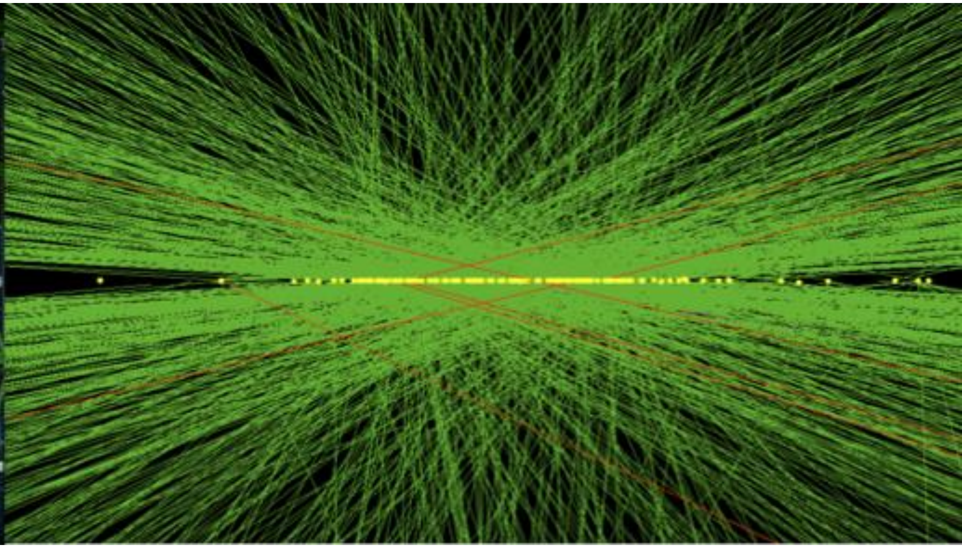
P05: 402.02 Outer Tracker

Steve Nahn and Petra Merkel

CD-1 Director's Review

March 19, 2019



Outline

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

Charge #5

Biographical Sketch (Apparatus bias)

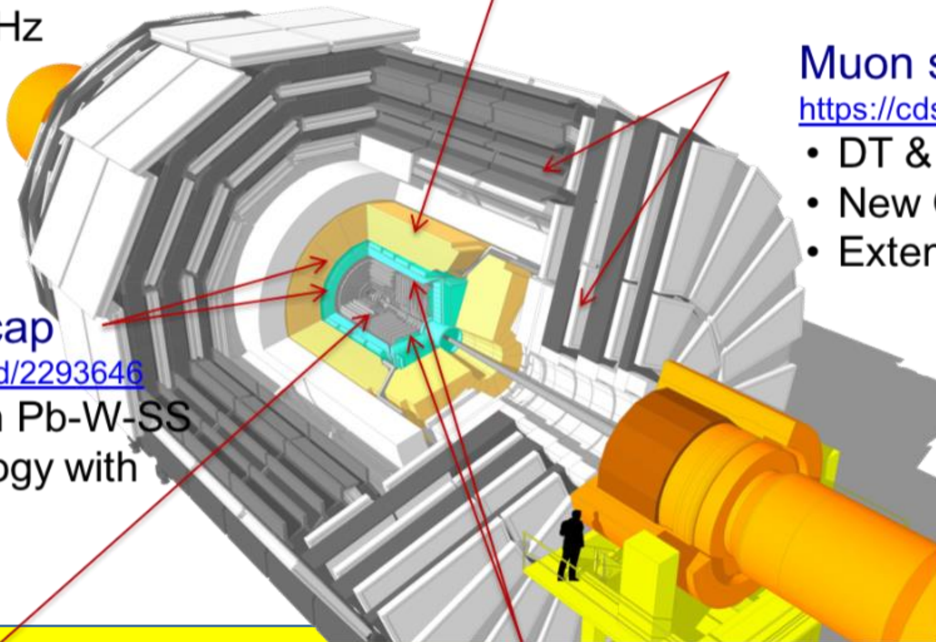
- Steve Nahn
  - MIT 91-98 (Grad Student)
    - L3 Forward Backward Muon Chamber Upgrade, L3 Muon Operations
  - Yale 98-05 (Postdoc)
    - CDF Silicon Detectors (SVXII, ISL, L00) Run 2 Upgrades, Silicon Operations
  - MIT 05-13 (Faculty)
    - CMS Strip Tracker – Co-Operations Manager at Tracker Integration Facility, CMS Strips Operations (through Post-docs and Students)
  - FNAL 13-present (Scientist)
    - Project Manager for the LHC CMS Detector Upgrade (aka" Phase 1")
      - Forward Pixel, L1 Trigger, Hadron Calorimeter Photosensors and electronics
      - $45M TPC, currently 99.9% complete, (CPI, SPI) = (0.98, 1.00)
- Petra Merkel
  - UHamburg and DESY 95-00 (Grad Student)
    - H1 Muon System Operations
  - Postdoc @ Fermilab (2000-2004)
    - CDF Silicon Detectors (SVXII, ISL, L00) Run 2 (and 2b) Upgrades, Silicon Operations
  - Scientist @ Purdue (2004-2014)
    - CMS Forward Pixel module assembly
    - CMS Pixel DQM: main developer and convener; CMS Tracker DPG convener
  - Scientist @ Fermilab (2014-)
    - L3 CMS Forward Pixel Testing and Integration
    - Fermilab Detector R&D Coordinator
    - L3 CMS OT Electronics

CMS HL-LHC Upgrade Overview

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

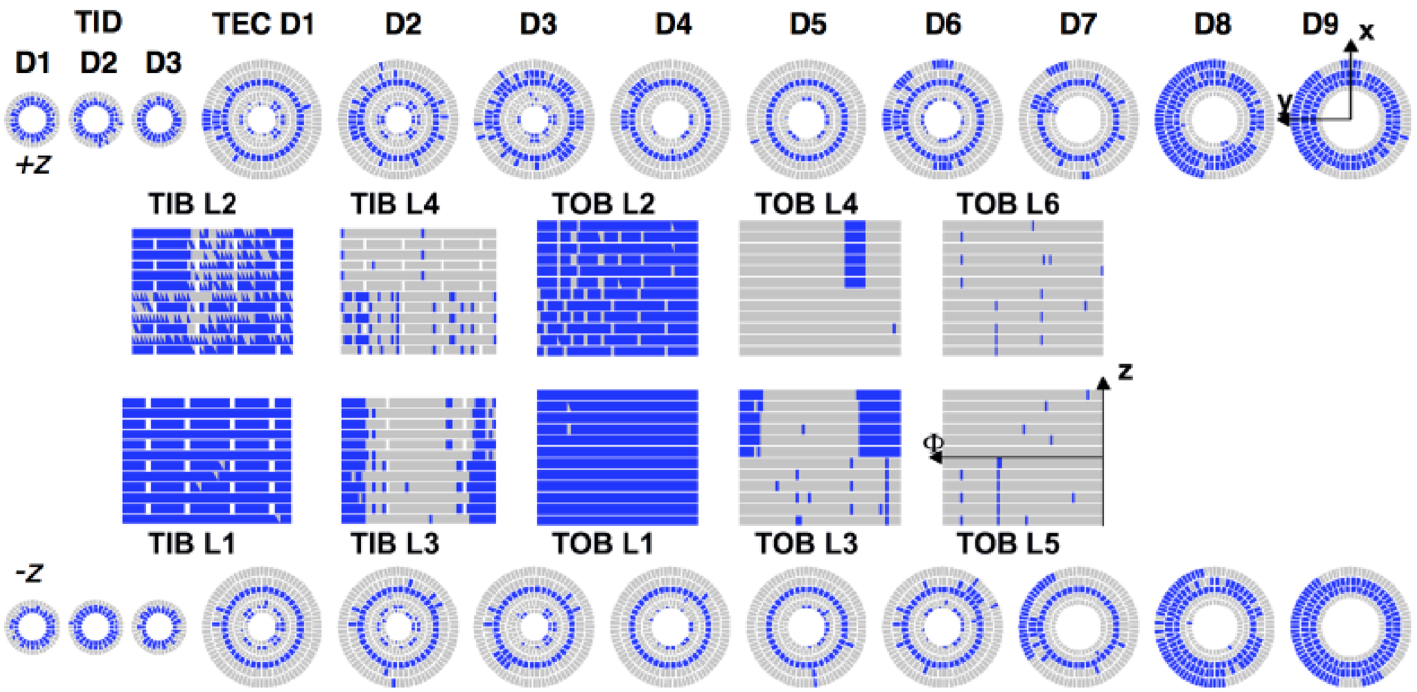
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

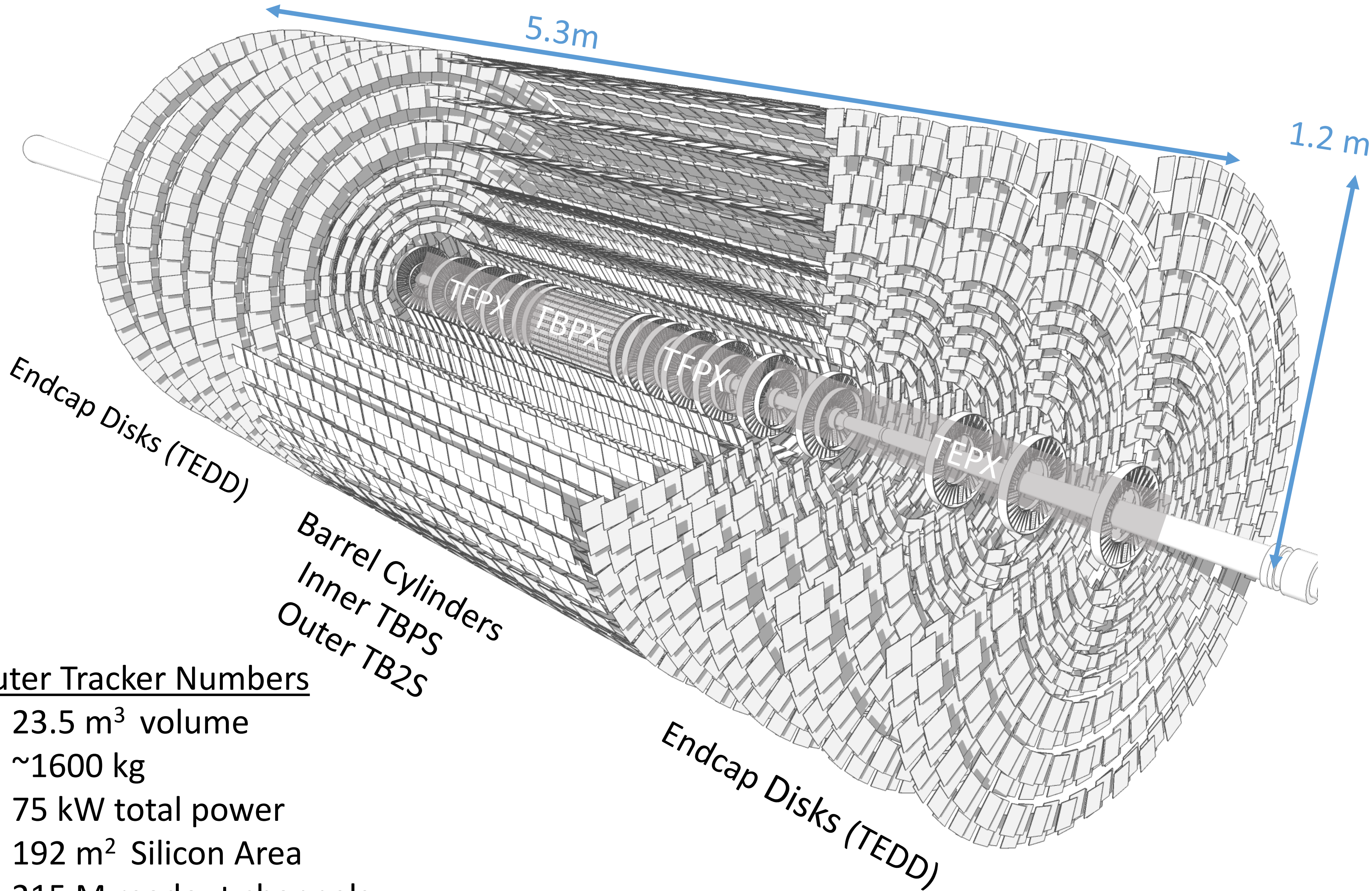
Outer Tracker Motivation

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



Design Overview

OT in numbers

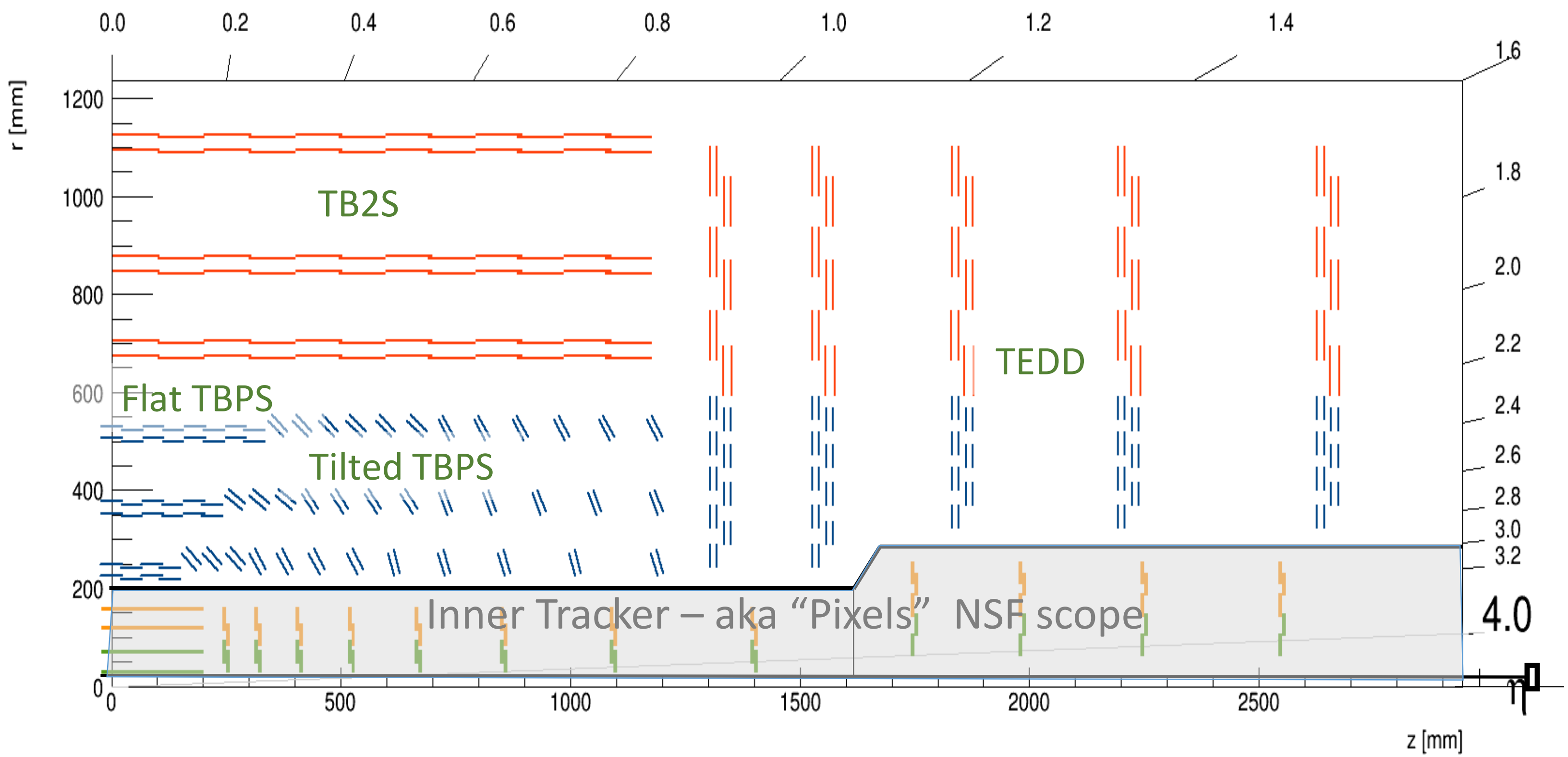


Outer Tracker Numbers

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

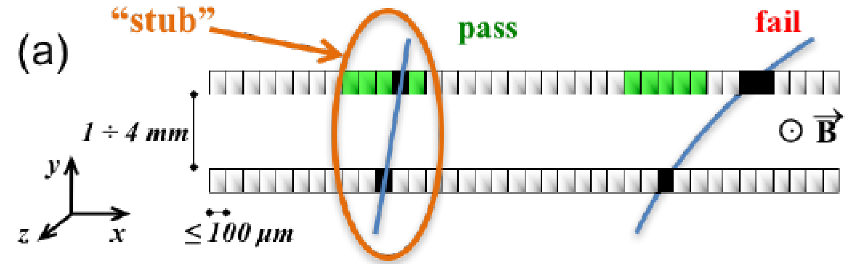
OT Detector Layout

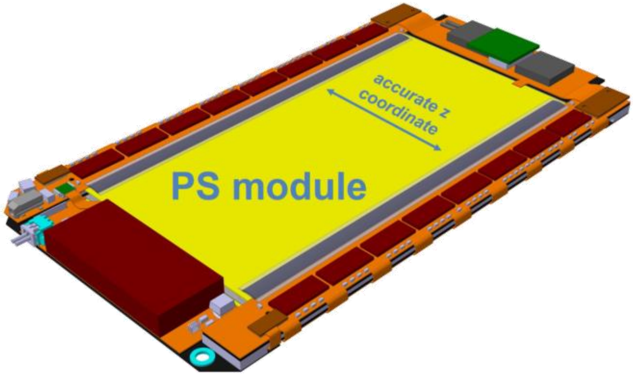
- Divided into 6 barrel layers and 5 endcap disks
  - Barrel has “Flat” section and “Tilted Section”
  - Trigger: Each layer is a sandwich of sensors (next slide)
    - Two flavors of pairs, “PS” and “2S”

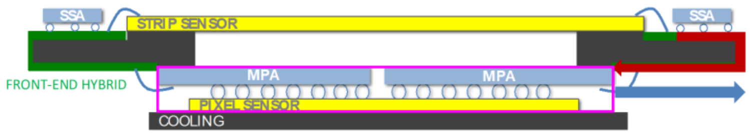


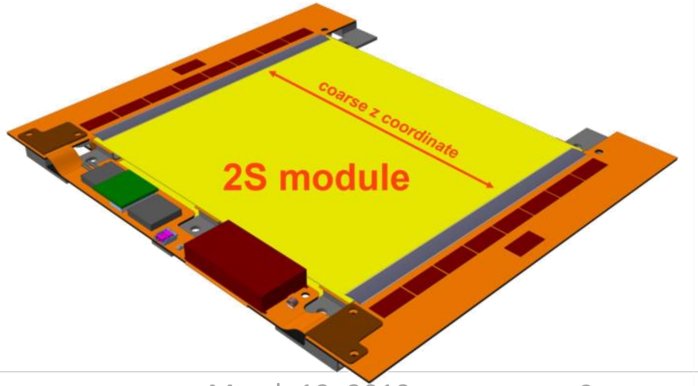
OT – Fundamental Unit: Module

- 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 (PS-s) provide 1D information, Pixelated sensor (PS-p) provide 2D information. Used at lower radius, balance between precision and cost
  - Strip-Strip (2S): Strip Sensors (2S) for both slices of sandwich at high radius
- Modules include sensors, ASICs, power and readout hybrids, spacers and mechanical support
  - Sensors and Electronics may differ, Mechanics similar





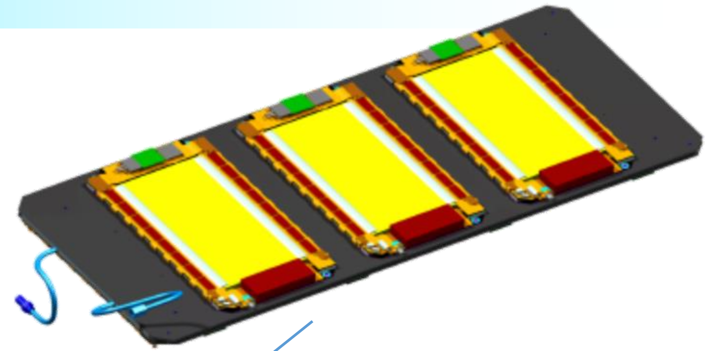


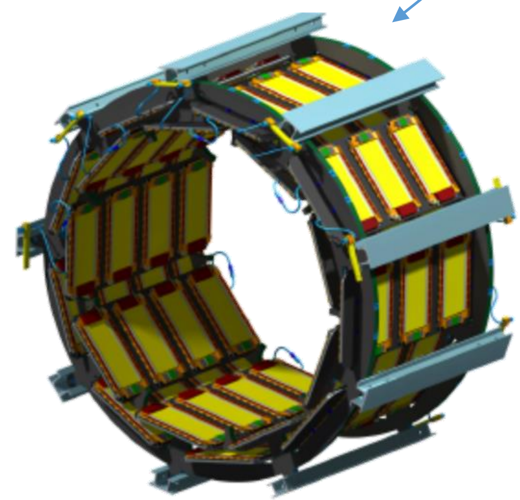


Charge #2

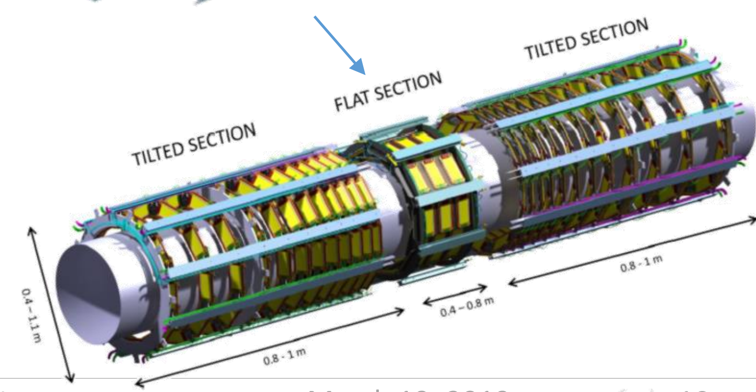
OT Structure and Accessories

- 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
    - (Trigger part of 402.07)



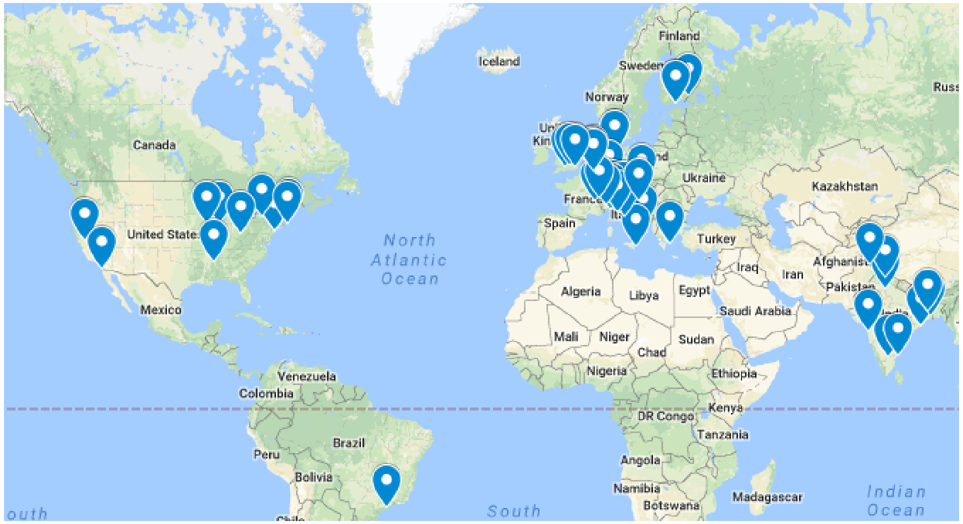


U.S. scope: Flat Barrel (layer 1 shown)



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



HL-LHC US CMS

OT – U.S. Involvement

Charge #2

KPPs: DocDb-13237

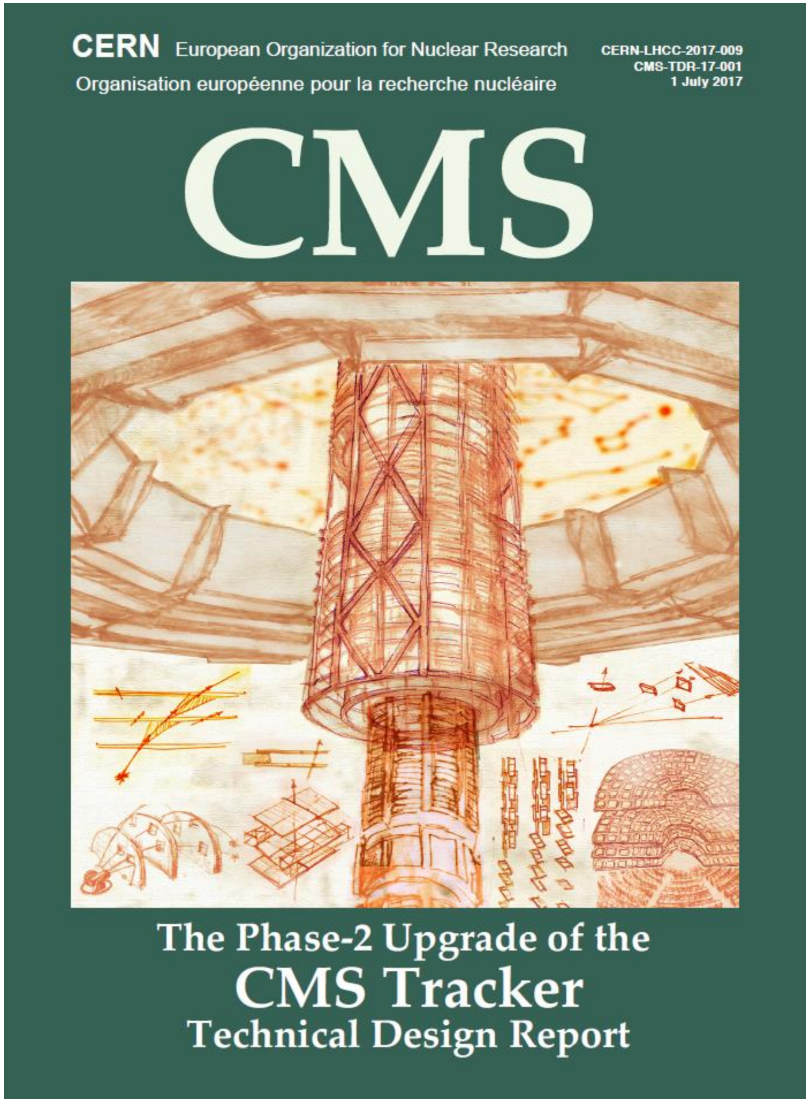
- Modules (Key Performance Parameter #2)
  - Deliverable: 2500 PS and 2000 2S working production modules, plus 5% preproduction and 10% spares
    - 952 PS go to Flat Barrel (below), rest to iCMS collaborators
  - Sensors – Procurement (CD-3a, later slide), QC
  - Electronics
    - Development of Test systems for iCMS, Procurement for U.S. needs
    - Development of Sensor-ASIC assembly: MacroPixel Sub Assembly (MaPSA)
  - Modules
    - Development of assembly sites
      - East Coast and FNAL
    - Module component procurements and QC
    - Assembly of components into modules and QC
- Flat Barrel Fabrication (Key Performance Parameter #1)
  - Fabrication of Planks and Rings for the PS Flat Barrel (inner 3 layers)
  - Assembly of (U.S.) PS Modules onto Planks/Rings, QC
- U.S. scope mixes homogeneously with international scope
  - We are independent, but not necessarily the unique supplier
- Threshold KPPs are not tied to LHC schedule and tunnel access
  - Objectives include integration, installation, and commissioning activities

Charge #2

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 Cost/Schedule approval received end of 2017
    - iCMS Design Reviews: June 2016, April 2017, Dec 2017
    - U.S. Design Reviews: Sept 2017, April 2018, June 2018
  - U.S. CDR is essentially the same, but restricted to U.S. Scope
    - CDR: DocDb 13151
- Conceptual design unchanged since June 2018 IPR



402.2 Technical Progress since June 2018 IPR

- 402.2.3 Sensors
  - Sensor final design thickness, last decision for CD-3a
  - Development of Sensor QC Sites
  - Fermilab Irradiation Test Area
- 402.2.4 Electronics
  - Further prototyping of MaPSA
  - Final versions of Test Systems
  - Development of DAQ and Firmware
  - Proto-Module testing
- 402.2.5 Modules
  - Development of Module Assembly Sites
  - Feasibility of partial automation of assembly
  - Construction of first functional modules
  - Construction Materials studies
- 402.2.6 + 402.2.7 Mechanics and Integration
  - Flat Barrel design refinement
  - Prototype Plank and Ring fabrication
  - Plank and Layer QC

Punchlines in Plenary, details in Breakout

(28 slides reduced to 4)

Charge #2

402.2.3 Sensors

- Sensor final design thickness, last decision for CD-3a
  - Single vendor left in Market Survey
    - One pulled out, one cannot satisfy throughput demands
  - Vendor withdraws preferred sensor doping option: Deep Diffused Float Zone, due to concerns with yield
  - Now testing two thickness variants (standard and thinned) of Float Zone Silicon for robustness, Decision aimed for May 2019
- Development of Sensor QC Sites
  - Sensor testing fully specified and regularly practiced
    - Some progress on Optimization
  - Process QC – test structures fully defined since CD1, procurement of equipment nearly complete
  - Equipment being moved into clean room space
- Fermilab Irradiation Test Area
  - Necessary for methodical assessment of Silicon quality through production
  - Preparations underway for operational clearance in summer 2019

Charge #2

402.2.4 Electronics

- Further prototyping of MaPSA
  - "Dummy" program completed, delayed by component issues
    - Disqualified one vendor on basis of quality
    - Found excessive bowing from high temperature cure underfill, looking at other options
  - First round of functional MaPSA prototypes ongoing at 2 vendors
- Final versions of Test Systems
  - Single Module Test System, Multi-module burn-in, and MaPSA Test stand apparatus all in final version after experience with prototypes
- Development of DAQ and Firmware
  - Data decoder firmware evolving – balancing functionality vs FPGA resource usage
  - Hardware-level code consolidated from diverse set of prototype code to a consistent maintainable platform
    - Also provides optimization and considerable reuse for different devices
- Proto-Module testing
  - 2S flavor: Mini-module demonstrates full efficiency after irradiation to full HL LHC dosage
  - PS flavor: Mini-MaPSA currently in testbeam, 2SSA module being assembled and bench tested

402.2.5 Modules

- Development of Module Assembly Sites
  - All cleanrooms now available, equipment already in or migrating to space
- Feasibility of partial automation of assembly
  - Gantry delivered in September at Fermilab for 2S Module automation
    - Demonstrated repeatability of laser-based metrology scan
    - Pursuing gluing algorithms, encapsulation
  - Similar efforts ongoing at Brown for the PS Module
- Construction of first functional modules
  - 2S construction based on 8CBC2 hybrid, limited by hybrid and sensor supply
    - FNAL has built 2, East Coast has built 1
    - 8CBC3 hybrids and more sensors available mid-2019
  - PS still in mini-module stage, will not get full modules until 2020
    - Several "wire-bondable" versions built for jig and assembly testing
- Construction Materials studies
  - Tweaks to assembly jigs based on experience with prototypes
  - Development of module carriers for transport and testing
  - Studies of module mechanics material for robustness vs. thermal performance
    - Through prototyping and FEA analysis

Charge #2

402.2.6 + 402.2.7 Mechanics and Integration

- Flat Barrel design refinement
  - Final details of service connections for cooling, power, readout under discussion
    - Routing and location of CO_2 manifolds finished, agreed upon with CERN
    - Considering integrating manifolds within Flat Barrel
- Prototype Plank and Ring fabrication
  - Full Layer 1 mock-up with final ring support structure
    - Tests design feasibility and plank insertion apparatus
  - New High Pressure curing apparatus and Large Volume autoclave
- Plank and Layer QC
  - Defining plans for
    - Plank Testing during Module Loading, after fully loaded, and after insertion
    - Full Layer testing, calibration, cosmic ray running, at nominal operating point

402.2 Technical Design Maturity

- Design has been essentially complete since June 2018 IPR
  - Changes now driven by either prototyping experience, either from performance or fabrication perspective, or by cost
  - Maturity estimate went from 60% to 80% between March and December, 2018

Design	Completion
PS-P Sensor Design	70
PS-S Sensor Design	70
2S Sensor Design	80
Process QC Design	30
Sensor QC Design	60
Irradiation QC design	60
Burnin Box Design	80
Single Module Test Design	40
Hybrid Test Design	40
MaPSA Testing Design	70
MaPSA Design	70
DAQ Firmware	15
DAQ Software	80
PS Module Design	60
2S Module Design	80
PS Module Assembly Design	50
2S Module Assembly Design	70
Plank Design	80
Ring Design	60
Integration Design	30
Cooling Design	50

Change in Maturity Estimate between March and December

Completion	Open investigation
90	Thickness
90	Thickness
90	Thickness
60	Final test structure design, exact measurement procedure
95	Optimization, documentation of procedure and compliance
90	Establishment of ITA, interplay with Sensor QC process
90	Carrier card and cooling interface for PS
80	Optical connection, dark box
60	
100	
75	Continued validation of vendors, including testing plan
80	Includes simulations to verify the performance and also synthesis in the FPGA
80	
65	Mounting points, Hybrid design and spacer design and materials, delamination
85	Spacer design and materials, delamination
60	Pending design issues, influencing jigs and glues, Automation, limited prototype parts
80	Pending design issues, influencing jigs and glues, Automation, limited prototype parts
80	Electrical and Mechanical verification
80	Mechanical verification
60	Grounding, Detailed interface and electical/optical/cooling layout
90	Formal concurrence within iCMS

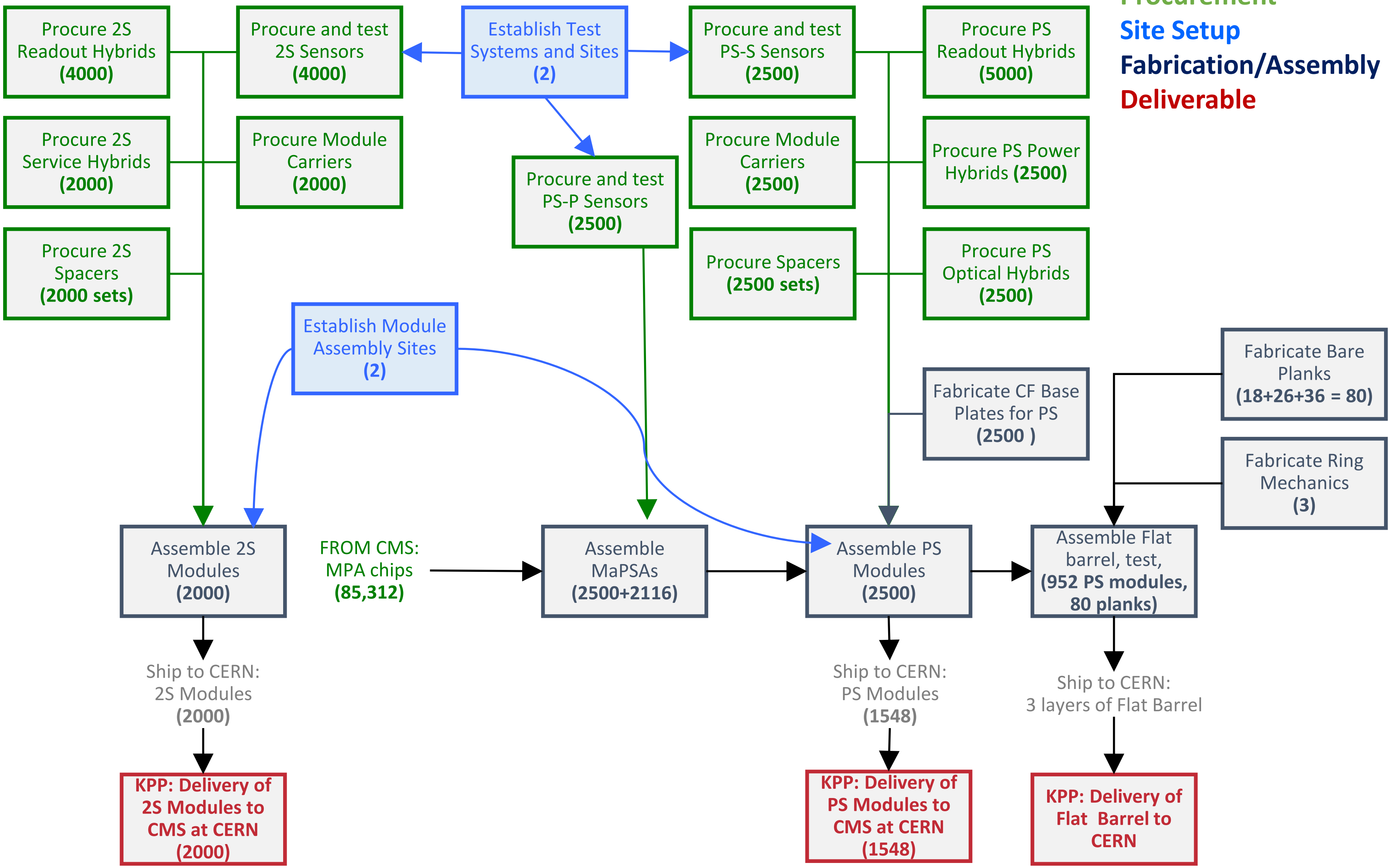
- Overall Design Completion estimate is 38%
  - 40% is "Preliminary Design Complete"

402.2 Organization

U.S. Deliverable flowchart

Charge #3

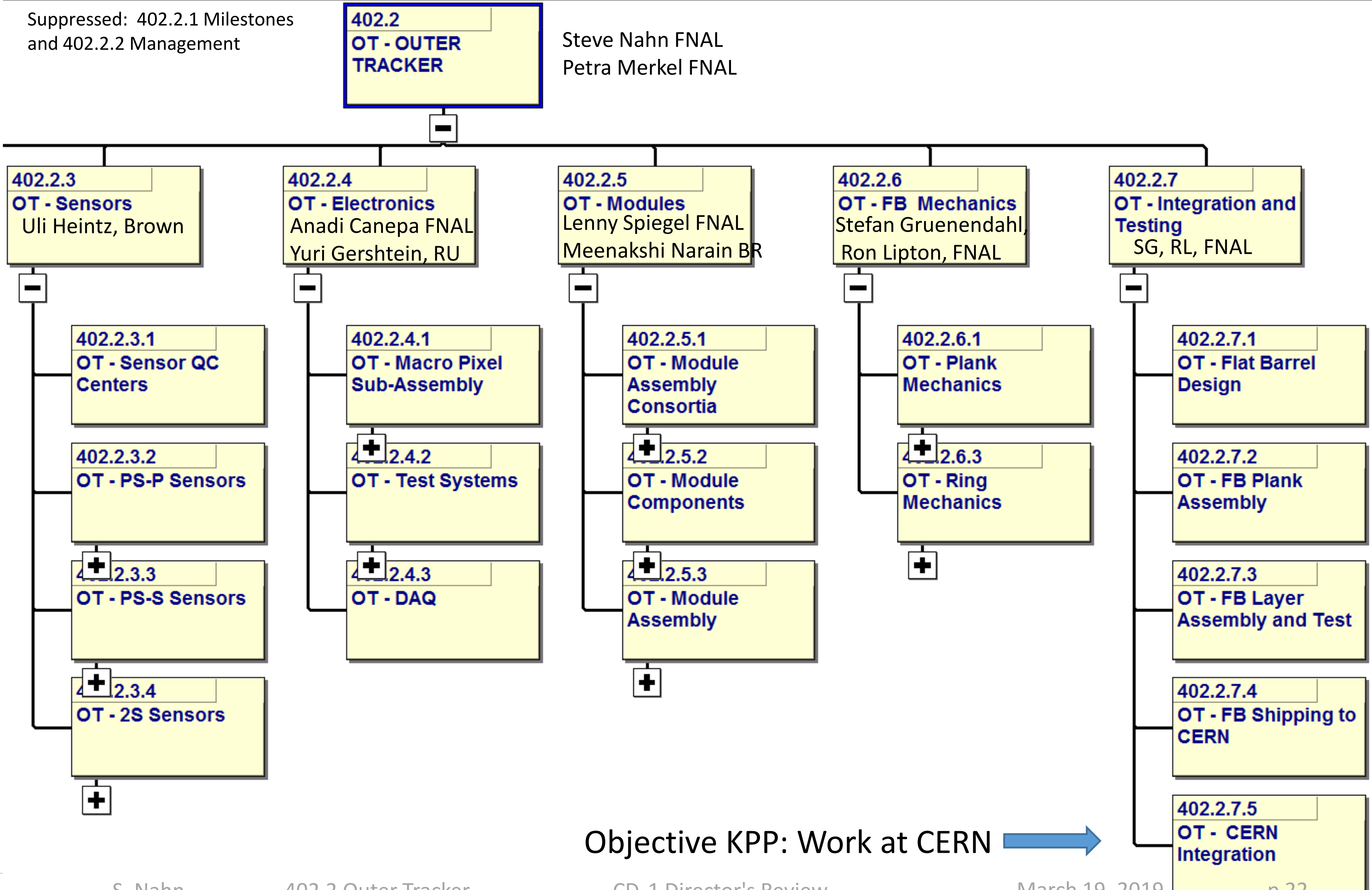
Procurement
Site Setup
Fabrication/Assembly
Deliverable



WBS to Level 4

Charge #5,7

WBS dictionary: DocDb 13216



402.2 Cost Evolution

- Overall cost reduced by 3.7% since June 2018 IPR
  - 561k BAC, 1,555k in Estimate Uncertainty
    - Activities are being completed, EU → 0 but BAC does not
  - Labor hours increased, mostly Uncosted Labor in Flat Barrel Testing
- Completely expected degree of changes as we head to baseline

June 2018 IPR

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
402.2 OT - OUTER TRACKER	**$21,420,779**	**340404**	**192.55**	**$42,593,399**	**$13,350,307**	**$55,943,706**
402.2.2 OT - Management	**$658,000**	**40664**	**23.00**	**$844,022**	**$84,402**	**$928,424**
402.2.3 OT - Sensors	**$7,582,541**	**30447**	**17.23**	**$9,651,654**	**$2,672,348**	**$12,324,001**
402.2.4 OT - Electronics	**$1,436,802**	**30484**	**17.24**	**$4,427,137**	**$1,361,562**	**$5,788,698**
402.2.5 OT - Modules	**$8,990,428**	**204978**	**115.94**	**$21,172,433**	**$6,615,628**	**$27,788,061**
402.2.6 OT - FB Mechanics	**$433,000**	**20031**	**11.33**	**$2,212,199**	**$1,024,739**	**$3,236,938**
402.2.7 OT - Integration and Testing	**$2,320,008**	**13800**	**7.81**	**$4,285,955**	**$1,591,629**	**$5,877,583**

March 2019

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
CD1-v2-DR-402.2 402.2 OT - Outer Tracker	**20,983,424**	**360846**	**204.11**	**42,032,757**	**11,795,390**	**53,828,147**
CD1-v2-DR-402.2.2 OT - Management	**863,000**	**40664**	**23.00**	**1,013,630**	**90,548**	**1,104,178**
CD1-v2-DR-402.2.3 OT - Sensors	**7,019,120**	**30447**	**17.23**	**9,277,050**	**2,426,319**	**11,703,369**
CD1-v2-DR-402.2.4 OT - Electronics	**1,431,801**	**32086**	**18.15**	**4,822,400**	**951,826**	**5,774,226**
CD1-v2-DR-402.2.5 OT - Modules	**8,861,491**	**202140**	**114.33**	**20,360,272**	**5,724,588**	**26,084,860**
CD1-v2-DR-402.2.6 OT - FB Mechanics	**543,000**	**20289**	**11.48**	**2,368,234**	**1,058,502**	**3,426,736**
CD1-v2-DR-402.2.7 OT - Integration and Testing	**2,265,012**	**35220**	**19.92**	**4,191,172**	**1,543,607**	**5,734,779**

Cost and Labor changes: New/Old

WBS	Direct M&S	Labor	BAC	EU	Total	Total ($)
402.2.2 Management	1.31	1.00	1.20	1.07	1.19	$1,104,178
402.2.3 Sensors	0.93	1.00	0.96	0.91	0.95	$11,703,369
402.2.4 Electronics	1.00	1.05	1.09	0.70	1.00	$5,774,226
402.2.5 Modules	0.99	0.99	0.96	0.87	0.94	$26,084,860
402.2.6 Mechanics	1.25	1.01	1.07	1.03	1.06	$3,426,736
402.2.7 Integration	0.98	2.55	0.98	0.97	0.98	$5,734,779
TOTAL	0.98	1.06	0.99	0.88	0.96	$53,828,147

- Management - Contract for System Engineering for 8 years
- Sensors - Updated Exchange Rate for Sensor Procurements
- Electronics - Added Testbeam support, DAQ Optical Link development
- Modules – Labor Rates updated
- Mechanics - Autoclave infrastructure (400k → 500k)
- Integration – Contributed Oversight labor added for life of project

- All changes are small and understood

402.2 Cost Drivers > 1.5M

CMS Driver	Labor (FTE-yrs)	Labor (M$)	M&S (M$)	Labor + M&S (M$)	Estimate Uncertainty (M$)	Total (M$)
OT.5 - Produce and test modules	50.1	7.4	1.5	9.0	2.6	11.6
OT.3 - Procure Sensors	0.0	0.0	6.6	6.6	1.9	8.5
OT.5 - Module mechanics	1.5	0.2	2.9	3.1	1.2	4.3
OT.5 - Procure hybrids	0.0	0.0	3.3	3.3	1.0	4.3
OT.6 - Plank and Ring mechanics	11.2	1.7	0.7	2.4	1.1	3.4
OT - Outer Tracker integration and commissioning	0.0	0.0	2.4	2.4	0.7	3.1
OT.5 - Establish / maintain module assembly site (East Coast)	4.9	0.7	1.8	2.5	0.4	2.9
OT.7 - Flat Barrel design, assembly and test	5.5	1.4	0.2	1.7	0.8	2.4
OT.4 - DAQ development	8.7	1.7	0.1	1.8	0.3	2.1
OT.3 - Sensor prototyping, production and testing	14.5	1.3	0.1	1.4	0.3	1.8
OT.4 - MaPSA purchase and testing	2.3	0.1	1.2	1.3	0.4	1.7

- Large M&S Procurements
  - Sensors, Hybrids, Al-CF mechanics, MaPSA = $14M BAC out of $21.4M
    - Investigating less expensive mechanics solutions, lower cost/higher risk Bump Bonding vendors
- Substantial Labor Costs
  - Manual Module Assembly – $7.4M
    - Investigating options for automatization
  - Significant Engineering effort – $6.1M
    - DAQ firmware, Engineering for Mechanical Substructure and Integration, Sensor testing

402.2 Cost and Cost Profile

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
CD1-v2-DR-402.2 402.2 OT - Outer Tracker	20,983,424	360846	204.11	42,032,757	11,795,390	53,828,147
CD1-v2-DR-402.2.2 OT - Management	863,000	40664	23.00	1,013,630	90,548	1,104,178
CD1-v2-DR-402.2.3 OT - Sensors	7,019,120	30447	17.23	9,277,050	2,426,319	11,703,369
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CD1-v2-DR-402.2.6 OT - FB Mechanics	543,000	20289	11.48	2,368,234	1,058,502	3,426,736
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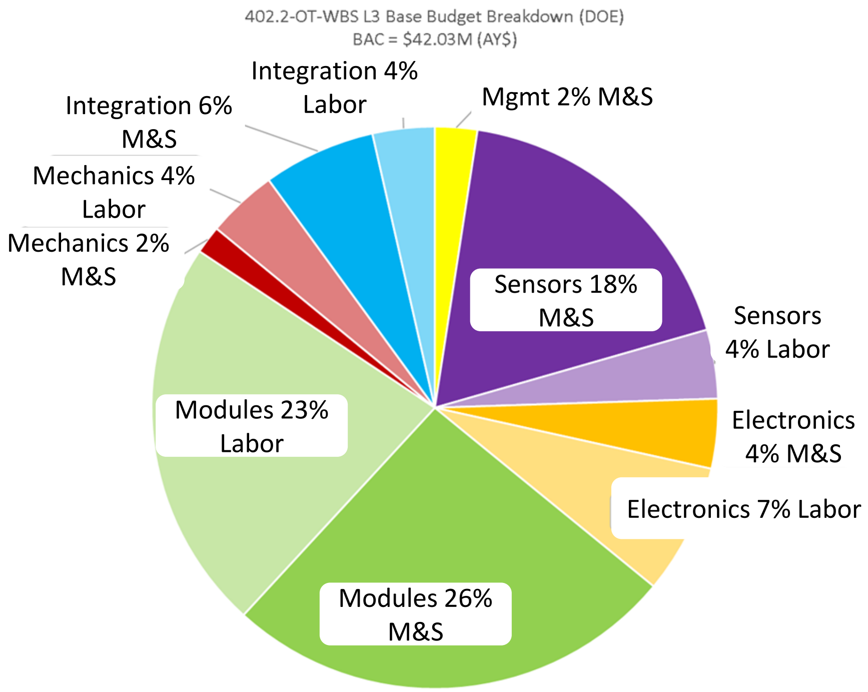
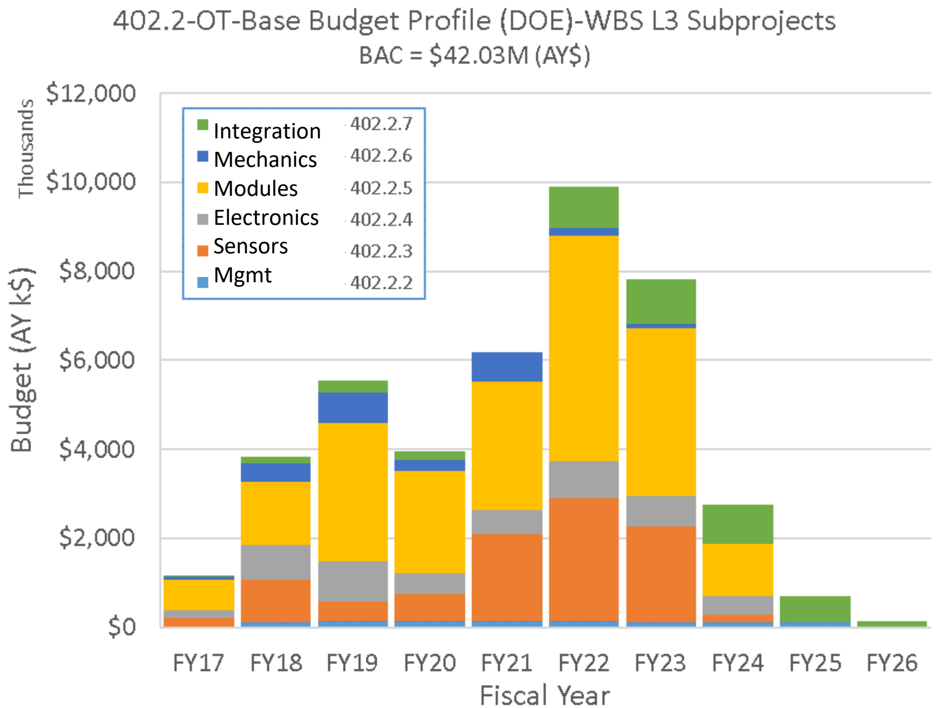
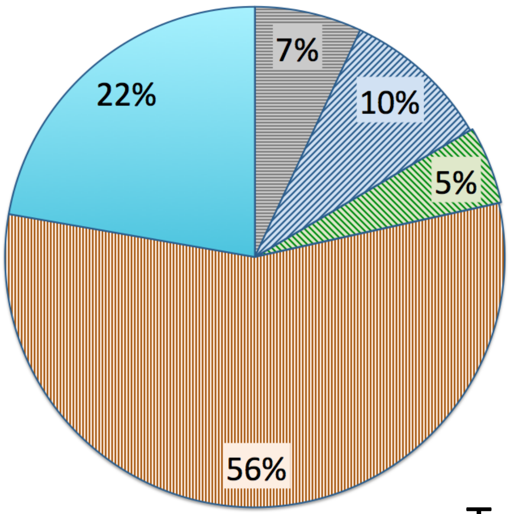




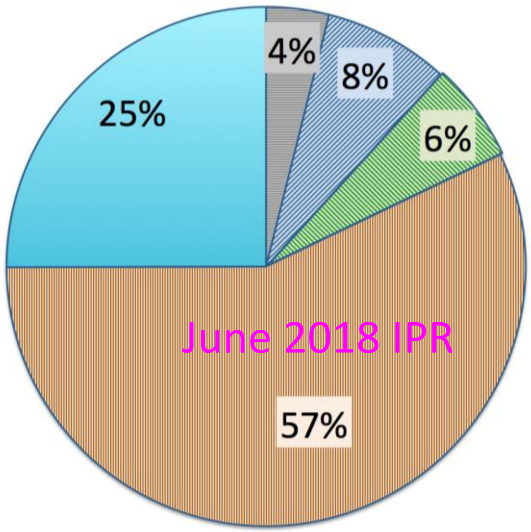
Cost Estimate Maturity

Cost-weighted estimate maturity: 402.2 Outer Tracker

Key Assumptions: DocDB 12919



- L1/M1 (Actual)
- L2/M2 (LoE & support)
- L3/M3 (Advanced)
- L4/M4 (Preliminary)
- L5/M5 (Conceptual)



Total Estimate Uncertainty $11.8M

- Bottom-up aggregation based on confidence in accuracy of cost estimate
  - Reflects knowledge of costs and quantities needed
- 28.1% of Budget at Completion
  - 30.8% on Cost to Go
  - Does not include contribution from Risk→ 33.9%

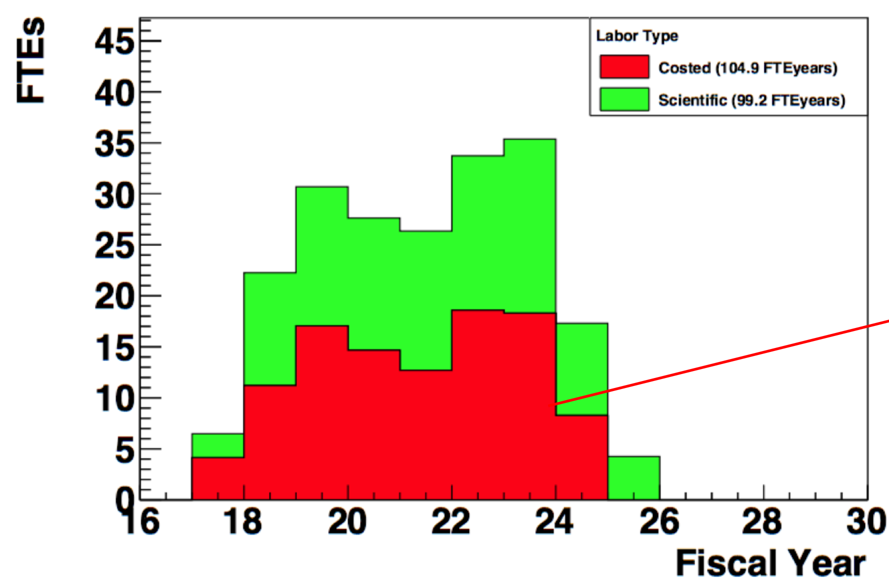
Charge #3

402.2 Labor Profiles

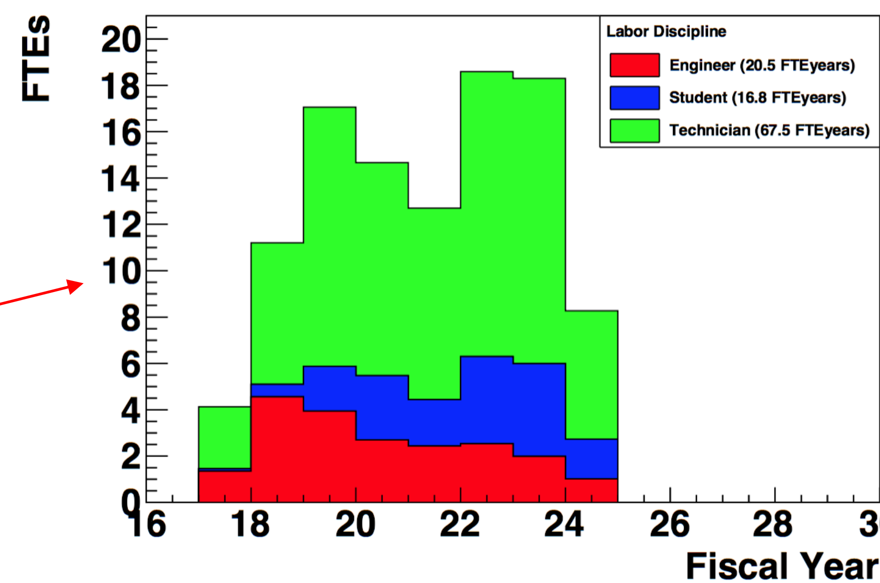
- Labor dominated by module assembly
  - Skilled work done by technicians/engineers
  - Testing done by contributed labor and undergraduate students

WBS	Labor hours	FTE-years	Direct + Indirect + Escalation ($)	Estimate Uncertainty ($)	Total Labor Cost ($)
CD1-v2-DR-402.2 402.2 OT - Outer Tracker	360846	204.11	17,483,046	4,692,091	22,175,137
CD1-v2-DR-402.2.2 OT - Management	40664	23.00	0	0	0
Uncosted	40664	23.00	0	0	0
CD1-v2-DR-402.2.3 OT - Sensors	30447	17.23	1,663,807	404,566	2,068,373
Uncosted	1312	0.74	0	0	0
Costed	29135	16.49	1,663,807	404,566	2,068,373
CD1-v2-DR-402.2.4 OT - Electronics	32086	18.15	3,140,386	446,646	3,587,032
Uncosted	11658	6.59	0	0	0
Costed	20428	11.56	3,140,386	446,646	3,587,032
CD1-v2-DR-402.2.5 OT - Modules	202140	114.33	9,495,639	2,425,967	11,921,606
Uncosted	96244	54.44	0	0	0
Costed	105896	59.90	9,495,639	2,425,967	11,921,606
CD1-v2-DR-402.2.6 OT - FB Mechanics	20289	11.48	1,694,415	742,707	2,437,122
Uncosted	496	0.28	0	0	0
Costed	19793	11.20	1,694,415	742,707	2,437,122
CD1-v2-DR-402.2.7 OT - Integration and Testing	35220	19.92	1,488,798	672,205	2,161,003
Uncosted	25028	14.16	0	0	0
Costed	10192	5.76	1,488,798	672,205	2,161,003

402.2-OT Costed and Scientific Labor



402.2-OT Costed Labor by Labor Discipine



HL-LHC US CMS

OT Basis of Estimates

Charge #3

https://go.usa.gov/xnSwv

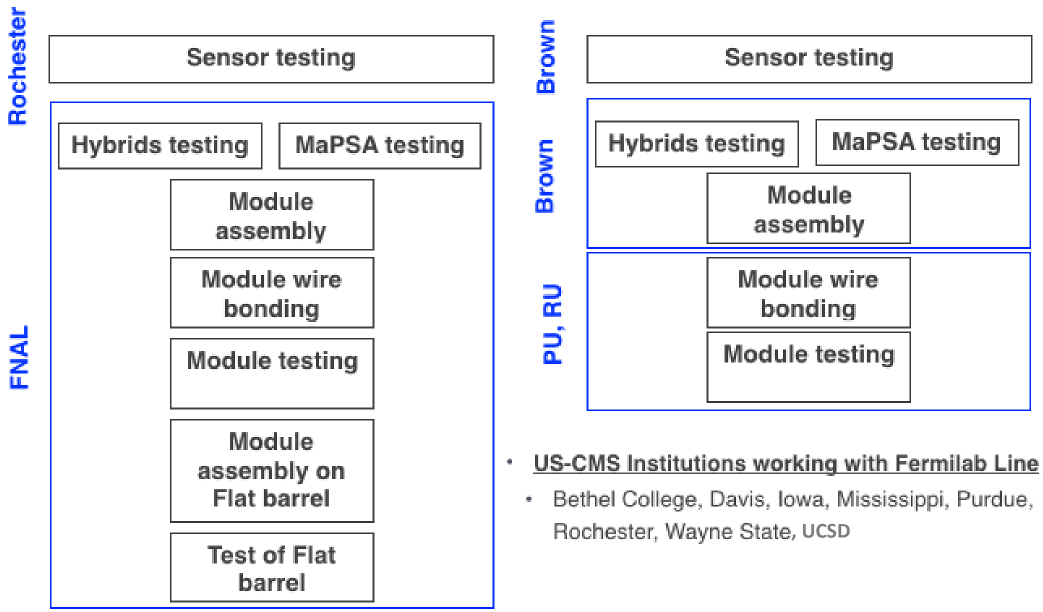
- Cost Estimate follows project standards laid out in Cost Estimating Guide and Key Assumptions Document
- Several workshops involving full management team to scrub cost estimates
- Expect modest further refinements as prototyping informs estimates
- Details in the Breakout session

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

Charge #4

Human Resources

- Main Labor needs at two Module Assembly "sites"
  - Mitigates schedule risk
  - Training up technicians as production draws closer



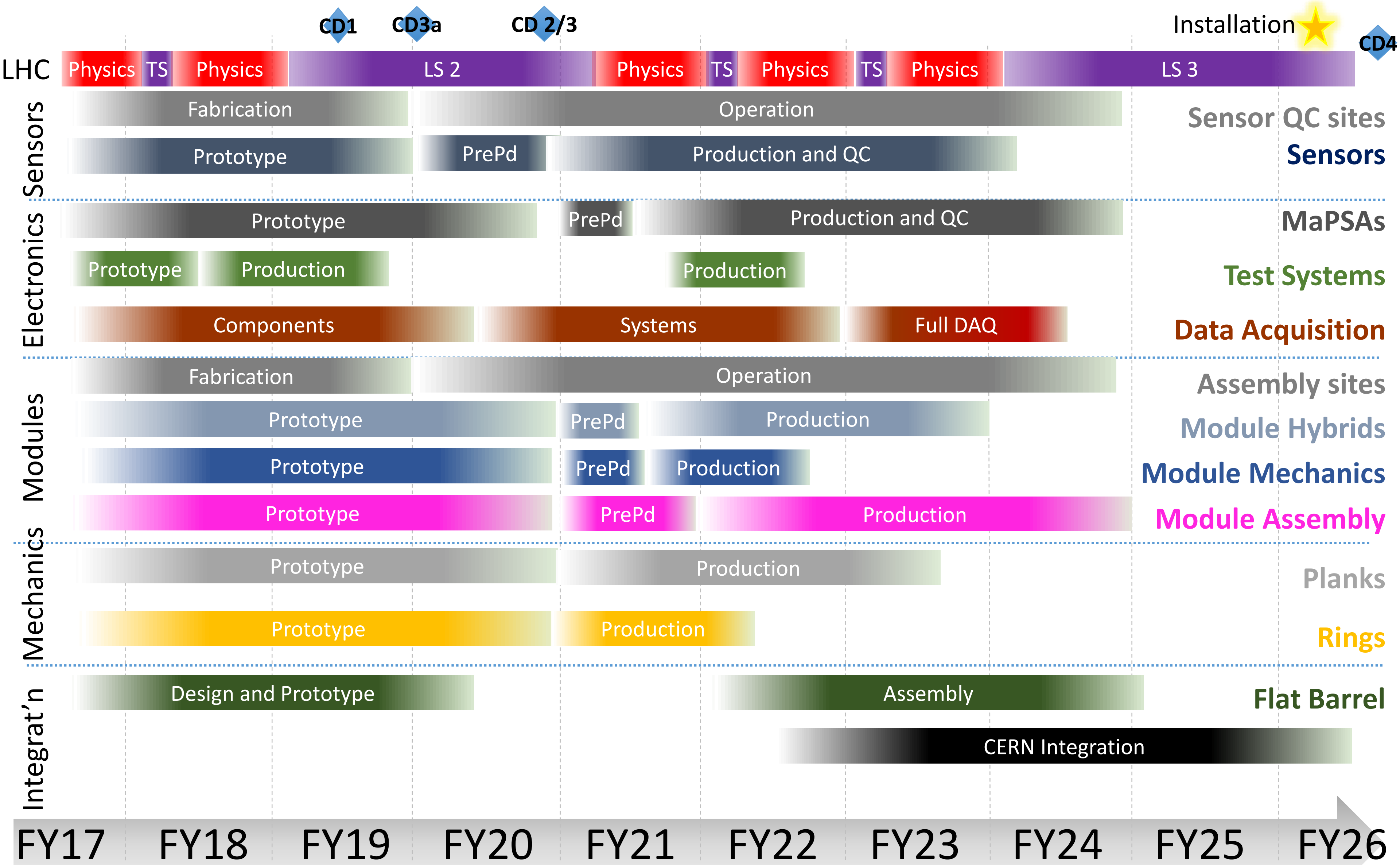
- <u>US-CMS Institutions working with Fermilab Line</u>
  - Bethel College, Davis, Iowa, Mississippi, Purdue, Rochester, Wayne State, UCSD

- Critical skills personnel
  - "Floor managers" at Brown, Rutgers, Princeton 100% OT
  - Module Mounting super-tech at FNAL – mostly OT
  - DAQ guru at FNAL – mostly OT (and testbeam)
- Other institutes have niche roles and/or provide students and postdocs to do QC

	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
Mississippi		X	X		
Princeton		X	X		X
Purdue			X		X
Rochester	X	X			X
Rutgers		X	X		X
Wayne State		X	X		X
UCSD		X			X

OT Cartoon Schedule

Charge #3



Schedule Changes

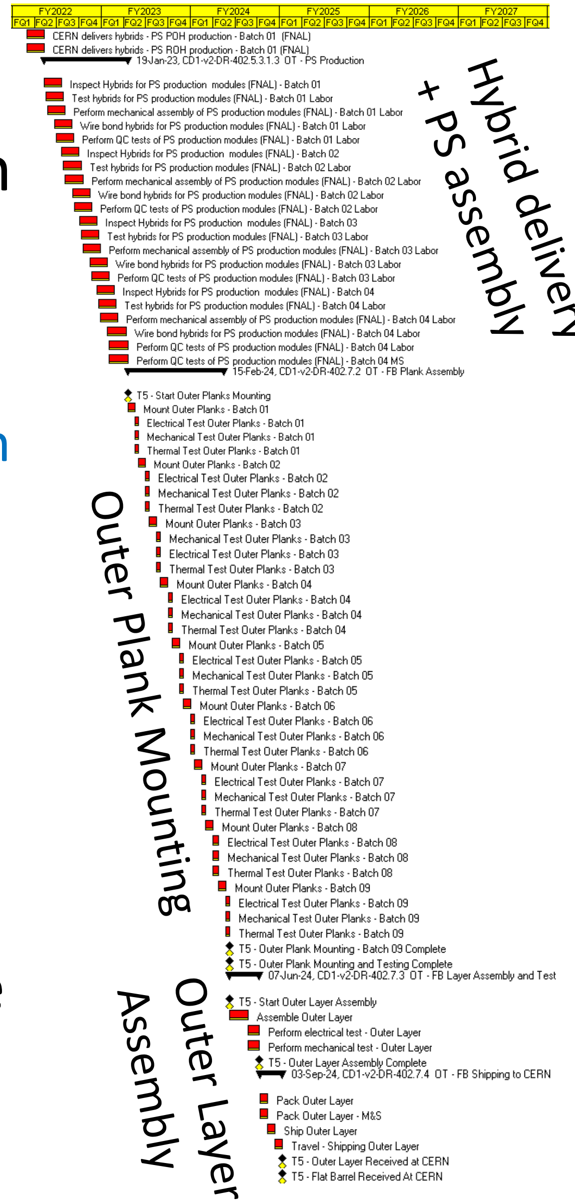
- Large Shifts (>100 days)

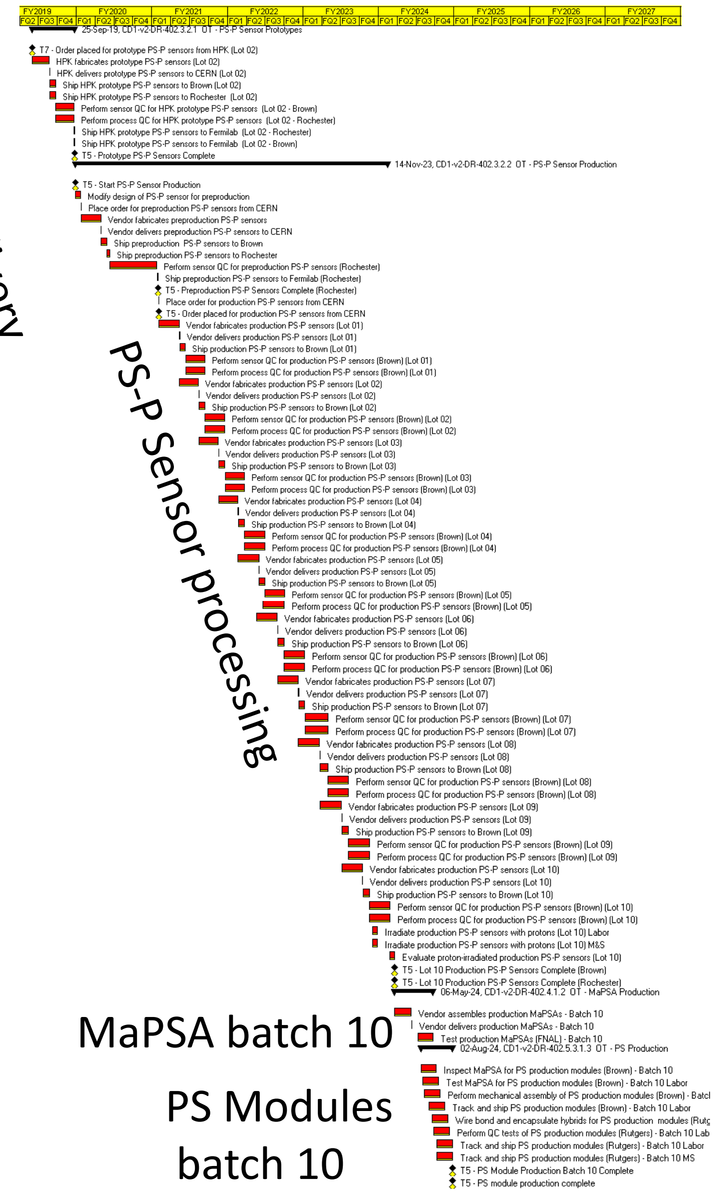
Activity	June 2018 IPR	Now	Δ (wd)	Comment
Jigs and Fixtures	30-Sep-19	30-Mar-20	129	Added support in FY20
Plank and Ring Production	27-Apr-20	17-Sep-20	100	CD-3 moved 1 year
Hybrid Delivery	03-Sep-19	17-Sep-20	262	CD-3 moved 1 year
2S preproduction	27-Feb-20	17-Sep-20	142	CD-3 moved 1 year

- KPP milestones did not move

Critical Path for OT

- Critical path assessed separately for each KPP
  - Flat Barrel KPP goes from CERN Hybrid delivery, into PS production to batch 4 then Outer Plank Assembly
  - Modules is driven by Sensor delivery, then last batch of PS modules
- All of this will evolve as we move toward baseline





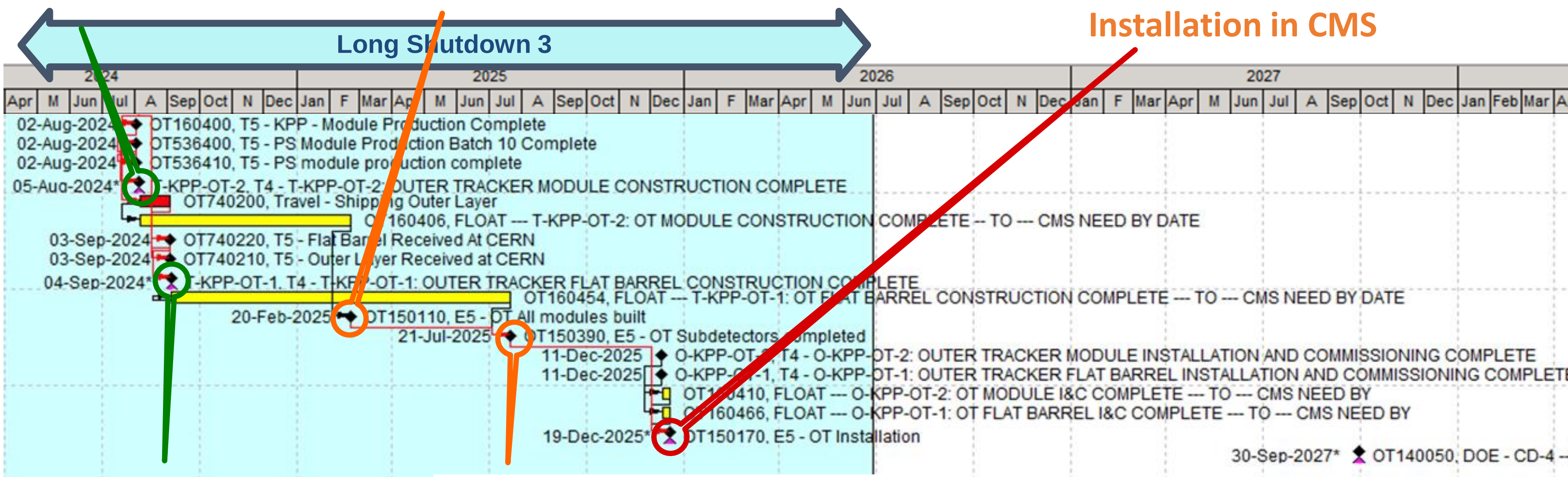
Critical Path Endgame

- Modules KPP
  - 6.5 months float to CMS request-by date
  - Additional 9.9 months to Installation
- Flat Barrel KPP
  - 10.5 months float to CMS request-by date
  - Additional 5.0 months to Installation

<u>Threshold KPP</u>: **Aug 2024 Modules Complete**

Feb 2025: CMS requests-by date Modules

Dec 2025: Outer Tracker Installation in CMS



<u>Threshold KPP</u>: **Sep 2024: Flat Barrel Complete**

August 2025: CMS requests-by date Flat Barrel

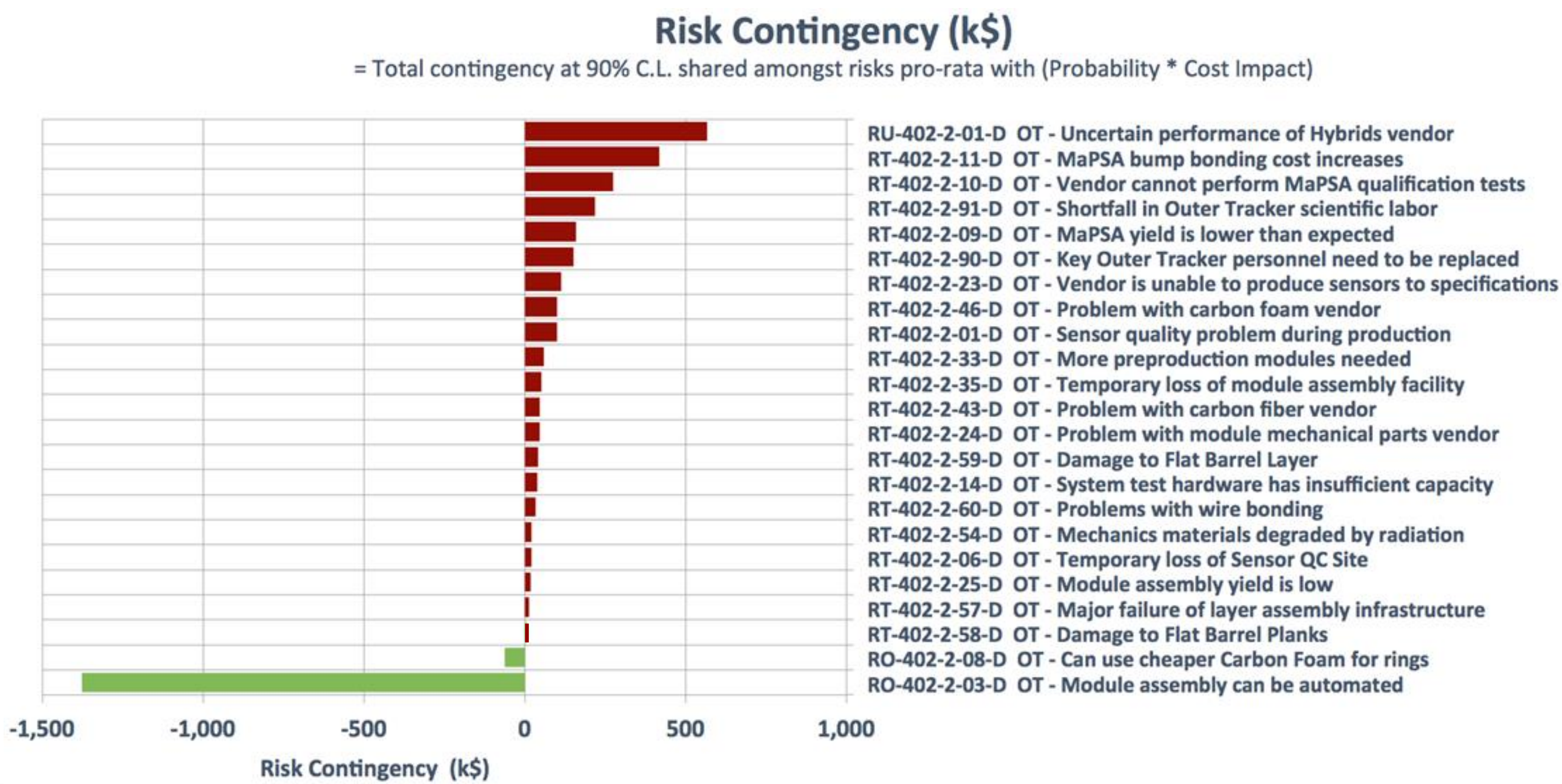
402.2 OT Risks

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

- At June 2018 IPR
  - Project Office owns Exchange Rate, Contributed Labor, Fermilab Overhead, and Critical Attrition risks – all impact OT
  - OT Specific: 16 Threats, 2 Opportunities, and 1 Uncertainty
- Since then
  - Risk Workshop 9/7/2018 Agenda
    - External Reviewers: Aseet Mukherjee, Jeff Spalding
    - Outcome: One Risk split into two with high/low impact, added critical personnel at Rutgers, wirebonding risk, modified burn rates to be L3 specific
  - Critical Attrition and Contributed Labor risks moved into L2 areas
- Outer Tracker Threats: 1.8M $\rightarrow$ 2.5M @90% C.L.
  - {Probability $\times$ Impact}: \$720k $\rightarrow$ \$1.2M

Quick Risk Summary

- 20 Threats and 1 Uncertainty: $P \times \$ = \$1,198k$
  - Was $720k in June 2018, (Contributed Labor + Key personnel = 178k)
- 2 Opportunities: $P \times \$ = \$690k$ (666k in June 2018)
  - Dominated by Automation opportunity
- Risk Assessment constantly evolving



402.2 Response to Previous Reviews

- March 2018 Director's Review (DocDB 13535)

1. *The review committee recommends that Fermilab work with the DOE to establish a proton irradiation facility at Fermilab. This is particularly important during LS2 when the CERN PS facility will be down. This is critical not only for the CMS Outer Barrel but also for all the HL-LHC projects*.
    - Fermilab is actively establishing a proton irradiation test area
2. *Finalize the plan for automation of module construction by CD-2.*
    - We continue to pursue automation and will have the plan finalized by CD-2

- June 2018 Independent Project Review

2. Based on the assessment above, 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.

- We fully continue to pursue automation and will have the plan finalized by CD-2. Note in June 2018, CD-2 was Sept 2019. It is now Sept 2020, so we assume this date should shift accordingly (and will satisfy it earlier anyway)

3. Proceed to CD-1.

402.2 Progress towards CD-3a

- CD-3a: Silicon Sensor Procurement (Breakout topic)
  - CD-3a required for Sensors (long lead time)
  - CERN-wide negotiation with Silicon vendor, incl. ATLAS iTK, CMS CE
    - 46,000 wafers! Need to coordinate across LHC
    - "Frame Contract": Costed Menu of small number of options and coordinated delivery schedule
      - Ordering from menu comes later
  - Prerequisites
    - Final Silicon thickness choice, May 2019
    - Silicon Sensor Production Readiness Review
    - Approval from CERN Finance Board
  - Project Office actively working with Fermilab Management and Procurement to put together an Acquisition Plan

402.2 Progress towards CD-2/3

- Focus is moving from design stage towards getting experience and optimizing based on prototypes
  - Sensors: QC procedures now exist for sensors and test structures, still working on optimizing speed and designing a long term test
  - Electronics
    - MaPSAs have a defined development path of 2 rounds of prototyping before pre-production
    - Test Systems are nearly complete, may have continuous improvement with experience
    - DAQ/FW still in development, likely to be true until many modules available
  - Modules: Main Focus is on gaining experience with module assembly as parts become available
    - Incorporate automation
  - Mechanics and Integration
    - Build full plank from prototype modules, test system aspects
- Overall goal is to improve knowledge of assembly procedures and further validate final performance before baseline

Charge #6

ES&H

Preliminary Hazard Analysis Report: cms-doc-13394

- ES&H aspects are guided by the Fermilab Integrated Safety Management approach, with rules and procedures laid out in the Fermilab ES&H Manual
- In General, Safety is achieved through standard Lab practices
  - Items comply with local safety standards in site of fabrication and operation
  - Radiation campaigns/test beams require appropriate safety training and ORC
  - No construction, accelerator operation, or exotic fabrication
  - No imminent peril situations or unusual hazards
- Phase 1 FPIX provides an excellent recent template for ESH issues
  - 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 Operational Readiness Clearance
- Outer Tracker participated in Nov 29 2018 ESH&Q review

QA/QC

Quality Assurance Plan: cms-doc-13093

Charge #6

- QA/QC aspects are guided by the Fermilab Integrated Quality Management approach, with rules and procedures laid out in the Fermilab Integrated Quality Assurance Manual
- Both QA and QC are integrated into many aspects of OT
  - Quality Assurance = processes to prevent substandard fabrication
    - Sensors: Designing test structures into wafers for "Process Quality Control" to test sensor composition
    - Electronics: design/fabrication of test systems for hybrids, MaPSAs, Modules to verify quality
    - Prototype/Preproduction/Production cycles
  - Quality Control = actions to detect substandard fabrication
    - Sensor: Sensor Quality Control and Irradiation tests
    - Modules: Acceptance tests of components, final module burn-in tests
- Considerable development of QA/QC documentation since June 2018 IPR
  - Participated in Nov 29 2018 ESH&Q review
  - Developed OT specific QA appendix and list of QA/QC activities in QAP
  - International CMS working on overall QA/QC specification applicable to all major fabrication sites

402.2 Interfaces and Externals

- Key interfaces defined, unchanged since June 2018 IPR

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

  - iCMS and U.S. share same design for Modules, so interfaces handled at the international level
    - Gently encouraging our international colleagues to take a more formal approach to interfaces
  - Flat Barrel Integration design work requires specific handshaking
    - Design files shared between U.S. and CERN engineering
  - Codifying in Interface Documentation (cms-doc-13388 , ICD) ongoing
- Interface negotiation expedited by embedded U.S. team in international organization

Breakout Sessions

- Much more technical discussion in the Breakouts
  - Focused on previous review comments and recommendations

09:00 - 12:00 Breakout: Outer Tracker: Outer Tracker Technical Status / Updates since CD-1 / Cost and Schedule

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: Steve Nahn (Fermilab), Dr. Petra Merkel (Fermilab), Dr. Petra Merkel (Fermi National Accelerator Laboratory)

Location: Fermilab (Black Hole (WH2NW))

09:00 **Plan for CD3a - Sensors** *20'*
Speaker: Steve Nahn (Fermilab)
Material: **Draft Slides -- Mar 5**

09:30 **Progress on Automation** *20'*
Speakers: Leonard Spiegel (FNAL), Meenakshi Narain (Brown University)
Material: **Draft Slides -- Mar 5**

10:00 **Status of the Irradiation Test Facility** *15'*
Speaker: Dr. Petra Merkel (Fermi National Accelerator Laboratory)
Material: **Draft Slides -- Mar 5**

10:20 **Progress with Macro-Pixel Subassemblies** *15'*
Speakers: Steve Nahn (Fermilab), Dr. Anadi Canepa (Fermilab), Dr. Petra Merkel (Fermi National Accelerator Laboratory), Dr. Ron Lipton (Fermilab), Prof. Yuri Gershtein (Rutgers University)
Material: **Draft -- Mar 5**

10:40 **Progress on Site Infrastructure** *5'*
Speaker: Steve Nahn (Fermilab)
Material: **Draft Slides -- Mar 5**

10:50 **Test Systems and QC Plans** *15'*
Speaker: Dr. Anadi Canepa (Fermilab)
Material: **Draft Talk -- Mar 5**

11:10 **Outer Tracker Risk Status** *5'*
Speaker: Steve Nahn (Fermilab)
Material: **Draft Slides - Mar 5**

11:30 **Path to Baseline** *30'*
Speaker: Steve Nahn (Fermilab)
Material: **Draft Slides -- Mar 5**

Summary

- We have made technical progress in all areas since June 2018 IPR
  - On target for being ready for CD-3a in fall 2019, CD-2/3 fall 2020
  - Details in Breakout
- The management, cost, and schedule aspects of the project are essentially unchanged since June 2018 IPR
  - Natural evolution as we move towards a baseline
- We have addressed all recommendations
- We are ready for CD-1

Backup material

Threshold and Objective KPPs

CMS-doc-13237

WBS	Threshold KPP	Objective KPP
402.2 Outer Tracker	**T-KPP-OT-1: OUTER TRACKER FLAT BARREL CONSTRUCTION COMPLETE** The Outer Tracker "Flat" Inner Barrel consists of three layers of silicon modules, with 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 construct the Outer Tracker "Flat" Inner Barrel detector and deliver it to the CMS Tracker Integration Facility on the CERN Meyrin site. The detector shall be demonstrated to work standalone, then delivered to CERN.	**O-KPP-OT-1: OUTER TRACKER FLAT BARREL INSTALLATION AND COMMISSIONING COMPLETE** The Outer Tracker "Flat" Inner Barrel consists of three layers of silicon modules, with 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 construct the Outer Tracker "Flat" Inner Barrel detector and deliver it to the CMS Tracker Integration Facility on the CERN Meyrin site. The detector shall be demonstrated to work standalone, then delivered to CERN. The project shall integrate the "Flat" Inner Barrel detector into the full Outer Tracker, and test and calibrate it.

WBS	Threshold KPP	Objective KPP
402.2 Outer Tracker	**T-KPP-OT-2: OUTER TRACKER MODULE CONSTRUCTION COMPLETE** The Project shall establish and operate construction centers for the Outer Tracker module construction and shall build about 1/3 of the total modules needed to build the Outer Tracker. The modules shall be tested and graded before sending to CERN.	**O-KPP-OT-2: OUTER TRACKER MODULE INSTALLATION AND COMMISSIONING COMPLETE** The Project shall establish and operate construction centers for the Outer Tracker module construction and shall build about 1/3 of the total modules needed to build the Outer Tracker. The modules shall be tested and graded before sending to CERN.

Shifts at T3

- T3 Milestone Shifts
  - Red: June 2018 IPR
  - Black: Now
- Major changes
  - CD-3 move shifts Preproduction/Production starts
  - Tooling design complete
    - Added FY20 activities
- Endgame does not change
  - In particular, KPPs