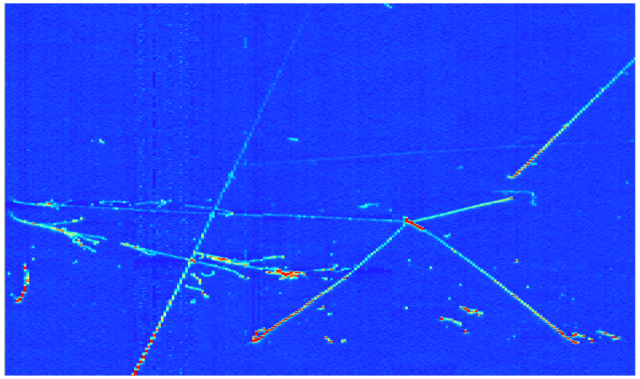
Noise Measurement

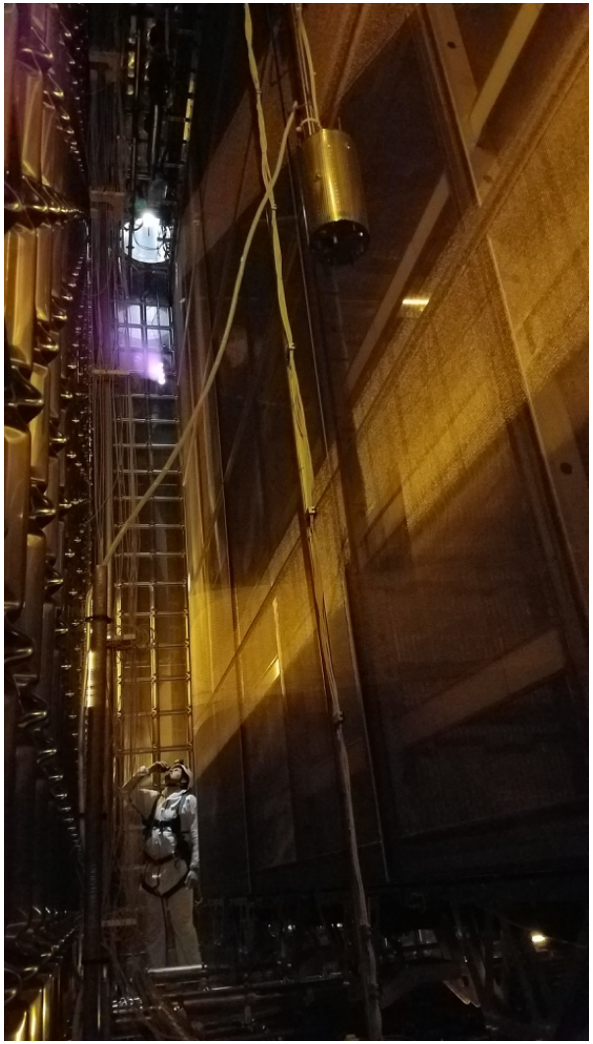




2018 - A great year for ProtoDUNE!

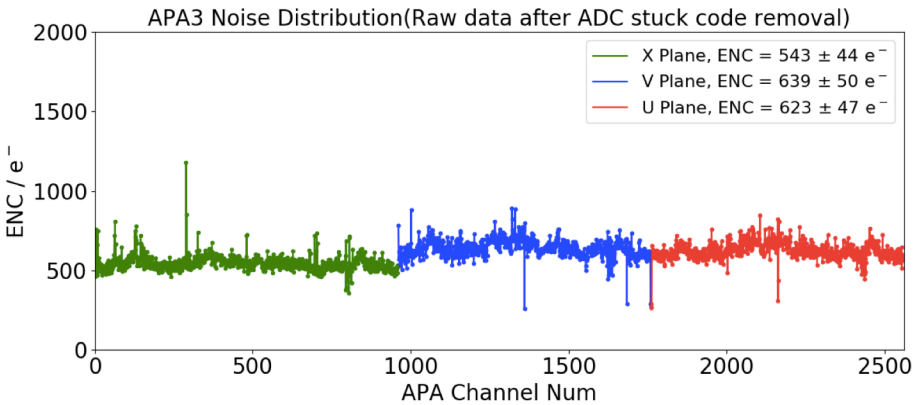
- April 2018 All the TPC elements are inside the cryostat
- June - July 2018 Commissioning of the detector
- August 8th – September 13th Filling of the detector
- September 18th LAr purification started
- September 21th HV ramp up to nominal value
- October 2th **First event seen from beam!**
- November 13th Beam is off



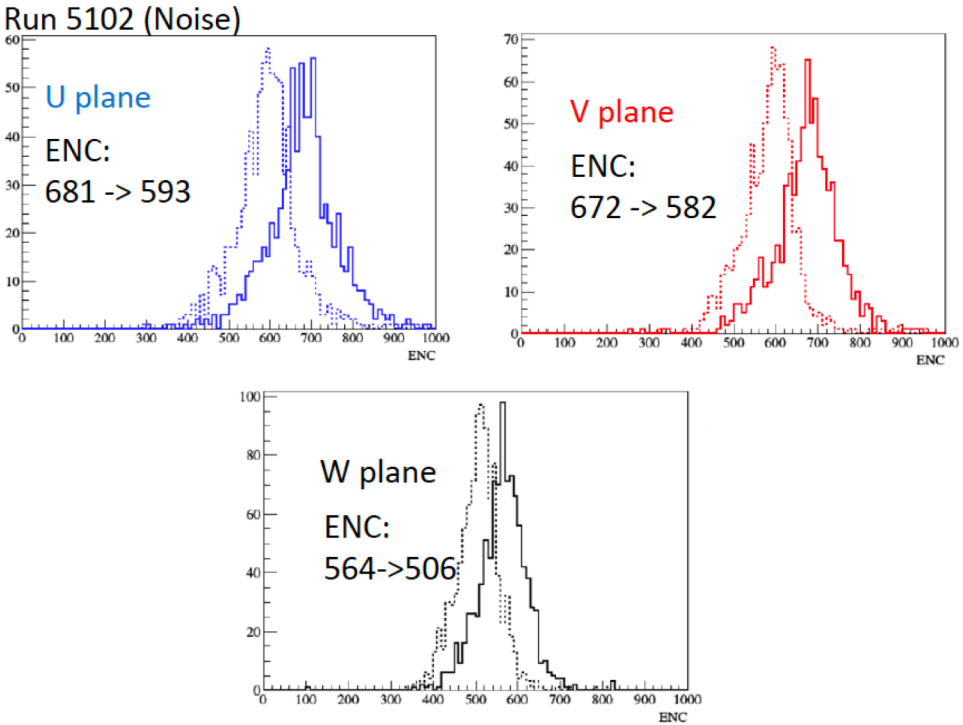


Cold Electronics Performance

- 99.74% (15320 of 15360) TPC channels are active
  - → 31 are missing or disconnected wire candidates
  - → 3 channels are missing in several runs
  - → just 6 inactive cold electronics channels in 9 months of operation
- 92.83% (14259 of 15360) TPC channels are working with excellent noise performance (ENC < 800 e^-)
  - → the abnormally high RMS of the remaining 7% is probably due to the TPC instrumentation
  - → more detailed noise performance study is now ongoing



Thanks to Shanshan Gao @ BNL for this plot



Thanks to Wenqiang Gu @ BNL for these plots

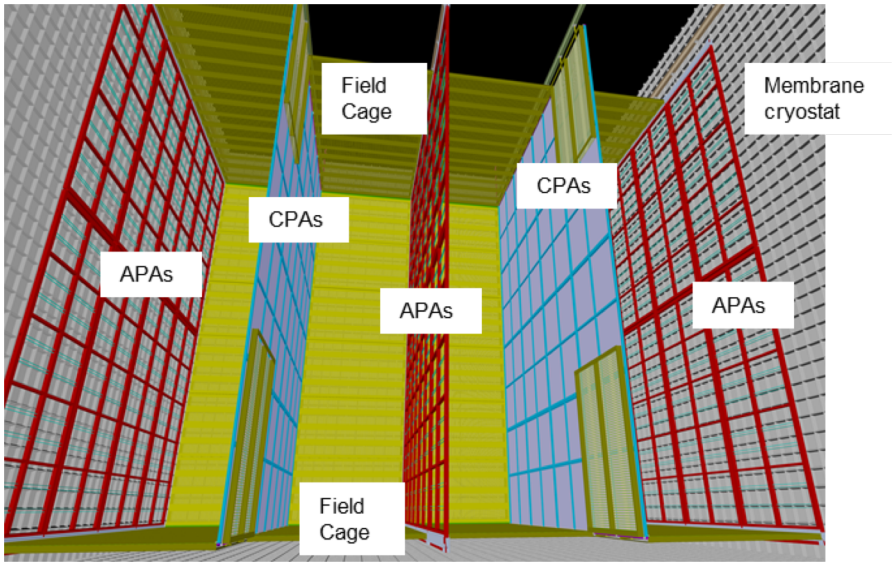
Summary and Conclusions

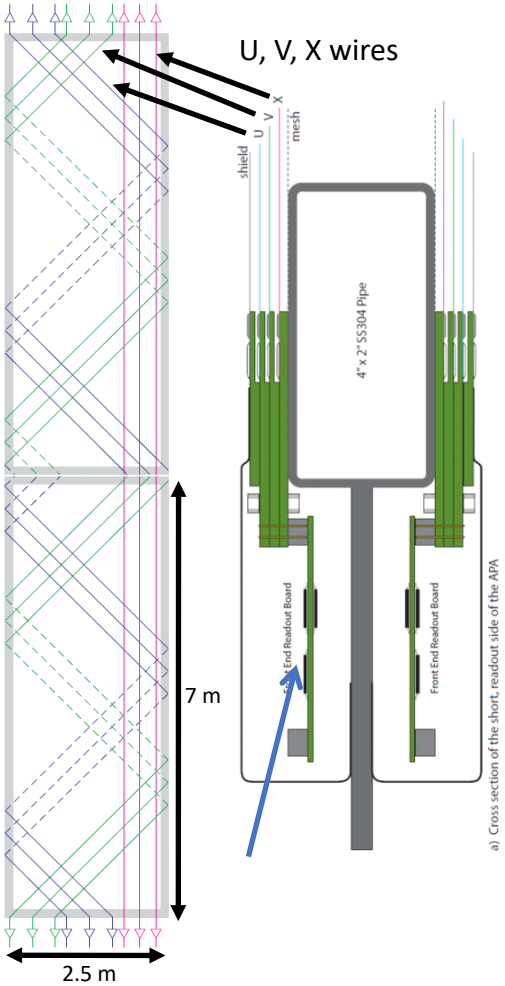
- ProtoDUNE-SP project at the CERN Neutrino Platform facility will provide validation of LAr-TPC technology, detector response and long-term stability for DUNE FD optimization
- The beam and cosmic data collected by the detector(s) will be extremely important to address and define the systematic uncertainties of DUNE measurements
- Readout electronics developed at BNL for low temperatures (77K-89K) has demonstrated to be an enabling technology for noble liquid detectors for neutrino experiments.
- The ProtoDUNE-SP will take cosmic rays data all over 2019 to demonstrate the long term operational stability of the detector, as well as improve the stability of the HV system and perform additional studies about CE noise performance

Thank you for your attention!

Backup slides

DUNE Far Detector

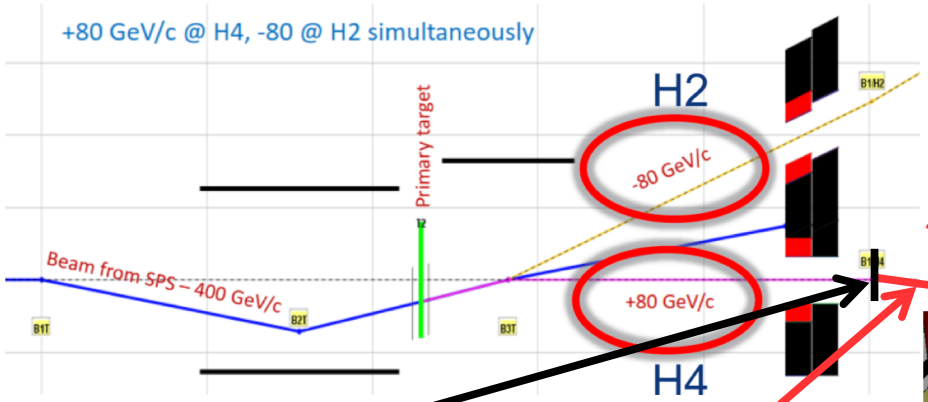




- APA, CPA & front end cold electronics system for single phase DUNE far detector
- DUNE 10 kt Far Detector
  - ***384,000 channels***
  - 24,000 FE ASICs/24,000 ADC ASICs
  - 6,000 COLDATA ASICs
  - 3,000 Front End Mother Board assemblies

ProtoDUNE SP facility – EHN1 at CERN

H4 VLE Beam line



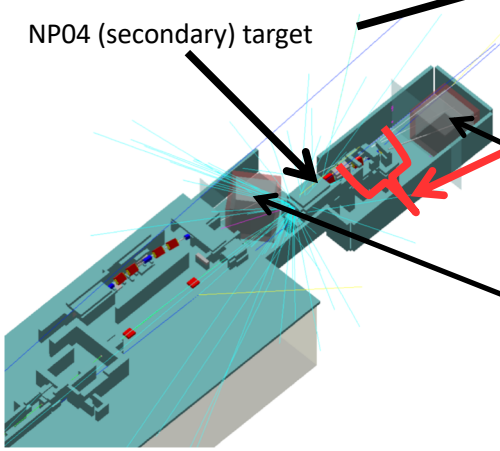
400 GeV/c P beam from SPS

80 GeV/c secondary π+ beam

~0.5 – 7 GeV/c tertiary e-,p,μ+,π+ beam

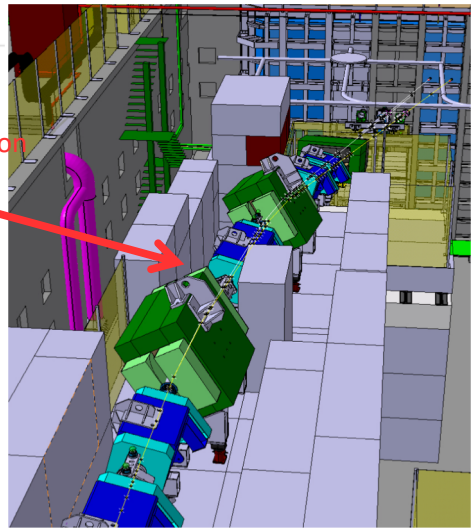
NP04 (secondary) target

H4 VLE beam line under construction

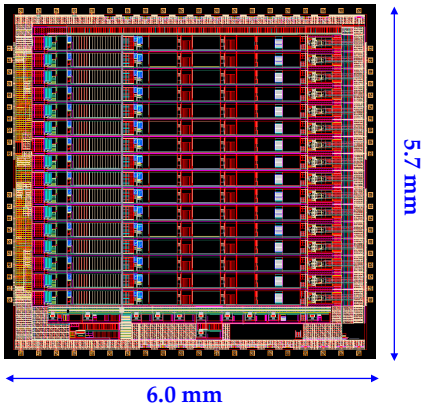


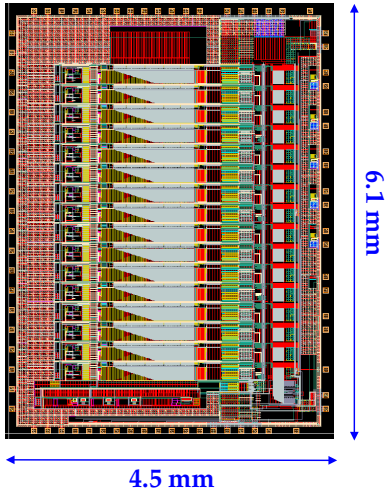
ProtoDUNE-SP cryostat

ProtoDUNE-DP cryostat



CMOS Cold ASICs Upgrades Implemented

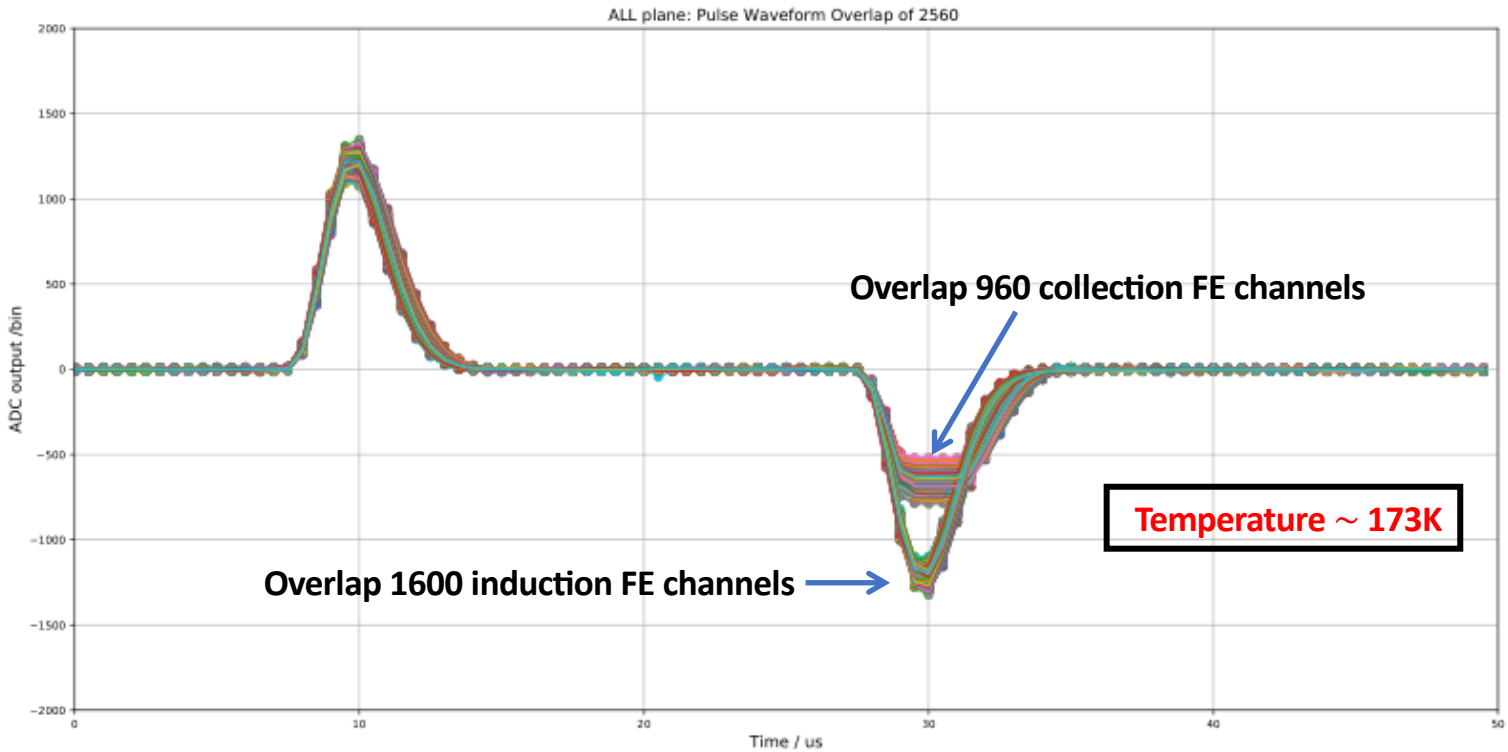




- FE ASIC
  - Built-in 6-bit DAC for calibration pulse generation
  - Built-in analog monitoring output for debug
  - Address pole-zero cancellation and drive capability in buffer-off mode
  - Add higher bias current (1nA and 5nA) options and smart reset
  - Revise BGR start-up circuit and increase ESD protection on I/O
  - ***Will be used to instrument SBND and ProtoDUNE-SP***
- ADC ASIC
  - Implement COLDATA (DUNE baseline design by FNAL, ***prototype expected in FY19***) compatible interface and FE ASIC compatible configuration
  - Address the early saturation and roll-back
  - Implement power-on default configuration and extend soft-control functions
  - Revise BGR start-up circuit and increase ESD protection on I/O
  - Improve ADC INL/DNL → <u>not completely resolved</u>
  - ***Will be used to instrument ProtoDUNE-SP***
  - ***SBND is exploring COTS ADC option***
  - Cold ADC ASIC development is very challenging given the ***amplified mismatch error*** and ***inaccurate simulation model*** in cryogenic temperature

APA1 - Pulse response

Inject bipolar pulses from electronics calibration circuit on FEMB

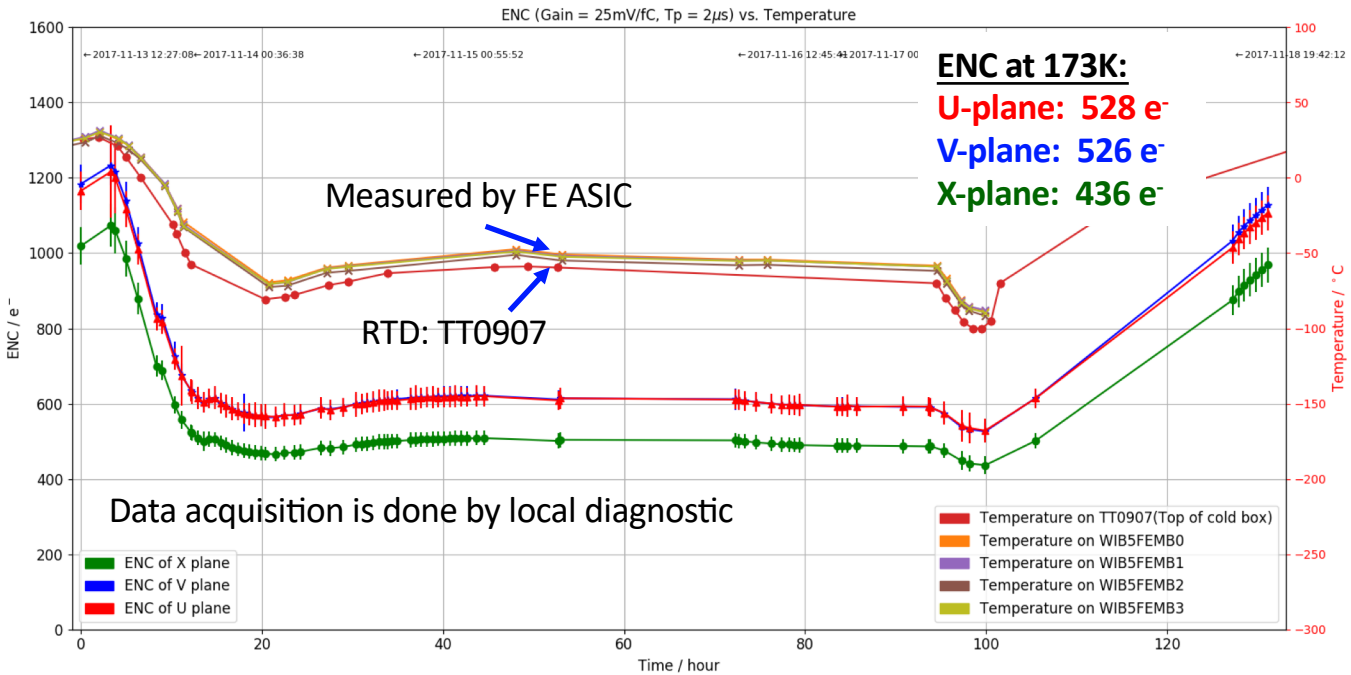


Noise vs Temperature – Cold Box Cooldown

APA1 (2017-11)

Lowest temperature reached

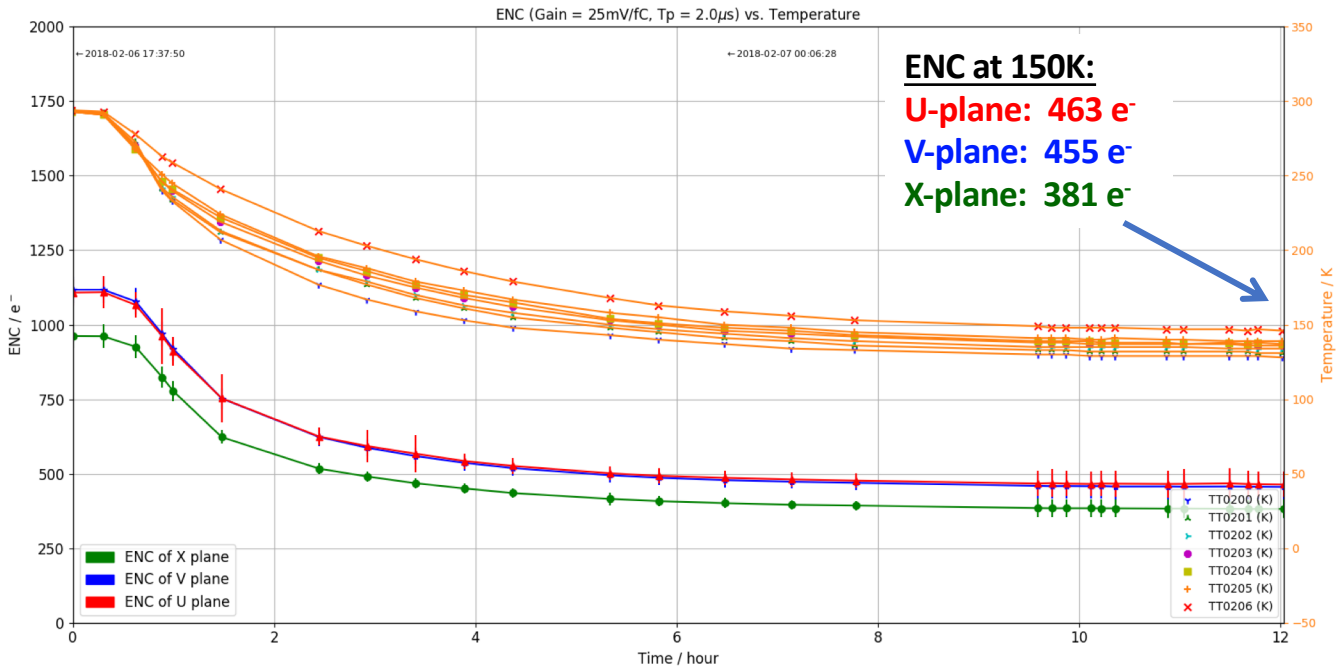
TT0907 ~**173K** FEASICs ~ **183K**



Noise vs Temperature – Cold Box Cooldown

APA3(2018-02)

Lowest temperature reached
TT0907 ~ **150K**

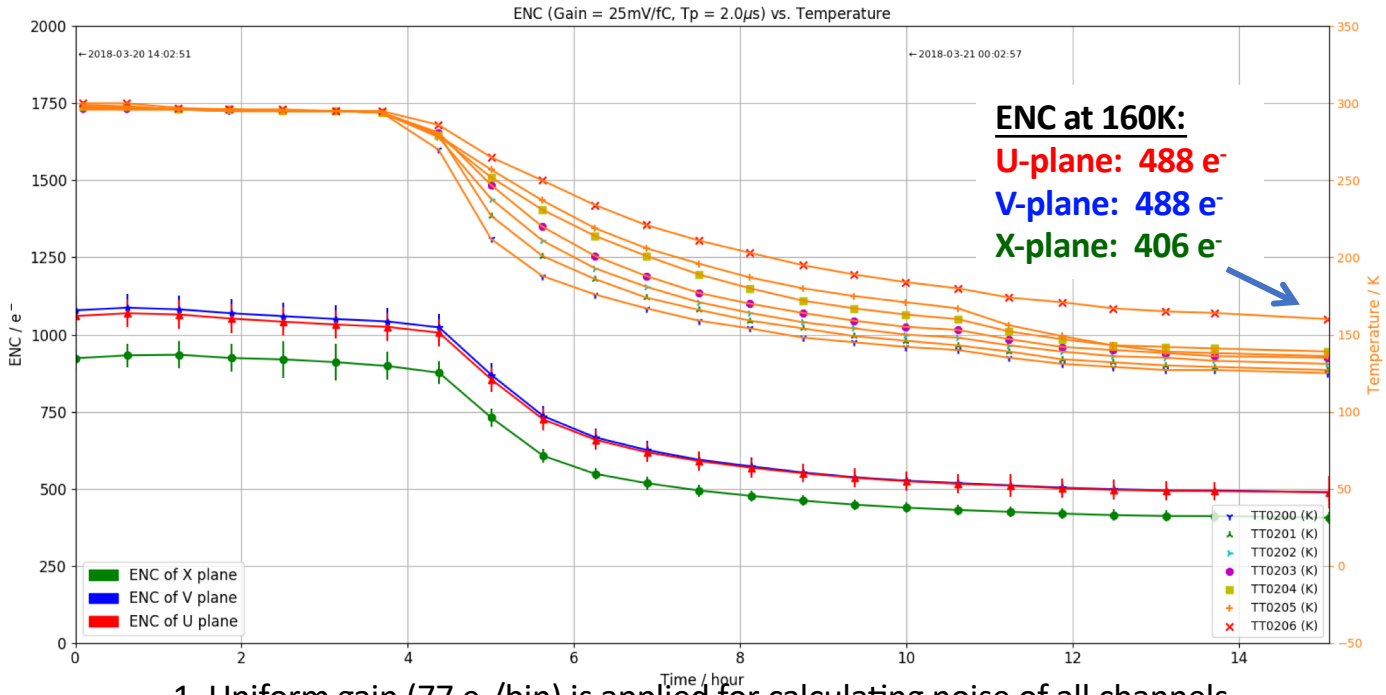


1. Uniform gain (77 e-/bin) is applied for calculating noise of all channels
2. Bias voltages were off

Noise vs Temperature – Cold Box Cooldown

APA4(2018-03)

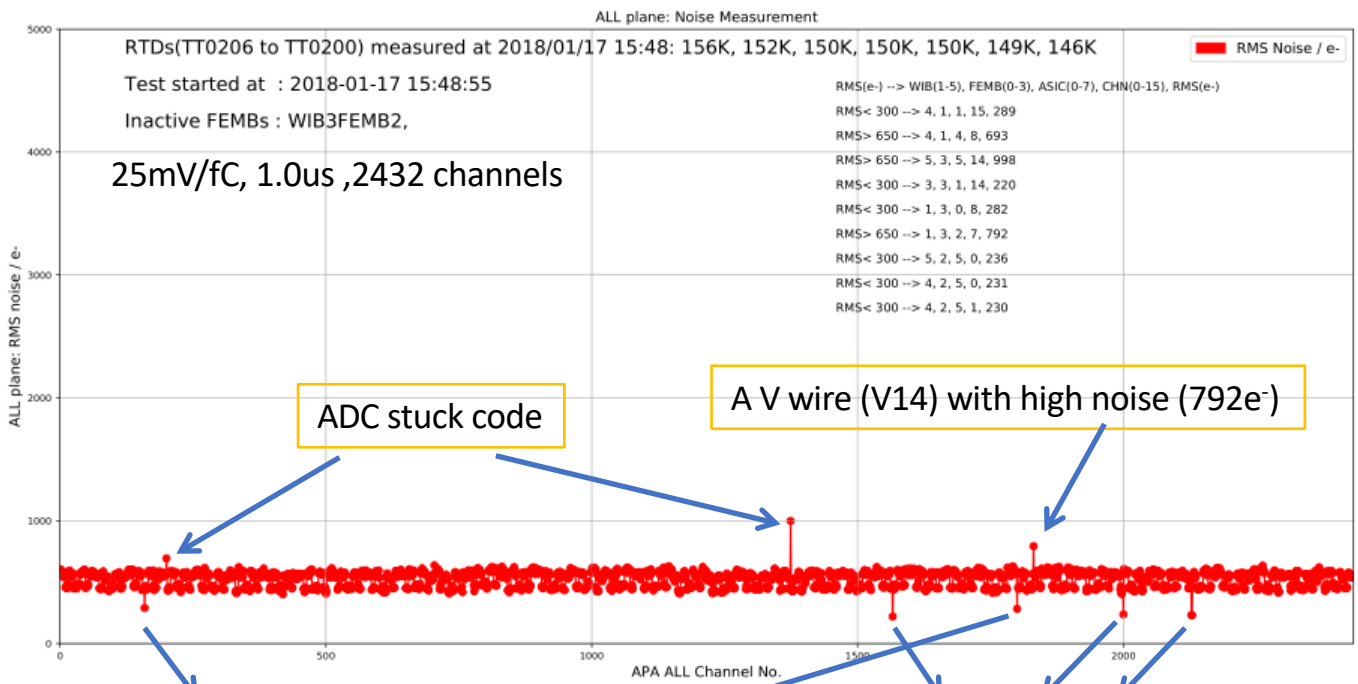
Lowest temperature reached
TT0907 ~ **160K**



1. Uniform gain (77 e-/bin) is applied for calculating noise of all channels
2. Bias voltages were off
3. WIB2FEMB1 was inactive before cooldown

Diagnostics on Abnormal Channels (18 Out Of 15360)

APA2 (2018-01)



Missing wire connections

ENC ~280e$^-$ → consistent with the FEMB seeing the additional capacitance from the CR board

Missing wire connections

ENC ~220e$^-$ → consistent with the FEMB when it sees nothing