R&D for PIONEER: a Next-generation Rare Pion Decay Experiment Testing Lepton Flavor Universality and CKM unitarity

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10/05/2022

BNL participation in PIONEER

BNL – one of ten national laboratories overseen and primarily funded by the Office of Science of the U.S. Department of Energy (**DOE**)
Prerequisites for participation in an experiment:

- Strong physics case, endorsed by Particle Physics Project Prioritization Panel (P5)
- BNL support/interest
  LDRD – Laboratory Directed Research and Development Program to promote the conduct of highly innovative and exploratory research; a stepping stone for us to participation in the full-scale experiment. Status: approved; budget: $200k/yr, duration: 2 yrs.
  Return on investment – future funding of the research work by DOE.
- Major/unique contributions to the experiment

BNL possesses unique technological expertise in two major detector components in PIONEER's conceptual design

- Low-Gain Avalanche Diodes (LGAD) and PIN diodes for the active target (ATAR): synergy with ongoing efforts at BNL to develop LGAD technology for LHC and EIC experiments *(Xin's and Gabriele's talks)*

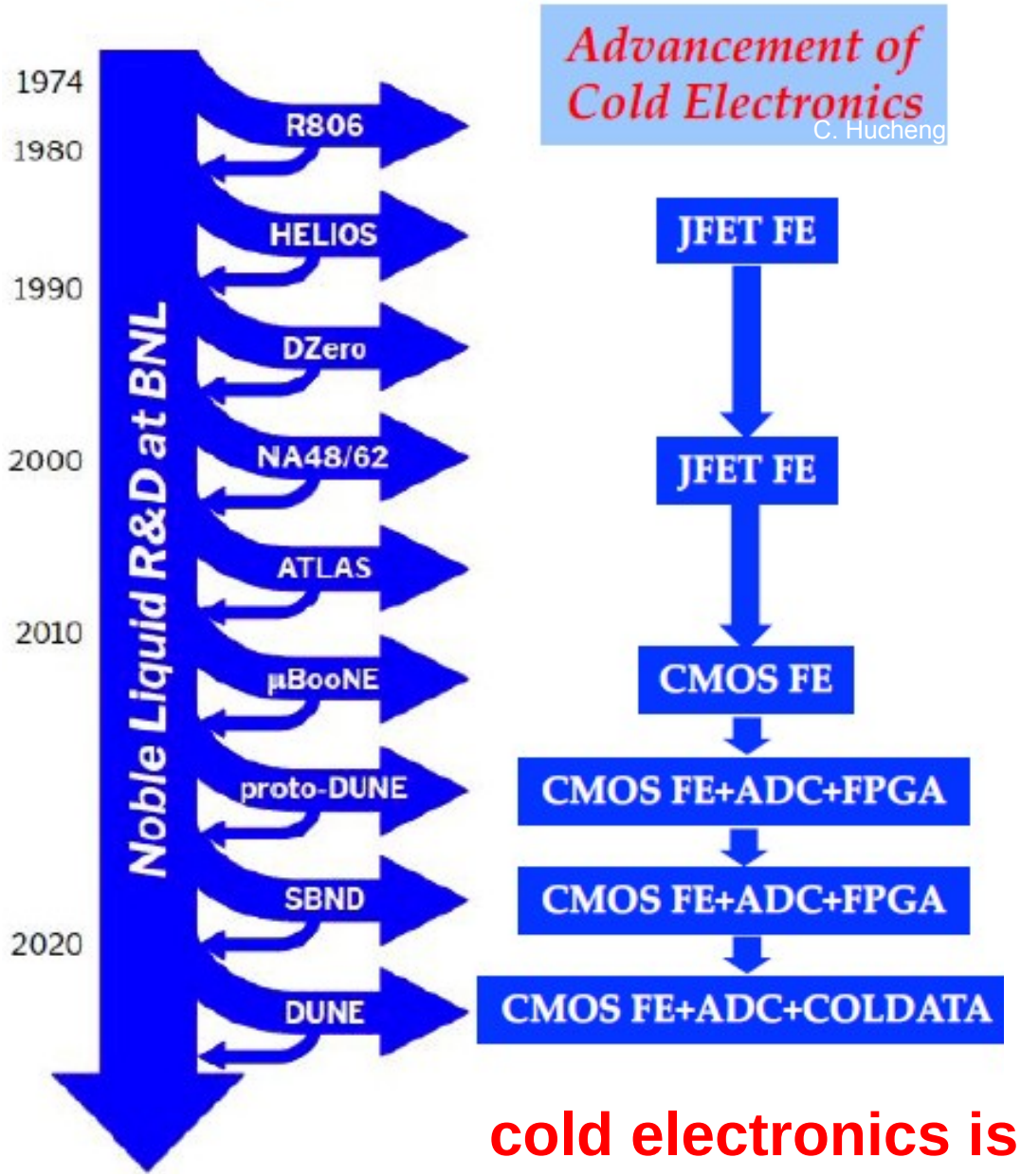
- LXe calorimeter: long history in developing Noble Liquid detector technology, dating back to 1970s, synergy with ongoing efforts at BNL for nEXO and DUNE LArTPCs *(Matt and Elizabeth)*

- Pattern recognition and event reconstruction techniques required for ATAR and LXe calorimeter match well with BNL's existing analysis expertise *(Chao's talk)*

Description of the LDRD Proposal

- **R&D for ATAR**
  LGAD sensor is a promising technology for PIONEER. While the excellent position and timing resolutions (4D tracking) has been demonstrated with the LGAD technology, the new requirement of energy measurement (5D tracking) needs to be demonstrated through dedicated R&D.
  This proposal will perform device-level (TCAD Silvaco) and Geant-4 simulations of LGAD-based ATAR to *i)* assess the performance of the chosen ATAR technology in discriminating between different processes in the target; *ii)* define the key requirements for ATAR components (position, energy, time resolution, etc.), and *iii)* optimize the ATAR design with a 2D strip readout concept.
- Based on the requirements to LGAD sensors deduced in simulations, **build and characterize prototype(s)** in collaboration with other institutions to identify optimal parameter configuration as well as to demonstrate the feasibility and capabilities of the chosen design.
- SiPM bench tests for LXe CALO option:
  - MEG-II observed degradation in performance of VUV SiPMs after operation in LXe, raising concerns about VUV SiPM use in PIONEER
  - This LDRD will perform **bench tests of the photon detection efficiency of MEG-II and next-generation VUV SiPMs before and after exposure to radiation and VUV light** using an existing test stand
  - Synergy: results of these tests will contribute to resolution of a problem affecting all LXe-based experiments, including nEXO.

Long History of Noble Liquid Development

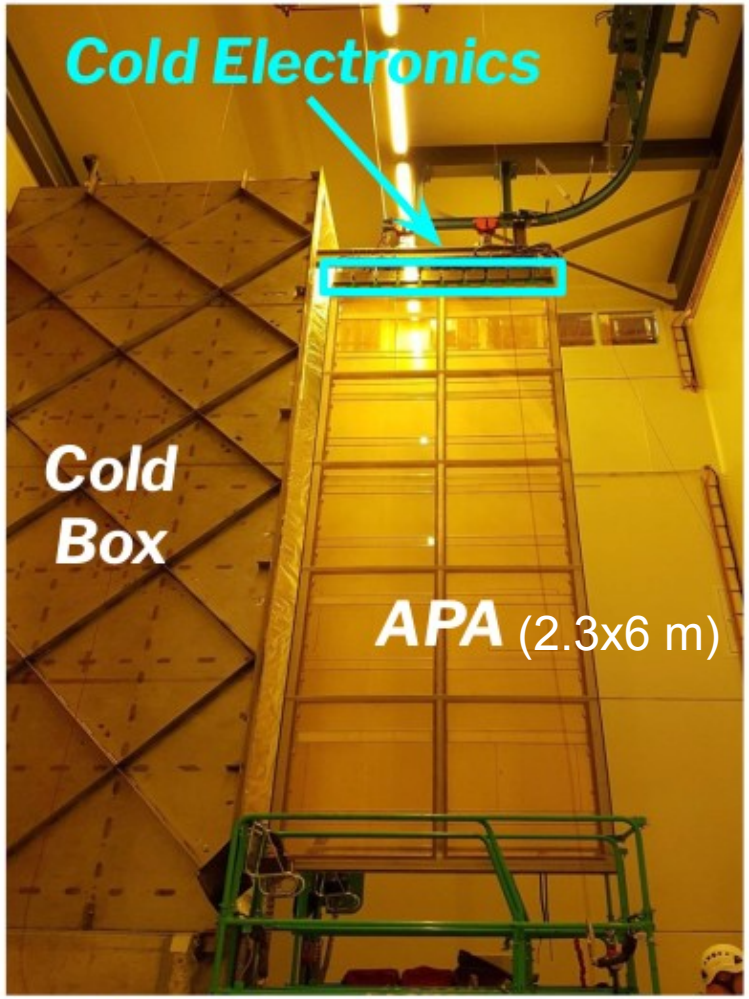


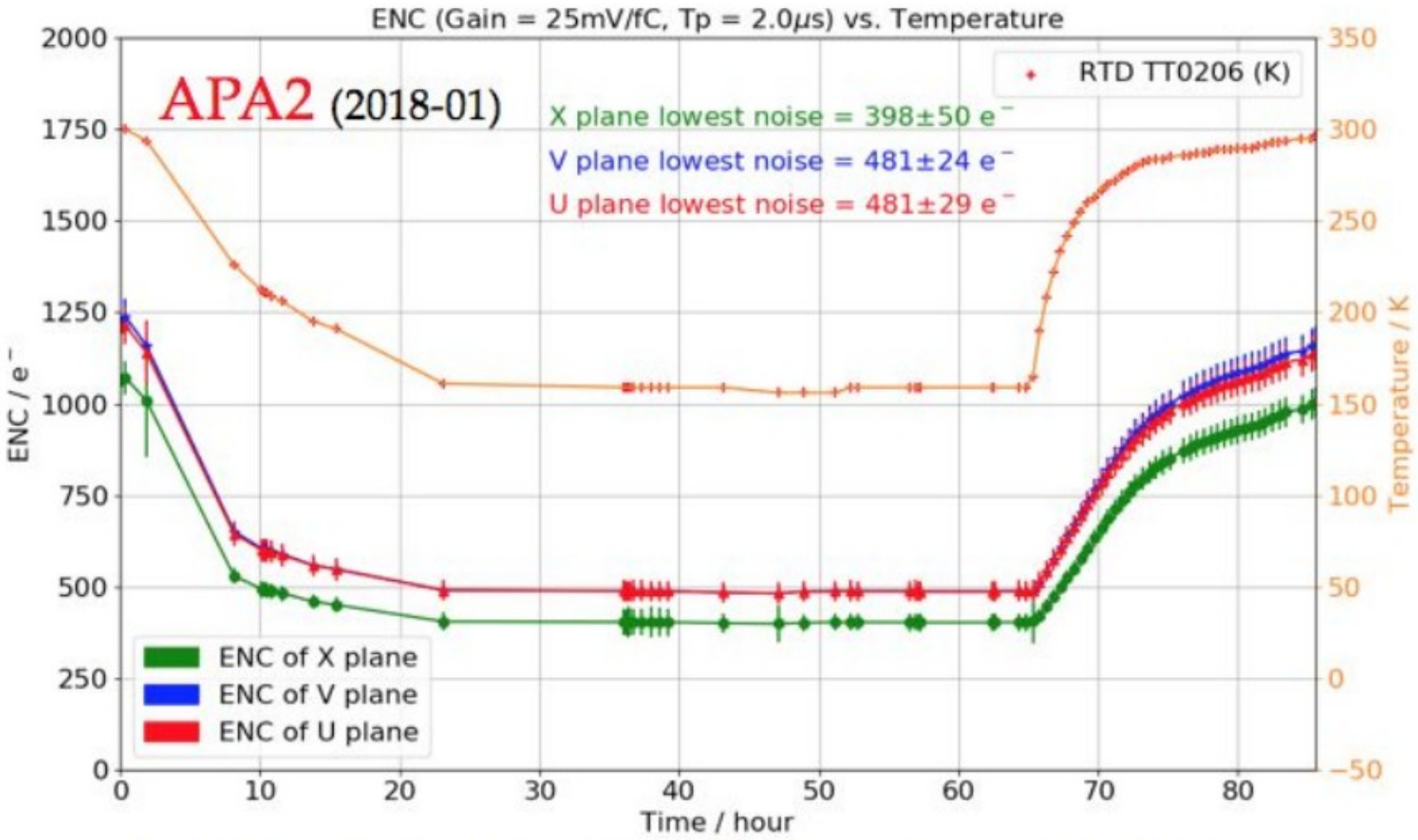
- BNL pioneered LAr based detector technology in 1974 [1]
- Physics/Engineering expertise which has made essential contributions to various programs, e.g. ATLAS, MicroBooNE
- Unique expertise in cryogenic electronics and micro-electronics
- The R&D effort makes the experiments possible; the experiments, in turn, feed information back into the R&D process
- Cold electronics development is making continuous advancement, from JFET to CMOS
- A strong cold electronics team is built up as a core BNL competence, in close collaboration with other institutes, to realize various LAr TPC experiments

[1] *W. Willis, V. Radeka, Nucl. Instr. Methods, 120 (1974) 221*

cold electronics is an enabling technology for large LArTPC

ProtoDUNE-SP Front End Electronics System Integration

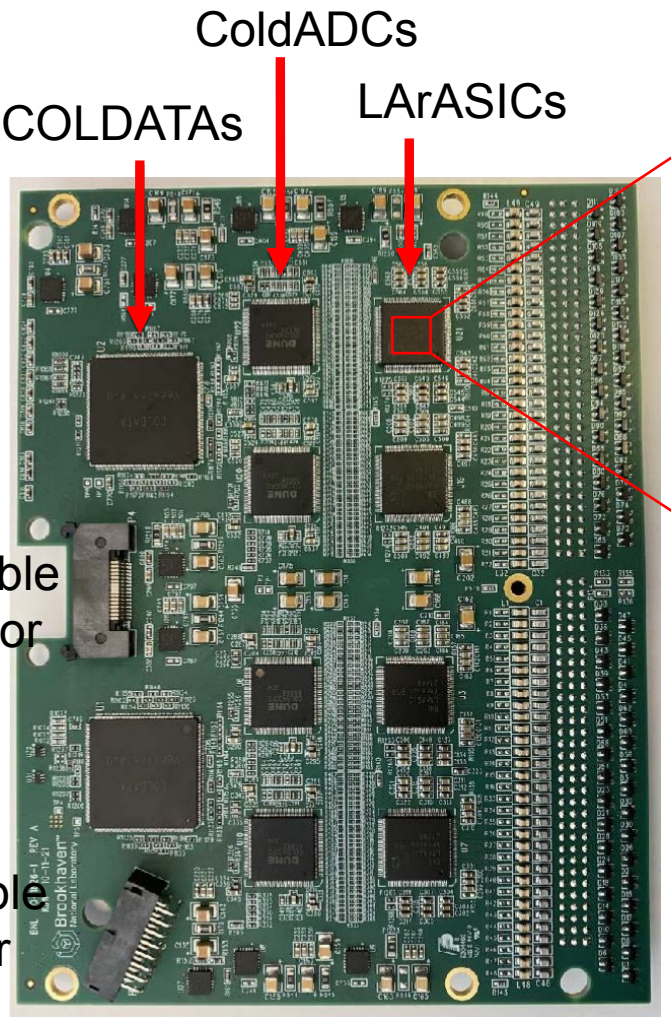




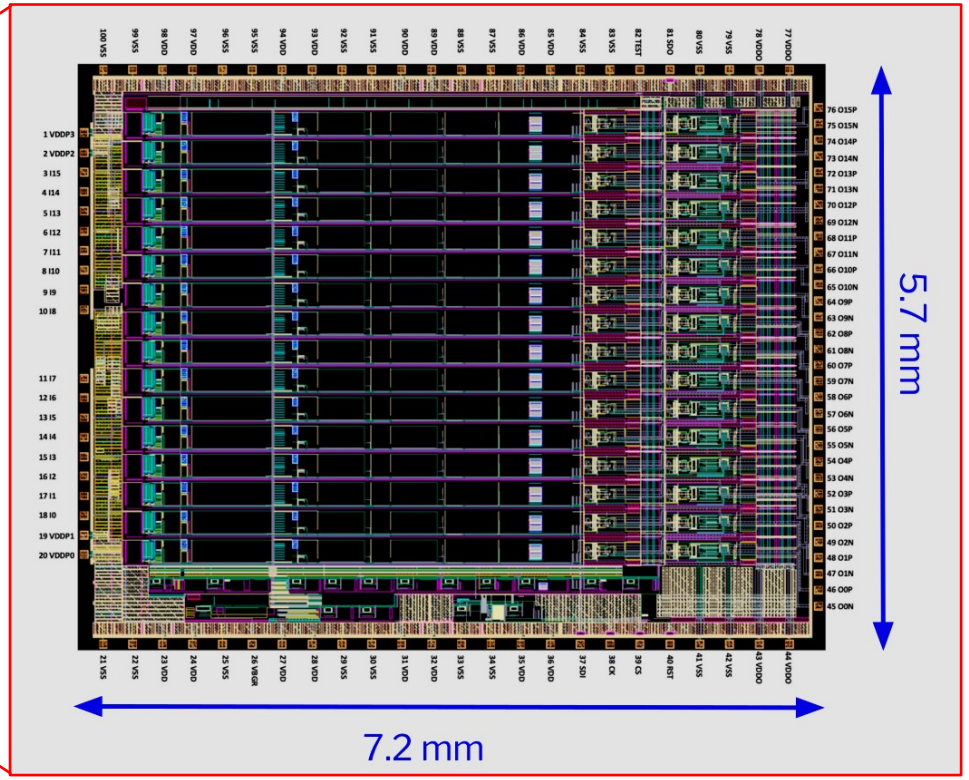
- ***Excellent noise performance (< 500 e⁻) obtained in cold box test at CERN***

(DUNE minimal requirement: ENC < 1000 e⁻)

Cryogenic Front End MotherBoard (FEMB)



128 analog input channels



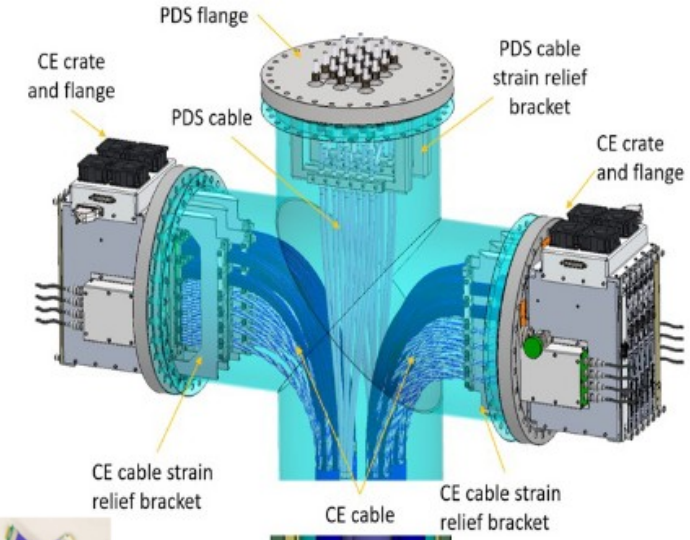
- Each FEMB contains 3 ASICs:
  - 8 LArASIC amplifier/shapers
  - 8 ColdADC “2 MHz” ADCs
  - 2 COLDATA data concentrator and controllers

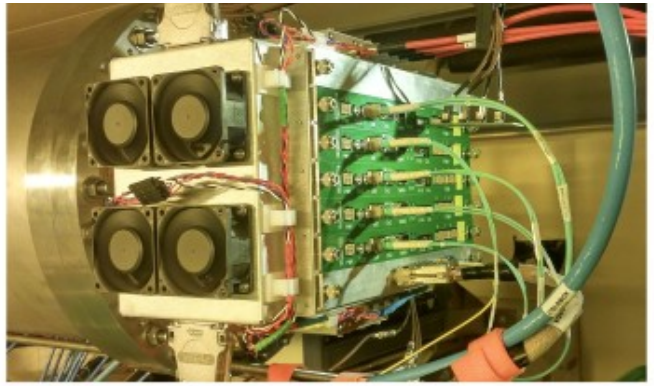
- Key specifications:
  - Low noise (<1000 e-)
  - High dynamic range (>500ke-)
  - ~2 MHz sampling frequency
  - At least 12 ADC bits

TPC ionization charge signal amplification, shaping, digitization, transmission.

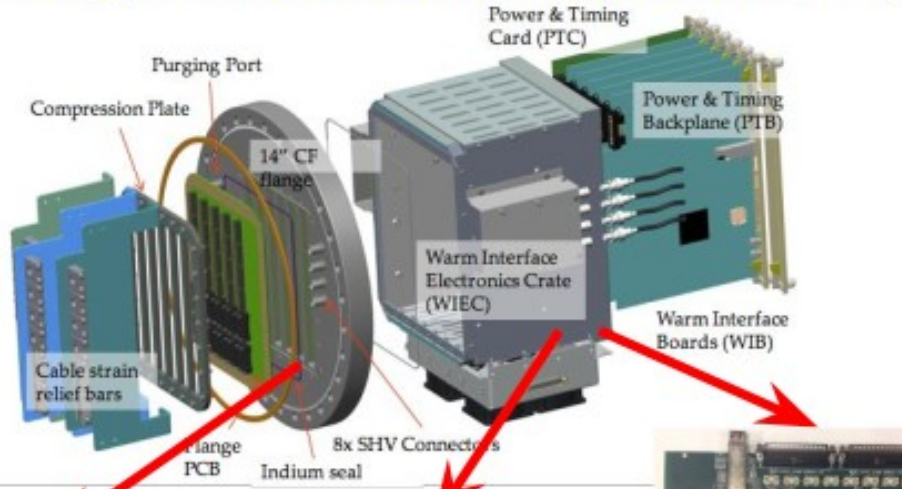
All signal processing takes place in LAr!

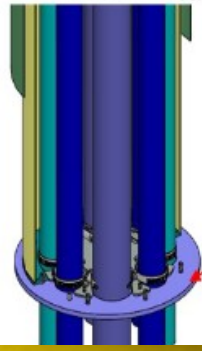
Warm Electronics + System Integration by BNL



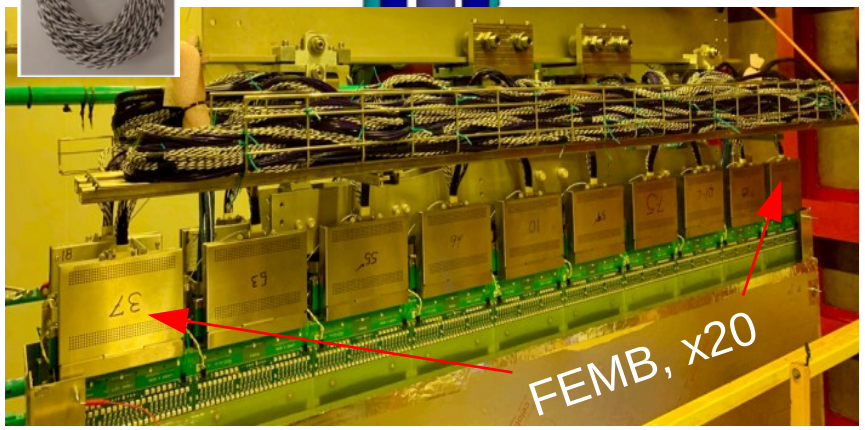


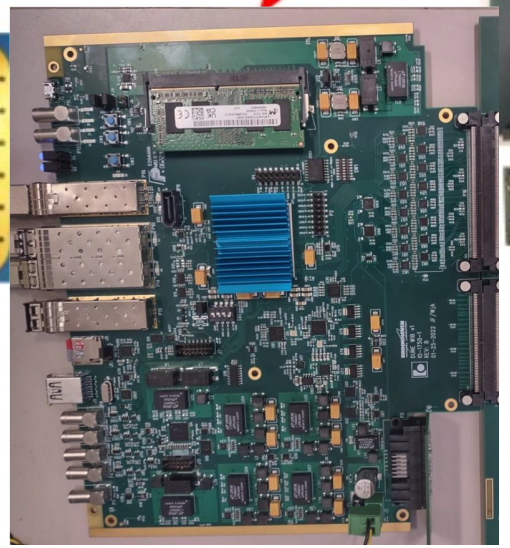
Signal Feed-through Assembly





Cable clamp plates

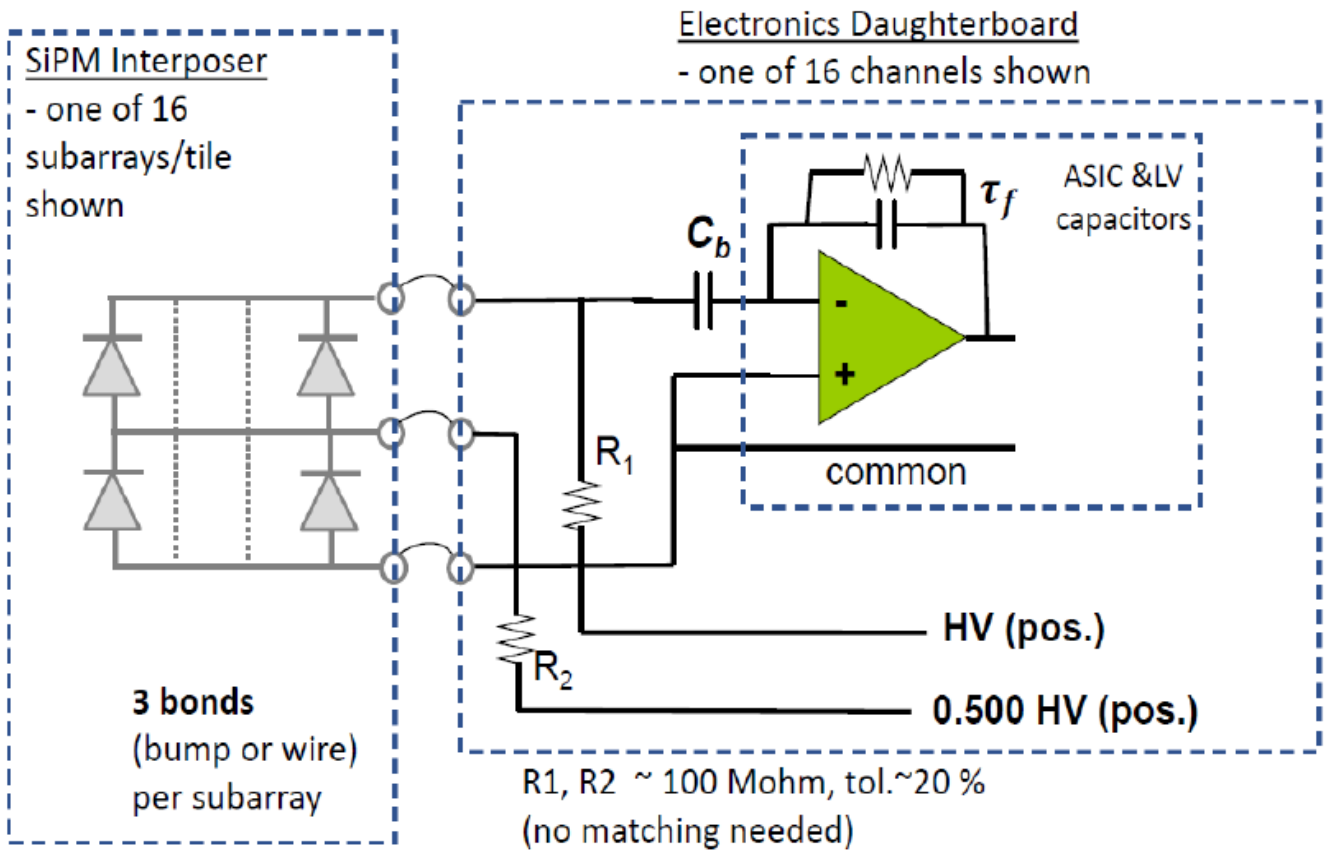




Integral design:
Cold Electronics, cold power and data cables, cable strain relief, feedthrough flange board, warm electronics crate, power and timing card, warm interface board with fiber optic links to DAQ

Warm Interface Board (x5)
Xilinx Zynq UltraScale+ SOC FPGA
(includes ARM cores; can run Linux

Ongoing work on SiPM readout for nEXO and DUNE



Electrostatic Transformer (series connection of SiPMs) ***n*=2** shown; readout scheme is independent of ***n***

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- Ongoing work to optimize SiPM readout for nEXO and DUNE with the cold electronics technology
- Weak coupling between SiPM and input transistor to optimize the S/N ratio for optimal detector performance
- Synergies with PIONEER CALO

Summary

1. LDRD funded by BNL will support R&D work towards realization of PIONEER experiment
   - Simulation studies, prototyping and characterization of LGAD and PIN diode based active target.
   - SiPM bench tests for LXe CALO option.
2. Broader expertise exists at BNL which can be relevant for PIONEER
   - Cold and warm detector electronics design, including ASIC design
   - System integration

Postdoctoral position opening at BNL in neutrino and PIONEER physics:
https://inspirehep.net/jobs/2159317