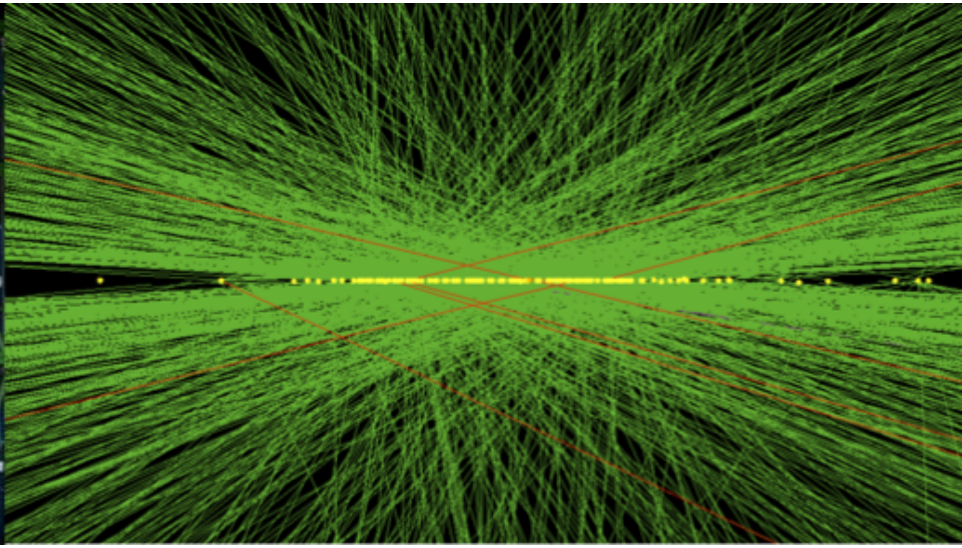
P05 - 402.2 Outer Tracker

Petra Merkel (L2 Manager), Ulrich Heintz (L2 Deputy)

HL LHC CMS Detector Upgrade CD-1 Review

October 22nd, 2019

Outline

- Introduction
- Design of the Outer Tracker
  - Motivation, Scope, and Deliverables
- Updates since 2018 IPR
  - Conceptual Design, Maturity
  - Organization, Cost, Schedule
  - Risks
- Response to Previous Reviews
- Progress towards CD-3a/CD-2
- Breakout Session topics
- Summary

Biographical Sketches

- Petra Merkel
  - Scientist at Fermilab (2014-)
    - L2 Manager HL LHC CMS Upgrade - OT (June 2019-)
    - L2 Deputy HL LHC CMS Upgrade - OT (2018-2019)
    - L3 Manager for HL LHC CMS Upgrade - OT Electronics (2017-2018
    - L3 Manager for USCMS Phase 1 Forward Pixel Testing and Integration (2014-2017)
    - Fermilab Detector R&D Coordinator (2016-)
  - Scientist at Purdue (2004-2014)
    - CMS Forward Pixel module assembly
    - CMS Pixel DQM: main developer and convener; CMS Tracker DPG convener
  - Postdoc at Fermilab (2000-2004)
    - CDF Silicon Detectors (SVXII, ISL, L00) Run 2 (and 2b) Upgrades, Silicon Operations
  - PhD from University of Hamburg at DESY (1995-2000)
    - H1 Muon System Operations
- Ulrich Heintz
  - Professor at Brown University (2009-)
    - L2 Deputy HL LHC CMS Upgrade - OT (June 2019-)
    - L3 Manager HL LHC CMS Upgrade - OT Sensors (2016-)
    - Co-coordinator of CMS OT Modules working group (2016-)
    - L3 Manager/CAM of USCMS Phase 1 HF FE upgrade (2013-2017)
    - L3 manager of D0 L2 Silicon Track Trigger (1999-2006)
      - Co-PI of NSF MRI award of about $1M
      - Coordinated design and construction at Boston U, Columbia, Stony Brook, FSU
  - Assistant/Associate Professor at Boston University (1998-2009)
    - QC for F-Disk Sensors
  - Wilson Fellow at Fermilab (1995-1998)
    - Responsible for development of F-Disk design for D0 Silicon Microstrip Tracker
  - PhD from Stony Brook University (1991)

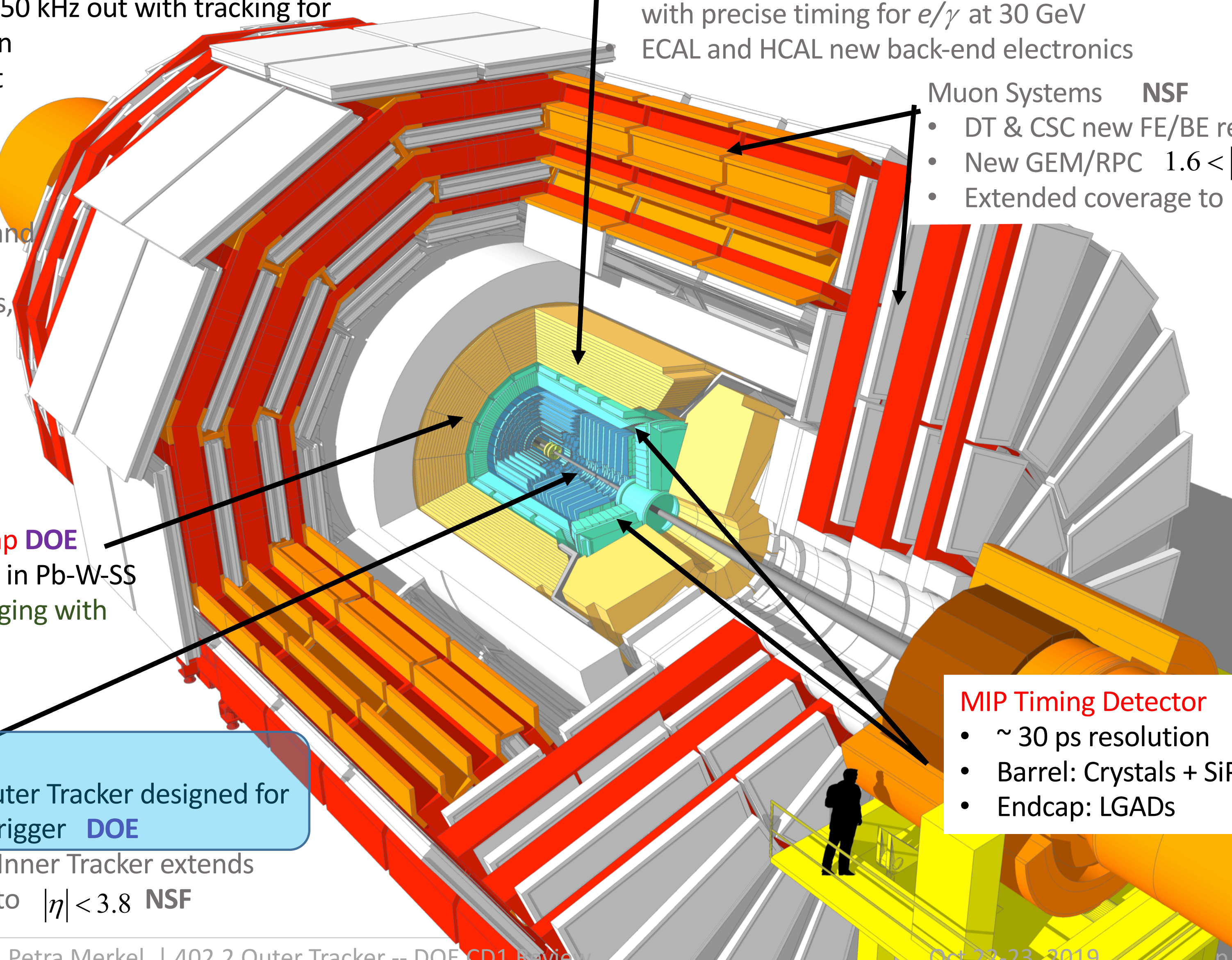
CMS Upgrade Scope

L1 Trigger/HLT/DAQ **NSF** and **DOE**
- L1 40 MHz in/750 kHz out with tracking for PF-like selection
- HLT 7.5 kHz out

Barrel Calorimeters **NSF**
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems **NSF**
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Beam Radiation and Luminosity, Common Systems, Infrastructure



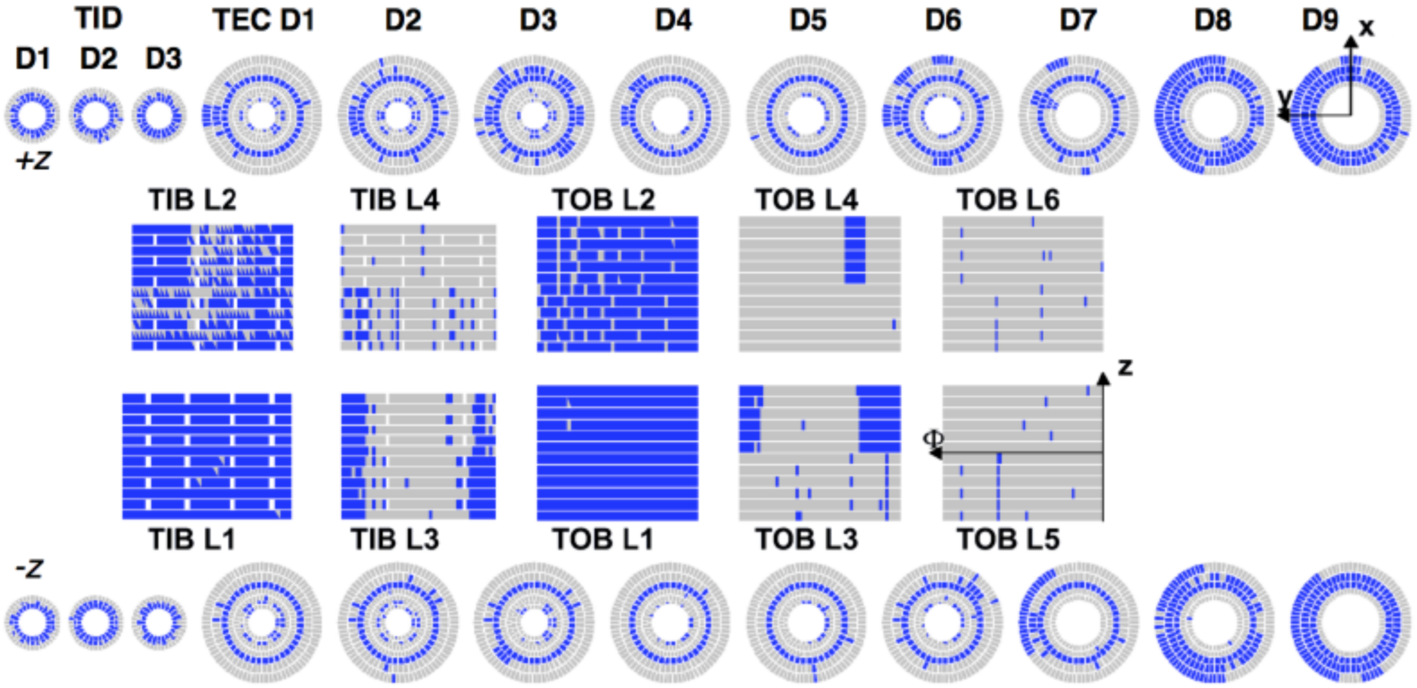
Calorimeter Endcap **DOE**
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

MIP Timing Detector **DOE**
- ~ 30 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger **DOE**
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$ **NSF**

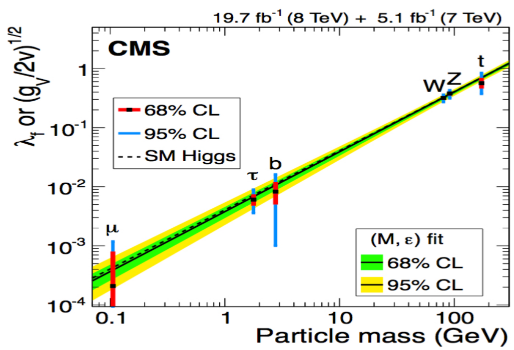
402.2 Upgrade Motivation

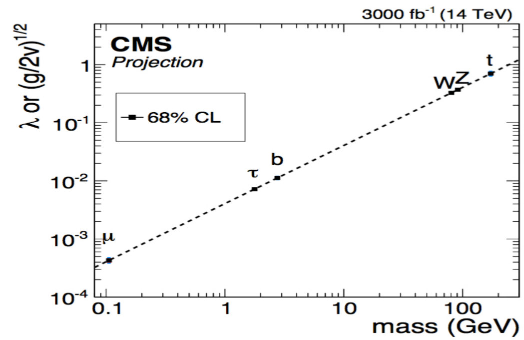
- Current Strip Tracker has been an undeniable success
  - Heart of the "Particle Flow" algorithm which is used ubiquitously in CMS physics analyses
- … but it does not survive 3000 fb^{-1}
  - Blue modules are non-operable after **1000** fb^{-1} at -20 °C



Science → Design Flowdown

Charge #2,7





CMS-wide

Science Drivers: P5 Snowmass Report

↓

Science Goals
CMS DocDB:13337

↓

Science Requirements
CMS DocDB:13337

↓

Outer Tracker

Science-Engineering Requirements
CMS DocDB:13388

↓

Engineering Requirements
CMS DocDB:13388

Measure the Higgs Couplings (sci-goal-1)

↓

Charged Particle Tracking Efficiency (sci-req-3)

↓

Robust Track Reconstruction (OT-sci-engr-001)

↓

Electrical Functionality (OT-engr-031)
Dimensional Tolerance (OT-engr-038)
Radiation Tolerance (OT-engr-007)

Charge #2

402.2 Conceptual Design

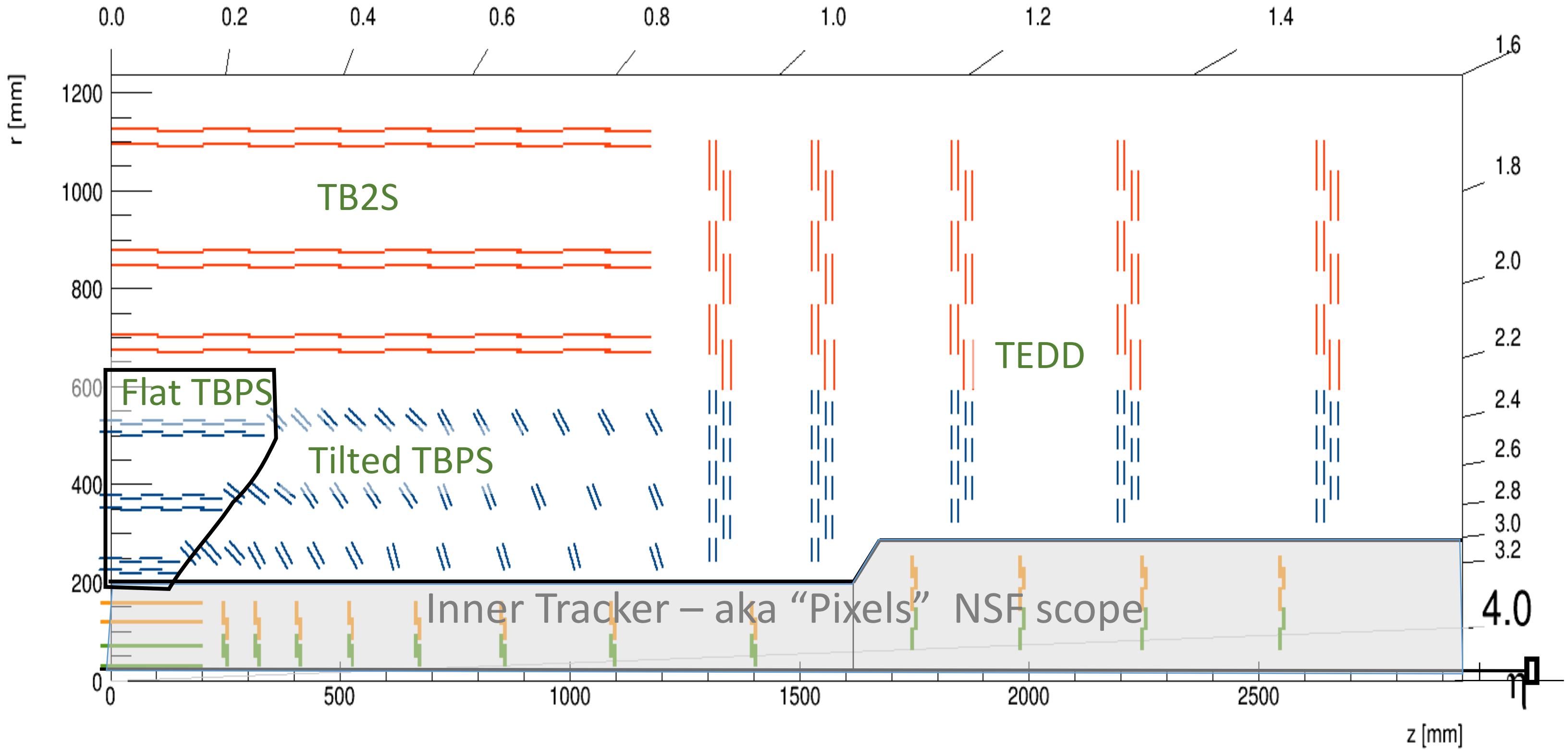
Requirements document: DocDB:13388

- Outer Tracker = Silicon Sensors arrayed inside Calorimeter and Magnet to collect ~ dozen space points from the ionization of a charged particle track
- Key technical considerations for any tracker
  - Layout: Number of hits to provide robust track reconstruction
  - Sensors:
    - Charge collection efficiency → high track efficiency
    - Space point precision → spatial and momentum resolution
  - Mechanics: minimal mass in tracking volume to mitigate track perturbation from interactions with structure (multiple scattering)
  - Electronics: Minimize deadtime, maximize information
    - Provide Trigger criteria at 40 MHz, Readout at 750 kHz
  - Everything: Robustness against acute and chronic radiation exposure

Charge #2

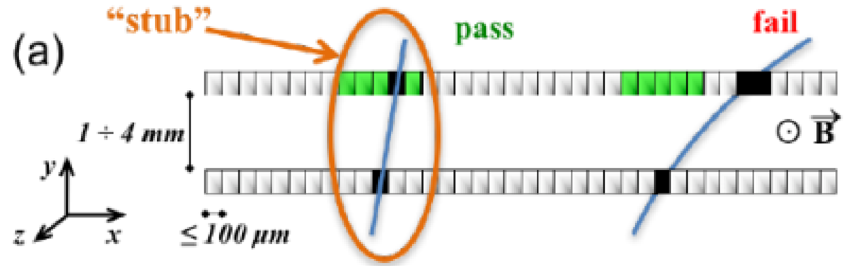
OT Detector Layout

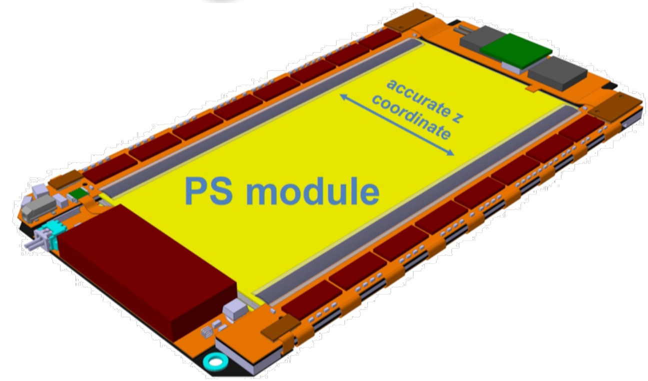
- Divided into 6 barrel layers and 5 endcap disks
  - Barrel has "Flat" section and "Tilted Section"
  - Trigger benefit: Each layer is a sandwich of sensors

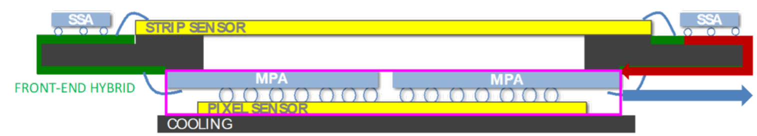


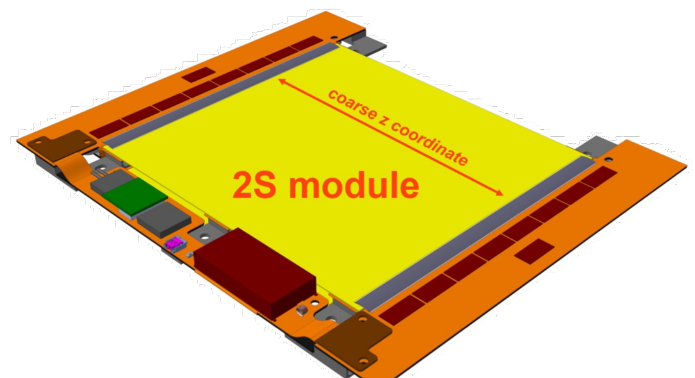
OT – Fundamental Unit: Module

- Sensor "sandwich" provides local curvature information for trigger
  - Different spacing in sandwich at different radii to match trigger
- Two types of module
  - **Pixel-Strip (PS):** strip sensor (1D information) + pixelated sensor (2D information). Used at lower radius, balance between precision and cost
  - **Strip-Strip (2S):** strip sensors for both sides of sandwich at higher radius
- Modules include sensors, ASICs, power and readout hybrids, spacers and mechanical support
  - Sensors and Electronics may differ, Mechanics similar





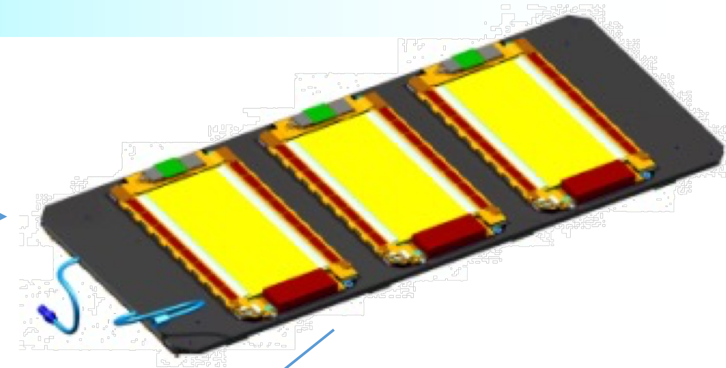




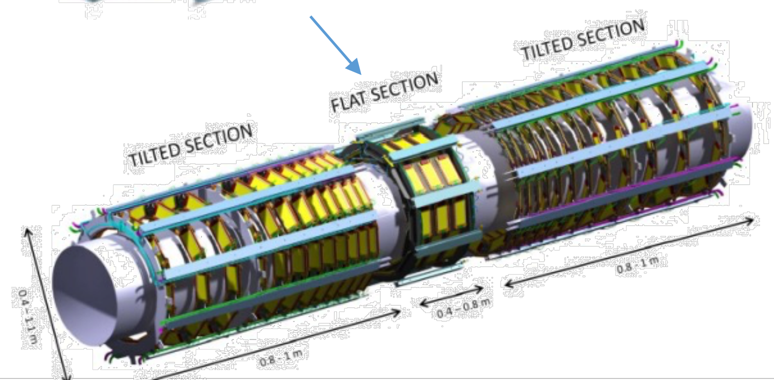
Charge #2

OT Structure and Accessories

- Mechanical Structure
  - Modules go on Planks
  - Planks go on Rings
  - Minimize mass: Carbon Fiber
  - Dual Phase CO_2 cooling
    - ala FPIX Phase 1
- Electronics
  - Test Systems to support component and module QC
  - Off-detector Data Acquisition electronics
    - Share of Design and Firmware



U.S. scope: Flat Barrel (layer 1 shown)



Charge #2

402.2 US Scope

KPPs: DocDB:13237

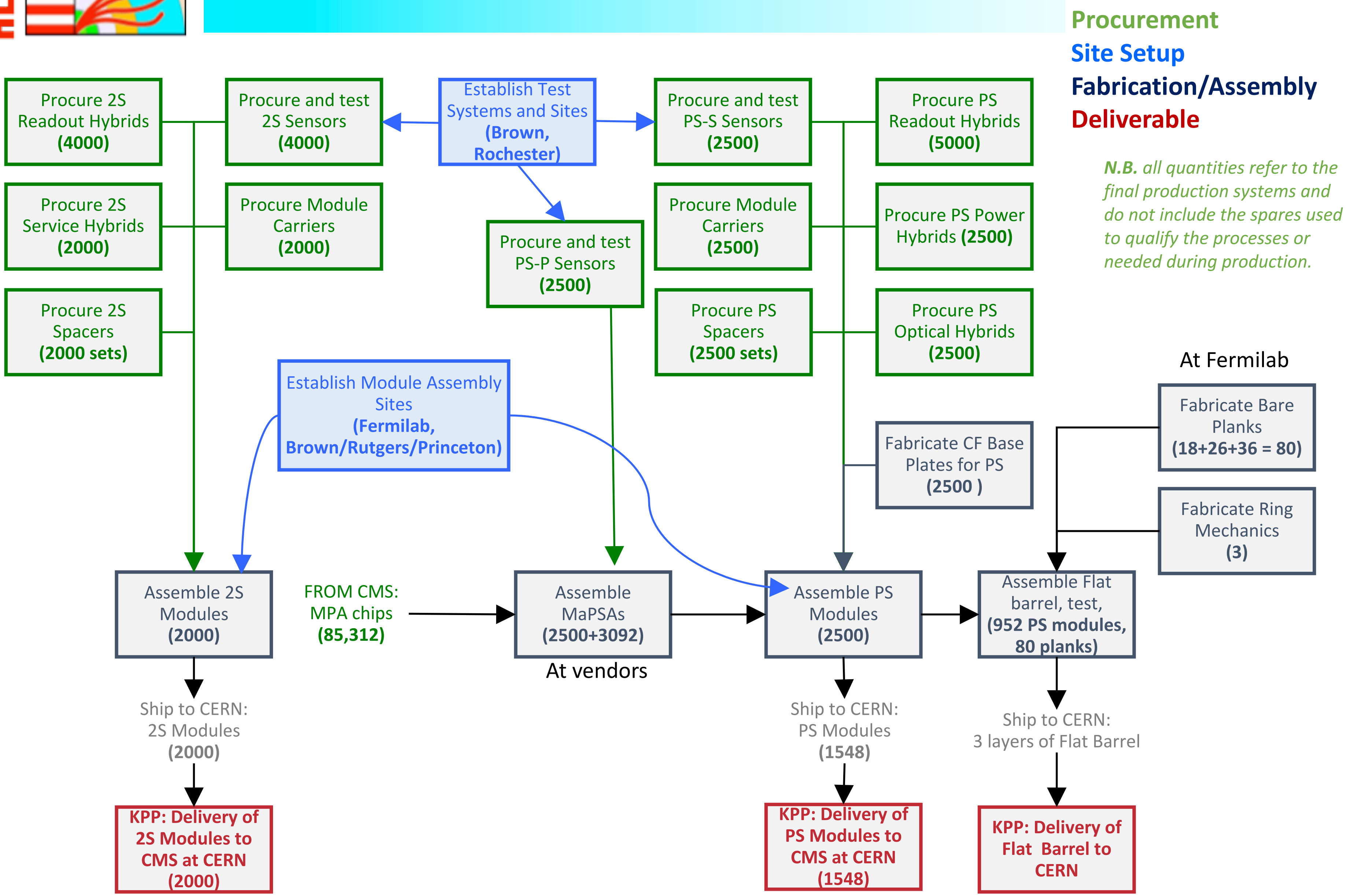
- Essentially unchanged since 2018 IPR
- Modules
  - Deliverable: 2500 PS and 2000 2S working production modules
    - plus 10% construction spares
    - 952 PS go to Flat Barrel (below), rest to iCMS collaborators
  - Sensors
    - Procurement (CERN group purchase), QC
  - Electronics
    - Development of Test systems for iCMS, Procurement for US needs
    - Development of Sensor-ASIC assembly (MacroPixel Sub Assembly, MaPSA), procurement and QC
  - Module Assembly
    - Development of assembly sites (East Coast and FNAL)
    - Module component procurements and QC
    - Assembly of components into modules and QC
- Flat Barrel Fabrication
  - Fabrication of Planks and Rings for the PS Flat Barrel (inner 3 layers)
  - Assembly of PS Modules onto Planks/Rings, QC
- US scope mixes homogeneously with international scope
  - We are independent, but not necessarily the unique supplier
- Threshold KPP is not tied to LHC schedule and tunnel access
  - Objective KPP includes last module assembly batch and installation and commissioning activities
- US team is embedded in iCMS: *System Test*, *Modules* and *CMS Upgrade Performance Studies* groups. Improves communication and coordination.

Threshold and Objective KPPs

KPPs: DocDb:13237

WBS	Threshold KPP	Objective KPP
402.2	T-KPP-OT-1: OUTER TRACKER CONSTRUCTION	O-KPP-OT-1: OUTER TRACKER CONSTRUCTION AND INTEGRATION
Outer Tracker	The Project will build, test, and grade approximately 30% of the total number of Modules needed for the Outer Tracker. 952 Modules will be used to construct the "Flat" Inner Barrel, the inner three layers of barrel modules. The modules and Flat Barrel shall have sufficient granularity and noise performance to ensure a projected occupancy of < 5%, and capable of forming and sending track pT information to the L1 trigger at LHC bunch crossing rates.	The Project will build, test, and grade approximately 33% of the total number of Modules needed for the Outer Tracker. 952 Modules will be used to construct the "Flat" Inner Barrel, the inner three layers of barrel modules. The modules and Flat Barrel shall have sufficient granularity and noise performance to ensure a projected occupancy of < 5%, and capable of forming and sending track pT information to the L1 trigger at LHC bunch crossing rates. The project shall integrate the “Flat” Inner Barrel detector into the full Outer Tracker, and test and calibrate it.

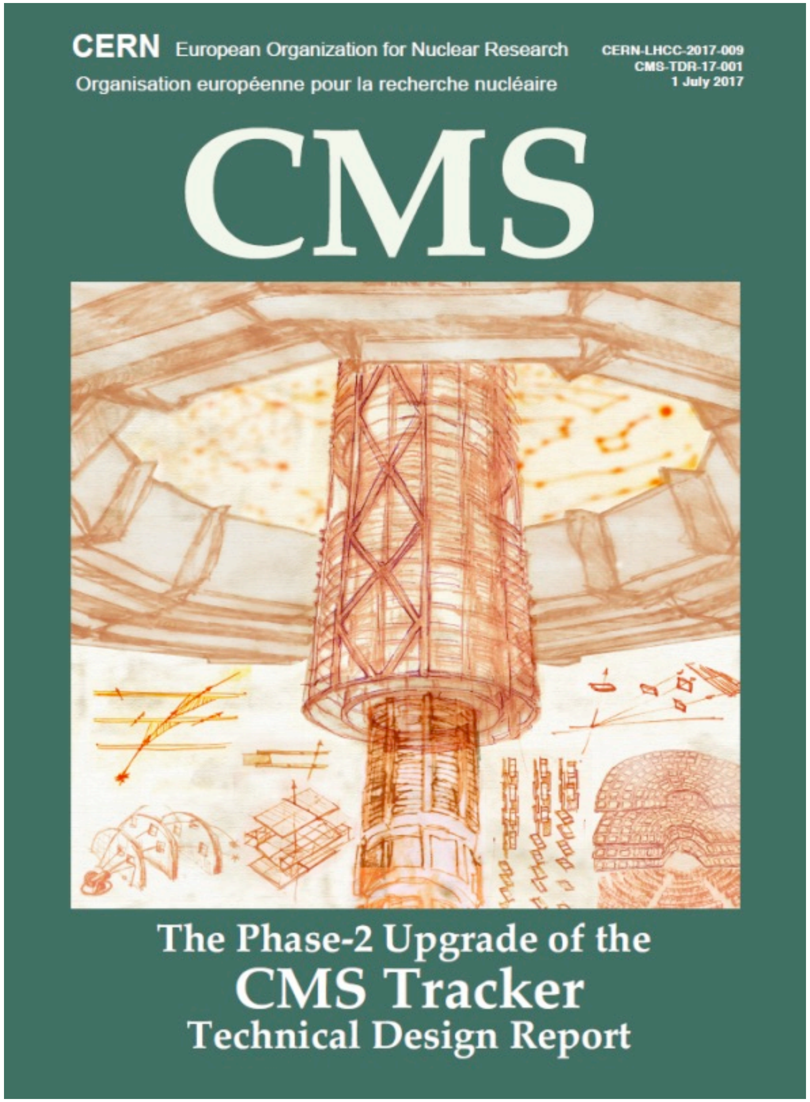
US Deliverables flowchart



Outer Tracker Design

CERN-LHCC-2017-009

- International Collaboration effort produced Technical Design Report
  - Based on Simulation with variation on layout and design choices to optimize performance without maximizing cost
- Scientific and Fiscal approval received end of 2017
- US CDR is essentially the same, but restricted to US Scope
  - CDR: DocDB:13151
- Approved and unchanged since 2017



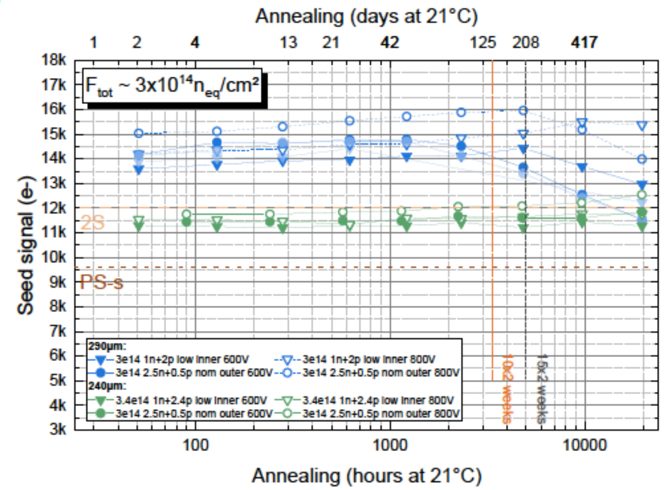
Charge #2,4

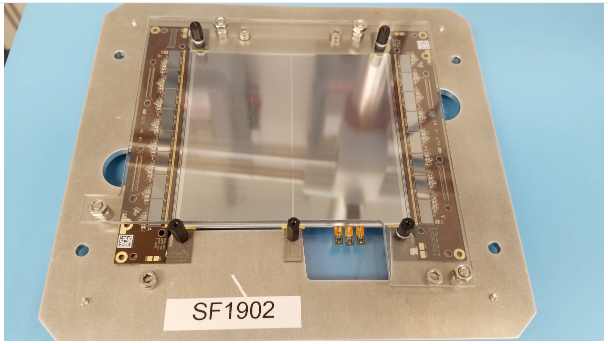
Design Evolution

- Design finalized for TDR
  - Main parameters established
  - No major changes expected
    - Layout, “Sandwich” design, all vetted by simulation
- Minor technical changes since TDR due to:
  - Prototyping experience
    - Proving the performance in prototyping
    - Establishing the ability to fabricate the modules
      - Already have provided small changes in early fabrication attempts
    - Uncovering any unforeseen “features”
  - Cost and Resource Optimization
    - Market survey for Sensors and MaPSA
    - Exploiting Value Engineering opportunities
      - Spacer R&D to replace expensive Al-CF composites
      - Gantry assembly to replace labor where possible
- Only small amount of design work remaining

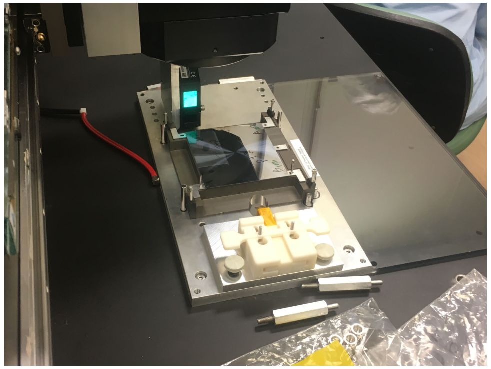
402.2 Technical Progress since 2018 IPR

- Sensor material choice and design finalized: standard thickness 290μm
  - Decision informed by:
    - Irradiation and test beam campaigns
    - QC procedure development
    - Standard thickness performs equally or better than thin sensors at lower cost and higher robustness
  - Design finalized for CD-3a





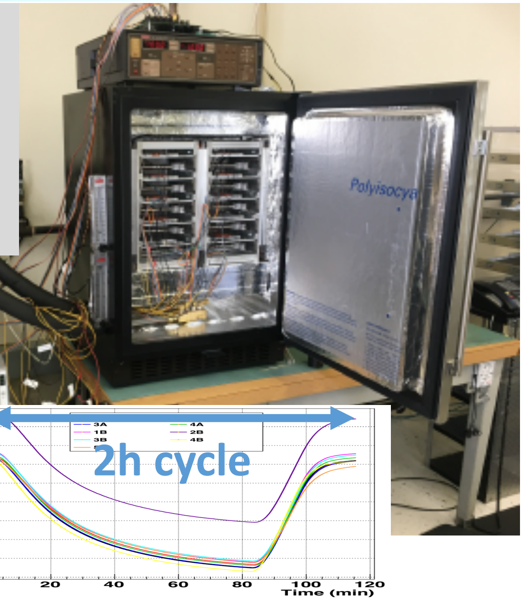
- Multiple functional and dummy modules built
  - Leading to:
    - Minor final design changes
    - Optimization of assembly procedures
    - Better workflow and labor needs estimates
    - Development of automation

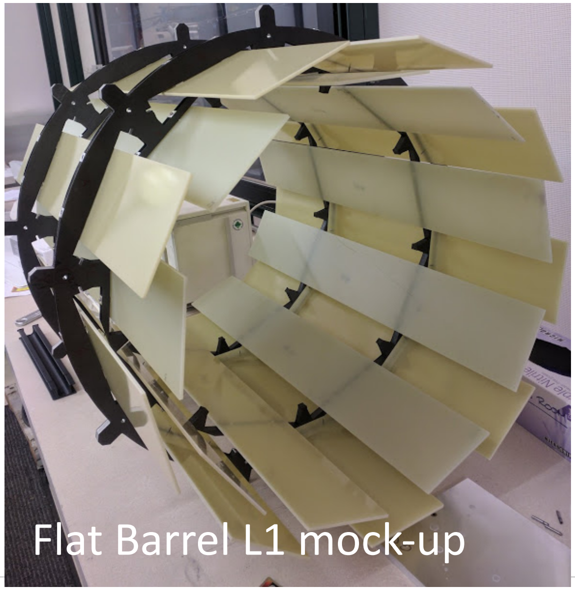


402.2 Technical Progress since 2018 IPR

- Finalizing test systems
  - Single-module system (done)
  - Multi-module burnin-box (done)
    - Endorsed at iCMS review
  - MaPSA probe test system (~done)
  - DAQ (sw & fw) development (advanced)
- First functional prototype MaPSA in hand
  - Vetting two vendors
  - Second round early next year
- Prototyping of support structures
  - Verify mechanical, thermal and electrical performance (e.g. grounding, noise)
  - Build prototypes and mock-ups

Multi-module burn-in box





Flat Barrel L1 mock-up

Charge #2

402.2 Maturity

WBS dictionary: DocDB:13417

- Split maturity into managerial and technical
- All L3 areas at or close to final designs
  - E.g. Sensor WBS ready for CD-3a
- Well on the way to detailed designs and construction readiness for CD-2

	Sensors		Electronics		Modules		Mechanics		Integration		AVE		BAC	
OT	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech
Conceptual Design	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Preliminary Design	100%	100%	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Final Design	100%	100%	100%	95%	100%	86%	93%	95%	87%	95%	96%	94%	99%	91%
Detailed Design	50%	80%	50%	20%	50%	20%	50%	20%	50%	20%	50%	32%	50%	31%
Construction Readiness	48%	75%	19%	20%	22%	20%	19%	20%	19%	20%	25%	31%	26%	30%

Charge #5,7

402.2 Organization

WBS dictionary: DocDB 13213

Not shown:
402.2.1 Milestones and Risk
402.2.2 Management

- **402.2 OT - OUTER TRACKER** — P.Merkel (Fermilab), U.Heintz (Brown)
  - **402.2.3 OT - Sensors** — R.Demina (Rochester)
    - 402.2.3.1 OT - Sensor QC Centers
    - 402.2.3.2 OT - PS-P Sensors
    - 402.2.3.3 OT - PS-S Sensors
    - 402.2.3.4 OT - 2S Sensors
  - **402.2.4 OT - Electronics** — Y.Gerschtein (Rutgers), A.Canepa (Fermilab)
    - 402.2.4.1 OT - Macro Pixel Sub-Assembly — R.Lipton (Fermilab), D.Berry (Fermilab)
    - 402.2.4.2 OT - Test Systems — E.Halkiadakis (Rutgers)
    - 402.2.4.3 OT - DAQ — L.Uplegger (Fermilab)
  - **402.2.5 OT - Modules** — M.Narain (Brown), L.Spiegel (Fermilab)
    - 402.2.5.1 OT - Module Assembly Consortia
    - 402.2.5.2 OT - Module Components
    - 402.2.5.3 OT - Module Assembly
  - **402.2.6 OT - FB Mechanics** — S.Gruenendahl (Fermilab)
    - 402.2.6.1 OT - Plank Mechanics
    - 402.2.6.3 OT - Ring Mechanics
  - **402.2.7 OT - Integration and Testing** — S.Gruenendahl (Fermilab), D.Berry (Fermilab)
    - 402.2.7.1 OT - Flat Barrel Design
    - 402.2.7.2 OT - FB Plank Assembly
    - 402.2.7.3 OT - FB Layer Assembly and Test
    - 402.2.7.4 OT - FB Shipping to CERN
    - 402.2.7.5 OT - CERN Integration

Added L4 Managers in Electronics to strengthen management team for diverse set of deliverables

402.2 WBS Description

Charge #7

WBS dictionary: DocDB 13213

- 402.2.2 Management
  - Travel for Organizational Meetings, Systems Engineer contractor, miscellaneous M&S
- 402.2.3 Sensors
  - Procurement of Sensors, Setup up and Execution of QC
- 402.2.4 Electronics
  - Oversight of MaPSA (bump bonding Ps-P sensors to MPA chips)
  - Design, Procurement of Component Test Systems
    - Hybrid, Single and Multi-Module, and MaPSA test systems
  - Outer Tracker Data Acquisition Firmware/Software
- 402.2.5 Module Assembly
  - Fabrication of Assembly sites, procurement of mechanical and electrical Components, Module Assembly
- 402.2.6 Mechanics
  - Fabrication of Plank and Ring Mechanical Structures
- 402.2.7 Integration
  - Loading of Modules onto Planks and Assembly of 3-layer Flat Barrel

HL-LHC US CMS

402.2 Cost Summary

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
DOE-CD1-402.2 402.2 OT - Outer Tracker (at DOE CD1)	**20,575,450**	**376978**	**213.22**	**42,871,529**	**9,891,026**	**52,762,555**
DOE-CD1-402.2.2 OT - Management	**959,000**	**43537**	**24.63**	**1,125,217**	**87,120**	**1,212,337**
DOE-CD1-402.2.3 OT - Sensors	**4,993,973**	**31778**	**17.97**	**7,371,148**	**1,309,487**	**8,680,634**
DOE-CD1-402.2.4 OT - Electronics	**2,740,374**	**33044**	**18.69**	**6,222,484**	**1,241,158**	**7,463,642**
DOE-CD1-402.2.5 OT - Modules	**9,074,091**	**212390**	**120.13**	**21,785,980**	**5,113,007**	**26,898,987**
DOE-CD1-402.2.6 OT - FB Mechanics	**543,000**	**20289**	**11.48**	**2,380,031**	**762,785**	**3,142,815**
DOE-CD1-402.2.7 OT - Integration and Testing	**2,265,012**	**35940**	**20.33**	**3,986,670**	**1,377,470**	**5,364,140**

- Recent cost scrubbing led to better estimates:
  - More precise labor hour estimates
  - Smaller estimate uncertainties due to prototyping experience and updated quotes
  - Decrease in sensor cost and estimate uncertainty
  - Swapped part of sensor payment to CERN for MaPSA cost, now pay for 100% of MaPSA (was 40%)
  - Increased Sensor process QC hours (Hamamatsu reduced testing)
  - Increased Module assembly hours (i.e. wirebonding)

	2019	Change: {Now/Then-1}				
L2/L3 Area	**BAC**	**M&S**	**Hours**	**Cost**	**EU**	**Total**
OT	**42,872**	**-4%**	**11%**	**1%**	**-26%**	**-6%**
OT - Mgmt	1,125	46%	7%	33%	3%	31%
OT - Sensors	7,371	-34%	4%	-24%	-51%	-30%
OT - Electronics	6,222	91%	8%	41%	-9%	29%
OT - Modules	21,786	1%	4%	3%	-23%	-3%
OT - Mechanics	2,380	25%	1%	8%	-26%	-3%
OT - FB Integration	3,987	-2%	160%	-7%	-13%	-9%

Legend
< -50%
-50%
-25%
0%
25%
50%
> 50%

	2019	Change
L2/L3 Area	**Contributed Hours**	**Hours**
OT	**177,843**	**16%**
OT - Mgmt	43,537	7%
OT - Sensors	1,376	5%
OT - Electronics	12,470	9%
OT - Modules	93,736	-2%
OT - Mechanics	496	2%
OT - FB Integration	26,228	627%

Charge #3

402.2 Cost Drivers > $1.5M

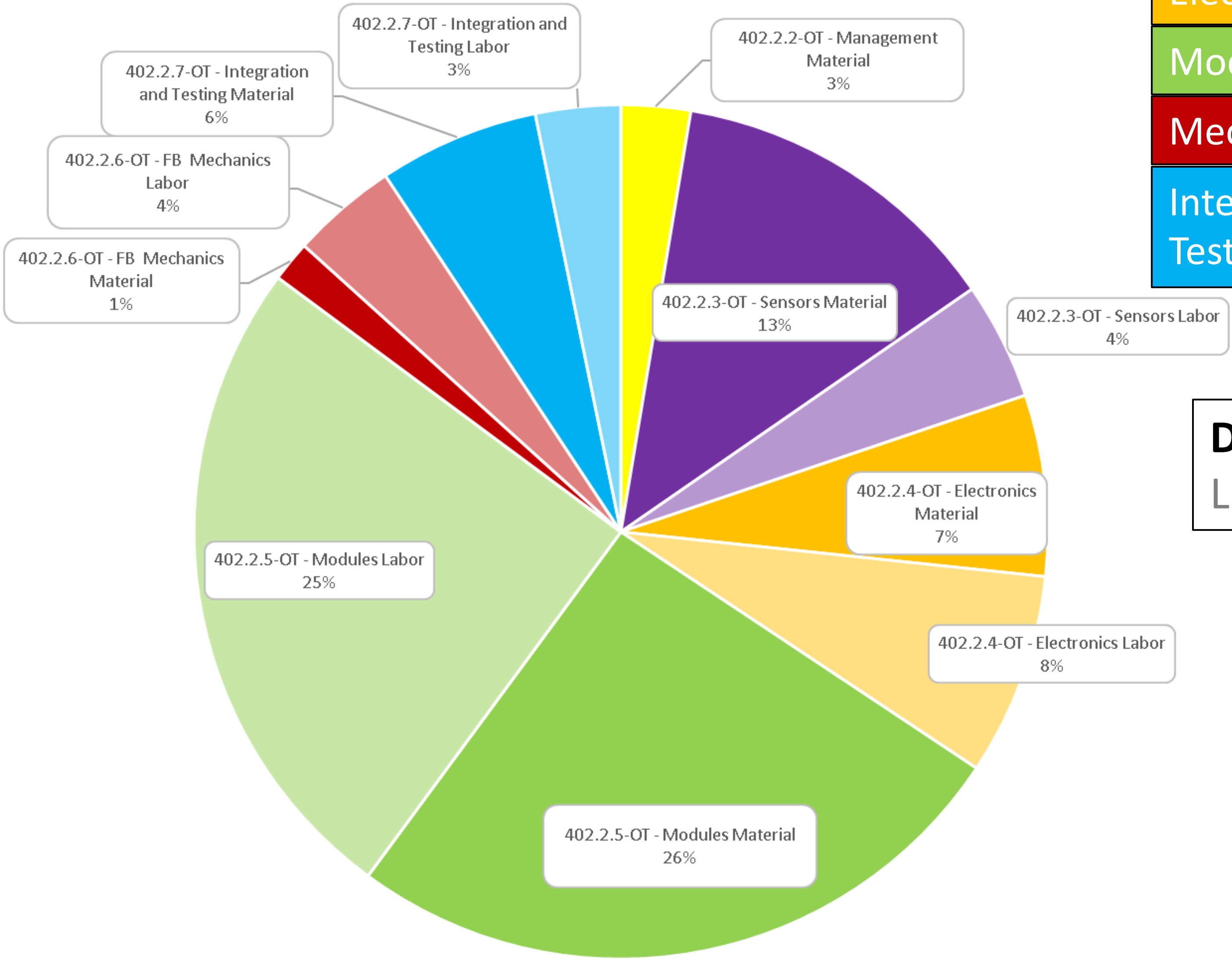
- Large M&S Procurements
  - Sensors+Hybrids+Al-CF mechanics+MaPSA = $13.0M BAC out of $19.9M
    - Investigating less expensive mechanics solutions, lower cost/higher risk Bump Bonding vendors
- Substantial Labor Costs
  - Manual Module Assembly – $8.6M
    - Investigating options for automation
  - Significant Engineering effort – $6.1M
    - DAQ firmware, Engineering for Mechanical Substructure and Integration, Sensor testing

CMS Driver	Labor (FTE-yrs)	Labor BAC (M$)	M&S BAC (M$)	Total BAC (M$)
OT.5 - Produce and test modules	57.3	8.6	1.5	10.2
OT.3 - Procure Sensors	0.0	0.0	4.5	4.5
OT.5 - Module mechanics	2.2	0.3	3.0	3.3
OT.5 - Procure hybrids	0.0	0.0	3.2	3.2
OT.5 - Establish / maintain module assembly site (East Coast)	5.0	0.7	2.1	2.8
OT.4 - MaPSA purchase and testing	2.3	0.1	2.3	2.4
OT.6 - Plank and Ring mechanics	11.2	1.7	0.6	2.4
OT - Outer Tracker integration and commissioning	0.0	0.0	2.3	2.3
OT.4 - DAQ development	8.0	1.6	0.1	1.7
OT.3 - Sensor prototyping, production and testing	14.6	1.5	0.1	1.6
OT.7 - Flat Barrel design, assembly and test	5.3	1.3	0.2	1.5

402.2 Cost Profile

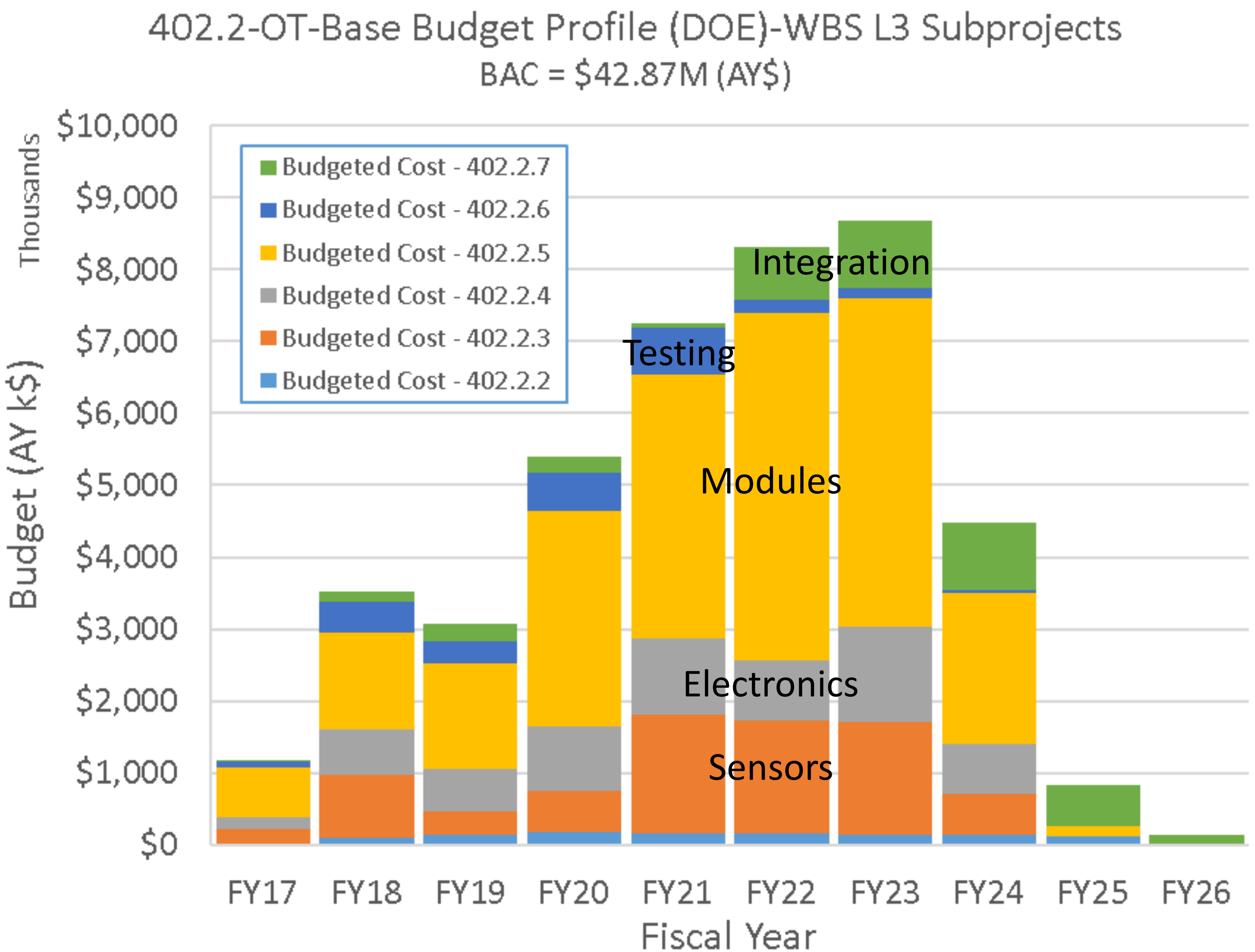
Management	3%
Sensors	17%
Electronics	15%
Modules	51%
Mechanics	5%
Integration & Testing	9%

402.2-OT-WBS L3 Base Budget Breakdown (DOE)
BAC = $42.87M (AY$)



DARK: M&S
Light: Labor

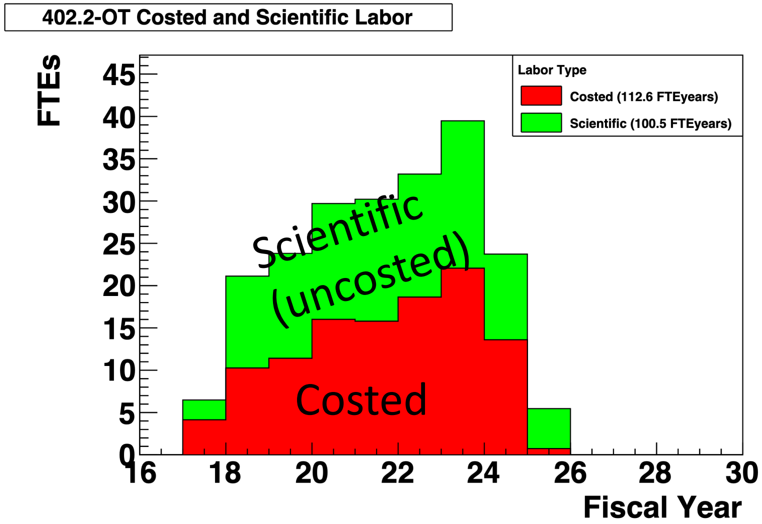
402.2 Cost Profile

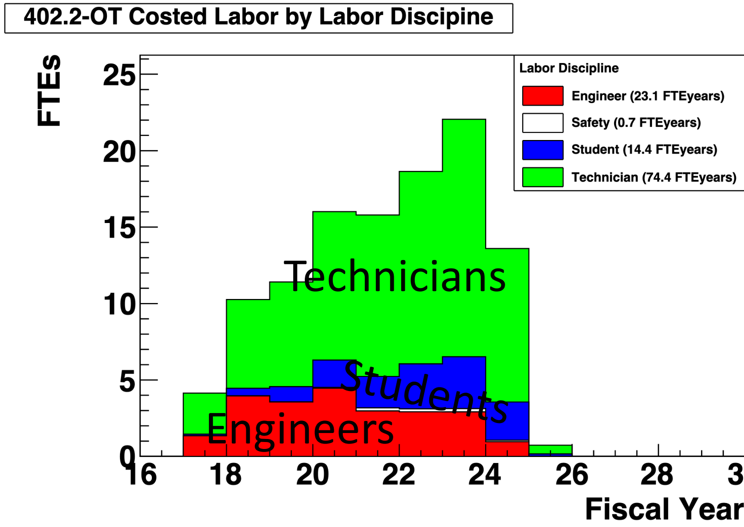


Charge #3,4

402.2 Labor Profiles

- Labor dominated by module assembly
  - Skilled work done by technicians/engineers
  - Testing done by contributed labor and undergraduate students

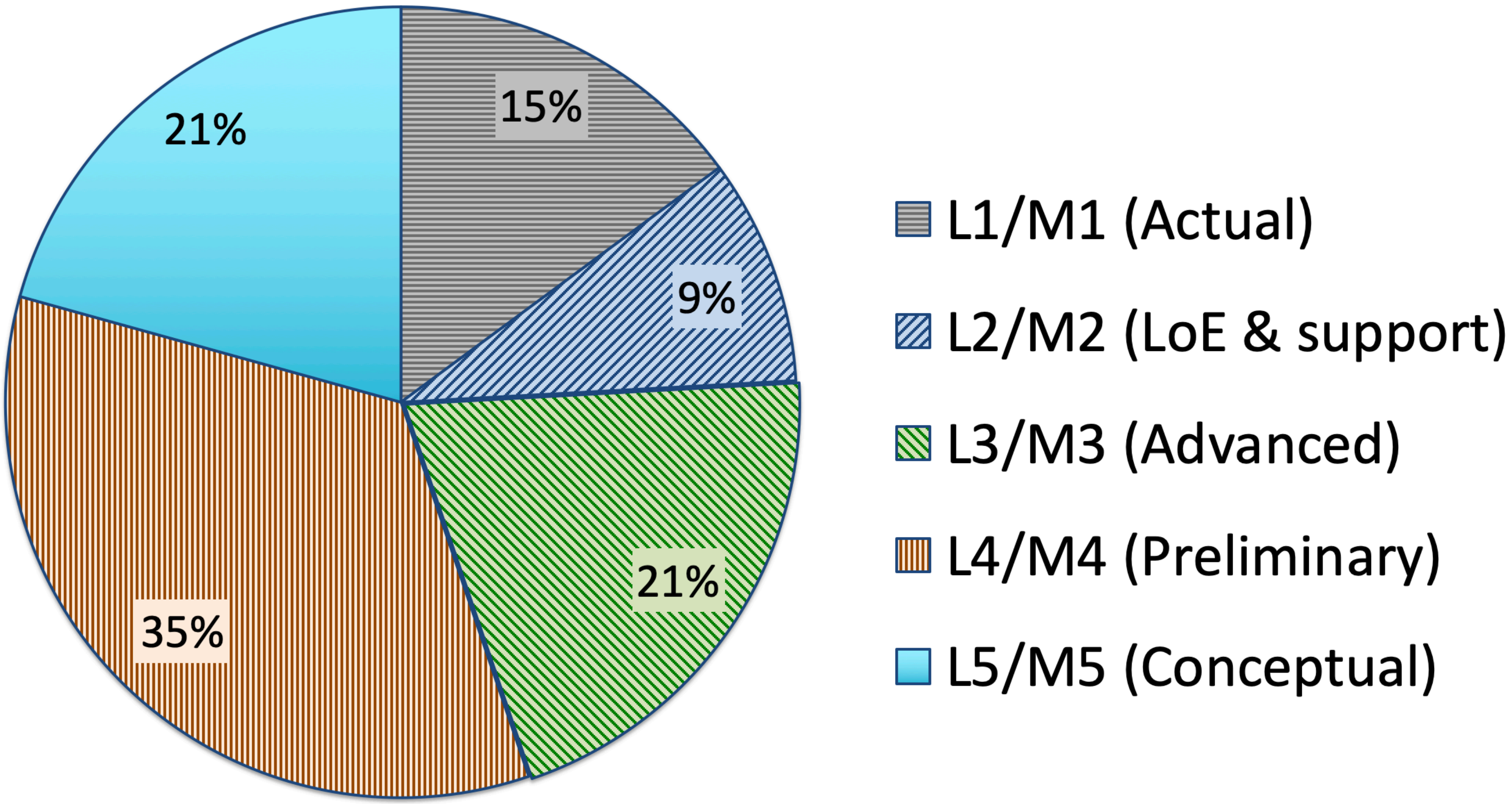




WBS	Labor hours	FTE-years	Direct + Indirect + Escalation ($)	Estimate Uncertainty ($)	Total Labor Cost ($)
DOE-CD1-402.2 402.2 OT - Outer Tracker (at DOE CD1)	376978	213.22	19,030,385	3,832,773	22,863,158
DOE-CD1-402.2.2 OT - Management	43537	24.63	0	0	0
Uncosted	43537	24.63	0	0	0
DOE-CD1-402.2.3 OT - Sensors	31778	17.97	1,904,942	406,816	2,311,757
Uncosted	1376	0.78	0	0	0
Costed	30402	17.20	1,904,942	406,816	2,311,757
DOE-CD1-402.2.4 OT - Electronics	33044	18.69	3,284,352	406,256	3,690,608
Uncosted	12470	7.05	0	0	0
Costed	20574	11.64	3,284,352	406,256	3,690,608
DOE-CD1-402.2.5 OT - Modules	212390	120.13	10,740,717	1,963,422	12,704,139
Uncosted	93736	53.02	0	0	0
Costed	118654	67.11	10,740,717	1,963,422	12,704,139
DOE-CD1-402.2.6 OT - FB Mechanics	20289	11.48	1,720,104	519,361	2,239,465
Uncosted	496	0.28	0	0	0
Costed	19793	11.20	1,720,104	519,361	2,239,465
DOE-CD1-402.2.7 OT - Integration and Testing	35940	20.33	1,380,270	536,919	1,917,189
Uncosted	26228	14.83	0	0	0
Costed	9712	5.49	1,380,270	536,919	1,917,189

402.2 Estimate Maturity

Cost-weighted estimate maturity: 402.2 Outer Tracker



402.2 Labor Resources

- US-CMS OT institutes have extensive experience:
  - **Fermilab**: SiDet facility used to construct D0, CDF, current CMS tracker, legacy and current Forward Pixel Detector
    - Symbiosis with LPC participants
  - **Brown**: D0 silicon, legacy Tracker operation, Phase 1 HCAL, FPIX assembly (@Purdue)
    - iCMS QA Manager and main module designer
  - **Princeton**: Built Belle II Silicon Detector
  - **Rochester**: D0, legacy CMS tracker construction and Operation
  - **Rutgers**: legacy and current FPIX electronics
  - **Iowa**: Phase 1 FPIX wafer testing
  - **Purdue**: CF symbiosis with IT

	Sensors	Electronics	Modules	Mechanics	Integration
Bethel			X		X
Brown	X		X		X
UC-Davis				X	X
Fermilab		X	X	X	X
Iowa		X	X		X
Princeton		X	X		X
Purdue			X		X
Rochester	X	X			X
Rutgers		X	X		X
Wayne State		X	X		X

- Personnel needs planned to ramp up for production phase (FY22-FY24); hiring at institutions (esp. Fermilab and Brown) will be staged accordingly

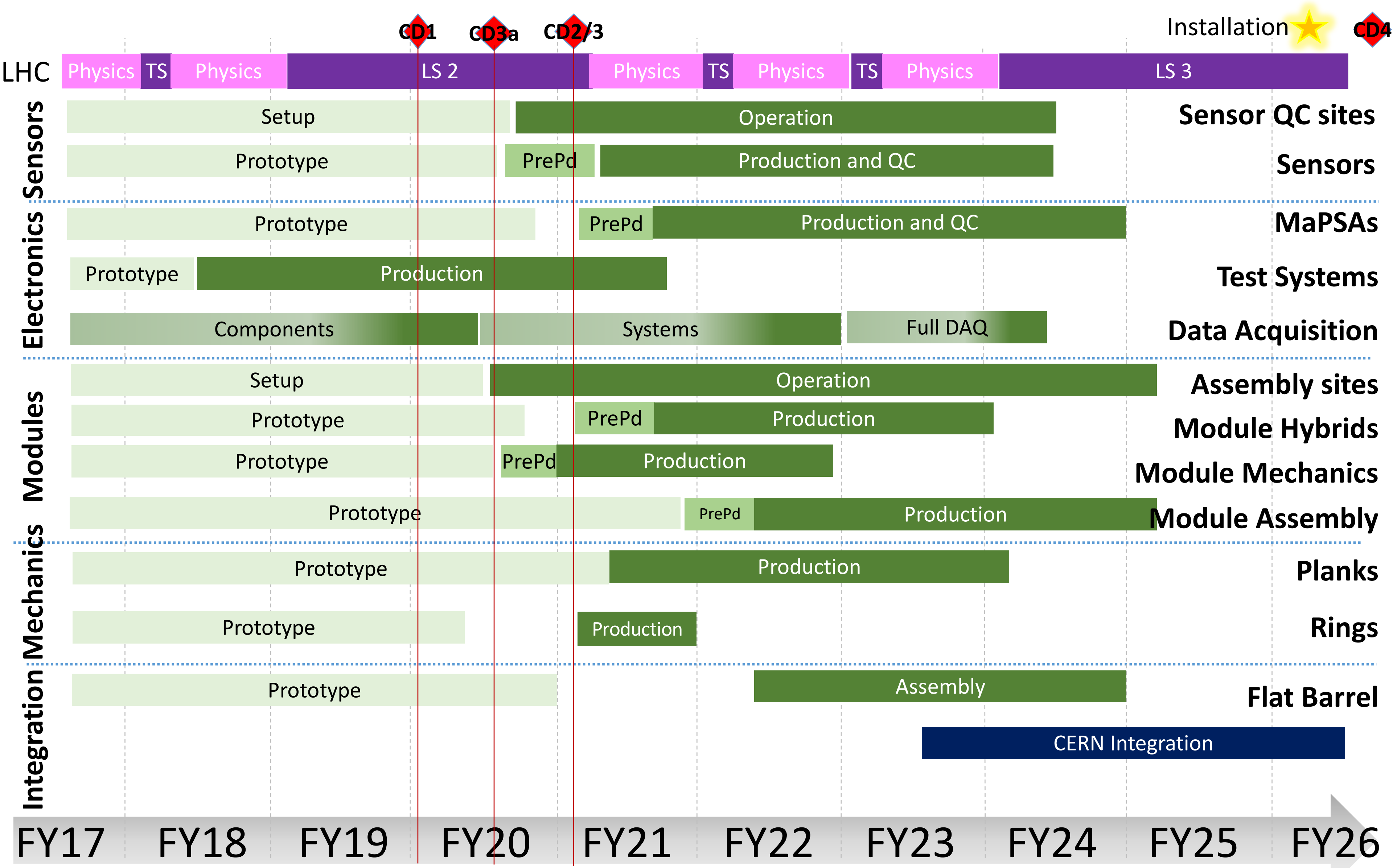
Charge #3,4

402.2 High Level Schedule

- Only few minor schedule changes since 2018 IPR:
  - Earlier start and longer duration for sensor delivery (mandated by Hamamatsu); reduced float for modules
  - Experienced technical problems during MaPSA prototyping (~6 months delay); no effect on production so far
  - Availability of parts (especially for PS modules) further delayed → some module prototyping delayed
  - Module mechanics used to delay start of module production
    - Added to CD-3a scope to be able to purchase Al-CF and CF earlier
- No significant impact on critical path, major milestones or resource needs

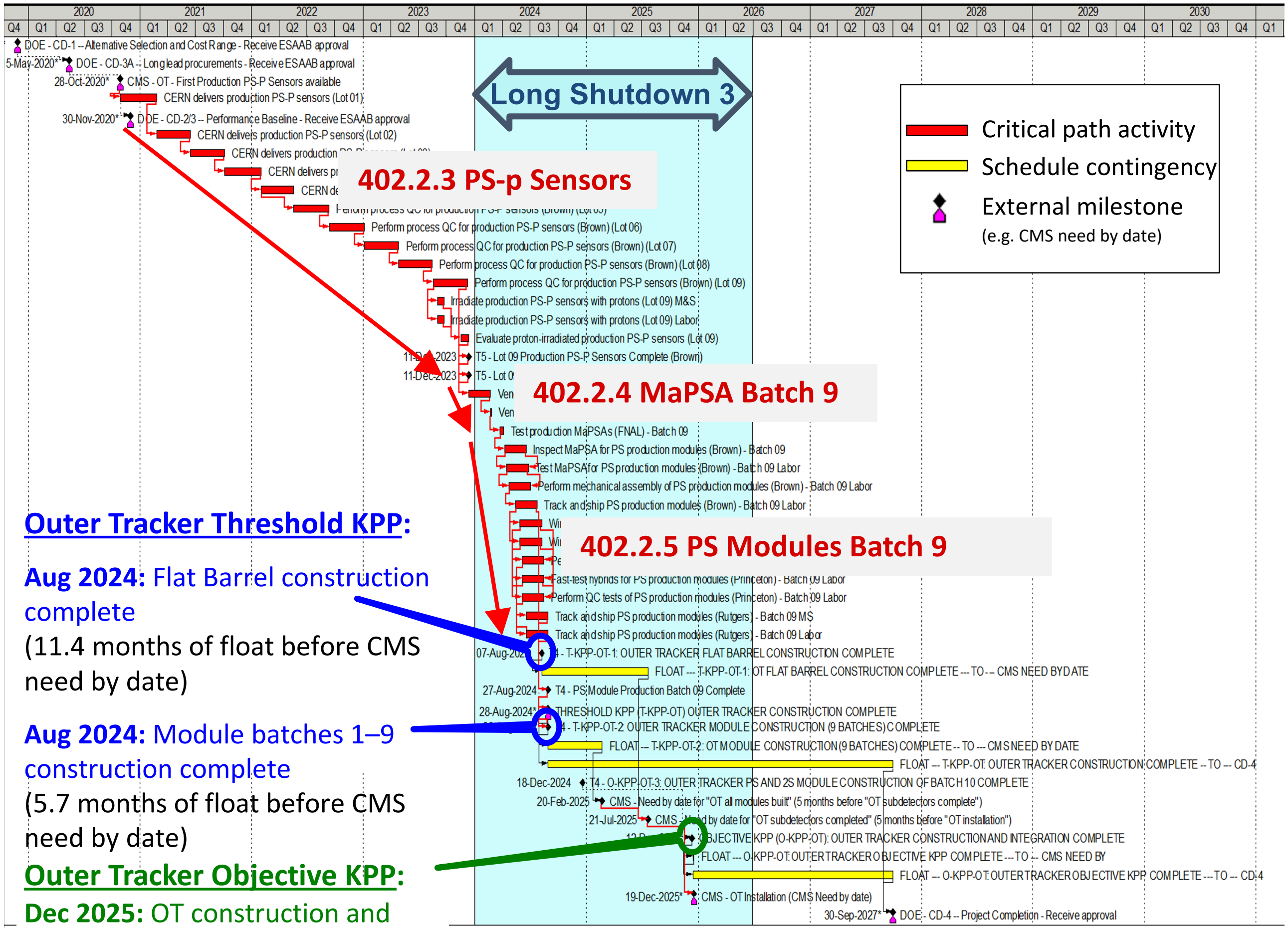
Charge #3

402.2 OT Cartoon Schedule



Critical Path and Schedule Contingency

- No significant changes since 2018 IPR
- Module KPP paced by PS-P sensor delivery
  - MaPSA and Module Assembly narrowly in the shadow
  - Test Systems and Mechanics have float
- Flat Barrel KPP driven by Hybrids, Modules, Plank/Layer assembly
  - Only need first 4 batches
- Prototyping effort and completion of vendor inquiries will inform durations between now and CD-2 Baseline



Outer Tracker Threshold KPP:

Aug 2024: Flat Barrel construction complete
(11.4 months of float before CMS need by date)

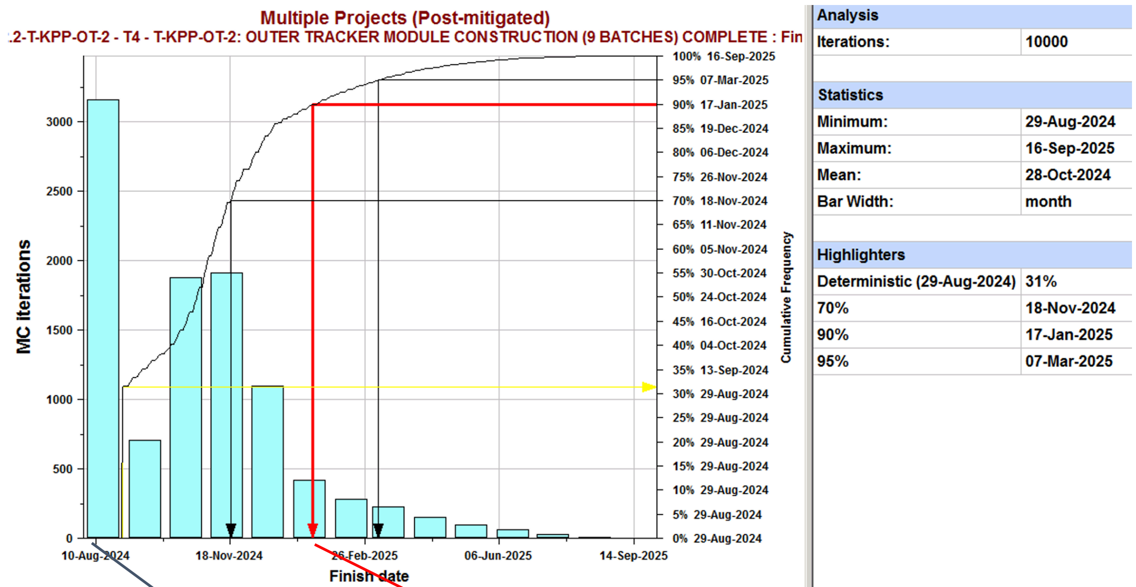
Aug 2024: Module batches 1–9 construction complete
(5.7 months of float before CMS need by date)

Outer Tracker Objective KPP:

Dec 2025: OT construction and integration complete

Schedule Contingency: Modules

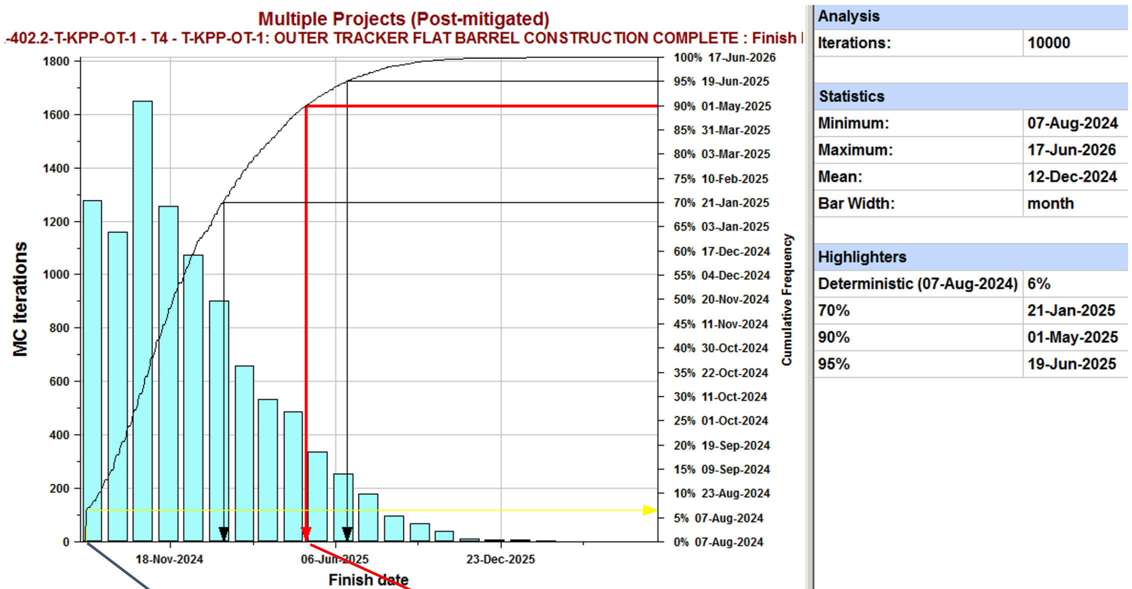
- Risk MC aggregates delays stochastically in the full P6 schedule
- Risks will delay finish by < **4.7 months** at 90% confidence level
- Plan has **5.8 months** of float before the CMS need by date
- T-KPP will finish before the need by date at 94% confidence level
- Will revisit schedule risk when new LHC schedule is known



Results of schedule risk MC		Finish date (early)	CMS need by date	Float to CMS need by date (months)	Finish date (90% C.L.)	Delay due to risk (90% C.L.) (months)	Confidence level to finish before CMS need by date
T-KPP-OT-2	Outer Module (9 Batches) Construction Complete	28-Aug-2024	20-Feb-2025	5.8	17-Jan-2025	4.7	94%

Schedule Contingency: Flat Barrel

- Risk MC aggregates delays stochastically in the full P6 schedule
- Risks will delay finish by < **8.8 months** at 90% confidence level
- Plan has **11.4 months** of float before the CMS need by date
- T-KPP will finish before the need by date at 97% confidence level
- Will revisit schedule risk when new LHC schedule is known



Results of schedule risk MC		Finish date (early)	CMS need by date	Float to CMS need by date (months)	Finish date (90% C.L.)	Delay due to risk (90% C.L.) (months)	Confidence level to finish before CMS need by date
T-KPP-OT-1	Outer Tracker Flat Barrel Construction Complete	7-Aug-2024	21-Jul-2025	11.4	1-May-2025	8.8	97%

402.2 Risks

Charge #3,7

FNAL Risk Procedures: PPP-doc-65
Risk Register: DocDb 13480

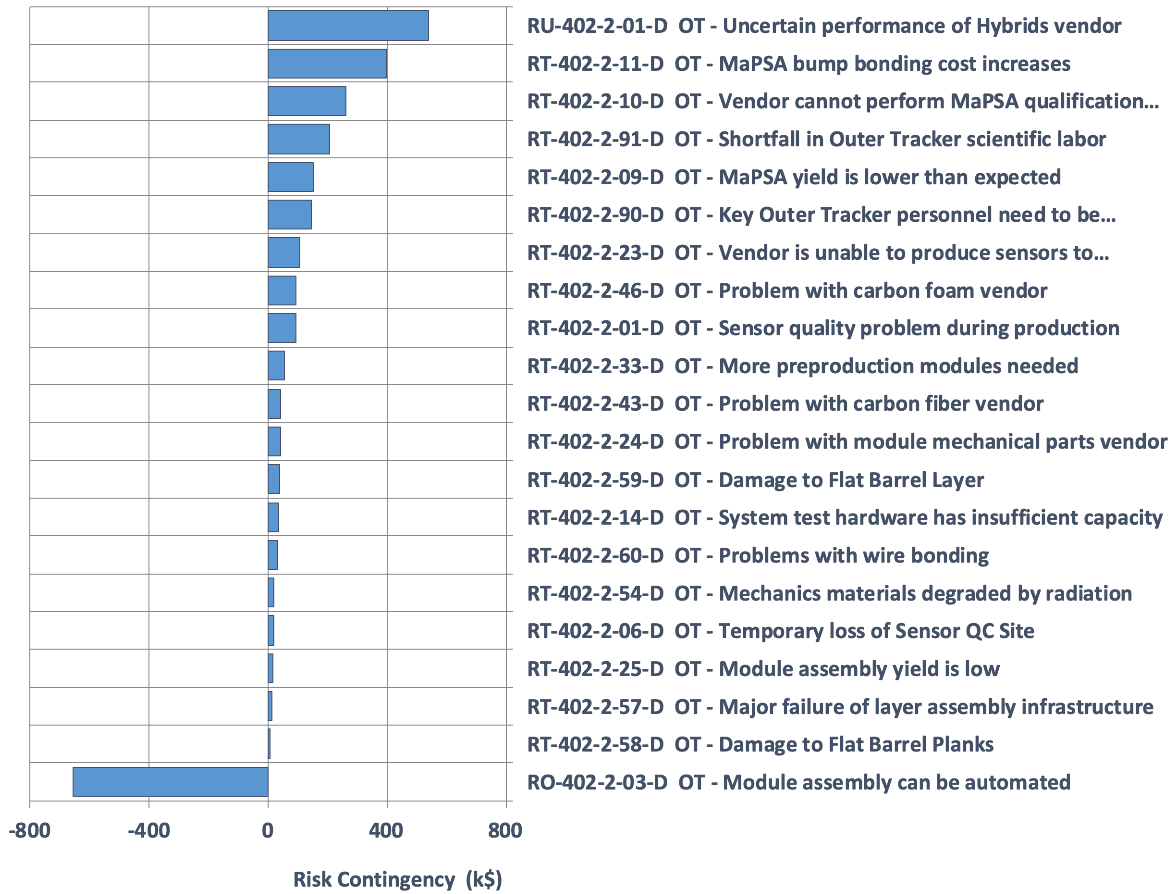
- Only minimal changes since 2018 IPR
  - Updated single source risk for sensors (CD-1 DR Recommendation)
  - Reduced Module Assembly Automation Opportunity (based on prototyping experience)
- OT follows project-wide Risk Assessment procedure
  - Project Office owns Exchange Rate and Fermilab Overhead risks – all impact OT
  - OT Specific: 19 Threats, 1 Opportunity, and 1 Uncertainty
  - Details in the Breakout session

RI-ID	Title	Probability	Cost Impact	Schedule Impact	P * Impact (k$)	P * Impact (months)
Risk Rank : 3 (High) (5)						
RU-402-2-01-D	OT - Uncertain performance of Hybrids vendor	100 %	0 -- 168 -- 648 k$	0 -- 2 -- 12 months	272	4.7
RT-402-2-91-D	OT - Shortfall in Outer Tracker scientific labor	30 %	0 -- 0 -- 1049 k$	0 months	105	0.0
RT-402-2-01-D	OT - Sensor quality problem during production	50 %	46 -- 79 -- 163 k$	2 -- 3 -- 6 months	48	1.8
RT-402-2-46-D	OT - Problem with carbon foam vendor	25 %	23 -- 158 -- 396 k$	1 -- 6 -- 12 months	48	1.6
RO-402-2-03-D	OT - Module assembly can be automated	66 %	-500 k$	-2 months	-330	-1.3
Risk Rank : 2 (Medium) (15)						
RT-402-2-11-D	OT - MaPSA bump bonding cost increases	20 %	500 -- 1000 -- 1500 k$	0 months	200	0.0
RT-402-2-10-D	OT - Vendor cannot perform MaPSA qualification tests	33 %	200 -- 400 -- 600 k$	0 months	132	0.0
RT-402-2-09-D	OT - MaPSA yield is lower than expected	15 %	370 -- 640 k$	0 months	76	0.0
RT-402-2-90-D	OT - Key Outer Tracker personnel need to be replaced	25 %	75 -- 225 -- 570 k$	0 -- 0 -- 3 months	73	0.3
RT-402-2-23-D	OT - Vendor is unable to produce sensors to specifications	5 %	210 -- 315 -- 2720 k$	6 -- 9 -- 12 months	54	0.5
RT-402-2-33-D	OT - More preproduction modules needed	25 %	0 -- 0 -- 330 k$	0 -- 0 -- 6 months	28	0.5
RT-402-2-24-D	OT - Problem with module mechanical parts vendor	20 %	0 -- 0 -- 324 k$	0 -- 0 -- 6 months	22	0.4
RT-402-2-43-D	OT - Problem with carbon fiber vendor	25 %	23 -- 79 -- 158 k$	1 -- 3 -- 6 months	22	0.8
RT-402-2-59-D	OT - Damage to Flat Barrel Layer	1 %	930 -- 1880 -- 3150 k$	6 -- 9 -- 12 months	20	0.1
RT-402-2-14-D	OT - System test hardware has insufficient capacity	10 %	71 -- 169 -- 292 k$	2 -- 3 -- 4 months	18	0.3
RT-402-2-60-D	OT - Problems with wire bonding	80 %	13.5 -- 27 k$	1 -- 2 months	16	1.2
RT-402-2-06-D	OT - Temporary loss of Sensor QC Site	20 %	22 -- 48 -- 86 k$	1 -- 2 -- 4 months	10	0.5
RT-402-2-54-D	OT - Mechanics materials degraded by radiation	10 %	48 -- 96 -- 144 k$	1 -- 2 -- 3 months	10	0.2
RT-402-2-25-D	OT - Module assembly yield is low	10 %	0 -- 40 -- 240 k$	0 -- 0 -- 6 months	9	0.2
RT-402-2-58-D	OT - Damage to Flat Barrel Planks	5 %	30 -- 91 -- 141 k$	1 -- 1 -- 2 months	4	0.1
Risk Rank : 1 (Low) (1)						
RT-402-2-57-D	OT - Major failure of layer assembly infrastructure	5 %	56 -- 112 -- 178 k$	2 -- 4 -- 6 months	6	0.2

Outer Tracker risks

Charge #3,7

- Main risk changes in past 12 months are
  - Key personnel and scientific labor risks now managed at L2
  - Sensor vendor now single source
  - Module Assembly automation opportunity reduced



OT risk contingency ≈ $3.58M * (8.4% of OT BAC)

* Total includes the OT share of common risks (escalation, OH, exchange rates, etc.)

Was $0.3M at DOE IPR, June 2018
= $1.8M threats - $1.5M opportunities

402.2 Response to Previous Reviews

- June 2018 IPR:
  - 2. The Committee recommended finalizing the plan for automation of module construction in close collaboration with international CMS by June 2019. This would allow to gain some experience and collect some statistics about production speed and alignment precision before CD-2.
    - June 2019 date set in anticipation of CD-2; agreed with DOE to move this deadline when CD-2 date moved
    - We will finalize the plan for automation by the end of 2019. We are working closely with colleagues in Germany, who have been pursuing this as well.
  - 3. Proceed to CD-1.
- March 2019 CD-1 DR:
  - 1. Update the risk register, the requirements document, and reflect in the US schedule the updates recently done to the international schedule, prior to proceeding to a DOE CD-1 IPR.
    - We updated the risk register, the requirements document, and have incorporated the latest international OT schedule.
- Recommendations/comments from earlier reviews regarding proton irradiation facility:
  - The review committee recommends that Fermilab work with the DOE to establish a proton irradiation facility at Fermilab.
    - Identified and cleaned up area at Fermilab for Irradiation Test Area (ITA). Just received DOE funding for construction and operation. Aim to be ready for first users in February 2020.

Charge #3

402.2 Progress towards CD-3a/CD-2

- CD-3a scope:
  - Sensors (achieved in October 2019)
  - Mechanical components for modules
    - Material type and amount well known
    - CMS PRR expected soon

  → Ready for CD-3a in March 2020

- Plan towards CD-2 Readiness:
  - Sufficient progress made so far, expect to meet the following milestones:

Technical Achievement	P6 Milestone
MaPSA prototyping complete	August 2020
First functional 2S prototype module built with final CBC3 chips	July 2020
Functional PS prototype modules built at Fermilab and East Coast	October 2020
Ring mechanics prototype complete	March 2020
Inner plank prototype tested	January 2020
Inner layer prototype assembly complete	July 2020

Charge #6

402.2 ES&H

Preliminary Hazard Analysis Report DocDb 13394

- In general, safety is achieved through standard Lab/Institute practices
  - Items comply with local safety standards at site of fabrication and operation, e.g. for ESD safety
  - Radiation campaigns/test beams require appropriate safety training and Operational Readiness Clearance (ORC)
  - Initial site visits by ES&H coordinator and L2 Deputy performed (Fermilab's SiDet, Brown, Rutgers, Princeton)

- Phase 1 FPIX provides an excellent recent template for ES&H
  - Both are fabrication of Silicon + electronics on Carbon composite support structure w/ CO_2 cooling, much of it done at FNAL
  - CO_2 cooling system at SiDet already has ORC

Charge #2,7

402.2 QA/QC

Project-wide Quality Assurance Plan: DocDb 13093

- QA/QC designed to verify OT detector requirements

- Quality Assurance
  - **Sensors:** Designing test structures into wafers for "Process Quality Control" to test sensor composition
  - **Electronics:** design and fabrication of test systems for MaPSAs and Modules to verify quality
  - Prototype/Preproduction/Production cycles
- Quality Control
  - **Sensors:** Sensor Quality Control and Irradiation tests
  - **Modules:** Acceptance tests of components, final module burn-in tests

- QA/QC documented per L3 area in the CDR
- QA/QC activities are in P6 and resource loaded
- QA/QC plan updated since March CD-1 DR following recommendation (DocDb 13388)

Charge #2,7

402.2 Interfaces and Externals

Interface Control Document: DocDb 13388

- Key interfaces defined
  - Modules: iCMS and US share same design, interfaces handled at international level
    - Implementation in EDMS ongoing, based on 402.4 CE example
  - Flat Barrel: integration design work requires specific handshaking
    - Design files shared between US and CERN engineering

L3 Area/Interface	Voltage	Readout data flow	Mech. Support	Cabling	Cooling
Sensors	Hybrids	Hybrids, MaPSA	Module Mechanics		Module Mechanics
Electronics		Hybrids, MaPSA, DTC, FC7, DAQ, Modules	Module Mechanics	Hybrids	
Modules	Hybrids	DTC, FC7, DAQ	Jigs, Planks		Planks
Mechanics			Planks and Rings		
Integration	Bulk Power system	Environmental Control and Monitoring	Tilted Barrel, IT Support Tube	PS power and optical cable plants	CO_2 distribution system

- Interface negotiation vastly expedited by embedded US team in international organization
- We are monitoring high-level external international milestones: DocDB:13742

402.2 Breakout Session

08:00 - 12:30 **Breakout: Outer Tracker**

Please join the meeting by clicking this link: https://vidyoportal.cern.ch/join/wj7gAHvgGyiW9HRoiatWTcxqVM

*If you want to join by phone, please use one of the phone numbers listed in the link below:
http://information-technology.web.cern.ch/services/fe/howto/users-join-vidyo-meeting-phone
and enter the meeting extension 105676591 in order to join.*

Conveners: Dr. Petra Merkel (Fermilab), Prof. Ulrich Heintz (Brown University)

Location: Fermilab (Black Hole (WH2NW))

08:00 **B01: Sensors** *35'*
Speaker: Regina Demina (University of Rochester)
Material: Slides

08:35 **B02: Modules** *50'*
Speaker: Meenakshi Narain (Brown University)
Material: Slides

09:25 **Coffee break** *15'*

09:40 **B03: Electronics** *35'*
Speaker: Prof. Yuri Gershtein (Rutgers University)
Material: Slides

10:15 **B04: Macro Pixel Sub-Assemblies** *20'*
Speaker: Douglas Berry
Material: Slides

10:35 **B05: Mechanics & Integration and Testing** *35'*
Speaker: Stefan Gruenendahl (Fermilab)
Material: Slides

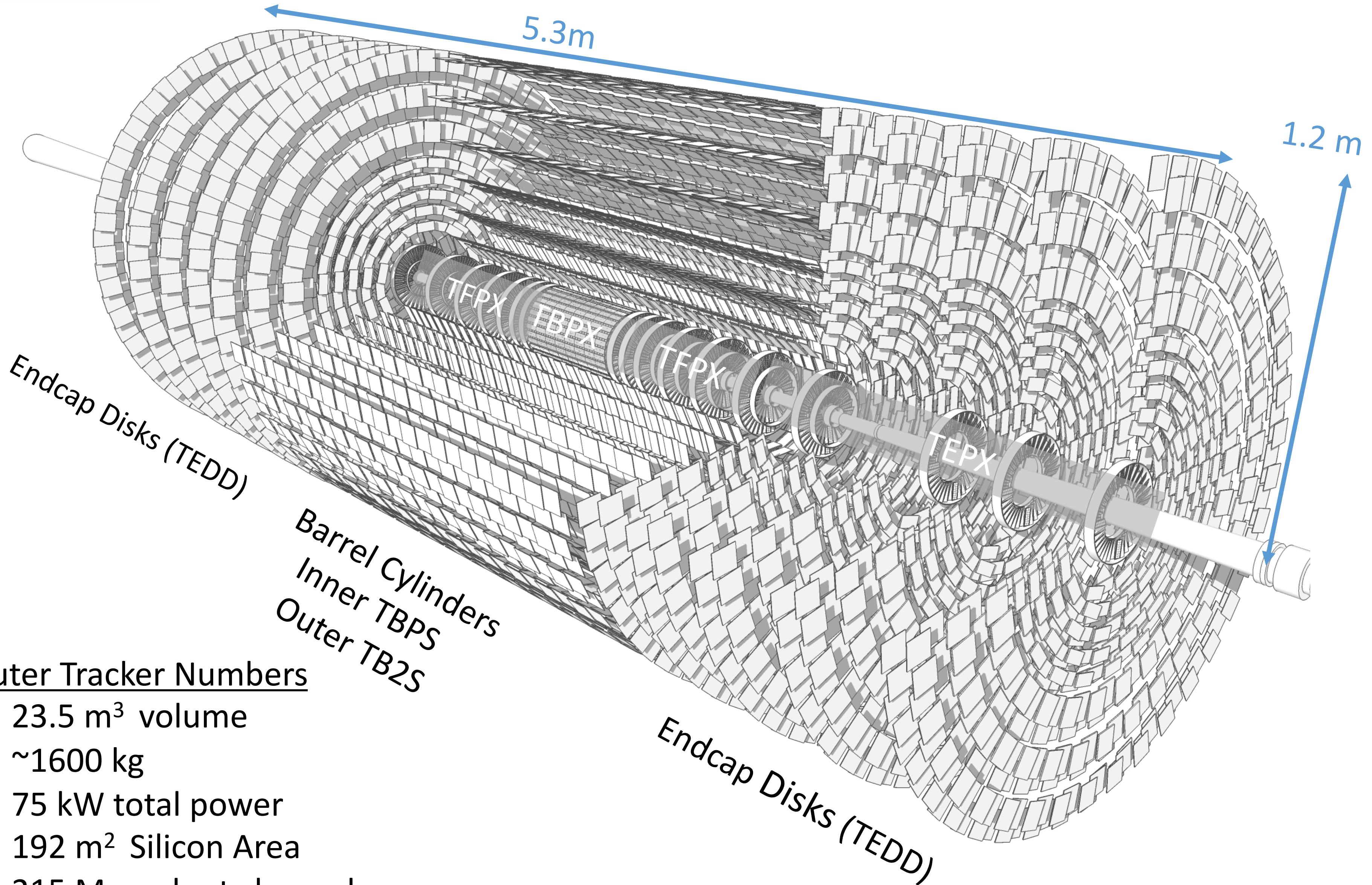
11:10 **B06: Path to Baseline** *20'*
Speakers: Prof. Ulrich Heintz (Brown University), Ulrich Heintz
Material: Slides

Summary

- Lots of progress with prototyping across all L3 areas
  - In many cases final or close-to-final designs
  - Well beyond CD-1 requirements
- Will be ready for CD-3a / CD-2
  - Already close to ready for CD-3a
  - Clear plan of technical milestones for CD-2 readiness
- OT has addressed all recommendations from previous reviews
- Ready for CD-1

Backup slides

HL LHC CMS Tracker Upgrade

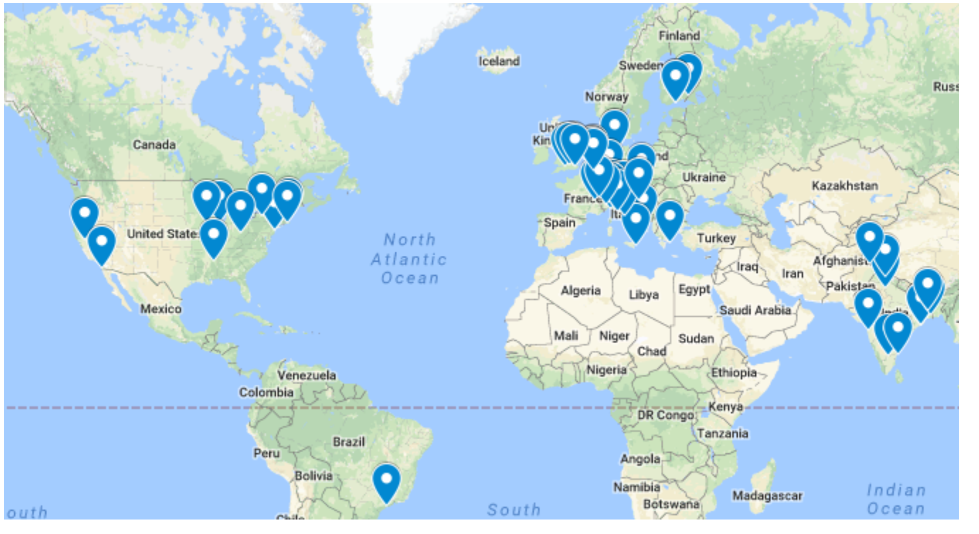


Outer Tracker Numbers

- 23.5 m^3 volume
- ~1600 kg
- 75 kW total power
- 192 m^2 Silicon Area
- 215 M readout channels

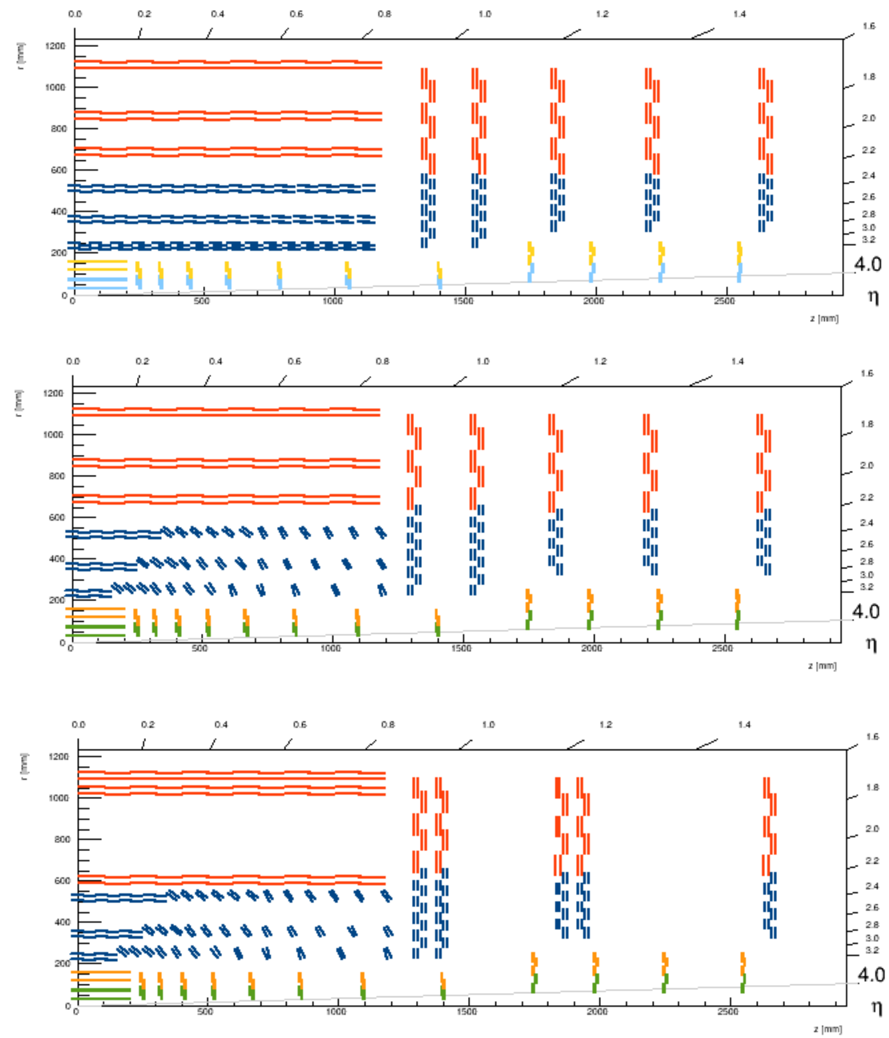
International relations

- U.S. OT intertwined with the international CMS ("iCMS")
  - Both with design validation and actual fabrication
    - Many shared procurements to guarantee consistency, organized through CERN
  - U.S. supplies ~ 25% of the "CORE costs" for the OT
    - CORE = accounting system to facilitate international comparison
    - Comparison and negotiations at the international level
- U.S. is embedded in international organization
  - U.S. team co-coordinators "System Test" group and "Modules" group, as well as "CMS Upgrade Performance Studies" group



Simulation of Tracker Design

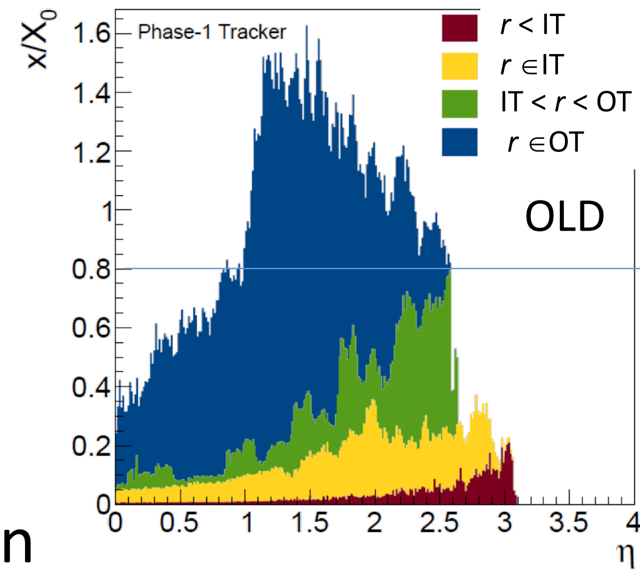
- tKLayout Tool
  - Allows easy exploration of layout alternatives in terms of solid angle coverage, tracking resolution, power dissipation, cost, bandwidth, trigger performance …
  - Output is compatible with CMSSW (full simulation of CMS)
- CMSSW
  - Full simulation of detector response, digitization, and offline reconstruction
    - Material effects
    - Trigger emulation
    - Pileup

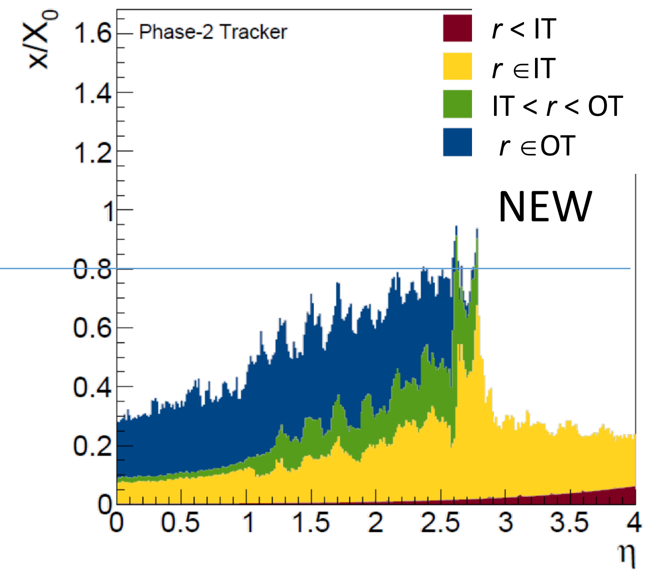


Resulting Design performance (examples)

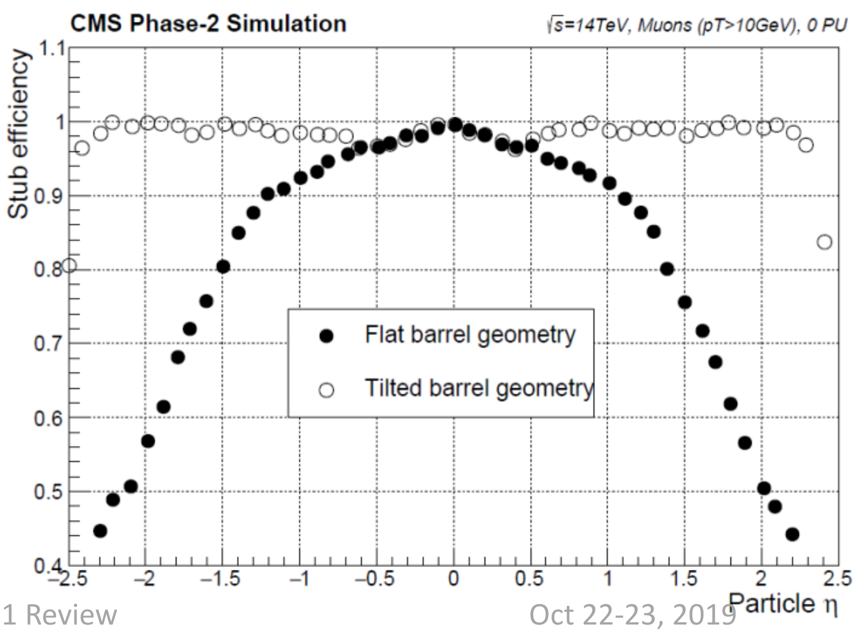
Charge #2

- Mass budget vs η
  - Service routing much different
  - CO_2 Cooling





- p_T stub efficiency in TBPS Layer 1 vs. η
  - p_T Stub = trigger
  - > 10 GeV stubs, Gaussian beam spot
  - Tilted geometry ⇒ normal incidence allows sensor hit correlation



OT Basis of Estimates

Charge #3

https://go.usa.gov/xnSwv

- Cost Estimate follows project standards laid out in Cost Estimating Guide and Key Assumptions Document
- Several workshops involving full management team to scrub cost estimates
- Expect modest further refinements as prototyping informs estimates
- Details in the Breakout session

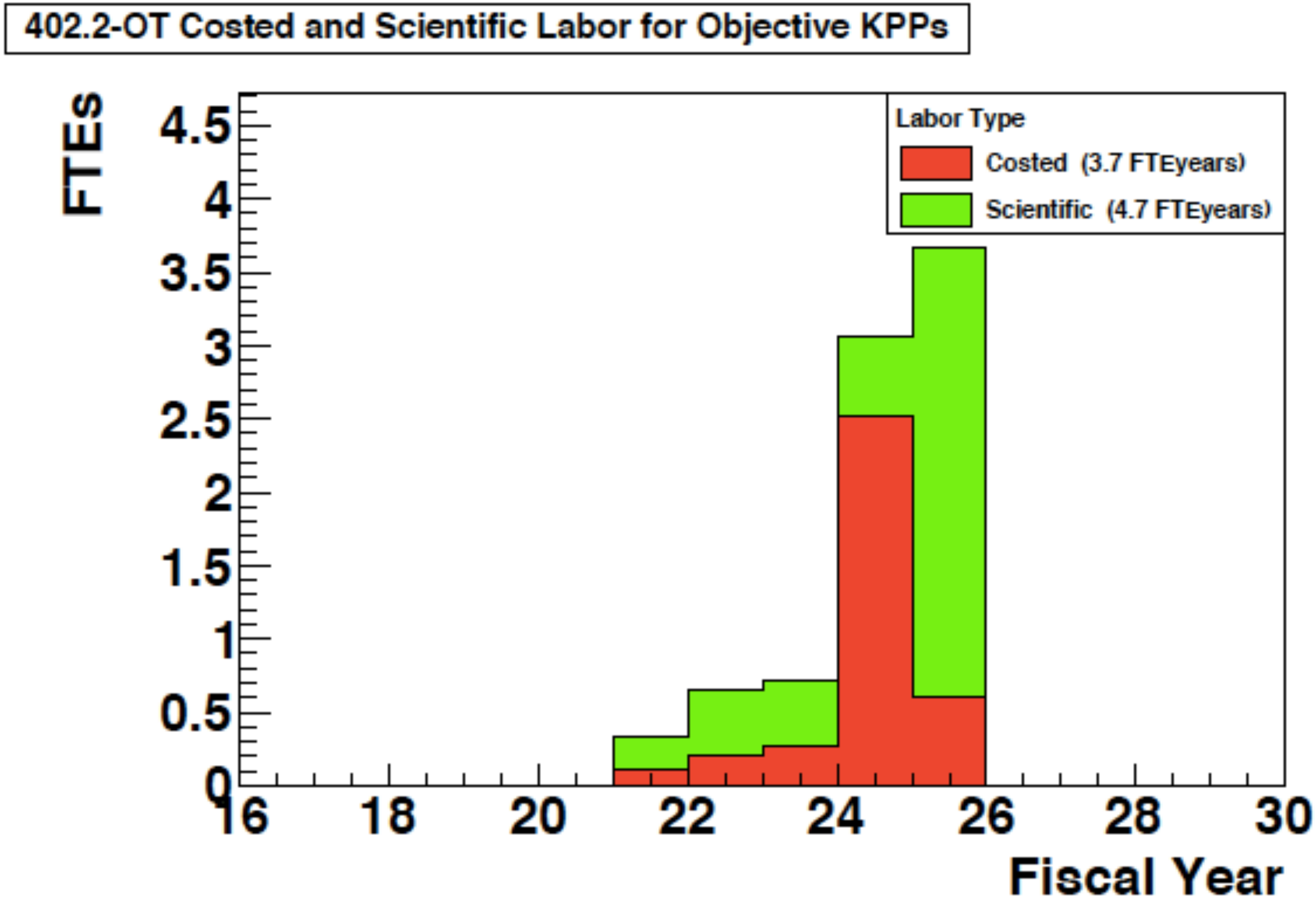
L2 Parent:WBS : 402.2 OT - OUTER TRACKER (15)

L3 Parent:WBS : 402.2.2 OT - Management (1)	
402.2.2 OT - Management	CMS-doc-12824
L3 Parent:WBS : 402.2.3 OT - Sensors (4)	
402.2.3.1 OT - QC Centers	CMS-doc-12989
402.2.3.2 OT - PS-P Sensors	CMS-doc-12991
402.2.3.3 OT - PS-S Sensors	CMS-doc-12993
402.2.3.4 OT - 2S Sensors	CMS-doc-12995
L3 Parent:WBS : 402.2.4 OT - Electronics (3)	
402.2.4.1 OT - Macro Pixel Sub-Assembly	CMS-doc-12997
402.2.4.2 OT - Test Systems	CMS-doc-12998
402.2.4.3 OT - DAQ	CMS-doc-13000
L3 Parent:WBS : 402.2.5 OT - Modules (5)	
402.2.5.1.1 OT - Module Assembly Facilities - East Coast	CMS-doc-13008
402.2.5.1.2 OT - Module Assembly Facilities - Fermilab	CMS-doc-13009
402.2.5.1.3 OT - Module Assembly Infrastructure	CMS-doc-13002
402.2.5.2 OT - Module Components	CMS-doc-13010
402.2.5.3 OT - Module Assembly	CMS-doc-13012
L3 Parent:WBS : 402.2.6 OT - Mechanics (1)	
402.2.6 OT - Mechanics	CMS-doc-13005
L3 Parent:WBS : 402.2.7 OT - Integration and Testing (1)	
402.2.7 OT - Integration and Testing	CMS-doc-13014

402.2 Cost Summary

WBS	Direct M&S	FTE	Direct+Indirect+Esc.	Estimate Uncertainty	Total Cost
402.2 Outer Tracker	$20,575,450	213.22	$42.871,529	$9,891,026	$52,762,555
2018 IPR	$21,420,779	192.55	$42,593,399	$13,350,307	$55,943,706
% change	-4%	+11%	+1%	-26%	-6%
402.22 OT - Management	$959,000	24.63	$1,125,217	$87,120	$1,212,337
2018 IPR	$658,000	23.00	$844,022	$84,402	$928,424
% change	+46%	+7%	+33%	+3%	+31%
402.23 OT - Sensors	$4,993,973	17.97	$7,371,148	$1,309,487	$8,680,634
2018 IPR	$7,582,541	17.23	$9,651,654	$2,672,348	$12,324,001
% change	-34%	+4%	-24%	-51%	-30%
402.24 OT - Electronics	$2,740,374	18.69	$6,222,484	$1,241,158	$7,463,642
2018 IPR	$1,436,802	17.24	$4,427,137	$1,361,562	$5,788,698
% change	+91%	+8%	+41%	-9%	+29%
402.25 OT - Modules	$9,074,091	120.13	$21,785,980	$5,113,007	$26,898,987
2018 IPR	$8,990,428	115.94	$21,172,433	$6,615,628	$27,788,061
% change	+1%	+4%	+3%	-23%	-3%
402.26 OT – FB Mechanics	$543,000	11.48	$2,380,031	$762,785	$3,142,815
2018 IPR	$433,000	11.33	$2,212,199	$1,024,739	$3,236,938
% change	+25%	+1%	+8%	-26%	-3%
402.27 OT – Integr.&Testing	$2,265,012	20.33	$3,986,670	$1,377,470	$5,364,140
2018 IPR	$2,320,008	7.81	$4,285,955	$1,591,629	$5,877,583
% change	-2%	+160%	-7%	-13%	-9%

Objective KPP Labor



Highest OT risk

RU-402-2-01-D OT - Uncertain performance of Hybrids vendor

Risk Rank:	3 (High) **Scores:** Probability : 5 (VH) ; Cost: 2 (M) Schedule: 3 (H))	**Risk Status:**	Open
Summary:	There is uncertainty in the performance of the vendor of hybrids for modules which could have a range of impacts from negligible to significant cost impact and delay.		
Risk Type:	Uncertainty	**Owner:**	Leonard G Spiegel
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	External Risk / Vendors
Probability (P):	100%	**Technical Impact:**	1 (L) - somewhat substandard
Cost Impact:	PDF = 3-point - triangular Minimum = 0 k$ Most likely = 168 k$ Maximum = 648 k$ Mean = 272.0 k$ P * <Impact> = 272.0 k$	**Schedule Impact:**	PDF = 3-point - triangular Minimum = 0.0 months Most likely = 2.0 months Maximum = 12.0 months Mean = 4.67 months P * <Impact> = 4.67 months
Basis of Estimate:	Minimum impact: no extra cost nor delay Likely impact: issues with the vendor causing a delay at delivery of 2 months. Use a module assembly labor burn rate of $54k/month without escallation. Maximum impact: we need to find an alternative vendor or significant rework is needed at the selected vendor. This implies a cost impact of $648k (12 * 54k/month).		
Cause or Trigger:		**Impacted Activities:**	Module assembly. This risk should be implemented in series with the module risk on receiving the mechanical parts.
Start date:	1-Apr-2020	**End date:**	31-Dec-2024
Risk Mitigations:	The prototyping experience should inform the hybrid fabrication time estimates		
Risk Responses:	Increased resources for labor and infrastructure to parallelize downstream activities in Module Assembly and Plank/Layer Assembly to recoup delays from Hybrids		
More details:	CMS-doc-13481		

2nd highest OT risk

RT-402-2-91-D OT - Shortfall in Outer Tracker scientific labor

Risk Rank:	3 (High) **Scores:** Probability : 3 (M) ; Cost: 3 (H) Schedule: 0 (N))	**Risk Status:**	Open
Summary:	If a significant amount of the (uncosted) scientific labor is unavailable, then the project would then need to fund additional (costed) personnel to perform the work. It is assumed that the risk is triggered by a seriously unfavorable overall base program funding situation.		
Risk Type:	Threat	**Owner:**	Steven C. Nahn
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	Management Risk / Funding or Resources
Probability (P):	30%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 3-point - triangular Minimum = 0 k\$ Most likely = 0 k\$ Maximum = 1,049 k\$ Mean = 349.7 k\$ P * <Impact> = 105.0 k\$	**Schedule Impact:**	PDF = 1-point - single value Minimum = N/A Most likely = 0.0 months Maximum = N/A Mean = 0 months P * <Impact> = 0 months
Basis of Estimate:	In the past US-CMS has not experienced a significant lack of scientific labor (postdocs and graduate students). When shortfalls occured they were usually resolved by collaborators at US-CMS institutes or sometimes from iCMS. We assign a 30% probability that a significant shortfall occurs in future, due to unfavorable funding conditions in the base program. The contributed labor for the scope of this L2 area is 60.8 FTE-years spread over about 5 years. This does not includethe more secure L2 and L3 managers who are tenuredfaculty and senior Fermilab scientists. We estimate the loss could be up to 20% of the total contributed labor or 12.2 FTE-years (e.g. this is a loss of 50% of all contributed labor for a two year period or a loss of 1/3 of the contributed labor for 3 years). The missing labor could be replaced by costed personnel: a mixture of mid-range technicians, junior technicians, or undergraduates costing respectively 62\$/hr, 50\$/hr and 18\$/hr fully-burdened (43\$/hour on average). Allowing for four years of escalation at 3.1% per annum yields an average cost of 49\$/hr or 86k\$/FTE-year (1768hrs worked per year). The (min/likely/max) cost impact is therefore: 86k\$ per FTE-year * (0/0/12.2) FTE-years = \$(0/0/1049)k.		
Cause or Trigger:	The risk is triggered by an unfavorable base program funding situation.	**Impacted Activities:**	
Start date:	1-Oct-2018	**End date:**	
Risk Mitigations:	Work with institutes and agencies to ensure the anticipated amount of scientific labor will be available. Where shortfalls look likely to occur, seek alternatives amongst other US-CMS institutes or even from iCMS institutes.		
Risk Responses:	Seek replacement scientific labor in other institutes. If this labor cannot be found then contingency will need to be spent to supplement the effort with costed labor (e.g. technicians).		
More details:	CMS-doc-13509 (FTE data at CD1)		

3rd highest risk

RT-402-2-01-D OT - Sensor quality problem during production

Risk Rank:	3 (High) **Scores:** Probability : 4 (H) ; Cost: 1 (L) Schedule: 2 (M))	**Risk Status:**	Open
Summary:	If the sensor vendor delivers sensors that do not meet specifications then the degraded performance of the tracker jeopardizes the physics performance of the upgraded detector.		
Risk Type:	Threat	**Owner:**	Ulrich Heintz
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	External Risk / Vendors
Probability (P):	50%	**Technical Impact:**	2 (M) - significantly substandard
Cost Impact:	PDF = 3-point - triangular Minimum = 46 k$ Most likely = 79 k$ Maximum = 163 k$ Mean = 96.0 k$ P * <Impact> = 48.0 k$	**Schedule Impact:**	PDF = 3-point - triangular Minimum = 2.0 months Most likely = 3.0 months Maximum = 6.0 months Mean = 3.67 months P * <Impact> = 1.835 months
Basis of Estimate:	The contract will be written for the vendor to deliver a specified number of good sensors that satisfy CMS specifications. Thus we do not have to pay for sensors that do not satisfy the specifications and there is no impact on sensor cost. The only cost impact is that we will have to repeat the QC testing of the replacement sensors. Minimal impact: this happens during production and is corrected quickly after feedback from sensor QC leading to a delay of about 2 months and negligible direct cost. Maximal schedule impact: this happens during preproduction and the preproduction cycle has to be repeated, leading to a delay of about 6 months and extra labor cost of about $25k (cost for preproduction cycle of one sensor type). The L3 burn rate due to the delay of downstream activities is $23k/month (CMS-doc-13481). Min cost = $0k + 2months * $23k burn rate = $46k. Likely cost = $10k + 3month * $23k burn rate = $79k. Max cost = $25k + 6months * $23k burn rate = $163k. The problem has to either persist over many batches or not be noticed during QC at the vendor (for example a degradation of performance over some time). Problems that affect a single batch of sensors (eg because of some contamination or processing mistake) will not lead to a significant delay because reprocessing a batch will only add a week or two to the production period. Based on past experience with the vendor we expect this to happen at least once during production and we assign 50% probability for each sensor type.		
Cause or Trigger:	Sensors do not satisfy specifications	**Impacted Activities:**	Sensor procurement activities and downstream activities. This applies to each type of sensor, but the probability should be 5% per type (PS-s, PS-p, 2S). This should be implemented for each of the three sensor types (2S, PS-p, PS-s) so that the probability of 50%/sensor type.
Start date:	1-Apr-2020	**End date:**	31-Dec-2024
Risk Mitigations:	We carry out extensive prototyping work with the vendors prior to placing the contract for sensor production to make sure that vensors understand our specifications and can meet them. The vendor will carry out a first set of QC measurements before the sensors are shipped to CERN and distributed to QC centers. This ensures that most problems will be caught quickly and do not lead to significant impact on the project. The cost of these measurements is factured into the sensor cost.		
Risk Responses:	If a modest problem occurs, work closely with vendor to solve it (e.g. testing). Replace the flawed sensors.		
More details:	CMS-doc-13481		

External Dependencies and Deliverables

- We are monitoring international CMS deliverables and milestones (DocDb:13742)
- Included a set of external milestones in our P6 schedule

Activity ID	Activity Name	Activity Type	Start	Finish
OT150410	CMS - OT Substructures validated	Finish Milestone		25-Oct-19*
OT150330	CMS - OT PS POH production ordered by CERN	Finish Milestone		08-Nov-19*
OT150130	CMS - OT Detector mechanics design complete	Finish Milestone		20-Dec-19*
OT150180	CMS - OT Integration mechanics design complete	Finish Milestone		06-Feb-20*
OT150350	CMS - OT PS ROH production ordered by CERN	Finish Milestone		16-Mar-20*
OT150050	CMS - OT 2S module design finalized	Finish Milestone		31-Mar-20*
OT150210	CMS - OT Module Mechanics Finalized	Start Milestone	31-Mar-20*	
OT150291	CMS - OT PS FEH final proto validation - 1.6mm left and right	Finish Milestone		13-Apr-20*
OT150120	CMS - OT CBC submission completed	Finish Milestone		11-May-20*
OT150280	CMS - OT PS FEH production ordered by CERN	Finish Milestone		09-Jun-20*
OT150372	CMS - OT - First Pre-production 2S Sensors available	Finish Milestone		08-Jul-20*
OT150374	CMS - OT - First Pre-production PS-P Sensors available	Finish Milestone		08-Jul-20*
OT150376	CMS - OT - First Pre-production PS-S Sensors available	Finish Milestone		08-Jul-20*
OT150150	CMS - OT EDR	Finish Milestone		20-Jul-20*
OT150300	CMS - OT PS module design finalized	Finish Milestone		20-Jul-20*
OT150220	CMS - OT Production MPA/SSA/CIC submission	Finish Milestone		24-Jul-20*
OT150377	CMS - OT - First Production 2S Sensors available	Finish Milestone		28-Oct-20*
OT150378	CMS - OT - First Production PS-P Sensors available	Finish Milestone		28-Oct-20*
OT150379	CMS - OT - First Production PS-S Sensors available	Finish Milestone		28-Oct-20*
OT150010	CMS - OT - MPA/SSA chips available	Finish Milestone		22-Jan-21*
OT150310	CMS - OT PS Module design validated	Finish Milestone		02-Mar-21*
OT750340	CMS - OT - Availability of Test Systems	Finish Milestone		15-Mar-21*
OT150060	CMS - OT 2S Module design validated	Finish Milestone		11-May-21*
OT150091	CMS - OT - First Pre-production 2S Service Hybrids available	Finish Milestone		23-Jun-21*
OT150362	CMS - OT - First Pre-production PS Service Hybrids available	Finish Milestone		23-Jun-21*
OT150420	CMS - OT Integration of TIF final prototype system	Start Milestone	07-Jul-21*	
OT150033	CMS - OT - First Pre-production 2S FE Hybrids available	Finish Milestone		21-Jul-21*
OT150292	CMS - OT - First Pre-production PS FE Hybrids available	Finish Milestone		21-Jul-21*
OT150070	CMS - OT 2S Module ready for production	Finish Milestone		09-Nov-21*
OT150320	CMS - OT PS Module ready for production	Finish Milestone		09-Nov-21*
OT150093	CMS - OT - First Production 2S Service Hybrids available	Finish Milestone		10-Nov-21*
OT150364	CMS - OT - First Production PS Service Hybrids available	Finish Milestone		10-Nov-21*
OT150035	CMS - OT - First Production 2S FE Hybrids available	Finish Milestone		08-Dec-21*
OT150294	CMS - OT - First Production PS FE Hybrids available	Finish Milestone		05-Jan-22*
OT150020	CMS - OT 30 percent modules built	Finish Milestone		13-Dec-22*
OT150400	CMS - OT Substructures built	Finish Milestone		06-Jun-23*
OT150100	CMS - OT 60 percent modules built	Finish Milestone		11-Jul-23*
OT150110	CMS - Need by date for "OT all modules built" (5 months before "OT subdetectors complete")	Finish Milestone		20-Feb-25
OT150390	CMS - Need by date for "OT subdetectors completed" (5 months before "OT installation")	Finish Milestone		21-Jul-25
OT150170	CMS - OT Installation (CMS Need by date)	Finish Milestone		19-Dec-25*

Charge #2,3

Remaining steps to CD2 (details-L3 talks)

- Iteration of prototype components of ever increasing functionality
  - Driven by availability of common components (and funds)
    - Prototype sensors, hybrids, etc
  - Example: Module Iterations
    - Scaled down versions with limited components
      - "Mini-module", "MaPSA-lite"× 2 = "Micro-module"
    - Dummy modules
      - "Type 1": Cheap components (Al mechanics, Blank silicon, mock hybrids)
        - Alignment Testing
        - Thermal Studies
      - "Type 2": Above, with wire-bond pads
        - Testing wire-bonding techniques, jigs, etc
    - Functional Modules: Full sensors, Al-CF mechanics, functional hybrids
      - Assembly techniques and QC, testbeam performance tests
- Leads to a validation of design and refined point estimate of cost and schedule for baseline

	2017		2018		2019		2020	
	PS	2S	PS	2S	PS	2S	PS	2S
Dummy Prototypes	10	10	25	26	35	16	10	8
Functional Prototypes				10	20	12	20	8