FD2 PDS
Risks, Qualification, Validation, and Production Flow

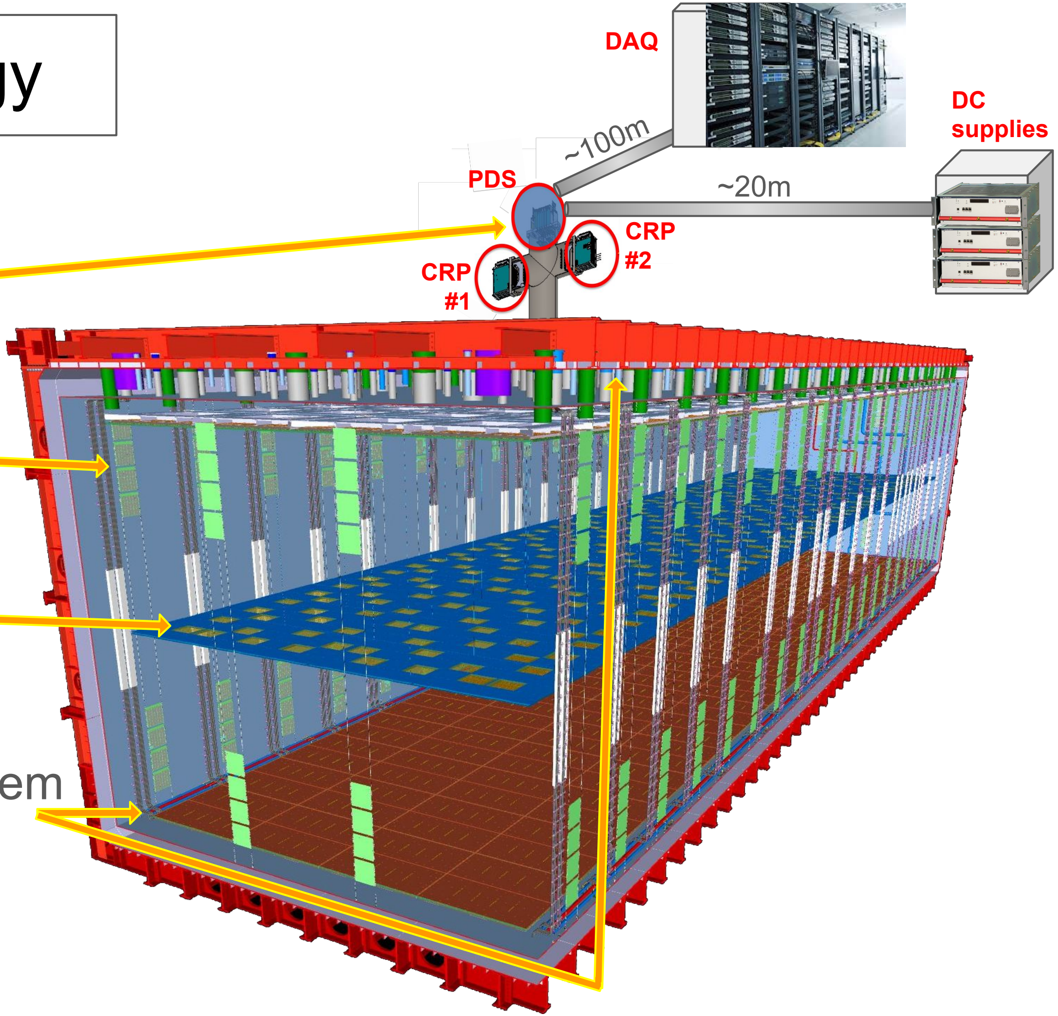
18 April 2023
FD2 PDS Final Design Review
Ryan Rivera - FD2 PDS L2

Overview

- Plan to PRRs
  - Validation plans
  - Opportunities for optimization
- Summary of Risk Register
- Failure Mode Analysis
- Production Test Stands and Assembly/Integration Centers
  - Parts flow

DUNE FD2 PDS Topology

1. Warm electronics
2. 352 Membrane X-ARAPUCA
3. 320 Cathode X-ARAPUCA
4. 176 Response Monitoring System light diffusers at floor/ceiling



Progress in one year - Flashback

- One year ago - **April 2022**:
  - Plan **forming** to mitigate the risk of HV impact on PDS
    - Topology change
    - Shielding addition
    - Bias generation
  - Power-over-Fiber (PoF) vendor and collaboration relationships **maturing**
    - Opportunity for GaAs **within reach**
  - Signal-over-Fiber LAr **flooding issues**
  - Interfaces **maturing**
    - Membrane mounting
    - Cathode mounting
    - Response Monitoring System mounting
  - **Preliminary Design Review** - May 3-5, 2022

Progress - Flashforward

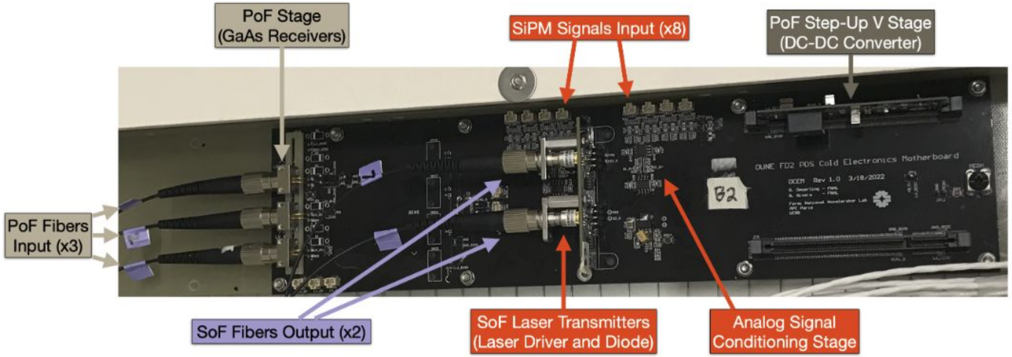
- Today - **March 2023**:
  - Plan **implemented** to mitigate the risk of HV impact on PDS
    - Topology change
    - Shielding addition
    - Bias generation
  - Power-over-Fiber (PoF) vendor and collaboration relationships **established**
    - Opportunity for GaAs **implemented**
  - Signal-over-Fiber LAr **defocus solution**
  - Interfaces **defined**
    - Membrane mounting
    - Cathode mounting
    - Response Monitoring System mounting
  - **Final Design Review** - April 18-19, 2023

Plan to PRRs

- The plan for the next 9 months is as follows:
  a. **Apr-Jun**: Optimize and test
     - Lessons learned from Cold Box operation and ProtoDUNE2-VD installation
     - Complete qualification of CMOS cold qualification components
     - Photo-Detection Efficiency Measurement of module-0 design
  b. **Jun-Aug**: Design, Procure, and Fabricate final Cold Box modules
     - 4 cathode XA and 8 channels of Membrane XA readout
  c. **Sep-Oct**: Install and Operate Cold Box
  d. **Nov-Dec**: Lessons learned and documentation for PRRs
- International consortium agreements to split resources
- Lifetime Plan Brief is posted at https://edms.cern.ch/document/2882322/1
- A few component highlights…

PoF Plan to PRR

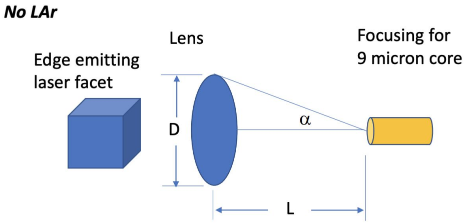
- 70 high-efficiency GaAs PPC units expected in early May
- **Apr-Jun**: Optimize and test
  - Demonstrate high-efficiency PPC yields 400mW in LAr at test stands at Fermilab, SDSMT, and Stony Brook. 400mW enables one used PPC and one spare. Focus on thermal cycling tests.
- **Jun-Aug**: Design, Procure, and Fabricate final Cold Box modules
  - Populate 2 PPC units per cathode module for Cold Box on cold motherboards
- **Sep-Oct**: Install and Operate Cold Box
  - Demonstrate fully redundant PPCs
- **Nov-Dec**: Lessons learned and documentation for PRRs

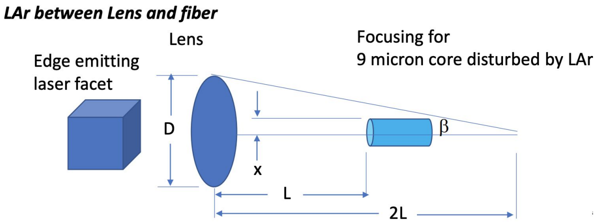


SoF Plan to PRR

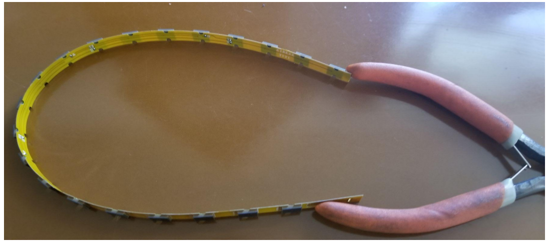
- SoF laser (1310 nm Transmitter Optical Sub-Assembly -TOSA) has been limiting factor in SPE, S/N, and dynamic range demonstration at the Cold Box, but took year to understand why and resolve.
  - In December 2021, SoF demonstrated at Cold Box with ~3 S/N, 300 PE dynamic range
  - In deep LAr, laser assembly floods under hydrostatic pressure and light misses fiber.
  - March 2023, demonstration of PD Consortium-vendor developed defocused laser, for LAr-flooded operation, at Cold Box with ~4.8 S/N, 1500 PE dynamic range
- **Apr-Jun**: Optimize and test
  - Demonstrate stable performance in pressurized test representing full depth.
  - In parallel, start procurement for (16) downselected 2.5mm defocused lasers.
- **Jun-Aug**: Design, Procure, and Fabricate final Cold Box modules
  - Populate 2 laser units per cathode module for Cold Box on cold motherboards
- **Sep-Oct**: Install and Operate Cold Box
  - Demonstrate and characterize performance at Cold Box
- **Nov-Dec**: Lessons learned and documentation for PRRs

Modified COTS Laser Diode (1310 nm TOSAs)

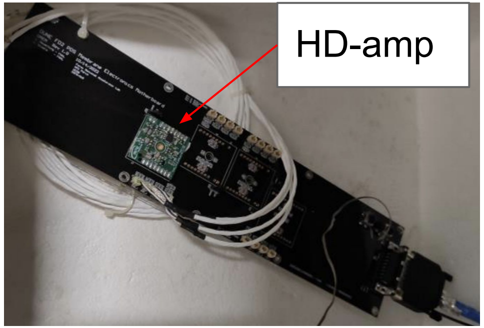


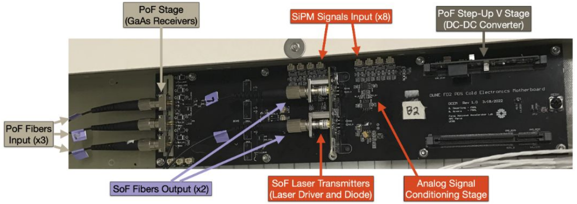


Cold Signal Conditioning Plan to PRR



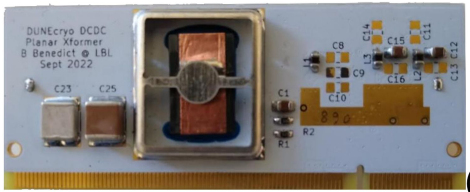
- No changes anticipated for SiPM flex circuit, Membrane motherboard, nor HD-amplifier.
- **Apr-Jun**: Optimize and test
  - Initial pre-production run (20 cathode cold electronics kits) with vendor reflow techniques for capacitor population of PCBs (motherboard, laser adapter, and bias generator) to demonstrate reproducibility.
  - In parallel, stress tests of cathode cold electronics CMOS LDO and CMOS amplifier components with temperature and overvoltage for hot-carrier effect consideration.
- **Jun-Aug**: Design, Procure, and Fabricate final Cold Box modules
  - Final pre-production cold box run (20 cathode and 20 membrane cold electronics kits) incorporating optimizations.
- **Sep-Oct**: Install and Operate Cold Box
  - Demonstrate and characterize performance at Cold Box
- **Nov-Dec**: Lessons learned and documentation for PRRs



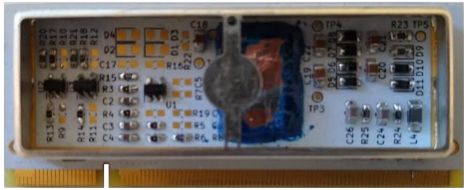


Bias Generation Plan to PRR

- March 2023 Cold Box performance with downselected bias generation solution was ~4.8 S/N. Installed at ProtoDUNE2-VD.
- All active components have been demonstrated in other long-term cryogenic experiments.
- Full redundancy of the operational amplifier.
- **<u>Apr-Jun</u>**: Optimize and test
  - Initial pre-production run (10 for FBK and HPK SiPMs) with vendor reflow techniques for capacitor population of PCBs to demonstrate reproducibility.
  - Optimize output voltage filter - copied from Iowa prototypes.
  - Transfer production assembly and testing knowledge from LBL to Iowa.
- **<u>Jun-Aug</u>**: Design, Procure, and Fabricate final Cold Box modules
  - Final pre-production cold box run (10 for FBK and HPK SiPMs) incorporating final optimizations.
- **<u>Sep-Oct</u>**: Install and Operate Cold Box
  - Demonstrate and characterize performance at Cold Box
- **<u>Nov-Dec</u>**: Lessons learned and documentation for PRRs

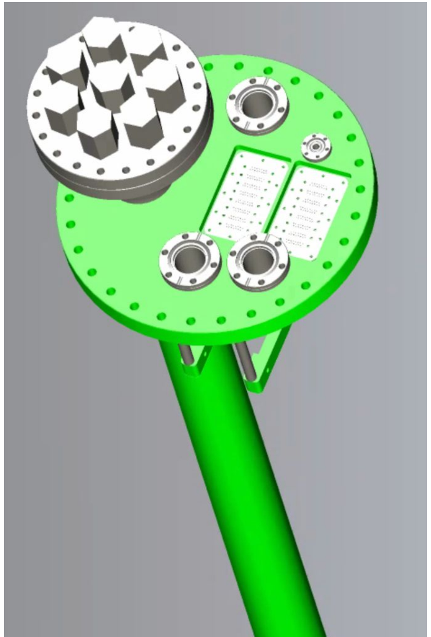


(A)


(B)

Flanges and Feedthroughs Plan to PRR

- **Apr-Jun**: Optimize and test
  - Demonstrate successful integration with BDE by completing the installation of the ProtoDUNE2-VD flange
- **Jun-Aug**: Design, Procure, and Fabricate final Cold Box modules
  - A helium leak check is planned for the final optical feedthrough assembly process to confirm vendor leak rate specifications and procedures.
- **Sep-Oct**: Install and Operate Cold Box
  - Continue validation of performance at Cold Box
  - Incorporate fiber and RMS feedthrough modifications into design and installation procedure
- **Nov-Dec**: Lessons learned and documentation for PRRs



FD2 PDS Risk Registry

Risk Type	RI-ID	Title	Probability	Cost Impact	Schedule Impact	Risk Rank	Risk Status
Project:ID plus Title: LBNF / DUNE -- Project 131 (9)							
WBS / Operations Activity: 131.FDC - Far Detectors + FS Cryogenic Infrastructure (9)							
Opportunity	RO-131-FDC-FD2-037	[FD2-PDS] Additional collaborating funding agencies identified	15 %	0 -- -1000 k$	0 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-010	[FD2-PDS] Simulations show additional detection efficiency required	10 %	500 -- 1000 k$	0 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-014	[FD2-PDS] Insufficient Power-over-Fiber efficiency	10 %	200 -- 1000 k$	3 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-029	[FD2-PDS] Components fail 30-year cold validation testing	25 %	200 -- 1500 k$	0 -- 1.5 -- 6 months	2 (Medium)	Open
Threat	RT-131-FDC-FD2-030	[FD2-PDS] Underestimate in level of effort required for 30-year cold validation	15 %	100 -- 350 k$	0 -- 3 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-031	[FD2-PDS] Production mechanical packaging costs exceed estimated cost	20 %	10 -- 80 -- 100 k$	0 months	0 (Negligible)	Open
Threat	RT-131-FDC-FD2-033	[FD2-PDS] Production phase infrastructure and test stand M&S costs exceed initial est...	20 %	100 -- -- 250 k$	0 -- 3 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-034	[FD2-PDS] Additional on-project labor required during installation	30 %	100 -- 750 k$	1 months	1 (Low)	Open
Threat	RT-131-FDC-FD2-036	[FD2-PDS] Photon detector electronics generates noise on the TPC strips readout	10 %	100 -- 500 k$	2 -- 4 months	2 (Medium)	Open

Pre-PRR Risks

- Insufficient Power-over-Fiber efficiency compared to baseline expectations.
- Simulations show additional detection efficiency required
- PDS Components fail 30-year cold validation testing
- Photon detector electronics generates noise on the TPC strips readout

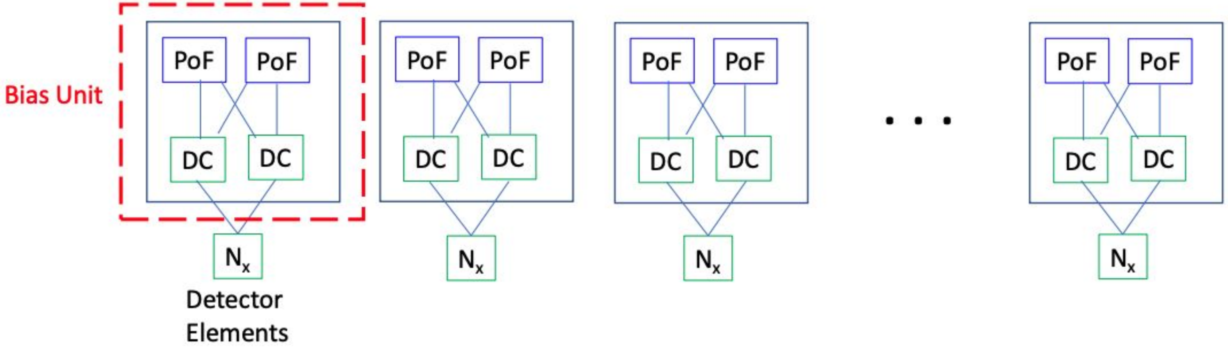
Production/Installation Risks

- Production mechanical packaging costs exceed estimated cost
- Production phase infrastructure and test stand M&S costs exceed initial estimate
- Additional on-project labor required during installation

Failure Mode Analysis

- Loss of both readout channels for fewer than 1% of XA ⇒ translates to 3 cathode XA and 3 membrane XA
- PoF PPC is limiting lifetime factor as data points to 3% efficiency reduction in first year, and 1% each remaining year.
  - Conclusion is > 20 years MTTF
- Other active and passive components expected lifetime at least an order of magnitude longer.
- Redundancy is key feature to mitigate against performance hit
- Two scenarios were modeled:
  - Redundant component with redundant PoF
  - Single-point-of-Failure component with redundant PoF
- The models give a **sense of scale of required reliability** for redundant components vs single-point-of-failure components to meet the 1% loss requirement.

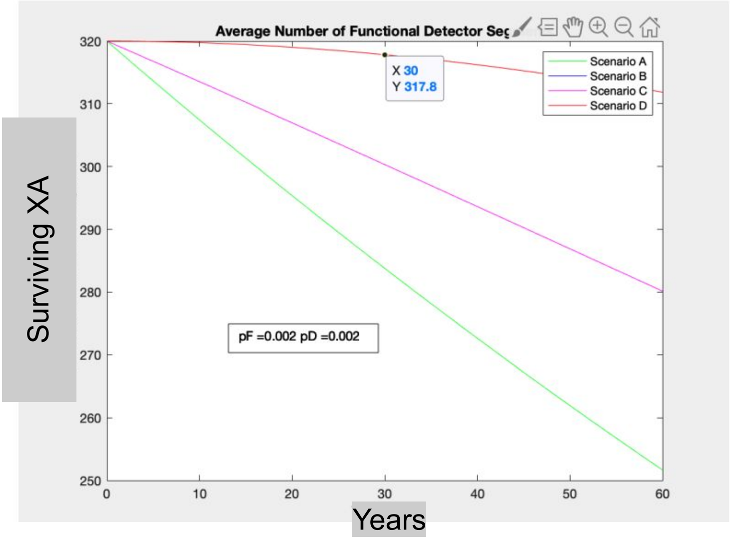
Redundant Scenario

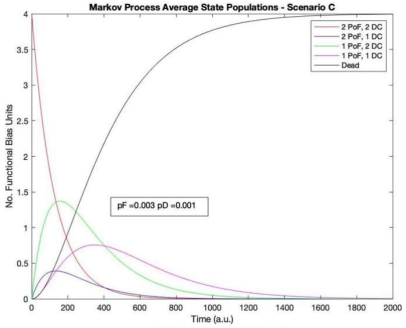


"Scenario D" in model

- In this example, a detector modules is lost if both PoF PPCs have failed or both DC-DC operational amplifiers have failed.

Redundant Scenario



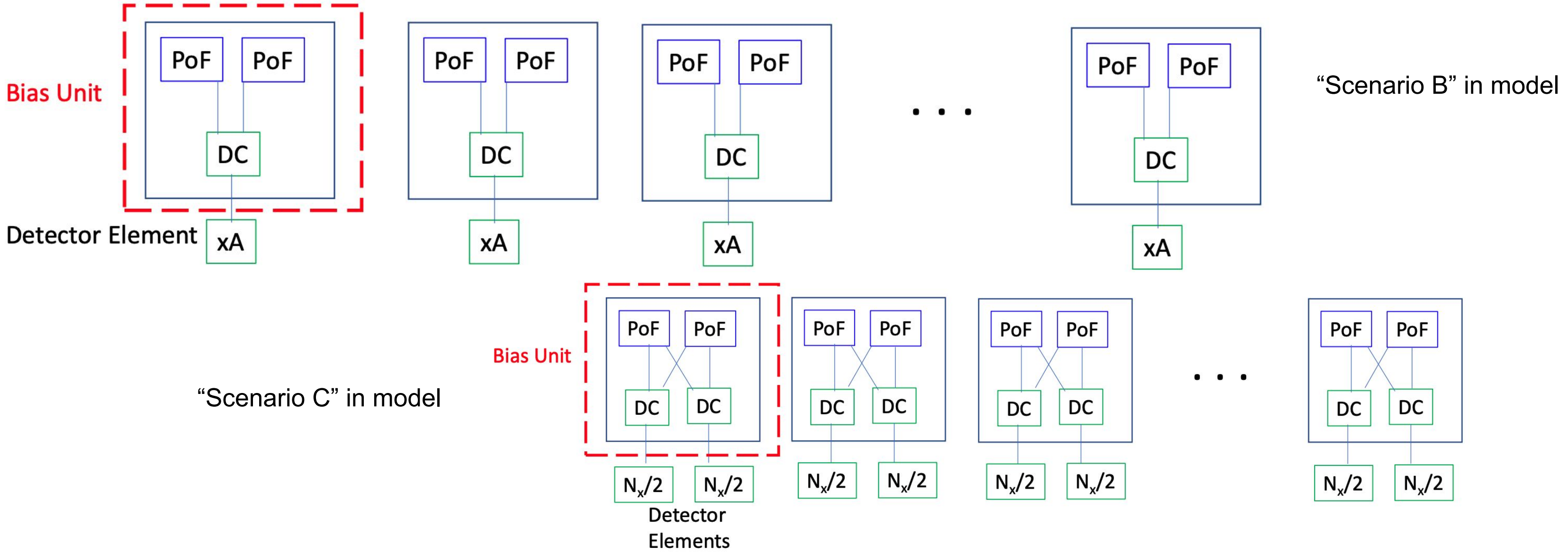


State Populations

- Using a state-based Markov Model, different failure probabilities failure modes could be considered.
- pF = Probability of PoF failure per year
  - Estimated probability of 2 out of 1000 per year based on MTTF > 20 years

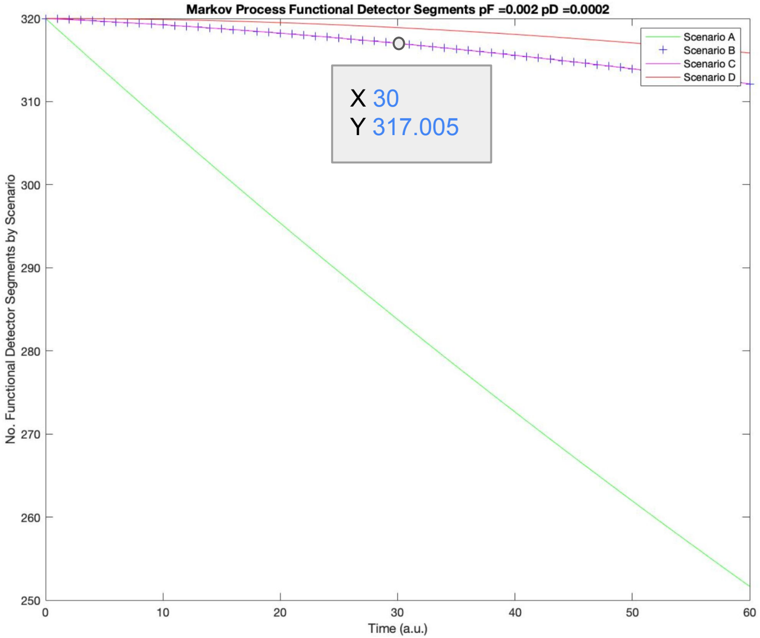
    Yamaguchi, Masafumi. (2020). High-Efficiency GaAs-Based Solar Cells. doi:10.5772/intechopen.94365.
- pD = Probability of DC-DC failure per year
  - Estimated probability of 2 out of 1000 per year
- The model shows, for Scenario D from previous slide, the expected XA loss after 30 years is 2.2 modules based on the failure probability assumptions.
- Note: The the probability of failure = 1/MTTF
  - Reference:
    - Probability and Random Processes, Wilbur Davenport, McGraw Hill, 1970, P. 124

Single-point-of-Failure Scenario



- In this example, a detector modules is lost if both PoF PPCs have failed or a single component (ignore "DC") has failed. Or equivalently, the example of a single component serving half the detector fails.

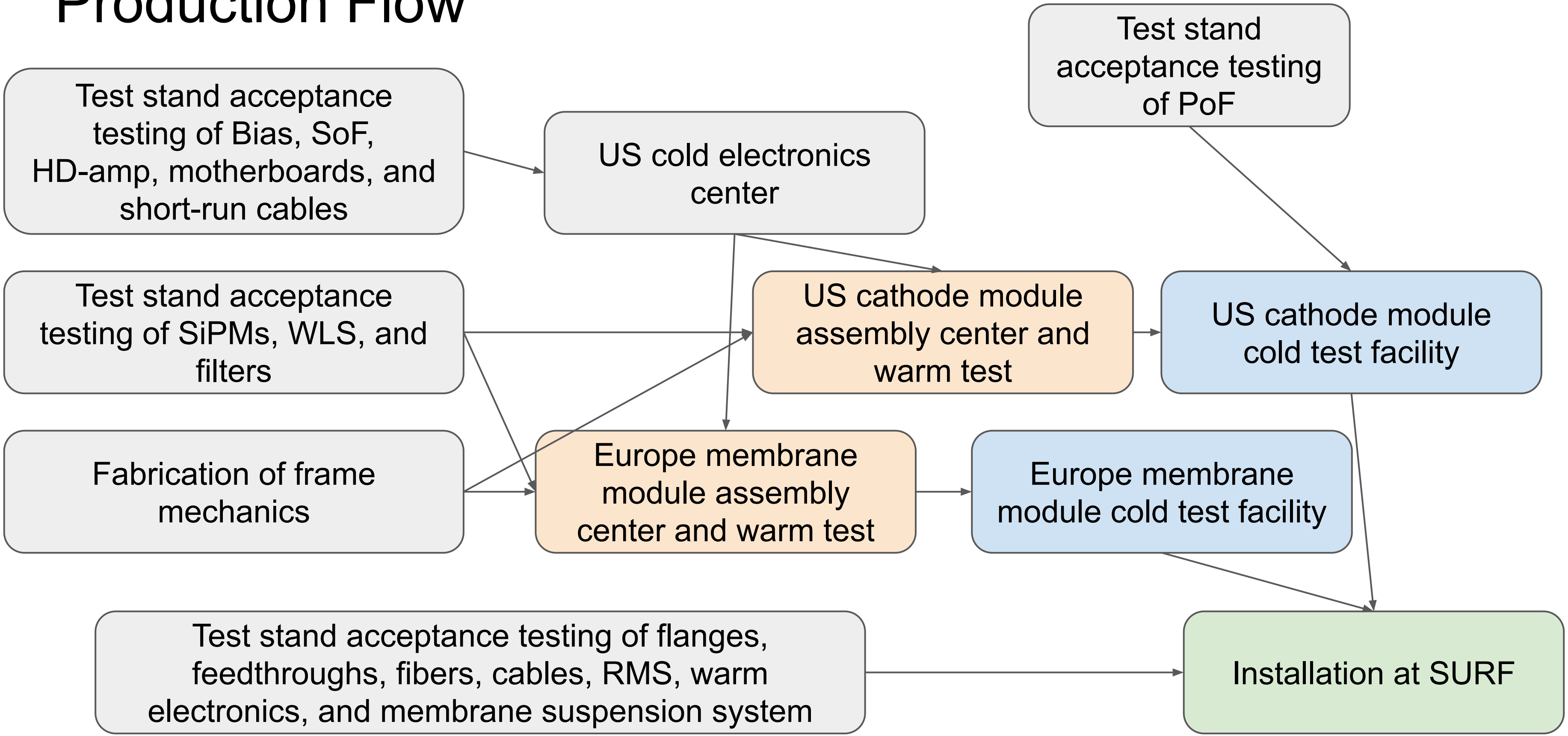
Single-point-of-Failure Scenario



- Using a state-based Markov Model, different failure probabilities failure modes could be considered.
- pF = Probability of PoF failure per year
  - Estimated probability of 2 out of 1000 per year based on MTTF > 20 years
- pD = Probability of single-point-of-failure per year
  - Estimated probability of 2 out of 10000 per year
    - An order of magnitude better
- The model shows, for Scenario B and C from last slide, the expected XA loss after 30 years is 2.995 modules based on the failure probability assumptions.

- The models give a **sense of scale of required reliability** for redundant components vs single-point-of-failure components to meet the 1% loss requirement.

Production Flow



Production Test Stand Assignments

- Institution responsibility:
  - Prepare test stand infrastructure to meet required testing rate
  - Handle procurements and vendor visits
  - Execute acceptance testing
- Acceptance testing to be fully defined in QA/QC plan in advance of PRR

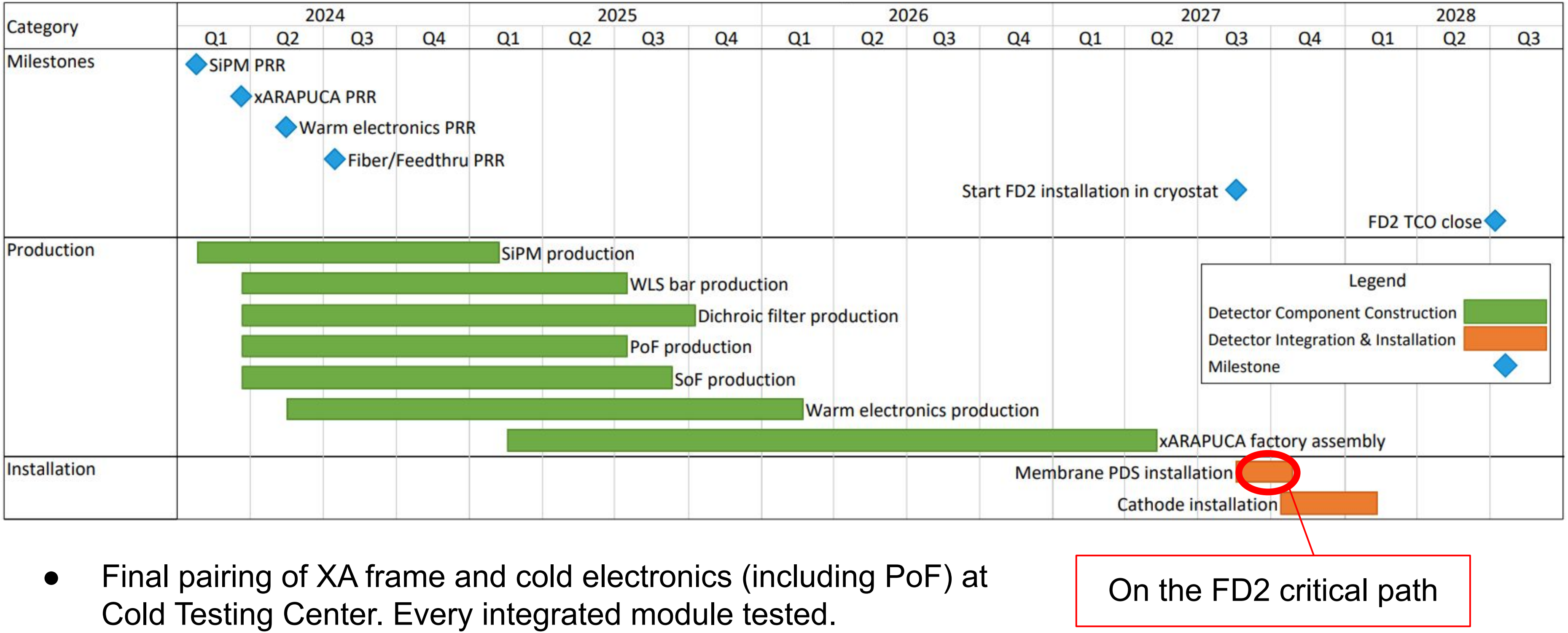
Production Test Stand	Responsible Institution
SiPMs Acceptance Testing	INFN
SiPM flex circuits Acceptance Testing	UCSB
WLS bars Acceptance Testing	INFN
Dichroic filters Acceptance Testing	INFN
PoF transmitter kit and receivers Acceptance Testing	SDSMT and SBU
Cold electronics motherboard and components Acceptance Testing	UCSB
SoF transmitter daughtercard and components Acceptance Testing	APC
Bias daughtercard and components Acceptance Testing	Iowa
Copper transmitter daughtercard and components Acceptance Testing	UCSB
short-run cables Acceptance Testing	UMich
X-ARAPUCA frame components Acceptance Testing	Iowa, CSU, and NIU
Warm electronics digitizer cards Acceptance Testing	INFN
Warm optical-to-electrical converters Acceptance Testing	APC
PoF & SoF warm and cold fibers Acceptance Testing	SDSMT and SBU
Membrane long-run warm and cold cables Acceptance Testing	CSU
Fibers for Response & Monitoring warm paths Acceptance Testing	SDSMT and ANL
Fibers for Response & Monitoring cold paths Acceptance Testing	Spain
Flanges Acceptance Testing	Indiana
Membrane-module feedthroughs Acceptance Testing	UMich
Cathode-module feedthroughs Acceptance Testing	SDSMT and SBU
Response Monitoring feedthroughs Acceptance Testing	Spain
Membrane-module Support System Acceptance Testing	Spain
SiPMs population on flex circuits Acceptance Testing	INFN

Production Center Assignments

- Institution responsibility:
  - Prepare assembly or integration testing infrastructure to meet required rate
  - Execute assembly and/or integration testing
- Integration testing to be fully defined in QA/QC plan in advance of PRR

Production Center	Responsible Institution
US module assembly center and warm testing infrastructure	NIU
Europe module assembly center and warm testing infrastructure	Spain
US cold electronics center	UCSB
US PoF transmitter box assembly center	SDSMT:1, SBU:1
Europe warm electronics center	INFN
US module final cold testing center	CSU:10, FNAL:1
Europe module final cold testing center	INFN
US fiber and feedthrough assembly center	SDSMT:1, SBU:1
Europe cable and feedthrough assembly center	INFN
Response Monitoring System warm path assembly center	SDSMT
Response Monitoring System cold path assembly center	Spain
Flange assembly center	Indiana

Critical Path and Float



- Final pairing of XA frame and cold electronics (including PoF) at Cold Testing Center. Every integrated module tested.
- More float for Warm Electronics and Fiber/Feedthroughs.

Conclusion

- December 2021 CERN Cold Box run saw the first full-chain and full-scale X-ARAPUCA prototype
  - S/N ~3 and dynamic range of 300 PE
- Now, in March 2023 CERN Cold Box run
  - S/N > 4 and dynamic range of 1000 PE for cathode and membrane full-chain
    - 2 Cathode X-ARAPUCA with PoF and local bias generation
    - 1 Membrane full readout chain with baseline warm-electronics
- The international PD Consortium is fully engaged
- Module-0 installation on schedule at NP02
- Optimizations to be demonstrated at CERN Cold Box September 2023
- While tests are ongoing, designed redundancy and preliminary measurements show that with reasonable component reliability our goal for 1% module reliability is within reach

Backup