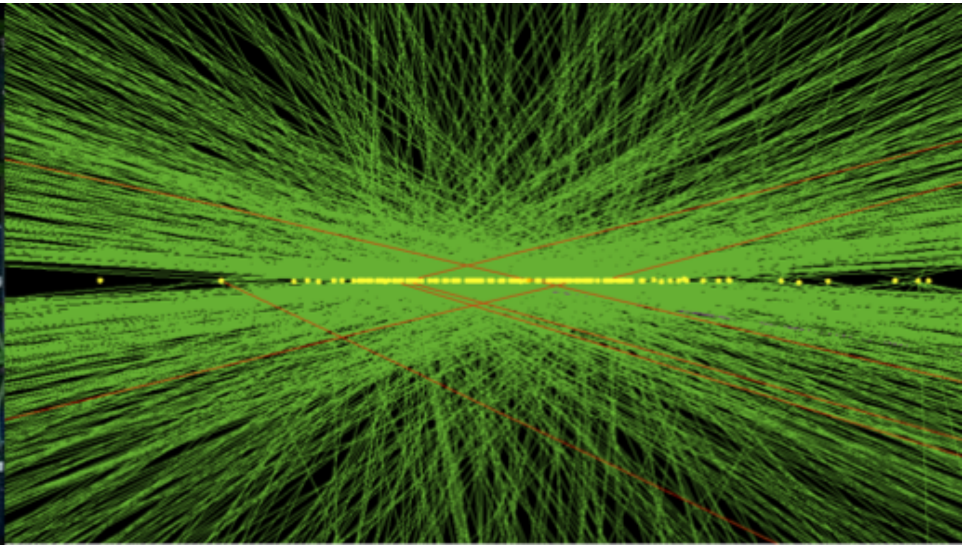
MTD-B0 2   In-depth: BTL SiPMs

402.8.3.2

Mitch Wayne

HL-LHC CMS Upgrade CD-1 Director's Review

20 March 2019



Charge #5

Brief Biographical Introduction

- Mitch Wayne, Professor, University of Notre Dame
  - Within MTD International, head of the Notre Dame MTD group, Level 4 manager tasked with leading the SiPM R&D and subsequent QA/QC of the production SiPMs
  - Within US MTD, Level 4 manager of the BTL SiPM project
  - Co-leader of the HB/HE Front End Phase I upgrade effort for international CMS. US CMS Level 4 manager of the SiPM and ODU projects for the HCAL Phase I upgrades. Led team that carried out the R&D and then successful testing and characterization of 25k channels of SiPM for HE and HB – installations in 2017 and 2019, respectively.

Outline

- Scope and Deliverables of BTL SiPMs
- Conceptual Design
- Cost and Schedule
- Contributing Institutions
- Resource Optimization
- ES&H
- QA/QC
- Summary

Scope and Deliverables for 402.8.3.2

Charge #4

- The BTL reference design has 165,888 LYSO bars, read out by two SiPMS, one at each end
  - Total channel SiPM channel count is 331,776
  - With 5% spares the total number of SiPM is 348,365
- The US MTD project is responsible for the purchase of 34% of the SiPMs, and the testing and characterization of 50% of the SiPMs. The packaging of the SiPMs into 16-channel arrays will be carried out by the vendor.
  - US MTD will purchase 118,750 channels of SiPM
  - US MTD will test and characterize 174,183 channels
  - US MTD will develop packaging for the SiPMs

Conceptual Design

Design Considerations for 402.8.3.2

Charge #1,2

- Silicon Photomultipliers (SiPM) are the photodetectors of choice for the BTL. Features of SiPMs include:
  - Compact size, 3mm x 3mm for the BTL
  - Small pixels (15 micron or less) provide extended linear dynamic range and keep dark count manageable
  - High photon detection efficiency (PDE) of > 20% for 15 micron pixels
  - Fast recovery time of < 10 ns
  - Insensitivity to magnetic fields
  - Low power consumption
  - Good uniformity over large numbers of channels
  - Relative ease of operation
  - Sufficiently radiation resistant for use in the BTL → still performant at end of life of the detector
- Given the constraints from the detector design and the features listed above, SiPMs are the only reasonable option for the BTL

R&D Achieved

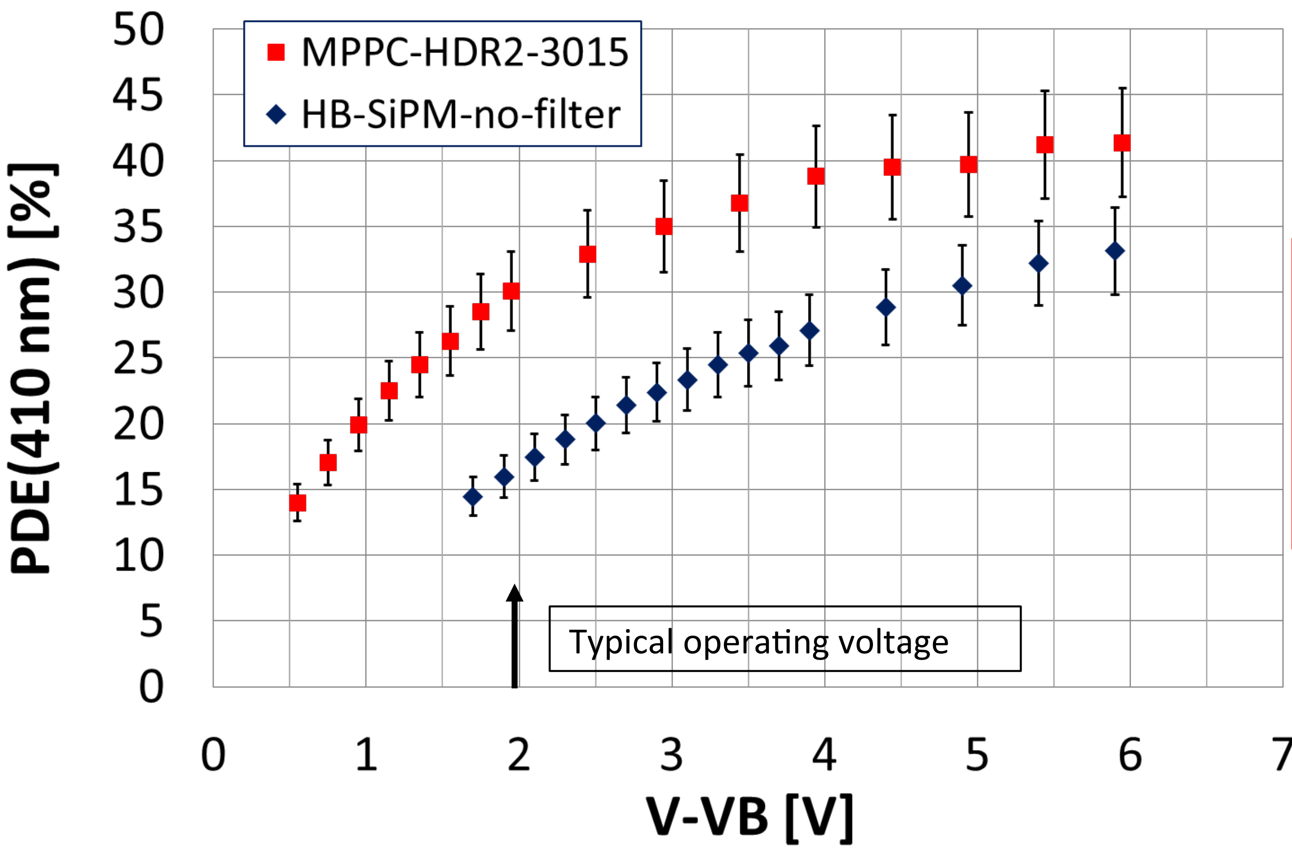
Charge #1,2

- The HE/HB SiPM from Hamamatsu has been tested extensively and is well understood
- Studies show that this SiPM could meet the timing requirements for the BTL, but there would be little margin for error, so we have been actively working with two vendors (Hamamatsu and FBK) to improve upon this device's performance
- The SiPM R&D has three main areas of focus
    - Improve PDE as much as possible for pixel size of 15 microns
    - Improve radiation resistance to reduce dark count rate
    - Design a cost effective package that positions the SiPM on the LYSO crystal, brings in bias voltage and brings out signal, and transfers heat away from the SiPM

R&D Achieved

Charge #1,2

- HPK has developed a promising new SiPM with higher PDE than the HE/HB device

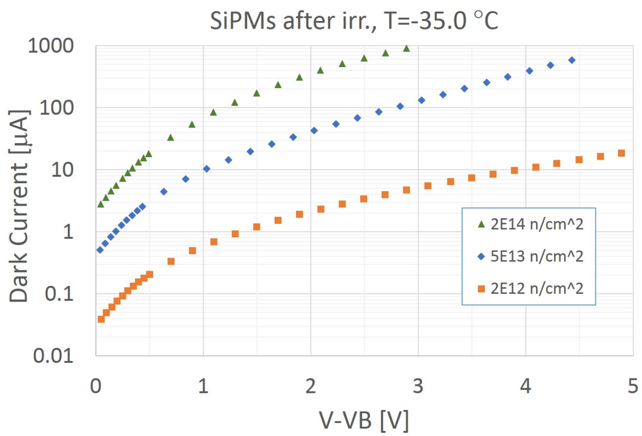


New 15 micron SiPM from Hamamatsu (red points) with significant increase in PDE compared with HB SiPM (blue points)

R&D Achieved

Charge #1,2

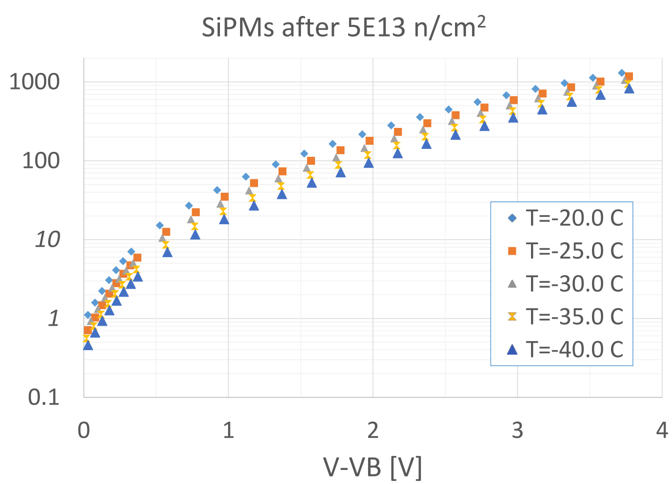
- We have done extensive studies of radiation damage, including temperature effects and annealing

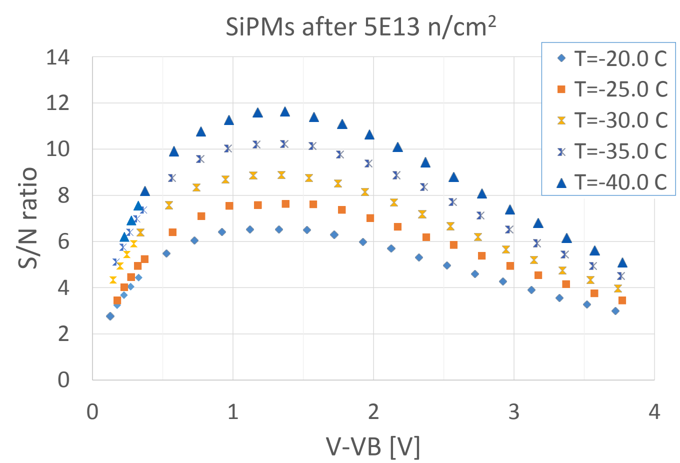


Increased dark current with dose

Reduction of dark current with lower temperature

Improved S/N with lower temperature





Charge #2, 4

R&D needed before production

- A new round of irradiations were carried out at the Ljubljana reactor in early 2019. We are doing detailed comparisons of SiPM candidates from HPK and FBK to determine which one will provide the best timing resolution over the lifetime of the BTL.
- Example: dark current at -30^{o}C, dose of 2E14 (end of life for BTL)
  - Hamamatsu – HDR2 SiPM

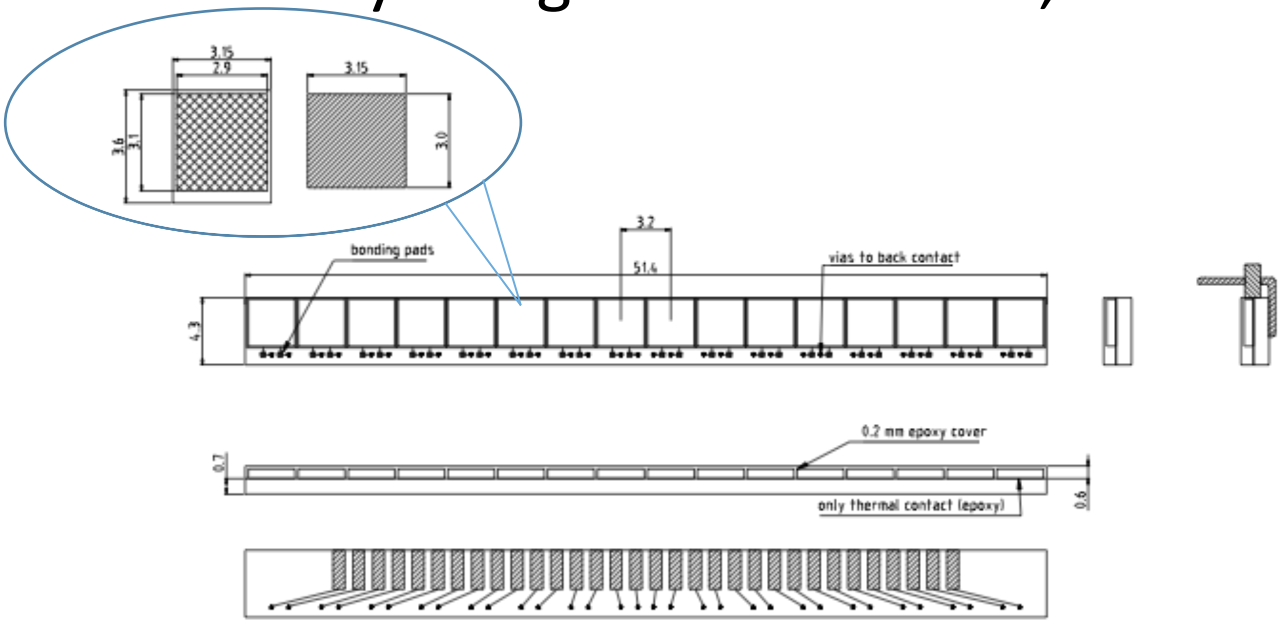
dVB, V	Dark Current (2.1E12n), A	Dark Current (2E14n), A - calc.	Dark Current (2E14n), A - measured before anneal.	Dark Current (2E14n), A - measured after anneal.	Ratio (meas./calc.)
0.5	4.91E-06	4.68E-04	9.5E-04	3.90E-04	0.83
1	1.68E-05	1.60E-03	3.87E-03	1.76E-03	1.1
1.5	3.55E-05	3.38E-03	9.74E-03	-	-

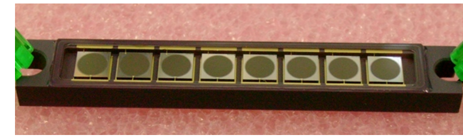
- Key points:
  - SiPM still works after this dose
  - Dark currents are consistent with predicted values

R&D needed before production

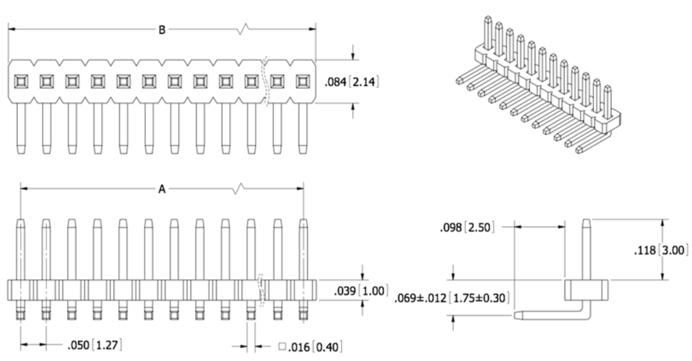
Charge #2, 4

- Preliminary design of 16 channel, ceramic package





Phase I HE/HB Ceramic Package

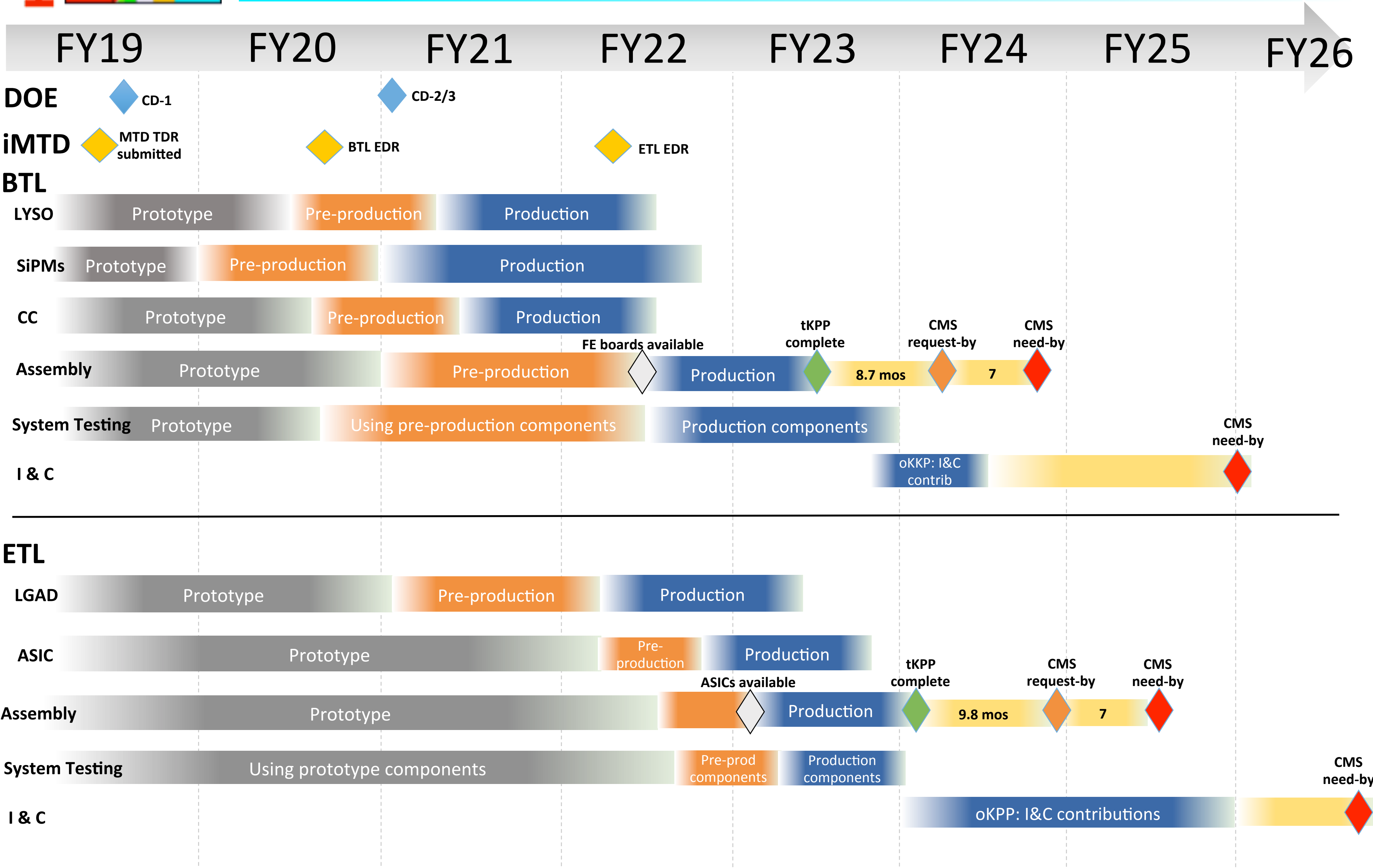


estimated thermal conductivity

component	material	size	inner dia	Thickness	TH. Cond	Grad for 50 mW
		mm	mm	mm	W/mK	deg C
die	Si	3.2		0.35	100	0.017
Die attach	solder	1.5	4 x 0.7	0.05	50	0.021
Top pad	Cu	3		0.035	377	0.001
Substrate	Al2O3	3.2		0.7	20	0.171

Schedule and Cost

US-MTD Schedule in P6



Charge #3

SiPM Schedule Overview

Activities	Dates	Key Dates
R&D on SiPM prototypes, radiation testing, develop package, choose preproduction designs	Now – November 2019	
Design and produce test stands for pre- and full production testing, develop software	April 2019 – October 2019	Nov. 2019: Readiness review Nov. 2019: Preproduction P.O.
Thorough testing of preproduction SiPMs on the bench and in beams, choose final SiPM and packaging designs for full production	May 2020 – October 2020	May 2020: Preproduction SiPMs delivered to CERN
Prepare PO for full production, readiness review	September 2020 – October 2020	Oct. 2020: Readiness review Oct. 2020: P.O. for production
SiPM production at vendor	October 2020 – October 2022	Oct. 2020: Begin SiPM full production
Testing and characterization of first 50% of production SiPMs	April 2021 – December 2021	Apr. 2021: 1st SiPMs at CERN Dec. 2021: QC 50% complete

- These key dates are consistent with MTD milestones (see CMS-doc-13321)

Charge #3

Timing Layer Cost Estimates to L4

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
CD1-v2-DR-402.8 402.8 TL - Timing Layer	6,561,457	161764	91.50	11,364,763	3,026,706	14,391,469
CD1-v2-DR-402.8.2 TL - Management	433,000	26520	15.00	568,714	144,562	713,276
CD1-v2-DR-402.8.2.1 TL - Management Labor	0	26520	15.00	0	0	0
CD1-v2-DR-402.8.2.2 TL - Management Travel	233,000	0	0.00	349,488	34,949	384,436
CD1-v2-DR-402.8.2.3 TL - Common Infrastructure	200,000	0	0.00	219,226	109,613	328,840
CD1-v2-DR-402.8.3 BTL - Barrel Timing Layer	3,352,236	49800	28.17	5,410,860	1,318,476	6,729,336
CD1-v2-DR-402.8.3.1 BTL - LYSO Scintillator	1,178,868	2946	1.67	1,301,006	191,882	1,492,888
CD1-v2-DR-402.8.3.2 BTL - SiPMs	1,135,400	5384	3.05	1,740,686	296,166	2,036,852
CD1-v2-DR-402.8.3.3 BTL - Concentrator Cards	492,896	5147	2.91	925,645	306,932	1,232,577
CD1-v2-DR-402.8.3.4 BTL - Assembly	343,120	19353	10.95	989,999	383,042	1,373,042
CD1-v2-DR-402.8.3.5 BTL - System Testing	78,952	6322	3.58	110,401	49,734	160,135
CD1-v2-DR-402.8.3.6 BTL - Integration and Commissionin	123,000	10648	6.02	343,123	90,719	433,842
CD1-v2-DR-402.8.4 ETL - Endcap Timing Layer	2,776,221	85444	48.33	5,385,188	1,563,669	6,948,857
CD1-v2-DR-402.8.4.1 ETL - LGAD Sensors	0	3872	2.19	0	0	0
CD1-v2-DR-402.8.4.2 ETL - Frontend ASICs	1,922,500	22588	12.78	3,874,081	1,039,579	4,913,660
CD1-v2-DR-402.8.4.3 ETL - Assembly	680,860	30088	17.02	1,145,013	397,283	1,542,296
CD1-v2-DR-402.8.4.4 ETL - System Testing	79,561	6322	3.58	103,418	38,340	141,759
CD1-v2-DR-402.8.4.5 ETL - Integration and Commissionin	93,300	22574	12.77	262,676	88,467	351,143

BTL SiPM Cost Drivers

Charge #3

CMS Driver	Labor (FTE-yrs)	Labor (M$)	M&S (M$)	Labor + M&S (M$)	Estimate Uncertainty (M$)	Total (M$)
TL - ETL frontend ASIC development (v3) - M&S	0.0	0.0	1.9	1.9	0.3	2.2
TL - ETL frontend ASIC prototyping (v2) - Labor	7.7	1.2	0.0	1.2	0.5	1.7
TL - ETL module assembly	11.3	0.3	0.8	1.1	0.4	1.5
TL - BTL LYSO crystals [CORE]	0.0	0.0	1.2	1.2	0.2	1.4
TL - BTL assembly	10.8	0.6	0.4	1.0	0.4	1.4
→ TL - BTL SiPM production [CORE]	0.0	0.0	1.0	1.0	0.2	1.2
TL - BTL Concentrator Cards - production	1.6	0.2	0.5	0.7	0.2	0.9
TL - ETL frontend ASIC development (v3) - Labor	3.7	0.5	0.0	0.5	0.2	0.7
→ TL - BTL SiPM QC labor	3.0	0.5	0.0	0.5	0.1	0.6
TL - BTL installation and commissioning	3.0	0.1	0.2	0.3	0.1	0.4
TL - Management Travel and misc. support M&S	0.0	0.0	0.3	0.3	0.0	0.4
TL - BTL Concentrator Cards - prototyping and preproduction	1.3	0.2	0.1	0.3	0.1	0.4
TL - ETL installation and commissioning	1.1	0.2	0.1	0.3	0.1	0.4
TL - ETL frontend ASIC prototyping (v2) - M&S	0.0	0.0	0.3	0.3	0.0	0.3
TL - iCMS common infrastructure [CORE]	0.0	0.0	0.2	0.2	0.1	0.3
TL - BTL system testing	0.1	0.0	0.1	0.1	0.0	0.2
TL - ETL system testing	0.0	0.0	0.1	0.1	0.0	0.1
TL - BTL SiPM NRE and preproduction SiPMs [CORE]	0.0	0.0	0.1	0.1	0.0	0.1
TL - BTL SiPM prototyping and preproduction - misc.	0.0	0.0	0.1	0.1	0.0	0.1
TL - BTL LYSO travel and COLA	0.0	0.0	0.1	0.1	0.0	0.1
TL - BTL SiPM travel and shipping	0.0	0.0	0.1	0.1	0.0	0.1

- Two main cost drivers:
  - SiPM purchase – based on recent vendor quote
  - SiPM labor – based on previous experience with HCAL upgrade

BTL SiPM Risks

Charge #3

Risk Rank	RI-ID	Title	Probability	Schedule Impact	Cost Impact	P * Impact (k$)
⊞ **WBS / Ops Lab Activity : 402.8 TL - Timing Layer (general risks)** (3)						
⊟ **WBS / Ops Lab Activity : 402.8.3 BTL - Barrel Timing Layer** (15)						
⊟ Risk Type : Threat (15)						
2 (Medium)	RT-402-8-05-D	BTL - Change in interfaces of tray assembly components	20 %	3 months	150 -- 250 -- 350 k$	50
2 (Medium)	RT-402-8-33-D	BTL - Difficulties procuring LYSO from international suppliers	10 %	3 -- 6 -- 9 months	200 -- 450 -- 700 k$	45
2 (Medium)	RT-402-8-14-D	BTL - Problems with SiPM vendor	20 %	2 -- 6 -- 8 months	32 -- 96 -- 128 k$	17
2 (Medium)	RT-402-8-30-D	BTL - Concentrator Card requires significant design changes	10 %	1 -- 3 -- 6 months	1 -- 50 -- 100 k$	5
2 (Medium)	RT-402-8-07-D	BTL - Concentrator Card delay in external component deliveries	20 %	1 -- 3 -- 6 months	0 k$	0
1 (Low)	RT-402-8-15-D	BTL - Batch shipment of SiPMs lost in transport	5 %	1 months	224 k$	11
1 (Low)	RT-402-8-35-D	BTL - Delays or damage of tray in transport to CERN	5 %	1 months	220 k$	11
1 (Low)	RT-402-8-04-D	BTL - LYSO matrices not meeting specifications	10 %	1 -- 2 -- 3 months	100 k$	10
1 (Low)	RT-402-8-36-D	BTL - Interface to iCMS changes	20 %	1 -- 2 -- 3 months	30 k$	6
1 (Low)	RT-402-8-34-D	BTL - Delay in delivery of components from iCMS	20 %	1 -- 2 -- 3 months	10 -- 20 -- 30 k$	4
1 (Low)	RT-402-8-08-D	BTL - Delay in cooling plate delivery	10 %	1 -- 2 -- 3 months	10 -- 20 -- 30 k$	2
1 (Low)	RT-402-8-18-D	BTL - Concentrator card production & testing facility problem	20 %	0.5 -- 1 -- 2 months	10 k$	2
1 (Low)	RT-402-8-42-D	BTL - Problems with module assembly site	10 %	1 -- 2 -- 3 months	10 -- 20 -- 30 k$	2
1 (Low)	RT-402-8-16-D	BTL - Problems with SiPM QC test site	20 %	0.25 -- 0.5 -- 1 months	2 -- 5 -- 10 k$	1
1 (Low)	RT-402-8-44-D	BTL - Concentrator Card batch shipment lost/damaged/delayed	5 %	0 -- 0.5 -- 1 months	0 -- 3 -- 9 k$	0
⊞ **WBS / Ops Lab Activity : 402.8.4 ETL - Endcap Timing Layer** (12)						

- Problems with SiPM Vendor
  - If production SiPMs don't meet specs, estimate a 6 month delay
  - If other vendor problems slow production, estimate 2-8 month delay
  - Mitigate by doing a preproduction run, and possibly by splitting the order between two vendors if quality/price are comparable

Contributing Institutions and Resource Optimization

Contributing Institutions

Charge #4

- University of Notre Dame
  - Past experience: Successfully carried out the SiPM R&D, production and QA/QC for the HE and HB Phase I upgrades
  - Key Personnel
    - Arjan Heering: Extensive experience with SiPMs and associated readout electronics since the early days of CMS HCAL. Developed the packaging for the HE/HB SiPMs.
    - Yuri Musienko: Expert in photodetectors, many years of experience within CMS, first with ECAL and then with the Phase I HCAL upgrades. Developed the test stands and QA/QC procedures for the HE/HB SiPM projects.

Quality Assurance and Quality Control

- Based on our experience with the HCAL Phase I upgrade, the production QA/QC plans are as follows:
- For every channel (~175k) we will measure:
  - IV curves with and without illumination
  - Forward resistance
- For 2% of the channels in each batch we will measure
  - Capacitance
  - Pulse shape
- For 1% of the channels in each batch we will perform destructive tests, including
  - Radiation studies
  - Long term aging studies
  - Environmental studies (temp. cycling, humidity, etc)
- See CMS-doc-13093

Summary

- An experienced team is in place to carry out the R&D, preproduction and 50% of the production SiPM QA/QC for the Barrel Timing Layer (BTL)
- There is an active R&D program underway to determine the optimal candidate SiPM for the BTL
- Existing facilities and test stations will be modified for the preproduction and full production testing
- A reasonable and achievable schedule has been developed for this effort that matches the needs and expectations of the overall BTL project

Backup

Charge #6

ES&H

- 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)
- We are following our Integrated Safety Management Plan (cms-doc-13395) and have documented our hazards in the preliminary Hazard Awareness Report (cms-doc-13394)
- In General Safety is achieved through standard Lab/Institute practices
  - No construction, accelerator operation, or exotic fabrication
  - No imminent peril situations or unusual hazards
  - Items comply with local safety standards in site of fabrication and operation
  - Site Safety officers at Institutes identified in the SOW
- There are no Specific Hazards for 402.3.8.2
  - Our R&D and QA/QC efforts will take place in lab settings that follow standard safety procedures.

Charge #4

Resource Optimization

- The extensive experience with the HCAL Phase I upgrades and with other CMS projects makes the Notre Dame SiPM group the natural choice to carry out this effort for the BTL
  - The testing and characterization of the SiPMs will be carried out at CERN, in the same labs used for HCAL Phase I
  - Existing test stations can be modified and used for the BTL
  - Equipment exists for long term aging and environmental studies
  - We have multiple options for irradiating SiPMs – Ljubljana reactor, Dubna, CHARM, IRRAD
  - We have a long, positive working relationship with both SiPM vendors under consideration
    - The SiPMs will be fabricated and packaged at the vendor, who will also carry our some preliminary testing