CODEX: the high resolution visual spectrograph for the E-ELT

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ABSTRACT

A number of outstanding scientific problems require a high resolution, visual spectrograph at the E-ELT. Measuring the dynamics of the universe, finding earth-like planets with radial velocity techniques, determining the chemical evolution of the intergalactic medium and if physical constants varied in the past, all require a superior capability of measuring exceedingly small Doppler shifts. We have started a Phase A study for CODEX at the E-ELT. We present here the scientific cases, the requirements, the basic technical choices and trade offs, as well as a couple of design under evaluation. We aim at a super stable instrument, capable of obtaining a radial velocity precision of 2 cm/sec over several decades. It will be located at the coudè focus. The design will make use of anamorphosis, pupil slicing, slanted VPH gratings and a novel calibration system based on laser frequency combs. Several CODEX-related R&D activities are running, and, in addition, a Call for Proposal for a precursor at the VLT has been issued.

Keywords: Times Roman, image area, acronyms, references

1. INTRODUCTION

Within the E-ELT Phase A feasibility study, ESO has decided to sponsor the Phase A study of a set of instruments. Among them CODEX is a high resolution, optical super table spectrograph. The Phase A study is carried on by a consortium led by ESO, which includes Instituto de Astrofisica de Canarias (Spain), INAF-Trieste and Merate (Italy), Observatoire de Geneve (Switzerland) and the Institute of Astronomy in Cambridge (UK). The phase A study will end at the end of year 2009; this contribution shall therefore be considered as a preliminary report; since the study has not been reviewed yet, the concept is still not yet fully consolidated.

2. WHY AN HIGH RESOLUTION SPECTROGRAPH AT THE ELT?

The Extremely Large Telescope will have such a huge collecting power that it will allow for the first time some outstanding applications. In April 2006 the report of the E-ELT Science Working Group presented the full Science Cases and Requirements for E-ELT; these cases are further developed and quantitatively analyzed in the E-ELT Design Reference Mission (DRM). Out of the most prominent cases, several must be addressed by an optical, high resolution spectrograph:

Dynamical measurement of Universal expansion

Extrasolar Planets

Metallicity of the low density IGM

Additional cases considered include Variability of Physical Constants, Astroseismology and Big Bang Nucleosynthesis. One interesting aspect of all these cases is that they require a superior capability of measuring very small Doppler shifts. Both the expansion cases (see below) and the search for terrestrial planets around solar type stars with radial velocity techniques call for a long term radial velocity precision of a few cm/sec, while the determination of the variability of the fine structure constant, for instance, should aim at an accuracy of the measurement of better than 1 unit in 10^8 to compete with the measurements planned in the laboratory. We argue that any high resolution spectrograph fed by a giant telescope should therefore aim at the highest long term stability and precision. High resolution and high accuracy need photons; the giant telescope will give us for the first time a tremendous opportunity, and we shall make use of it.

Rather than exploring many scientific opportunity, the CODEX team concentrated on a few scientific cases, considered outstanding; most of these cases have been discussed in literature, and a full workshop has been dedicated to Precision Spectroscopy in Astrophysics [1].

The quest for high resolution and high precision applied to exo-planets science is evident, and extremely accurate measurements will be required to find and to characterize terrestrial planets. The discussion as well as the controversial results on the variability of the fine structure constant all emphasize that high quality data are required, and how the effects of systematic errors can result in misleading conclusions, enhancing the quest for high resolution, high S/N ratio, but precision as well (see e.g. [2]).

These studies will acquire an even stronger relevance, once they will be coupled to the study of the variability of the electron to proton mass which also requires an optical high resolution, high accuracy spectrograph [3].

The case for a very accurate measurement of ^{7}Li and of the ^{6}Li/^{7}Li isotopic ratio is well illustrated by the work of [4], who find a ^{7}Li plateau at least half of what expected from WMAP result, and, in addition, a fairly high level of ^{6}Li, which is not supposed to be produced by primordial nucleosynthesis. Observations in very metal poor as well as extra-galactic objects will help to solve this puzzle.

We finally note as, in order to reach a real high S/N ratio, photons must be coupled to excellent flat fielding capabilities able to eliminate the detector imperfections (fringes) and other instrumental effects such as the blaze function in cross-dispersed echelle spectra.

All these cases call for a high resolution, super stable spectrograph, fed by a very stable input (fibre) system equipped with a superior quality calibration system.

Out of these scientific cases it is worth examining with some detail the case of the measurement of the dynamical expansion of the Universe, because on the one hand is really a novel approach, no much explored in the past, and, on the other hand , because is most likely the most demanding for the instrument.

2.1 Measuring the dynamic expansion of the Universe

This experiment is conceptually very simple: by making observations of high redshift objects over a time interval of several years, we want to detect and use the wavelength shifts of spectral features of light emitted at high redshift to directly probe the evolution of the expansion of the Universe. This concept is not new, and to the best of our knowledge, can be found for the first time in literature in 1962 [5]. The expected amount of shift is extremely small, and brought Sandage at that time to conclude that such a measurement was beyond our capabilities. We think that this experiment is possible now because of three reasons:

(1) Extremely Large Telescopes such should be capable of providing the huge number of photons required. (2) In the last two decades our capability of accurately measuring wavelength shifts of astronomical sources has dramatically improved. (3) A suitable class of astronomical objects for this measurement has been identified: the Lyα forest lines, which are extremely numerous and beautifully trace the cosmic expansion with negligible peculiar motions (at least ten times smaller than the Hubble flow.

A full study of the problem has been recently completed by [6], who has shown as the measurement is indeed feasible within a period of 20-30 yrs with an ELT, using a group of QSOs already known. The interested reader should look at [10] for a full and complete discussion.

The wavelength change expected by observing an object at redshift = z in a time interval dt is given by

$$\dot{z} = dz/dt(obs) = (1+z)H_o - H(z)$$

And it is directly related to the de- or acceleration of the Universe. Figure 1 shows the expected change of redshift for a range of relativistic models with no curvature as a function of redshift. The expected wavelength shift has a very characteristic redshift dependence. At some redshifts the wavelengths are ``stretched" while in others they are “compressed”. The wavelength shift corresponds to a Doppler shift of about 1-10 cm/s over a period of 10 yrs.

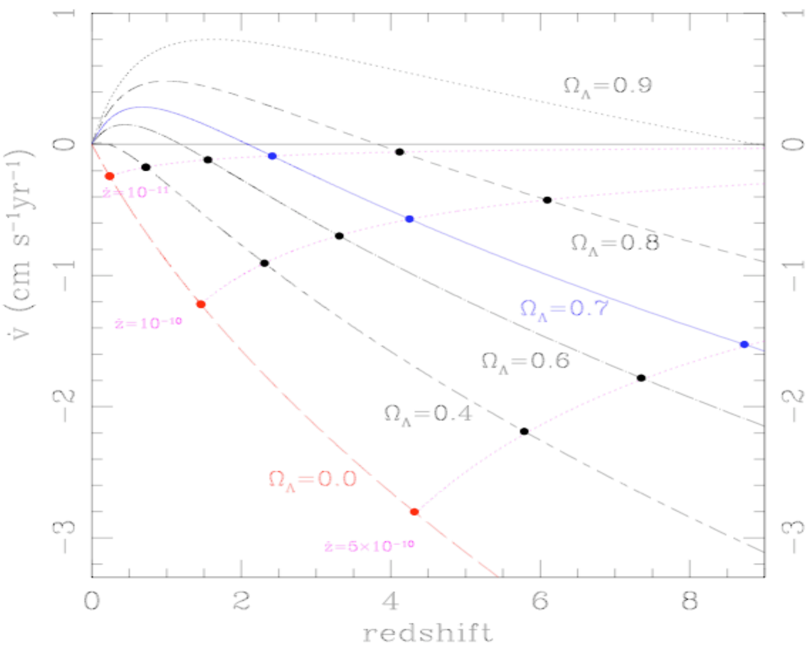


Figure 1 Redshift drift/yr as a function of redshift. The curves refer to relativistic models with no curvature and different values of the cosmological constant**.**

A priori it is not obvious which objects and which spectral features are best suited for a precise measurement of $\dot{v}$. For a given energy flux the precision of the final measurements will increase with the sharpness of the spectral features (less noise) and increasing wavelength (more photons). Another important consideration is the expected peculiar acceleration associated with peculiar motions relative to the Hubble flow, which will act as additional noise.

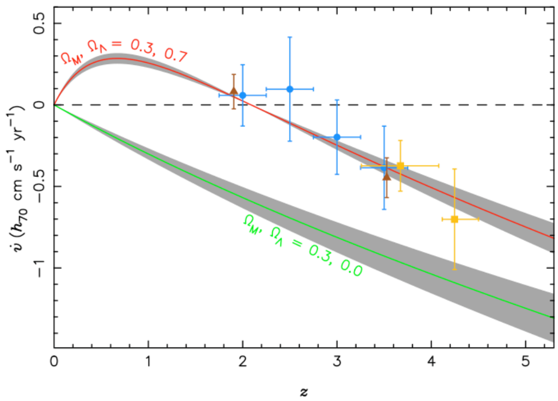


Figure 2 Result of three full simulations: maximizing dz/dt (yellow squares), maximizing S/N ratio (brown triangles), maximizing constraints on Ω_λ (blue circles)

The numerous absorption lines in the spectra of high-redshift QSOs, which make up the so-called Lyα forest, appear to be ideal targets for a measurement of $\dot{v}$. There are about one hundred suitable features in a single spectrum which have a typical width of 30 km/s. With QSO absorption spectra we can probe a wide redshift range from z ~ 1.5 up to 4 and beyond.

In order to quantitatively assess the feasibility of the measurement, Monte Carlo simulations have been carried out independently by several groups. The high resolution spectra of QSOs were simulated, noise added and the process repeated for the second epoch. The pairs of spectra so produced were compared and the 'measurement' performed. Figure 2 shows the result of a full simulation, and shows how the results of three sets of simulated data points; in the simulations a telescope diameter of D = 42m, a global Efficiency of 0.25 a Total integration time of 4000 Hours and a 20 years baseline have been assumed. The results show three different cases, selected according to different measurement criteria.

3. PHASE A STUDY REQUIREMENTS

From the scientific cases a number of requirements have been derived, they are summarized below.

AO Feeding: CODEX shall be conceived to work routinely without post-focal AO. The possibility to introduce an AO or tip-tilt post-focal subsystem shall be explored as an optional; if it is proved that it can enhance the efficiency of the spectrograph without hindering the operation of the primary mode.

Radial Velocity Accuracy: 2 cm/sec over 30 yrs**.**

Spectral coverage: Fix spectral coverage**.** It is not expected to have any movable part inside the spectrograph**.**

Reddest wavelength limit is *686 nm* ; 720 nm is a goal.

Bluest wavelength limit is *370 nm*. This corresponds to Lyα at z ~ 2, the extension to the blue of CODEX is important to include lower redshifts QSOs, to include important stellar lines, to increase the redshift range for accurate fine structure constant measurements. A limit at 350 nm is a goal, but the blue limit of the range will be most likely a compromise, for instance, with telescope coatings. Within the limits specified above, the largest range is obviously the best and 316 nm is the minimum spectral coverage.

Resolving Power: Primary mode resolving power: R > 120000 (Goal: 150000)
Secondary mode Resolving power: R > 32000 (Goal: 40000)
Spectral Sampling At least 4 pixels/resolution element (mid of an echelle order) for the high resolution Primary mode.

Photon detection efficiency (including telescope): At least 18% at peak, not less than 12% all over the spectral range, for a 0.8 arcsec DIMM (500 nm) seeing, including seeing losses.

Aperture on the sky: CODEX is a single-object fiber-feed spectrograph. The FoV of the fiber projected on the sky shall be 1 arcsec ± 0.2 arcsec (indicative).

Instrument sky coverage: The Instrument shall not limit the sky coverage of the telescope. The highest Doppler Shift performances are however ensured only to airmass as high as 1.7

Mid Observation :Time The real mid observation time shall be established with accuracy better than 0.5 seconds for all wavelengths covered by the spectrograph.

Sky subtraction: CODEX shall be equipped with a simultaneous sky subtraction capability,

Simultaneous calibration: The monitoring of the instrument shifts during the exposures is made through a simultaneous wavelength calibration source. The need for such a simultaneous calibration is one of the items which could be tested by a precursor at the VLT.

A special attention is devoted to **Wavelength calibration accuracy:** The instrument and its calibration plan will allow calibration of the wavelength scale to better than 1 cm/sec and for a period extending over 20 yrs.

ADC, Thermal Control, Vacuum, high Scrambling capabilities, high centering accuracy, are required.

Data Reduction and Data Analysis

CODEX shall be equipped with a full data reduction and data analysis package, able to extract the best Doppler shift performances from the instrument, for stellar and non stellar (QSO absorption line) objects

4. FROM REQUIREMENTS TO DESIGN

In passing from requirements to design we have taken into account the HARPS experience [7], and the study developed in the past for the OWL proposal [8]. A number of guidelines and of critical points have been individuated, and a vigorous program of R&D related to this project have been started at ESO. A list of points to improve the spectrograph stability and Radial Velocity performances are listed below (underlined are those items which are separately reported by other authors in this book).

Scramblers to reduce effect of guiding errors This point is absolutely critical, when considering that 1 cm/sec corresponds to about 10^{-5} arcseconds on the sky . Tests are performed at ESO to measure different configurations.

Simultaneous wavelength calibration.

Use of wavelength calibration based on "laser comb" (cfr. Araujo et al. [9]): The analysis of the Th-A lines from HARPS shows clearly that this kind of lamps represent a limitation at present, at the level of ~10 cm/sec. As discussed e.g. in [10], a calibration based on laser frequency combs seems the ideal candidate to overcome these limitations.

Fully passive instrument, ultra-high temperature stability

Instrument in vacuum tank

High precision control of detector temperature

Underground facility, zero human access

System PRECURSOR @ VLT (cfr. Spano' et al. [11]) We are conscious that, in order to be successful we must be able to make the whole system performing at its best, including interface with the telescope and operations. We have strongly advised the construction of a precursor at the VLT as a tool to validate the CODEX concept.

On a similar way, we have identified some design principles to follow:

Limit the grating and the pupil size : we felt that, in order to contain costs, and to facilitate the thermal stability of the system, the spectrograph should have a limited volume. Therefore we opted for a limited pupil size**.**

Pupil slicer (at entrance and/or in the spectrograph)

Multiple spectrograph units / cameras: The use of multiple spectrographs or cameras has not been seen as a limitation. It seems unavoidable to keep the large telescope diameter and aperture on the sky together with the high resolving power and spectrograph range, still keeping a very high efficiency (optimal coatings can be obtained on a limited spectral range).

Large use of anamorphism

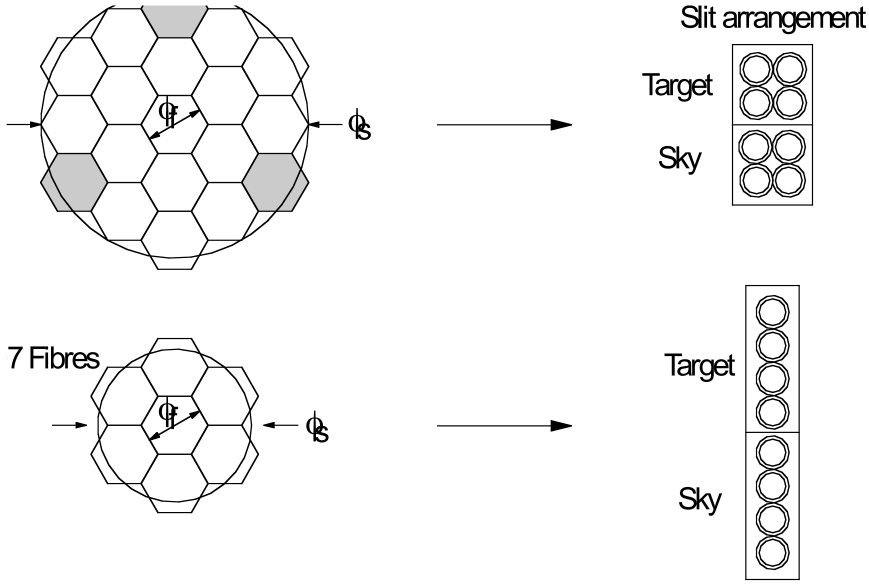
Slanted VPH as X-dispersers (cfr. Arns et al. [12])

Nested thermally and mechanically controlled environment

5. THE CODEX DESIGN

The CODEX design is based on an extension of the positive HARPS experience. At present we are evaluating two main concepts, with a different design. A task of the Phase A study is also to perform a trade-off between different design and to propose an optimization of the parameter space.

Figure 3: Possible arrangement of CODEX fibres



The multi-spectrograph concept

The light at the coude' focus of the E-ELT is sliced in relatively small , relatively short fibres, to several identical spectrographs**. Figure 4** illustrates the spectrograph concept and **Figure 3** shows some possible slicing and slit arrangement. This concept is that presently adopted by ESPRESSO, and the spectrograph optical concept has been presented in [11] and [13], where a full mechanical concept is also shown.

The spectrograph design contains several novel concepts, and makes use of pupil splitting and anamorphism in order to keep the dimensions of the optics and of the echelle grating reasonable. The camera largest lens is 35 cm in diameter and the echelle grating is only twice the UVES size: 20*160 cm.

The two arms design has been chosen to optimize the efficiency and to keep each detector (and therefore cryostat) limited in size; for the same purpose slanted VPHs are used as cross-dispersers, and they produce an anamorphism of a factor 1.5 to 2.5 perpendicular to the main dispersion.

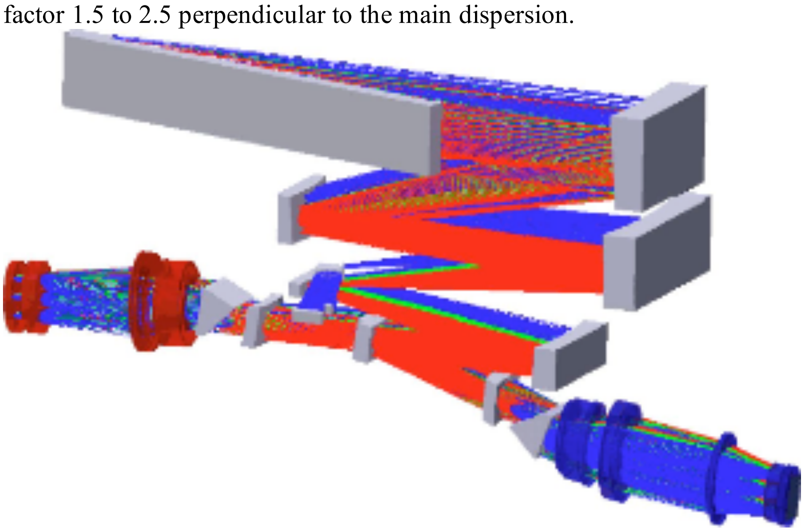


Figure 4: Optical scheme of one CODEX unit spectrograph**.**

One big advantage of this concept is that it allows to play on a large parameter space, by changing the number of spectrographs, giving the possibility to choose for the best compromise between resolution, sky aperture and spectral coverage. Some examples are given in Table 1, which summarizes some realistic cases.

Aperture (Arcseconds)	N Fibres	Resolving Power	N Spectrographs	Coverage (nm)
0.7	18	128000	3	350-780*
1.0	16	90000	4	350-780*
0.7	7	147000	2	385-670**
1.0	7	100000	3	385-670**

Table 1: Some options for the CODEX design: the first two options, marked as *, are exact copies of the present VLT precursor, with a VPH anamorphism factor of 1.5 . The bottom two options use a more extreme configuration, with an anamorphic factor 2.5

5.1 The multi-camera concept

Even if the previous design has very interesting aspects and it is very appealing, it suffers of two main limitations: the splitting of the telescope pupil is not optimized and the splitting and anamorphosis application in the spectrograph is relatively complicated. The use of the detector area is not optimal, and the design might be simplified, still keeping the same concepts. Some concern is also present if it will possible to make the spectrograph input independent of the unavoidable sub-pupils intensity variations. We are therefore exploring a different concept, which includes no pupil splitting before the spectrograph entrance and which envisages only one spectrograph, but with 4 cameras.

The optical concept is given in Figure 5: only 1 big (500 microns at F/3) fibre is entering the spectrograph (plus one dedicated to record the sky, of course). The pupil has an anamorphism by a factor 12, and it is splitted in 6 parts, grouped in 2 slits. Each of the two slits is separated by a dichroic in a red and in a blue spectrum, after cross-dispersion (obtained with a slanted VPH with anamorphosis by a factor 2), the image is collected by an F/2.2 cameras. Table 2 shows the summary of the characteristics for this configuration. This design has also some very attractive parts (compact, contained costs), and the trade-off between the two designs will soon follow. The initial 500 microns fibres are imaged on the detector in two 60 x1100 micron slits. Figure 6 gives a description of the pupil and image evolution.

Resolving Power	130.000 (for 0.82 arc sec)
Projection on Detector	2 slits of 60 x 1100 μm on the detector
Orders RED Detector Size RED: VPH groove density RED:	87 to 68 (530-680 nm) 6K (cross dispersion) x 8K 1100 mm^{-1}
Orders BLUE : Detector Size BLUE: VPH groove density BLUE:	122 to 88 (380-540 nm) 8K (cross dispersion) x 6K 2100 mm^{-1}
Minimum order separation on the detector	2.3 mm
Cameras:	4 Cameras (2 RED, 2 BLUE)

Table 2: Summary of the characteristics of the new CODEX optical design

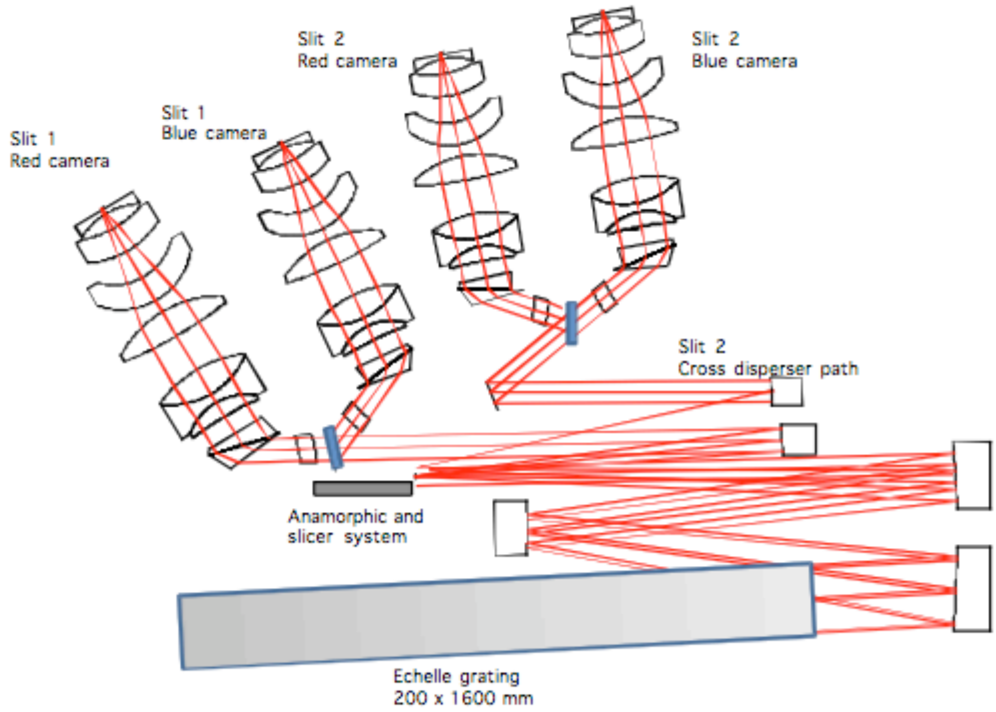


Figure 5: Optical arrangement of the new multi camera CODEX design

We have therefore 2 possible design for the implementation of the spectrograph, mostly depending if an early slicing of the telescope light is needed or not. Scrambling properties of the designs and overall transmission will be fundamental parameters to be considered in the evaluation. No show-stopper are presently individuated and R&D is developed for the most critical items. The possible feeding by some AO module is also under scrutiny.

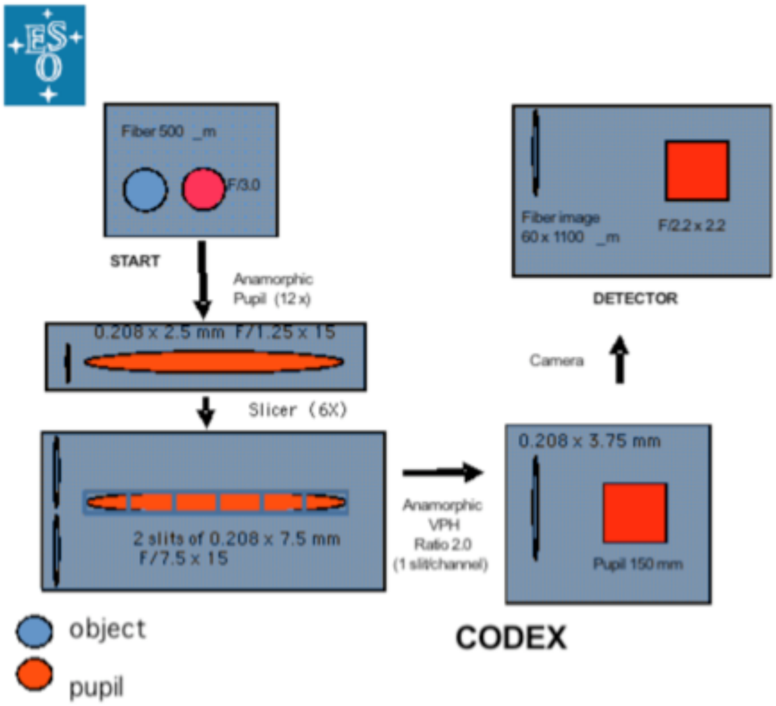


Figure 6: Pupil and Image evolution with the proposed new design. Pupil is elongated and then sliced by 6 ; finally re-arranged on 2 slits.

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