High resolution spectrograph with R4 Echelle for LAMOST

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ABSTRACT

A preliminary design study for a high-resolution echelle spectrograph to be used for LAMOST (The large Sky Area Multi-Object Fiber Spectroscopic Telescope) that is currently under construction is presented. In order to obtain a resolution-slit product of about 40000 as required by science case, the less expensive design used a 105mm beam feeding a 408mm deep Echelle is good solution.

The optical design of high resolution Echelle spectrograph for LAMOST is given. This spectrograph will be more powerful tool for astrophysical research using high-resolution spectroscopy in China. Some new technology and novel design concepts have been adopted in this spectrograph, such as white pupil collimator system, R4 Echelle with large blaze angle, and the fold and off-axial Schimidt camera without center obstruction and so on.

Keywords: Instrumentation; spectrograph; high resolution; Echelle grating.

1. INTRODUCTION

The double beam echelle grating spectrograph for the Chinese 2.16m telescope was successfully made in China during 1990-to 1995, which is the first echelle spectrograph developed by Nanjing Institute of Astronomical Optics & Technology， Chinese Academy Sciences. Following the success of the double beam echelle grating spectrograph at the Chinese 2.16m telescope, we consider the design of a similar facility for an 4m-class telescope, the Large sky Area Multi-Object fiber Spectroscopic Telescope(LAMOST). This new telescope has been granted for construction by the Chinese government in 1997. The start of science operation is expected in the middle of 2006. There are 4000 optical fibers on the telescope focal surface that will feed 16 Low Resolution Spectrographs (hereafter referred to as LRS) and one High Resolution Spectrograph (hereafter referred to as HRS).

2. OPTICAL CONFIGURATION OF LAMOST

LAMOST is a meridian reflecting Schimdt telescope laid on the ground with its optical axis fixed in the meridian plane. It is composed of three parts: reflecting Schimidt corrector plate (MA) in the north, primary spherical mirror (MB) in the south and focal plane in the middle part, while primary spherical mirror (MB) and focal plane are fixed on the ground. MA takes the task of tracking of the observed objects and relaying the star light to the primary mirror of MB in the direction of fixed optical axis. Finally, the star light are reflected to focal plane by MB. The fundamental structure of LAMOST is shown in Fig.1.

The telescope parameters in connection with the design of high resolution spectrograph as following:

Aperture:	$D_t = 4m$
Focal length:	$f_t = 20m$
Focal ratio:	$F_t = 5$
Scale in focal plane:	0.097mm/arcsec

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Fiber size: ω = 0.2mm (the angle projected on the sky φ=2″)

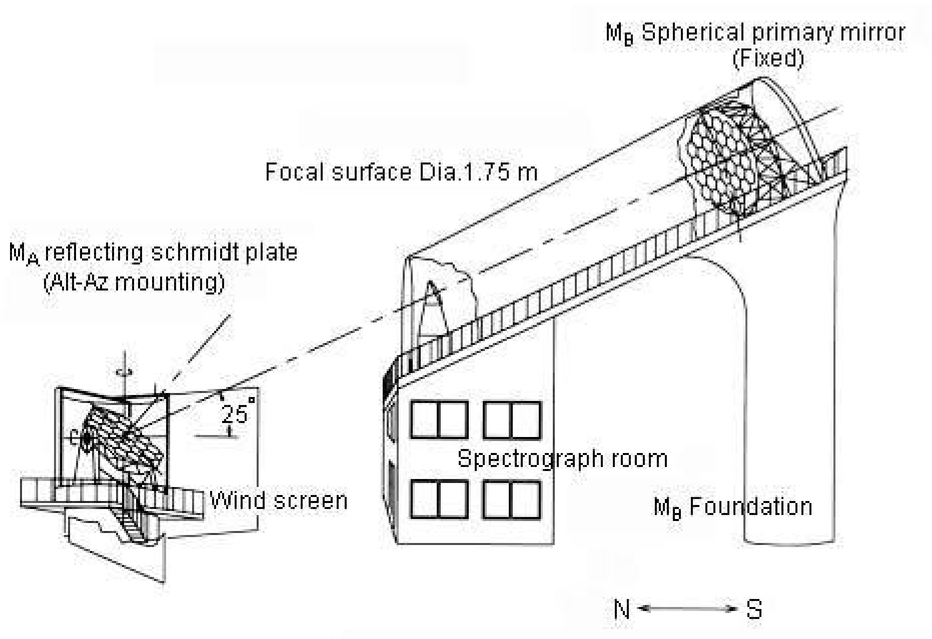

Fig.1 Perspective view of LAMOST

3. CHOICE OF THE ECHELLE GRATING

The two design parameters that define an echelle grating are its groove frequency *G* (= 1/*d*) and its blaze angle $_b$. Echelles presently range in groove frequency from 23 to 316 g/mm, and the typical blaze angles $_b$ supplied in the market are respectively63°26′、69°and 76°for astronomy. Their tangents are 2, 2.6 and 4.Often echelles are specified by their "R number", which equals this tangent, for example, an R4 echelle in one with blaze angle is arctan(4) = 76°. Commonly echelle used sizes vary from 50 by 100 mm to 308 by 408 mm, where the shorter number specifies the groove length and the longer number the ruled width. A recent development has been to make echelles larger than the standard 408 mm ruled width limit, in order to satisfy the needs of large astronomical spectrographs.

The relation among R×Φ, collimator aperture D_c and the ruled length L of the echelle is shown in Fig.2 and Fig.3, while high resolution spectrograph for telescope with aperture of 4-meter selects the above three echelles. In order to achieve the same resolution, the ruled length of the three echelles are close, but collimator beam with R4 echelle is the least, consequently, the size and the cost of spectrograph are the lowest.

The main dispersion component of high resolution echelle spectrograph for LAMOST is R4 echelle, which is replicated on the zerodur glass by the master R4 echelle in the Richardson grating Laboratory of U.S.A. the echelle grating parameters as following:

Ruling density: 31.6/mm;

Blaze angle: $\theta_b = 76°$;

Ruling area: 105mm×408mm.

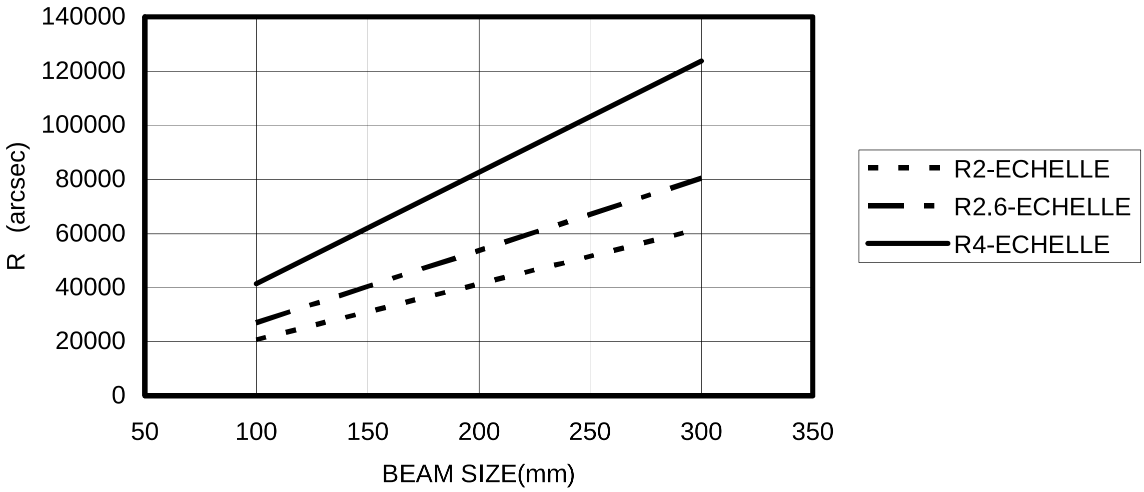

Fig.2 Resolution-Luminosity product (R×Φ) as function of collimated beam size

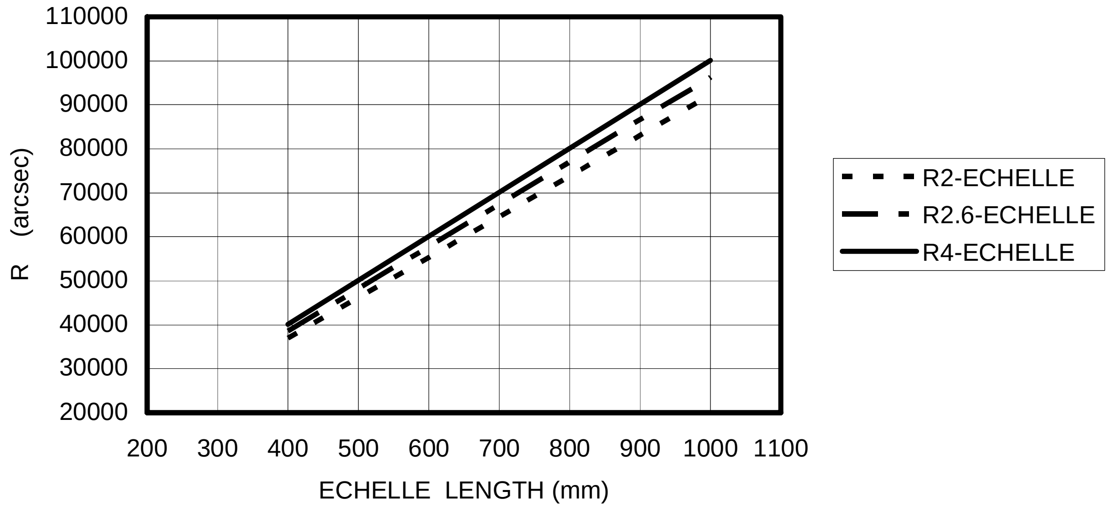

Fig.3 Resolution-Luminosity product (R×Φ) as function of Echelle size

4. THE CROSS DISPERSERS

Echelle can use in high interference order. There are overlapping of so many spectral orders, so an auxiliary dispersion component which is perpendicular to the echelle dispersion direction is required in order to separate spectral order overlapping. As cross dispersion component, plane reflective grating and prism are both used in echelle spectrograph.

Compared with prism, plane reflective grating can acquire large separation of echelle spectra orders, but the disadvantage is low optical efficiency and the serious uneven dispersion for different wavelength, and the second order spectra must be eliminated. It is general to make two kind of cross dispersion gratings work at different wave band for appropriate cross dispersion. Prism has the advantage of high optical efficiency and more uniform cross dispersion, thus, it can work in a larger range of spectra without spectral order overlapping . Many echelle spectrograph for middle-sized or small-sized telescopes select prism as cross dispersion component, however, a large telescope needs large beam, so most designer prefer grating to prism as cross dispersion component , because large prism costs very much on material and is difficult to manufacture.

For LAMOST, echelle works between 55^{th} to 147^{th} orders, about 92 orders spectra overlap together. There are two kinds of plane grating for the separation of overlapping orders: 300 g/mm and 150 g/mm. According to the observation requirement, different cross grating should be selected. The cross grating works at 1st order, and the least separation between orders is 4.5″.

Figure 4 and Figure 5 show the nominal spectral format for HRS. The horizontal lines represent the echelle orders and their lengths represents one free spectral range. With a 2K×2K CCD of 15 m pixel size, the wavelength coverage in a single observation extends from 420nm to 640nm in the blue, and need two exposure to observe wavelength from 640nm to 1100nm.

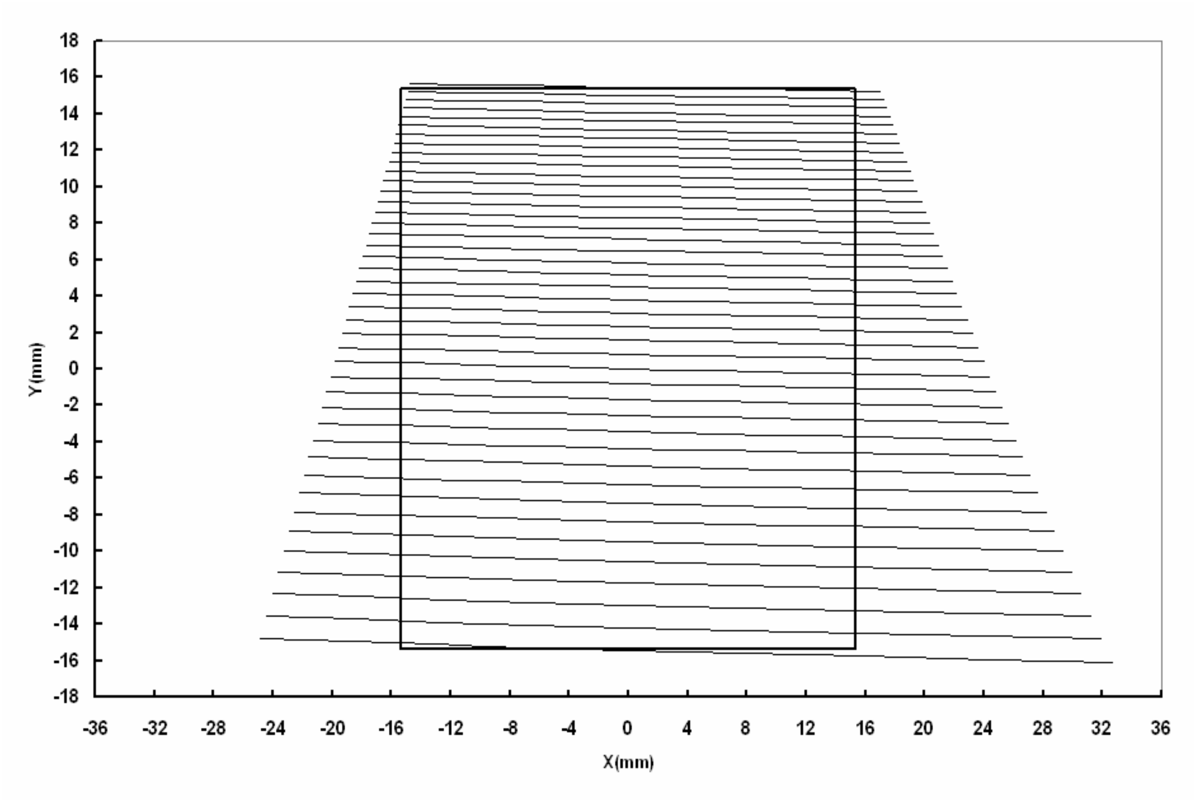

Fig.4 Echellogram with 150-g/mm cross grating, λλ640-1100nm, order95-55

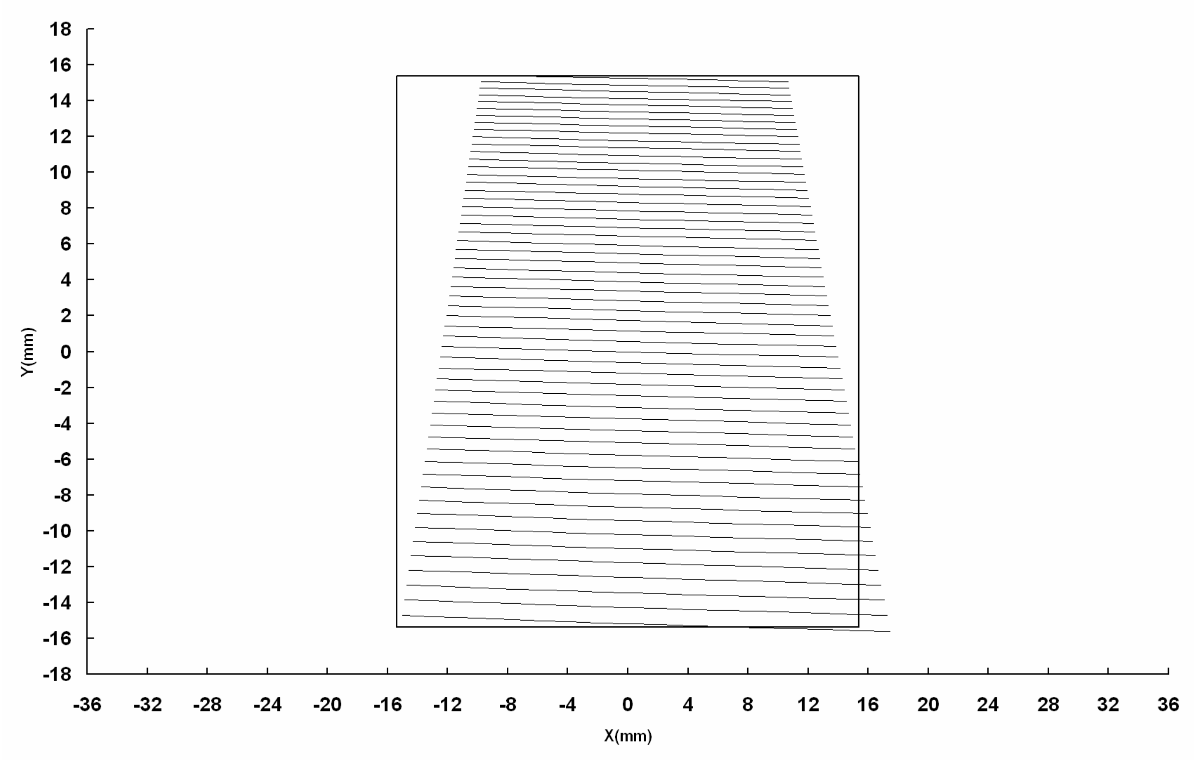

Fig.5 Echellogram with 300-g/mm cross grating, λλ420-640nm, order147-95

5. THE COLLIMATOR SYSTEM

Baranne (1972) introduced a white pupil concept for spectrograph design which eliminates the vignetting and aberrations found in some conventional spectrographs. The Baranne white pupil design has been adopted for both the UV-Visual Echelle Spectrograph (UVES) for the ESO Very Large Telescope (Dekker and D'Odorico 1992) and for the high-resolution spectrograph on the Hobby-Eberly Telescope (Tull 1994).

The white-pupil layout similar to UVES or HET-HRS has been selected for the collimator system of LAMOST-HRS, because the very steep echelle grating angle (76°) requires a small angle between camera and collimator to preserve the efficiency of the echelle grating. This collimator system consist of two off-axis paraboloid mirrors M1 and M2, which have the same parameters and the same master axis and focus in the layout. The off-axis angle of M1 and M2 is 6.52° .The curvature radius of parent paraboloid is 2100mm. The main off-axis paraboloid collimator (M1) is used in double pass to reduce the angle between incident and dispersed beams to nearly zero. A second identical collimator (M2) cancels off-axis aberrations of the first and casts a white pupil onto the cross-dispersing grating. R4 echelle exactly imaged at the cross dispersion grating, for this reason, the size of cross dispersion grating need no enlargement along with the magnifying of main dispersion beam.

The optical layout of collimator system for LAMOST-HRS is shown in Fig.6. In the optical layout, R4 echelle works at the quasi-littrow orientation, where is $\theta = 0$, $\gamma = 0.8°$. After R4 echelle, the dispersed beam goes through the collimator system M1 and M2 and becomes a parallel beam, then incident to cross plane grating, which separates the overlapping order of R4 echelle.

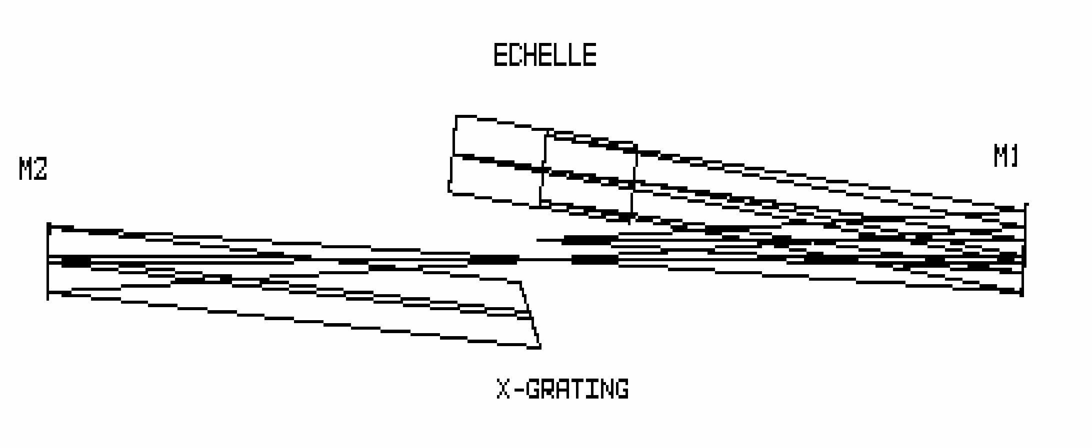

Fig.6 Collimator unit of high resolution spectrograph for LAMOST

6. CAMERA

Compared to exist camera optical system used for spectrographs, transmission camera or catadioptric camera with off-axis has higher efficiency, no central obstruction and external focus. In generally, such camera with transmission systems is very complex and expensive to achieve excellent image quality over abroad wavelength range and wide field. Its price will beyond our financial budget. It was for this reason that we decided to use classical Schmidt camera design in off-axis situation.

The optical arrangement for camera of LAMOST-HRS is shown in Fig.7. The stop of camera is just at the location of cross dispersion grating. To avoid the obstruction of the incident beam to cross grating, it is usually necessary to move off-axis Schmidt corrector plate to a distance of 200mm to the cross grating, thus the aperture of the off-axis Schmidt corrector plate enlarges to 140mm, while the off-axis distance is 120mm and the camera focal length is 400mm, actually the focal ratio of parent camera is F/1.05.

Actual detectors are only available with flat sensitive surfaces. The addition of a positive single lens close to the detector allows to achieve flat field design. The lens with 9 mm thickness, made of fused silica, also serve for cryostat window of detector.

The detail ray trace optimize for the camera has been done with optical analysis program ZEMAX-EE. Image quality is shown in figure 8.

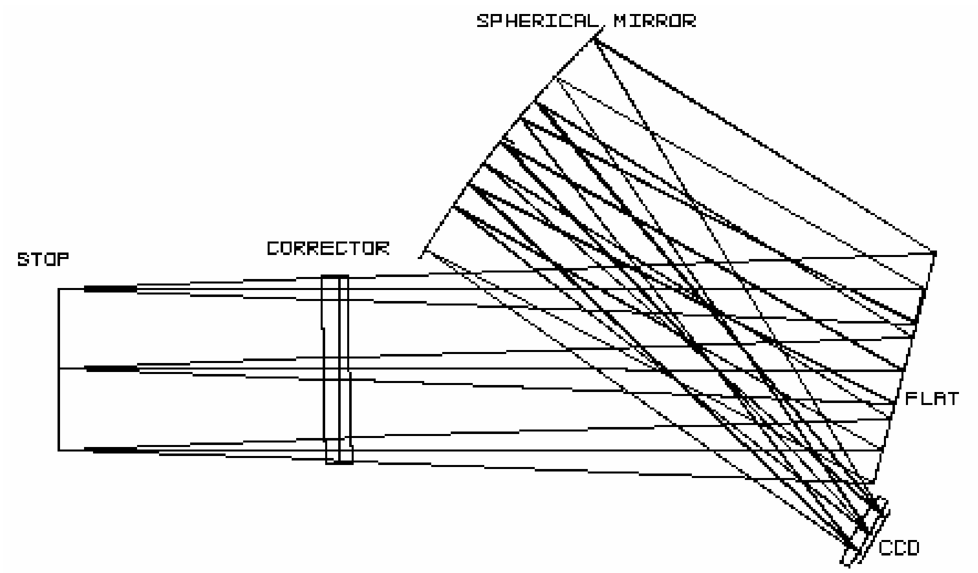

Fig.7 Optical layout of off-axis and folded Schmidt camera

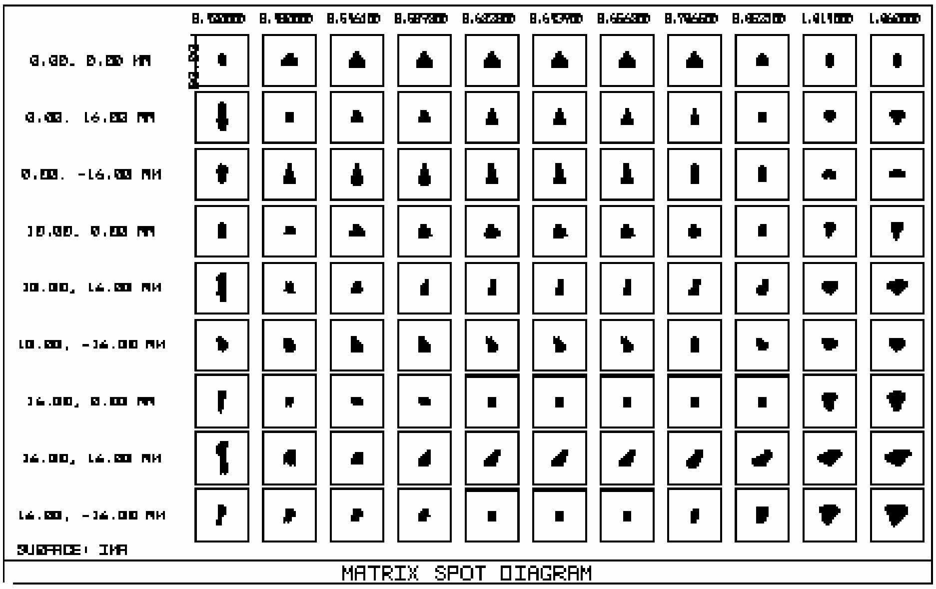

Fig.8 Spot diagrams of off-axis and folded Schmidt camera itself

7. DESIGN RESULT

The optical scheme of the high resolution spectrograph for LAMOST is shown in Fig.9, telescope and spectrograph are connected by fiber, a mini mirror is laid behind the slit, thus the devices before the slit are relayed out of the layout to avoid the obstruction to star light. It takes R4 chelle as the main dispersion component, the echelle grating groove is 31.6 g/mm, the ruling area is 105mm×408mm. As shown in Fig.10, the resolution can reach from 30000 to 100000 while the slit width changes from 1″ to 0.33″. It is convenient to exchange between two cross dispersion grating: 300 g/mm and 150 g/mm. The 300 g/mm grating is selected when observing the spectra of 420~640nm wave band, while observing the spectra of 640~1100nm, the 150 g/mm is selected. Detector is 2048×2048 CCD with pixel size of 15μm ×15μm. The spectra which belong to waveband between 420nm and 1100nm can be recorded in thrice exposures. The detail ray trace and optimize for the entire spectrograph has been done with the software ZEMAX. The image quality for entire spectrograph is shown in Fig.11.

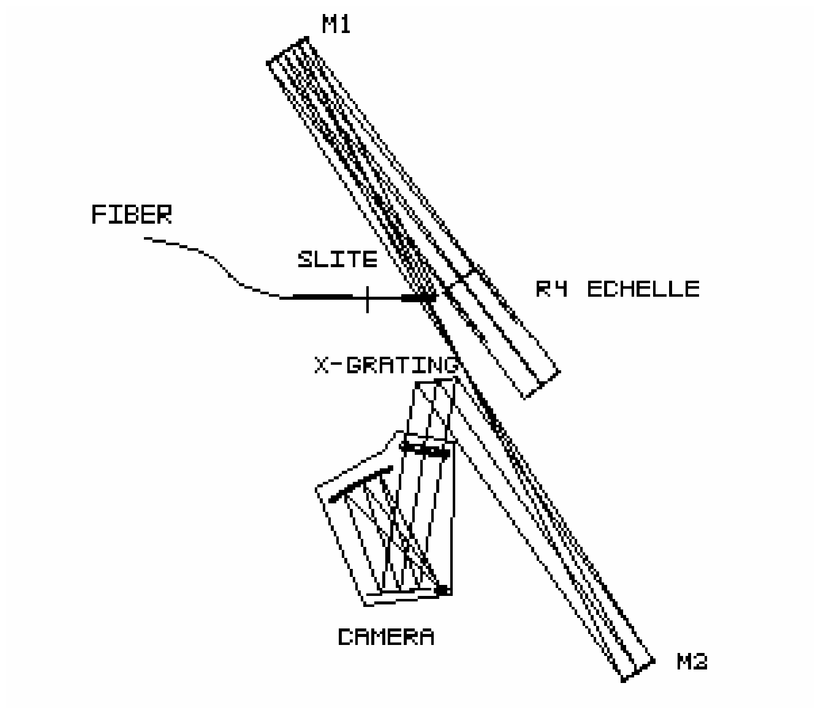

Fig.9 Optical layout of high resolution spectrograph for LAMOST

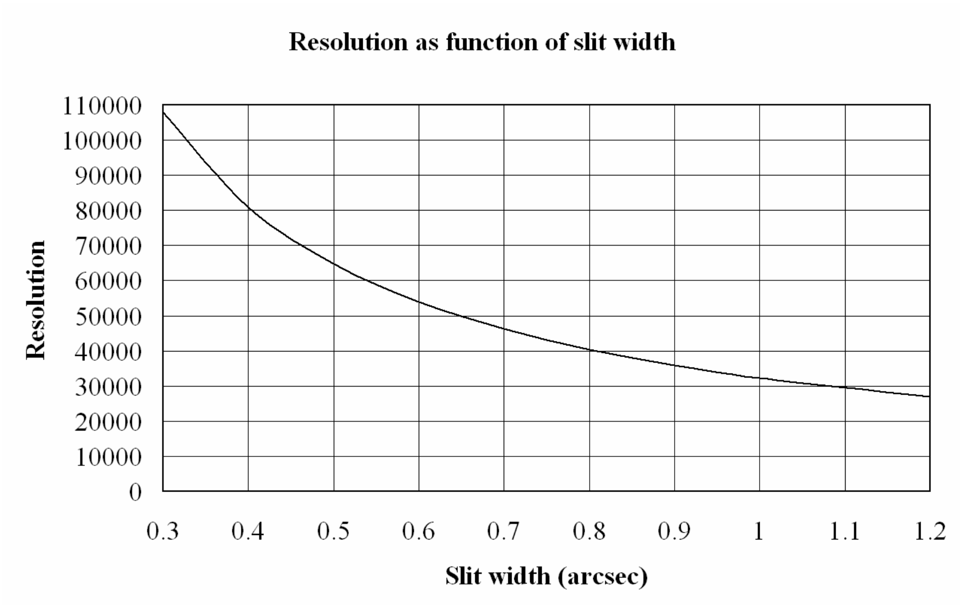

Fig.10 Resolution as function of slit width

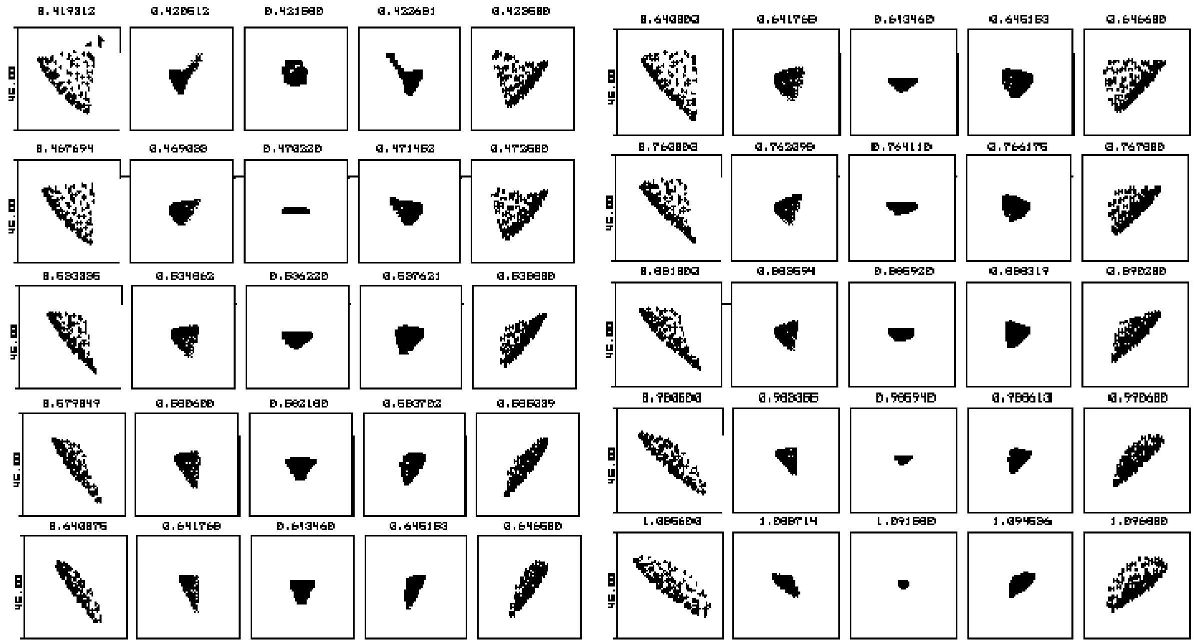

Fig.11 Spot diagrams of high resolution spectrograph for LAMOST

The optical system of high resolution echelle spectrograph for LAMOST has no obstruction, some new technology and novel design concepts have been adopted in this spectrograph. The design characteristics are summarized: white pupil collimator system, R4 Echelle with large blaze angle, and the fold and off-axial Schimidt camera without center obstruction.

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