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Advanced LIGO Interferometer Integration

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1 Introduction

This document outlines plans for the testing and integration of the full Advanced LIGO (aLIGO) interferometers within the aLIGO Project scope, marked by the milestone of achieving a 2 hour lock for each interferometer.

2 Overview of Integration Phases

The integration plan for aLIGO includes the integration and testing of five interferometer sub-configurations, planned as intermediate milestones to the full interferometer integration. These sub-configurations are:

- Single arm cavity. This is the H2 One Arm Test (H2OAT), where a single 4km long arm cavity is the first installation at LHO (in the H2 Y arm). This integration phase is described in [T1100080](#). The basic goals of this configuration are to test the integration and low-frequency performance of the BSC 2-stage ISI (Internal Seismic Isolation) and the test mass quadruple suspension, and to test some aspects of the Arm Length Stabilization (ALS) system.
- PSL, IO and Input Mode Cleaner. This is the first integration phase for L1 (LLO), where the interferometer is built up from the laser source outwards. The integration at this phase involves everything up to and including the in-vacuum Input Mode Cleaner (power recycling cavity optics are installed, but are not part of the integrated testing at this point). The basic goals are implementing and testing the controls for the Input Mode Cleaner, and testing the configuration at high laser power; these and other goals are described in [T1100201](#).
- Dual Recycled (Corner) Michelson Interferometer (DRMI). This is the second integration phase for L1, and it includes all the interferometer components in the corner station—a power- and signal-recycled Michelson. The goals of this phase of integration are discussed in section 6 of this document.
- Arm Cavity with Half-Vertex. This sub-configuration consists of one arm cavity, the PSL/IO/IMC, the beamsplitter, and all power recycling cavity optics. In this state the ALS system is further commissioned, using both the green ALS beam in the vertex and the PSL beam in the arm cavity (neither of which are part of the H2OAT). This sub-configuration is also known as HIFO (half-interferometer), and will be first implemented on H1. Beyond this first implementation, each interferometer will be operated in this sub-configuration twice (once for each arm cavity), in order to commission the ALS system.
- Full Arm Length Stabilization. This refers to the configuration consisting of both arm cavities and the power recycling cavity optics. In this state the full arm length stabilization system is implemented: both arm cavities locked on the green ALS beams; common/differential feedback of the ALS signals; PSL beam injected into each arm cavity.

3 Interferometer configuration

The aLIGO Project milestone of a stable lock is to be achieved with the full interferometer configuration—meaning a power- and signal-recycled interferometer with arm cavities. The signal recycling mirror (SRM) will most likely be a temporary, composite mirror at this stage. Recent

modeling, documented in [T1200128](#), examined the effect of the SRM transmission on interferometer sensitivity at various laser power levels. This shows that a transmission larger than the nominal 20% is better for early operation. This will be realized with a smaller, ‘surrogate’ SRM (2" diameter, $T = 37\%$), mounted in a larger metal mass, which in turn is suspended at the bottom of a HAM Small Triple Suspension. It is not known how far we will be able to progress with this composite mirror, beyond the stable locking milestone.

4 Modes of operation

There are several differences between the global sensing and control configuration used for lock acquisition and that used for the final, low-noise operation. We define the following modes of operation:

- **Acquisition mode.** The acquisition mode includes all the steps involved in bringing an uncontrolled interferometer to its operating point. By ‘operating point’, we mean that all cavities are on resonance (Michelson at the dark fringe) and the orientation alignment is close enough to optimal that the power buildup in the arms is within 90% of maximum.
- **Locked mode.** The locked mode includes all steps between acquisition mode and the final, low-noise mode suitable for science data. These steps, discussed in detail below, involve: switching to low-noise sensors; increasing the laser power; activating thermal compensation; and fine-tuning numerous control loops.
- **Low-noise or Science mode.** Relatively self-explanatory, this is the mode where low-noise operation is achieved, and science data can be collected.

The anticipated steps involved in Acquisition mode and Locked mode are outlined in sections 8 and 9, respectively.

5 Two hour lock milestone

At the end of acquisition mode, the interferometer is at its operating point, and should be stably locked. The two hour lock milestone can therefore be achieved when the interferometer has just completed the acquisition mode steps and has transitioned to locked mode.

6 Dual Recycled Michelson phase testing

There will be several months of testing of the DRMI configuration on L1, before the arm cavities become available. This period will be used to investigate and develop the interferometer controls for this state, and to test various components of the system, as described below.

6.1 Readout & actuation chains: sub-configurations

Sub-configurations of the full corner Michelson configuration will be used to test and confirm the sensing and actuation chains. These sub-configurations are:

MICH	ITMY & ITMX aligned
PRIX/PRIY	PRM and ITMX/ITMY aligned
SRIX/SRIY	SRM and ITMX/ITMY aligned
PRMI	PRM, ITMX & ITMY aligned
SRMI	SPRM, ITMX & ITMY aligned

The sensing signals that are generated in these sub-configurations are calculated in [T1200289](#) (*Simple LSC Configurations for Early Advanced LIGO Commissioning*). The DC and RF demodulation signals measured when sweeping the length DOF of these states will be compared to these modeled signals. Furthermore, the states can be locked, and closed-loop transfer functions measured, to check the actuation chain through the suspensions.

6.2 Cavity lengths

The lengths of the power- and signal-recycling cavities need to be measured and potentially adjusted to set them to within their tolerances (the input mode cleaner length will already have been measured in the IMC testing phase). One method for doing this is to compare the demod phases for the PRIX & PRIY states against the demod phase for MICH. The tolerances on the lengths of the recycling cavities still need to be determined.

6.3 Suspension drive tuning

To minimize the unintended conversion of global length drive to optic orientation in the suspensions, the drive channels at each stage of a suspension need to be appropriately balanced. This requires an angle sensor external to the suspension. The ITMs, BS, PR3 and SR3 have optical levers that can be used for this drive tuning. The small recycling mirrors do not have optical levers and need a different method. For some optics (PRM, e.g.), we may be able to make *ad hoc* optical levers using the PSL beam and a quadrant detector (temporarily set up on an in-air optics table). The other option would be to use wavefront sensors in locked sub-configurations.

The degree to which length drive must be de-coupled from angle depends on the amount of length correction required at each suspension stage. The goal is to limit the unintended optic angle fluctuations to be much smaller than the angular fluctuations due to the ISI (seismic) motion. Due to the large isolation of the ISI above 0.5 Hz, the de-coupling should only be important below about 0.5 Hz.

6.4 Mode matching

The mode matching between the IMC output beam and the power recycling cavity will be measured. Diagnostics and procedures for measuring the mode matching are described in [T0900407](#).

6.5 Thermal compensation system

While there will not be any significant thermal distortions to compensate in this phase, the compensation system can still be tested at some level. The components of the TCS will be in place: Hartmann sensors for each Michelson arm; ring heaters on the ITMs; CO₂ laser projectors for the compensation plates. The key aspects of these components to test are:

- *Hartmann sensors*. Sensitivity and stability of the sensors. Cross-talk between the X and Y arm paths.
- *Ring heaters*. Verification of expected optical path profile (using Hartmann sensors). Spatial uniformity of the profile.
- *CO₂ laser projectors*. Verification of expected optical path profile (using Hartmann sensors). Spatial uniformity of the profile.

6.6 Low frequency performance of seismic isolation

The locked sub-configurations discussed in section 6.1 will enable us to investigate the relative motion of different ISI platforms, especially at frequencies below ~ 0.1 Hz where the internal ISI sensors may not tell the real story (due to tilt coupling, or contamination from other noises). Feedforward corrections from ground sensors may be applied to minimize low-frequency cavity length fluctuations.

6.7 Dual-recycled Michelson (DRMI) operation

The main goal of the corner Michelson phase is to achieve robust locking of the dual-recycled Michelson, using the ‘3-f’ acquisition sensors. This would be verifying Step 6 of the acquisition sequence (section 7). It is not expected that WFS alignment control will be needed at this stage.

There may also be an opportunity to make some meaningful noise measurements in this configuration. Modeling of the locking and potential readout sensitivity is currently being performed to see what is achievable. The basic idea would be to lock the DRMI on a carrier resonance in the power recycling cavity¹, and measure the Michelson degree-of-freedom using DC readout and the OMC (output mode cleaner). The sensing noise for this configuration could be of order 10^{-17} m/rtHz, and the displacement noise would be limited by the BS (beamsplitter) motion. The question of how much effort should be put into noise investigations at this stage depends on several factors: modeling results for what is achievable; amount of testing time in this phase before the arm cavities are available; availability of the output mode cleaner. As these factors become better known, more specific plans will be made.

6.8 Laser power

In the nominal sequence of Acquisition mode steps (see section 8), the laser power when the DRMI is initially locked is at one to several watts of power. This is the laser power at which we intend to establish the robust DRMI locking described in the previous section. However, it may be worthwhile to operate the DRMI phase at higher laser power, with the DRMI locked on a carrier resonance in the power recycling cavity; this could allow us to look for any thermal or other power handling issues (not expected to be a problem at this level), or to achieve more sensitive Michelson displacement noise measurements.

¹ In the full interferometer acquisition sequence, when the DRMI is first locked, the carrier is not resonant in the power recycling cavity (it is essentially anti-resonant), since the arm cavities are still far from carrier resonance. However, by appropriate use of error signals, the power recycling cavity can be locked on a carrier resonance.

6.9 Summary of corner Michelson objectives

Only a few of the activities and measurements described above are really required before moving on to full interferometer locking. Once both ETMs have been installed and their seismic isolation and suspension systems sufficiently checked out, we will move to working on full interferometer locking. The required testing in the corner Michelson phase is:

Activity/Measurement	Target
Locking of the DRMI using the acquisition sensors	DRMI should be lockable at any time of the day, and remained locked for >10 hour stretches. Power level in the power recycling cavity should be stable to better than 10%.
Recycling cavity length measurements	To a level (TBD) that verifies they are adequate for full interferometer locking
Mode matching	Mode matching between IMC output beam and the power recycling cavity mode should be >85%

The power stability in the power recycling cavity is an issue of alignment stability, and achieving the required level of stability could involve a combination of improvements to the seismic isolation controls and the suspension controls (local damping and force-to-angle decoupling).

The additional testing that is considered optional during this phase is:

- Suspension drive tuning
- Thermal compensation system characterization
- Seismic isolation performance optimization
- Investigations on the noise performance of the DRMI
- Wavefront sensor (WFS) implementation on the DRMI
- Higher laser power operation of the DRMI

7 Arm Cavity with Half-Vertex phase (Half-Interferometer)

The configuration in this phase consists of a single arm cavity, the beamsplitter, the power recycling cavity mirrors, the input mode cleaner, and the PSL; see Figure 1. The goal of this phase is to advance the implementation and testing of the Arm Length Stabilization system. Referring to the Acquisition Mode steps outlined in the following section, the LHO single arm cavity phase (H2OAT) tested only **Step 1** (locking the ALS 532 nm beam to the arm cavity). In this half-interferometer (HIFO) phase, we will be testing **Steps 0, 1, 2, and 5**. Since **Step 3** is just a repeat of **Step 1**, but for the other arm cavity, the only part of the ALS system that will not be tested after this phase is **Step 4**, which uses the beat signal between the two arm cavity 532 nm beams. Also, **Step 4** is where the ALS signals are used to actually stabilize the arm length, with feedback to the arm cavity. It may be possible to test the arm cavity feedback in this HIFO phase, depending on the noise level of the corner station beat signal.

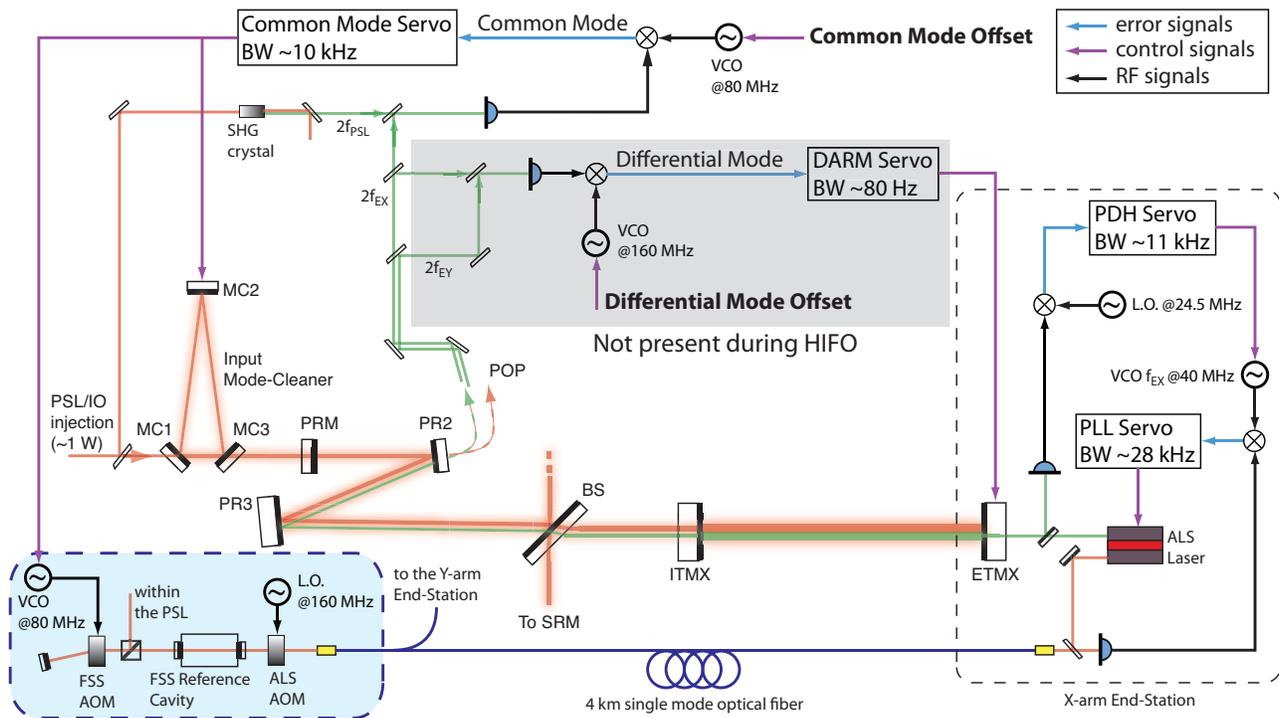


Figure 1. Configuration for the half-interferometer testing phase. This drawing shows the setup for the X-arm cavity, though the first implementation will be on the H1 Y-arm.

7.1 Specific HIFO commissioning tasks

The following list of tasks for the first HIFO phase is more-or-less in chronological order.

1. Implement frequency doubling of the PSL sample beam on ISCT1, including appropriate diagnostics.
2. Re-establish locking of the ALS 532 nm beam to the arm cavity.
3. Find the ALS 532 nm beam in the vertex; establish propagation of the beam onto ISCT1. Verify expected parameters of the beam (power, beam size, pointing stability).
4. Lock the arm cavity to the PSL 1064 nm beam, using the REFL detector and the Common Mode servo (no ALS locking in this step). Establish alignment of the TransMon 1064 nm quad-photodiodes (QPDs).
5. Establish an overall alignment procedure.
6. Establish the beat signal between the two 532 nm beams on ISCT1, and the error signal created by mixing it with the low-noise VCO in the Phase/Frequency Discriminator chassis.
7. Implement the Common Mode servo feedback, using the above as the error signal.
8. Determine if the arm is locked on an even or odd 532 nm resonance (see next section), and tune beat frequency if necessary. Demonstrate fine tuning of the PSL frequency relative to the arm cavity resonance, at the resolution level of ~ 10 Hz.

9. Characterize the stability of the system: stability of the PSL frequency relative to the arm resonance; stability of the PSL beam power buildup in the arm cavity; stability of the vertex beat signal.
10. Characterize the TransMon 1064 nm QPDs, in terms of cavity alignment sensing and stability.
11. Implement feedback to the arm cavity length (actuating on quad suspension), rather than to the laser frequency (via the Common Mode servo). The goal would be to stabilize the arm cavity length to ~ 1 nm residual motion. Whether this can be achieved in this state will depend on whether the error signal noise is low enough (i.e., laser frequency stability), given the dynamic range of the suspension actuators.
12. Automation of procedures.

7.2 Configuration customizations

For the first HIFO phase on H1, there are some differences in the setup compared to the nominal design that are worth noting for reference:

- The H2OAT end-station installation in BSC6 is used, rather than the eventual installation in BSC10. This means that the arm cavity length is a few meters longer than the design; this should have no impact on the test.
- ETMY has an ITM-type coating on the HR surface (as in the H2OAT). This means that the arm cavity finesse for 1064 nm is 225, half the nominal design; also, essentially all the 1064 nm light incident on the arm will be transmitted to the TransMon, rather than 10^{-3} of the incident power. Finally, the transmission efficiency of the 532 nm beam through the vertex will be about 2x higher than nominal.
- Nominally, 95% of the REFL beam is dumped in HAM1. However, since we would like to lock the PSL 1064 nm beam to the arm cavity using the ISCT1 REFL error signal, we may change this splitter and direct more of the light to ISCT1.

8 Acquisition Mode steps

The following lists the envisioned steps that go from an uncontrolled interferometer to one locked at the operating point. The final sequence developed will surely be different in detail, but the main ingredients should not change much.

Step 0. The input mode cleaner is locked to the PSL, at low power (nominally 1 W, possibly several watts). The power and signal recycling mirrors are mis-aligned, but all other optics are nominally aligned.

Step 1. The X-end Arm Length Stabilization (ALS) laser is phase locked to the PSL light with some frequency offset (see below). The ALS 532 nm beam is then locked to the X arm cavity, using the reflection (PDH) error signal, and feeding back to the VCO that drives the phase-lock loop.

Step 2. The interferometer Common Mode servo is engaged, with the error signal derived from the beat frequency ($B_{X/PSL}$) between the X-arm ALS beam and a frequency-doubled PSL beam sample (in the corner station). This ties the PSL frequency to the X arm length. At this point a

determination is made as to whether the X arm is locked on an even or odd 532 nm resonance (see Figure 2). If the X-end phase locking is done with a frequency offset equal to an integral number of arm cavity free-spectral-ranges, then for an even resonance the PSL light should also be resonant, which can be checked with the TransMon detectors. If the arm is not on an even 532 nm resonance, the beat frequency $B_{X/PSL}$ is changed by 37.5 kHz, shifting the arm cavity length by 256 nm.

Step 3. The Y-end ALS laser is phase locked to the PSL light, then locked to the Y arm cavity, as in Step 1. (Note: the ALS-PSL phase locking is mentioned here in Steps 1 & 3, but nominally the ALS laser will always remain phase locked to the PSL light.)

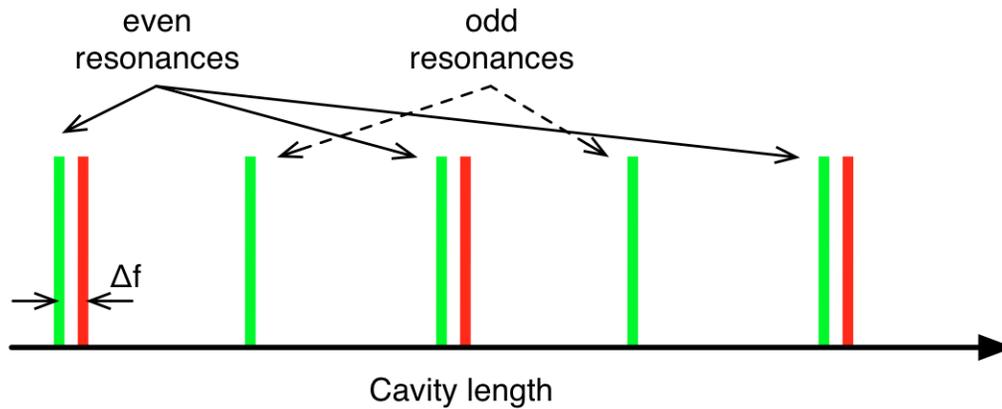


Figure 2. As a function of the arm cavity length, there are two 532 nm resonances for every one 1064 nm resonance. The ALS needs to lock on a resonance for which the initial frequency offset between the ALS 532 nm beam and the PSL light is the desired Δf .

Step 4. The beat signal between the two ALS beams in the corner station ($B_{X/Y}$) is used to stabilize the Y arm length. As in Step 2, the even/odd resonance condition is checked, and if necessary the beat frequency $B_{X/Y}$ is changed by 37.5 kHz to shift the Y arm length by 256 nm.

Step 5. The beat frequency $B_{X/PSL}$ is shifted by ~ 1 kHz, which will change the length of the arm cavities to that they are ~ 10 nm away from a resonance of the PSL light.

Step 6. The PRM and SRM are aligned. The dual-recycled Michelson in the corner station is then locked, using the ‘3-f’ acquisition error signals for the recycling cavities (PRC and SRC) and the Michelson; see [T1000294](#) (*Lock Acquisition Study for Advanced LIGO*).

Step 7. In this stage the arm cavities are brought into resonance for the PSL 1064 nm light, and the arm cavity error signals are switched to RF demodulation signals from 1064 nm photodetectors. The arm cavities are brought towards the PSL resonance by controlling the beat frequency $B_{X/PSL}$. A possible procedure for transitioning the sensors is described in [T1000294](#). For the Common Mode servo error signal, T1000294 simulated the following (TRX/Y is the 1064 nm power in transmission from the X/Y arm):

$$\text{ALS signal} \rightarrow (TRX + TRY)^{1/2} \rightarrow (TRX + TRY)^{1/2} + \text{REFL_DC} \rightarrow \text{REFL I1}$$

Much depends on the stability of the ALS 532 nm resonances, relative to the PSL 1064 nm resonances. If this is quite stable, it should be possible to simplify this sequence, and possibly even

transition directly from using the ALS signal ($B_{X/PSL}$) to using REFL_I1 (9 MHz demodulation signal from the reflection photodetector).

For DARM control, the error signal is switched from the ALS signal ($B_{X/Y}$) to the 1064 nm RF error signal (AS_Q2) when the arm cavity 1064 nm power is about 100 times the single cavity power.

Step 8. In the final stage of acquisition mode the alignment system is engaged in its acquisition mode. In this mode, described in T0900511, the alignment of the arm cavities is controlled with a relatively high bandwidth (~ 1 Hz), and slow drift control only is applied to the recycling cavities and Michelson. This allows the use of a simple diagonal sensing matrix. Some parts of the alignment control may be engaged in earlier steps, if found to be necessary or beneficial.

9 Locked Mode steps

Locked mode includes all the steps required to take the interferometer from a state where it is locked at its operating point to low-noise operation. The steps involved in making this transition are:

- Switching to low-noise sensors. The ‘3-f’ signals used for sensing PRCL, SRCL and MICH are switched to their nominal RF signals (POP_I1, POP_I2, POP_Q2). This is in fact envisioned to be a two step process: first the error signals are switched to those derived from the in-air LSC photodetectors; later they are switched to those derived from the in-vacuum detectors.
- Increasing the laser power. The laser power is increased via the IO power control. This may be done in multiple steps, with power increases interleaved with some of the other steps in this list.
- Activating thermal compensation. The test mass ring heaters and the CO₂ laser projector beams are engaged as needed. The first level of compensation is expected to be achieved with the ITM ring heaters, followed (when necessary) by optimization using the CO₂ beams. The ETM rings heaters should only be required at higher levels of arm cavity power.
- Engaging low-noise mode for the suspension drivers. Low-pass filters in the suspension coil drivers are engaged (if not already done). The test mass electro-static drivers (ESDs) are also switched into low-noise, low range mode.
- Optimizing suspension damping filters (if necessary). To reduce noise from the suspension local sensors, damping levels may be reduced or different filters engaged.
- Optimizing length control loops. This step is aimed at reducing the DARM noise contribution from the auxiliary length loops to an acceptable level. It will involve a combination of: bandwidth tuning; engagement of above-band low-pass filters; engagement and tuning of auxiliary length-to-DARM correction paths.
- Transitioning alignment control to operational mode. To achieve low-noise mode for the alignment control, the sensor matrix becomes more complex to better reconstruct each degree-of-freedom, loops bandwidths are adjusted, and better low-pass (cut-off) filters are implemented (see T0900511).

10 Summary of Integration Sequences

The sequencing of the integration phases for L1 and H1 is coordinated to be complementary: operation of the long arm cavities and the Arm Length Stabilization system is pioneered at LHO, while the vertex operation is the focus at the beginning for LLO. More specifically:

- The Input Mode Cleaner is commissioned first on L1, where a relatively long commissioning period is available while the rest of the vertex components are being installed. Thus more in-depth testing of the L1 IMC can be done, such as higher power operation. For the H1 IMC, on the other hand, we anticipate a relatively short commissioning period to achieve reliable and stable operation before moving on to the next phase.
- The Arm Length Stabilization system will be fully implemented first on H1, first with the H2OAT, then the HIFO-Y phase. This is followed by a HIFO-X phase, which includes a period when both HIFO-X and HIFO-Y are functional. This is the Full Arm Length Stabilization configuration that fully tests the ALS system. The lessons learned along the way can be applied to the L1 ALS at the outset.
- The Dual Recycled Michelson configuration is first implemented on L1, with a relatively long commissioning time (twice as long as on H1). This affords more in-depth testing, such as higher-power operation and Michelson displacement noise investigations.

10.1 H1

The planned integration sequence for H1 is shown below. A HIFO-X phase follows the HIFO-Y phase, to continue the ALS implementation. This is motivated by the anticipation that demonstrating one of the key requirements of the ALS—reducing the relative arm length fluctuations to ~ 1 nm—will not be possible until we have two arm cavities.

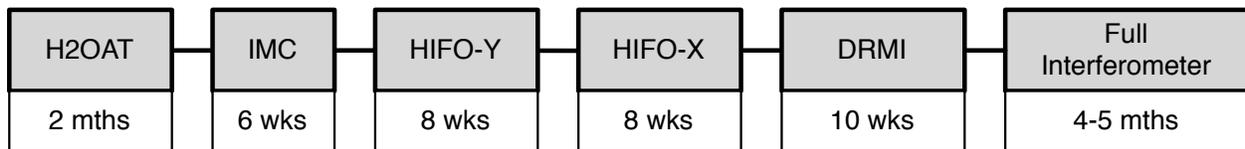


Figure 3. Integration sequence for H1.

10.2 L1



Figure 4. Integration sequence for L1.