LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-E1900261-v6 *A+ Project* 10/18/2019

LIGO A+ Facility Modification Specification

A+ Facilities Team (M. Zucker, ed.)

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1 Introduction and General Description

The *A+ Upgrade to Advanced LIGO* (A+) is a U.S. National Science Foundation (NSF) initiative to enhance sensitivity of the Advanced LIGO gravitational wave detector systems, which are operated by Caltech and MIT at the Hanford, Washington and Livingston, Louisiana LIGO sites.

The upgrade will include installation at each site of an additional optical *filter cavity* (FC), 300 meters in length, to support *frequency-dependent squeezing* (FDS), a new technique for reducing the quantum uncertainty that limits each detector's observing horizon.

The FC systems require new optics, supporting vibration isolation and suspension systems, and a new 300m laser beam path, all of which will be maintained under high vacuum. The requisite vacuum chambers and beamtubes will extend the existing LIGO vacuum envelope. To accommodate this expansion, this project will

a) modify existing LIGO buildings, and

b) develop new enclosed spaces on previously undeveloped parts of each site.

This document is based upon and supersedes LIGO-T1800395, *A+ Project Facilities Modification Design Requirements Document*. Any reference to that prior document is provided exclusively for historical context.

1.1 Scope of work

The new FC vacuum system is shown in Figure 1, overlaid on a portion of the Livingston site plan. The Hanford layout is similar. A portion of the new equipment is housed within the existing LIGO corner station *Laser and Vacuum Equipment Area* (LVEA), shown circled. Another section of the new FC beamtube (designated FC-C), which is approximately 10 inches in diameter, will continue outside this existing building for approximately 755 feet to join a new vacuum chamber designated HAM8 (*Horizontal-Axis Module #8*). The tube extension and new chamber will occupy previously unimproved portions of the observatory site.

The scope of construction thus comprises four components:

1) Modify each site's LVEA wall to pass the FC-C beamtube, to access a new enclosure being provided for this beamtube, and to mitigate any collateral consequences (e.g., to emergency egress, utility routing, personnel access, etc.);
2) Provide a new supporting foundation and accessible weather shelter for the FC-C beamtube, adjoined to the LVEA boundary;
3) Provide a new high-bay laboratory and supporting auxiliary equipment space to house and support operation of HAM8 with its associated equipment, adjoined to item 2, and;
4) Provide utilities and exterior access for items 2. and 3. to conform with functional requirements detailed below and with local, state and federal regulatory requirements.

1.2 Program constraints

Implementation is subject to several identified constraints:

1) LIGO instruments are highly sensitive to vibration and noise while making astrophysical observations. Construction-related disturbances, including vehicle traffic, will be prohibited

in certain periods, and types of construction activity may be restricted at other times. Specific non-observing periods have been provisionally set aside for A+ construction.

2) For the same reason, there is a preference for plant machinery that is intrinsically quiet and low in vibration, or that can be economically rendered quiet by aftermarket modification. LIGO engineering can provide assessment and selection guidance when candidate equipment examples are identified.
3) The Hanford and Livingston detectors must be equipped as identically as possible to minimize specialization of hardware, software, and operating protocols. As a result, the two sets of facilities (particularly, technical spaces and their associated utilities and climate-control provisions) should be *as identical as possible*; however,
4) Available site footprints, ambient climates, geotechnical basis, and regulatory environments differ, potentially forcing certain design divergences.
5) In particular, exterior construction at Hanford is subject to desert habitat and cultural artifact protection regulations, whereas Livingston is subject to wetland preservation requirements.
6) The award budget is fixed and sharply limited. With the construction schedule also constrained, there may be little opportunity for descoping or value-engineering in response to unplanned budget growth.
7) As a consequence, we begin at the *minimum* set of features to support essential functions; and actively seek opportunities for proactive value-engineering from the concept stage onward.

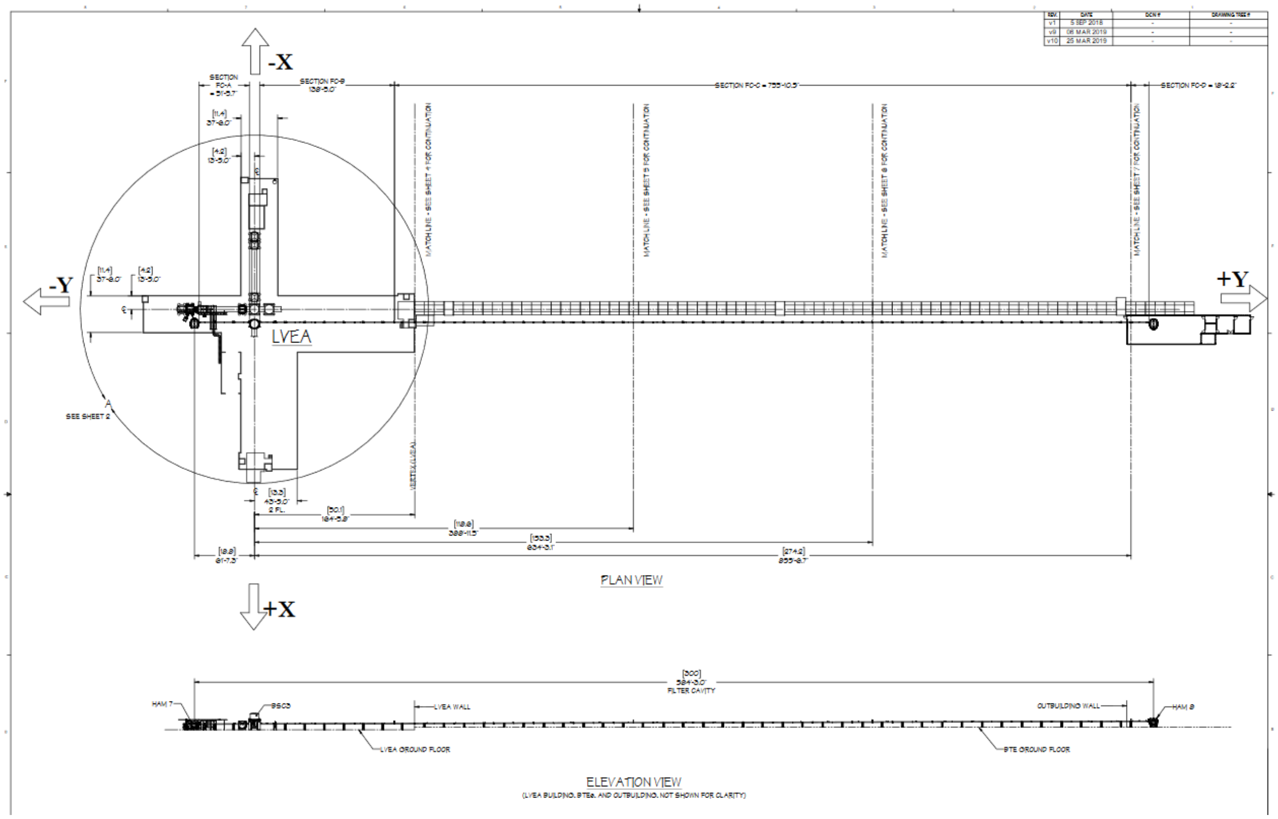

Figure 1: A+ FC vacuum system overlaid on Livingston site plan (from LIGO-D1800238; D1800241 shows the corresponding view for Hanford.)

2 Existing site infrastructure and conditions

For reference we provide here a brief orientation[1] to existing Hanford and Livingston site conditions, with links to supporting documentation.

2.1 Corner station LVEA

Although Hanford and Livingston floor plans differ, most features relevant to the A+ facility modifications are identical. Figure 2 shows the Hanford corner station LVEA floor plan in the region affected by the upgrade.

Each LVEA is climate- and humidity-controlled, and is maintained at a nominal positive overpressure of 0.15" wg (0.4 mbar) with respect to ambient[2] to prevent introduction of dust and pollen. Floor and wall materials and HVAC equipment have been selected to minimize dust generation and retention. Exterior doors are furnished with a vestibule and inner door to contain contamination and minimize air exchange. These measures allow cleanroom conditions (approximately ISO Class 5) to be temporarily established locally over sensitive equipment during maintenance, using portable soft-wall enclosures equipped with ULPA or HEPA filter/blowers.

In normal operation the sensitive scientific apparatus is sealed under vacuum, and the portable filter/blower units are depowered. While the LIGO detector is operating, the LVEA is unoccupied, dark and silent.

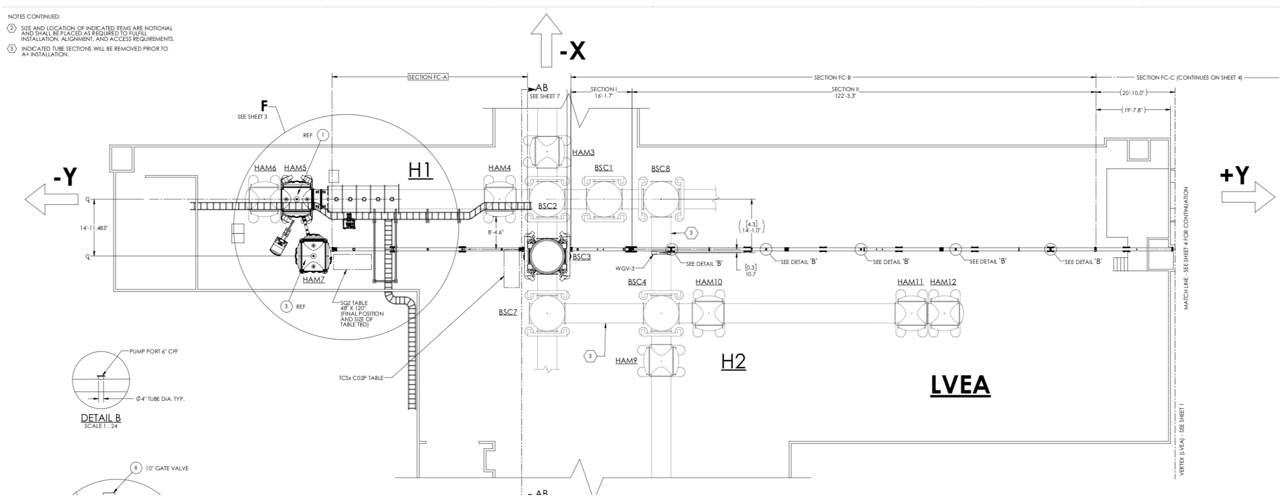

Figure 2: Hanford corner station LVEA plan view showing A+ vacuum modifications (from D1800241-v13 sheet 2)

[1]For convenience, both sites are laid out in *LIGO Global Coordinates* (LGC), rooted in the plane defined by axes of the site's main 4 km beamtubes. These axes intersect at right angles at the site's LGC origin. In Hanford, the LGC +Y axis is oriented at a bearing of approximately 234° true (WSW); in Livingston, LGC +Y corresponds to approximately 162° true (SSE).

[2] LIGO-C961574, section 2.5.2.2.1, Table 2.5-2

2.2 Site topography and property bounds

2.2.1 Hanford

Figure 3 gives a satellite view of the Hanford corner station. The position of the FC beamtube is shown in red. Vehicle access to the interior of the LIGO arms from the highway and main observatory complex is obtained via a paved overpass crossing the X beamtube enclosure (top center). This overpass is rated for vehicles up to 20 tons[3]. However, only unpaved roads currently extend beyond the immediate vicinity of the station complex on the "inside" of the L, which is effectively fenced in by the beamtube enclosures and the corner station building. Paved roads along the "outside" of the X and Y arms extend their full length (4 kilometers).

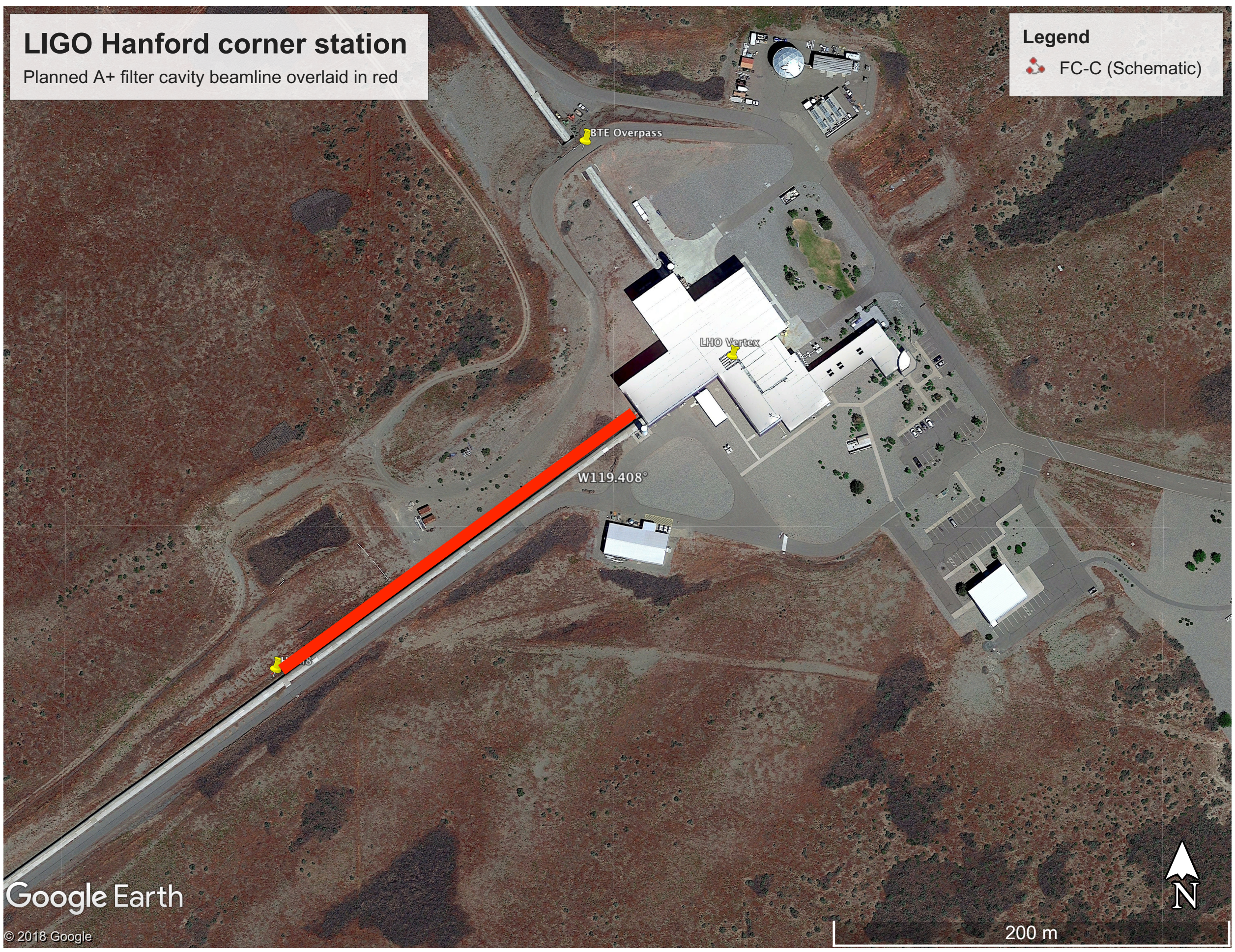

Figure 3: Hanford corner station satellite view showing planned position of filter cavity tube FC-C (in red). Yellow markers denote existing vehicle overpass spanning X arm (top center) and planned position of new HAM8 chamber (below left).

[3] J. Jones, private communication

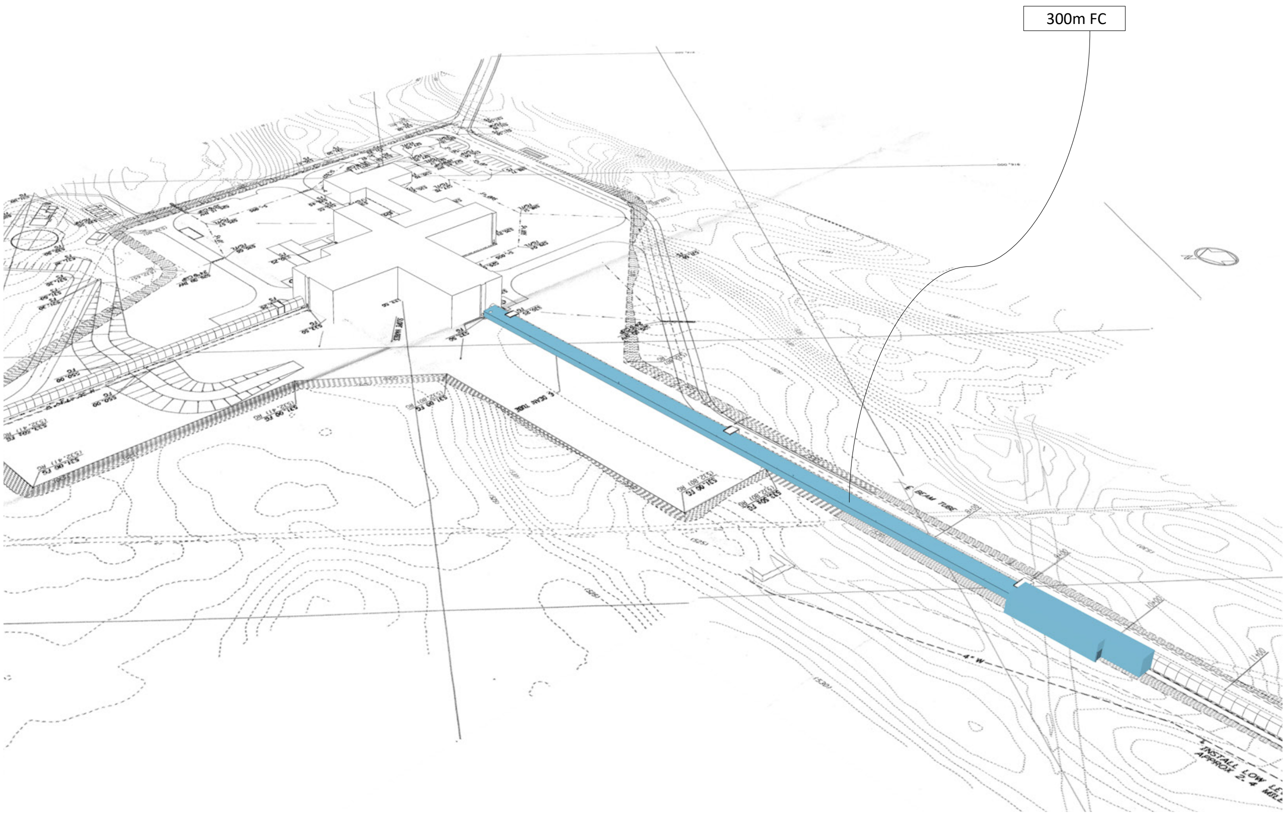

Figure 4: Aerial view of Hanford site corner station and portion of Y arm (lower right) superimposed on site elevation contours. Notional filter cavity tube enclosure and end station are shown in blue.

2.2.2 Livingston

The Livingston site layout (Figure 5) is similar, including the X arm beamtube overpass, but has a width restriction in the proposed construction area. While the available property line is over 100' clear of proposed improvements, much of this width is occupied by a water-filled borrow ditch created during initial site construction that currently provides wetland habitat. This feature affects the available footprint for new construction.

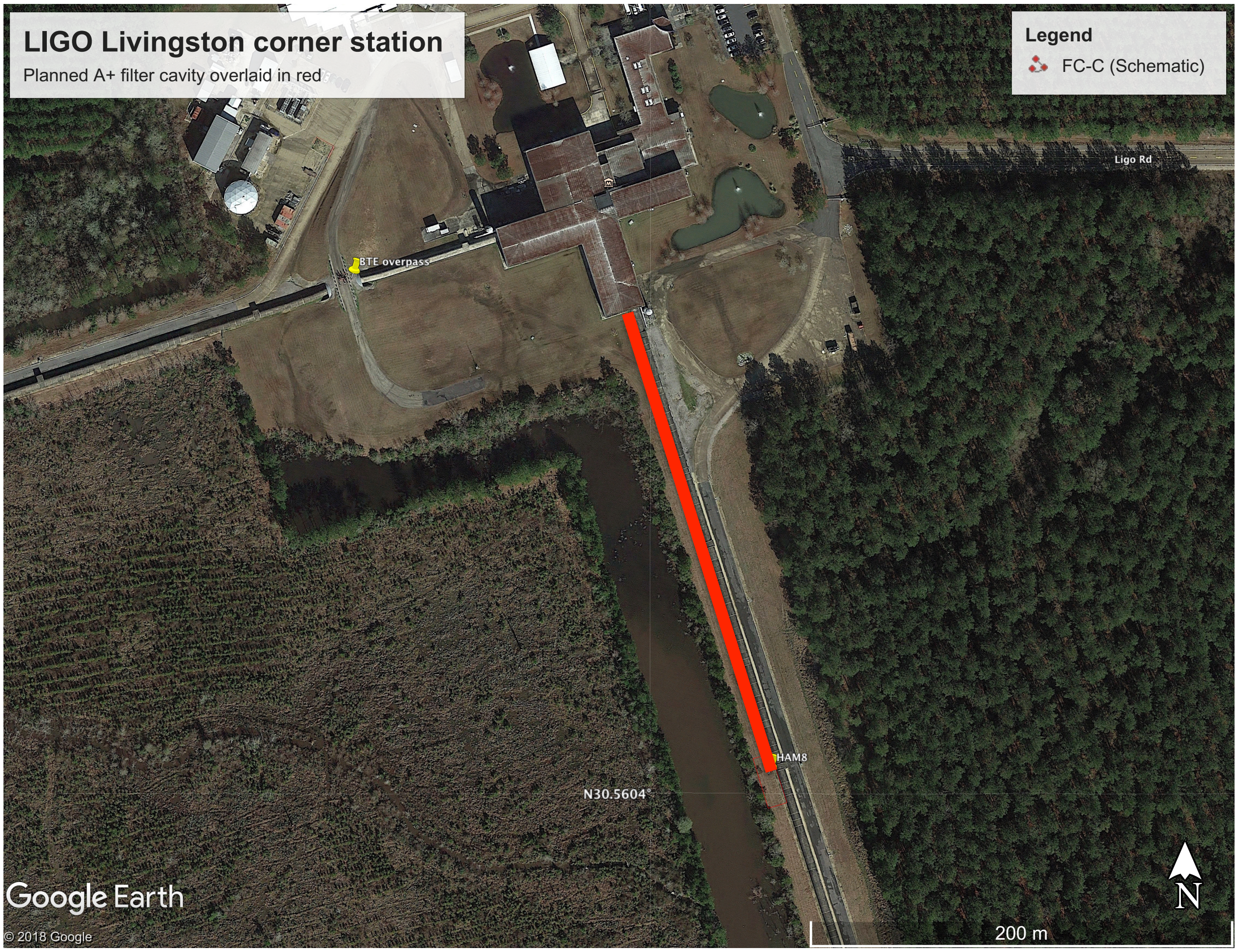

Figure 5: Livingston corner station satellite view showing planned position of filter cavity tube FC-C and notional representation of new end station (in red). Yellow markers denote the existing vehicle overpass spanning X arm (top left) and planned position of new HAM8 chamber (bottom right).

2.3 Main beamtube enclosures (BTE)

The existing LIGO main beamtube enclosures (BTE) are semi-elliptical reinforced concrete shells approximately 10' in height and 13' wide, resting on reinforced concrete slabs. These protect the main LIGO beamtubes which are 48 inches in diameter. The planned FC beamtube axis runs parallel to the Y arm BTE, approximately 7 feet horizontally from the edge of its footing. The planned FC beamtube will be approximately 10 inches in diameter.

The existing BTE is moderately weatherproof. In Livingston, the internal space is dehumidified to prevent condensation, but it is otherwise unregulated. In Hanford there is no fixed BTE ventilation or climate control. At Livingston the BTE's carry fiberoptics and other instrumentation cabling. However neither site's BTE is furnished with electrical power distribution or fixed lighting.

Each BTE has access doors at approximate 400 foot intervals. These open to the roadway side (away from the FCTE).

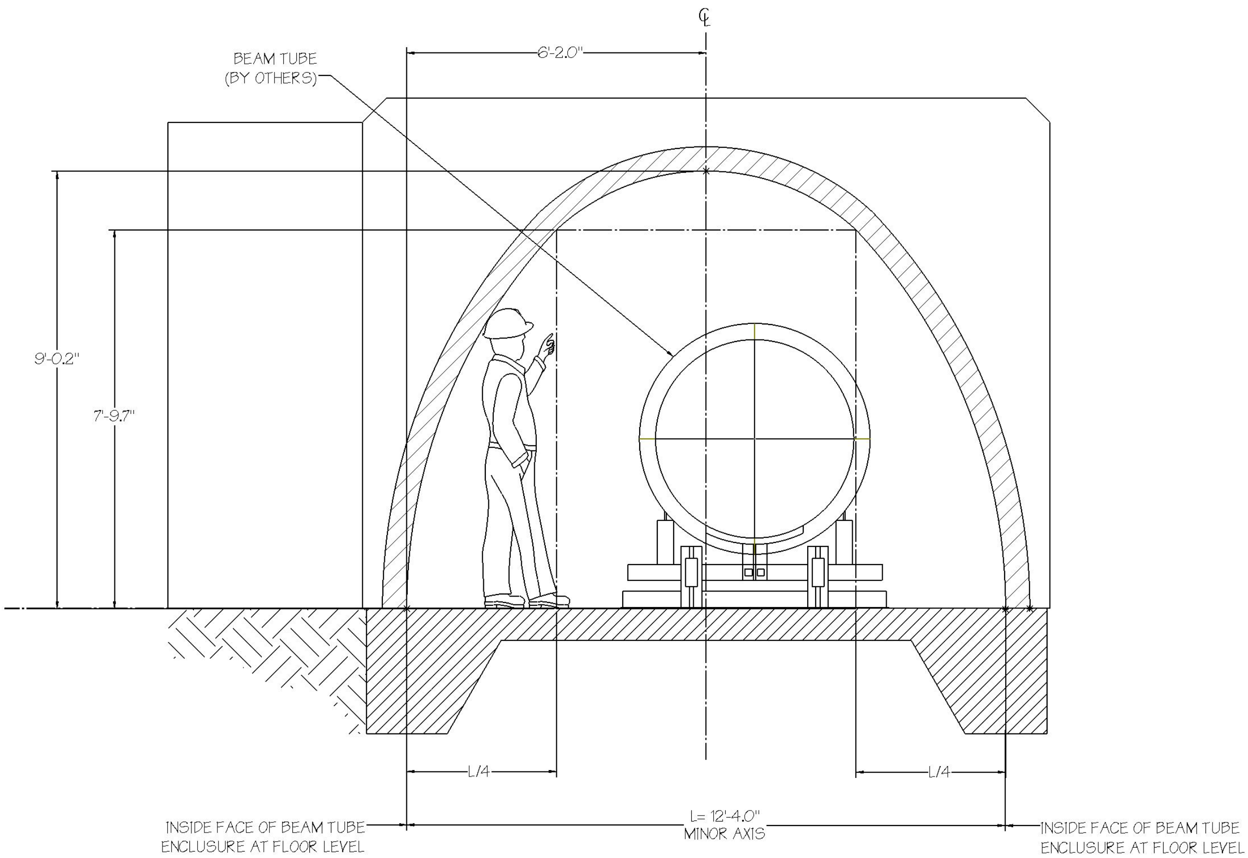

Figure 6: Cross section of LIGO main beamtube enclosure (BTE) showing main beamtube (48" ID) and human for scale. In this view facing +Y, the new FC tube will be installed 13' to right of the main tube axis (see Figure 9 below).

3 Program space requirements

Here we outline functional requirements for each space. Requirements found to trigger significant cost or schedule impact should be flagged to enable investigation of alternative engineering solutions.

3.1 Existing corner station LVEA modifications

An access door is needed for personnel to enter the filter cavity tube enclosure, and a framed penetration is required for the filter cavity beamtube to do the same.

The required position of the tube (Figure 7) impinges on an existing exit door and vestibule. This exit will therefore be removed from service. If required by code, a new LVEA emergency exit will be furnished elsewhere. In this case LIGO will work with architects to locate an appropriate location and specify the installation. The relative location within the LVEA may differ between Livingston and Hanford.

The tube penetration comprises removal or immobilization of the exit door(s) and introduction of an oversized framed aperture for the tube. The aperture will be sealed with flexible membrane material and insulation (by others) to prevent transmission of structural vibrations or stress.

The filter cavity tube enclosure (FCTE) must abut and be sealed against the LVEA exterior wall and adjacent beamtube enclosure. A new access door must be provided to conduct personnel into the FCTE. The FCTE floor is approximately at exterior grade height, whereas the LVEA floor is about 2' below grade. A light-duty ramp system will be introduced to facilitate transport of wheeled equipment and carts between the LVEA and the FCTE.

During demolition and construction of these modifications, contractors will be required to minimize duration and degree of particulate and hydrocarbon contamination, and must deploy containment barriers to prevent spreading of contaminants into adjacent space.

Figure 7: Hanford LVEA +Y wall. Main Y beamtube is shown at left where it enters the BTE (Figure 6). New FC tube penetration intersects the existing exit door pictured at right. Access

door into new FCTE is required to the left of this. Top of raised concrete slab is approximate BTE and new FCTE floor level.

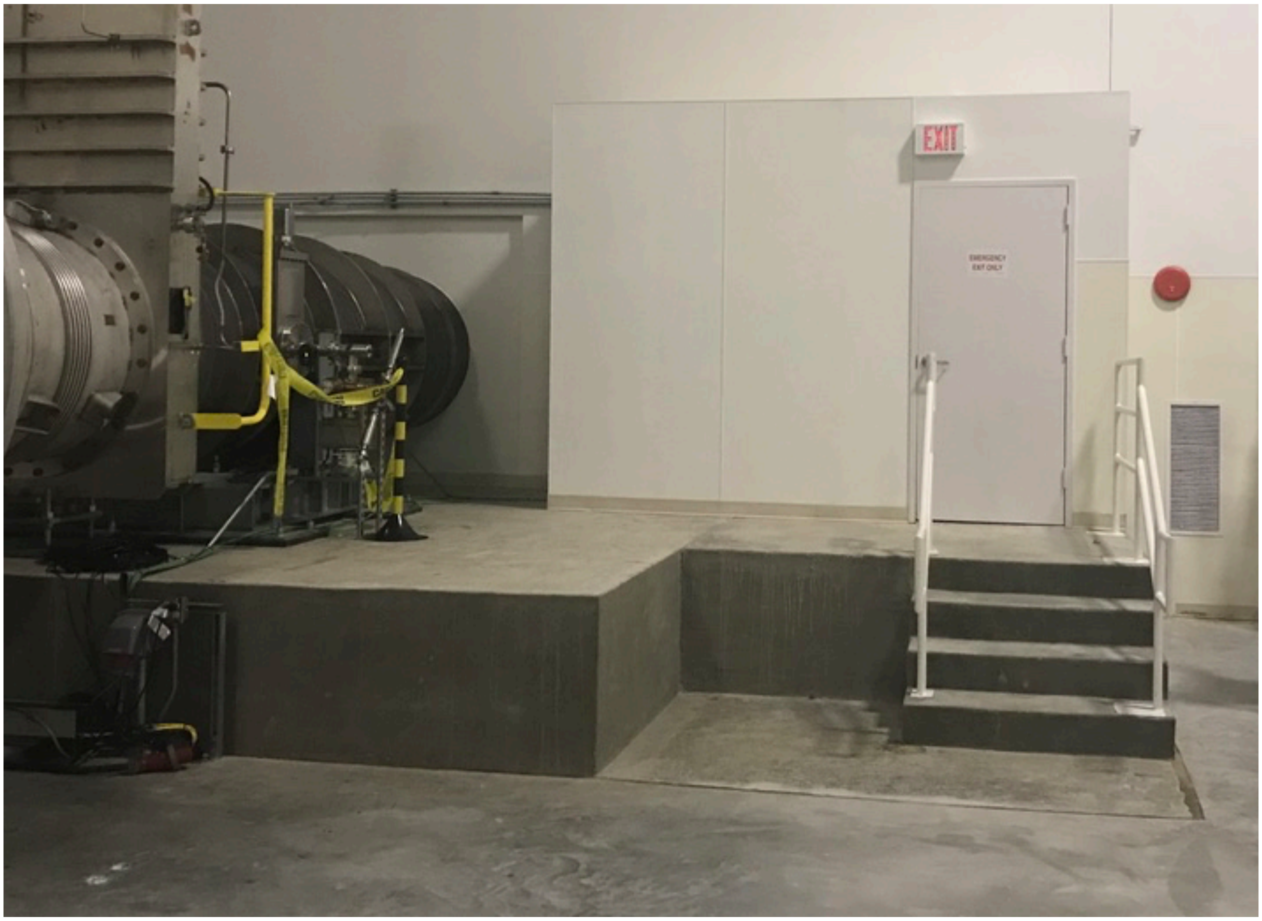

Figure 8: Livingston LVEA +Y wall. Main Y beamtube is shown at left as it enters the BTE (Figure 6). New FC tube penetration may intersect the existing exit door, pictured at right. Access door into new FCTE is required to the left of this. Top of raised concrete slab is approximate BTE and new FCTE floor level.

3.2 FC Tube Enclosure (FCTE) requirements

The FCTE protects filter cavity tube run FC-C from the ambient environment over its 755' length, while affording occasional intermittent access for maintenance or repair. It is normally unoccupied but is accessible to personnel and cart-mounted equipment from each end (corner station LVEA and filter cavity end station FCVEA, respectively).

For purposes of material and equipment selection and life cycle maintenance estimates, the target FCTE design lifetime should be 20 years.

3.2.1 FCTE climate control and utilities

No interior temperature control is required.

Power distribution and fixed lighting are not required.

(Vacuum pumps, instrumentation, and temporary task lighting, all by others, will be powered by umbilical cables from either end).

3.2.2 FCTE humidity control (Livingston only)

The Livingston FCTE (only) will be equipped to control internal humidity to 75% RH or less under all seasonal conditions.

3.2.3 FCTE personnel access, doors and egress

The FCTE affords a covered walkway, bounded by the FC beamtube and the existing BTE wall, that can serve as a transport path and temporary workspace for workers, lightweight equipment carts, and maintenance tools.

Personnel access is required between the covered walkway and the corner LVEA, and between the covered walkway and the FCAUX and FCVEA. Doors should be equipped to limit infiltration of dust, moisture and vermin.

An additional exit door is required at the approximate midpoint of the FCTE.

Standing headroom and body clearance is required on the outboard (+X) side of the FC tube for inspection and repairs. The FC tube is at such a height that workers can duck underneath to reach this auxiliary space from the interior walkway.

Fixed vacuum plant equipment (by others) will be mounted preferentially above or beneath the FC tube, to avoid obstructing the walkway and the outboard access spaces.

3.2.4 FCTE windows

No windows are required.

3.2.5 FCTE mounted equipment loads

In addition to foot or cart traffic, the FCTE floor slab is required to support and anchor FC tube supports (by others) at approximate 20' (6m) intervals (TBR). These will be anchored by others in a manner compliant with seismic zone safety requirements, to be specified by the supplier.

Maximum design FCTE floor loading, including fixed and movable equipment plus personnel, will be XXX TBR pounds per square foot.

3.2.6 FCTE floor height, slope, and flatness

The FCTE finish floor will run parallel to the main BTE foundation slab at about the same elevation. It may slope away from the BTE as required to afford drainage.

Aside from drainage slope, local variations in finished height should not exceed ±0.25" (±6mm) within any 10 feet and ±0.75" (±19mm) overall with respect to nominal, in order to respect the vertical adjustment range of owner-furnished tube supports.[4]

3.2.7 FCTE interior height

The FCTE should afford standing headroom throughout.

3.2.8 FCTE sealing

Wall, ceiling and floor joints should be sealed and water-tight to prevent infiltration of water, dust, and vermin.

3.2.9 FCTE fire protection

Fire protection is not required except as stipulated by local codes.

3.2.10 FCTE lightning protection

Lightning protection is not required except as stipulated by local codes.

3.2.11 FCTE ballistic protection (Livingston only)

In Livingston only, LIGO abuts managed forest land used for recreational hunting. An accidental bullet strike on the FC tube, which is thin-walled, might trigger catastrophic loss of vacuum. The Livingston FCTE should therefore incorporate means to protect the tube from stray hunting rounds fired from abutting property.

[4] Note that tube supports will be graduated in height along the run to account for ~27" gain in elevation from the LVEA to the FCVEA; the FC tube is pitched at a 3 mrad (0.17°) angle from horizontal.

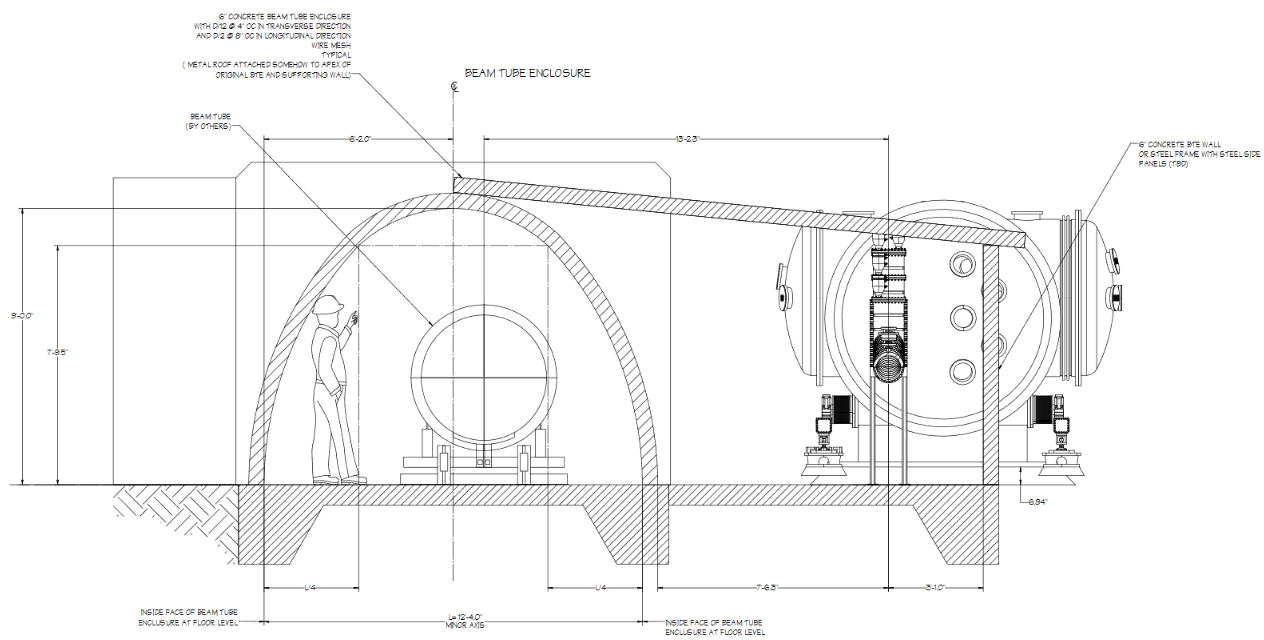

Figure 9: Physical arrangement of FC tube with respect to main beamtube enclosure. A notional concept for the new FC tube enclosure is shown, incorporating a covered access walkway between the existing concrete BTE and the new FC tube (LIGO-D1800238). HAM8 is shown in projection for reference. The FCES building is omitted for clarity. ***Dimensions and structural capacities of existing BTE and foundation are subject to analysis and should not be inferred.***

3.3 Filter cavity end station (FCES) overall requirements

FCES functions require that the building be divided into at least two sub-spaces. HAM8, which houses the end mirror of the filter cavity, will reside in a dust-sensitive high bay designated as the *Filter Cavity Vacuum Equipment Area* (FCVEA).

This high-bay laboratory space is augmented by a support space, which provides for equipment transfer and accommodates mechanical and electrical infrastructure. This *Filter Cavity Auxiliary* (FCAUX) space will have conventional (typically, low-cost commercial) environmental requirements.

In existing LIGO structures, support spaces are shared by detector electronic and data systems, vacuum system support, and facility mechanical and electrical plants. This shared role in also assumed for FCAUX. However, internal partitioning may also be considered if deemed helpful.

We begin with general requirements for the building as a whole. We then address special technical needs for the FCVEA, and finally describe supporting functions of the FCAUX.

3.3.1 FCES occupancy and usage modes

For purposes of material and equipment selection and life cycle maintenance estimation, the nominal FCTE design lifetime should be 20 years.

The filter cavity end station is typically unoccupied during **normal operation**. Technical equipment is monitored and controlled remotely from the site control room. Workers may visit briefly (e.g., weekly) for scheduled equipment maintenance, inspection or cleaning. For sporadic detector troubleshooting, one to three technicians may occasionally visit the FCES for alignment, adjustment or tests. For such minimal interventions the vacuum system remains sealed, no heavy equipment is activated, and no unusual utility loads are incurred.

During **major equipment installation** (i.e., upon initial occupancy), the vacuum system will be vented and doors removed. Temporary lifting and installation fixtures (by others) will be staged in the FCVEA (Figure 12). Portable soft-wall cleanrooms (by others) will be erected around HAM8, and their filter/blower units and task lighting will be operating 24/7. Up to six workers may be present at a time.

Upon beneficial occupancy the initial **major equipment installation** phase, including placement of the HAM8 vacuum chamber and FC beamtube, is expected to extend for 3-5 months. The vacuum chamber and beamtube configuration are permanent; subsequent major equipment installation episodes will be for servicing internal components only, and will be shorter (typically 1 month or less) and infrequent (perhaps every 2-4 years).

3.3.2 FCES worker and small equipment access

Convenient means is required for personnel, light equipment and light hardware to reach the FCES from the main LIGO corner station complex. Options (which may be combined) include, but are not limited to:

a) the FCTE interior walkway connecting the new spaces to the corner station LVEA,
b) an improved path or driveway connecting to the existing X beamtube overpass, and/or
c) existing site roadways on the opposite side of the BTE, augmented by stairs, lifts, or ramps to transfer people and materials over the BTE.

3.3.3 FCES safety access

Access for emergency response personnel and their equipment and means to evacuate injured workers are required to comply with applicable codes.

3.3.4 FCES fire protection

Smoke detectors, fire detectors, pull stations, extinguisher stations and emergency egress lighting are required to comply with local codes.

Fire systems must interface with existing LIGO site-wide monitoring systems.

Sprinklers or other automatic suppression is not required, except as stipulated by local codes.

Emergency vehicle access should be afforded as required to comply with applicable codes.

3.3.5 FCES large equipment delivery

Means are required to deliver and install large equipment, including the HAM8 chamber and its internal systems (up to 5 tons each); EIA electronic equipment racks (up to 1/2 ton each nominal); vacuum pumps (up to 1/4 ton); and HVAC equipment (TBD by architect). Long narrow loads up to 30' in length, such as cleanroom struts and lift beams, must also be accommodated.

Large deliveries will be infrequent (possibly only at initial occupancy). Mobile cranes may be employed to lift trucked loads from the existing roadways over the BTE. An improved driveway linking the FCES to the existing X arm overpass, and thus to the existing site road system, may also be suitable.

Once on location, large equipment will be rigged into the FCAUX by forklift, machinery skates or pallet jack. Exterior laydown pads, ramps, expansion joints and thresholds should be designed to minimize obstruction of heavy rolling loads.

An exterior rollup door should be provided to accept payloads up to 10' wide and 12' high into the FCAUX space. This door should be configured to resist rattling or vibration in typical high winds.

An interior rollup door of similar dimensions is required to transfer payloads into the FCVEA.

Interior and exterior rollup doors should be separated by at least 16' and arranged in series, such that longer payloads can be introduced to the FCVEA with both doors open.

The stay-clear between the rollup doors will be designated for Large Equipment Transfer, but is not physically partitioned.

3.3.6 FCES lightning protection

Lightning protection is required.

3.3.7 FCES restrooms

Fixed lavatory facilities are not required. Portable outdoor lavatory units (by others) may be staged temporarily as needed.

3.3.8 FCES attachment to existing BTE

The FCES may need to be structurally independent of the existing BTE and its foundation, which were not designed for additional loads. However it is necessary to protect and shield the narrow space between the required FCTE footprint and the BTE from accumulating tumbleweeds, rain, snow, debris and vermin.

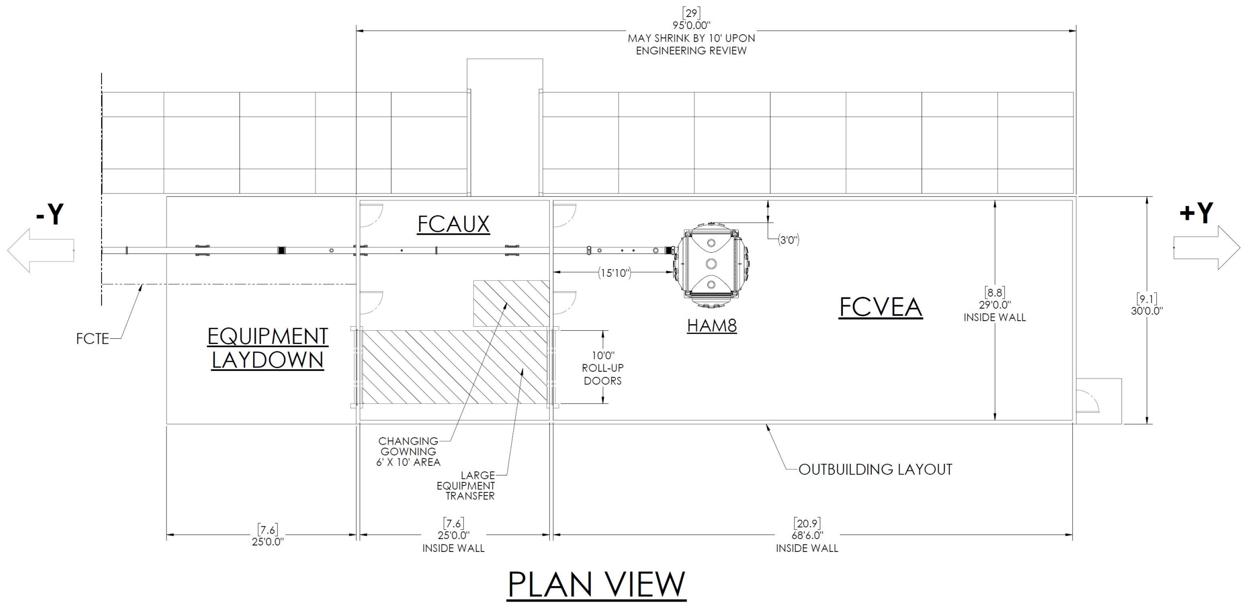

Figure 10: FCES concept plan. Nominal FCVEA interior height is 20'; nominal FCAUX interior height is 14' in designated Large Equipment Transfer zone, 10' elsewhere. Paved exterior slab (shown schematically, left) is for equipment laydown and crane transfer. Dimensions subject to review.

3.4 Filter cavity vacuum equipment area (FCVEA) requirements

The FCVEA high bay provides an operating, installation and maintenance environment for the HAM8 chamber and its internal and external equipment.

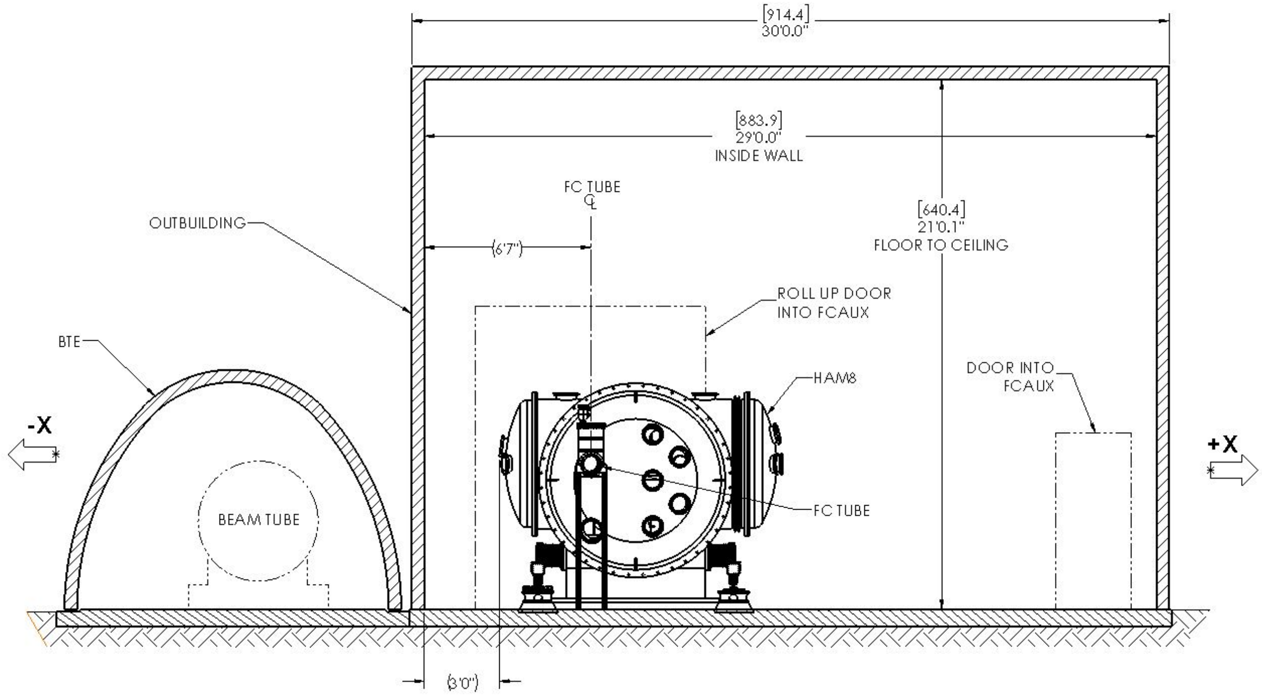

Figure 11: FCVEA internal elevation concept looking +Y global, showing existing BTE for orientation. Shelter to protect debris trap between BTE and building has been omitted for clarity. Dimensions and details subject to review.

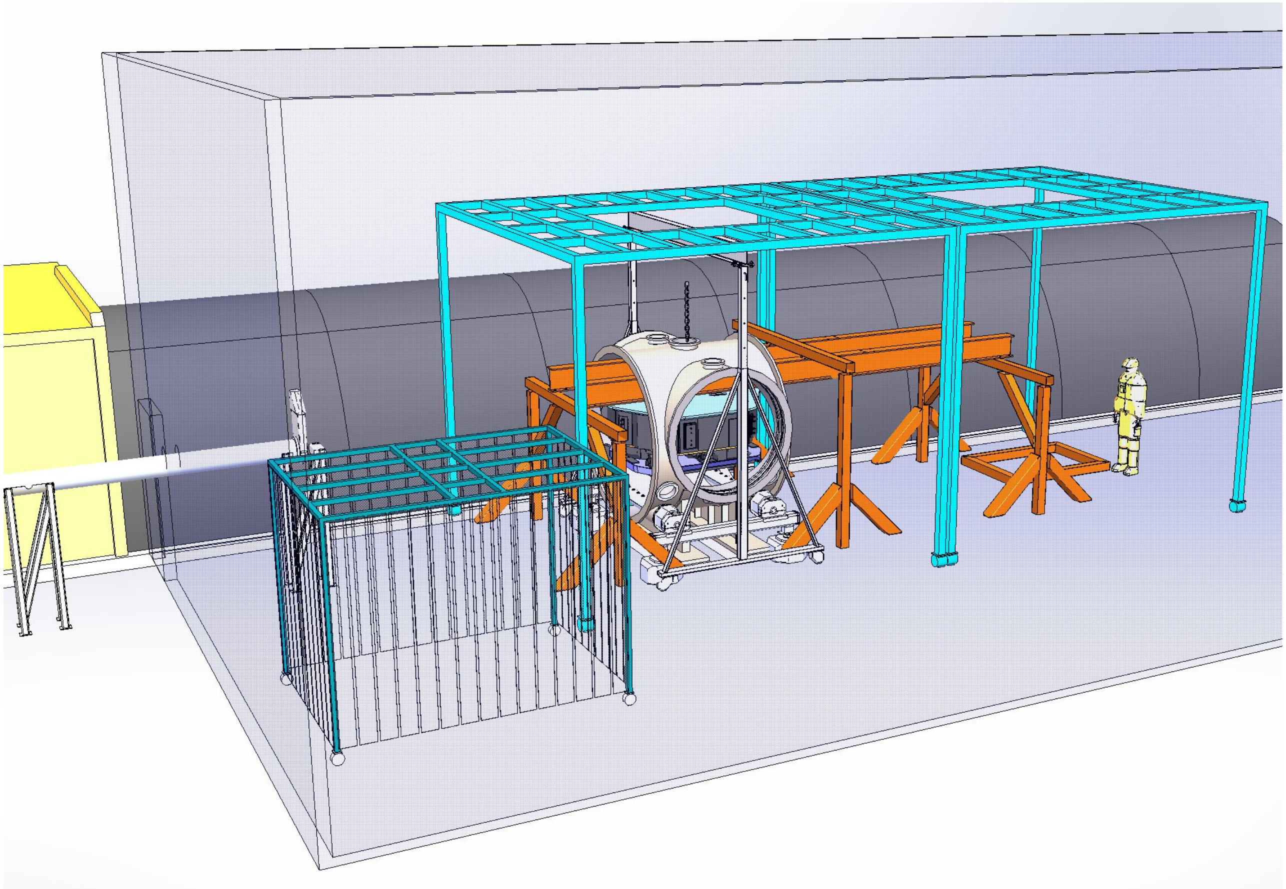

Figure 12: HAM8 chamber and support equipment in FCVEA, configured for installation of internal chamber payload.

3.4.1 FCVEA internal dimensions

Obstruction-free interior height must be 20' (6.1m) above finish floor. Isolated exemptions (e.g., structural bracing, plumbing or electrical runs) may be allowed subject to LIGO engineering review.

Clear interior floor space must be at least 27'(X) x 70'(Y) (8.5m x 21.3m).

Interior columns are not permitted.

3.4.2 FCVEA fixed and movable equipment

The FCVEA will accommodate owner equipment according to Table 1.

item	footprint	mass (lb)	mobility	usage
HAM8 chamber	10'x10'	10,000	(anchored)	fixed
SEI HAM ISI & support	12'x12'	5,000	(anchored)	fixed
FC-C and FC-D tube supports	2'x30'	2,000	(anchored)	fixed
SUS assembly bench and tool cart	3'x6'	1,000	wheeled	permanent
CDS control and data workstation	3'x6'	300	wheeled	permanent
ISC optical table	4'x6'	2,500	pallet jack	permanent
CDS EIA electronics rack assembly A	6'x3'	1,000	pallet jack	permanent
CDS EIA electronics rack assembly B	6'x3'	1,000	pallet jack	permanent
Softwall cleanroom assembly	16'x32'	3,000	wheeled	temporary
Cleanroom gowning & transfer area	16'x8'	500	wheeled	temporary
VAC vacuum pump station	3'x2'	300	wheeled	temporary
VAC leak tester	3'x2'	200	wheeled	temporary
electric 5T forklift	3'x9'	10,000	wheeled	temporary
gantry crane	8'x16'	3,000	wheeled	temporary

Table 1: FCVEA fixed and movable equipment (preliminary)

Floor capacities should safely accommodate forklift, portable gantry, pallet jack or equipment skate delivery of items above to final locations.

Equipment anchor requirements, mass moments and approximate floor locations will be furnished by LIGO to inform foundation design and structural analysis. Final equipment arrangement and installation will be the responsibility of LIGO.

3.4.3 FCVEA access

Personnel and light equipment access doors will be provided to the FCES auxiliary equipment space(s), to the FCTE enclosure walkway, and direct to outside. Doors will be weatherstripped to limit dust and air exchange.

3.4.4 FCVEA windows

No windows are permitted (at certain times the FCVEA will be a designated LASER Hazard Zone).

3.4.5 FCVEA utilities

House power for owner equipment will be required according to capacities listed in Table 2. Receptacle and terminal locations will be defined by LIGO as required.

Surface-mounted conduit, receptacles and junction boxes are acceptable, subject to conditions noted in section 3.4.11 below.

Receptacles and junction boxes will typically be mounted to walls 4' above finish floor, unless otherwise specified.

No under-floor utility stubs or floor receptacles are required.

No house water is required in the FCVEA (a janitorial sink will be located in FCAUX).

No chilled water is required for owner equipment.

function	voltage/phase	total capacity	no. points
cleanroom blowers and lighting	480/3	50 kVA	4
rotary vacuum pump	208/3	8 kVA	2
ion vacuum pump	120/1	2 kVA	2
getter vacuum pump	120/1	2 kVA	2
CDS electronic equipment	120/1	5 kVA	16
task lighting	120/1	2 kVA	8
test equipment	120/1	5 kVA	8

Table 2: FCVEA electrical power and distribution points (preliminary)

3.4.6 FCVEA cranes

No fixed crane system is required.

Equipment rigging (by others) will employ forklifts, pallet jacks, equipment skates or portable gantries as needed.

3.4.7 FCVEA lighting

Overhead illumination corresponding to commercial warehouse usage should be provided on two or more separately-controlled banks. Local task lighting will be provided by others as needed.

Long-life fixtures (e.g., LED) are preferred to reduce or eliminate life cycle maintenance. Limited and sporadic occupancy (section 3.3.1 above) should be considered in balancing initial vs. operating costs.

Lighting fixtures should be sealed, cleanable and insect-resistant to discourage infestation.

3.4.8 FCVEA thermal loads

In addition to exterior ambient conditions and building mechanical and lighting systems, cooling systems for the FCVEA should accommodate the following user heat loads in the different phases of operation:

1) Normal operation: **5.0 kW**, comprising
    a) 5.0 kW technical electronics
2) Major equipment installation: **61.7 kW**, comprising
    a) 5.0 kW technical electronics
    b) 6.7 kW vacuum pumping and instrumentation

c) 50.0 kW cleanroom HEPA/ULPA fan units

3.4.9 FCVEA temperature regulation

In **normal operation**, temperature year-round must be regulated to 68°F ± 3.5°F as measured 6' above the floorplan center point, and to 68°F ± 5°F everywhere within 10' of the finish floor.

During **major equipment installation** (i.e., with maximum owner heat loads active, as above), temperature regulation may be relaxed to 70°F ± 10°F.

Given the contrast between normal and sporadic peak loads (section 3.4.8 above), as well as relaxed requirements during peak activity, consideration may be given to combination of fixed and temporary (e.g., owner rental) HVAC equipment in order to minimize fixed plant costs.

3.4.10 FCVEA humidity regulation

Relative humidity must be regulated below 70% under all seasonal conditions.

3.4.11 FCVEA surface finishes

Finish floor must be seamless vinyl over sealed reinforced concrete[5].

Wall and ceiling finishes must be non-shedding and compatible with damp mop cleaning. Semi-gloss non-VOC latex paint is suggested.

Exposed structural elements and surface-mounted utilities may be permitted, provided that they:

- have non-shedding and cleanable surface finishes as above;
- respect interior clear dimensions;
- do not obstruct or impede technical cleaning;
- do not compromise exterior moisture, air or dust seals; and
- do not attract or harbor vermin.

3.4.12 FCVEA floor slope and drains

At least two floor drains are required. Drains should be placed near the perimeter.

3.4.13 FCVEA internal overpressure

To control dust and pollen ingress, the HVAC system will introduce filtered makeup air to maintain internal positive overpressure of 0.15" WG (0.4 mbar) with respect to exterior ambient under all seasonal conditions.

3.4.14 FCVEA particulate control

Where feasible, HVAC equipment selections should employ components, materials, and construction methods that are *nominally compatible* with applications requiring ISO Class 7 particulate limits.[6]

[5] For example, *Mannington Lifelines II* and *Mannington Commercial V-82 Adhesive* system or similar, with heat-sealed seams (cf. LIGO-C1300750-v2).

However fan and filter capacity, supply velocity, and air volume exchange rates should **NOT** be sized to formal cleanroom standards.[7] Airflow capacities should be established at the minimum consistent with standard commercial practice, in order to achieve required internal pressure, temperature, and humidity control.

3.5 FCAUX auxiliary equipment space requirements

The FCAUX affords economical and flexible space for engineering support and physical plant functions. It also provides a transition zone for uncrating and decontamination of equipment entering the FCVEA. Equipment functions, approximate dimensions, utility requirements and WBS responsibilities are given in Table 3. Common features and requirements for the shared space are described in subsections that follow.

equipment or function	format	LxWxH (')	SF	V/p/I	REQ
VAC backfill & purge skid	skid	3x5x6	15	208/3/30	A+ VAC
VAC roughing pump	skid	2.5x3.5x3	9	208/3/20	A+ VAC
VAC control and power	EIA rack	2x3x6	6	120/1/20	A+ VAC
VAC aux pump (portable)	cart	2x2x3	4	120/1/20	A+ VAC
VAC leak detector (portable)	cart	2x2x3	4	120/1/20	A+ VAC
VAC tool & equipment storage	cart	3x3x4	9	-	A+ VAC
VAC consumables & supply storage	cabinet	2x3x6	6	-	A+ VAC
VAC flammable liquids locker	cabinet	2x3x6	6	-	A+ VAC
CDS DC power	EIA rack	2x3x6	6	120/1/20	A+ CDS
CDS analog/interface	EIA rack	2x3x6	6	120/1/20	A+ CDS
CDS digital A	EIA rack	2x3x6	6	120/1/20	A+ CDS
CDS digital B	EIA rack	2x3x6	6	120/1/20	A+ CDS
CDS control workstation	cart	3x3x5	9	120/1/20	A+ CDS
CDS repair station (shared w/VAC)	bench	3x6x3	18	120/1/20	A+ CDS
CDS test equipment (portable)	cart	3x3x5	9	120/1/20	A+ CDS
SYS Overhead cable/pipe trays	stay-clear	TBD	TBD	-	A+ SYS
SYS Changing/Gowning area	stay-clear	6x10x7	60	-	A+ SYS
SYS Large Equipment Transfer	stay-clear	12x16x16	192	-	A+ SYS
FCES building electrical distribution	panel(s)	TBD	TBD	TBD	A&E
FCES HVAC plant	skids/fans	TBD	TBD	TBD	A&E
FCES plumbing, janitorial	sink	TBD	TBD	TBD	A&E

[6]Equivalent to retired Federal Standard 209D Class 10,000.

[7]High airflow produces unwanted acoustic noise and vibration.

Table 3: FCAUX functions, approximate size, estimated power, and WBS unit/group responsible for furnishing detailed requirements

3.5.1 FCAUX interior dimensions

Dimensions should suit the complement of equipment and required stay-clears in Table 3 above. Sufficient space should be allocated around fixed equipment, workstations and work benches to allow inspection, operation and maintenance.

For example, EIA electronic racks should have access stay-clears of 30" in front and 18" in back to enable cable connections, equipment troubleshooting and service.

3.5.2 FCAUX interior clear height

Clear height should be at least 14' in the Large Equipment Transfer stay-clear to allow erection and operation of portable gantry cranes (by others).

Clear height should be at least 10' in other FCAUX areas, unless partitioned or otherwise specialized. Limited local exemptions (e.g., for structural bracing, conduit or plumbing) may be allowed subject to LIGO engineering review.

3.5.3 FCAUX entries/exits

Personnel entry/exit will be via exterior door to outside, and via interior door into FCVEA. The latter is reached through a designated Changing/Gowning area.

Equipment entry/exit will be via exterior equipment rollup door outside, and via interior equipment rollup door to the FCVEA. The latter is reached through a designated Large Equipment Transfer area.

3.5.4 FCAUX exterior equipment laydown

An outdoor paved area abutting the FCAUX large equipment transfer door should be furnished, suitable for crane, van and forklift transfer of delivered payloads. This feature should be sized to support convenient load transfer and maneuvering of a loaded forklift.

Pad space may be shared with exterior HVAC, mechanical or electrical utility units as needed.

3.5.5 FCAUX temperature and humidity

Temperature should be regulated to 70°F ± 10°F year-round.

Relative humidity should be regulated to a maximum of 70%.

3.5.6 FCAUX floor and interior finish

The floor should be finished in seamless vinyl or vinyl composition tile over sealed concrete.

Wall and ceiling materials should be non-shedding.

Exposed structural elements are acceptable, insofar as they do not interfere with intended use.

All building joints and penetrations should be fully sealed against water and vermin.

3.5.7 FCAUX lighting

Overhead illumination should be provided corresponding to commercial warehouse or fabrication usage. Local task lighting will be provided by others as needed.

Long-life LED fixtures are preferred to reduce or eliminate life cycle maintenance.

Lighting fixtures should be sealed, cleanable and insect-resistant to prevent infestation.

3.5.8 FCAUX electrical utilities

Electrical utilities should support operation of owner and building plant equipment (Table 3).

Surface mounted conduit, receptacles and junction boxes are acceptable.

Electrical panels should be located to discourage obstruction while conserving usable floor space. Designated stay-clear zones (e.g., the Large Equipment Transfer area) may be shared to insure protected access.

Convenience outlets should be provided 4' above finish floor on all walls.

3.5.9 FCAUX plumbing utilities

Water for custodial cleaning should be provided to a hose bib accessible from the Large Equipment Transfer area.

A janitorial sink should be provided separately or in combination with above.

An additional outdoor hose bib should be provided to service the exterior equipment laydown pad.

Potable water is **not** required.

3.5.10 FCAUX floor drains

At least one floor drain should be provided near the Large Equipment Transfer area. This drain and approaching floor slopes should be arranged to minimize potential interference with rolling equipment traversing the Transfer Area en route to and from the FCVEA.

4 Glossary of acronyms

A+, Upgrade to Advanced LIGO
aLIGO, Advanced LIGO
AWP, Annual Work Plan
BOE, Basis of Estimate
BTE, BeamTube Enclosure
CDR, Conceptual Design Review
CDS, Control and Data Systems
CIT, California Institute of Technology (Caltech)
COC, Core Optics Components
DRR, Design Requirements Review

FAC, Facilities
FC, Filter Cavity
FCAUX, Filter Cavity Auxiliary Equipment Area
FCES, Filter Cavity End Station
FCVEA, Filter Cavity Vacuum Equipment Area
FCTE, Filter Cavity Tube Enclosure
FDR, Final Design Review
FDS, Frequency-Dependent Squeezing
FTE, Full Time Equivalent Employee
FY19, Fiscal Year 2019 (etc.)
HAM, Horizontal-Axis Module
HD, Historical Data
HSTS, Ham Small Triple Suspension
ISC, Interferometer Sensing and Control
LIGO, Laser Interferometer Gravitational Wave Observatory
LVEA, Laser and Vacuum Equipment Area
MIT, Massachusetts Institute of Technology
NSF, National Science Foundation
PDR, Preliminary Design Review
PM, Project Management
Q1, First quarter of the fiscal year
SEI, Seismic Isolation
STFC, Science and Technology Facilities Council
SUS, Suspensions
SYS, Systems Engineering
UK, United Kingdom
VAC, Vacuum Systems
VQ, Vendor Quote
WBS, Work Breakdown Structure

5 References