Final design and build progress of WEAVE: the next generation wide-field spectroscopy facility for the William Herschel Telescope.

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ABSTRACT

We present the Final Design of the WEAVE next-generation spectroscopy facility for the William Herschel Telescope (WHT), together with a status update on the details of manufacturing, integration and the overall project schedule now that all the major fabrication contracts are in place. We also present a summary of the current planning behind the 5-year initial phase of survey operations. WEAVE will provide optical ground-based follow up of ground-based (LOFAR) and space-based (Gaia) surveys. WEAVE is a multi-object and multi-IFU facility utilizing a new 2-degree prime focus field of view at the WHT, with a buffered pick-and-place positioner system hosting 1000 multi-object (MOS) fibres, 20 integral field units, or a single large IFU for each observation. The fibres are fed to a single (dual-beam) spectrograph, with total of 16k spectral pixels, located within the WHT GHRIL enclosure on the telescope Nasmyth platform, supporting observations at R~5000 over the full 370-1000nm wavelength range in a single exposure, or a high resolution mode with limited coverage in each arm at R~20000. The project is now in the manufacturing and integration phase with first light expected for early of 2018.

Keywords: Multi-Object Spectroscopy, Fibre Optics, High Resolution Spectroscopy

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1. INTRODUCTION

The WEAVE[1,2] project began in early 2010 with a series of national meetings within the partner countries (The UK, The Netherlands, and Spain) of the Isaac Newton Group of telescopes, aimed at developing a comprehensive strategy for the 4.2 William Herschel Telescope (WHT) for the next decade. These meetings identified the need for a dedicated high-multiplex spectroscopic facility to complement upcoming large-scale survey programs in Galactic and extra-Galactic astrophysics, particularly from new facilities such as ESA's Gaia satellite[3] and the European Low Frequency Array (LOFAR[4]). Gaia will provide an unprecedented picture of the structure and dynamics of the Milky Way from measurements of precise positions, proper motions and parallaxes for 10^9 stars with ($V \leq 20$) over the whole sky, but is unable to measure the radial component of velocity for the majority of the stars, and has limited spectroscopic capabilities that restrict chemical abundance measurements to only the brightest ($V<12$) stars in the survey. LOFAR will detect more than 10^7 radio sources from high-resolution radio imaging at 30, 60, 120 and 200 MHz over 10000 square degrees of the Northern Sky, but the majority of these will be continuum detections with no spectroscopic information to provide redshifts or information on the evolutionary state of the sources. APERTIF[5] will provide detailed information on the kinematics and dynamics of neutral hydrogen in galaxies at low and intermediate redshifts ($z\sim0.3$), but complementary observations are required at visible wavelengths to connect these data with the stellar populations and star-formation activity.

WEAVE was initially developed as a joint project between the UK, Spain and the Netherlands, but the project has been open to wider participation, and the partnership now includes France, Italy, the Konkoly Observatory and INAOE.

Over the last 18 months, final design reviews have been completed for most of the major WEAVE systems, and a substantial manufacturing effort is now well underway. In this paper we will summarize the overall state of each system, and the project as a whole, and leave the details to specific papers that can be found elsewhere in these proceedings [6,7,8,9,10,11]. Section 2 defines the overall instrument parameters, and describes ongoing infrastructure developments at the WHT required for WEAVE. In section 3 we report on progress with the optical components of the prime focus corrector. Section 4 covers the development of the WEAVE fibre positioning system, with details of the fibre system design and test planning discussed in Section 5. Section 6 summarizes the manufacturing progress with the spectrograph, and Section 7 describes the expected final performance based on detailed end-to-end modeling of the instrument. We conclude with a summary of the overall project schedule to completion as it sits at the time of writing.

2. THE WEAVE FACILITY

Telescope, diameter	WHT, 4.2m
Field of view	2º ø
Number of fibers	960 (plate A)/940 (plate B)
Fiber size	1.3″
Number of small IFUs, size	20 x 11″x12″ (1.3″ spaxels)
LIFU size	1.3′x1.5′ (2.6″ spaxels)
Low-resolution mode resolution	5750 (3000–7500)
Low-resolution mode wavelength coverage (Å)	3660–9590
High-resolution mode resolution	21000 (13000–25000)
High-resolution mode wavelength coverage (Å)	4040–4650, 4730–5450 5950–6850

Table 1: Summary of WEAVE's capabilities.

The WHT was designed to provide an extremely flexible development environment for instrumentation, and has fostered an extremely productive visitor instrument programme over the last 25 years. This environment includes full enclosures for both Nasmyth platforms, a prime-focus capability, and options for instruments at full and folded Cassegrain foci. For WEAVE, the Nasmyth enclosure at GHRIL provides an ideal gravity- and temperature-stable location for the spectrograph, whilst the GRACE enclosure on the opposite platform provides an excellent environment for the positioner control electronics to allow for heat removal, and to keep the drive voltages well-away from the CCD readout electronics in GHRIL. However, the existing top-end structure is not capable of supporting the corrector optics required for a 2 degree field of view together with a suitable instrument payload, and this has required major modifications (Figure 1).

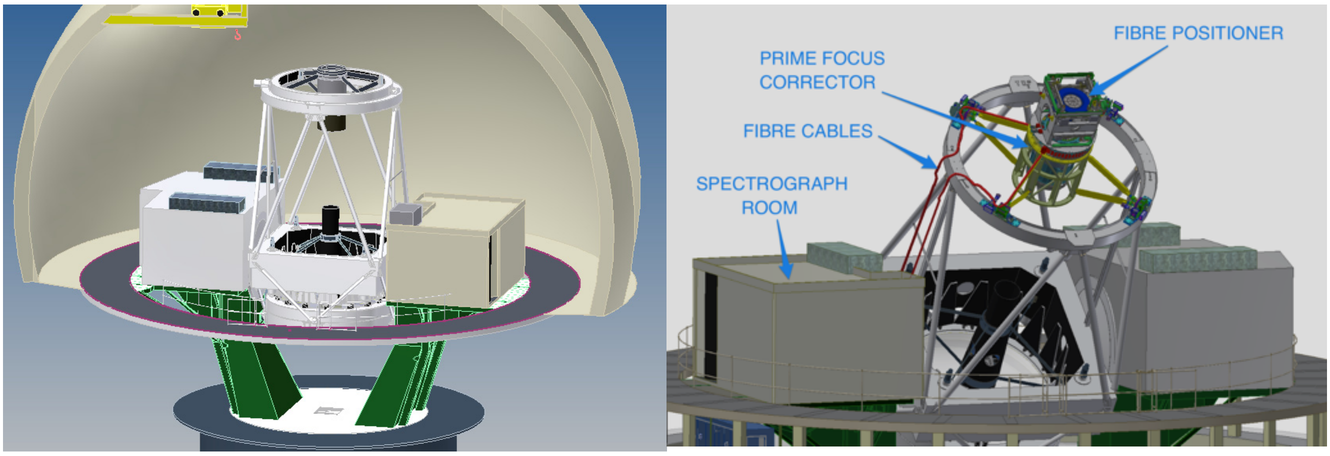

Figure 1: *(left)* The current layout of the WHT showing the two Nasmyth enclosures, GRACE (left) and GHRIL (right). The current top-end assembly is housed in the inner flip-ring. (*right)* Illustration of the new configuration for WEAVE showing the new top end structure and the route of the fibre cables to GHRIL.

The new top end requires a means of focus adjustment. Initially it was thought that this could be achieved by the translation along the optical axis of the last lens of the corrector, but it was found that the rate of change of the plate scale implied by typical temperature changes during the night would be unacceptable. Since the main contributor to a change in the telescope focus is the thermal expansion of the telescope truss, we therefore concluded that the best focus solution could be achieved by a translation of the whole top end unit together. This is achieved by a cam-driven adjustment of the location of each of the spider vanes at the points where they join the top end ring. The new top end structure, including the spider vanes, central section and focus translation units has been manufactured by SENER NTE in Barcelona, and is currently under test at the IAC[7] (Figure 2). The system is designed such that the current inner-ring assembly can be removed as a single unit and stored for an easy return to classical observing modes. A test removal of this ring took place at the end of July 2016 (Figure 3), and represents a major milestone for the project.

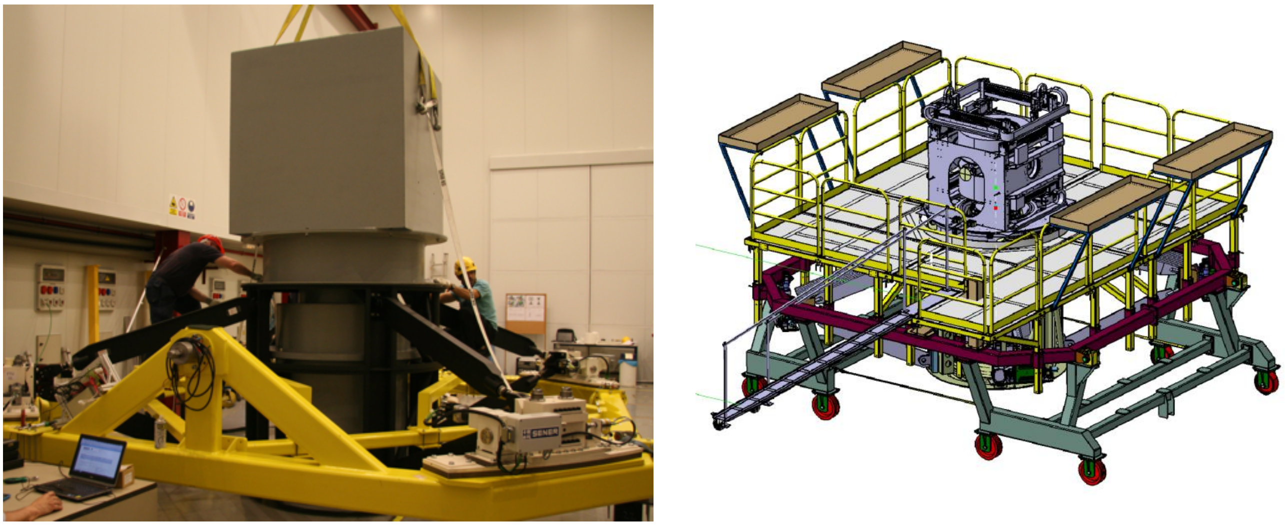

Figure 2: (left) The new top end under test at the IAC, complete with full-size mass dummies for the positioner, corrector and instrument rotator. (right) Handling frame (red) and access platform for the WEAVE top end storage and maintenance.

In addition to storage of the current top ring, experience with 2dF[15] indicates that WEAVE will require additional facilities off the telescope to allow the instrument to be worked on for maintenance purposes when not in use.

Figure 3: First trial removal of the current top-end ring as an operational test in mid-July 2016.

3. PRIME FOCUS CORRECTOR PROGRESS

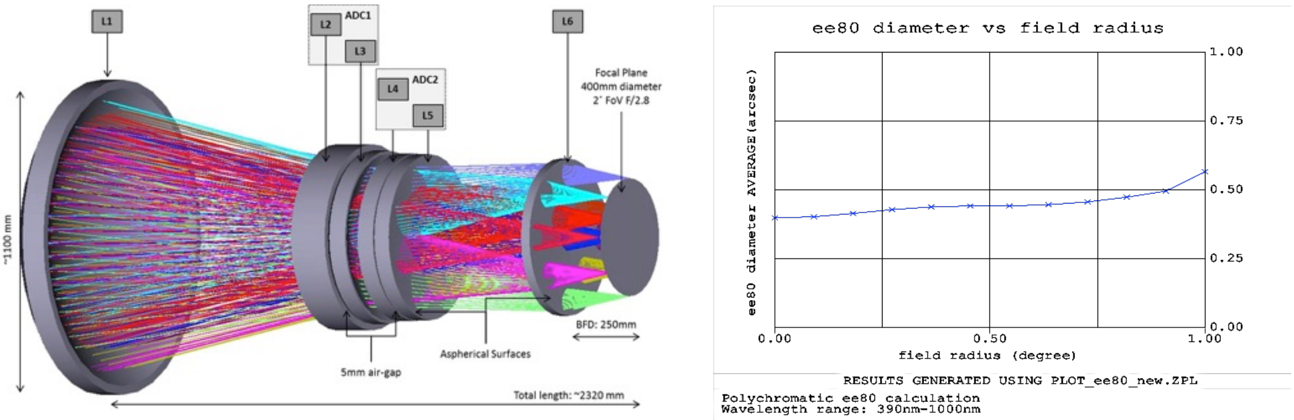

Figure 4: *(left)* The optical layout of the corrector. *(right)* Polychromatic image quality (80% encircled energy in arcseconds) across the field of view.

The prime focus corrector design has been presented elsewhere[14]. Lens 1 is an extremely large (1100mm diameter) fused silica meniscus lens, and was fabricated as a slumped blank by Corning. Lenses 2,3 and 4,5 form prismatic doublets, which have been left air-spaced to allow some extra freedom in the optical design, as well as to avoid any possible issues with cementing such large elements, lenses 3 and 4 are Ohara PBL1Y glass and were delivered with above-spec homogeneity. Lens 6, also supplied by Ohara, is fused silica. Lenses 2 and 5 were designed to use N-BK7 of homogeneity grade H2, but it proved difficult to achieve this in the large blank size (160mm thick) required for lens 2, and so this has been replaced with S-BSL7.

The lenses are being polished in New Zealand by Kiwistar optics. Lens 4 is now complete (Figure 4) and in the process of being coated, and the other lenses are still in the polishing stage. For more details on the polishing progress please refer to [6].

Figure 5: (left) Lens 4 completed. (right) Lens 6 at Kiwistar with the front surface completed, ready to be sent off for asphérisation.

The remaining issue with the the prime focus system is that we are behind schedule on placing a contract with industry for the final assembly. Funding is now in place for this, and the contract is expected to be in place by the end of the year. This is currently driving the critical path of the whole project. After detailed tolerancing of the manufacture of the lenses and the assembled corrector the expected image quality is < 1" (80% EED, <0.66" FWHM). When combined with the expected 75th percentile of the seeing distribution at the WHT this implies a recovered PSF of FHWM < 1.15" for stellar sources, which we have adopted as a baseline for our performance simulations[11].

4. FIBRE POSITIONER

The fibre positioning system (Figure 5) is now in manufacture following a final design review in January 2015, with over 90% of parts in hand, and the delivery of the robot gantry systems expected from Schunk GMBH in mid-September. Extensive testing has been ongoing in Oxford using a prototype gantry[8], so much of the low-level MLC control interface is already in place. Including the fibre retractors and buttons, the positioner comprises over 50,000 parts, the majority of which have been fabricated in the Oxford physics workshop. The 360 fibre retractor units each house 6 indidvidual fibres for the MOS mode, with a design that isolates each fibre in a separate compartment to avoid breakage cascades impacting on the instrument availability.

Two aspects of the positioner are critical to the overall survey performance of WEAVE: the positioning accuracy that can be achieved by the robots, and the overall timing budget for an individual fibre move. These have been investigated in some detail, as reported in [8], with the conclusion that the timings are well-within the required budget, and that the accuracy of the gantry positioning system exceeds the manufacturer's quoted performances by some margin. Simple scheme's have been developed for calibration of the gantry flexures as the telescope moves around the sky. A detailed simulation of the combined action of the two robots suggests that there is a small latency involved due to access conflicts in the middle of the field, but this appears to be <5% of the total timing budget.

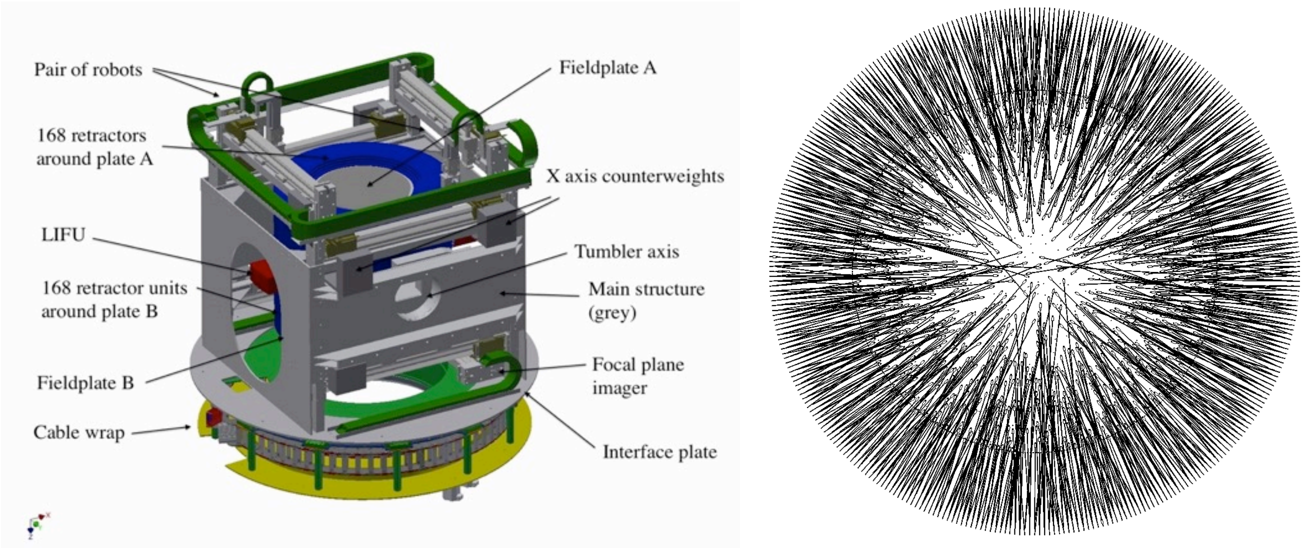

Figure 6: *(left)* The general layout of the fibre positioner system. *(right)* Example of a fully configured field. The black circle marks the optical field of view.

The 20 mini-IFUs are mounted within the 10 of the retractor slots on one of the field plates, thus reducing the total count of MOS fibres to 940 on that plate. The mini-IFUs, each comprised of a close-packed array of 37 fibres with the same 1.3” fibre aperture as the MOS mode, will use a scaled-up version of the MOS retractor, and a compatible button design, but with only two bundles per unit (Figure 6). Each field plate will also be equipped with 8 dedicated fibres for acquisition and auto-guiding. These will be coherent imaging bundles, as currently used in AF2 at the WHT, with a field of view of ~3.5”. With 8 guide stars per field, WEAVE aims to correct for the bulk effect of differential refraction over the observation by tracking the position of each star across its target bundle.

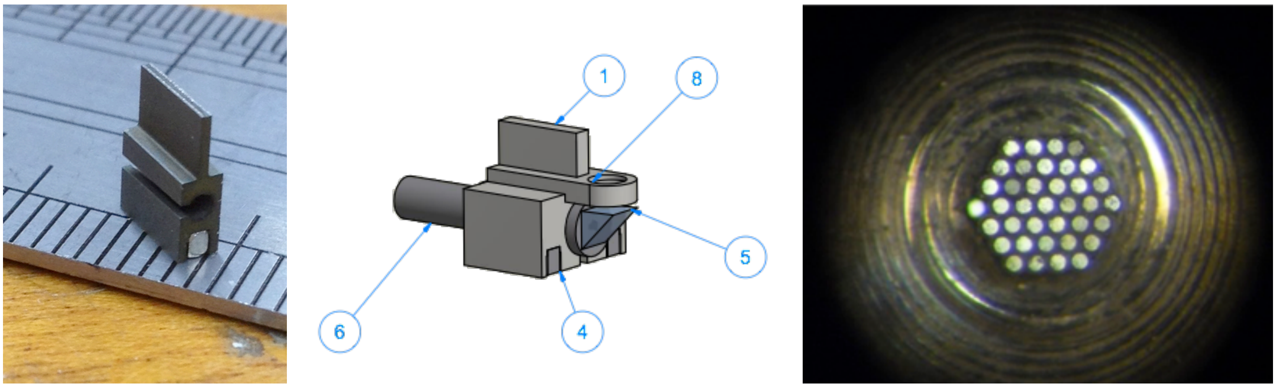

Figure 7: (left) a single MOS fibre button ready for assembly with magnet installed. (centre) Design of the mIFU button which uses two identical magnets and a machined lens holder. (right) Example mIFU ferrule manufactured in Oxford. Very careful quality control is required in the gluing of the magnets to ensure that these do not protrude below the button surface and cause positioning uncertainties.

5. FIBRE SYSTEM

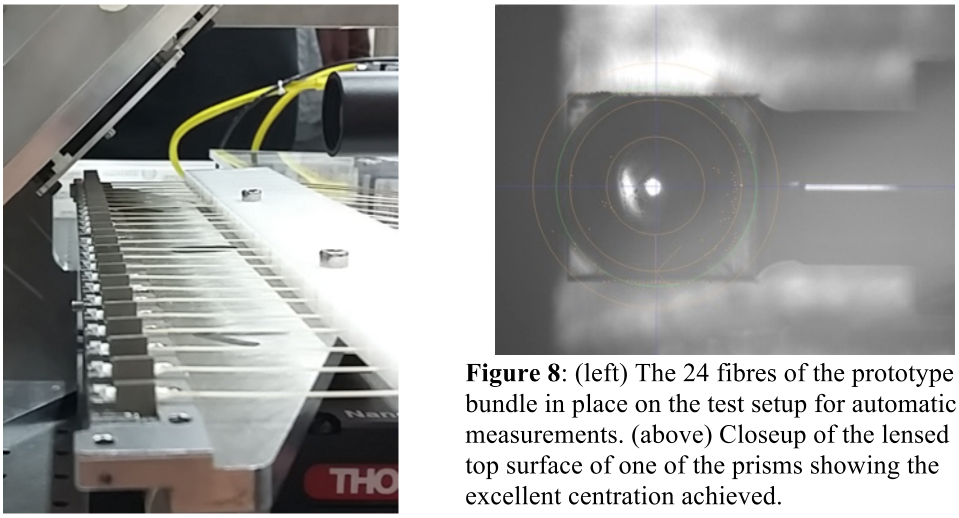

Figure 8: (left) The 24 fibres of the prototype bundle in place on the test setup for automatic measurements. (above) Closeup of the lensed top surface of one of the prisms showing the excellent centration achieved.

The fibre system design deals with the assembly and management of the full length of all 3200 WEAVE fibres from the button, though the retractors and tumbler structure, around the prime focus instrument rotator cable wrap, along the spiders and down the telescope to where they pass over the cable wrap for the telescope elevation axis and into the GHRIL enclosure to the spectrograph slits. We have designed WEAVE to have no interruption to the 32m fibre cable, and so the slit units in the spectrograph must be removed and the cables stored on the top end when the instrument is removed from the telescope. For manufacturing and integration purposes the system is divided into modules of 24 fibres for the MOS mode, which will fill 4 retractors in a sector of the field plate at the positioner end, and a single subslit v-groove array at the spectrograph end. Within the retractors, the 6 MOS fibres (85 micron core, 120 micron outer diameter) are each clad in a protective PEEK tubing, 0.5mm outer diameter, until they merge into a single polyurethane tube of cross-section 2.7x4mm. Each group of four retractors then feeds into a further junction to give 24 fibres in the same polyurethane tubing which passes through the prime cable wrap, down the telescope and over the elevation cable wrap inside a ruggedized conduit. Inside the GHRIL room, this bundle of 24 fibres emerges into a smaller outer PEEK tube of cross-section 1.2x1.7mm which feeds into a cable clamp on the back of a 24-fibre subslit block (Figure 4). The subslit blocks are angled to approximate a curve in two dimensions to form the input slit of the spectrograph, with the angle being common to each group of four blocks. An end-end prototype of one 24-fibre cable from fibre-buttons to subslit has been fabricated by SEDI-ATI.

An automated test-bench has been developed at GEPI[10], which can accommodate a single fibre module and provide mesaurements of the end-to-end focal ratio degradation as well as geometric parameters of the alignment and concentration of the prism-lens to the button. Once characterization of the prototype is completed at GEPI it will be sent to Oxford for lifetime testing in a retractor unit back for re-characterization and then to the telescope where it will be mounted to monitor the effects of ~4 months of telescope movements on the performance.

6. SPECTROGRAPH DESIGN

The spectrograph system held its FDR in Marc 2015 and manufacturing is underway. All of the blanks for the optical elements are in hand, and some of the lenses are in progress at Fineoptic and at TNO in the Netherlands. The main set of lenses for both blue and red cameras will be polished within the WEAVE project at INAOE. Fabrication of most of the mechanical structure is in progress at ASTRON. All four science grade CCD-231 C6 CCDs, two thinned blue chips and two deep depletion red chips, have been delivered by e2V and exceed specifications. Of particular note is that the flatness of the chips over the full area is around 11 microns. Detailed design of the detector cryostats is now complete and manufacturing and integration is underway at LJMU (Figure 10). More details on the optical design (Figure 9) and expected performance can be found at ref [16].

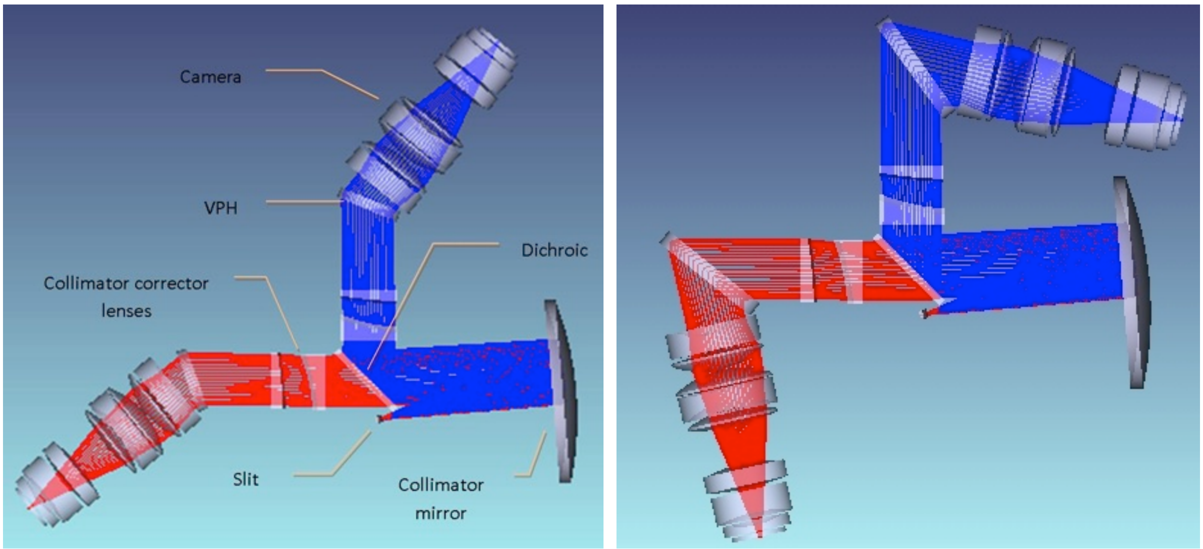

Figure 9 WEAVE optical layout, low (left) and high (right) resolution mode.

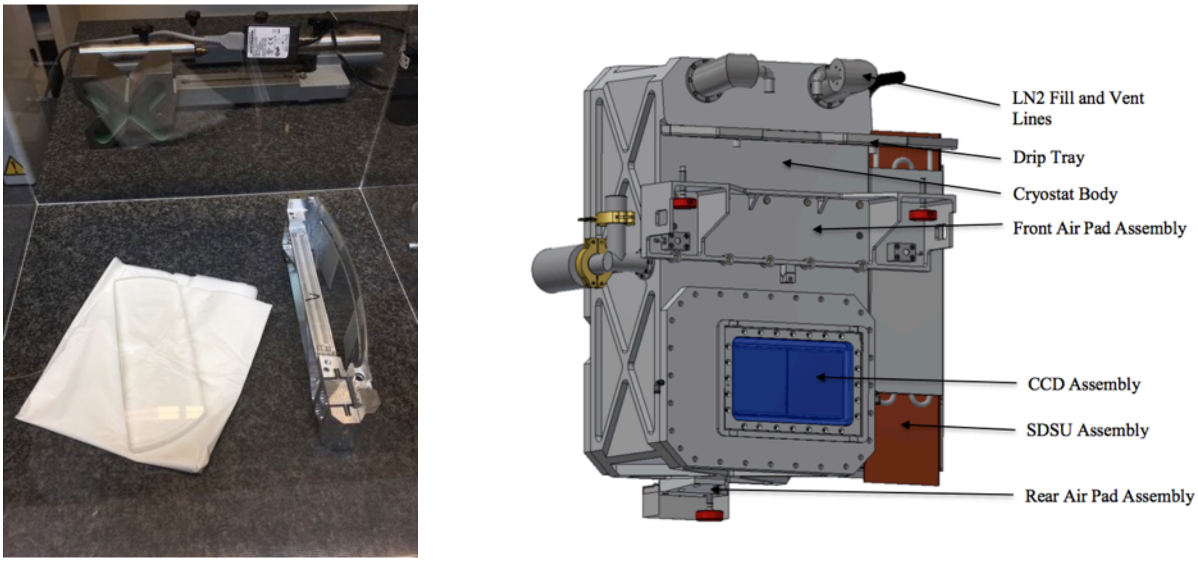

Figure 10 (left) Slit lens (FineOptic) and slit mounting plate at ASTRON. (right) Final design of the detector cryostat.

7. WEAVE END-TO-END PERFORMANCE

We have developed a full image simulator for WEAVE, which includes atmospheric effects, vignetting losses at the corrector and within the spectrograph, telecentricity mis-match losses at the fibres, detector characteristics and a full PSF mapping of the spectrograph for all fibres[2]. The simulator starts with a configured fibre field, assigns random template spectra to each of the fibres drawn from a magnitude and velocity distribution, and generates a full set of output images for each observation with full metadata compliance with the observing system interfaces. Outputs from the simulator are being used to tests the overall science performance of the facility, and also to provide development input an a saturation test for the WEAVE data processing systems[13]. Figure 11 shows the final extracted spectrum (after wavelength calibration and sky-subtraction) of an 18th magnitude representation of a BVII star (input spectrum was HD 34797 from the XShooter Spectral Library[17])

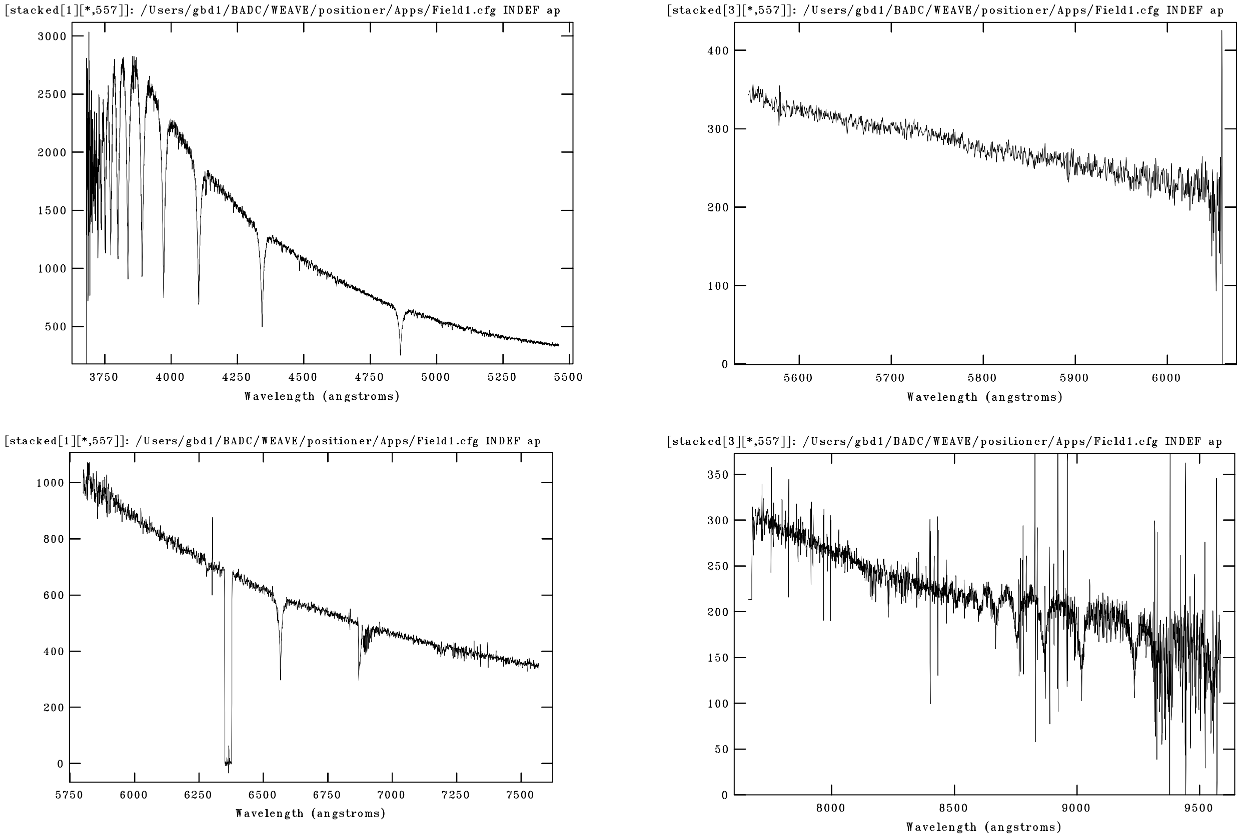

Figure 11: Simulated spectrum from fibre 82 of Figure 6, processed through an early version of the WEAVE CPS pipeline at CASU. The input star is HD 34797 from the Xshooter Spectral Library, scaled to 18th magnitude for a 1 hour exposure.

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REFERENCES

[1] Balcells, M., et al., Proc. SPIE 7735 (2010).
[2] Dalton, G., et al., Proc. SPIE, 8466, 23 (2012).
[3] Prusti, T. et al., EAS 45, 9 (2011).
[4] van Haarlem, M., EAS 15, 431 (2005).
[5] Oosterloo, T, et al., Proceedings of ISKAF Science Meeting (2010).
[6] Lhomé, E., et al., Proc SPIE 9912, 254 (2016).
[7] Casalta, J.M., et al., Proc SPIE 9912, 220 (2016).
[8] Lewis, I.J., et al., Proc SPIE 9908, 293 (2016).
[9] Dominguez, L., et al., Proc SPIE 9908, 326 (2016).
[10] Sayéde. F., et al., Proc SPIE 9112, 70 (2016).
[11] Dalton., G.B., et al., Proc SPIE 9113, 139 (2016).
[12] Molinari, E., et al., Proc SPIE 9113, 71 (2016).
[13] Walton, N., et al., Proc SPIE 9152, 25 (2014).
[14] Agócs, T., et al., Proc SPIE 9147, 266 (2014).
[15] Lewis, I.J., et al., MNRAS 333, 279 (2002).
[16] Rogers, K, et al., Proc SPIE 9147, 212 (2014)
[17] Chen, Y-P. et al., A&A, 565, A117 (2014)