# New developments in Integral Field Spectroscopy

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## ABSTRACT

The field of integral field spectroscopy is approaching maturity with a large range of devices built or under construction. The integral field unit (IFU) of the GEMINI Multiobject Spectrographs (GMOS) is currently being developed by the Durham Astronomical Instrumentation Group (AIG). This gives 0.2 arcsec sampling over a field exceeding 60 square arcseconds. A prototype has been built for the near-infrared which is now in operation at UKIRT and another instrument using fibre-lenslet technology is under construction for use with Adaptive Optics systems at the Herschel telescope in La Palma.

The next generation of integral field spectrographs will address yet more ambitious targets which arise from opportunities presented by the new ground-based and space-borne telescopes. Foremost among these is the desire to (a) obtain finer spatial resolution so as to exploit the excellent images available from AO and space telescopes; (b) exploit the thermal infrared, in order to understand the evolution of galaxies at very high redshift; and (c) to provide a multiplexed integral field capability.

Realisation of these requirements will, most likely, involve a combination of fibre-lenslet and image-slicer technology.

**Keywords:** Integral field spectroscopy, large telescopes, spectroscopy

## 1. THE SCIENTIFIC CASE FOR INTEGRAL FIELD SPECTROSCOPY

Integral field spectroscopy (IFS) provides a spectrum of each spatial element in a two-dimensional field[1]. As well as the advantage for studies of extended objects, work on single unresolved objects or integrated spectroscopy of extended objects also benefits because light from the full extent of the object is collected simultaneously without the need for a wide slit which would degrade spectral resolution. Target acquisition is easier because it is not necessary to position the object carefully on a narrow slit and because the precise pointing may be determined after the observation by forming a white-light image from the spectral data.

Applications include the following. (a) *Studies of the distribution of star formation in distant galaxies in the field and clusters. HST* reveals their morphologies and colours but spectroscopy is required to study details of the stellar populations. (b) *Kinematical studies of galaxies at intermediate redshift.* This requires both good spectral and spatial resolution and a large wavelength range if results from different spectral features are to be combined. Since nearer galaxies might completely fill the field of the IFU, it is necessary to provide a separate offset field dedicated to background estimation. (c) *Distance estimation at intermediate redshift.* For example, the Tully-Fisher relationship at $z \simeq 0.6$ requires the velocity field to be measured to several scale lengths (1-2 arcsec) via an emission line such as [OII]3727. This requires good image quality, high throughput and a full two-dimensional capability to ensure that the *global* velocity field is recovered. (d) *Reconstruction of lensed galaxies.*

Gravitational amplification by foreground clusters increases the detectability of faint galaxy populations. By reconstructing the original (x,y,$\lambda$) datacube, the above studies can be repeated on even more distant galaxies. Even if the signal/noise in a single element in insufficient, the integrated light may yield the redshift and broad details of the stellar populations. In the infrared, other opportunities arise, including studies of the obscured nuclear regions of active galaxies; the optical-radio co-alignment of distant radio galaxies; and studies of shocks in star forming regions.

## 2. THE GMOS INTEGRAL FIELD UNIT

Both *GEMINI* telescopes will be provided with a *GMOS*[2]. The instruments are of identical design, with a $5.5 \times 5.5$ arcmin$^2$ field sampled at 0.07 arcsec/pixel. The detector format is $6144 \times 4608$ with 13.5$\mu$m pixels. They are optimised for the wavelength range 0.4–1$\mu$m and provide resolving power up to $R \equiv \lambda/\Delta\lambda = 5,000$ with a slit width of 0.5 arcsec (although slit widths of 0.25 arcsec will be possible). The spectrographs have three main modes: *multiobject*, via multiaperture masks made off-line at the telescope; *imaging*, for target acquisition and mask design; and *integral field*.

The integral field mode[3] is selected by remote insertion of the IFU at the telescope focus using the mask-exchange mechanism. This is possible because the IFU will be packaged into a space not much greater than that of a slit mask (Fig. 1). The main parameters of the IFU for GMOS-North are given in Table 1.

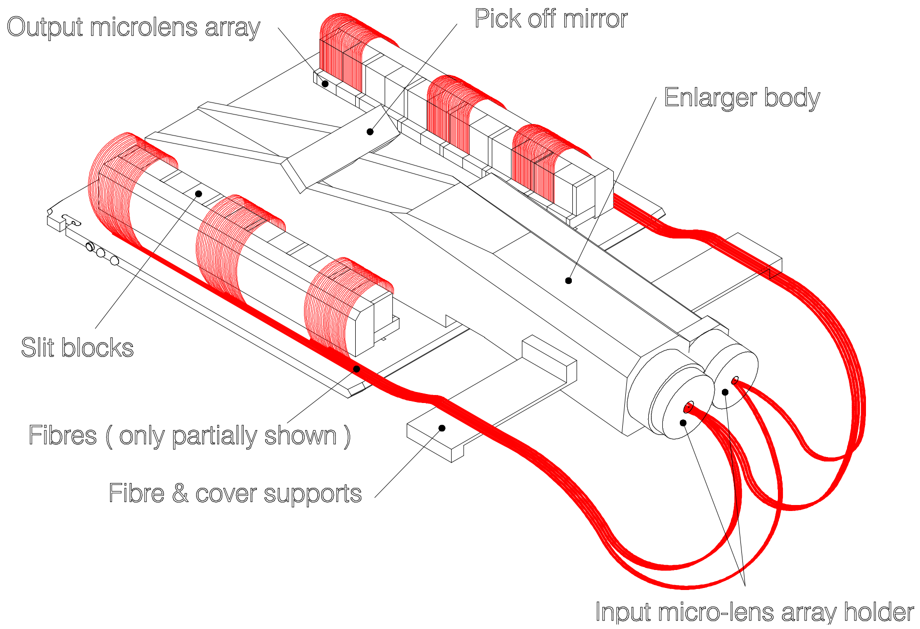


Figure 1: *Interim design of the GMOS IFU presented at the GMOS Critical Design Review. The cover and some of the fibres are not shown.*

The basic principle is illustrated in Fig. 2. The f/16 beam from the telescope is sent through an enlarger to magnify and telecentrically-correct the image formed by the telescope. This image is sampled by a microlens array which forms images of the telescope pupil at the entrance to optical fibres. Since the pupil images are smaller than the aperture of the lenslets, no loss is experienced at the gaps between fibres cores, leading to complete filling of the field, in constrast to fibre-only designs. The lenslets also speed the beam to f/7 to reduce *focal ratio degradation* (FRD) so that the Etendue of the system is maintained. The fibres are reformatted to form

Table 1: Summary of the GMOS Integral Field Unit (CDR design)

| | |
|---|---|
| Spatial sampling | 0.2 arcsec |
| Object field area | 62 arcsec$^2$ |
| Object field aspect ratio | $\sqrt{2}$ |
| Object:background field area | 10:1 |
| Object-background field distance | 1 arcmin |
| Number of reformatted slits | 2 |
| Width (FWHM) of spectral resolution element | 0.27 arcsec |
| Number of spectral resolution elements | 800–1600 |
| Number of spatial resolution elements | ~2000 |

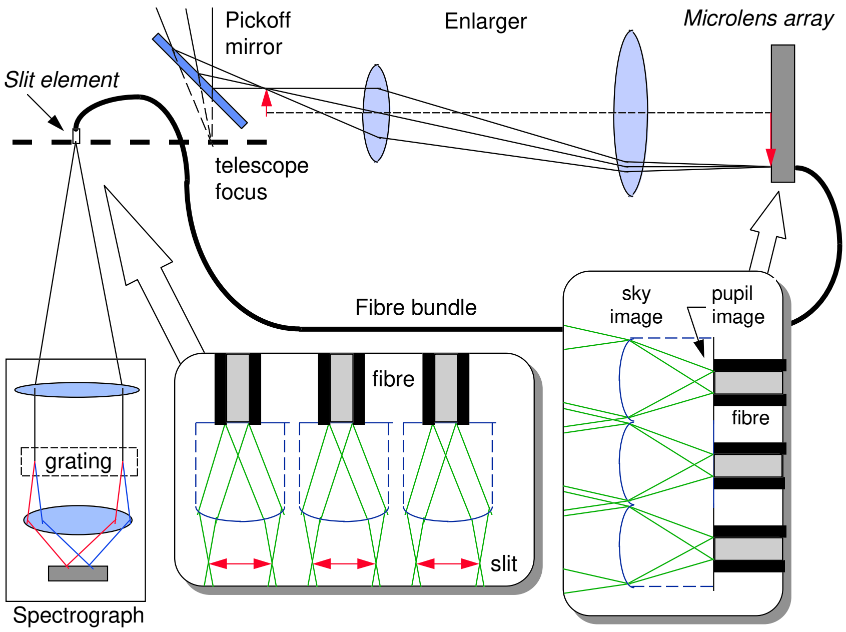


Figure 2: *The principle of the GMOS integral field unit.*

two long pseudo-slits which are located at the original telescope focal surface. The light is then dispersed by the spectrograph in the same way as if it had come straight from the sky through a normal slit. The field layout is shown in Fig. 3.

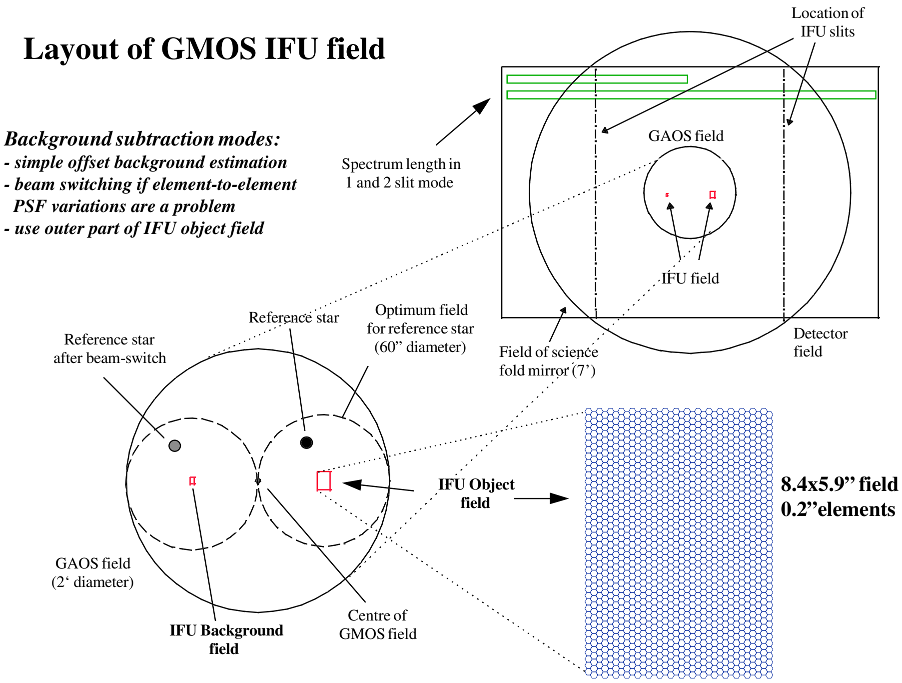


Figure 3: *The layout of the field of GMOS, the IFU and the GEMINI Adaptive Optics System. The format of the detector and spectra are also indicated. The latest IFU design has a slightly larger field than shown here.*

A full-length spectrum, covering 6144 pixels can be produced by blocking one of the slits at the expense of halving the field (Fig. 4). Even in the two-slit mode, when used with a passband filter, the spectrum length exceeds that obtainable from lenslet-only systems[1]. The field-slit mapping is such that elements which are adjacent on the sky are also adjacent at the slit[3]. This allows elements to be packed closer at the slit resulting in an increased field of view. Cross-talk between light emerging from adjacent elements at the IFU output has negligible effect on the spatial resolution when the input image is critically sampled at the IFU input[4].

A separate, but optically identical, field is provided at an offset of 1 arcmin from the main field for background estimation (Fig. 3). If necessary, the two fields can be beam-switched to eliminate any variation in the point spread function produced by different elements[3,4]. Ideally, the two fields would be the same size, but this is not possible without reducing the overall field of view when beam-switching is not used. Fig. 3 also shows how the beam-switching is achieved when GMOS is used with the GEMINI Adaptive Optics System. Here it is important to ensure that the wavefront sensor can access the reference star during both parts of the beam-switch cycle. This imposes a 1 arcmin limitation on the field offset and requires that the two fields are symmetrically disposed about the field centre.

## 3. CURRENT FIBRE-LENSLET PROGRAMME IN DURHAM

The GMOS IFU is expected to be completed in 1999/2000. The design will be finalised in 1998 to allow us to learn as much as possible from the constructions of the other IFUs in our programme.

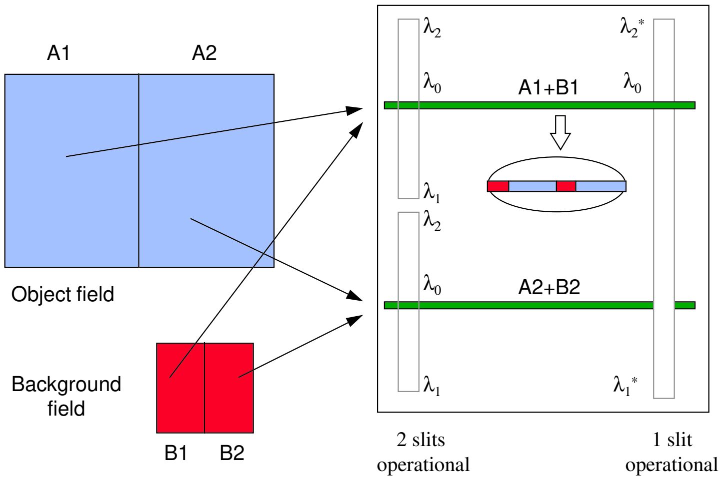


Figure 4: *Illustration of the one and two-slit modes. The one-slit mode more than doubles the available length of spectrum at the expense of halving the field area.*

The current programme of the Durham AIG in fibre-lenslet IFU construction comprises the following. (a) The *SMIRFS-IFU*, a near-IR system retrofitted to the *CGS-4* 1-5$\mu$m spectrograph on *UKIRT*. This 72-element device, working in the $J$ and $H$ bands, has now been successfully commissioned[5,6] and used to investigate star formation and nuclear processes in active galaxies. (b) The *Thousand Element Integral Field Unit (TEIFU)*[7] which will exploit adaptively-corrected images provided by the *ELECTRA* and *NAOMI* AO systems at the 4.2-m *Herschel* telescope at scales down to 0.13 arcsec/element (completion 1998). (c) The *GMOS-IFU*.

## 4. SCIENTIFIC DRIVERS FOR FUTURE DEVELOPMENTS

The major objectives for the next generation of integral field spectrographs are to: (a) improve performance in the thermal infrared ($> 1.6\mu$m); (b) improve spatial resolution; and (c) provide a multiobject IFS capability. It is interesting to note that surveys of scientific requirements for large telescopes do not give prominence to increasing the field of individual IFUs beyond the current 50-100 square arcsec of current fibre-lenslet systems. This is largely because 8/10-m telescopes will be efficient at targeting faint objects which will generally be small in angular extent.

The need to work further into the *infrared* arises from two main directions. Firstly, investigations of the evolution of galaxies over larger spans of cosmic time lead to the study of ever more distant galaxies. This is possible because of the increased light-grasp of the new 8-10m telescopes. The spectral energy distribution of these galaxies is shifted further and further into the infrared as are the spectroscopic features from which the redshift is determined and the stellar populations studied. For example, at redshift of $z = 3$, the key diagnostic emission line [OII]3727 is observed at 1.5$\mu$m while H$\alpha$ appears at 2.6$\mu$m (Ly$\alpha$ is unreliable for this work). Secondly, HST has allowed us to obtain greater understanding of processes in star-forming regions. One of the main areas of study is of shock-heated molecular hydrogen so that processes of momentum and energy transfer in star-forming clouds can be understood. This requires two-dimensional spectroscopic capabilities at relatively long wavelengths, from the K band redwards.

The desire for *better spatial resolution* is a direct consequence of the excellent image quality of HST and terrestrial Adaptive Optics systems which can provide comparable performance from the ground. With the advent of laser beacons, high-order AO systems will be used more and more routinely. This allows telescopes to approach their diffraction limit ($0.025\lambda(\mu m)$ arcsec for an 8-m telescope) which implies sampling by an IFU on scales of a few tens of milliarcseconds. It is a major objective to obtain spectra on spatial scales similar to those of the spectacular images obtained by HST on the Hubble Deep Field (HDF) and for the star-forming regions in M16.

A *multiple IFS capability* is also required so that spatially-resolved spectra of different objects can be obtained simultaneously. The HDF provides an obvious example. Spread over a field of a few arcmin are a hundreds of well-resolved field galaxies covering a large range of redshift and morphology. At present, it is only possible to measure integrated spectral properties for a number of them. Spatially-resolved spectroscopy is needed to study their stellar populations and internal dynamics. This requires large telescopes, perhaps bigger than 8-10m, or space-borne telescopes with exceptionally low backgrounds such as NGST. Their increased sensitivity results in a higher surface density of targets, making it more efficient to study large number of different types of object with a multiobject instrument. At the brighter levels, which are more accessible from the ground, the main driver is the study of galaxies in clusters.

Another type of multiobject capability could be provided by an IFU with a very large number of elements. This would carry out multiobject spectroscopy by segmenting the entire field which would be an advantage in a space environment where moving parts must be avoided. This approach might be suitable when the surface density of targets is very high as large statistical samples could be obtained even in quite small fields. For instance NGST would probably produce $\sim$600 galaxies/arcmin$^2$ with $z > 5$.

## 5. TECHNOLOGICAL DEVELOPMENTS

The main techniques of integral field spectroscopy are summarised in Fig. 5.

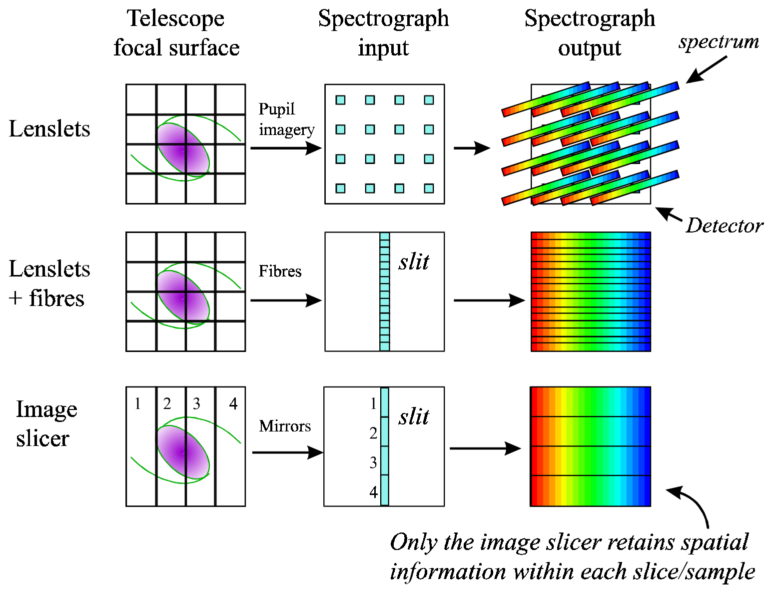


Figure 5: *Illustration of the three main techniques of integral field spectroscopy.*

### 5.1. Image-slicing IFUs

When working at infrared wavelength beyond $\sim 1.6\mu$m, it is necessary to cool the IFU. This is difficult for fibre-based systems because the properties of fibres at low temperatures are not well understood and because the fibre-lenslet joint is unlikely to survive temperature cycling. However, the design for SINFONI, proposed for VLT, does use cooled fibres[8]. This seeks to avoid the problem of the integrity of the fibre-lenslet interface by deforming and machining the fibre ends to form lenses.

Another approach is the 3D integral field spectrograph[9] which uses an image-slicing technique. The optical system employs only mirrors which provides the benefits of achromatism and high efficiency. This design has now been developed to make it easier to adapt to existing optical designs[10] (Fig. 6). The new concept is being developed[11] for use with the GEMINI Near-Infrared Spectrographs (GNIRS[12]) and the UKIRT imaging spectrograph (UIST[13]) and is being studied for NGST as part of an integral field/panoramic IR spectrograph[14]. The mirrors have a more complicated figure than for 3D so we are investigating the use of diamond-turning to produce complete mirror sub-assemblies which are integrated with their mounting surfaces in such a way that the optical surface and mounting interfaces are precisely registered. The problem of alignment and confocality under cooling can be minimised by attaching these units to a mount made from the same material as the mirror sub-assemblies.

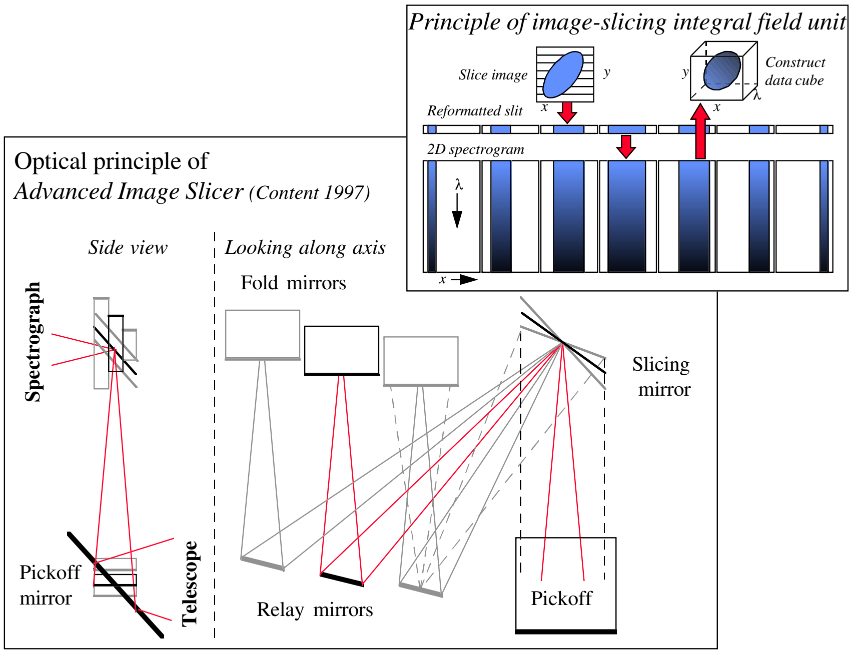


Figure 6: *Illustration of the principle of an image-slicing IFU and the optical principle of the Advanced Image Slicer.*

Image slicers also offer the potential of improving spatial resolution. Ultimately, two-dimensional spectroscopy at high spatial resolution and long wavelengths is limited by the problem of diffraction. With fibres, this can be considered as an additional form of FRD. Since this is a loss of Etendue it represents an increase in entropy which ultimately limits the information which can be obtained from an optical system. For a well-designed fibre system, the diffraction is the same as would be obtained by passing the light through a physical aperture which subtends the same angle on the sky as each IFU element. For examples, with GEMINI, a 0.05 arcsec IFU element gives the same diffraction as an element which is $0.05 \times 621 = 31\mu$m since the plate scale is $621\mu$m/arcsec. At a wavelength of 2$\mu$m, this produces a diffraction cone angle with FWHM $\sim 4°$ equivalent to an f/15 beam, comparable to the required spectrograph beam for a beam-fed instrument. Image-slicing IFUs reduce this problem because the diffraction is now a one-dimensional, rather than two-dimensional, problem.

### 5.2. Multiple IFUs

For multiple-IFS, fibre-lenslet technology is the most applicable. This is because the flexible fibre bundle allows independent units (*mini-IFUs*) to be positioned as desired within a large field of view, perhaps via a pick-and-place robot in the same way as multi-fibre instruments such as Autofib-2/WYFFOS and 2DF. Such an approach has been considered for Australis[15] and FMOS[16] on SUBARU (Fig. 7).

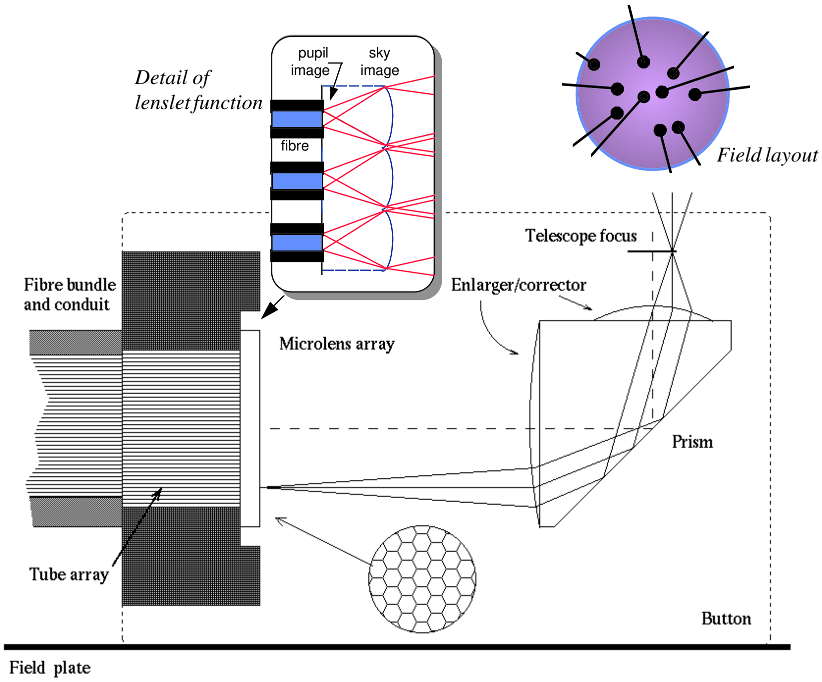


Figure 7: *Scheme for a mini-IFU unit as part of a multiple integral field spectrograph. The prism and telecentric enlarger are combined into a single unit for simplicity and to reduce fresnel losses. The unit can be positioned within a larger field as indicated. For FMOS, the field diameter is around 5 arcsec = 0.4mm. The full field is 30 arcmin.*

The number of mini-IFUs and the field of each is limited by the detector format since this determines the total number of elements. For example, GMOS can accommodate 2000 elements, but an instrument dedicated wholely to IFS could probably achieve 4000 elements within the same 4608$\times$6144 detector format (e.g. using two pseudo-slits and a pitch of 2.3 pixels at the slit). To be competitive with spectrographs with sub-arcsec slits on the new telescopes (e.g. GMOS), the field covered by each mini-IFU should be at least 4 arcsec$^2$. Otherwise, it would be simpler to use multiple exposures with the longslit stepped across the object. This means that the maximum number of mini-IFUs is $N = 4000 \times d^2/4 = 1000d^2$ where $d$ is the sampling of the IFU. For GMOS, $d = 0.2$ arcsec so $N = 40$ but for an instrument with finer sampling, $d = 0.1$ arcsec, $N = 10$ only. Since this is probably the minimum useful multiplex gain, this illustrates the likely limit on the spatial resolution which can be achieved with this technique.

### 5.3. Panoramic IFUs

If the number of elements was sufficient to cover a large field of view with adequate spatial resolution, then it would be possible to dispense with multiaperture spectroscopic techniques altogether. This would be major advantage for use in space, because there would be no moving parts or consumables. Even micro-mirror arrays have potential failure points and require power to operate.

To take an example, a field of $1 \times 1$ arcmin could be covered with 0.3 arcsec sampling with 40,000 elements. To give each element a useful spectrum length of 800 pixels and with critical sampling in the spatial direction implies a detector format of $8000 \times 8000$. This could be provided by an array of $4 \times 4$ detectors of format $2048 \times 2048$, such as those currently under development by Rockwell. The detectors need not necessarily be edge-buttable since sparse filling of the field would be acceptable for many applications.

Since the number of elements is ultimately limited by the detector format, it appears that this capability is, *in principle*, obtainable. The AIS concept might prove the most feasible, requiring 10 output slits offset from each other in the dispersion direction by 800 pixels.

1 square arcmin is a relatively small field by today's standards but it must be remembered that the surface density of targets rapidly increases with limiting magnitude and the next generation of space telescopes (e.g. NGST) will provide the combination of large aperture and low background necessary to achieve this. This means that a statistically significant sample of field galaxies (e.g. like the HDF only deeper) can be obtained via quite small fields. The sampling of 0.3 arcsec is reasonably well matched to the typical effective radius of faint galaxies, although not really sufficient to spatially resolve the smaller galaxies. To study these, a fine-scale IFU would also be required. The same 40,000 elements would cover a field $10 \times 10$ arcsec with 0.05 arcsec sampling.

## 6. CONCLUSIONS

The GMOS IFU represents a staging point in the development of integral field spectroscopy because of its large format and fine sampling. Another large-scale IFU is under construction for the VLT VIRMOS instrument[17]. Beyond this, there is a growing consensus amongst astronomers for developing integral field spectrographs with finer spatial resolution, improved performance in the infrared and a multiobject capability. The basic technology to do this already exists (fibre-lenslet and image-slicing) and is being developed further to meet these new challenges.

## ACKNOWLEDGEMENTS

We are indebted to my colleagues in the Durham AIG for their work on much of the integral field instrumentation discussed in this paper, in particular David Robinson, John Webster, George Dodsworth, David Robertson, Ray Sharples, James Turner and Ren Deqing. We also thank David Lee, now at AAO, and our GMOS colleagues at DAO and ROE.

We also acknowledge helpful conversations with many colleagues in the various groups around the world who have made valuable contributions to this field.

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