IceCube Upgrade: Risks & Risk Registry

IceCube Upgrade NSF Rebaselining Review

26-28 April 2022

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Upgrade Technical Coordinator

Charge Question M1

Brief Bio

- Technical Coordinator for the IceCube Upgrade
- 10+ years with WIPAC science & engineering and the IceCube Collaboration (2010-)
- 25+ years of experience with spacecraft, balloon, remote observatory, particle detector, and telescope hardware (1993-)
- 25+ years of fieldwork leadership (1996-), >10 Antarctic excursions
- Successful project construction experience as a senior designer: Pierre Auger Observatory, ANITA/CREAM/CREST balloon payloads, ARA experiment, HAWC Observatory
- As a junior participant: Ulysses HET, CRRES satellite, HEAT balloon experiment, MINOS

Main Technical Issues/Response Summary

- Accepted mDOM high radioactivity PMTs
  - Did not exercise enough oversight during PMT production, at least partially due to COVID travel restrictions
  - Some noise data can be mitigated in firmware and software (ongoing work)
  - Minimal physics impact
- Supply chain problems
  - Several impacts, especially electronics part availability on mDOM mainboards
  - Working to mitigate this with new designs and early purchases
- Drill control system progress
  - Held a status review
  - Will monitor progress over the next 9-10 months going into a final review.
  - The current plan ships hardware this season, with software design finalizing in early 2023

Risk Register

Risk Management Plan

- Based on the US GAO cost estimating guide, NSF Research Infrastructure Guide, and ANSI standard and industry best practice PM-Book of Knowledge
- Risk Register is built from the risks, organized by WBS and also by Risk Breakdown Structure (External, Organizational, PM, Technical)
- Risks are mitigated or accepted
- Evaluate their impact in cost and schedule of realized risks
- Monte Carlo is run for the full set of risks (threats and opportunities) using the @Risk tool within Excel
- Upgrade project takes the 80% confidence level for additional contingency required to cover the identified risks
- Mitigation and monitoring of risks continues

Risk Breakdown Structure

Risk Breakdown Structure

- **Technical**
  - **ES&H**
    Environmental, Safety, or Health issues
  - **Requirements**
    Requirements poorly defined, incomplete, late, or evolving. Changes in system architecture, specifications, deployment strategy.
  - **Technology**
    Technology must be developed or is beyond state of the art. Uncertainty due to e.g. obsolete parts, lack of support.
  - **Complexity and Interfaces**
    Design complexity renders manufacturing difficult. Workers insufficiently trained in the process. Interfaces ill-defined.
  - **Performance and Reliability**
    System after assembly does not meet performance or reliability requirements.
  - **Quality**
    Inconsistent quality between prototype/preproduction/production processes. QA/QC process inadequate and/or requires excessive time and/or resources.
- **External**
  - **Subcontractors and Suppliers**
    Failure of subcontractor or vendors to deliver on budget and on schedule.
  - **Regulatory**
    Risks due to changing regulations: e.g. inport/export controls, labor laws.
  - **Market**
    Change in availability of critical materials, foreign currency exchange, escalation.
  - **Collaborators**
    In-kind contributors fail to deliver. International partners have problems securing funding or materials.
  - **Weather**
    Project construction or deployment delayed due to weather events.
- **Organizational**
  - **Project Dependencies**
    Risk due to poor management of project dependencies, e.g. communication with NSF/AIL/ASC, international partners
  - **Resources**
    Critical personnel, equipment, or facilities, either on or off project, not available to the project when needed.
  - **Funding**
    Funding is inadequate or not matched to spending profile.
  - **Prioritization**
    Project lacks priority at collaborating institutions, vendors, subcontractors.
- **Project Management**
  - **Estimating**
    Errors in cost estimation due to e.g. errors with analogies, extrapolations, optimistic learning curves.
  - **Planning**
    Incomplete scope, cost, or schedule. Incorrect assumptions.
  - **Controlling**
    Inadequate or overly onerous tools or mechanisms for controlling project configuration.
  - **Communication**
    Not all stakeholders identified. Inadequate tools or processes to track and communicate project status.
  - **Logistics**
    Poor management of supply chain within or outside of the project; loss, damage, or delays in transit; customs/excise; unforeseen storage needs; unavailability of logistics resources.
  - **Experience/Capability**
    Management, technical, or other personnel lack required skills. Key technical capabilities not available within budget or schedule.

Impact x Probability = Rank

Probability	Impact Level				
	Very Low	Low	Moderate	High	Very High
Very High (75%-95%)	**Moderate Rank**	**Moderate Rank**	**High Rank**	**High Rank**	**High Rank**
High (50%-75%)	**Low Rank**	**Moderate Rank**	**High Rank**	**High Rank**	**High Rank**
Moderate	**Low Rank**	**Moderate Rank**	**Moderate Rank**	**High Rank**	**High Rank**
Low (5%-25%)	**Low Rank**	**Low Rank**	**Moderate Rank**	**Moderate Rank**	**Moderate Rank**
Very Low (1%-5%)	**Low Rank**	**Low Rank**	**Low Rank**	**Low Rank**	**Moderate Rank**

Scale for Impacts in each performance metric

	Very Low	Low	Moderate	High	Very High
Technical Impact	No impact	Somewhat substandard	Significantly substandard	Extremely substandard	Scientific objectives in jeopardy
Cost Impact	Less than $10k	$10k - $50k	$50k - $250k	$250k - $1M	> $1M
Schedule Impact	Less than 1 week	1 month	3 months	6 months	Greater than 6 months
Scope Impact	Scope decreases barely noticeable	Minor areas of scope affected	Major areas of scope affected	Scope reduction unacceptable to sponsor	Project item is effectively useless
Quality / Performance Impact	Quality / performance degradation barely noticeable	Only very demanding applications are affected	Quality / performance reduction requires sponsor approval	Quality / performance degradation unacceptable to sponsor	Project item is effectively useless

Risk Register

Charge Question R2 & R4

- Held a risk workshop (25 Jan 2022) and rebuilt the Risk Registry essentially from scratch for the re-baselined project (project office + L2s + SMEs)
- In parallel, we have the FMEA (more technical, hooked to quality rather than cost/schedule) and the cargo/logistics plan with analysis of schedule delays
- Total of 77 threats, 1 opportunity
- Will give a quick tour of the Risk Registry
  - Risks are re-evaluated semi-annually
  - New risks, or risk retirement, any time
  - Many significant risks are tied to drill season
  - Some risks are in logistics, out of direct control

WBS L2	Active Threats	Retired Threats
1.1	10	7
1.2	35	4
1.3	10	6
1.4	15	1
1.5	2	2
1.6	5	3
Total	77	23

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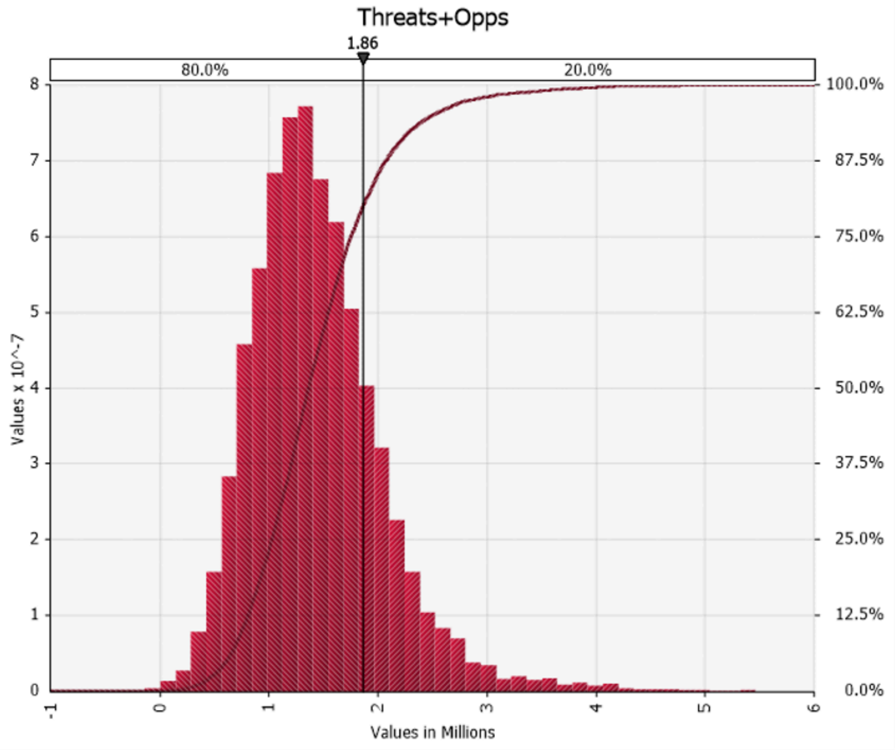
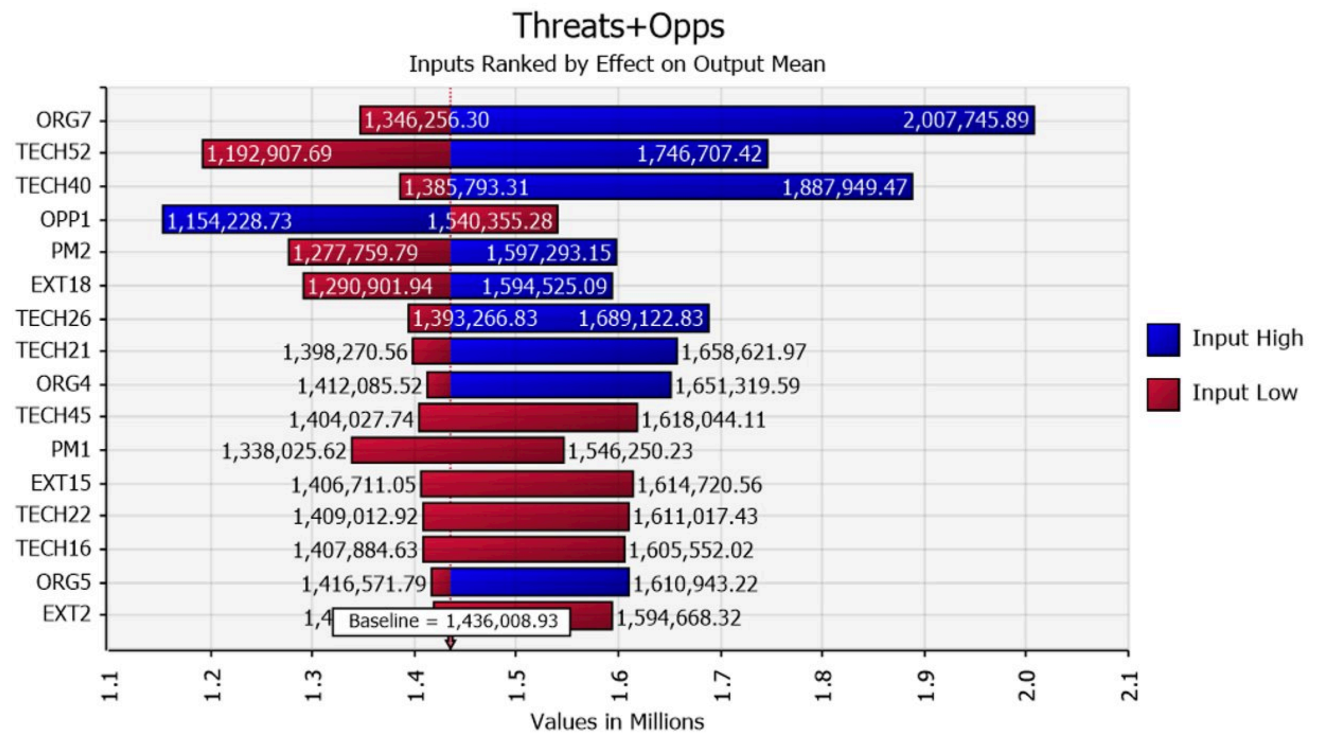
Risk Monte Carlo (@risk)





	Confidence Level		
	70%	80%	90%
All Threats + Opportunities	$1,663,149	$1,861,241	$2,170,439

UPGRADE

Top Five Risks (we can look at others in the RR directly)

		Risk Identification and Tracking	Major Risk Flag	Post-Mitigated Risk Evaluation							Comments / Notes	Risk Cost Exposure		
				Probability and Impacts				Exposure				NSF $		
Risk ID	Associated WBS	Risk Description		Risk Probability	Impact on schedule	Impact on cost	Impact on technical performance	Schedule Risk Score	Cost Risk Score	Technical Performance Risk Score	Basis for the risk and schedule exposure	Risk Cost Exposure	Low Estimate	High Estimate
ORG7	1.2.8	Driller Talent Aquisition and Retention - EHWD drill operation in Antarctica is unique and specific skill-set. Recruiting experienced drillers key for project success		Low	Low	Moderate	Low	Low	Moderate	Low	Increased salary costs to recruit/entice experience. 16 direct-hires increased salaries (average) across 2 seasons TECH rate -> ENGR rate, delta $38/hr, 525 hr/season 16*2*38*525 = 640k	$640,000	$300,000	$800,000
TECH52	1.4.1.1	Because MCA breakout terminations are a custom solution, the costs of breakout installation may exceed the MSU commitment, requiring project support for MCA costs		High	Low	High	Very low	Moderate	High	Low	High cost estimate based on initial bids from two suppliers (JDR and HGS), cost exposure reflects some assumed cost reductions. Schedule risk reflects possibility of extended design phase	$400,000	$0	$750,000
TECH40	1.4.1.1	Because the MCA prototype has not completed mechanical testing, we may need to select an alternate Main Cable supplier, which will necessitate project support for cost and/or impact communications and timing performance		Very Low	High	Very High	Moderate	Low	Moderate	Low	Likely to be delays in switching to new main cable supplier, most vendors are less responsive than Hexatronic.	$ 1,500,000	$300,000	$3,500,000
OPP1	1.1	If contributed drillers (from collaborating institutions) are provided as in-kind contributions, the project can save seasonal driller labor costs.		Moderate	Very low	High	Very low	Low	High	Low	Contributed drillers (up to 10 person*seasons) replace $50000 in direct costs.	$250,000	$100,000	$500,000
PM2	1.1	The great resignation can affect the project team, and could result in departures of personnel in critical roles.		High	Moderate	Moderate	Very Low	High	High	Low	20% increase on 10% of key roles for PY5-8 labor rates, difficulties in finding new personnel	$240,000	$200,000	$400,000

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Logistics Delay Sensitivity Analysis

Our approach to logistics sensitivity analysis

- Follow our project general Risks Registry rubric of impacts and probabilities
- For each shipping package (72) and personnel arrival at Pole (11), assess probability of delays and estimate cost of recovery from those delays
- Delay probabilities and costs of recovery are assessed for 48 hour delay, one week, two week, and four week delays
- Cost of recovery is based on the personnel cost of extending stays at South Pole or bringing in alternates later in the season for catchup work, this is worked out in detail for each season's on-ice drill network flow

- Note: This only includes paid labor, and does not track contributed labor

Excerpt from the Cargo delay spreadsheet

Cargo Item #	WBS L2	Item Description	Contents	Date Item expected or *arrived* to MCM	Date/Month for Items needed at South Pole	Logistical Mode	48hrs		168hrs (1 wk)		336 hrs (2 wks)		672 hrs (4 wks)		1 week delay impact notes	2 week delay impact notes	4 week impact notes
							Probability	Estimated Cost Impact	Probability	Estimated Cost Impact	Probability	Estimated Cost Impact	Probability	Estimated Cost Impact			
		UW/PSL															
20	1.2	ARA Drill System Components - Crate 1	ARA (Antarctic Rodwell Appartus) - downhole pump controller, ePump controller, splash cam kit, and accessories - Do Not Freeze	2/6/2023	12/6/2023	LC-130	Moderate	0	Low	0	Low	0	Very Low	25760			224 hours of labor pushed - season extended to accomodate
21	1.2	Computing/controls components # 1	Motor drives, PLCs, electrical hardware, and motor drive mounting kits. Components and equipment to support field season 1 controls system tasking - ComSur - Do Not Freeze	2/6/2023	11/15/2023	LC-130	Moderate	0	Low	12420	Low	24840	Very Low	82915	work stoppage of 108 hours	work slowdown of 216 hours	216 hours lost in field season 1 additional EE FTE added to field season 2, 505 hours (on-ice labor is not reallocated elsewhere -
22	1.2	Computing/controls components #2	Computing and controls equipment (Motor drives and other sensitive electronics) - Do [illegible]	11/1/2023	11/15/2023	LC-130	Moderate	0	Low	26335	Low	52670	Very Low	85445	229 hours of labor delayed	458 hours of labor delayed	743 hours of labor delayed
23	1.2	Computing/controls components #3	Computing and controls equipment (Sensor, motor drives and other sensitive electronics) - Do Not Freeze	11/1/2024	11/15/2024	LC-130	Moderate	0	Low	173880	Low	347760	Very Low	983000	Drill season extended by 1 week 1512 hours	Drill season extended by 2 weeks 3024 hours	Drilling can no longer be accomplished
24	1.2	20' Refit Container C	Bull wheel assembly - used to install main cable on reel in event of main cable damage/failure; Spare cable for Return Water Cable Reel - on spool; ARA new downhole pumps, spares, accessories and tools	2/6/2023	1/22/2025	SPoT	Moderate	0	Low	24840	Low	49680	Very Low	99360	work stoppage 8 people 3 days or 216 hours	work stoppage 8 people 6 days or 432 hours	work stoppage 8 people 12 days or 864 hours
25	1.2	Driller resupply/refit components - 8' Container FY25	8' Mini Milvan; Consumables/drill components - difficult to estimate. Placeholder for emergent items	11/1/2024	11/15/2024	LC-130	Moderate	0	Low	4140	Low	8280	Very Low	24840	36 hours potential delay	72 hours potential delay	216 hours potential delay

Notes: These are items 20-25, all currently in Wisconsin.
Includes one item, item 23, which if 4 weeks late, causes a project failure (”drilling cannot be completed”)
Shipping dates, required at Pole dates, and float are all for the new agreed-to logistics plan
Significantly fewer routes to failure than in old logistics plans
And in all cases would know about these delays in real time, for potential mitigation

Monte Carlo treatment

- Thousand realizations of the three field seasons
- Cost impacts calculated for each realized risk instance
- Events which lead to failure are excluded, but these are <1.5% of simulations
- Annual 95% confidence level cost exposures:

Risk Exposures

	95% Level	Hours
FS1	**$26,258**	**228**
FS2	**$81,420**	**708**
FS3	**$70,171**	**610**

	Population	Available Hours	Risk Hours	percentage needed for risk coverage
FS1	8	4128	228	6%
FS2	14	7224	708	10%
FS3	28	14448	610	4%

Monte Carlo Shortcomings

- Assumes all events are uncorrelated, so impact on the critical path is determined by latest item in a season
- And mitigated with more person-hours on ice, whether through alternates or extended season
- More nuanced analysis is difficult to automate
- Roughly this cost agrees with the Risk Registry cost of just the logistics-related items

Failure Mode & Effects Analysis

Upgrade In-Ice Failure Modes & Effects Analysis (FMEA)

- Explicit FMEA was not done in Gen1
- Hazard analyses were conducted for processes, human safety, *etc*. and will be done in the Upgrade as well
- FMEA was suggested by the Project Advisory Panel
- We adopted an industry standard form, and launched an FMEA effort
- Ultimately changed the form significantly to better match the project characteristics, and zoomed in on in-ice/string failures
- FMEA is focused strictly on the in-ice, deployed string, where processes and production mistakes are non-reversible
- In March 2022, we rebuilt the Risk Registry, harmonized the FMEA with the Risk Registry, and put the FMEA into revision control

1	Top Item Name	Upgrade String		FMEA Number: Upgrade
2	Subsystem	All	Analysis	Prepared By:
3	Component	All	(FMEA)	FMEA Date:
4	Design Lead	L2s		Revision Date: 3/8/2022
5	Initial Team	Haugen, Sandstrom, Zernick, Duvernois		Page: 1 of 1

7														Action Plan		Action Results
8	Original Entry Order	Parent Item(s)	Failed Item Name (sub components of "Parent Item")	Failure mode (How requirements for item are not met)	Observable symptoms and impact of failure mode (Potential Effect[s] of Failure)	Additional notes on Impacts (Potential Cause[s] / Mechanisms of Failure)	Item location	Failure prevention or mitigation / detection method OR Process Control OR Design result (Current Design Controls)	Sev	Prob	Det	RPN	Additional notes on failure mode	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken
23	12	**xDOM, Calibration, or R&D Instruments**	**xDOM main board**	insufficient ESD protection	Immediate or latent damage to DOMs during preparation or deployment		any	Validate design of ICM, xDOM mainboard and Mini-Mainboard for ER3 of Ice Comms Module. Ensure reliable bond between MCA, BCA, PCA during deployment. Ensure bond between MCA shield and TOS during deployment. Use conductive brush to neutralize surface charge on MCA during deployment.	4	5	3	60	probability based on Gen1 failure rates	Ensure charge neutralization between MCA/BCA cable shields and TOS frame during deployment.		
24	13	**xDOM, Calibration, or R&D Instruments**	**ICM firmware/main cable**	comms provides insufficient S/N over real cable	high bit error rate (BERR) leads to insufficient bandwidth over real cable	Cable related	any	comms must be tested on realistic/actual cable as early as possible	8	3	1	24	If we have a final cable prototype soon, detectability for this should be much better, no? (TK) Agree, detectability changed to 1			
25	14	**xDOM, Calibration, or R&D Instruments**	**ICM Hardware**	Latent failure in one or more ICM components	Comms loss of sensors where part failure is manifest.		any	Review BOM and assembly procedure for potentially unreliable parts or steps. Include ICMs into Mainboard burn-in / HASS	4	6	2	**48**		Extensive testing		
26	15	**xDOM, Calibration, or R&D Instruments**	**ICM Hardware**	insufficient ESD protection	Comms loss of sensors where part failure is manifest.		any	Review BOM and assembly procedure for potentially unreliable parts or steps. Explicit ESD testing during ICM and Integrated xDOM design verification	4	6	2	**48**				
27	16	**xDOM, Calibration, or R&D Instruments**	**xDOM Mainboard, Mini-Mainboard**	Latent failure in one or more mainboard components	Partial or complete loss of any proportion of devices with failure-prone part in their BOM.		any	Review schematics of ICM and host boards	4	6	2	**48**				

Backup Slides

Scope of Technical Coordination & Project Engineering

- Design Baseline Library – Defines the technical design of the project – System Engineering scheme using four document templates
  - Configuration Management Document (CMD): hierarchical subsystems listing
  - Engineering Requirements Document (ERD): traceable to physics requirements
  - Design Status Notes (DSN): ongoing change log, links to meeting updates, vendor links
  - Interface Description Document (IDD): manages interfaces
- Project Technical Board – weekly call with Issue Tracking, edited and shared notes
- Project Change Control Board – weekly L2 call plus change control process
- Design Reviews
- Non-conforming Materials Report – Plus review process on these materials
- Production Coordination, assistance with vendor relations, contracting, and purchasing

Weekly calls

- Technical Board Call (0800 Madison Tuesdays)
  - Focused on general updates of technical progress across the Upgrade Project, a lot of D-Egg reporting recently, managing the technical issue tracker, connects Europe, US, and Asia groups, open attendance
- Change Control Board (CCB/L2) (1100 Madison Wednesdays)
  - L2 Reports, Change Control, Budgets & schedules
- Gen2 Hardware Call (0800 Madison Thursdays)
  - Mainboard electronics have been a major topic recently
- Calibration Group, mDOM Group, Mainboard Firmware & Software, IceCube "Extensions," NSF Coordination, ASC Coordination Calls, Chiba+UW Coordination calls at Japan-friendly times
- Local WIPAC Upgrade and Drill meetings

SCIENCE OBJECTIVES - THE ICECUBE UPGRADE

		Tau Neutrino Appearance and the Unitarity of the PMNS Matrix (2.1)	Neutrino Oscillations (2.2)	Sterile Neutrinos (2.2)	Indirect Dark Matter (2.2)	Ice Characterization for better LE & HE flavor physics (2.3)							
PRIMARY SCIENCE REQUIREMENTS	Event Energy Range	**few to 100 GeV**	**few to 100 GeV**			**TeV to >PeV**							
	Expected Detectable Event Rate	**Measurement in 2-3 years**	**5-10% tau measurement**	**Any detection/improved limit**	**Any detection/improved limit**	**100s / year**							
	Desired Angular Resolution	**<5 deg at O(20 GeV)**											
	Time Resolution Within Event	**2-5** ns	**2-5ns**										
	Absolute Time Accuracy					50 ns							
InIce Sensor Array Geometry	Instrumented Ice Volume	About 2 million cubic meters								√	√	√	√
	Array Shape	Compact								√	√	√	√
	Effective Volume	Varies with energy level and event orientation (derived from other properties)								√	√	√	√
	Number of Strings	7								√	√	√	√
	multi-PMT Digital Optical Modules (mDOM) per String	108 (90 in the dense physics region, others above and below for primarily calibration purposes) - 46 mDOMs, 38 D-Eggs, & 6 pDOMs								√	√	√	√
	Total Number of mDOM	~750 (photocathode area is key parameter here)								√	√	√	√
	mDOM Spacing - Horizontal	22 meters (compromise between closer and drill constraints)								√	√	√	√
	mDOM Spacing - Vertical	3.0 m								√	√	√	√
	Detector Depth	Physics region: 2150-2425m Upper region: 1450-2150 Deep region: 2425-2600m								√	√	√	√
Individual mDOM Performance	Sensitivity of mDOM	Single Photo Electron (SPE)								√	√	√	√
	mDOM Photon Event Dynamic Range	SPE to >200 PE / 15 ns								√	√	√	√
	mDOM Field of View	Spherical with <10% variation, except for cable shaddowing.								√	√	√	√
	Digitization Rate Waveforms < 400 ns	300 megasamples / second								√		√	√
	Digitization Rate Waveforms > 400 ns	40 megasamples / second								√		√	√
	Absolute Amplitude Calibration Accuracy	< 5 %								√	√	√	
	Timing Accuracy	< 5 ns								√	√	√	
Event / Background Discrimination (Noise Reduction)	mDOM Noise Rate	O(10kHz) total noise rate, <850 Hz per PMT										√	√
	mDOM Data Processing	Initial waveform capture and digitization in DOM, context sensitive compression of data prior to transfer								√		√	
	Local Coincidence Function	In mDOMs, might require N of 24 PMTs hit within time window to suppress noise.								√		√	
	Event Trigger Function	Global (surface) trigger logic to package event data and discriminate noise								√	√	√	√
	Veto Function	Surface Array (IceTop) allows identification and discrimination of downgoing background								√	√	√	√
Data Transport and Storage	Incoming Data Stream from Sensor Array	150 Gig / day								√	√	√	√
	Non-Volatile Storage at South Pole	1-2 Day Buffer / Archive Capacity & Full Redundancy Requirements							√			√	
	South Pole High Priority Communications	At all times, it must be possible to complete a minimum 10KB transfer to the Northern Hemisphere within 10 minute period. (SNEWS and GRB Reporting)							√			√	
	South Pole Medium Priority Communications	500 MB / day							√			√	
	South Pole High Volume Data Transfer	>30 GB / day							√			√	
	Northern Hemisphere Data Warehouse	Fully Buffered / Archive Capacity & Redundancy Requirements							√			√	

Change Management Process

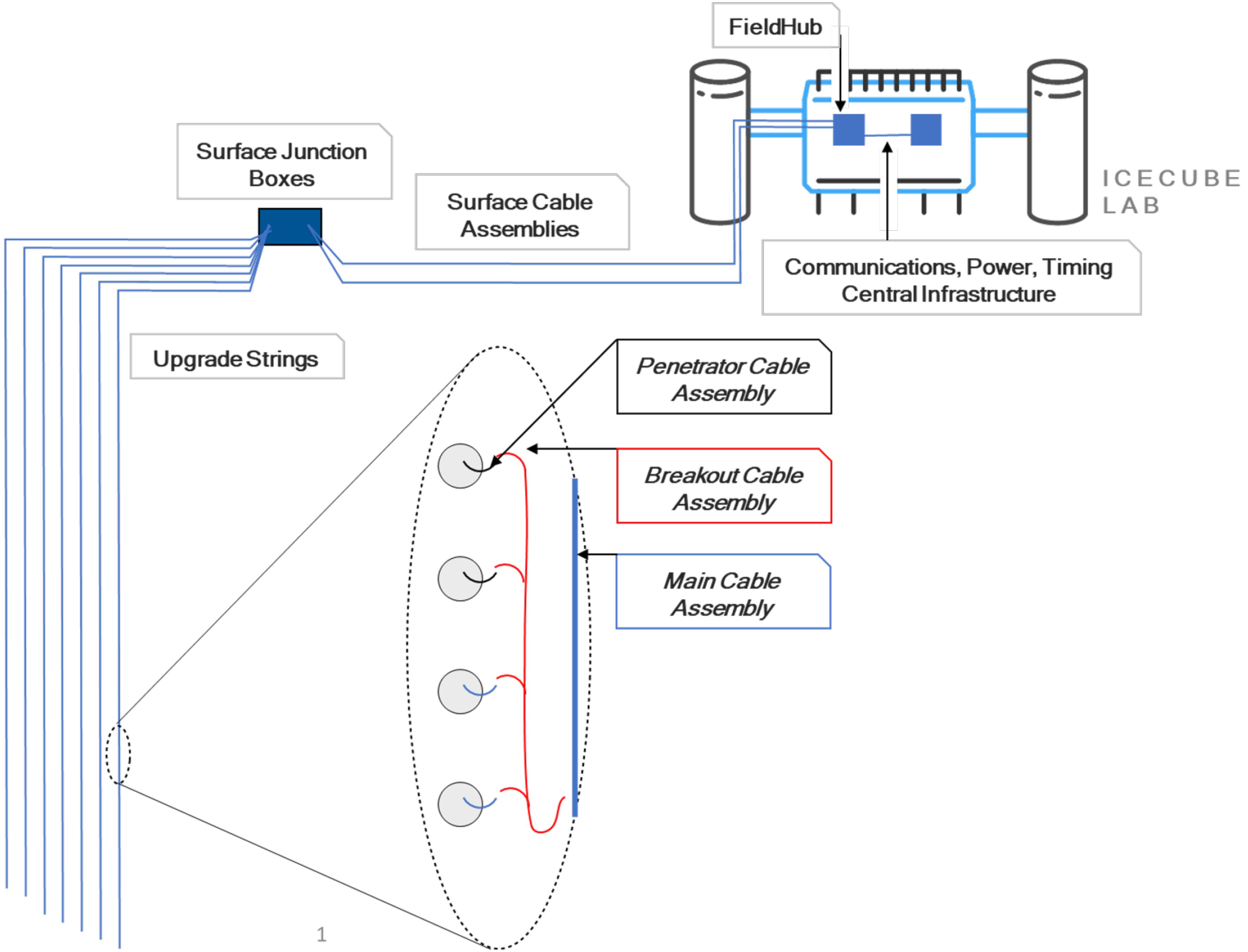
- L2 (or others as needed) initiates the Change Request with the Change Request Form
- Presentation at the weekly Technical Board Call (Tuesdays)
- Technical Board sends request with recommendation(s) to the L2/Change Control Board (with a weekly call on Wednesday)
- Request and recommendations discussed with the CCB recommendation going to the Project Manager
- Project Manager makes the decision, if necessary, in concert with the PIs, the host institutions, and the funding agencies
- Baseline costs, schedule, and technical documentation are updated
- Change Request Log is kept up to date, signatures obtained/logged
- Process is documented in Quality Control

Reviews

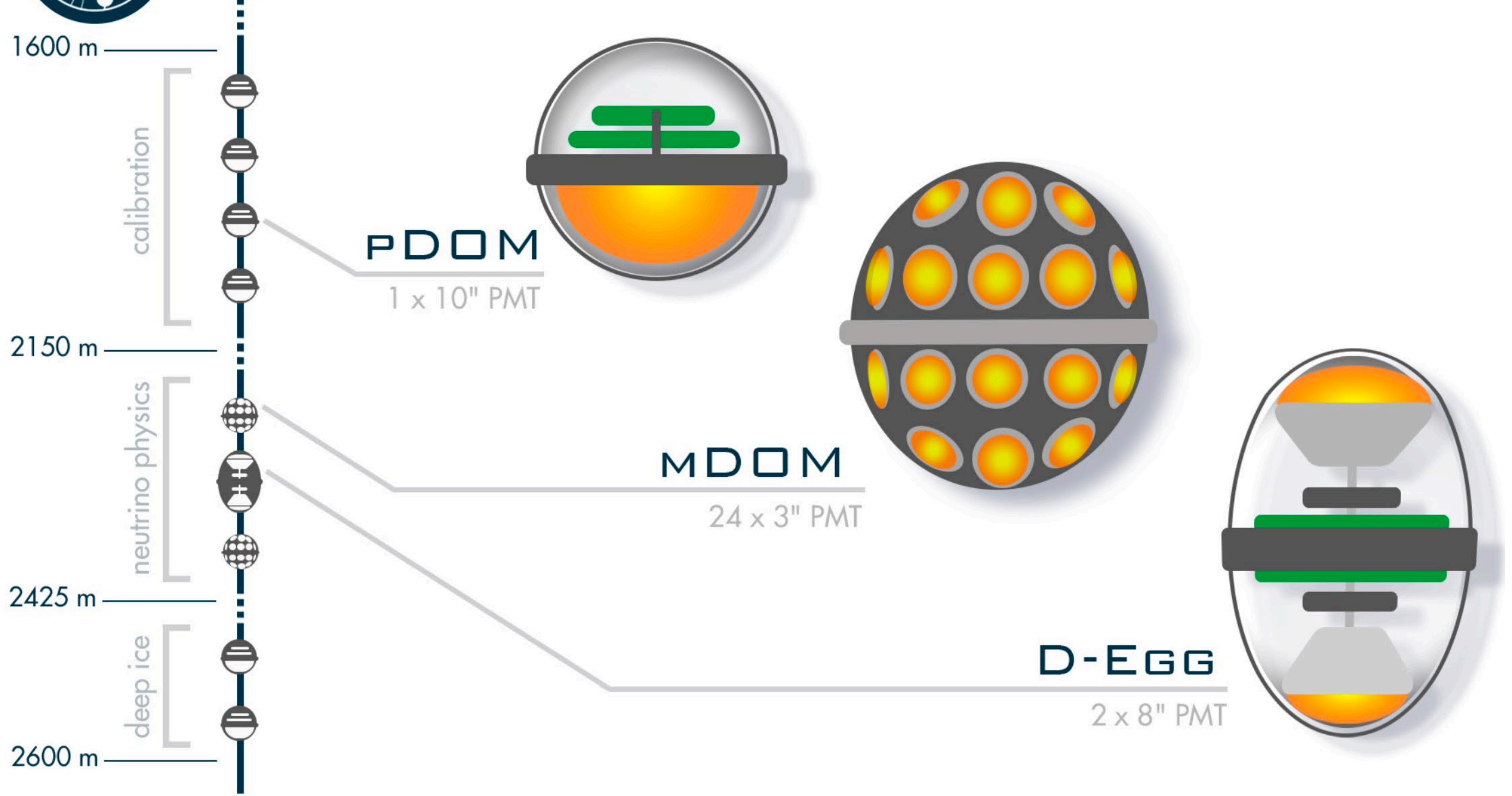
- Designs will pass through conceptual, preliminary, final, and (for some systems) production reviews
  - Later there are shipping readiness & deployment readiness reviews
- Some recent and upcoming example reviews:
  - In-module software and firmware status review (Dec 2021)
  - WOM (R&D device) preliminary design review (Dec 2021)
  - Shipping review for the surface cable assemblies (Mar 2022)
  - Final design review & production readiness review for mDOMs (Apr 2022)
- Reviewers have been a mix of internal (IceCube) and external people as needed
- Status of review findings kept in SharePoint
- Design flow through the reviews on next slide…

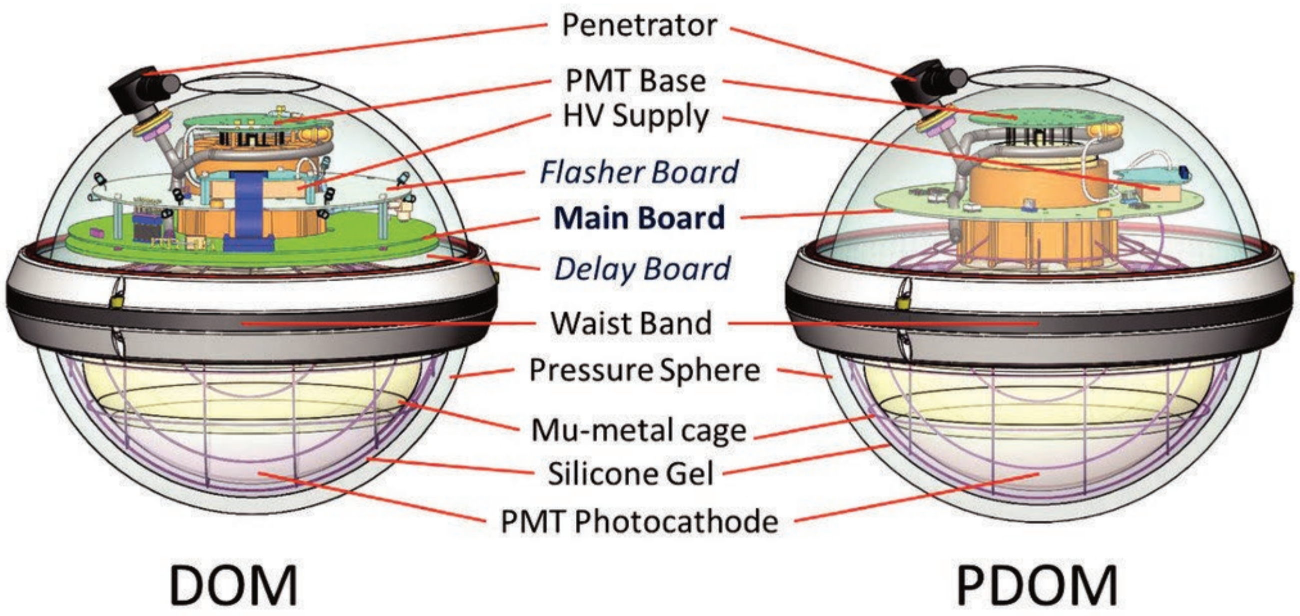
Design Flow

Instrumentation Design Deliverable	Work Product/Baseline Document	to exit Conceptual Design, you need	to exit Preliminary Design, you need	to exit Final Design, you need	to exit Production Readiness, you need	Comment
Description	Design Status Notes (DSN) and ConfCMD	Initial	Update	Update and controlled		
Requirements	ERD	Initial	Update	Update and controlled		
Block Diagram	slide 4 in DSN	Initial	Update	Update and complete		
Mechanical Drawings	slide 5 in DSN	Initial	Update	Update and controlled		integrate with Bill of Materials if possible
Schematic Circuit Diagrams	slide 5 in DSN	Initial	Update	Update and controlled		if applicable
Circuit Board Layout	slide 5 in DSN	Initial	Update	Update and controlled		if applicable
Bill of Materials	slide 5 in DSN	Initial	Update	Update and controlled		integrate with Mechanical Drawings if possible
Interfaces Identified	IDD	Initial	Update	Complete		
Design Verification	Coordinate with Project Engineer	Initial	Update	Update and controlled		
Investigate alternatives, rationale for design	Slide 6 in DSN, if needed	Initial	Complete			
Risk Assessment	Risk Register	Initial	Update	Update	Update	Document changes throughout lifetime of product, apply to project
Conceptual Design Review		**Completed Review**				**Exit to Preliminary Design with meeting minutes 'approval' or Skip review and proceed with Preliminary Design with L2 / CCB OK**
Integration Procedure	Integration PCR		Initial	Update and controlled		must include materials, tools, process, training
Test Procedure	Test PCR		Initial	Update and controlled		must include materials, tools, pass/fail criteria, process
Shipping Procedure	Shipping PCR		Initial	Update	Finalize	must consider all transport modes for delivery
Installation Procedure	Installation PCR		Initial	Update and controlled		if needed
Production Plan	slide 11 in DSN		Initial	Update	Finalize	include labor, sites, rate, equipment, capacity, bottleneck indentificaiton, shipping plan
Procurement Plan ppt	slide 11 in DSN		Initial	Update	Finalize	
Prototype - Rev 0	something in hand + slide 8 in DSN		Initial			
Preliminary Design Review			**Completed Review**			**Exit to Final Design with meeting minutes 'approval' or Skip review and proceed to Final Design with L2 / CCB OK**
Prototype Yield	slide 8 in DSN			Initial	Update	if applicable, include failure analysis, pareto chart, actions to fix
Prototype - Rev 1 or more	slide 8 in DSN			Update	Update	if needed
Hazard Analysis	Coordinate with Safety Engineer			Initial	Finalize	if needed
Final Design Review				**Completed Review**		**Exit to Production Readiness with meeting minutes 'approval'. All instrumentation MUST have a Final Design Review.**
Production Readiness Review					**Completed Review**	**Exit to Production / Procurement with meeting minutes 'approval'**


FieldHub
ICECUBE
LAB
Surface Junction Boxes
Surface Cable Assemblies
Communications, Power, Timing Central Infrastructure
Upgrade Strings
Penetrator Cable Assembly
Breakout Cable Assembly
Main Cable Assembly
1

IceCube Upgrade Optical Sensors

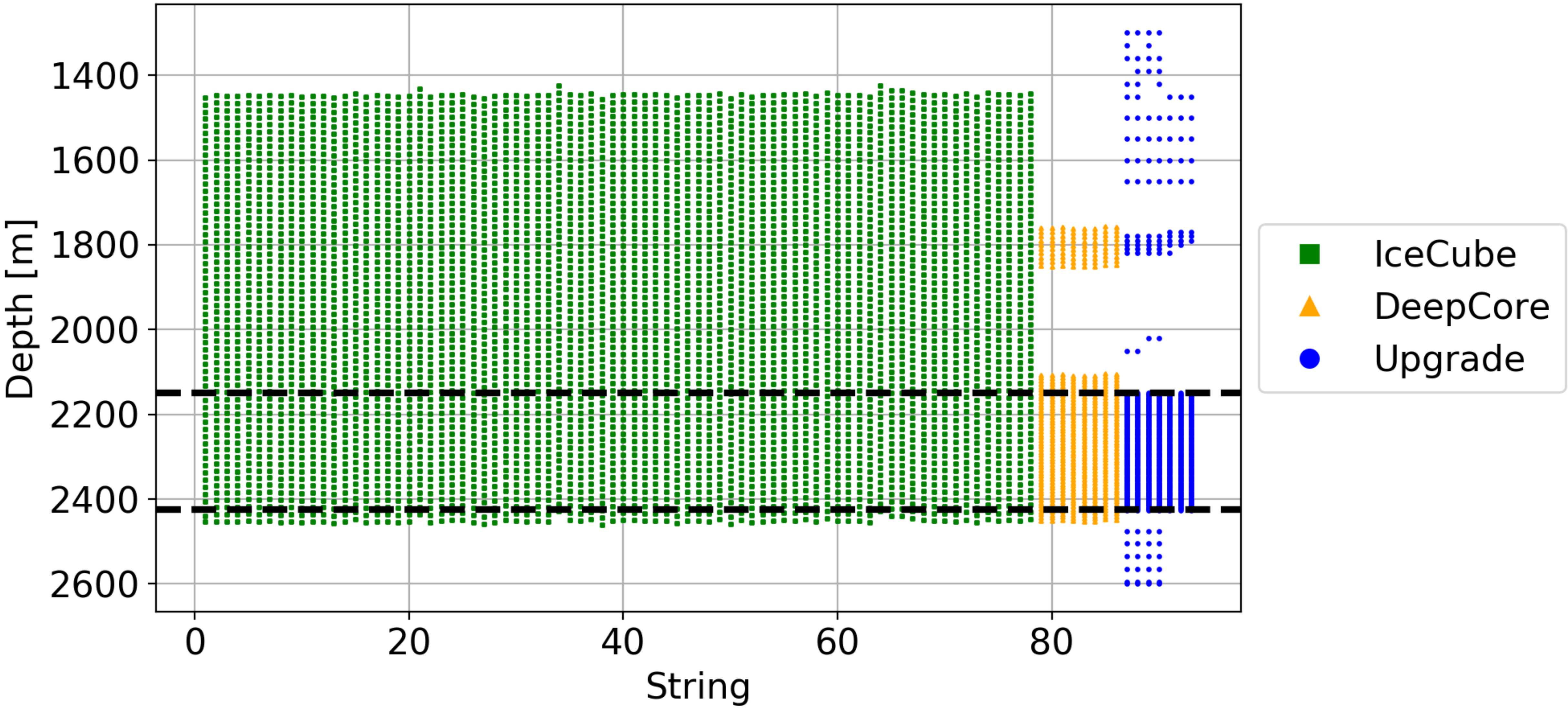




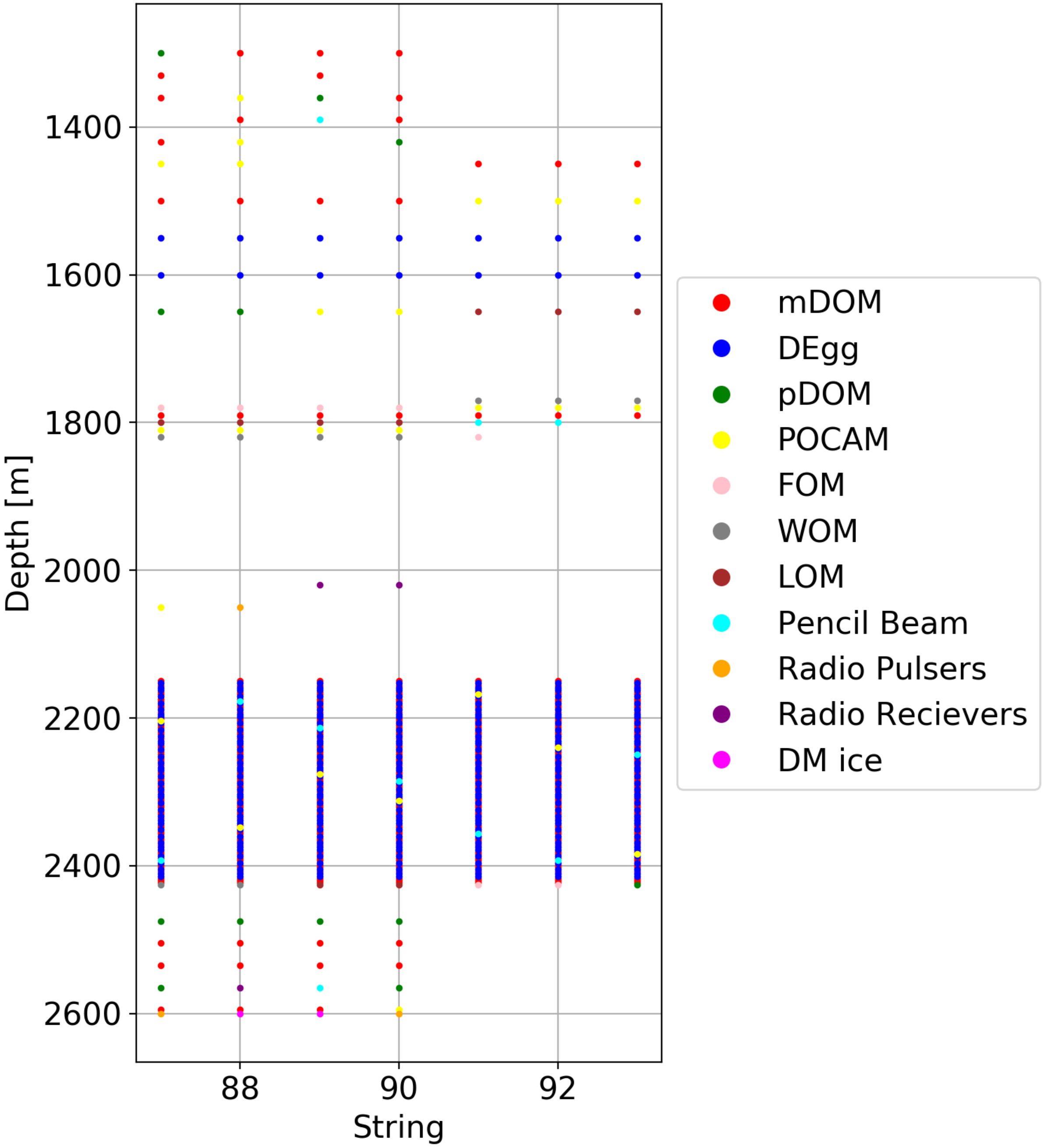
Optical sensor details:
Upper left: pDOM simplifies and updates Gen1 DOM
Lower left: mDOM image
Right: D-Egg image

ICECUBE UPGRADE

Gen1 + DeepCore + Upgrade Layout

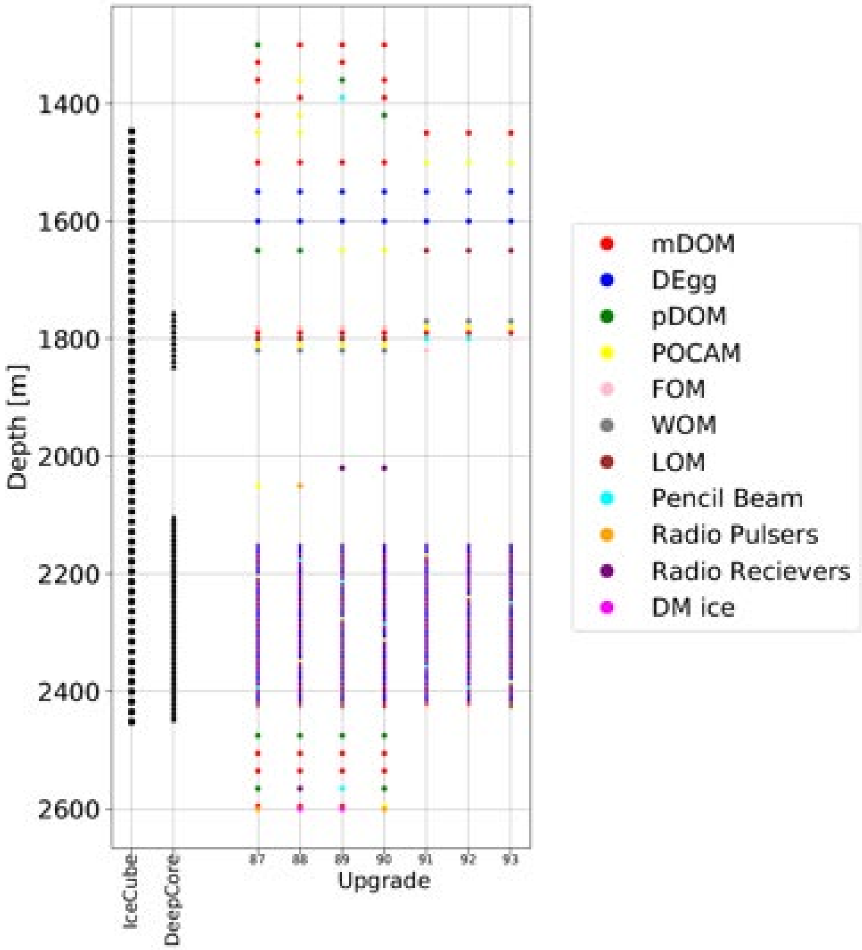


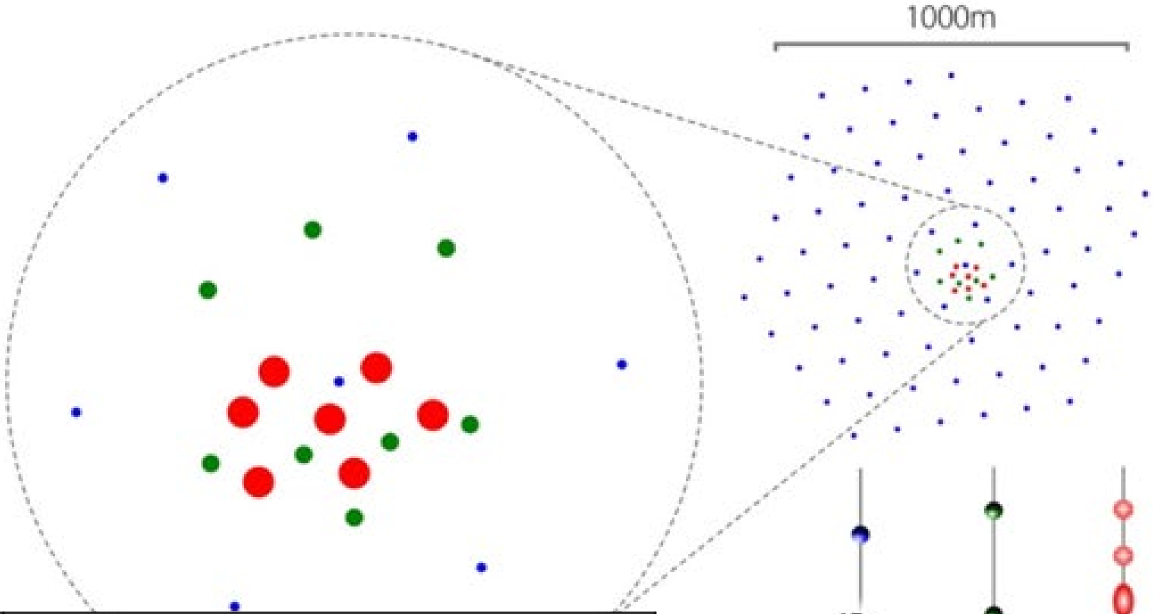
"Many module types, one project"

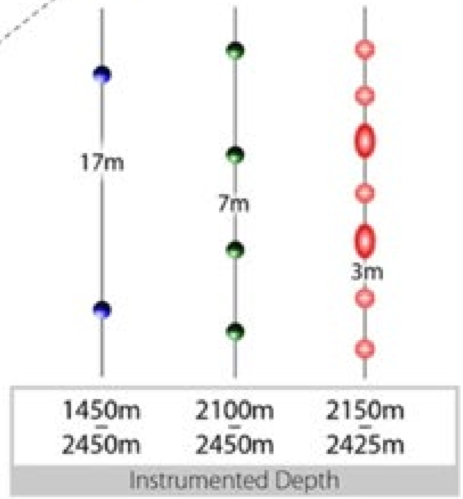


- mDOM & D-Egg primary optical modules (concentrated in physics region)
- pDOM, Pencil Beam, POCA\, & acoustics calibration modules
- Others are "special devices" for R&D towards Gen2
- All devices have common comms, power, timing, DAQ & mechanical interfaces

Upgrade String CMD







String	87	88	89	90	91	92	93	TOTAL
mDOM	55	56	58	53	61	59	60	402
DEgg	39	39	40	39	40	40	40	277
pDOM	1	1	2	1	2	4	3	14
WOM	2	2	1	2	1	1	1	10
FOM	2	2	0	0	1	1	1	7
POCAM	2	2	5	3	2	3	4	21
PB	1	2	1	2	3	1	1	11
PS	1	1	1	1	1	1	1	7
DM ice	0	0	1	0	0	1	0	2
RP	0	1	0	0	1	0	1	3
RR	1	0	0	0	0	2	0	3
AH	0	0	1	1	0	0	0	2
LOM	2	1	1	3	0	1	1	9
AP	2	1	2	1	1	1	2	10
ALL	108	108	113	106	113	115	115	778

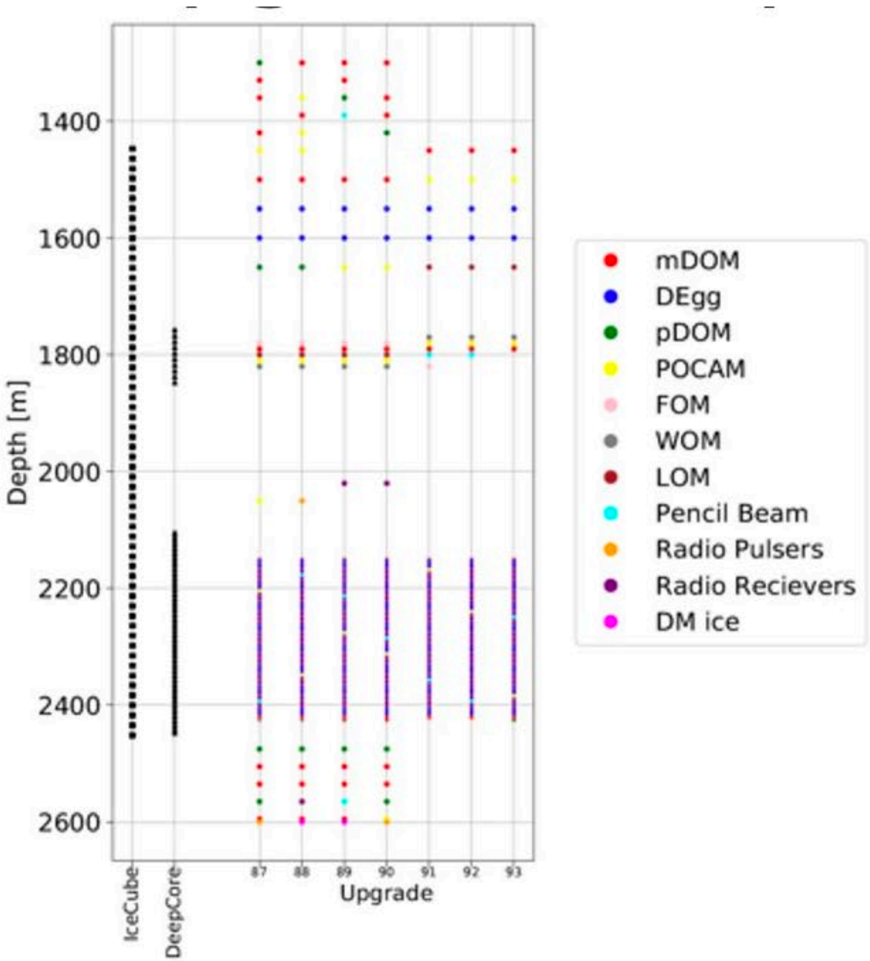
Lots of additional detail in the CMD, including all the precise depths, cable assignments…

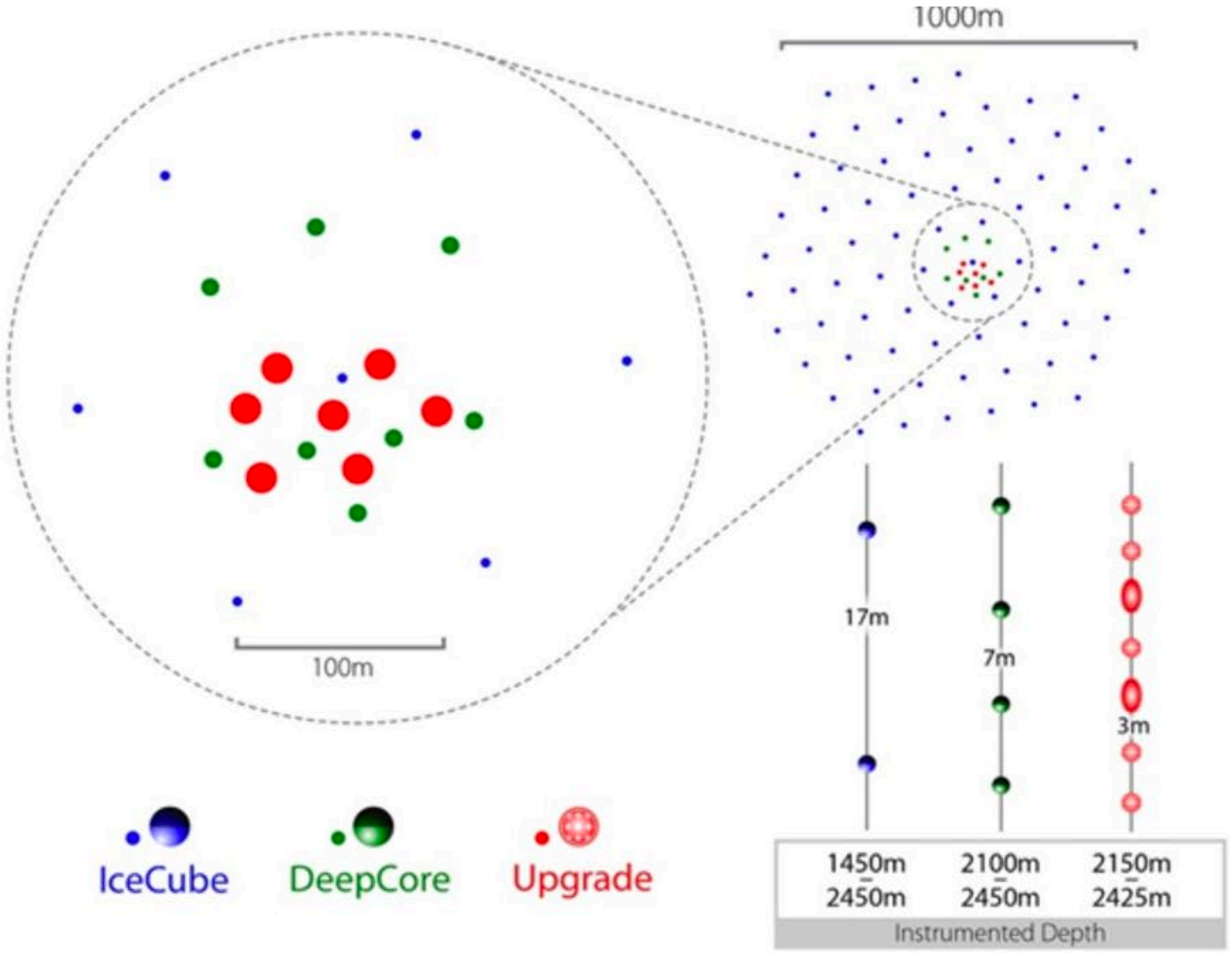
Cable and Communications

- See more in the WBS 1.4 Talk
- New production quads have been shown to support 2 Mbps on a wire pair with IceCube Upgrade (ICM and FieldHub) devices on the ends
- All in-ice modules have an ICM, and all are readout on the surface with a FieldHub
- On-module feature extraction to compress hits
- 20% overhead for multi-PE, 5% protocol overhead
- 8b10b encoding
- ~14kHz of compressed hits per 1 Mbps in pair
- This is sufficient for two mDOMs per pair

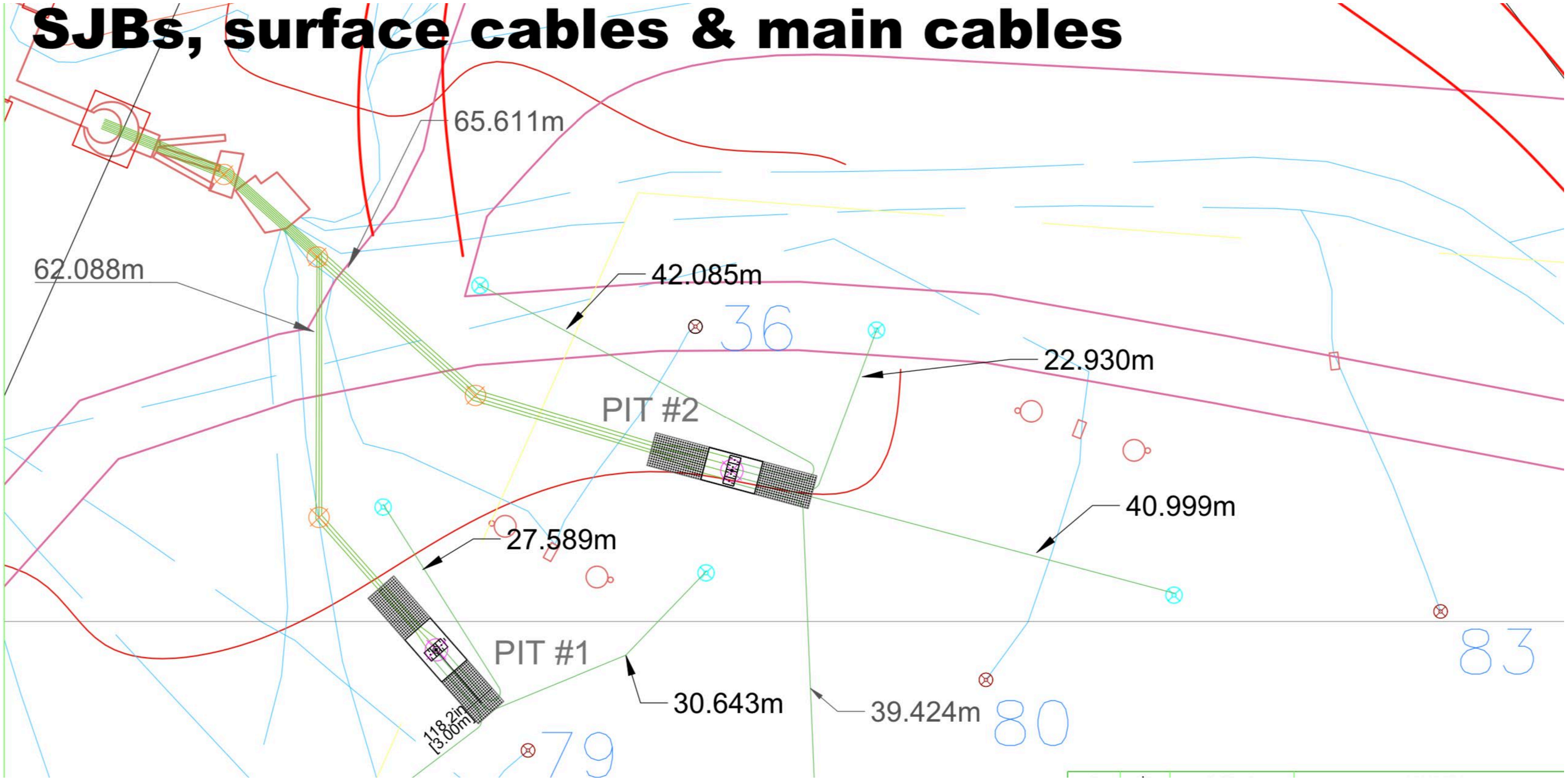
Field	Bits required
Channel ID	5
Trigger flag	0–2
Clock LSBs	20–25
Pulse amplitude	7–8
Pulse offset	7–8
Total	**39–48 (5–6B)**

Reminder of the detector layout





Surface layout near the ICL



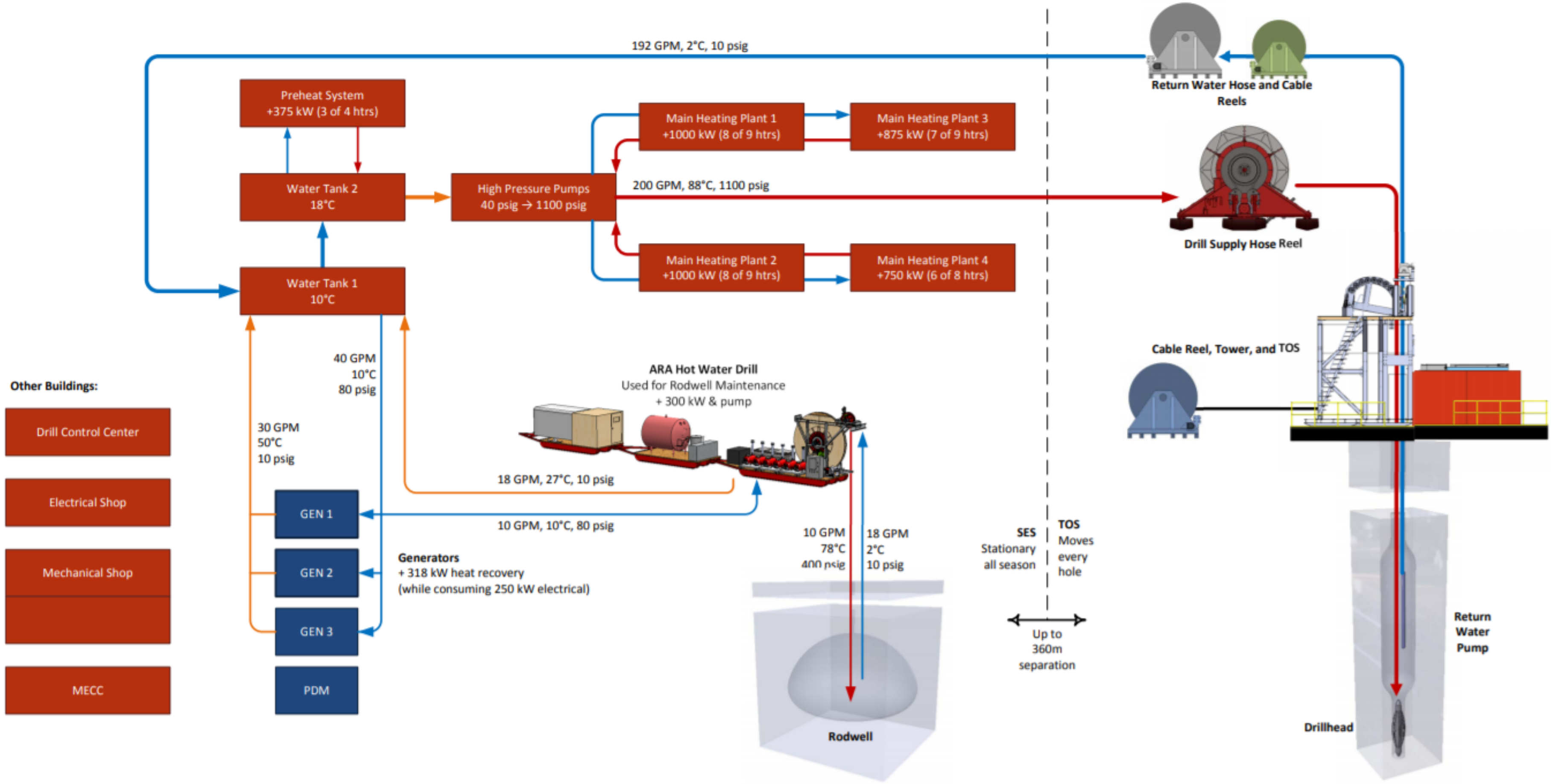
Drill - Schematic

ENHANCED HOT WATER DRILL – IceCube Upgrade

PSL v20190301

SYSTEM SCHEMATIC

Intent: Drill 7 IceCube-magnitude holes in one season to support installation of the IceCube Upgrade
Capacities: 4.6 MW thermal delivered to drill nozzle; 250 kW system electrical load
Run two gensets at a time, each at 125 kW, third genset is online backup
Makeup water obtained from stationary Rodwell, supported by ARA Hot Water Drill (pump, heat, hose reel – RWS no longer available)



WBS

- **1.3 Deep Ice Sensor Modules**
  - 1.3.1. Multi-PMT Digital Optical Module (mDOM)
  - 1.3.2. D-Egg
  - 1.3.3. PDOM
  - 1.3.4. Ice Comms Module
  - 1.3.5. Special Devices
- **1.4 Comms, Power, and Timing (CPT)**
  - 1.4.1. Downhole Cable Assemblies
  - 1.4.2. Surface Cables
  - 1.4.3. FieldHub
  - 1.4.4. CPT Central Infrastructure
  - 1.4.5. Northern Test System (NTS)
- **1.5 Characterization & Calibration**
  - 1.5.1. Module Calibration
  - 1.5.2.Calibration Assemblies
  - 1.5.3. Array Calibration
  - 1.5.4. Calibration Management
- **1.6 M&O Data Systems Integ.**
  - 1.6.1. Online Software
  - 1.6.2. Offline Software
  - 1.6.3. Simulation Software
  - 1.6.4. Computing Infrastructure
  - 1.6.5. Upgrade String Commissioning