*LIGO Laboratory / LIGO Scientific Collaboration*

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Suspensions Acceptance Documentation:

Test Mass Quadruple Suspension (ETM/ITM)

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# Introduction

The DCC tree for suspensions (SUS) documentation starts at [E1200482](https://dcc.ligo.org/LIGO-E1200482-x0): aLIGO, SUS. From that top-level DCC page the related documents appropriate to this type of suspension are

[E1200933](https://dcc.ligo.org/LIGO-E1200933https:/dcc.ligo.org/LIGO-E1200933): aLIGO SUS General Documentation

[E1100290](https://dcc.ligo.org/LIGO-E1100290https:/dcc.ligo.org/LIGO-E1100290): aLIGO SUS QUAD Assembly and Installation Documentation

[E1000495](https://dcc.ligo.org/LIGO-E1000495): aLIGO SUS QUAD Testing and Commissioning Documentation

[E1201038](https://dcc.ligo.org/LIGO-E1201038): aLIGO SUS QUAD Acceptance Documentation

The SUS electronics documentation tree is found by following the path

[E1200482](https://dcc.ligo.org/LIGO-E1200482-x0): aLIGO, SUS

> [E1200933](https://dcc.ligo.org/LIGO-E1200933-x0): aLIGO SUS General Documentation

> [E1100337](https://dcc.ligo.org/LIGO-E1100337-v2): Suspension Electronics Drawing Tree

In sections 1 to 10 below we address the 10 items as sited in the Acceptance Review template E1300457-v3 with information appropriate to all quad suspensions. Individual suspensions will have their own acceptance documentation, to be found from the filecard for this document (i.e. from E1201038) going to related documents, and then following the link to [E1201044](https://dcc.ligo.org/LIGO-E1201044-x0) aLIGO SUS Quad Individual Acceptance Reports.

# Requirements documentation

*The design requirements document must be brought up to date, and pointers to background material, analyses, etc. added to the Requirements document. Pointers to prototyping endeavors including testing results if they are not superseded by subsequent testing should be included here.*

*a. Design Requirements Document (DRD)*

[T010007](https://dcc.ligo.org/LIGO-T010007) Cavity Optics Suspension Subsystem Design Requirements

[T060067](https://dcc.ligo.org/LIGO-T060067) AdL Quad Suspension UK Coil Driver Design Requirements

*b. Supporting documents (models, analyses, …)*

# Design overview and detailed design documentation

*a) Final Design Document (FDD): must bring the FDD up to date.*

[T1000286](https://dcc.ligo.org/LIGO-T1000286) aLIGO Quadruple Suspension (QUAD) Final Design Document

[T1000337](https://dcc.ligo.org/LIGO-T1000337) Quadruple Suspension Monolithic Stage Final Design

*b) Review reports:*

*- cite the final design review committee's report*

*- cite the design team's response to the final design review (note that any resulting changes to the design should have been incorporated into the FDD).*

[T1200463](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=96948): Summary of Suspension Final Design Reviews, of which items 1, 2, 3, 4, 5, 6, 7, 8, 15, 16, 17, 18 and 20 are quad related. References to the reports for each of these reviews are given in this summary document.

*c) Supporting design documents: models, analyses, specifications, etc. If not applicable, then state so.*

[E1200933](https://dcc.ligo.org/LIGO-E1200933-x0): aLIGO SUS General Documentation: this DCC filecard lists references to aLIGO SUS documentation that this generic to many or all suspensions.

[E1300848](https://dcc.ligo.org/LIGO-E1300848) aLIGO SUS QUAD ESD Documentation. This DCC filecard brings together various documents (mechanical, technical, cabling) addressing aspects of the ESD design.

[T1100595](https://dcc.ligo.org/LIGO-T1100595) ETM/ITM Quad Suspension Control Ranges

[G1300537](https://dcc.ligo.org/LIGO-G1300537) aLIGO QUAD "Level 2" Damping Loop Design

[T1100185](https://dcc.ligo.org/LIGO-T1100185): Summary of technical documentation for University of Birmingham deliverables

[E1100337](https://dcc.ligo.org/LIGO-E1100337-v2): Suspension Electronics Drawing Tree: this leads to electronics documentation.

Also for electronics, the following link is to a wiki in which information on requirements, sensor and actuator electronics chains and wiring diagrams for all suspensions are linked:

https://awiki.ligo-wa.caltech.edu/aLIGO/SuspensionElectronics

See also links at [E1100604](https://dcc.ligo.org/LIGO-E1100604) aLIGO SUS Quad Design Documentation

Further info on modeling is found on the SVN, see section 8.

*d) Drawings: cite the top level assembly drawing for each major assembly or subsystem. In the DCC, all subsidiary drawings (sub-assemblies and part drawings) must be linked in a drawing tree manner.*

[D0901346](https://dcc.ligo.org/LIGO-D0901346) Advanced LIGO Quadruple Suspension Assembly

[D1000759](https://dcc.ligo.org/LIGO-D1000759) Advanced LIGO SUS ETM Production Monolithic Assembly

*e) Bill(s) of Materials (BOM): cite any collected BOMs. If the BOMs are only to be found on the Assembly and Sub-Assembly drawing sheets, then state so.*

These are found on the relevant drawings.

*f) Interface control: cite any documents (such as RODAs) with interface definition/control and/or cite the relevant sections of the DRD and FDD.*

Relevant RODAs:

[M040005](https://dcc.ligo.org/LIGO-M040005) Record of Decision/Agreement (RODA) - CP to be the Ultimate Mass in the ITM Reaction Chain

[M040020](https://dcc.ligo.org/LIGO-M040020-x0) Record of Decision/Agreement (RODA) - Sapphire/fused silica downselect date

[M040099](https://dcc.ligo.org/LIGO-M040099) Record of Decision/Agreement (RODA) - Decision on ETM/ITM Quad Pendulum Structure Length

[M040135](https://dcc.ligo.org/LIGO-M040135) Record of Decision/Agreement (RODA) - Detailed Scope of Work on Advanced LIGO by the UK AdL Team

[M050397](https://dcc.ligo.org/LIGO-M050397) Record of Decision/Agreement (RODA) - Core Optic sizes, including TMs, BS, FM and RM

[M050418](https://dcc.ligo.org/LIGO-M050418) Record of Decision/Agreement (RODA) - Separation of chains in quad suspensions

M060305 Record of Decision/Agreement (RODA) - Compensation Plate dimensions

This is out of date. Garilynn confirmed it is on her to-do list to address.

[M060043](https://dcc.ligo.org/LIGO-M060043) Record of Decision/Agreement (RODA) - Determine Need for OSEM Sensors for UIM and PUM in the ETM and ITM and Determine Need for OSEM Cable Electrical Shielding

[M080109](https://dcc.ligo.org/LIGO-M080109) No Fibre Pulling Machine for Adv LIGO at LLO

[M080134](https://dcc.ligo.org/LIGO-M080134) E/ITM and BS/FM pitch frequencies and d-values

[M080363](https://dcc.ligo.org/LIGO-M080363) Record of Decision/Agreement (RODA) - ETM/ITM suspensions will use tapered circular cross-section silica fibres

[M0900034](https://dcc.ligo.org/LIGO-M0900034) Use of SmCo and NdFeB Magnets in Advanced LIGO Suspensions

[M0900087](https://dcc.ligo.org/LIGO-M0900087) All in vacuum cabling will be shielded

[M0900271](https://dcc.ligo.org/LIGO-M0900271) Division of Responsibilities for Harnesses for Adv. LIGO Suspensions

[M0900293](https://dcc.ligo.org/LIGO-M0900293) Delivery of Electrostatic Drivers from UK

[M1000312](https://dcc.ligo.org/LIGO-M1000312) Use of SS 316 in AOSEMs and BOSEMs

[M1100053](https://dcc.ligo.org/LIGO-M1100053) RODA to reserve real estate for ACD on ETM / ITM optic and associated parent assemblies

[M1100256](https://dcc.ligo.org/LIGO-M1100256) Suspension Earthquake Stops to be Set at 0.75 mm

[M1200147](https://dcc.ligo.org/LIGO-M1200147) RODA: Removal of eddy current damping magnets in various suspensions.

Also see technical review board decision on use of thin CP:

[T1000175](https://dcc.ligo.org/LIGO-T1000175) Thinner Compensation Plates for reduced Squeeze film damping

*g) Software: cite any software design description documentation. If not applicable, or not available, then state so.*

Software is documented on the SVN, see section 8.

*h) Design source data:*

*- Confirm that all mechanical design CAD models are in the SolidWorks/PDMWorks vault, or explain what is not and why.*

Mechanical CAD models are in PDM works.

*- Confirm that all electronics design CAD models (schematics and PWB layouts) are backed up and available on LIGO Lab archives, or explain what is not and why.*

Electronics CAD models are available on the DCC.

# Materials and fabrication specification

*Any special materials, or treatment of materials including preparation for in-vacuum use; this may be integrated into the Design documentation.*

The process used for manufacturing maraging steel blades is given in [E0900023](https://dcc.ligo.org/LIGO-E0900023). Producing acceptable blades is a complex multi-step process which has been developed from external input and internal experience with prototypes over several years.

Particular materials and processes for monolithic parts such as ears and fibres are called out on the relevant drawings.

# Parts and in process spares inventoried

*All elements of aLIGO must be recorded in the ICS or in the DCC using the S-number scheme. As-built modifications for parts or assemblies should be found here.*

Assemblies are recorded in ICS. Individual spare mechanical parts which have gone through clean and bake are in general recorded in ICS. In some cases spare sub-assemblies have been put together but not yet recorded as such. Electronics are recorded using the S-number scheme. A separate document has been prepared which summarises storing of spare parts, see T1300908.

# Assembly procedures

*All assembly procedures must be in the DCC and annotated or updated for lessons learned. Storage, if used, should be described here along with procedures to maintain the equipment in good condition (e.g., purge frequency). Transportation procedures and cautions must be noted.*

[E1000006](https://dcc.ligo.org/LIGO-E1000006) Advanced LIGO Quad Suspension Metal-Build Assembly Procedure

[T1000521](https://dcc.ligo.org/LIGO-T1000521) Monolithic Final Design Review Documentation and Drawing Overview

[E1000366](https://dcc.ligo.org/LIGO-E1000366) QUAD Monolithic Fiber Pulling/Welding Procedure

# Installation procedures

*All installation procedures must be in the DCC and annotated or updated for lessons learned.*

[T1100406](https://dcc.ligo.org/LIGO-T1100406): Quad cartridge installation procedure check list

Chamber installation procedures are also used. These are specific to a chamber and thus will be referenced in the acceptance documentation for specific suspensions.

# Test documents

*Test rationale, plans, and data for each unit must be documented as described in M1000211. That tree structure should be pointed to by the overall tree structure laid out in this Acceptance prescription. The top-level objective is to make clear how the measurements performed, which often will not directly measure a required performance parameter, give confidence that the subsystem will fulfill the requirements.*

**7.1 Suspension testing**

[G1100693](https://dcc.ligo.org/LIGO-G1100693): Ideal Order/Contents of aLIGO QUAD Testing / Commissioning

This is the top level description of testing.

A useful link for key testing procedures is the Checkout/Testing page in the Operation Manual at

<https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/Testing>

Testing related documentation is kept on the SVN repository at

<https://redoubt.ligo-wa.caltech.edu/websvn/>

The "SUS" svn, linked from the above site contains:-

(a) Suspensions models (Mathematica & Matlab, Damping Filter Design)

(b) Testing tools (DTT templates & Matlab Testing Scripts)

(c) Results from all testing Phases 1-3 (i.e. Transfer Functions (TFs), Power Spectra & B&K)

The measurement list for all quads is found by following the route as shown below

"sus" -> "trunk" -> QUAD -> "Common" -> "MatlabTools" -> plotallquad\_tfs.m

This gives TFs. Other types of results are found in a similar way.

Key test results for each individual suspension are linked from the DCC filecard for the acceptance documentation for that suspension.

In addition to TFs, spectra and B&K results, which are found on the SVN, the following results which are called out under phase 1 testing in G1100693 can be found on the DCC (or as noted) as follows:

a) [T1000068](https://dcc.ligo.org/LIGO-T1000068): aLIGO Quad blade and clamp pairing and characterization data

b) Vibration Absorber Test Reports [E1101122](https://dcc.ligo.org/LIGO-E1101122), and the testing procedure, described in [E1200009](https://dcc.ligo.org/LIGO-E1200009).

c) OSEM inventory with open light current data, [E1200343](https://dcc.ligo.org/LIGO-E1200343) (continually being updated as builds proceed)

d) AOSEM Pre-Bake Test Data [E1000417](https://dcc.ligo.org/LIGO-E1000417) (includes coil resistance and inductance)

e) AOSEM Electronic Noise Test Data [E1101030](https://dcc.ligo.org/LIGO-E1101030)

f) BOSEM test data, [T0900496](https://dcc.ligo.org/LIGO-T0900496)

BOSEM and AOSEM test data are also archived on the SVN at

WebSVN link:-

https://redoubt.ligo-wa.caltech.edu/websvn/listing.php?repname=sus&path=%2Ftrunk%2Felectronicstesting%2FAOSEM%2F&#a44646e7e36d81f2cf1e45386c48e2dda

and

https://redoubt.ligo-wa.caltech.edu/websvn/listing.php?repname=sus&path=%2Ftrunk%2Felectronicstesting%2FBOSEM%2F&#aac680895873bf8fd434d4adf1cffdf72

g) Confirmation of magnet strengths within +/-5%. This requirement was developed after the purchase of the magnets to be used in the quads. Hence checks were made on the purchased magnets. See “Information on Magnets for BSC Suspensions”, [T1000618](https://dcc.ligo.org/LIGO-T1000618), and references therein for details of these checks and the procedures followed to choose magnets for use in the suspensions.

h) Information on as-built alignment/positioning of suspensions is captured in alog entries.

**7.2 Electronics testing**

The results of the reports are posted in the DCC, under the serial number of the chassis, e.g.

<https://dcc.ligo.org/LIGO-S1000254-v6>

These can be found for LLO by following through the electronics tree, an example of which is given here:

E1100337 - Suspension Electronics Drawing Tree

> S1200522 - LLO Suspension Electronics Racks

A similar structure for LHO is TBC at time of writing.

# User interface software

*User interface software, and the test routines indicating proper functioning of the software, must be described in words and have code under configuration control (SVN). Watchdog and Guardian routines must also be treated in this way.*

Each suspension has a user model that is constructed referencing wiring diagrams, built and installed, which runs on a front-end computer. MEDM screens are created to present an operator with model information and enable interaction with a running model. Filter coefficients, gains and other settings can be captured using BURT snapshots, which also provide a safe state to revert to following model restarts e.g. due to power loss etc, as well as retaining alignment offsets for the suspension. All of the aforementioned items; Simulink models, MEDM screens, BURT snapshots, and filter coefficients are maintained under svn revision control. For example, the "cds\_user\_apps" contains:-

(a) SUS Simulink front-end models, located at

- LHO *${userapps}/sus/h1/models/*

*-* LLO *${userapps}/sus/l1/models/*

Guide:- <https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/Simulink>

(b) BURT snapshots of model configurations (SAFE, ALIGNED, MISALIGNED etc), located at

- LHO *${userapps}/sus/h1/burtfiles/*

*-* LLO *${userapps}/sus/l1/burtfiles/*

Guide:- <https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/BURT>

(c) FOTON filter blocks deployed in front-end models, located at

- LHO *${userapps}/sus/h1/filterfiles/*

*-* LLO *${userapps}/sus/l1/filterfiles /*

Guide:- <https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/FOTON>

(d) MEDM screens for interacting visually with front-end models, located at

- LHO *${userapps}/sus/h1/medm/*

*-* LLO *${userapps}/sus/l1/medm /*

Guide:- <https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/MEDM>

(e) Scripts to automating processes, interact with suspensions and saving alignments etc, located at

- *${userapps}/sus/common/scripts/*

Guide:- <https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/PythonTools>

Other useful links,

<https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/Computing> (overall cds guide)

<https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual/SVN> (svn guide)

<https://redoubt.ligo-wa.caltech.edu/websvn/listing.php?repname=cds_user_apps> (websvn GUI)

<https://redoubt.ligo-wa.caltech.edu/svn/cds_user_apps/> (websvn html interface)

Links to html interfaces for snapshots of currently running Simulink models at each site,

LHO <https://lhocds.ligo-wa.caltech.edu/simlink/>

LLO <https://llocds.ligo-la.caltech.edu/daq/simlink/>

# Operation Manual

*A manual appropriate for operators, written in accordance with M1200366, covering setup/initialization, check-out, operating instructions, calibration, maintenance, storage/transport and troubleshooting. It must be accessible from standard user screens.*

[E1200633](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=93052): aLIGO SUS Operation Manual.

Note that this covers quads and triple suspensions due to the large element of commonality between suspensions.

There is also a “rogues gallery” to aid in troubleshooting transfer functions, called “TransferFunctionColoringBook”. It is located on the aLIGO wiki at

<https://awiki.ligo-wa.caltech.edu/aLIGO/TransferFunctionColoringBook>

# Safety

*Safety documentation must be in the DCC for all phases of the subsystem development, including any needed for normal use or foreseen maintenance/repair scenarios.*

[E1000030](https://dcc.ligo.org/LIGO-E1000030) QUAD Suspension Metal Assembly Hazard Analysis

[M1000334](https://dcc.ligo.org/LIGO-M1000334) LHO\_CO2 Silica Fiber Welding Machine Operating in the LVEAs and END Station, Standard Operating Procedure

[E1100814](https://dcc.ligo.org/LIGO-E1100814) Cartridge Assembly Hazard Analysis

[E1200925](https://dcc.ligo.org/LIGO-E1200925) BSC Cartridge Installation (Universal) Hazard Analysis, aLIGO

[E1000489](https://dcc.ligo.org/LIGO-E1000489) Hazard Analysis for Silica Fiber Pulling and Welding In the LHO Fiber Lab and In the LHO and LLO LVEAs and VEAs

[T080231](https://dcc.ligo.org/LIGO-T080231) ERGO Arm Hazard Analysis