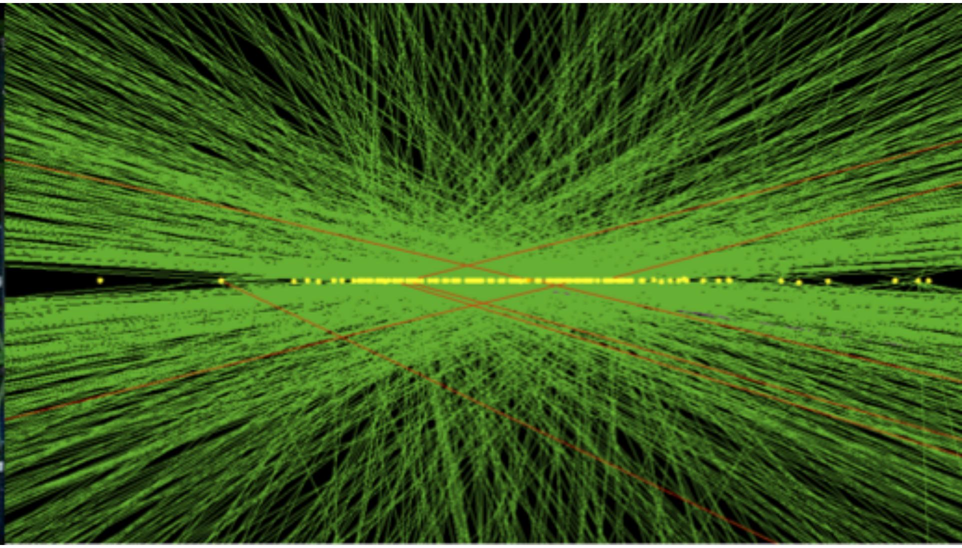
B01: 402.4.3 Endcap Calorimeter Sensors

Rachel Yohay (FSU), L4 for Sensor Testing

HL LHC CMS CD-1 Review

October 23, 2019



Outline

- Technical Aspects of Sensors
  - Conceptual Design
  - Scope and U.S Deliverables
  - Progress since June 2018 IPR
  - QA/QC

- Managerial aspects of Sensors
  - Cost, Schedule, and Risks
  - Contributing Institutions
  - ES&H
- Summary

Who am I?

- L4 Manager for Sensor Testing
  - Responsible for crystal calorimeter endcap LED light injection system in LHC Run 1
  - Deputy L2 manager for USCMS tracker operations
  - CMS pixel operations coordinator (2014-2016)
  - Assistant Professor, Florida State University (2016-)
  - Analysis interests: exotic decays of the Higgs boson
  - Co-editor of the CE chapter of the CMS Phase 2 upgrades Conceptual Design Report
- CAM for Sensors is Nural Akchurin (TTU)

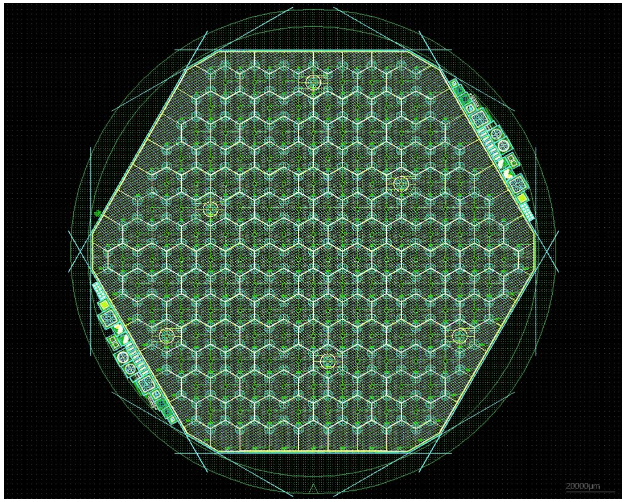
Conceptual Design

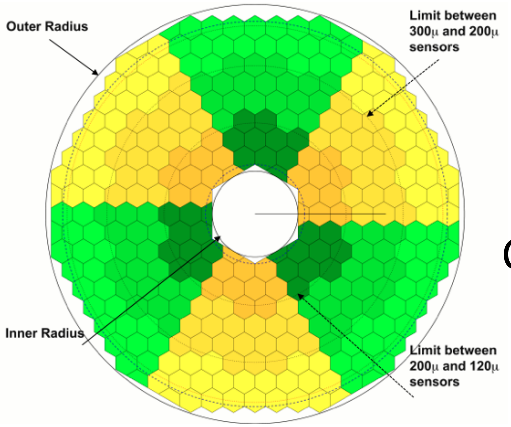
Charge #2

Design Considerations for 402.4.3

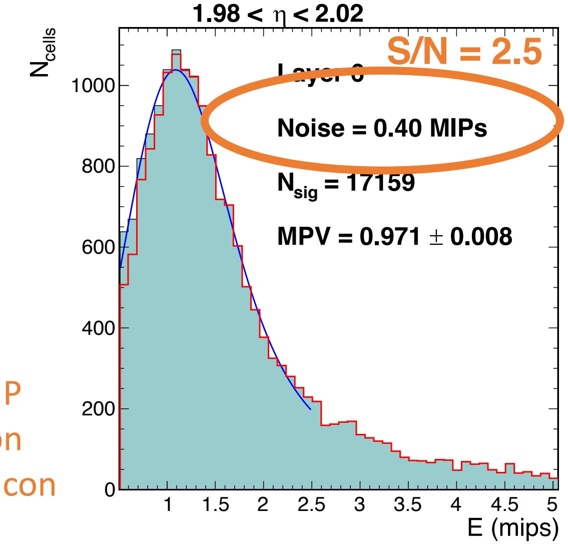
- MIP reconstruction (CE-sci-engr-002)
  - **CE-sci-engr-002**: "The CE active materials shall be radiation tolerant enough to achieve MIP detection with S/N > 5(1.7) in each scintillator(silicon) cell."
  - **Cell sizes** (~ capacitance ~ noise) set by MIP S/N requirement at end of life
  - Cost optimization
    - Hexagonal sensors from 8" wafers (CE-engr-024)
    - Thickness decreases as expected fluence increases
- Minimal dead area (CE-engr-025)
  - Fractional variants to cover inner and outer boundaries
- High transverse granularity (CE-sci-engr-004)
  - **CE-sci-engr-004**: "The CE shall have fine transverse and longitudinal granularity to optimize its utility in particle flow reconstruction."
  - Small cell sizes for narrow jets to mitigate pileup (CE-sci-engr-007)

Low-density wafer layout





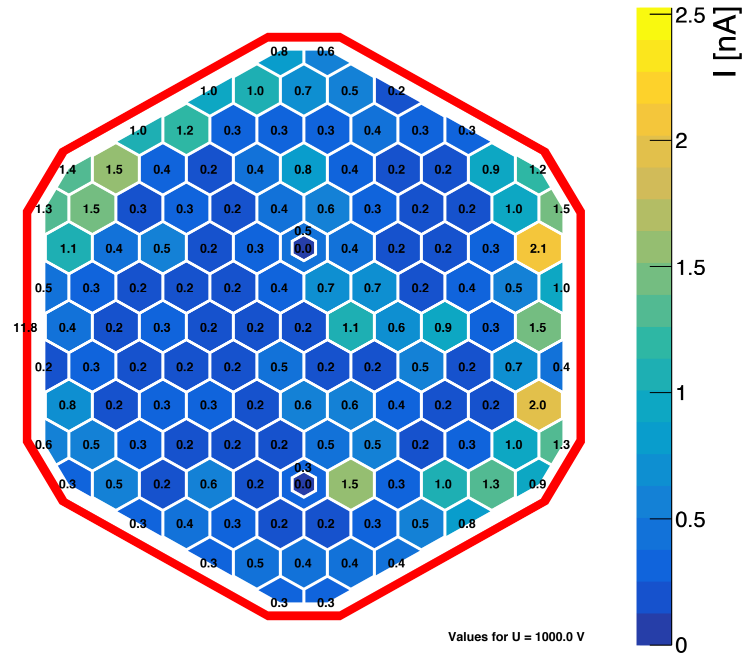
CE-E layer 9



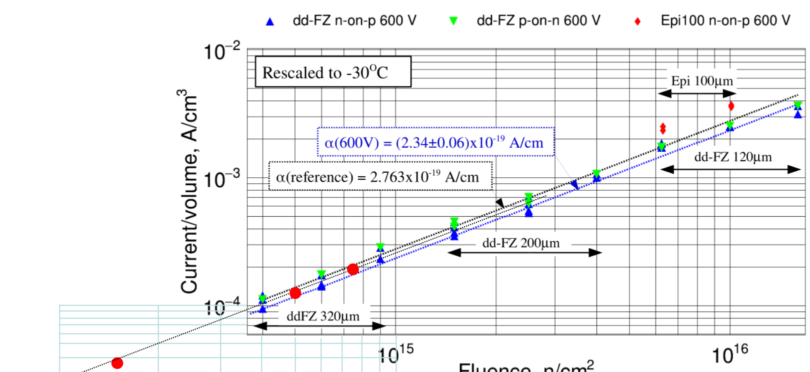
Simulated MIP reconstruction in 200 μm silicon

Design Considerations for 402.4.3

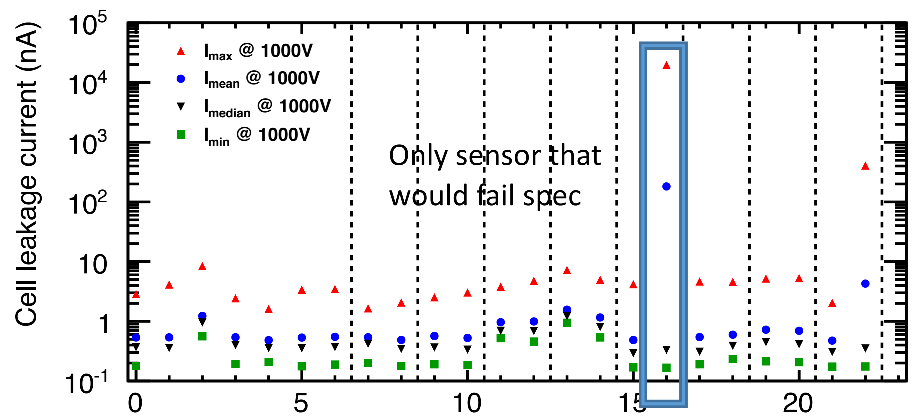
- Radiation hardness (CE-engr-021)
  - **CE-engr-021**: "CE silicon sensors shall be designed to be tolerant to 10E16 n_{eq}/cm^2 at inner radius, and vendors and sensor types qualified for radiation hardness"
  - Require **low leakage current and depletion voltage** before irradiation
    - Up to 10 cells allowed with leakage current >100 nA per cell; total leakage current ≤20 µA per sensor at 600 V and 20°C
    - Depletion voltage <370(160)(70) V for 300(200)(120)-µm thickness
  - Require **high breakdown voltage** (>800 V)



Per-cell leakage current at 1 kV bias for one prototype 6" sensor



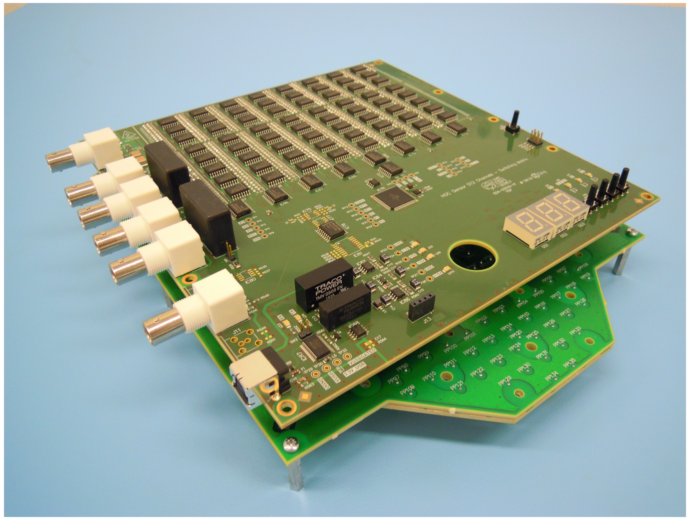
= Typical leakage current at 1 kV from prototype sensor irradiation



Leakage current measured with switch + probe card setup (23/200 6" sensors)

Deliverables for 402.4.3

- This WBS element ensures that **high quality sensors reach the module assembly centers**
  - Silicon sensor prototyping and development (402.4.3.1)
  - Silicon sensor procurement (402.4.3.2)
  - Silicon sensor quality control (402.4.3.3)

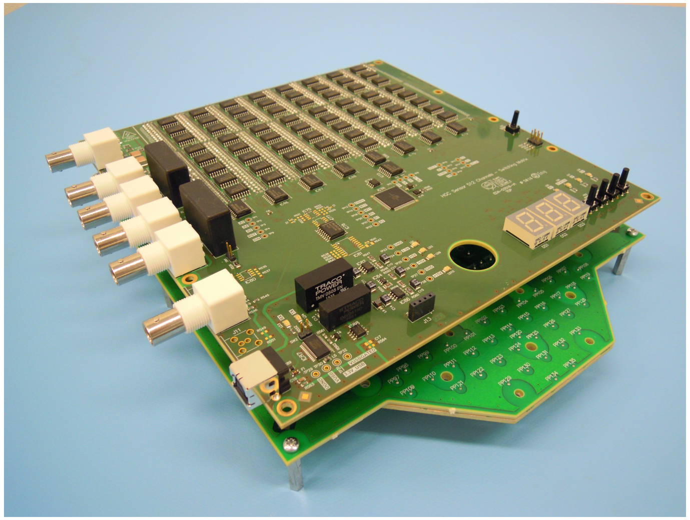


Sensor type	No. full-wafer equivalents* purchased	Unit cost/ Total cost	No. full-wafer equivalents used in US-built modules**	No. full-wafer equivalents‡ to be tested
Full 300 µm and 200 µm	7854	$739.13/ $5,805,200	10140	527 (5.2%)
Full 120 µm	0	$965.22/ $0	0	0%†
Odd 300 µm and 200 µm	1086	$739.13/ $802,696	2650	534 (5.0%)
Odd 120 µm	102	$965.22/ $98,452	669	0%†

Charge #2

Deliverables for 402.4.3

- *The project is charged by the full-wafer equivalent, not by the module. For odd-sized modules, 1 full-wafer equivalent ~ 2 modules (but there are different numbers of fives and threes needed).
- **US-built modules are all CE-H modules and all CE odd-sized modules. These counts include detector modules, spares, and test beam modules.
- †0% tested only means that the US tests 0%—international partners will cover this task.



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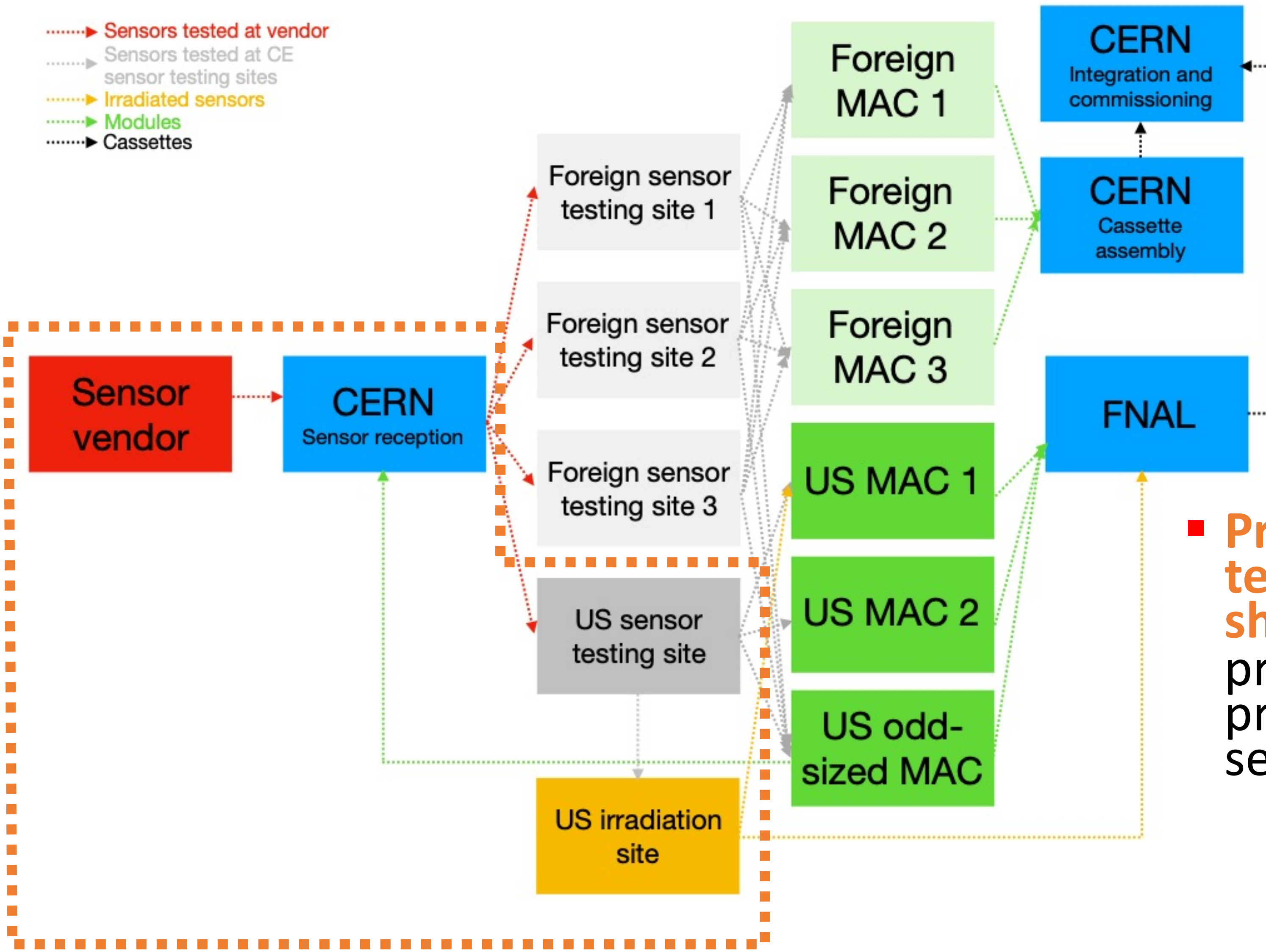
Charge #2

Deliverables for 402.4.3

- Silicon sensor prototyping and development (402.4.3.1)
  - Sensor testing site setup (winter 2019-2020)
  - Prototype sensor testing (summer-fall 2020)
  - Prototype sensor irradiation (summer-fall 2020)
  - Testing required for Major System Prototype 2 and to commission the sensor testing and irradiation sites
- Silicon sensor procurement (402.4.3.2)
  - 30% of the total CE sensor cost (including spares and test beam sensors)
- Silicon sensor quality control (QC) (402.4.3.3)
  - More detail below

Charge #2

Deliverables for 402.4.3

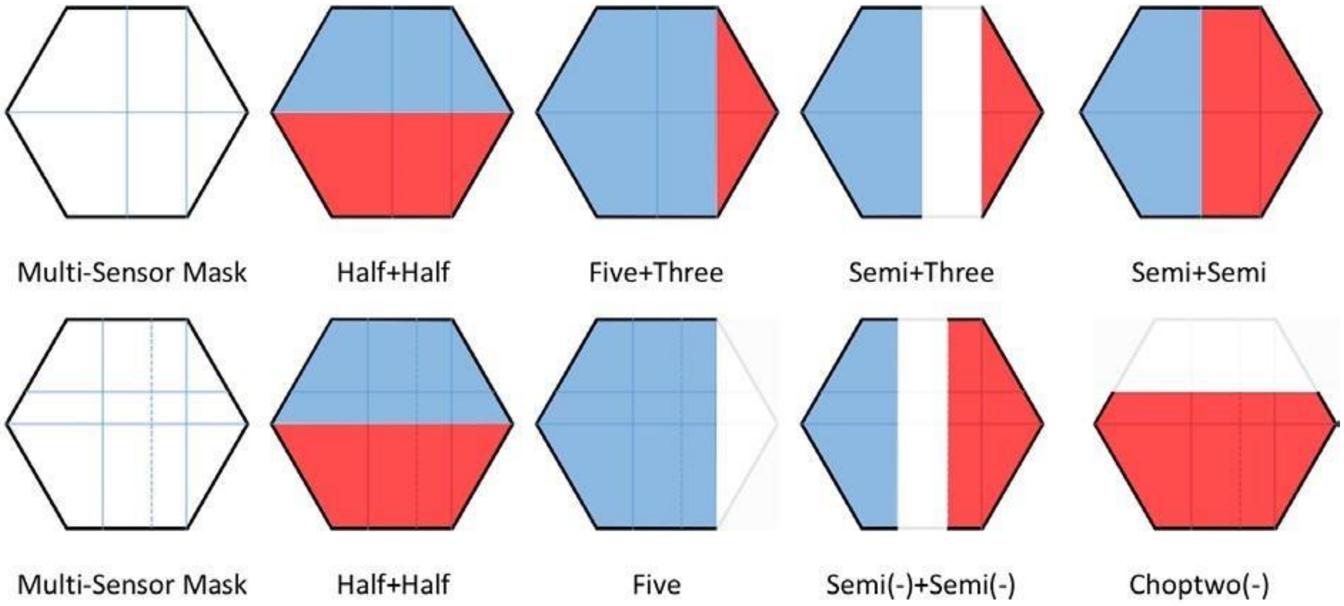


- **Procurement, testing, and shipping** of prototype and production sensors

R&D Achieved

- **Sensor design exists and is accepted by vendor**
- Choice of sensor thicknesses and processes
  - 300-, 200-, and 120-µm used in regions of low, medium, and high neutron fluence, respectively
  - Physically thinned float zone process for 300- and 200-µm sensors
  - Epitaxial high-resistivity layer on low-resistivity substrate for 120-µm sensors
- Choice of p-type substrate material
- Defined test structures
- High-throughput SQC hardware and software developed
- Irradiation campaign on test structures to validate the thickness, process, and bulk substrate choices
- Extensive testing of prototype sensors using the same SQC methods as will be employed during production
- O(200) modules constructed and operated in test beams
- **We are nearly complete with R&D and will be ready for construction start approval early next year (CD3A)**

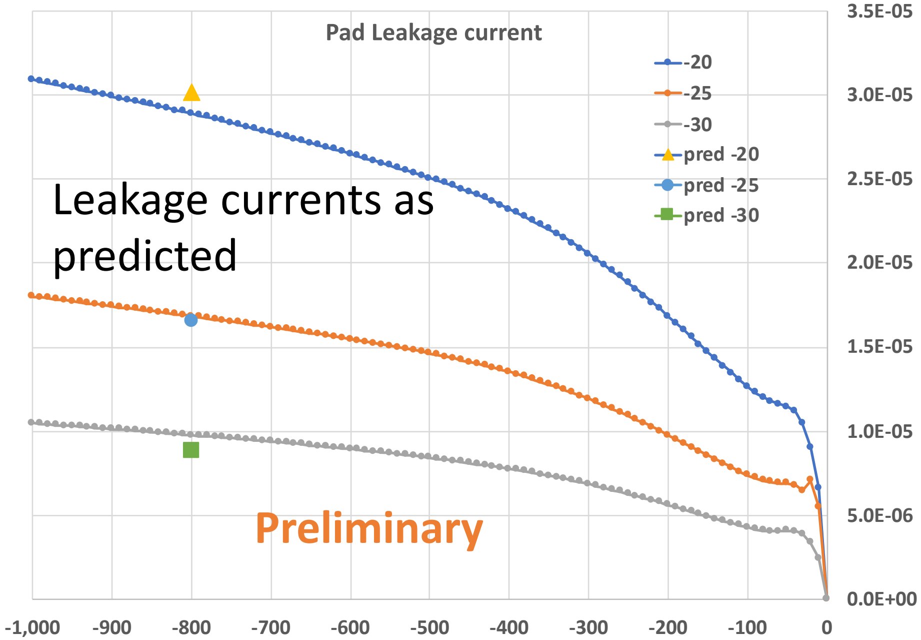
R&D Achieved

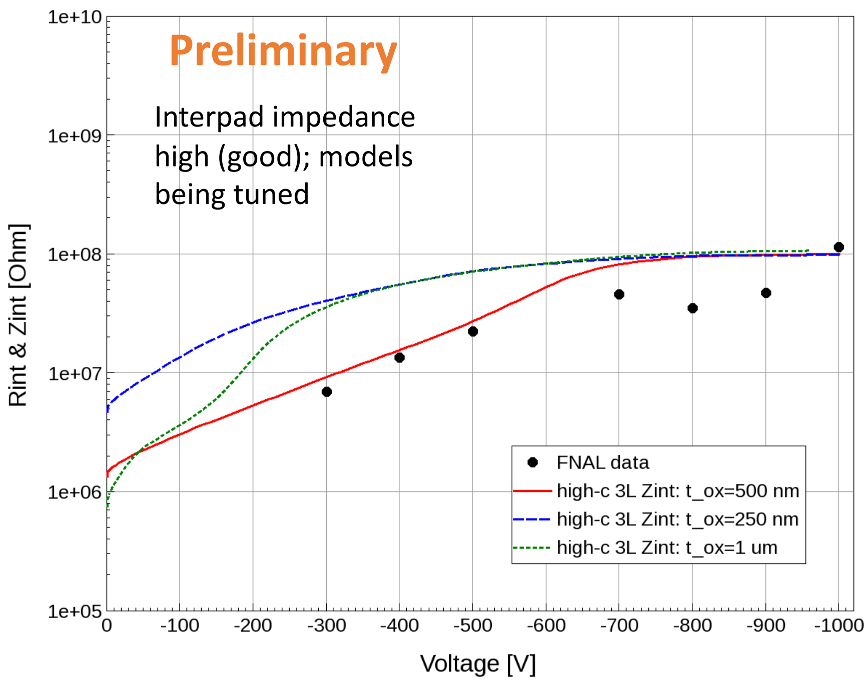


- Special wafer to be designed with cut lines to allow for dicing any odd-sized sensor variant
- Significant value engineering
  - Reduced mask setup costs for vendor ⇒ reduced unit cost
  - Tiny price paid in dead area at the cut lines

Work before CD3A

- Radiation testing of 8” low density sensors
  - Neutron irradiation (dominant species at the location of the CE)
  - Initial investigations ongoing
- Testing of odd-sized sensors diced from multi-sensor mask
- Pre-series sensors due to arrive around the same time as CD-3A—not critical for approval, but data will build additional confidence in design





Charge #2

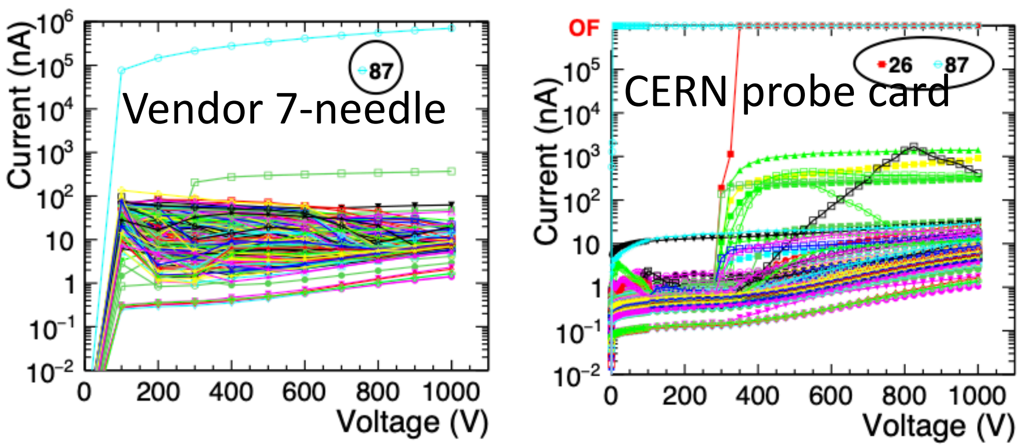
Design Maturity

- Currently at the level of “Detailed Design”
- Anticipate “Construction Readiness” by early 2020
- Well documented
  - 95% final design for full-sized sensor and test structures
  - Similar design for odd-sized sensors needs prototyping
    - Utilizes the same concept as the full-sized sensors
    - Not a critical path item for CD-3A
- Clear plan for addressing remaining design issues
- **More than sufficient for CD-1**

Quality Assurance and Quality Control

- QA plan
  - Vendor to perform per-sensor IV measurements on each sensor delivered to CERN using probe card designed and commissioned by CMS
  - Vendor measurements to be made available to CMS
  - Contract with vendor stipulates concrete acceptance criteria that must be met, including (but not limited to):
    - Leakage current
    - Depletion voltage
    - Fraction of dead channels
    - Stability

Per-cell IV curves for prototype 300 μm low-density sensor



○ = Cells with high current or breakdown

- Vendor QA exercised during prototyping

Charge #2

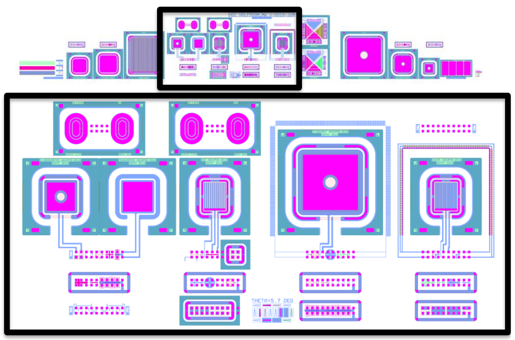
Quality Assurance and Quality Control

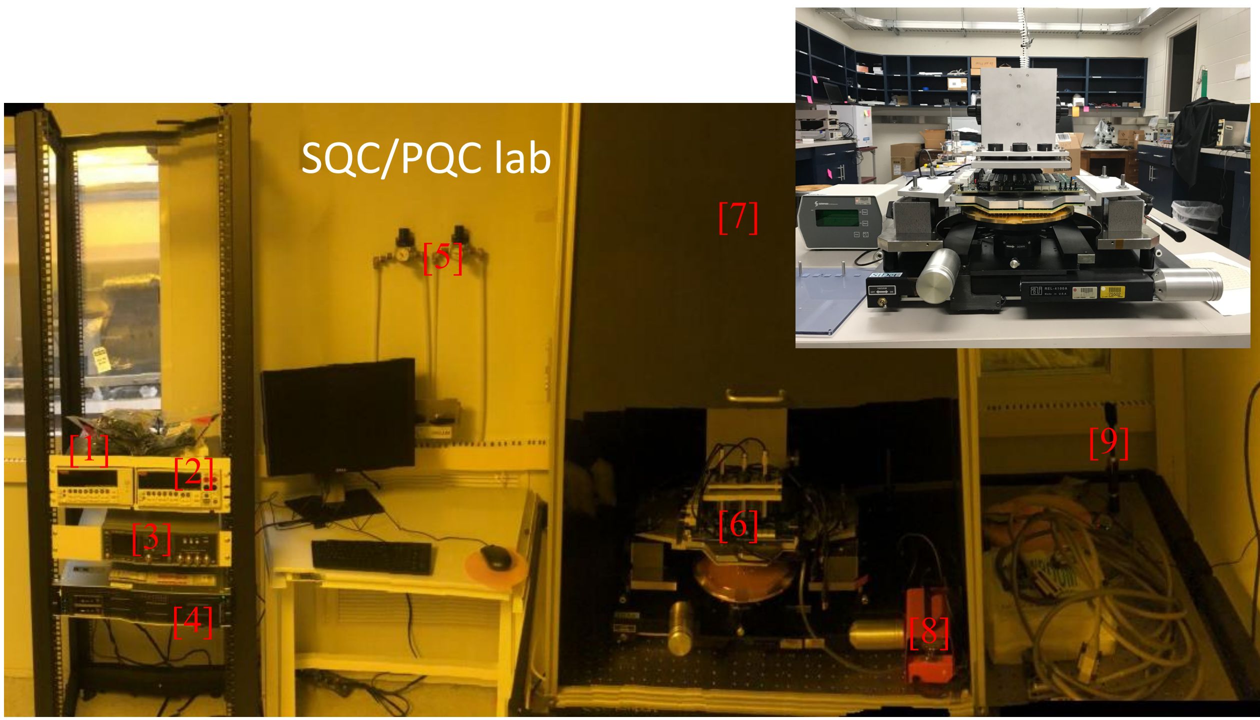
- QC plan
  - Modeled after highly successful CMS “Phase 0” Tracker QC
  - Sensor quality control (SQC) and process quality control (PQC) testing on 5% of production sensors and 10% of preseries sensors
  - Current-voltage (IV) measurements on each sensor to check leakage current per channel and per sensor
  - Capacitance-voltage (CV) measurements on each sensor to check depletion voltage
  - Detailed QC of the vendor process on test structures (oxide quality, bulk resistivity, interpad resistance, and carrier lifetimes, among others)
  - Annual radiation testing of 2 per mille for more thorough checks of sensor quality

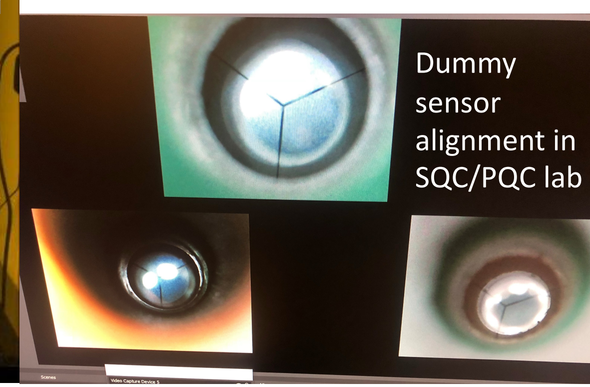
Quality Assurance and Quality Control

- QC lab already set up for probe card measurements
- Process QC measurement setup to occur in 2020
- PQC in common with CMS OT
- **QA/QC plan well established**

OT/CE test structure design







Cost and Schedule

Charge #3

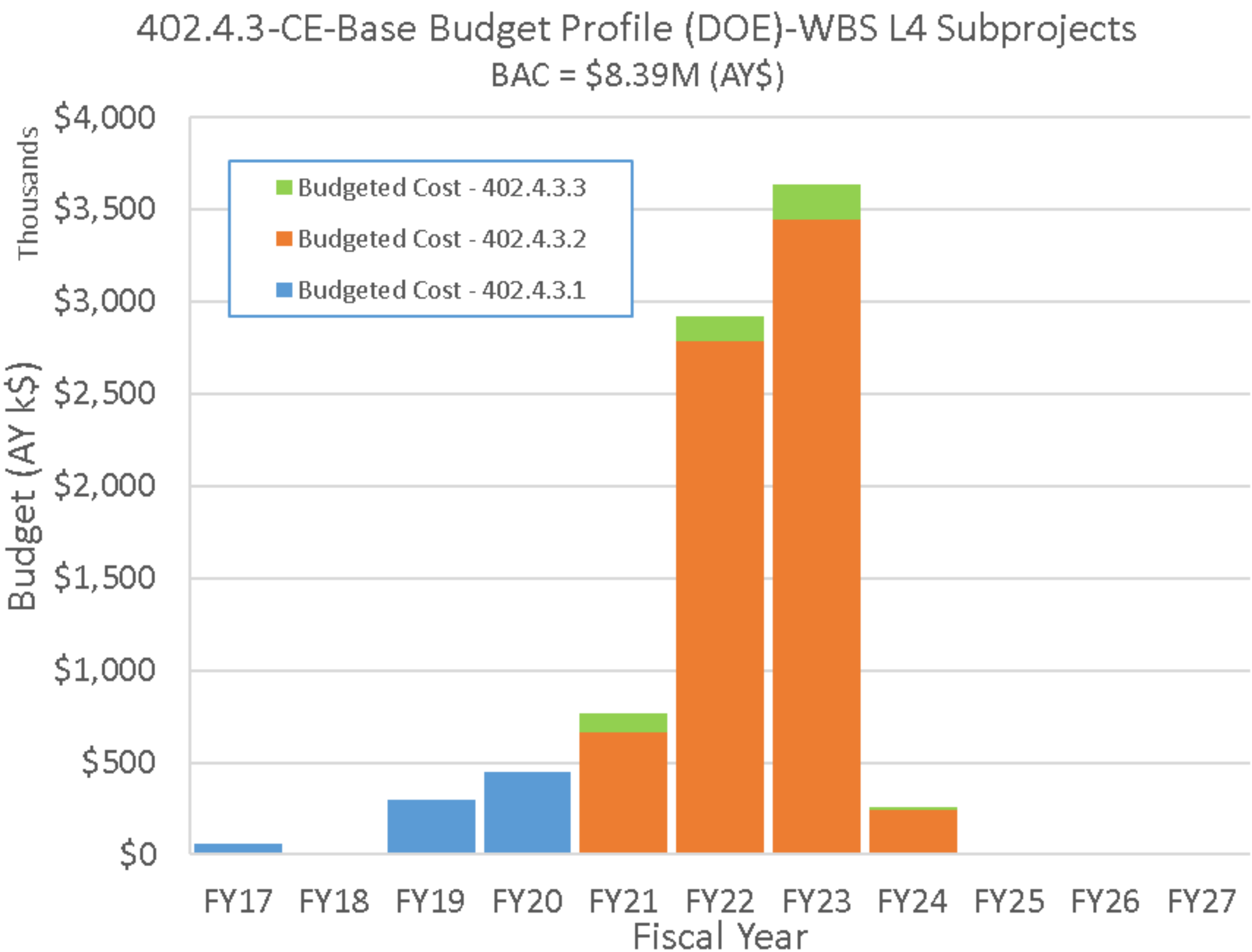
Cost Estimate

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
DOE-CD1-402.4 402.4 CE - Calorimeter Endcap (at DOE CD1)	21,051,786	332579	188.11	40,672,474	10,143,585	50,816,059
DOE-CD1-402.4.2 CE - Management	1,934,243	82022	46.39	3,807,266	622,019	4,429,285
DOE-CD1-402.4.3 CE - Sensors	7,501,635	14846	8.40	8,393,032	1,722,630	10,115,663
DOE-CD1-402.4.3.1 CE - Silicon Prototyping and Development	641,385	4000	2.26	822,076	85,464	907,540
DOE-CD1-402.4.3.2 CE - Silicon Production	6,809,750	0	0.00	7,126,403	1,530,407	8,656,810
DOE-CD1-402.4.3.3 CE - Silicon Quality Control	50,500	10846	6.13	444,553	106,759	551,313
DOE-CD1-402.4.4 CE - Modules	2,932,730	96412	54.53	8,405,886	1,435,046	9,840,932
DOE-CD1-402.4.5 CE - Cassettes	3,677,813	47416	26.82	9,422,794	3,065,143	12,487,937
DOE-CD1-402.4.6 CE - Scintillator Calorimetry	2,084,047	60875	34.43	4,196,710	1,244,785	5,441,494
DOE-CD1-402.4.7 CE - Electronics and Services	2,921,318	31008	17.54	6,446,786	2,053,962	8,500,748

- Sensor procurement is largest single item for endcap calorimeter, common procurement organized through international CMS
- Sensor testing is a significant effort in terms of labor (estimates updated since March 2019 Directors' Review)

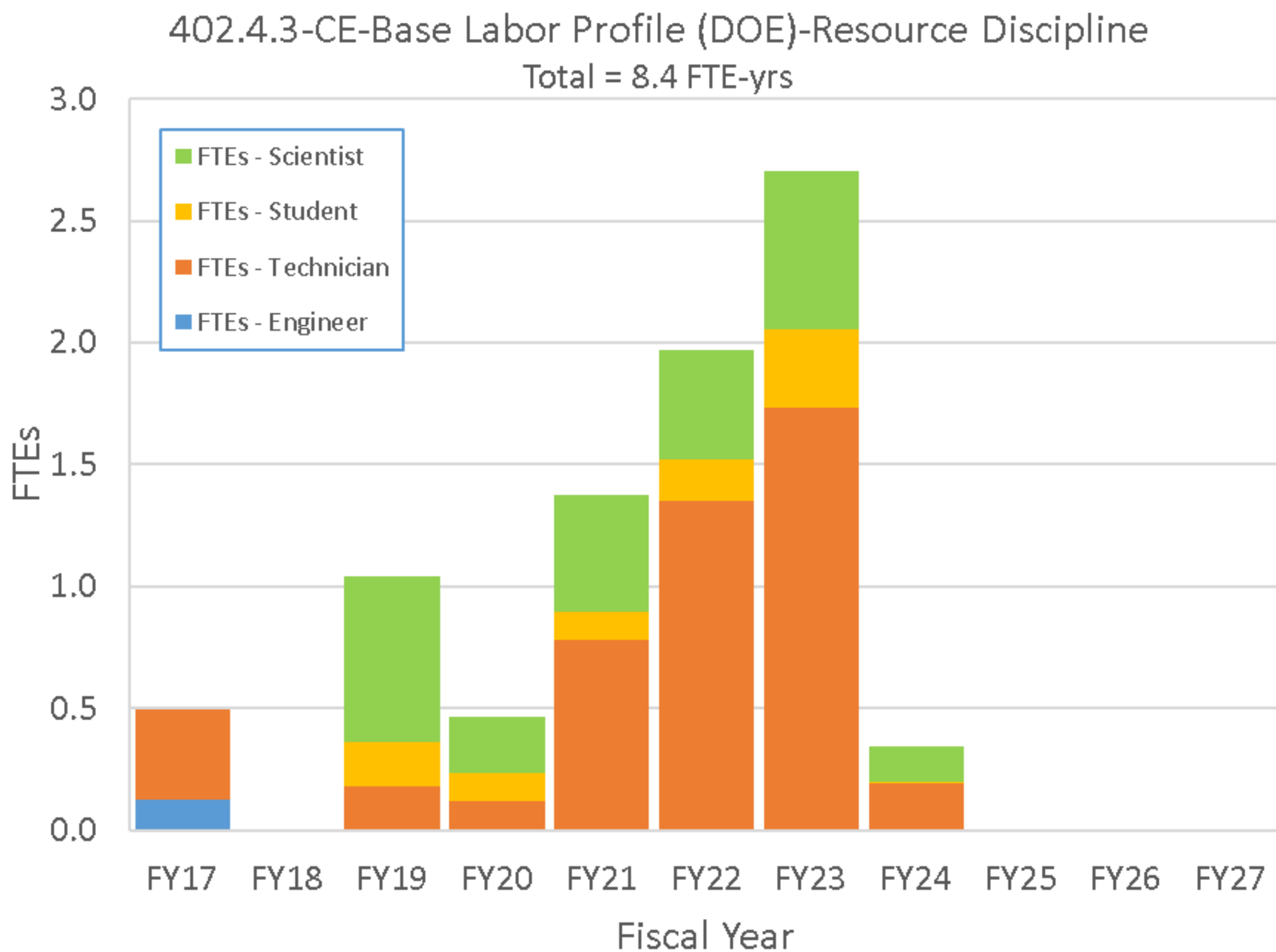
Charge #3

Fiscal Year Cost Profile



Charge #3

Fiscal Year Labor Profile



Charge #3,5

Risks

- Main sensors risk is low yield, which could slow module production
  - Contract with vendor specifies that we pay for good sensors only
- Extensive pre-series campaign to root out issues with sensor production

Schedule Overview

- Schedule driven by vendor delivery schedule
- Critical path item (drives speed of module production)
- Prototyping ends summer 2020
- Preseries summer 2020 – spring 2021
- Production spring 2021 – end 2023
- Odd-sized sensor testing accelerated to be completed by August 2023 to prevent delay of cassettes due to a particular missing odd-sized sensor

Charge #3,5

Critical Path items for 402.4.3

- Although sensor production will start early (through CD3A approval), delivery of final sensors drives the final critical path
  - Capacity of vendor is limited
  - Could be partially mitigated by reducing tested fraction (based on demonstrated good yield)
  - If a problem develops at the US sensor testing site, could rely on international testing sites
- Schedule concern about odd-sized sensors has been reduced by new design
  - Previously, we were concerned to have enough of each design available, since each odd-sized sensor was a separate mask while all types of modules are needed to assemble the first set of cassettes
  - With the new design, the choice is made at the point of dicing, which is much simpler for maintaining throughput at the vendor

Contributing Institutions and Resource Optimization

Charge #4

Contributing Institutions

- Florida State University
  - Pre-series and production sensor testing
  - Rachel Yohay: former CMS pixel operation coordinator (2014-2016)
- Brown University
  - Sensor radiation testing
  - Ulrich Heintz: major contributions to CMS Phase 0 strip tracker, D0 silicon vertex detector, and CMS Phase 2 OT
- Fermilab
  - Sensor design team, prototype sensor testing and radiation testing
  - Ron Lipton: long career in silicon detector development, including D0 silicon vertex detector
- University of Rochester
  - Prototype sensor testing, planned role is complete (focused on tracker), but could serve as a backup testing facility
  - Regina Demina

Resource Optimization

- Fermilab has been a leader in CMS silicon detector development and construction
- With Brown, we profit from parallel involvement in the CMS OT (for example, use of common test structures) and shared infrastructure
- Florida State could already supply a clean room, light engineering support, and scientific labor, and has been supported by Fermilab (e.g. donated probe station)
- All work done in-house save for the sensor production
- **Sensor testing by project is a crucial step in QC**

ES&H

- As with entire project, we follow the Integrated Safety Management Plan (cms-doc-13395) and have documented our hazards in the preliminary Hazard Awareness Report (cms-doc-13394)
- Specific Hazards for 402.4.3 are
  - Exposure to ionizing radiation
    - Irradiation campaigns at RINSC follow defined protocols at RINSC during irradiation and for release of samples, Brown University protocols during measurement
  - Work with high voltages
    - Safe design of bias configuration and appropriate training for all staff members involved
- Planning ES&H and QA/QC site visit to FSU in early 2020

Summary

- Sensor design well advanced, accepted by vendor and quality sensors received
- Procurement, prototyping, and QA/QC plan well documented and budgeted (labor hours and cost)
- Plan for remaining R&D items exists and does not pose a serious risk to the project
  - "Fine-tuning" activities to streamline testing and maximize yield
- **Ready for CD-3A in early 2020**

Cost Estimate

CMS Driver	Labor (FTE-yrs)	Labor BAC (M$)	M&S BAC (M$)	Total BAC (M$)
CE.3 - Si sensors purchase (M&S)	**0.0**	**0.0**	**7.7**	**7.7**
CE.7 - Concentrator ASIC (labor)	**9.7**	**2.8**	**0.0**	**2.8**
CE.5 - Silicon motherboard (M&S)	**0.0**	**0.0**	**2.5**	**2.5**
CE.5 - Cassette assembly and testing (labor)	**15.9**	**2.4**	**0.1**	**2.4**
CE - Calo Endcap integration and commissioning	**5.0**	**0.6**	**1.7**	**2.3**
CE.4 - Module circuit boards	**2.8**	**0.3**	**1.6**	**1.9**
CE.7 - Power system	**1.3**	**0.2**	**1.6**	**1.9**
CE.6 - Scintillator panels	**12.9**	**0.9**	**0.8**	**1.7**
CE.7 - Concentrator ASIC (M&S)	**0.0**	**0.0**	**1.7**	**1.7**
CE.4 - Module assembly and testing (UCSB)	**14.1**	**1.4**	**0.1**	**1.5**
CE.5 - Cassette tooling and test stands	**1.8**	**0.4**	**0.9**	**1.3**
CE.4 - Module assembly and testing (Texas Tech)	**14.4**	**1.2**	**0.1**	**1.3**
CE.4 - Module assembly and testing (CMU)	**13.5**	**1.1**	**0.1**	**1.2**
CE.5 - Silicon motherboard (labor)	**4.3**	**1.1**	**0.0**	**1.1**
CE.2 - Travel	0.0	0.0	1.0	1.0
CE.2 - Project engineering	2.7	0.9	0.0	0.9
CE.6 - SiPM purchase (M&S)	0.1	0.0	0.9	0.9
CE.6 - Scintillator motherboards	2.4	0.4	0.5	0.9
CE.5 - Cassette cooling plates (labor)	3.6	0.8	0.0	0.8
CE.5 - Cassette interface and cables	1.7	0.3	0.4	0.7
CE.4 - Establish site (UCSB)	3.9	0.6	0.1	0.7
CE.3 - Si sensors testing	8.4	0.5	0.2	0.7

Dead cell energy resolution study

- EM energy resolution in CE-E for scenarios with randomly killed silicon channels
  - 0%, 0.5%, 1.0%, 1.5%, and 5.0% killed scenarios
- *Averaging hits in neighboring layers can mitigate the resolution loss (1.98% → 1.84%)

Fraction randomly killed CE-E channels	EM energy resolution constant term
0%	1.76%
0.5%	1.83%
1.0%	1.98%*
1.5%	2.01%
5.0%	2.38%