QUIET Phase II

The Search for B-Mode Polarization in the Cosmic Microwave Background Using Coherent HEMT Detectors

A Proposed New Initiative for Fermilab

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October 19th, 2009

1 Executive Summary

The Fermilab scientific team consisting of Fritz Dejongh, Scott Dodelson, Dave McGinnis, Hogan Nguyen, and Albert Stebbins are proposing to join the QUIET CMB polarization experiment at the Phase-II level. QUIET is currently funded at the Phase-I level, and has successfully completed operation of a 19-element Q-band telescope in Chile. It is currently operating a 91-element W-band telescope. QUIET Phase-II is factor of 15 increase in array size. The proposal calls for 2 years of construction and 3 years of operation, following Phase-I completion. It is currently under review by the NSF.

The science explores the nature of inflation and HEP physics at the GUT scale. Not only is the science in line with the mission of the FCPA, we also wish to convey our enthusiasm at the prospects of engaging the Lab and ourselves intellectually in this profound science at a very deep level.

This document describes our major proposed contributions to the QUIET Phase-II project. They represent discussions with the QUIET collaboration over a 2-year period. The major contributions would be:

- Production assembly of approximately 1500 W-band modules and spares (section 2).
- Production testing of W-band modules (section 3).
- Receiver Integration of one W-band cryostat at Fermilab, in collaboration with the University of Chicago (section 4).

Section 5 gives an estimate of total cost and effort. In analyzing our proposed contributions, we have carefully considered the lab's available facilities, the expertise of the technical, engineering, and scientific staff, and the competitiveness and strength of the QUIET collaboration. We feel our proposal is a great fit for Fermilab. It presents a healthy and vibrant collaborative effort between Fermilab, the University community, and other national labs within the US, Japan, and Germany.

We thank the FCPA management, PPD management, and the Associate Director of Research for providing support for us to develop this proposal thus far. We look forward to further discussions and receiving guidance from the Directorate.

2 W-band Module Assembly Plan at Fermilab

2.1 Introduction

The QUIET Phase-II proposal calls for deploying approximately 1500 W-band modules. Caltech, Fermilab, and JPL will be the lead institutions responsible for producing and delivering the modules to the 3 integration sites, for a 2-year production cycle. This document describes the proposed role for each institution, and describes the work at Fermilab in detail.

Caltech and JPL will be responsible for delivering fully cold-tested Monolithic Microwave Integrated Circuits (MMIC) components to Fermilab. These MMIC components utilize High Electron Mobility Transistors (HEMTs), which have the required speed to operate in the W-band (90 GHz). Caltech and JPL are responsible for the overall circuit design, and establishing the component specifications.

Fermilab receives these components, as well as other passive components from vendors, and is responsible for assembling them into modules. Due to the large number of modules, totaling approximately 150,000 components, the technique of choice is automated assembly.

The plan described here is based on the JPL experience with delivering 91 W-band modules in Phase 1. Before describing the assembly work in section 2.4, we provide some technical background material in sections 2.2 and 2.3 to describe how the modules work.

2. 2 Functional Description of the W-band Modules

This section provides background material for how the W-band modules work. This material is not important for understanding the W-band production assembly plan. It is included here for completeness, and is more relevant for understanding the production testing plan, which is provided in a separate document.

Each module is attached to the two waveguide outputs of an orthomode transducers (OMT), which uses an internal septum polarizer, shown in figure 2.1. An OMT receives linearly polarized microwaves from a particular 0.15° diameter circular patch in the sky.   It decomposes the fields into E_x**x** and E_y**y**, where **x** and **y** are orthogonal axes defined by the septum polarizer.

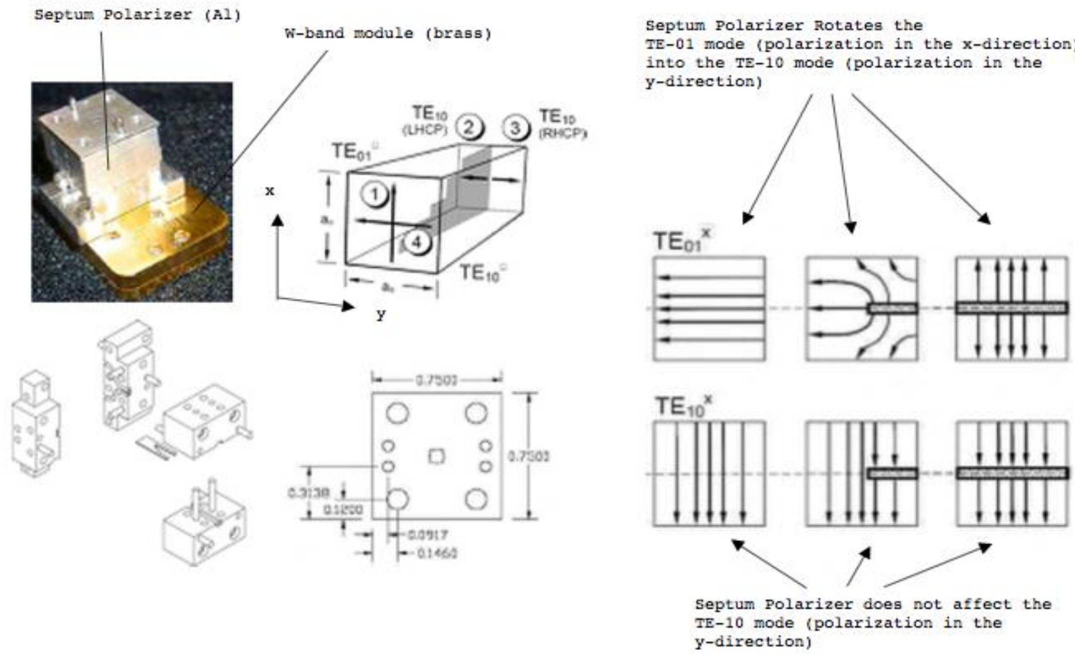

Figure 2.1 :   Description of Orthomode Transducer used by QUIET

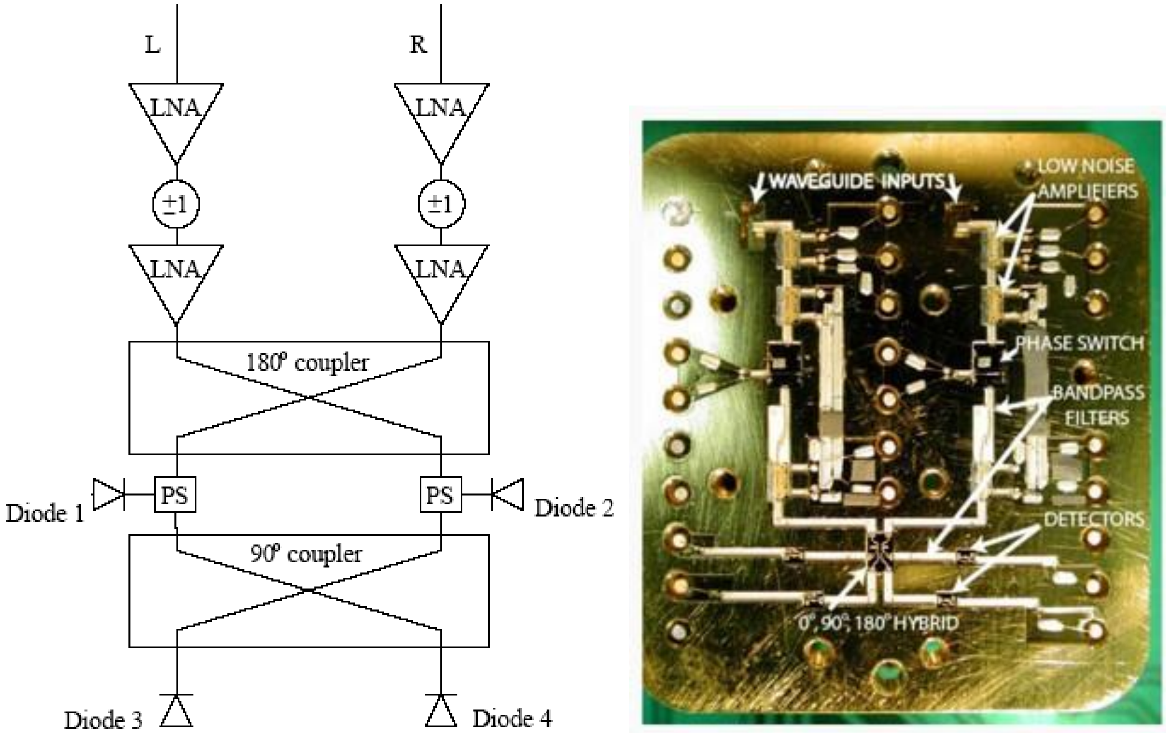

Figure 2.2: Functional diagram of W-band module (left) and the 1.25" x 1.14" module with top clamshell removed (right). Microwaves with amplitudes $E_x + iE_y$ (R) and $E_x - iE_y$ (L) enter from the top. Phase switches in each arm (indicated by ±1) are operated one at a time and provide the Dicke-switching which separates the polarized signal from the total power, as described in the text. The signals pass through low noise amplifiers (LNA), and then enter a series of hybrid couplers, detailed in the text. PS indicates power splitters. The demodulated outputs of detector diodes 1 and 2 are proportional to the Stokes parameter Q while diodes 3 and 4 encode U after demodulation. Filters have been omitted for clarity.

It rotates one polarization direction into the other, recombines them so that only *one* polarization state is propagated, and then forms two linear combinations with amplitudes $E_x + iE_y$ (R) and $E_x - iE_y$ (L) respectively. These two linear combinations are sent to the two waveguide inputs of the module. The module amplifies these fields, manipulates them, and returns the time-averaged electric field double correlations $\langle E_x^2 \rangle$, $\langle E_y^2 \rangle$, and $\langle E_x E_y \rangle$ that are needed to calculate the Stokes Q and U polarization observables.

The functional diagram of a module is given in figure 2.2. There are two amplifier chains, one for each waveguide input. The two amplifier chain outputs are combined in a (0°, 180°) hybrid coupler, whose two outputs are sampled by 2 "detector diodes". These are simply RF rectifier diodes, converting the RF signal into a DC voltage. The two outputs of the (0°, 180°) circuit are combined again in a (90°, 270°) hybrid coupler, and subsequently sampled by 2 more detector diodes. Therefore, the detector diodes sample linear combinations of E_x and E_y, with complex coefficients. And it can be shown that the 4 detector diode output voltages encode the correlations above. The detector diodes voltages are sampled by 800 kHz FADC's.

An important feature is the high speed switching circuitry internal to the modules. Each of the two amplifier chains contains an active phase switch (PS) that can either maintain (+1) or invert (-1) the signal, for a total of 4 possible phase states: (+1,+1), (+1, -1), (-1, +1), and (-1,-1). By sampling all 4 phase states, the 4 detector diodes sample *additional* linear complex combinations of the amplified signals. This allows the relative gains of the two amplifier chains to be calibrated away. For Phase-I operation, the two PS's switched at 4 kHz and 50 Hz respectively. This allowed for canceling the time variations of the gains over a large frequency range and resolving other important systematics.

For Phase-I, when the Stokes Parameters Q and U have been calculated using information from all 4 phase states, in an operation called "Double Demodulation", the 1/f noise component is essentially absent at frequencies higher than 0.1 Hz.

2.3 Component Description of the W-band Modules

A QUIET W-band module consists of 106 miniature components attached to a 1.25" x 1.14" brass clamshell via high temperature-cure silver epoxy. Figure 2.2 shows a picture of the module, with the top clamshell removed. The components are listed in table 2.1. There are passive RF components such as waveguide antenna couplers, microstrips and waveguide bends, band passes filters, and hybrid couplers. There are active RF components such as the low noise amplifiers (LNA), phase switches (PS), and detector diodes. The active components are DC-biased and utilize capacitors for power filtration. The electrical connections are made via wire bonding or ribbon bonding. The component sizes range from as large as 2 mm x 3 mm, to as small as 230 μm x 230 μm. The RF and non-RF components have a 12.5 μm and 50 μm placement accuracy requirement, respectively.

Table 2.1: Components in the W-band Module

Component	Responsible institution	Fermilab Role
Low Noise Amplifiers	Caltech/JPL	Deliver to Fermilab
Detector Diodes	Caltech/JPL	Deliver to Fermilab
(0,180) and (90, 270) hybrid couplers	Caltech/JPL	Deliver to Fermilab
Phase Switches	Caltech/JPL	Deliver to Fermilab
Brass Chassis	Specified by Caltech/JPL and machined by an outside vendor	Fermilab to oversee procurement process, vendor qualification and organize delivery schedule
Other Passive Components: waveguide couplers, microstrips, microwave bends, capacitors, band pass filters	Specified by Caltech/JPL and purchase from Applied Thin Film Products, Freemont, CA	Fermilab to oversee procurement process and organize delivery schedule
Miniature microwave absorbers for internal module isolation	Purchase from Emerson & Cuming	Fermilab to oversee procurement
RF gaskets and silver epoxy	Purchase from Epotek	Fermilab to oversee procurement

2.4 Overview of Fermilab Work

The assembly work per module consists mainly of attaching 106 miniature components onto a brass chassis, performing the wirebonding, and performing the production testing. The step of production testing is covered in another document. This represents an attachment of approximately 150,000 components. Due to the large volume of parts, automated assembly techniques will be used.

The assembly work is similar in many ways to a silicon detector assembly project for an HEP collider experiment. For this reason, we would utilize the experience of the Sidet staff[1] and the Sidet Lab D 2350 ft^2 class 10,000 clean room. The placement accuracy and ESD requirements are similar to HEP silicon detector needs. The important exceptions are:

- there are far fewer wire bonds than a typical HEP silicon detector
- the components are smaller, requiring smaller vacuum pickup and epoxy dispensing tools to be used
- due to the large temperature difference between the assembly process (300K) and operation (20K), care is needed to minimize thermal stresses. Components with similar CTE to metals will be used.
- the heat load of approximately 40 mW per module (dominated by the LNAs) is far less than a typical HEP silicon detector, which typically performs highspeed digitization at the front end.
- the majority of the components is relatively inexpensive and does not need special handling. The only components requiring special handling are the LNAs. In contrast, nearly every component in an HEP silicon detector requires special handling and represents a huge investment of time and money.

The tooling at Sidet will need to be modified for this work. New vacuum pickup and epoxy dispensing tools will need to be fabricated. This is a relatively straight forward process.

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[1] the Sidet staff has extensive experience with silicon projects for CDF, D0, CMS Tracker Outer Barrel, and CMS Forward Silicon Pixels. Currently it is engaged in CCD assembly for DECAM, and silicon assembly for the PHENIX project at BNL.

The single most important upgrade is to retrofit 4 motorized Zeiss 500 coordinate measuring machines (CMMs) to perform automated assembly (figure 2.3) . The tools would be mounted on the CMM optical head, and computer-controlled to perform the die attachment step:

- dispense silver epoxy into desired location on chassis
- pickup component from tray with the correct orientation (rotation)
- place component into desired location on chassis

The Zeiss machines have a large work space and a positioning accuracy exceeding the needs of QUIET. A single pick-and-place operation has been measured to require 15 seconds, which is adequate for QUIET needs. However, the Zeiss machines are currently interfaced to very old Hewlett Packard computers running proprietary Zeiss software, with limited I/O and interrupt handling capability.

A critical upgrade is to replace the HP machines with modern PC's running Labview and Vision software. The Vision System software provides automated pattern recognition and parts measurements. It is needed for automatic determination of the parts location and orientation. The Labview software is now a widely-accepted multi-purpose graphical programming tool that is easy to use by non-experts and can programmed without extensive computing expertise[2].

We believe this upgrade will turn the Zeiss 500's into very powerful general purpose machines. The upgrade will benefit not only QUIET Phase-II, but also the future silicon assembly projects at Sidet.

[2] The Sidet staff recently programmed the Vision and Labview software to automatically measure the size of plastic extrusions for the NOVA experiment.

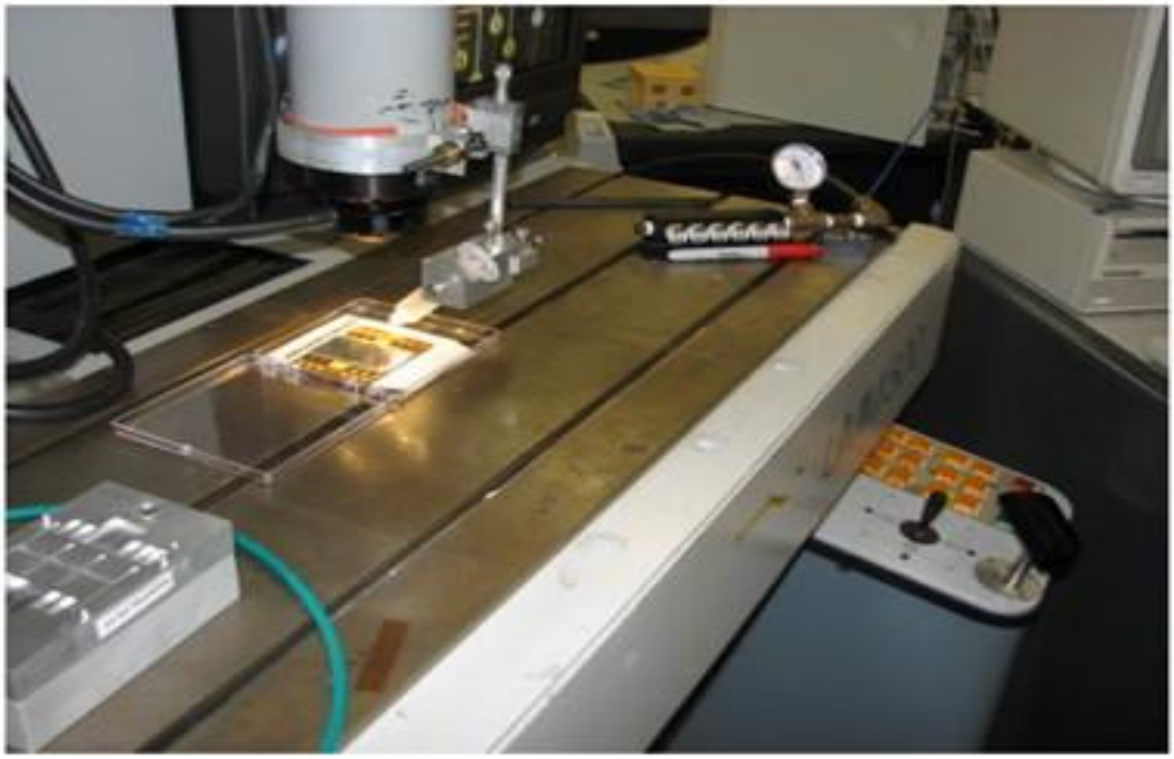

Figure 2.3: Zeiss 500 machine, as being utilized for epoxy deposition for the CDF Run-IIb R&D project.

2.5 Production Rate

We estimate the production rate based on the availability and the intrinsic speed of the Zeiss machines. We plan on using 4 machines, out of an available number of 8. These machines are in good working condition but are considered obsolete. However, Sidet has sufficient spare parts, and the staff is trained to perform machine maintenance and calibration. We measured an intrinsic pick-and-place speed of 15 seconds per component.

Additional labor assumptions are:

- 4 mechanical technicians (Class II) for operating the Zeiss machines.
- 1 mechanical technician (Senior Tech) for wirebonding.
- 1 mechanical technician (Technical Supervisor) for inspection and supervision.
- 5 work hours per 8-hour work day, and 260 work days per year.

Assuming that personnel is allowed to be dedicated to this project, we estimate 0.1 years for Zeiss machine operation, 0.9 years for wire bonding, and 1.3 years for inspection and supervision. This is in agreement with experience with the CMS Tracker Outer Barrel Silicon Project, where automatic assembly was also utilized. The actual automatic assembly machine operation is relatively brief. The dominant labor is in the inspection, wirebonding, and supervision. Table 2.2 summarizes the production rate estimates for 1600 W-band modules (100 spares).

For QUIET Phase-II, we need to meet a production rate of delivering modules in 2 calendar years. Assuming that existing light-duty mechanical technicians are allowed to be dedicated to this project, we can meet this production rate.

Table 2.2: Labor and Time Estimate for Production

Time Estimate assuming 100% Efficiency

Time Estimate for W-band Module Assembly of 1600 Modules						
Parts Placement utilizing 4 Tech-II Full time						
Time to Place One Part (minutes)	Number of Parts Per module	Modules Per Hour	Number of Zeiss machines	Total Number Per hour	Number of Modules	Total Number of hours
0.75	100	0.8	4	3.2	1600	500
Inspection time, setup, organization (Tech Supervisor)						
Time per module (hours)	Number of Modules	Total Time (hours)				
1	1600	1600				
Wirebonding Time (Sr. Tech)						
Time Per Module (hours)	Number of modules	Total Time (hours)				
0.75	1600	1200				
Actual Calendar Time Estimate	**Total assembly time (hours)**	**Total inspection/org time (hours)**	**Total Wirebonding Time (hours)**			
	500	1600	1200			
Number of days (5-hour work day)	100	320	240			
Number of Personnel	4	1	1			
Number of days	25	320	240			
Number of years (260 work days/year)	0.096153846	1.230769231	0.923076923			

2.6 Experience from Phase-I Production Assembly

JPL was responsible for delivering 91 W-band modules to the Chicago integration site. The first half of the modules was manually assembled at JPL. The remaining modules were assembly jointly by NxGen and JPL. NxGen performed the automated die attachment procedure, while JPL completed the remaining steps of wire/ribbon bonding, RF-gasket attachment, and attaching the Eccosorb isolators[3]. The modules were then sent to Chicago for integration into the receiver.

However, there was significant rework requiring some fraction of the modules to be sent back to JPL for repair. If a module does not work satisfactorily, a process of troubleshooting is carried out to identify the location of the problem(s). Due to time constraints, the lack of certainty about the origin of the problem and the desire to minimize the number of times a module is opened, rework may involve many changes at once.

For example, a loose bond may be re-bonded, an apparently loose substrate is replaced, and epoxy is cleaned from various areas. Then the module is tested again. If the module works, it is often not obvious which of the various 'fixes' resulted in the improvement. Therefore it is not always possible to associate a given problem with its solution. In the example given, it is not clear if a bond had failed or a substrate was loose. This makes it difficult to compile bond or die-attachment failure rates in general.

A common problem with the modules was a low signal on one or both legs of the amplifier chain. It was usually difficult to identify which MMIC in the chain was responsible, and so the MMICs were replaced in a process of elimination. Thus, some MMICs were inevitably replaced even though they were functioning correctly. Also, if a MMIC chip was replaced on one chain, it was not always possible to ensure that it was from the same wafer as the corresponding chip on the other chain. If the new chip was from a different wafer, then the corresponding chip on the other chain would also be replaced. Therefore, not every case of MMIC replacement was due to a faulty chip which might result from a die-attachment fault.

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[3] Small Eccosorb microwave absorbers and gaskets are used to isolate the circuit components from each other. They prevent unwanted RF leakage.

Taking the above into consideration, for 5/48 modules, loose substrates were recorded which were replaced. For 12/48 modules, the replacement of amplifier, phase-switch, or hybrid chips was recorded.

The following table 2.3 summarizes the repairs performed on modules built by NxGen/JPL and other important lessons during the assembly procedure.

Table 2.3 Summary of Issues Encountered for Phase I W-band module assembly

Assembly Step	Issues Encountered
Die Attachment at NxGen	Initial die attachment used insufficient amount of epoxy. The die components flexed during wirebonding, which compromised the wire and ribbon bond strength.
Die Handling at NxGen	Handling of very small parts (230 μm x 230 μm capacitors) was difficult. NxGen used up more parts than required. There is evidence that some parts were also manually assembled.
MMIC Handling	MMIC chips from failed modules were analyzed and were visibly damaged. It is unclear where the damage occurred. It occurred either during the MMIC preparation process, or during the die attachment process at NxGen.
Wirebonding failure	24/48 modules had at least 1 wirebonding problem. There were 31 wirebonding problems in total. These fall into two categories: bonding errors (11/31, e.g. missing or misplaced bonds) and bond quality (20/31, e.g. bonds too low or high and therefore shorting to the brass chassis). However, considering that a typical module will have over 200 bonds, the failure rate per bond is 0.3%.
Miscellaneous failures	Damaged phase switches and hybrids due to handling Eccosorb and Indium[4] crushing bond Insufficient epoxy and epoxy shorting components

[4] For Phase I, the LNAs were attached by Indium, not silver epoxy. For Phase II, we plan to use entirely silver epoxy.

2.7 R&D Plan and Milestones Before Production

Considerable R&D has been performed, in the context of upgrading the tooling at Sidet. We summarize the important ones here:

-Tooling to handle small parts and for dispensing epoxy have already been fabricated. They are awaiting trial run in late October 2009. See figure 2.4.

-The upgrade of the Zeiss machine has been analyzed. The digital communications protocol necessary to control the Zeiss motors and position readback have been established. They have been determined to be relatively straight-forward. A digital I/O board is being designed. Prototype boards will be delivered in late 2009.

These milestones assure us that we have the right assembly tools (to allow initial manual assembly), and that retrofitting the Zeiss machines for automated assembly will be straight-forward.[5] The following are important R&D tasks, yet to be done, relating to mechanical and thermal properties of the module:

- thermal and vacuum mechanical stress analysis of the module.
- studies of the wirebond and epoxy adhesion strength as a function of thermal cycling.

We have access to a ready-to-use 5 Watt 20 Kelvin cryocooler, vacuum vessel and dry pumps at Fermilab for performing thermal cycling studies. These studies were not fully done for Phase-I, and we believe they will help improve the yield for Phase-II. Table 2.4 summarizes the milestones to be met before we can declare production readiness.

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[5] The group performing the tooling and Zeiss machine upgrade have extensive experience with fabricating automated precision tooling. Some of the relevant experience include the Fermi-Glast satellite cosmic veto shield, the CMS magnetic field mapper, the COUPP pressure vessel control, and the critical mechanical assemblies for the SDSS fiber spectroscopy.

Figure 2.4: Glue dispensing tool to guarantee uniform glue thickness (bottom of picture), and vacuum pickup tools riding on an air bearing (top of picture). These are being commissioned in late October 2009.

Table 2.4: Key R&D milestones before production, assuming a technically-limited schedule.

Milestone	Date
Commissioning of tooling to handle small parts and epoxy dispenser	October 2009
Assembly of a dummy representative module via manual control of the Zeiss 500 machine.	December 2009
Commissioning of Zeiss 500 with a modern PC and new I/O board.	December 2009
Completion of the Thermal and vacuum mechanical Stress analysis of the module.	December 2009
Completion of wirebond and epoxy adhesion strength studies.	February 2010
Commissioning of Vision Software to perform automatic determination of part location and orientation.	April 2010
Commissioning of Labview Software for overall assembly control.	May 2010
First pre-production module assembled by automated techniques	May 2010
Completion of layout of Lab D for QUIET production run.	July 2010

2.8 Summary of Fermilab Cost and Effort for Production Assembly

This section summarizes our estimate of the cost and effort for all aspects related to assembly. We include the tooling development costs. We use 30% contingency for directly purchasable items. We use 50% contingency for software and precision tooling development, even though our analysis indicates that the tooling fabrication and software development will be straight forward.

Table 2.5

Cost to Retrofit the 4 Zeiss 500 Machines						
Material Costs	**Cost Per Item**	**Number Of Items**	**Extended Cost**	**Contingency**	**Contigency ($)**	
Rotary Stage	1411	4	5644	**30%**	**1693.2**	
Linear Stage	1471	8	11768	**30%**	**3530.4**	
Motor Controller	800	12	9600	**30%**	**2880**	
Vacuum Pickup Tools	100	23	2300	**30%**	**690**	
Custom Carriage Trays	100	10	1000	**30%**	**300**	
Miscellaneous Tooling	10000	1	10000	**30%**	**3000**	
Sum			40312		12093.6	
Labor Cost for Developing Tooling	**Number of Weeks**	**Personnel**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Labview Programming	20	Computing Professional	62,624	**78.28**	**50%**	31312
Zeiss Programming	4	Senior Technician	9448	**59.05**	**50%**	4724
Labor to build tooling	10	Senior Technician	23,620	**59.05**	**50%**	11,810
Sum			95,692			47846
Labor Cost for W-band Assembly	**Labor Type**	**Number of Hours**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Wirebonding	Sr. Tech	1200	70860	**59.05**	**30%**	21258
Assembly	Technician-II	500	23375	**46.75**	**50%**	11687.5
Inspection and Organization	Technical Supervisor	1600	130880	**81.8**	**50%**	65440
Sum			225115			98385.5

3 QUIET Phase-II W-band Module Testing Plan

3.1 Introduction

The QUIET Phase-I W-band receiver uses 91 modules, each of which was manually tested and thoroughly studied and optimized. The Fermilab group has made three trips to JPL and held several discussions to understand the Phase-I testing process and testing requirements for Phase-II. Since Phase-II will consist of three receivers with 499 modules each, it is necessary to automate and streamline the testing process relative to Phase-I. This should be aided by an R&D effort at Caltech and JPL to improve the performance and uniformity of the modules. This document describes our plan, based on Phase-I experience, for testing W-band modules prior to their installation in the focal plane.

3.2 Overview of Module Operation

Fig. 3.1 shows a functional diagram of a W-band module. A module contains two legs, one for each polarization component of the input. Each leg includes three low-noise amplifier (LNA) stages, each of which contains four High Electron Mobility Transistor (HEMT) stages. There is both on-chip (Fig. 3.2) and off-chip sharing of the HEMT gate and drain biasing. Since the first stage amplifier has the greatest influence on noise, independent control of its gate and drain is provided. The second and third stages have independent gate control but share drain biasing.

Each leg also includes a phase switch, which delays the signal either 0 or 180 degrees. Each module contains four diode rectifiers, from which the total power in the Q and U polarization components is extracted.

The low-voltage biases needed to operate the module are:

- 3 independent gate voltages per leg for the LNAs.
- 2 independent drain voltages per leg for the LNAs
- 2 voltages per phase switch, one for each phase state. If both voltages are on or both are off, any signal is attenuated.
- 4 biases per module for the diode detectors.

There are a total of 18 biases needed per module.

The modules can be operated and tested warm, but are eventually cooled to 20K for the best noise performance. The needed bias voltages change with temperature so warm settings do not apply to cooled modules.

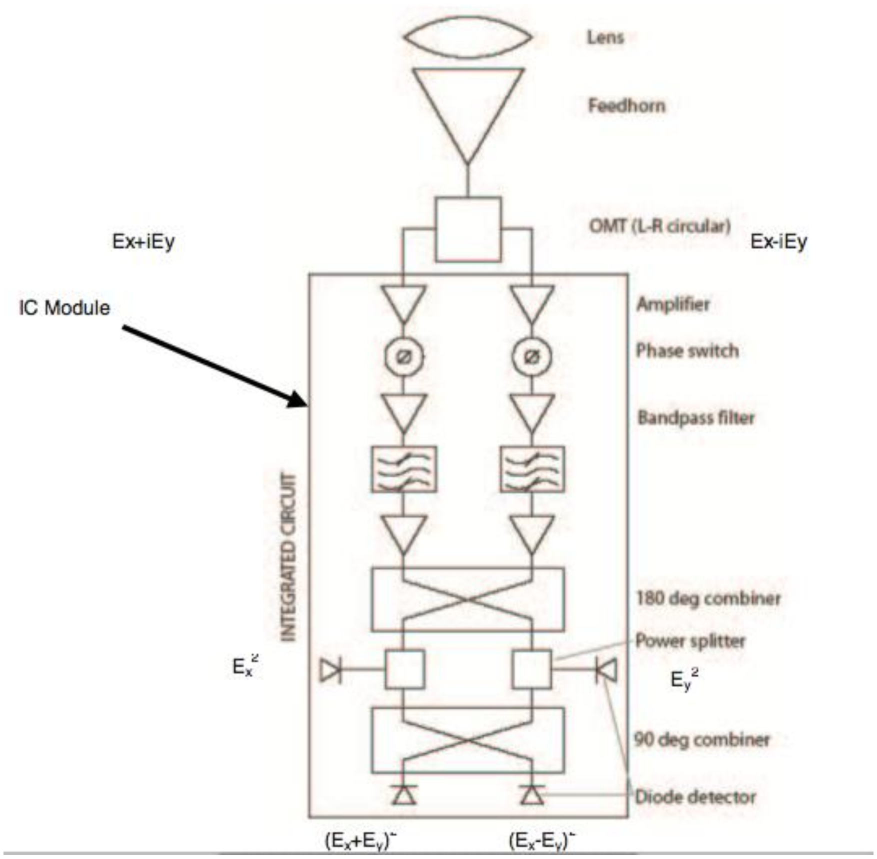

Figure 3.1: Sketch of a W-band module.

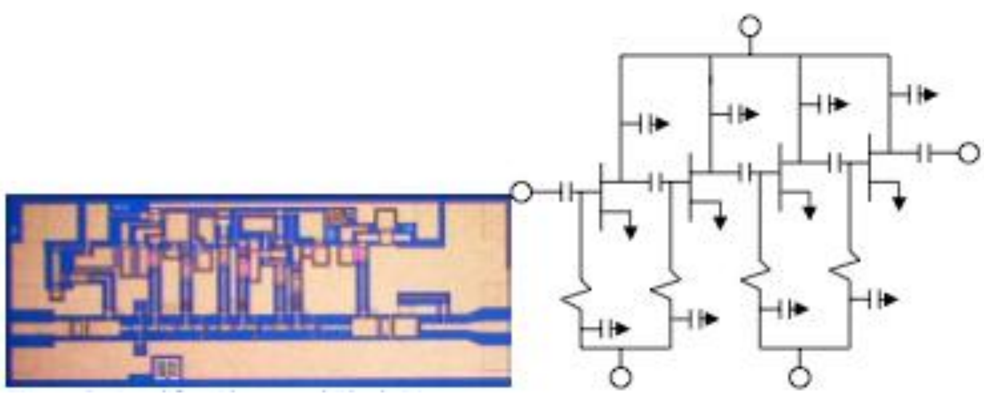

Figure 3.2: Photo and block diagram of one MMIC LNA

3.3 Summary of Phase-I Testing Process

The first step in the testing process is a basic power-on test. This tests that the components are functional and connections are in place. The procedure is simply to turn on bias voltages and read back the currents to check if they're in a reasonable range. This test is first done warm, and any problems are fixed. The module can then be rechecked cold.

The next step was to test the amplifiers and bandwidth using a frequency-swept signal, with the setup illustrated in Fig. 3.3. A magic tee is used for the input to the module, and provides equal inputs to the two legs. While this test can be done warm, it was performed cold for all modules in Phase-I.

This test also provides an approximate set of optimized low-voltage bias settings. The maximum signal-to-noise occurs when the gains and phases of the two legs of the module are matched. With this matching, and equal inputs to the two legs, half of the diodes have a null output for one state of the phase switches, and the other half of the diodes have a null output for the opposite state of the phase switches. Observing the diode outputs and adjusting biases by hand would find settings that achieve the desired matching.

These settings were then used as starting points for the final optimization of the biases after the modules were installed on the receiver. While on the receiver, the signal-to-noise of a small polarization signal can be optimized, but there is no direct way to verify the gain and phase matching of the two legs, so these starting points were felt to be helpful.

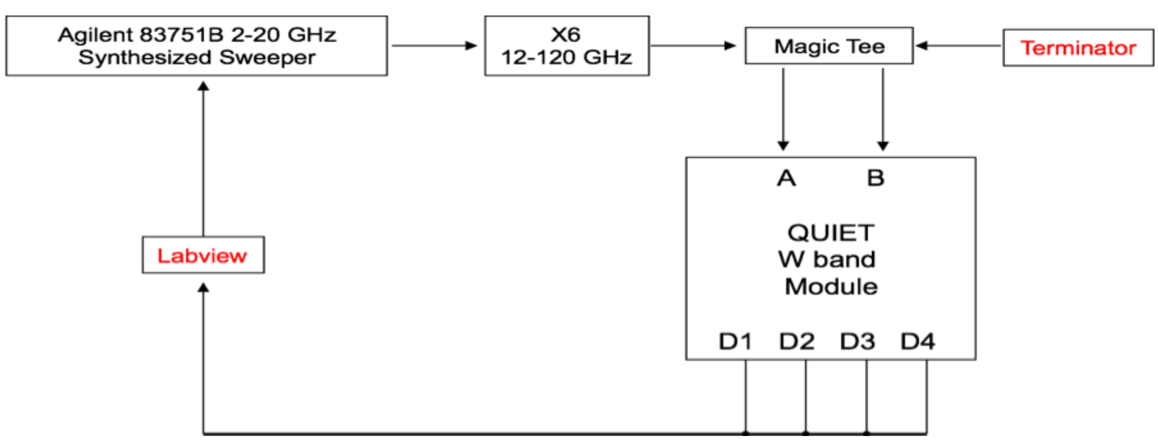

Figure 3.3: Setup for the frequency sweep test.

Finally, the noise temperature of the module was measured by measuring the diode output for inputs at various equivalent black-body temperatures, and extrapolating to zero input.

The overall experience from Phase-I is that manual testing of cold modules is very time consuming, given the time needed to cool the module and do the hand tweaking of the many biases. However, every module could be made to work, and bias settings known to be gain-matched provided confidence in the final module optimization.

3.4 Proposed Phase-II Testing Process

Our plan is to develop a warm test stand that automates the power-on test and RF frequency-sweep tests. We will also have a test stand to thermally-cycle modules down to 20 K and then back up to room temperature. Thermal cycling will expose weak bonds and die attachment issues. We have a ready-to-use vacuum vessel and cryocooler with a rating of 5W @ 20K. We've determined, via actual measurements, that we can cool down 350 grams of brass (equivalent to 7 modules) in about 2 hours: one hour for pump down, and one hour for cool down. The thermal cycling test is not a time intensive activity. We plan to perform these tests on all modules.

We will do especially intensive studies of the first ~20 modules to come off the assembly line. This will include bringing them to existing test stands at JPL or Caltech where we can perform cold tests and measure noise temperatures. Cold test stands are also available at collaborating institutions in MPI and KEK. After that, a small fraction of modules will be sent out for cold tests to monitor performance trends throughout production.

Therefore most modules will be operated cold for the first time after they are installed on the receiver, and will not have the starting points for the bias optimization that were provided for Phase-I. However, we feel this is necessary in order to keep the testing effort to a reasonable level, and for the following reasons believe it is adequate for optimizing the modules:

- From Phase-I experience, it is believed that the optimization procedure can work without the starting point, there is just less confidence that the best optimum can be found.

- There were various tests developed in Phase-I to check the noise temperature and bandwidth of modules on the receiver. If these checks can be done at the integration stage, and a module checks out well for both signal-to-noise and bandwidth, it is very likely that the legs are well gain-matched.
- Improvements in module uniformity from the R&D program being conducted at Caltech and JPL should help define better average starting bias settings.
- We will study whether it is possible to predict cold bias settings from warm bias settings. If so, warm settings derived from our test stand can provide good starting points for all modules.

3.5 Summary of Fermilab Cost and Effort for Production Testing

Table 3.1 below captures cost estimates related to developing, constructing, operating, and analyzing the test stand data, for the duration of the production run.

Table 3.1

Cost for Production Testing of W-band Modules						
Material Costs	**Cost Per Item**	**Number Of Items**	**Extended Cost**	**Contingency**	**Contigency ($)**	
Module Testing Hardware: Computers, NI Modules, electronics, Cryocooler, RF equipment, vac chamber.	100000	1	100000	**30%**	**30000**	
Other Labor	**Labor Type**	**Number of FTE-years**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Electrical Testing	EP-II or Electrical Engineer Equivalent (Testing Engineer)	2	339,582	**81.63**	**30%**	101,875
Teststand Assembly Technician	Mechanical Sr. Technician	0.5	61,417	**59.05**	**30%**	18,425
Computing support for teststand and cryostat assembly	Computing Professional	0.5	81,408	**78.28**	**30%**	24,422
Electrical and Mechanical Engineering required for Test Stand Design	Engineer II (average EE and ME)	0.5	91,343	**87.83**	**30%**	27,403
sum			573,750			172,125

4 QUIET Phase-II Receiver Integration Plan at Fermilab

4.1 Introduction

The QUIET Phase-II proposal calls for the deployment of 3 W-band receivers, each containing 499 W-band modules. There is planned to be 3 sites for receiver "integration", with one proposed site being at Fermilab.

The integration work would be primarily a partnership between QUIET collaboration members from the University of Chicago and Fermilab. This document describes the work involved, and outlines a suitable role for each institution. The plan is guided by experience with integrating the Phase-I receiver at the University of Chicago in 2008-2009. A man-power and cost estimate is given for the Fermilab effort.

4.2 Overview of Work

The receiver is defined to consist of the following components:

1. The vacuum vessel and everything contained therein
2. The 20 Kelvin cryocooler system, including the compressors
3. The vacuum pumping system
4. The electronics and the data acquisition computer

Figure 4.1 shows two views of the QUIET Phase-I 91-element W-band 22" diameter cryostat, which is about 5 times smaller than the proposed 42" diameter 499-element Phase-II cryostat. The integration work is defined to include:

1. Receiving all necessary components from the QUIET institutions, and assembling them.
2. Performing tests as necessary to guarantee that the receiver is science-capable.
3. Preparation for shipping the receiver to Atacama, Chile.

The following sections describe the steps in more detail, apart from shipping.

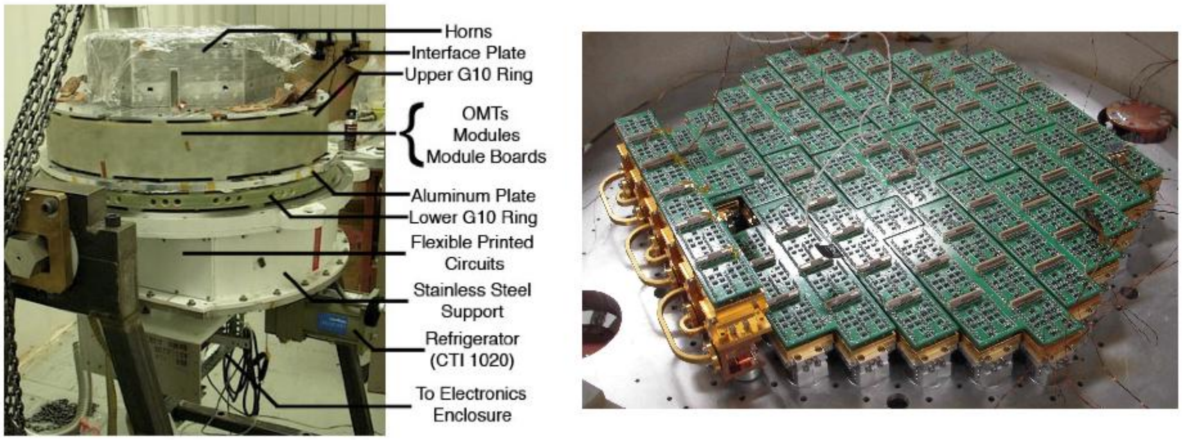

Figure 4.1: Details of the Phase-I 91-element W-band array.

4.3 Location for Integration Work

The integration work would take place in Lab A, part of the Sidet complex at Fermilab. Currently Lab A is being used for assembling the Dark Energy Camera (DECam). The DECam assembly work is expected to complete in advance of the work described here.

The Lab A infrastructure (figure 4.2) includes a 20T crane, a 6' wide x 9' high entrance door for easy transportation of large items by a fork-lift truck, readily available single phase and three phase AC208/240, a building height exceeding 45 feet, and approximately 2000 square feet of usable lab space. Lab A has backup UPS units, and a natural gas backup electrical generator.

The QUIET cryocooler system will use air-cooled compressors, therefore chilled water will not be needed. The cooling system will expel 38 kWatts of heat, which is 2/3 of the Lab A cooling capacity. There will be office space available to house visiting QUIET collaborators. Therefore Lab A would allow the integration work to proceed safely, smoothly, and without requiring large changes to the building infrastructure.

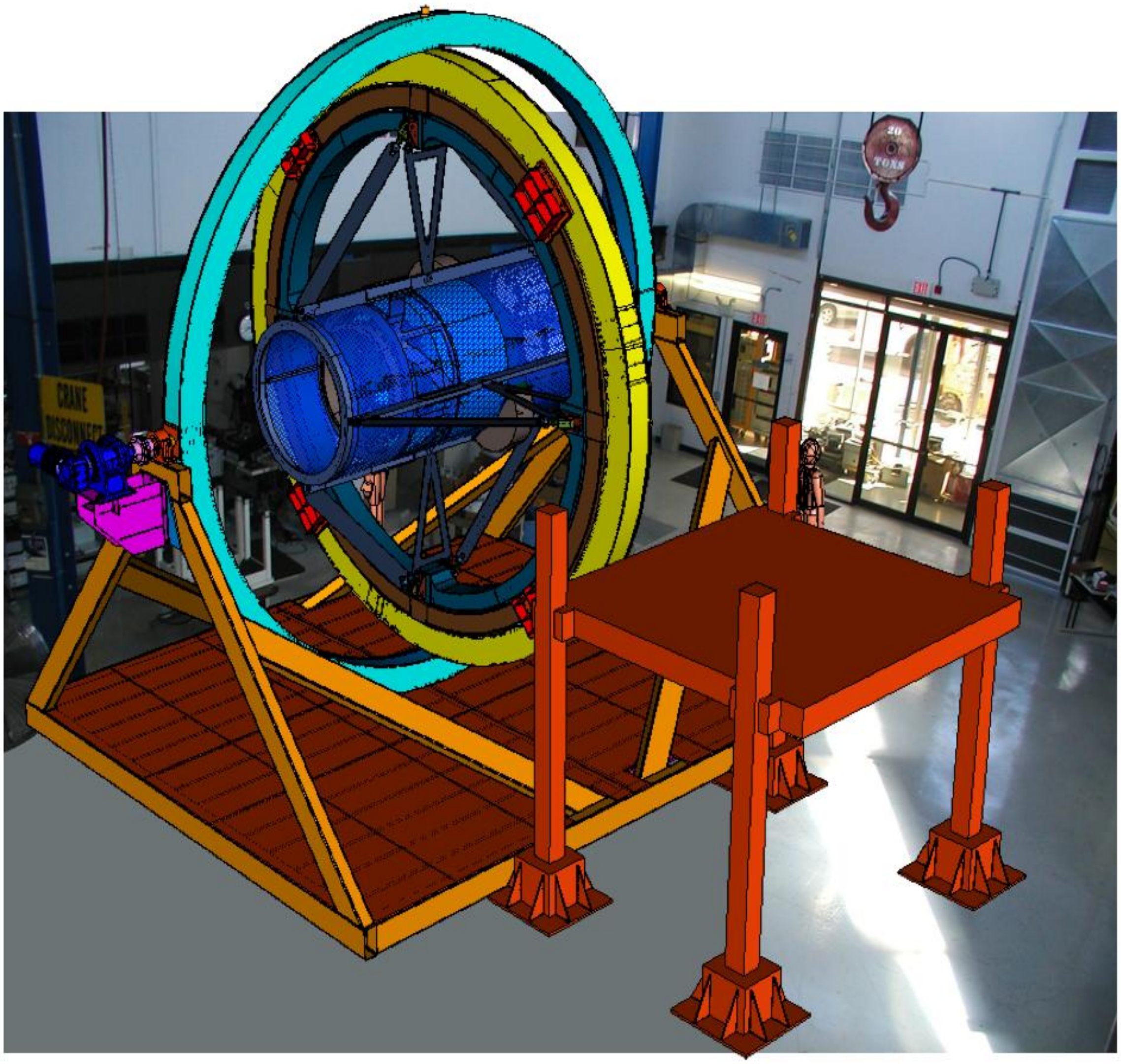

Figure 4.2: The work space in Lab A, and the DECam telescope simulator as it will look in Lab A.

4.4 Receiving and Assembling Components

Table 4.1 shows the detailed list of items that will be received at Lab A.

Table 4.2

Item	Institution Responsible for Delivery to Fermilab	Institution Responsible for Final Assembly
W-band Modules	Fermilab	Fermilab
Electronics, cabling, and DAQ and computer	Chicago and KEK	Chicago
Software for DAQ and Optimization	Chicago and KEK	Chicago
Cryocooler System	Columbia University	Fermilab
Vacuum Pump	Columbia University	Fermilab
Vacuum Tank and	Columbia University	Fermilab

Synthetic Microwave-transparent Window		
Orthomode Transducers (OMT)	Princeton University	Princeton
Flexible printed circuit boards for electrical penetration into vacuum tank	Princeton University	Princeton
Microwave Horn Platelet Array	University of Miami	Miami

There are three major subsystems: the vacuum vessel and window, the cryocooler system, and the detector array, which is housed inside the vacuum vessel and cooled to 20 K.

The detector array is 7 subarrays arranged in a flower pattern: 6 subarrays of 68 modules surrounding a center subarray of 91 modules (see figure 4.3). Each subarray (figure 4.4) consists of the platelet feed horn system, the OMTs, the W-band modules, and the Module Assembly Boards (MABs), which provide power, protection, and signal connections to the W-band modules. The cooling of the detector array will be achieved by copper-braid attachment from the coldheads to the interface plate of the platelet horn system. It is envisioned that the 91-module center subarray be reused from Phase-I.

We expect the assembly task to occur coincidentally with production. In other words, the assembly task will commence before completed delivery of all items, as the items will have a finite production delivery schedule.

The assembly task will also occur in between the testing steps (described below). This guarantees that problems are caught and fixed before proceeding to the next assembly step. Fermilab would be responsible for mechanical assembly (ie. Vacuum tank, cryocooler, pump) , and would provide mechanical technicians for these tasks using existing tools in Lab A. Fermilab would provide a stand to hold the vessel in a manner for safe and easy work access. This will likely require modest mechanical engineering to perform the stress calculations.

Instructions for vacuum vessel, cryocooler, and platelet assembly would be provided by Columbia, Princeton, and Miami. No specialty equipment or tasks, such as welding or machining is expected. Fermilab technicians will handle crane and fork-lift truck operations, equipment storage, and cleanup.

Fermilab staff will perform “Job Hazard Analysis” if deemed necessary. The University of Chicago would provide personnel to assemble electronics and cabling, DAQ, and computing. Fermilab QUIET scientist will handle interfacing the computers to the lab’s network.

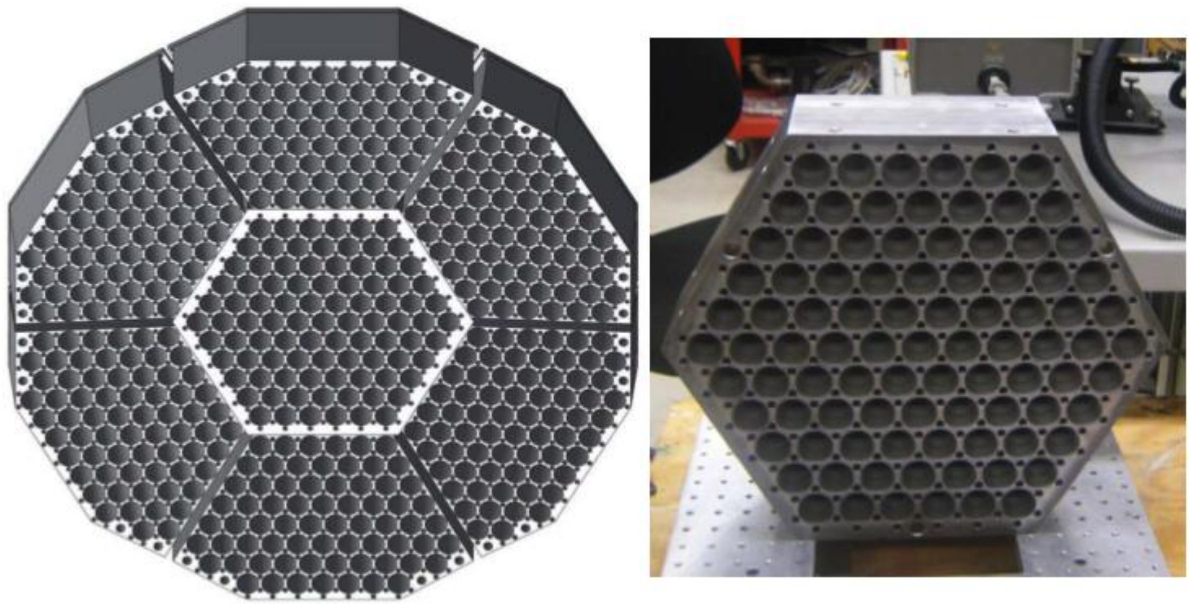

Figure 4.3: Horn Platelet Array for 499 elements (left) and the center 91 element (right). The width is approximately 40”.

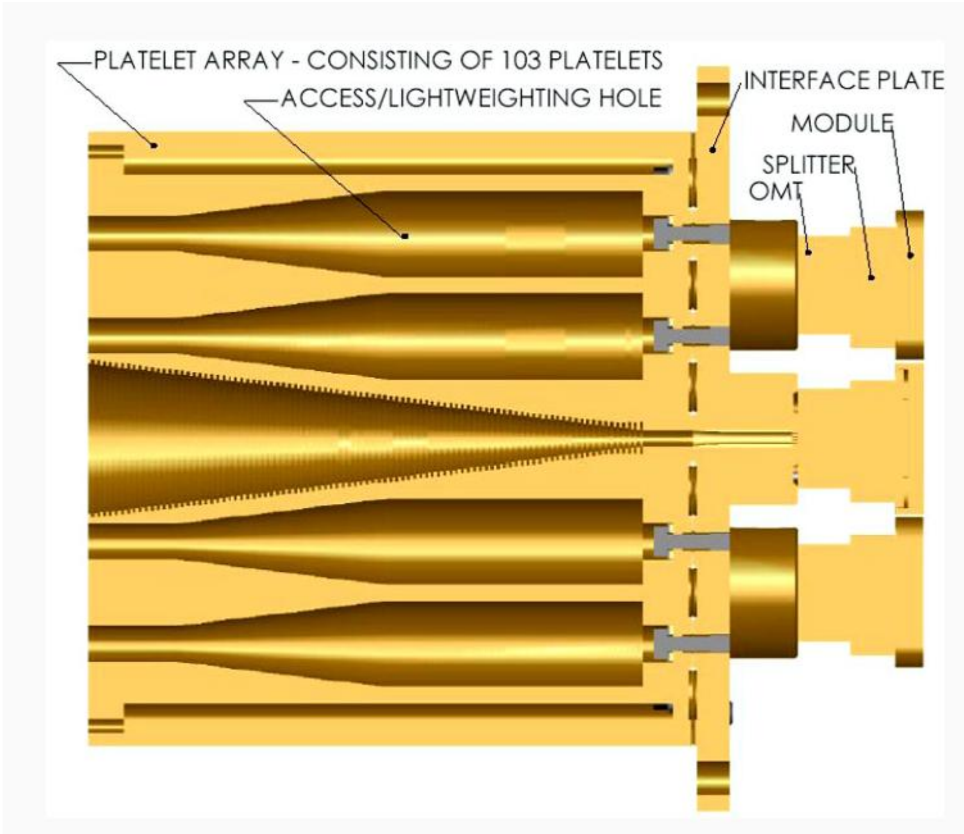

Figure 4.4: Detector detail. The Module Array Boards are not shown, but would attach directly to the module (right hand side of figure).

Figure 4.5 shows the assembly and testing steps. Assembly steps are shown in rectangles. Testing steps are shown in ovals. The assembly revolves around installing 7 subarrays (either 68-element or 91-element), one after the other in a sequential fashion. This minimizes the number of mechanical operations performed on the (very delicate) modules, MAB, and cables.

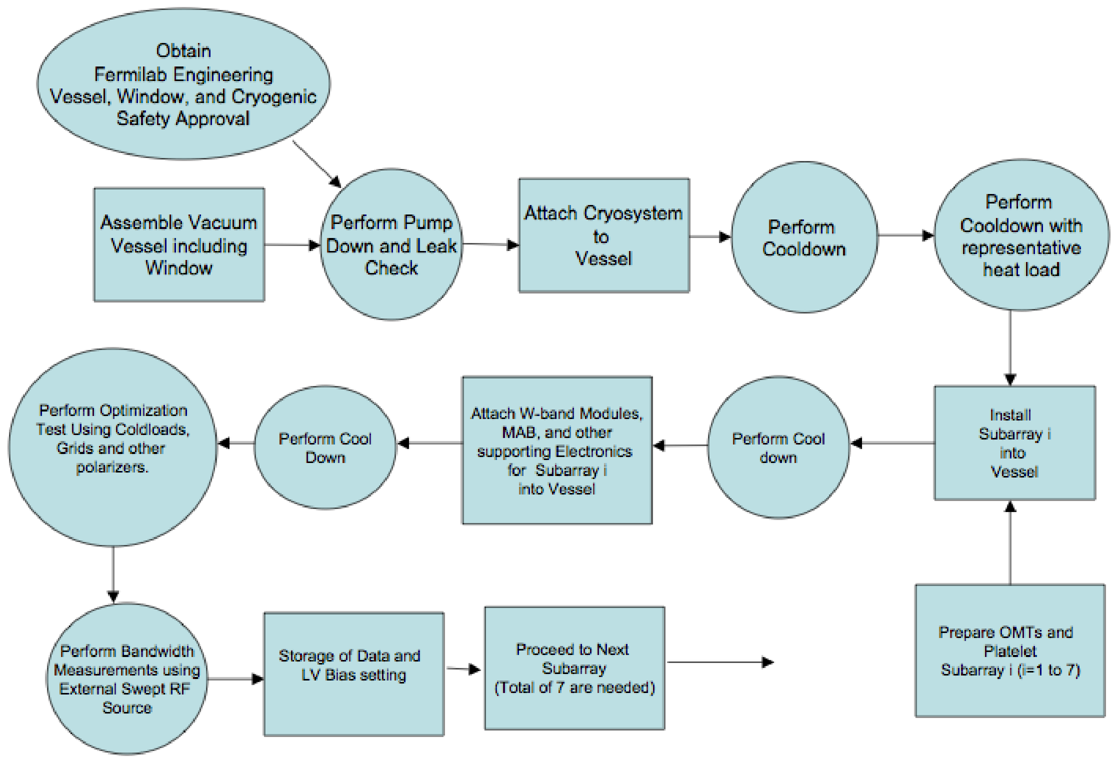

Figure 4.5: Assembly and Testing Steps of a QUIET W-band Receiver.

4.5 Performing Tests to Guarantee a Science-Capable Receiver

Fermilab "Operational Readiness Clearance" will be needed prior to operation. This will require a safety review of the window, the vacuum vessel, and the cryogenics. A QUIET Fermilab scientist will be responsible for obtaining lab approval. The FEA and long term studies of the window material, made of ultrahigh molecular weight polyethylene, is already under way at the lab.

The first step is to test the assembled vacuum vessel and cryocooler system, in the absence of RF components and electronics. Fermilab mechanical technicians will test the vessel for vacuum leaks. This is a non-trivial step, as the vessel has many vacuum penetrations that need to be checked. Following this, the cryocooler system will be tested using heaters to verify the required cooling capacity.

After installation of a subarray, another vacuum pumping and cool down cycle would be performed. Fermilab technicians will repair leaks as they arise using readily available leak checking equipment at Sidet.

A critical test is to "optimize" the modules while at 20 Kelvin operation. At this stage, the modules have already been verified to have good electrical connections during the production testing task (see production testing plan). The test will:

- verify the end-to-end electrical connection from the modules, through the vacuum interfaces, to electronics external to the cryostat.
- verify that the LV power consumption of the modules meet specifications.
- verify that the modules, operated with nominal LV settings, can detect a signal from a cold load whose polarized signal is modulated in time.
- determine the LV settings that optimize the modules' polarized signal sensitivity.
- verify that the resultant optimized modules meet specifications in signal sensitivity, white and 1/f noise frequency profiles, and noise temperature.
- using an RF signal generator, verify that the optimized modules have the required input bandwidth sensitivity in the W-band.

The cold load used for the optimization will be the one Fermilab built for QUIET Phase 1. Fermilab would provide the rotatable wiregrid used to polarize the load and modulate electric fields. The items are shown in figure 4.6.

The University of Chicago would be responsible for the optimization testing, which includes assembly of the FE and DAQ hardware, and providing software and analysis tools. Assuming that polarized signals are seen by the modules, the software automatically adjusts the LV settings to optimize the performance. All data and LV settings will be recorded. In Phase I, the LV settings were found within about 8 hours of running. Figure 4.7 shows the output of such an optimization run.

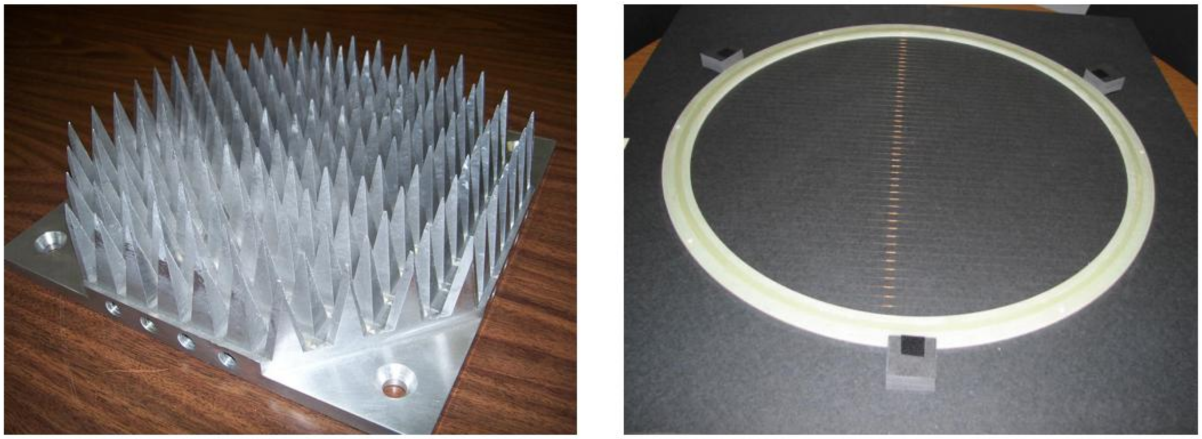

Figure 4.6: The black body load and 24” diameter grid built for QUIET Phase-I. The black body load would be housed in a vacuum vessel and cryostat, also built for Phase-I.

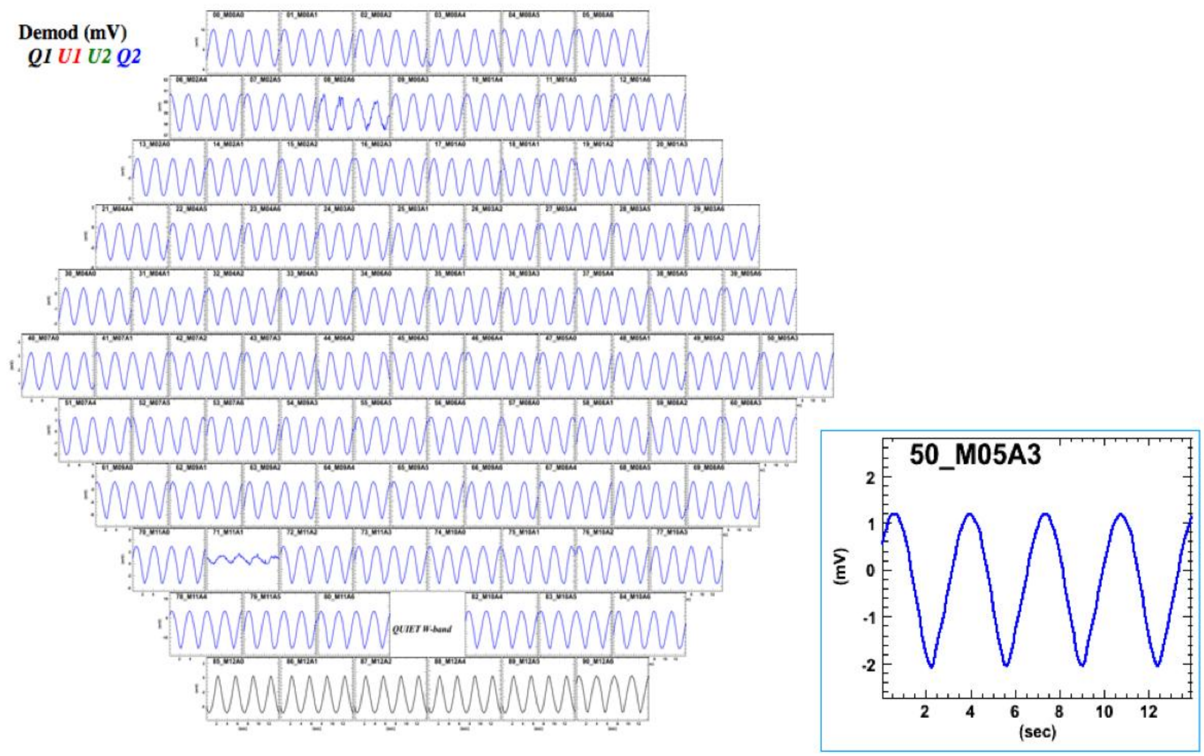

Figure 4.7: An optimization run of the Phase-I 91-element array. The array views a 77K black body load, seen through the grid shown in figure 4.6. The grid imposes approximately 2K of temperature polarization. The grid rotates at constant angular frequency of about 0.15 Hz.

We determine all the module performance features and then at the end, we decide which ones need further work. This strategy minimizes the mechanical operations done to the receiver.

An important outcome of this test is the overall array sensitivity. This together with the band passes for each detector found with the sweeper will give us all the important characteristics to predict performance on the sky.

4.6 A Collaborative Effort

This document has outlined suitable roles for the University of Chicago and Fermilab. However, we emphasize that this is a collaborative effort. The collaborators would naturally be expected to become experts in all aspects of the assembly and testing.

Additional collaborators from outside of Chicago and Fermilab may also chose to participate in the integration effort at Fermilab. The integration work is important training ground for the collaboration. Experience in Phase I has shown the importance of building a strong technical base within the collaboration, in order to provide good expertise coverage at the Chile site.

4.7 Summary of Fermilab Manpower Requirements and Costs for Receiver Integration

For the Phase-I integration work, the cost of material and services purchases was at the $50K level. The integration work included constructing the mechanical assembly for cable penetration through the vacuum vessel, purchasing additional cables and connectors, and cable plant organization. This was at the $10K level.

The integration work also included the cost of thermal regulation electronics (silicon diode thermometers) and miscellaneous vacuum equipment (pressure and humidity gauges). There were small additional costs for purchasing more spare consumable parts for the vacuum vessel (O-rings, Indium) and platelet array system (specialty screws).

The QUIET Phase I array optimizer cost exceeded $10K. This includes Eccosorb foam for use in making cryogenic loads, Styrofoam and Zotefoam insulation, and motorized rotatable mechanical plates. The cost of the rotatable wiregrid assembly built by Fermilab using US/Japan funding, was about $5K. Finally, the cost of dry air, LN2, LAr, and helium was about $300/week.

For Phase-II, we can expect some of these costs to be moved to the subsystems costs, rather than integration. However, we will include comparable costs for thermometry, cabling, and miscellaneous hardware.

There is additional relief by reusing components from Phase-I. In particular, we will use the existing 20 Kelvin load already at Fermilab. This is driven by a cryocooler, and so there is no significant cost for LN2, LAr, and dry air needed to prevent window frosting. It also simplifies the lab-required safety analysis, since there is no significant ODH (oxygen deficiency hazard) concerns with using cryocoolers.

Finally, we expect only incidental use of dry air, N2, LN2, and LAr. These costs as well as electrical power are typically provided by internal building infrastructure funding, and not charged to projects.

Table 4.2 summarizes the major items required from Fermilab for Phase II. The material and services costs appear comparable. However, the services work (light duty tech-shop machining) that was performed and paid explicitly for Phase I, now appear under general mechanical technician labor to be provided by the lab.

Table 4.3: Request to Fermilab for Phase II Receiver Integration

Use of Lab A Infrastructure and office space for QUIET collaborators. Occupancy of Lab A is expected to last 2 years. Existing equipment include dry vacuum roughing and turbo molecular pumps, dry leak checker, miscellaneous vacuum hardware from previous projects, UPS units, and a natural gas backup generator. Incidental usage of LN2, N2, He, and electrical usage are typically not charged to the project. These costs are not included here.	
Cold Black Body Load miscellaneous work.	$ 5K
42" rotatable wiregrid assembly	$ 5K
Cryostat Support Stand Engineering Design	1 month FTE (needed mainly for stress calculations)
Cryostat Support Stand Fabrication	$ 5K
Technician for Mechanical Assembly	6 months FTE
Operational Readiness Clearance by Lab Mechanical Engineering	5 months FTE
Thermometry	$10K
Cabling	$10K
Miscellaneous Hardware	$10K

5 Summary of Total Costs

In this section, we present again the costs presented in sections 2, 3, and 4. We also include travel to the site for shifts and collaboration meetings. Finally, we add the requested contribution to site construction (2 years) and operations (3 years). The site costs are distributed amongst the collaborating institutions. The proposed site cost is $50K annually per non-NSF supported institution.

Our estimate is a project cost of $1.35M and $0.42M contingency. Our operations cost estimate is $198K, over a 3 year running period. The costs do not include salaries of Fermilab scientists or postdocs.

Table 5.1a Cost Estimate Summary.

Material Costs	**Cost Per Item**	**Number Of Items**	**Extended Cost**	**Contingency**	**Contigency ($)**	
Rotary Stage	1411	4	5644	**30%**	**1693.2**	
Linear Stage	1471	8	11768	**30%**	**3530.4**	
Motor Controller	800	12	9600	**30%**	**2880**	
Vacuum Pickup Tools	100	23	2300	**30%**	**690**	
Custom Carriage Trays	100	10	1000	**30%**	**300**	
Miscellaneous Tooling	10000	1	10000	**30%**	**3000**	
Module Testing Hardware: Computers, NI Modules, electronics, Cryocooler, RF equipment, vac chamber.	100000	1	100000	**30%**	**30000**	
Receiver Integration Costs: thermometry, black body load, wiregrid, miscellaneous mechanical assemblies	45000	1	45000	**30%**	**13500**	
Sum			185312		55593.6	
Labor Cost for Developing Tooling	**Number of Weeks**	**Personnel**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Labview Programming	20	Computing Professional	62,624	**78.28**	**50%**	31312
Zeiss Programming	4	Senior Technician	9448	**59.05**	**50%**	4724
Labor to build tooling	10	Senior Technician	23,620	**59.05**	**50%**	11,810
Sum			95,692			47846
Labor Cost for W-band Assembly	**Labor Type**	**Number of Hours**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Wirebonding	Sr. Tech	1200	70860	**59.05**	**30%**	21258
Assembly	Technician-II	500	23375	**46.75**	**50%**	11687.5
Inspection and Organization	Technical Supervisor	1600	130880	**81.8**	**50%**	65440
Sum			225115			98385.5

Table 5.1b Cost Estimate Summary, Continued.

Other non-scientist Labor	Labor Type	Number of FTE-years	Extended Cost	Hr Rate	Contingency	Contingency (dollars)
Electrical Testing	EP-II or Electrical Engineer Equivalent (Testing Engineer)	2	339,582	**81.63**	**30%**	101,875
Teststand Assembly Technician	Mechanical Sr. Technician	0.5	61,417	**59.05**	**30%**	18,425
Computing support for teststand and cryostat assembly	Computing Professional	0.5	81,408	**78.28**	**30%**	24,422
Electrical and Mechanical Engineering required for Test Stand Design	Engineer II (average EE and ME)	0.5	91,343	**87.83**	**30%**	27,403
Cryostat assembly technician for Receiver Integration	Mechanical Tech Specialist	0.5	74661.6	**71.79**	**30%**	22398.48
Mechanical Engineering required for safety approval of Receiver Operation and misc.	Engineer II (average EE and ME)	0.5	91,343	**87.83**	**30%**	27402.9
sum			739,754			221,926
		Total Labor	1,060,561		**Total Labor Contingency**	368158
Other Costs	**Project or Operations**	**Annual Cost**	**Number of Years**	**Extended Cost**		
Contribution to Site Construction	Project	50000	2	**100000**		
Travel to JPL. 3 trips per year. 2K per trip per person	Project	6000	2	**12000**		
4 weeks of travel to Chile per Year. Cost is 5K per 2 weeks per person.	Operations	10000	3	**30000**		
Contribution to Site Operations	Operations	50000	3	**150000**		
Collaboration meeting trips. 1 meetings per year. 3 people. 2K per trip per person.	Operations	6000	3	**18000**		
Sum				**310000**		
Summary of All Project Costs		**Base**	**Contingency**			
Materials and Services		185312	55593.6			
All Non Scientist Labor		1,060,561	368158			
Other Costs (project)		112000	0			
Other Costs (operations)		198000	0			
Grand Sum		**1555873.1**	**423751.33**	**1979624.43**		
Grand Sum for Project Only		**1357873.1**	**423751.33**	**1781624.43**		