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E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR THE ELT-IFU

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Contents

Abbreviations

See applicable document AD1 (see section 2.1 herein for references of applicable documents).

1 Scope

The scope of this document is to define the Top Level Requirements for the E-ELT instrument: Integral Field Spectrograph (ELT-IFU).

The Top Level Requirements are derived from the Science Case of the E-ELT. For particular instruments, they were developed during the concept phase for the instruments (between 2007 and 2010), as well as in the process of defining the Design Reference Mission and Design Reference Science Plan for the E-ELT. The present document draws heavily on [RD3].

The Top Level Requirements are developed by the E-ELT project with the help of its Project Science Team. They can be refined by the Consortium contracted to deliver the instrument, and are the basis for setting up the Technical Specifications for the instruments.

2 Related documents

2.1 Applicable documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the content of the present document shall be taken as superseding.

AD1 Common definitions and acronyms;
E-ESO-SPE-313-0066 Issue 4

2.2 Reference documents

The following Reference Documents provide background information as to the present document. Under no circumstance shall the content of Reference Documents be construed as applicable to the present one, in part or in full.

RD1 E-ELT Science Case;
E-TRE-ESO-080-0806 Issue 1

RD2 Science Working Group input to the E-ELT Instrument Plan
E-PLA-ESO-080-0770 Issue 1

RD3 Harmoni Scientific Analysis Report
E-TRE-UOX-568-0018 Issue 2

RD4 The E-ELT Design Reference Mission
E-TRE-ESO-080-0717 Issue 2

RD5 The E-ELT Design Reference Science Plan
E-TRE-ESO-080-0840 Issue 2

3 Science Case for ELT-IFU

The unique spatial resolution of the E-ELT is one of its key defining characteristics. The scientific advances to be expected from the ability to operate a 40-m-class telescope at its diffraction limit form the core of the Science Case for the E-ELT [RD1], and the need for diffraction limited performance was hence a strong driver for the design of the telescope. Thus, the E-ELT clearly requires instruments that can exploit this capability.

The need for such instruments was recognized and strongly emphasized by the E-ELT Science Working Group (SWG) in its recommendation regarding the E-ELT's first-light instruments [RD2]. Having assessed all proposed first-light instruments, the SWG came to the conclusion that a diffraction limited imager and integral field spectrograph represented a particularly powerful combination of instruments, which covered a broad range of science cases for the E-ELT [RD1] and featured compelling discovery potential. Additional assessment criteria included immediate scientific impact, complementarity with other facilities, scientific flexibility, secure scientific return, and the capability of doing science in a broad range of atmospheric conditions.

In this document we derive the Top Level Requirements for ELT-IFU, a diffraction limited integral field spectrograph for the E-ELT. As has been well established, many of the sciences cases for the E-ELT [RD1] require such an instrument. In this section we assemble that sub-set of science cases that drive the requirements for ELT-IFU. Although not a complete list, this set is nevertheless representative of the science to be enabled by ELT-IFU. We provide brief descriptions of these cases, as well as the instrument requirements derived from them.

3.1 Solar System Science case

3.1.1 Outline of the science case

ELT-IFU is needed for imaging spectroscopy of small bodies of the solar system. The scientific objectives are as follows:

- Uranus and Neptune: meteorology (through CH_4 features), aurorae (through H_3^+ features), polar haze;
- Outer satellites: study of volcanic activity (Io), search for outgassing/cryovolcanic activity (other Galilean satellites + Enceladus), meteorology (Titan), mapping of ices (Triton);
- Comets: monitoring of jet structure, activity versus heliocentric distance, search for gaseous emissions (C_2, CN). The visible channel is required for the detection of C_2 fluorescence at 0.5 μm. Simultaneous wavelength coverage is required because comets are fast rotators (less than a few hours);
- Distant bodies (asteroids, Trans-Neptunian objects [TNOs], comets): search for activity; study of surface composition. The visible channel is required for TNOs as their absolute magnitude

is normally given in the V band. In addition, V observations are needed to complement IR data and determine the albedo and the size of the objects. Simultaneous wavelength coverage (V to K) is required because asteroids and TNOs are fast rotators (periods less than a few hours).

In all cases, the adaptive optics (AO)/telescope control should permit differential tracking between the AO source and the science target. This is needed for enabling long exposures of faint sources, which display a differential motion with respect to the AO guide source (e.g. observation of faint satellites using another brighter satellite as reference source for the AO system). High (~ 70%) Strehl ratios are very significant for this case, as they would, for example, greatly improve our ability to resolve cloud features and storms on the outer planets and Titan.

3.1.2 Derived requirements from the science case

This science case requires simultaneous low-R spectral coverage from the V to the K band (0.5 – 2.4 μm). The reason is the variability of solar-system objects, due to their rotation period. Most objects (planets, asteroids, comets, TNOs) are fast rotators, with rotation periods of less than a few hours. Many TNOs are possibly binary systems, with strong variations of their light-curves. Long exposures (> 1 hour) will be required for observing weak TNOs, those presently beyond the VLT detectability limit. Simultaneous spectral coverage is thus required. Low-resolution spectroscopy (R = 500 – 1,000) is best suited for obtaining high S/N spectra of minor bodies, and sufficient for investigating their icy content, their dilution state, temperatures and degree of alteration, all parameters needed for constraining space weathering effects and evolution processes. High-resolution spectroscopy (R = 4,000 – 10,000) in the near-IR will allow us to study the atmosphere of Uranus, Neptune, and Titan, and identify distinct regions on the moons of Jupiter. The visible channel is important for solar-system science for three reasons: 1) for primitive asteroids having experienced aqueous alteration, absorption features could fall in the 0.55 − 0.82μm range; 2) for comets, a strong C_2 fluorescence band appears at 0.52 μm; there are no other C_2 bands of equal or larger intensity at longer wavelengths; 3) the absolute magnitudes of solar-system minor bodies are always referred to the V filter. In addition, the V photometric point is needed in thermal models, in combination with infrared data, to derive both the diameters and the albedos of the objects. As regards AO, differential tracking is needed. Tracking rates for solar-system objects range from a few arcsec/hour (outer satellites, TNOs) to over 100 arcsec/hour (nearby comets, near-Earth asteroids). Depending upon the size and brightness of the target, various types of AO could be needed. In most cases (small bodies) on-axis correction should be sufficient, with the possibility of using either natural (NGS) or laser guide stars (LGS). It would be greatly beneficial to be able to reach high (~ 70%) Strehl ratios.

AO	on-axis correction, NGS (Strehl ratio ~70%) and LGS, differential tracking
R	500 – 1,000 (0.5 – 2.4 μm); 4,000 – 10,000 (1.5 – 2.4 μm)
Spectral range	0.5 – 2.4 μm, simultaneous (R = 500 – 1,000)

Table 1. Summary of requirements for Science Case 1

3.2 High-contrast spectroscopy of planetary mass companions to nearby stars

3.2.1 Outline of the science case

Radial velocity (RV) detections of extra-solar planets have been a watershed for observational studies of planet formation, assembling a sample of planets large enough (~850 to date, see http://www.exoplanet.eu) for statistical studies. Properties of the derived orbital and physical elements (period, eccentricity, mass and density thanks to transit) and the stellar-host characteristics (metallicity, multiplicity, mass and age), provide stringent constraints to test model predictions. In that sense, the planet occurrence frequency has been determined for giant and telluric planets, confirming that planet formation is not rare (50% of solar-type stars harbor at least one planet of any mass and with period up to 100 days, 14% at least one giant planet with a period shorter than 10 years, Mayor et al. 2011, arXiv1109.2497). The planet-metallicity correlation, the multiplicity, the frequency of telluric planets (35% with super-Earth with period shorter than 100 days, Bonfils et al. 2013, A&A, 549, A109), the giant planet-host star mass correlation within 3 AU (Bowler et al. 2010, ApJ, 709,396), the density measurement and interior characterization with CoRoT and Kepler revealing their internal structures (Seager et al. 2011, Exoplanets Book) and the presence of core and heavy elements (De Sousa et al. 2011, A&A, 533, 141), all are strong insights that core-accretion is operating at relatively short separations. However, these discoveries are inherently limited, since RV and transit studies are confined to the inner regions (< 6 AU for a 15-yr survey) and we know very little about the planet population in the outer regions of other solar systems. At wide orbits (P > 10 yrs; > 5 AU) the direct imaging technique offers the unique ability to detect and characterize the population of giant planets to constrain their formation mechanisms (possibly alternative to core accretion, which is inefficient at large separations), but also the opportunity to explore the planetary system architecture and evolution (planet – planet or planet – disk interactions). The analysis of actual planetary photons finally offer a unique way to directly characterize non-strongly irradiated giant planet's atmospheres through colours, luminosities and spectra of the exoplanets, thereby providing temperatures, pressures, cloud-coverage, compositions, but also a possible link to their formation mechanism. Finally, the combination of RV and direct imaging could enable a direct dynamical mass measurement to calibrate the mass – luminosity relationship of evolutionary interior models. Several instruments are currently being designed and built to achieve this goal within the next few years, e.g., SPHERE at the VLT (Beuzit et al. 2006, The Messenger, 125, 29), and GPI at Gemini (Soummer et al. 2009, SPIE, 7440, 1). To achieve the highest contrast possible all instruments use differential imaging techniques to detect planets. Combined with the Spectral Deconvolution (SD) differential detection technique integral field spectroscopy allows the simultaneous detection and characterization of exo-planets (Sparks & Ford 2002, ApJ, 568, 543) with similar contrast as achieved by both Simultaneous Differential Imaging (SDI) and Angular Differential Imaging (ADI) (Thatte et al. 2007, MNRAS, 378, 1229). However the ability of these surveys for detecting exoplanets will be limited by the telescope diameter in two ways: the telescope collecting area limits the sensitivity; and the diffraction point spread function (PSF) sets a lower limit to the separation between the exo-planet and the parent star. Furthermore, many of the exo-planets detected with SDI, ADI, and SD will be so faint and/or so close to the parent star that they cannot be spectroscopically characterized with current 8m class telescopes. An ELT-IFU instrument, combined with high-contrast techniques such as coronagraphy, can provide spectroscopic follow-up of these direct detections, and even enable the inner characterization of this imaged planetary systems to search/characterize closer giant planets in synergy with RV or astrometric surveys.

3.2.2 Derived requirements from the science case

The ideal AO system for this science case needs to correct on-axis and achieve Strehl ratios ~70% for NGS brighter than 9th magnitude (which can be the target stars mainly observed with SPHERE and

GPI, which will be relatively bright). It will also need to have a coronagraphic mode, probably a focal plane coronagraphic mask (occulting bar, Lyot coronagraph or Phase-mask coronagraph) combined with adapted atmospheric dispersion compensator to ensure a proper centering behind the mask. Combining all of this with spectral deconvolution will allow the ELT-IFU to achieve a contrast ratio approaching 15 magnitudes (a factor of 10^{-6}) at 0.5 arcsec, with a goal of 20 magnitudes (a factor of 10^{-8}) enabling the detection of faint exo-planets at small separation from the parent star. A relatively high (> 500) resolving power will also improve the efficacy of the SD technique in detecting exo planets and will also allow us to reach a much more detailed characterization of the spectral features and thus of the exo-planet's atmosphere. A wide instantaneous spectral range, covering the H and K bands (1.45 – 2.45 μm), is also required to optimize PSF subtraction and increase the capability of accessing small inner working radii.

Spaxel scale	4 mas spaxel
AO	on-axis correction, NGS, diffraction limited core (Strehl ratio ~70%)
R	> 500
Spectral range	1.45 – 2.45 μm, simultaneous
Coronagraph	If focal plane coronagraph: coronagraph type and centering accuracy behind the mask to be defined/specified
Contrast ratio	$\leq 10^{-6}$ at 0.5 arcsec ($\leq 10^{-8}$: goal)

Table 2. Summary of requirements for Science Case 2

3.3 Intermediate mass black holes

3.3.1 Outline of the science case

Black holes (BHs) with 10^2 M⊙ ≤ M ≤ 10^5 M⊙, that is intermediate between stellar-mass and supermassive BHs, could form as a natural result of the evolution of dense star clusters, in the same (as yet unknown) process that produces supermassive black holes, or they could be remnants of the first generation of stars (Population III). Such intermediate-mass BHs (IMBHs) have been invoked to explain, inter alia, the origin of the ultraluminous X-ray sources detected in nearby galaxies, the anomalous positions and velocities of some pulsars observed in globular clusters (GCs), and the existence of young star clusters at the Galactic centre.

However, so far there is no unambiguous observational evidence that they exist. Natural places to look for them are in the centres of Galactic GCs and the Nuclear Star Clusters (NSCs) found at the centres of most late-type galaxies. By using an ELT-IFU instrument to obtain deep kinematics of stellar populations to trace the gravitational potential at the centre of the cluster, one can disentangle the effects of mass segregation from that of an IMBH. This will allow a census of IMBH masses to be obtained, from which one can constrain their formation mechanism and their relation to supermassive and stellar-mass BHs. It will also lead to more accurate predictions for gravitational-wave experiments. Testing whether IMBHs exist and understanding their demographics is also an essential part of understanding the formation and co-evolution of galaxies and active galactic nuclei (AGN), and more generally, the overall formation of cosmic structure (e.g., Regan & Haehnelt 2009, MNRAS, 396, 343).

The fundamental idea in detecting IMBHs in NSCs and GCs is the same: use stellar kinematics to look for evidence of a dark, central concentration of mass over and above what one would expect from dynamical mass-segregation processes. In practice the techniques used for NSCs and GCs are slightly different, however. In NSCs one cannot resolve individual stars and so must adopt integrated-light methods similar to those used for finding SMBHs in external galaxies. On the other hand, in nearby GCs one expects of order of one star per central spaxel, meaning that one can measure radial velocities of individual stars.

3.3.2 Derived requirements from the science case

Detailed simulations in RD3 show that detection of an IMBH within a faint NSC requires: (a) R ≥ 10,000; (b) a PSF with a FWHM < 14 mas (K band: 2.0 – 2.3 μm) and < 8 mas (I band: 0.8 – 1.0 μm). These last constraints require diffraction-limited performance, that is a spaxel scale of 4 mas. These two bands provide the best possible prior constraint on the stellar mass distribution in the galaxy (K-band) and achieve the best possible spatial resolution for kinematics (I-band). The giant stars in galactic globular clusters are bright enough to act as NGS if they are close enough to the centre. Otherwise laser guide stars (LGS) will be needed. It would be good to be able to reach high (~ 70%) Strehl ratios.

Spaxel scale	4 mas
AO	on-axis correction, NGS (GCs) (Strehl ratio ~70%: goal) or LGS (NSCs), diffraction limited core
R	≥ 10,000
FoV	0.2 arcsec
Spectral range	0.8 – 1.0 μm and 2.0 – 2.3 μm

Table 3. Summary of requirements for Science Case 3

3.4 Stellar Populations

3.4.1 Outline of the science case

The study of galaxy formation and evolution is one of the hottest topics of modern astrophysics. Detailed information on the star formation history (SFH) and the chemical and dynamical evolution of galaxies are imprinted in the resolved stellar populations. Until now sensitivity and resolution limitations have meant that detailed spectroscopic studies of individual stars have only been possible within the Local Group and mostly around our own Galaxy (e.g., Tolstoy, Hill & Tosi 2009, ARAA, 47, 371). The Local Group contains only two massive galaxies (spiral systems M31 and the Milky Way) and around 60 smaller, mostly dwarf, galaxies. To make significant progress we need to study large numbers of resolved stars in a range of galaxy types and this requires us to look beyond the halo of the Milky Way and even the Local Group. This means reaching a large variety of spiral systems in nearby galaxy groups, nearby starburst galaxies, compact dwarf elliptical galaxies, faint low surface brightness systems, and relatively close-by elliptical galaxies up to ≈ 15 Mpc. All of these, however, are too crowded to be accurately studied with current telescopes but represent key targets for spectroscopy of individual stars over a range of ages to define their detailed evolutionary properties.

The basic requirements to make direct measurements of the chemo-dynamical properties of resolved stars as probes of the evolutionary history of a range of systems beyond the halo of the Milky Way are accurate velocity measurements (where accurate means a velocity resolution less than the expected velocity dispersion) combined with metallicity indicators for samples covering their different components (e.g., thin disc, thick disc, halo, bulge).

Systematic and homogeneous spectroscopic surveys aimed at measuring key chemical elements released by stars with different mass progenitors and hence on different time scales, have also a strong astrophysical impact in drawing the global picture of galaxy formation and evolution. For example, the [α/Fe] abundance ratio is a powerful tracer of the relative enrichment by type II and Ia SN at any given time in the SFH of a galaxy. Most abundance work to date on resolved stellar populations beyond the Milky Way has been done in the visible wavelength range. CNO, α elements, Fe, Al, Na all have useful IR (atomic and molecular) lines in the IR. However V, R & I band (0.5 – 1.0 μm) spectroscopy is best suited to study resolved red giant stars and Main Sequence stars in galactic environments not severely affected by extinction. The near infrared spectral region is best suited to study both resolved and integrated cool stellar populations in the nuclear region of galaxies, where extinction can be severe.

3.4.2 Derived requirements from the science case

Detailed simulations in RD3 show that this science case requires a range of spectral resolutions, with R ≈ 4,000 suitable for radial velocities and metallicity measurements, ≈ 10,000 sufficient to measure chemical abundances in dwarf stars and for integrated light studies of unresolved stellar populations, and ≈ 20,000 best suited for detailed chemical abundances and velocity dispersions in clusters. The required spaxel size of 20 mas is a good compromise between spatial resolution and field of view to find a few measurable (in the IR, where the AO works best) bright stars in relatively dense stellar fields as well as to resolve distant stellar clusters out to ~ 20 Mpc. 100 - 200 mas would be more suited for deep observations in the visual range of faint stars in the Galaxy and Magellanic Clouds and should be considered as a goal. As regards AO, the desire to include as much flux as possible in the chosen spaxel area implies the need for LGS.

Spaxel scales	20 mas (IR) and 100-200 mas (optical: goal)
AO	on-axis correction, LGS, diffraction limited core
R	4,000 (0.5 – 1.0 μm), 10,000 and 20,000 (0.8 – 2.4 μm)
Spectral range	0.5 – 2.4 μm

Table 4. Summary of requirements for Science Case 4

3.5 Chemical tagging of the stellar populations in the Galactic Centre

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3.5.1 Outline of the science case

Recent spectroscopic investigations based on high-resolution optical and NIR spectra indicate that the metallicity gradient of the Galactic thin disk becomes steadily more metal-rich when moving from the solar circle (R_G ~ 8 kpc) to the inner edge (R_G ~ 4 – 5 kpc). In particular, the metallicity gradient based on Classical Cepheids attains super-solar iron abundances ([Fe/H] ~ 0.4) at R_G ~ 4.5 kpc (Bono et al. 2012). On the other hand, detailed spectroscopic investigations based on blue and red supergiants either belonging to young massive star clusters (Arches, Quintuplet) of the nuclear bulge or located in the near end of the Galactic Bar clearly show solar iron abundances (Davies et al. 2012). We are facing a well-defined discontinuity in the iron abundance gradient when moving from the inner edge of the thin disk to the Nuclear Bulge. Theoretical (Athanassoula 1992, Friedli 1995) and observational (Zanmar 2008) investigations indicate that the abundance gradient in barred galaxies is shallower than in unbarred galaxies. The typical explanation for this trend is that the bar is dragging gas from the inner disk into the Galactic Centre (Kim et al. 2011). The pileup of the new fresh material triggers a steady star formation activity. One of the key consequences of the above scenario is that the typical metallicity distribution along the Galactic Bar and in the Galactic Centre should be quite similar to the metallicity distribution in the inner disk.

The above evidence concerning the sharp decrease in iron abundance does not seem to support the hypothesis that the presence of a bar might be the main culprit in shaping the metallicity gradient between the inner disk and the Galactic Center. The main advantage in the current analysis is that we are using stellar tracers with similar ages, since both supergiants and Cepheids are either massive or intermediate-mass stars with typical lifetimes shorter than 100 Myr.

A more quantitative understanding of this phenomenon has an impact into the formation and the evolution of classical bulges and pseudo-bulges (Kormendy et al. 2009; Matsunaga et al. 2011). However, to address this crucial issue we need accurate chemical abundances (iron, α, and CNO elements) not only for evolved stars but also for old and intermediate-mass main sequence stars in the Nuclear Bulge. This requires high-resolution (R ≥ 20,000) near-infrared spectroscopy in very crowded regions for stars with K-band magnitudes ranging from 23 to 25. The key advantage in using the IFU is that we simultaneously trace the abundances and kinematics of cluster and field stars.

3.5.2 Derived requirements from the science case

One of the main science drivers of the current experiment is to perform accurate spectroscopic measurements (kinematics and abundances) of intermediate and old main sequence stars in the Nuclear Bulge. This is the Galactic region with the highest stellar density, since together with local stars are also projected bulge and thin disk stars. The same region is also highly reddened (A_K~3 mag). This means that we need to cover the J- to K-bands (1.2 – 1.3, 1.5 – 1.7, and 2.1 – 2.3 μm) and perform accurate spectroscopy down to K ~ 23 - 25 mag, Preliminary simulations indicate that this case requires a PSF in the K-band with a FWHM smaller than 14 mas, and in turn almost diffraction limited performance. NGS might be used efficiently. Moreover, to trace back the chemical enrichment (iron, CNO and alpha elements) of both intermediate and old stars requires a spectral resolution ≥ 20,000 with a goal of R ~ 30,000 – 40,000. A field of view of the order of 2.5 arcsec (with a goal of 5 arcsec) is a very good compromise with the spaxel scale. The Nuclear Bulge is the Milky Way region with the highest fraction of very massive young stars.

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Spaxel scale	10 mas
AO	on-axis correction, NGS, diffraction limited core
R	≥ 20,000 [req.] 30,000 – 40,000 [goal]
FoV	2.5 arcsec [req.] 5 arcsec [goal]
Spectral range	1.2 – 1.3, 1.5 – 1.7, and 2.1 – 2.3 μm

Table 5. Summary of requirements for Science Case 5

3.6 The evolution of the M_{bh} - M_{bulge} - σ relations using QSOs

3.6.1 Outline of the science case

It has now become well established that the nuclei of both active and quiescent galaxies harbour supermassive black-holes (e.g., Magorrian et al. 1998, AJ, 115, 2285). Furthermore, it has become clear that the mass of the central black-hole is directly proportional to that of the surrounding bulge, as traced by either the stellar velocity dispersion or bulge luminosity (e.g., Magorrian et al. 1998; Tremaine et al. 2002, ApJ, 574, 740). Taken together these results demonstrate that the formation and evolutionary history of supermassive black holes and their host galaxies must be intimately related processes. Moreover, given that the dominant mechanism for the build-up of black-hole mass is very likely accretion, it is now clear that the evolution of massive galaxies, supermassive black holes, and quasars must be investigated together.

The locally observed correlations between black-hole mass and both velocity dispersion and bulge luminosity (M_{bh} - σ and M_{bh} - L_{bulge} relations) are now routinely used to estimate the black-hole masses of non-active galaxies, but neither can be trivially applied to active galactic nuclei (AGN) because of the luminous unresolved nuclear emission. However, many recent AGN studies have employed the so-called virial method (e.g., Kaspi et al. 2000, ApJ, 528, 445) to estimate the central black-hole masses. Based on the assumption that the broad-line emitting region gas is virialized, the virial mass estimator is simply: $M_{bh} = R_{blr} V^2/G$, where R_{blr} is the radius of the broad-line region (BLR) and V is the orbital velocity of the BLR gas (usually estimated from the Hβ FWHM). It is now common practice to estimate quasar black- hole masses based on only the Hβ FWHM and the continuum luminosity (e.g., McLure & Dunlop 2002, MNRAS, 331, 795). Indeed, based on re-calibrations of the virial estimate using the rest-frame UV emission lines of MgII and CIV (McLure & Jarvis 2002, MNRAS, 337, 109; Vestergaard 2002, ApJ, 571, 733) it is now possible to estimate the black-hole masses of large samples of quasars at high redshift (e.g., McLure & Dunlop 2004, MNRAS, 352, 1390; Vestergaard 2004, ApJ, 601, 676). Based largely on HST imaging data, McLure & Dunlop (2002) have demonstrated that the virial estimator and the M_{bh} - L_{bulge} relation are consistent for AGN host-galaxies at $z < 0.5$. In addition, using long-slit spectroscopy, Nelson et al. (2004, ApJ, 615, 652) have shown that low-redshift ($z < 0.1$) Seyfert galaxies have consistent stellar velocity dispersions and virial black-hole mass estimates. However, using Keck long-slit spectroscopy, Treu et al. (2004, ApJ, 615, L97) found that Seyfert galaxies at $z \approx 0.3$ have significantly smaller velocity dispersions than suggested by their virial black-hole masses. Further work on the evolution of the M_{bh} - L_{bulge} relation using both distant quasars (Peng et al. 2006, ApJ, 649, 616) and radio galaxies and radio-loud quasars (McLure et al. 2006, MNRAS, 368, 1395) has further strengthened this argument (see Treu et al. 2007, ApJ, 667, 117, as well, who also find similar results for low-redshift Seyfert galaxies). A clean method of establishing whether there is evolution in the properties of the M_{bh} and the mass of the host galaxy comes from measuring the stellar velocity dispersion.

Assuming that the velocity dispersion can be measured by binning up in an annulus which is beyond the unresolved nuclear emission, which even for a relatively poor AO correction should be achievable, it should be easily possible to determine the stellar velocity dispersion of the host galaxies by fitting the absorption line complex of the Calcium triplet as it moves through the H- and K-band windows and to measure the velocity dispersion of the QSO hosts using the whole rest-frame optical spectrum, which would be redshifted into the J-, H- and K-band windows at z ~ 2. A successful measurement of the host-galaxy velocity dispersions will allow us to compare the M_{bh} - σ correlation against the virial mass estimate in luminous quasars for the first time. Furthermore, by subtracting out the nuclear contribution and then collapsing the 3D datacube in the spectral dimension, ELT-IFU observations offer the prospect of reconstructing a clean 2D image of the underlying host-galaxy, which will provide an accurate measurement of the bulge luminosity allowing us to compare the virial black-hole mass estimates with both the M_{bh} - σ and M_{bh} - L_{bulge} relations, something which has so far proven to be impossible with current instrumentation.

3.6.2 Derived requirements from the science case

Typical velocity dispersions for massive AGN host galaxies are > 100 km/s. Given that it is possible to use different absorption lines at a variety of rest-frame wavelengths for different redshift ranges there is very little requirement for high-resolution spectroscopy for this science case (R ~ 1,000). The entire spectral range from J- through to K-band (1.1 – 2.4 μm) would be hugely advantageous as full modelling of the absorption features can be achieved, allowing greater accuracy. As regards AO, high signal-to-noise ratio spectra are required with a desire for a high Strehl ratio to reduce the nuclear contamination to the host galaxy light. A relatively wide field is desirable to ensure that a reasonable model of the bulge of the host galaxy can be obtained after the PSF of the nucleus has been subtracted. Host galaxy modelling based on HST data indicates that recovering reliable host-galaxy parameters requires that the host surface brightness profile can be traced to a radius of $2R_{1/2}$. Thus the minimum field of view is 4 arcsec. However, a complete study to ensure that the host galaxy is fully sampled would benefit from a slightly larger field-of-view of around 7-8 arcsec, which fits with a spaxel size of 40mas.

Spaxel scales	40 mas
AO	on-axis correction, LGS, diffraction limited core
R	1,000
FoV	4 – 8 arcsec
Spectral range	1.1 – 2.4 μm

Table 6. Summary of requirements for Science Case 6

3.7 Gamma-Ray bursts and their hosts

3.7.1 Outline of the science case

Gamma-ray bursts (GRB) are the brightest electromagnetic sources known in the universe. Since they are produced by a single stellar progenitor, they select galaxies independently of their luminosity, allowing us to obtain samples of star-forming galaxies across the entire luminosity function and therefore providing a substantially complete census of all star formation at z > 3 (e.g., Fynbo et al. 2008 ApJ, 683, 321). GRB hosts are therefore very complementary to other galaxy samples selected in flux-limited surveys. This can be very relevant to shed light on the epoch of reionization by detecting faint, possibly low surface brightness, proto-galaxies, which are not being accounted for in current surveys. Detection of the GRB afterglows enables also moderate- to high-resolution spectroscopy (e.g., de Ugarte Postigo et al. 2010, A&A, 513, A42), which can probe the details of the interstellar medium within the host directly (e.g., metallicities, hydrogen column densities).

The nature of short duration bursts ($t_{90} < 2$ s, where t_{90} is the duration of the period during which 90% of the burst's energy is emitted) remains enigmatic, in large part because of the faintness of their afterglows and consequent difficulty in obtaining redshifts and studying them spectroscopically. The ELT-IFU instrument, especially if reaching down to ~ 0.5 μm, will allow access to common interstellar absorption lines at moderate redshifts, enabling the determination of the redshift (and hence absolute luminosity) distribution, the study of their environments (e.g., interstellar versus intergalactic, and possibly self-contamination in the immediate vicinity of the progenitor), and relationship with host galaxies in terms of offsets and star formation histories of the hosts.

Finally, most GRB hosts are too faint for spectroscopic follow-up with present facilities in reasonable exposure times. By contrast, many will be feasible with ELT-IFU allowing measurements of emission lines, which provide diagnostics such as star-formation rate estimates. A wide wavelength range would provide access to common emission lines from redshift zero to about z ~ 5.5. Even very high redshift hosts may well be observable spectroscopically, particularly their emission lines, notably Lyα and HeII 1640.

3.7.2 Derived requirements from the science case

If sub-arcsec optical positions are already known, then ~ 1 arcsec field of view could be used. Otherwise up to ~ 5 arcsec would allow coverage of Swift-like X-ray positional errors. In any case ~ 2 arcsec will be useful to observe the host galaxies. A minimum wavelength of 0.5 μm is strongly motivated by the desire to obtain afterglow spectroscopy for faint sources, particularly short-duration GRBs. A maximum wavelength of 2.4 μm will allow the Lyα break to be seen in bursts out to very high redshifts, and OII3727 from host galaxies up to redshift z ~ 5.5. A spectral resolution R ~ 4000 is required (to deal with OH lines). A simultaneous wavelength range from the V to the K band would be desirable to ensure that the redshift can be determined for afterglows which fade rapidly and as many lines as possible are observed. As regards AO, LGS are required for faint sources, as otherwise the AO performance would be too poor, since the targets are point sources. Bright targets ($m_{AB} < 20$) could be observed with a lower AO correction (slightly improved PSF). A rapid response mode needs also to be implemented to allow the automatic trigger of observations soon after the burst is detected by other telescopes.

AO	on-axis correction; faint targets ($m_{AB} > 20$): LGS, diffraction limited core bright targets ($m_{AB} < 20$): improved PSF

R	4,000
FoV	1 - 5 arcsec
Spectral range	0.5 – 2.4 μm (simultaneous coverage: goal)
Other	rapid response mode

Table 7. Summary of requirements for Science Case 7

3.8 The physics of high redshift galaxies

3.8.1 Outline of the science case

The theoretical framework of galaxy formation is, in principle, straightforward. Dark matter halos form due to gravitational attraction, gas cools within these halos to form stars and galaxies that then grow through the accretion of cool gas, or via merging. This basic model suggests that the building blocks of galaxies are disks that can be disturbed by mergers. However, the baryonic physics of galaxy formation is not a well-understood process. Indeed, since baryon cooling is very efficient, in the absence of heating sources, gas quickly loses pressure support and collapses into stars. Since much of the star-formation activity responsible for galaxy formation occurred in the young Universe, an era when many of the properties of local galaxies were defined, empirical observations of the dynamical state of galaxies, the interplay between star-formation and gas dynamics and chemical composition are key to guiding the models. Recent models of galaxy formation have suggested that the star-formation rate density is dominated by the low mass galaxies at all redshifts (e.g. Bower et al. 2006, MNRAS, 370, 645). However, studying the internal properties of ordinary galaxies at z>2 (the peak epoch of galaxy formation) is incredibly difficult, even with the light grasp and resolution of the largest aperture telescopes available today. As such, prior to the construction of ELTs, constraints on processes of star-formation, chemical abundances and feedback are only possible from statistical studies of the high redshift population as a whole, neglecting the complex physics of star-formation, merging, supernovae explosions, and AGN activity of individual galaxies.

One of the most compelling extra-galactic science drivers for the construction of the next generation of telescopes is the study of the internal structures of galaxies on scales corresponding to HII regions, requiring both superb sensitivity and resolution which only a 40m telescope operating with laser tomography AO can deliver. A scale of 10 mas, in fact, corresponds to a physical scale of ~ 80 pc at z ~ 3, which is sufficient to resolve the largest HII regions (which have characteristic sizes of ~40 – 60pc in the local Universe; Gonzalez Delgado et al. 1997, ApJ, 108, 199). Such observations will probe the relation between star-formation activity and gas dynamics to provide detailed constraints on the physics of star-formation in young galaxies in the distant Universe.

In more detail, key science goals will include: 1) the determination of the masses and velocity structures in galaxies at z = 2 – 5; 2) a test of the star formation conditions in these galaxies on ~ 100pc scales; 3) a study of the chemical abundance gradients to figure out if galaxies formed “inside-out” or “outside-in”; 4) internal evolution in the formation of galactic disks can also be tested for through resolved spectroscopy around the diffraction limit by checking if these primordial systems are very different from the local ones; 5) the impact of AGN on the host galaxy through the determination of the central black hole mass, to constrain models for the growth of black holes and probe the contribution of feedback from star-formation with that from AGN.

3.8.2 Derived requirements from the science case

High redshift galaxies show both unresolved and extended structures (which are limited by surface brightness) and therefore access to at least two spatial scales is necessary. A spatial scale of 40 mas for a galaxy at z = 3 corresponds to a physical scale of ~ 300 pc. In both local and high redshift galaxies, this corresponds to scales typical of star-forming complexes, comprising many giant molecular clouds. For masses of the order 10^7 - 10^8 $M_\odot$ within 400 pc, this suggests line widths (assuming virialized motions) of 30 – 60 km/s, which are well matched to a resolution of R = 5000. Since large pixels increase the background (which has a severe impact on sensitivity for unresolved sources) diffraction limited spectroscopy in H&K-bands is clearly the goal. For Nyquist sampling of HII regions (e.g., 4mas) the pixel size is well matched to the local characteristic size of HII regions at z = 3 (~ 40 pc). For HII regions in the local Universe, which have typical masses of 10^6 – 10^7 $M_\odot$ within 40pc this suggests line widths of 10 – 20 km/s and implies the need for R ~ 20,000 to measure the velocity dispersion of individual HII regions. HST imaging of z ~ 2 galaxies suggest that a field of view up to 5 – 10 arcsec is required. The range of emission lines needed implies a wavelength range between 1.0 and 2.4 μm. The combination of high spatial and spectral resolution needed to allow the processes occurring within galaxies to be probed on scales of individual star-forming regions (i.e. ~100 pc) demands high Strehl ratios. NGS might be used efficiently, as shown by Genzel et al. (2006, Nature, 442, 786). However, the surface density of spectroscopically confirmed z ~ 2 galaxies, which lie within ~ 30 arcsec of R < 16 mag stars (and have sufficiently bright nebular emission lines, such as H-alpha or [OIII]) is limited to only a handful of galaxies, which is why LGS are required to open up substantially more sky. It would be good to be able to reach high (~ 70%) Strehl ratios.

Spaxel scales	4 and 40 mas
AO	on-axis correction, NGS (close to bright stars; Strehl ratio ~70%: goal)) and LGS, diffraction limited core
R	5,000, 20,000
FoV	0.5 – 1 arcsec (4 mas spaxel scale), 5 – 10 arcsec (40 mas spaxel scale)
Spectral range	1.0 – 2.4 μm

Table 8. Summary of requirements for Science Case 8

3.9 From first light to the earliest galaxies

3.9.1 Outline of the science case

Measuring light from the first stars and galaxies as they emerge from the “dark ages” is one of the most compelling prospects for ELTs. As predicted more than 40 years ago by Partridge & Peebles (1967, ApJ, 147, 868), it seems relatively certain that the large collecting area of the E-ELT coupled to highly sensitive instruments such as the ELT-IFU will yield the first detailed spectroscopic information from the very earliest galaxies (z~10) emerging from the neutral intergalactic medium (IGM). With 8m-class telescopes galaxies at $5 < z < 7$ are routinely detected. These coincide with a period when systems with dark matter halos comparable to the Milky Way are thought to have first collapsed and undergone their most rapid evolution (Mo & White 2002, MNRAS, 336, 112). However, detecting and, more importantly, spectroscopically confirming fainter galaxies and/or those at higher redshifts remains challenging. The ELT-IFU will solve this issue, and will allow the determination of the properties of high-redshift galaxies even at the faint end of the luminosity function, which produce the bulk of the starlight at these redshifts and may be responsible for the re-ionisation of the Universe. In addition, the spatially resolved and moderate spectral resolution data afforded by the ELT-IFU will permit us to study the impact of the first galaxies on the high-redshift intergalactic medium (IGM) in detail. Key science questions will include: 1) how did the Universe change during the first billion years? 2) What sources were responsible for re-ionisation and what is the nature of the process of re-ionisation? 3) How did the first stars form and can we detect their signatures? 4) Are the early galaxies progenitors of present-day massive galaxies? 5) How was the IGM enriched with metals? This will be done through studying prominent high-ionisation lines (NV, SiIV, CIV) and broad lines (MgII, NV, FeIII), which are useful AGN indicators. The study of Lyα will be valuable, also to investigate Lyα escape from the earliest star-forming galaxies and QSOs and Lyα halos around the first stars and galaxies. Using the diffraction limited capability of ELT-IFU one will also be able to trace the process of metal enrichment within individual galaxies and the immediate IGM using a host of metallicity indicators. This will reveal key information regarding the metal transport into the ISM of the galaxies themselves and into the IGM through winds and outflows. ELT-IFU provides also a unique opportunity to study and spatially resolve HeII on an HII region scale and as a function of metallicity within the galaxy for a wide redshift range ($3.9 < z < 15$, subject to the standard NIR atmospheric windows), which has been suggested, together with strong Lyα, to be a tracer of Population III stars. Finally, ELT-IFU deep field(s), using laser tomography AO to concentrate the diffuse light into single pixels and with the largest field-of-view, will be a productive investment of observing time. In particular, conducting these surveys on "critical lines" or areas of high magnification around massive lensing clusters can achieve a sensitivity increase of 1-4 magnitudes (Richard et al. 2008, ApJ, 685, 705). Assuming a 2:1 aspect and 40mas pixels with a FoV of 5 x10 arcsec, in 12 pointings one can expect to find ~ 33 high redshift galaxies to m(AB) ~ 30.5, according to current models. In any case, given the sensitivity of the ELT-IFU, failure to detect any high-redshift galaxies in such a survey would place strong constraints on theoretical models of the early Universe.

Targets for ELT-IFU observations will be provided by a large number of wide area, and deep, multi-wavelength surveys such as VIDEO, VHS, Ultra-VISTA/ELVIS, DAZLE, SERVS, SEDS etc. and instruments like WFC3, Gemini Genesis-F2T2, MOSFIRE etc., together with a host of high-redshift candidates that will be discovered by the surveys carried out with JWST and E-ELT-CAM.

3.9.2 Derived requirements from the science case

For most of the science goals presented the widest possible wavelength range obviously permits investigation of the widest redshift range. Extension to at least 0.8 μm is desirable in all cases permitting the detection of Lyα to z ~ 5.5 and HeII to z~3.9 so that one can probe the Universe only a few hundred Myr after it was largely ionised (z~6). Extension to even bluer wavelengths (e.g. 0.5 μm) is preferable, as it would widen the baseline out to which we can trace the evolution of galaxy and IGM properties. The proposed blind survey also requires the widest wavelength range to be sensitive to a large number of sources across different redshifts and simultaneous, multiple-band observations would be preferable. For detailed kinematics and to study winds, outflows and metal transport in individual galaxies one would like to investigate down to the levels of normal HII regions (~50 pc or several mas) therefore diffraction limited performance is desirable in the H- and K-bands. Since Lyα emission is diffuse and the first halos may be > 20 kpc in size (see Ouch et al. 2009, ApJ, 696, 1164) one can also derive significant information regarding the high redshift IGM with larger scales, requiring FoVs of order 10 arcsec (40 mas). For the deep survey, a larger FoV (e.g., 30 arcsec) would be desirable. Sensitivity requirements need accurate OH line subtraction and therefore R ~ 4000 is required. This resolution is also more than adequate to constrain the typically p-Cygni profiles of Lyα and HeII and will be sensitive to gas motions of 60 km/s. Detailed kinematics and the deep survey achieve the best sensitivity with LGS correction, however all aspects of this program can be conducted also with a lower AO correction (slightly improved PSF).

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Spaxel scales	4 and 40 mas
AO	10 – 30 arcsec FoV, improved PSF [req.], diffraction –limited (LGS) [goal]
R	4,000
FoV	0.5 arcsec (4 mas spaxel scale), 10 and 30 arcsec (goal) (40 mas spaxel scale)
Spectral range	0.8 (0.5 goal) – 2.4 μm

Table 9. Summary of requirements for Science Case 9

4 Derived science requirements

The requirements derived from the science cases discussed above are summarized here.

4.1 Compilation of requirements from the science cases

	Spaxel scale	AO	R	FoV	Spectral range	Contrast ratio	Other
Solar System		on-axis correction, NGS (Strehl ratio ~70%) and LGS, differential tracking	500 – 1,000, (0.5 – 2.4 μm); 4,000 – 10,000 (1.5 – 2.4 μm)		0.5 – 2.4 μm, simultaneous (R = 500 – 1,000)		
High-contrast spectroscopy of planetary mass companions to nearby stars	4 mas	on-axis correction, NGS, diffraction limited core (Strehl ratio ~70%)	> 500		1.45 – 2.45 μm	$\leq 10^{-6}$ at 0.5 arcsec ($\leq 10^{-8}$: goal)	Coronagraph
Intermediate mass black holes	4 mas	on-axis correction, NGS (GCs: Strehl	≥ 10,000	0.2 arcsec	0.8 – 1.0 μm and 2.0		

		ratio ~70% as goal) or LGS (NSCs), diffraction limited core			– 2.3 μm		
Stellar populations	20 (IR) and 100-200 (optical) mas	on-axis correction, LGS, diffraction limited core	4,000 (0.5 – 1.0 μm), 10,000 and 20,000 (0.8 – 2.4 μm)		0.5 – 2.4 μm		
Chemical tagging of the stellar populations in the Galactic Centre	10 mas	on-axis correction, NGS, diffraction limited core	≥ 20,000 [req.] 30,000 – 40,000 [goal]	2.5 arcsec [req.] 5 arcsec [goal]	1.2 – 1.3, 1.5 – 1.7, and 2.1 – 2.3 μm		
The evolution of the M_{bh}-M_{bulge} - σ relations using QSOs	40 mas	on-axis correction, LGS, diffraction limited core	1,000	4 – 8 arcsec	1.1 – 2.4 μm		
GRBs		on-axis correction; faint targets (m_{AB} > 20): LGS, diffraction limited core bright targets (m_{AB} < 20): improved PSF	4,000	1 – 5 arcsec	0.5 – 2.4 μm (simultaneous coverage: goal)		Rapid response mode
Physics of high-z galaxies	4 and 40 mas	on-axis correction, NGS (close to bright stars: Strehl ratio ~70% as goal) and LGS, diffraction limited core	5,000, 20,000	0.5 – 1 arcsec (4 mas spaxel scale), 5 – 10 arcsec (40 mas spaxel scale)	1.0 – 2.4 μm		
From first light to the earliest galaxies	4 and 40 mas	10 – 30 arcsec FoV, improved PSF [req.], diffraction – limited (LGS) [goal]	4,000	0.5 arcsec (4 mas spaxel scale), 10 and 30 arcsec (goal) (40 mas spaxel	0.8 (0.5 goal) – 2.4 μm		

				scale)			

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4.2 Science requirements for instrument ELT-IFU

Spaxel scale	Based on the science cases described above, the ELT-IFU needs to provide a range of spaxel scales, to permit the user to optimally configure the instrument. The coarsest scale, with spaxels of 40 mas, provides a relatively large (5 – 10 arcsec) FoV, while the finest scale, 4 mas, samples the diffraction limit of the E-ELT at near-infrared wavelengths over a 0.5 – 1 arcsec FoV. As a goal, a spaxel scale of 100 – 200 mas would be more suited for deep observations in the visual range.
Adaptive optics	Most science cases require on-axis correction and a diffraction limited core, while a couple of cases can manage with just an improved PSF. Natural guide stars can be used when bright stars (m_V < 15) are available but laser guide stars are also required. High Strehl ratios (~70%) are needed by the exo-planetary and Solar System cases and would be good to have for the intermediate mass black hole and high-z galaxy cases. In one case the AO correction needs to be done over a 10 – 30 arcsec field of view (goal).
FoV	The FoV needs to cover the 0.2 – 10 arcsec range. The requirements on a FoV of 5 – 10 arcsec come from the Galactic Centre case, the need to encompass galaxies at z ~ 1 – 2, to trace quasar host galaxies up to a radius of $2R_{1/2}$, and to cover Swift-like X-ray positional errors in the case of GRBs. As a goal, 30 arcsec would allow a blind survey for high-redshift galaxies. The FoV is obviously related to the spaxel scale.
R	The required resolving power covers the 500 – 20,000 range. R values above 4,000 are only required above 0.8 μm, while below that wavelength resolutions up to 4,000 are sufficient. The largest values are required to measure chemical abundances in dwarf stars and velocity dispersions in stellar clusters (in external galaxies), to study HII regions in high-redshift galaxies, and to measure chemical abundances in the Galactic Centre. Resolving powers up to 30,000 – 40,000 are a goal for the latter case. The lowest values are needed by the Solar System and exo-planetary cases.
Spectral range	The spectral coverage has to extend over the 0.5 – 2.4 μm range. The low end is needed for comets, primitive asteroids, and Trans-Neptunian Objects, to study the afterglow of faint, short-duration GRBs, to widen the baseline out to which one can trace the evolution of galaxy and IGM properties (goal), and to expand discovery space. A large maximum wavelength is obviously important to study high redshift sources (e.g., Lyα up to very high redshift for 2.4 μm). Simultaneous coverage over the whole band is required for Solar System targets and is a goal for the GRB case.
Contrast ratio	A large contrast ratio of $\leq 10^{-6}$ at 0.5 arcsec, with a goal of $\leq 10^{-8}$, is required by the exo-planetary science case.

Other requirements	A coronagraph is also needed by the exo-planetary science case, with type and centering accuracy behind the mask to be defined. A rapid response mode is required for quick follow-up of GRBs.