Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

DUNE FDR: FD2 Photon Detector System

W Pellico (PD Team)

Power over Fiber

18-4-2023

PoF Outline

- Overview (1-2 slides)
  - Progress over the past three years
  - Our final operation parameters
- Technology Components Highlights
  - Lasers (1 Slide)
  - Fiber (1 Slide)
  - Photovoltaics (1 Slide)
- Complete System Layout (2 slides)
  - From PoF housing to Cathode Electronics
  - Control and Operations
- Safety (1 Slide)
  - Testing
  - Operations
- Conclusion (1 Slide)

PoF Team

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PoF R&D Roadmap (previous review – now)

2018
Proposed
Concept

Si based
PoF
Initiation –
Prototyping

2019
Si Based Testing
977 nm 3 W system
Commercial System
Worked but ……
Noisy
Low Efficiency

2021
Si 977 nm system
Tested in First CB tests
Successful but not FD

Cold box
Proof of
Principle
PoF
Demo

Resolve
Issues
from CB1

2022
GaAS 808 nm system
Improved efficiency
Reduced hardware test

2022
Improved
GaAs
Light leakage

Plan for
FY22 CB

PoF Tests/

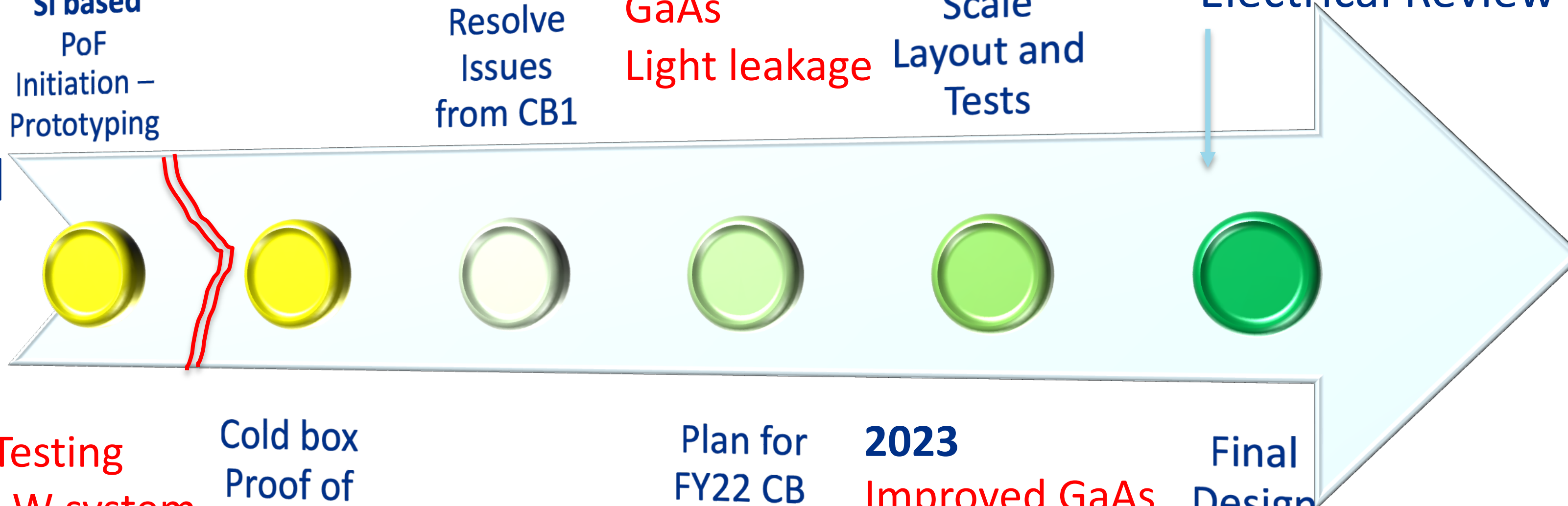
Certified

Ramp up
PoF Large
Scale
Layout and
Tests

2023
Improved GaAs
Met noise Req.
Power optimized

Today-ish
Sign off on Safety
Final Layout
Electrical Review

Final
Design
Delivery
with
Installation
Plan



PoF Operating Guidelines

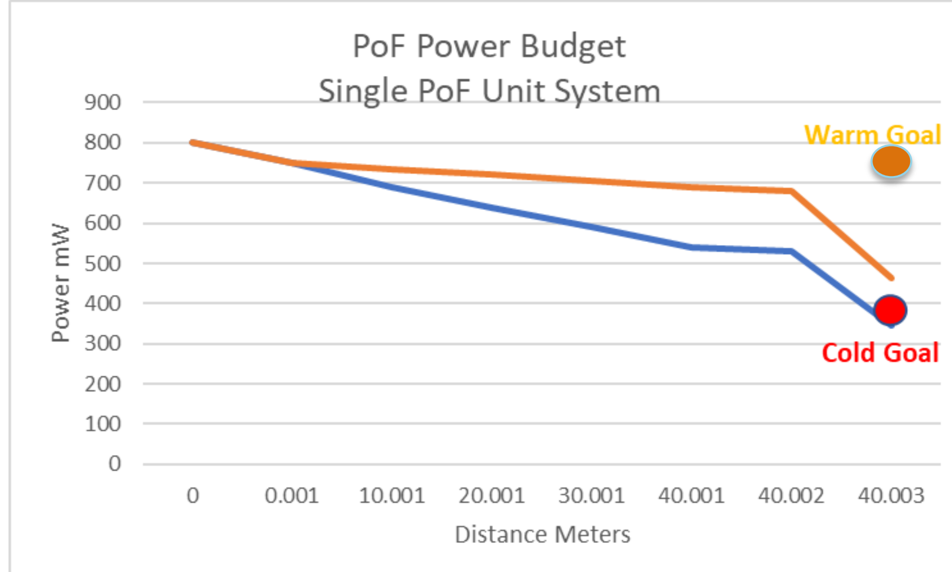
PoF System

COLD SIDE POWER NOTES

- Designed to above required/unit for 30-year viability
- To have redundancy the system is designed to be capable of >2x/unit
- Noise – < 1 PD per 10us
- Safety – meets DUNE/FNAL ES&H
- Contamination - mostly previously used

WARM SIDE POWER NOTES

- Safety – Class 4 to Class 1 conversion
- Capability – Cold plus system loss budget
- Cost – OTS products as much as possible
- Viability – Designed to be repairable



Laser Power	OPC (Optimum)	Fiber
2 W/unit Max	400 - 700 mW	6 W
800 mW Op Pt	600 mW Op Pt	600-800 mW

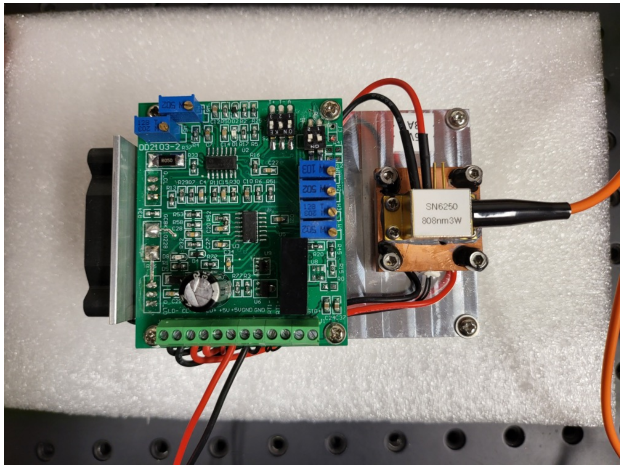
Plan

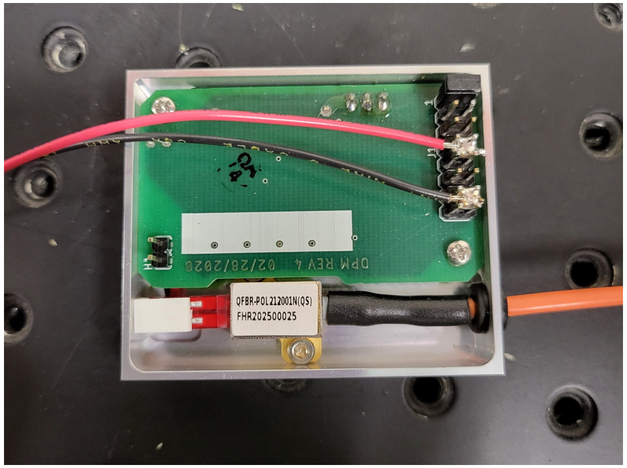
To test warm, it will be necessary to have both OPCs on.

The final cold operating point will be either one unit at ~800 mW or Two units at 400 mW. Neither will stress the system -

Lasers

- We have tested several 808 nm cw lasers.
  - Power: Wanted a laser capable of 2x operating point
  - Stability: Better than 10% power flatness
  - Cost: Commercial unit with limited features required
  - Lifetime: >10-year lifetime at full power





The AFBR-POL2120 is equipped with a pigtail fiber and an FC/PC optical connector. It consists of a laser chip, operating at 808 nm wavelength at a case temperature of 25°C. The hermetically sealed package protects the laser chip.

Fiber

Fiber type	Item	Description
MM	Numerical Aperture (NA)	0.27
	Index Profile	GI
	Core Diameter	62.5 ± 3 µm
	Cladding Diameter	200 ± 4 µm
	Coating Diameter	230 ± 10 µm
	Diameter of Buffer	500 ± 50 µm
	Fiber Attenuation	< 3.5 dB/km (@980nm)

- We tested about 10 fibers
  - Light Leakage: Several parameters play a role
  - Power handling: Not a concern at our level but we started higher
  - Efficiency: PoF choices all had similar efficiency numbers @ 808
  - Cryogenic Compatibility: Jacket was only concern – not the fiber
  - Durability: Jacket was only concern – not the fiber
  - Cost: Most of our fiber choices were not significant costs

Why is this fiber unique?

It has a large 200 um cladding – helps contain light leakage

It has a double jacket – 500 um and 1.5 mm – again for better light containment.

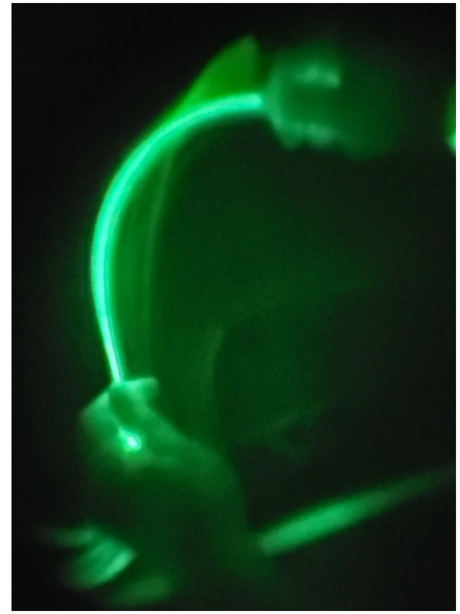
The fiber could be improved – but not under the pressures of the project. A significant improvement in fiber efficiency could be found in changing the coating to a 'softer' material – like silicon. I believe that would improve delivery efficiency 25% to 30%.

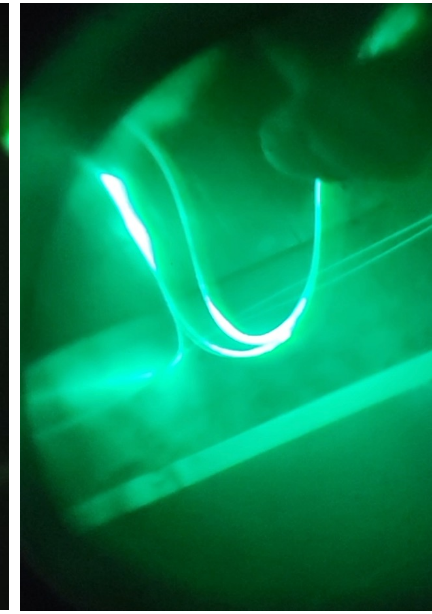
Fiber Tests Examples

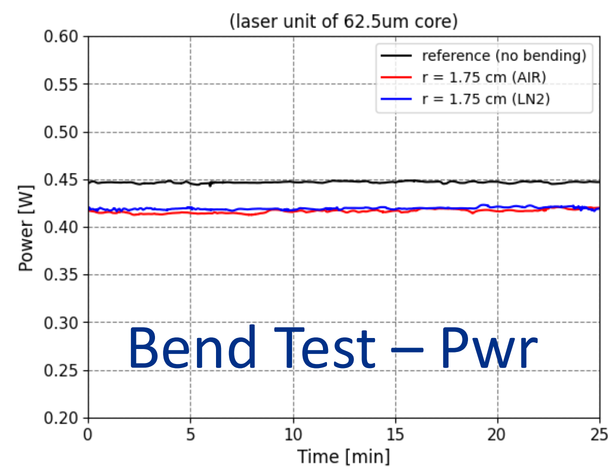
Fibers underwent a number of tests:
Bending stress testing
Light leakage
Thermal Cycling
Loss measurements

Comparing results to literature, with vendors, NASA and other experts.

No surprises were found – but optimization was required. More could be done to improve performance – less loss or if desired to carry more power in the future.





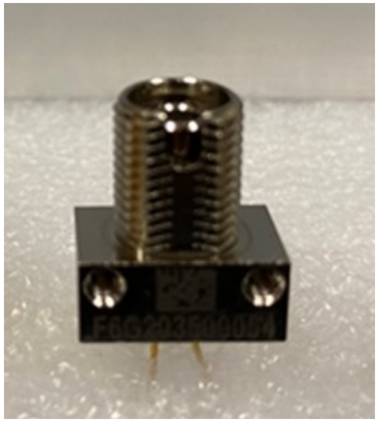


Optical Photovoltaic Converter - OPC

- We examined both Si and GaAs
- Si – 977nm based system
  - Si is cheaper for standard warm operations more W/$
  - Si was our proof of principle test in 2020
- GaAs – 808nm based system
  - Higher efficiency at cryo temps
  - R&D is rapidly expanding due to space-based systems
  - Improved rad hardness
  - Higher cost – but improving due to demand
- We went two routes – needed to improve from off the shelf
  - UIUC – Researching improved efficiency through semiconductor
  - Broadcom – Improved efficiency through packaging
    - Focal length, Material Size/Power Handling
    - Wrote a paper on the improvements – good press for Broadcom

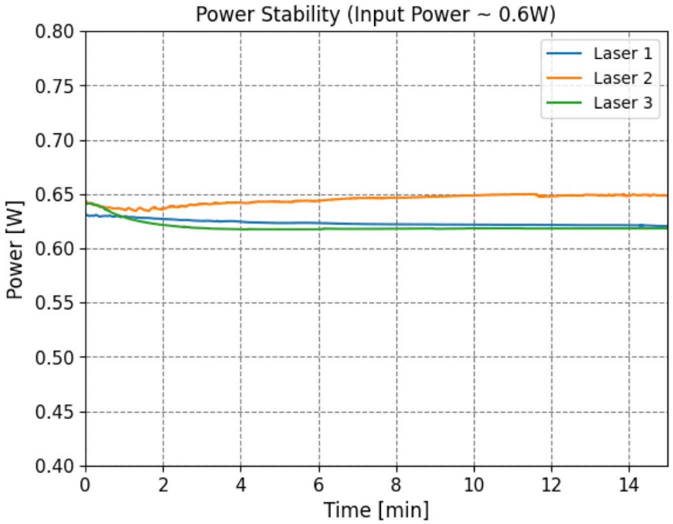
GaAs
Achieved power needs, regulation and relibility

- During the development of the GaAs cryo use – additional R&D was/is desired.
  - A contract with University of Illinois school of engineering was started
    - GaAs potential at cryo temps was not fully investigated
      - Carrier freeze out was evident
      - Tunnel junctions at cold temp became more resistive
    - Build units that meet VD PD specification
      - Extreme low temp ops with efficiencies of room temp devices
      - No contaminants
      - Use of approved material – namely epoxies/sealants



In the end a partnership between FNAL, Broadcom, UIUC and GoPower

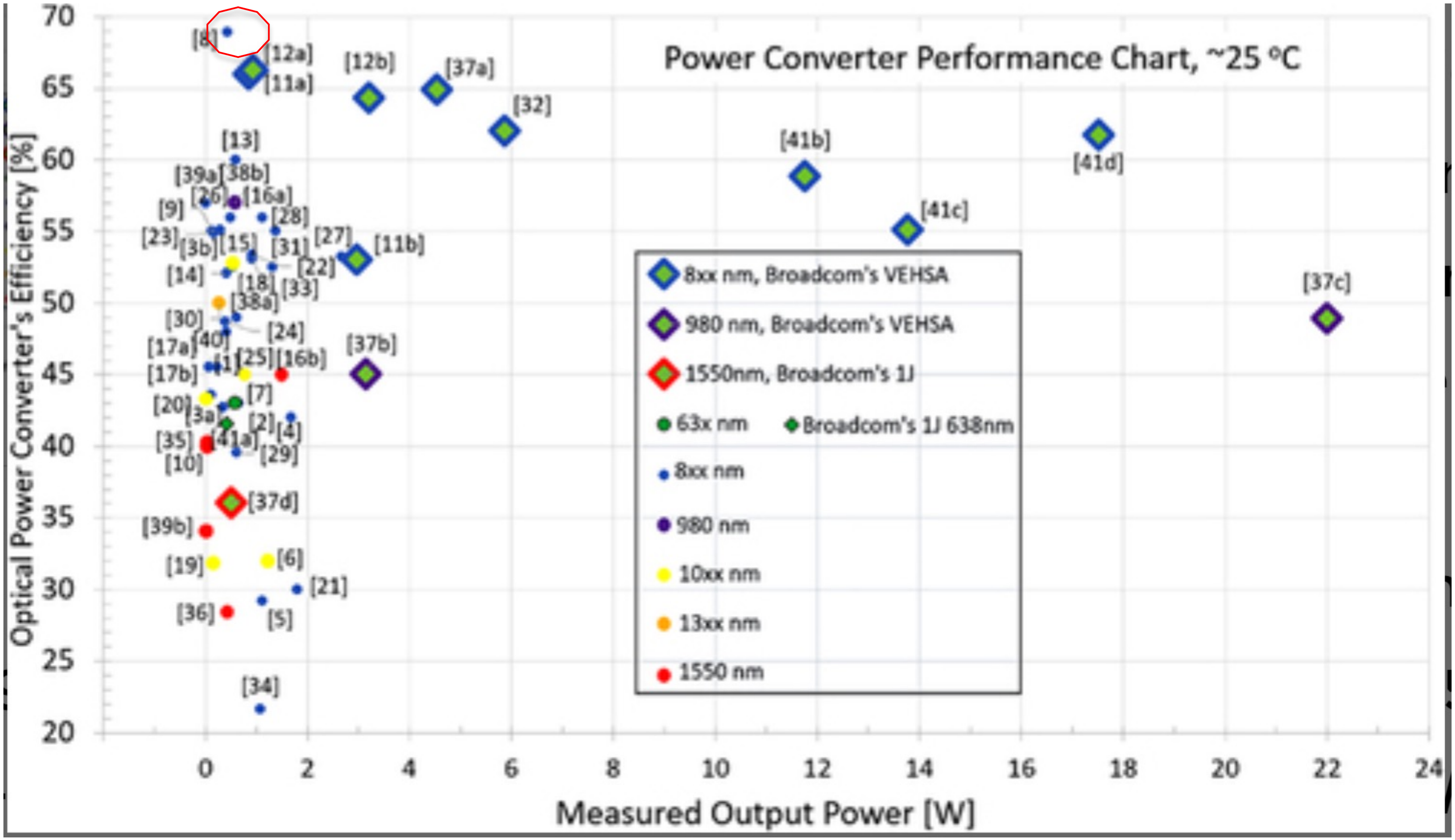
The final version (V4) has undergone several noteworthy improvements to achieve the higher efficiency at cryo Temps and to reduce impact of cryo on optics.



The work will continue outside of the VD project to test new ideas – 1500 nm, Rs reduction etc…..

DUNE/PD has helped push the technology

We have worked with our industrial partner to set new limits!



We have both industrial and university partners in this effort.

PoF Rack - Safety

- Meetings with lab laser safety and project safety has continued to ensure we meet all ES&H requirements.
- This work has been progressing with the development of smaller systems for the past three years. Several documents describing the system and deployment have been written with final documents expected to be completed over the next couple of months. We are starting with the prototype PoF housing unit – then will provide to our VD partners.

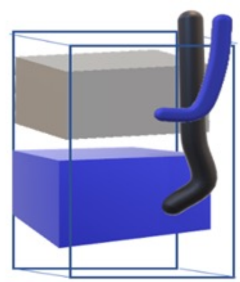
Safety Documentation Underway

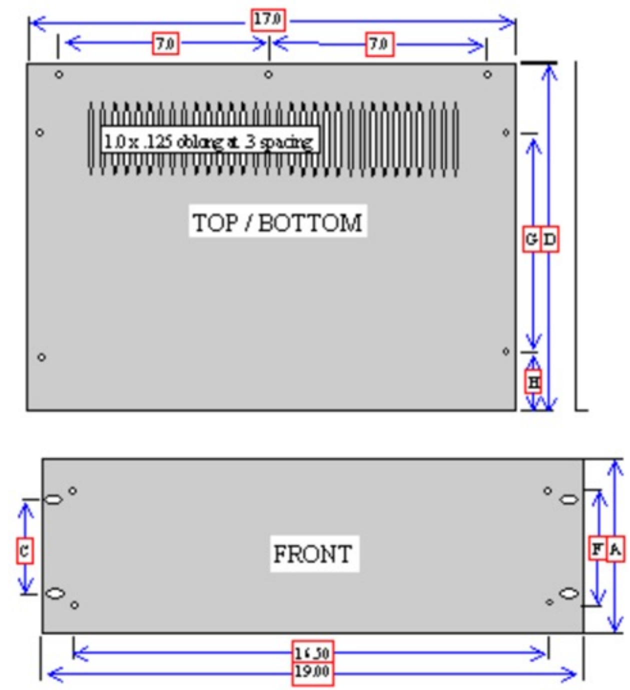
- **PoF Laser Housing Unit**
- **Version 2.b 4/01/2023**

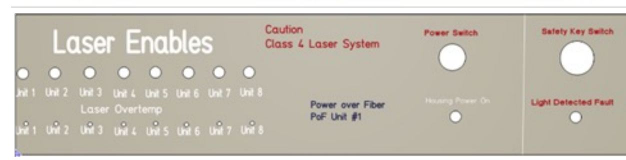
- The description provided in this document is for a prototype 8 laser system design. The housing unit has undergone several iterations to better meet VD rack layout, fiber routing and laser safety guidance. The design is done to ensure safe reliable extended operation.
- The design is based upon 8 lasers per housing unit with two housing units per power over fiber (PoF) rack. The laser housing units consists of the following key components:

Final Rack Layout and Controls

The optimization of the Laser housing and controls is in progress with a module being assembled and expected to be tested in May.







The work will move to Stony Brook and SDSM this summer for full testing and training.

Conclusion

PoF has been proven to deliver clean power at required levels to an isolated cryogenic electronic system. Work moved form concept, to an optimization stage, to deployment in serval short years.

The work ahead will focus on documentation, production and deployment testing.

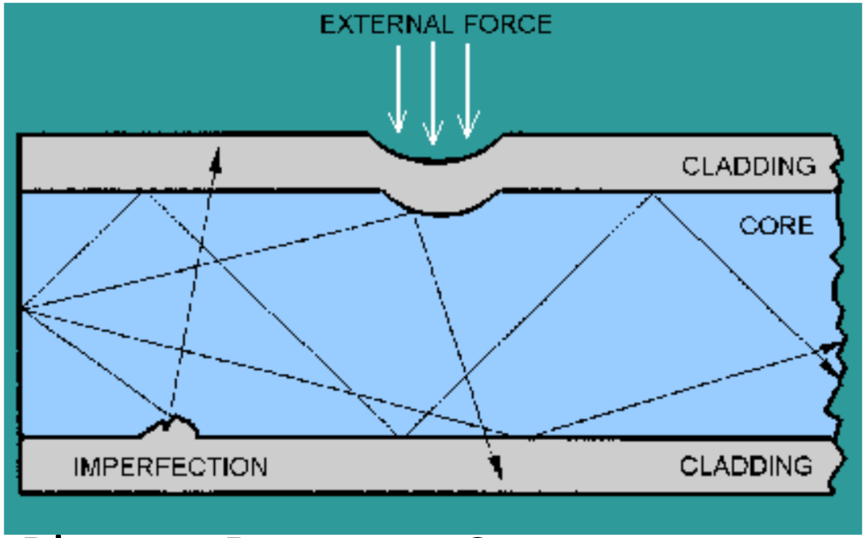
Would like to think about PoF for future uses – this effort has significant LAB/DOE support and industrial partnerships.

Extra Slides

- Cold Temp Fiber Paper:

Analysis of optical fiber performance at extreme temperature in low earth orbit
. OptikVolume 250, Part 2, January 2022, 168344

The loss of optical fiber at low temperature is mainly caused by micro bending loss. It is a kind of bending loss, which can be divided into micro bending loss and macro bending loss.
……at low temperature, the temperature coefficients of the coating layer of the fiber are inconsistent with those of the fiber core and the fiber cladding, which are different due to deformation, resulting in micro bending loss.



•We are considering a backup optical fiber from Molex company that meets our VD SoF and PoF requirements.

Fiberoptic Cable

Fiber: FIA105125245

Low-OH Silica Core: 105 ± 3μm

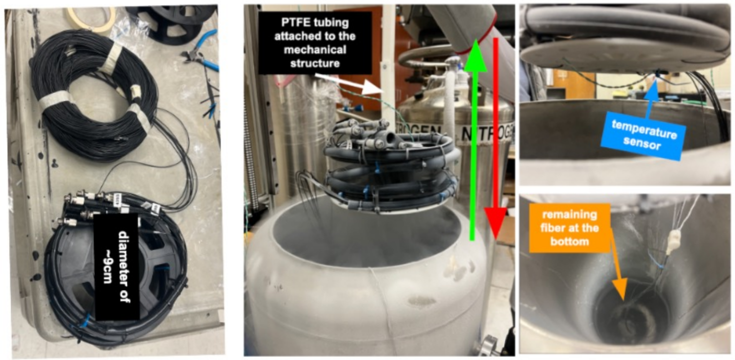
Doped Silica Clad: 125 ± 3μm

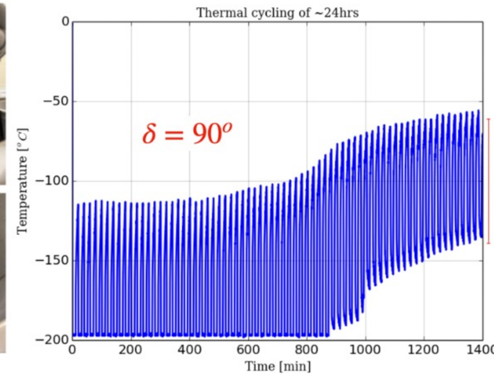
Acrylate Buffer: 245 ± 15μm

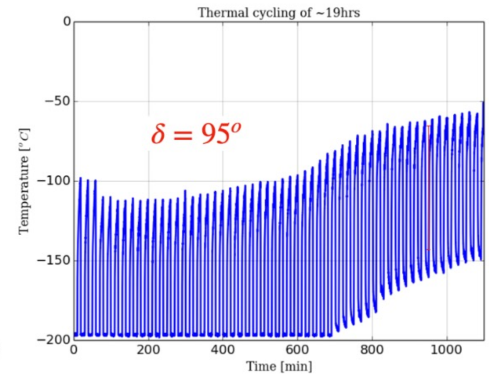
NA: 0.22 ± 0.02

Black PFA Jacket: 1.5mm (nominal)

Optical Fiber: Thermal Stress





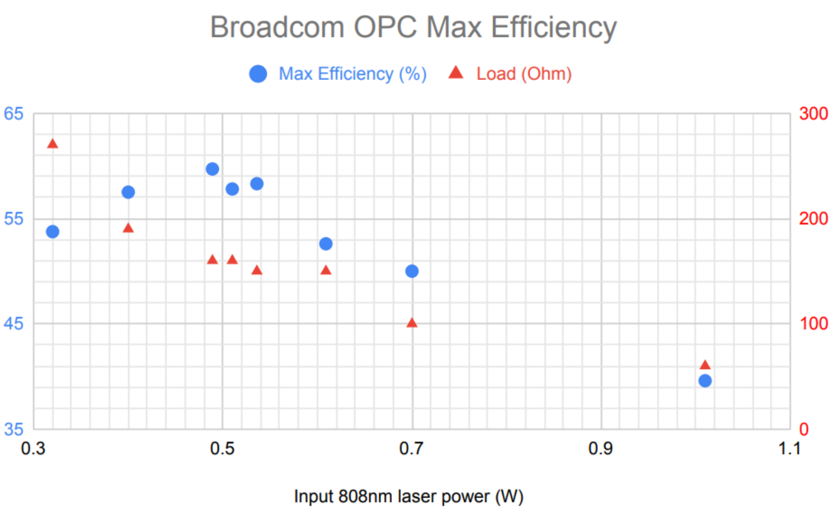


Optical Fiber [62.5um core and 40m length]	
$ratio = P_{output}[nW]/P_{input}[nW]$ Before	$ratio = P_{output}[nW]/P_{input}[nW]$ After
0.78 ± 0.02	0.78 ± 0.01

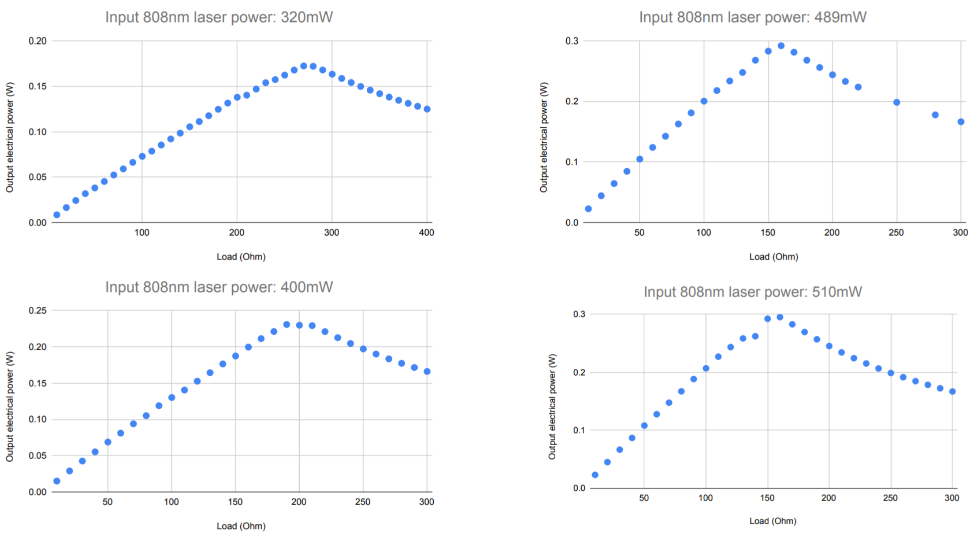
- We have performed a thermal cycling stress test, submerging and extracting the fibers and PTFE tube sample from the LN2.
    - We inserted eight optical fibers into a tube and bent it into a circle with a diameter of 9cm
    - The cycling submerges the material for 9 min, takes 1 min raise up, waits 9 min in air and then takes 1 min to lower back into the LN2 (~129 cycles).

Full set of tests for each OPC unit
Power, Efficiency, Leakage (I-V curves across loads)

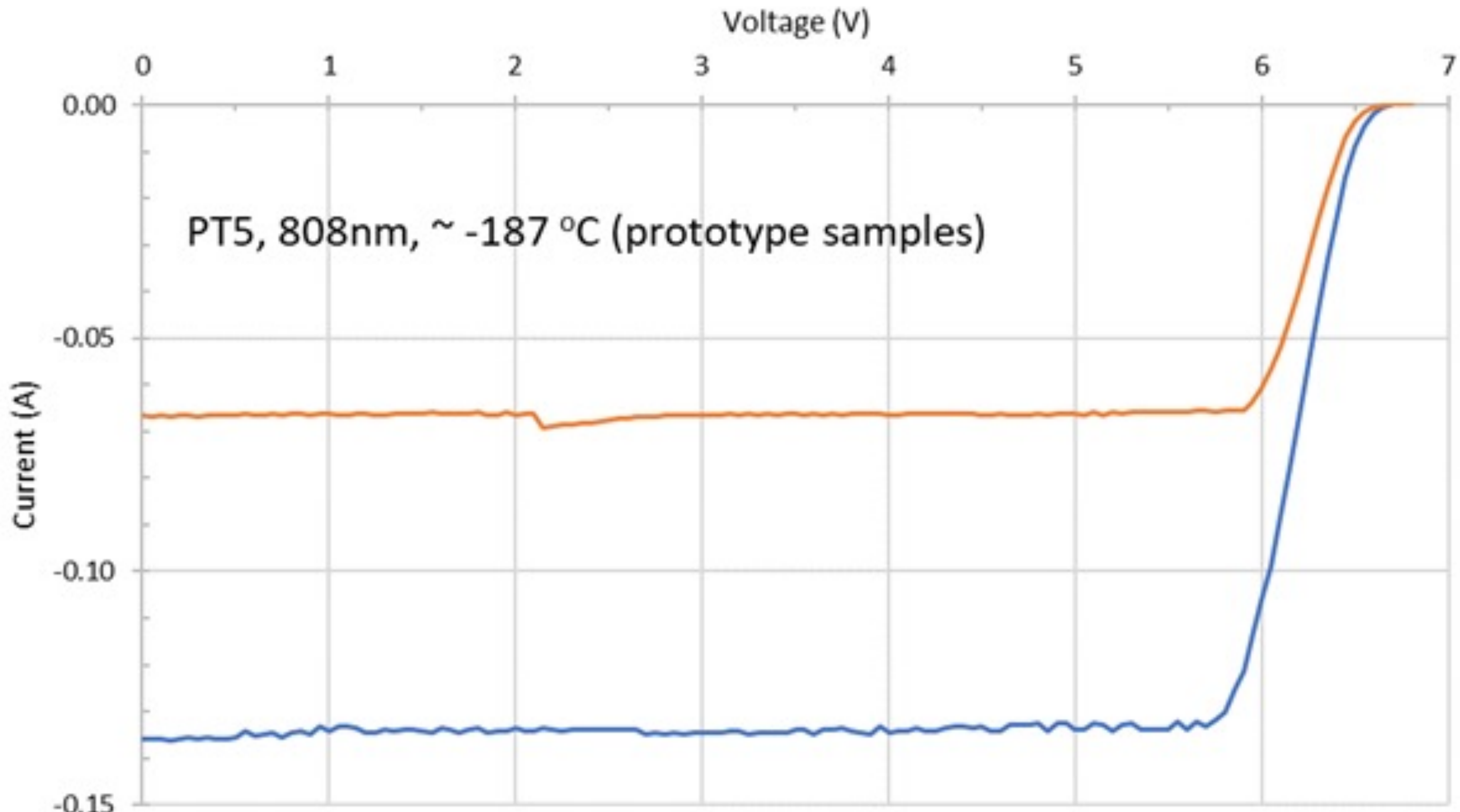
We have been putting together a testing and assembly standards.
Each laser, fiber and OPC will have a traveler that provides information on assembly and test performance.



Broadcom OPC Power conversion



Vendor updated unit tests – V4 OPC



Newer OPCs have are slightly larger and matched cryo optics
Higher current and power capability -

Backup –Reliability Examples (More from JPL)

We did conduct some reliability tests over the 62.5um black fiber in the past. The fibers are installed in an outdoor high voltage (22.4kV) environment, one end was secured on the high voltage busbar and the other end on the ground. In this test setup, the fibers were exposed to high voltage, high humidity (with rain falls), and UV from the sun. Over 3 years of testing, we did not see any problem with the fibers.

Regards,

John Wu
VP, System Engineering Dept.

I was recently told by Siemens, one of the first to deploy PoF in the late 90's that an HVDC installation between Australia and Tasmania has been running non-stop without any component failure, incl OPC, laser and fiber, for more than 23 years. Likewise, even earlier installations by ABB in the north of Sweden have been, and still are, running non-stop since 1997. In fact, at one point I was there to replace all lasers which had been sourced from ……. The problem was that on very cold nights (-35C), the current sensing system had stopped working. It turned out that using 850nm lasers with OPCs optimized for 808nm meant that at the cold temperatures for the OPCs, they no longer responded to 850nm light. At least not as long as the lasers were comfortably located inside a control room at room temperature….; after switching all the lasers to 808nm, the problem disappeared. Little did I know back then that fast-forward 25 years, we'd be pushing the OPC to longer wavelengths for ostensibly the same reason albeit lowering the operating temperature by another 150 K.
Best regards
Jan
Chief Photonics Scientist, Broadcom

Hello Bill, Ryan (NREL), Nikos (NREL),

+also added Denis from the Broadcom team for the technical discussion.

As part of our standard product qualifications, we've done **many tens of thousands of device*hours of each of high-temperature-operating-life (HTOL), low-temperature storage (LTS), high-temperature storage (HTS), and temperature cycling (TMCL)**, as well as other reliability tests that are probably less relevant in this case, such as temperature humidity bias (THB), mechanical shock (MS), mechanical vibration (MV), etc.

The good news is that for our laser power converters, I do not recall seeing any real signs of degradation from these tests, i.e. within the uncertainty of the measurements, the performance after is not really distinguishable from the performance before or from a group of devices without any aging.

Now of course, the conditions for the lower temperatures for the LTS and the TMCL is only ~-40 ^{o}C, but as Ryan mentioned similar III-V PV chips are also known to work well within extreme conditions in the context of space PV.

Furthermore, we expect the degradation mechanisms to be thermally activated, so the HTOL should be the best test for that (normally done at 85 ^{o}C with the laser ON). For the cryogenic case, all such degradation mechanisms would be super slow because of the low temperatures.

As for the hot electrons as in CMOS or FET, the device design does not include such tight geometries, so we do not expect this should be a concern.

Anyway, Denis and I were thinking maybe we could try to run some devices at 1W of optical input at 77K continuously for 100 hours or something like. Presumably we would not be able to see any degradation. I do not think we can detect < than 1 part in ~500, so at best it would be sort of less than 5 years equivalent.

What do you think?

Or is NREL or FNAL readily equip for testing in cryogenic conditions for longer than that?

I do not think it is necessary to monitor during the test, just maintain the cryogenic temperature with the laser ON with a dummy load, and then we can re-test after from our side.

My son is working at the David Florida Labs of the Space Agency, they do a lot of testing like that but he tells me they do not do "long" runs in cryo conditions.