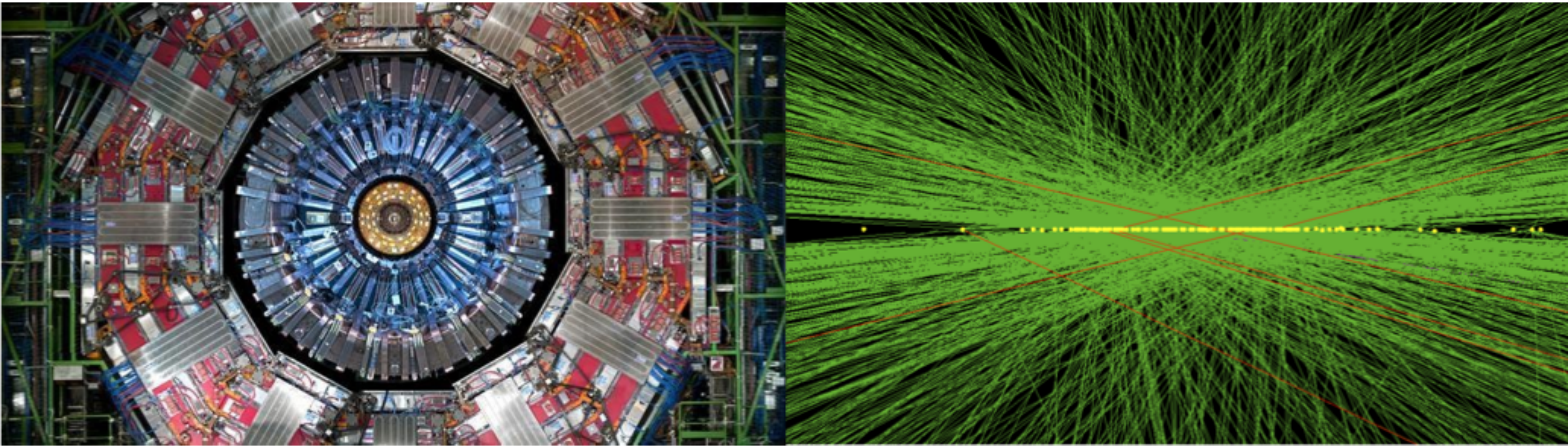
B04: 402.2.4.1 MaPSA

Doug Berry (Fermilab), Ron Lipton (Fermilab)

HL LHC CMS Detector Upgrade CD-1 Review

October 23rd, 2019



Outline

- Macro Pixel Sub-Assembly (MaPSA) overview
- R&D and Prototyping efforts
- Plans towards production
- Costs and Risks
- Summary

Biographical Sketch

Charge #5

- Brief biographical sketch for the L4 managers
  - Doug Berry
    - Associate Scientist at Fermilab
    - Manager of CMS Phase I Upgrade Forward Pixel Test Stand and Database (2014-2017)
      - Received CMS Achievement Award for Work
    - LPC Distinguished Researcher
    - Experience Reassembling and Commissioning of CMS Phase I Upgrade Forward Pixel detector at CERN
  - Ron Lipton
    - Senior Scientist at Fermilab
    - APS Fellow
    - Co-Manager of D0 Silicon tracker and L0 upgrades
    - R&D on 3D integration, 8” thin wafer development, radiation hard AC LGADs, ILC detectors, Induced current detectors, and Muon Collider detectors

MaPSA Overview

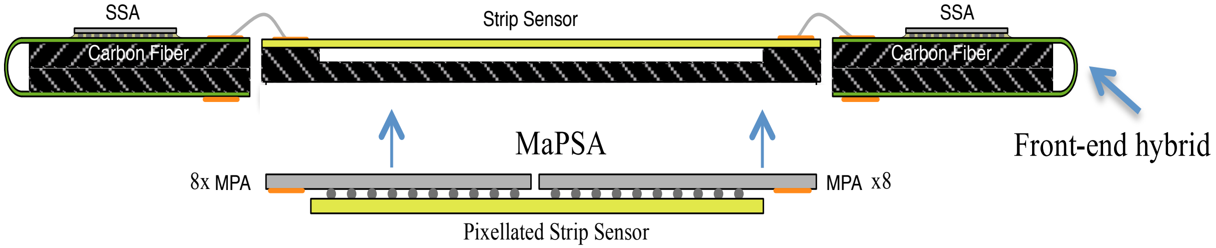
MaPSA Overview

- US is responsible for managing the production of the MaPSA (Macro Pixel Sub-Assembly) component of the PS module.
  - Assembly description
  - Development Phases
  - Requirements
  - Responsibilities

MaPSA

Charge #2

- The MaPSA (Macro Pixel Sub Assembly) is the bump bonded assembly of the pixelated PS-p sensor and the MPA (Macro Pixel ASIC) readout chip
  - The lower component of the PS module assembly



  - Pixels are on 1446x200 micron pitch
    - 200 µm pitch is staggered (effective 283 µm pitch)
  - 2x8 MPA chips, 1 PS-p sensor per assembly
  - Underfill used for mechanical stability
    - Either underfill or polymer film for HV protection

Production Phases

Charge #2

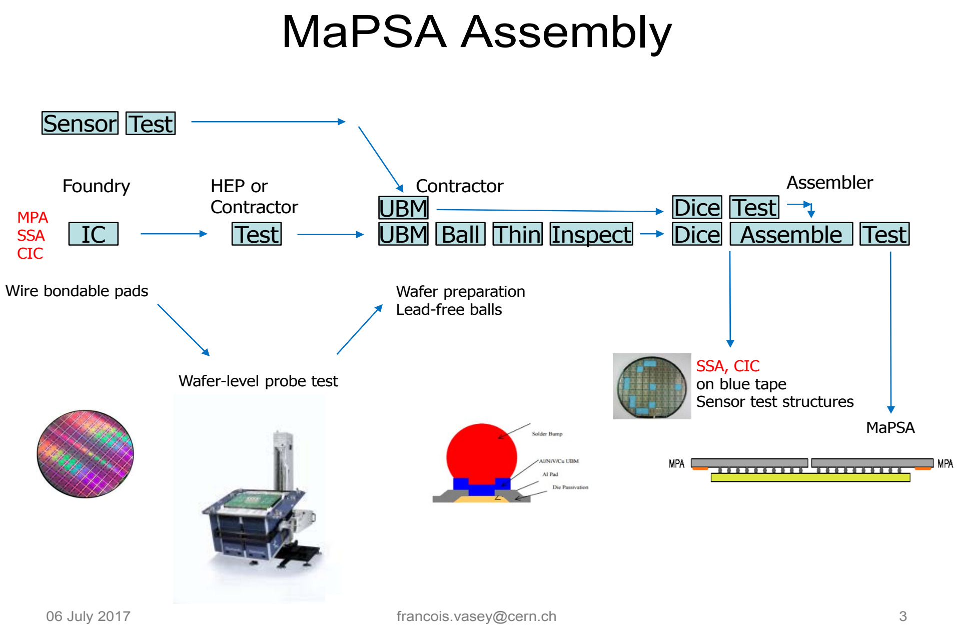
1. Dummy MaPSAs built in order qualify vendors and produce mechanical grade MaPSAs
    - The final dummies processed at AEMTec and I3
        - AEMTec met our quality specifications
2. Prototypes using initial MPA and sensor submissions
    - Round 1 quantities limited by the number of MPA wafers available
        - 30 setup and 20 active assemblies order from two vendors (AEMTec and HPK)
            - 12 out of 15 ordered setup components were delivered in August
                - AEMTec had several technical issues
            - 10 active components arrived from AEMTec in mid-October
            - HPK are processing their components (15 setup and 10 active)
                - Expected delivery in January
    - Round 2 prototypes were out for bids in August
        - Two vendors (HPK and Quik-Pak) have been awarded the contract for 40 MaPSAs each
        - Vendors selected based on past experience and fabrication capabilities
3. Production
    - 2 vendors to be qualified for production

Design and QA/QC

MaPSA Assembly

Charge #2

- The number of prototype assemblies is limited by the cost of pre-production 65nm fabrication
- Tested PS-p and thinned MPA wafers with UBM and bumps were provided by sensor institutes and CERN
- MPA wafers are then diced and bump bonded to sensors



MaPSA Assembly

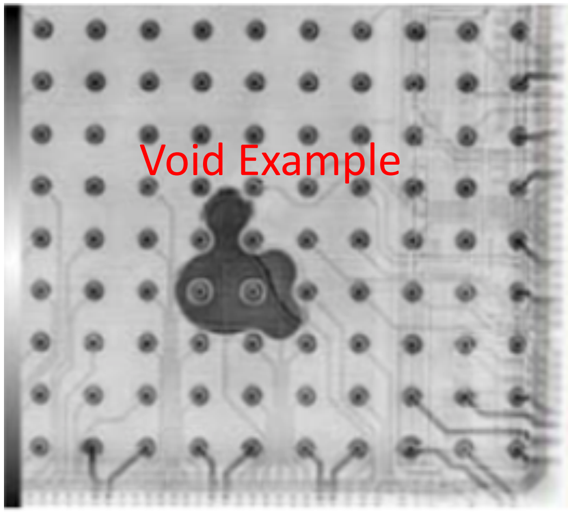
06 July 2017 francois.vasey@cern.ch 3

Type	Total
Dummy	40
Prototype	130
Production	6400
Required	5592
Spares	808

Requirements

Charge #2

- Underfill must fully cover the edges of the assembly to resist sensor to ASIC breakdown
  - Verified by sonographic inspection
  - A variety of candidate materials are being tested
    - Must withstand 800 V during assembly tests
  - Underfill may not cover wirebond pads or extend to the surface of the assembly in the spacer area
    - Verified by scanning acoustic microscopy
  - Kapton strips are being investigated as an alternative to the underfill near to edge of the sensor
- Bump yield must be >99%
- Vendor must test each production MaPSA both for readout and HV breakdown
  - Verify sensor characteristics unchanged
  - Verify functionality of bump bonded MPA chips
  - Test hardware and software provided by CMS

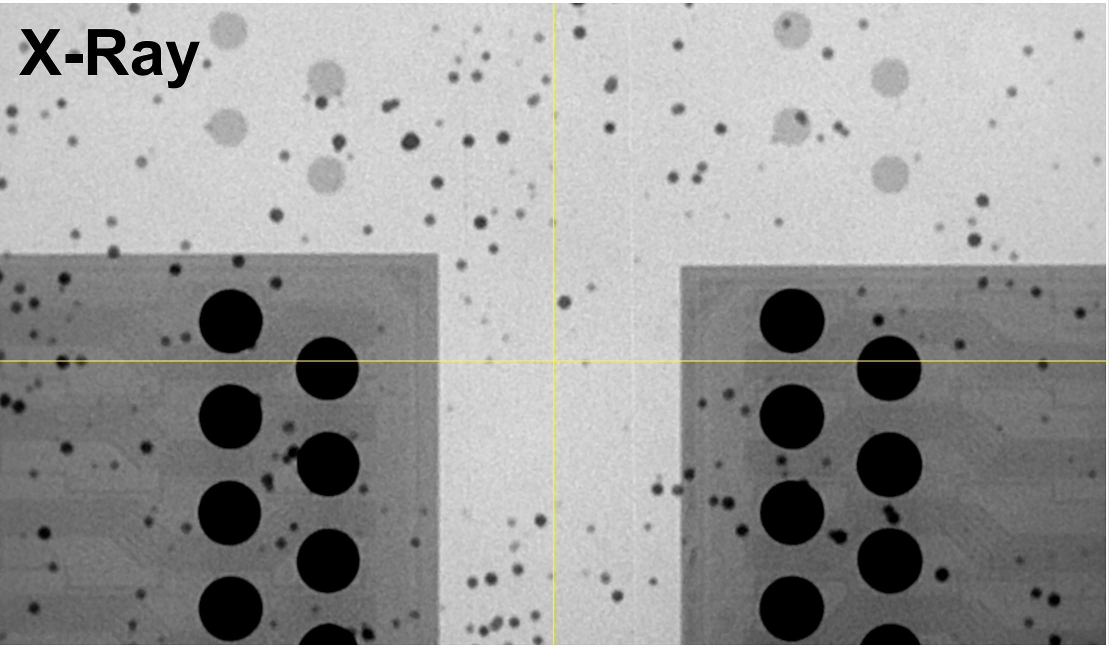


MaPSA Quality Assurance

Charge #2

- Need to ensure that the MaPSA passes quality requirements before installation on the PS module
- Bump bonds not visible after assembly
  - Visual inspection of prototype MaPSAs
    - X-Ray assembled MaPSAs
    - Ultrasounds measurements of bump bonds by Sonoscan


Ultrasound


X-Ray

MaPSA testing probe-card system

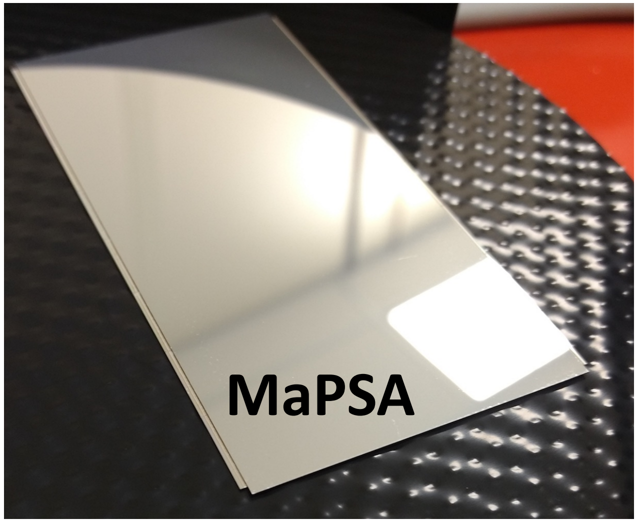
Charge #2

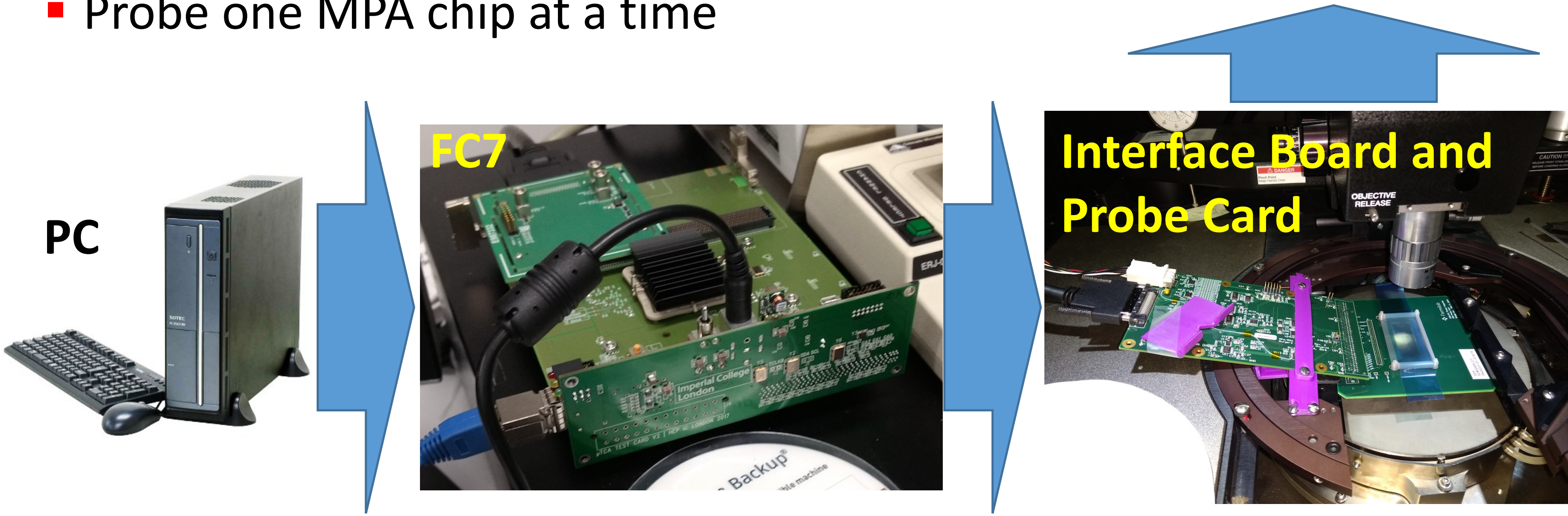
- Probe testing is our primary QA/QC tool for the MaPSA
  - As the MPA chips are bump bonded to the sensor and not on wafer, this is not a standard probe test
  - Probe card and stand and readout system are being prepared on a single MPA chip
    - Finalizing probe card and electrical tests for module qualification
      - Using pixel noise measurement as qualification of bump bond connectivity
  - Once QA/QC is finalized on single chip, generalize the process to 16 chip assembly
    - Distribute the system to vendors and production centers
- Assemblies to be tested for basic functionality
  - All MPA chips must be programmable and fully operation
  - Bump bond yield must be > 99%
  - IV performance of sensor up to 800V

MaPSA Probe System

Charge #2

- Details covered in B03 (Yuri Gershtein)
  - Probe card connects to MaPSA via probe pins
  - Probe card and interface board readout by FC7
  - FC7 connected to PC via IPbus
- Using early MaPSA prototypes to develop test stand
- Probe one MPA chip at a time

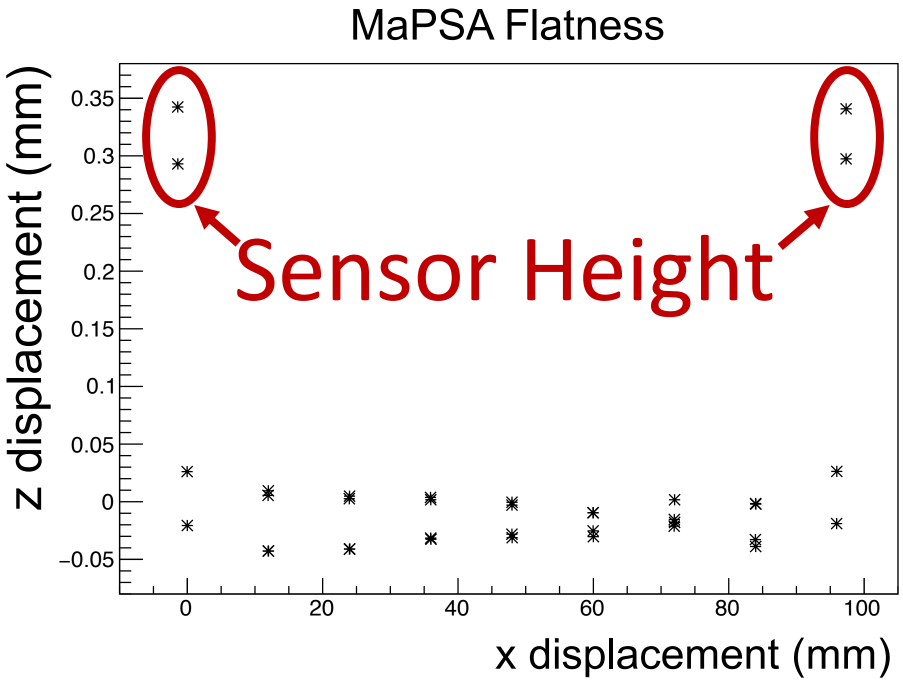




Setup MaPSA Quality

Charge #2

- First components received from AEMTec
  - Setup components received in mid-August
    - Not capable of performing electrical tests
  - Active components delivered in mid-October
- 3 production issues at vendor and sub-contractor
  - Difficulty removing dicing tape from MPA wafer (AEMTec)
  - Contamination from UBM process on sensor back plane (AEMTec)
  - Damage to MPA and sensor back plane from dicing (DISCO)
- Also suitable to commissioning MaPSA probe station
- Issues at vendor may not effect electrical performance

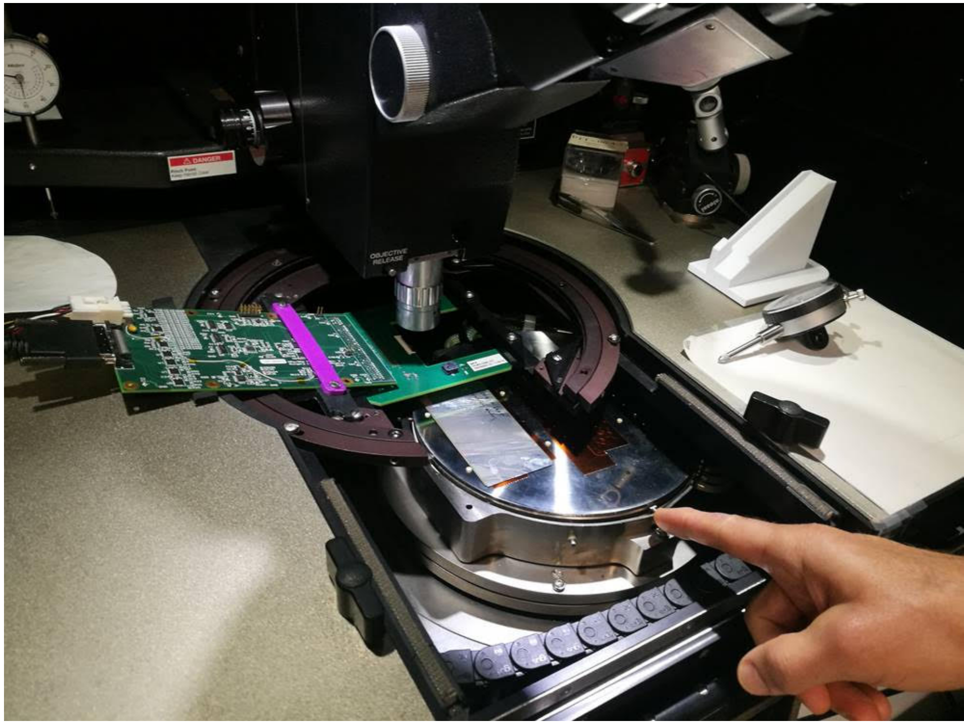


- Setup MaPSAs are sufficiently flat
  - Critical for probe testing
  - Commissioning of assembly sites

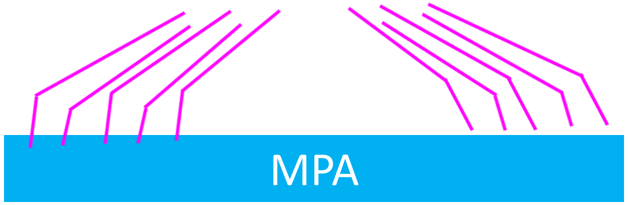
MaPSA Probe Card

Charge #2

- MPA chips bump bonded to sensor
- Unique issues with MaPSA assembly
- Probe card needles make contact with MPA wirebond pads
- MPA chip is readout through probe card and FC7
- Alignment of probe card is dependent on MaPSA geometry



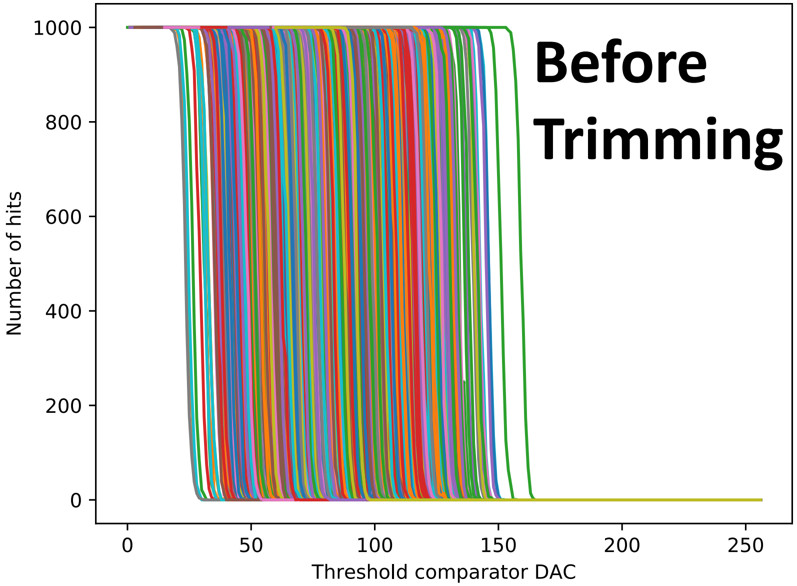
MaPSA Probe Station



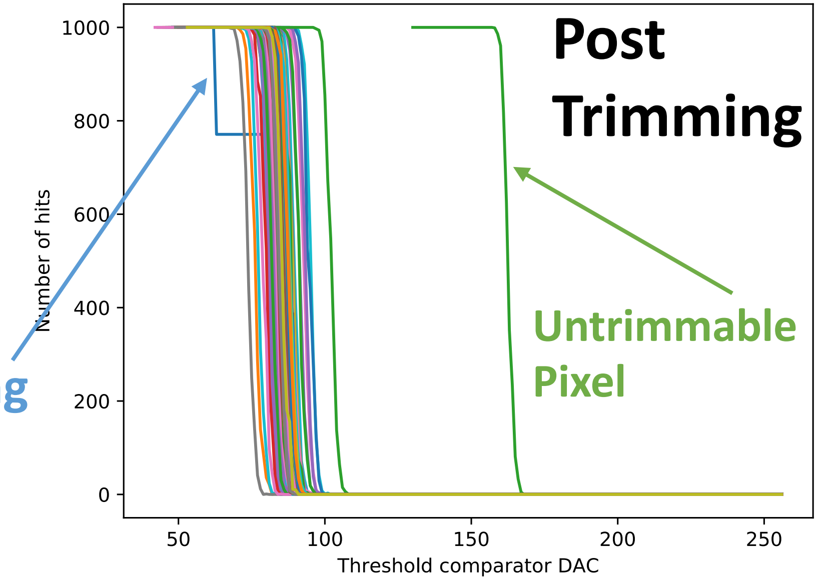
Electrical Tests with Probe Card

Charge #2

- Tests performed one chip at a time on a biased sensor
- Power on sequence: ~30 seconds
- Read/write register:
  - ~30 seconds to write and read out one random value to each register
  - ~30 minutes to write and read out every possible value for each register
- Initial s-curve: ~30 seconds
- Trimming: ~1 minute
- I-V curve: ~2 minutes
  - Measured only once per MaPSA



Before Trimming



Post Trimming

Untrimmable Pixel

Plotting Error

Project Organization

Institutional Responsibilities

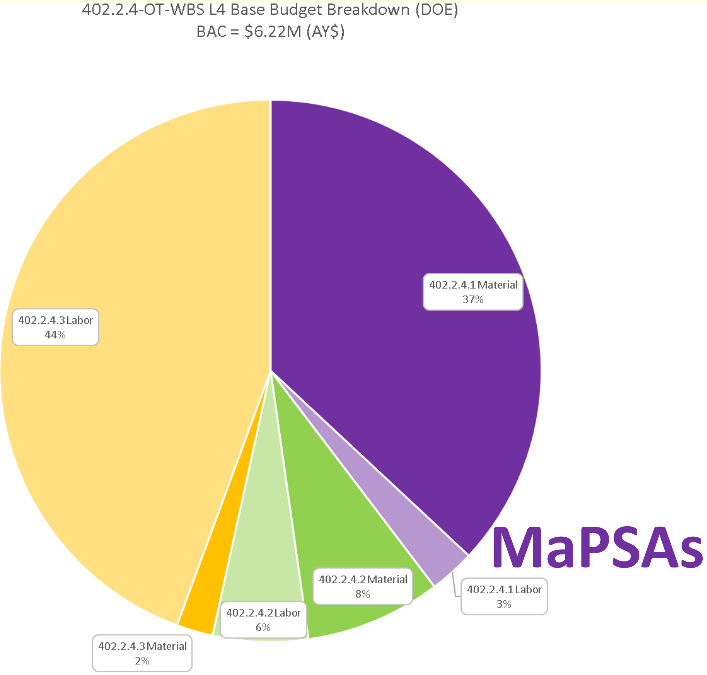
Charge #4,5

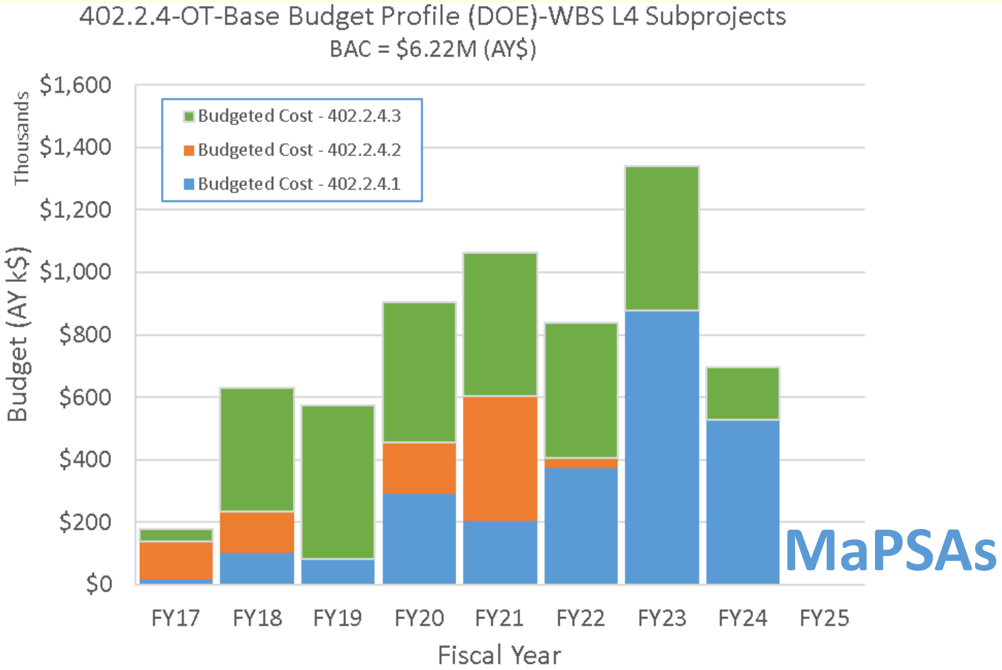
- Fermilab
  - Physicists: Doug Berry and Ron Lipton
  - Organize production and testing of the MaPSA sub-assemblies
  - MaPSA test system development
  - Vendor-based QA/QC validation
- Rutgers
  - Test system development (in separate WBS 402.2.4.2)

Cost

Charge #4

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-CD1-402.2.4.1 OT - Macro Pixel Sub-Assembly	2,162,244	4645	2.63	2,468,116	737,873	3,205,989
DOE-CD1-402.2.4.1.1 OT - MaPSA Prototypes	328,000	2025	1.15	486,140	136,020	622,159
DOE-CD1-402.2.4.1.2 OT - MaPSA Production	1,834,244	2620	1.48	1,981,976	601,853	2,583,829





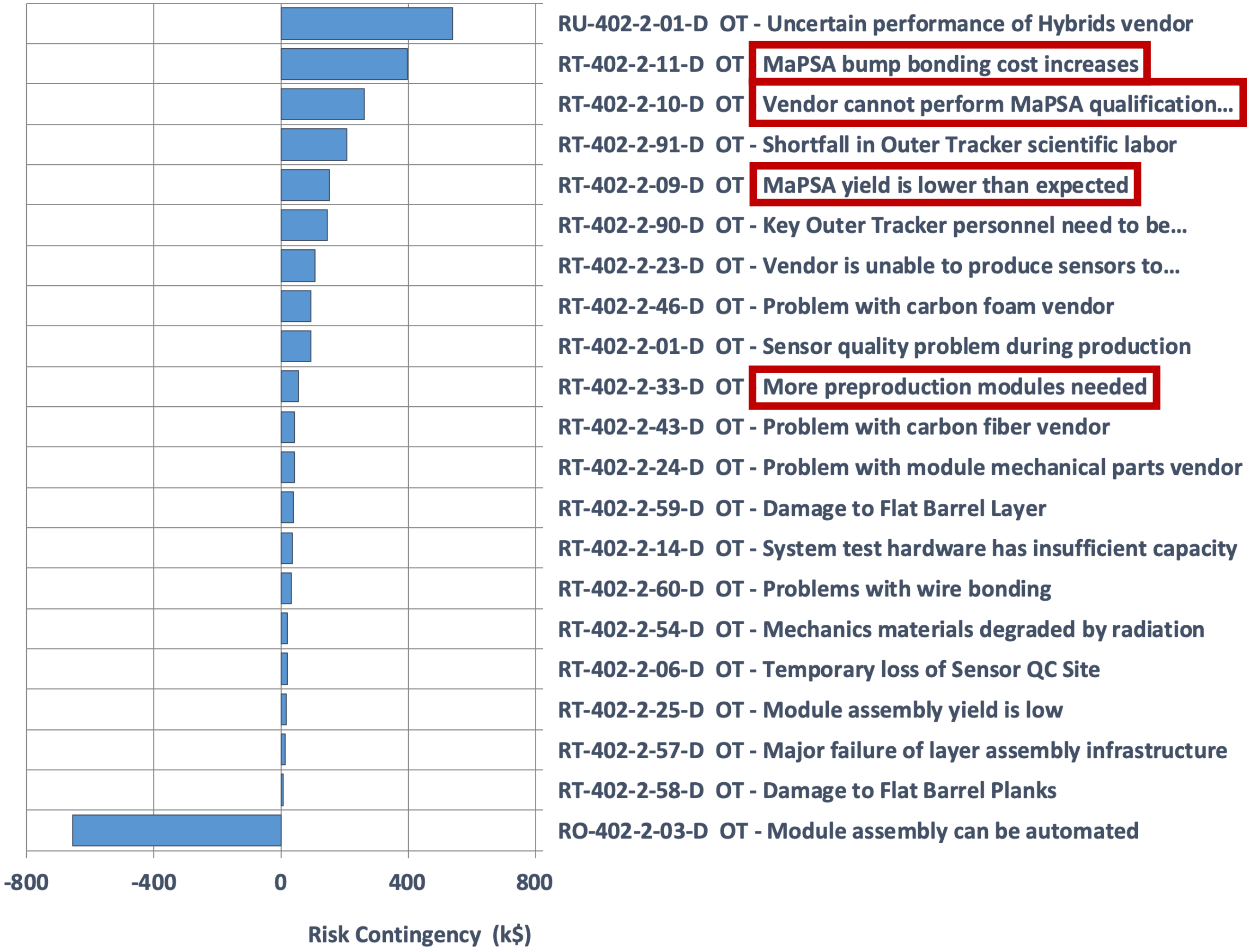
- The bulk of the production effort is covered by M&S at the assembly vendors.
- Added an Engineer to the MaPSA testing task

Risks

Charge #4

Risk Mitigation

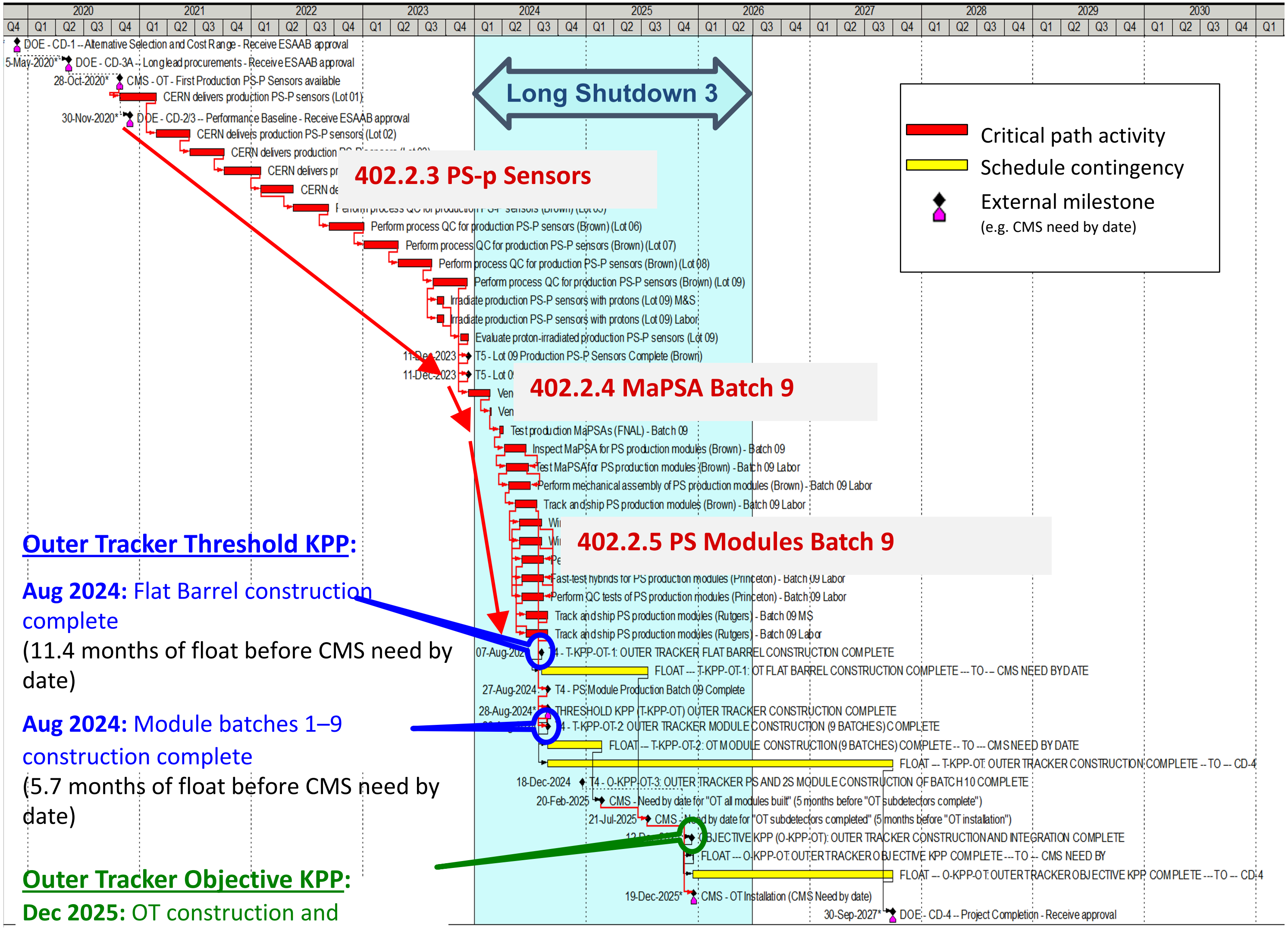
- Multiple vendors (2 or 3)
  - Value engineering
- Pitch is larger than previous detectors
  - Staggered 200 µm (283 µm effective)
  - Widely available from commercial vendors
- Sensors and MPAs are delivered pre-tested



Critical Path

Charge #3

- MaPSA are a critical component of the PS modules



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

Reviewer Question

- 4. Clarify MaPSA situation and risk factor - is there a mitigation or fall-back plan in case all vendors fails or go below expectations? Add this to the dedicated presentation.
- We believe there is only a very small probability that all vendors we are vetting will fail to deliver an acceptable product. Technically, the bump bonding of the MaPSA is less challenging than previous projects we have experience with, such as the original FPIX and Phase1 FPIX modules. The UBM and bump placement R&D is done and these vendors are secure (HPK and StatsChipPak). The flip chip assembly is not technically challenging, but the form factor is unusual for most vendors. Initial dummy parts we received from the first vendor show good quality of the bumps themselves in terms of uniformity of size and placement. The actual assembly did not cause the delay in the last round. This was caused by the vendor working through problems serially (picking parts off dicing tape, slow delivery of waffle packs, communication with the dicing vendor). The actual module assembly went smoothly and took only a few days. HPK assembly is delayed because they were waiting for parts from the first vendor.
- We have had acceptable setup parts from two vendors. We are now starting to test the first fully active modules. An outstanding issue is the transfer of MaPSA probe testing from Fermilab to a commercial testing vendor, which had to wait until active parts were available.
- Additional risk mitigation can consist of probe testing of the bump bonded modules at the vendor, allowing for replacements of individual, faulty chips.
- If the best vendors do deliver acceptable parts, but at a slightly lower quality than our specifications for example with respect to fraction of functional pixels, we would have to evaluate the impact on physics performance through simulation. However, even having a factor of two more bad bumps than specified for example, will have only a minimal, if not negligible impact on tracking efficiency and resolution. We do have a risk that covers lower performance of MaPSA (RT-402-2-09-D) with a probability*impact of $76k and 0 months.

ES&H

Charge #6

- ES&H issues for this project
  - High voltage
    - All current limited applications
  - Hazardous waste generation
    - Lead-free bumps specified
  - Epoxies (at vendors)
- To mitigate these hazards, follow local laboratory safety procedures at each institution

Summary

Summary

- The MaPSA probe card setup is being commissioned

- Early MaPSAs received from vendors
  - Round 1 is being completed
  - Round 2 vendors have been selected

- Currently commissioning the full size MaPSA setup
  - Perform on-wafer measurements of MPA ASICs before dicing
  - Measure the MPA chip performance after bump bonding
  - Measure IV of sensor after bump bonding

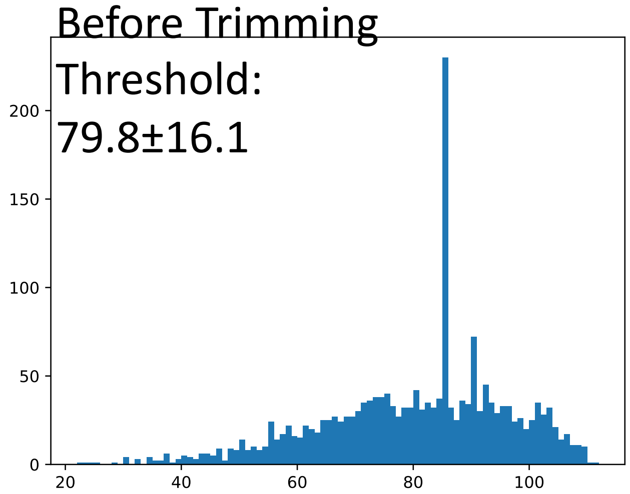
- QA/QC is being validated
  - Process will be replicated at the vendors for quick quality control tests

Backup

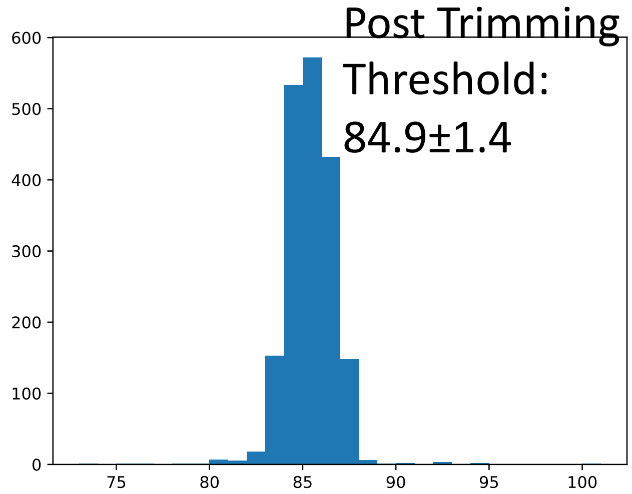
Trimming and SCurve Measurement

Charge #2

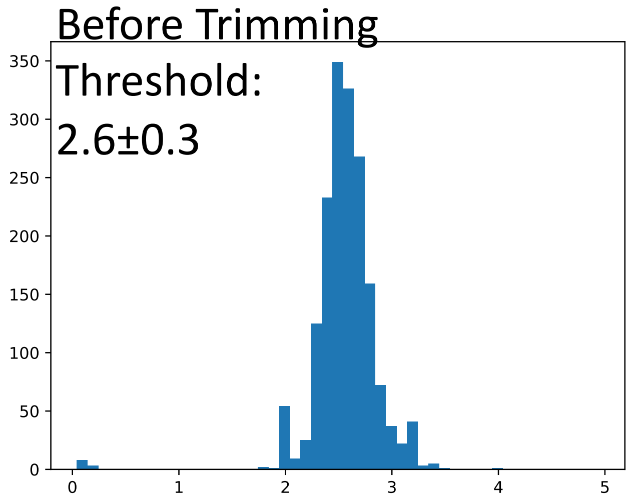
- Calibrate system using injected charge
- Trimming is performed by looking at scanning the threshold comparator THR for a fixed calibration pulse


Before Trimming

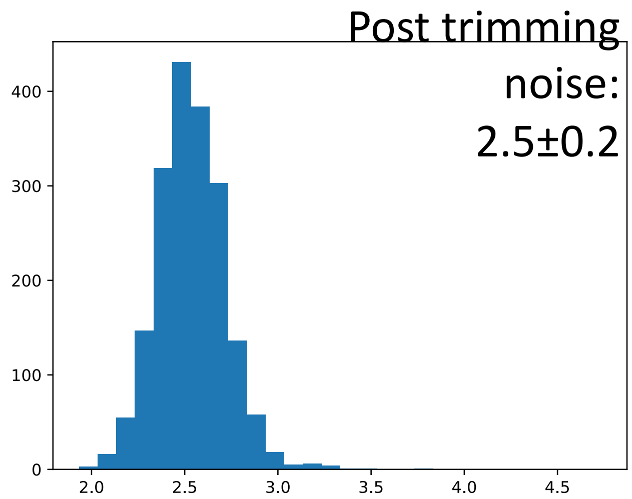
Threshold: 79.8±16.1


Post Trimming

Threshold: 84.9±1.4

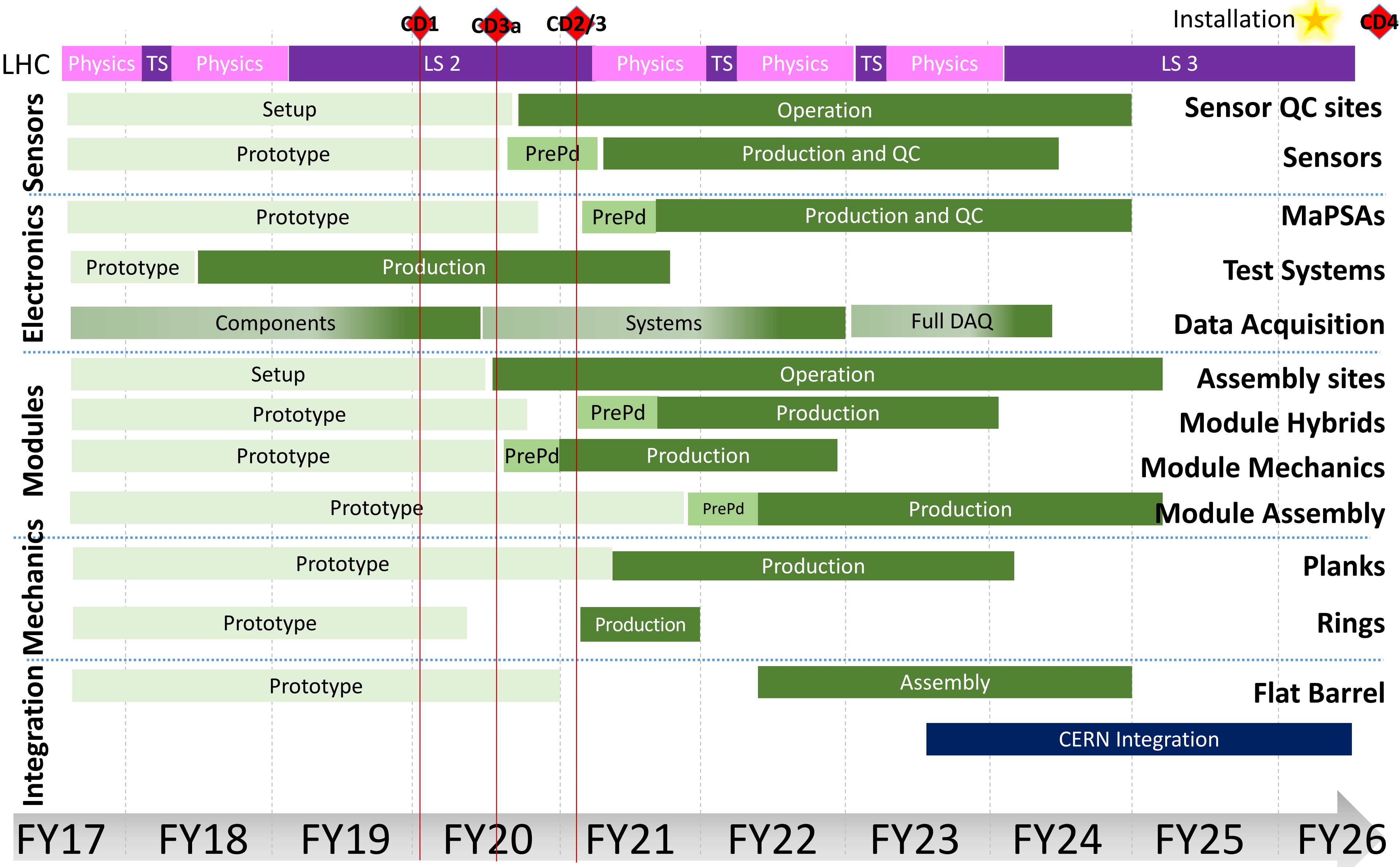

Before Trimming

Threshold: 2.6±0.3


Post trimming

noise: 2.5±0.2

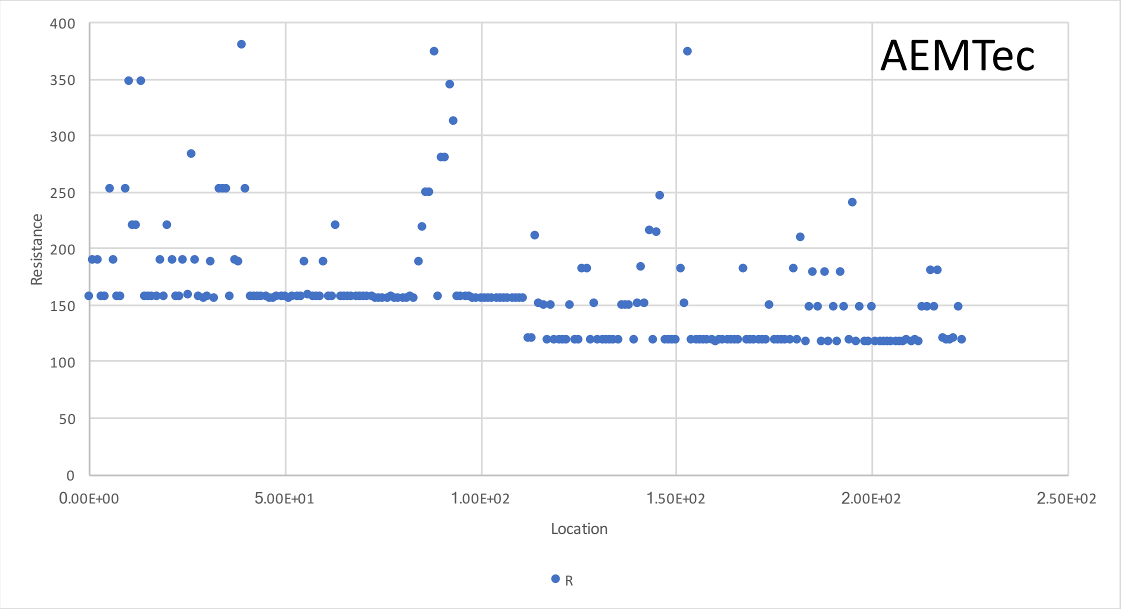
402.2 OT Cartoon Schedule

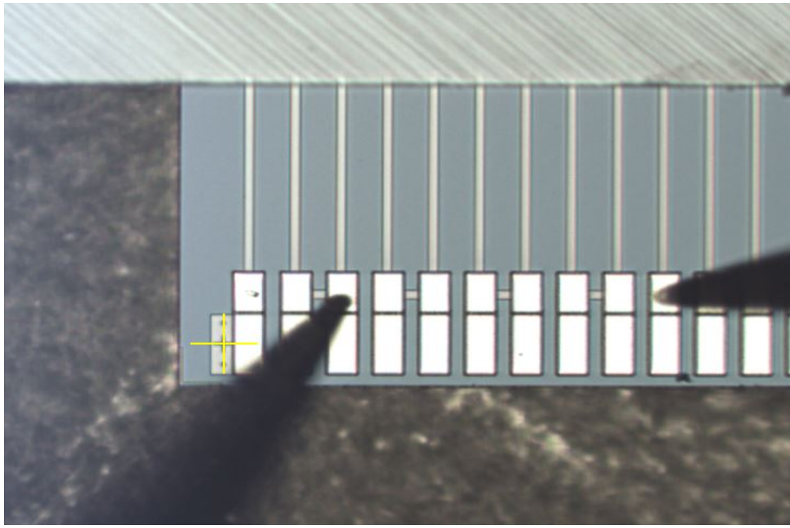


Dummy MaPSA QA/QC

Charge #2

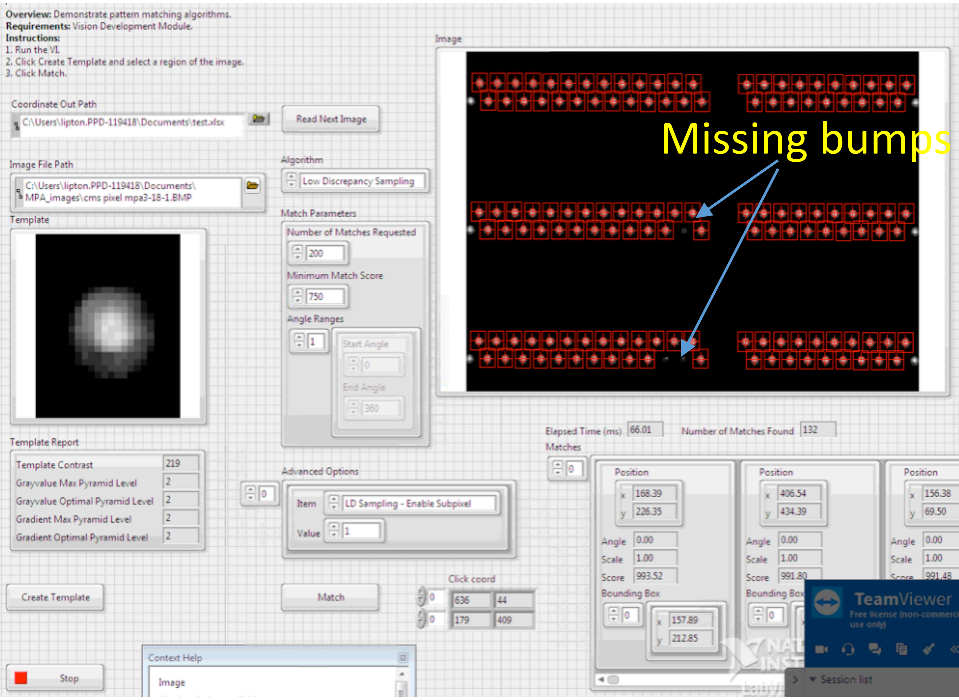
- 4 Serpentines tested in series
- Expected resistance ~ 180-200 ohms (varies with wafer)
  - Missing bump corresponds to 40—50 ohms
- First and last 8 MPA different # of strings per measurement – different baselines





AEMTec Bump Quality

- The wafers from AEMTec are only partially bumped
  - Only about 10% of the MPA chips are fully bumped (156 good chips within 22 wafers: full yield = 10%)
  - We received maps for the 6 wafers that have fully bumped chips
  - Partially bumped chips used for dummy MaPSA
- Used the OGP (optical CMM) to photograph the wafer surfaces to survey the bumps
  - Labview vision program to locate good and missing bumps



Missing bumps

Overview: Demonstrate pattern matching algorithms.
Requirements: Vision Development Module.
Instructions:
1. Run the VI.
2. Click Create Template and select a region of the image.
3. Click Match.

Coordinate Out Path: C:\Users\lipton.PPD-119418\Documents\test.xlsx

Image File Path: C:\Users\lipton.PPD-119418\Documents\MPA_images\cms pixel mpa3-18-1.BMP

Algorithm: Low Discrepancy Sampling

Match Parameters
Number of Matches Requested: 200
Minimum Match Score: 750
Angle Ranges: 1
Start Angle: 0
End Angle: 360

Template Report

Template Contrast	219
Grayvalue Max Pyramid Level	2
Grayvalue Optimal Pyramid Level	2
Gradient Max Pyramid Level	2
Gradient Optimal Pyramid Level	2

Advanced Options: 0
Item: LD Sampling - Enable Subpixel
Value: 1

Click coord: 0 0 | 636 44 | 179 409

Elapsed Time (ms): 66.01
Number of Matches Found: 132

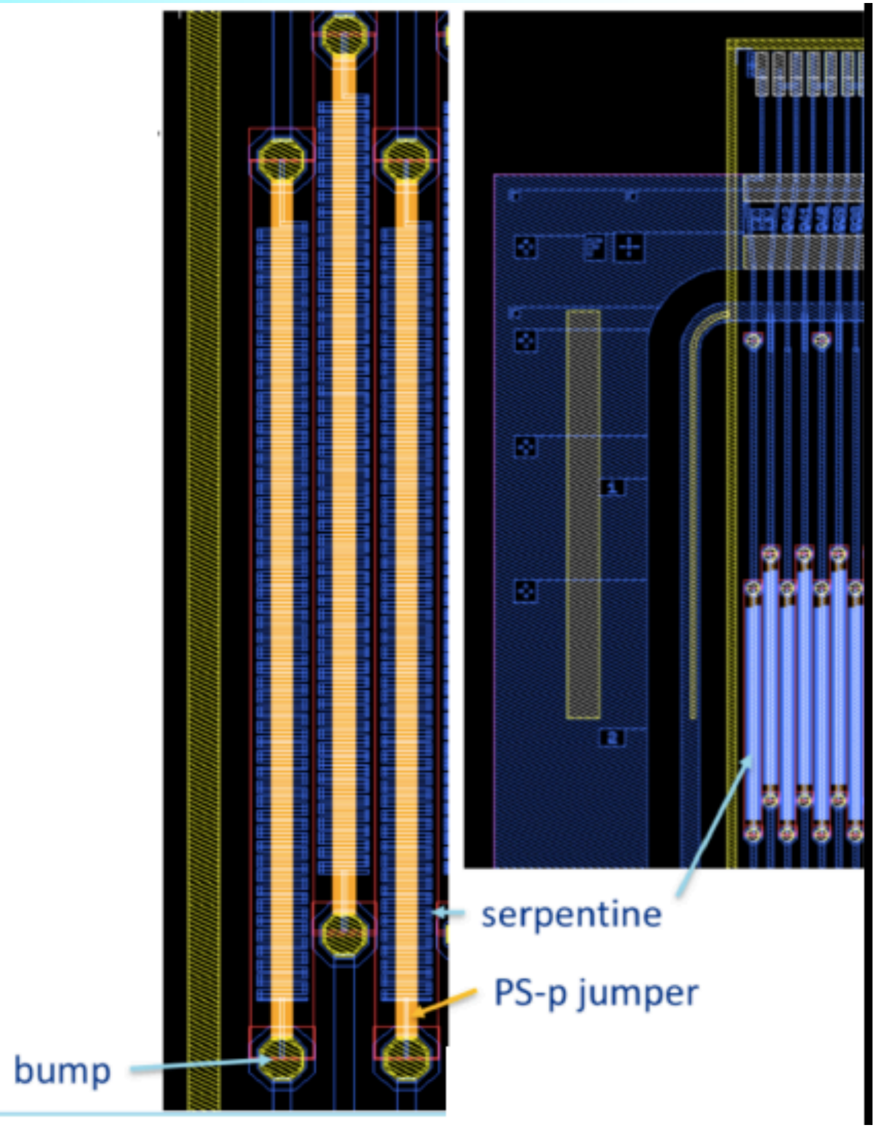
Matches: 0

	Match 1	Match 2	Match 3
Position x	168.39	406.54	156.38
Position y	226.35	434.39	69.50
Angle	0.00	0.00	0.00
Scale	1.00	1.00	1.00
Score	993.52	991.80	991.48
Bounding Box	0	0	
x	157.89		
y	212.85		

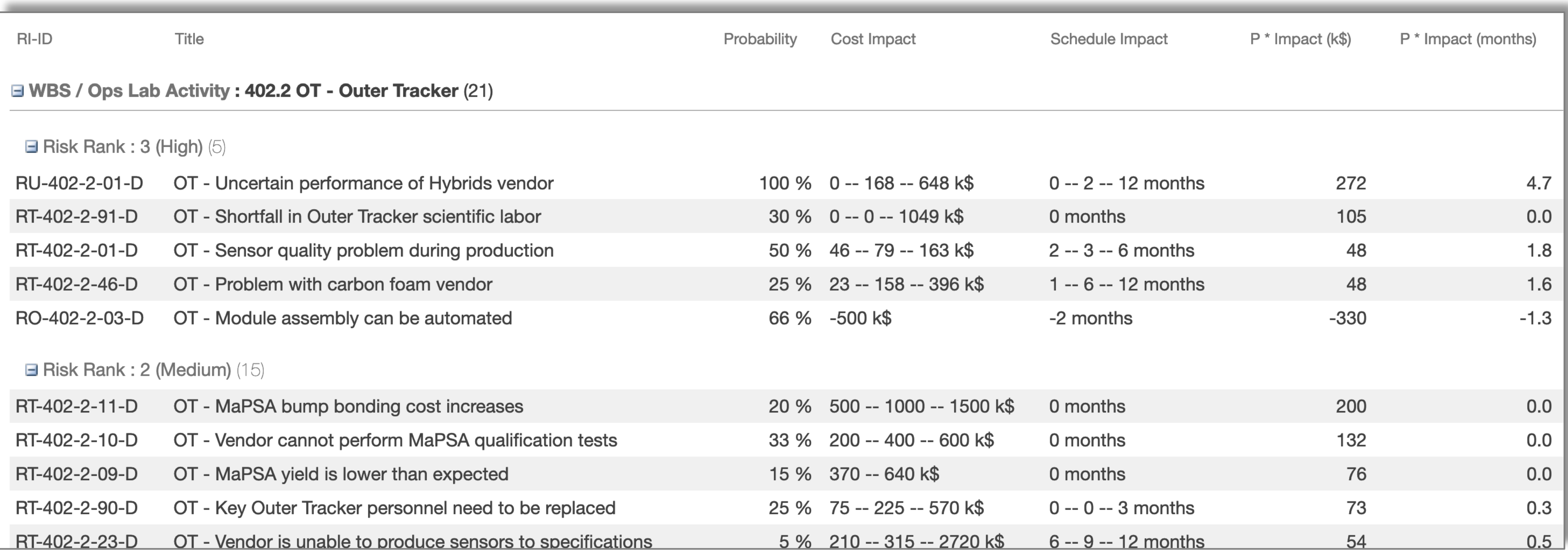
Dummy MaPSA QA/QC

Charge #2

- If we see an open in the daisy chain, it is not clear whether it is due to a missing bump or a flaw in the dummy wafer lithography
  - We saw examples of flaws and scratches in the initial batch from RTI/Princeton
- To verify the quality of the MPA before bumping we added a set of serpentine resistors to the MPA layout
  - Each serpentine resistor is about 40 ohms
  - They are shorted by the PS-p bumped part of the daisy chain
  - Normal jumpers are about 36x lower ~1 ohm
  - Each good chain are about 12-20 ohms



Risk Table



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

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