Building the HARMONI Engineering Model

T. Foster[a], J. Capone[a], A. Earle[b], A. Hidalgo[a], I. Lewis[a], J. Lynn[a], K. O'Brien[d], M. Rodrigues[a], I. Tosh[b], B. Watkins[a], F. Clarke[a], H. Schnetler[c], M. Tecza[a], N. Thatte[a]

[a]University of Oxford - Department of physics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK; [b]RAL space - Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire, OX11 0QX, UK; [c]STFC UK Astronomy Technology Centre Royal Observatory, Edinburgh Blackford Hill Edinburgh, UK; [d]Durham University, Department of Physics, South Rd, Durham, DH1 3LE, UK

ABSTRACT

HARMONI (High Angular Resolution MOnolithic Integral field spectrograph)[1] is a planned first-light integral field spectrograph for the Extremely Large Telescope. The spectrograph sub-system is being designed, developed, and built by the University of Oxford. The project has just completed the Preliminary Design Review (PDR), with all major systems having nearly reached a final conceptual design. As part of the overall prototyping and assembly, integration, and testing (AIT) of the HARMONI spectrograph, we will be building a full-scale engineering model of the spectrograph. This will include all of the moving and mechanical systems, but without optics. Its main purpose is to confirm the AIT tasks before the availability of the optics, and the system will be tested at HARMONI cryogenic temperatures. By the time of the construction of the engineering model, all of the individual modules and mechanisms of the spectrograph will have been prototyped and cryogenically tested. The lessons learned from the engineering model will then be fed back into the overall design of the spectrograph modules ahead of their development.

Keywords: HARMONI, ELT, Integral-Field Spectrograph, systems engineering, prototyping

1. INTRODUCTION

The spectrograph sub-system is responsible for dispersing the light from the slicer with the required spectral resolving power and imaging the spectra on to a detector. Each image slicer creates a single exit slit feeding a single spectrograph containing visible (VIS) and infrared (IR) cameras. The four HARMONI slicers in total create four exit slits, feeding four spectrograph comprising of collimator, dispersers, and cameras. The focal plane of each camera contains a mosaic of two 4K x 4K detectors, leading to 8K pixels along the length of the slit.

The spectrograph is split into 9 modules, as shown in the block diagram and optical layout in Figure 1. The image slicer creates a single entrance slit that feeds the light toward the collimator module. The beam is then redirected towards either the VIS or NIR channels, both consisting of 3 modules: a grating module, a camera module and a science detector module. All of these modules are framed in the spectrograph main structure which interfaces with the IFS cold structure. The shared collimator and fold layout are key to achieving a compact spectrograph that will fit in the relatively small volume allocated in the IFS cryostat.

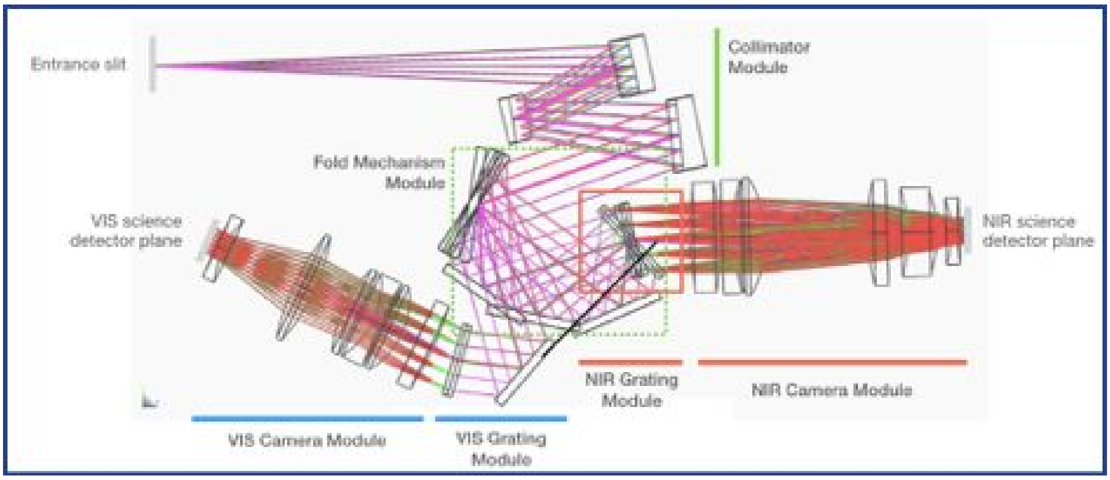

Figure 1. Optical layout of the HARMONI spectrograph from PDR. Light enters from the entrance slit, whereupon it is collimated, and then folded onto the disperser with the correct angle of incidence. It is then focused onto a detector by one of two cameras.

Each of the major modules of the spectrograph performs important functions with tight tolerances on alignment, accuracy, and repeatability. Therefore, it is necessary to test each module individually under the HARMONI system parameters to determine the effectiveness to which it works. Once each individual unit has passed the testing phase, an engineering model (EM) of the full spectrograph will be built, with tests performed on the full sub-system (without optics) to see how well the individual units function together. The EM will be key for testing the assembly and verification process as well, and refining the way in which we will test the actual spectrograph sub-systems.

Once the tests for the individual units and EM are passed, HARMONI will be nearing its Final Design Review (FDR). Upon passing, work will start on building and testing the four HARMONI spectrographs (all to be built and tested within two years). This will be quite a large task, and will rely on the same tests used with the EM units. As such, designing tests that are simple and effective will be necessary to ensure the real spectrographs can be tested and verified on time, one after another in a streamlined process.

The size of the individual modules, as well as the complete EM, pose the second major challenge when prototyping. They are very large and need to be tested at cryogenic temperatures, and require multiple dedicated cryogenic test chambers as well as a suite of instruments.

The rest of the paper will focus in detail on these two challenges: the repeatability requirements of the mechanisms and the designing of simple and accurate tests, and the size of the modules when prototyping and the facilities and instruments required.

2. PROTOTYPING

2.1. Mechanisms and Repeatability

The repeatability tolerances for all modules are driven by the HARMONI system requirement that the spectra be repeatable to within 1/10th of a resolution element on the timescale of 24 hours (goal 7 days). This allows for calibration data to be taken the following morning, with all relevant on-sky science observations taking place at night. A resolution element is 2.2 pixels, so the spectra must be repeatable to ~0.2 pixels. On timescales of one hour, the spectra must be stable to better than 0.05 pixels. Each pixel is 15 µm in size, leading to a required stability of <1.5 µm over 24 hours, and <0.075 µm over one hour.[2] These tolerances are extremely tight, and pose the first major challenge we face in the prototyping of HARMONI.

2.1.1. Fold Mirror Mechanism

To meet HARMONI's spectral coverage and spatial resolution requirements, 10 infrared configurations are needed in the spectrograph design. Each of these configurations uses a separate volume phase holographic grating, mounted on a movable wheel. While the gratings can be selected, their angles cannot be changed, and the camera is fixed within the wheel. This means that the collimated pupil must be folded onto the grating to achieve the correct angle of incidence, with this angle changing for different gratings.

A fold mirror mechanism (FMM) was designed to do this with two adjustable flat mirrors. The first mirror (Swing Arm Unit - SAU) is articulated about its centre, with the second (Articulated Fold Unit - AFU) mounted on a movable swing arm. As HARMONI will be run for extended periods of time at cryogenic temperatures of around 130K, it is important that the fold mirror mechanism not only functions for extended periods of time at these temperatures, but does not deform at all while cooling down.

The FM1 and FM2 mirrors have to be repositioned with tight tolerances after changing configurations. FM1 has been identified as the dominant contribution to the non-repeatability of the spectra in the spectral direction.[3] Figure 2 shows the proposed mechanical design, which has been optimized to deliver repositioning accuracy below 1 micrometer. The prototype is on-going, and outlined in Section 2.2.1.

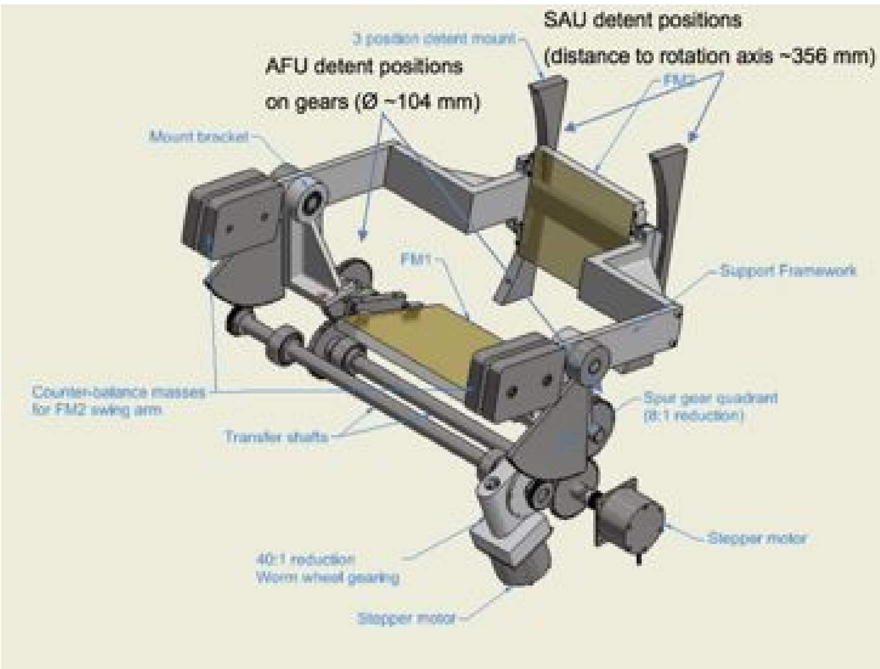

Figure 2. Image showing the FMM PDR design, as well as the detents.

2.1.1.1. Detent mechanism

Both systems will, as of the PDR design, use a detent mechanism to lock the fold mirror and swing arm in place after each movement. These have been designed to achieve the necessary levels of repeatability. We have begun on testing the detents (as discussed in Section 2.2.1.1), of which there are three different prototypes - a spring plunger, a 6.5cm long beam with plunger, and a 13cm long beam with plunger. These are shown in Figures 3-5.

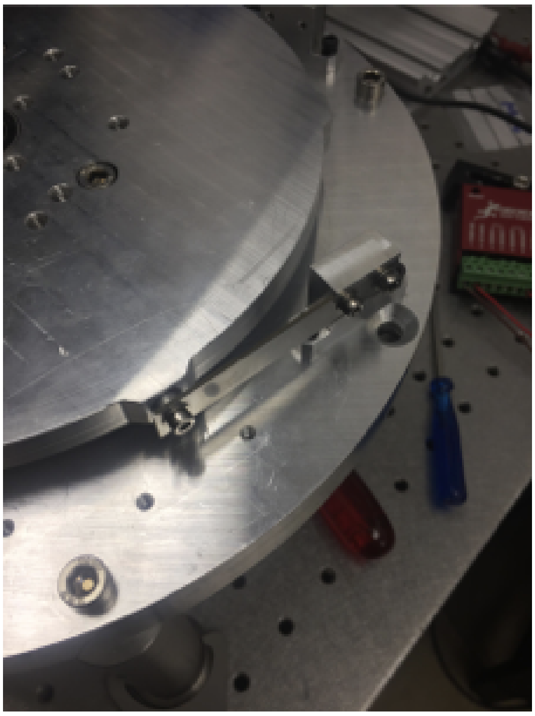

Figure 3. Configuration 1: Cantilever. This configuration consists of a single-length beam, which can bend based on the force applied. Measured forces for each range from 10-40N.

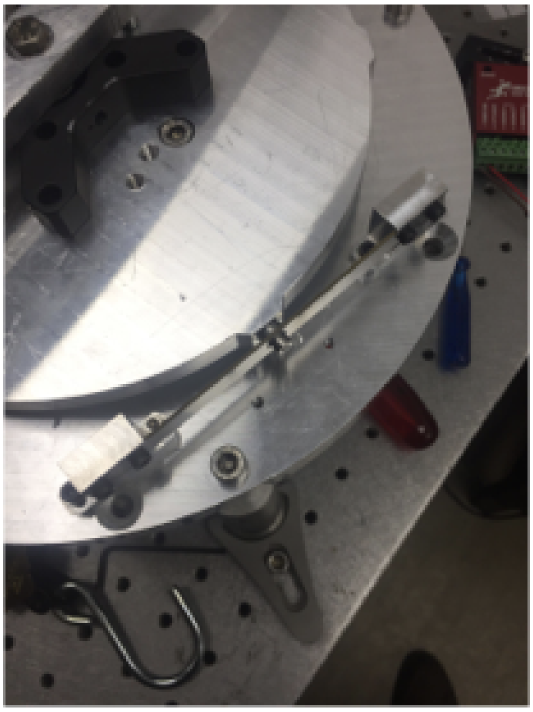

Figure 4. Configuration 2: Built-in ends. This configuration consists of a double-length beam, which can bend based on the force applied. Measured forces for each range from 100N-130N.

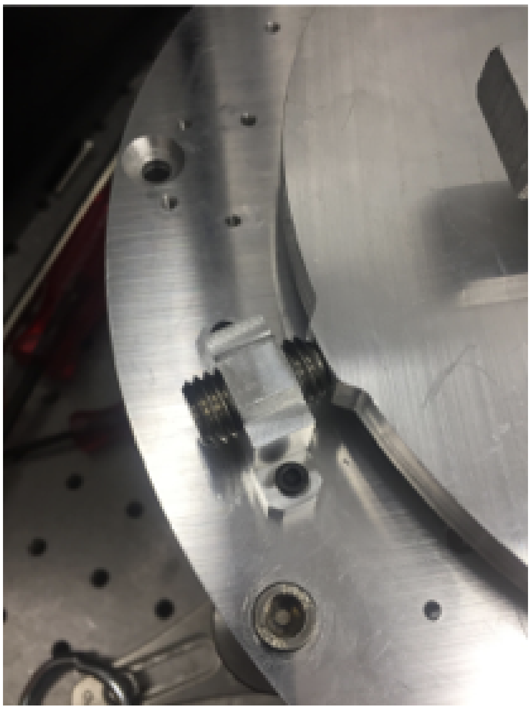

Figure 5. Configuration 3: Spring Plunger. This configuration consists of a spring plunger fastened directly into the detent. Measured forces for each range from 25N-50N.

2.1.2. IR Grating Module

The IR Grating Module (shown in Figure 6) consists of the grating wheel and drive. The drive consists of an indexing unit base with worm wheel reduction gearbox (210:1), similar to that used on KMOS[4], and a grating mount flange upon which the 10 grating cradle assemblies are mounted. The non-repeatability of the IR grating wheel drive has been identified as the main contributor to the spectra repeatability in the spatial direction.[5] The design has been optimized to deliver high repositioning accuracy and minimize wobbling, on the order of 5 micrometers. Prototyping of the mechanical parts is on-going to verify the achieved repeatability of the mechanisms. The prototyping activities and a test plan are outlined in Section 2.2.2.

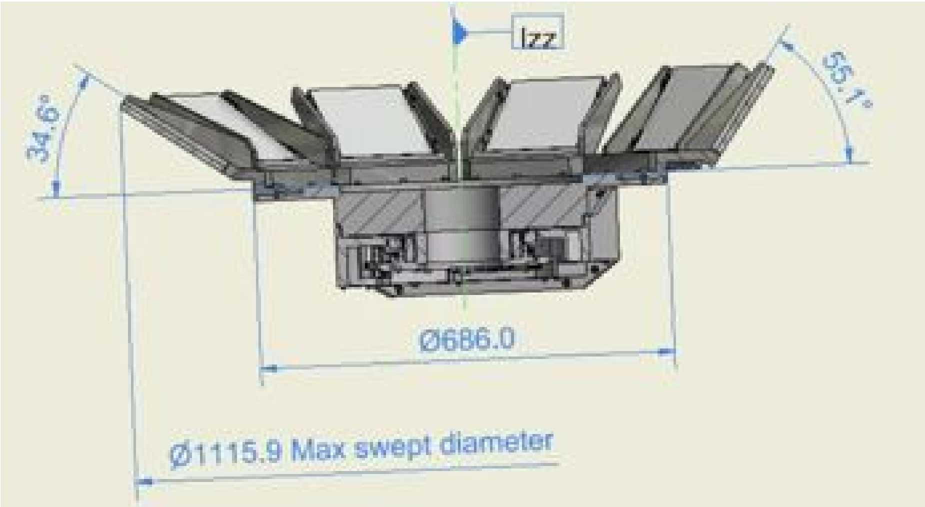

Figure 6. Image showing the IGM PDR design.

2.1.3. IR Camera Module

The IR camera module, shown in Figure 7, is mounted inside of the grating wheel, and is responsible for focusing the input beam onto the detector. While there are no moving parts, the camera must be able to focus not only the chief ray, but also all off-axis rays. These are inclined at 10° either side of the chief ray.

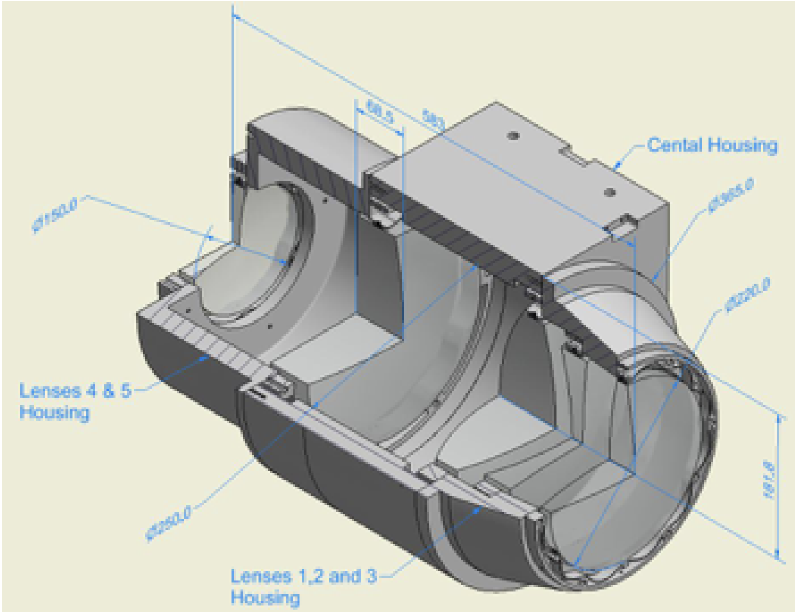

Figure 7. Image showing the NIR camera module.

2.1.4. Collimator Module

The collimator module, shown in Figure 8, takes the beam from the entrance slit and collimates it, preparing it before it enters the FMM and dispersing element. While there are no moving parts, the collimator must be able to collimate not only the chief ray, but also all off-axis rays. These are inclined at 10° either side of the chief ray.

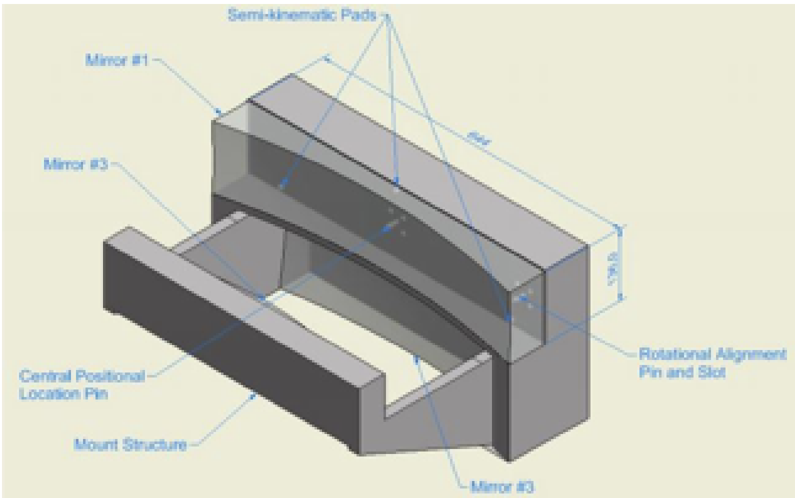

Figure 8. The collimator module. Light from the slit hits Mirror #1 first.

2.2. Prototyping and Testing

Each of these modules will be tested individually ahead of building the EM. These same tests will be used during the assembly, integration, and verification phase for the four 'real' HARMONI spectrographs. As such, these tests must not only be able to accurately measure movements to sub-micrometer levels of precision, but also easy to setup and replicate.

For all mechanical modules the tests will be:

- Measurements of the stability of the system in warm environment
- Measurements of the repeatability of re-positioning after movement in warm environment
- Measurements of the stability of the system in a stable cold temperature environment
- Measurements of stability of the system against temperature changes around the operational temperature (130K)
- Accelerated lifetime testing at the operational temperature

The warm testing will take place first. If the warm repeatability tests do not meet the repeatability requirements, the test will be considered failed. If it meets the requirements it will pass on to cold testing. If the cold repeatability tests do not meet the repeatability requirements, the test will be considered failed. If it meets the requirements it will pass on to cold accelerated lifetime testing.

2.2.1. Fold Mirror Mechanism

To test the accuracy of the axial movements of each individual mirror in the FMM, and the two together, at cryogenic temperatures, the entire module will be mounted inside a cryostat and cooled down to 130K.
The test will require an interferometer and four static mirrors, and one reference flat. The FMM will be oriented inside the chamber in the same orientation it will be mounted in HARMONI, so as to replicate the gravity vector. The reference flat will be placed directly in the optical path of the interferometer, returning some of the beam immediately back (whether the flat will be inside or outside the chamber is still to be determined). This will be used to subtract off movements of the interferometer relative to the chamber.

The first mirror will be placed so that the beam of the interferometer is reflected towards the fold mirror at the same angle of incidence that would come from HARMONI's collimator. The beam will then travel through the mechanism as normal. At the pupil location there will be three smaller mirrors, each at a different angle, representing the three different types of grating orientations. Depending on the position of the FMM, the light will hit one of these mirrors, and return backwards through the system. The interferometer can then take a measurement, and this will be done before and after movements and compared. As the beam will travel through the system twice, the output values of mirror tilt will need to be divided by two. The setup can be seen in Figure 9.

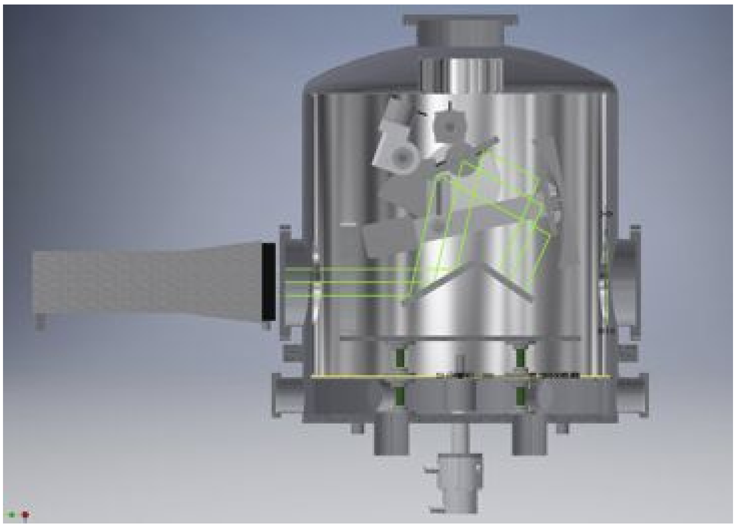

Figure 9. Image showing the planned test for the FMM inside a cryostat (in this image the chamber is 1.4m tall). The Interferometer is shown on the left side of the chamber.

2.2.1.1. Detent mechanism

As part of the testing of the FMM, the detents will be first prototyped and tested individually. The test mechanism consists of two discs mounted on top of one another, with the detents fixed to the bottom disc (shown in Figure 10), and the upper disc rotating with set lockable positions. Two co-aligned right-angle mirrors are used, with one mounted on the lower disc, and one mounted on the upper disc (Figure 11). Tests will involve the use of solenoids that will act as linear actuators, pulling the detents out of position before the wheel rotates. Measurements are taken with an interferometer aligned to the mirrors.

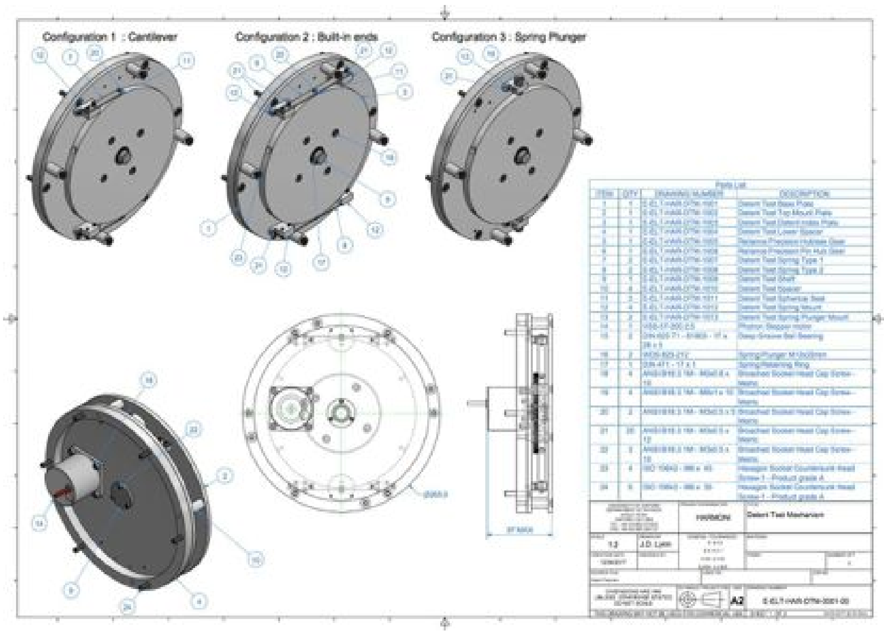

Figure 10. Image showing the detent test mechanism for each of the three detent prototypes.

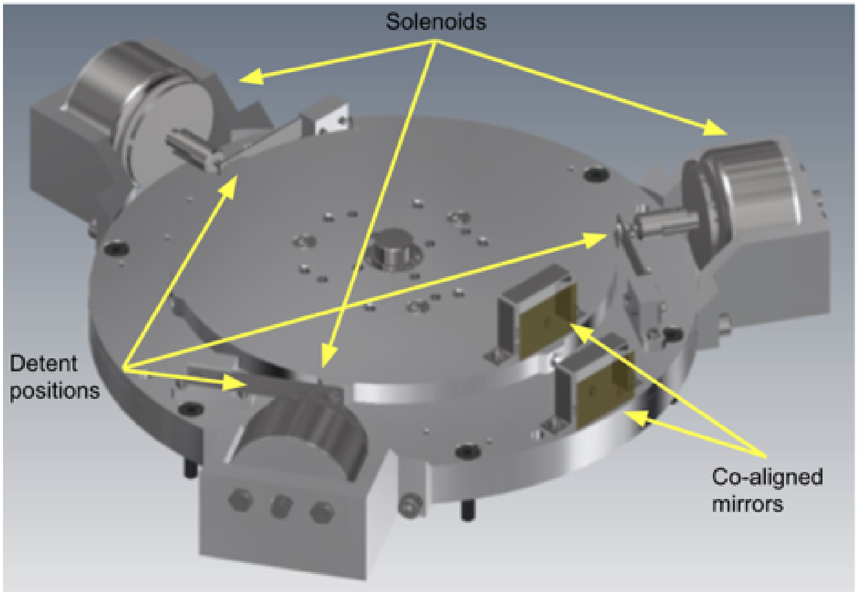

Figure 11. Image showing the setup of the detent test mechanism including co-aligned mirrors and solenoids.

The test is driven by a McLennan 23HSX stepper motor, which has been connected to a Geckodrive GM203V controllable stepper motor drive and to a computer via an Arduino. A worm gear with a 70:1 gear ratio is used alongside the stepper motor so as to apply sufficient torque to rotate the mechanism.

One measurement will be taken before each movement, and five measurements will be taken at 1 minute intervals after each movement. This will be done for 18 detent setups:

1. For each of three different detent types (single-beam, double-beam, spring plunger)
   A. Test with one, two, and three detents in position
      a. For each of (A), test with two different forces applied per detent (normal amount, maximum amount)

Exposures will be taken, with two interferograms produced per measurement. The angular shift of the mirror mounted on the lower static disc will be subtracted from the angular shift of the upper rotating disc, leaving the amount the detent mechanism has rotated in between movements. Five measurements are taken after each movement to see if the detent 'settles' back into place over time.

The accuracy of the rotations could also be lowered by deformations of the mechanisms or the mirrors. Deformations could be caused due to changes in temperature or by prolonged use.

2.2.2. IR Grating Module

To avoid stress on the gratings, the IGM will first be tested without gratings. It will be a test purely of the motors and other moving mechanisms, with dummy masses placed on the wheel instead of the gratings. This will allow us to test the repeatability and accuracy of the movements without needing any gratings.

To test the repeatability of the centroid movements of the wheel at cryogenic temperatures, the IGM will be mounted inside a cryostat (as shown in Figure 12) and cooled down to 130K. The wheel will be inclined from vertical at 17.5 degrees, which is the same orientation as in HARMONI. An mirror will be attached to the edge of the wheel. This mirror will be viewed through the side port of the chamber, and aligned with the interferometer (mounted externally). Measurements will be taken before and after movements to determine the repeatability between movements.

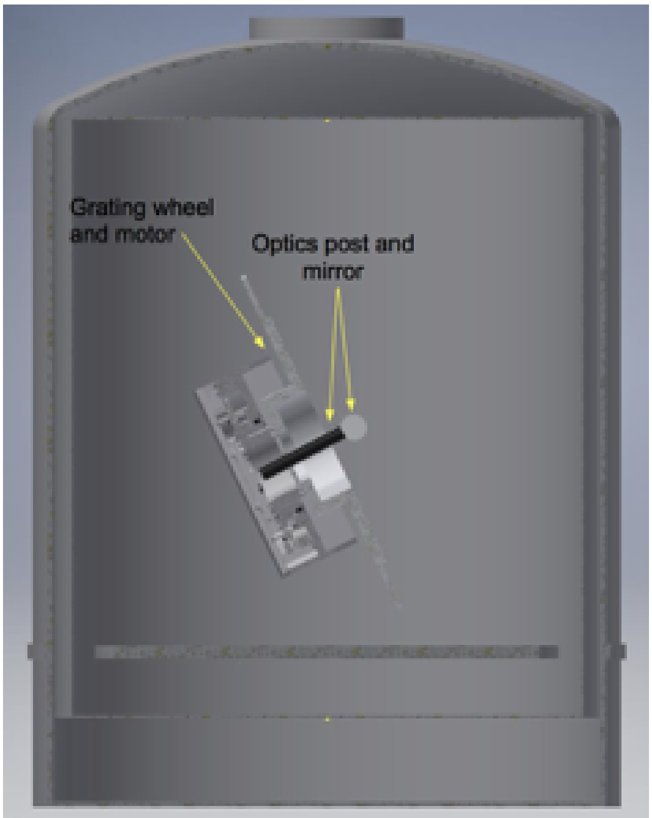

Figure 12. Image showing the test setup for the IGM inside a cryostat Mounting units and dummy masses are not shown.

2.2.3. IR Camera Module

As there are no moving parts, the test is of the optical quality of the six lenses within the camera barrel, as well as how they deform while cooling to, and at, 130K. The off-axis rays will also be tested (+/- 10° either side).

The unit will be mounted inside a cryostat as seen in Figure 13 and cooled to 130K. It will be mounted vertically, and high enough inside the chamber such that the pupil is above the top flange.

The interferometer will be mounted above the chamber, pointing down, and will be able to articulate about its axis. The transmission flat must also be able to articulate +/- 10° and be placed inside the cryostat (otherwise the only measurement would be the optical quality of the cryostat window). A return sphere will be placed at the focus, and will be mounted on an X-Y-Z translation stage, allowing it to be positioned at the correct point depending on which beam is being tested. The quality of the lenses will be tested such that the beam does not deviate more than 0.2 pixels on the detector, and is stable to within 0.05 pixels.

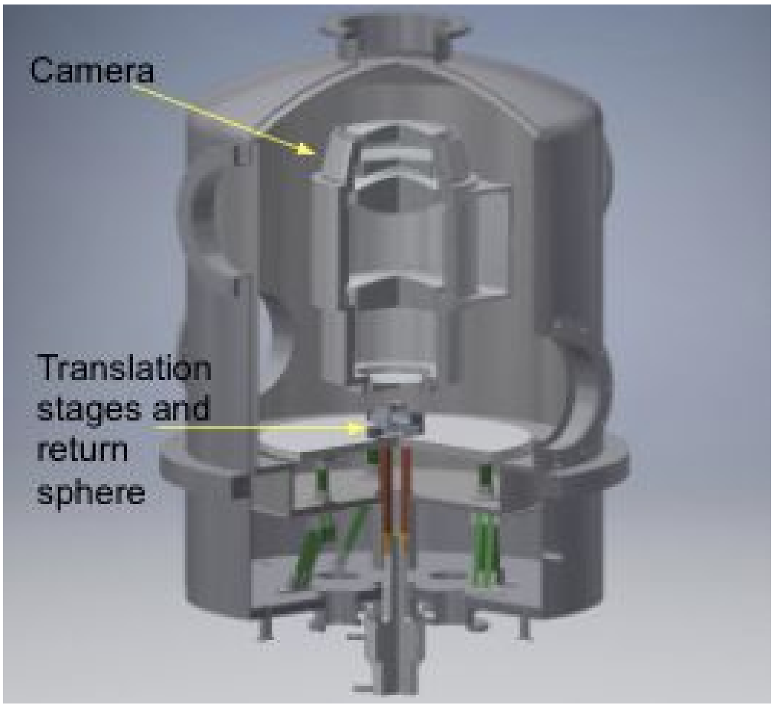

Figure 13. Image of the camera test setup inside a cryostat, with translation stages shown just below the final lens.

2.2.4. Collimator Module

As there are no moving parts, the test is of the optical quality of the three mirrors within the unit, as well as how they deform while cooling and cold. The unit mounted inside a cryostat can be seen in Figure 14.

The unit will be mounted inside a cryostat and cooled to 130K. It will be positioned such that the top of the chamber is directly above the third mirror, and the exit pupil is outside the chamber. The interferometer and transmission flat will be mounted as in the test of the IR camera module.

In this test, the light from the interferometer, which is already collimated, will pass through the collimator in reverse, and will be de-collimated. It will be focused at the position of the slit. However, the distance from M1 to the slit is 869mm, and so the beam needs to be folded within the chamber. This will be done by mounting a static mirror that will fold the light back towards the centre of the chamber. A return sphere will be placed at the focus in place of a slit.

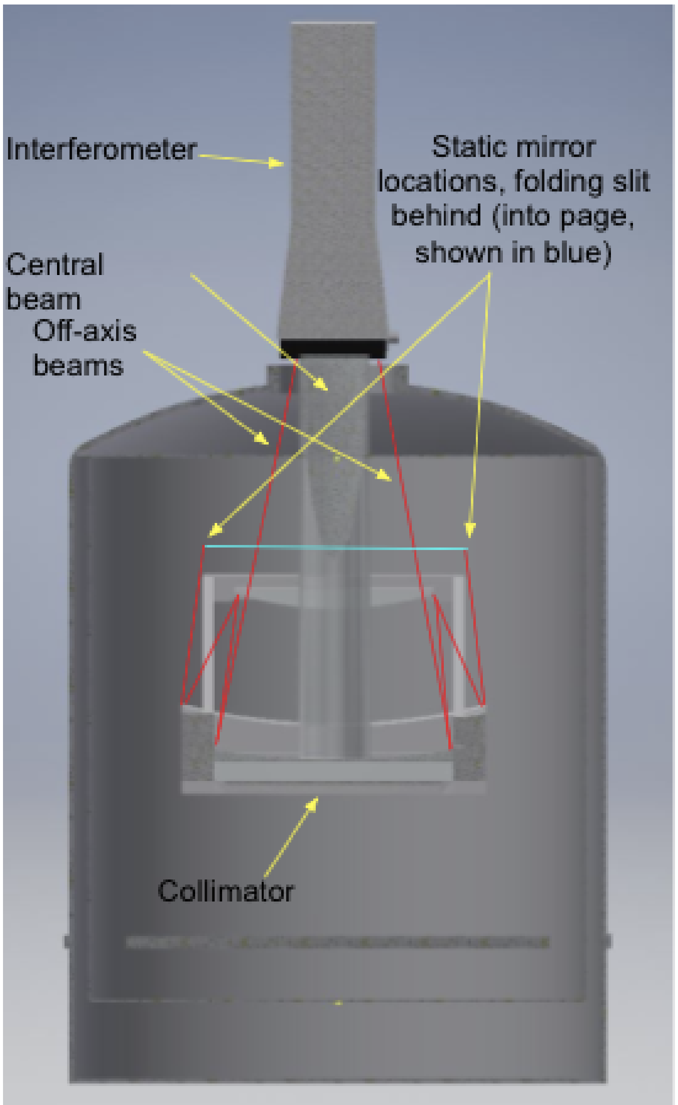

Figure 14. Image showing the collimator test setup with central and off-axis beams.

3. FACILITIES AND INSTRUMENTS

3.1. Cryogenic Chambers

To conduct the tests of the modules at the HARMONI system specifications, various instruments and mechanisms are needed. The most significant of these are two large cryogenic chambers, so that the tests can be carried out at 130K - the temperature of the HARMONI cryostat. The first is a 'smaller' chamber roughly 1 meter in diameter, designed for testing of the individual modules. The chamber will be ordered early this summer. The second is a larger chamber roughly 2.2 meters in diameter, which will be used to test the EM. This chamber has been in use by the University of Oxford for many years. Two separate chambers are needed so that modules can be tested in the 'small' chamber while the EM of a second spectrograph is being tested in the 2.2m chamber. This will allow for significantly faster AIT when the four HARMONI spectrographs are being built. These chambers will be placed in two separate laboratories at the University of Oxford.

3.1.1. 'Small' Chamber

We have designed the first chamber to be used for and facilitate the testing of the individual modules. This has been relatively difficult as the design must be able to not only accompany each individual module, but all the testing infrastructure as well, while still being 'general use' for future purposes and not overly large, expensive, or complicated. Thermal and structural limitations must also be considered. The chamber's design is almost complete, with a thorough review of all four tests taking place before placing an order later this month. We have conducted basic thermal and structural analyses of the chamber while it is cold to make sure the design is sufficient.

3.1.2. 2-Meter chamber

The second chamber is a much larger cryostat with a 2.2m diameter, as seen in Figures 15 and 16. It will be used to test the entire engineering model and spectrograph sub-systems at the HARMONI system specifications. The chamber had previously been used for blackbody target testing, and we spent over 50 hours preparing the chamber for HARMONI use. This was a valuable exercise as it familiarized us with all the various parts and components needed when designing a cryostat and an experiment within it. It was pumped down successfully this past December, and an initial cool down is targeted for spring of this year. As this chamber will most likely be ready for use before the 'small' chamber arrives, it will be used to conduct the initial prototype tests. All modules will be mounted on a cold plate previously used when testing the KMOS spectrograph.

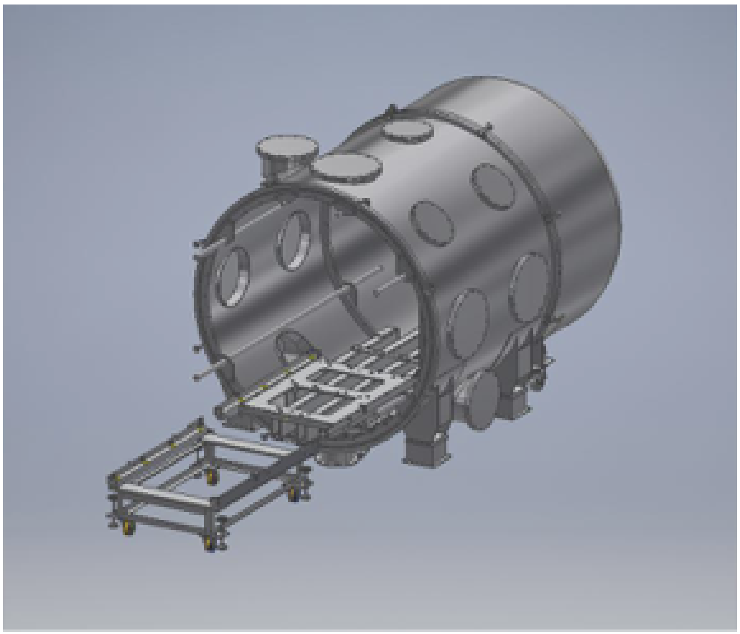

Figure 15. The large 2.2m tall cryostat that will be used for testing of the EM and full spectrographs.

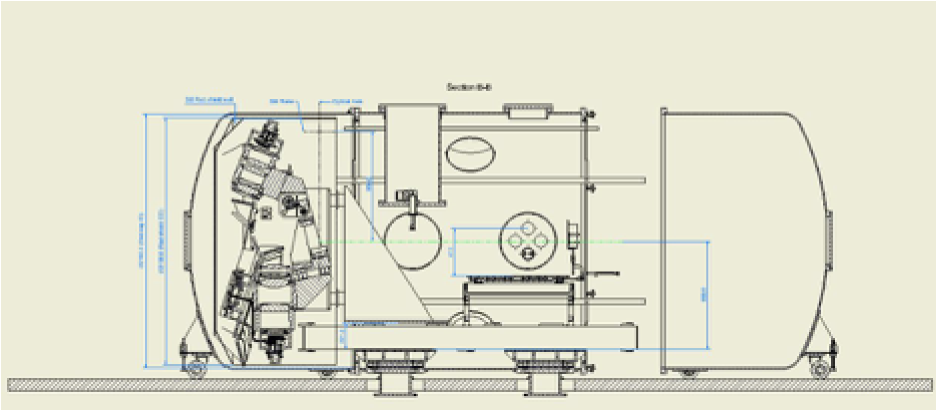

Figure 16. CAD drawing of the 2-Meter chamber showing the engineering model mounted in the left end cap. The right end cap will be used for testing of the individual modules.

3.2. Instruments

Several instruments are required to conduct these tests. The most significant are described below.

3.2.1. Interferometer

All four tests (outlined in the following section) will require the use of a 4D Technologies Fizeau interferometer. Already owned by the department, the interferometer allows us to measure deviations in optical path by creating an interference pattern relative to a reference pattern. This can be done to extremely high levels of accuracy, and will be used to measure mechanical repeatability of the moving mechanisms (FMM, IGM) as well as optical quality (collimator, camera). This model has a 6-inch diameter beam, which will be more than large enough for our tests. At this level, vibrations can greatly corrupt the data, so the interferometer will be 'bolted on' to the side or top of the cryostat depending on the test being conducted. Mounting the transmission flat inside the chamber, as well as using the interferometer in its dynamic mode, will mitigate the effects of vibration.[6]

3.2.2. Interferometer Articulation Mechanism

The optical tests of the collimator and IR camera module will require the interferometer to be articulated +/- 10°. To do this, a cage system involving a system of rails and detents is currently being designed. This system will be designed alongside the construction of the 'small' chamber, and will be tested next year.

3.2.3. Transmission Flat Articulation Mechanism

The optical tests of the collimator and IR camera module will require the transmission flat to be placed in the chamber and simultaneously aligned with the interferometer. This requires on-axis tilts of up to 10°. A mechanism has been designed that is similar to a kinematic mount that will hold the transmission flat, and be able to be controlled externally while the cryostat is at operating temperature. This is shown in Figures 17 and 18. The mechanism is currently being built at the University of Oxford, and will be tested this summer.

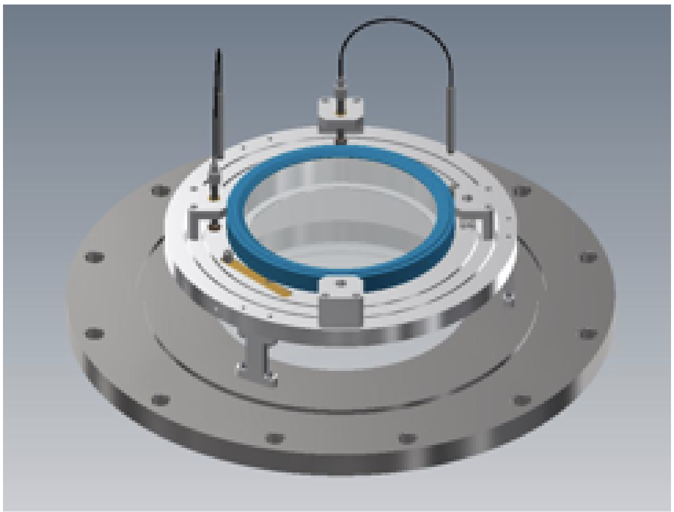

Figure 17. Image showing the mechanism, with the transmission flat inside the blue ring. This side is inside the chamber.

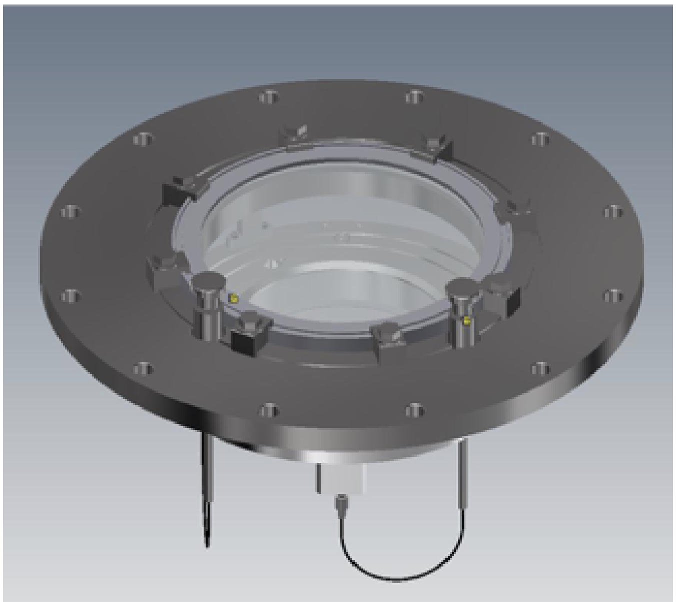

Figure 18: Image showing the mechanism from the opposite side, which will sit outside the chamber. Note the adjustment pins that will articulate the transmission flat.

4. CONCLUSION

This document has outlined the prototyping and testing of the individual modules involved in the construction of the HARMONI engineering model. Initial testing of the detent mechanisms has already begun, with further testing of the FMM, IGM, and transmission flat articulation mechanism being conducted this summer. Once all of the tests have been passed and the modules approved, the engineering model will be constructed and tested. This is planned for the first half of 2019.

REFERENCES

1. Thatte, N. et al., "The E-ELT first light spectrograph HARMONI: capabilities and modes," *Proceedings of SPIE*, 9908. (2016).
2. Clarke, F. et al., "HARMONI System Design and Analysis Report," (2017)
3. Capone, J., "Spectrograph - FMM-IGM Repeatability," HRM-00418 (2018).
4. Fairley, A., Sharples, R., Ritchie, L. et al., "KMOS: A Near-Infrared Multiple-Object Integral Field Spectrometer for the VLT," VLT-PLA-KMO-146601-009 (2007).
5. Capone, J., "Spectrograph - FMM-IGM Repeatability," HRM-00418 (2018).
6. Brock, N. et al., "Dynamic Interferometry," (2005).