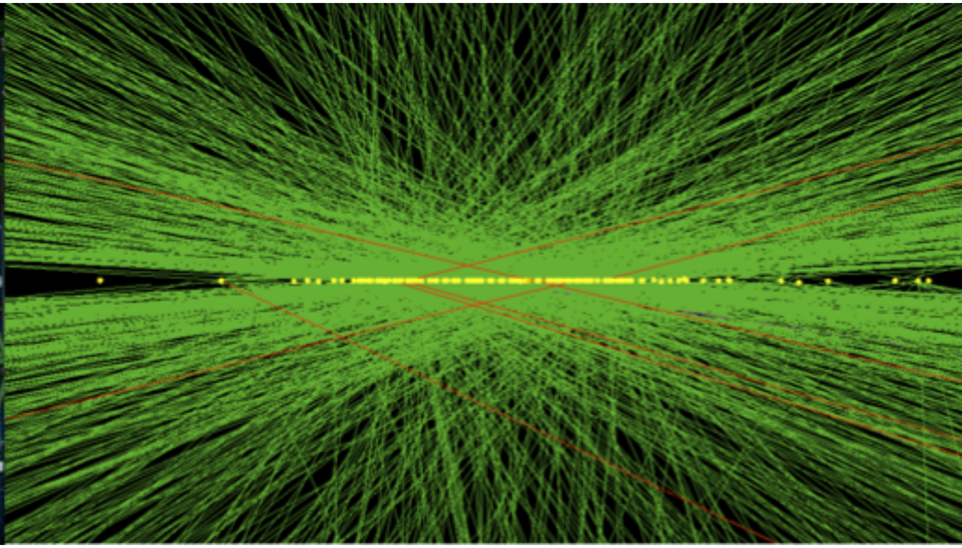
B03 - 402.2.4 OT Electronics

Anadi Canepa (Fermilab), Yuri Gershtein (Rutgers)

HL LHC CMS Detector Upgrade CD-1 Review

October 23rd, 2019



Outline

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

Biographical Sketch

Charge #5

- Brief biographical sketch for the L3 managers
  - Anadi Canepa
    - Purdue 01-06 (Grad Student)
      - CDF Silicon Detectors (SVXII, ISL, L00), Run2b Sensor characterization
    - UPenn 06-08 (Postdoc)
      - CDF L2 Calorimeter Trigger Upgrade
    - TRIUMF 08-15 (Scientist)
      - ATLAS Phase 1 Upgrade, ATLAS Online DQM
    - FNAL 15-present (Scientist)
      - CMS Outer Tracker, System Test Co-convener for iCMS
  - Yuri Gershtein
    - PhD @ ITEP, Moscow (1992-1996)
      - GEM (SSC) muon system
      - CMS Quartz Fiber calorimetry R&D
    - Staff @ ITEP, Moscow (1997-1999)
      - DØ upgrade: muon system, track trigger
    - PostDoc @ Brown (1999-2004)
      - DØ silicon detector
    - Faculty @ Florida State (2004-2008)
      - CMS ECAL
    - Faculty @ Rutgers (2008 -)
      - CMS Phase 2 upgrades, System Test Co-convener for iCMS

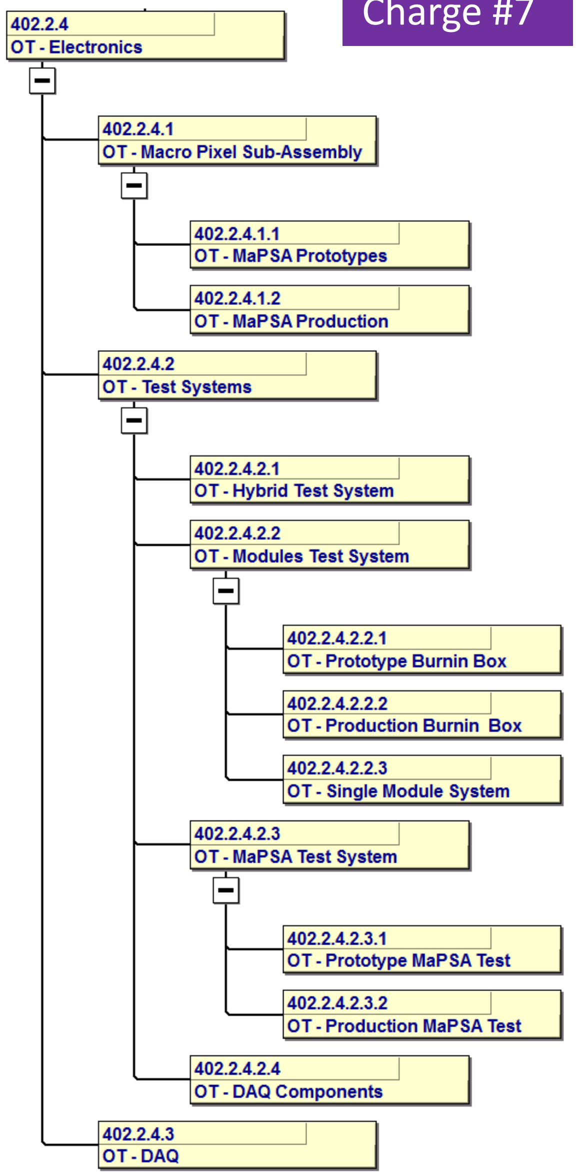
Scope

402.2.4 Electronics WBS Structure

Charge #7

Electronics includes:

- MaPSA assembly for entire OT
  - L4 managers: Ron Lipton and Doug Berry (FNAL)
- Test Systems for hybrids, MaPSAs, modules, module burn-in, larger structures
  - L4 manager: Eva Halkiadakis (Rutgers)
- DAQ development for test systems; firmware and software development
  - L4 manager: Lorenzo Uplegger (FNAL)



Deliverables for 402.2.4 Electronics

Charge #2

- Macro Pixel Sub-Assembly (MaPSA)
  - Produce for “dummy” prototypes
  - Produce MaPSA for the entire OT

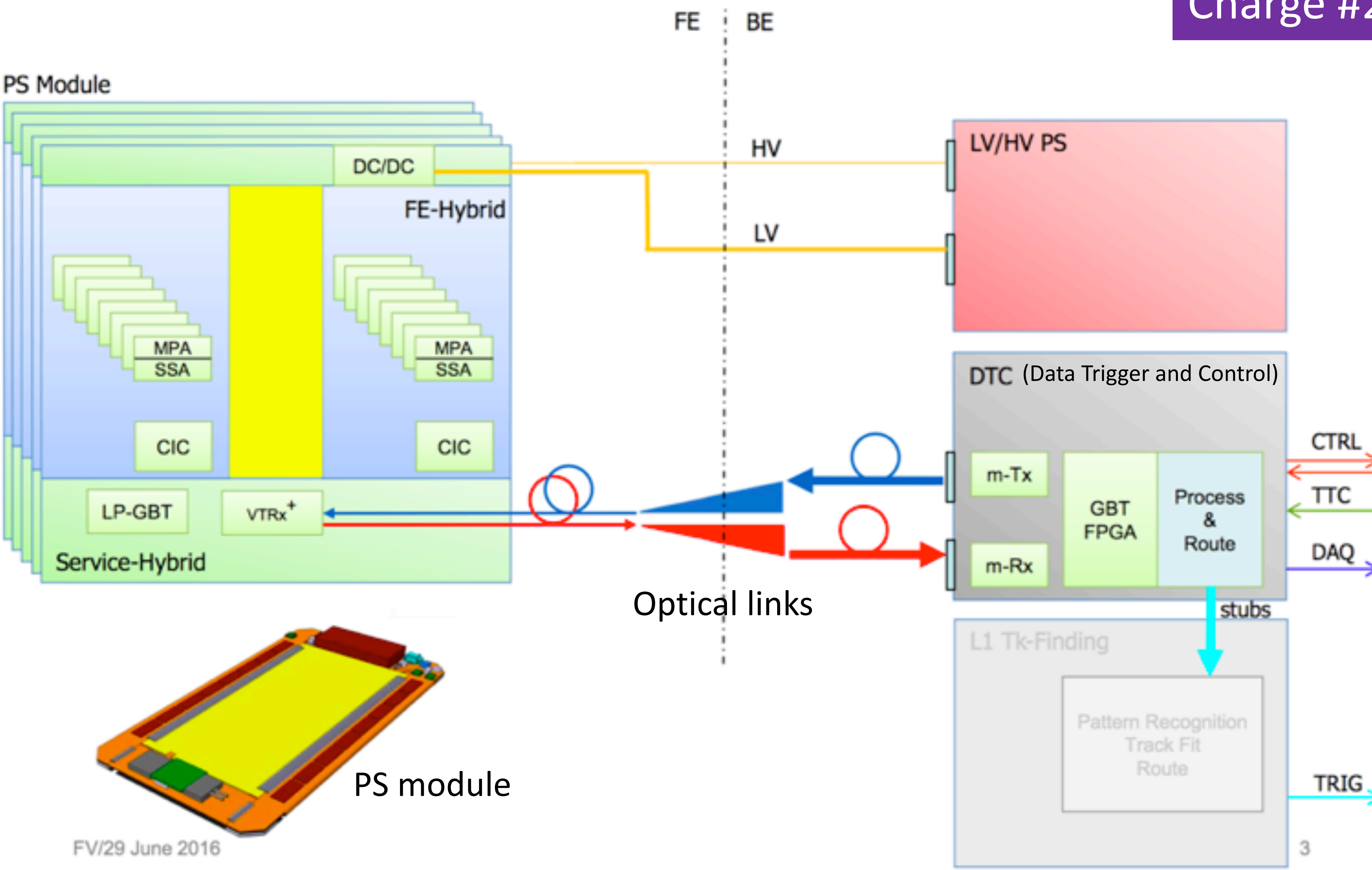
> today covered in a dedicated talk

- Test Systems
  - Design responsibilities for test systems shared internationally
  - Procurement for US-CMS needs only
    - **Hybrids:** purchase and assemble test system
    - **Single Modules:** purchase readout boards for single module test systems
    - **Multi-Modules:** design burn-in boxes, prototype and production; purchase boards and crates
    - **MaPSAs:** design and produce MaPSA probe card and interface board, prototype and production
    - **System Tests:** purchase DTC prototype and ATCA/AMC13 system
- DAQ
  - Develop and maintain OTSDAQ for testing on test benches and in test beams for MaPSAs, single modules, module burn-in and larger systems of modules; evolve into DAQ for OT in CMS
  - Develop and maintain DTC firmware and middleware (MW) software for FE and BE interfaces

Conceptual Design

OT Readout Components

Charge #2



Design Considerations for Electronics

Charge #2

- Test Systems
  - Quick and reliable way for QC of MaPSAs, hybrids and modules
  - Cold tests for 10-module burn-in at -33C and long term stability tests
  - Operate a system of large number of modules mounted on planks at FNAL
- DAQ
  - Software (OTSDAQ, Middleware): capability to provide multi module synchronization, compatibility with OT DB, module calibrations and CMS DAQ
  - Firmware (DTC): firmware and software compatibility with to-be designed hardware

R&D Achieved – 402.2.4.2 Test Systems

Charge #2

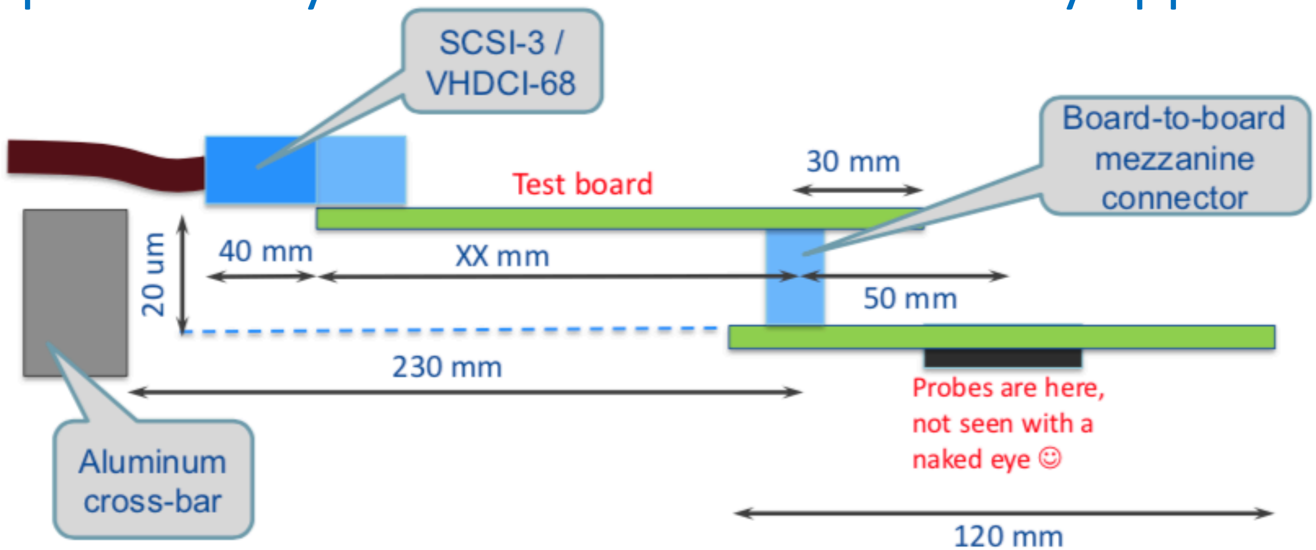
- While the primary goal of this R&D is to make sure CMS has appropriate Test Systems for QA and QC during the production, the prototypes of these systems are used by US CMS and iCMS to validate all other design elements
  - Sensors
  - ASICs
  - Hybrids
  - Modules
  - Large integrated structures

The tests provided important feedback to the designs: this is a large part of US CMS intellectual contribution to the OT

R&D Achieved – 402.2.4.2 Test Systems

Charge #2

- MaPSA Test System
  - Goal: verify performance of the MaPSA before it's committed to a module
  - Challenge: dense packaging, 320 MHz SLVS clock and data lines
  - Elements:
    - 117-needle probe card to connect to an MPA chip
    - Connected to an interface board, which translates signal voltages, measures voltages and currents and handles I^2C communications
    - Connected via VHDCI cable to an FPGA board (FC7)
  - The design proved very versatile and is used in many applications in CMS



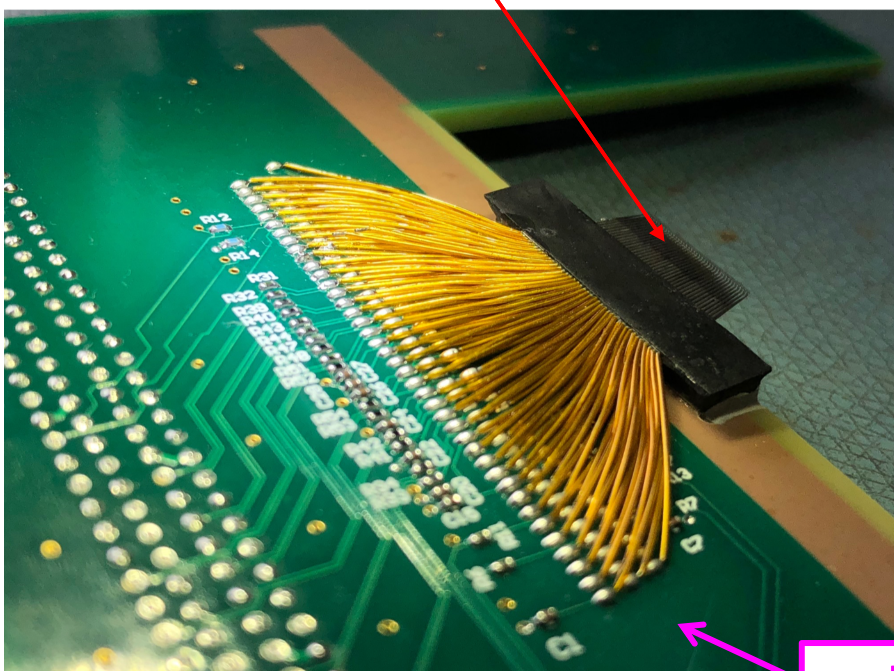
R&D Achieved – 402.2.4.2 Test Systems

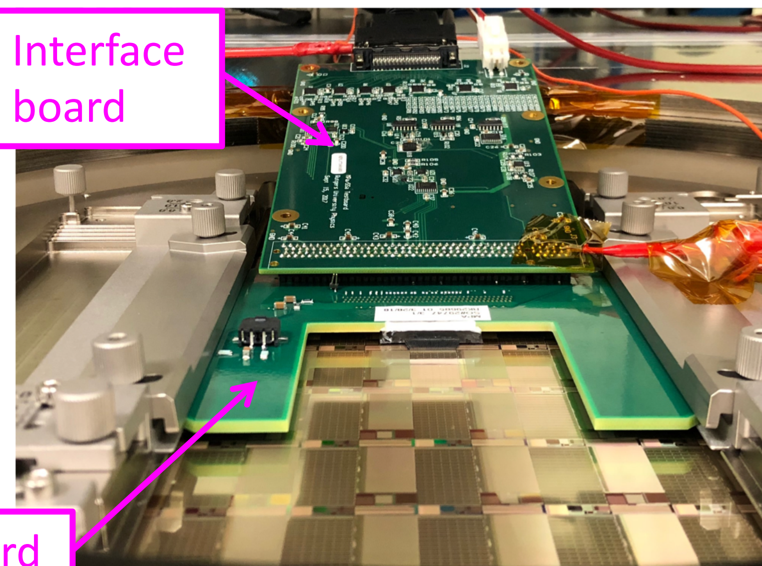
Charge #2

- Probe Card lowers to contact wire-bonding pads on MPA
- Probe Station programmed with wafer map to facilitate moving from MPA to MPA

Probe card needles

Probe Station has image recognition for easy alignment





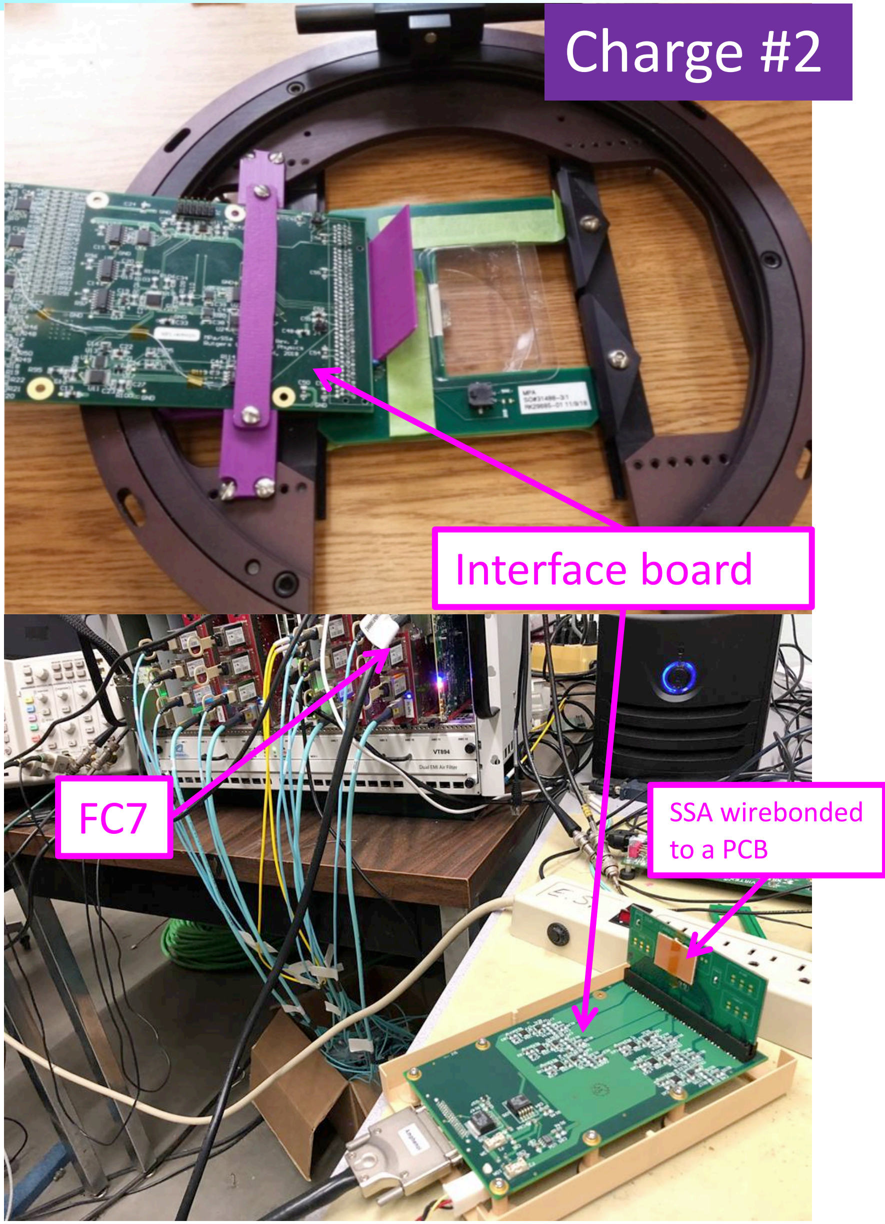
Interface board

probe card

R&D Achieved – 402.2.4.2 Test Systems

Charge #2

- MaPSA Test System
  - MaPSAlite probe card designed, built and tested successfully
  - Prototype MaPSA interface board (v1 and v2) designed, built and tested successfully
    - Has been used as the test system for MPA and SSA evaluation
    - Now is the system that is used for on the wafer good die tests at CERN and (in the future) at the vendor
    - Test beams (baby-MaPSA in 2018, 2xSSA in Jan 2020). PS FE hybrids will be available in late 2020.
  - MaPSA production interface board has been designed and procured. Testing now.



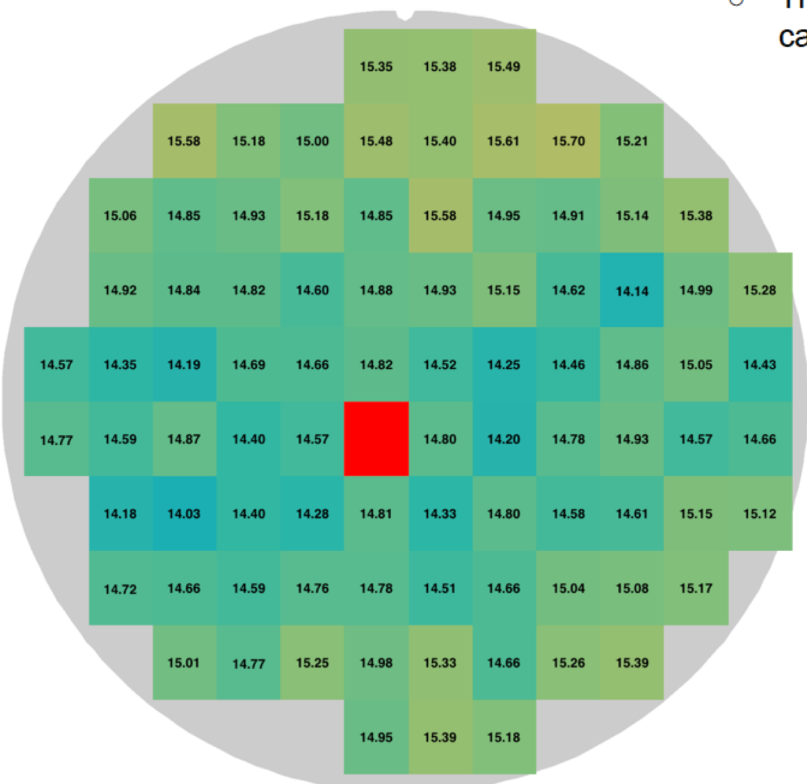
R&D Achieved – 402.2.4.2 Test Systems

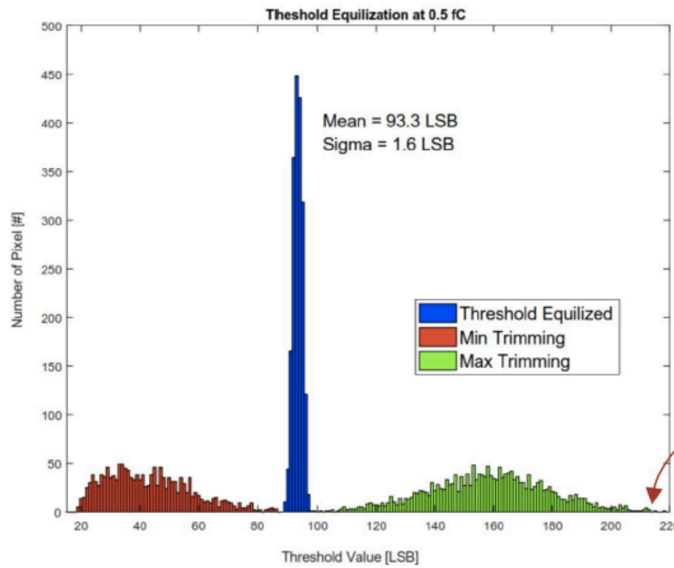
Charge #2

▪ MaPSA Test System: applied to good die tests

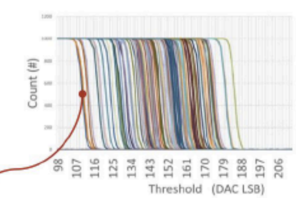
- Individual MPAs also tested. No major issues reported.
  - Trimming of Threshold DAC based on injected charge shows good ability to calibrate the entire chip.

2st Wafer





Bin *x* counts how many pixels show the mid-point of the Scurve at a the threshold value = *x*



S-Curve Trimming Spread @ 0.5 fC: $\pm$1.6 Threshold DAC LSB
$\pm$ 0.55 Trimming DAC LSB

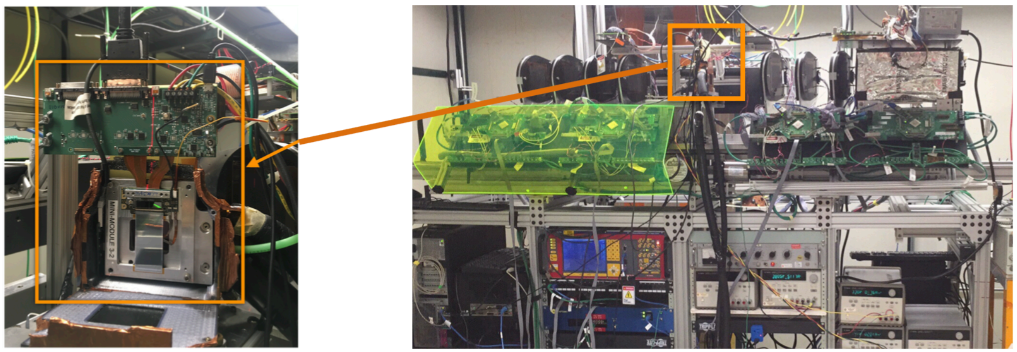
Average value of calibration on each chip, **red** chips failed to calibrate

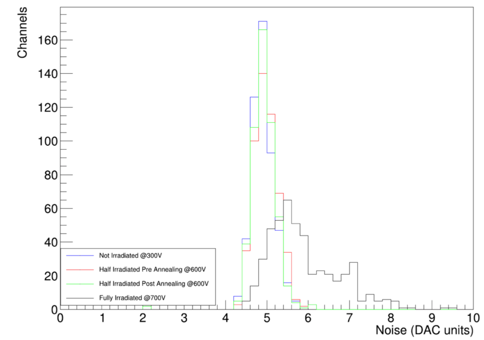
problem uncovered with outsourced memory circuit, a fix is now available

R&D Achieved – 402.2.4.2 Test Systems

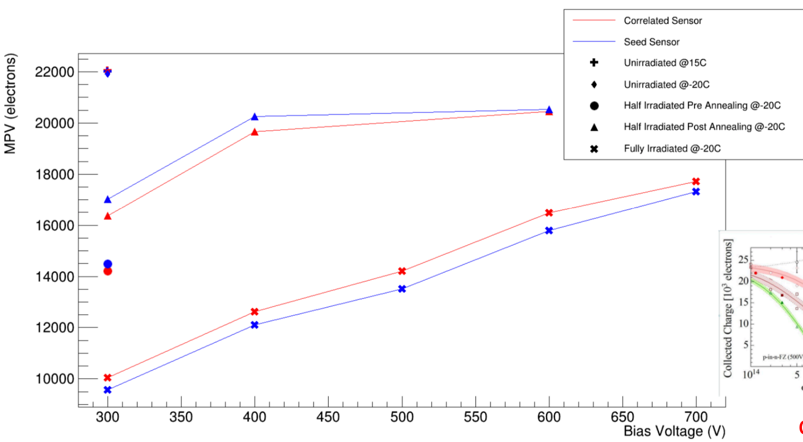
Charge #2

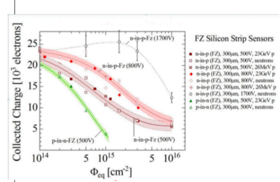
- 2S Module Test System in action



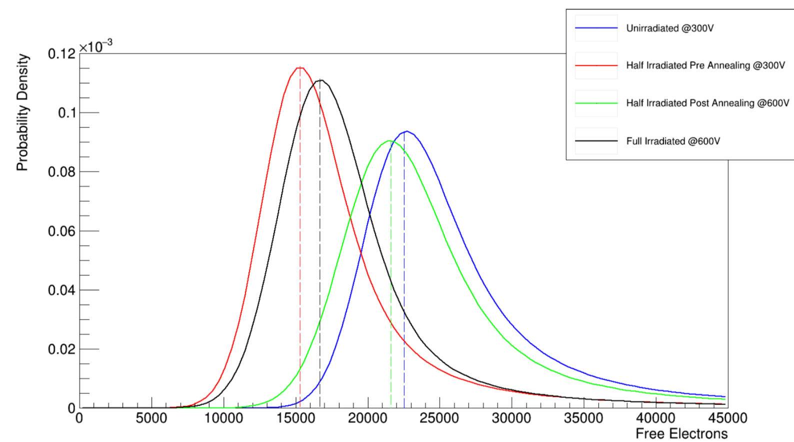


Noise and signal vs irradiation





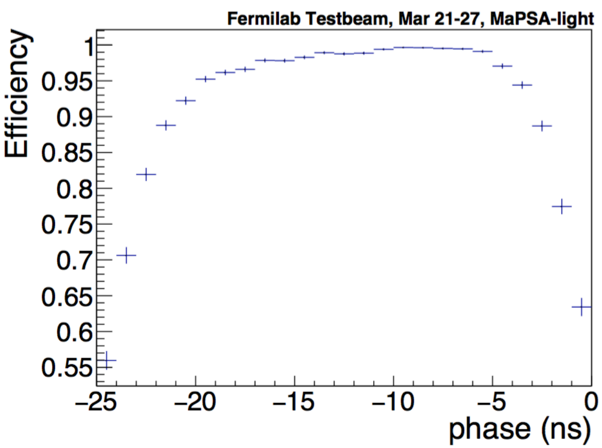
consistent with literature

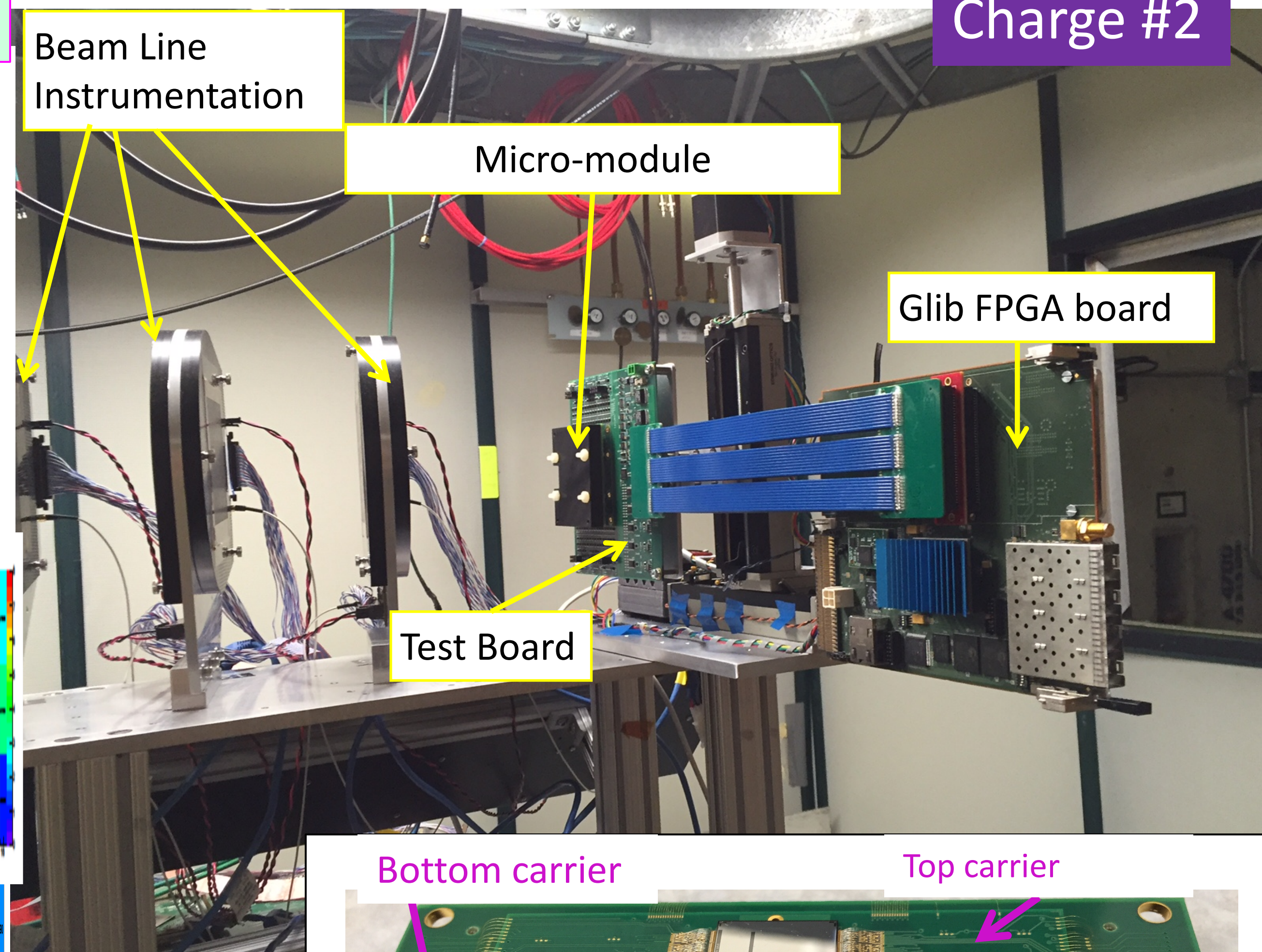


R&D Achieved – 402.2.4.2 Test Systems

Charge #2

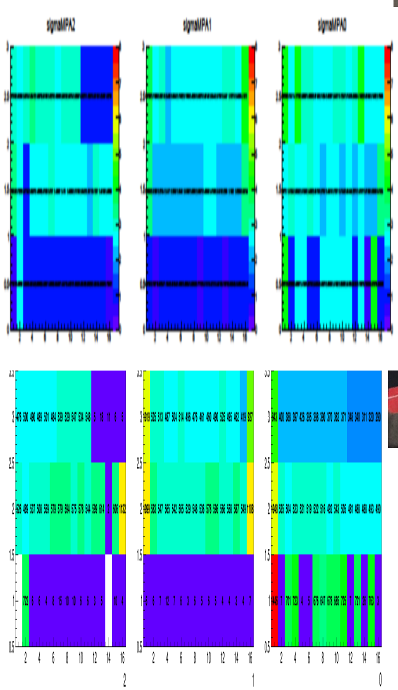
FE timing is validated



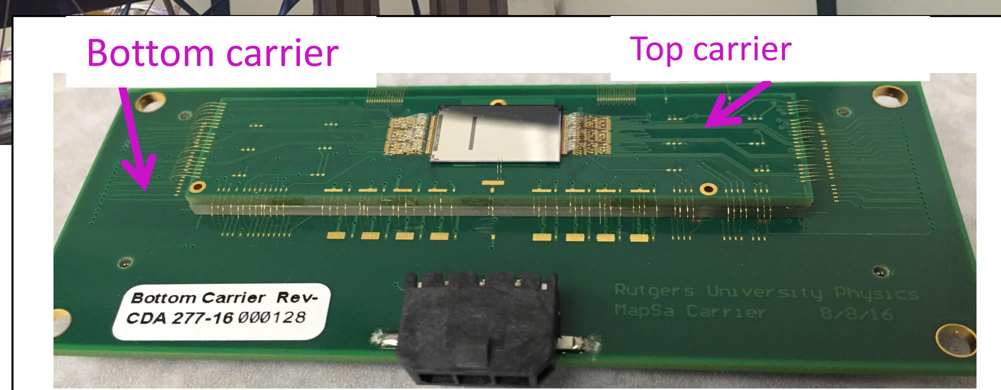


hits

noise



Bad bumps can be found using measured noice



R&D Achieved – 402.2.4.2 Test Systems

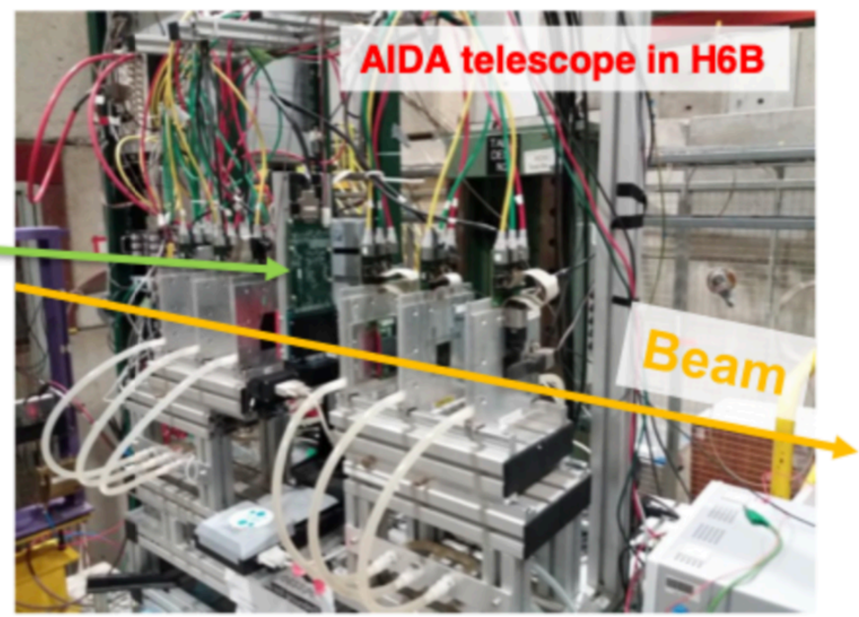
Charge #2

Baby MaPSA beam tests (1/2)

- CERN H6 test beam with AIDA telescope
- Baby MaPSA devices gold-stud-bonded at KIT
- Electronics and DAQ from the US
- Firmware help from CERN and DESY

Same interface board as used for probe station

Baby MaPSA

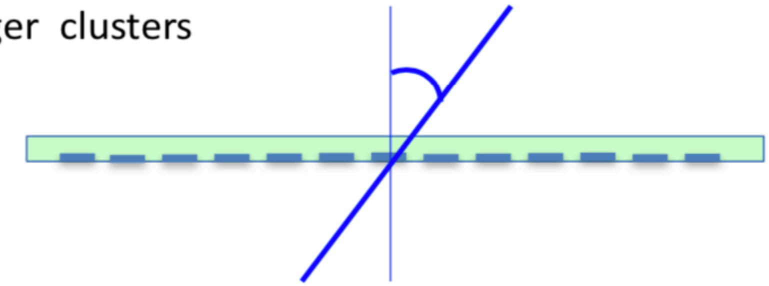


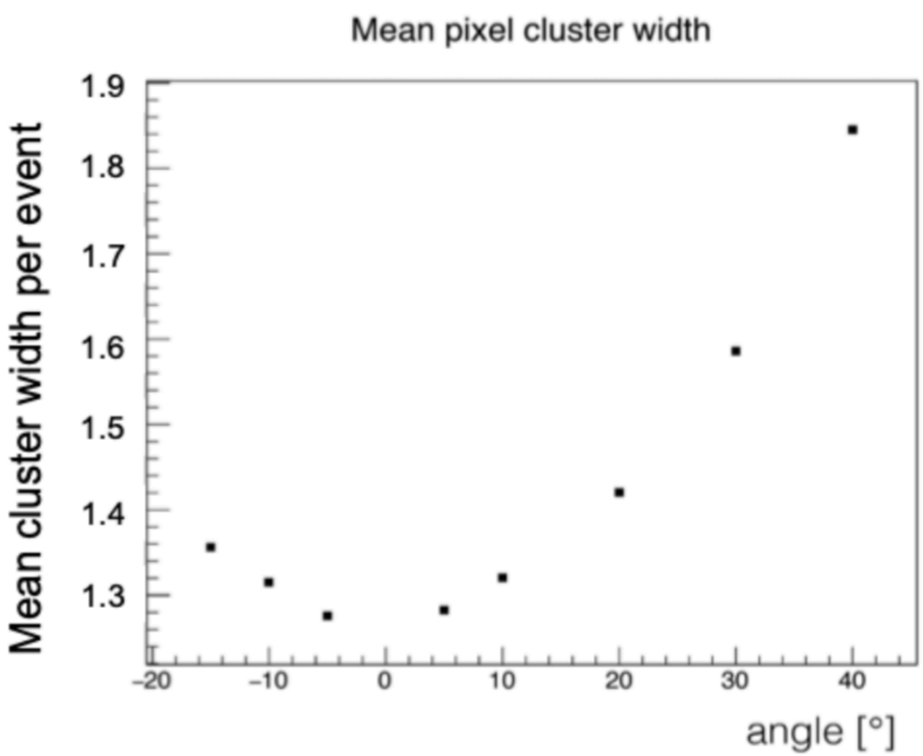
R&D Achieved – 402.2.4.2 Test Systems

Charge #2

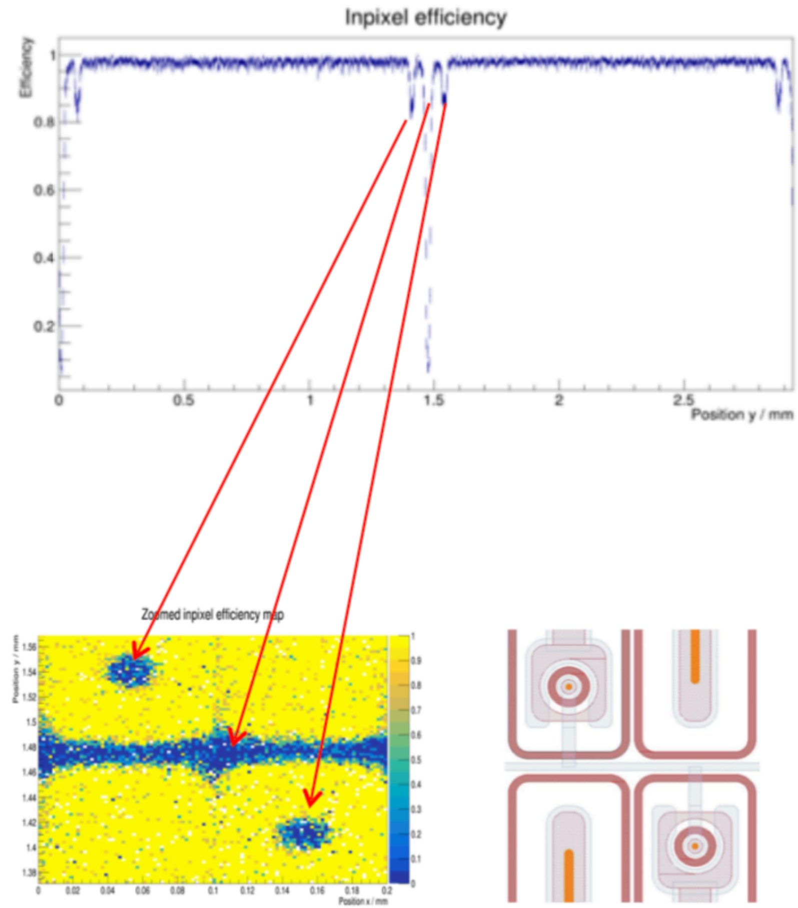
Baby MaPSA beam tests (2/2)

Angular scan: longer path through the sensor leads to larger clusters



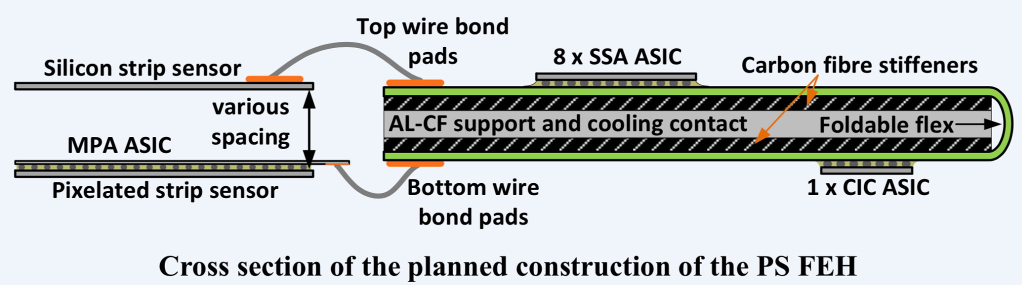


Hit efficiency >98%, with small expected inefficiencies due to bias rail and bias punchthrough

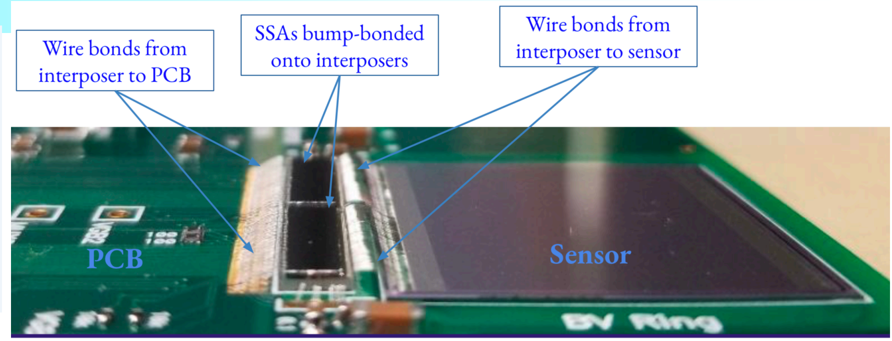


Charge #2

R&D Achieved – 402.2.4.2 Test Systems

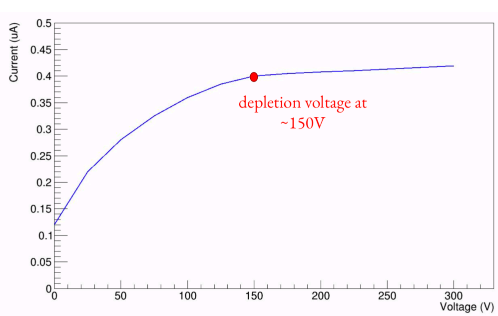


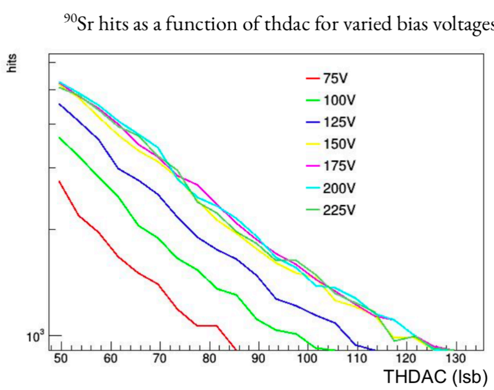
Cross section of the planned construction of the PS FEH

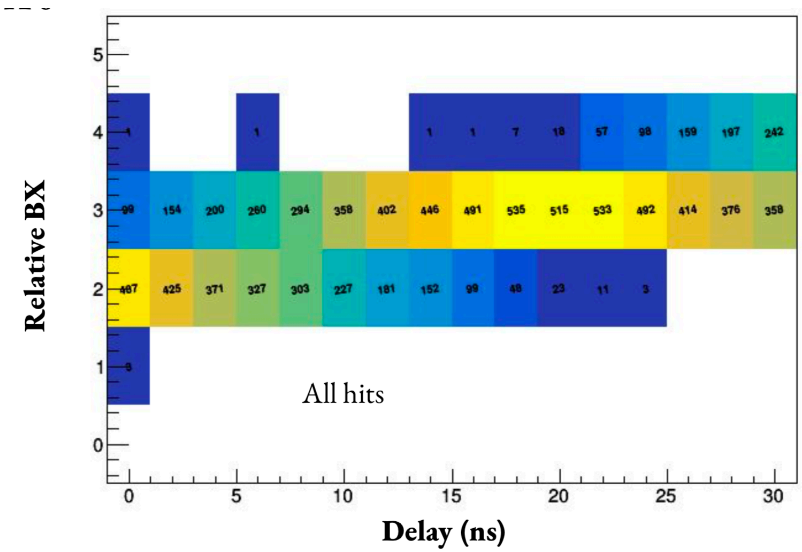


- The last Outer Tracker FE ASIC to be tested
  - Required fairly complex packaging:
    - SSA is bump-bonded to a hybrid, which was not even designed yet
    - Too large density for regular PCB production
    - Sapphire “interposer” on a PCB.
    - Measured noise consistent with the design
    - To be tested in FNAL Test Beams Facility in Jan 2020

2xSSA module







R&D Achieved – 402.2.4.2 Test Systems

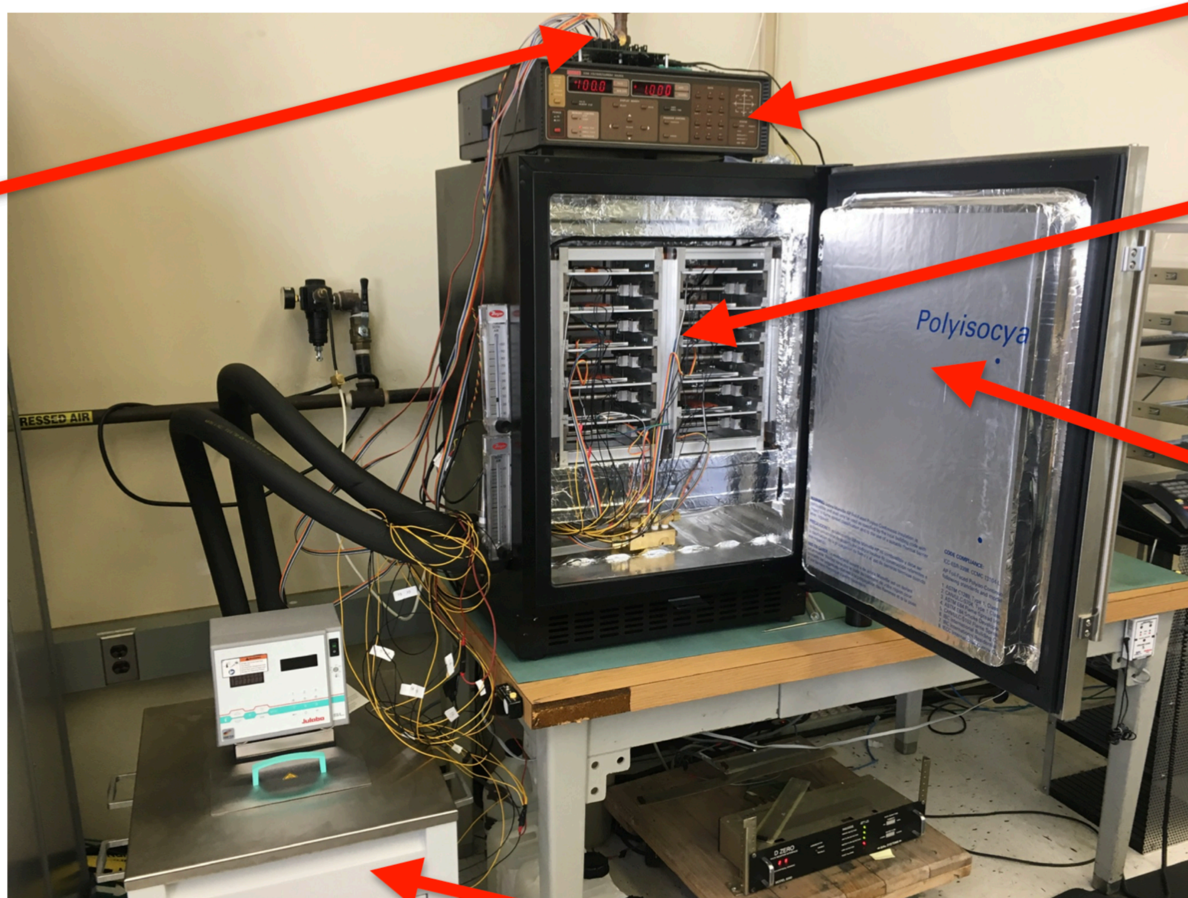
Charge #2

- Long term module test system – aka burn-in
  - 5 main components: Enclosure, Chiller, Module support, Controller board, Power supplies

Power supplies

Controller board

Module support



Enclosure

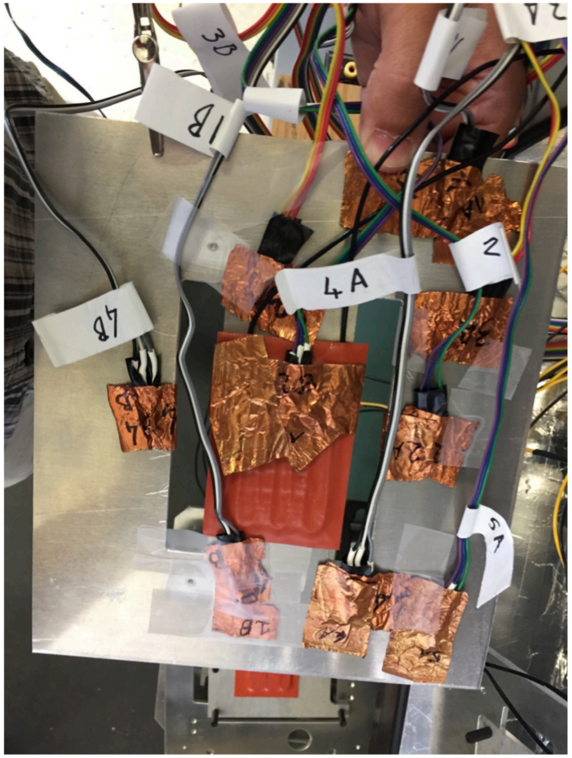
Chiller

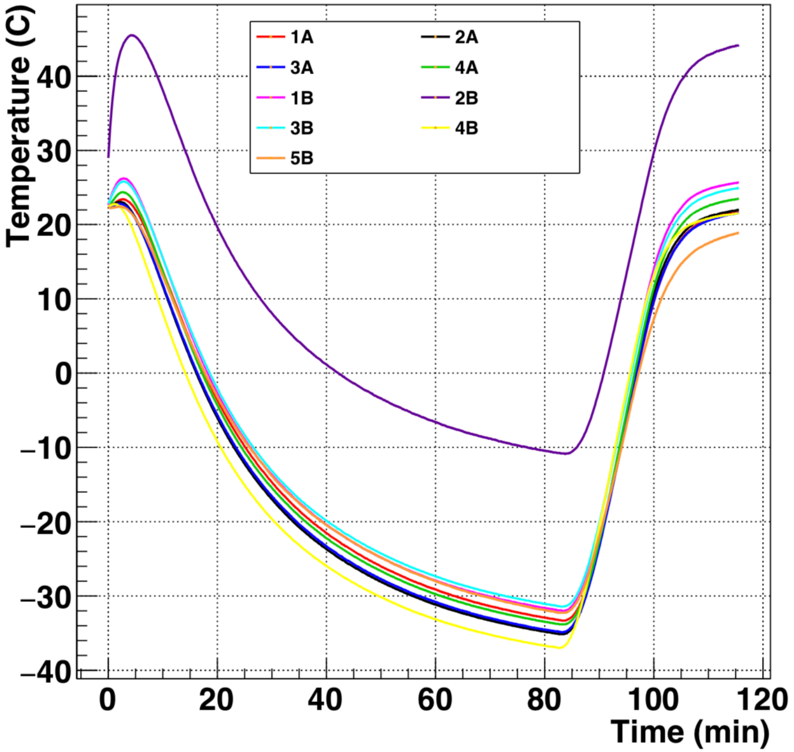
*No peltier coolers are needed

R&D Achieved – 402.2.4.2 Test Systems

Charge #2

- Long term module test system – aka burn-in
  - Both 2S and PS module carriers have been designed and tested
  - 2 hours per cycle is achievable





R&D Achieved – 402.2.4.3 DAQ

Charge #2

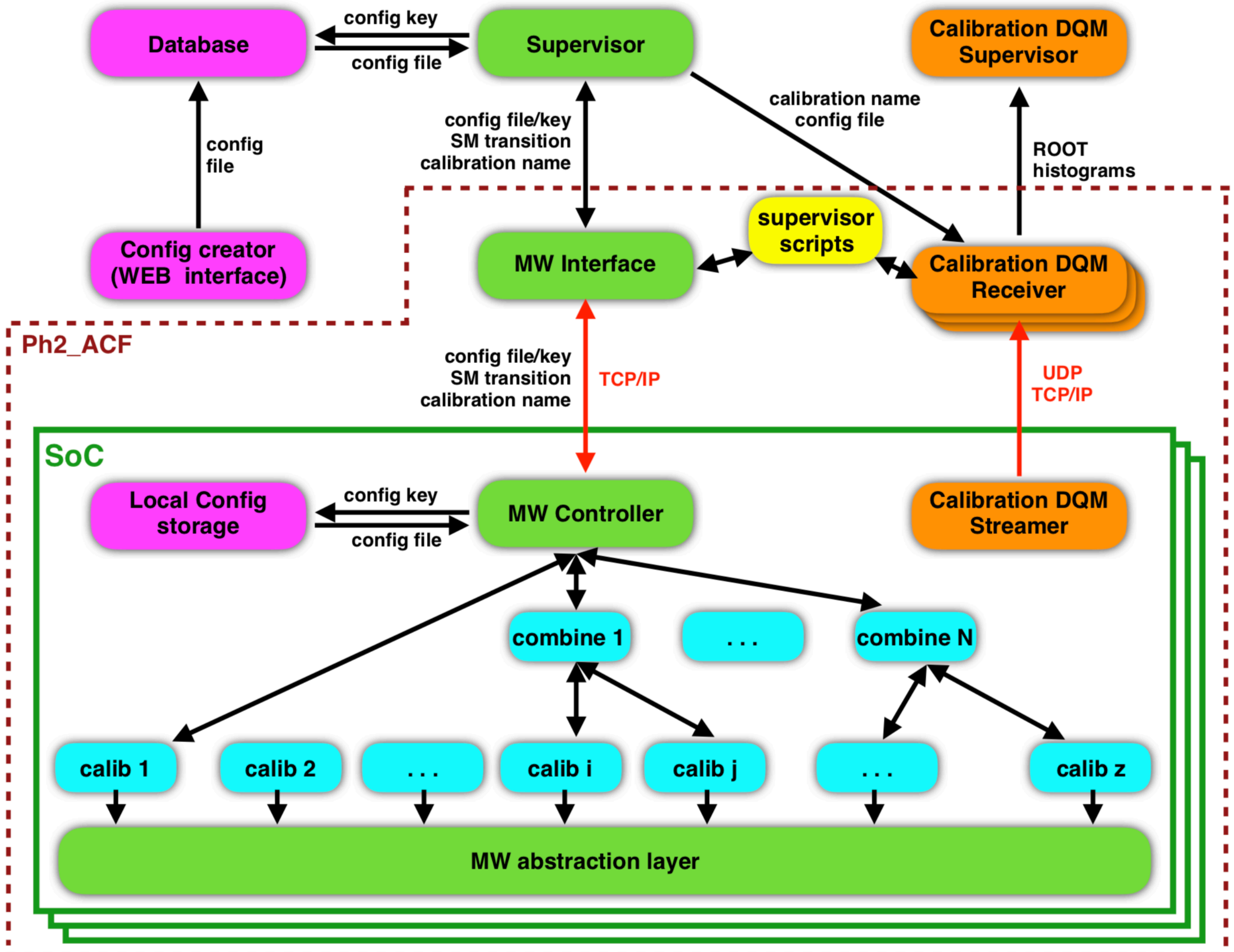
- Firmware and software development for various test systems
  - Middleware and OTSDAQ
    - single module, GLIB-based and FC7-based systems developed, built and used in test beams and on test benches
    - integrated 2S module with μTCA setup (including calibrations)
  - DTC and μDTC
    - Contributed to the FW (data decoding and sorting, infrastructure, etc)
    - DTC iCMS FW effort recently defined and started, roles of Fermilab and Rutgers are being finalized

R&D Achieved – 402.2.4.3 DAQ

Charge #2

Middleware: abstraction layer between FE and software

- Responsible for configuration, calibration, and DAQ



US institutions are playing the leading role in defining MW architecture and the way it runs on the FPGA's System On a Chip (SoC), as well as its implementation

R&D Achieved – 402.2.4.3 DAQ

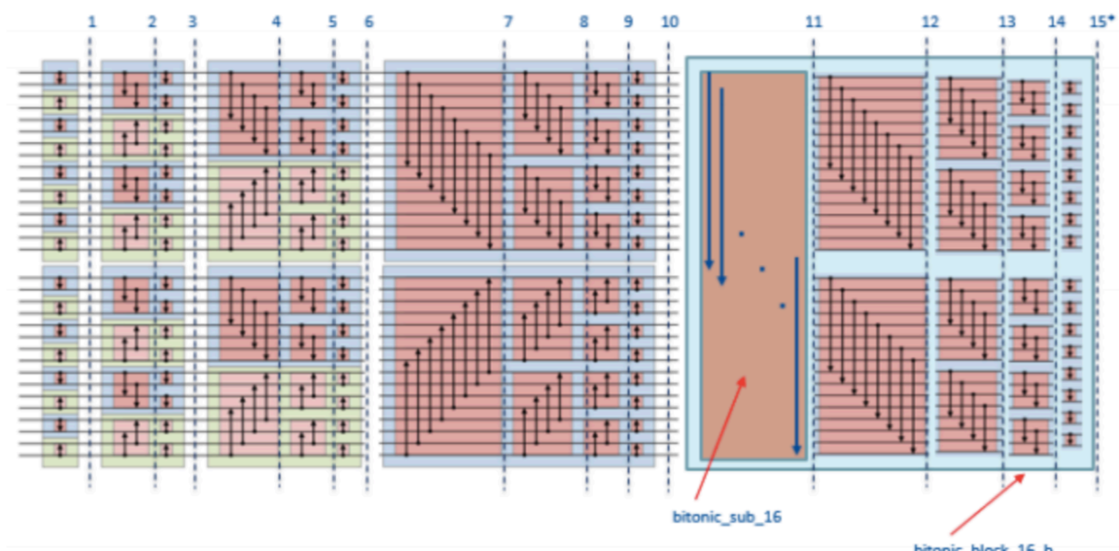
Charge #2

μDTC firmware – FC7 prototype of the DTC firmware

CIC 2S trigger output (*5G FEC12*)						
L1	L2	L3	L4	L5	L6	
C	Status					BX1
Status						
BCID						
BCID						
BCID		Nb Stubs				
Nb Stubs			$O1^{2}$	$O1^{1}$		
$O1^{0}$	$A1^{2}$	$A1^{1}$	$A1^{0}$	$S1^{7}$		
$S1^{6}$	$S1^{5}$	$S1^{4}$	$S1^{3}$	$S1^{2}$		
...						...
$O15^{2}$	$O15^{1}$	$O15^{0}$	$A15^{2}$	$A15^{1}$		BX8
$A15^{0}$	$S15^{7}$	$S15^{6}$	$S15^{5}$	$S15^{4}$		
$S15^{3}$	$S15^{2}$	$S15^{1}$	$S15^{0}$	$B15^{3}$	*Unused*	
$B15^{2}$	$B15^{1}$	$B15^{0}$	$O16^{2}$	$O16^{1}$		
$O16^{0}$	$A16^{2}$	$A16^{1}$	$A16^{0}$	$S16^{7}$		
$S16^{6}$	$S16^{5}$	$S16^{4}$	$S16^{3}$	$S16^{2}$		
$S16^{1}$	$S16^{0}$	$B16^{3}$	$B16^{2}$	$B16^{1}$		
$B16^{0}$	0	0	0	0		
C	Status					BX9
Status						
Bclk ID						
Bclk ID						
Bclk ID		Nb S				
Nb S			$O1^{2}$	$O1^{1}$		
$O1^{0}$	$A1^{2}$	$A1^{1}$	$A1^{0}$	$S1^{7}$		
$S1^{6}$	$S1^{5}$	$S1^{4}$	$S1^{3}$	$S1^{2}$		

Definitions	
C	CIC conf. : MPA or CBC
Status	Status bits
BCID	Bunck clock ID
Nb Stubs	Number of stubs in block
OX^{Y}	BX offset for stub X (bit Y)
AX^{Y}	Chip ID for stub X (bit Y)
SX^{Y}	Stub address for stub X (bit Y)
BX^{Y}	Bend info for stub X (bit Y)

- Stubs arrive in 8 bunch crossing long “boxcars” ordered by bend (pT)
- Need to get sorted in proper by bunch crossing
- Bitonic sorting network deployed



32 input bitonic sorting network
(can handle all 320 MHz options)

Development needed before production

Charge #2

- 402.2.4.2 Test Systems
  - Develop procedures for fast MaPSA tests – minimize the probe landing time through better vision systems and automation
  - Help develop procedures for the module tests
  - Almost at the finish line

Development needed before production

Charge #2

- 402.2.4.3 DAQ
  - OTSDAQ software development:
    - Develop DAQ for MaPSA (merge MaPSA and official iCMS middleware, add calibrations for MaPSA)
    - Optimize user interface and testing procedures
    - Develop burn-in version (multi-module)
    - Add detector construction database capabilities
    - In parallel with production:
      - Development for bigger systems of modules
      - Development for integration into central DAQ in CMS, including calibrations and running in global runs

Development needed before production

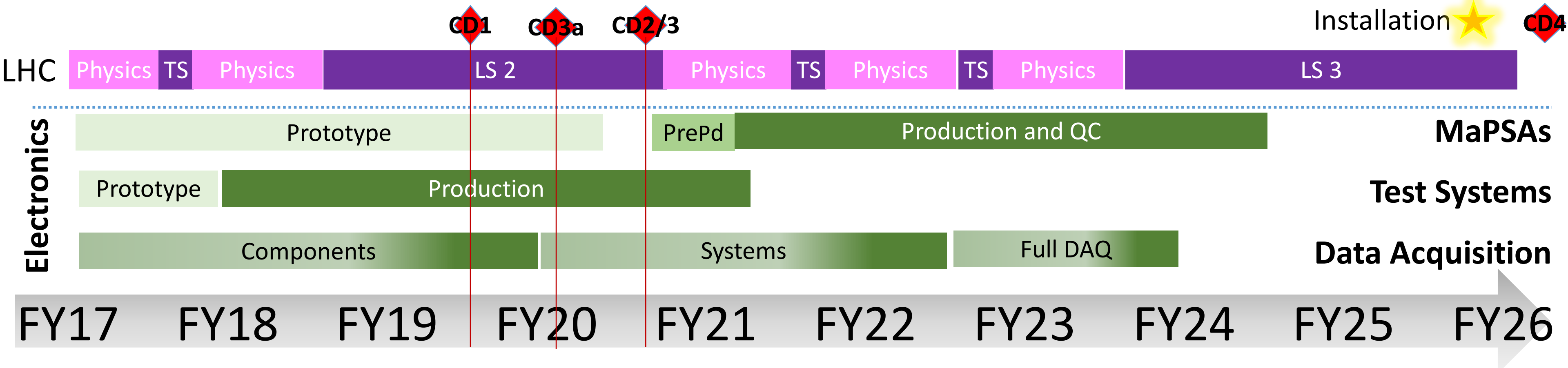
Charge #2

- 402.2.4.3 DAQ
  - DTC hardware is not part of the US OT scope. Fermilab and Rutgers are involved in developing software and firmware for the DTC.
  - Current and future R&D
    - μDTC: current FC7-based DAQ
      - Optical readout development
      - MPA, SSA, and PS module readout
    - DTC prototypes: ATCA blades
      - Firmware for transmission lines
      - Firmware for fast data unpacking / sorting
      - Support new hardware developments

Schedule and Cost

Major Milestones for 402.2.4 Electronics

Charge #3



- Test Systems
  - MaPSALite test system complete 5-May-17
  - Proto/prod burn-in system complete: 3-Jan-18/21-Jul-21
  - Electrical/optical module test systems complete: 24-Mar-20/8-Apr-20
  - MaPSA proto/prod test systems complete: 2-Apr-18/23-Oct-20
- DAQ
  - Development for GLIB test setup complete 20-Jul-17
  - Development of FC7 test setup for single module complete 24-Jan-18
  - OTSDAQ/Middleware ready for single module testing 31-Mar-20
  - OTSDAQ/Middleware ready for integration in global runs 31-Mar-23

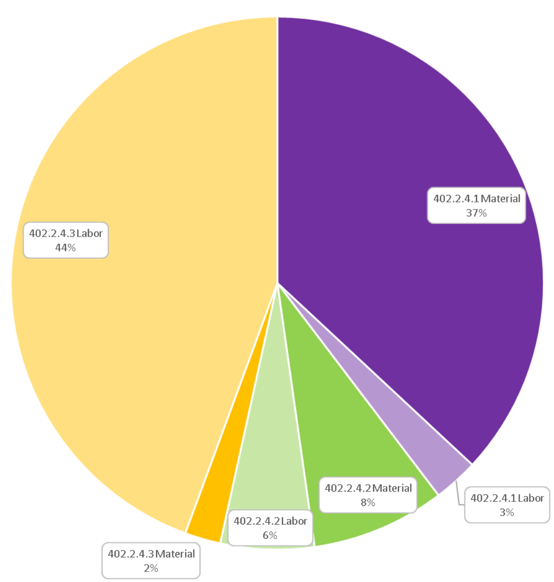
Critical path: Electronics is not on a critical path, except for the last batch (1/9) of MaPSAs. Will be covered in Doug's talk.

Overall Cost 402.2.4 Electronics

Charge #3

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-CD1-402.2.3.3 OT - PS-S Sensors	889,677	7262	4.11	1,356,764	286,122	1,642,885
DOE-CD1-402.2.3.4 OT - 2S Sensors	2,608,708	13706	7.75	3,516,318	721,577	4,237,895
DOE-CD1-402.2.4 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-CD1-402.2.4.2 OT - Test Systems	451,140	5081	2.87	857,430	162,291	1,019,721
DOE-CD1-402.2.4.3 OT - DAQ	126,990	23318	13.19	2,896,938	340,994	3,237,932
DOE-CD1-402.2.5 OT - Modules				1,785,980	5,113,007	26,898,987

402.2.4-OT-WBS L4 Base Budget Breakdown (DOE)
BAC = $6.22M (AY$)

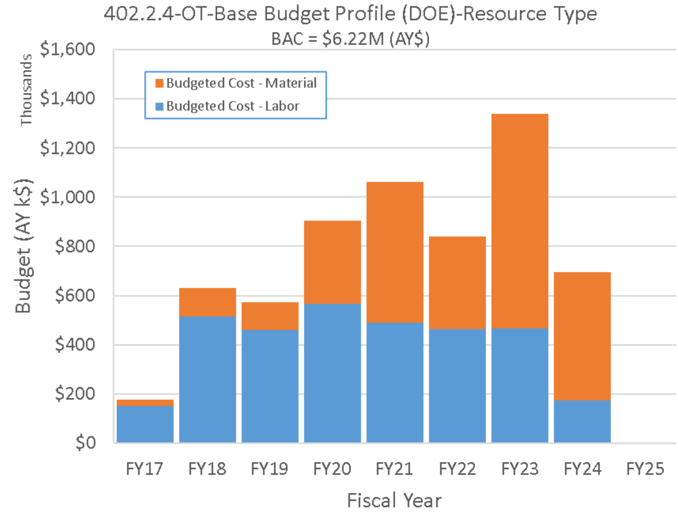


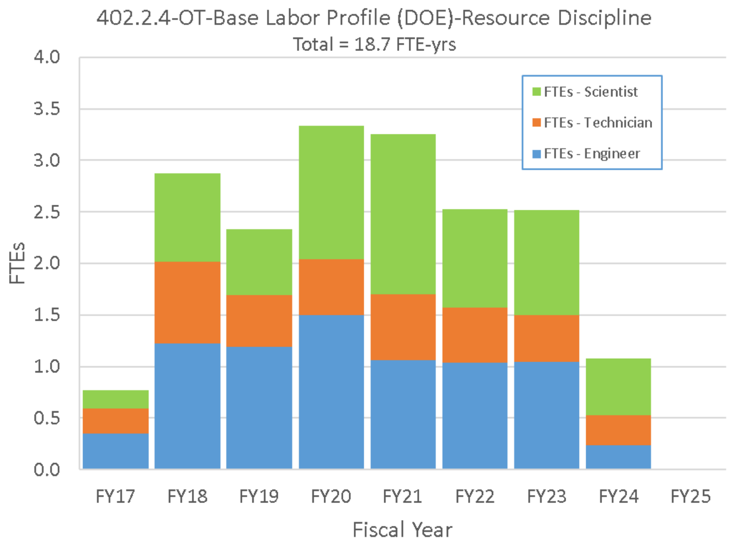
Fiscal Year Cost Profile

Charge #3

- M&S
  - FY17-19: components for test systems
  - FY21-24: MaPSA assembly
- Labor
  - FY17-24: DAQ development
  - FY17-20: test systems development

FTE	Total
AD	0.00
EN	7.63
TE	4.00
SC	7.05
Grand Total	18.69



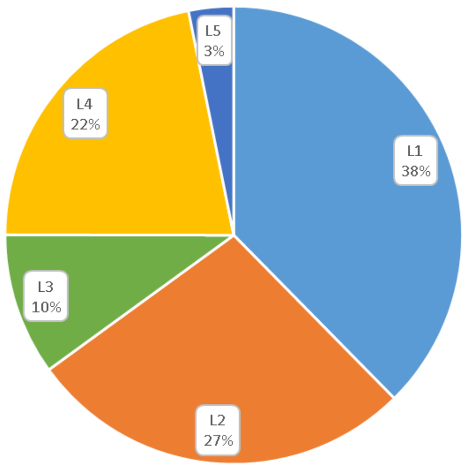


Contingency Breakdown

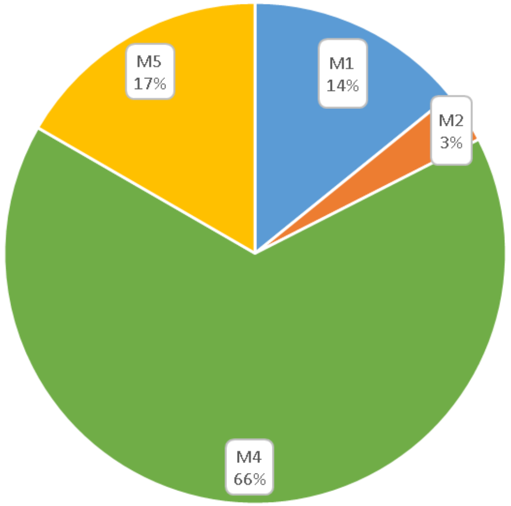
Charge #3

- Labor
  - Most of labor is on DAQ development, which is scheduled over the entire duration of the project and detailed needs are still uncertain
- M&S
  - Large variance in MaPSA bump bonding cost; EU will go down with vendor selection, and when final contracts are in place (<Q4/20)

402.2.4-OT-Estimate Uncertainty Breakdown-Labor (DOE)
BAC (Labor Budget)=$3.28M (AY$)



402.2.4-OT-Estimate Uncertainty Breakdown-M&S (DOE)
BAC (M&S)=$2.94M (AY$)



HL-LHC US CMS

Risks

Charge #3

CMS-doc-13480

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

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

- MaPSA vendor cannot perform QC tests
  - In that case we will perform QC for all MaPSAs at Fermilab (additional labor)

- P=33%
- 0.2-0.4-0.6 M$
- No delay
- Impact = 132 k$

- System Test hardware has insufficient capacity
  - In that case we will acquire additional hardware and pay for additional labor

- P=10%
- 0.07-0.17-0.3 M$
- 2 – 3 – 4 months
- Impact = 0.02 M$ and 0.3 months

Project Organization

Contributing Institutions

Charge #4,5

- Fermilab
  - Scientists:
    - Doug Berry: CMS phase 1 FPIX, CMS ECAL operations
    - Anadi Canepa: CDF L00 Silicon, CDF L2 Trigger upgrade, ATLAS New Small Wheel upgrade, CMS L2 Deputy OT, iCMS Systems Test Convener
    - Ron Lipton: D0 Silicon Microstrip Tracker, CMS OT & HGCal sensor design, L3 manager CMS OT Mechanics & Integration
    - Petra Merkel: CDF Silicon Strip Tracker, CMS phase 0 FPIX bump bonding & construction, L3 CMS phase 1 FPIX Assembly & Testing, L3 CMS OT Electronics
    - Lorenzo Uplegger: CMS phase 0 & phase 1 FPIX DAQ, test beam DAQ
  - Engineers:
    - Greg Derylo: CDF Silicon Tracker, DES camera, CMS phase 1 FPIX mechanics
    - Sergey Los: CMS phase 0 & 1 FPIX electronics
    - Alan Prosser: CMS phase 1 FPIX & phase 2 IT/OT optical link development
    - Ryan Rivera: CMS phase 0 & phase 1 FPIX DAQ, test beam DAQ
  - Technicians:
    - John Chramovicz: CMS phase 1 FPIX & phase 2 IT/OT optical link development
    - Bert Gonzalez: chief technician at SiDet, leading technician on many projects
    - Michelle Jonas: wire bonding technician, has worked on many silicon projects
    - Jorge Montes: CMS phase 1 FPIX & DES metrology, mech. tech.

- Rutgers University
  - Scientists:
    - Yuri Gershtein: D0 track trigger, silicon detector, muon system upgrades, SSC GEM muon system R&D, CMS Quartz Fiber calorimetry R&D, CMS ECAL
    - Eva Halkiadakis: CDF Silicon detector, CMS PLT
    - Bob Stone: CMS phase 0 & 1 FPIX, CMS PLT
  - Technician:
    - Jonathan Harrop (senior in Rutgers Engineering, expect to keep him on the project after graduation)
  - Engineer:
    - Ed Bartz: CMS phase 0 & 1 FPIX TBM chip development, CMS phase 0 FPIX FEC firmware

- Princeton University
  - Scientist:
    - Dan Marlow: Belle Silicon detector, CMS PLT
  - Technician:
    - Bert Harrop: Silicon detector packaging expert, Belle, CMS PLT

Contributions to test beam campaigns:

- **Rochester:** Regina Demina (fac), Sergey Korjenevsky (eng), Otto Hindrichs (pd)
- **Boston:** Tulika Bose (fac), Shouxiang Wu, Eric Hazen (eng), Dylan Rankin (stu)
- **Iowa:** Maksat Haytmyradov (stu)
- **Wayne State:** Nabin Poudyal (stu)

Resource Optimization

Charge #4

- Previous expertise
  - Senior personnel at all three institutions have expertise in silicon detectors, electronics and DAQ development.
- Infrastructure
  - All infrastructure needed for electronics and DAQ development and MaPSA testing existed and R&D work could start immediately.
- Intellectual engagement
  - With the development of electronics for test systems for all levels of components, firmware and software development for the readout system and DAQ, as well as responsibility in MaPSA vendor qualification and process optimization and QC, and convenership in the iCMS System Tests Working Group, this WBS is very well positioned within iCMS.
- Vendors
  - Due to large spread in quoted assembly costs, extensive vendor qualification has to take place during the prototyping phase. Bump bonding vendors provide first level (all) of QC.
  - Equipment is generally purchased off the shelf or from iCMS partners.

ES&H

Charge #6

- All ES&H aspects of the HL LHC CMS Detector Upgrade Project will be handled in accordance with the Fermilab Integrated Safety Management approach, and the rules and procedures laid out in the Fermilab ES&H Manual (FESHM)
- In General Safety is achieved through standard Lab/Institute 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
- Specific Hazards for Electronics
  - NONE

Summary

Summary

- Test Systems
  - Prototypes for all test systems already exist
  - Final versions expected well in advance of module production
- DAQ
  - Firmware and software development ongoing
  - Will provide maintenance and support throughout construction phase
- Cost and schedule aspects are suitable for CD-1

Backup

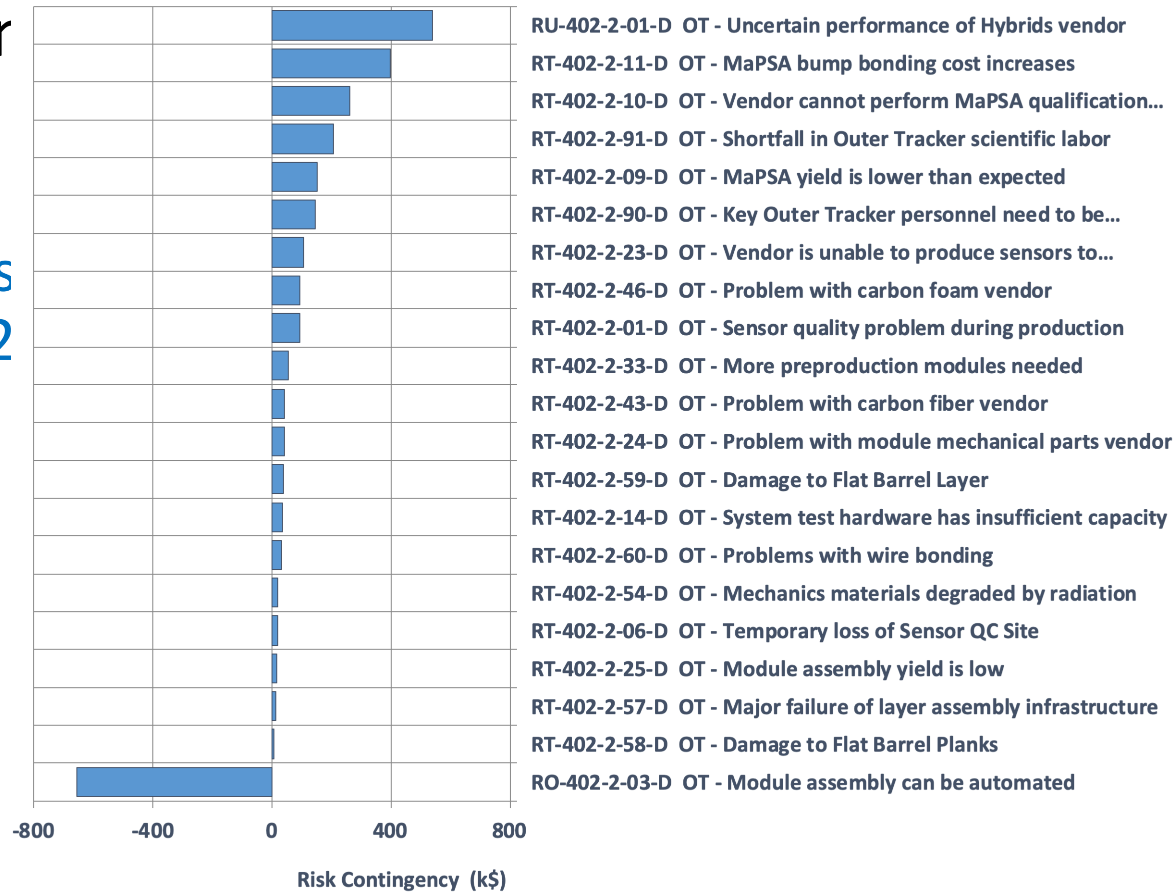
Technical Milestones - Electronics

402.2W.4.1 OT - Macro Pixel Sub-Assembly		3-Oct-16	26-Jul-24	
OT410010	T5 - Start MaPSA Prototypes	3-Oct-16		T5
OT410115	T5 - Vendor 2 prototype MaPSAs delivered - Round 1		13-Sep-19	T5
OT410095	T5 - Vendor 1 prototype MaPSA delivered - Round 1		13-Sep-19	T5
OT410205	T5 - Vendor 3 delivers prototype MaPSA - Round 2		13-May-20	T5
OT410175	T5 - Vendor 2 delivers prototype MaPSA - Round 2		13-May-20	T5
OT410145	T5 - Vendor 1 delivers prototype MaPSA - Round 2		13-May-20	T5
OT410230	T4 - MaPSA Prototyping complete		12-Aug-20	T4
OT410750	T4 - MaPSA Production Complete		26-Jul-24	T4
402.2W.4.2 OT - Test Systems		3-Oct-16	17-Dec-21	
OT421700	T5 - Beginning of MAPSALite Test System Develoment	3-Oct-16		T5
OT421710	T5 - Beginning of MAPSALite probe card development	3-Oct-16		T5
OT421730	T5 - Completion of MAPSAlite probe card design		5-Jan-17	T5
OT420300	T5 - Beginning of Prototype Burnin Box	3-Apr-17		T5
OT421790	T5 - Completion of MAPSAlite probe card		15-May-17	T5
OT421800	T5 - Beginning of MAPSA test system development	16-May-17		T5
OT420400	T5 - Completion of Burnin Proto Design		26-Jun-17	T5
OT420430	T5 - Completion of Burnin Proto Development		20-Sep-17	T5
OT421860	T5 - Completion of MAPSA prototype probecard design		4-Dec-17	T5
OT421850	T5 - Completion of MAPSA prototype interface board design		4-Dec-17	T5
OT420580	T4 - Prototype Burn-in system complete		3-Jan-18	T4
OT422010	T5 - Completion of Prototype MAPSA Test System		2-Apr-18	T5
OT422200	T5 - Start Production MAPSA Test System	1-Oct-19		T5
OT420700	T5 - Beginning of Burnin Final	1-Oct-19		T5
OT421300	T5 - Start Building Single Module Test System	19-Dec-19		T5
OT421299	T5 - Test systems for electrical readout available	19-Dec-19*		T5
OT421610	T5 - Electrical test system complete		24-Mar-20	T5
OT422230	T5 - Completion of production MAPSA probecard design		25-Mar-20	T5
OT422300	T5 - Completion of production MAPSA interface board design		25-Mar-20	T5
OT750520	T5 - Module test system complete		8-Apr-20	T5
OT420750	T5 - Final Burnin box design complete		4-Aug-20	T5
OT422400	T5 - Completion MAPSA test system development		23-Oct-20	T5
OT422600	T5 - Start Procurement of DAQ Components	16-Mar-21		T5
OT420000	T5 - Beginning prod test systems for hybrids	16-Mar-21		T5
OT420200	T5 - Completion of prod test systems for hybrids (BR)		6-Apr-21	T5
OT420190	T5 - Completion of prod test systems for hybrids (FN)		6-Apr-21	T5
OT421200	T4 - Final Burn-in system complete		12-Jul-21	T4
OT422740	T5 - DAQ Components Complete		17-Dec-21	T5
402.2W.4.3 OT - DAQ		3-Oct-16	10-May-24	
OT430000	T5 - Start DAQ for System Test	3-Oct-16		T5
OT430020	T5 - Completion of Test System (GLIB)		20-Jul-17	T5
OT430040	T5 - Completion development of FC7 test setup for single module		24-Jan-18	T5
OT430135	T5 - OTSDAQ ready for module testing		31-Mar-20	T5
OT430225	T5 - OTSDAQ ready for integration in global runs		31-Mar-23	T5
OT430550	T5 - End DAQ for System Test		10-May-24	T5

Outer Tracker risks

Updated 8 Oct 2019

- Main risk changes in past 12 months are
  - Key personnel and scientific labor risks now managed at L2
  - More stuff?
  - More stuff?
  - More stuff?



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

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

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

Risk Register CMS-doc-13480

Risk Register for the HL-LHC CMS Detector Upgrades Project

RT-402-2-09-D OT - MaPSA yield is lower than expected

Risk Rank:	2 (Medium) **Scores:** Probability : 2 (L) ; Cost: 2 (M) Schedule: 0 (N))	**Risk Status:**	Open
Summary:	If MaPSA yield is lower than expected, the additional wastage also sacrifices the associated sensors and MPA chips, which would need to be replaced at the project's cost.		
Risk Type:	Threat	**Owner:**	Ron Lipton
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	Technical Risk / Quality
Probability (P):	15%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 2-point - flat range Minimum = 370 k$ Most likely = k$ Maximum = 640 k$ Mean = 505 k$ P * <Impact> = 76 k$	**Schedule Impact:**	PDF = 1-point - single value Minimum = months Most likely = 0 months Maximum = months Mean = 0 months P * <Impact> = 0.0 months
Basis of Estimate:	For each loss of 10% in yield, we would need 10% more sensors, estimated at 245k, and 10% more MPA chips, estimated at 125k. The range covers wastage between 10 and 20%. Implemented between Testing batch 3 and Vendor producing batch 5.		
Cause or Trigger:	A myriad number of problems at the bump bonding stage might reduce the yield, or handling during the assembly.	**Impacted Activities:**	Increased wastage during the MaPSA assembly would require additional components, namely PS sensors and MPA chips
Start date:	2/Sep/2021	**End date:**	20/Sep/2023
Risk Mitigations:			
Risk Responses:			
More details:			

Risk Register CMS-doc-13480

RT-402-2-10-D OT - Vendor cannot perform MaPSA qualification tests

Risk Rank:	2 (Medium) **Scores:** Probability : 3 (M) ; Cost: 2 (M) Schedule: 0 (N))	**Risk Status:**	Open
Summary:	MaPSA qualification is done at the vendor site. The current cost estimate may increase considerably if the vendors do not have the proper infrastructure to qualify the parts.		
Risk Type:	Threat	**Owner:**	Ron Lipton
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	Technical Risk / Complexity
Probability (P):	33%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 3-point - triangular Minimum = 200 k$ Most likely = 400 k$ Maximum = 600 k$ Mean = 400 k$ P * <Impact> = 132 k$	**Schedule Impact:**	PDF = 1-point - single value Minimum = months Most likely = 0 months Maximum = months Mean = 0 months P * <Impact> = 0.0 months
Basis of Estimate:	Qualification of MaPSAs may require sophisticated probing equipment, which can cost up between 200-600k for procurement, installation, and comissioning of the requisite equipment, potentially at several vendors.		
Cause or Trigger:		**Impacted Activities:**	MaPSA procurement costs would increase. Implemented as a cost increase after round 2 of MaPSA prototyping.
Start date:	1/Jan/2019	**End date:**	14/Jun/2023
Risk Mitigations:			
Risk Responses:	Work with vendor to improve their infrastructure or move testing to different site (other vendor or collaborator)		
More details:			

Risk Register CMS-doc-13480

RT-402-2-11-D OT - MaPSA bump bonding cost increases

Risk Rank:	2 (Medium) **Scores:** Probability : 2 (L) ; Cost: 3 (H) Schedule: 0 (N))	**Risk Status:**	Open
Summary:	Currently we have several MaPSA estimates,with a very broad range between high and low, indicating the industry does not give a clear indication of the actual cost. This risk is to cover the possibility that this high cost item exceeds the nominal estimate uncertainty, M5 at the moment.		
Risk Type:	Threat	**Owner:**	Ron Lipton
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	External Risk / Vendors
Probability (P):	20%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 3-point - triangular Minimum = 500 k$ Most likely = 1000 k$ Maximum = 1500 k$ Mean = 1000 k$ P * <Impact> = 200 k$	**Schedule Impact:**	PDF = 1-point - single value Minimum = months Most likely = 0 months Maximum = months Mean = 0 months P * <Impact> = 0.0 months
Basis of Estimate:	Currently we have several MaPSA estimates,with a very broad range between high and low, indicating the industry does not give a clear indication of the actual cost. This risk is to cover the possibility that this high cost item exceeds the nominal estimate uncertainty, M5 at the moment.		
Cause or Trigger:		**Impacted Activities:**	The costs of MaPSA bump bonding would increase, increasing the costs of PS module fabrication.
Start date:	1/Jan/2019	**End date:**	14/Jun/2023
Risk Mitigations:	Prototypes will be used to validate low bidders, for which there is not yet confidence of delivering with requisite quality. There is more confidence for high cost bidders, which will also be validated in the prototyping phase, but even there the quotes are still preliminary.		
Risk Responses:			
More details:			

Risk Register CMS-doc-13480

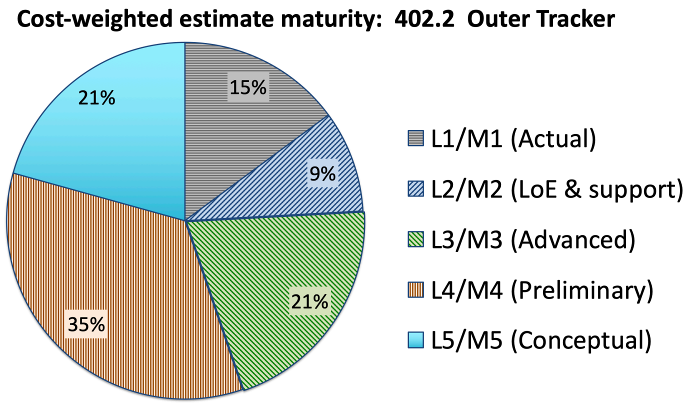
RT-402-2-14-D OT - System test hardware has insufficient capacity

Risk Rank:	2 (Medium) **Scores:** Probability : 2 (L) ; Cost: 2 (M) Schedule: 2 (M))	**Risk Status:**	Open
Summary:	If unforeseen problems occur during assembly and testing, then the baseline testing systems may not be sufficient to maintain the required throughput. This would necessitate the procurement and commissioning of additional test systems and additional labour for testing.		
Risk Type:	Threat	**Owner:**	Anadi Canepa
WBS:	402.2 OT - Outer Tracker	**Risk Area:**	Technical Risk / Reliability or Performance
Probability (P):	10%	**Technical Impact:**	0 (N) - negligible technical impact
Cost Impact:	PDF = 3-point - triangular Minimum = 71 k$ Most likely = 169 k$ Maximum = 292 k$ Mean = 177 k$ P * <Impact> = 18 k$	**Schedule Impact:**	PDF = 3-point - triangular Minimum = 2 months Most likely = 3 months Maximum = 4 months Mean = 3 months P * <Impact> = 0.3 months
Basis of Estimate:	The maximum cost impact corresponds to a scenario in which the capacity of all the production test systems (total cost about $200k) needs to be doubled, i.e. a cost impact of $200k. The minimum and likely costs reflect the need to duplicate parts of the test systems. The min/likely/max schedule impact of 2/3/4 months is estimated assuming that the problem becomes apparent during production. The L3 burn rate due to the delay of downstream activities is $23k/month (CMS-doc-13481). **Min impact = $25k + 2 months * $23k/month = $71k.** **Likely impact = $100k + 3 months * $23k/month = $169k.** **Max impact = $200k + 4 months * $23k = $292k.**		
Cause or Trigger:		**Impacted Activities:**	More module testing equipment would be required, possibly more cold boxes, single module testing, or hybrid testing equipment. Implemented as a cost impact on FNAL PS module production, A, East Coast PS Module production (B), FNAL 2S Module Production (C), and East Coast 2S module production (D). Sites should be delayed the same amount, but the probability should be split evenly between PS (A,C) and 2S (B,D)
Start date:	1/Jan/2022	**End date:**	31/Dec/2024
Risk Mitigations:	The testing hardware is an external deliverable. We will monitor the progress of the USCMS module production and ensure that new testing equipment is purchased when necessary and delivered when the production rate is increased to meet the schedule. Labour is increased accordinly to support the higher production rate.		
Risk Responses:			
More details:	CMS-doc-13481		

Design Maturity

Charge #2

	L3s													
	Sensors		Electronics		Modules		Mechanics		Integration		AVE		BAC	
OT	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech
Conceptual Design	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Preliminary Design	100%	100%	98%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Final Design	100%	100%	100%	95%	100%	86%	93%	95%	87%	95%	96%	94%	99%	91%
Detailed Design	50%	80%	50%	20%	50%	20%	50%	20%	50%	20%	50%	32%	50%	31%
Construction Readiness	48%	75%	19%	20%	22%	20%	19%	20%	19%	20%	25%	31%	26%	30%



- Test Systems
  - MaPSA: components already exist, adapt test systems for vendors
  - Module burn-in: system exists
- DAQ
  - OTSDAQ: software design/development for MaPSA, burn-in, DB capabilities, large systems, cDAQ in CMS still largely missing
  - DTC: international effort recently defined; BE fw/sw and FE fw/sw design/development starting up

402.2 Outer Tracker

Costs: Electronics CMS-doc-13215

Updated 6 Oct 2019

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
DOE-CD1-402.2.4.2 OT - Test Systems	**451,140**	**5081**	**2.87**	**857,430**	**162,291**	**1,019,721**
DOE-CD1-402.2.4.2.1 OT - Hybrid Test System	20,724	160	0.09	29,059	9,620	38,679
DOE-CD1-402.2.4.2.2 OT - Modules Test System	287,490	3493	1.98	507,211	122,939	630,150
DOE-CD1-402.2.4.2.3 OT - MaPSA Test System	95,406	1388	0.79	261,696	0	261,696
DOE-CD1-402.2.4.2.4 OT - DAQ Components	47,520	40	0.02	59,464	29,732	89,196
DOE-CD1-402.2.4.3 OT - DAQ	**126,990**	**23318**	**13.19**	**2,896,938**	**340,994**	**3,237,932**
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**