Development and focal ratio degradation optimisation of integral field units on Hector

Adeline Haobing Wang, Rebecca Brown, Julia Bryant, Sergio Leon-Saval

Adeline Haobing Wang, Rebecca Brown, Julia J. Bryant, Sergio Leon-Saval, "Development and focal ratio degradation optimisation of integral field units on Hector," Proc. SPIE 11115, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts IX, 1111509 (9 September 2019); doi: 10.1117/12.2529212

Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

Development and focal ratio degradation optimisation of integral field units on Hector

Adeline Haobing Wang[a,c,], Rebecca Brown[a,b,c], Julia J. Bryant[a,c], and Sergio Leon-Saval[a,c]

[a]Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia;
[b]Australian Astronomical Observatory, Faculty of Science and Engineering, Macquarie University, NSW 2109, Australia
[c]ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)

ABSTRACT

New optical fibre spectroscopic imaging devices for astronomy are being developed with very high throughput and excellent optical performance. Hector is a new generation multi-object Integral Field Spectroscopy (IFS) instrument that will utilise these high-performance fibre imaging devices called "hexabundles". They are being developed in the Sydney Astrophotonic Instrumentation Laboratories (SAIL) at the University of Sydney. Hector is planned to be using these hexabundles on-sky by 2020 to carry out one of the world largest IFS galaxy surveys at the Anglo-Australian Telescope (AAT). The hexabundles contain up to 169 multi-mode Ceramoptec WF103/123um fibres per device, subtending a 26 arcseconds view with a spectrum at each fibre position for each galaxy. For astronomical instruments, optical fibres give significant flexibility in configuring a focal plane, but focal ratio degradation (FRD) can affect the performance of the optical fibres and directly influence the efficiency of any galaxy survey observed. Breakthroughs in glass fibre processing at SAIL have enabled hexabundles with minimal FRD - and therefore optimal performance. We will present the new developments in the SAIL labs and the resulting performance of new hexabundle devices for Hector and for other future applications.

Keywords: Hector, Integral field units, Hexabundles, FRD

1. INTRODUCTION

‘

1.1 SAMI and Hexabundles

Large galaxy surveys have led to new understanding of galaxy evolution in the last few decades. Most large surveys produce spectra taken with a single spectrum which are then limited because the fixed fibre does not account for which part of the galaxy is seen in galaxies of different sizes and distances. Single fibres also lack spatial information across each galaxy. Recent developments in Integral-field spectroscopy (IFS) is enabling a resolved view of spectra across large galaxy samples, such that dynamics of gas and stars can also be measured. To enable many galaxies to be observed simultaneously deployable Integral field Units (IFUs) have been developed in place of monolithic IFUs. They can then be aligned with each galaxy at the focal plane of a telescope. New optical fibre integral field units called *hexabundles*[1,2,4] were first demonstrated on the Sydney-AAO Multi-object Integral-field spectrograph (SAMI[3,5,8]). SAMI has undertaked a 3400-galaxy survey in a 5-yr survey which began in 2013, aiming for covering a broad range in stellar mass and environment.

Further author information: (Send correspondence to Adeline Haobing Wang)
A.H.W.: E-mail: hwan5380@uni.sydney.edu.au, Telephone: +61 434036990

UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts IX, edited by Allison A. Barto,
James B. Breckinridge, H. Philip Stahl, Proc. of SPIE Vol. 11115, 1111509 · © 2019 SPIE
CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2529212

1.2 Hector

Hector is the next generation multi-object IFS instrument after SAMI. Hector consists of 21 hexabundles. Different sizes of hexabundles from 37-core to 169-core are being developed at the Sydney Astrophotonics Instrumentation Laboratory (SAIL) at the University of Sydney.[6] The diameter of the hexabundles will cover up to 26 arcseconds on sky with 1.6 arcsec diameter field of view per fibre.

Hector fibres are etched to a cladding thickness of 5μm to increase their core fill fraction when being packed into hexagonal shape. Core fill fraction is very important because the higher the fill fraction, the more photons we receive within the area of interest in the galaxy. The cladding needs to have certain thickness to enable the core to transfer light. We have previously shown that over short distances, that thickness can be reduced with minimal effect on light transmission.[4] We use Hydrogen Fluoride acid to etch the cladding off to 5um thickness. In collaboration with Australian National Fabrication Facility (ANFF), this extremely delicate work was finished in three months, with 7,000 etched fibres ready to be packed.

Our unique fusing technology enables our hexabundles to have excellent optical performance (throughput and no extra focal ratio degradation) while maintaining the highest core fill fraction (∼75%) of any optical fibre bundles in the world.

We have recently developed the 169-core hexabundle and tested the focal ratio degradation of this bundle. It will be discussed in Section 3.

1.3 Focal ratio degradation (FRD)

An important part of collecting more photons on each of the galaxies is to build hexabundles with low FRD. FRD means the light cone angle into an optical fibre will become larger at the output (see Figure. 1), therefore some light is not captured by the spectrograph. A perfect optical system without any FRD should have constant light cone angle at the input and the output of a fibre. Focal ratio is the ratio of the focal length to the aperture of the light. When the output cone angle increases, the focal ratio gets numerically smaller and we call it focal ratio degradation.[10]

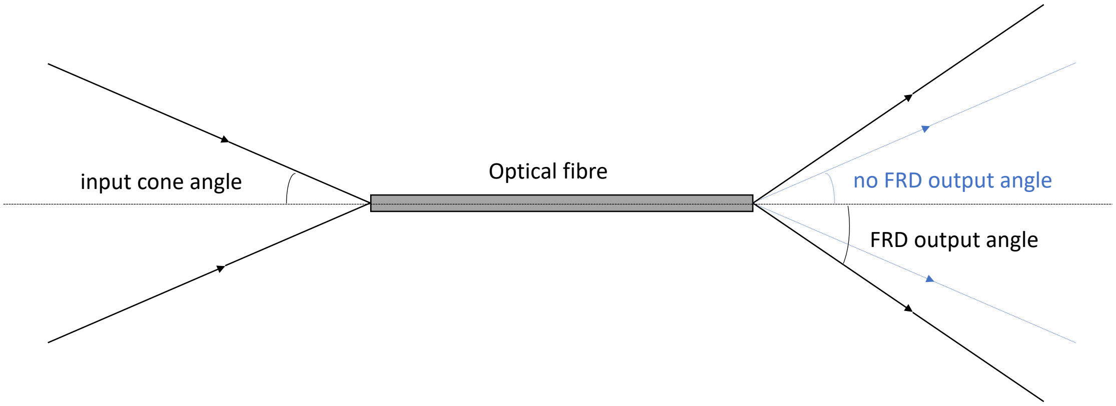

Figure 1: FRD through optical fibre.

There are several effects that contribute to FRD. The impurity of the fibre core, the microbends and distortion along the fibre, any stress or compression, the cleaving or polish quality of the fibre end all can result in bad FRD.[4,9,11]

To ensure the best throughput we aim for no additional FRD in our hexabundles. My work involves a complex setup and code I have written to accurately assess the FRD in the hexabundles we build so that our process for making them can be continually optimised until there is no additional FRD. This is important to the Hector throughput and the amount of light we will get from the galaxies.

2. FIBRE CHOICE FOR HECTOR

2.1 The need for fibres with low FRD

Good fibre quality supports the data throughput of the sky survey, allowing us to see the faint objects on the sky. The fibre chosen for SAMI was tested to have the best FRD 6 years ago.[4,5] However, due to production processes which may have changed over the years, the new fibres produced now may have different optical performance. Therefore we need to test the new fibre samples. For Hector we aimed for fibres with same optical quality as the SAMI fibres. New fibres from Ceramoptec were tested to ensure they had performance as good as SAMI fibres.

2.2 Testing ceramoptec fibre

The spectrograph acceptance cone of Hector is within a numerical aperture (NA) of 0.154 and the input light cone is NA=0.147 from the AAT 2-degree field top end. The spectrograph was designed with a slightly bigger acceptance cone as is typical to compensate for light loss from FRD. In the FRD test setup, the input beam is set as NA=0.147. Tested fibres are attached into a SMA connector and placed at the focus of the input beam. Both ends of the fibre are cleaved with an angle $<<$ 1 degree to avoid geometric FRD, and the end finished checked by microscope. The output end of the fibre is imaged onto a CCD. The whole system was strictly aligned, with errors associated with any geometrical FRD assessed. The NA errors from the geometrical FRD, code calculation, focus light input and all aspects of the setup were added in quadrature. The FRD are tested both in blue ($\sim$457nm) and red ($\sim$596nm) wavelengths with two different Bessel filters that are put in the collimated beam.

Figure. 2 shows three kinds of cleaving. The left one is considered as perfect cleaving. Even thought there is a small chip at the left-top of the cladding, it is too small to affect light propagation. The middle image in Figure. 2 is a bad cleave because there is a heavy chip which goes through the cladding into the core. This will worsen the FRD. The right image has some grazed structures on the core surface which means the cleaving tension was too high such that the cleave crack did not propagate across the core before the fibre tore apart. This will also impact FRD. Therefore, when testing the FRD, both input and output end of the fibre need to be cleaved perfectly.

Figure 2: The left image is a perfect cleaving example. The middle image shows a bad cleave with the impact crack in the glass penetrating to the core. The right image has surface structures which also worsens the FRD.

2.3 Results

The new FRD code analyses the output and input images, to calculate *NA versus Encircled Energy* curves. Encircled Energy means the ratio of the total counts in the encircled area to the total counts of the entire light spot. The shape of such curves changes with FRD. The measured NA range is from zero to 0.4 which extends beyond the spectrograph acceptance cone angle. This range ensures a model can be fit out to where the encircled energy curve flattens out at the background level of the image. Since all fibres have some mode mixing during light propagation,the output curve should have a slightly different shape to the input curve. However, worse

FRD is indicated by the curve shifting to higher NA. The aim is for FRD as good as the SAMI fibre. Therefore, if the new fibres are not shifted to higher NA than the SAMI fibre curve within errors, we consider it is behaving as well as SAMI fibre.

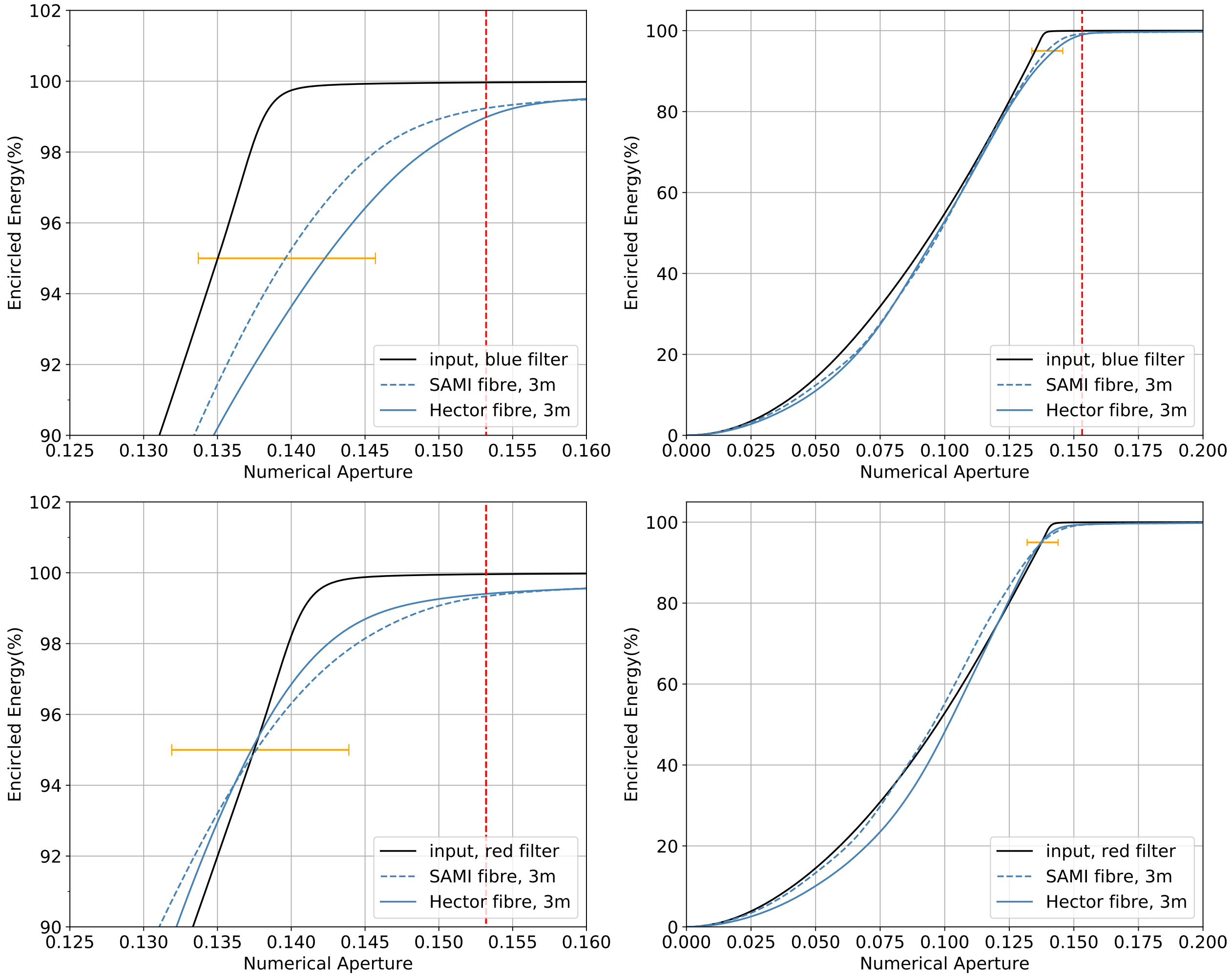

Figure 3: FRD test result. The new Ceramoptec fibre being test is the “Hector” fibre. See more description in Section 2.3.

Figure. 3 shows the comparison NA versus Encircled Energy curves of the light input into the fibre, as well as the SAMI fibre and new Ceramoptec fibre output light. The curves shown are the typical curves from many repeated measurements of each fibre type. The first row is measured at blue wavelengths and the second row at red wavelengths. The error bar of the test system is NA=±0.003 (see orange line in the plots), which comes from the alignment error of the FRD system as discussed above. The dashed red line marking the NA=0.154 of the spectrograph acceptance cone, is the key NA at which to measure the difference in the light loss between two fibres. Table. 1 shows the encircled energy number at NA=0.154. Both the SAMI and new Hector fibre have $> 99.1\%$ of their light within the acceptance cone of the spectrograph. The red wavelengths retain more light within that NA. The results for both fibres agree within errors.

Our results show that the new Ceramoptec fibre (WFNS103/123) to be used for Hector, has a similar throughput and FRD to the SAMI fibre (WF105/125). We found that the 100km of this fibre was made using two types of deposition process. One process is only using Plasma activated Chemical Vapour Deposition

Table 1: Encircled Energy at NA=0.154

NA	Filter	Input light	SAMI fibre	New Ceramoptec fibre
0.154	blue	99.97%	99.30%	99.13%
0.154	red	99.96%	99.38%	99.43%

(PCVD) for the outer cladding layer. The second process is PCVD for the first layer and process the second layer with Plasma-based Outside Vapor Deposition (POVD). This is important because two different kinds of depositions result in two chemical etching rates for the fibre cladding. To get a evenly packed hexabundle, all the fibres should be etched to the same diameter. The etching rate with different depositions is discussed in an extended abstract[12] and in detail in Wang et al. in prep. Nevertheless, the two deposition processes didn't make a difference to the optical performance of the fibres based on FRD tests.

3. 169 CORE HEXABUNDLE FRD RESULTS

The 169-core hexabundle is the largest size in Hector with the highest light collecting power in the world and it is the hardest one to build. It enables a 26 arcsec degree field of view which can receive larger galaxies compared to SAMI's 61-core[6] (15 arcsec) hexabundles.

Figure. 4 shows one of our prototype 169-core bundles with random light illumination. Its physical size is less than 2mm. The right image in Figure. 4 shows the bundle under the microscope beside a 10 cent coin. The fibres are aligned in a perfect hexagonal grid which will improve the data reduction for dithered images.

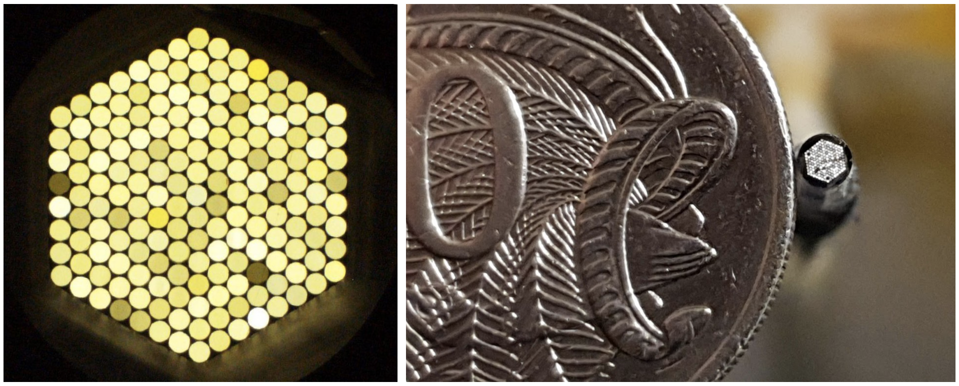

Figure 4: A prototype 169-core Hector hexabundle.

We selected each fibre core in each hexagonal ring from outside to inside (8 rows in all) to test the FRD. The cores at outer row can have worse FRD than the inner rows due to the pressure in the processing. However, our new method for building this 169-core bundle enables almost no FRD compared to a single bare fibre even at the outer row.

4. CONCLUSION

FRD is not avoidable. However, with good quality fibres, we can reduce the FRD compared to the input light. With an optimised method for building hexabundles, the FRD can be reduced to as low as a single bare fibre. The low FRD and high throughput will ensure Hector will capture more light from the Hector Galaxy Survey galaxies than any previous hexabundles. Hector will be in commissioning early next year, enabling a 15,000-galaxy survey in order to achieve new science such as different galaxies merger histories by measuring the spin parameters and specific stellar angular momentum and the ongoing dynamical interactions within galaxies. The 169-core hexabundle covers 26 arcseconds on sky that will provide clear emission lines and stellar continuum at the outer area of the galaxies. The next step for hexabundle development is to complete the construction of

91 and 127-core bundle with the new method and select out the final 21 best behaving IFUs to build into the instrument.

ACKNOWLEDGMENTS

This research was supported by the Australian Research Council (ARC) Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. Hector is partial supported through ARC LIEF grants LE150100144, LE170100242, LE170100242, LE190100018. AHW would like to acknowledge support from an AAO student scholarship. JJB acknowledges support from an ARC Future Fellowship FT180100231. We acknowledge the assistance of Dr Chris Betters with some of the equipment in SAIL.

REFERENCES

[1] Bland-Hawthorn J., Bryant J. J., Robertson G., Gillingham P., OByrne J., Cecil G., Haynes R., Croom S., Ellis S., Maack M., Skovgaard P., Noordegraaf D, "Hexabundles: imaging fibre arrays for low-light astronomical applications" , Optics Express, 19, 2649 (2011)

[2] Bryant J. J., O'Byrne J. W., Bland-Hawthorn J., Leon-Saval S. G., "Characterisation of hexabundles: initial results", MNRAS 415, 2173 (2011)

[3] Bryant J. J., Bland-Hawthorn J., et al., "SAMI: a new multi-object IFS for the Anglo-Australian Telescope", SPIE 8446, 250 (2012)

[4] Bryant J.J., Bland-Hawthorn J., Fogarty L., Lawrence J., Croom S., "Focal ratio degradation in lightly-fused hexabundles", MNRAS, 438, 869, (2014)

[5] Bryant J. J. et al., "The SAMI Galaxy Survey: instrument specification and target selection", MNRAS, 447, 2857 (2015)

[6] Bryant J. J. et al. "Hector - a new massively multiplexed IFS instrument for the Anglo-Australian Telescope", SPIE Conference Series (2016)

[7] Brown R., Wang A. H., et al. "New-generation hexabundles: development and initial results", SPIE Conference Series (2018)

[8] Croom S., et al. "The Sydney-AAO Multi-object Integral field spectrograph (SAMI)", MNRAS 421, 872 (2012)

[9] D. M. Haynes, M. J. Withford, et al. "Relative contributions of scattering, diffraction and modal diffusion to focal ratio degradation in optical fibres MNRAS", Volume 414, Issue 1, 11 June 2011, Pages 253263

[10] Ian R.Parry, "Optical fibres for integral field spectroscopy", New Astronomy Reviews, Volume 50, Issues 45, June 2006, Pages 301-304

[11] Ramsey L.W., "Focal ratio degradation in optical fibers of astronomical interest",Fiber optics in astronomy; Proceedings of the Conference, Tucson, AZ, A90-20901 07-35 (1988)

[12] Wang A. H., Brown R., et al. "Hexabundle optical fibre imaging devices for the Hector instrument", submitted (2019).