Fermilab Internal Review of GQuEST Technology Demonstrators Presentation from PIs

Sept 22, 2023

Chris Stoughton, Kathryn Zurek, Lee McCuller

Precursors to Quantum Sensing upgradable experiments in quantum gravity, dark matter, and macroscopic quantum mechanics

Outline

1. The Charge
2. GQuEST Overview:
    a. The Collaboration: People and Institutions – DOE, Caltech, JPL, HSF, and Fermilab
    b. theory motivation; photon counting; conceptual design
3. Theory/Experiment collaboration
4. Progress and Plans
5. Our response to the charge

1. The Charge

Charge - part one.

This is an internal (ETD) review of the cost, schedule, and project management aspects of GQuEST.

We originally proposed $11.45M over five years through QuantISED DOE/HEP.

After review, we were asked for a one-year FWP for $910k (down from ~$2M for the first year.)

In FY23 we received $200k initially, followed by $335k in the last quarter and $325k in August, for a total of $860k.

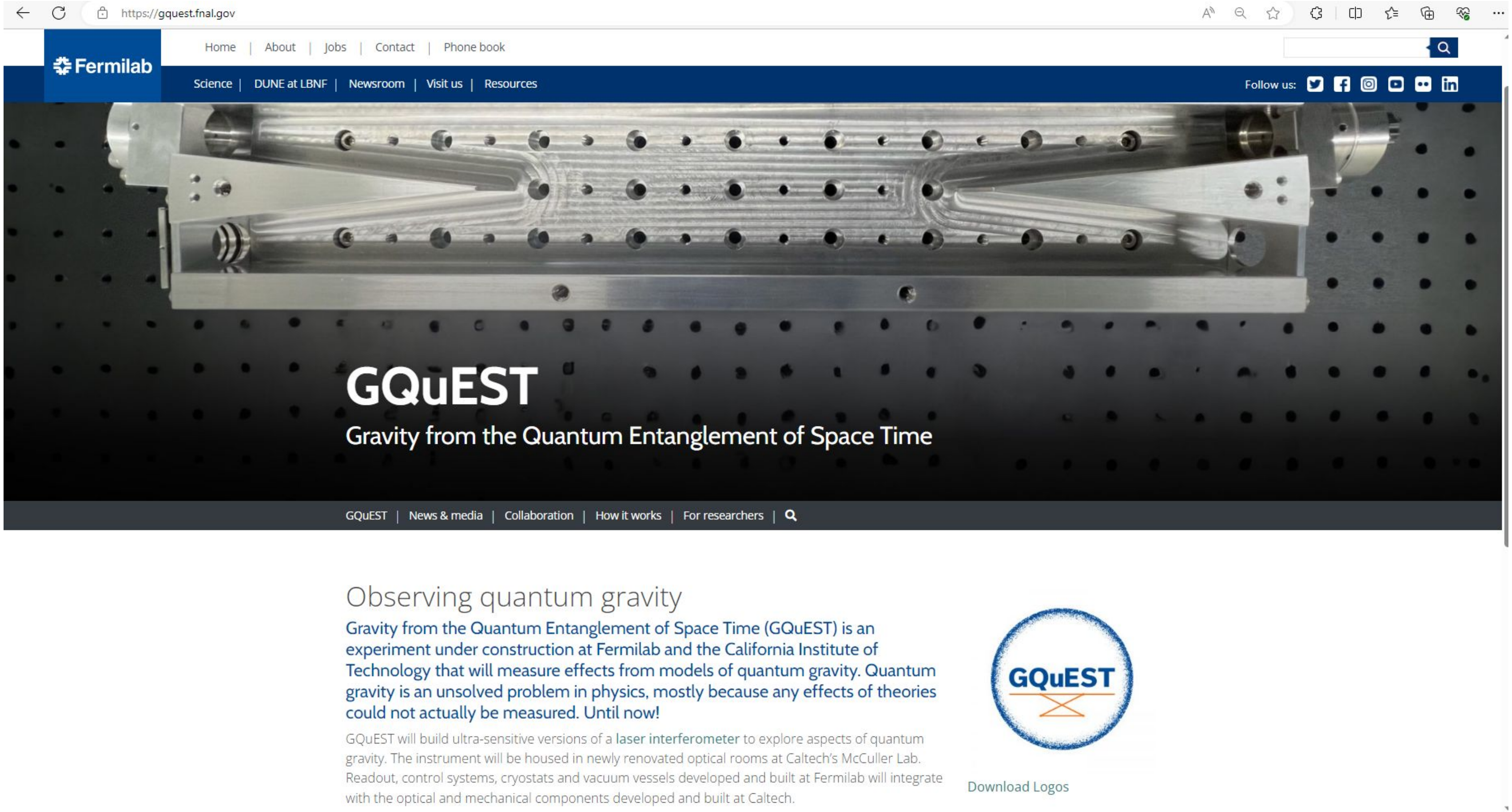
Given this funding profile, the focus of this review is on the cost, schedule, and management aspects of GQuEST towards producing a detailed experiment conceptual design, science goals, and corresponding technology demonstrators to support the path to PD0 (mission need) and PD1 (cost and schedule range) approvals.

Charge – questions to address

1. Has the GQuEST collaboration adapted its scope and plan to the new funding profile to produce well defined deliverables and milestones for the first 2 years of funding?
2. Are the milestones and deliverables clearly identified and appropriate to support the development of a mature conceptual design and corresponding technology demonstrators?
3. Are all required M&S and labor resource needs understood and described at the appropriate level of detail and are the associated costs and schedule durations realistic?
4. Is the collaboration engagement (groups outside Fermilab) appropriate for the plan?
5. Is the necessary infrastructure necessary for GQuEST at Fermilab and collaborating institutions available and sufficient?
6. Is the project management team sufficient, and is it being properly supported, to ensure the completion of the plan in a timely manner?

2. GQuEST Overview

Draft of the (soon to be) public website gquest.fnal.gov



Chris Stoughton (Fermilab), Principal Investigator
Lee McCuller (Caltech), co-Principal Investigator – Experiment
Kathryn Zurek (Caltech) co-Principal Investigator – Theory

Fermilab

Gustavo Cancelo, Jason Greskoviak, Chris James, Glenn Nelson, Cristian Pena, Leandro Stefanazzi

Caltech

Rana Adhikari, Matthew Bub, Yanbei Chen, Torrey Cullen, Yufeng Du, Daniel Grass, Vincent Lee, Dongjun Li, Ian A. MacMillan, Andrew Mueller, Alexander J. Ramirez, Sander Vermeulen, Yiwen Zhang

Jet Propulsion Laboratory

Boris Korzh, Matt Shaw, Sasha Sypkens

https://gquest.fnal.gov/institutions/

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GQuEST is a collaboration between Fermilab, California Institute of Technology, and the Jet Propulsion Laboratory. Funding is provided by the Department of Energy Office of Science and the Heising-Simons Foundation.

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Technology Demonstrator: Interferometers as HEP Particle Sensing Platforms

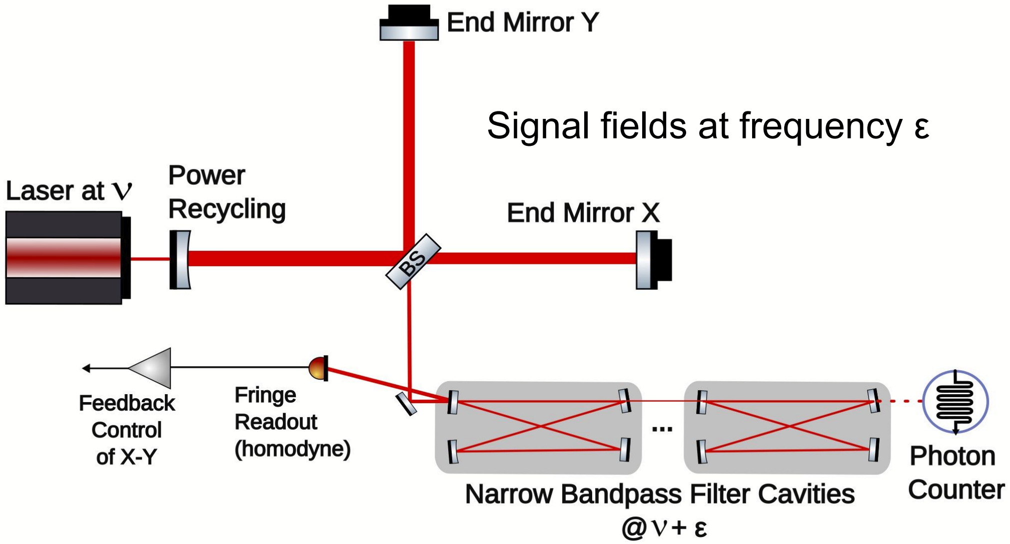
Concept

Interferometer experiments utilize precision sensing to measure spacetime and particle interactions with optical fields. As platforms they are useful both for HEP physics and for development of important technology.

Example: LIGO is often cited to show a science platform that is readily upgradable with quantum enhancements. LM's past work on squeezing enables LIGO to overcome *two* engineering limits – laser power and mirror mass – using quantum technology.

But: interferometers typically operate unlike other HEP experiments. Measuring a signal time-series rather than particle counts and tracks.

Proposal: Convert interferometers into HEP detectors by directly measuring signal photons using low-background single-photon detectors.



For measuring incoherent signals, or incoherent *components* of signals. An HEP style of photon counting has significant sensitivity advantages.

Notably: counting avoids the so-called *Standard quantum limit* from fringe shot noise. Thus, it can immediately viewed as a technology that can out-perform squeezed light at certain tasks

GQuEST

Advantages

Our technology demonstrator for GQuEST targets a stochastic signal from quantum gravity - VZ fluctuations

Well suited signal properties: high frequency and wide-band stochastic signal

Measurable with 5m scale apparatus.

Using technique from Holometer:
SNR=1 takes 160 hours

Using HEP Photon counting:
In principle: SNR=1 takes 1 second
(currently) Practical: SNR=1 takes 2.4 hours

Technology comparison:
using 6db of squeezing would give 16x speedup. This can give 4e5 speedup, fundamentally. Practically can give 16x* with our sub-optimal demonstrating implementation.

By showing this is possible we can push to 100x and greater speedup

Challenges

Other fields, like spectroscopy and AMO physics, use photon counting.

kW high power detectors:
1e22 photons/s down to < 1Hz detection rates. Must filter ~240dB.

kHz, [MHz], GHz, THz signal.
More difficult to filter than usual GHz/THz spectroscopy.
Tabletop cavity filters can do this. Coatings and gratings cannot.

-160dBc Laser noise from "amplified stimulated emission" is significant background - needs experienced laser experimentalists.

All reasons why no one has done this.
The realization of the signal benefit is also new

Opportunities

Further use cases for SNSPD quantum technologies in HEP fundamental physics context.

Gravitational physics and dark matter can be targeted.

Opens doors to new forms of quantum enhancements for DOE to champion. E.g. Fock States. Caltech PIs now studying channel quantum fisher information on stochastic signals.

Cavities+SNSPDs are just one, known way to achieve low background counting. Opens doors to AMO+quantum memory methods.

Noise isolation of lasers is useful for all manner of quantum limited sensing

Unique new path to enhance tests of GR in gravitational wave detectors.

*only 16x due to using less bandwidth than available from signal. WIthin the measured bandwidth, the speedup is 1e5, far better than achievable with squeezing. We are using only 1e-3 of the available bandwidth.

Technical Advantage, for context (should also use paper)

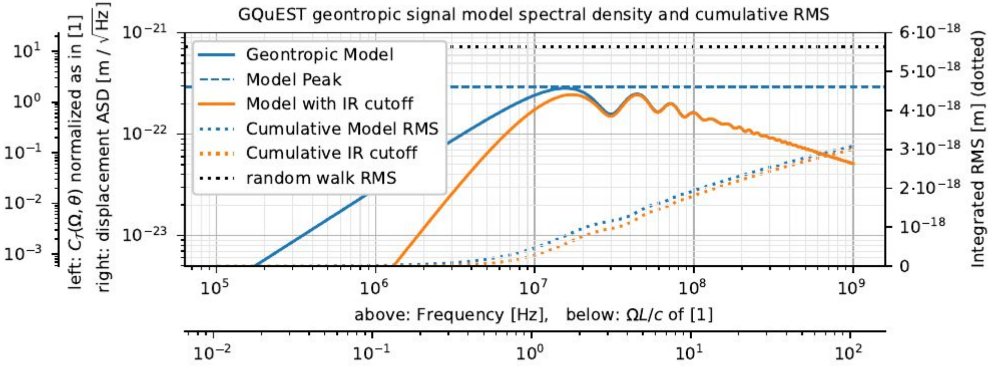
Standard Quantum Limit (Shot noise)

$$\bar{S}_L^q = \frac{\hbar c}{2kP_{\rm BS}} \approx \left(6\cdot 10^{-19}\frac{\rm m}{\sqrt{\rm Hz}}\right)^2\left(\frac{10\rm kW}{P_{\rm BS}}\frac{\lambda}{1.5\mu\rm m}\right). \qquad (5)$$

$$\mathrm{SNR}^2_{\rm fringe} = \int_0^T\int_0^\infty\left(\frac{S_L^\phi(f)}{S_L^q(f)}\right)^2 df\,dt \approx T\Delta f\left(\frac{\bar{S}_L^\phi}{\bar{S}_L^q}\right)^2, \qquad (6)$$

$$\boxed{\approx \alpha^2\left(\frac{T}{160\rm hr}\right)\left(\frac{10\rm kW}{P_{\rm BS}}\right)^2\left(\frac{5\ \rm m}{L}\right)}. \qquad (7)$$

Signal Spectrum $\bar{S}_L^\phi = \alpha\frac{l_p L^2}{c8\pi^2} \approx \alpha\left(3\cdot 10^{-22}\frac{\rm m}{\sqrt{\rm Hz}}\right)^2\left(\frac{L}{5\ \rm m}\right)^2$



Perfect case, full bandwidth no background

$$G \equiv \frac{\partial\dot{N}}{\partial\langle\delta L_{12}^2\rangle} = \frac{kP_{\rm BS}}{\hbar c}, \qquad S_{\dot{N}}^\phi(\epsilon) = G\frac{S_L^\phi(f)}{2} = \frac{S_L^\phi}{4S_L^q}$$

$$N_{\rm peak}^\phi = \int_{-f_{\rm pk}-\Delta f}^{f_{\rm pk}+\Delta f} S_{\dot{N}}^\phi(\epsilon)d\epsilon = \mathcal{O}(1)\,\mathrm{Hz},$$

$$\mathrm{SNR}^2_{\rm count} = \int_0^T\frac{(dN_{\rm peak}^\phi)^2}{dN_{\rm peak}^\phi} \approx T\Delta f\frac{\bar{S}_L^\phi}{2S_L^q}, \qquad (12)$$

$$\approx\boxed{\alpha\left(\frac{T}{0.25\rm s}\right)\left(\frac{10\rm kW}{P_{\rm BS}}\right)\left(\frac{5\ \rm m}{L}\right)}, \qquad (13)$$

Imperfect case, small band with classical background

Accelerated 30x in time

$$\mathrm{SNR}^2_{\rm counting} \approx \frac{T\Delta\epsilon}{4}\frac{\left(\bar{S}_L^\phi\right)^2}{S_L^q\bar{S}_L^c} \qquad (20)$$

$$\boxed{\approx \alpha^2\left(\frac{T}{2.4\ \rm hr}\right)\left(\frac{10\rm kW}{P_{\rm BS}}\right)\left(\frac{5\ \rm m}{L}\right)^4\left(\frac{S_L^c(f)}{\bar{S}_L^c}\right)}, \qquad (21)$$

Significant Technologies

a. Superconducting Nanowire Single-Photon Detectors (SNSPDs) with low dark count
b. 1550nm communications C-band choice of laser wavelength
c. Silicon substrate optics
d. FPGA processing for high frequency readout and control
e. Real-time noise regression using ML
f. Cryogenic operation to reduce thermal gradients
g. Ultra-low loss optics to reduce thermal distortion and decoherence
h. Multiple free-space filtering cavities, simultaneously operated
i. Narrow linewidth lasers, stabilized and noise-suppressed beyond standard performance

Experimental Risks

1. Carrier-power Isolation
2. Laser noise
3. Black-body Radiation on SNSPDs
4. Isolate SNSPDs from noise
5. High power operation
6. Thermal Distortion of Mirrors
7. Coating Thermal Noise
8. Bulk-mode Thermal noise
9. RFI: RF coupling
10. Characterize Backgrounds,
11. Subtraction or Correlation

Red- Unexplored risks of new photon counting technique

Orange- Known risks made somewhat More challenging from photon counting needs

Yellow-standard experimental needs, Requires full setup and time

Technology Demonstrator Goals

For the demonstrator phase of the experiment we target the red risks.

This prevents the time requirement to immediately develop a fully functioning high power interferometer.

We target demonstrating photon counting to achieve a sensitivity that surpasses any other competing technology - squeezing. 6dB is the best SQZ seen in real experiments, and would accelerate a Holometer/GQuEST type experiment by ~16x (12db, in time).

Goal: Demonstrate a signal search accelerated by >100x using a photon-counting Michelson interferometer, over a standard interferometer readout.

Note: this is for an apple-to-apples comparison for a signal search in a narrow, 20kHz band. GQuEST accelerates science-case 30x, but can't use full signal bandwidth and has background noises, so is not apples-to-apples comparable. GQuEST's performance by this metric is around 50db, 1e5, time-accelerated.

Demonstrator Requirements:

Choose a target experiment of a 1W interferometer, locked to 1mW (1e16 photons/s) dark fringe output. And choose to measure over a 25kHz (effective) cavity bandwidth at 15MHz.

This corresponds to a 25kHz count rate by standard fringe readout. To get 100x faster readout, we need a 16*100x lower background count rate than the readout bandwidth, under the assumption that a signal is smaller than the readout.

<u>This corresponds to a background count rate of 10Hz or less.</u>

This is only achievable using SNSPDs (or extremely good SWIR cameras). SNSPDs in Maria Spiropulu's lab have demonstrated 1e-2Hz dark count rates at 1550nm using a nearly room temperature fiber. https://doi.org/10.1364/OPTICA.444108

Cavity Requirements

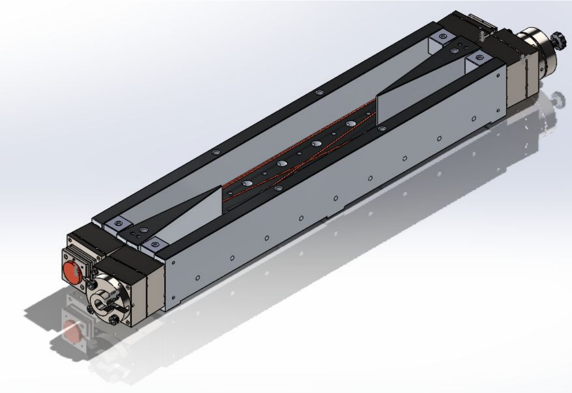
4 Cavities are already mechanically designed and procured. IBS dual coated mirrors from five-nine optics already in hand.

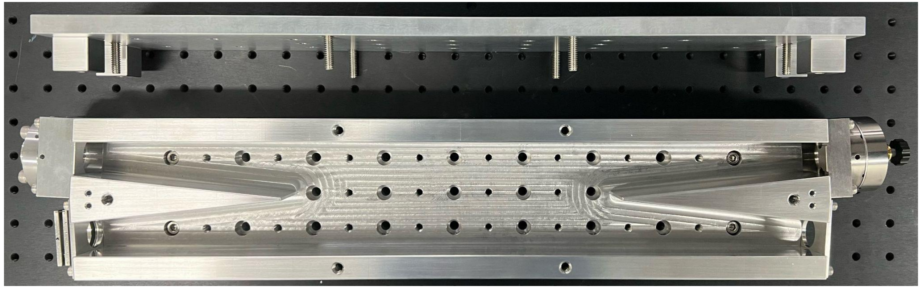
Each cavity has >2m path length and 882ppm input/output coupler. This makes them 42kHz wide and 21kHz pole.

Their isolation saturates at (881ppm)^2/4 = 67db. Operated at 15MHz, they will have an isolation of (21e3 / 15e6)**2 = 57db.

Three such cavities then has 171db of isolation. We have 4 cavities. A fourth, in a cryostat for ultra-low dark count rates, is an enhanced goal.

Their free-spectral range is 150MHz.
The cavities are designed with a Gouy phase of ⅔π. This causes 3rd order modes (and multiples) to be near-degenerate and choosably above or below the fundamental, to ensure they do no overlap with -15MHz carrier frequency.





Laser Noise

The largest next noise is leakage from the laser’s amplified stimulated emission

Count rate from 1e-7 rad/rtHz, (-140dBc). (Laser amp specified to be -150dBc). The 1mW has 1e16/s * 1e-14/Hz = 100 photons/sec/Hz. This will get through the 25e3 Hz of filtering as a background count rate of 2.5 MHz. This is clearly visible on an avalanche diode - corresponding to ~250fW. So we will need a lot of filtering on the laser to pull this off. How much? In amplitude, need sqrt{10Hz / 2.5 MHz} = 2e-3 factor of (amplitude) filtering.

Input mode cleaner of 4m, using the already procured 882 ppm mirrors, has cavity pole of c/4m / (pi / 882 ppm) / 2 < 15kHz (more like 11kHz). 15kHz / 15MHz = .001, so we can filter sufficiently.

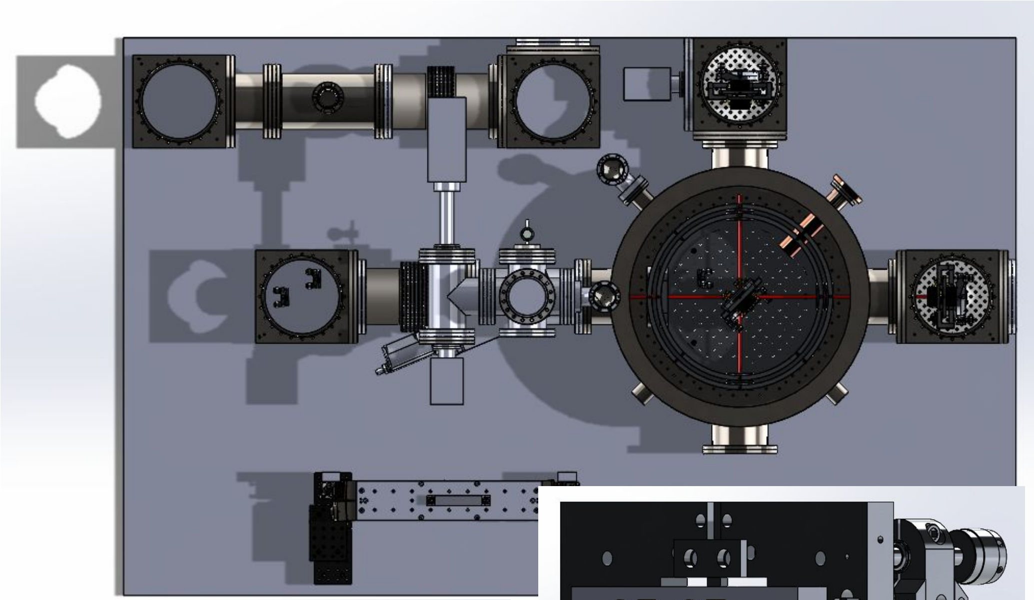
Can we hedge? If the interferometer power recycling is functioning. It will be another 16kHz pole, which will apply similar and more filtering (another 1e6 improvement in count rate). That is necessary for the final experiment at 1e-2Hz count rate, but not for the demonstrator.

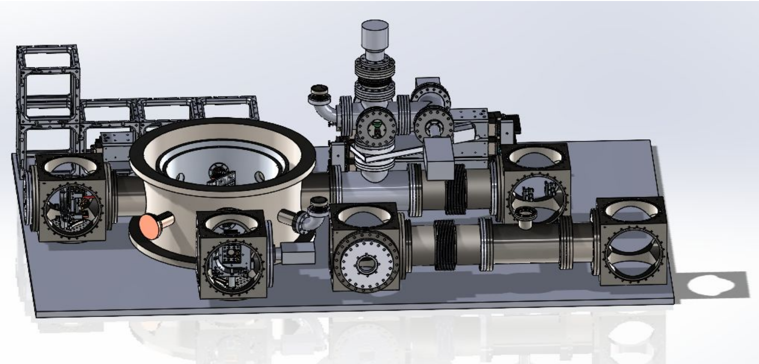
Engineering

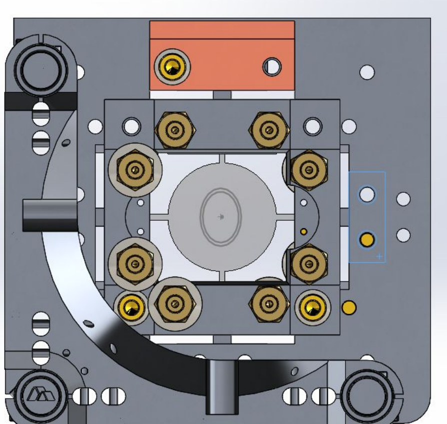
Student led solidworks designs

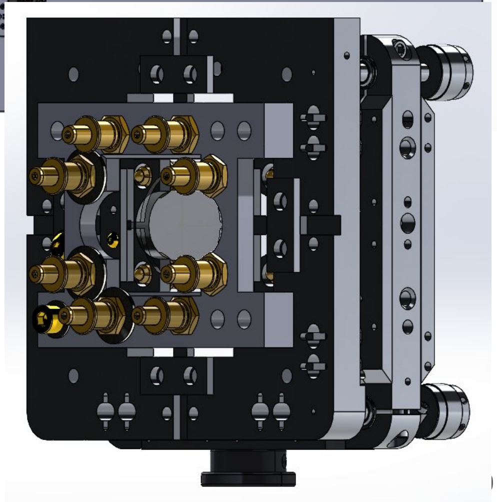
LIGO Engineering design review/support (tolerancing, vacuum compatibility, vendors)

CS, LM and Fermilab integration









Equipment in hand

Thorlabs 70Hz linewidth laser 100mW.

Backup options: RIO DFBs (Rana), Teraxion (Rana), and NP photonics (pending)

NKT Photonics 15W Erbium fiber amplifier. ASE at 150dBc. Plenty of power 10W for interferometer, and 1W for SHG generation.

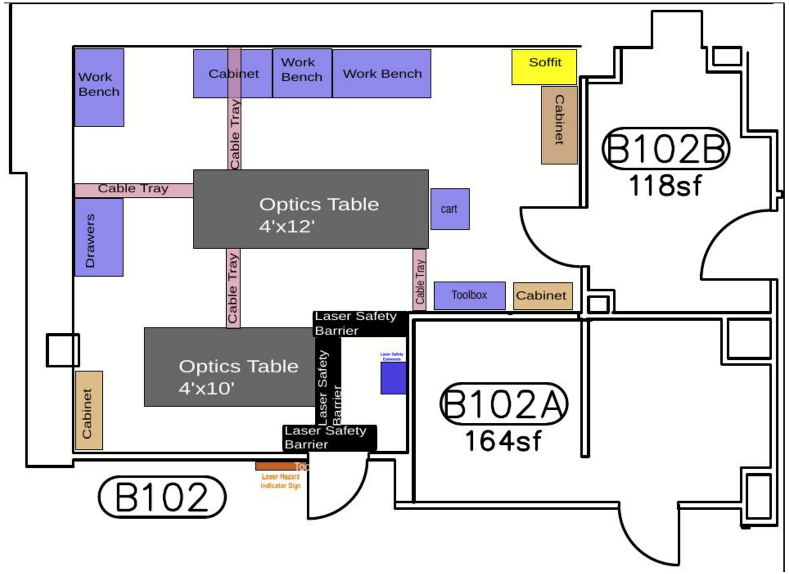
775nm cavity control: Covesion fiber SHG.

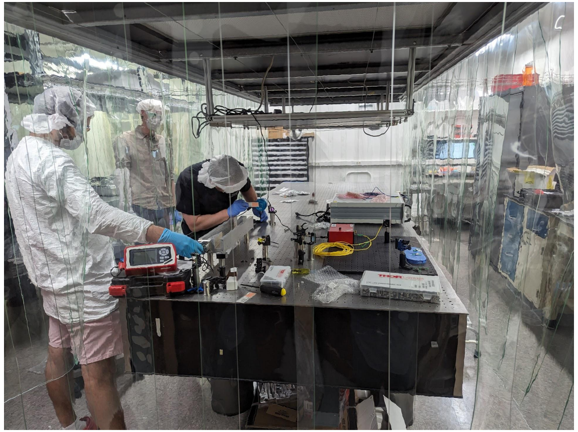
Cavity mirrors (in hand): IBS coated 1550nm/775nm dual coated 1” mirrors. From fivenines.

Facilities

Existing laser rooms at Caltech have been in use for this work. Recently given access to a moderately renovated clean laser space.

New facilities at McCuller Lab will be available for beneficial occupancy in December.





Coming in Dec. 2023

1500 sq foot clean lab space split in two areas. Vestibule entryway for garb.

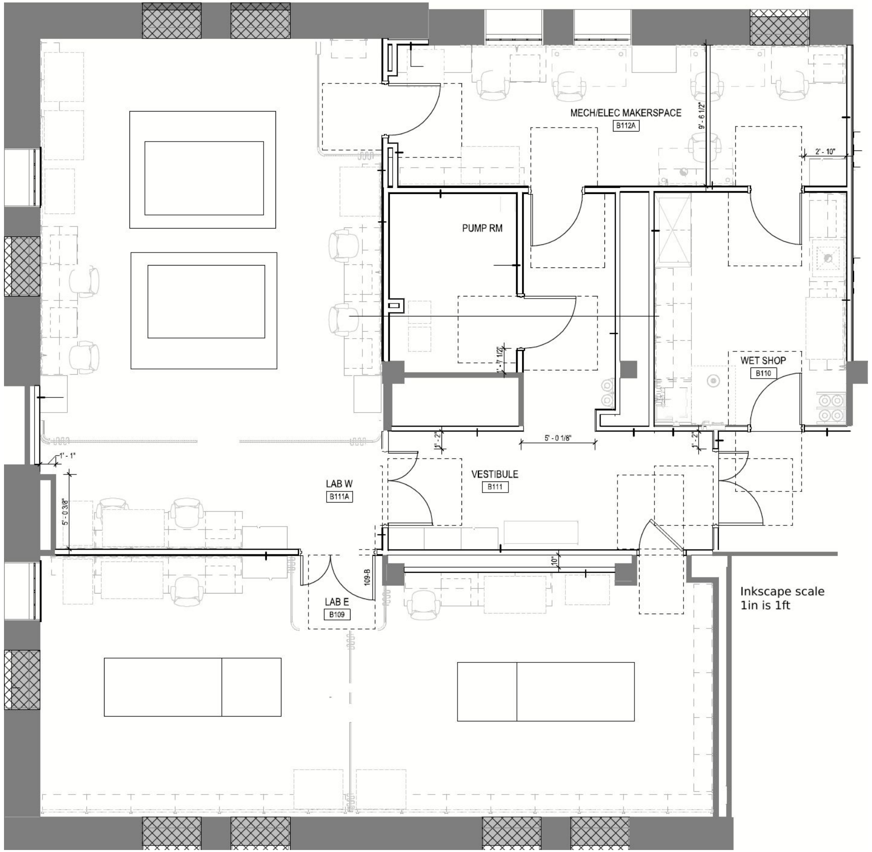
LAB W two 8’x10’ softwall cleanrooms

LAB E two 4x12’ hard shell cleanrooms

Additional pump room for cryogenics

Wet shop for UHV Prep

Maker space for electronics and simple machining

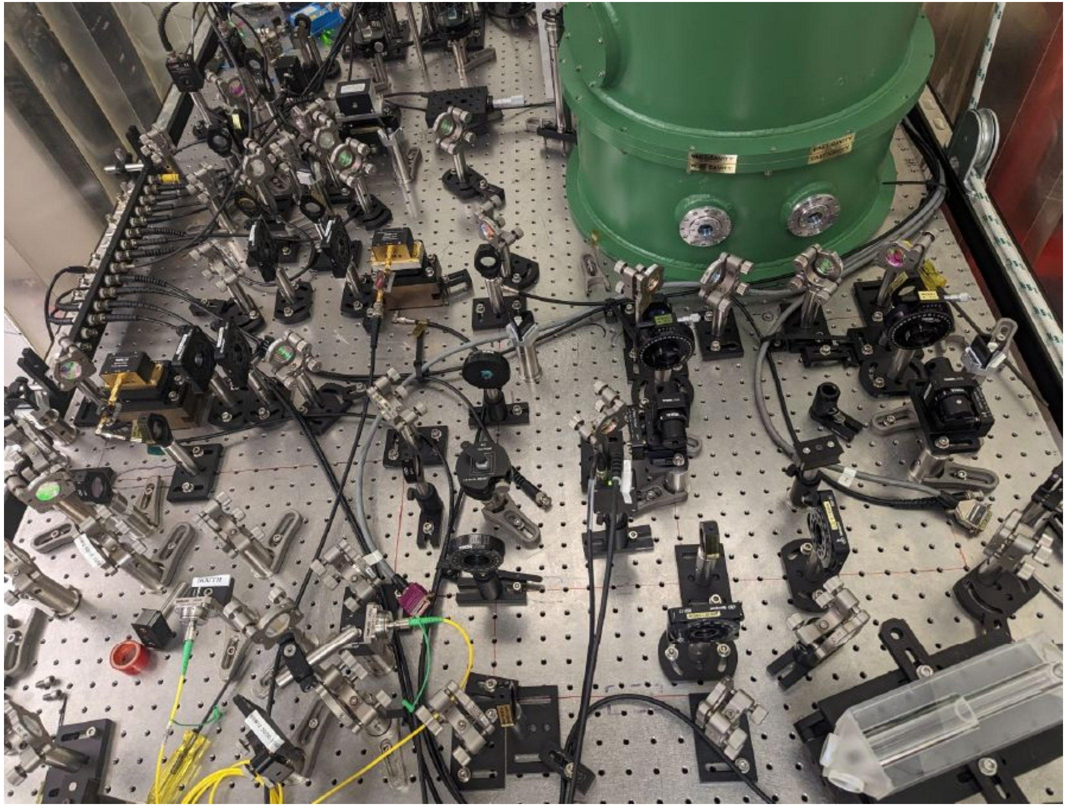


3. Theory/Experiment Connection

Kathryn has a separate set of slides that she will present at this time.

4. Progress and Plans

Optics Test Stand @ Caltech



LM's lab commissioned a test stand to evaluate laser frequency noise using a fiber Mach-Zehnder interferometer (fiber in lower left).

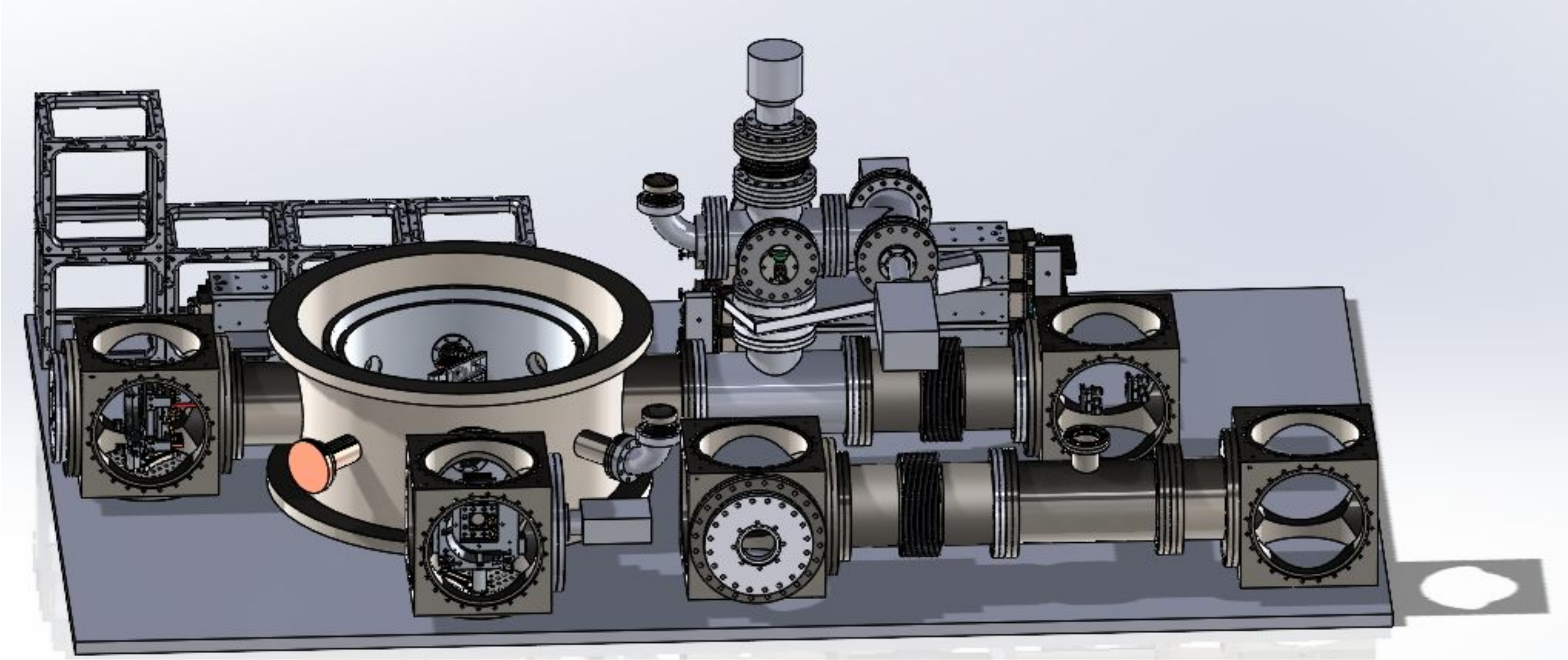
They repurpose high-finesse cavities from Rana Adhikari (inside green vacuum chamber), locking the cavities to study high-frequency noise suppression.

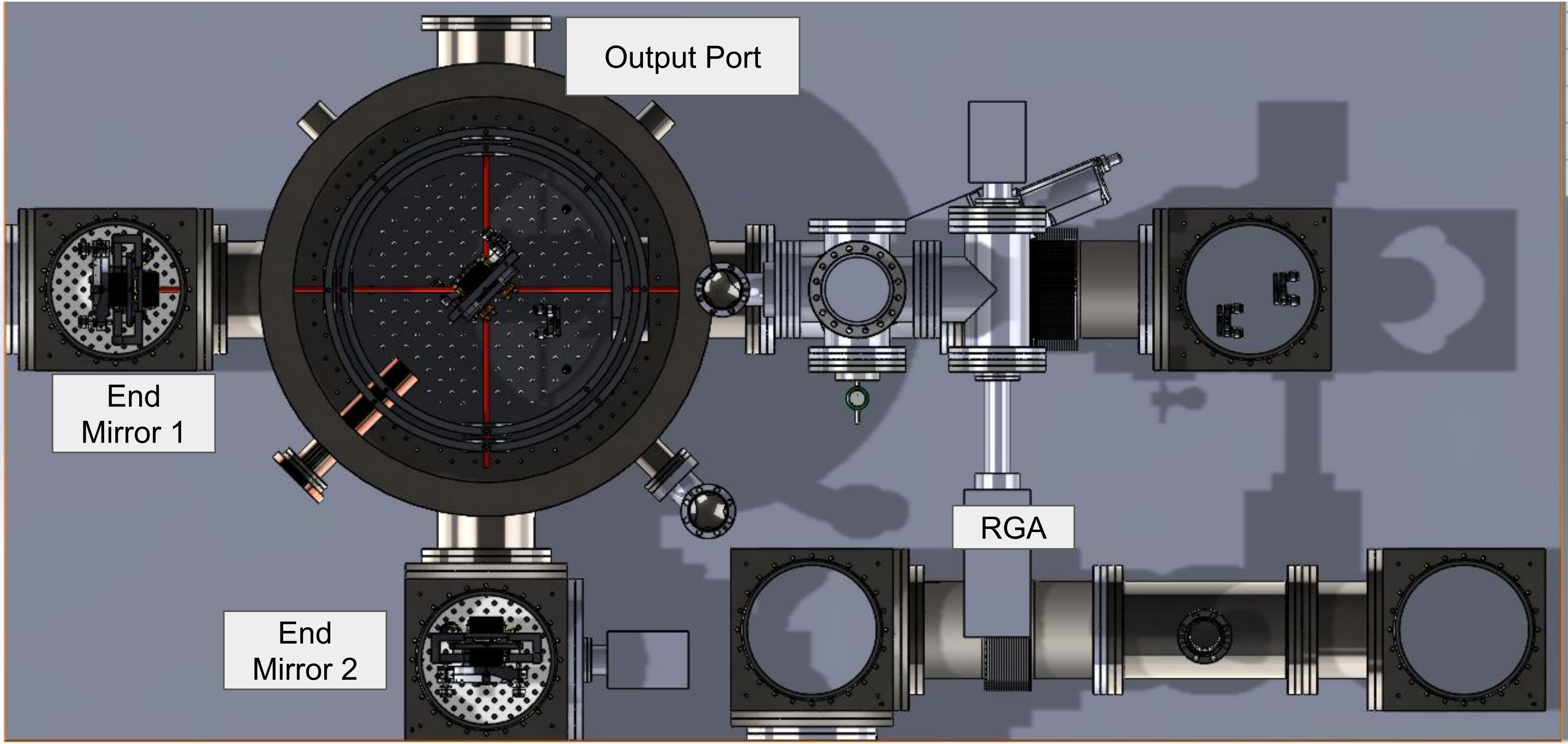
They will migrate this setup to the GQuEST Bowtie cavities once they are available.

Vacuum System: FNAL → Caltech

Holometer parts shipped include:
- Cylindrical “beam splitter” chambers
- 12” end cubes
- Bellows & valves
- In-vacuum mirror mounts (piezo&picomotor)

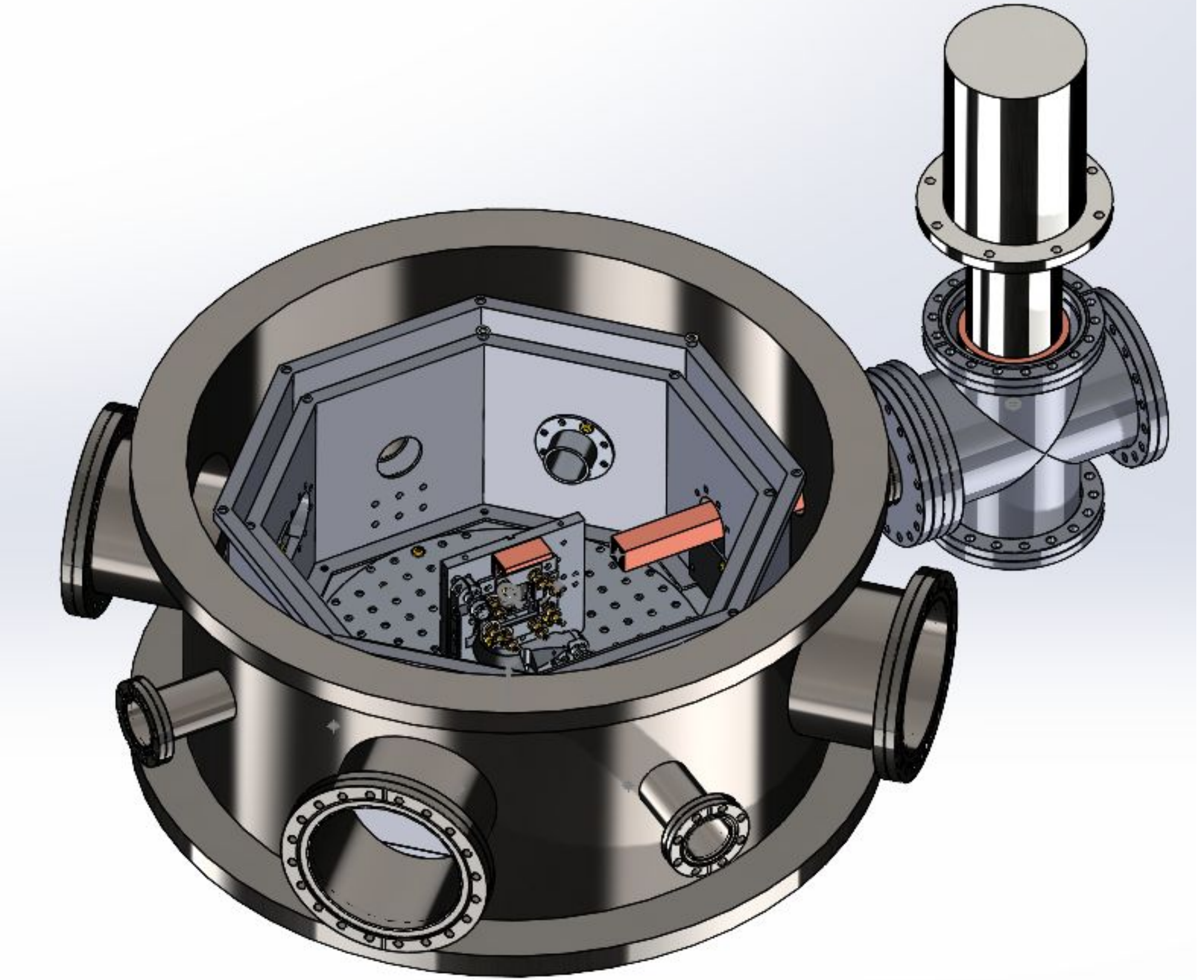
Mechanical Layout – Daniel Grass




Output Port
End
Mirror 1
End
Mirror 2
RGA

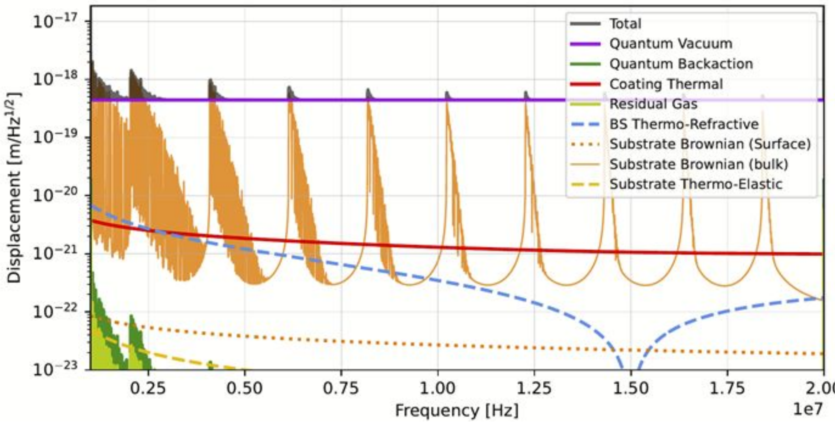
"Octostat" keeps Beam splitter cold

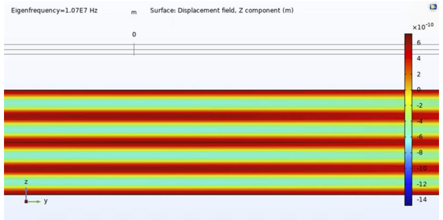
- 123 K
- Reduce charge carrier refractive noise in substrate
- Increase Q of the vibration modes
- Fabricate ~ March 2024

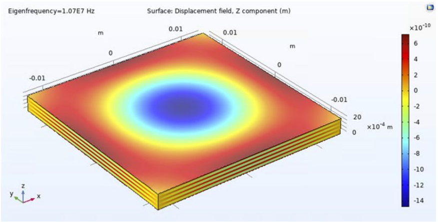


Thermal noise is dominant background

Analytically calculated from Holometer models

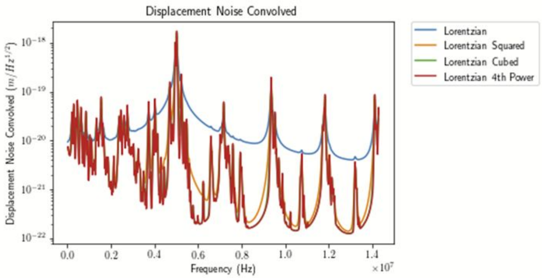


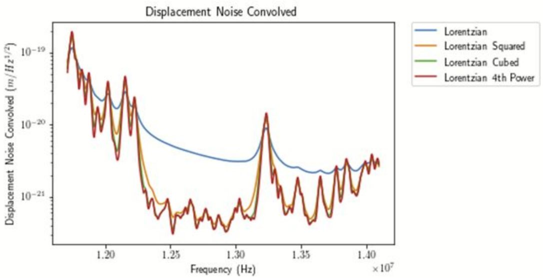




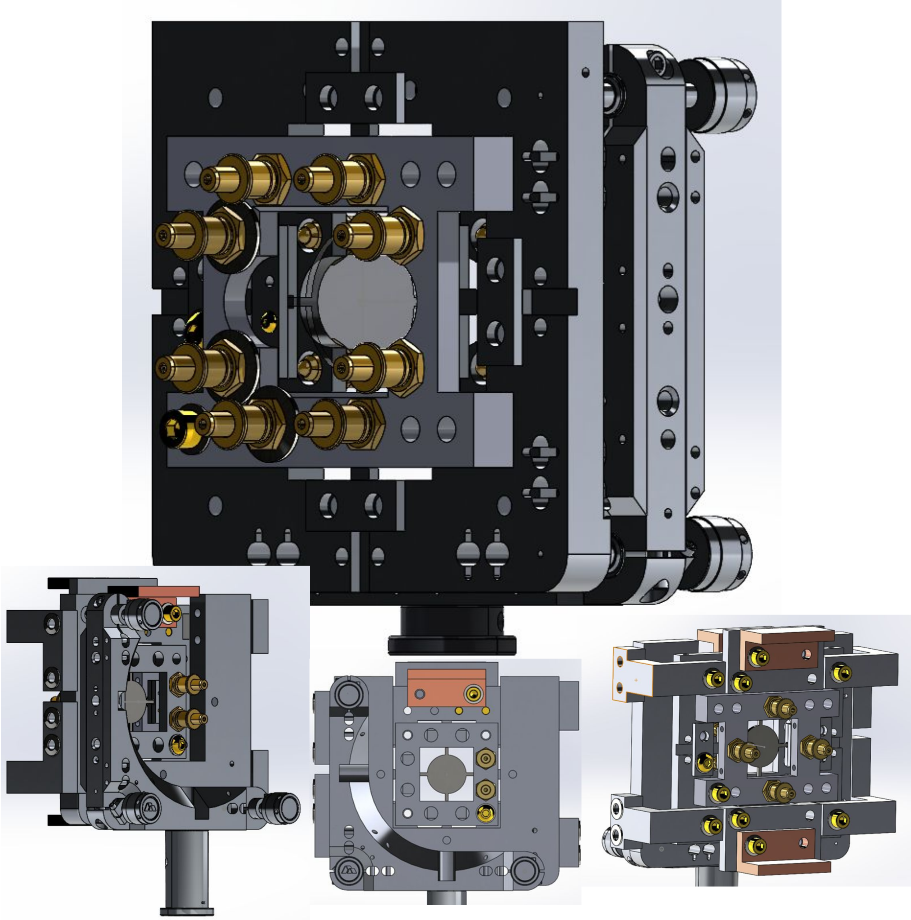
COMSOL modeled, finds "modest" additional structure

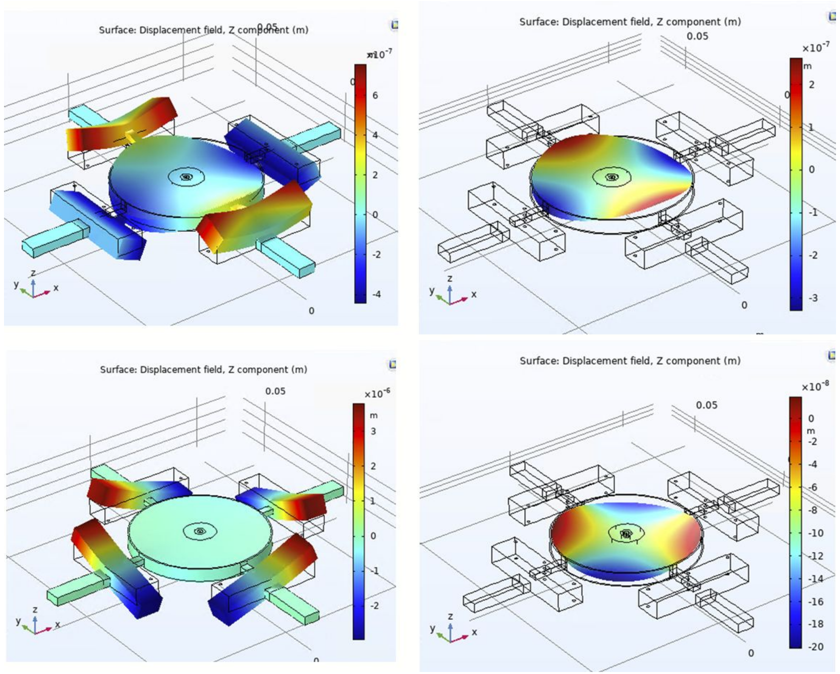
$$\chi^2(\omega) = \frac{4k_B T k\phi(\omega)}{\omega[((k - m\omega^2)^2 + k^2\phi^2(\omega)]}$$





Beam Splitter and End Mirror designs w/astigmatism correction

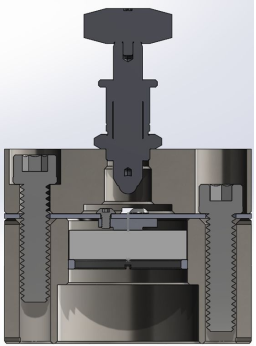


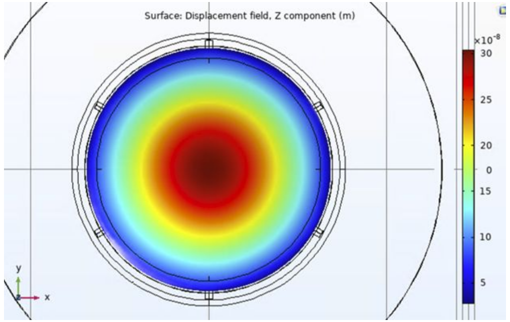


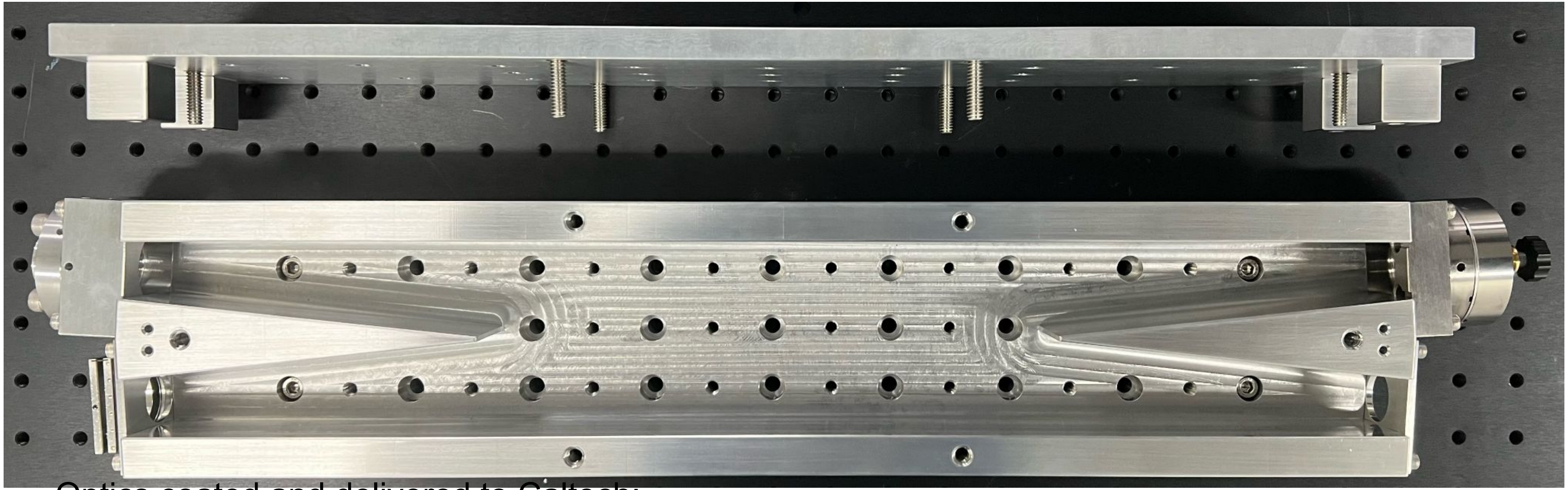
Fabrication ~ Dec 2023

Readout Cavity Fabricated; optic modeled in COMSOL

Fine Gouy adjuster
Displacement model
with 55 N force applied







Optics coated and delivered to Caltech;
Cavities cleaned; ready for installation.

Laser Enclosure at FNAL for R&D

An enclosure with interlocks was made available from the AD, courtesy of Vic Scarpine

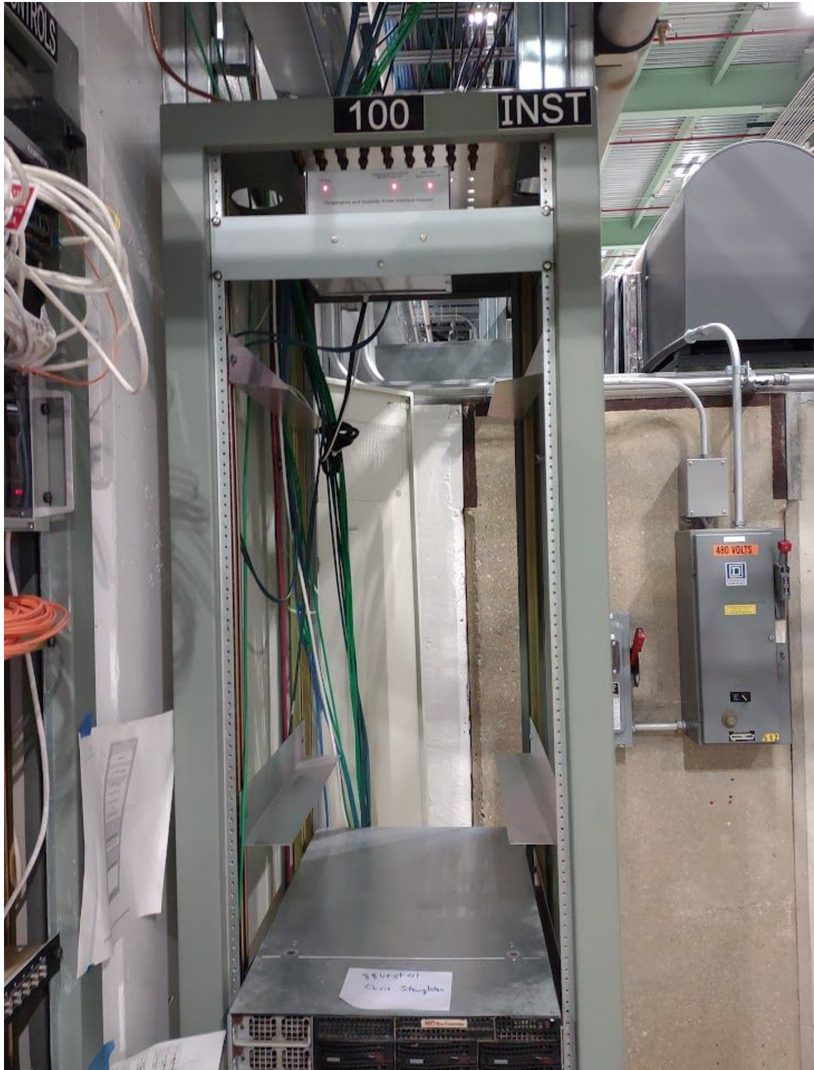
It is located in the Cryo Module Test Facility (CMTF) located north of the Holometer and SiDET.

It was equipped with a small laser table and electronics rack. The FNAL carpenter shop added storage shelves.

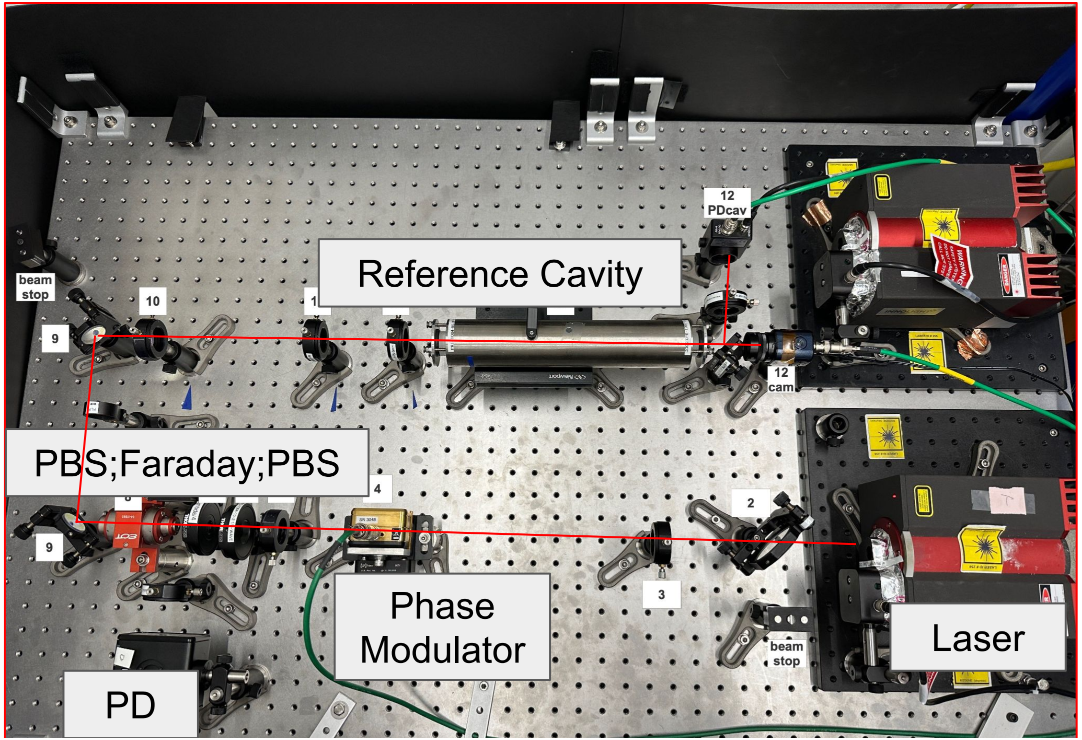
Currently we use a spare Laptop to control the RedPitaya system.

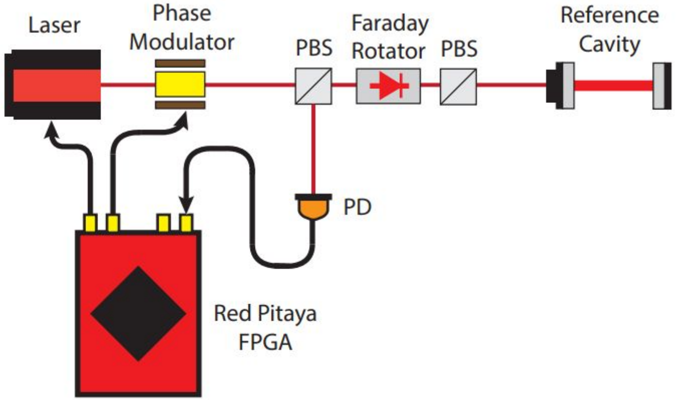
Fermilab AD pulled cables for server outside the enclosure (Julie) to connect to Fermilab network and to a local network inside the enclosure.

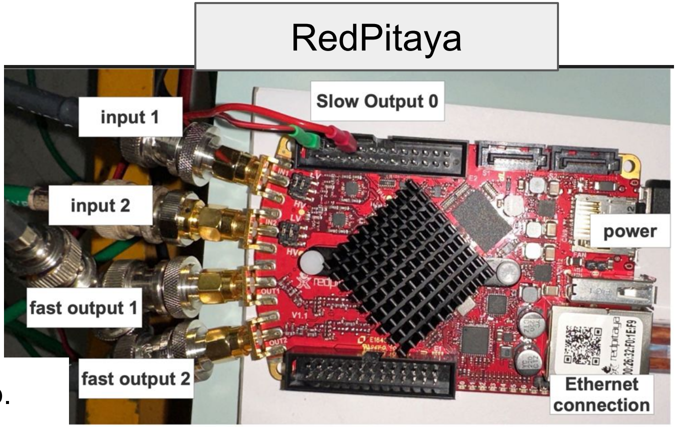
Fermilab SLAM department supports the server.



PDH setup at FNAL for R&D





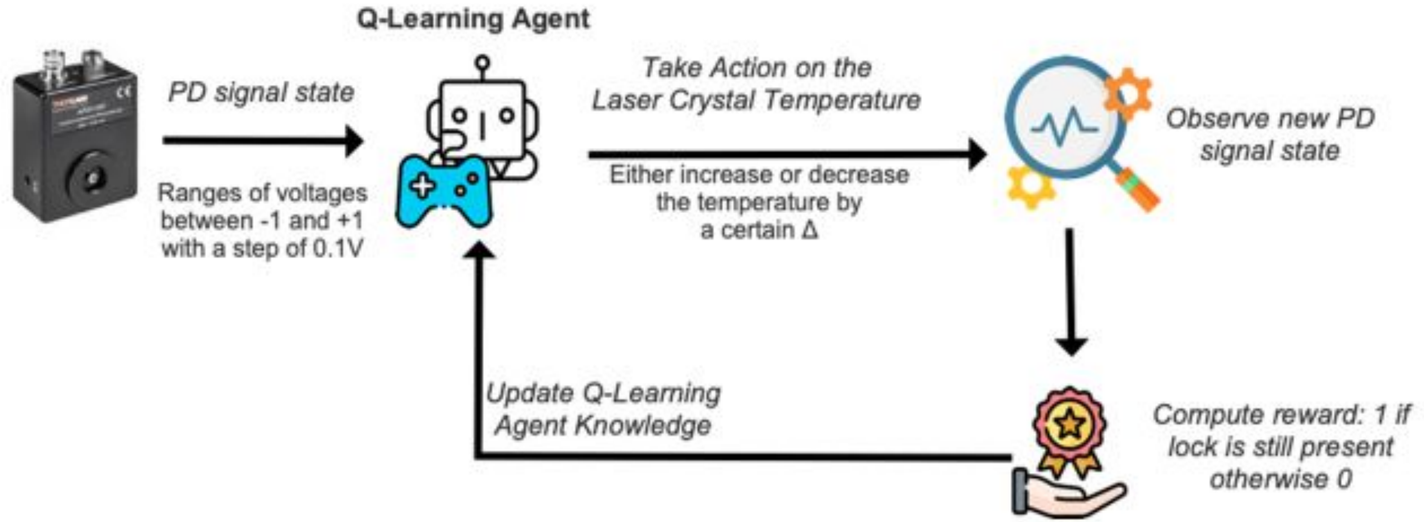


Optics and controls set up by Hudson Loughlin, MIT graduate student, from Matt Shaw's Lab. Interest in FPGA/RFSoC system controls. SQMS/Microwave-Optical-Transducer (Silvia Zorzetti), atomic physics labs, "laser tweezers" for quantum computing.

PDH Lock Maintainment using Q-Learning

Q-Learning is a Reinforcement Learning tabular method that can learn autonomously from interactions with the environment at every action taken without waiting for a final outcome (it bootstraps).

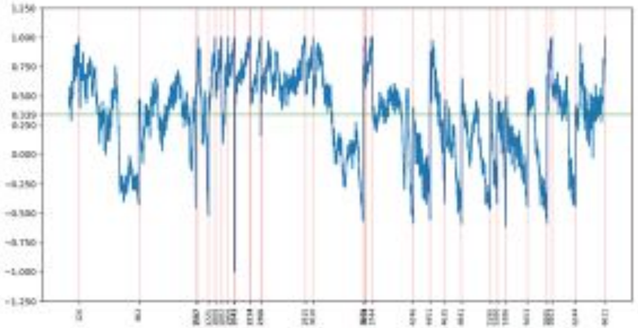
Our Q-Learning Agent interacts in real-time with the experimental setup without the need of historical data.



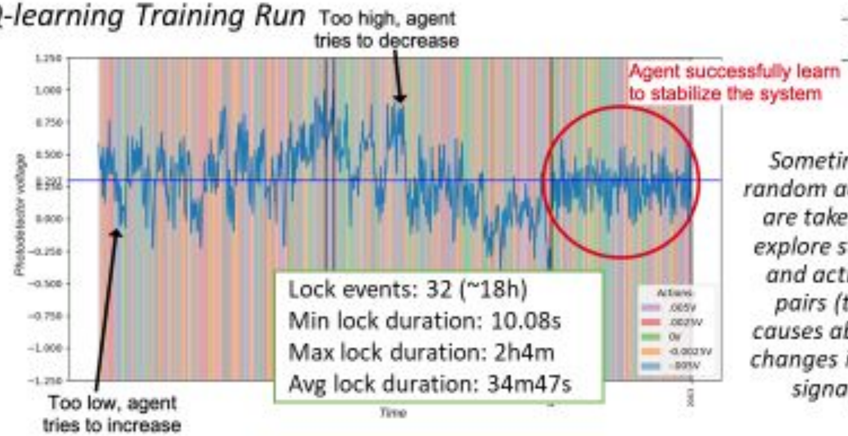
Work by Edoardo Fazzari, Graduate student from Pisa at FNAL as summer intern

PDH Lock Maintainment using Q-Learning

First Run (w/o Q-learning)



Q-learning Training Run

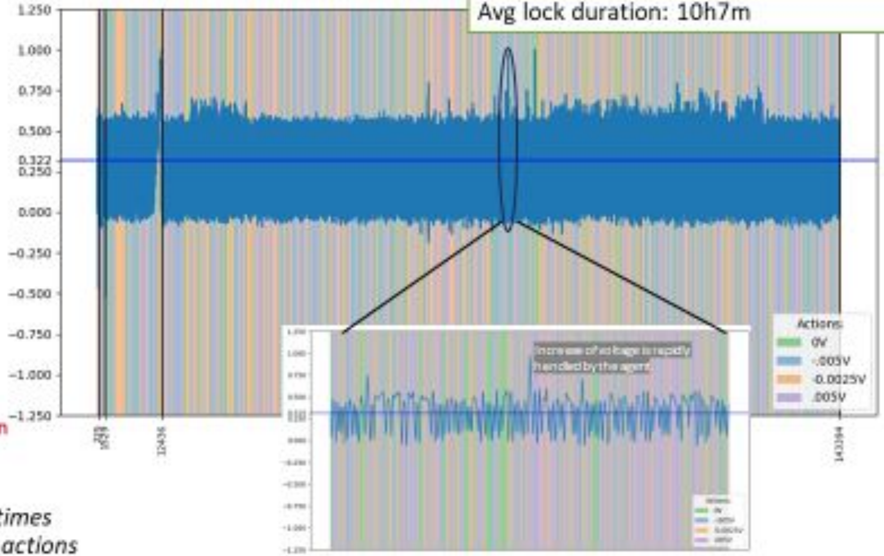


Lock events: 32 (~18h)
Min lock duration: 10.08s
Max lock duration: 2h4m
Avg lock duration: 34m47s

Sometimes random actions are taken to explore states and actions pairs (this causes abrupt changes in the signal)

Q-learning Test Run

Lock events: 4 (~39h49m)
Min lock duration: 269.89s
Max lock duration: 36h23m (still running)
Avg lock duration: 10h7m



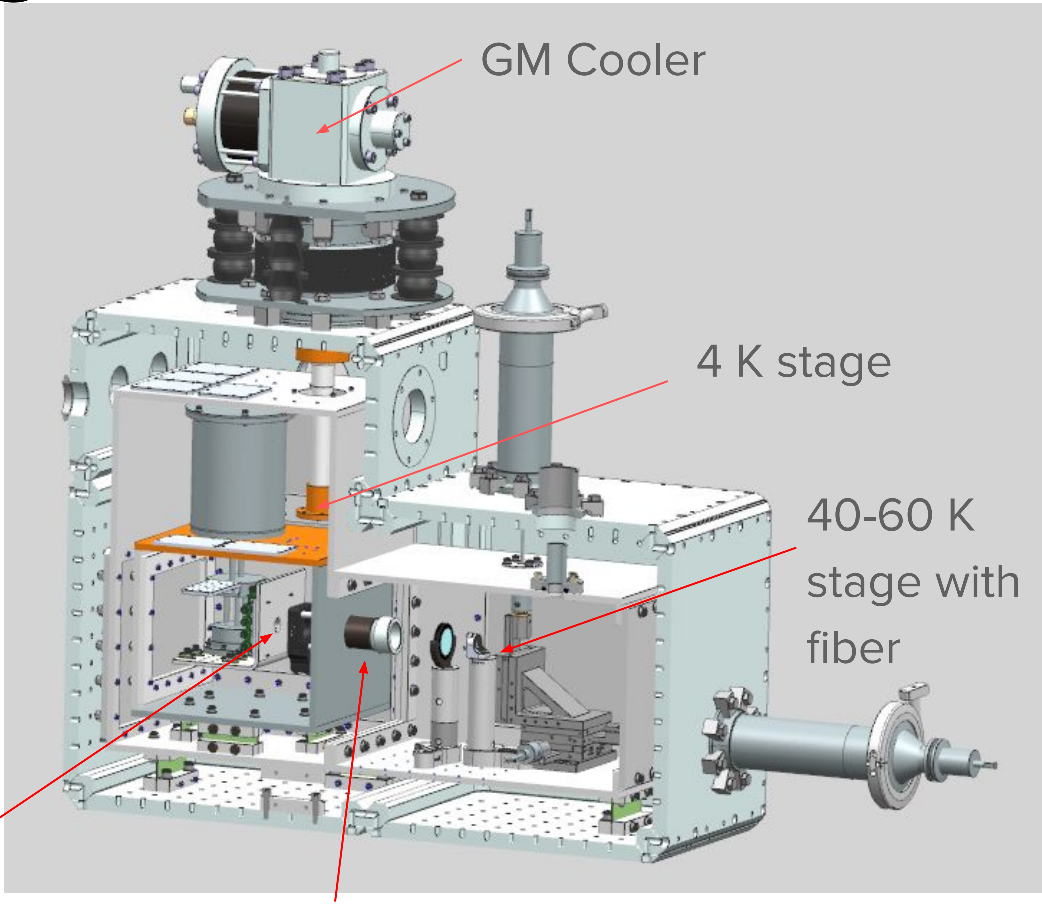
FUTURE WORK

Q-Learning is limited to a discrete set of states and actions. *Deep Deterministic Policy Gradient* approximates the Q-matrix using *Deep Learning* using continuous states and actions.

Continuous learning will enable better performance and even lower fluctuations on the photodetector signal.

SNSPD Dewar Design @ FNAL

Chris James has additional slides to show here



GQuEST Design Overview

Chris James

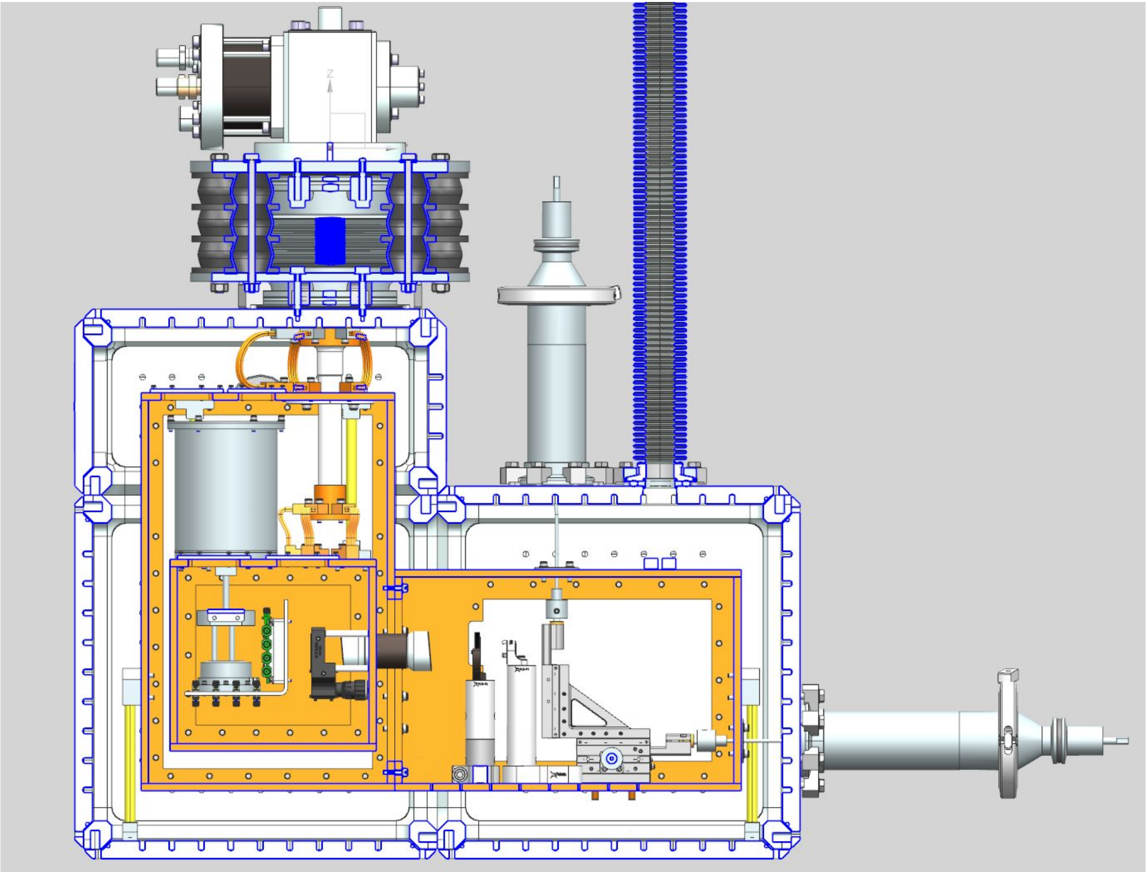
GQuEST Internal Review

9/18/2023

Overview

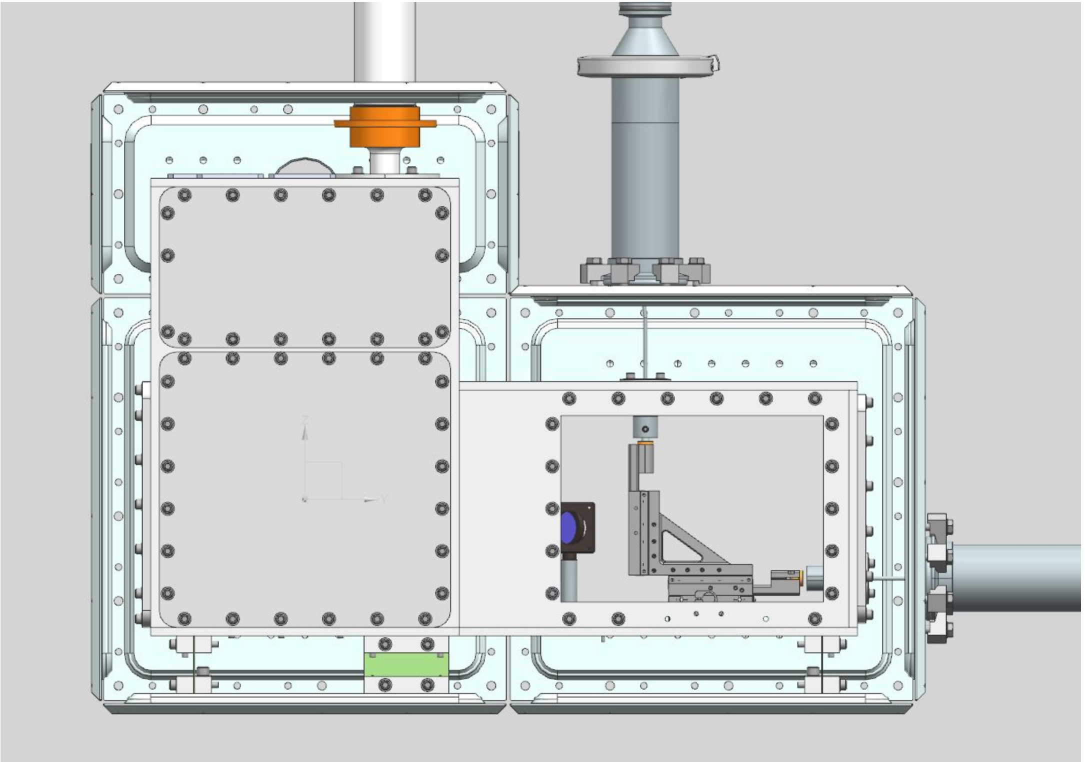
- System Overview
- Initial design
- Reasons for design changes
- Final design
- Basis of Estimates
- Timeline

System Overview



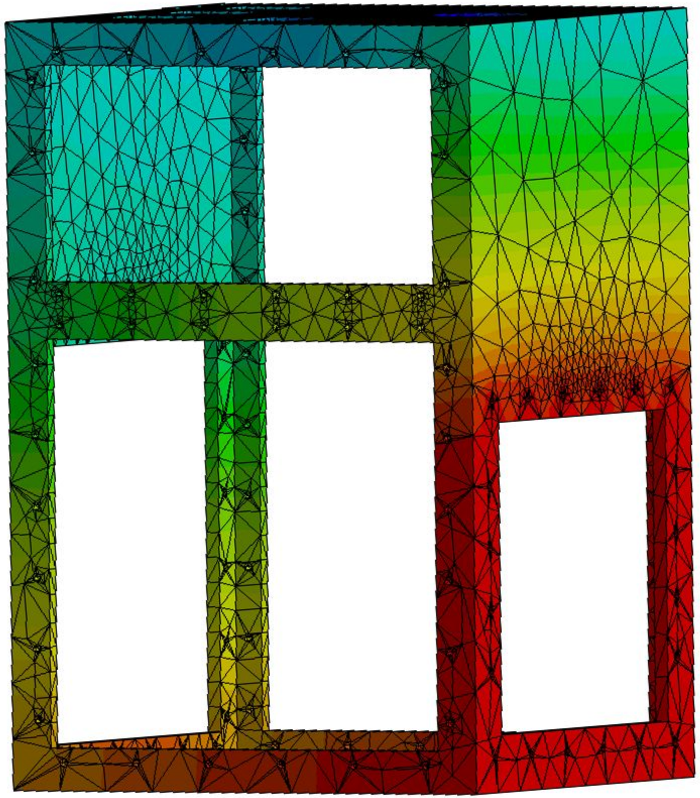
Fermilab

Initial Design



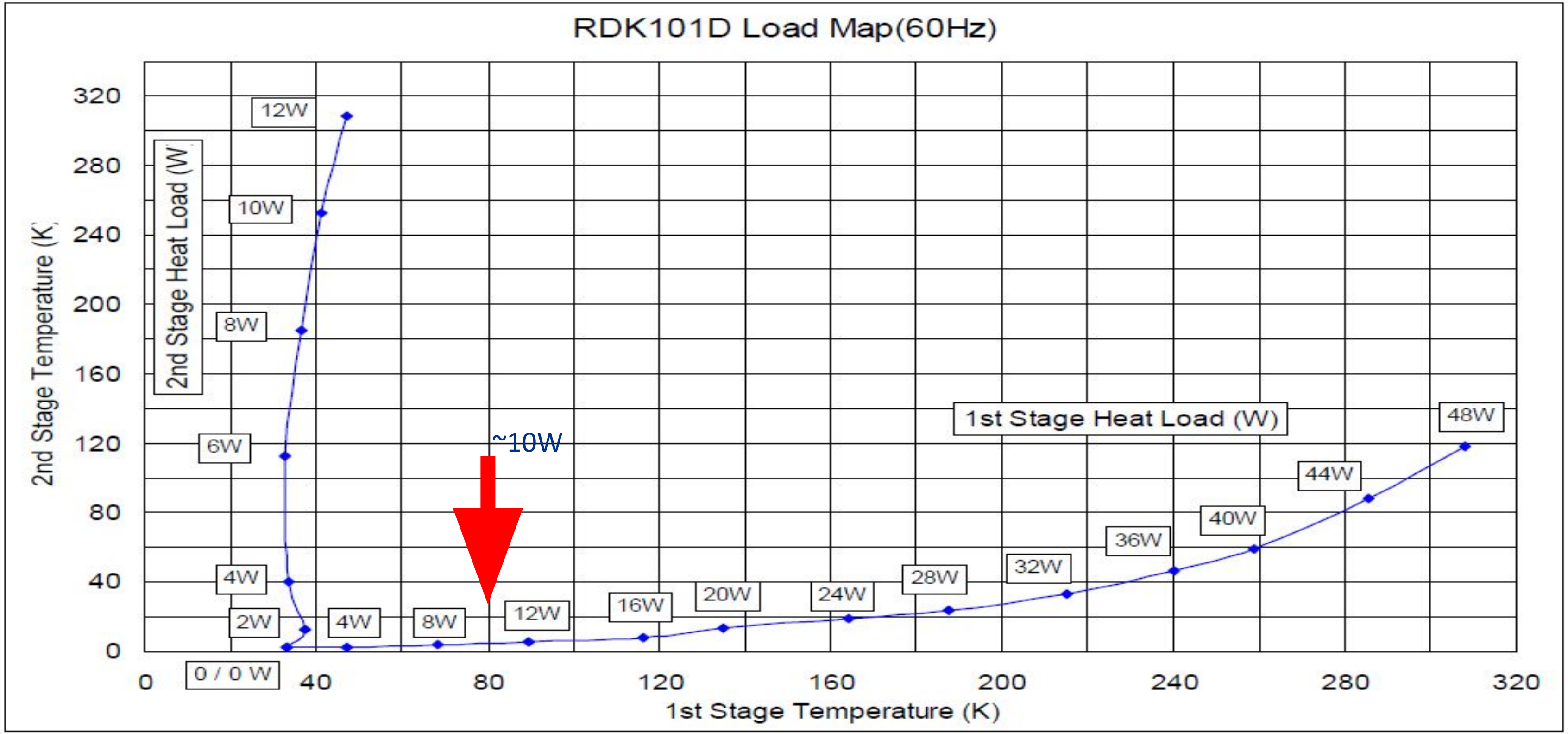
- PT1 was initially AL
- G10 feet used to support PT1 and PT2

Reasons for Design Changes



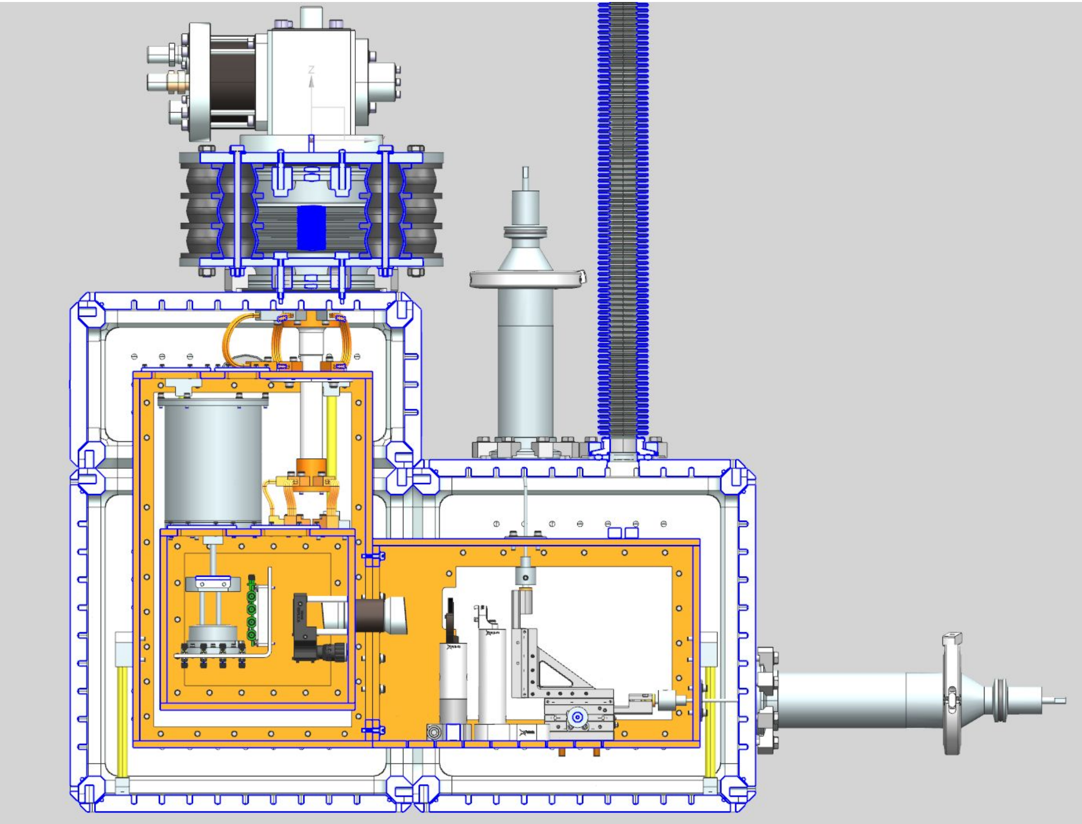
- Heat loads at PT1 and temperature distribution were both too high
  - Aluminum has worse thermal conductivity than copper
  - Aluminum has a higher emissivity than copper
  - Temperatures on PT1 exceeded 100K
  - Heat load was >10W
  - Area where PT2 g10 supports made contact with PT1 were ~94K causing the heat load to PT2 to exceed what the cryocooler could handle, resulting the sorption fridge to be at ~10K where Helium would not condense

Reasons for Design Changes



Fermilab

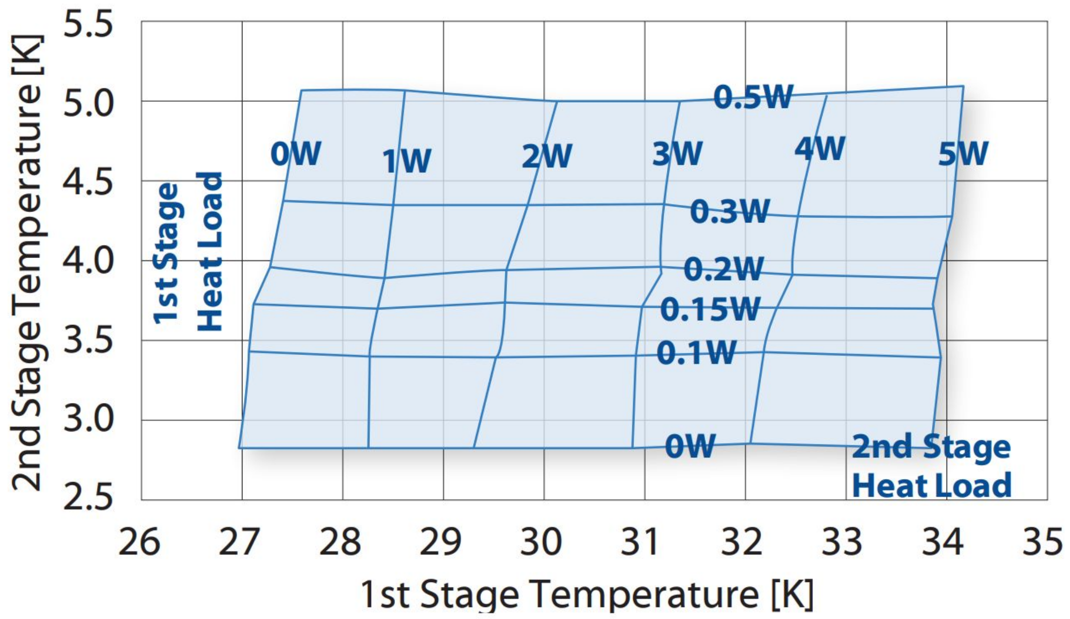
Final Design



- PT1 and PT2 are made of copper
- G10 supports changed from sheets to longer tubes

Final Design

- With PT1 being copper, and new G10 design, PT1 heat loads are closer to 5W allowing the sorption fridge to condense



Bases of Estimates

Item	Qty			Price per pack	Extended Price	Oder Status	Ordered By	Vendor	Model Number
	packs/Items	Qty/pack	Total						
50K vertical Box	1	1	1	$ 13,984.00	$ 13,984.00			Precision Cryo	
50K horizontal Box	1	1	1	$ 13,560.00	$ 13,560.00			Precision Cryo	
4K Box	1	1	1	$ 12,960.00	$ 12,960.00			Precision Cryo	
Feedthrough Plate	6	1	6	$62.94	$ 377.64			Xometry	FC0109713
Access Cover Rear	1	1	1	$857.12	$ 857.12			Xometry	F10207029
ISO100 Clamping Ring	1	1	1	$342.02	$ 342.02			Xometry	F10204628
SMA Feedthrough	1	1	1	$875.18	$ 875.18			Xometry	FC0109128--
Bellows Plate	1	1	1	$471.39	$ 471.39			Xometry	F10198017
Thermal Can Cover	1	1	1	$235.78	$ 235.78			Xometry	F10202759
Access Panel Front	2	1	2	$459.86	$ 919.72			Xometry	F10197672-
Access Panel Lower Left	1	1	1	$657.97	$ 657.97			Xometry	F10197613
Cover Port	6	1	6	$79.33	$ 475.98			Xometry	F10198344
Cover Port 4k	2	1	2	$117.40	$ 234.80			Xometry	F10198343-
Upper Left Access Cover	1	1	1	$550.17	$ 550.17			Xometry	F10197615
Access Cover Lower Right	1	1	1	$683.31	$ 683.31			Xometry	F10197620
Access Cover Right Rear	1	1	1	$660.98	$ 660.98			Xometry	F10198511-
Thermal Can Weldment	1	1	1	$ 953.39	$ 953.39			Xometry	F10211861-
50K Support Rod Assembly	4	1	4	$ 550.00	$ 2,200.00			Xometry	F10211867
4K Support Rod Assembly	4	1	4	$ 550.00	$ 2,200.00			Xometry	F10211868
Thermal straps	11	1	11	$ 1,200.00	$ 13,200.00				
			0		$ -				
			0		$ -				
bellows with iso 100 flanges	1	1	1	$ 1,120.77	$ 1,120.77			Demaco	MEM-100-50K
springs	4	4	16	$ 14.03	$ 56.12			McMaster	1840N7
Spring guide bolts	1	5	5	$ 6.41	$ 6.41			McMaster	92800A225
washers for spring guide bolts	1	100	100	$ 13.29	$ 13.29			McMaster	90107A030
Nuts for spring guide bolts	1	10	10	$ 14.34	$ 14.34			McMaster	90670A160
ISO 100 Clamps and bolts	16	1	16	$ 3.92	$ 62.72			Lesker	QF-SSC-ALI
ISO 100 O-rings			0		$ -				
KF 50 to 25 reducer	5	1	5	$ 47.88	$ 239.40			Lesker	QF50XQF25CA
KF 50 spool piece for XYZ actuators	3	1	3	$ 205.72	$ 617.16			Lesker	FN-Q44063
KF10-KF40 Claw clamp kit	18	4	72	$ 33.49	$ 602.82			lesker	VKF1050CCS
KF50 blanks	6	1	6	$ 8.58	$ 51.48			lesker	QF50-200-AB
KF40 blanks	3	1	3	$ 7.81	$ 23.43			lesker	QF40-150-AB
KF25 blanks	5	1	5	$ 4.66	$ 23.30			lesker	QF25-100-AB
KF50 centering ring and o ring	12	1	12	$ 11.10	$ 133.20			lesker	QF50-200-ARV
KF40 centering ring and o ring	6	1	6	$ 9.77	$ 58.62			lesker	QF40-150-ARV
KF25 centering ring and o ring	5	1	5	$ 6.79	$ 33.95			lesker	QF25-100-ARV
KF50 Cast clamp	6		0	$ 11.62	$ 69.72			lesker	QF50-200-C
KF40 Cast clamp	3		0	$ 7.11	$ 21.33			lesker	QF40-150-C
KF25 Cast clamp	5		0	$ 6.16	$ 30.80			lesker	QF25-100-C
Hardware and Mic	1	1	1	$ 2,500.00	$ 2,500.00				
			0		$ -				
			0		$ -				
			0		$ -				
			0		$ -				
			0		$ -	Total	$ 72,078.31		
			0		$ -				

Approximate M&S remaining: $72,078.31

Fermilab

Timeline

Completion of Fabrication drawings

- Estimated 2 weeks

Procurement and manufacturing

- The thermal shields will likely drive this section of the schedule
  - Due to the price, they will have to go out for bid (~1 month)
  - Manufacturing and delivery estimated to take ~100 days

Assembly and testing

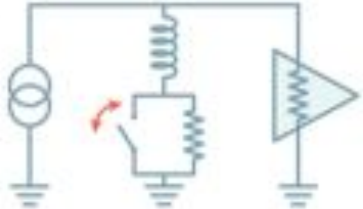
- 1 week to assemble and complete vacuum testing

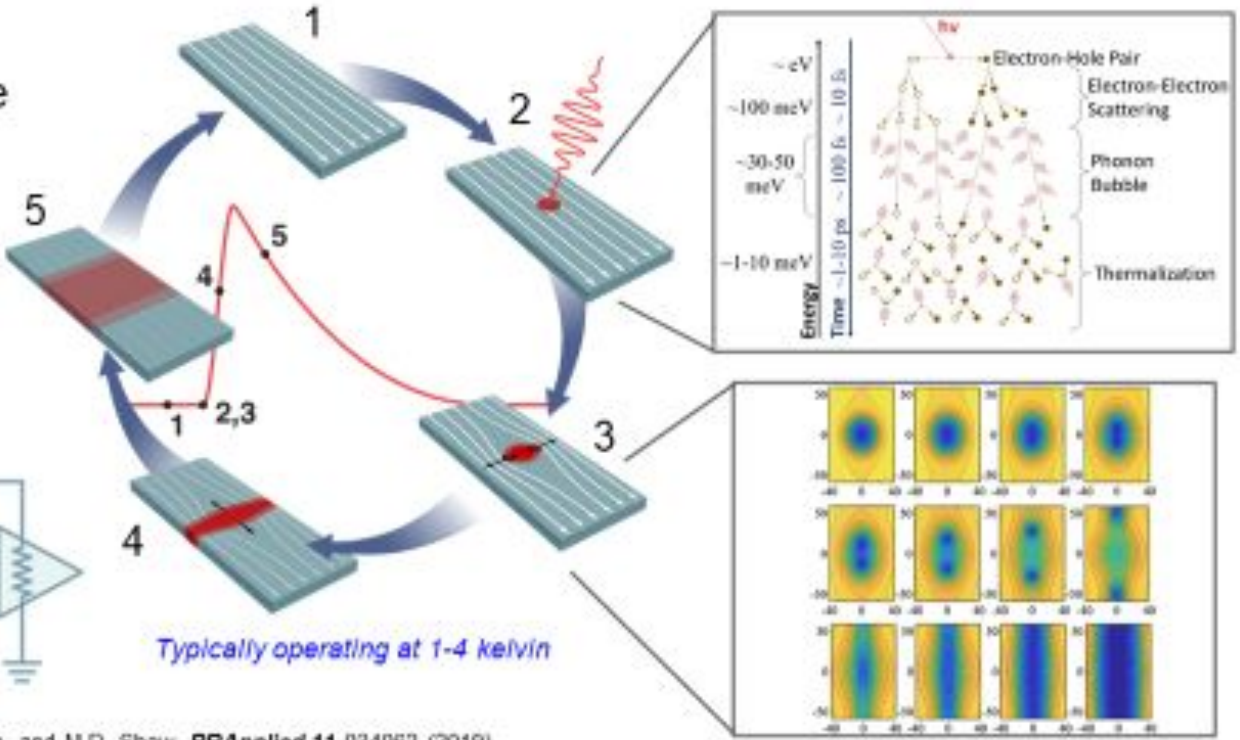
Timeline

Task	Estimated time	Date
Complete Fabrication drawings	2 weeks	Oct 2nd
Procurement and delivery	19 weeks	Feb 12th
Assembly and testing	1 week	Feb 19th

Superconducting Nanowire Single Photon Detector

1. Current-biased superconducting nanowire
2. Photon absorption & Hotspot formation
3. Suppression of superconductivity
4. Normal domain growth - ***internal gain***
5. Recovery

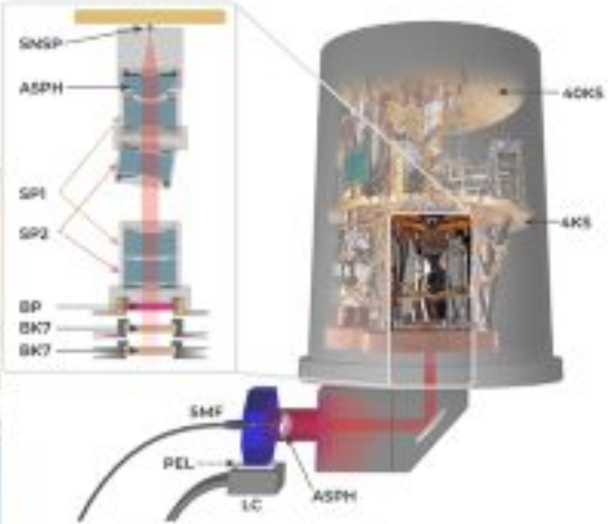




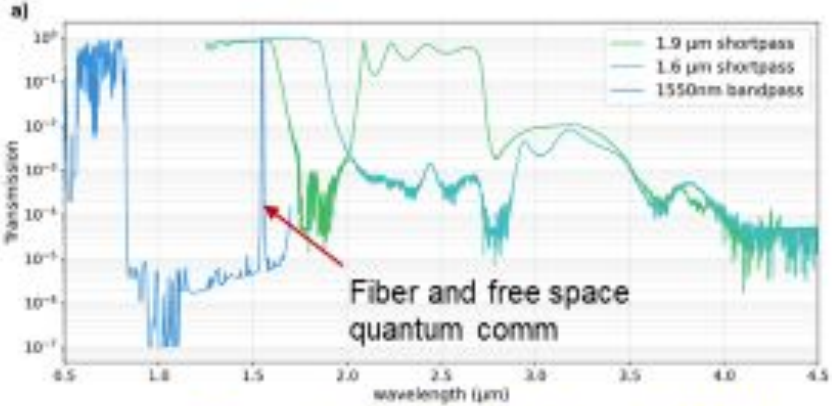
G. Goltsman, et al., **APL** 79, 705 (2001)
J.P. Allmaras, A.G. Kozorezov, B.A. Korzh, K.K. Berggren, and M.D. Shaw, ***PRApplied* 11** 034062 (2019)
J.P. Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors*. **Ph.D. Dissertation**, Caltech (2020)

Background filtering for SNSPDs

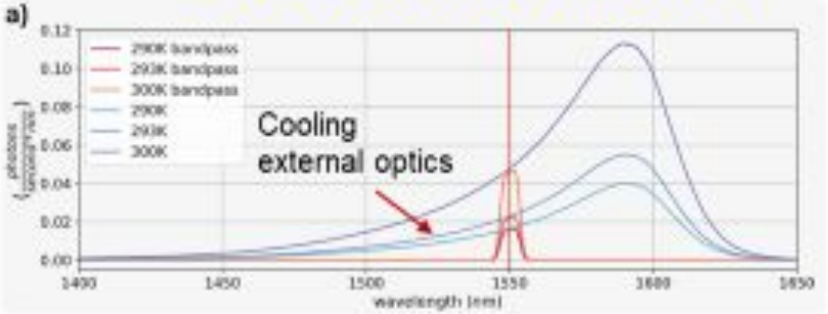
IdealVac cryostat for SNSPDs



PhotonSpot Inc. Cryostat



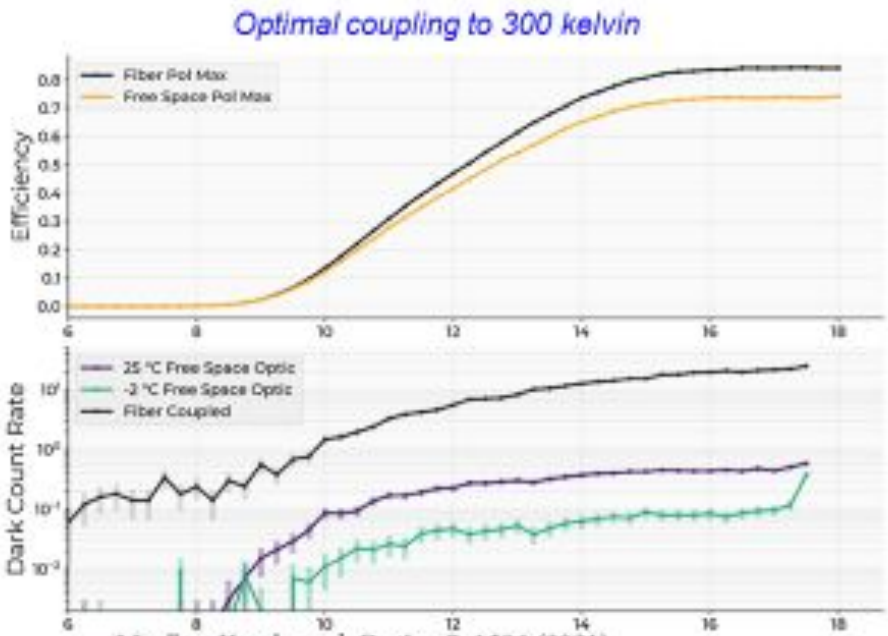
Remaining black body photons for 300 K



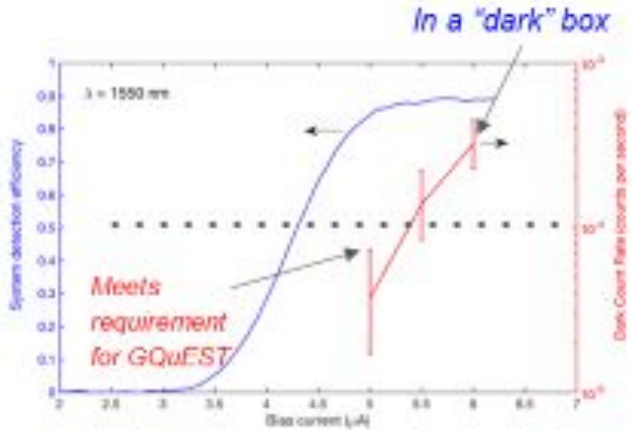
Mueller, Korzh *et al*, **Optica 8,** 1586 (2021)

jpl.nasa.gov

Low dark count measurements



Mueller, Korzh *et al*, **Optica 8,** 1586 (2021)



- Intrinsic DCR is an exponential function of bias current

Next steps:

- Efficient coupling to cryogenic environment → BCR vs. temperature
- Couple to cavity cryostat

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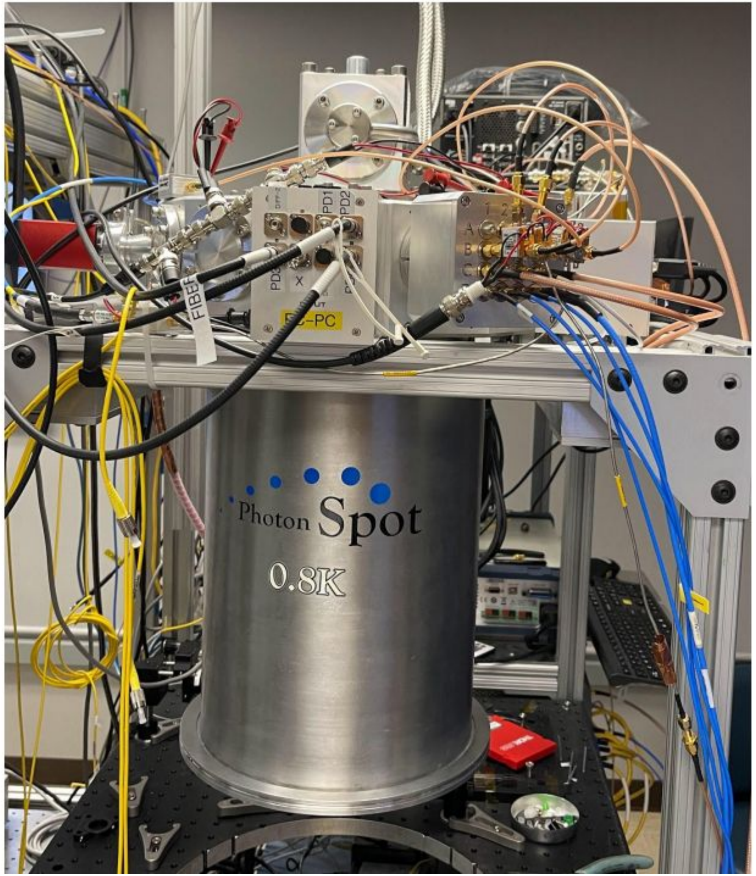
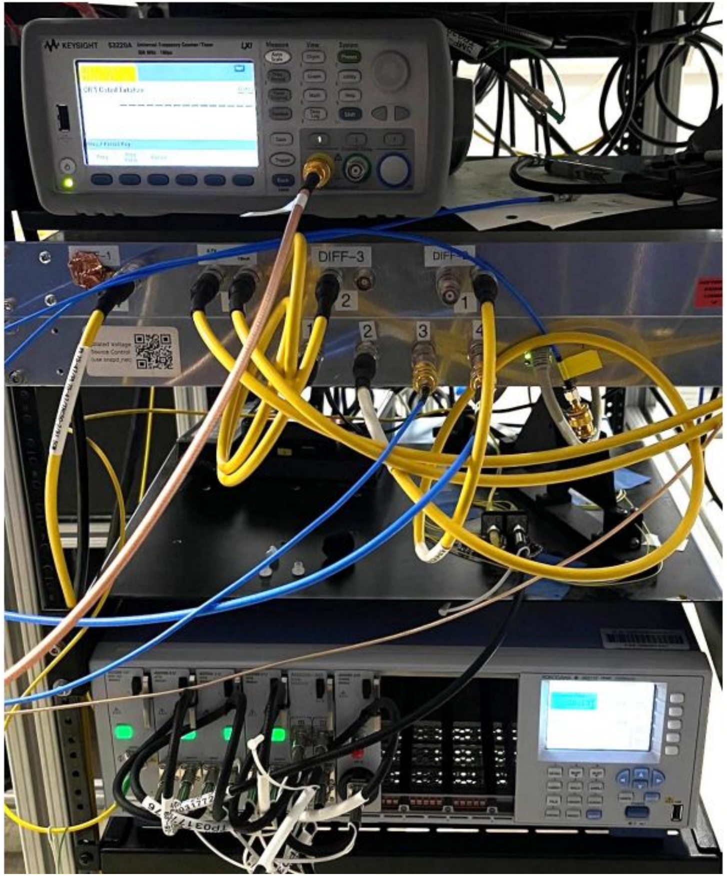
SNSPD in INQNET/JPL Lab at Caltech: efficiency and dark rate





SNSPD in Maria’s Caltech Lab: Alex Ramirez

SNSPD Pulse Readout and Threshold

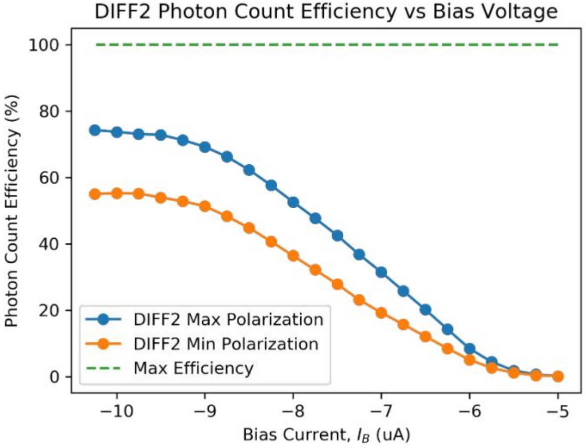
Yokogawa Frame Controller

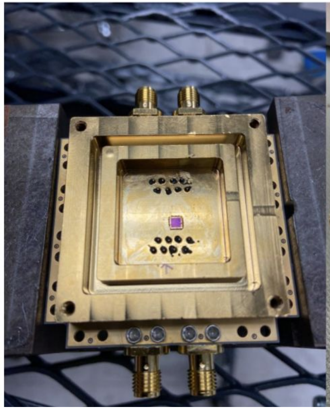
Tunable Laser

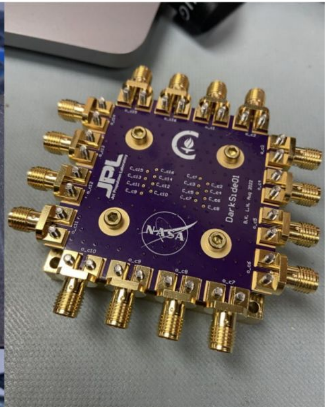
Attenuators

Optical Switch

Power Meter







Quarterly Agenda

Q4 2023

Optics in Readout cavities; control and characterize cavities; begin mount fabrication

Control system migrated to pynq

Q1 2024

Laser noise; SNSPD cryo assembled and tested; SNSPD dark rate measured

Q2 2024

Integrate Demonstrator: vacuum, IFO optics, readout cavities, SNSPD readout

Q3 2024

Characterize classical noise and dark rate; V1 design, cost, and schedule

5. Our Responses to the Charge

Responses to question 1: adapting to new funding profile

Compared to Original 2-year Deliverable and Milestones:

- IFO planning and risk mitigation
  - Technology Demonstrator designed for stable control, low-power recycling, characterize RFI couplings
    - Vacuum systems from FNAL sent to Caltech
  - Measuring laser noise, coating noise, bulk modes deferred to 2nd year
    - Substrate and coatings in process
  - Cryo cooling is an extended goal of the demonstrator
- Readout Cavities
  - Initial version built and optics delivered
  - On track for multi-cavity readout and measure isolation
- FPGA signal processing milestones
  - SNSPDs meet minimum goal of 1e-2 Hz background counts; push to 1e-3 or 1e-4 Hz
  - Initial versions of SNSPD readout in testing
  - Control toolkits in pyrpl migration to pynq deferred to 2nd year
  - Optical equipment installed at FNAL to demonstrate; initial ML on simple system

Responses to question 2: clear and appropriate milestones and deliverables

MILESTONES and DELIVERABLES

- Publish a fiducial design with defined performance parameters
  - Recirculating power on beam splitter
  - Readout cavity bandwidth and isolation
  - Photon counting efficiency and background
- Construct “Technology Demonstrator”
  - Short armed, low power recycled IFO in vacuum
  - Enhanced goal: cryogenic IFO optics
  - Control laser stabilization, IFO, readout cavities, and photon counters
- Operate technology demonstrator
  - Measure readout cavity performance
  - Measure SNSPD background rate
- Propose mature design
  - Construction cost and schedule
  - Operations cost and schedule

Responses to question 3: M&S and Labor for Year 2

- FNAL
  - Labor:
    - Sr. Scientist (10%), partial postdoc, student:
    - Cryo engineer, firmware engineer, technician:
  - M&S:
    - Cryo Equipment:
    - Electronics:
    - Supplies and Travel to Caltech:
- Caltech subcontract (including JPL)
  - Labor:
    - Professors and Research Scientists:
    - Experimental Graduate Students and Postdocs:
    - Engineers and Techs
  - M&S
    - Lasers, optics, electronics:
    - Vacuum mechanical parts:
    - Supplies and Travel:
- TOTAL FNAL and Caltech, Labor and M&S, NO OVERHEAD:

Responses to question 4: Appropriate Collaboration Engagement (part 1)

- McCuller Lab @ Caltech
  - IT infrastructure for log, chat, git; Laser labs from LIGO and new construction
  - Lee is coordinating HSF funding
  - Personnel:
    - Lee McCuller
    - Torrey Cullen
    - Daniel Grass
    - Ian A. MacMillan
    - Alexander Ramirez
    - Sander Vermeulen
- Rana Adhikari
  - 1.5 micron experience; control co-development; Inspiration; Lab & Equipment availability

Responses to question 4: Appropriate Collaboration Engagement (part 2)

- INQNET Lab @ Caltech
    - Cutting edge SNSPD R&D for several projects
    - Coordination with FNAL mechanical/cryo engineers established for Quantum Networking
    - Key Personnel:
        - Matt Shaw
        - Lautaro Narvaez (eng) (engineer)
        - Raju Valivarthi (quantum engineer)
        - Boris Korzh
        - Sasha Sypkens
- Kathryn Zurek @ Caltech
    - Foundational and continuing theory work guiding design
    - QuRIOS: Seeking to bridge the divide between theory and observability
    - Personnel:
        - Matthew Bub
        - Yanbei Chen
        - Yufeng Du
        - Vincent Lee
        - Dongjun Li
        - Yiwen Zhang

Responses to question 5: Infrastructure available and sufficient?

- Fermilab
  - Cryo Engineering and mechanical assembly (From SQMS)
  - Analog/Digital electronics (QICK framework; Firmware engineering)
  - Laser Enclosure repurposed at CMTF; AD controls group for safety interlocks
  - Lasers and optics repurposed from Holometer
  - Administrative support from CSAID.
  - FQI for intellectual support; Budget, Finance, and Reviews, too!
- Caltech/JPL
  - LIGO R&D labs and equipment readily available
  - Newly renovated space for McCuller Lab to hold the experiment
  - Support for postdocs, students
  - Strong theory/experimental connection
  - INQNET Labs located on Caltech campus
  - Expertise on SNSPD, cryogenics, electronics

Responses to question 6: Project Management Team

- Chris and Lee use project management tools combined with common sense experience.
  - We are pre CD-0; seeking combined CD-0 and CD-1 approval by ~ Q4 2024
- Project Accomplishments:
  - Successful proposal reviewed; FWP awarded
  - Formed a new team in 1 year
  - Execute subcontract with Caltech and paid invoices
  - CSAID “self service” purchase requisition system; Jason G. for procard/emarket
  - Web presence managed by CSAID (Marcia T.) plus we have logo!
  - ~ 50% progress in 1 year; on track to complete demonstrator and measurements
  - First Full In-Person Collaboration Meeting: September 27, 2023 @ Caltech
- Challenges:
  - More clear communication with ETD regarding funding and resources would help
  - We need accounting help to prepare budget with proper rates for overhead and salaries

GQuEST