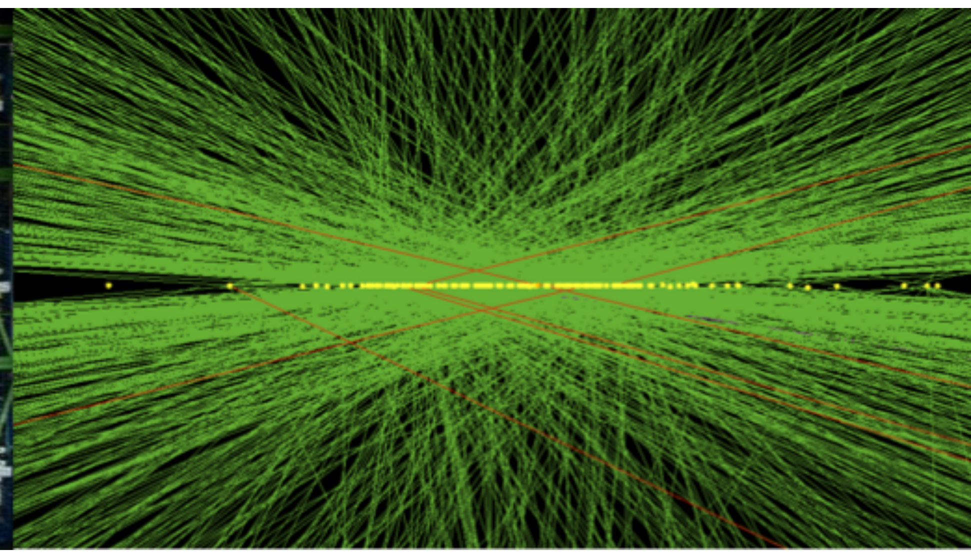
# B01: 402.2.3 Sensors

Regina Demina (University of Rochester)

HL LHC CMS Detector Upgrade CD-1 Review

October 23rd, 2019



# Outline

- Scope and Design
  - Deliverables
  - Design
  - R&D Activities
- Cost and Schedule
  - Schedule
  - Risk
  - Resource Optimization
- Project Organization
  - Participating institutes
  - ESH&Q
  - Quality Assurance/Control
- Summary

# Bio Sketch – Regina Demina

- Education/ employment:
  - BS, MS – Novosibirsk State University, 1988
  - Researcher – Budker Institute of Nuclear Physics, 1988-1991
  - PhD – Northeastern University, 1995
  - Research Associate – Fermilab 1995-1999
  - Assistant Professor – Kansas State University, 1999-2003
  - Associate, Full Professor – University of Rochester, 2003-now
- Experience
  - Drift chamber construction – CMD at Budker
  - Fiber tracker construction – D0, CDF at FNAL
  - Silicon detectors since 1998: L00, ISL (CDF), L0 (D0), TOB (CMS), RD50
  - Low level silicon clusters reco, tracking – D0, CMS
  - Bottom, charm-tagging – CDF, D0, CMS
  - Top quark, Higgs, SUSY, b-physics – D0, CDF, CMS
- Awards:
  - OJI – 2001
  - American physics society fellow - 2015

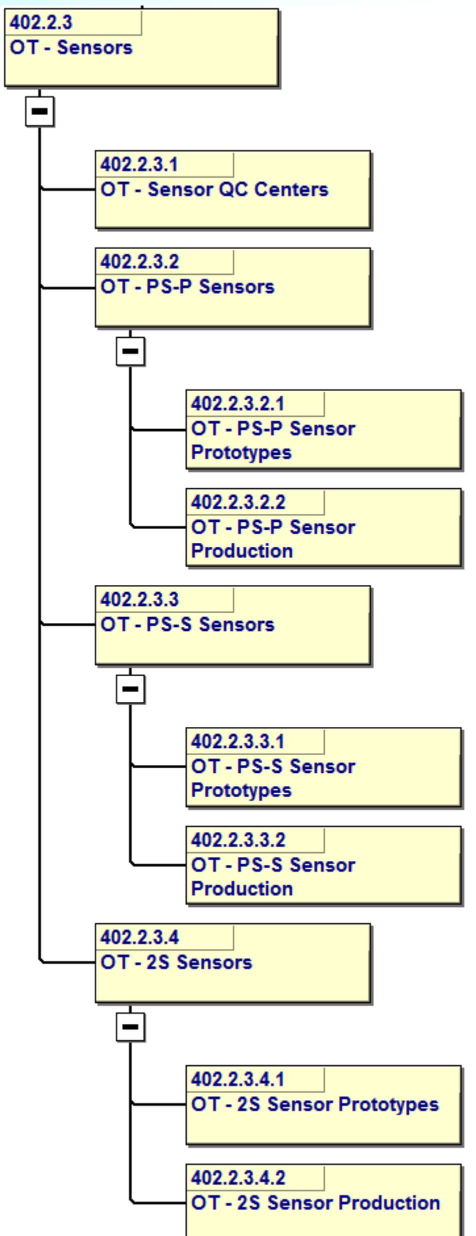
# Scope for Sensors

- The outer tracker consists of 13200 modules
  - Each module is built of two coplanar sensors, the mechanical structure, and the associated readout and service electronics
- Ultimate goal
  - Ensure high-quality and radiation hardness of silicon sensors for the modules assembled at US institutions
- Activities
  - Prototyping sensor design
  - Evaluation of sensor vendors
  - Development of QC centers
  - QC of production sensors
  - Irradiation of test structures
- Module types
  - PS modules at radii of 20-60 cm
    - one pixel sensor (PS-p) and one strip sensor (PS-s), 5 cm x 10 cm in size
  - 2S modules at radii of 60-120 cm
    - two strip sensors (2S), 10 cm x 10 cm in size

# Sensors WBS Structure

Charge #7

- 402.2.3 Sensors
  - 402.2.3.1 QC Centers
    - Setup of the QC centers for the sensor production at Brown University and University of Rochester. Costs include labor and equipment needed to set up these centers. Costs also include general expenses for consumables and maintenance of the centers.
  - 402.2.3.2 PS-p Sensors
    - Procurement and evaluation of PS-p sensor prototypes (40 sensors) and market survey (20 sensors)
    - Procurement and QC of 125 preproduction and 2750 production PS-p sensors
  - 402.2.3.3 PS-s Sensors
    - Procurement and evaluation of PS-s sensor prototypes (40 sensors) and market survey (20 sensors)
    - Procurement and QC of 125 preproduction and 2750 production PS-s sensors
  - 402.2.3.4 2S Sensors
    - Procurement and evaluation of 2S sensor prototypes (60 sensors) and market survey (20 sensors)
    - Procurement and QC of 200 preproduction and 4400 production 2S sensors



# Design and QA/QC

# Design Considerations

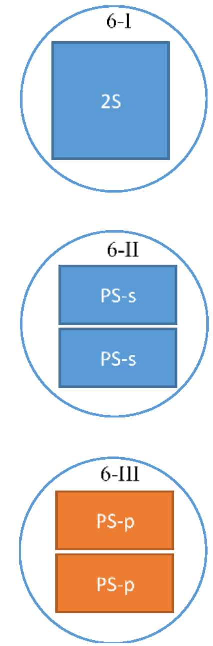
Charge #2

- Occupancy
  - Efficient tracking performance requires low occupancy
  - Fine granularity – macro pixel sensors and short strips in outer tracker
- Support of the level-1 track trigger
  - L1 track trigger requires on-detector data reduction
  - pT modules allow local track stub reconstruction
- Radiation hardness
  - The lifetime of the upgraded tracker must be matched to the target integrated luminosity of 3000/fb +safety factor, variable n/p ratio
    - High efficiency, low noise, avoid thermal runaway
- Reduced material
  - Tracker and calorimeter performance can be improved by reducing the material in the volume of the current tracker
- Practical cost
  - Higher cost must be justified by significant improvement in performance

# Sensor geometry

Charge #2

- Sensor size
  - Segmentation chosen to ensure fine granularity
  - Dimensions optimized to fit on 6” wafers
- Sensor types
  - 2S sensor
    - AC coupled sensor with 2×1016 strips
    - Two per 2S module
  - PS-s sensor
    - AC coupled sensor with 2×960 strips
    - One per PS module
  - PS-p sensor
    - DC coupled sensor with 32×960 macro pixels
    - One per PS module




in mm

Numbers do not include spares

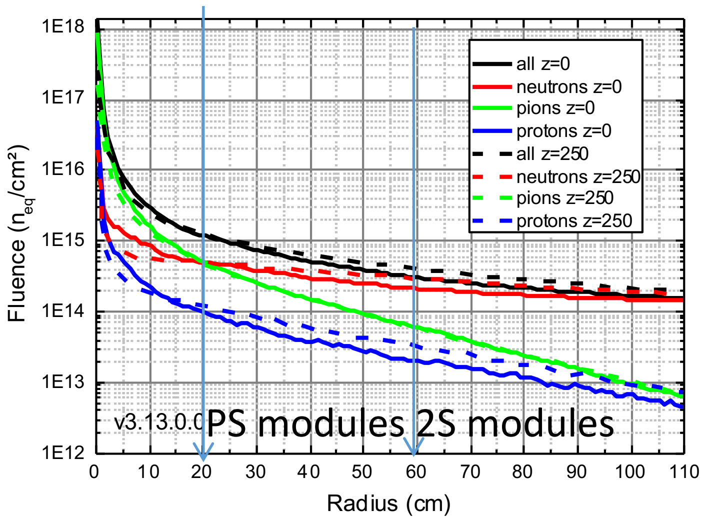
| Sensor type | Physical | | Active | | Segmentation | | Total number |
|---|---|---|---|---|---|---|---|
| | Width | Length | Width | Length | Pitch | Length | |
| 2S | 94.183 | 102.700 | 91.440 | 100.548 | 0.090 | 50.274 | 15216 |
| PS-s | 98.140 | 49.160 | 96.000 | 46.944 | 0.100 | 23.472 | 5592 |
| PS-p | 98.740 | 49.160 | 96.000 | 46.944 | 0.100 | 1.467 | 5592 |

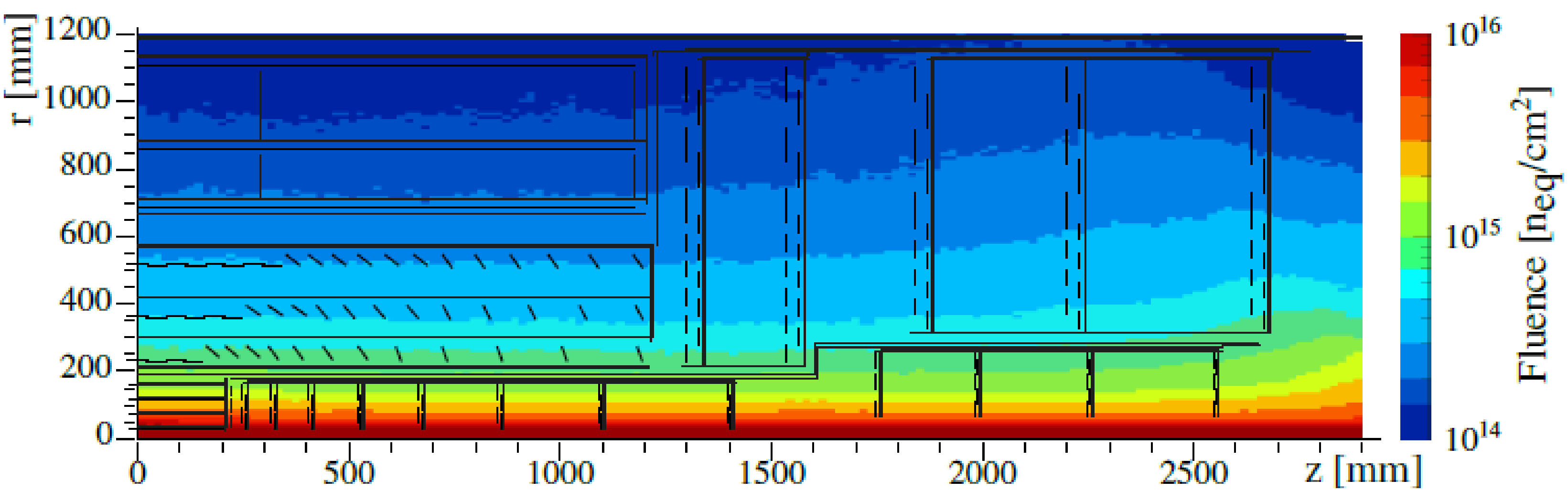
# Radiation levels

Charge #2

Fluencies after 3000/fb at sqrt(s)=14 TeV simulated by FLUKA

| Module type | Neutrons $10^{14} n_{eq}/cm^2$ | Protons $10^{14} n_{eq}/cm^2$ | Total $10^{14} n_{eq}/cm^2$ | $F_n/F_{tot}$ |
|---|---|---|---|---|
| **2S** | **2.5** | **0.5** | **3** | **83%** |
| **PS** | **4** | **6** | **10** | **40%** |

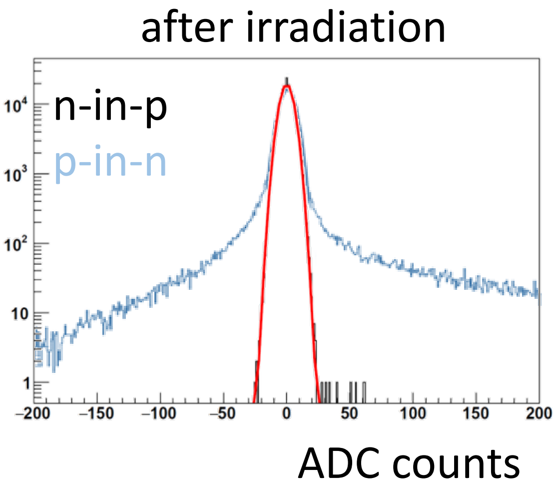


# Design choice

Charge #2

- Vendor choice
  - CMS conducted extensive market survey
  - Three vendors were qualified and considered – Novati, Infineon, HPK
  - Novati, Infineon withdrew themselves from further consideration
  - HPK is a reliable long term partner
- Radiation hard material choice
  - n-in-p doping
    - p-in-n (used in current tracker): smaller signal after irradiation, non Gaussian noise
  - P-stop isolation
    - p-spray: poor performance, disfavored by vendors
  - Material choice
    - MCz: reduced reverse annealing but high noise and yield concerns
    - Deep diffusion (active thickness of 200 $\mu$m): HPK had difficulties producing deep diffusion
    - Float Zone (FZ) Silicon with active thickness of $\approx$290 $\mu$m and thinned 240 $\mu$m



# Sensor material/thickness choice

**ddFZ200: deep diffused sensor**

- Originally considered in the TDR for better rad hard performance
- Deep diffusion introduces defects and contamination to the bulk
  - Significantly higher [O] might improve radiation hardness
- Fixed physical thickness at 320 µm
- Backside implant can be up to 120 µm thick reducing active thickness to 200 µm

**FZ290: "HPK standard" sensor**

- Same production technology as currently used sensors (now in n-on-p)!
- Fixed active (physical ) thickness at 290(320 ) µm
- Robust against mechanical damage due to 30 µm deep backside implant
- Backside implant acts as excellent field stop improving IV characteristics

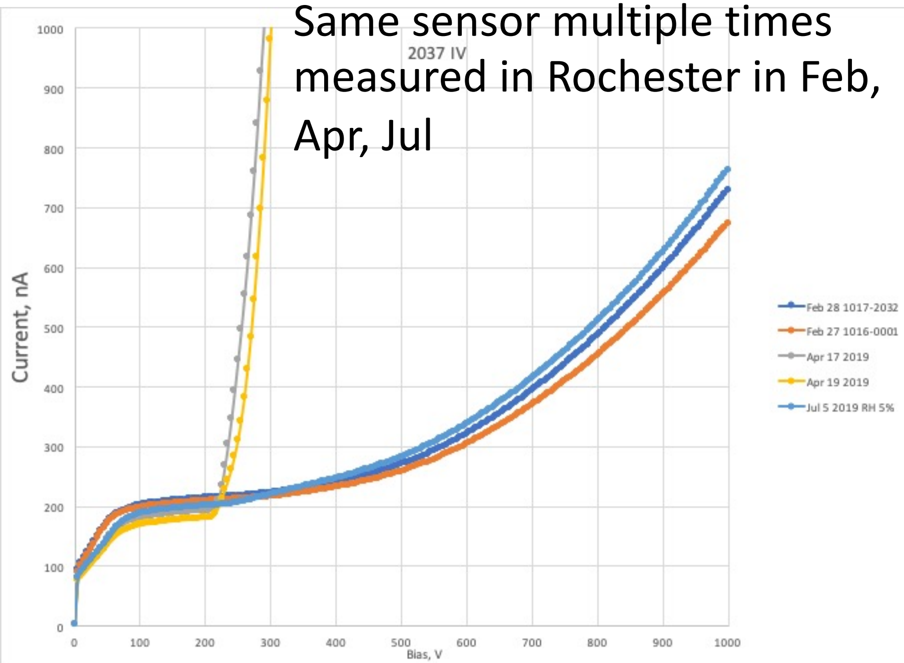
**thFZ240: thinned sensor**

- Initially uses same wafer material as FZ290
- Thinning at HPK after most of frontside processing
- Backside implant can only be 1 µm thick
- Active thickness (almost) identical to physical thickness
- More complex production (additional process, higher losses) leads to +15% higher costs and longer lead times
- HPK suggested withdrawing this option due to unreliable results during processing

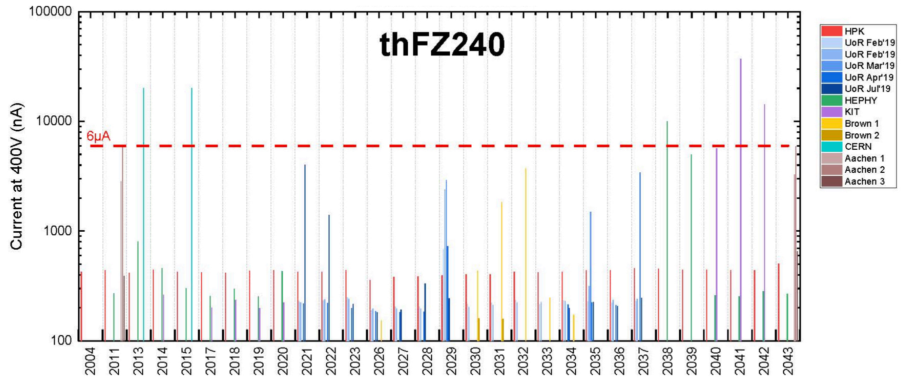


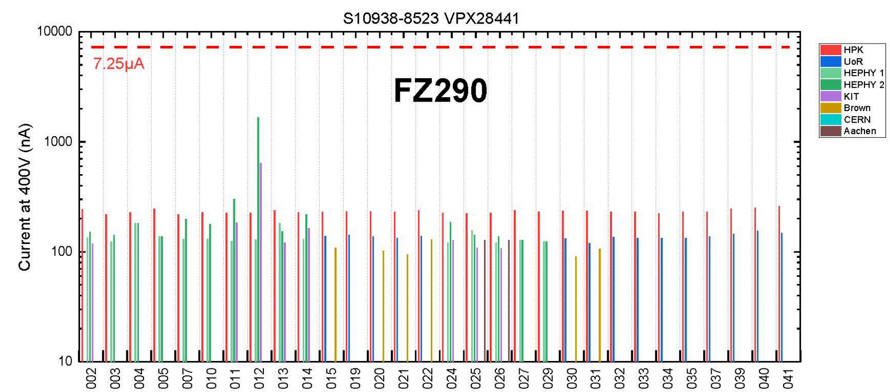
Wafer pre-thinned to 320 µm thickness with a 30 µm backside implant

# Sensor qualification




Same sensor multiple times measured in Rochester in Feb, Apr, Jul



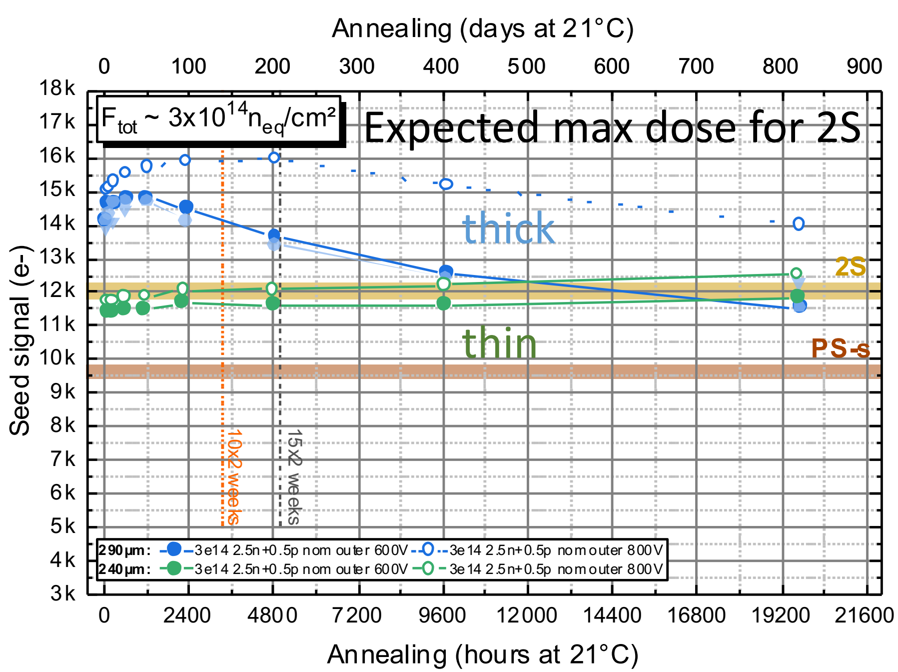



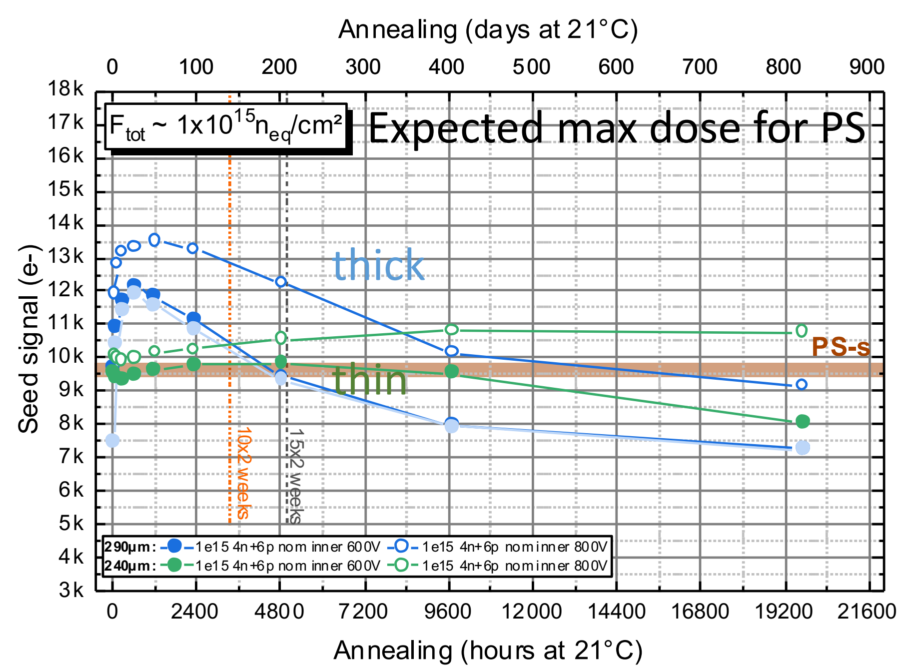

- Tests on pilot sensors were performed at multiple QC centers
  - US sites played a crucial role in identifying problems with thin sensors
- Thin (240 µm) sensors delivered by HPK this spring demonstrated higher leakage current, breakdown after reaching the depletion voltage, unstable performance

# Irradiation studies

Charge #2

- Irradiation studies of thick and thin sensors
  - Thin (240 μm) sensors delivered by HPK this spring demonstrated higher leakage current, breakdown behavior
  - They did not show the expected advantage in irradiation campaign
  - Thin sensors are 15% more expensive
  - **After discussions and based on the feedback from HPK the final decision was made on Sep 17 to order thick (290μm) sensors**

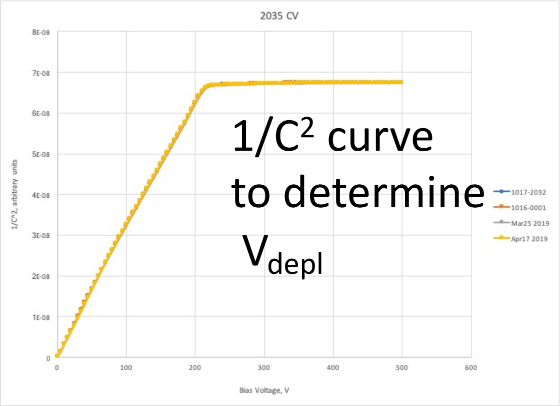


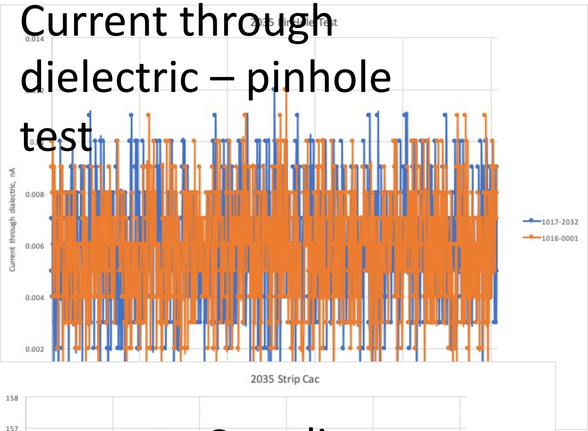



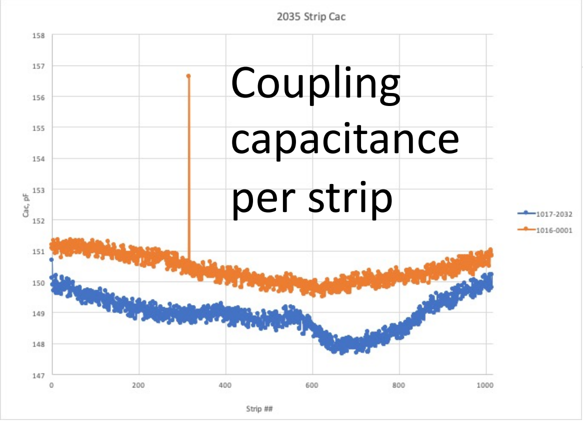
# Quality Control

Charge #2

- A detailed QC plan developed in the framework of international CMS - - workshop at Brown in November to finalize the tests and specs
- Vendor QC
  - IV on sensors and test structures
  - IV, CV and strip conductivity tests are carried out by vendor for every sensor, but no quantitative strip tests
- Sensor QC
  - 2 sensors per batch will be tested (8%)
  - Visual inspection
  - IV, CV, strip and interstrip properties
  - Setup is operational at both QCs
    - Rochester – final version
    - Brown – optimized
- Process QC
  - Carried out by QC centers for 1-2 test structures per batch
  - PQC Setup
    - Brown – fully operational
    - Rochester(backup) – setup in progress
- Irradiation QC
  - Carried out by QC center for a sample of test structures and small sensors
  - We characterized research reactor at Rhode Island Nuclear Science Center for neutron irradiation
    - Routinely used during OT sensor R&D
  - FNAL proton irradiation facility



# Development before Production

- Basic sensor design - done
- Decided about thickness of sensors - done
  - Irradiation tests of 320 μm silicon with neutrons
- Finalized wafer layout design - done
  - Validation of prototypes
  - Finalize design of test structures
- Contract with HPK signed
  - Frame contract signed August 2019 – done
  - Placement of order - imminent
- Quality Control
  - Complete setup of QC equipment infrastructure
    - Final at Rochester
    - Under optimization at Brown
  - Optimize sensor QC procedure
  - Develop process QC infrastructure
    - Done at Brown
    - In progress at Rochester
  - Set up long term test station
    - Complete at Brown
    - Single sensor at Rochester
  - Setup local database, interface with central CMS database

| OT Sensor Procurement | |
|---|---|
| CMS Pre-PRR Part 1 | 29 January 2019 |
| Finalisation of draft IT documents and related documents | 13 March 2019 |
| CMS Pre-PRR Part 2 | 14 March 2019 |
| Specification Committee | 25 March 2019 |
| Dispatch of IT documents | 3 April 2019 |
| Reply to IT documents | 29 April 2019 |
| Submission of FC paper | 29 April 2019 |
| Peers review meeting for FC | 9 May 2019 |
| FC meeting | 18/19 June 2019 |
| Frame contract signature with both materials/thicknesses as option | (June/July)<br>23 August 2019 |
| Baseline irradiation plan completed | (July)<br>September 2019 |
| Additional Studies completed | (August)<br>September 2019 |
| Review of all results and decision on material/thickness | 17 September 2019 |
| Placement of order | 30 September 2019 |
| CMS PRR | Early 2020 |
| (Pre-) production start | (April )<br>July 2020 |

# Design Maturity

Charge #2

- Design completion percentage

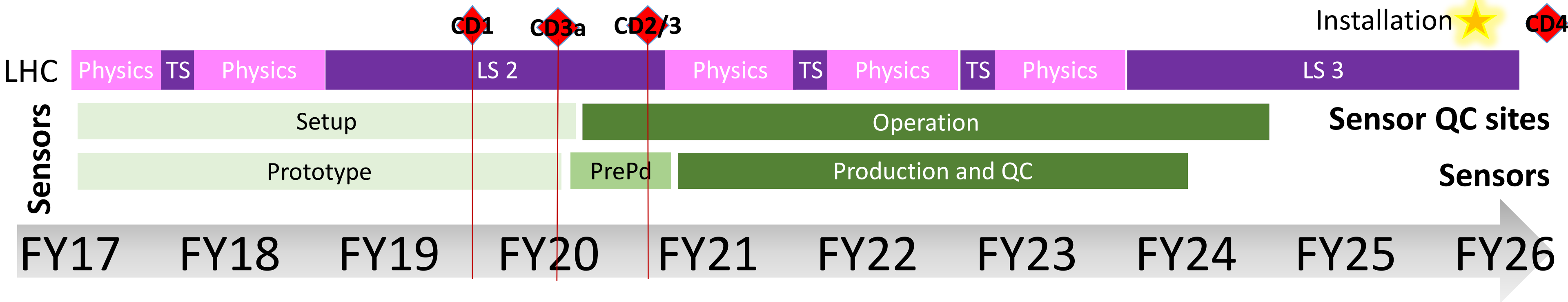
| OT | Sensors Mgmt | Sensors Tech |
|---|---|---|
| Conceptual Design | 100% | 100% |
| Preliminary Design | 100% | 100% |
| Final Design | 100% | 100% |
| Detailed Design | 50% | 80% |
| Construction Readiness | 48% | 75% |

- Sensor design is final; detailed design for PS-s sensors done, first order is imminent. 2S and PS-p detailed designs next.
- See also cms-doc-13417

# Cost and Schedule

# Cartoon Schedule

Charge #3

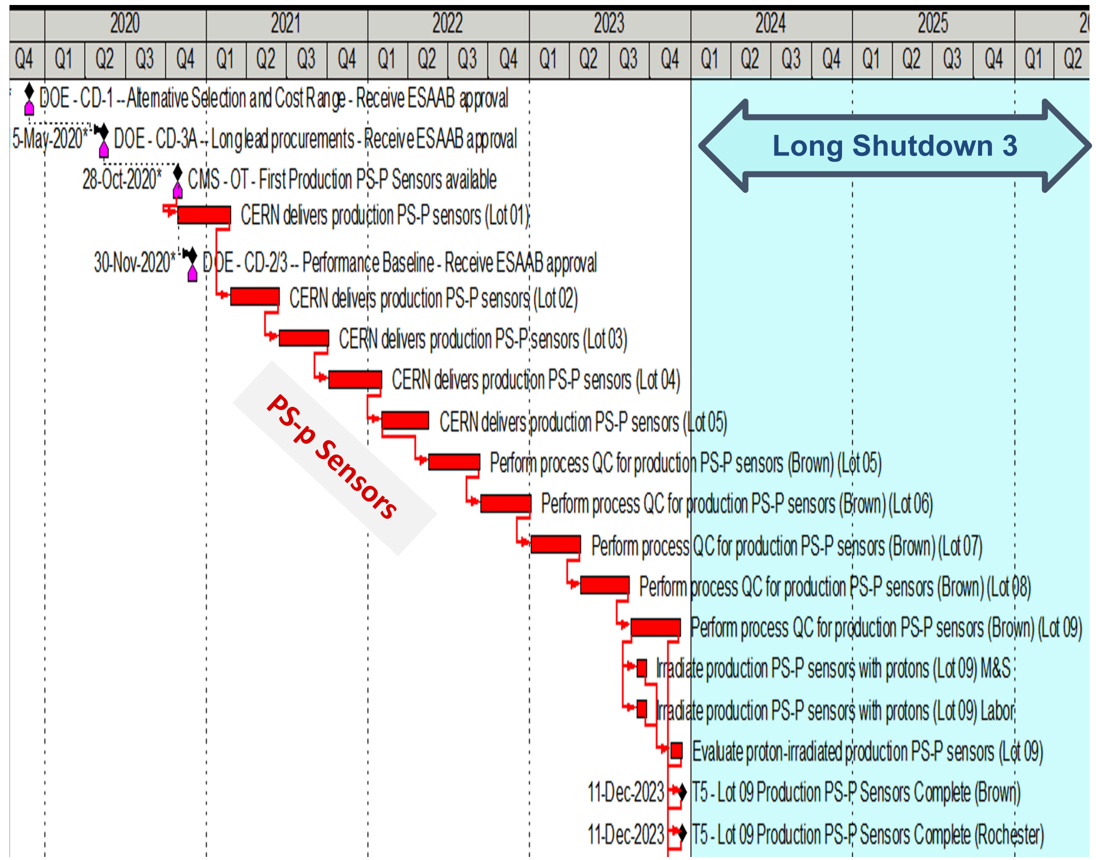



- The sensor schedule has three phases
  - Setup of QC centers, prototyping of sensors, evaluation of vendors
  - Preproduction
  - Production
    - Driven by sensor delivery schedule
    - Drives module assembly schedule for most of the project

# Critical Path Items for Sensors

Charge #3

- Sensor production distributed over 3 years
  - At this rate QC and module assembly can keep up
  - Schedule driven by sensor production



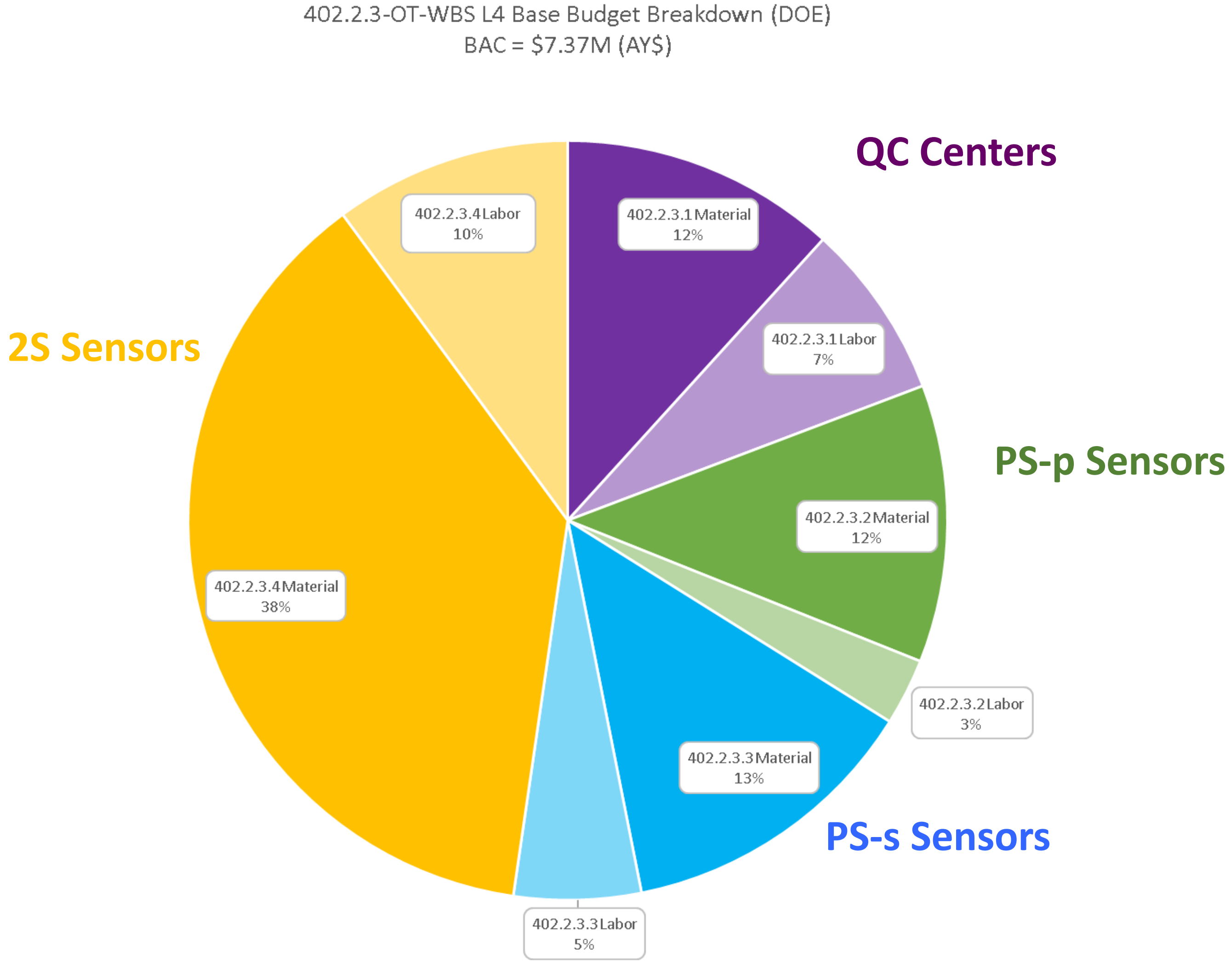
# Costs: Sensors

CMS-doc-13215

| 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-CD1-402.2.3.1 OT - Sensor QC Centers | 682,480 | 7678 | 4.34 | 1,418,107 | 95,316 | 1,513,423 |
| DOE-CD1-402.2.3.2 OT - PS-P Sensors | 813,108 | 3132 | 1.77 | 1,079,959 | 206,472 | 1,286,431 |
| DOE-CD1-402.2.3.2.1 OT - PS-P Sensor Prototypes | 62,957 | 1470 | 0.83 | 160,177 | 8,080 | 168,257 |
| DOE-CD1-402.2.3.2.2 OT - PS-P Sensor Production | 750,151 | 1662 | 0.94 | 919,782 | 198,392 | 1,118,175 |
| DOE-CD1-402.2.3.3 OT - PS-S Sensors | 889,677 | 7262 | 4.11 | 1,356,764 | 286,122 | 1,642,885 |
| DOE-CD1-402.2.3.3.1 OT - PS-S Sensor Prototypes | 41,110 | 1387 | 0.78 | 129,963 | 7,953 | 137,917 |
| DOE-CD1-402.2.3.3.2 OT - PS-S Sensor Production | 848,567 | 5875 | 3.32 | 1,226,800 | 278,168 | 1,504,969 |
| DOE-CD1-402.2.3.4 OT - 2S Sensors | 2,608,708 | 13706 | 7.75 | 3,516,318 | 721,577 | 4,237,895 |
| DOE-CD1-402.2.3.4.1 OT - 2S Sensor Prototypes | 141,781 | 2203 | 1.25 | 283,904 | 12,374 | 296,278 |
| DOE-CD1-402.2.3.4.2 OT - 2S Sensor Production | 2,466,927 | 11503 | 6.51 | 3,232,414 | 709,203 | 3,941,617 |
| 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 |

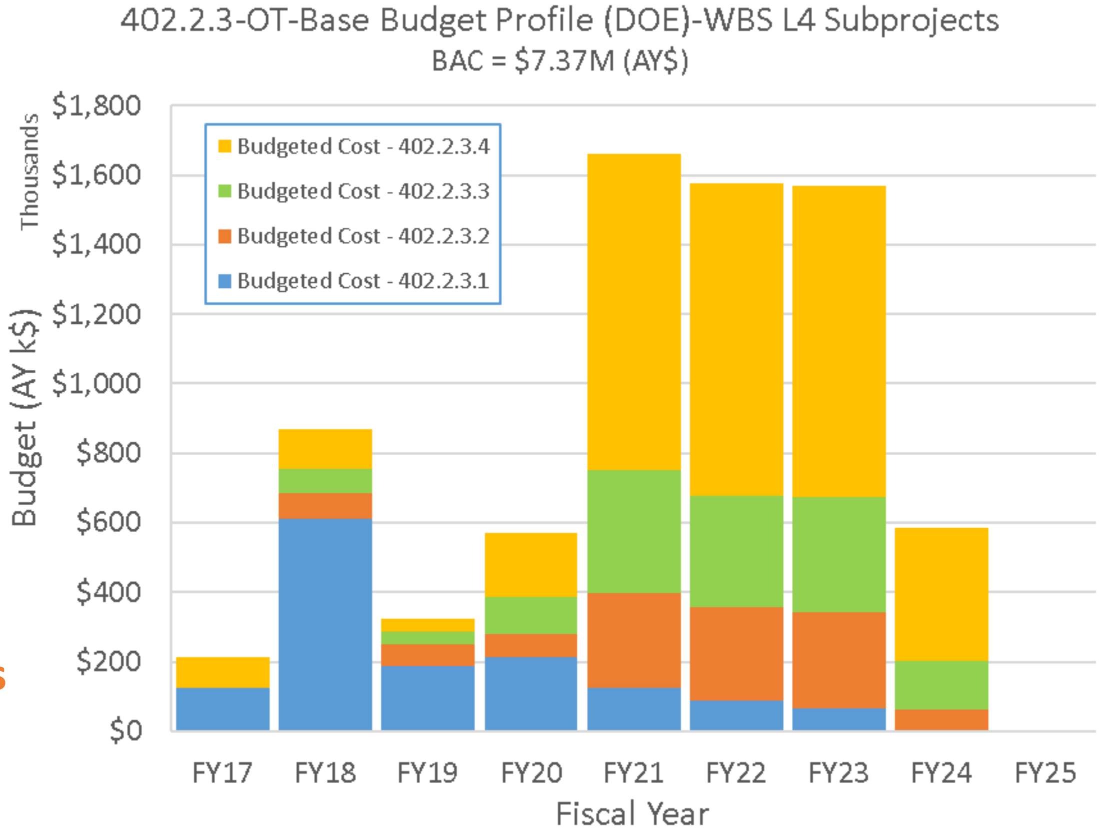
# Budget Breakdown By WBS L4 Labor & Material (chart)

402.2.3



# Base Budget Profile By WBS Level 4 (chart)

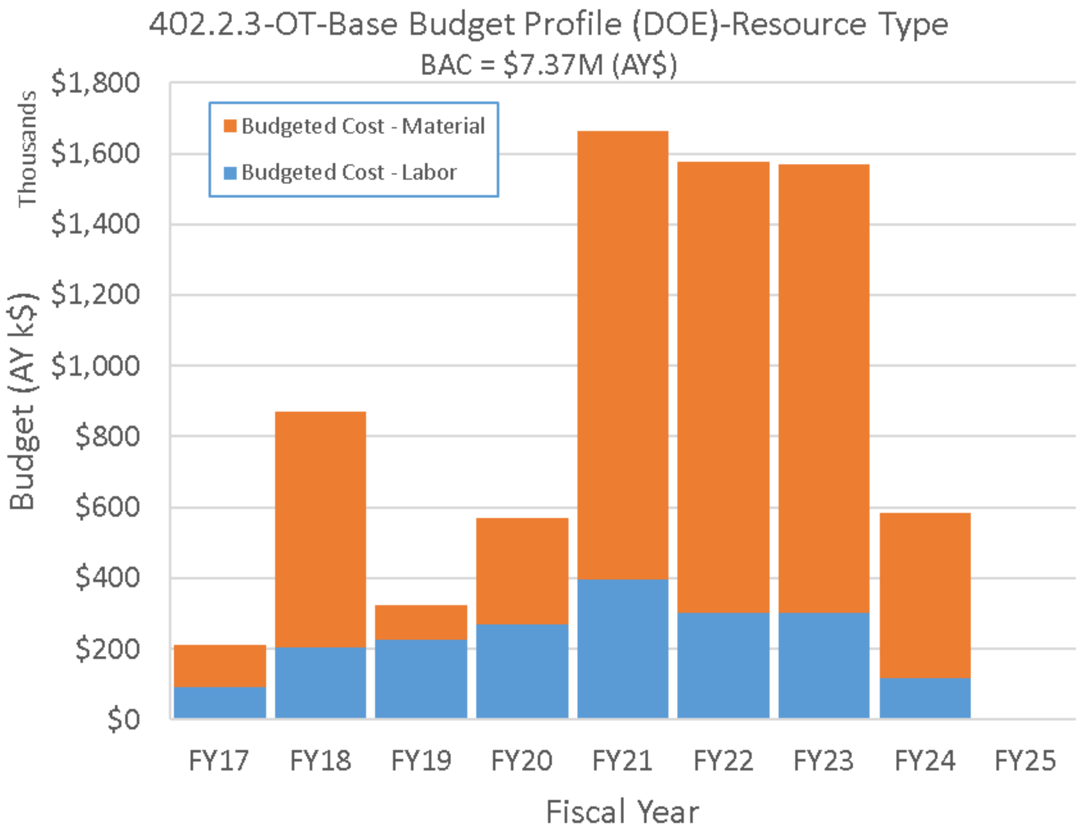
402.2.3




2S Sensors
PS-s Sensors
PS-p Sensors
QC Centers

# Base Budget Profile By Resource Type (chart)

402.2.3

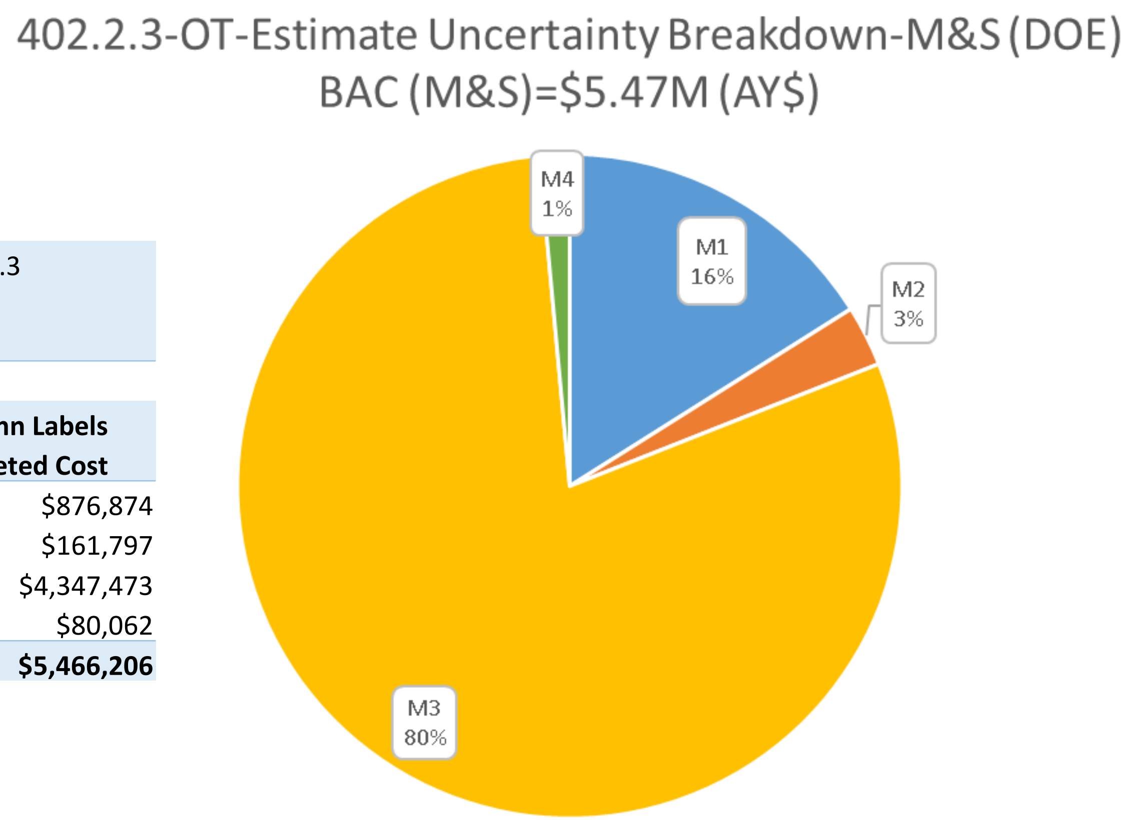


# M&S Budget Breakdown By Est. Uncertainty Code (chart)

402.2.3

| | |
|---|---|
| WBSL3 | 402.2.3 |
| Funding Type | (All) |
| Scope Type | (All) |

| **Sum of Value** | **Column Labels** |
|---|---|
| **Row Labels** | **Budgeted Cost** |
| M1 | $876,874 |
| M2 | $161,797 |
| M3 | $4,347,473 |
| M4 | $80,062 |
| **Grand Total** | **$5,466,206** |

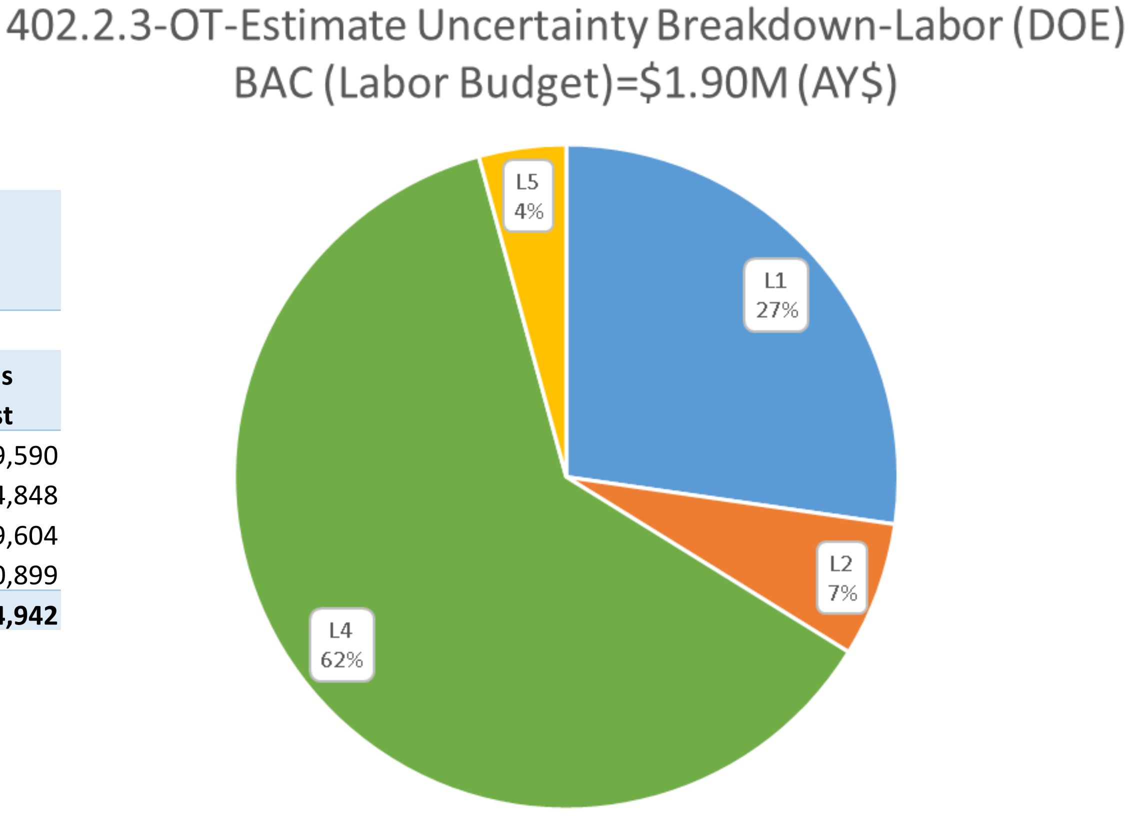


# Labor Budget Breakdown By Est. Uncertainty Code (chart)

402.2.3

| | |
|---|---|
| WBSL3 | 402.2.3 |
| Funding Type | (All) |
| Scope Type | (All) |

| **Sum of Value** | **Column Labels** |
|---|---|
| **Row Labels** | **Budgeted Cost** |
| L1 | $519,590 |
| L2 | $124,848 |
| L4 | $1,179,604 |
| L5 | $80,899 |
| **Grand Total** | **$1,904,942** |

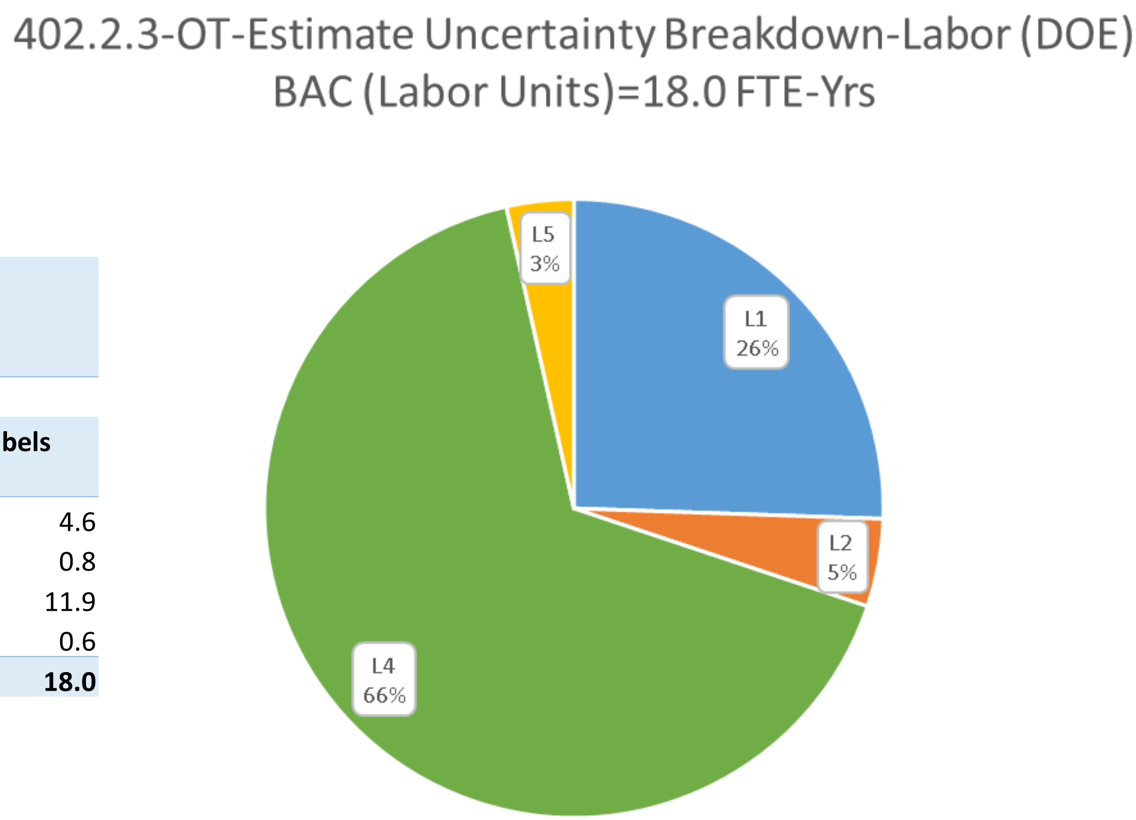


# Labor FTE Breakdown By Est. Uncertainty Code (chart)

402.2.3

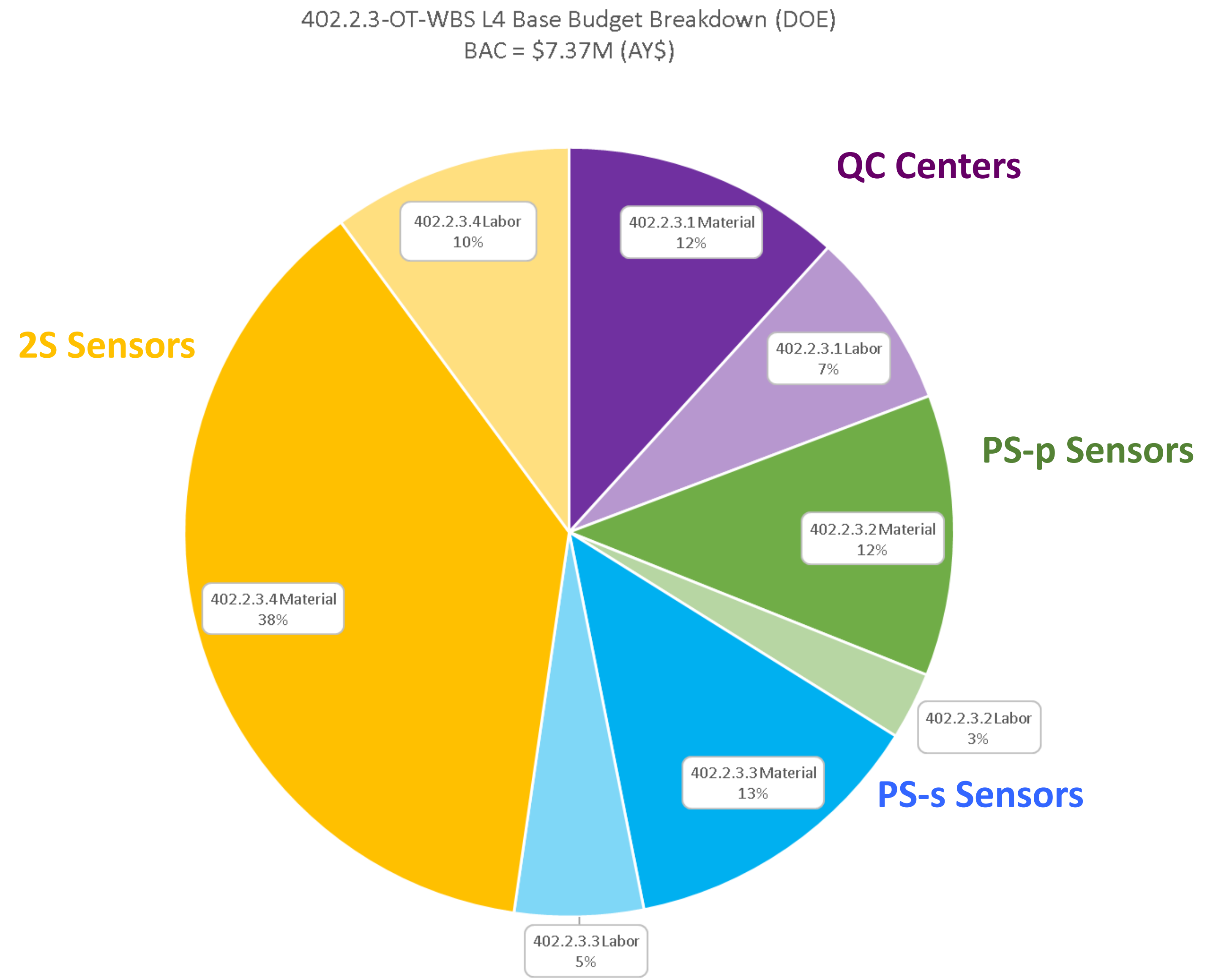
| WBSL3 | 402.2.3 |
|---|---|
| Funding Type | (All) |
| Scope Type | (All) |

| **Sum of Value** | **Column Labels** |
|---|---|
| **Row Labels** | **FTEs** |
| L1 | 4.6 |
| L2 | 0.8 |
| L4 | 11.9 |
| L5 | 0.6 |
| **Grand Total** | **18.0** |



# Overall Cost

Charge #3



HL-LHC US CMS

# Cost Drivers

Charge #3

- M&S drivers
  - Sensor procurement is a significant cost driver for the project
  - Handled centrally through CERN
    - Market survey
    - Call for tender
    - Signing frame contract
    - Placement of order

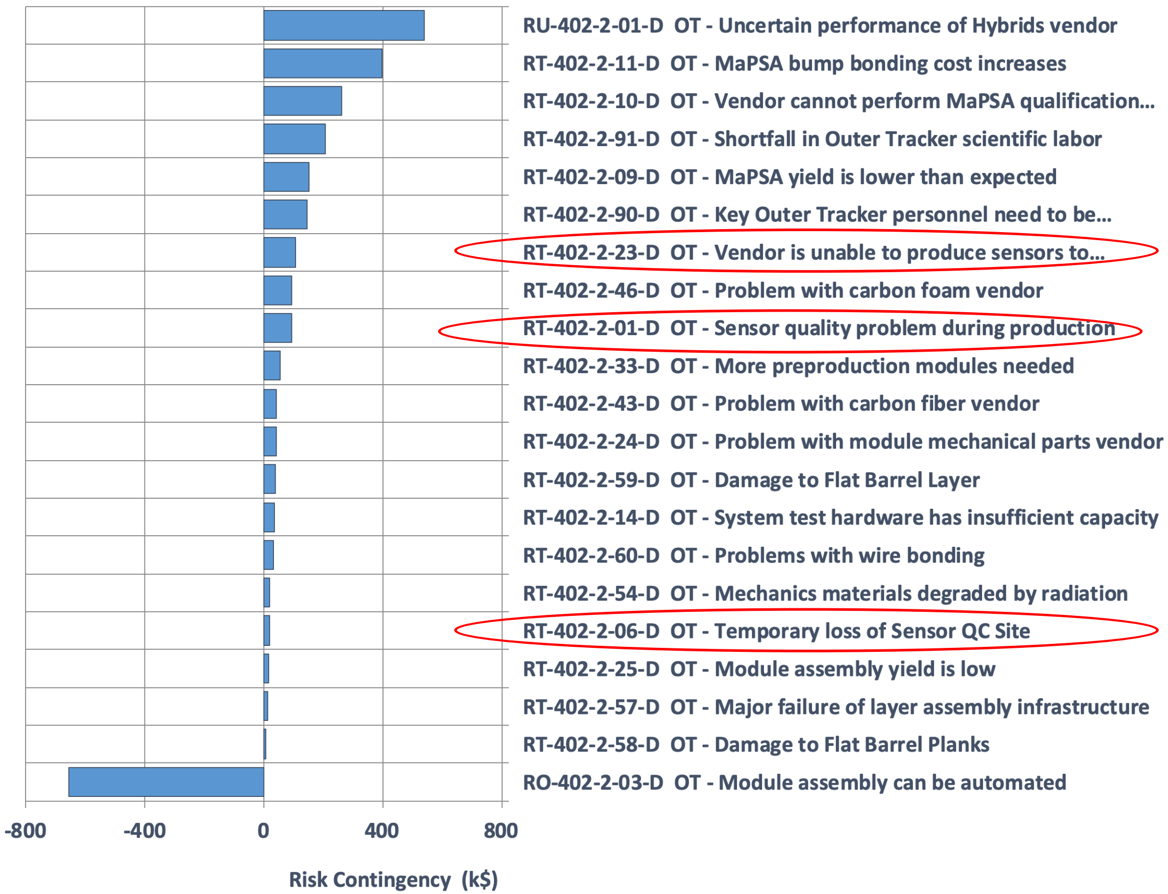
| CMS Driver | Labor (FTE-yrs) | Labor BAC (M$) | M&S BAC (M$) | Total BAC (M$) |
|---|---|---|---|---|
| OT.5 - Produce and test modules | 57.3 | 8.6 | 1.5 | 10.2 |
| OT.3 - Procure Sensors | 0.0 | 0.0 | 4.5 | 4.5 |
| OT.5 - Module mechanics | 2.2 | 0.3 | 3.0 | 3.3 |
| OT.5 - Procure hybrids | 0.0 | 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 |

- Labor drivers
  - Sensor labor is not a significant cost driver of the OT project

# Risks

Charge #3

- Vendor is unable to produce sensors to specification
  - Requires 1 – 3 preproduction cycles
- Sensor quality problem during production
  - Min: 2 months delay
  - Max: 6 month delay
  - Depending on when/how quickly it is diagnosed
- Temporary loss of sensor QC site
  - If one center becomes unavailable the other one can pick up the load
  - Delay is time needed to transfer activities
  - Cost covers repair of equipment



# Project Organization

# Contributing Institutions

Charge #4, 5

- **Brown University**
  - Faculty: Ulrich Heintz
    - F-disk design and sensor QC for D0 Silicon Microstrip Tracker 1996-1998
    - L2 manager of D0 Silicon L2 Track Trigger 1999-2006
    - L3 manager/CAM of Phase 1 CMS HF FE upgrade 2013-2017
    - L3 manager/CAM of USCMS phase-2 Outer Tracker Sensors since 2016
    - Co-coordinator of CMS modules group since 2017
  - Research Scientist:
    - Andrei Korotkov, PhD Phys & Math, Russian Acad. Sciences, Nizhny Novgorod, CMB Spectrometry
  - Technical stuff:
    - Nick Hinton, BS Eng Phys UIUC, phase 1 FPIX construction at Purdue 2012-2017
    - Eric Spencer, MS physics UCSD, phase 0 FPIX construction 2002-2007
- **University of Rochester**
  - Faculty: Regina Demina
    - Silicon QC for CDF L00 and ISL
    - Development of sensors for D0 L0
    - Deputy L2 project manager for phase 0 TOB construction 2000-2009
    - L2 manager of the US tracker operations 2009-2013
  - Engineer: Sergey Korjenevski
    - Rad testing and QC for D0 Silicon Microstrip Tracker
    - Sensor QC, cosmic ray testing, and commissioning for phase 0 CMS Tracker
    - Rad hard sensor development with CMS/RD50

# Resource Optimization

Charge #4

- Previous expertise
  - Senior personnel at both institutions have expertise in silicon detectors and sensor QC
- Infrastructure
  - Part of the infrastructure needed for sensor QC existed and allowed to start R&D work immediately
- Intellectual engagement
  - Brown has participated in sensor R&D since 2012 with the CMS sensor group and provided a strong link with international CMS
  - Rochester developed rad hard sensor technology since 2005 as a part of RD50, and since 2009 for CMS upgrade
- Vendors
  - Equipment is generally purchased off the shelf (used/refurbished if possible)
  - Some modifications are made in house if more cost-effective
  - Silicon vendor(s) are(is) selected by CERN market survey
  - Silicon vendor provides first level of QC. Past experience (CMS phase 0, D0) has shown that we need to verify vendor qualification and carry out more detailed measurements that would drive up the sensor cost if done by vendors

# ES&H

Charge #6

- FNAL ES&H policy
  - Project-wide development through ESH coordinator in PO
    - Documented in DocDb 13394 and DocDb 13395
- Specific Hazards for 402.2.3 Sensors are
  - Radioactivity
    - Sr-90 source for sensor testing – comply with institutional radiation safety practices
    - Irradiated sensor materials – left at irradiation site until safe for handling
  - Laser
    - For sensor testing - comply with institutional laser safety practices

# Summary

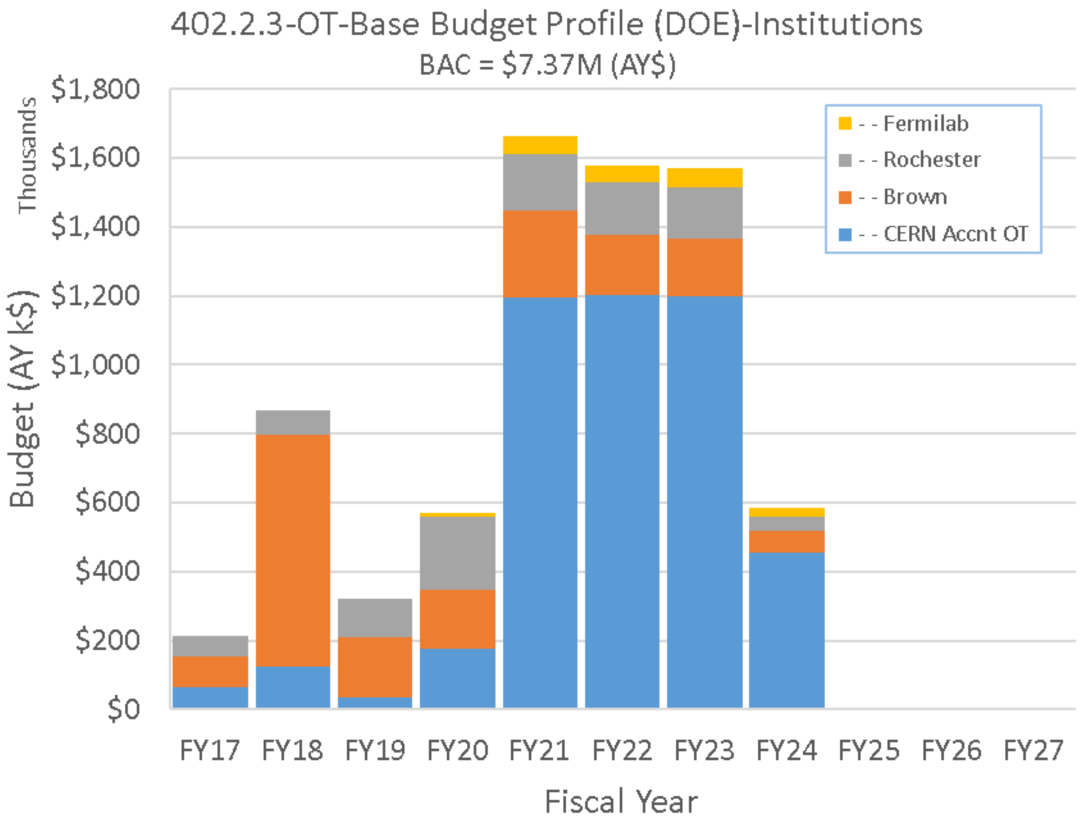
# Summary

- We have developed the sensor technology to satisfy the requirements of the HL LHC tracker upgrade
- We have performed a market survey and qualified vendors
  - We are down to one vendor, HPK, but it is a reliable long term partner
  - Frame contract with HPK was signed in Aug2019
- We have evaluated sensor prototypes
  - Based on the prototype studies the decision on sensor thickness has been reached – order thick (290 μm) sensors
- We have developed an extensive QC program for sensor production
  - In November we will have a workshop at Brown to finalize the testing procedures
- The team includes physicists and engineers/techs, all with experience in silicon tracking systems
- Cost estimate is solid, labor based on experience with existing tracker and prototyping and M&S based on quotes
- Schedule has been developed based on experience with previous projects, prototyping and schedule agreed with the vendor
- The risks are understood and mitigation plans are in place

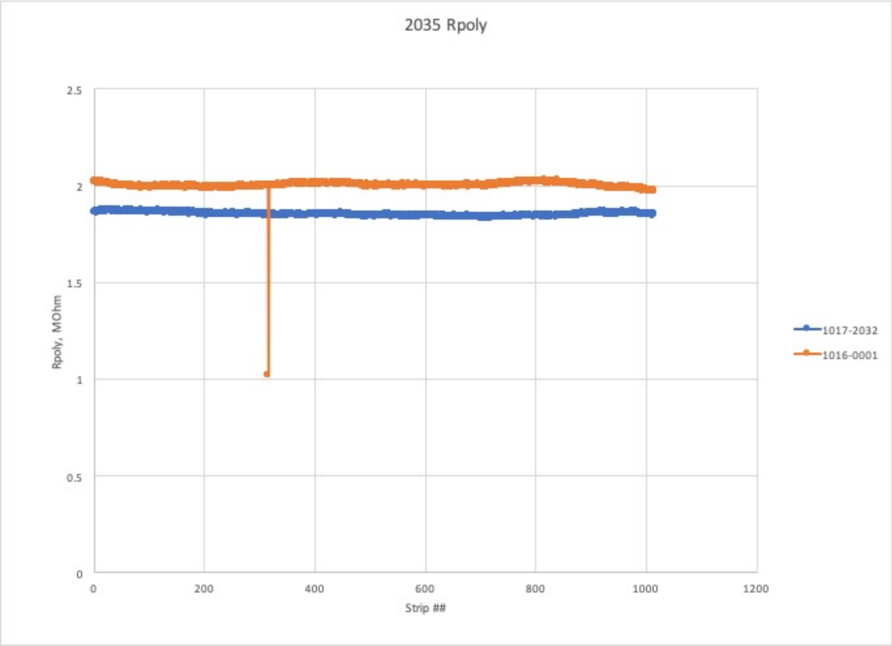
# Backup

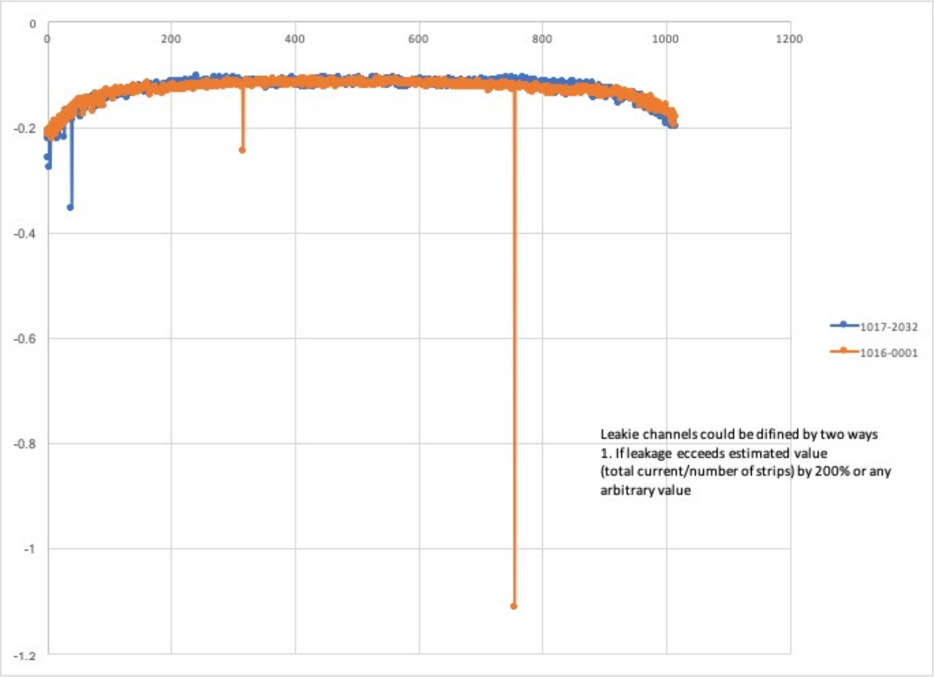
# Base Budget Profile By Institution (chart)

402.2.3



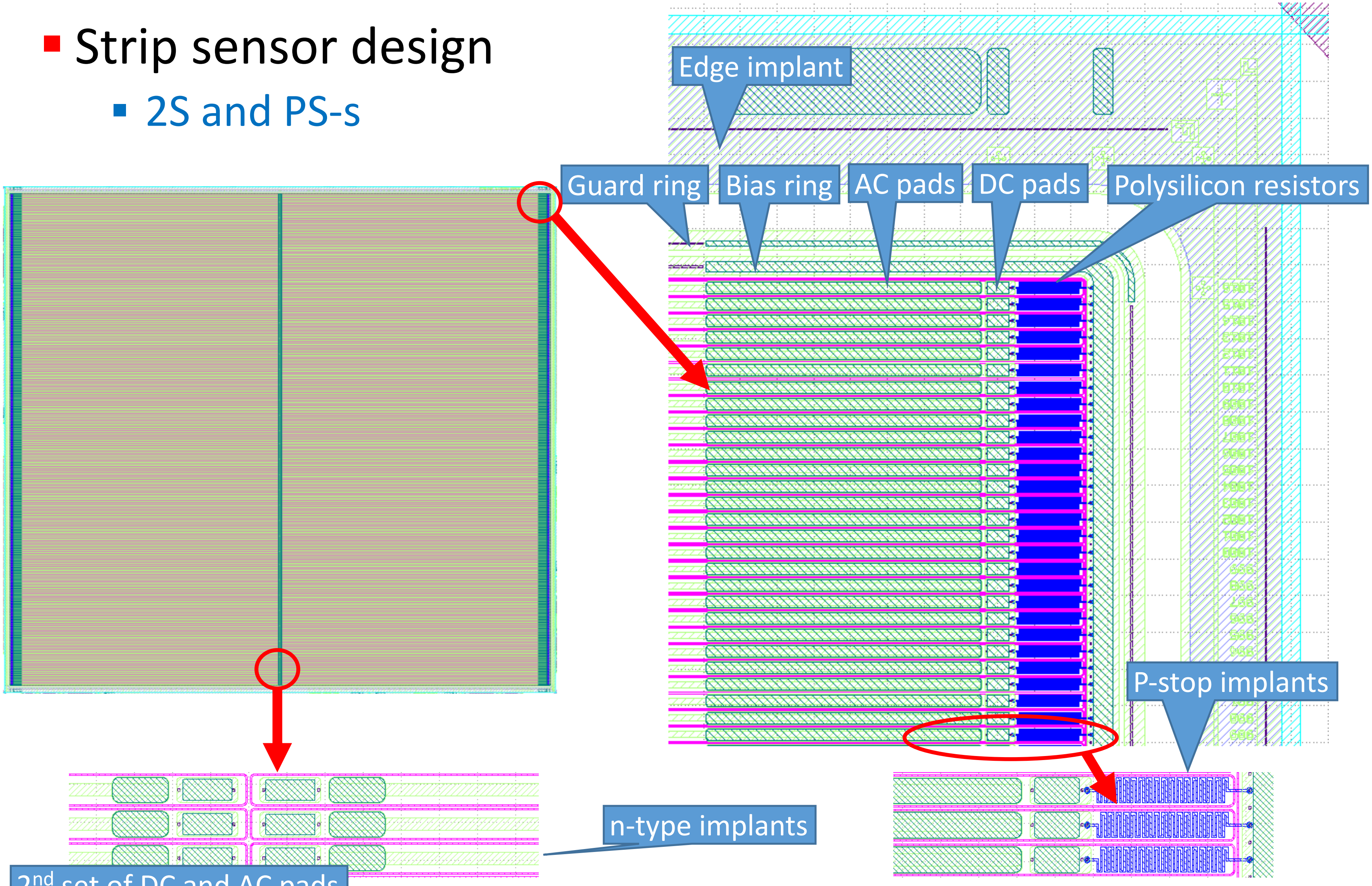
# More tests


2035 Rpoly
Rpoly, MOhm
Strip ##
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
1200
1017-2032
1016-0001


0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
200
400
600
800
1000
1200
1017-2032
1016-0001
Leakie channels could be difined by two ways
1. If leakage ecceeds estimated value
(total current/number of strips) by 200% or any
arbitrary value

# Sensor Design

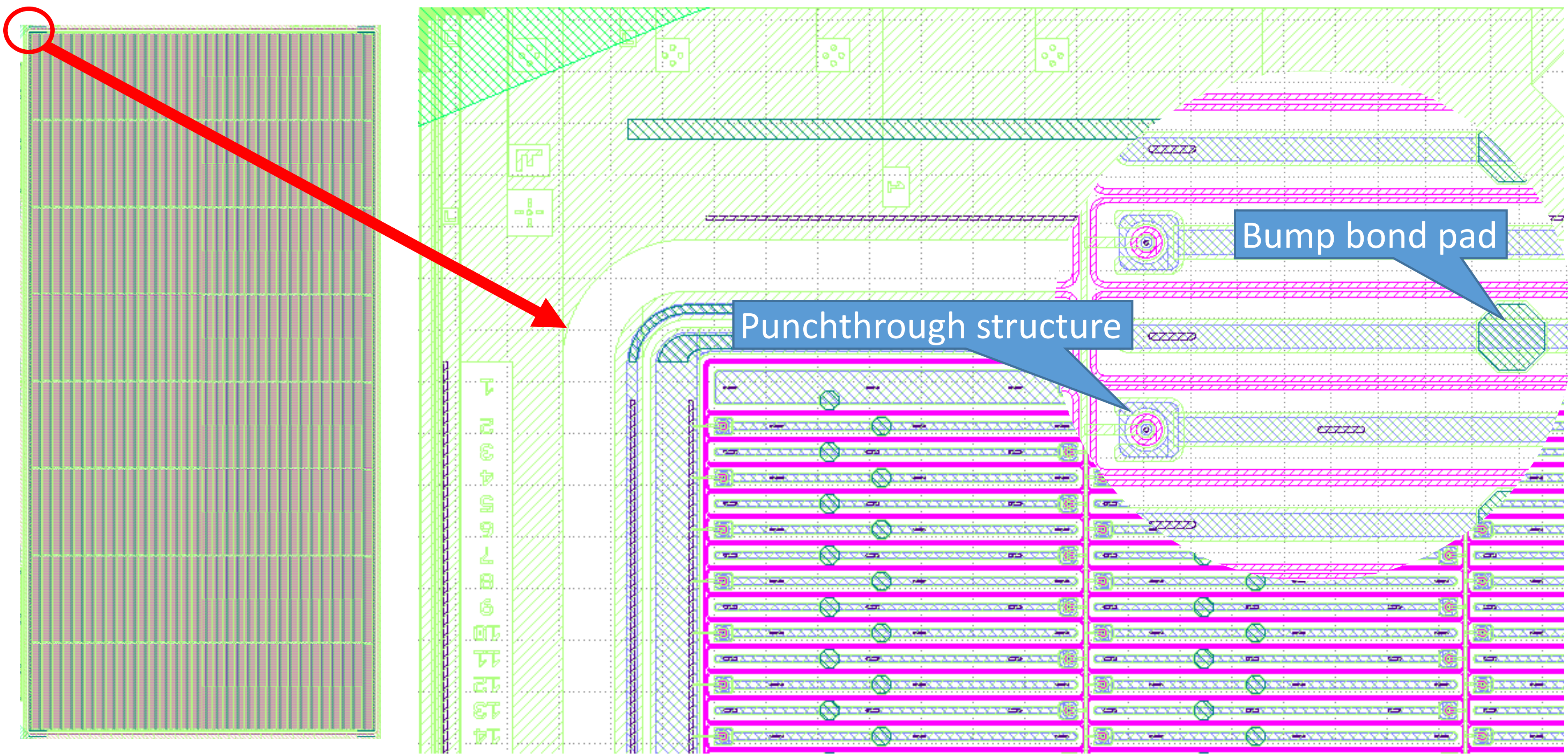
- Strip sensor design
  - 2S and PS-s



# Sensor Design

Charge #2

- Pixel sensor design
  - PS-p



# Quality Assurance

Charge #2

- Specification
  - Develop suitable specifications to ensure that sensors satisfy the requirements
  - These specifications have been developed in the framework of international CMS
- Evaluation of prototype sensors
  - Verify that performance of sensors satisfies requirements
  - Confirm that vendors can produce sensors within specifications
- Design of wafer layout
  - Include test structures to monitor production quality

# CMS QC plan

Charge #2

- Measurement matrix

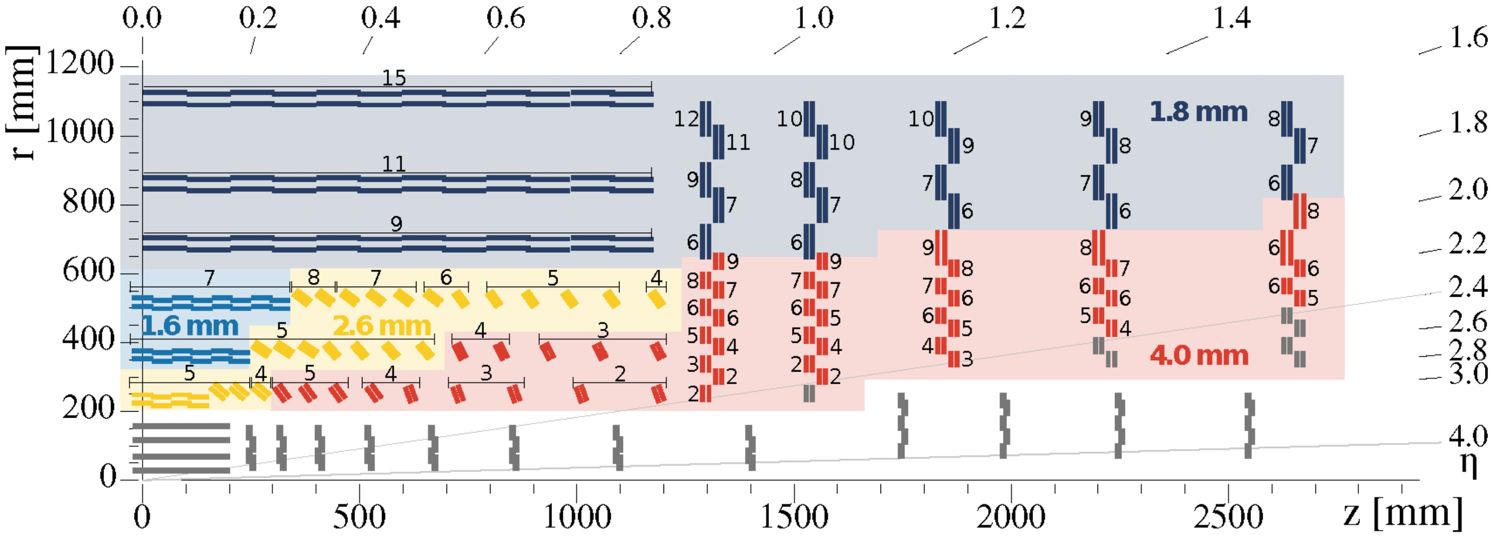
| | VQC | SQC | PQC | IQC |
|---|---|---|---|---|
| Global measurements (2S, PS-s, PS-p) | | | | |
| Depletion voltage, current, break down | ✓ | ✓ | ✓ | ✓ |
| Long term stability | | ✓ | | |
| Measurements after irradiation | | | | |
| Breakdown and interstrip resistance | | | | ✓ |
| Strip measurements (2S, PS-s) | | | | |
| Strip current | | ✓ | | ✓ |
| Bias resistor median | | ✓ | ✓ | |
| Bias resistor uniformity | | ✓ | | |
| Coupling capacitance | | ✓ | ✓ | |
| Interstrip capacitance and resistance | | ✓ | ✓ | ✓ |
| Pinhole check | ✓ | ✓ | | |
| Bad strips | | ✓ | | |
| Pixel measurements (PS-p) | | | | |
| Pixel current, interpixel resistance | | | ✓ | |
| Number of bad pixels | | | | |
| Test structure measurements | | | | |
| Strip/pixel implant/aluminum resistivity | | | ✓ | |
| Dielectric breakdown | | | ✓ | |

# BoEs

| 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 |

# Proposed Design

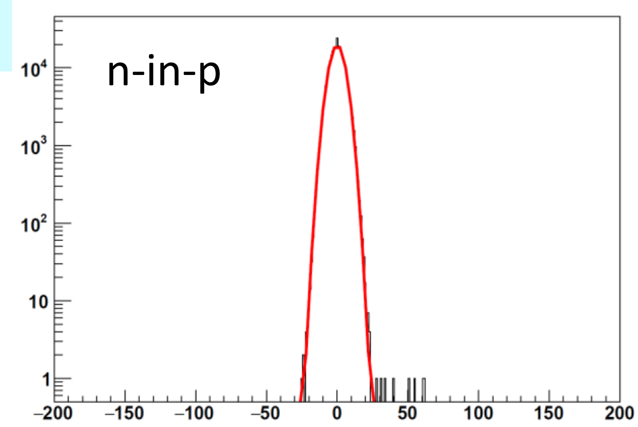
- Geometry of upgraded tracker

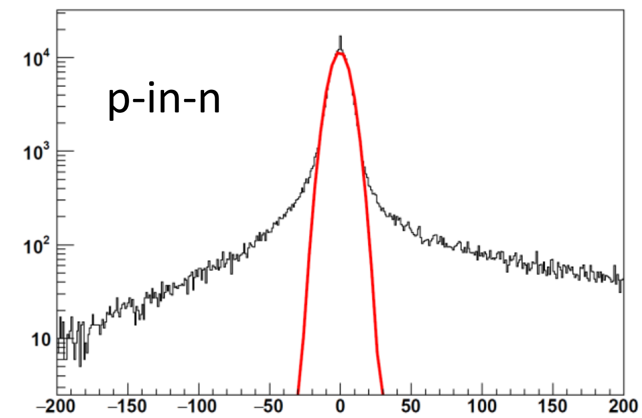


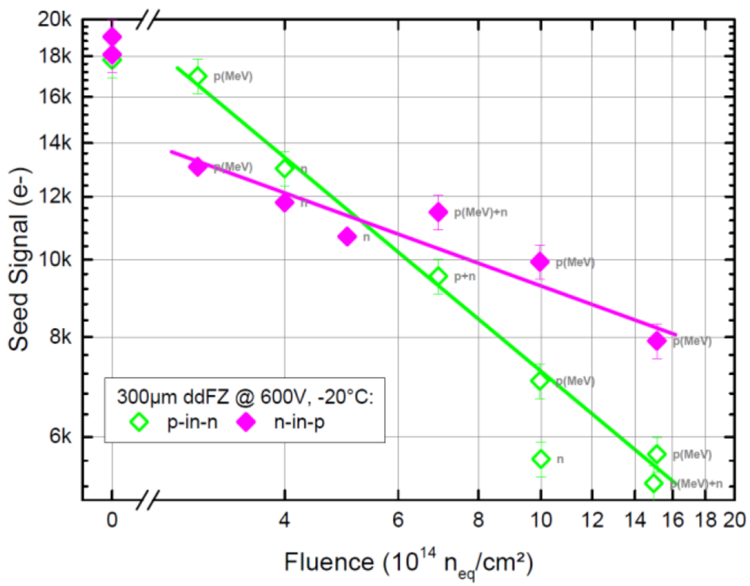

- Module types
  - 2S modules
    - Consist of two strip sensors (2S)
    - Radius > 600 mm
  - PS modules
    - Consist of one strip sensor (PS-s) and one macro pixel sensor (PS-p)
    - 200 mm < radius < 600 mm

# Proposed Design

- Bulk and implant doping
  - Pedestal distribution after irradiation with fluence = $5 \times 10^{14} n_{eq}/cm^2$
  - High fields at p+ implants lead to non-Gaussian noise in p-in-n sensors



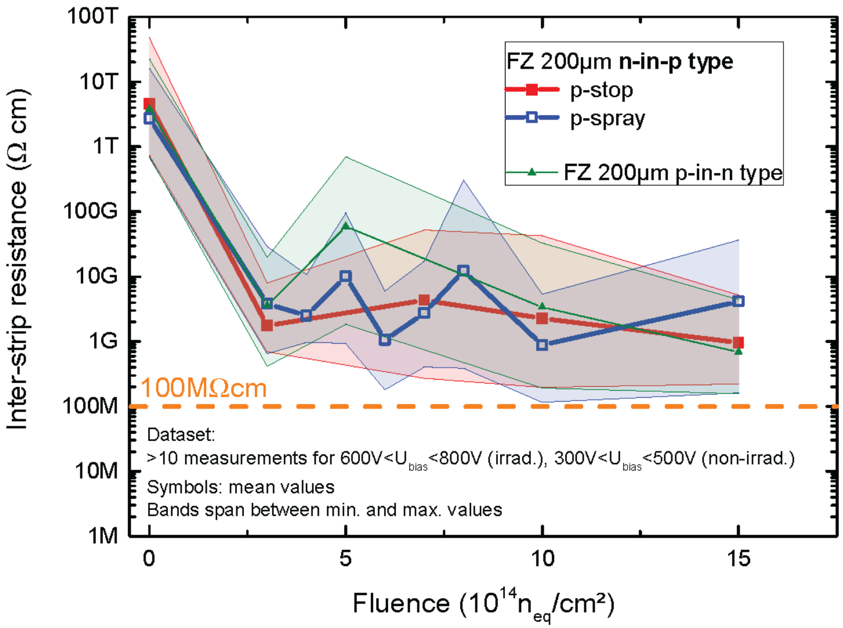




- Seed signal larger for n-in-p than p-in-n for fluence > $5 \times 10^{14}\, n_{eq}/cm^2$

# Proposed Design

- Strip isolation
  - Isolate n+ strips against shorts to neighboring strips through electron accumulation layer at Si-$SiO_2$ interface
  - p-stop or p-spray implants are feasible




  - p-stop appears more reliable and preferred by vendors

# Risk Register CMS-doc-13480

| WBS / Ops Lab Activity : 402.2 OT - Outer Tracker (21) | | 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 |

# Risk Register CMS-doc-13480

## 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<br>Minimum = 46 k$<br>Most likely = 79 k$<br>Maximum = 163 k$<br>Mean = 96.0 k$<br>P * <Impact> = 48.0 k$ | **Schedule Impact:** | PDF = 3-point - triangular<br>Minimum = 2.0 months<br>Most likely = 3.0 months<br>Maximum = 6.0 months<br>Mean = 3.67 months<br>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.<br>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.<br>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).<br>The L3 burn rate due to the delay of downstream activities is $23k/month (CMS-doc-13481).<br>Min cost = $0k + 2months * $23k burn rate = $46k.<br>Likely cost = $10k + 3month * $23k burn rate = $79k.<br>Max cost = $25k + 6months * $23k burn rate = $163k.<br>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).<br>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 | | |

# Risk Register CMS-doc-13480

## RT-402-2-06-D OT - Temporary loss of Sensor QC Site

| | | | |
|---|---|---|---|
| **Risk Rank:** | 2 (Medium) **Scores:** Probability : 2 (L) ; Cost: 0 (N) Schedule: 2 (M)) | **Risk Status:** | Open |
| **Summary:** | If a Sensor QC facility temporarily becomes inoperable due to loss or damage of critical equipment (e.g. due to a water leak) then the resultant dip in sensor throughput may jeopardize timely completion of the project. | | |
| **Risk Type:** | Threat | **Owner:** | Ulrich Heintz |
| **WBS:** | 402.2 OT - Outer Tracker | **Risk Area:** | Technical Risk / ES&H |
| **Probability (P):** | 20% | **Technical Impact:** | 0 (N) - negligible technical impact |
| **Cost Impact:** | PDF = 3-point - triangular<br>Minimum = 22 k$<br>Most likely = 48 k$<br>Maximum = 86 k$<br>Mean = 52.0 k$<br>P * <Impact> = 10.0 k$ | **Schedule Impact:** | PDF = 3-point - triangular<br>Minimum = 1.0 months<br>Most likely = 2.0 months<br>Maximum = 4.0 months<br>Mean = 2.33 months<br>P * <Impact> = 0.466 months |
| **Basis of Estimate:** | Probability = 20% is approximately estimated from 2 sites * 10% per site. This is based on experience from original CMS tracker, original pixel, and Phase 1 pixel where one incident occurred in O(10) sites.<br>If one center has a major equipment failure the second center can pick up the additional load within the 100% cushion.<br>Min/likely/max delay = 1/2/4 months delay for the inefficiency in the logistics to transfer materials and people back and forth. Min/likely/max repair estimate is 10/25/40 k$. This assumes insurance will cover loss/damage of major equipment. The L3 burn rate due to the delay of downstream activities is $23k/month (CMS-doc-13481).<br>Min cost = $10k + 1 month * $23k burn rate = $33k.<br>Likely cost = $25k + 2 months * $23k burn rate = $71k.<br>Max cost = $40k + 4months * $23k burn rate = $132k. | | |
| **Cause or Trigger:** | | **Impacted Activities:** | This is implemented as two independent risk events for the two QC sites (Brown and Rochester). At each site, 3 tasks are impacted in a correlated way, representing the QC work on the 3 sensor types. The impact is modeled in the middle of the QC work (Lot 5). |
| **Start date:** | 1-Apr-2020 | **End date:** | 31-Dec-2024 |
| **Risk Mitigations:** | Having two sites is already a hedge against the complete stoppage of sensor testing, and should one site become temporarily inoperable, sensors would be redirected to the other site temporarily to mitigate the impact. | | |
| **Risk Responses:** | Sensors can be diverted to the unaffected site to utilize its full throughput, and additional resources added to increase module production throughput at both sites (once the affected one is re-established) to regain time in the schedule. | | |
| **More details:** | CMS-doc-13481 | | |

# Risk Register CMS-doc-13480

## RT-402-2-23-D OT - Vendor is unable to produce sensors to specifications

| | | | |
|---|---|---|---|
| **Risk Rank:** | 2 (Medium) **Scores:** Probability : 1 (VL) ; Cost: 3 (H) Schedule: 3 (H)) | **Risk Status:** | Open |
| **Summary:** | If vendor is unable to produce sensors that meet CMS Specification then the additonal cost and delay of identifying a new vendor jeopardizes the timely and on-budget completion of the project | | |
| **Risk Type:** | Threat | **Owner:** | Ulrich Heintz |
| **WBS:** | 402.2 OT - Outer Tracker | **Risk Area:** | External Risk / Vendors |
| **Probability (P):** | 5% | **Technical Impact:** | 3 (H) - extremely substandard or KPP in jeopardy |
| **Cost Impact:** | PDF = 3-point - triangular<br>Minimum = 210 k$<br>Most likely = 315 k$<br>Maximum = 2,720 k$<br>Mean = 1,081.7 k$<br>P * <Impact> = 54.0 k$ | **Schedule Impact:** | PDF = 3-point - triangular<br>Minimum = 6.0 months<br>Most likely = 9.0 months<br>Maximum = 12.0 months<br>Mean = 9 months<br>P * <Impact> = 0.45 months |
| **Basis of Estimate:** | If the selected vendor is unable to produce sensors to specifications a new vendor has to be developed. At a minimum this will require another preproduction run (6 month delay). At a maximum one to two prototype runs may also be required (12 months delay).<br>The burn rate for the entire Outer Tracker is $70k/month (CMS-doc-13481). We assume half of the OT scope is impacted by a delay from this risk, thereby incurring a burn rate of $35k/month.<br>Min impact = no direct cost increase. Burn rate = 6 *$35k = $210k.<br>Likely impact: cost increase is covered by the 30% sensor estimate uncertainty.Burn rate = 9 *$35k = $315k.<br>Max impact: the worst case scenario based on informal cost information received during the market survey is an increase in the cost of the sensors by 2/3 = 66%. 30% are covered by the cost uncertainty. The additional cost of 36% of the $6.5M sensor purchase is $2.3M.Burn rate = 12 *$35k = $420k. Total = $2,720k.<br>We have identified a vendor (HPK) who has already produced sensors of all types that satisfy our specifications. Together with the historically reliable performance of HPK it is very unlikely that this threat will occur. We are not aware that HPK has ever failed to produce sensors to specifications after a purchase was negotiated. Hence the probability is considered to be low. | | |
| **Cause or Trigger:** | Sensors delivered by vendor are substandard and vendor is unable to fix the problem. | **Impacted Activities:** | Sensor production and QC. Cost risk is implemented as a single risk. Schedule risk is implemented as three seperate risks (probability depends on sensor type). There are three risk hooks for the three sensor types, but because 2S and PS-s are similar, would split the probability: 1% for PS-s (hook A), 2% for 2S (hook C), 2% for PS-p (hook B). Note: PRA does not support fractions of percent. |
| **Start date:** | 1-Apr-2020 | **End date:** | 3-Dec-2024 |
| **Risk Mitigations:** | CERN is carrying out a market survey to identify possible vendors. Companies are selected based on their capability to produce sensors that satisfy CMS specifications and to produce all the sensors needed by CMS and ATLAS within a two-year period. Companies have to be qualified by producing prototype sensors to CMS specifications. This minimizes the probability that the selected company cannot deliver the order. | | |
| **Risk Responses:** | A new vendor has to be identified and production restarted. | | |
| **More details:** | CMS-doc-13481 | | |