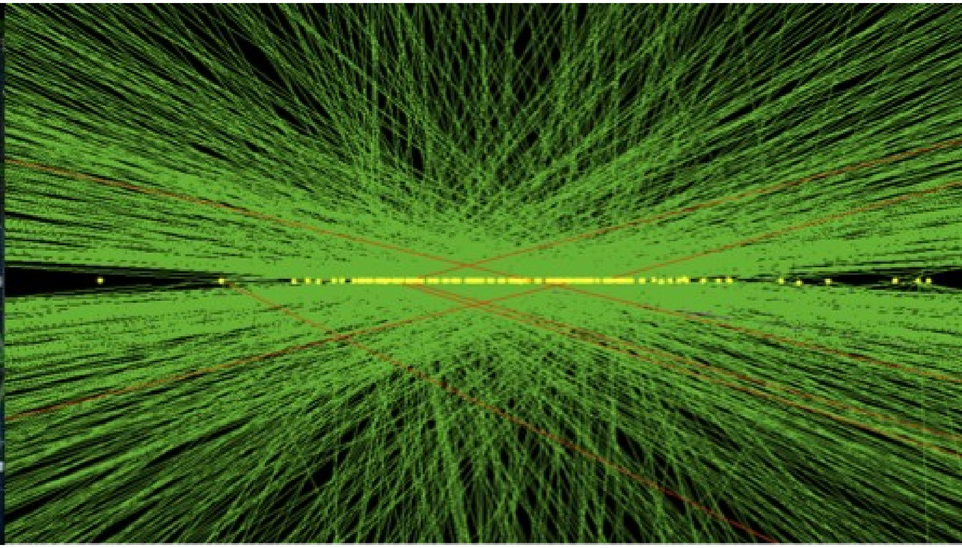
B03 - Endcap Calorimeter: Si Modules

Manfred Paulini

HL LHC CMS CD-1 Review

October 23, 2019



Outline

- Technical Aspects of 402.4.4.3 - 402.4.4.5
  - Conceptual Design
  - Scope and U.S. Deliverables
  - Module Assembly Overview and Workflow
  - Progress since June 2018 IPR
  - QA/QC
- Managerial aspects of 402.4.4.3 - 402.4.4.5
  - Cost, Schedule, and Risks
  - Contributing Institutions
  - ES&H
- Summary

Charge #5

Biographical Sketch

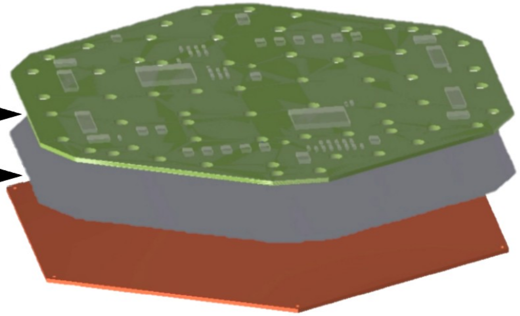
- **Manfred Paulini:** L3 manager for CE Sensors & Modules 402.4.3 and 402.4.4 together with Nural Akchurin (TTU)
- Professor of Physics (Carnegie Mellon University - 2000)
- Work on CMS: ECAL Data Quality Monitoring
- Physics: Search for new physics with photons in final state
  - Co-convener of SUSY-Photon subgroup (2012 - 2013)
- Leadership:
  - Chair of US-CMS ECAL Institutional Board (2013 - 2015)
  - LPC Management Board (2015 - 2017)
  - LPC Guest & Visitor Program (2018 - present)
  - Senior CMS Distinguished Researcher (2013)
  - Fellow of APS
- Hardware Experience: Work on CDF Silicon Vertex Detector
  - Test of SVX3 readout chip, production of hybrids, design of HDI cables
  - Commissioning and maintenance of Run I Silicon Vertex detector

Conceptual Design

Deliverables for 402.4.4.3-5

Charge #2

- Assembly of 8" modules consisting of base-plate, silicon sensor, and hexaboard PCB with readout ASIC, all glued to form solid stack & wire-bonded for electrical connection



- Operation of CE at -30° C requires good contact of base-plate to cooling plate and thermal matching of base-plate to Si sensor resulting in PCB as choice for base-plate
- Wire-bonding through holes in hexaboard PCB
- U.S. is responsible for all hadronic (CE-H) Si-modules consisting of 10,140 full-size hexagon modules plus all partial (odd-size) modules for CE-H & electromagnetic section CE-E (6041 total) including 5% for construction spares and 4.2% for test-beam unit

402.4.4.3-5 Module Factories

Charge #4

- U.S. (UCSB) is leading development of common and reliable process for assembly and testing of modules:
  - US module assembly sites: UC Santa Barbara [odd-size], Carnegie Mellon (CMU) & Texas Tech (TTU) [standard size]
  - International assembly sites for standard electromagnetic modules: China, India, Taiwan
- Design and commissioning of custom tooling (UCSB)
- Setup of 3 U.S. module assemble factories almost complete with sites in commissioning phase
- Each factory established ISO7 (class 10000) clean room
- Procurement of major equipment mostly achieved
  - Automated gantry for parts pick-up & placement (AEROTECH AGC10000, 1.25x1.25 m) plus epoxy dispensing unit
  - Automated wire-bonder (Hesse BJ820) & wire-bond pull tester
  - Optical measurement tool for inspection (OGP) [not yet acquired]
  - Thermal testing enclosure for thermal cycling tests of modules
  - Shipping crates for safe module delivery to cassette site

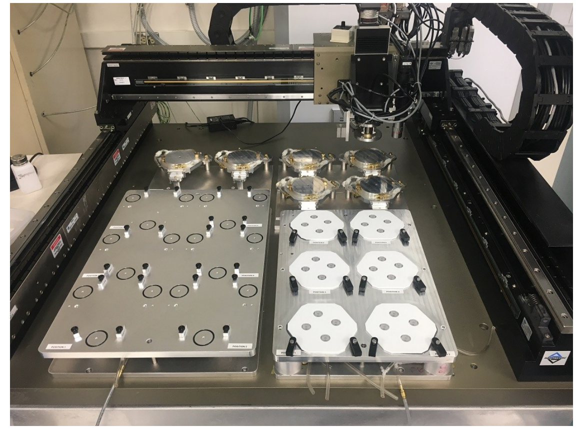
Module Assembly Workflow

Charge #4

Base-plates

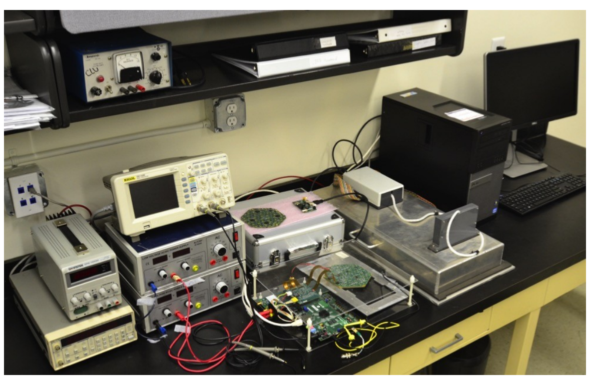
Silicon sensors

Module PCB



Assembly/gluing on gantry

Wire-bonding



Testing

Module Assembly Requirements

Charge #4

Manpower Estimates

- Module assembly procedures modeled after CMS Run 1 Outer Tracker experience and 6" module assembly R&D at UCSB
- Senior engineer for supervising technicians, students, overall production quality and schedule of modules
- Day shift to produce 16 modules per day
  - 2 Senior technicians handling module assembly on gantry and for wire-bonding of modules
  - 2 Junior technicians for supporting gantry operations, setup of thermal cycling system, receiving, inspection, stocking of parts, etc.
  - 2 FTE undergraduate student technicians for module thermal cycling, testing, data analysis and cataloging
- Evening shift to produce 8 modules per day
  - 1 Senior plus 1 Junior technician plus 1 FTE undergraduate technician for module assembly on gantry, wire-bonding, module testing, etc.

Module Assembly Requirements

Charge #4

- Production requirements for CE-H standard modules
  - 24 complete modules per day each at CMU and TTU
  - Production rates and task distributions with >75% duty factor on equipment
  - Ship 2x120 modules per week to cassette assembly site
  - Capacity to produce 2x160 per week exists, if needed
  - 46 weeks is estimated to complete production of standard modules
- Production of odd-shaped modules for all of CE-H
  - Odd-shaped modules require specialized assembly procedure at UCSB resulting with lower rate and setup time to switch shapes
  - Estimate 80 modules per week to complete task of assembling 2552 odd-sized CE-H modules in ~22 weeks
- Production of odd-shaped modules for all of CE-E
  - U.S. also constructs odd-shaped modules for entire CE-E section
  - Estimate another 31 weeks production with 80 modules/week to assemble 3489 odd-sized CE-E modules

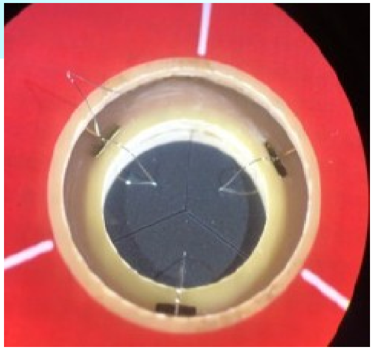
R&D Achieved

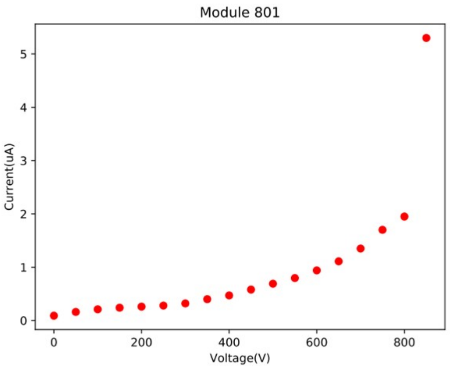
- Development of assembly and test procedures is main R&D focus
  - Successfully assembled and operated about 55 6" prototype modules for test-beams in late summer 2018
  - Prototype versions of 8" hexabords produced with SkiROC2-CMS chip
  - Tooling adapted for 8" modules and six 8" silicon modules were built at UCSB pilot site
    - All 6 modules are functional - currently tested at UCSB & CERN
  - CMU & TTU assembly sites have most equipment in place undergoing hardware commissioning process
  - Using dummy silicon & base-plates together with new hexaboards allowing assembly centers to be on track for site certifications

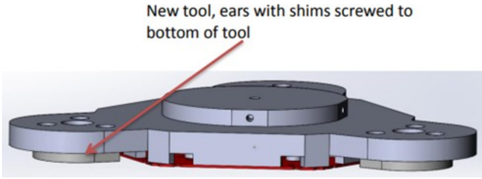
Status of UCSB Pilot Site

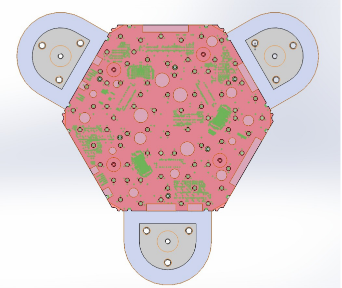
Status

- Six 8" modules built at UCSB
  - All modules are functional and currently further tested at UCSB and CERN
- Further R&D with module testing
  - Updated test-stand firmware
  - Continue thermo-mechanical studies
  - Validate 8" pick-up tools with dummy parts
  - Refine and test automation of data entry from assembly steps into DB for QC
- Setup of other module assembly sites
  - Distribute gantry-head fixed pick-up tools to TTU & CMU assembly sites
  - Same for tools and components



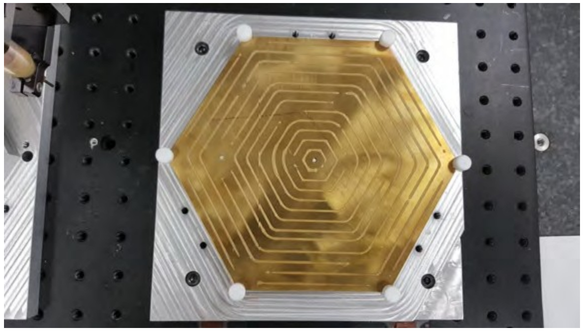


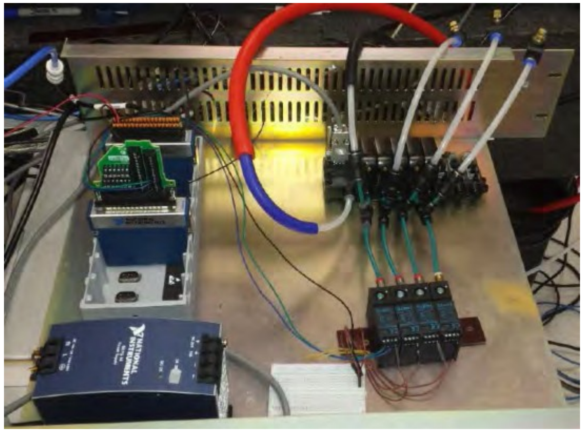


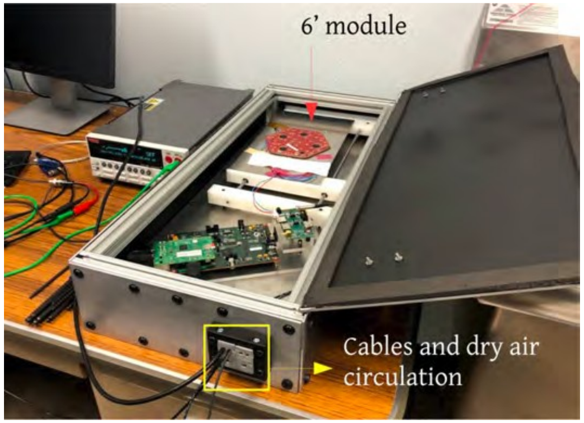


Status of TTU MAC

- Gantry and wire-bonder operational
  - Glue dispensing studies conducted with different gantry speeds and dispensing parameters
  - Vacuum valves and switches setup for pick-up and place tools
  - Awaiting gantry tooling from UCSB
- Setup of single module test-stand
  - Test-stand ready for dry air circulation
  - Measured IV characteristics for some 6" modules
  - Get familiar with module test operation
- Other:
  - Air dryer installed
  - Thermal chamber setup in lab







Status of CMU MAC

- Wire-bonder operational
  - Wire-bonder exercises: threading, bonding, pull testing on test plates
- Gantry delivered
  - Complicated delivery successful but
  - Gantry arrived damaged: Broken sensor and rust on rail
  - Working with vendor on repairs
- Other:
  - Humidity stabilized and monitoring
  - Purchased vacuum components
  - 2nd clean room for module testing almost completed
  - Getting test-stand from CERN setup

R&D Needed Before Production

Status

Schedule organized in 3 major phases:

- R&D Phase (completed)
  - Construction of modules for test-beam and mechanical 8" mock-up
  - Demonstrated automated assembly of 55 6" modules for test-beam
- Prototyping Phase (ongoing)
  - 2 Prototyping cycles (Prototype-1, Prototype-2)
- Production Phase (planned)
  - 5% Pre-series with full review
- Goal to establish automated assembly procedures at all module assembly sites by August 2020
  - Demonstrated automated 8" module assembly at UCSB
  - Winter 2019/20: Prototype-1 to assemble full CE-H cassette (produce 100 modules with mix of dummy and live sensors)
  - Winter 2020/21: Prototype-2 assembly with all live silicon sensors and module PCB's with HGCROCV3 readout chip

R&D Needed before Production

Charge #2

- Readiness review before full production phase
  - 5% pre-series construction of modules in 2022 with full review of all assembly procedures
  - Full production at assembly sites in 2022-24 following procedures established at pilot site
- Both Prototype cycles used to establish procedures
  - Prototype-1 will validate key design choices
  - Prototype-2 will validate engineering for baseline design
- Experience with Prototype-1&2 phases crucial to develop list for quality control
- We understand how to build modules (design maturity more than sufficient for CD-1 and documented)
- Module assembly close to have reached full CD-2 maturity

Quality Assurance & Quality Control

Charge #2

- For module assembly: UCSB as "pilot site" is taking lead at establishing common module assembly and testing procedures for other U.S. and international assembly sites
  - Simple robust production design
  - Continuous study and improvements of work-flows during prototype phases and pre-series
  - Automation of assembly procedure (gantry robot, wire-bonding)
  - Develop detailed procedures for every task and logistical plans for assemble and quality control to be shared among sites
  - Extensive testing, burn-in, and thermal cycling procedures
  - Cross training of technicians to work at other sites if needed
- Uncover/analyze failure modes through 2 prototype cycles and 5% pre-series review before full production

Quality Assurance & Quality Control

Charge #2

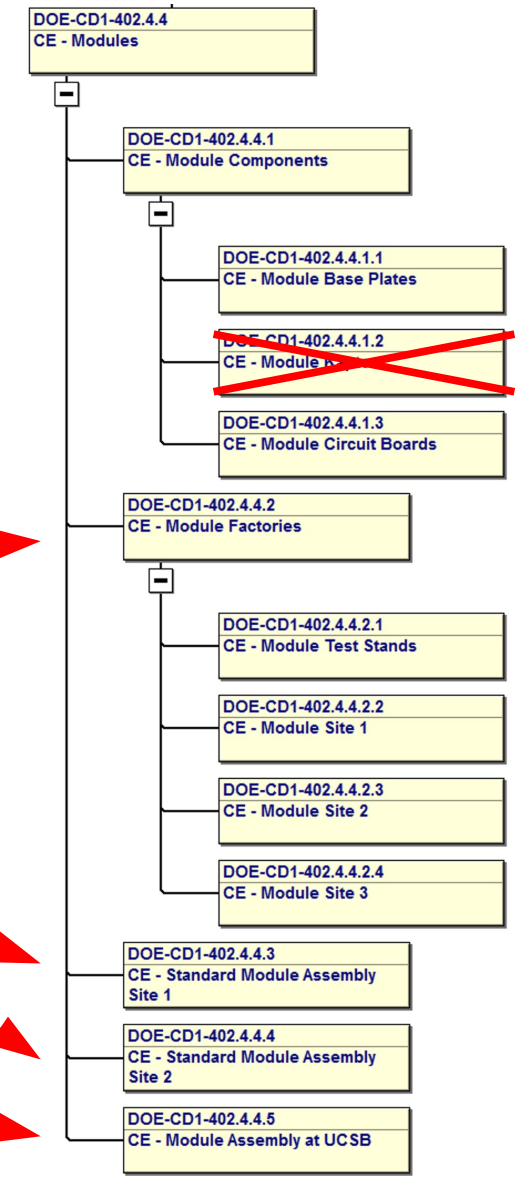
- Overall strategy defined by project in Quality Assurance Plan (CMS-doc-13093)
- Quality Assurance
  - Use of prototype sequence to validate procedures and availability of vendors
  - Testing of assembled modules in test-beams and through irradiation contributes to QA
- Quality Control
  - Module components arrive tested at assembly sites
  - Extensive testing of complete modules at assembly sites including thermal cycling before shipment
  - Use database to track all components through assembly and testing (development of DB under FNAL lead)

Cost and Schedule

402.4.4 WBS Structure

Module Assembly

- US develops detector-wide standard procedures for silicon module assembly, constructs all hadronic silicon modules and all odd-size modules for the electromagnetic section
- 402.4.4.2: Setup of Module Factories (CMS-doc-13204)
- 402.4.4.3/4: CMU & TTU each assemble, test and deliver 5070 standard modules to cassette sites (CMS-doc-13031/13032)
- 402.4.4.5: UCSB assembles, tests and delivers 6041 odd-size modules (CMS-doc-13033)



Cost Estimate

Charge #3

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-CD1-402.4.4 CE - Modules	2,932,730	96412	54.53	8,405,886	1,435,046	9,840,932
DOE-CD1-402.4.4.1 CE - Module Components	1,382,564	7744	4.38	2,051,899	547,065	2,598,964
DOE-CD1-402.4.4.1.1 CE - Module Base Plates	24,153	1192	0.67	145,031	20,499	165,530
DOE-CD1-402.4.4.1.3 CE - Module Circuit Boards	1,358,411	6552	3.71	1,906,868	526,566	2,433,434
DOE-CD1-402.4.4.2 CE - Module Factories	948,868	7500	4.24	1,358,597	134,953	1,493,549
DOE-CD1-402.4.4.2.1 CE - Module Test Stands	104,364	6740	3.81	370,441	76,281	446,722
DOE-CD1-402.4.4.2.2 CE - Module Site 1	487,601	360	0.20	570,114	27,665	597,779
DOE-CD1-402.4.4.2.3 CE - Module Site 2	356,903	400	0.23	418,042	31,007	449,049
DOE-CD1-402.4.4.3 CE - Standard Module Assembly Site 1	141,706	25528	14.44	1,370,692	233,159	1,603,851
DOE-CD1-402.4.4.4 CE - Standard Module Assembly Site 2	134,670	23842	13.49	1,258,023	220,773	1,478,796
DOE-CD1-402.4.4.5 CE - Module Assembly at UCSB	324,922	31798	17.99	2,366,675	299,095	2,665,771
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

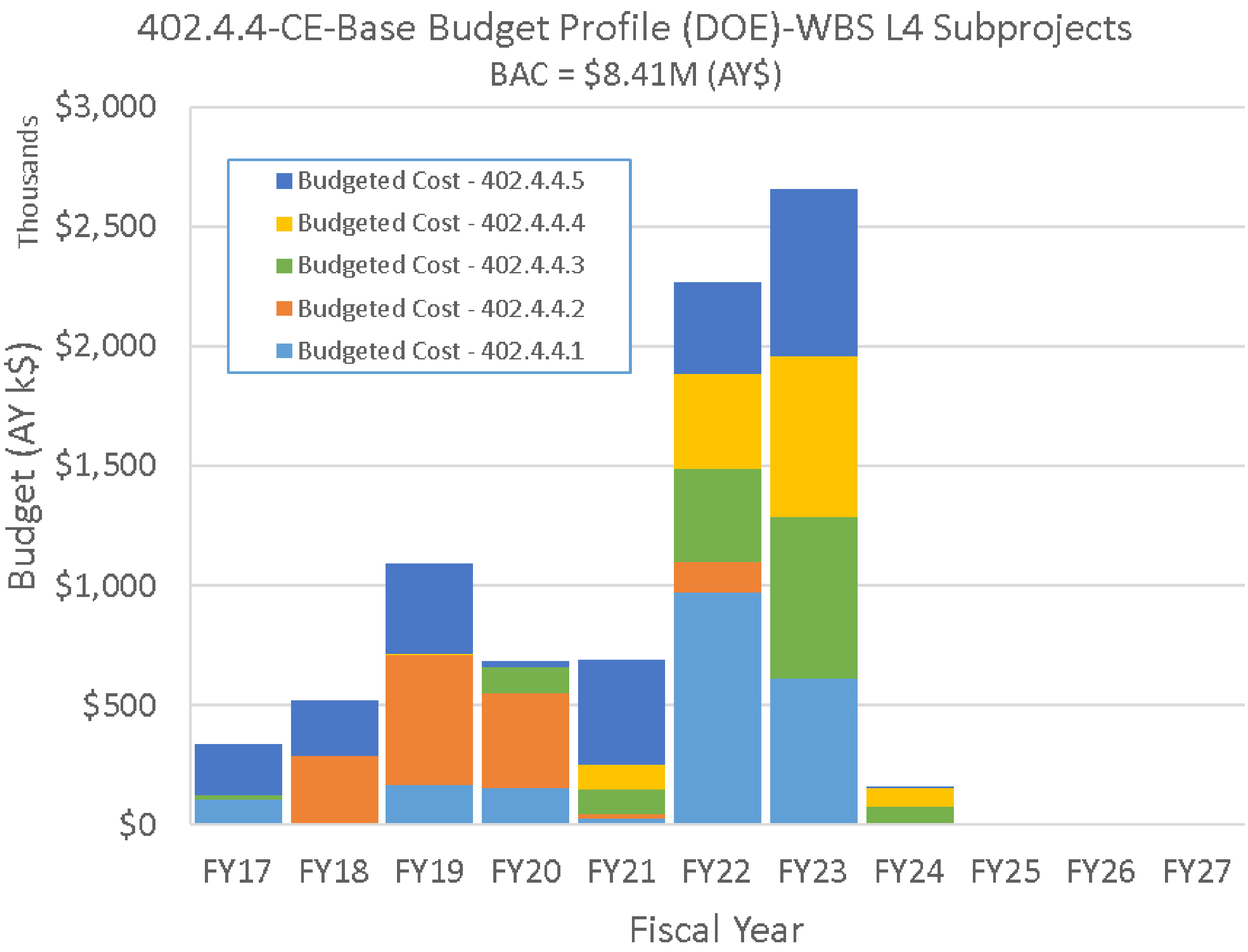
- M&S drivers
  - Module factories setup and labor for production

Cost Drivers

Charge #3

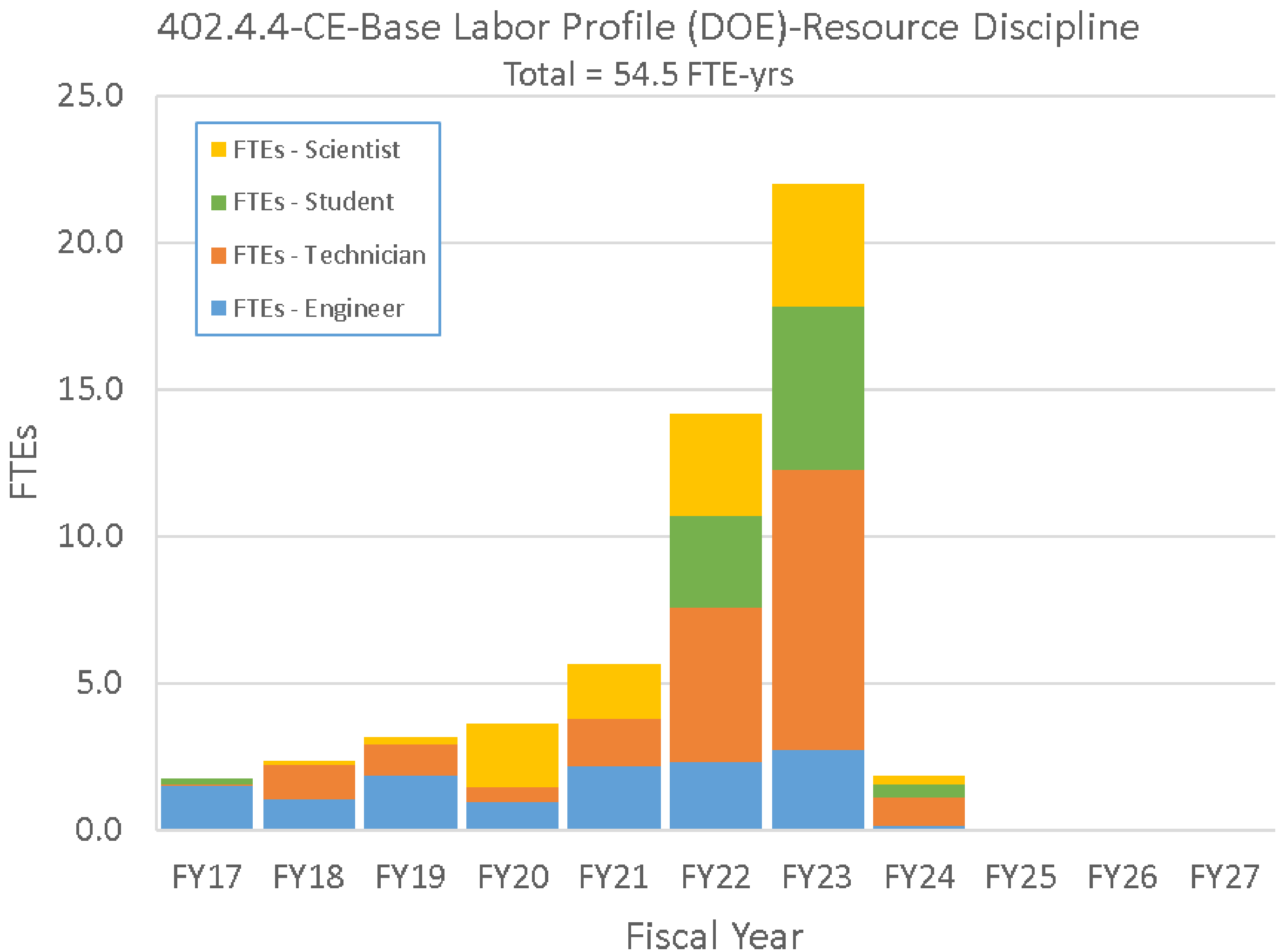
CMS Driver	Labor (FTE-yrs)	Labor BAC (M$)	M&S BAC (M$)	Total BAC (M$)
CE.3 - Si sensors purchase (M&S)	**0.0**	**0.0**	**7.7**	**7.7**
CE.7 - Concentrator ASIC (labor)	**9.7**	**2.8**	**0.0**	**2.8**
CE.5 - Silicon motherboard (M&S)	**0.0**	**0.0**	**2.5**	**2.5**
CE.5 - Cassette assembly and testing (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
CE.2 - Shipping	1.3	0.2	0.4	0.6
CE.6 - SiPM testing	2.7	0.6	0.1	0.6
CE.4 - Establish site (Texas Tech)	0.2	0.0	0.5	0.6
CE.4 - Establish site (CMU)	0.2	0.0	0.4	0.4
CE.4 - Module test stands	2.0	0.3	0.1	0.3
CE.4 - Module base plates	0.7	0.1	0.0	0.1
CE.2 - Miscellaneous (M&S)	0.0	0.0	0.1	0.1
CE.5 - Cassette cooling plates (M&S)	0.0	0.0	0.1	0.1

Fiscal Year Cost Profile



- Significant increase in costed labor during production

Labor Profile

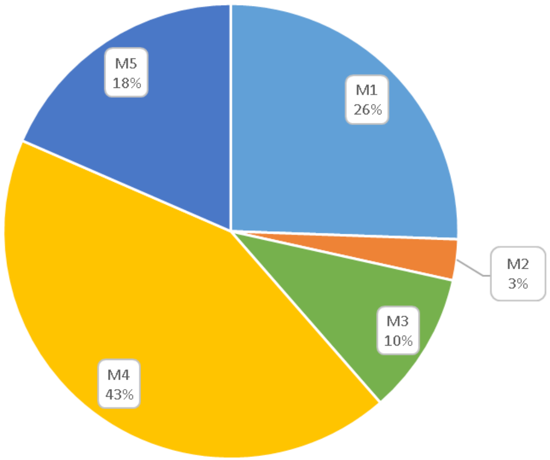


- Postdocs and grad students essential for module testing and data analysis

Estimate Uncertainty Breakdown

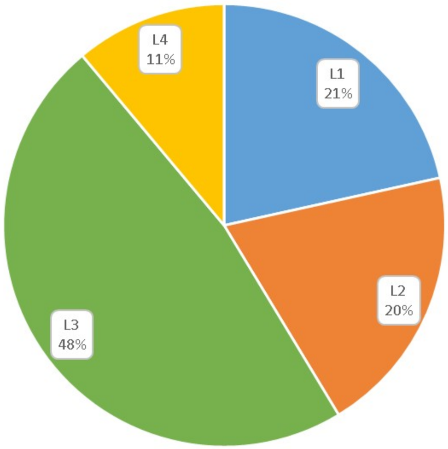
Charge #3

402.4.4-CE-Estimate Uncertainty Breakdown-M&S (DOE)
BAC (M&S)=$3.39M (AY$)



WBSL3	402.4.4
Funding Type	(All)
Scope Type	(All)
Sum of Value	**Column Labels**
Row Labels	**Budgeted Cost**
M1	$866,075
M2	$98,476
M3	$342,921
M4	$1,455,151
M5	$625,911
Grand Total	**$3,388,534**

402.4.4-CE-Estimate Uncertainty Breakdown-Labor (DOE)
BAC (Labor Budget)=$5.02M (AY$)



WBSL3	402.4.4
Funding Type	(All)
Scope Type	(All)
Sum of Value	**Column Labels**
Row Labels	**Budgeted Cost**
L1	$1,081,098
L2	$992,930
L3	$2,386,873
L4	$556,451
Grand Total	**$5,017,352**

Using standard OPSS EU method – the EU is reasonable for this stage of the project

Charge #3,5

Risks

RT-402-4-02-D CE - Infrastructure failure at module assembly facility

Risk Rank:	2 (Medium) **Scores:** Probability : 3 (M) ; Cost: 2 (M) Schedule: 2 (M))	**Risk Status:**	Open
Summary:	A significant failure could occur in a module assembly facility which renders it unable to operate for some period of time. Examples would include flooding of the facility or severe damage to the gantry system used for the gluing of modules.		
Risk Type:	Threat	**Owner:**	Manfred Paulini
WBS:	402.4 CE - Calorimeter Endcap	**Risk Area:**	External Risk / Facilities
Probability (P):	30%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 2-point - flat range Minimum = 100 k$ Most likely = N/A Maximum = 336 k$ Mean = 218.0 k$ P * <Impact> = 65.0 k$	**Schedule Impact:**	PDF = 2-point - flat range Minimum = 1.0 months Most likely = N/A Maximum = 4.0 months Mean = 2.5 months P * <Impact> = 0.75 months
Basis of Estimate:	Probability = 30% for 3 sites. Probability per site = 10%, based on experience from original CMS tracker, original pixel, and Phase 1 pixel where one incident occurred in O(10) sites. Cost: Cost for sufficient modules to recommission the system and a possible standing-army cost to maintain the team while repairs are carried out. Assume 40 modules for recommissioning at a cost (including labor) of $40k. Standing army costs are estimated at $58k/month. Costs for repair of flooding are assumed to be covered by insurance, while costs for a damaged gantry are estimated as 25% of total replacement cost or $64k. Total of $100k to $336k depending on damage and delay. Schedule: delay of 1 to 4 months.		
Cause or Trigger:		**Impacted Activities:**	In the risk MC this risk needs to be duplicated once for each centre
Start date:	1-Jan-2022	**End date:**	30-Sep-2023
Risk Mitigations:	Mitigate schedule delays and standing army costs by using uniform procedures at all module assembly sites. The plan is constructed to allow some excess capacity at each site.		
Risk Responses:	In the case of a serious failure, some staff and production work can be transferred to the other sites, possibly adding a weekend day to the shift cycle. Costs for travel would be incurred, assumed to be at the level of $4k/month/technican.		
More details:			

- Risks are understood from past experience
- Planning project accordingly (e.g. >1 assembly center)

Charge #3

Schedule Overview

- Production process of module assembly is sufficiently well understood for a project at this stage
- Documented workflow with associated cost and schedule in associated Basis of Estimate (BoE) documents
- Cost and schedule are loaded into P6 to create full Resource Loaded Schedule including relationships between activities and appropriate milestones

<u>Schedule organized in three major time-phases:</u>

- R&D Phase (completed)
  - Successful construction of 6" modules for test-beam
  - Construction of mechanical 8" mock-up for realistic mock-up cassette
- Prototyping Phase (FY19-21)
  - 2 Prototyping cycles to validate design before construction
- Production Phase (FY22-24)
  - 5% Pre-series with full review followed by production phase

Charge #3,5

Milestones for 402.4.4

Milestone	Date
Module assembly pilot site (UCSB) and procedures setup	Jun 2019
HGCROC V3 submission	Feb 2020
CMU & TTU Modules Sites qualified	Aug 2020
Final Hexaboard qualified	Feb 2021
HGROC ready for mass production	Apr 2021
Final system qualified	May 2021
Final modules qualified	Dec 2021
5% of modules completed	Jun 2022
50% of modules completed	Jun 2023
Module construction complete	Feb 2024

- Milestones above track project from prototype to production phase

Critical Path Items for Module Assembly

Charge #3,5

- Critical path includes production of all types of modules to begin cassette assembly
  - Especially critical at start of production and between 5% pre-series and main production
  - Lesser of an issue toward end of production
- Critical items are
  - Delivery of module PCB which depends on readiness of HGROC readout chip
  - Potential delay in silicon availability or low yield
- Mitigate standing army costs and risk of delay by procuring about 10% of module components (base-plate & PCB) for pre-series, which nominally only requires 5%
- Schedule allows for short-term 25% rate increase to address rework and fluctuations in component availability

Contributing Institutions and Resource Optimization

Charge #4

Contributing Institutions

- UC Santa Barbara
  - Module assembly pilot site with experienced personnel (Incandela) and engineers (Dean, Kyre) involved in Run 1 CMS Outer Tracker
  - Well matched experience as assembly site for odd-sized modules

- Carnegie Mellon and Texas Tech
  - Sites for assembly of standard modules
  - Group leaders (N.A. & M.P.) serve as L3 managers

- Kansas State University
  - Development of test-stands and hexaboard testing procedures with experienced electrical engineer
  - Motivated group leader serves as L4 manager (K. Kaadze)

HL-LHC US CMS

Charge #4

Resource Optimization

- Module pilot site (UCSB) with extensive experience from CMS Run 1 Outer Tracker construction
- Transfer of detailed assembly procedures to other assembly sites (cross training of technicians)
- Significant cost-savings in setup of module factories from previous detector construction project or setup cost-contributions from institutional resources
- Access to lower cost university labor resources
- Access to pool of low cost undergraduate labor resources at university
- More assembly sites allow for down time at one site
- Overall optimization of project across institutions

ES&H

- 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)
- ES&H review of HGC module activities at UCSB took place in July 2019. ES&H and QA reports with observations and recommendations documented in cms-doc-13856 and updated on routine basis
- In general, safety is achieved through standard Lab practices with module assembly carried out in clean-room
  - Automated gantry, automated wire-bonder, use of epoxy
- Specific hazards for module assembly are
  - Module testing will follow common practices (thermal cycling to -30 C, HV up to 1 kV)

Summary

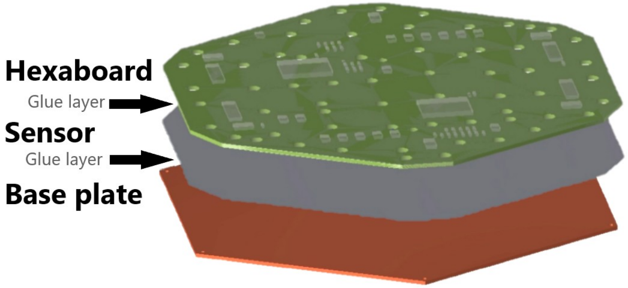
- Module assembly is based on pilot site developing robust and reproducible procedures
- Conceptual design is developed meeting requirements with module assembly essentially having reached full CD-2 maturity
- Standard module assembly sites procured most of the equipment - currently in commissioning
- Development of qualification procedures started
- Cost, schedule and risks are understood
- ES&H and QA/QC addressed
- Thank you for your comments

Additional Slides

BACK UP

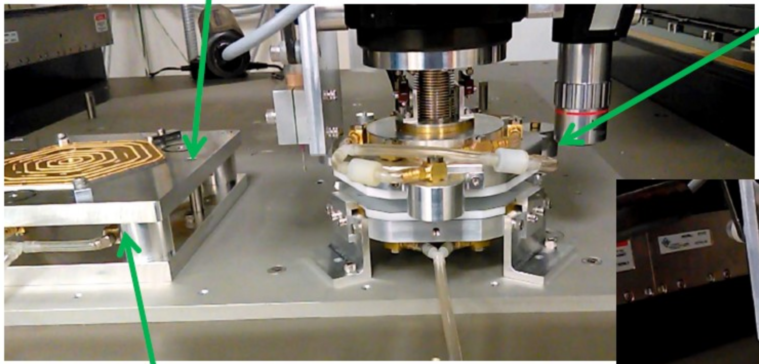
Gantry Processes

- Place and glue together base-plate to Si-sensor and module PCB with readout ASIC to form solid stack
  - Pipelined process (place/glue/cure) requiring 2 days
  - Duration and labor determined based on experience with test-beam modules
  - Tooling adapted for 8” modules from experience with 6”

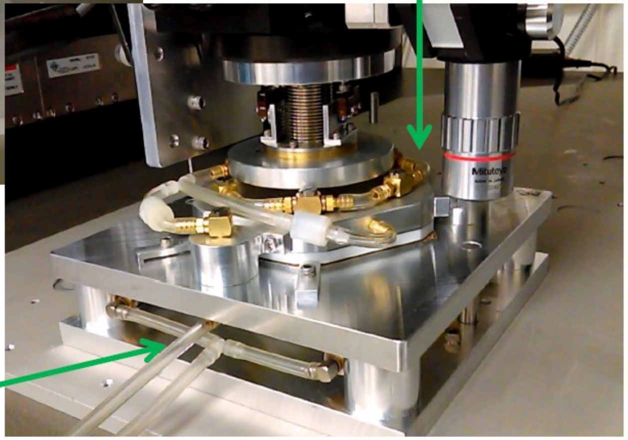


(1) Module assembly base plate is vacuum chucked during assembly to make sure it does not move.

(3) Just about to pickup sensor

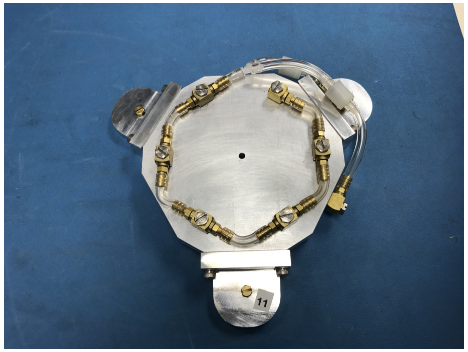


(4) Sensor just placed on to the baseplate.



(2) Glue dispensed on aluminum baseplate with kapton

(5) External vacuum applied so that module can be removed from gantry for overnight cure.

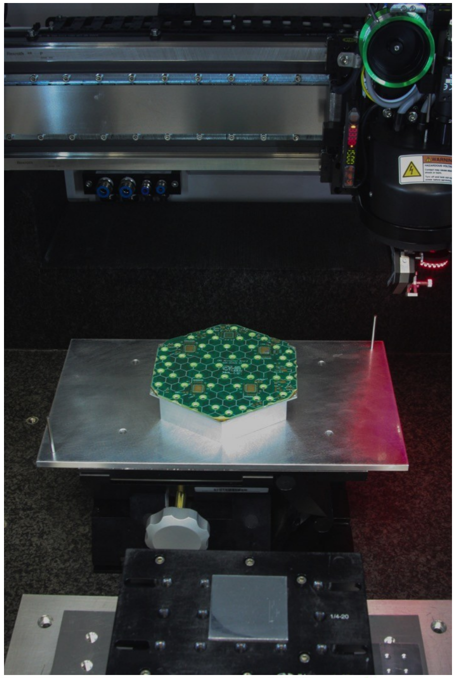


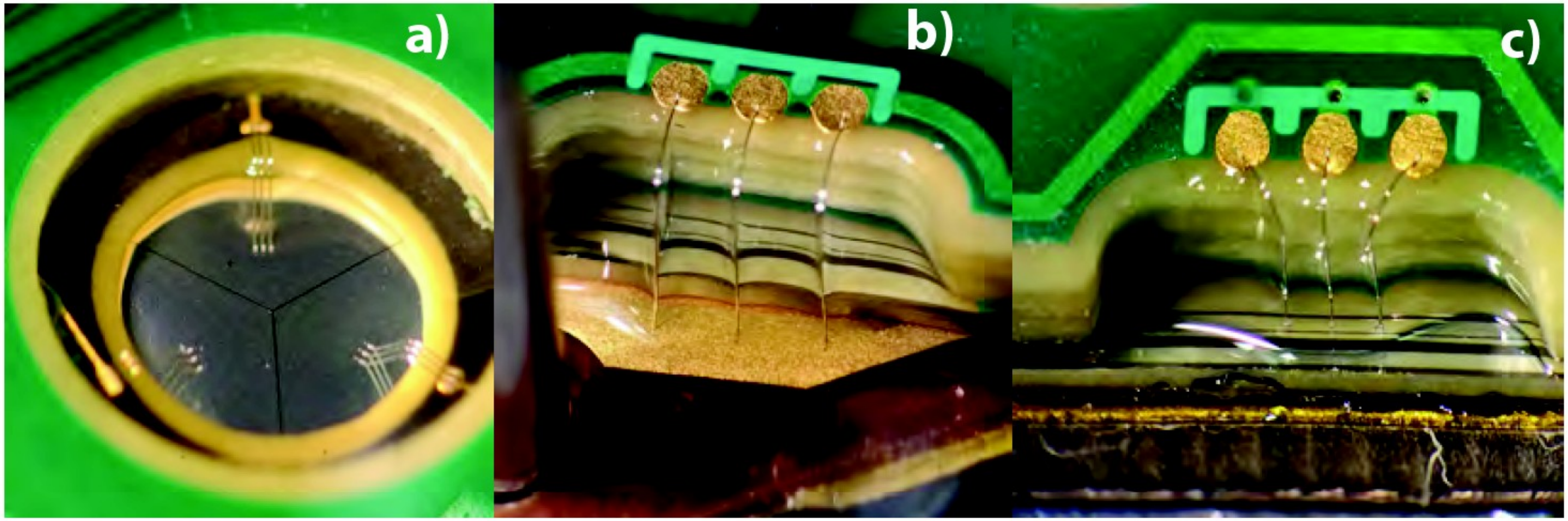
Sensor Pick-up Tool

Automated Wire-Bonding

Charge #4

- Precision wire-bonding required
  - (a) through stepped holes to sensor pads
  - (b) to backplane for sensor biasing
  - (c) at edge of module to sensor guard rings
- Duration/labor time determined based on test-beam experience, scaled to larger modules and faster bond rate

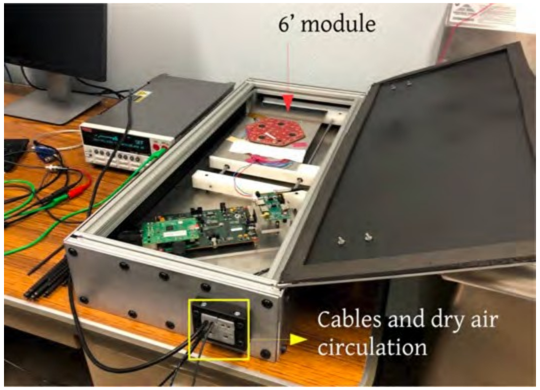




Module Assembly Procedure

Charge #4

Module Testing



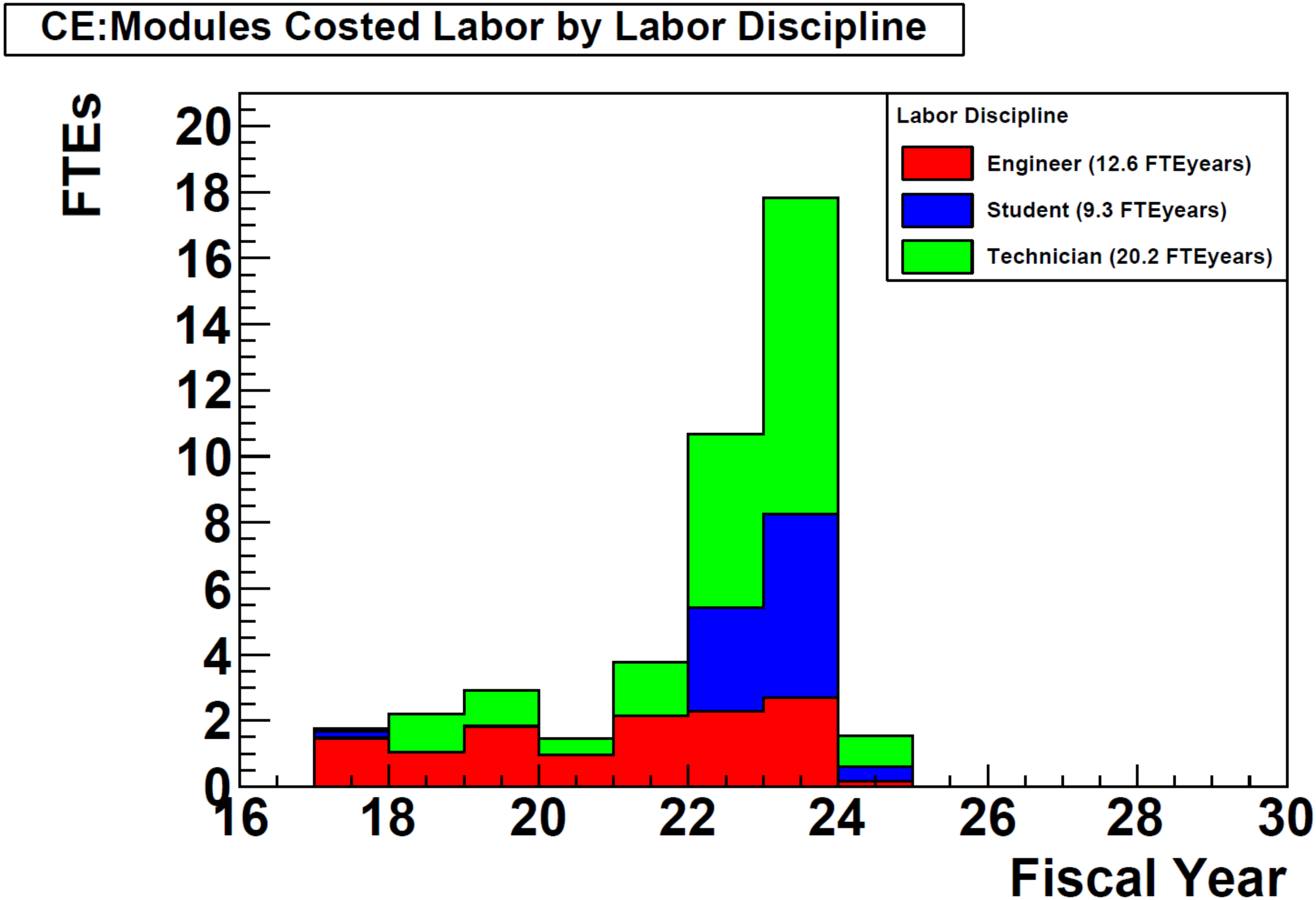
Testing of bonded modules

Thermal testing overnight

Shipping

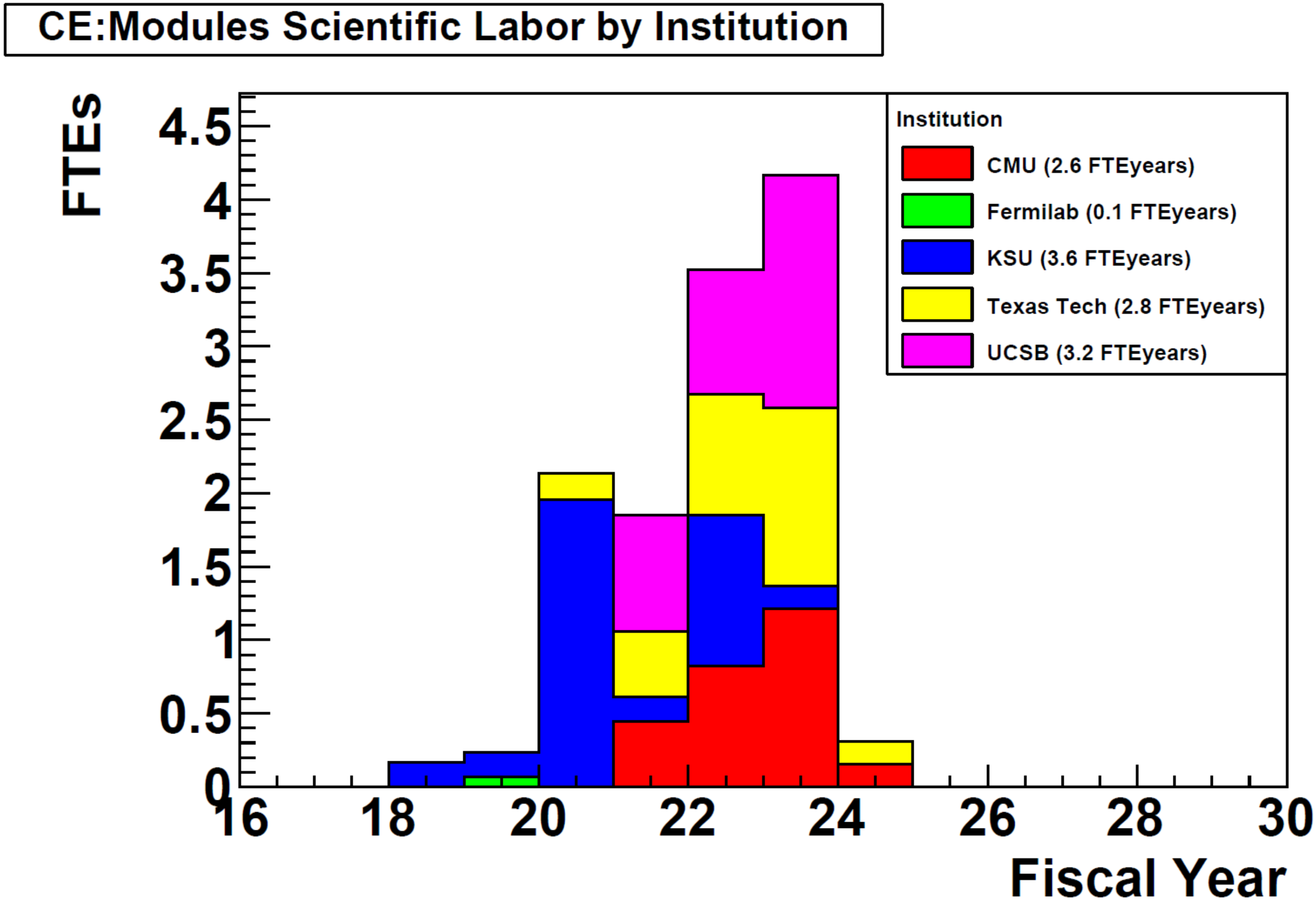
Packing and shipping of fully tested modules to cassette assembly site

Fiscal Year Cost Profile



- Significant increase in costed labor during production

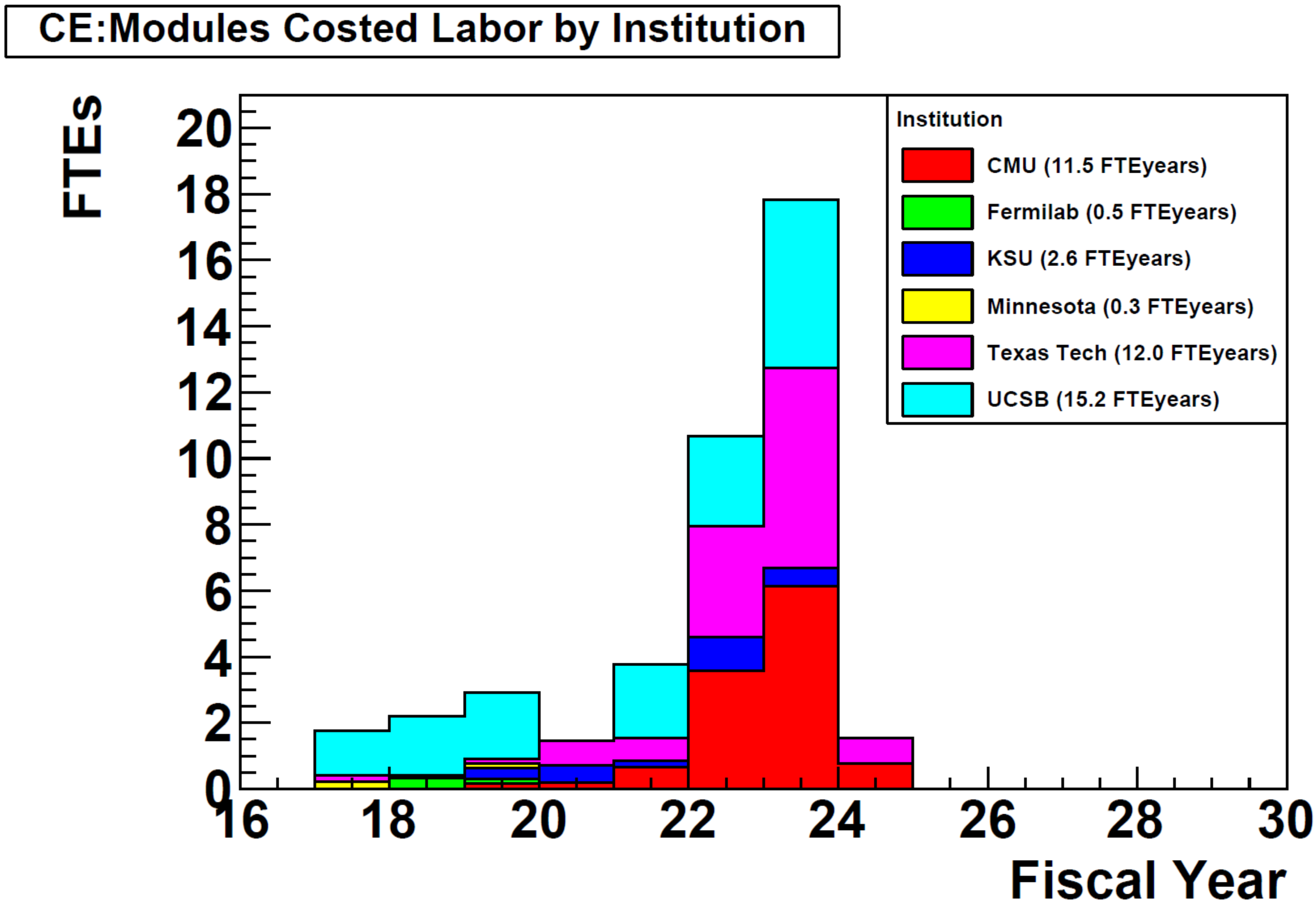
Contributed Labor Profile



- Postdocs and grad students essential for module testing and data analysis

Fiscal Year Cost Profile

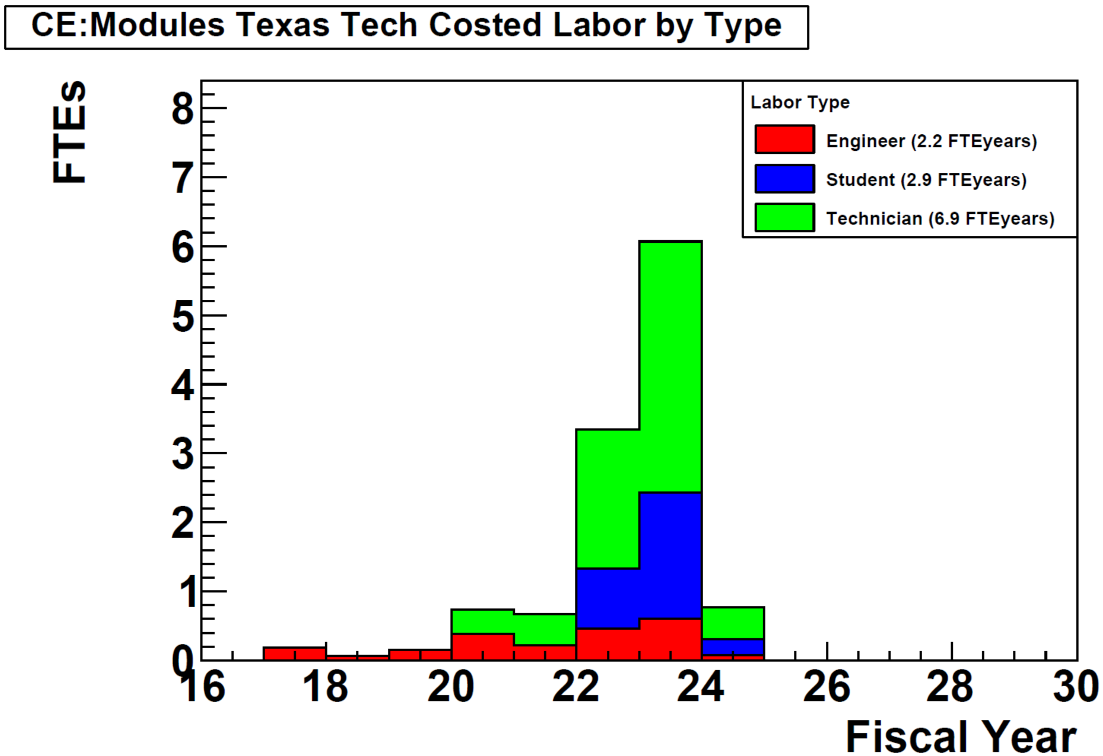
Charge #3

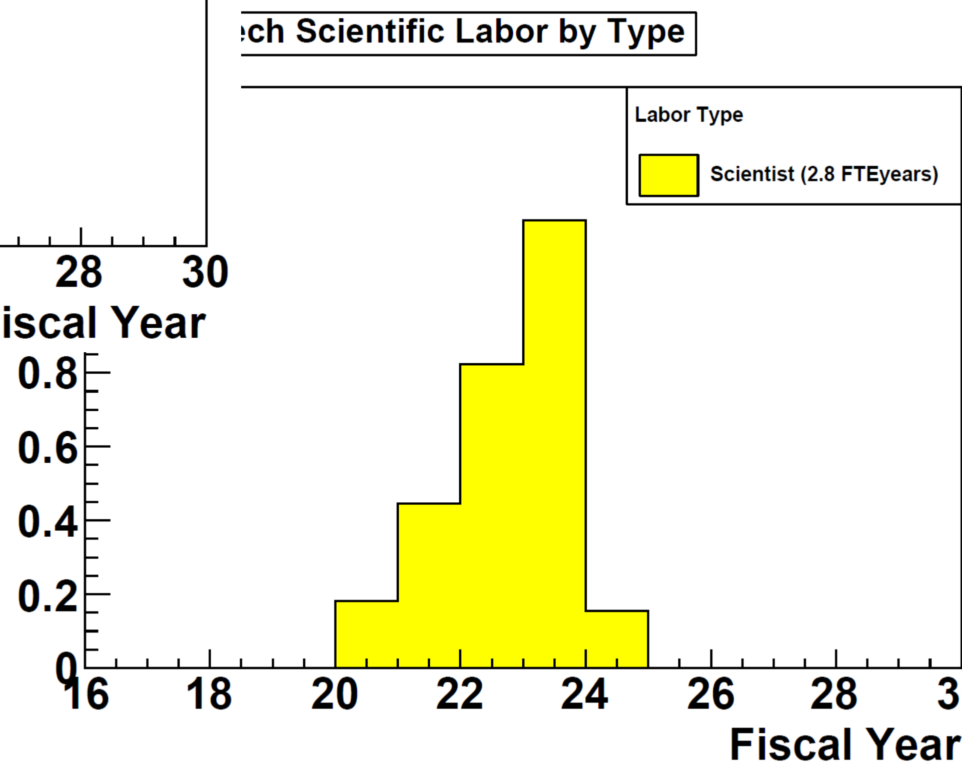


- Dominated by labor at the 3 assembly sites

Labor Profile for Assembly Site

Charge #3





- Example: TTU Site