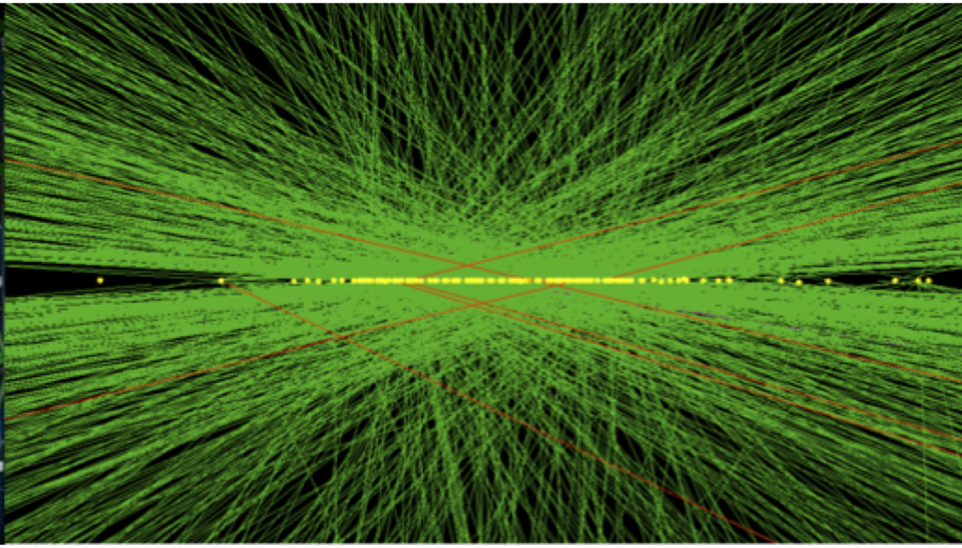
MTD-BO 4: ETL Overview Including LGADs, System Testing, I&C

Artur Apresyan

HL-LHC CMS Upgrade CD-1 Director’s Review

20 March 2019



Brief Biographical Introduction

- Associate scientist at Fermilab
  - L3: Endcap Timing Layer (ETL) in US-MTD
  - ETL Engineering in international MTD
- CMS Forward Pixel QC framework at Purdue, HCAL operations and reconstruction
- CMS/CDF data analysis: Higgs searches, SUSY and Exotica
- Development of precision timing detectors
  - Timing detectors R&D with SiPM, MCPs, and LGADs
  - DOE ECA award in 2018 to work on precision timing detectors
  - FNAL LDRD award in 2017 to work on LGAD sensors R&D

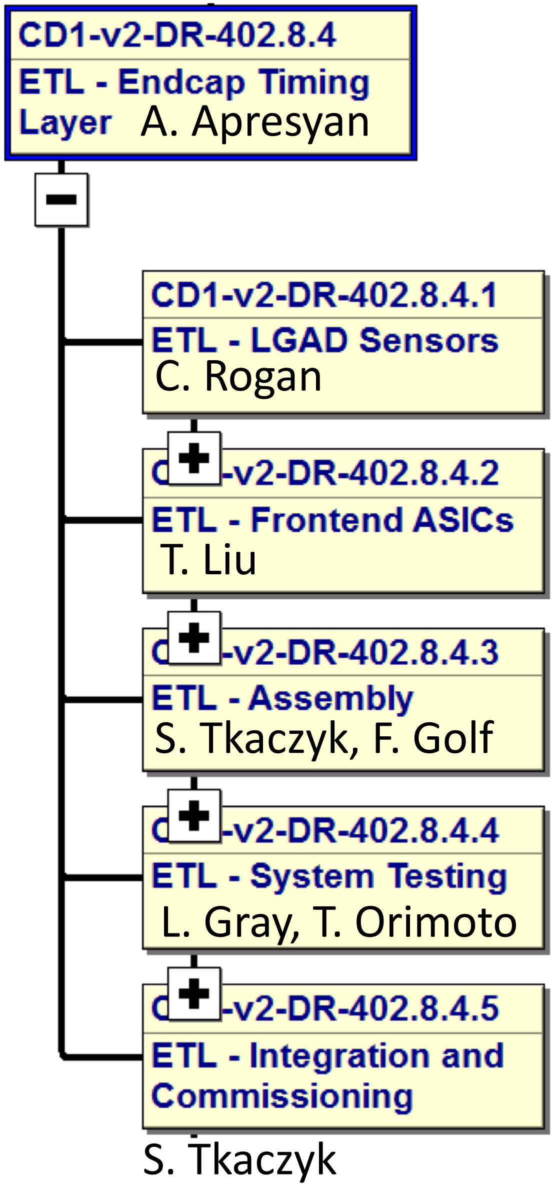
Outline

- Scope of 402.8.4
- Conceptual Design
- Deliverables of 402.8.4
- Interfaces and dependencies
- Cost and Schedule
- Contributing Institutions
- Milestones
- Risks
- Summary

402.8.4 WBS Structure

Charge #4

- 402.8.4.1: LGAD sensors
  - Sensor studies and qualification during the R&D phase.
- 402.8.4.2: Frontend ASIC
  - Design, fabrication, and testing of prototype and final ASICs
    - Details in Ted Liu's talk
- 402.8.4.3: Module assembly
  - Assemble, test, and deliver 50% of ETL modules
    - Details in Frank Golf's talk
- 402.8.4.4: System testing
  - Confirm operational performance of the module design, including grounding and service integration
- 402.8.4.5: Integration and commissioning
  - Integration of modules onto the ETL support structures, and commissioning on CMS



Charge #1,2

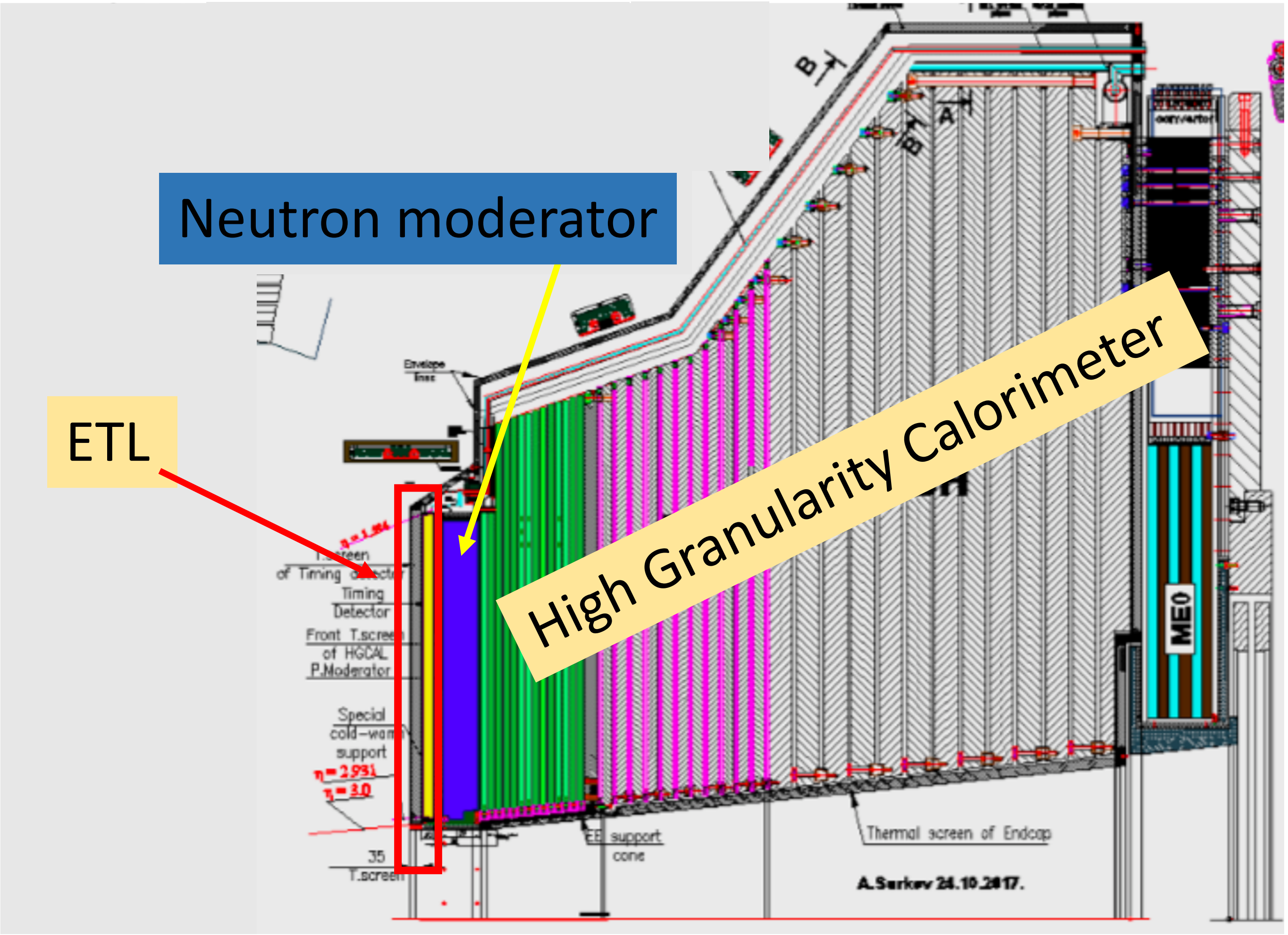
ETL Design and Performance Specification

- Time resolution 30-40 ps at the start of HL-LHC, <60 ps up to fluences 4000 fb^{-1}
- Particle flow reconstruction performance at high PU to comparable to Phase-1 CMS.
  - Extend physics reach in a broad class of new physics searches with long-lived particles
- Achieve radiation tolerance up to 1.7×10^{15} n_{eq}/cm^2 at $|\eta| = 3.0$
  - Fluence is less than 1×10^{15} n_{eq}/cm^2 for 80% of the ETL surface area
- Channel occupancy below 10% to ensure small probability of double hits, needed for unambiguous time assignment
  - Channel size of ~3mm^2 to achieve optimal time resolution
- The ETL detector designed to be accessible for repairs and replacements of faulty components
  - Maintain an independent cold volume which is isolated and operated separately from the HGCal
- MIP Timing Layer HL-LHC Design Specifications tracked in:
  - https://cms-docdb.cern.ch/cgi-bin/DocDB/ShowDocument?docid=13536

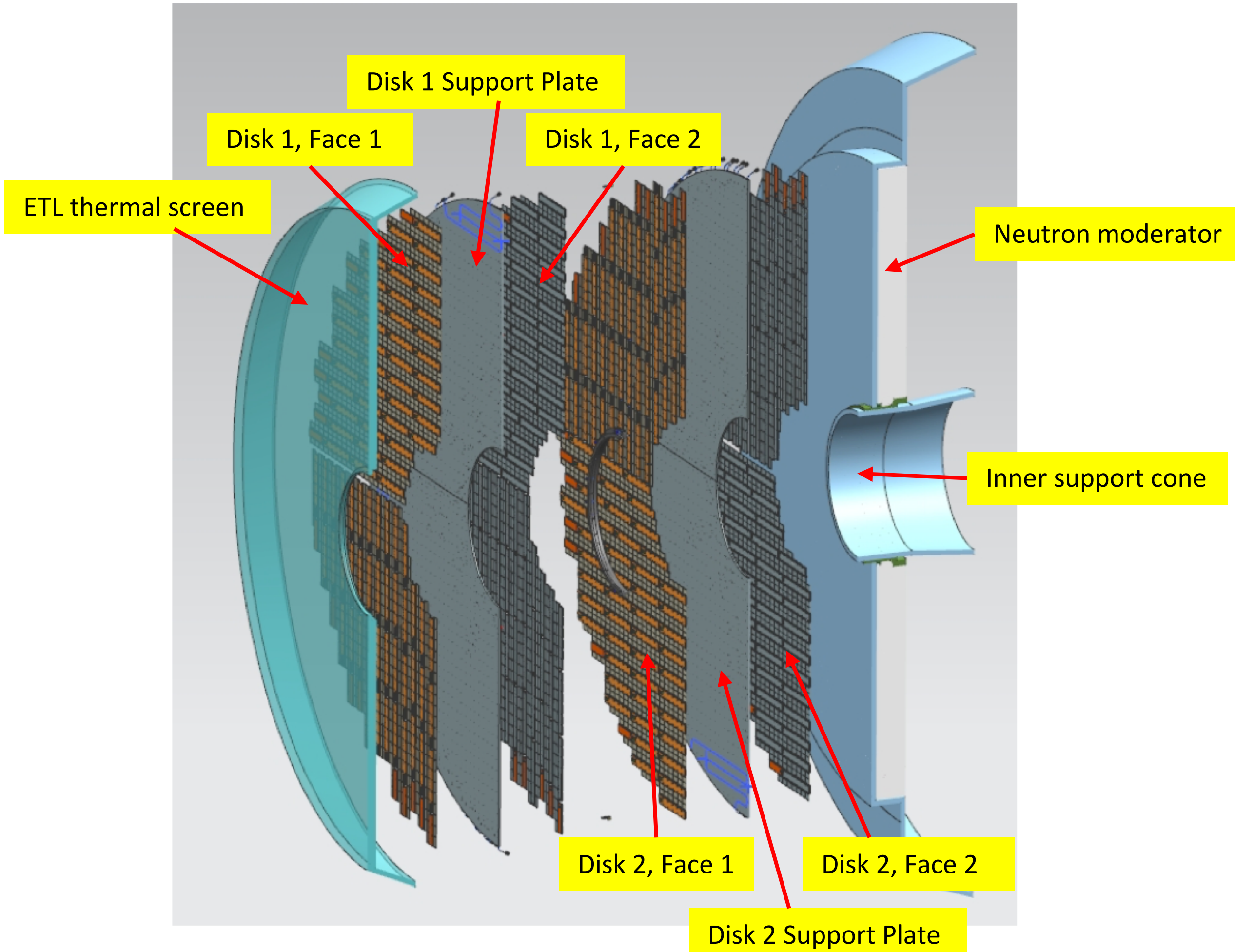
ETL Overview

Charge #1,2

- ETL detector will be placed on the nose of HGCal
  - Cover the range in 1.6<|η|<2.9



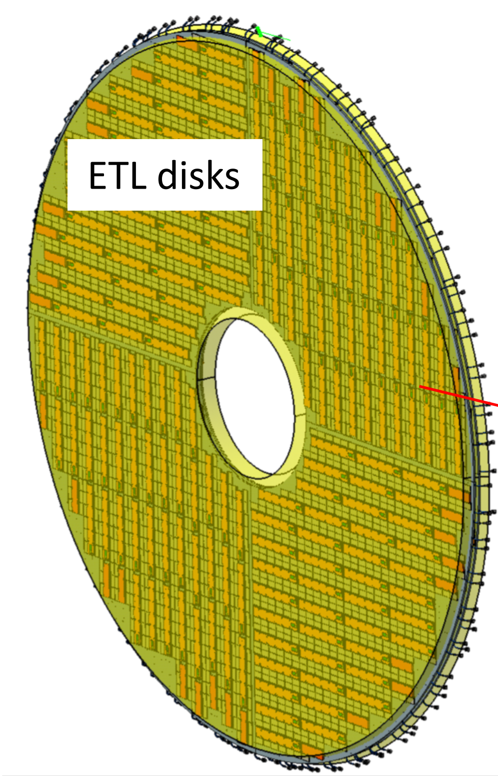
ETL Overview

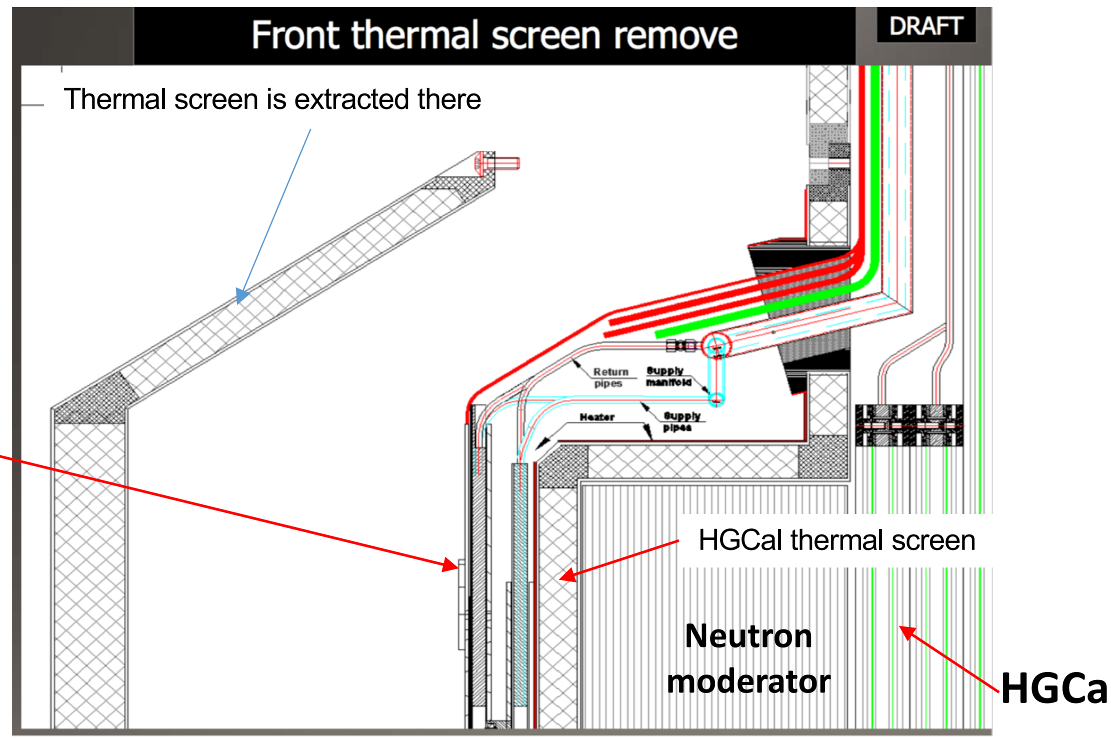


- ETL is designed to ensure that there are 2 hits for the majority of tracks
    - US-CMS will assemble 50 % of modules required to build ETL

ETL detector

- Total silicon surface area of 15.8 m^2 for the two Z-sides.
- Total thickness of the ETL detector is ~45 mm,
  - Disks populated with modules on both sides
  - Independent cold volumes, and accessibility for ETL

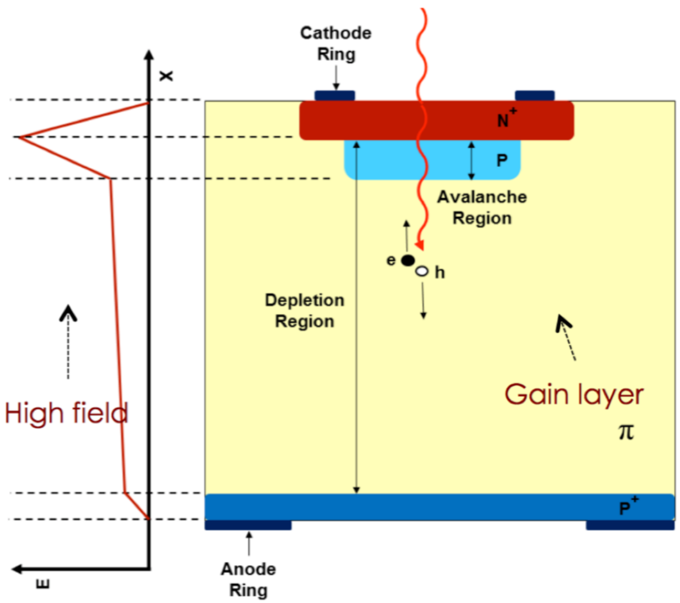




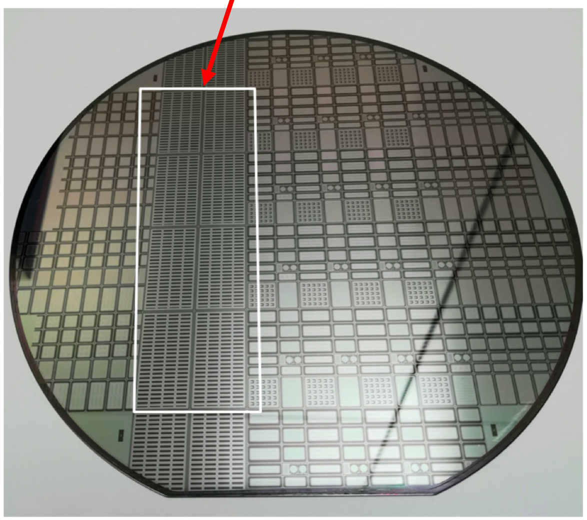
LGAD sensors

Charge #1,2

- Silicon sensors with specially doped thin region with high electric field → produces avalanche signal with 10-30 gain
  - Each sensor contains a 16 × 32 array of pads of size 1.3 × 1.3 mm²
- Large community:
  - RD50 collaboration, several manufacturers: CNM, FBK, Hamamatsu
  - CMS/ATLAS joint production runs with all three companies in 2018
- Demonstrated time resolution ~30 ps up to 1×10^{15} n_{eq}/cm^2, and about 40 psec up to 2×10^{15} n_{eq}/cm^2



CMS-designed 96-channel sensors

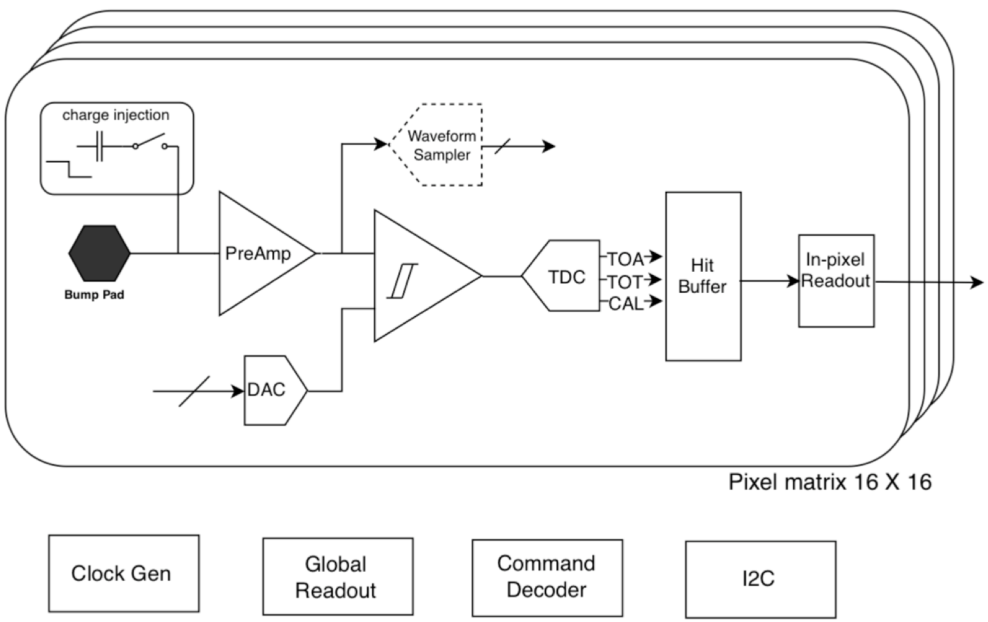


FBK wafer with CMS- and ATLAS- sensors

ETROC

Charge #1,2

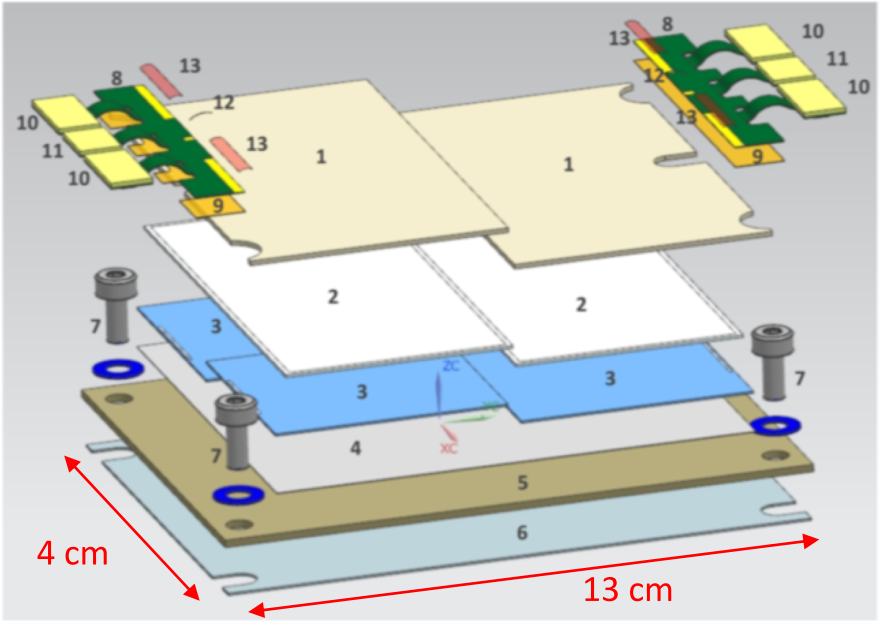
- ETROC is bump-bonded to LGAD sensor
  - 256 pixel matrix (16×16), each 1.3×1.3 mm^2
  - 65 nm technology for radiation hardness and low power (standard CERN contract)
  - ASIC contribution to time resolution < 40ps
- US-CMS will design, deliver, and test ETROCs
- *More details in Ted Liu's talk*



Modules

Charge #1,2

- The ETL modules are built from sub-assemblies containing LGAD sensors that are bump bonded to two ETROCs each
  - Flex circuits laminated to each edge of the AlN substrate provide electrical connections to service hybrids
  - A second AlN plate is fixed atop this structure to protect the sensors
- US-CMS will assemble and deliver 50% of ETL modules
- *More details in Frank Golf's talk*

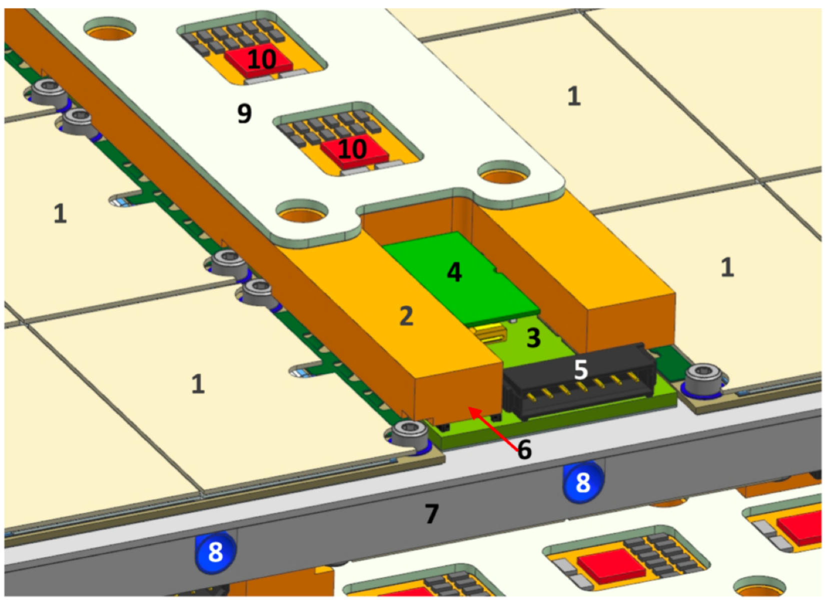


1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector
12: LGAD bias voltage wirebond
13: ETROC wirebonds

Service Hybrids

Charge #1,2

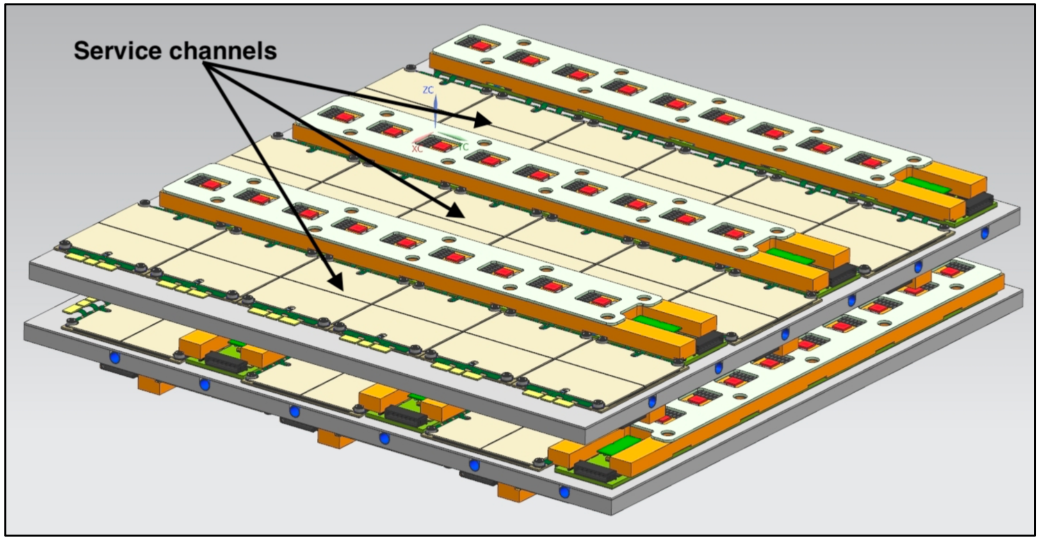
- Service hybrids: interfaces to modules via flex circuit connectors.
  - Deliver power to the ETROCs and the bias voltage to LGADs;
  - Deliver control and monitoring signals and the clock to the ETROCs;
  - Transfer of data from the ETROCs to the DAQ.
- Three types of service modules are used in the ETL, each servicing either 6, 12 or 13 modules

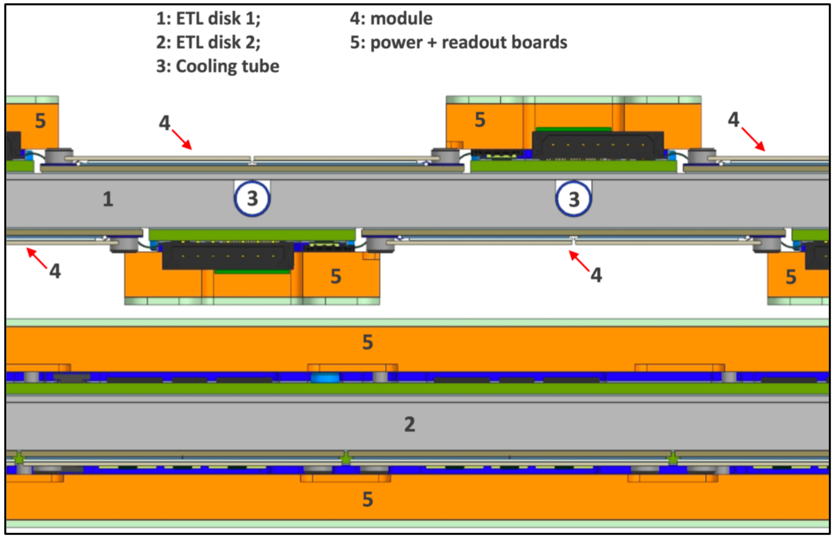


1: AlN module cover
2: Power board
3: Readout board
4: VTRx+
5: HV-PP0 connector
6: LV-PP0 connector
7: Support disk
8: CO_2 cooling tube
9: Power board cover
10: DC-DC converters
11: Front-end hybrid
12: Readout connector
13: HV connector

ETL Structure

- General structure
  - LGAD+ASIC assemblies mounted on AlN carrier plates
  - 2 sensors (each ~2x4 cm^2) and 4 ETROCs mounted on a common carrier
  - Flexible circuit wirebonded to ASICs, pigtail connectors connect to Readout PCB
  - Power and Readout PCB mounted on the same carrier
  - Dual-phase CO_2 cooling is used to evacuate the heat
  - One lpGBT per module, VTrx+ to send data with optical link to backend

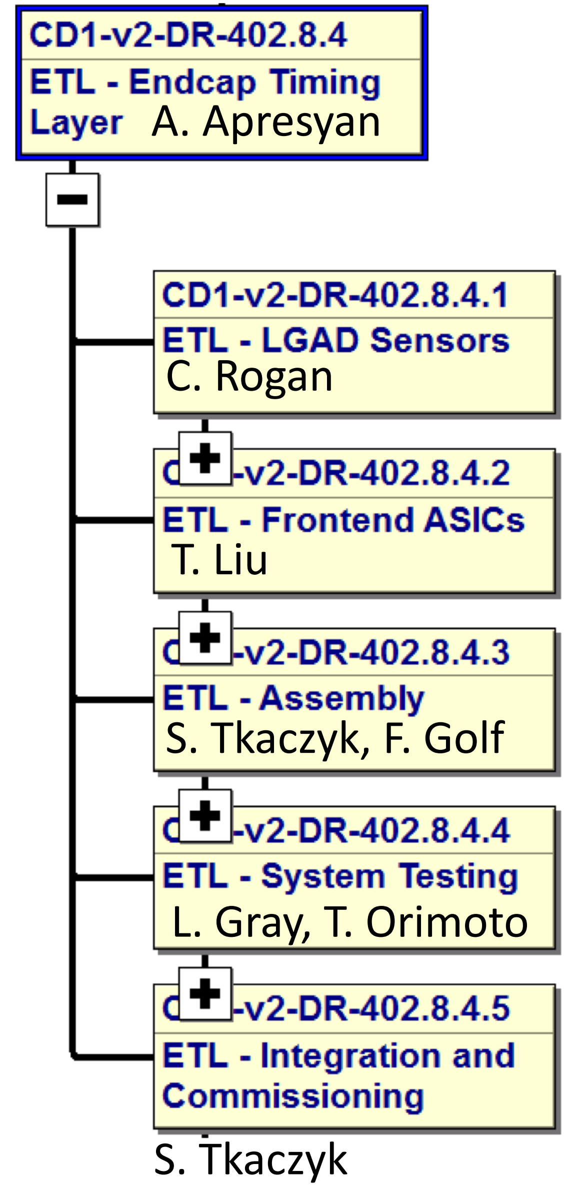




402.8.4 Deliverables

Charge #4

- 402.8.4.1: LGAD sensors
  - US-CMS will test sensor developed by iCMS, and test sensors delivered to US-CMS before assembly on modules
- 402.8.4.2: Frontend ASIC
  - Design and procure ASICs to cover 50% of ETL detector
- 402.8.4.3: Module assembly
  - Assemble, test, and deliver 50% of ETL modules
- 402.8.4.4: System testing
  - Confirm operational performance of the module design, including grounding and service integration
- 402.8.4.5: Integration and commissioning
  - Part of the O-KPP is to install on detector the modules delivered by US-CMS

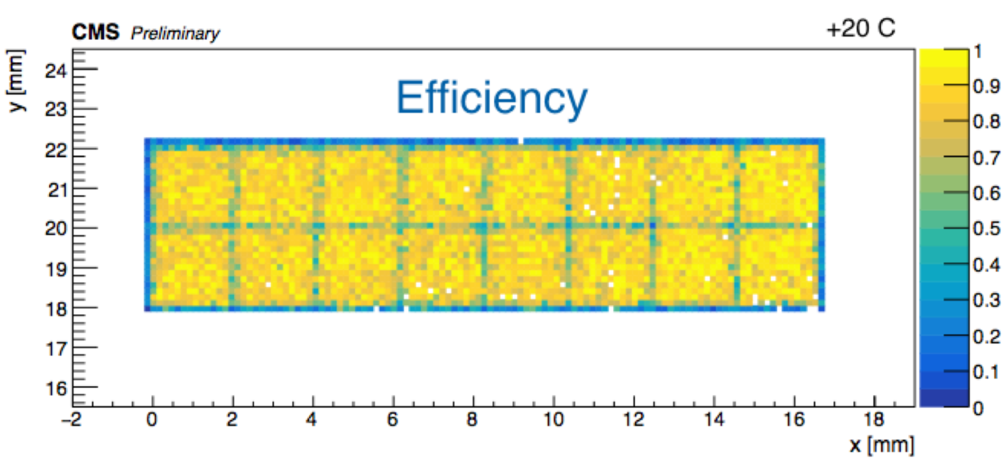


402.8.4.1: LGAD sensors

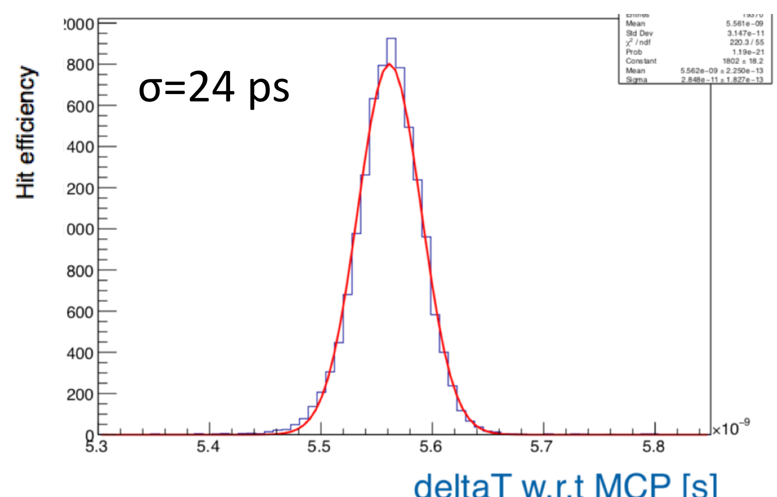
Charge #2, 4

- Basic unit of module sub-assemblies
  - Small pixels to limit the sensor capacitance needed to achieve performance
- LGADs need to survive up to 1.7×10^{15} n/cm^2
- Continued R&D program
  - Optimize sensor reference design, measurements in labs and test beams
  - Focus on maximizing yield and uniformity of large volume production
- Work will be carried out by postdocs/students at U of Kansas

Measurements of 2x8 array from FBK



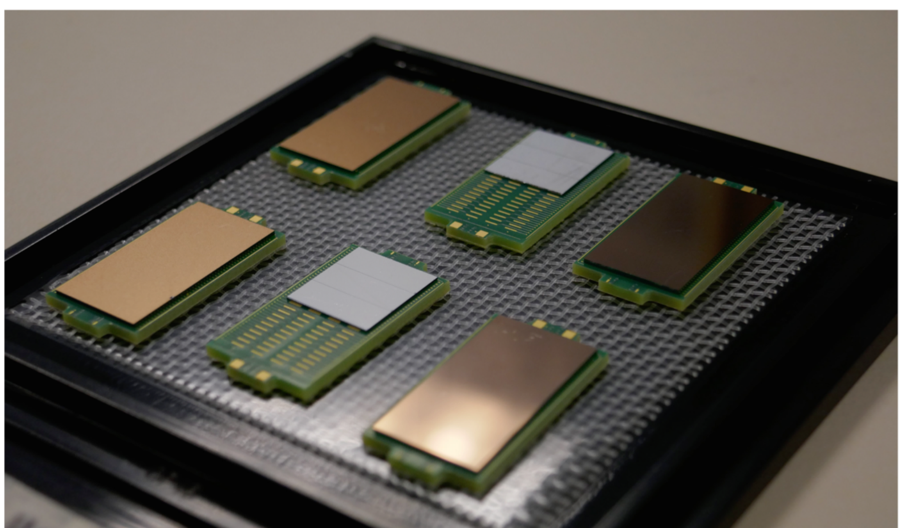
Measurements of the latest sensors from HPK



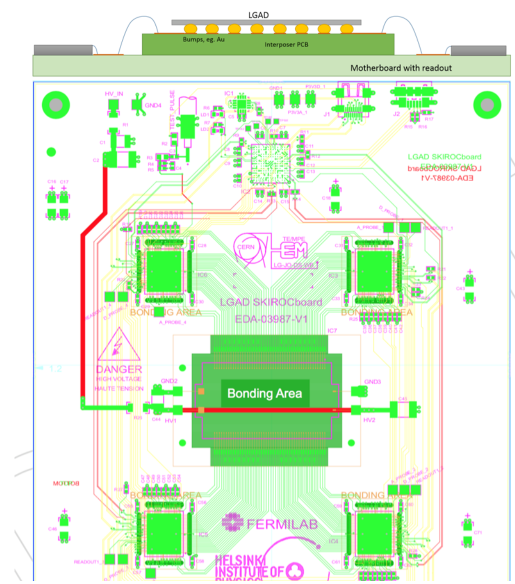
402.8.4.4: system testing

Charge #2, 4

- US-CMS will implement stands to test all aspects of the assembled modules
  - Modules with service hybrid connected to backend and clock distribution
- Prototypes will be used to assemble progressively complex system tests
  - Starting with the SKIROC assemblies to test aspects of the LGAD+system integration
  - Will Integrate ETROC prototypes with lpGBT, SCA and VTrx components
  - Integration with the CO_2 cooling and full DAQ stand
- Confirm operational performance of the module design, including grounding and service integration



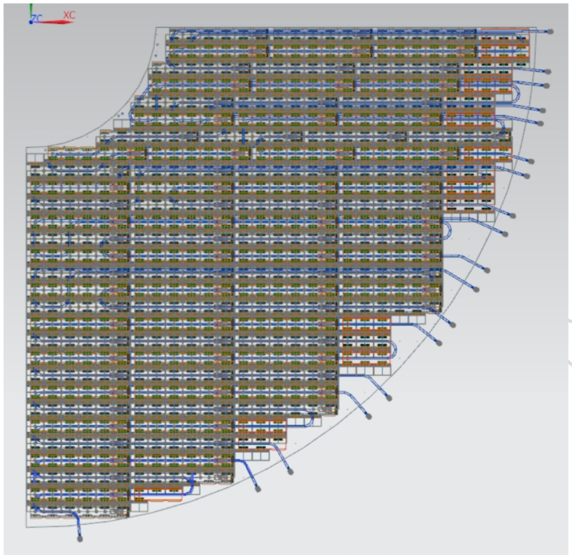
96-channel LGADs bump-bonded to interposer

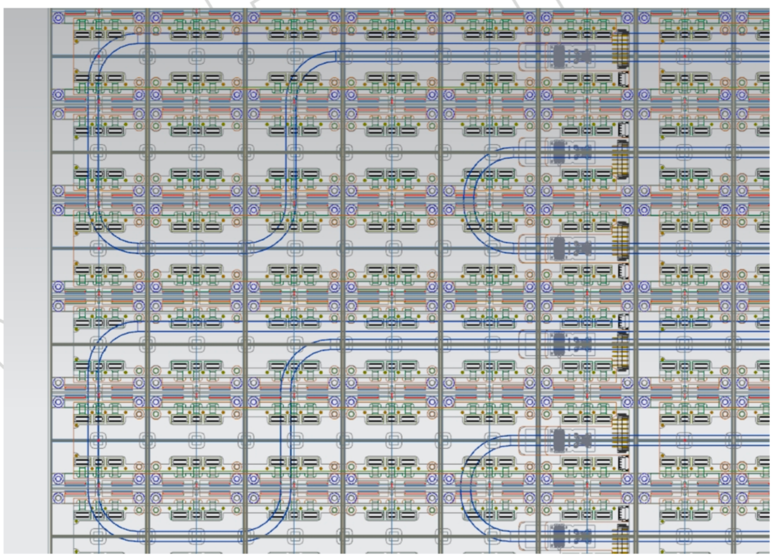


LGAD testing board using SKIROC chips

402.8.4.5: integration and commissioning

- Integration and commissioning is in the US-CMS O-KPP
- Components will be received at the Endcap Calorimeter Assembly Facility (ECAF)
  - Modules and service hybrids will be mounted on wedges using screws
  - Power and data services will be installed and routed on wedges
  - A warm test will be performed to verify the electrical connectivity of modules
  - Following the warm test, ETL will be connected to CO_2 and power services and a DAQ test stand and a longer-term, cold-temperature tests of the integrated wedge.
- Populated disks lowered to the experimental cavern for installation on CMS
  - ETL can also be installed on surface, on top of the completed HGCAL assembly





Interfaces and dependencies

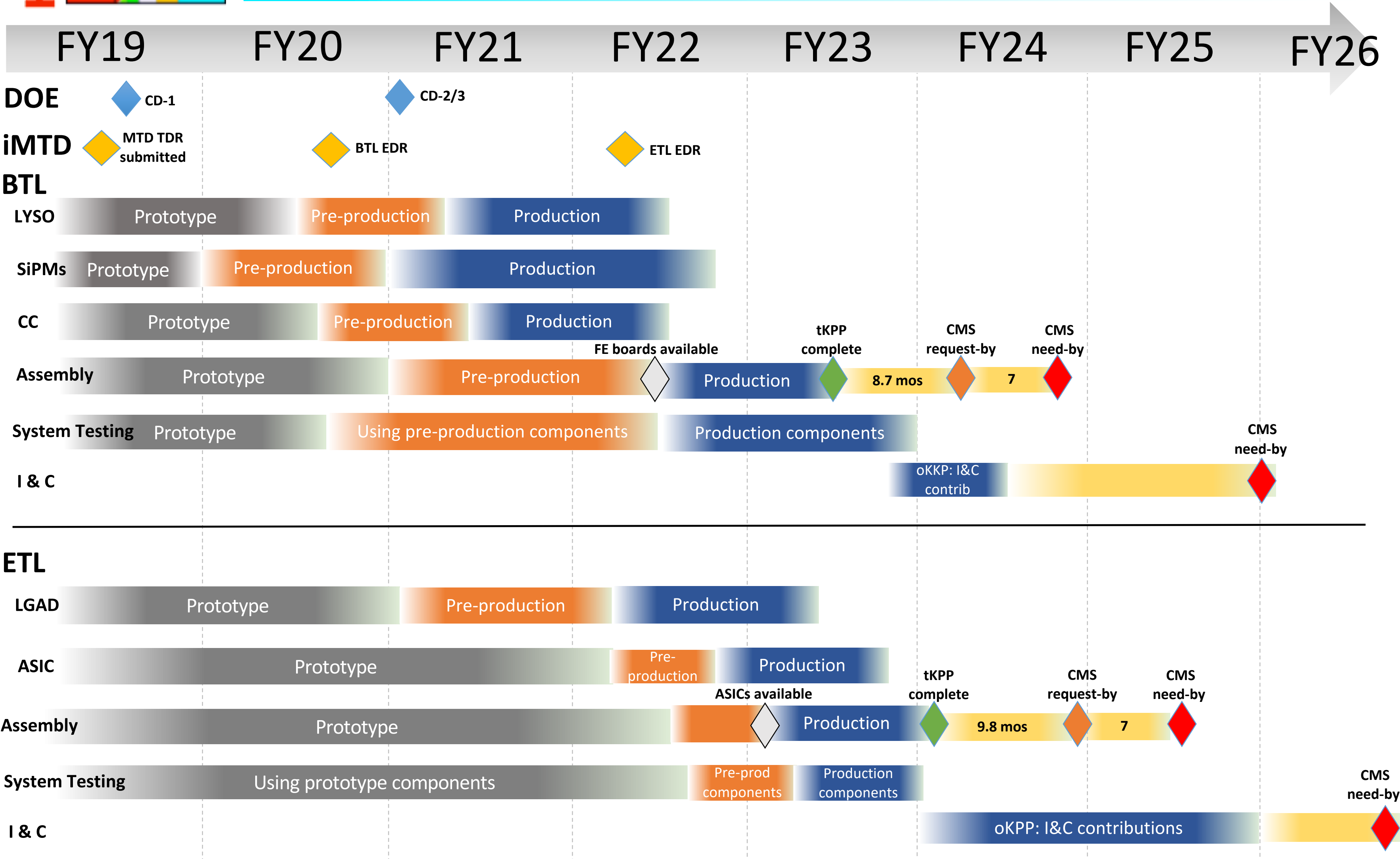
- There are a range of critical interfaces to be considered in the project

- iCMS and U.S. share same design for Modules
  - Interfaces handled at the international level
  - The System Interface Control Document for WBS 402.8 in docDB 13536

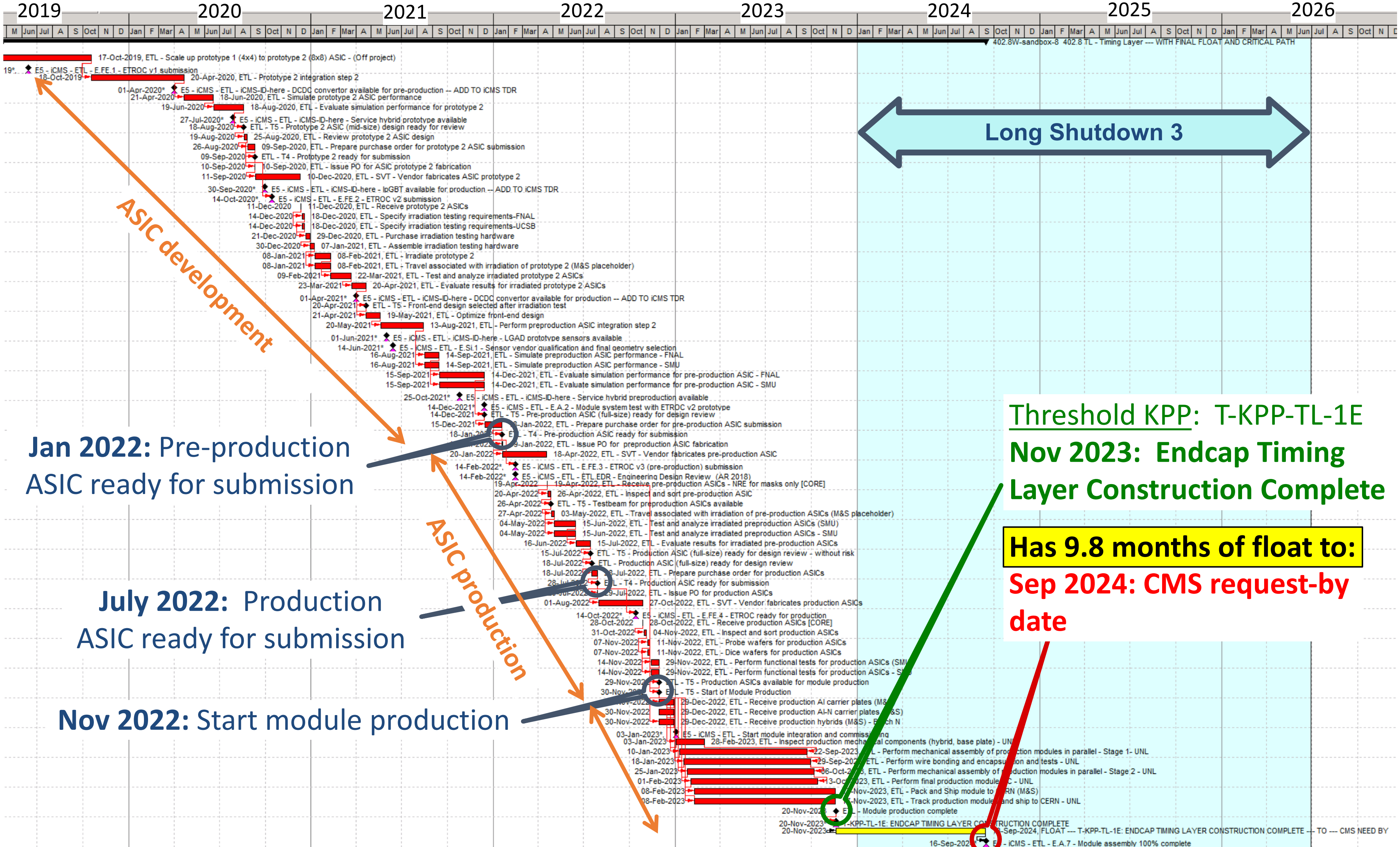
- Interface negotiation expedited by embedded U.S. team in international organization

US-MTD Schedule in P6

Charge #3



ETL Critical Path and Schedule Contingency



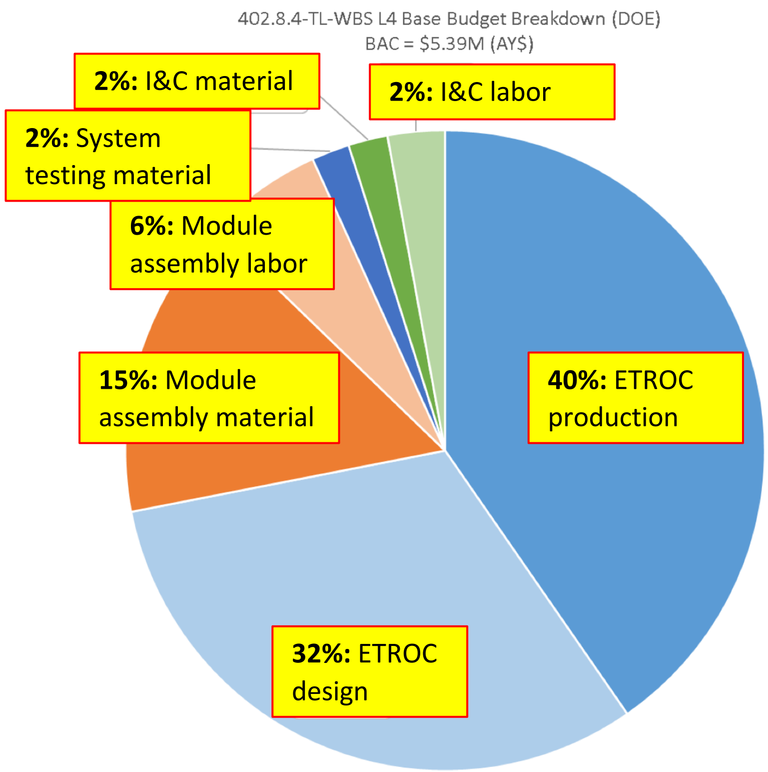
Contributing institutions

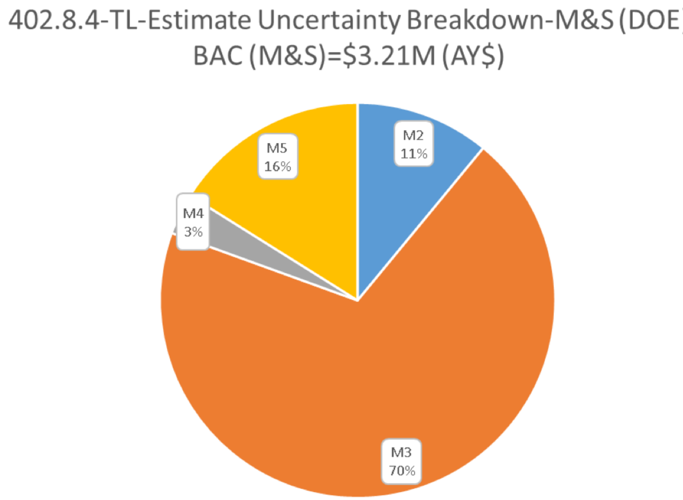
Charge #4

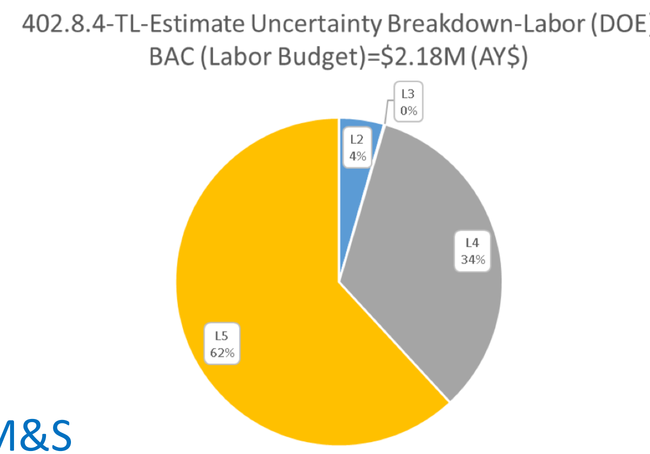
- LGAD sensor testing will be done at *U of Kansas*:
  - Extensive recent experience in QA sensor testing for Phase 1 pixel detector
- ETROC design will be done by *FNAL* and *SMU*
  - Effort led by FNAL team in collaboration with SMU
    - Years of experience in designing ASICs for HEP experiments
- Modules assembly and system testing will be done at *FNAL* and *UNL*
  - Extensive recent experience in design/assembly of silicon detectors for HEP
    - UNL and FNAL will serve as assembly sites. UCSB will provide additional labor.
    - SiDet and Test Beam facility at Fermilab for prototyping, assembly and testing
- Integration and Commissioning at CERN
  - Work performed largely by students and postdocs

Cost estimates for 402.8.4

Charge #3



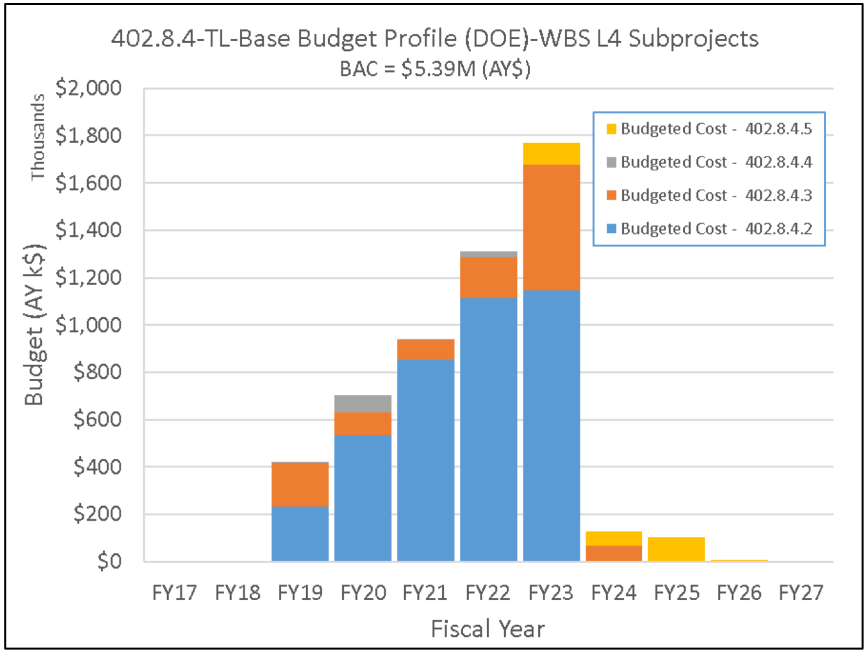


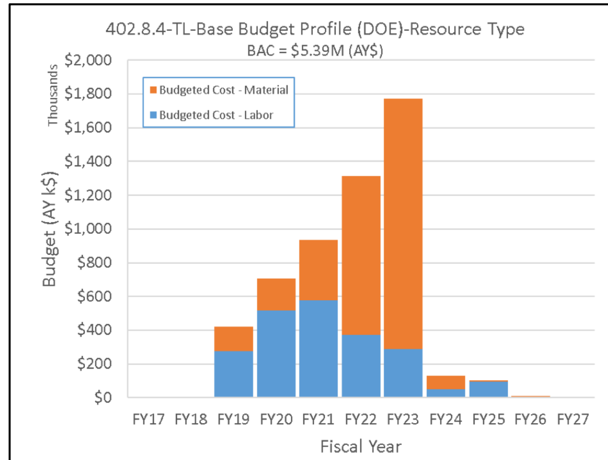


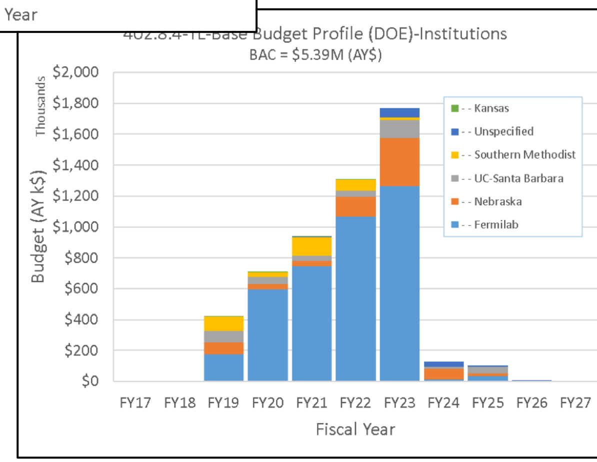
- 402.8.4.*2/3* are the main cost drivers:
  - ETROC production, and module assembly labor and M&S
- Cost drivers for 402.8.4.*1/4/5*:
  - Purchase of environmental chamber and electronics for system tests
  - COLA for students and postdocs; salaries for engineer/technician for I&C

Budget profiles for 402.8.4

Charge #3

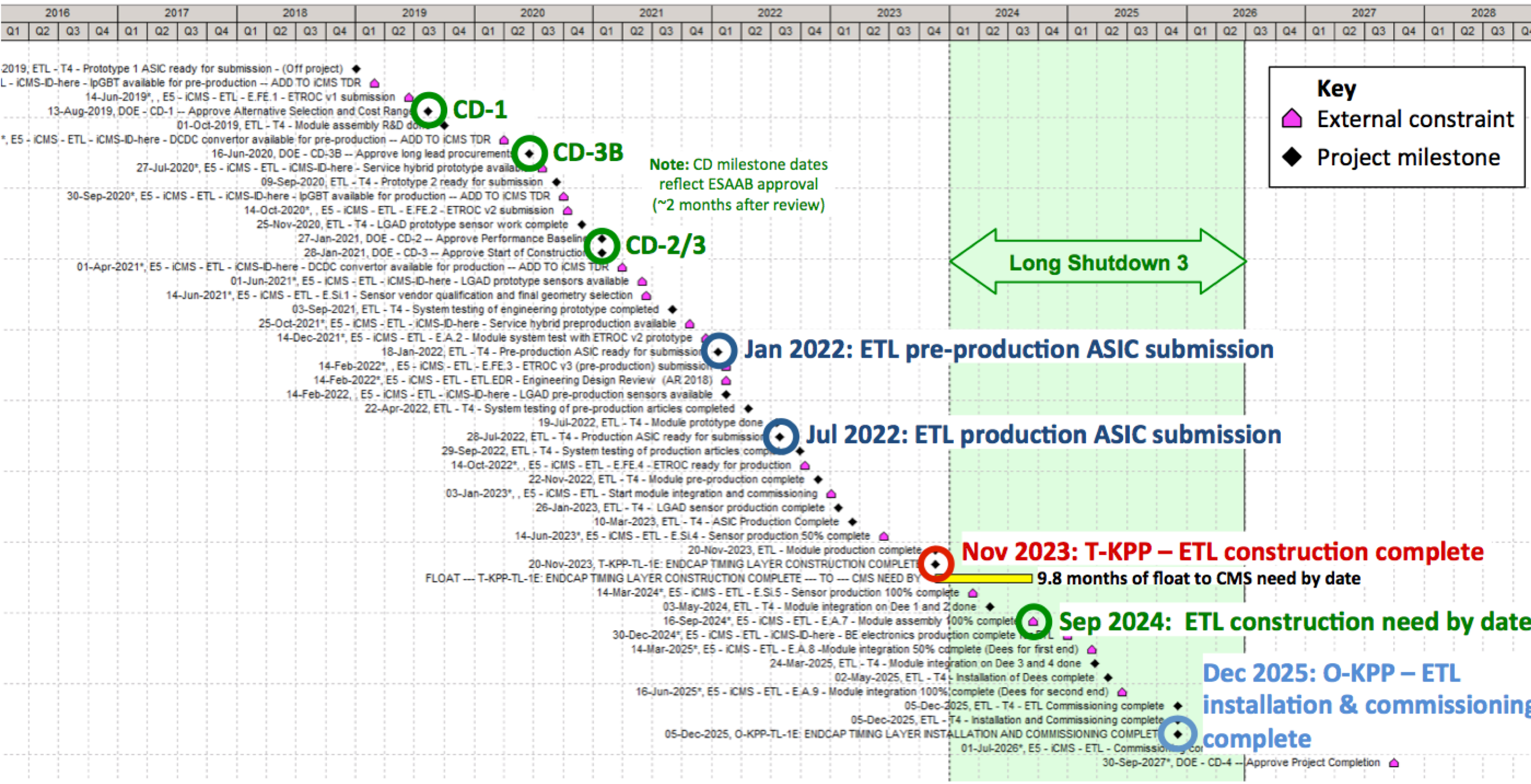






- 402.8.4.***2/3*** are the main cost drivers:
  - ETROC production, and module assembly labor and M&S
- Cost drivers for 402.8.4.***1/4/5***:
  - Purchase of environmental chamber and electronics for system tests
  - COLA for students and postdocs; salaries for engineer/technician for I&C

Milestones for 402.8.4



Threshold KPP: ETL construction is de-coupled from LHC schedule

Objective KPP: Participation in integration and commissioning with iCMS at CERN

HL-LHC US CMS

ETL risks

Charge #3

Risk Rank	RI-ID	Title	Probability	Schedule Impact	Cost Impact	P * Impact (k$)
WBS / Ops Lab Activity : 402.8 TL - Timing Layer (general risks) (3)						
WBS / Ops Lab Activity : 402.8.3 BTL - Barrel Timing Layer (15)						
WBS / Ops Lab Activity : 402.8.4 ETL - Endcap Timing Layer (12)						
Risk Type : Opportunity (1)						
2 (Medium)	RO-402-8-01-D	ETL - Use AltiROC	10 %	-8 months	-760 k$	-76
Risk Type : Threat (11)						
3 (High)	RT-402-8-01-D	ETL - Additional FE ASIC prototype cycle is required	50 %	4 -- 5 -- 6 months	500 -- 600 -- 700 k$	300
2 (Medium)	RT-402-8-03-D	ETL - FE ASIC does not meet specs - needs another pre-prod run	10 %	6 -- 7.5 -- 9 months	914 -- 970 -- 1026 k$	97
2 (Medium)	RT-402-8-02-D	ETL - Problems with ETL module assembly facility	50 %	1 months	30 k$	15
2 (Medium)	RT-402-8-10-D	ETL - Sensor quality problem during production	15 %	2 -- 3 -- 6 months	28 -- 52 -- 109 k$	9
1 (Low)	RT-402-8-53-D	ETL - Integration facility at CERN runs out of components	25 %	3 months	21 k$	5
1 (Low)	RT-402-8-48-D	ETL - Delay in delivery of parts from iCMS	20 %	1 months	10 -- 20 -- 30 k$	4
1 (Low)	RT-402-8-31-D	ETL - Storage-related degradation of LGADs	10 %	3 months	18 k$	2
1 (Low)	RT-402-8-52-D	ETL - Module Radiation Tolerance	10 %	1 months	15 k$	2
1 (Low)	RT-402-8-49-D	ETL - Delays or damage in transport of ETL modules to CERN	5 %	1 months	10 k$	1
1 (Low)	RT-402-8-50-D	ETL - Module assembly yield is low	10 %	0 -- 0 -- 1 months	0 -- 5 -- 15 k$	1
1 (Low)	RT-402-8-51-D	ETL - Problem with AlN vendor	5 %	1 -- 2 -- 3 months	0 -- 15 -- 30 k$	1

- Project governed by Fermilab Risk Management plan.
  - Risk workshop with external reviewers conducted.
- Dominated by risks related to ETROC, details in Ted’s talk

Summary

- We have made significant progress in all areas since June 18
  - Optimized the design of ETL
  - Prototype sensors from FBK and HPK look great, demonstrated radiation tolerance for HL-LHC
  - ASIC prototype submitted, first results very soon
  - Fast progress in the integration with CMS converging on service routing
- A strong team of contributing institutions with significant experience of designing, building, and testing silicon detectors and and ASICs for HEP experiments
- The project team has identified and documented risks, have defined the interfaces, and structured the project appropriately in the P6 system to ensure efficient project management in the construction phase.

Backup

Environmental, Safety and Health

Charge #6

- All ES&H aspects of the HL LHC CMS Detector Upgrade Project will be handled in accordance with the Fermilab Integrated Safety Management approach, and the rules and procedures laid out in the Fermilab ES&H Manual (FESHM)
  - The current construction plan involves no materials of identified environmental risk: cooling plant is based on CO_2 rather than Freon
- Detector will use high voltage (~ 600 V) and will be operated in a refrigerated mode (-30°C), similar to OT and HGCal
  - Standard operational procedures will be developed and documented to allow safe operation
- R&D and some production testing will involve the use of gamma, neutron, and proton radiation.
  - These tests will be performed at commonly-used radiation facilities and will follow the standard operational procedures defined at each facility

Responses to previous reviews

ETL-R1: It is crucial to follow the schedule of beam test and/or system integration tests to verify functionality of the LGAD/ROC/Back-end systems

A series of systems tests at each major stage of development for the ETL (final engineering prototype, pre-production prototype, and production modules) are being developed. The mechanical, thermal, electrical, and data integrity of ETL sensor modules affixed to their expected mechanical structures will be examined at each of these stages and then validated to the furthest extent possible. The results will be reported as recommendations for the next stage of ETL prototyping. Realistic backend electronics for read out and slow control will be used as soon as they are available in the testing procedures. Specific attention will be paid to developing a full sensor-to-DAQ chain of ETL with multiple modules using lpGBTs as soon as possible to identify scaling issues. This series of systems test will culminate in beam testing of the production modules to verify module timing performance before and after burn-in, in addition to other stress tests of the system.

Charge #4

Value Engineering

- Value Engineering seeks to maintain same functionality at reduced cost either up front or during operations
- Value engineering plan documented in cms-doc-13475
  - Development of the LGAD sensors: leveraging LDRD funded R&D, INFN and ATLAS collaboration for LGAD sensor productions, costs for irradiation and testing campaigns
  - Elements developed as common CERN projects, industry, or other CMS projects. These include the lpGBT, VTRx+, DC-to-DC converters, the e-link protocol, ATCA crates and communication standards, and FPGA-controlled boards for the backend and trigger.
  - The front-end ASIC for the ETL detector is following closely the design decisions of the ALTIROC developed for the ATLAS timing detector.
  - Reuse of the CO2 cooling plant at FNAL for testing of prototype modules and the validation of cooling designs.
  - Assembly and QC testing of ETL modules at two assembly centers: UNL and FNAL. Both facilities take advantage of infrastructure associated with building and testing silicon modules for CMS tracking.
    - A gantry and a wirebonder at each site, originally purchased for other projects, will be used for ETL module assembly.

Quality Assurance and Quality Control

- Quality Assurance & Control plan documented in cms-doc-13093
- Quality Assurance : Prevention of Issues
  - Prior to the production of ETL modules, several prototype rounds are planned to identify potential problems and minimize the impact to cost or schedule:
    - A series of prototypes, both mechanical dummy and functional
    - Checkpoints/reviews in early production for prototypes to identify issues
    - Fixed procedures for construction, automation
    - Testing procedures: test-beams, integration testbeds, radiation testing including operation of systems under irradiation, thermal cycling tests
  - System tests will be performed on assembled modules to assure quality
- Quality control : Identification of issues
  - The procedure for module assembly and quality control will be developed during prototyping period.
  - module components will be tested prior to the final assembly during production
  - Use databases to track all components through the assembly and testing processes
  - Verify that only good quality components (sensors, power and readout boards, and ASICs) are assembled into modules.