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The Hector Instrument: Performance of the Hector fibre integral field units

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ABSTRACT

Hector is a new generation multi-object Integral Field Spectroscopy (IFS) instrument that will utilise high-performance fibre integral field units called 'hexabundles'. We will present the performance of the hexabundles based on the focal ratio degradation (FRD) and throughput results. Hector is planned to be using these hexabundles on-sky by early 2021 to carry out one of the world largest IFS galaxy surveys at the Anglo-Australian Telescope (AAT). Hexabundles are developed in the AAO-USydney labs at the University of Sydney. They contain 37 to 169 multi-mode fibres per device and cover up to 26 arcseconds across each galaxy with a spectrum at each fibre position. For astronomical instruments, optical fibres give significant flexibility in configuring a focal plane, but FRD can affect the performance of the fibres and directly influence the efficiency of any galaxy survey observed. Novel techniques used in glass fibre processing have enabled hexabundles optimal performance with minimal FRD. In this paper, we display the optimisation of the Hexabundle design and the FRD performance of the units.

Keywords: Hector, Integral field units, Hexabundles, FRD

1. INTRODUCTION

Different techniques that were used on Integral Field Spectrographs have largely changed the way of doing astronomy research in the past decades. Lenslet arrays, optical fibre bundles and image slicers are three methods that are popularly used in current serving astronomical instruments such as Multi Unit Spectroscopic Explorer(MUSE[1]), Mapping Nearby Galaxies at APO (MaNGA[10]) and Sydney-AAO Multi-object IFS (SAMI[4,5,9]). Optical single fibres or fibre bundles are installed facing to the focal plane of the telescope. They transfer the image information to the spectrograph which is assembled in a temperature and motion controlled environment. The advantage of using fibre bundles rather than single fibres to observe galaxies is that more fibre cores can separate the galaxy information spatially and allow researchers to know which part of the galaxy has emission lines while a single fibre can only take the total spectrum of the whole galaxy or only one part of the galaxy.

Hector[7] is the new generation multi-object integral field spectroscopy at the Anglo-Australian Telescope (AAT). The previous instrument, SAMI, had been highly productive. The SAMI sky survey recorded 3000 galaxies with 12 IFUs over 6 years and Hector plans to be on sky in early 2021 with 19 hexabundles[2,6] targeting a 15,000 galaxy survey on AAT. The hexabundles have different sizes from 37 cores to 169 cores which cover up to 26 arcseconds on sky. The optical fibre bundle in Hector receives galaxy light at the focal plane and divides the galaxy image into each fibre core. Then at the other end of each fibre, a pseudo-slit helps reformat the light at the entrance to the spectrograph. A new plate design and novel positioning system will also be used in Hector. Hector deploys a magnetic robotic system to perform accurate fibre positioning including tilting the fibres to match the telecentricity at each point on the plate.

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The new generation of IFUs in Hector are hexagonally packed as "hexabundles". Compared to the circular packing of SAMI fibre bundles, Hector hexabundles' regular packing allows significant convience and high efficiency in data reduction and calibration. The technique to make the new hexabundles has been developed at the AAO-Usyd and Sydney Astronomical Instrumentation Lab (SAIL) in the University of Sydney. Our new packing technique and fibre etching process enables an extreme high fill fraction with 75% of core area to bundle area ratio. With higher fill fraction in the hexabundles, less light is lost between the cores.

Hector is designed to observe emission lines of galaxies, especially the outskirts of galaxies where the brightness is almost the same as the background. Faint light is extremely sensitive to any kind of light loss causing from the observing instrument. Therefore, to receive high signal-to-noise data, our aim for building hexabundles is to have the best throughput and the least focal ratio degradation (FRD).

When there is FRD on fibres, the output light cone angle slightly increases compared to the input light cone angle. End-surface scattering, external pressures, macrobending and microbending may lead to an increased FRD.[11,14] The cone angle of the input light that goes into the hexabundle is 0.147NA. The largest input acceptance cone angle of the Hector fibre is 0.22NA and the Hector spectrograph is designed to accept light from the output end of the fibres with a cone angle of 0.154NA. The expected FRD testing results of the fibre output should have no enlarged cone angle compared to the input within measurement error. The measurement error of FRD testing includes setup alignment errors[5] and fitting errors.[3] If the FRD result is within measurement error, we consider the fibre performance to have met the requirements.

Collimated beam method and cone-beam method are two common methods used for FRD tesing.[15] We use the full-beam method to test FRD in this work.[3,12] This method requires an extremely accurate alignment setup, otherwise the result may be largely affected by alignment errors. We compare the output cone angle for the fibres before and after built into hexabundles, using the same input cone angle. An increase in the cone angle shifts the encircled energy curves to higher effective NA.

When building hexabundles, each process such as etching, fusing, gluing and polishing could put extra stress on the fibres which would result in FRD. Therefore, it's necessary to measure the FRD between each process to make sure the final product meets the requirements.

In section. 2, we will discuss the hexabundle optimisation we made from the previous update and show the official hexabundle prototypes. We then present the optimisation for the polish and the surface roughness test results. We will also show the new design of the hector splice tube and the splice box based on the fibre bending limits. In Section.3, We will show the FRD and throughput results of the official Hector hexabundles.

2. OPTIMISED DEVELOPMENT

2.1 Packing optimisation

One of the most significant changes in the development of the Hector hexabundles since SAMI, has been the regular hexagonal packing of the fibres into the devices. To optimise this packing, the cladding can be etched away for a short length at the face of the device.[13] Careful testing and development during while building the SAMI hexabundles found that etching the cladding to a thickness of 5μm can enable a consistent 75% fill fraction while not degrading the optical performance of the individual fibres.

The fibres have been etched in a joint project with the Sydney Nanoscience Hub, the University of Sydney node of the Australian National Fabrication Facility Network (ANFF). The fibres are cut to length, stripped, aligned, and prepared in a custom-designed jig, then immersed in a low concentration of hydrofluoric acid until they are etched to the desired 5μm. The careful preparation and testing throughout this process ensures that all of the fibres are consistently etched to both the correct length and diameter. These dimensions are critical to the consistency of the packing, and success of the hexabundle.

Once the fibres are installed into the hexabundle, the device is lightly fused, and carefully glued into the custom designed ferrule, polished to a very high surface quality, and mated with the prism. This fully installed device is then entirely protected while being adjusted and plugged during observing on the telescope. Each of these steps has been developed and tested to specifically minimise stress on each of the fibres, as it is imperative to the galaxy survey that the FRD is minimised across the bundle.

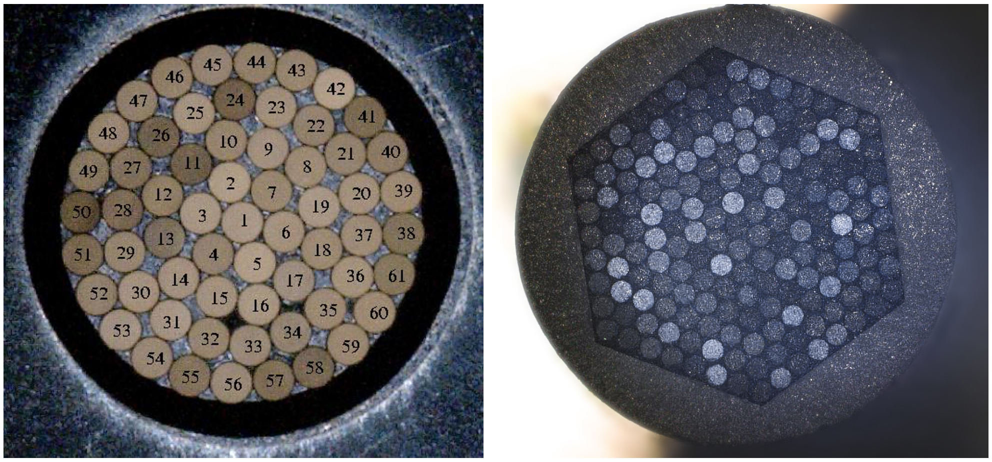

Figure 1: The left image shows the packing of the SAMI hexabundle. The right image is the improved packing of Hector hexabundle. The Hector hexabundle has not been fully polished yet. It will be polished to $< 1\mu$m surface finish once it is assembled into the ferrule. The fibres were randomly back illuminated for this image.

One of the latest on-sky 127-core Hector hexabundles, before being installed into its ferrule and its final polish is shown in the right image of Figure.1. It has random back illumination of each of the fibres.

Fusing of optical fibres leads to FRD. However our unique process has been carefully optimised with an aim for the FRD in the final hexabundle to be no worse than that of the bare fibre it is made from. Section 3 will compare the FRD performance of one of the prototypes to bare fibre. These fused hexabundles are installed into the instrument at 90 degrees to the focal plane. They lie along the field plate, at any position across the 2-degree-diameter focal plane. To redirect light from the primary mirror into the hexabundle there will be a prism attached to each hexabundle face. The fibres coming out of the back of the ferrule will be spliced to either the 40m fibre cable which routes to the AAOmega spectrograph or the 60m cable to the Hector spectrograph.

2.2 Polish optimisation

After the the glass process to create the hexabundles, the faces are polished to a precise length and surface finish. If the surface is rough or has scratches, the light accepted by the fibres will be reduced and scattered which will impact the throughput and FRD. To avoid geometrical FRD, the input section surface has to be perpendicular to the bundle. Therefore, it's essential to make the surface smooth, no scratches, no chips and perpendicular to the axis.

Rough surfaces can be improved by being polished with a set of polish paper with different grit sizes. We start the polish with a grit size of 20μm gradually lowering to 0.02μm. Further scratches and chips can be avoided if the process is extremely clean. A balance between the polish friction and the temperature of the glue is required to prevent the glue from softening during the polish. This requires careful monitoring of the pressure applied to the fibre during polishing. If the pressure is too light, only the glue part is polished and the fibre core surface remains rough. If the pressure is too heavy, the cladding of the fibre core could be chipped off because the glue will become soft and segregated from the cores due to the increased temperature caused by friction.

Figure 2 shows the targeted finish on the final product. The final polish surface should look as smooth as the left image of Figure 2, also the surface should be perpendicular to the side as shown in the right image of Figure 2. The final 127-core hexabundle shown in Figure 1 will be polished to this standard.

Apart from the deep scratches and chips that can be seen with naked eyes, each more delicate grit of polish can produce scratches that can be observed under larger magnification. For example, when under 40 times magnifications, the 1μm grit of polish (see the left image of Figure.3) still shows remaining scratches on the surface while no scratches show under 10 times magnifications. The 0.02μm grit polish (see the right image of Figure.3) appears smooth without any scratches under 40 times magnification, but more delicate scratches will

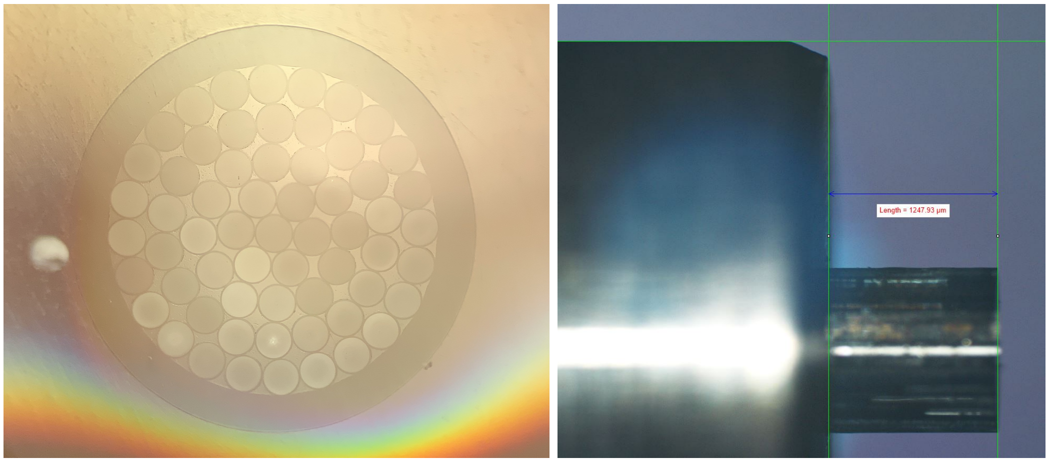

Figure 2: These two images show the requirements for the final products. The left image is a well polished testing bundle (for polish practice) with no scratches and chips. The right image shows the side view of the bundle. The surface of the bundle is perpendicular to the side of the connector, which will introduce no geometrical FRD to the bundle.

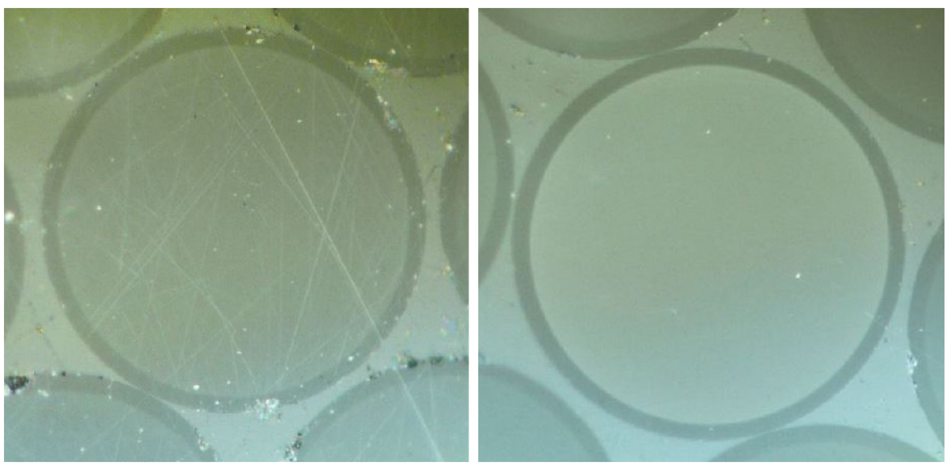

Figure 3: This image shows the final step of polishing a bundle with circular packing. The left one stops at 1μm polish and the right one stops at 0.02μm polish. They are from the same core and the same bundle. We tested the FRD and throughput of these two different final surface and found no difference within error.

show under much larger magnifications. Therefore, we tested which grit size to stop the polish based on the FRD performance.

We tested FRD and throughput for the same core in the same bundle shown in Figure 3. The bundle was polished to 1μm roughness and tested, then polished to 0.02μm roughness and tested again, so that other causes for FRD can stay consistent.

The FRD test results show that the output light cone angles coming out of the core with 1μm and 0.02μm roughness are in agreement at 95% encircled energy within measurements errors. Also, the total counts that are received by the cores are the same. Therefore, we consider the 1μm final surface and the 0.02μm final surface to behave the same from an FRD perspective and scratches at this scale does not impact to the performance of the hexabundles. More testing information about the polish surface can be found in the coming paper (Wang et al. in prep).

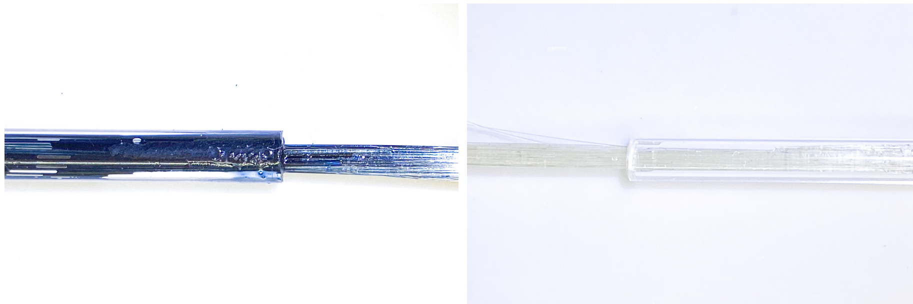

Figure 4: This image shows the glue testing for the splice tube. 60 fibres are randomly packed through the acrylate tube and the tube is filled with glue. The transparent glue in the right image is the Dymax (optical adhesive coating OP-4-20632) glue. The blue glue in the left image is the AngstromBond (AB9320) glue and it shows better agreement with the fibres on FRD and throughput results.

2.3 Optimised design for the splice tube

The whole Hector instrument will have 1453 60m-long fibres. The hexabundles made in the lab are 3 metres long and will be spliced to 60 metres fibre cables. The spliced parts will be protected with splice tubes and then assembled inside the splice box. The design of the splice box is required to be as small as possible due to the limited space. The fibres will be circled for two rounds inside the splice box ensuring a minimum bend radius. The bend radius is important to prevent throughput loss in the fibre. Our test result for the bend radius shows that when the fibre is bent no smaller than a 5cm-diameter circle, the FRD and throughput will keep the same.

In SAMI we use a conventional splice protector tube for each fibre. Now in Hector, to reduce the space and the weight, we use one acrylic splice tube to hold 60 fibres and use the glue to bind between the fibres and the tube (see Figure 4). During the glue curing and drying process, extra stress may be added to the fibres which will cause extra FRD. We tested several glue and found that the Norland (optical adhesive 68) glue introduces a 2% drop on the total counts, while the Dymax (optical adhesive coating OP-4-20632) glue gives a 0.9% drop and the AngstromBond (AB9320) glue produces no change on both FRD and total counts within error. We will use the AngstromBond glue for the final splicing. More information about the bend radius tests and the splice tube tests can be found in the paper (Wang et al. in prep).

3. FRD AND THROUGHPUT TESTING RESULTS FOR THE OFFICIAL HEXABUNDLE

The left image of Figure 55 shows a 169-core hexabundle prototype, which is the largest size of all Hector hexabundles. We tested to see if the fibre cores in this prototype have extra FRD due to the optical fibre etching process, fusing process, gluing process or polish process. Our unique techniques in all these processes are being optimised based on frequent tests on the FRD.

The right image of Figure 5 shows the FRD testing result of this 169-core bundle shown in the left. The x axis of the plot is Numerical Aperture (NA) of the output light of the other end of the hexabundle. Encircled energy at the y axis presents the ratio of encircled counts to the total counts. The dashed curve is from a single bare Hector fibre that wasn't etched or packed into a bundle. The full line shows the typical curve from many repeated measurement of different cores in this 169-core bundle. The orange line is the error bar of the system measurement error. And the red dashed line sits at 0.154NA which is the acceptance NA of the Hector spectrograph. The plot shows that at 95% encircled energy, the output cone angle of the fibre core increases but is within measurement error, which means the hexabundle building process didn't generate extra FRD on the fibres and the bundle reaches the final production standard.

4. CONCLUSION

From these results, we are confident that a 1μm polish is sufficient to prevent FRD increase. We aim for 0.02μm polish but due to hexabundle length constraints (the length must be a specific length out of the connector to

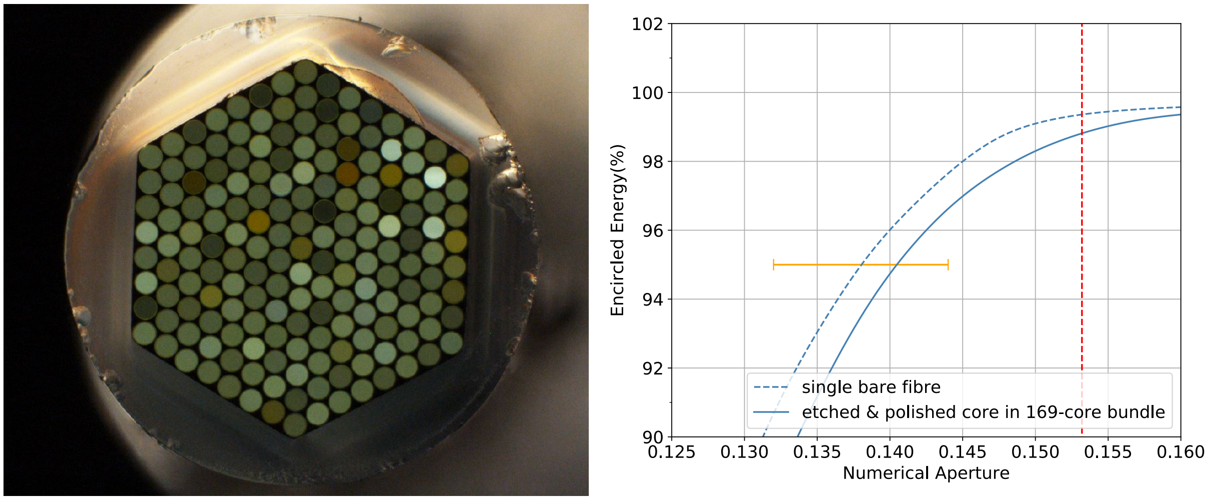

Figure 5: The left image is a 169-core bundle that is being tested. The right image shows the NA-EE curve of the fibre inside the hexabundle compared to a single bare fibre. The FRD of the hexabundle core is shifting to the right, however the difference is within system error. Therefore we consider this hexabundle we made has no extra FRD.

sit behind a prism at the telescope focus), we will stop at 1μm if needed. The design of the splice box has been confirmed based on the FRD test for the bending radius of Hector fibres. As well as the new method for protecting spliced fibres with splice tube and the choice for the glue that will be used to protect the fibres. Also, the 169-core prototype are tested and confirmed to be successful with no extra FRD. We will use this prototype as one of our official bundles.

The 19 hexabundles for Hector will be installed early next year. Our results show the Hexabundle production meets the expected performance. These next-generation hexabundles will enable the Hector Galaxy Survey to observe 15,000 galaxies out to typically 2 effective radii.

ACKNOWLEDGMENTS

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