The BigBOSS Spectrograph

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ABSTRACT

BigBOSS is a proposed ground-based dark energy experiment to study baryon acoustic oscillations (BAO) and the growth of structure with a 14,000 square degree galaxy and quasi-stellar object redshift survey. It consists of a 5,000-fiber-positioner focal plane feeding the spectrographs. The optical fibers are separated into ten 500 fiber slit heads at the entrance of ten identical spectrographs in a thermally insulated room. Each of the ten spectrographs has a spectral resolution ($\lambda/\Delta\lambda$) between 1500 and 4000 over a wavelength range from 360 - 980 nm. Each spectrograph uses two dichroic beam splitters to separate the spectrograph into three arms. It uses volume phase holographic (VPH) gratings for high efficiency and compactness. Each arm uses a 4096x4096 15 µm pixel charge coupled device (CCD) for the detector. We describe the requirements and current design of the BigBOSS spectrograph. Design trades (e.g. refractive versus reflective) and manufacturability are also discussed.

Keywords: dark energy, multi-object spectrograph, baryon acoustic oscillations, Mayall Telescope

1. INTRODUCTION

BigBOSS is a proposed multi-object spectrograph planned for the Mayall 4 meter telescope at NOAO's Kitt Peak National Observatory (KPNO) in Arizona. The main objective of BigBOSS is to study dark energy using baryon acoustic oscillations (BAO)[1]. It will survey 14,000 square degrees and measure the redshifts of over 20 million galaxies.

Figure 1 shows the proposed implementation at the Mayall 4 meter telescope. BigBOSS will use the existing mount and telescope (including primary mirror and struts). The top ring, cage, barrel, spider vanes, fiber bundles and spectrograph stacks will be new. The light from the galaxy is reflected off of the primary mirror, passes through the corrector and focuses onto one of 5,000 robotic fiber actuators. The fiber transports the captured galaxy light to the slit of the spectrograph where it is then dispersed and focused onto the detector. The spectrographs are placed in the temperature controlled Fourier Transform Spectrograph (FTS) Laboratory. More details on the BigBOSS interfaces to the Mayall telescope are given by Besuner et al[2].

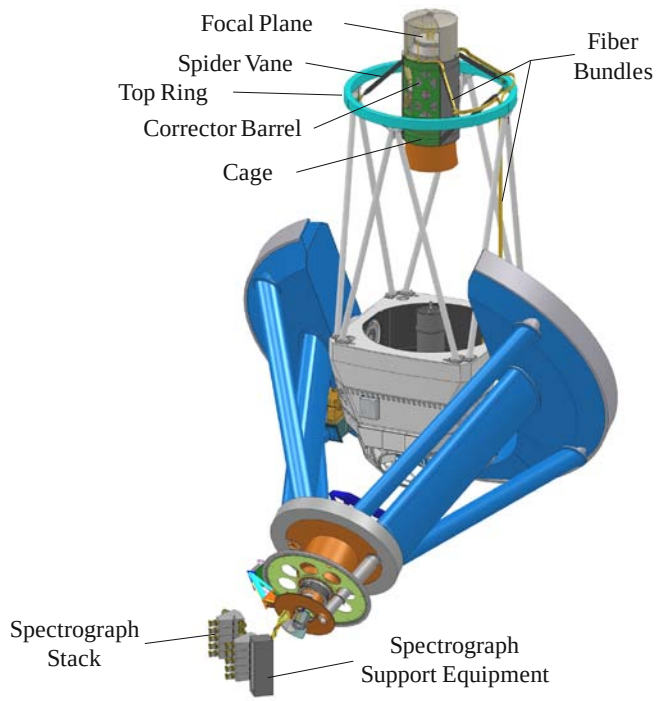

Figure 1 Proposed BigBOSS implementation on the Mayall 4 meter telescope.

2. REQUIREMENTS

The requirements for the BigBOSS survey are divided into three levels. Level 1 is the science requirements, Level 2 consists of the data set requirements and Level 3 specifies the instrument requirements.

2.1 Level 1 Science requirements

The main science requirements for the BigBOSS survey are to measure the distance scale error σ_R/R to < 1% for redshifts (z) between 0.5 and 3.0, measure H(z) to 1.5 % up to a z=2.5, constrain growth σ_g f(z) with < 2% relative error, and measure the galaxy power spectrum to < 1% up to z=1.5. In addition, there are scientific goals relating to inflation and the sum of neutrino masses.

2.2 Level 2 Data set requirements

The BigBOSS survey will use four types of objects to trace the mass of the universe. It will use luminous red galaxies (LRG) for $0.5 < z < 1.0$; emission line galaxies (ELG) for $0.5 < z < 1.6$; tracer quasi-stellar objects (QSO) for $0.5 < z < 3.5$; and Lyman α forest QSO for $2.2 < z < 3.5$. The redshifts must be measured to an accuracy of $\sigma_z < 0.001\ (1+z)$. To ensure that Level 1 requirements are met, at least 20 million redshifts over an area of at least 14,000 square degrees must be measured.

2.3 Level 3 Instrument requirements

The BigBOSS instrument is proposed to be installed on the 4 meter Mayall telescope at Kitt Peak National Observatory. It is proposed to use 500 nights over a period of five years to complete the survey. In order to complete the survey in 500 nights the instrument must have at least a 3° diameter field of view and be able to measure the redshift of 5,000 objects in this field simultaneously. A summary of the bandpass requirements is given in

Table 1. The overall required range is the union of required range for each type of object, and then rounded to the nearest 10 nm. The overall spectral range is 360 nm < λ < 980 nm.

Table 1 Bandpass requirements (object spectral features in rest frame)

Object spectral Feature	**z**	λ_{min}	λ_{max}
Lyman-α forest (121.57nm)	2.2 < z < 3.5	389 nm	547 nm
Balmer Jump (364.56nm)	-	365 nm	365 nm
CdI calibration line (361 nm)	-	361 nm	361 nm
400 nm break in LRG	0.5 < z < 1	600 nm	800 nm
OII doublet in ELG	0.5 < z < 1.6	559 nm	969 nm

The spectral resolution requirements are driven by the observations of the OII doublet in the ELGs. A typical spectrum of an ELG at zero redshift is shown in Figure 2[3]. The brightest line is Hα at 656.3 nm, the next brightest is the OII doublet at 373 nm. There are several other lines that can be used, including OIII and Hβ.

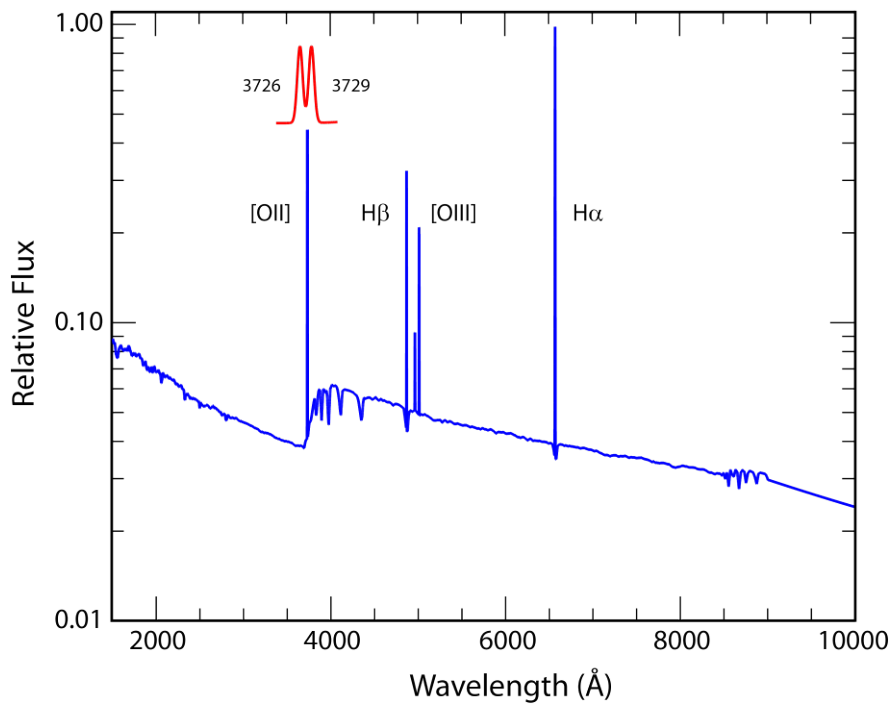

Figure 2 Typical spectrum of an emission line galaxy (ELG) at zero redshift.

For redshifts < 0.49 both the OII and the Hα lines are observed, so there is a strong constraint on the spectral resolution. The spectral resolution requirement is driven by the QSOs and LRGs. The required spectral resolution, $\lambda/\Delta\lambda$, full width at half maximum (FWHM) must be greater than 1500.

If the observed bright line is below 656 nm it cannot be Hα, so the doublet does not need to be resolved. But in this wavelength range sky lines are starting to become significant and higher spectral resolution allows access to more dark space between the lines. For 555 nm < λ_{OII} < 656 nm, the required spectral resolution is $\lambda/\Delta\lambda$ FWHM > 3000.

If the OII lines are > 656 nm, the OII doublet must be resolved to ensure a proper redshift identification. Figure 3 shows the effect of spectral resolution on the fitting of an OII doublet. The signal was adjusted so the fit to a doublet had a 7 σ significance. A broad singlet line was also fit (shown in red). At a spectral resolution of 2000 the $\Delta\chi^2$ for the two fits was only 1, so a broad singlet is not ruled out. At a spectral resolution of 4000 the $\Delta\chi^2$ was 9, so a broad singlet can be ruled out. For λ_{OII} > 656 nm, the required spectral resolution $\lambda/\Delta\lambda$ > 4000. The sky lines in this band are also bright and the increased spectral resolution allows access to more dark space between the lines.

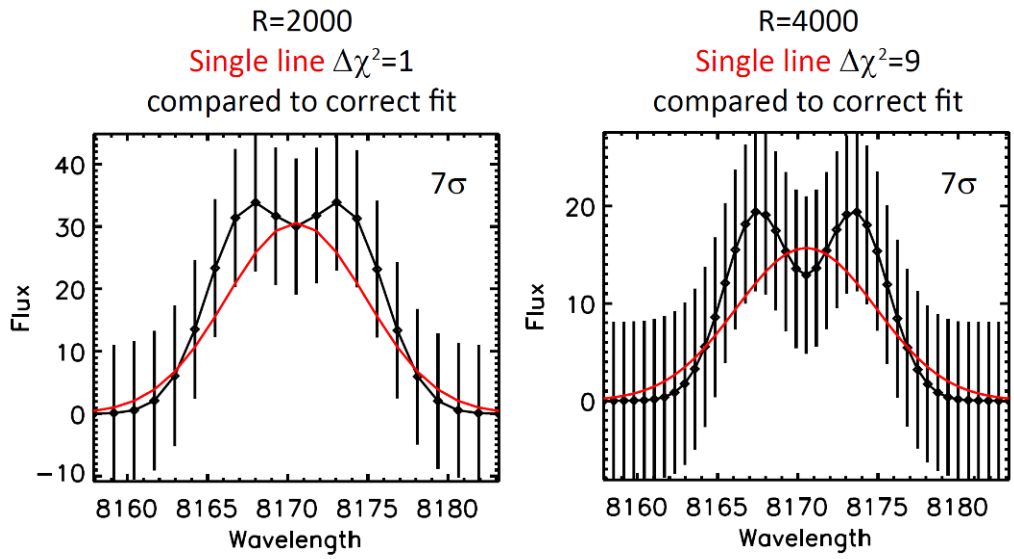

Figure 3 Effect of spectral resolution on fitting the OII doublet line. Doublet fit shown in black, singlet fit shown in red.

2.4 Spectrograph Requirements

The BigBOSS spectrograph is fiber fed. The 5,000 fibers from the focal plane are separated into 10 spectrographs, each with 500 fibers arranged on a slit. The layout of the slit is similar to the slit on the Baryon Oscillation Spectrographic Survey[4] (BOSS) spectrograph. The fiber core diameter is driven by the sky background, telescope seeing, etc. The fiber size (given the focal length of the corrector) that gives the best signal to noise ratio on galaxies is 120 µm. The diameter of the projected fiber should be at least 3 detector pixels to ensure sufficient sampling. The final slit is ~136 mm high.

The spatial resolution requirements on the spectrograph are driven by crosstalk between adjacent spectra which should be less than 5%. This means that 95% of the energy must be contained in a circle of diameter equivalent to the projected spacing between fibers on the detector. This includes the convolution of the fiber size, spectrograph optics, grating scatter, CCD pixelization, charge diffusion and photon conversion depth.

The BigBOSS spectrograph will use CCD detectors with 4096x4096 15 µm pixels with a 13 pixel exclusion zone along the edges. This leaves 4067 x 4067 pixels or 61 mm of detector that the spectrograph can use.

The corrector on the Mayall telescope illuminates the input of the fiber with an obscured f/4.5 beam. The output beam from the fibers is assumed to be a filled f/4 beam. The focal ratio degradation (FRD) of the fibers causes this change[5].

The throughput requirements on the spectrograph drive the selection of glasses and the grating parameters. Only glasses with > 90% transmission in the band are used. Poppett[6] et al. show that to achieve grating efficiencies greater than 80% at the edges of the band, the volume phase holographic (VPH) grating must have an angular dispersion, $\Delta\beta$, < ~16°. The blue edge of the shortest bandpass cannot get to 80% efficiency even with the small angular dispersion. This sets a minimum size for the lenses and grating. A portion of the instrument throughput budget has been allocated to the spectrograph. The required throughput for the spectrograph (from fiber to detector, not inclusive) is shown in Table 2. Since the spectrograph may have multiple arms the requirement is for the sum of the throughputs for each arm.

Table 2 Spectrograph Throughput Requirements

Wavelength (nm)	Throughput
360	> 0.3
400	> 0.5
450	> 0.6
500	> 0.65
980	> 0.65

In addition to performance requirements, there are several functional requirements for the spectrograph. It must have a shutter to block the light during readout. A light source to back illuminate the fibers for the fiber view camera is required. A light source to flat field the CCD detectors is required. The spectrographs must be placed in a temperature controlled to 20°C ± 1°C. The humidity of the spectrographs must be controlled since some of the optics coatings are sensitive to humidity changes.

3. SPECTROGRAPH DESIGN PARAMETERS

Since the spectral range is more than a factor of two, the spectrograph bandpass needs to be split into at least two arms, using dichroic filters, to eliminate second order contamination. To achieve the required spectral resolution the spectrograph must be split into three arms. BigBOSS plans to use a spectrograph that has four main components, the collimator, the dichroic, the disperser, and the camera (see Figure 4). The collimator collimates the beam coming from the fibers. The collimated beam then passes to a series of dichroic filters that split the bandpasses. There must be some spectral overlap between the arms since a dichroic transitions from reflection to transmission in a few tens of nanometers. The current designs have the dichroics in the collimated beam so all arms of the spectrograph must have the same magnification. The separated collimated light then passes through a disperser to disperse the colors of the light. Volume phase holographic gratings (VPH) disperse the light. The dispersed light then passes through the camera which focuses the light onto the detector. The collimator and camera can either have reflective or refractive (as in Figure 4) optics.

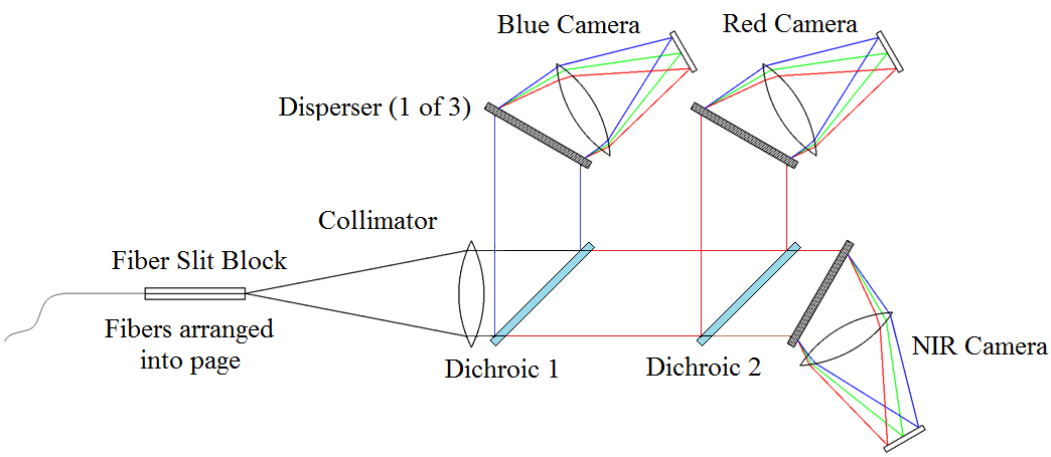

Figure 4 Elements of a three arm spectrograph. The collimator, dichroic, disperser, and camera are considered part of the spectrograph, while the slit and detector are considered separate elements.

The magnification of the spectrograph is the ratio of the camera to collimator focal ratios. The collimator accepts the f/4 light from the fibers. The fiber diameter is 120 µm and it must project to a minimum of 45 µm (3 pixels) on the detector. This gives the minimum spectrograph magnification of 0.375. Given the slit height of 132.4 mm, which must map to less than 61 mm on the detector, the maximum spectrograph magnification is 0.46.

If the optics of the spectrograph have no aberrations, the projected fiber diameter on the detector is just $m \cdot d$, where m is the magnification of the spectrograph and d is the diameter of the fiber. The spectral resolution of an arm of the spectrograph can then be estimated from

$$\Delta x = \frac{\sqrt{3}md}{2}$$

$$\Delta\lambda = \frac{\Delta x(\lambda_{\max} - \lambda_{\min})}{D}$$

$$R(\lambda) = \frac{\lambda}{\Delta\lambda}$$

where Δx is the one dimensional (1D) full width at half maximum (FWHM) of the spot in detector units, $\Delta\lambda$ is the 1D FWHM of the spot in spectral units, λ_{max} is the maximum wavelength in this band, λ_{min} is the minimum wavelength in this band, D is the width of the detector and R is the spectral resolution. Since the diameter of the fiber and the detector width are fixed the only variables in the spectrograph design are the magnification and the minimum and maximum wavelengths of the bandpass. Initial spectrograph design parameters were derived using these equations and the spectral requirements from section 2.3. There is no unique solution; the design chosen has the maximum magnification possible that met the resolution requirements. This results in the slowest possible camera, which is easier to manufacture. To meet the requirements three arms were required: blue, red and near infrared (NIR). The parameters for the design are given in Table 3 and the spectral resolution versus wavelength is shown in Figure 5.

Table 3 Spectrograph Design Parameters

Magnification	0.45		
Fiber Diameter	120 µm		
Collimator f/#	4.0		
Camera f/#	1.8		
Slit			
Slit Height	135.6 mm		
Number of Fibers	500		
Detector			
Detector Width	61 mm		
Detector Height	61 mm		
Pixel size	15 µm		
	Blue Arm	**Red Arm**	**NIR Arm**
λ_{min} (nm)	360	566	747
λ_{max} (nm)	593	772	980

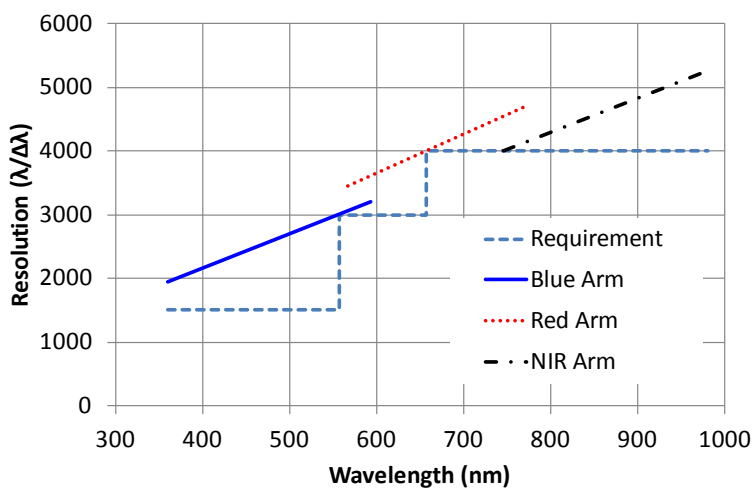

Figure 5 Spectral Resolution

4. SPECTROGRAPH DESIGN

The collimator and camera can either have reflective or refractive optics. The advantage of reflective optics (Schmidt) is that there are fewer optical surfaces (as few as one). A disadvantage of a reflective collimator is that there is an obscuration caused by the light passing over the fiber slit block. The BOSS spectrograph[7] uses a lensless Schmidt reflective collimator. The BOSS design has an obscuration below 3%. Disadvantages of a reflective camera are that there is obscuration caused by the detector and that the entire camera must be in the cryostat (since the detectors operate cold). With an axisymmetric Schmidt Camera, the central linear obscuration diameter is set by the image height. The corresponding linear fractional obscuration is then proportional to the fiber diameter, the number of fibers feeding each spectrograph, and the camera's f/number. The obscuration varies inversely with the diameter of the grating (and hence the collimator/camera optics size and cost). To meet the throughput requirement, along with other requirements, the Schmidt camera needs optics and cryostats that are much larger than the alternative, the refractive camera. For this reason the initial BigBOSS design starts with variations on the BOSS spectrograph, using a reflective collimator and refractive cameras.

4.1 Collimator Design

The initial design of the collimator is a variant on the collimator used on the BOSS spectrograph. A schematic of the BOSS spectrograph is shown in Figure 6. The collimator is a lensless Schmidt design with the fiber at the focus of a spherical mirror and the grating at the center of curvature of the mirror.

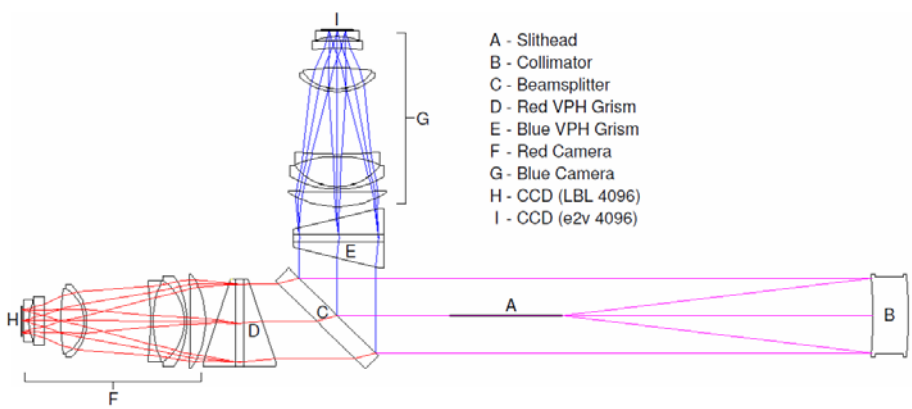

Figure 6 The BOSS spectrograph

4.2 Grating Design

The initial design uses VPH gratings between plane parallel plates. The fringes of the grating are tilted to remove the Littrow ghost[8] off of the detector. The diffracted angle range ($\Delta\beta$) is chosen to ensure the grating will have high efficiency at the edges of the band. The incident angle, α, and line density are chosen to place the Bragg wavelength at the center of the band. The actual grating from the vendor may be slightly different from these parameters once the vendor optimizes the efficiency.

4.3 Camera Design

The refractive cameras for the spectrograph are a variant of the field flattened Petzval[9] design. This design has the pupil in front of the lens (at the grating) followed by two separated positive groups followed by a negative field flattener. Since the magnification of the spectrograph is 0.45, the focal ratio of the camera must be 1.8.

The first part of a refractive camera design is the glass selection. The first criterion is high transmission in the band of interest. The second criterion is low potassium content. Potassium 40 is radioactive and will increase the background of the CCD detectors. Ohara[10] and Schott[11] were contacted to determine which glasses had no potassium. The third criterion is ready availability.

The next part of glass selection is to find combinations of glasses that are achromatic. At first combinations of two glasses were tried but the aberrations were too large, especially in the blue arm. The search was then extended to a larger

number of glasses by minimizing a metric based on a system of equations that evaluates both net chromatic aberration and total lens element power. For a combination of three thin lenses the error in the power of the combination is

$$e_i = (n_a(\lambda_i) - 1)X_a + (n_b(\lambda_i) - 1)X_b + (n_c(\lambda_i) - 1)X_c - B$$

where e_i is the error in power of the combination, $n_a(\lambda_i)$ is the index of refraction for lens a at wavelength λ_i, X_a is the curvature of lens a, $n_b(\lambda_i)$ is the index of refraction for lens b at wavelength λ_i, X_b is the curvature of lens b, $n_c(\lambda_i)$ is the index of refraction for lens c at wavelength λ_i, X_c is the curvature of lens c and B is the power of the combination. A series of these equations for 5 wavelengths over the band is solved simultaneously to minimize Σe_i^2. This system of equations is over-determined and is solved using the technique of Lampton[12]. The ΣX_i^2 is also minimized to reduce the aberrations. Several of the most promising of these glass combinations are modeled in detail with Zemax® optical design software to find designs that will meet the requirements.

4.4 Integrated Spectrograph Design

Finally the collimator is combined with the gratings, dichroics and cameras to produce a spectrograph that is globally optimized with Zemax®. The final lens of the camera is also a dewar window so the minimum allowed central thickness is 10 mm. The distance from the detector to the last lens is fixed at 3 mm. Optically the design works better with the detector closer to the dewar window, but mechanical and thermal issues prefer larger spacings. Currently, two designs are being optimized. The first allows the close spaced lenses with index-matching oil between them. The second keeps the lenses more than 1 mm apart so no oil or optical bonding is needed. The BigBOSS spectrograph requirements can be met with either configuration. The two designs will be presented to vendors to determine which is more cost effective. Figure 7 shows a schematic of the spectrograph design with oil between some of the lenses. Each camera has two conic aspheric surfaces. The first asphere is on the front of the front lens which also helps correct the spherical aberration from the collimator. The blue camera requires many more lenses and lens types since the dispersion of the glasses varies more in the blue. Table 4 shows the general specifications for the spectrograph design.

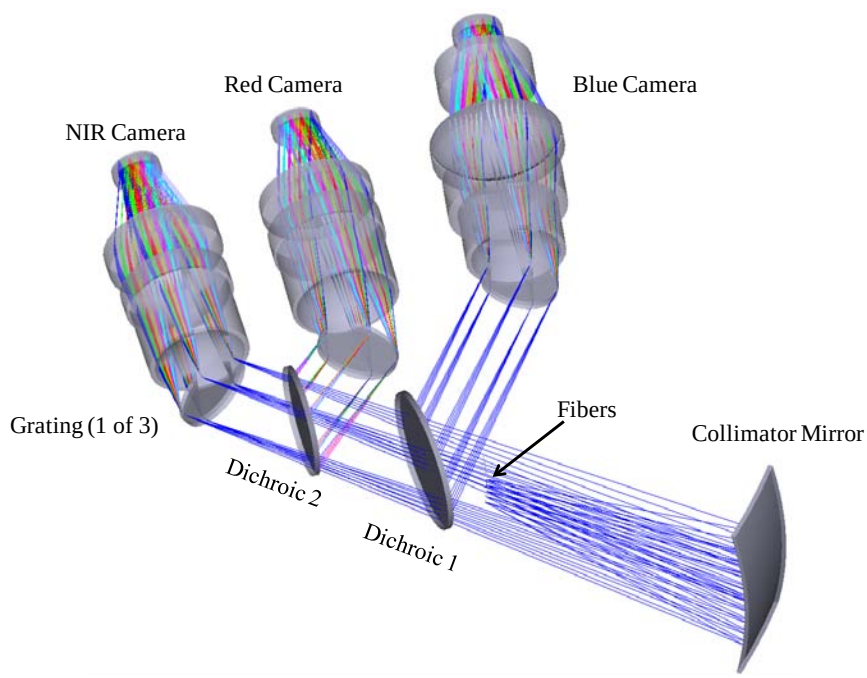

Figure 7 Three dimensional schematic of the spectrograph design, note that the full diameter of the collimator mirror is needed only in the direction perpendicular to the dispersion plane.

Table 4 General Spectrograph Optics Specifications

Collimator Mirror diameter (mm)	385		
Optics Volume	1.4 m x 0.9 m x 0.4 m		
	Blue Arm	**Red Arm**	**NIR Arm**
Grating Diameter (mm)	128	137	137
Largest Lens (mm)	223	187	192

The results for the raytrace of the blue arm are shown in Figure 8. The left figure shows the spot diagram where the circle represents the 54 µm diameter of a projected fiber. The spots are much smaller than the projected fiber. The right figure displays the root mean squared (RMS) radius of the distribution for the various wavelengths versus fiber position relative to the middle of the height of the slit. The average RMS radius is 3.4 µm and the maximum is 9.3 µm, both much smaller than the 27 µm radius of a projected fiber. The results for the red arm are shown in Figure 9. The average RMS radius is 4.8 µm and the maximum is 11.1 µm. Again the spots are much smaller than the projected fiber diameter. The results for the NIR arm are shown in Figure 10. The average RMS radius is 4.7 µm and the maximum is 10.5 µm.

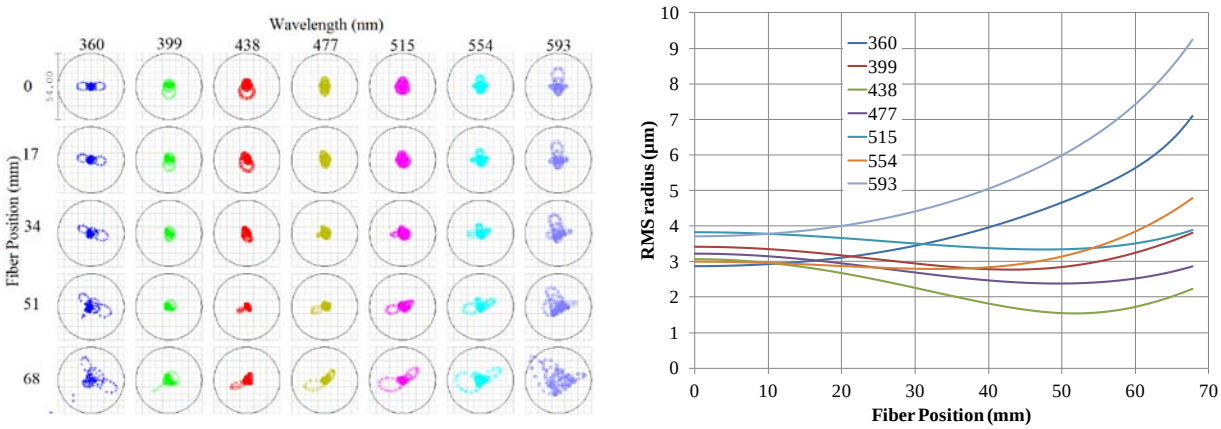

Figure 8 Raytrace results for the blue arm. The spot diagram is in the left figure. The circle is the projected fiber diameter (54 µm). The right figure is the RMS radius versus fiber position on the slit for each wavelength.

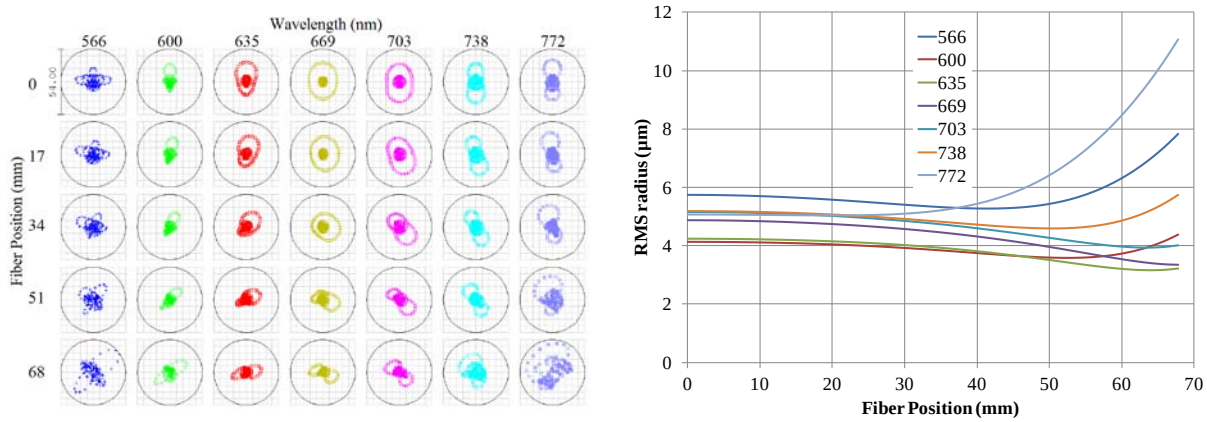

Figure 9 Raytrace results for the red arm.

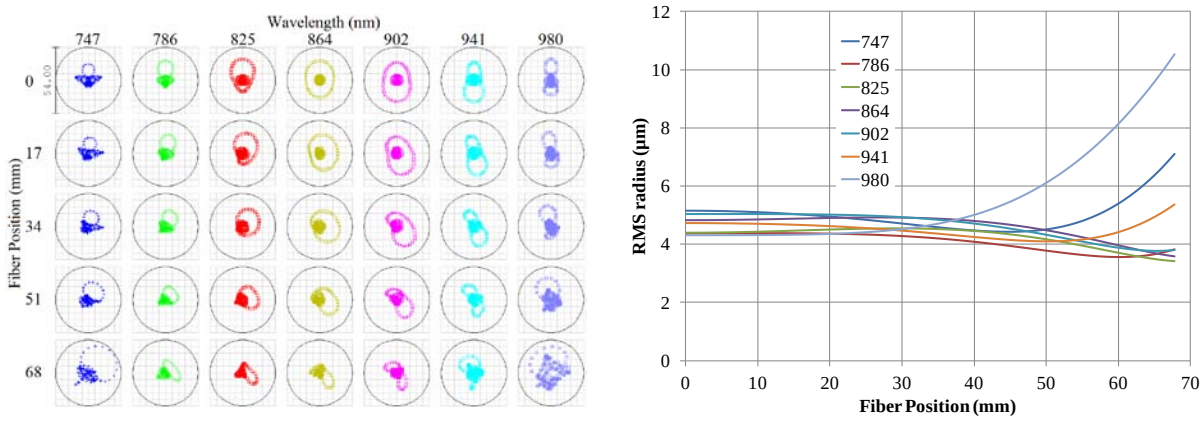

Figure 10 Raytrace results for the NIR arm.

The spectral resolution was determined by raytracing eleven wavelengths for each of 5 fiber positions on each arm. A dispersion relation was fit using the centroids of the raytraced images. The one dimensional FWHM for each wavelength was measured from the image of each wavelength. The spectral resolution is shown in Figure 11. The spectral resolutions are shown in the solid lines for both the center and edge fibers. The requirement is shown in the dashed blue line and met at all wavelengths.

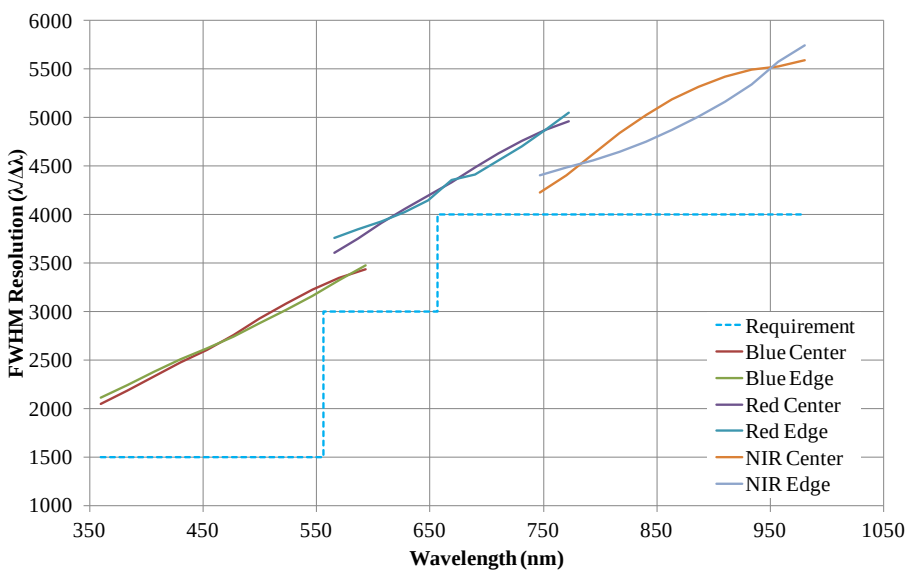

Figure 11 FWHM spectral resolution. The solid curves are the resolution determined from raytraces at both the center and edge fibers. The dashed curve is the requirement.

The throughput of the spectrograph was estimated by multiplying the throughputs of all the components. The collimator mirror reflectance is from the BOSS measurements. The dichroic transmissions and reflections were estimated by scaling measurements of the BOSS dichroics. The grating efficiencies were calculated using GSolver® rigorous diffraction grating analysis software[6]. The transmission of the lens materials was estimated using the published vendor transmission data and Zemax®. The antireflection coatings on the lenses were assumed to have a transmission of 99.5%. The final result is shown in Figure 12. The total throughput, shown in the dashed green curve, is greater than the requirement, shown in the dashed blue curve.

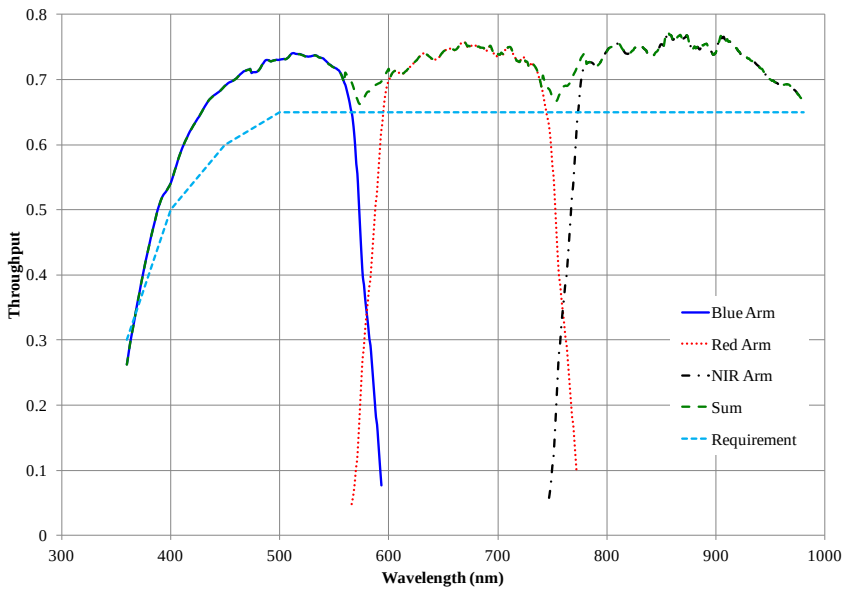

Figure 12 Throughput of the spectrograph. The dashed green curve is the sum of the arm throughputs. The dashed blue curve is the requirement.

5. FUTURE WORK/CONCLUSIONS

There are several analyses that need to be completed on the current design. A tolerance analysis needs to be completed to determine how well the lenses must be manufactured and aligned. A ghost analysis needs to be completed to ensure that scattered light and ghost images will not affect the science. Diffraction, grating scatter and detector effects need to be added to the raytrace images to determine if the wings of the point spread function are small enough to enable the science analysis.

The current spectrograph design meets all the BigBOSS spectrograph requirements. This design along with an all reflective and an all refractive design will be sent to vendors to determine the cost and manufacturability of the each spectrograph design. Cost/performance trade studies can then be completed to finalize the design of the BigBOSS spectrograph.

ACKNOWLEDGMENTS

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REFERENCES

[1] Schlegel, D., et al., "The BigBOSS Experiment", arXiv:1106.1706 (2011)

[2] Besuner, R., Bebek, C., Dey, A., Goble, W., Joyce, D., Levi, M. E., Reil, K., Schlegel, D., Sholl, M., "Integrating BigBOSS with the Mayall Telescope", Proc. SPIE 8446-194 (2012)

[3] Bruzual, G. and Charlot, S., "Stellar population synthesis at the resolution of 2003", Mon. Not. R. Astron. Soc. 344, 1000-1028 (2003)

[4] Eisenstein, D. J. et al., "SDSS-III: Massive Spectroscopic Surveys of the Distant Universe, the Milky Way, and Extra-Solar Planetary Systems", AJ 142, 72-95 (2011)

[5] Edelstein, J., Poppett, C. L., Sirk, M. M., Besuner, R. W., Lafever, R. E., Murray, G. J., Allington-Smith, J. R. and Bebek, C. J., "Optical fiber systems for the BigBOSS instrument", Proc. SPIE 8450-114 (2012)

[6] Poppett, C. L., Edelstein, J., Arns, J., and Lampton, M., "Comparing modelling techniques when designing VPH gratings for BigBOSS", Proc. SPIE 8450-151 (2012)

[7] Gunn, J. E. et al, "The Multi-Object, Fiber-Fed Spectrographs for SDSS and the Baryon Oscillation Spectroscopic Survey", in prep (2012)

[8] Burgh, E. B., Bershady, M. A., Westfall, K. B., and Nordsieck, K. H., "Recombination Ghosts in Littrow Configuration: Implications for Spectrographs Using Volume Phase Holographic Gratings", PASP 119, 1069-1082 (2007)

[9] Smith, W. J., [Modern Lens Design], McGraw-Hill, New York, 426-429 (2005)

[10] http://www.oharacorp.com/xls/glass-data-2012.xls

[11] http://www.us.schott.com/advanced_optics/english/download/schott_optical_glass_catalogue_excel_june_2012.xls

[12] Lampton, M., "Damping–undamping strategies for the Levenberg–Marquardt nonlinear least-squares method", Computers in Phys., 11 110-115 (1997)