Power Over Fiber DEVELOPMENT 4 HEP Detectors

Pisa Meeting 2024

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Emerging Technology

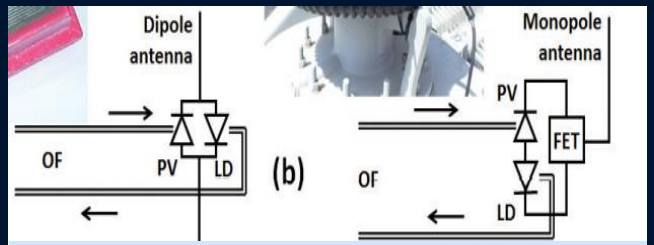
Fermilab

Power Over Fiber (PoF)

PoF has been used for a long time in harsh industrial environments

The applications are typically found in two areas:

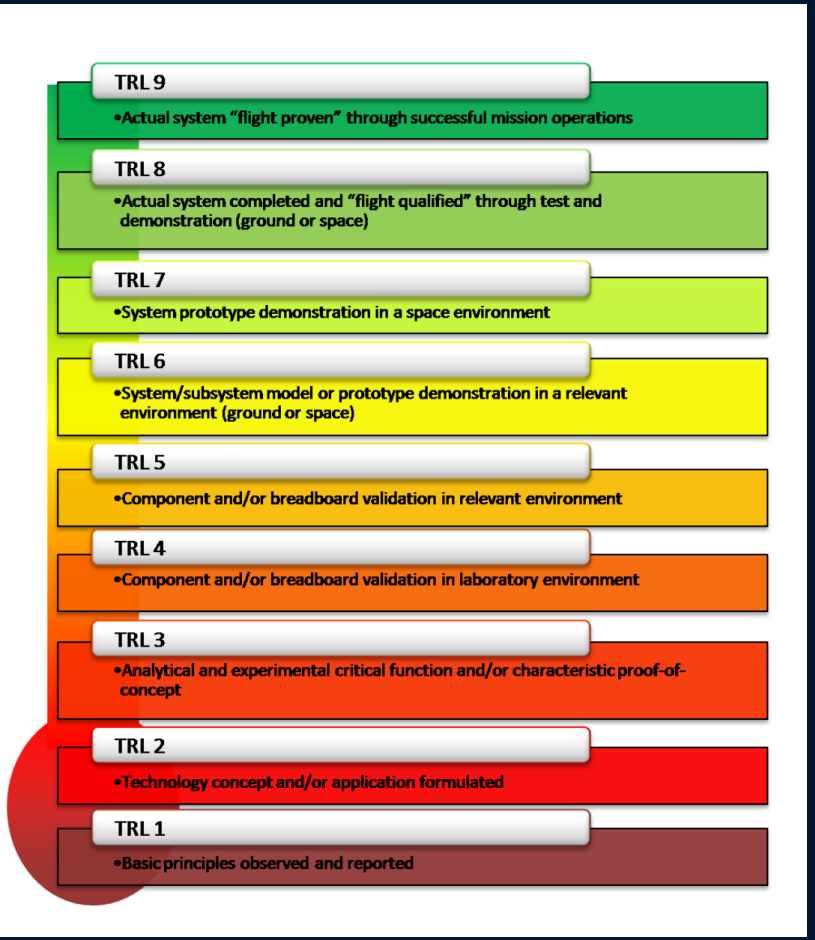
1. Ground Isolation
    1. High Voltage Systems: Ion Sources, Modulator Decks
    2. Radar Towers: Controls and Diagnostics
    3. Power Distribution Monitoring Systems: HV Monitoring and Power Lines
2. Electromagnetic Noise Reduction and Protection
    1. Military installments (Filed applications)
    2. PoF and Data on the same fiber for secure distributed communication



Breaker Monitoring Antennas

Transformer Electronics Power

Ion Source Systems

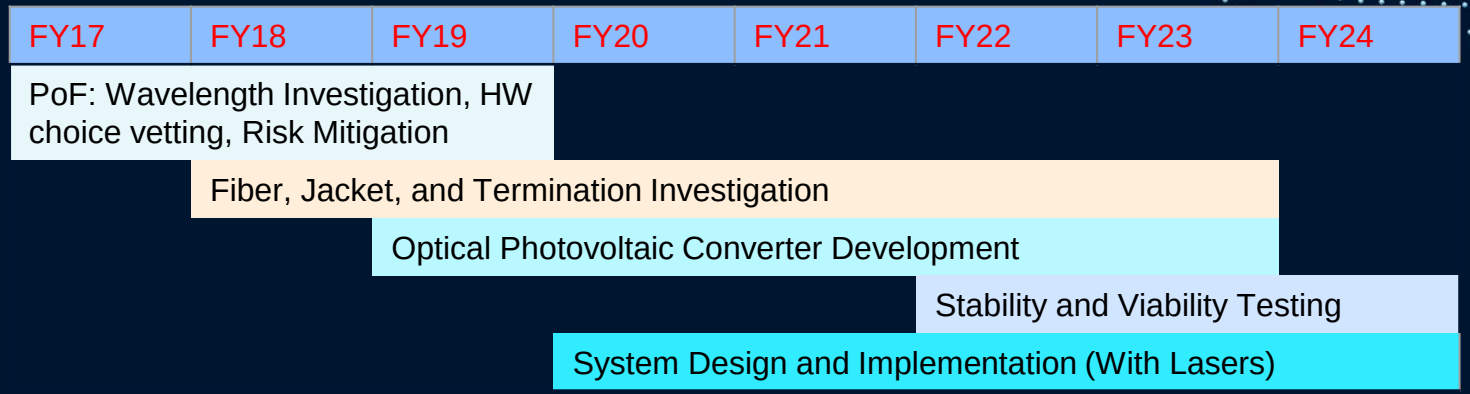


This talk is a technology development talk that follows a development similar to other emerging technologies.

I apply a NASA TRL definition.
DUNE/Large Detectors are a lot like a space launch technology. (without the budget)

HEP – DUNE offered a new use case

We have been working on PoF since 2017 for use in a cryogenic systems where a HV potentials exists

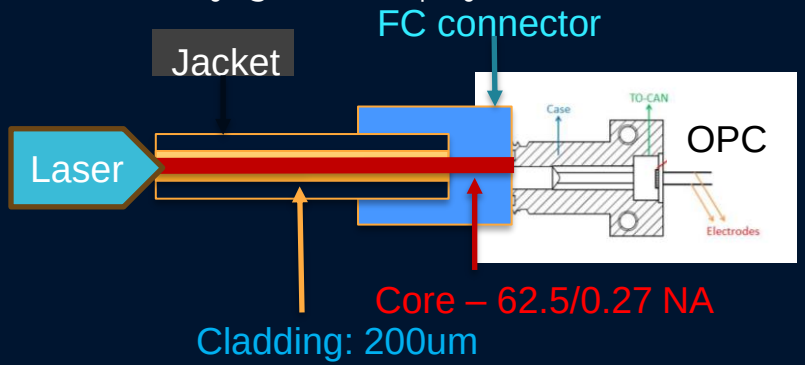


This PoF effort is similar to other technology developments for implementation of a new use case.

The work took a path for a system from TRL2 to TRl7 (TRL8). (TRL = Technology Readiness Level)
Lasers: TRL 10
Fibers TRL 4
Optical Photovoltaic Converters TRL2

PoF System – Photon Detector

- The three components to a PoF system
  - Laser, Fiber, OPC
- There are warm systems under development pushing the power, but we were the only cryogenic R&D player.



OPC

- Liquid Cryo Compatible
- HV Isolation
- Power Conversion Efficiency
- Viability
- Noise

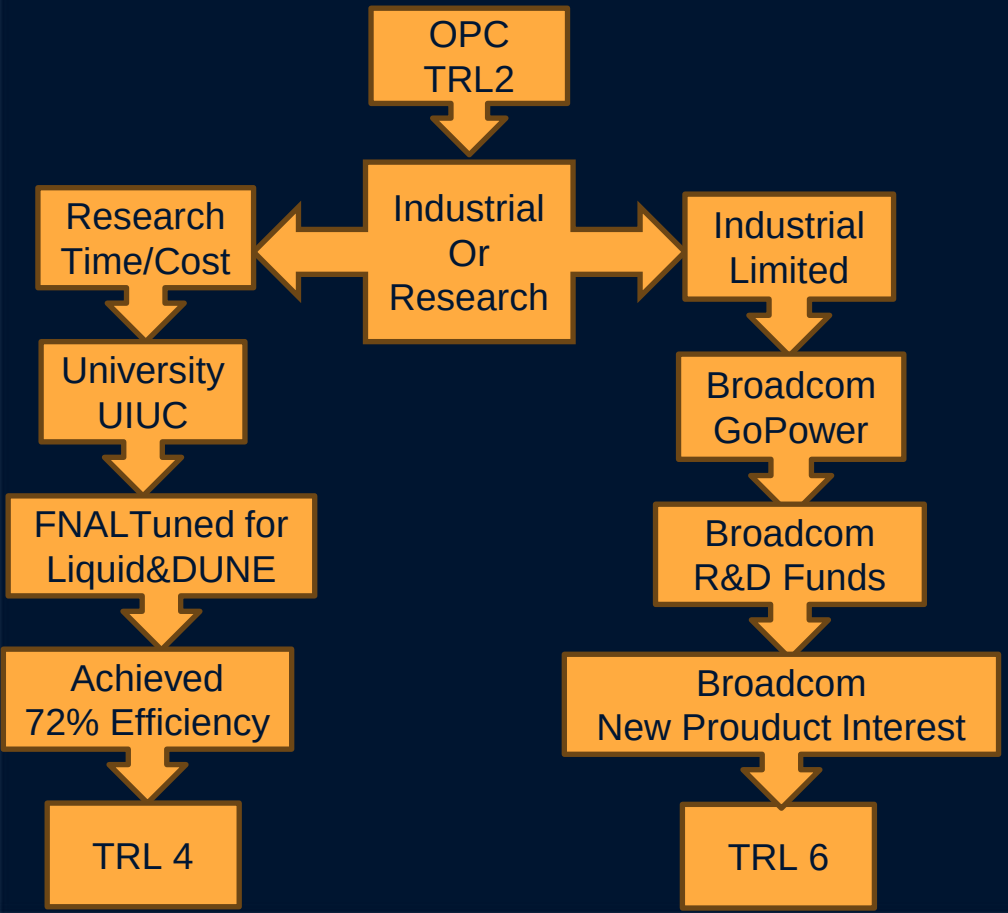
Fiber

- Liquid Cryogenic Compatibility
- Power Handling
- Light Leakage
- HV Compatibility

Laser

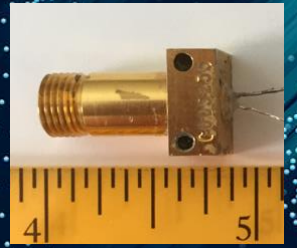
- CW Regulation/Stability
- Safety

OPC Development

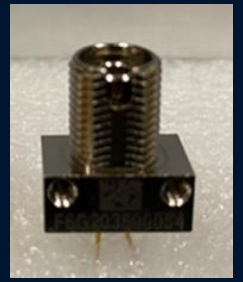


The success of this work hinged on road mapping out the technology quickly and convincing DUNE/DOE that we should pursue this work. The OPC was our biggest concern and the path was not clear.

OPC – Initial Evaluation



- First tests on off the shelf OPCs
  - Silicone: Cheap, Low Efficiency with no path, 977 nm Laser
  - GaAs: Medium Price, Low Efficiency with path, 808 nm Laser
  - InGaAs: Higher Price, Low Efficiency with path, 1477 nm Laser
- Voltage output is a reflection of layer count and conduction R
  - Tested units from 4 volts up to 36 volts (cold values)
- Power/Current IV curves /Efficiency verses Load/



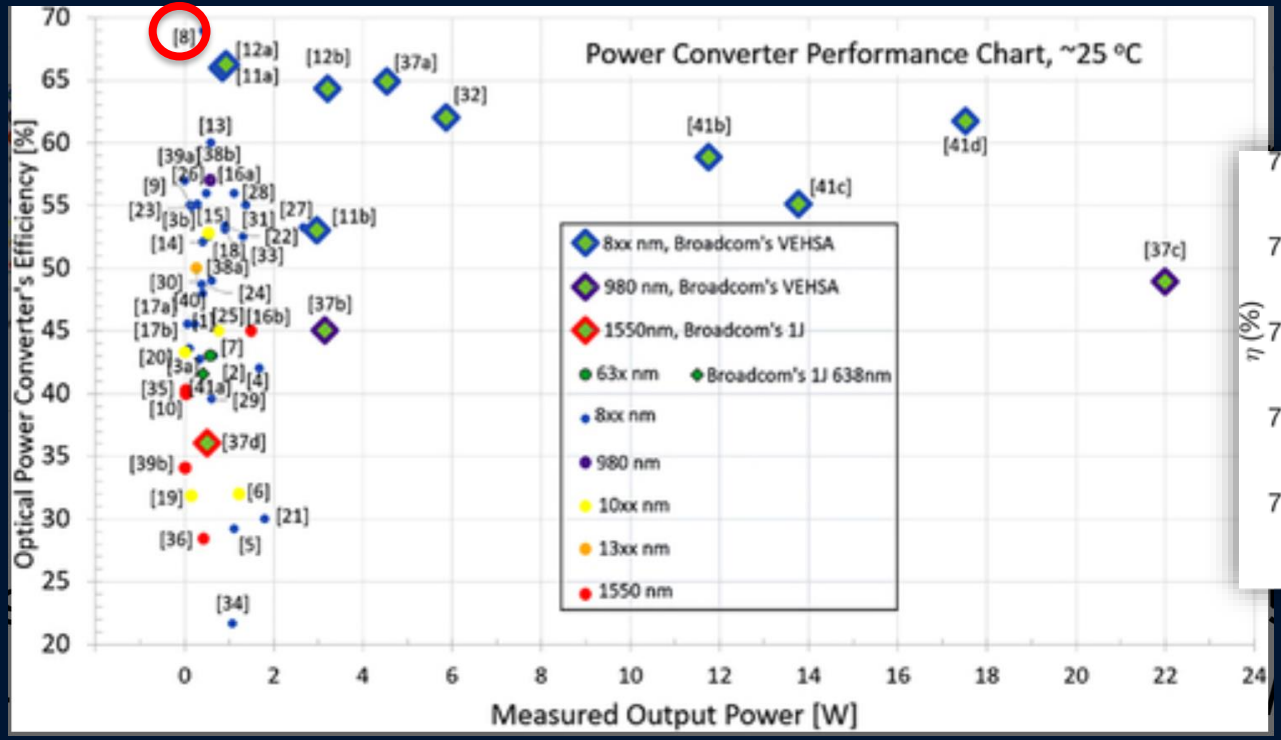
- Selected GaAs for DUNE VD2
  - **InGaAs may be FD3 OPC and optimized for future detectors**

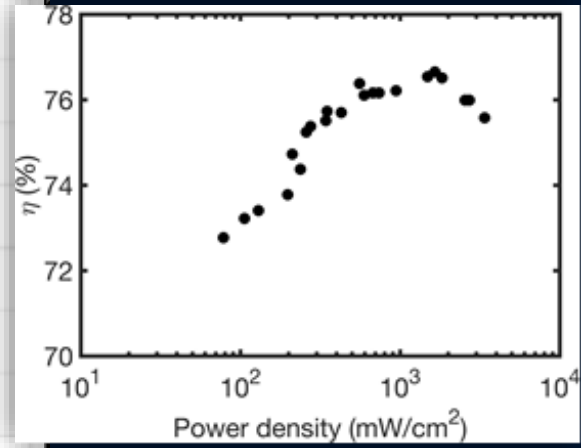
OPC – DUNE – FD2

- Working with Industrial Partner Broadcom
  - Limits on modifications – too small a market
    - What could be changed in their process to improve cold
    - Cost Share – reduce their risk
    - Testing Shared
- Achieved a doubling in efficiency at high power (1W)
  - Enlarged the footprint
  - Added some metal to the substrate
- Package remained the same.
- Produced a new product – published
- Efficiency stays mostly flat from warm to cold (slightly higher cold)

DUNE/PD has helped push the technology

We have worked with our industrial partner to set new limits!
Never used at cryogenic temperatures





Pushing the power/efficiency

We believe we can achieve > 72% above 1 W.

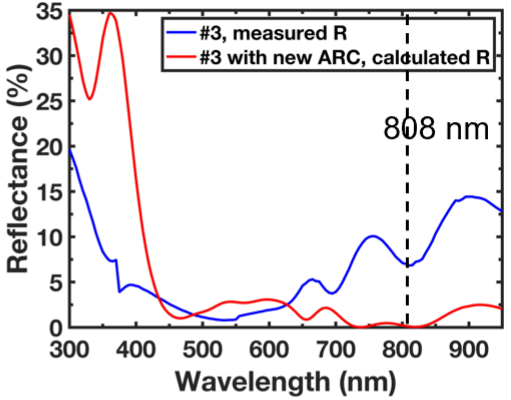
Some of the OPC changes

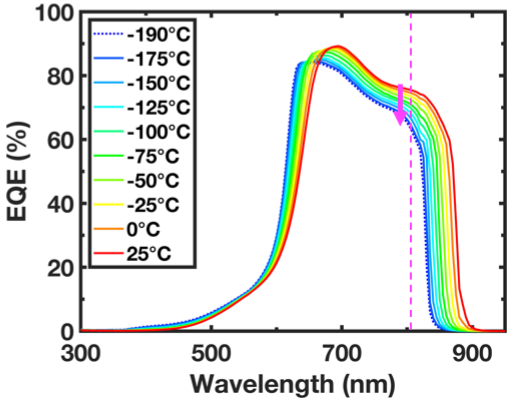
Near-Term Roadmap for 60+% Efficiency GaAs LPC at Low T

- **Optimized OPC – several tech updates**
  - Simply, with optimum anti-reflective coating, efficiency at 190˚C will be ↑ to 54%.
- **Larger Surface Area**
  - **2x2 mm to 2.4x 2.4mm**
- **Adding metal to the tunnel junction**
  - **p+$Al_{0.1}GaAs$ BSF**
    - Diffusion length ↑, barrier for minority carrier

Device	Power	$EQE_{808\ nm}$ at RT	$EQE_{808\ nm}$ at -190˚C
H1 BC Unit	300mW	52%	28%
H2 BC Unit	300mW	54%	37%
F1 BC Unit	500mW	58%	45%
F2 BC Unit	600mW	65.4%*	62.2%*
#3 with optimum ARC	0.2%	80.9%**	66.8%**

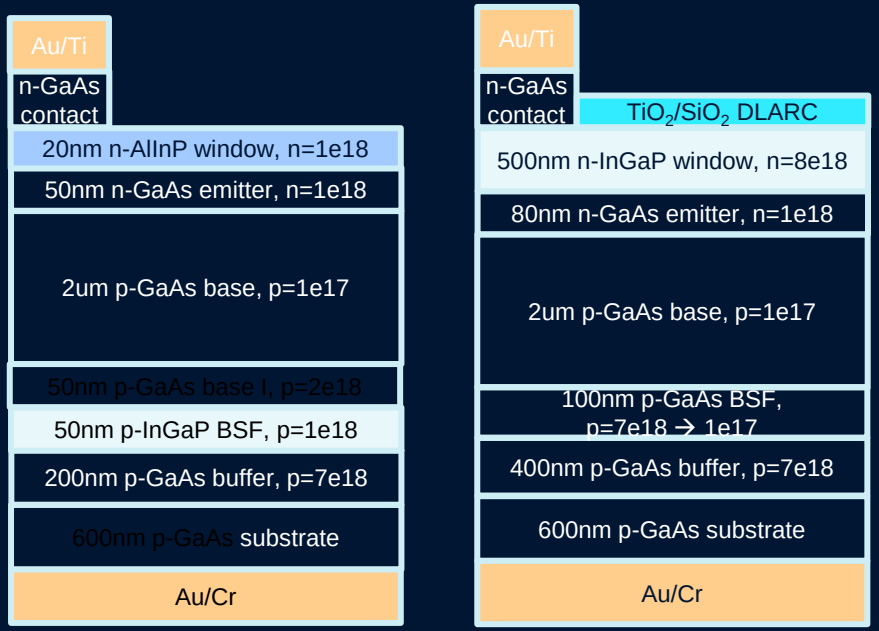
- *TBD Feb 2023
- **TBD Fall 2023



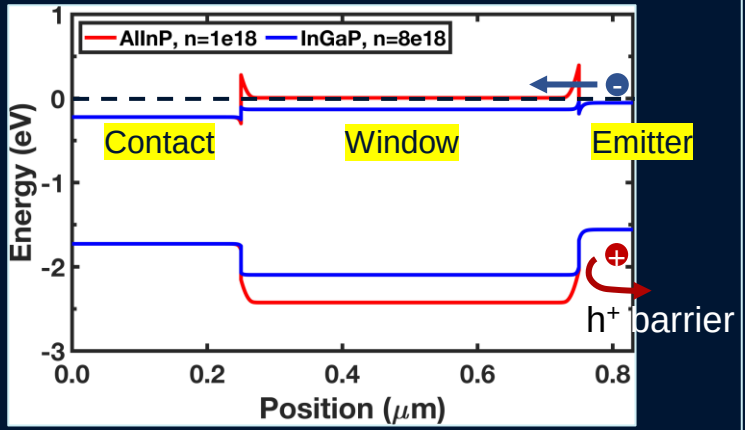


New LPC Design to Lower Series Resistance (R_S)

- **Design**
- #1 → #3



- **Aspects expected to be improved**
  - Low R_S enabled by thick, n+-InGaP
    - Suppressed majority carrier blocking



    - Low R_{sheet} (33-35 ohm/sq)
  - EQE enhancement by DLARC

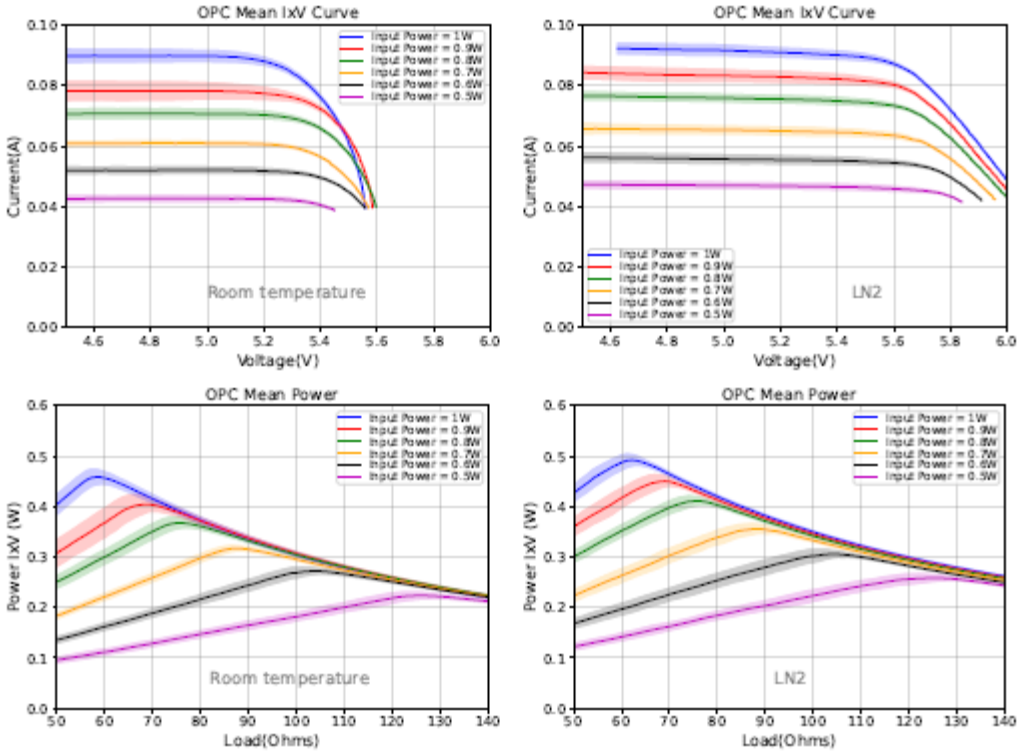


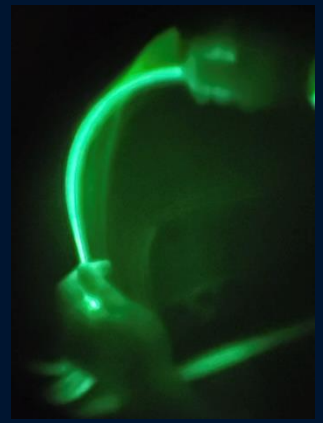
Figure 3: I-V curves (upper panel) and P-R curves (lower panel) for 12 OPCs (shaded color bands represent standard deviation) at room temperature (left column) and cryogenic temperatures (right column).

The development and viability is now based upon large number of unit testing. Statistics and documentation to ensure a reliable technology.
Testing is becoming automated.

Fiber

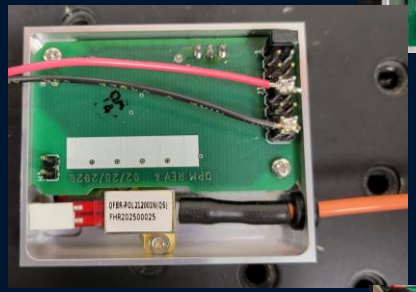
- TRL4 –>TRL8

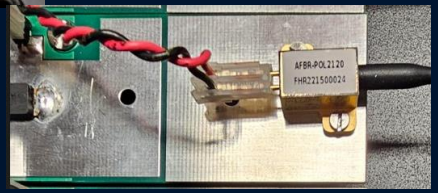
- Working with Industrial Partners
  - Limits on modifications – too small a market
  - What could be changed in their process to improve cold pwr
    - Compression Loss
    - Bend Radius
    - Light Leakage
    - Tensile Strength
  - What options work at high power densities in cryo
    - 50kW/cm^2
  - Safety – Ensure Class 4 laser system operating in Class 1



Laser

- TRL10



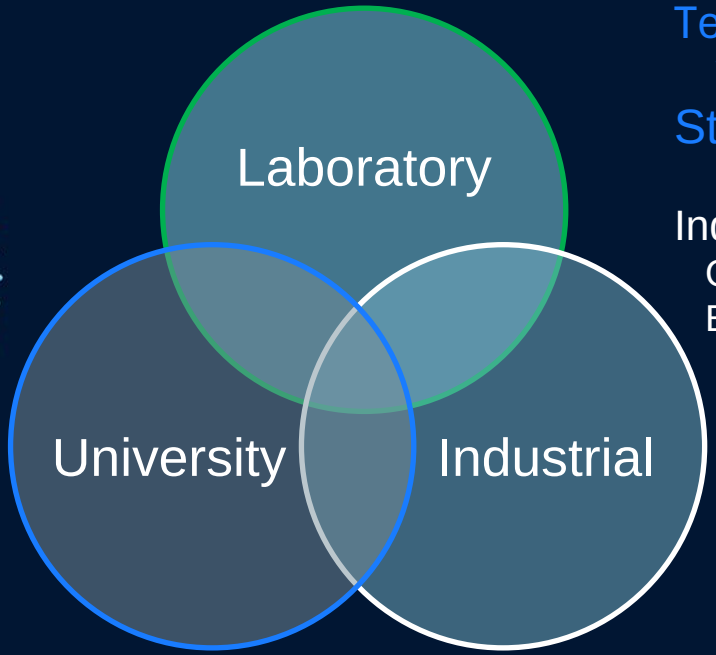


The laser system was not R&D

- Cost
- Stability
- Features for DUNE Operations
  - Safety
  - Longevity at CW Operations

- Final Laser design includes a FNAL high efficiency driver and off the shelf 808 nm Laser in a compact footprint.
  - 25% wall to light efficiency
  - 2cmx5cm unit size

PoF Effort



Special Thanks

Fermilab Team
- Low TRL/Testing

South Dakota School of Mines and Technology
- Viability and Stability Testing

Stoney Brook
- PoF Certification Testing

Industrial
- GoPower (Silicon and Fiber)
- Broadcom (GaAs, InGaAs, Lasers)

Considerations for Future Proposal

Working with industrial partners in packaging our next version of higher efficiency and tuned voltages is underway.

The next stage:

- > 70 units at > 1 W
- Units that can generate higher voltages to directly power SiPMs.
- Looking to bond OPC and communication links.

Conclusion

- The PoF has been very successful in not only generating a tool for HEP detector use – we have forged a collaboration with industrial partners and universities..
- The first use case for the DUNE VD2 PDS has expanded the coverage of PDS.
- The work will continue beyond this application into industrial applications.

A publication by Broadcom has been completed.
The PD team has just published our work:
"Characterization and Novel Application of Power Over Fiber for Electronics in a Harsh Environment" at DUNE DocDB 30532-v1
ARXIV publication submitted
Thanks for the invitation to speak at your corner of paradise.