B02: In-depth: BTL SiPMs

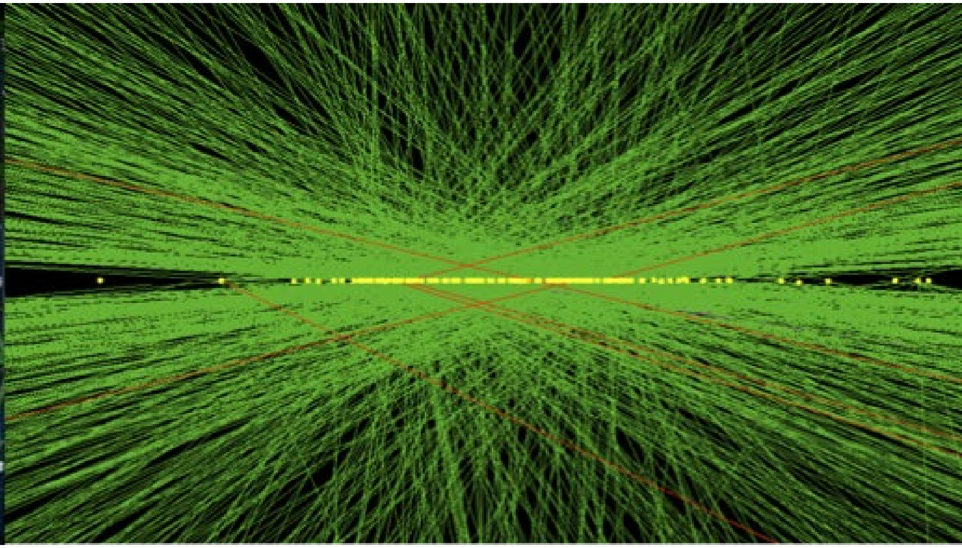
402.8.3.2

Mitch Wayne

University of Notre Dame

HL-LHC CMS CD-1 Review

23 October 2019



Brief Biographical Introduction

- Mitch Wayne, Professor, University of Notre Dame
  - Within US MTD, Level 4 manager of the BTL SiPM project
  - 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
  - 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.

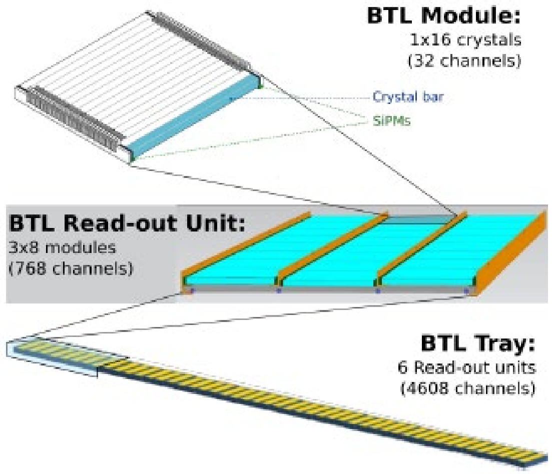
Outline

- 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 SiPM channel count is 331,776
  - With 5% spares the total number of SiPMs is 348,365



- The US MTD project is responsible for the purchase of 57% of the SiPMs ($1.6M), as well as 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 200,00 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 Focus

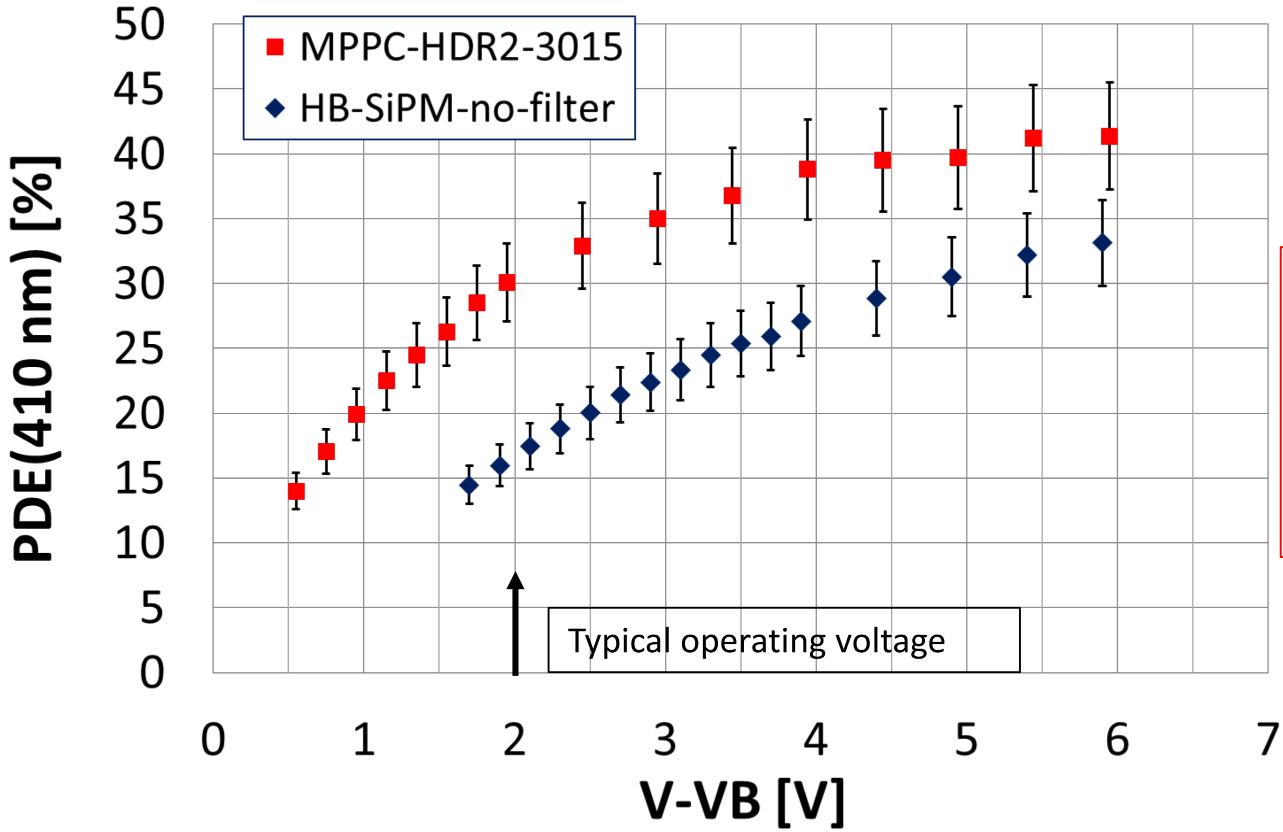
Charge #1,2

- The HE/HB SiPM from Hamamatsu has been tested extensively and is well understood
- Studies show that HE/HB SiPM could meet the timing requirements for the BTL, but there would be little margin for error
- We have been actively working with two vendors (Hamamatsu and FBK) to improve upon this device's performance
- This 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 (DCR)
    - Design a cost effective package that accurately 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 - HPK

Charge #1,2

- HPK has improved upon the PDE of the HE/HB SiPM

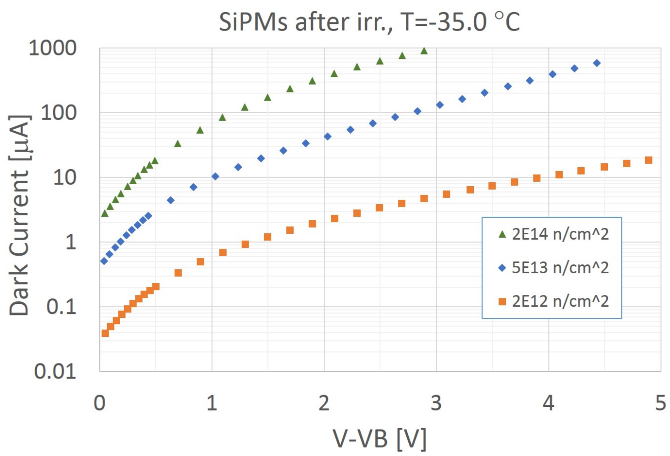


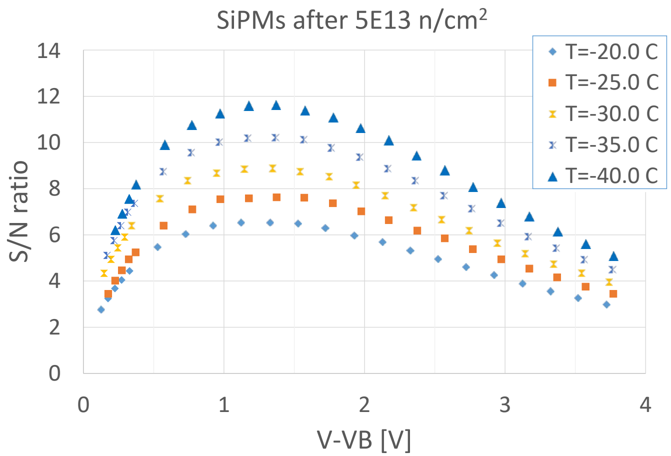
New 15 micron SiPM from Hamamatsu (red points) with significant increase in PDE compared with HB SiPM (blue points)

R&D Achieved

Charge #1,2

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



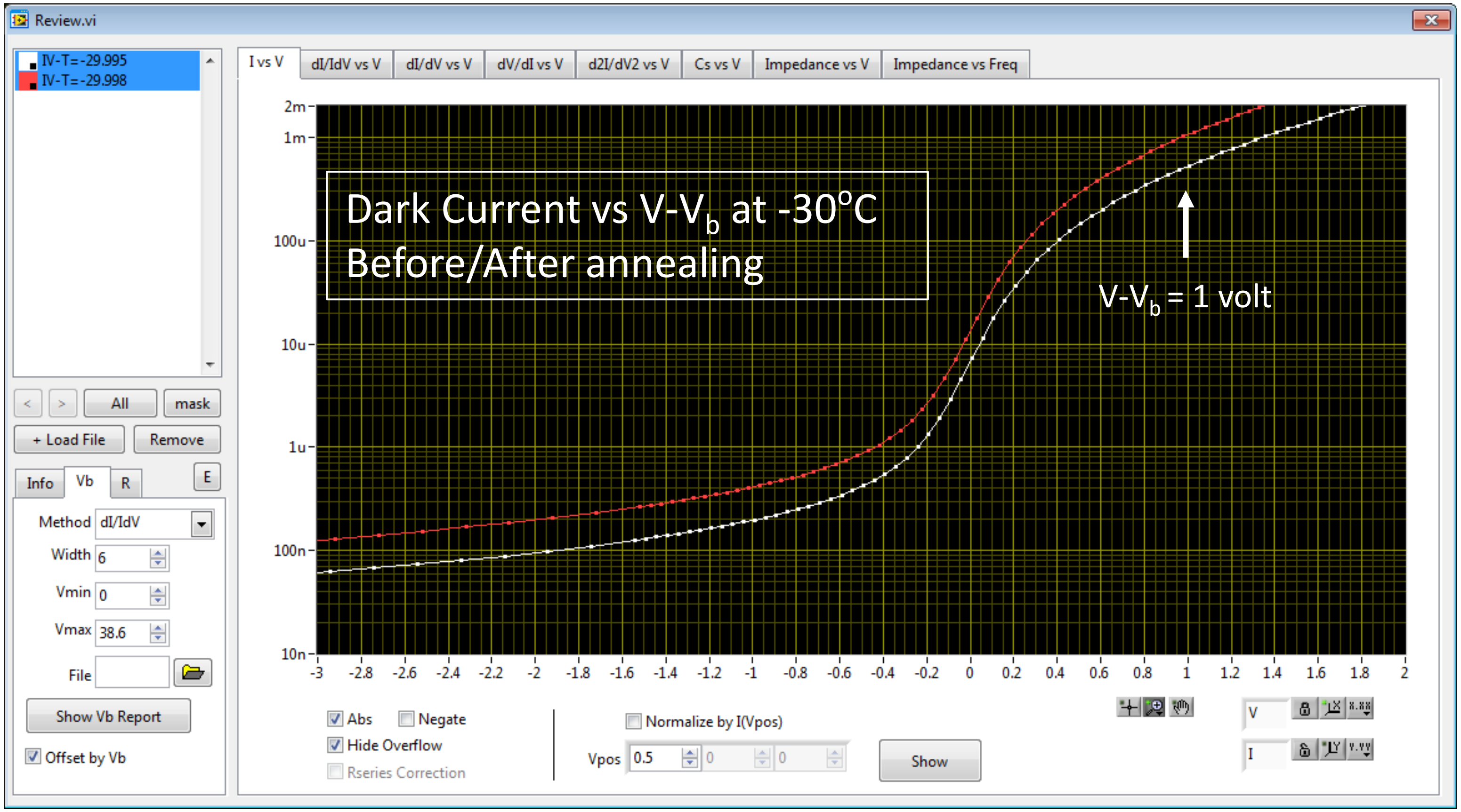


- Irradiations of several candidate from FBK and HBK SiPMs were carried out at the Ljubljana reactor in early 2019.
  - SiPMs still work after dose of 2E14 one-MeV neutrons/cm^2 equivalent, corresponding to 3,000 fb^{-1} integrated luminosity
  - Dark currents are consistent with predicted values
  - SiPM power consumption after 2E14 dose is within design limit

R&D Achieved – Annealing of SiPMs

Charge #1, 2

Hamamatsu HDR2 after 5E13: Annealed for 80 minutes at 60°C

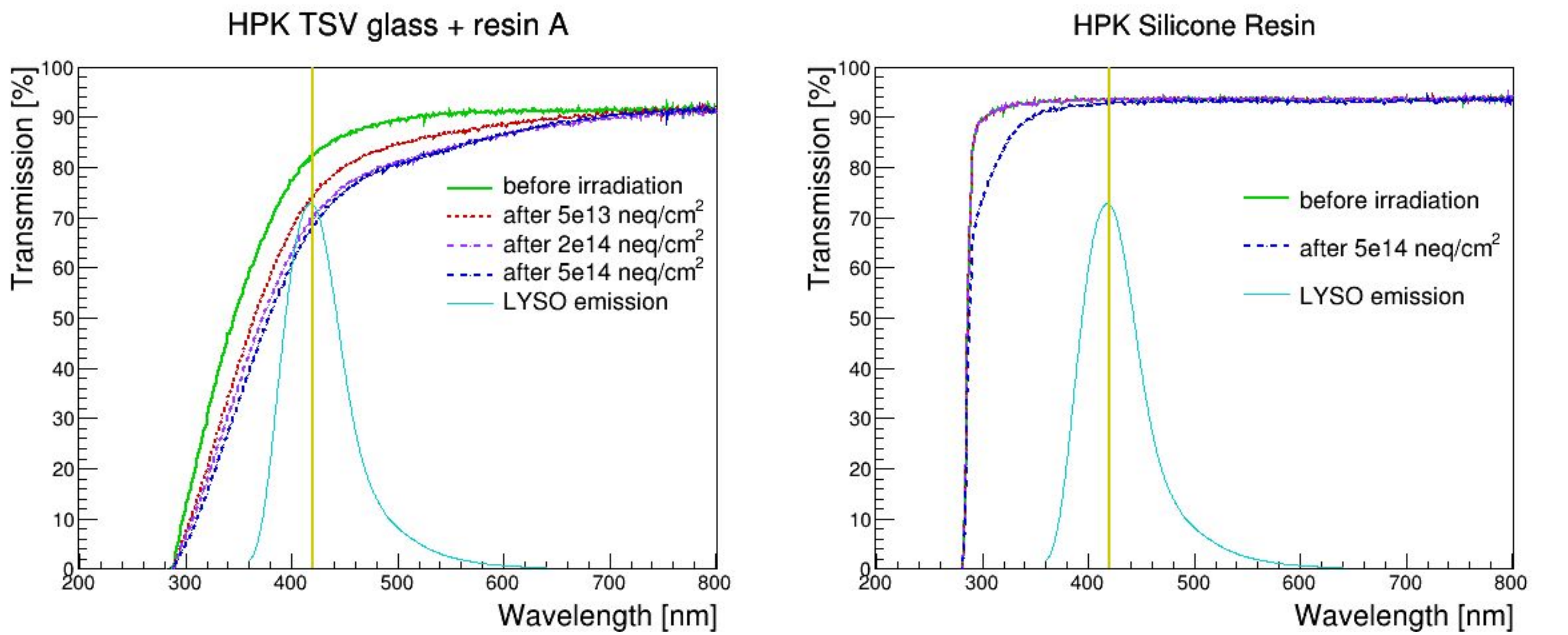


- Factor of two reduction in dark current
- BTL is studying how to optimize SiPM annealing during operation

R&D Achieved – SiPM Coating Optimized

Charge #1, 2

300 µm thick TSV glass and silicon resin irradiated with neutrons at JSI



Glass shows before/after loss of ~20%. Transmission after 2E14 down to ~70%. Silicon resin shows almost no loss of transmission up to 5E14 neutrons. Silicon also maintains good transmission after radiation with protons and gammas.

Charge #2, 4

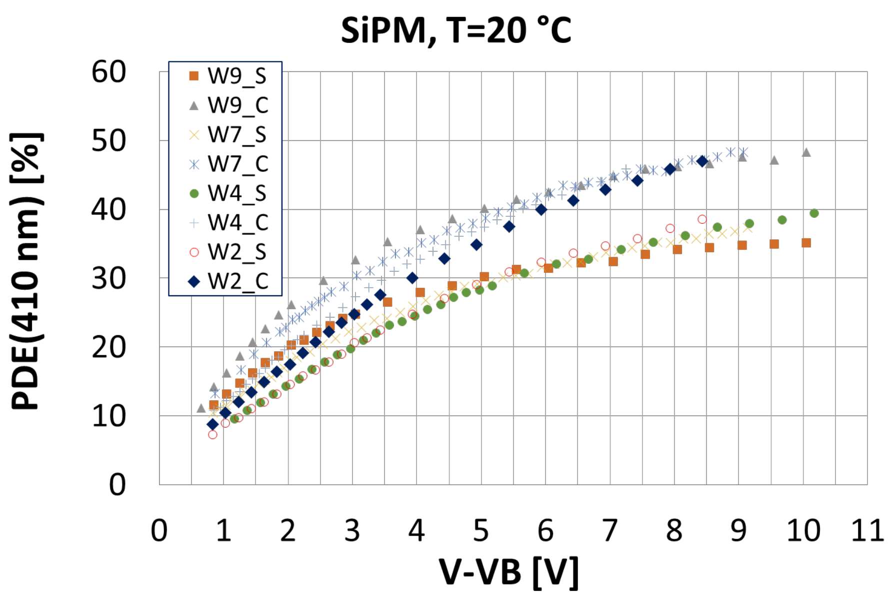
Current Prototype Studies

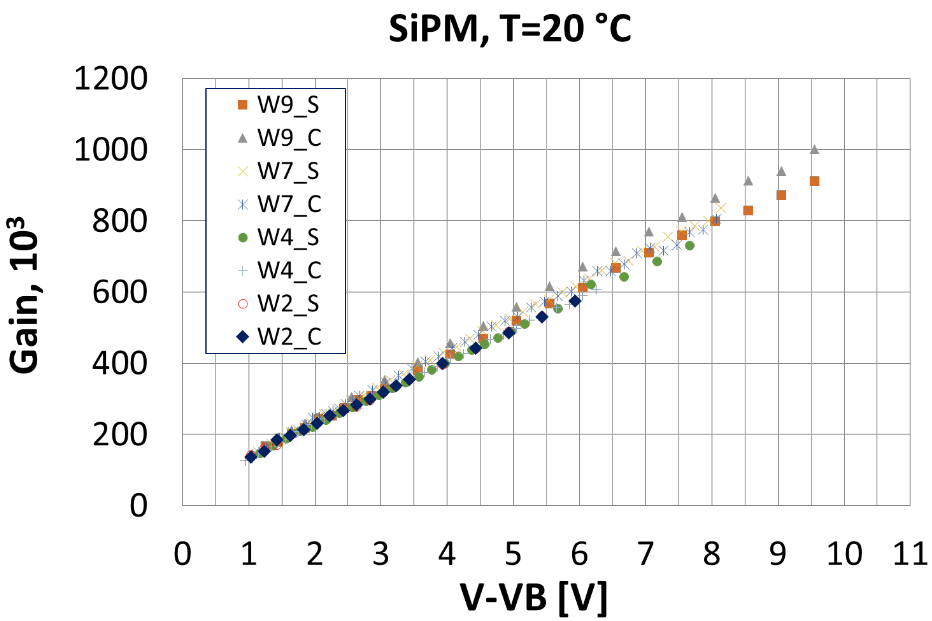
- Based on our studies early in 2019 and after consultation with the BTL SiPM team, FBK fabricated several SiPMs varying both the internal structure and silicon doping.
- A new round of irradiations were carried out at the Ljubljana reactor in late summer 2019, with doses up to 4E14 one MeV neutron/cm^2 equivalent – a factor of two greater than expected for the BLT at end-of-life. This included both the new FBK SiPMs and the HDR2 from Hamamatsu.
- Irradiated SiPMs from both HPK and FBK recently arrived at CERN and measurements are underway. At this time we have preliminary results at lower dose (1.4E13), with results from higher doses to come soon.
- Key parameters to compare:
  - Loss of intrinsic QE (if any) at the highest doses
  - Signal-to-noise
  - Power consumption at optimal $V - V_b$

Current prototype studies

Charge #2, 4

FBK results after irradiation to 1.4E13

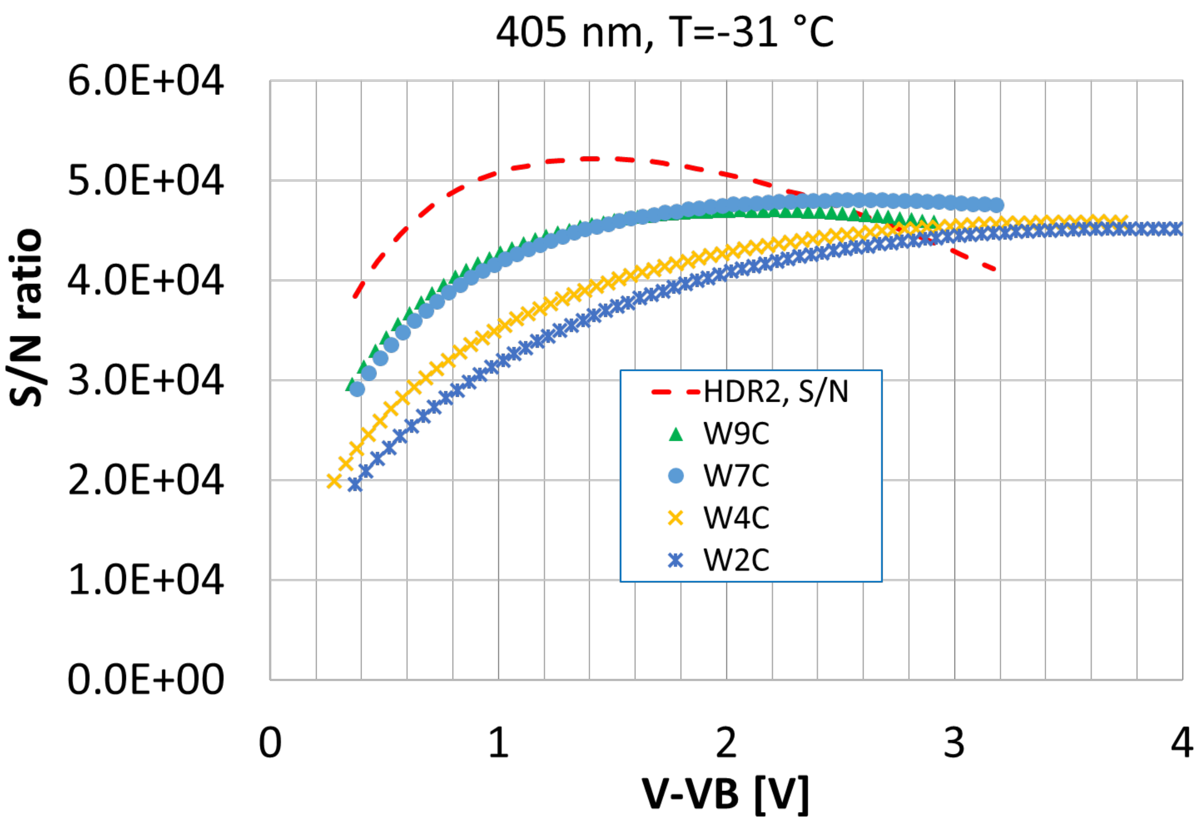




- Several candidates show marked improvement in PDE
- Good uniformity of gain across all 8 different SiPM candidates

Current prototype studies

Charge #2, 4



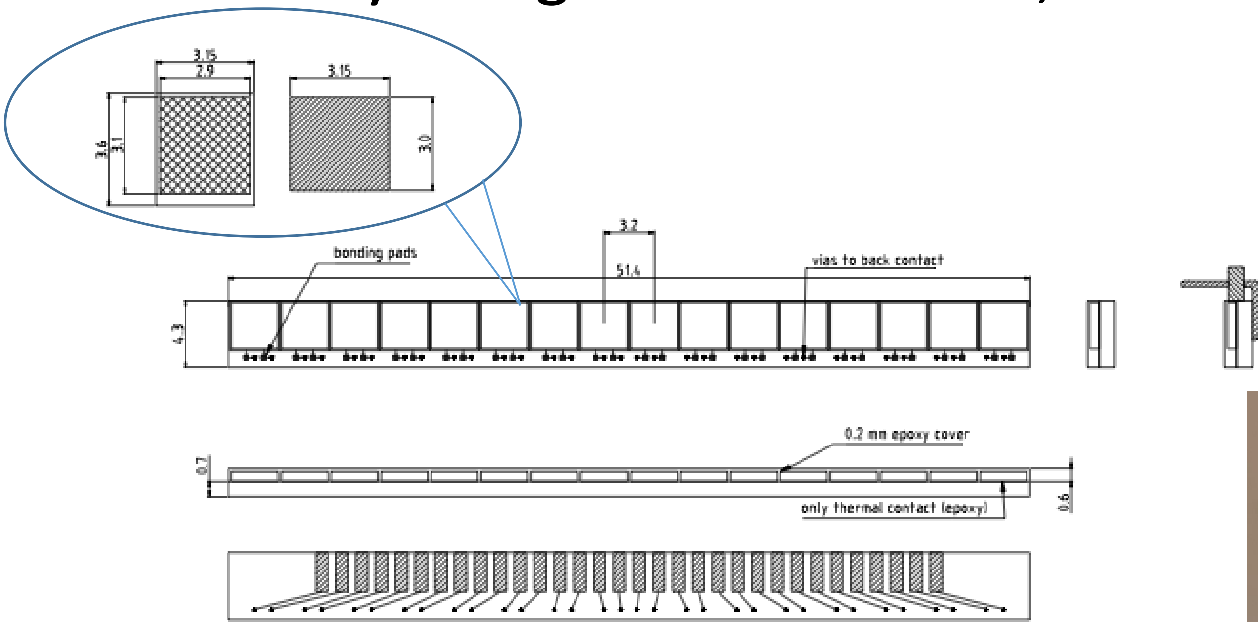
Comparison after irradiation to 1.4 E13

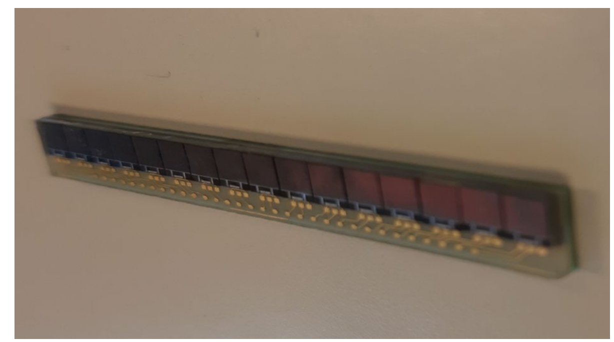
- Based on S/N comparison two FBK designs (W9C and W7C) have been chosen for packaging and further studies, along with the HDR2 from Hamamatsu
- We expect to have acceptable candidate SiPMs from both HPK and FBK by the time of our readiness review in January 2020

Charge #2, 4

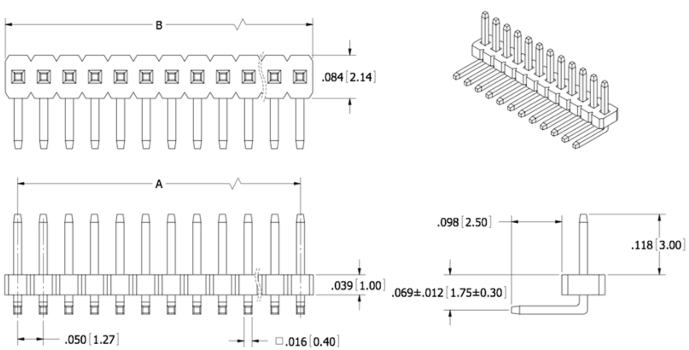
R&D needed before production

- Preliminary design of 16 channel, ceramic package





Prototype BTL 16-channel Package

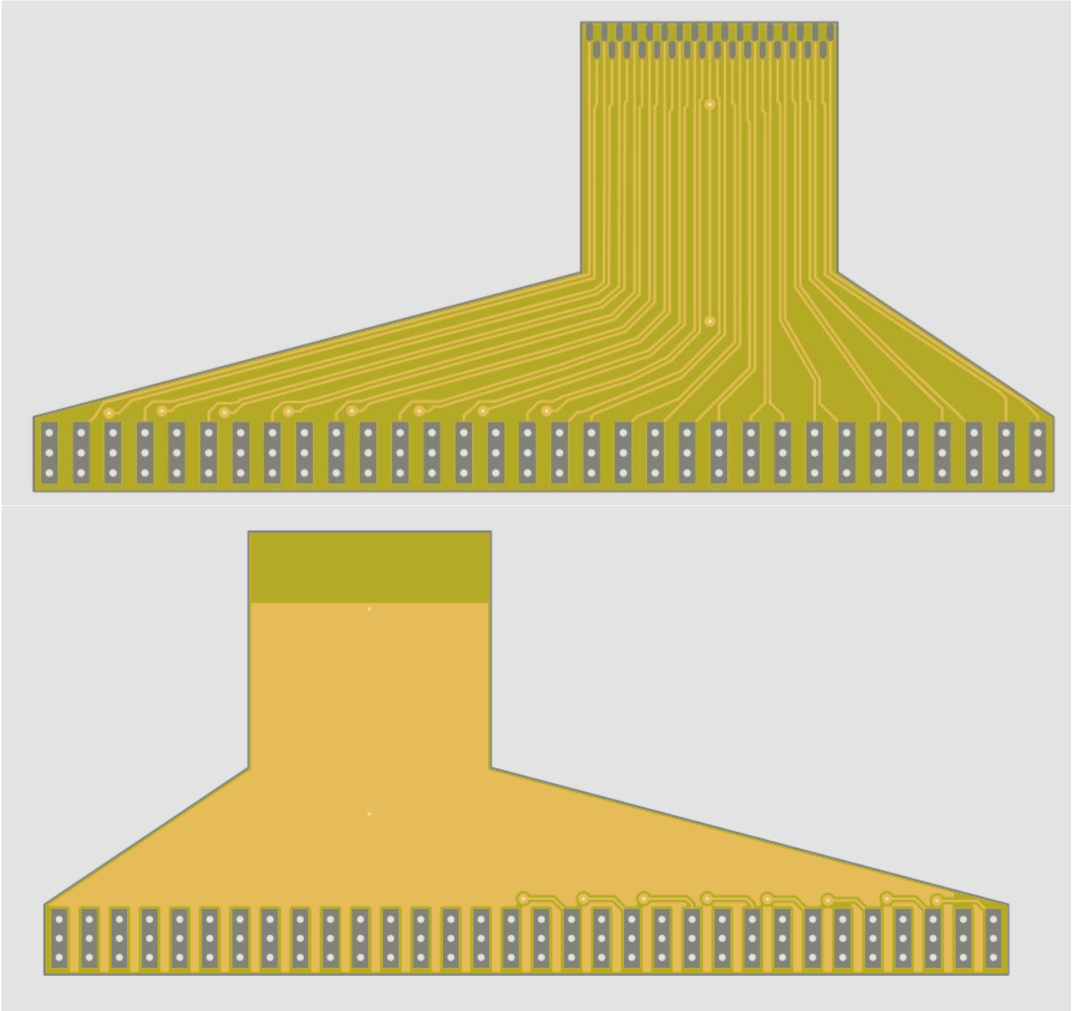


estimated thermal conductivity

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

R&D needed before production

- Alternate design replaces rigid connector with a flex circuit

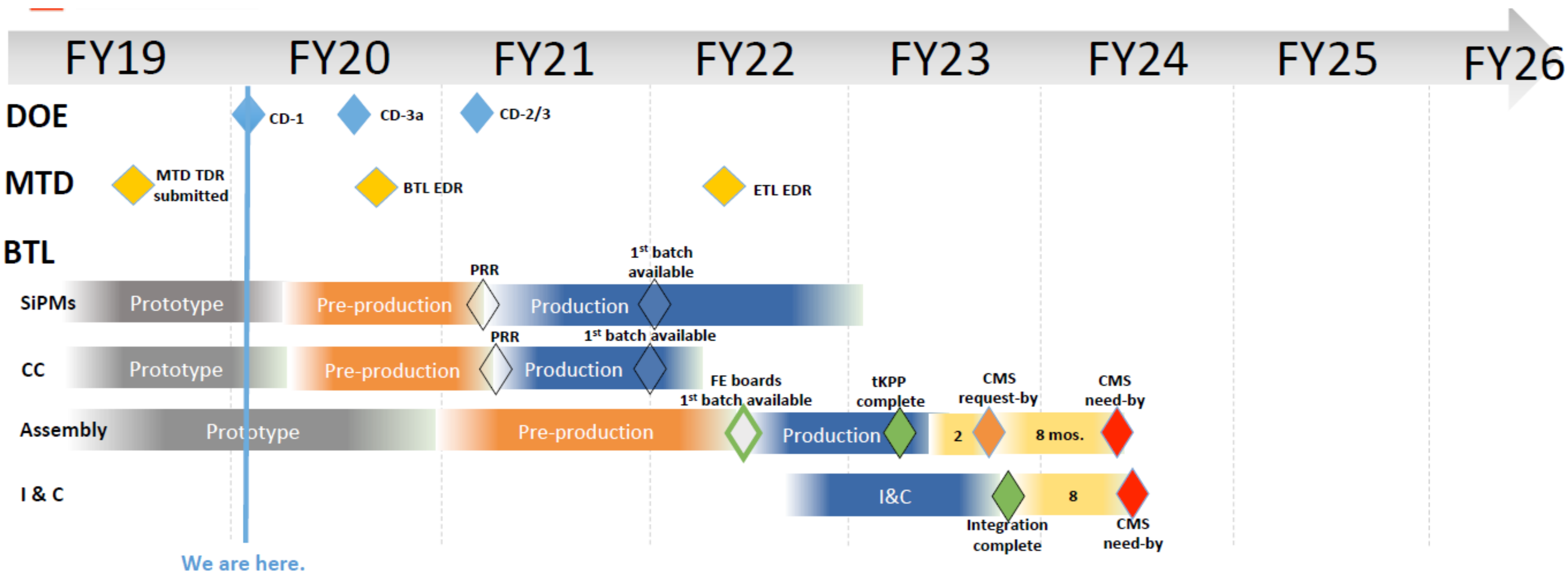


Flex circuit would attach to back of the SiPM package. Assembly done at the SiPM vendor.

Package design will be optimized over the next several months.

Schedule and Cost

BTL Schedule in P6



HL-LHC US CMS

SiPM Schedule Overview

Charge #3

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

- Testing and characterization 100% complete – October 2022

BTL SiPM – Labor Costs from BOE

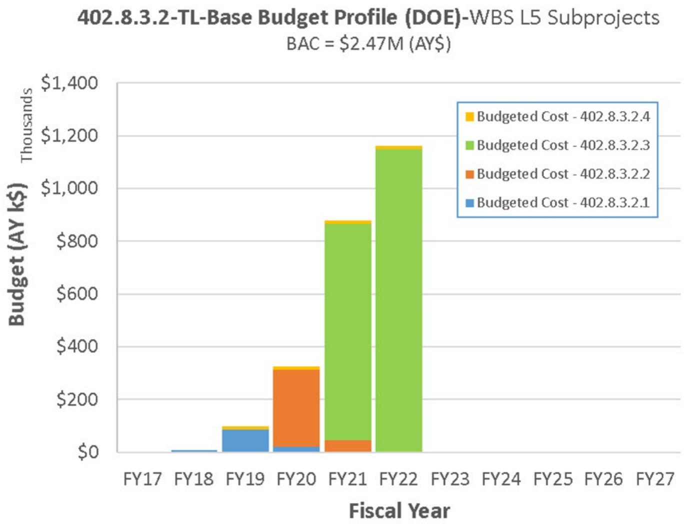
WBS - Name	BoE Ref	Name	Labor Type	Est. Type	Institute	Total Hours
402.8.3.2.1 BTL - SiPMs - Prototyping	CMS-doc-13590-LBR-001	SiPMs - Test Stands Development	EN	L1	ND	140
			TE	L1	ND	40
	CMS-doc-13590-LBR-002	SiPMs - Prototype Testing	EN	L1	ND	340
	CMS-doc-13590-LBR-003	SiPMs - Packaging	EN	L4	ND	240
	CMS-doc-13590-LBR-004	SiPMs - Reporting and Reviews	EN	L2	ND	120
402.8.3.2.1 Total						**880**
402.8.3.2.2 BTL - SiPMs - Preproduction	CMS-doc-13590-LBR-005	SiPMs - Procurement	EN	L3	ND	80
	CMS-doc-13590-LBR-006	SiPMs - Test Stands Fabrication	EN	L4	ND	280
				L3	ND	40
			TE	L4	ND	400
				L3	ND	160
	CMS-doc-13590-LBR-007	SiPMs - Database Development	TE	L3	ND	160
	CMS-doc-13590-LBR-008	SiPMs - Preproduction Testing	EN	L3	ND	700
			TE	L2	ND	80
	CMS-doc-13590-LBR-009	SiPMs - Reporting and Reviews	EN	L2	ND	120
402.8.3.2.2 Total						**2,020**
402.8.3.2.3 BTL - SiPMs - Production	CMS-doc-13590-LBR-010	SiPMs - Procurement	EN	L4	ND	80
	CMS-doc-13590-LBR-011	SiPMs - Production Testing and QA/QC	EN	L4	ND	180
				L3	ND	360
			TE	L4	ND	720
				L3	ND	360
	CMS-doc-13590-LBR-012	SiPMs - Test Stands Maintenance	TE	L2	ND	72
	CMS-doc-13590-LBR-013	SiPMs - Packing and Shipping	TE	L2	ND	72
	CMS-doc-13590-LBR-014	SiPMs - Production Testing and QA/QC	EN	L3	ND	280
			TE	L2	ND	360
402.8.3.2.3 Total						**2,484**
Grand Total						**5,384**

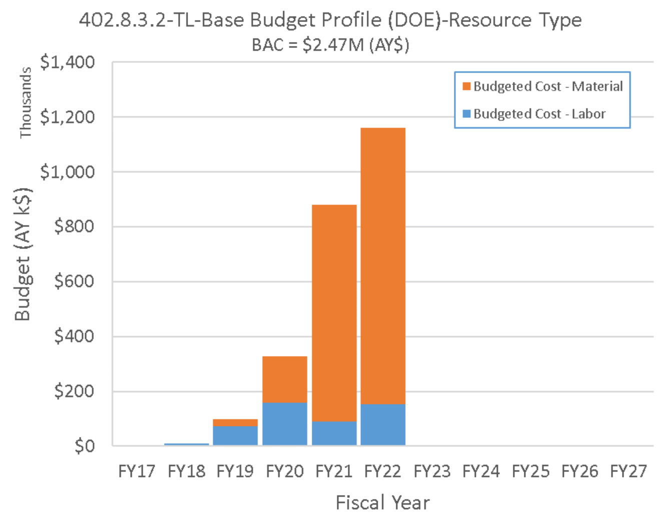
BTL SiPM - M&S Costs from BOE

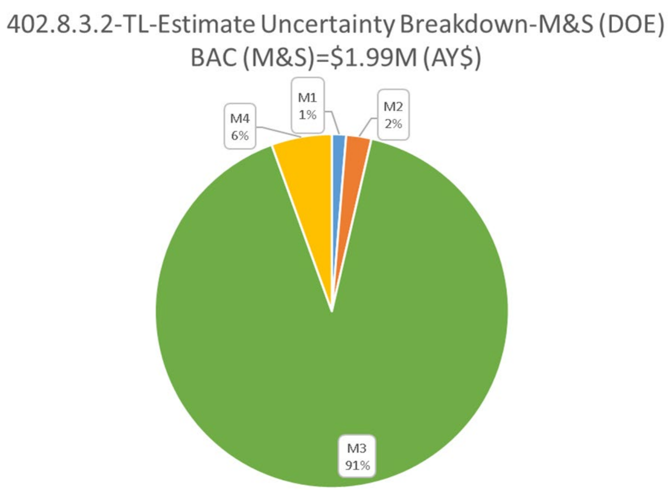
WBS - Name	BoE Ref	Name	Est. Type	Institute	Direct M&S
402.8.3.2.1 BTL - SiPMs - Prototyping	CMS-doc-13590-MS-001	SiPMs - Test Stands Development	M1	ND	10,000
402.8.3.2.1 Total					**10,000**
402.8.3.2.2 BTL - SiPMs - Preproduction	CMS-doc-13590-MS-002	SiPMs - Preproduction Devices	M3	ND	42,500
	CMS-doc-13590-MS-003	SiPMs - Preproduction NRE	M4	ND	40,000
	CMS-doc-13590-MS-004	SiPMs - Test Stands Fabrication	M4	ND	50,000
402.8.3.2.2 Total					**132,500**
402.8.3.2.3 BTL - SiPMs - Production	CMS-doc-13590-MS-005	SiPMs - Production Devices	M3	ND	1,600,000
	CMS-doc-13590-MS-006	SiPMs - Packing and Shipping	M2	ND	4,500
402.8.3.2.3 Total					**1,604,500**
402.8.3.2.4 BTL - SiPMs - Travel and COLA	CMS-doc-13590-MS-007	SiPMs - Domestic Travel and COLA	M2	ND	4,500
			M1	ND	1,500
	CMS-doc-13590-MS-008	SiPMs - International Travel and COLA	M2	ND	24,300
			M1	ND	8,100
402.8.3.2.4 Total					**38,400**
Grand Total					**1,785,400**

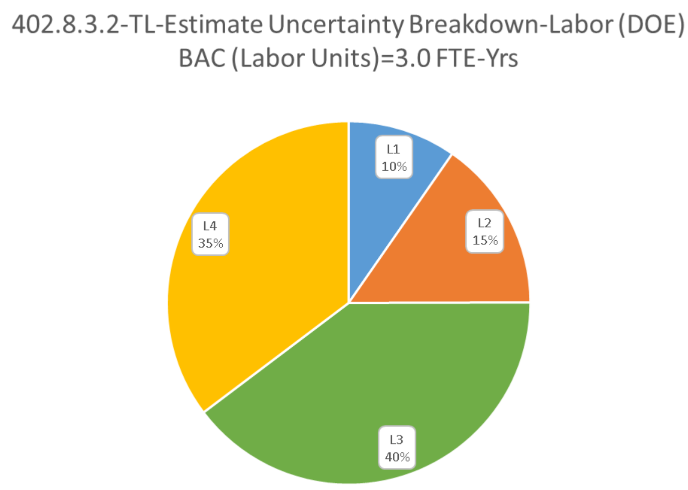
- Total SiPM cost (M&S plus Labor): $2,867,005 including an estimate uncertainty of $392,929 based on SiPM production quote from HPK and prior HCAL experience

BTL SiPM Cost Breakdowns









BTL Risks

WBS / Ops Lab Activity : 402.8.3 BTL - Barrel Timing Layer (14)

Risk Rank : 3 (High) (2)						
RT-402-8-30-D	BTL - Concentrator Card requires significant design changes	50 %	40 -- 135 -- 175 k$	1 -- 3 -- 6 months	58	1.7
RT-402-8-07-D	BTL - Concentrator Card delay in external component deliveries	50 %	50 k$	3 -- 6 -- 9 months	25	3.0
Risk Rank : 2 (Medium) (4)						
RT-402-8-05-D	BTL - Change in interfaces of tray assembly components	20 %	150 -- 250 -- 350 k$	3 months	50	0.6
RT-402-8-46-D	BTL - Problems with sensor gluing facility	50 %	90 k$	1 -- 2 -- 3 months	45	1.0
RT-402-8-33-D	BTL - Difficulties procuring LYSO from international suppliers	10 %	100 -- 250 -- 400 k$	3 -- 6 -- 9 months	25	0.6
→ RT-402-8-14-D	BTL - Problems with SiPM vendor	20 %	32 -- 96 -- 128 k$	2 -- 6 -- 8 months	17	1.1
Risk Rank : 1 (Low) (8)						
→ RT-402-8-15-D	BTL - Batch shipment of SiPMs lost in transport	5 %	224 k$	1 months	11	0.1
RT-402-8-35-D	BTL - Delays or damage of tray in transport to CERN	5 %	220 k$	1 months	11	0.1
RT-402-8-04-D	BTL - LYSO matrices not meeting specifications	10 %	100 k$	1 -- 2 -- 3 months	10	0.2
RT-402-8-36-D	BTL - Interface to iCMS changes	20 %	30 k$	1 -- 2 -- 3 months	6	0.4
RT-402-8-34-D	BTL - Delay in delivery of components from iCMS	20 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	4	0.4
RT-402-8-18-D	BTL - Concentrator card production & testing facility problem	20 %	10 k$	0.5 -- 1 -- 2 months	2	0.2
RT-402-8-08-D	BTL - Delay in cooling plate delivery	10 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	2	0.2
RT-402-8-42-D	BTL - Problems with module assembly site	10 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	2	0.2

- Two risks in register – 1 medium and 1 low

BTL SiPM Risks

- Details of SiPM Medium Level Risk:

RT-402-8-14-D BTL - Problems with SiPM vendor

Risk Rank:	2 (Medium) **Scores:** Probability : 2 (L) ; Cost: 1 (L) Schedule: 3 (H))	**Risk Status:**	Open
Summary:	This is a general catagory that includes multiple problems associated with the SiPM vendor. 1) If the production SiPMs do not meet specifications due to a processing error at the vendor, then there will be a six month delay in the schedule for testing and characterizing the SiPMs. This may impact the overall project schedule and cost. 2) If the production of SiPMs is delayed at the vendor, that delay will propogate to the SiPM testing and characterization schedule, and in turn the overall project schedule.		
Risk Type:	Threat	**Owner:**	Mitchell Wayne
WBS:	402.8.3 BTL - Barrel Timing Layer	**Risk Area:**	External Risk / Vendors
Probability (P):	20%	**Technical Impact:**	2 (M) - significantly substandard
Cost Impact:	PDF = 3-point - triangular Minimum = 32 k$ Most likely = 96 k$ Maximum = 128 k$ Mean = 85.3 k$ P * <Impact> = 17.0 k$	**Schedule Impact:**	PDF = 3-point - triangular Minimum = 2.0 months Most likely = 6.0 months Maximum = 8.0 months Mean = 5.33 months P * <Impact> = 1.066 months
Basis of Estimate:	1) In the event the production SiPMs do not meet specifications, we estimate a 6 month schedule delay to produce a new set of production SiPMS. This delay includes fabrication of new wafers, testing and packaging of the SiPMs. The cost impact will be 6 months of half-time support for two engineering physicists. 2) In the event delivery of the production SiPMs is delayed by some amount of time, we estimate the impact from a minimal delay of 2 months up to a maximum delay of 8 months. The cost impact will be additional support for two engineering physicists for each month of delay.		
Cause or Trigger:		**Impacted Activities:**	Risk could delay any batch of SiPM QC
Start date:	1-Oct-2019	**End date:**	18-Jan-2022
Risk Mitigations:	Work with vendor to establish quality and good yield through prototype and preproduction SiPM runs. Could use multiple (currently there are 2) vendors if the quality is comparable.		
Risk Responses:	1) In the event of SiPMs not meeting specifications, work with vendor to identify the source of the problem, then restart the production process. 2) In the event of a delay in SiPM delivery, work to the extent possible to speed up testing and characterization once they are delivered.		
More details:			

Contributing Institutions and Resource Optimization

Charge #4

Contributing Institutions

- 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 at -30^{o}C
  - 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

HL-LHC US CMS

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)
- 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.

Resource Optimization

Charge #4

- 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 out some preliminary testing