# WIYN Bench Spectrograph Upgrade Report

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*This report was prepared on behalf of the Bench Upgrade Project Team who have all contributed to the content: George Jacoby (Project Manager), Di Harmer (Bench Instrument Scientist), and Charles Harmer (Optical Design). We also acknowledge Pat Knezek in her role as Project Manager at an earlier phase of the project as well as Sam Barden for his critical role in the VPH grating development and earlier overall involvement in the project.*

*September 15, 2003*

## Executive Summary

The Bench Upgrade Team has completed a "baseline upgrade" concept for the Bench Spectrograph. This consists of developing and implementing (i) a new, off-axis collimator with a shorter focal length (800mm instead of the current 1021mm); (ii) the capability to use volume-phase holographic (VPH) gratings on the existing bench; (iii) two new VPH gratings at densities of 740 and 3300 l/mm. The baseline upgrade also includes (iv) developing a plan to complete the upgrade with a suite of VPH gratings, a new CCD and controller, and upgraded fiber toes. Implementation of the elements in latter plan is referred to as the "full upgrade." The total cost of the baseline upgrade is currently estimated to be $191.5k, with gains between a factor of 2.8 and 3.5 in higher throughput expected with insignificant changes in spectral resolution at the highest-resolution settings. This document records the analyses and design studies which establish the baseline concept. We estimate that we are somewhere between concept-level and preliminary-design-review phases. The full upgrade is estimated to cost an additional $215k with equally significant gains over a broader range in wavelength (particularly in the blue and red) and spectral resolution, better sampling, lower noise, and much faster read-out times. This document outlines aspects of the items in the full upragde.

We request authorization from the WIYN Board to spend $68k between now and March 2004 to reach a proposed Critical Design Review (CDR) for the baseline project. We will request authorization to spend the balance from the Board in March 2004 pending a successful CDR. At this time we seek the endorsement of the WIYN SAC towards proceeding with an optical design for shorter focal-length collimator for the Bench Spectrograph as outlined herein. We also recommend WIYN agressively pursue over-coatings of the LLNL-variety at this time for telescope secondary and tertiary.

# CONTENTS

# 1. Project Scope

## 1.1. Goals & Constraints

The goal of the Bench Upgrade project is to significantly fix the very low throughput (3-4%) of the existing system for a small cost. Significant gain in throughput is defined as a factor of 2 or greater. "Small cost" means significantly less than the cost of building an entirely new spectrograph, which we estimate to be in excess of $2M. We suggest an expected rough ceiling for the Bench Upgrade should be $\sim$ $300-600k.

Further constraints on the project are to maintain (a) the versatility of configurations with existing cables and gratings; (b) the existing high-resolution capabilities; and (c) an ergonomically effective layout which facilitates changing configurations. Finally, financial constraints dictate the upgraded spectrograph must fit within the available space for bench spectroscopy at WIYN.

## 1.2. Competitiveness

*Can even an upgraded Bench Spectrograph be competitive? How?* A suitable metric is to compare the competitiveness of the Bench Spectrograph and its feeds to Hectospec and Hectochelle on the MMT (see http://cfa-www.harvard.edu/oir/MMT/MMTI/index.html and links therein). The MMT has 3.4 times the collecting area as WIYN.

Hectochelle will deliver spectral resolutions of 32000-40000 ($\lambda/\Delta\lambda$) for 250 objects over a single echelle order with an absolute efficiency of 6-10% (telescope plus instrument, not including atmosphere). For high-resolution multi-object spectroscopy, then, MMT has a 3-fold multiplex gain, 2-2.5 times the efficiency and achieves a factor of 1.5-2 higher spectral resolution. Within the context of the Bench Upgrade, we can gain back a factor of 2 in throughput, but not the combined factors of 4.5 to 6 in source multiplex and spectral resolution. *Is this where we should aim the Bench Upgrade project to try and compete?*

Hectospec will deliver spectral resolutions of 1000-6000 for 300 objects at absolute efficiencies peaking at 30% at 500nm, with 600-900 spectral resolution elements. These are resolutions which are easily achievable with the Bench Spectrograph, and the number of resolution elements is comparable. While the multiplex advantage is daunting, the gain in grasp (area times solid angle), when compared to SparsePak is minor: 29%. The question, then, is whether we can come close to matching the absolute efficiencies of Hectospec with an upgraded Bench. The plan we have developed using a combination of off-axis collimator and VPH gratings indeed comes within a factor of 2 of Hectospec's throughput. Since WIYN has fiber feeds with comparable grasp and unique configurations (i.e., IFUs), this is where we can compete. *We find this a compelling argument for optimizing our redesign for efficiency over spectral resolution.* However, we're in luck: The optimization we propose also significantly enhances the performance for the highest-resolution configurations of the Bench Spectrograph, and *insignificantly* degrades the highest resolutions currently achievable.

### 1.3. History of the "Bench Upgrade" and Related Projects

- Initial field-lens design to minimize vignetting in echelle configuration (Vaughnn, 1994).
- Development of VPH gratings (Barden, ongoing)
- FRD measurements for existing cables (Conselice, Smith & Sawyer, Aug. 1998)
- Bench Working Group constituted in 1998; 1st report to SAC in April 1999 (Bershady [Chair], Deliyannis, Pierce, Sawyer Smith, and Zepf).
- All-refractive spectrograph design (Pierce, 1999)
- 2nd Report to SAC on Bench Upgrade (Bershady, Feb 2000)
- NIR camera for Bench proposal to NSF/ATI (Zepf, Aug 2000)
- Director's meeting (Feb 1-2, 2001): Kick-off for present process
- SparsePak commissioning and lab measurements (Bershady, May 2001)

## 2. Present Upgrade Plan

**Scope.** The present upgrade plan consists of (a) replacing the existing collimator with a new, shorter off-axis collimator and corrector plus field-lens, (b) developing the capability of using low and high-density VPH gratings on the current optical bench in addition to the existing reflection gratings; (c) delivery and commissioning of two VPH gratings, one low- and one high-density; and (d) definition of future upgrade components with a clear path for development and definition of costs and gains. We define elements (a)-(d) to be the **"Baseline Upgrade,"** with the implementation of the items in (d) to be the **"Full Upgrade."**

The off-axis collimator optics improves the throughput and provides a more compact geometry suitable for using low and high-density VPH gratings on the existing bench. Throughput is improved (i) by decreasing the focal length to to capture more of the light output from the fibers into a beam that does not substantially overfill the grating and camera; and (ii) by controlling placement of the pupil to further minimize vignetting. By placing the collimator off-axis we also remove the foot vignetting and allow the grating to be moved forward to the natural pupil. This minimizes the overall distance to the camera, which further improves our ability to minimize vignetting (with the smallest possible collimator diameter), and allows us to consider geometries on the existing bench where the camera-collimator angle exceeds 90°. This is needed for implementation with low-density VPH gratings. The VPH grating development consists specifically of manufacturing, polishing, coating, mounting and testing two VPH gratings at effective ruling densities of 740 and 3300 l/mm.

**Opto-mechanical design and fabrication** of the off-axis collimator and other new mounting hardware is still under development, but we expect to out-source some of the design and fabrication; some hardware components may be fabricated at UW. Manufacturing and polishing of VPH gratings are out-sourced to CSL (Belguim) and Lawrence Livermore National Laboratories, respectively, while the remaining tasks are expected to be done at NOAO in Tucson.

**What we have considered fixed** are (i) the Bench Camera; (ii) the Simmons Camera; (iii) the basic fiber feeds in length, geometry, and mounting hardware (we do envision modifications to the "toes" of the fiber "feet," but these modifications will work with existing filters and their optomechanics, e.g., SparsePak); and (iv) the existing reflection grating suite. The new system we propose will indeed work with the existing suite of reflection gratings, the Bench Camera, and fiber feeds. (We have not yet checked performance of the upgraded system with the Simmons camera, but we will do this.) It is unlikely, however, that the upgraded system will be easily reconfigurable to return to the current on-axis collimator and so a choice needs to be made about the focal length of the off-axis collimator. The issues are summarized in §3.5. *We strongly recommend adopting a new collimator with a shorter focal length of ∼800mm.* We have not considered an all-refractive collimator because of complexity and cost and the likelihood of little additional gains beyond the proposed off-axis design.

**Future upgrades components**, including items in the full-upgrade that are *not* part of the baseline-upgrade, are discussed in §7: developing a suite of VPH gratings, upgrading the fiber-feed toes to further reduced vignetting, a new CCD for better sampling and higher QE in the blue (and possibly the red), and a faster CCD controller.

## 3. Progress Report

The progress report outlines several steps we have taken over the past 1.5 years in understanding and characterizing the existing system, and then builds on this information to develop a design of an upgraded system. Section 3.1-3.4 outline what we understand about the existing system, and therefore establishes the rationale for our upgrade plan described in §3.5 and 3.6 A summary of gains and outstanding issues in the upgrade design are listed in the two concluding sub-sections.

### 3.1. Bench GUI

Crawford and Bershady have designed a new GUI to model the setup and performance of the Bench Spectrograph, illustrated in Figure 1. (Crawford is a graduate student at UW-Madison, under supervision of M. Bershady; this work was done in part as a course requirement for Astornomy 920 in Spring 2003.) The GUI is designed to replace the old `setup.f` program, and contains significant improvements over the calculations in this code. The GUI model calculates the vignetting in the system using a real beam profile and geometric model, and has estimated values for the different grating efficiencies including blaze functions modulated by the camera-collimator angle, $\theta_{cc}$. The previous setup program assumed a constant throughput value and $\theta_{cc}$ fixed for each grating ($11^\circ$ for echelle and $30^\circ$ for low-order gratings). The S/N and exposure time calculator also uses real astronomical spectra; the grating and cable list is updated, the camera-collimator angle is now a free parameter; and a number of plotting tools have been implemented to allow the user to optimize the setup for trade-offs in spectral resolution and throughput. The GUI is a java applet and is publicly available as a beta-release at http://www.astro.wisc.edu/ crawford/Spectrograph/intro.html. The code is still under development. Key upgrades include completed documentation, an improved S/N estimator, and inclusion of VPH gratings. *Please try out this interface and provide us with feedback.*

## 3.2. Confirmation of Optical Design for the Existing System

### *3.2.1. Geometric Model*

Crawford and Bershady have established a geometric model of the Bench Spectrograph for estimating the vignetting in the system. The model reproduces the shape of the slit function to better than 5% for a variety of configurations, and is able to reproduce the subtle differences between configurations with different camera-grating distances (see Figures 4 and 5 in Bershady et al. 2003, submitted to ApJS). C. Harmer, D. Harmer, and M. Bershady inspected and verified Bench Spectrograph clear apertures at site in February 2003, using a white-light illumination at appropriate f/. As a result of these efforts, we now have an excellent quantitative picture of where light is lost due to obstructions in the spectrograph. While the geometric model is not a ray-trace of the spectrograph capable of modeling aberrations, *because ZEMAX cannot be used easily with a realistic beam profile, our geometric model is currently the only reliable tool for estimating obstructions, vignetting and hence total throughput.* The geometric model is used in §3.4 below to estimate vignetting losses in the throughput budget, and is incorporated into the GUI described in §3.1 above.

### *3.2.2. Ray-trace Model*

C. Harmer has completed a new ZEMAX model of the existing Bench Spectrograph with the Bench Spectrograph camera (BSC), in consultation with D. Harmer and M. Bershady. (See Figures 2 and 3 for an example of one of the modeled configurations.) Initial comparisons of ZEMAX spot diagrams (Figure 8) with observed ThAr spectra are encouraging, although a final comparison by Bershady is pending. Outstanding issues for the ZEMAX optical design are (a) to properly model the input beam to include FRD effects (currently we are using an undegraded beam at constant f/); (b) model optimization by C. Harmer that matches the setup-optimization of the spectrograph by D. Harmer. To minimize the effects of (a) we have chosen configurations where the resultant spot size is not a strong function of input f/. At this time we believe our understanding of the current optical system is sufficiently good to proceed with a preliminary design for an "upgraded" system (§3.5). *The final redesign will be optimized once we have completed the analysis of the model of the current optical system.*

### 3.3. Assessment of Scattered Light

Based on an assessment of SparsePak commissioning data (see Bershady et al. 2003 Figures 9-11) it appears there is significant scattered light for $\lambda > 700$nm using the echelle grating and BSC. For typical extraction apertures the contamination is at the 10% level at 870nm, but as low as 1% at 510nm. It was verified that this was a generic effect for all fiber cables. New measurements by D. Harmer and M. Bershady have been taken in 2003 to verify if the scattering is from the echelle grating, interference filters, or the coatings in the BSC. Preliminary indications are that the coatings in the BSC are the cause. Bershady aims to present a final analysis to the SAC in Fall 2003. The preliminary implications of this result are that *it is not sensible to tune optimization of Bench Spectrograph in the red (>700-800nm) with the current Bench Camera unless we consider recoating the camera optics.*

### 3.4. Establishing Losses in Existing System

We have created a "throughput budget" based on measurements near the H$\alpha$ region using the echelle grating and SparsePak. This allows us to assess where the maximum losses are in the existing system, and hence where the greatest gains can be had in an upgraded system. The results are tabulated in Appendix A, along with an assessment of the fidelity of the measurements and estimates.

• *The number of elements in the throughput budget is large. There are no single outstanding points of loss.*

• *Half the photons incident at the top of the atmosphere are lost by the time they exit the fibers.* The most significant loss at the "top-end" (before the spectrograph) is from the three mirror reflections. (Only in the blue will fiber transmission dominate"top-end" losses.)

□ **We recommend overcoating the secondary and possibly the tertiary, as LLNL-type coatings become available for mirrors of these sizes.**

• The largest losses in the spectrograph are, in order:

a. **Vignetting** from the combined obstructions and stops of a 5 critical surfaces: toes, collimator, foot, grating, and camera objective. The total vignetting ranges from 50% with the echelle and higher-ruled gratings (>600 l/mm) to 30% for low-order gratings ($\leq$ 600 l/mm). Off-order echelle setups vignette as much as 65%. The most significant losses come from the camera, except for the off-order echelle setups, but in general vignetting of the grating is also significant. The foot obstruction is 7%, and collimator losses are typically 3% on-axis and 12% off-axis. We have not yet included obstruction losses due to the toes. This is not a factor for SparsePak but is important for other cables – see §7.

b. **Grating efficiency**, with peak efficiencies of 50% for the echelle, rising to 70% for the lower ruled gratings. The echelle has a steep blaze function and effective efficiency over observed wavelength th ranges are significantly lower than peak value even if on-order.

c. **Camera throughput**. Reflection losses estimated to be roughly 25%; see Appendix A.

d. **CCD response**, including dewar window reflection is a 20% loss in the visible and significantly lower at the extreme red and blue ends of the spectral range (<400nm and >800nm).

e. **Echelle order-separating filters** have 10% loss for cwl > 580nm, but lower peak transmissions lead to 40% losses by 370nm.

These five items are put into *two priority groups:* 1. Vignetting and grating efficiency represent the dominant pan-chromatic losses. These will be considered directly in the first phase of the upgrade, i.e., the "baseline upgrade." 2. The CCD response, camera throughput, and order-separating filters represent losses which are more extreme at the blue and red ends of the spectrograph range. The CCD response will be addressed as part of the "full upgrade." The echelle order-blocking filters will be addressed for those setups for which there are VPH grating replacements. The camera throughput is not currently envisioned as part of the upgrade because of risk and down-time. However, the CCD upgrade will require modifications to the current bench camera, so we may want to revisit this coating decision.

### 3.5. Optical Redesign: Gains from Minimizing Vignetting

Our optical redesign has evolved considerably from the initial concept of adding a field lens to move the pupil to minimize vignetting (e.g., Vaughnn 1994). In an early examination of the problem C. Harmer deemed field-lens placement complicated for the echelle configuration (where the most gains could be made): The field lens must be placed *after* the order-blocking interference filters, and hence at significant distance from the focus. Image quality could not be maintained in this configuration.

C. Harmer's suggestion is to consider, instead, an off-axis collimator whereby the grating could be moved up to the natural pupil (the collimator focal length), and develop a corrector that would reduce the off-axis aberrations. A proof-of-concept level design is now complete which includes a refractive corrector and off-axis segment of a parabolic mirror. *This unit is proposed to replace the current on-axis parabolic mirror.* There are three, all-glass, all-spherical refractive elements in the corrector, with the most unusual aspect of the design the tilt between these elements. See Figures 4-7. There are probably a family of workable solutions with an off-axis collimator but the general problem is highly constrained by the existing camera optics. *The current solution with a tilted-lens corrector appears to provide slightly better image quality (compare Figures 8 and 9) and also permits the pupil distant to be controlled to further improve throughput.*

The current proof-of-concept has the gratings at the same distance from the collimator (1824mm), places a pupil on the grating, and maintains the grating-camera distance. The latter is fixed for the existing gratings. *We estimate the mean gain across the slit from such system is 30±4 % over all setups. with the end fibers gaining 50% for low-order gratings and 70% for the echelle grating.* The analysis is presented in Appendix B and Figures 10,12-17.

We believe we can significantly improve on these gains by modifying the existing design in the following ways, in order of importance but decreasing in difficulty:

**1. Decrease collimator focal length** to capture more light but not significantly degrade spectral resolution. See Appendix B and Figures 10-19. As shown in Figure 18, the measured fiber output irradiance has 90% encircled energy at f/5, while the optics are sized for an f/6.7 beam. *We conclude that by decreasing the collimator focal length from its present value of 1021mm to 800mm we will* **double the gains in an off-axis design** *with marginal-to-no degradation in the observed spectral resolution for the smallest fibers and highest-dispersion setups* (where the anamorphic factors are also the largest).

**2. Optimize pupil placement.** See analysis in Appendix C and Figures 20-22. We conclude the optimum pupil placement is between the grating and the collimator at roughly 1250mm from the collimator. The precise placement awaits modeling of the final system using VPH gratings, and will require a science-based decision on which setups to optimize. *This is a 2nd-order effect compared to gains had by shortening the collimator focal length.*

**3. Decrease collimator-grating distance.** In the upgrade design the grating-camera distance remains unchanged from the present design for a given grating, and varies between roughly 838mm for typical echelle setups at camera-collimator angles of 11° to 381mm for low-order gratings where the camera-collimator angle is 30°. The shorter the collimator-grating distance, the smaller the off-axis collimator mirror will have to be in order to move the pupil to its optimum position between grating and camera. *Our goal is to make the collimator-grating distance the same as the collimator focal-length.*

In summary, we see a workable path to designing an off-axis collimator that will deliver 60% more light on average, and typically twice the light for end fibers with no appreciable degradation of the highest spectral-resolution configurations. Outstanding issues, which we will address, include fine-tuning the optimum focal length for the new, off-axis collimator, and the optimum placement of the pupil.

**□ We explicitly seek SAC recommendation and Board spending authorization for this off-axis collimator design with an effective focal length near 800mm.**

## 3.6. VPH Gratings: Gains in Maximizing Grating Efficiency

### *3.6.1. Advantages of VPH gratings*

• VPH gratings in general have improved efficiency over conventional gratings with 90% throughput at blaze peak, and a blaze-peak tunable over wide range of wavelengths (i.e., a superblaze) by modulating camera-collimator angle. We can take advantage of this tunablity by being on a bench with existing articulation.

• Since the VPH gratings are used in low order (1 or 2) there is no need for narrow-band filters for order separation at high resolution – normal glass filters can be used. Hence more throughput gains can be had, particularly in the blue (cf. §3.4).

• There is a good possibility of getting spectral resolutions comparable to the echelle ($\lambda/\Delta\lambda \sim$ 10,000 to 20,000) at very high grating angles ($\alpha > 60°$). This can be achieved without significant vignetting because the gratings can be made larger than standard reflection gratings. Figure 23 shows that with a smaller collimated beam, as proposed with the sorter focal-length collimator, we can go to higher $\alpha$ and hence higher spectral resolution without vignetting a grating of a given size. The outstanding issue remains to determine if gratings can be manufactured to be efficient at these high incidence angles, $\alpha$.

### *3.6.2. Present Status of VPH Grating Development*

We have continued with a program begun by Sam Barden to develop large, high throughput VPH gratings. One test grating is now in hand with characteristics of an effective groove density of 740 l/mm. This grating has been coated and mounted at KPNO (D. Harmer). The measured throughput by CSL is shown in Figure 24. Note that the first order peaks in the red where the current Bench Spectrograph is not particularly efficient and where scattering is large. However, the 2nd-order peak is near 500mn for $\alpha = 21°$ at comparable throughput to 1st order. This fills a gap in the current grating suite between the 1200 l/mm grating (1st order) and the 600 l/mm grating blazed at 13.9° (2nd order) as seen in Figure 28. For 300$\mu$m fibers this VPH grating should deliver $\lambda/\Delta\lambda \sim 2700$ at 500nm.

A second grating with an effective groove density of 3300 l/mm grating is currently under development. Barden's prediction for its performance is shown in Figure 25. If this grating can be delivered to specification and and properly coated it may deliver up to twice the throughput at echelle-like spectral resolutions of $8000 < \lambda/\Delta\lambda < 18000$. As shown in the key to Figure 29, for an unvignetted 150mm diameter beam (for which the Bench is currently designed), the grating must be 355 mm in the dispersion dimension to reach incidence angles $\alpha$ of 65°.

#### *3.6.3. Steps to implementing VPH gratings on the WIYN Bench*

**1. Test the 740 l/mm grating efficiency.** VPH gratings are use near-Littrow ($\alpha \sim \beta$), and hence low-density gratings are useful in the optical at large ($> 90^\circ$) camera-collimator angles, $\theta_{cc} = \alpha + \beta$. Because the current bench configuration cannot be used with such large angles. D. Harmer and C. Harmer have developed a system using a (flat) transfer mirror (212.6mm width in the dispersion dimension and 259mm in the spatial dimension). The test setup is shown in Figures 26 and 27. This system will be lossy because of vignetting, but we will be able to properly model these losses to determine grating efficiency relative to conventional grating setups.

**2. Continue with manufacture of 3300 l/mm grating** and ensure optimization for high incidence angles (55-70°) in both the grating specifications (size and DCG parameters) as well as the coatings. Mount and test efficiency relative to echelle.

**3. Develop plan for full articulation of $\theta_{cc}$** from 11° to ~170° without use of transfer mirror. Off-axis geometry, which should be more compact is critical for implementing low-ruled VPH gratings.

**4. Create prioritized list for additional VPH gratings.** Compare wavelength and spectral resolution covered with current suite (Figure 28) with a few examples of VPH gratings (Figure 29). Note spots in wavelength and resolution in current grating suite where we are not well sampled. We will develop a recommendation for the SAC.

### 3.7. Summary of Expected Gains and Costs

Summary of Expected Gains and Costs: "Baseline Upgrade"

| Item | Cost | Gain |
|---|---|---|
| 1. Off-axis collimator, 1021mm fl | $150k (est) | 30% mean, 50% at slit ends |
| 2. Off-axis collimator, 800mm fl | (same) | 60% mean, +100% at slit ends |
| 3. 2 VPH gratings | $30k | 50% (possibly higher for echelle) |
| 4. VPH order-blocking filters | none | 15% relative to echelle (visible, higher in blue) |
| TOTAL (items 2-4) | $180k | 180% mean, 250% at slit ends |

Note - Cost breakdown appears in §5.

### 3.8. Summary of Outstanding Issues

- Collimator focal-length trade-off between throughput and spectral resolution: Science trade decision made by SAC at THIS meeting.
- Determination of shortest grating location and off-axis collimator focal length that can be achieved while maintaining good image quality consistent with above trade-off decision.
- Optimization of pupil position consistent with items 1 and 2.
- Check design with Simmons camera.

  Items 1-4 ⟶ FINAL OPTICAL DESIGN
- Optical tolerance analysis. ⟶ OPTO-MECHANICAL DESIGN
- VPH manufacture and management for 3300 l/mm grating.
- VPH grating suite: design and optimization.

## 4. Proposed Schedule and Milestones

| | |
|---|---|
| Testing of 740 l/mm VPH grating | Oct 2003 |
| Final optical design | Nov 2003 |
| Tolerance analysis | Dec 2003 |
| Delivery of completed 3300 l/mm VPH from CSL | Dec 2003 |
| Optomechanical design: vendors and bids | Feb 2004 |
| **Critical Design Review** | **March 2004** |
| High-Fidelity Budget Presented to Board | Mar 2004 |
| Place orders and begin manufacture | Mar 2004 |
| Delivery of post-polished 3300 l/mm VPH from LLNL | Apr 2003 |
| Coating and mounting 3300 l/mm VPH from LLNL | May 2003 |
| Testing of 3300 l/mm VPH grating | Summer 2004 |
| Delivery of Off-Axis Collimator | Sept 2004 |

## 5. New Funding for 2003-3004

☐ **We request spending authorization of $68k from the Board for optical/optomechanical design of the off-axis collimator, development of the 3300 l/mm VPH grating, and testing of the 740 l/mm VPH gratin to reach CDR by March 2004.**

In March 2004 we will present the Board with a high-fidelity budget to build, deliver and commission the off-axis collimator, and to complete testing of two VPH gratings; and then request spending authorization for this amount from the Board. We also intend to approach the UW Graduate School for matching funds for this effort. The budget break-down is as follows.

New Funding Request Breakdown

| | |
|---|---|
| Pre-CDR Development: Oct 2003 - Mar 2004 | $51.5k tot |
| Optical design on corrector for off-axis collimator | $20k |
| Opto-mechanical design for new collimator and corrector | $20k |
| RA at UW for 3 months (50%) | $7.5k |
| Travel for Opt/Mechanical design oversight (4 trips @ $1k) | $4k |
| | |
| VPH Grating Development: Oct 2003 - Mar 2004 | $16.5k tot |
| 740 l/mm VPH grating testing | none |
| 3300 l/mm VPH manufacture | $5k |
| (post-polishing, over-coating, mounting and delivery) | |
| Travel for VPH manufacture oversight (1 trip) | $2k |
| Travel for VPH commissioning (1 trip, 2 people) | $2k |
| RA at UW for 3 months (50%) | $7.5k |
| | |
| VPH Grating Development: Apr 2004 - Sep 2004 | $9.5k est |
| *not in current request* | |
| 3300 l/mm VPH grating testing | none |
| Travel for VPH commissioning (1 trips, 2 people) | $2k |
| RA at UW for 3 months (50%) | $7.5k |
| | |
| Collimator Fabrication | $110k est. |
| *not in current request* | |
| Refractive optics | ... |
| Reflective optics | ... |
| Coatings for refractive elements | ... |
| Coatings for reflective element | ... |
| Opto-mechanical elements | ... |
| Assembly and alignment | ... |
| Shipping and insurance | ... |
| RA at UW for 3 months (50%) | $7.5k |

Notes - RA at Wisconsin will work with Project Scientist in the following areas: (1) final development of GUI; (2) geometric modeling to optimize optical design; (3) development of VPH grating suite plan; (4) testing and analysis of VPH gratings and new collimator data; (5) documentation of above.

## 6. Management

This project poses management challenges as the personnel are geographically separated and all are multiply (over-)committed to other projects. Our assessment is that it will require extremely aggressive management to maintain the proposed schedule.

### 6.1. Personnel

M. Bershady, Project Scientist

D. Harmer, Bench Instrument Scientist

C. Harmer, Optical Design

G. Jacoby, Project Manager

## 7. Future Efforts: The Full Upgrade

Future efforts in the Bench Upgrade project include completing the VPH grating suite, upgrading the toes to reduce vignetting, and upgrading the CCD system. At this time we have not considered new fiber feeds for the MOS. It is desirable to review the optimum fiber type as well as the diameter in view of WIYN's improved DIQ, but the optical quality at the MOS port should be quantified. This is beyond the scope of the currently-envisioned effort.

Summary of Future Upgrades: "Full Upgrade"

| Item | Cost | Gain |
|---|---|---|
| VPH gratings (4) | $100k | 50% in throughput and higher resolution |
| Upgraded Toes (3) | $15k | 20% in throughput |
| CCD+controller | $80-100k | 60% better sampling; >4× faster readout |
| | | >50% gain in throughput @ 350nm and 950nm |

- **VPH grating suite to replace surface-gratings.** We estimate of 4-6 gratings would be needed to replace or augment the current relief-grating suite, at a cost of roughly $25,000 per grating. This includes the two VPH gratings to be delivered as part of the "base-line" upgrade. Given the considerable expense

  ☐ **we suggest the SAC consider a reduced set of high-priority gratings and also advertise to individual users to obtain funds to procure specialty gratings for uncommon applications.**

- **New toes for existing cables.** Measurements with SparsePak indicate performance increases relative to existing cables consistent with $\sim$ 20% vignetting losses in all of the fibers due to obstruction cause by over-baffling in the toes. We will use our geometric model to estimate the losses due to the existing toes and recommend, on this basis, whether or not the existing DensePak and Hydra cables should have their toes rebuilt. We estimate 2 weeks for mechanical design, and then 2 weeks to manufacture each toe.

- **New CCD with smaller pixels, lower read-noise (RN), and improved response in blue and red.** Requirements for such a device are 15 $\mu$ pixels, 2 e- RMS read-noise, and $>$ 40% QE at 350 and 900 nm. The smaller pixel size is needed to better sample unresolved lines with the smallest fibers in configurations with high demagnification. Currently sampling in these configurations is typically 1.5 pixels per FWHM. Pixels significantly smaller than 15 $\mu$m are undesirable because of increased RN contribution.

  There are a number of products on the market. One outstanding device is the E2V/Marconi 2048$\times$4098 44-82 device. UW is gaining experience with these devices as part of their collaboration with SALT. Six excellent devices have been purchased. It is likely a second order will be placed for at least 2 additional devices for the SALT HRS within the coming year. The cost of a Grade 0 device is $85k with the following characterisics: 6 or less column defects (typically 1); 500 or less white spots (typically 75); 1250 total spots (typically 75); and 30 or less traps (typically 2).

  ☐ **Our recommendation at this time would be to purchase one of these devices or an equivalent, after considering whether a slightly lower grade is acceptable.**

- **New CCD controller with faster read-out (RO), better bias stability.** Requirements are RO times $<$ 15 sec for in 2048$\times$4098 pixel format (of order or less than integration times for calibration frames); and bias drift and pattern–noise $<<$ 1e- peak-to-peak (less than rms read-noise). NOAO is the only consortium member who has stepped forward with a viable upgrade path, and so at this time

  ☐ **we suggest waiting for the availability of the MONSOON controllers, and then moving aggressively to acquire one for the Bench.**

## 8. Future Funding

We expect the above future efforts will be funded via requests directly to the WIYN Board, science-PI contributions from within the consortium (e.g., for specific VPH gratings), and possibly through the submission of an ATI proposal in Fall 2004 for development of a large VPH gratings for use at large incidence angles and medium spectral resolutions.

## A. Throughput Budget of Existing System

We are using a good zeropoint measurement taken with SparsePak and the echelle in order 8, as analyzed by Westfall. The throughput measurement was made Feige 34 as observed on March 25, 2002 through fiber 52 of SparsePak and is converted to the on-axis and spatially-off axis (slit-edge) values using the vignetting function defined by dome flats, both for the central wavelength near 6687A. Note that in this echelle setup the peak efficiency is slightly redwards due to the blaze function. The efficiency on-axis is at 94% of this peak. Some small corrections for seeing effects still need to be done to account for light lost in the telescope focal plane (of order 4%) and in the spectrograph CCD focal plane due to a finite extraction aperture (of order 5%). The throughput is calculated taking into account the effective telescope aperture (i.e., including the secondary obstruction). We use a collecting area of 7.986 $m^2$, i.e. a 3.5m primary with a 17.1% central obstruction (in area).

Vignetting estimates come from Crawford's geometric spectrograph model using an excellent analytic approximation to the laboratory measurement of the encircled energy (EE) as a function of f/. (We adopted a Sersic function – see Figure 18.) This model matches the observed vignetting profile to better than 10%; it should contain all significant geometric obstructions in the spectrograph, including the foot, finite collimator, grating, and camera objective. (For SparsePak, there is no vignetting from the toes and filter. The camera enclosure vignetting should be minimal or non-existent for the camera back-distance used in this setup. Based on a visual inspection of a bright f/5 beam in the systems [D. Harmer, C. Harmer, and M. Bershady, Feb 12 2003], there are no other obstructions in the system. C. Harmer and M. Bershady determined that the first camera element [objective] is the limiting stop in the camera.) Filter, grating, and CCD efficiencies comes from the Hydra/Bench manual.

This is an ongoing exercise, but has been updated as of April 08 2003. Recent updates include more realistic telescope and collimator reflectance, final geometric model vignetting values for spectrograph, final aperture corrections (telescope and CCD focal planes), and CCD system losses including detector QE and dewar reflection.

We note that the current work was done by K. Westfall, a graduate at UW-Madison, under supervision of M. Bershady, in part as at course requirement for Astronomy 920 in Spring 2003.

**TABLE A1. BENCH SPECTROGRAPH THROUGHPUT BUDGET**

**Setup: Echelle, order 8, cwl=669nm, BSC, SPK**

| COMPONENT | | | ESTIMATE QUALITY | ON-AXIS | OFF-AXIS |
|---|---|---|---|---|---|
| **Top-End "Feed"** | | | | | |
| | **atmosphere** | | | | |
| | | transmission | reasonable estimate: 1.12 airmass at 6687A | 0.90 | |
| | **telescope (3 mirrors)** | | | | |
| | | reflectance | rough estimate / variable: assume 0.88-0.89 per surface | 0.69 | |
| | **fiber** | | | | |
| | | throughput | good estimate in lab | 0.88 | |
| | | ``slit losses" | high-fidelity aperture correction | 0.91 | |
| **Top-End subtotal** | | | | **0.50** | |
| **Spectrograph** | | | | **On-axis** | **Off-axis** |
| | **toes** | | | | |
| | | filter transmission | good estimate? (X19) | 0.90 | |
| | | vignetting | good estimate from model | 1.0 | 1.0 |
| | **collimator** | | | | |
| | | reflectance | ok estimate | 0.89 | |
| | | vignetting | good estimate from model | 0.98 | 0.89 |
| | **pupil obstructions (foot)** | | | | |
| | | vignetting | good estimate from model | 0.93 | 0.92 |
| | **grating** | | | | |
| | | efficiency | peak from Hydra Manual times theoretical blaze fnc for 6687A | 0.32 | (0.50x0.63) |
| | | vignetting | good estimate from model | 0.93 | 0.86 |
| | **camera** | | | | |
| | | transmission | *unknown* | $T_{Cam}$ | |
| | | vignetting | good estimate from model | 0.81 | 0.54 |
| | **ccd system** | | | | |
| | | window & det. QE | Hydra Manual | 0.80 | |
| **Spectrograph subtotal** | | | | **0.14** $T_{Cam}$ | **0.078** $T_{Cam}$ |
| **Spectral Extraction** | | | high fidelity measurement | **0.975** | |
| **Total** | | | | **0.069** $T_{Cam}$ | **0.038** $T_{Cam}$ |
| **Measurement** | | | | **0.054** | **0.028** |
| **Implied** $T_{Cam}$ | | | | **0.78** | **0.74** |

## B. Expected Gains In Off-Axis System

Figures 10-19 present the result of the analysis of gains in an upgraded Bench Spectrograph system with an off-axis collimator, and the tradeoffs between throughput gains and spectral resolution losses as a function of the off-axis collimator focal length.

Refer to Figures 10 and 11, respectively, for a comparison of gains in throughput vs changes in spectral resolution as a function of decreased collimator focal length. With a 800mm fl collimator, mean gains across the slit increase to 60%; gains for end fibers increasing to over a factor of 2; but geometric spectral FWHM for 200 and 300 $\mu$m diameter fibers remains under 1.5 pixels and 2 pixels, respectively, for the highest resolution setups. *The increased magnification in the spectrograph which results from a shorter collimator focal length will not contribute significantly to the delivered monochromatic image size for the smallest fibers and the highest resolution spectrograph configurations.* The proposed change in magnification with the shorter collimator is less than the difference between red and blue fiber diameters; some programs using blue fibers can take advantage of this and switch to red fibers if necessary. Figure 19 shows the light lost at the "top-end" by switching from blue to red fibers for stellar sources in typical seeing is significantly less than the gains from going to a faster collimator.

In this analysis it is assumed here that the transmission losses in the triplet corrector are won back by an LLNL overcoating on the off-axis collimator. So what is computed here are purely the increases in the throughput due to decreases in vignetting in the system. These decreases include the absence of a foot obstruction and a shorter collimator-grating and collimator-camera distances (grating-camera distances are the same as the existing system).

The calculations use a modified version of Crawford's Bench GUI which allow control over the location of various optical surfaces. While this program is not a ray-trace, it is a complete geometric model, uses an accurate beam profile, and is completely independent of ZEMAX. Because we cannot yet use a realistic beam in ZEMAX, the vignetting calculations with this GUI should be more accurate.

In all cases presented here we assume that the pupil is at a distance from the collimator equivalent to the collimator focal-length. In Appendix C we consider the case of varying the pupil distance assuming a fixed collimator focal length of 800mm.

## C. Optimum Pupil Placement

We have taken a preliminary look at the optimum placement of the pupil in an off-axis-collimator system. What placement minimizes the vignetting? The analysis assumes a collimator focal length of 800mm and that the grating is placed at this distance from the (off-axis) collimator. This focal length may not be optimal, but it is close. All of the modeling was done with Crawford's geometric model, so it uses the real fiber beam profile.

As Figures 20 to 22 show, the optimum pupil distance for this configuration depends on the grating-camera distance ($D_{gc}$), and hence the camera-collimator angle ($\theta_{cc}$). For the two cases of $\theta_{cc} = 11^\circ$ (echelle) and $\theta_{cc} = 30^\circ$ (all other gratings), $D_{gc}$ = 1022mm and 390mm, respectively. In both cases the optimum distance is slightly in front of the camera. Considering the two $\theta_{cc}$, the best pupil distance is roughly 12500mm, or about 450mm beyond the grating.

The pupil-placement has a second-order effect on the vignetting compared to the off-axis collimator, grating placement, and shorter collimator focal length. However, it's still important, so we will consider this carefully in the final design. The final choice must also consider the back-distance of the camera when used with VPH gratings. Because $D_{gc}$ can be shorter with VPHs (possibly as short as 200mm – half the distance used with the current low-order gratings), the optimum pupil distance may be smaller than what we have currently estimated. On the other hand, if the VPHs can be made tall enough, we can move the camera back to the pupil at 1250mm and not suffer significant vignetting from the grating. These are the type of design trades we will have to determine.

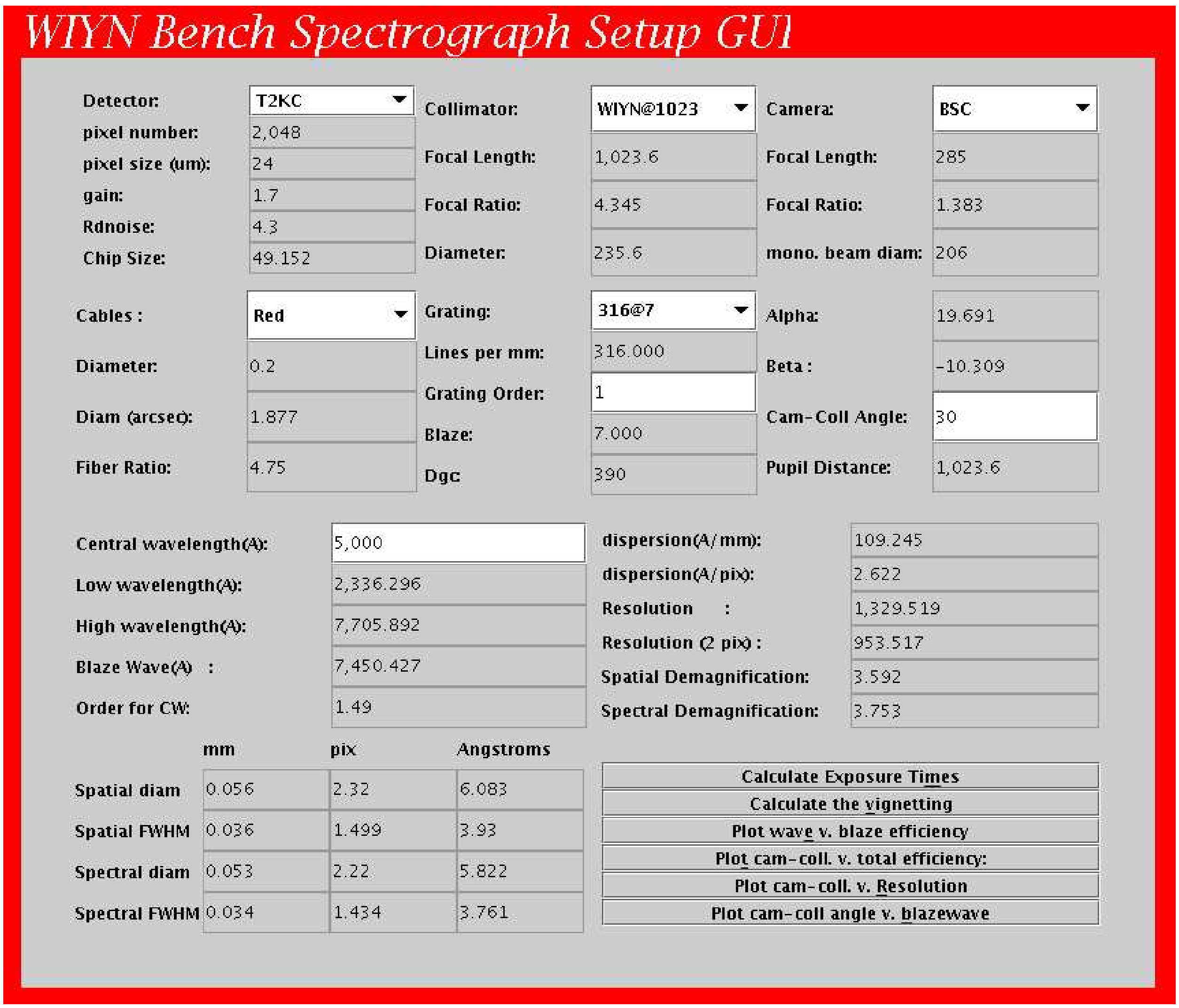



Fig. 1.— The new Bench GUI. Note the many plotting and diagnostic features.

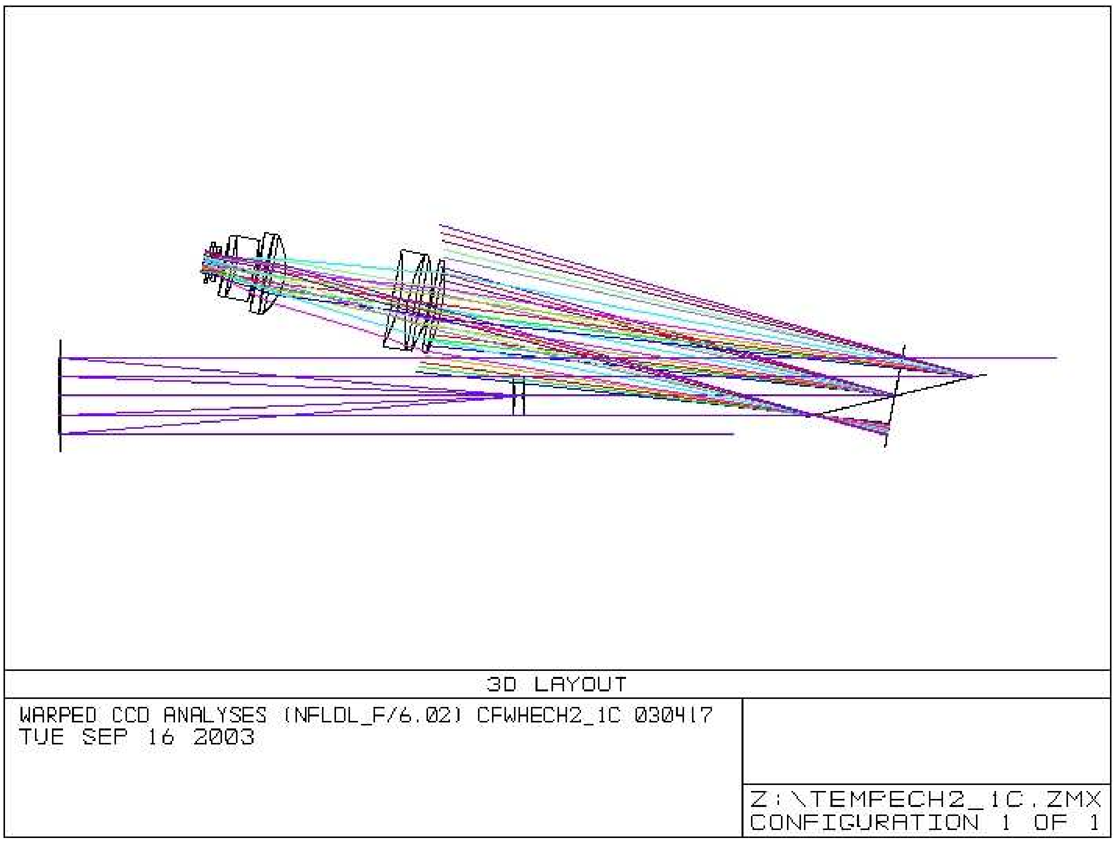



Fig. 2.— Existing on-axis system with a uniform f/6.02 beam with echelle in order 8 centered at 669nm as viewed looking down at the spectrograph. Color coding is by wavelength. Note vignetting at grating and camera. [Credit: C. Harmer, private communication.]

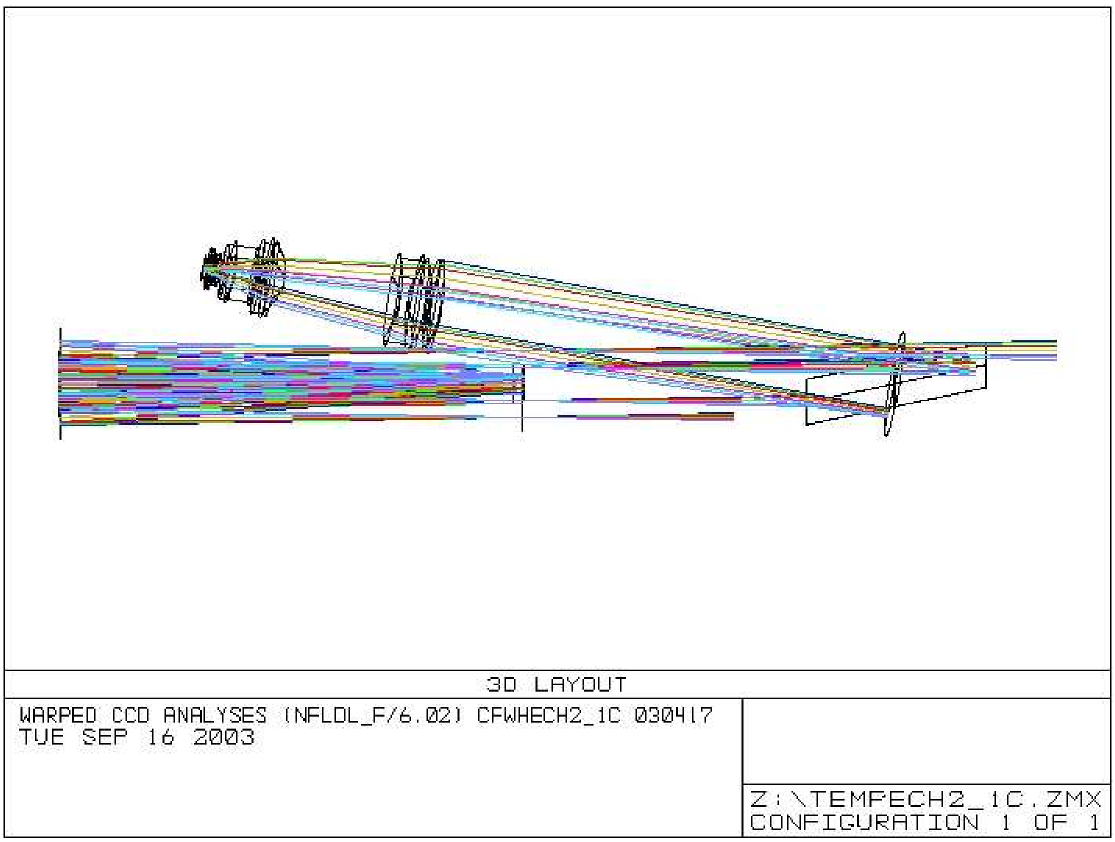



Fig. 3.— Existing on-axis system with a uniform f/6.02 beam with echelle in order 8 centered at 669nm as viewed looking across the spectrograph. Color coding is by field. Note vignetting at grating and location of pupil at the fiber feed. [Credit: C. Harmer, private communication.]

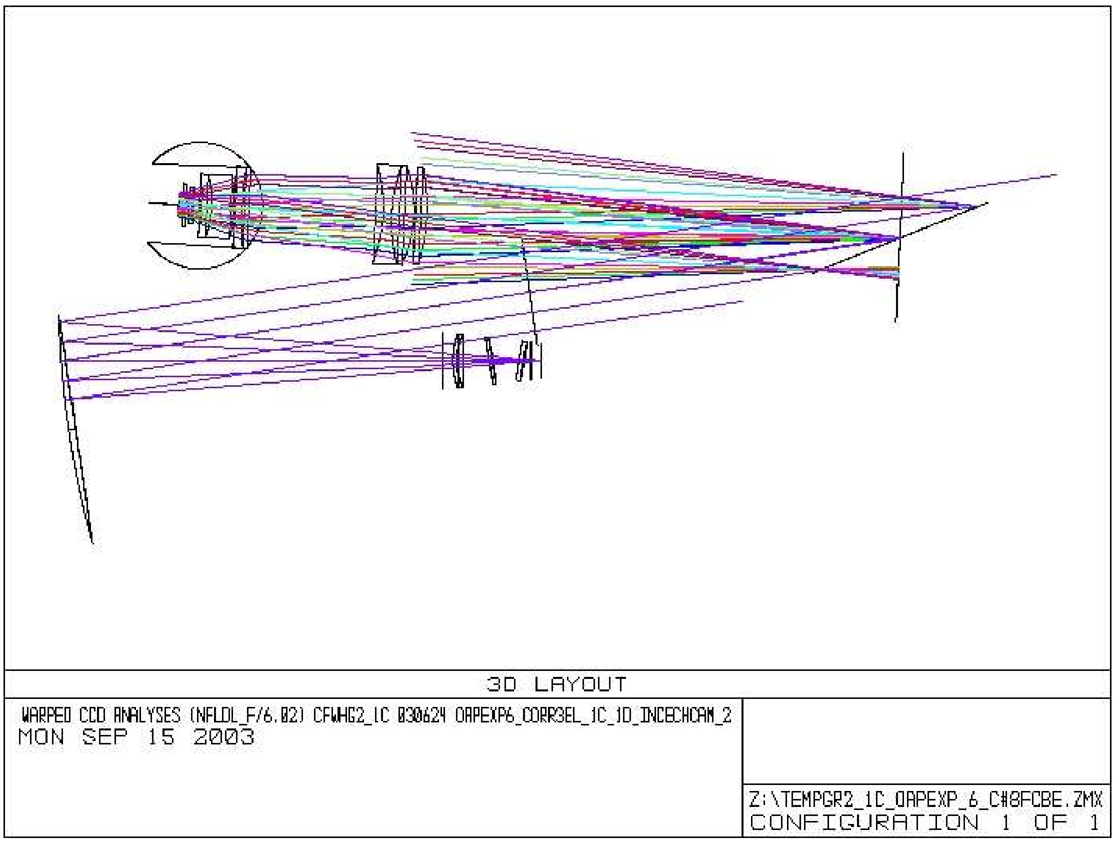



Fig. 4.— Proof-of-concept off-axis collimator system for echelle in order 8 centered at 669nm (same orientation as Figure 2 – color coding is by wavelength). Note tilted corrector–field-lens group in front of fiber feed. [Credit: C. Harmer, private communication.]

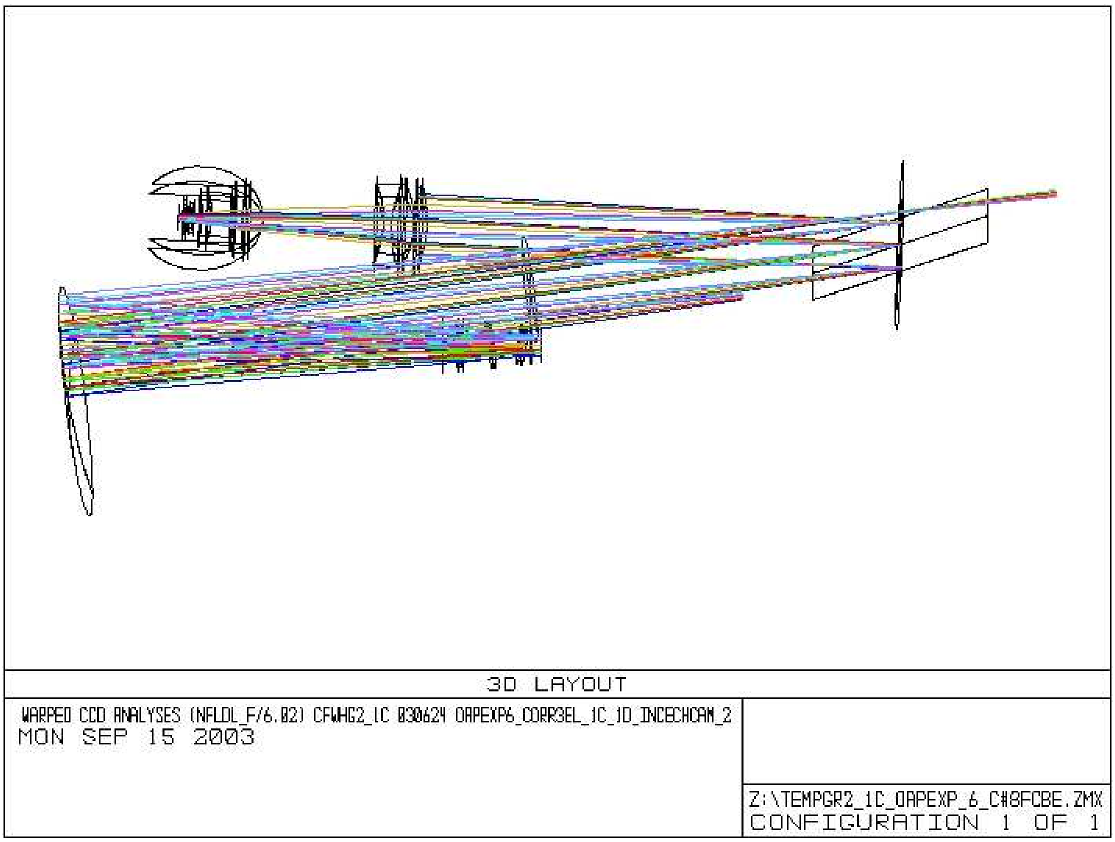



Fig. 5.— Proof-of-concept off-axis collimator system for echelle in order 8 centered at 669nm (same orientation as Figure 3 – color coding is by field). Note location of pupil at the grating. [Credit: C. Harmer, private communication.]

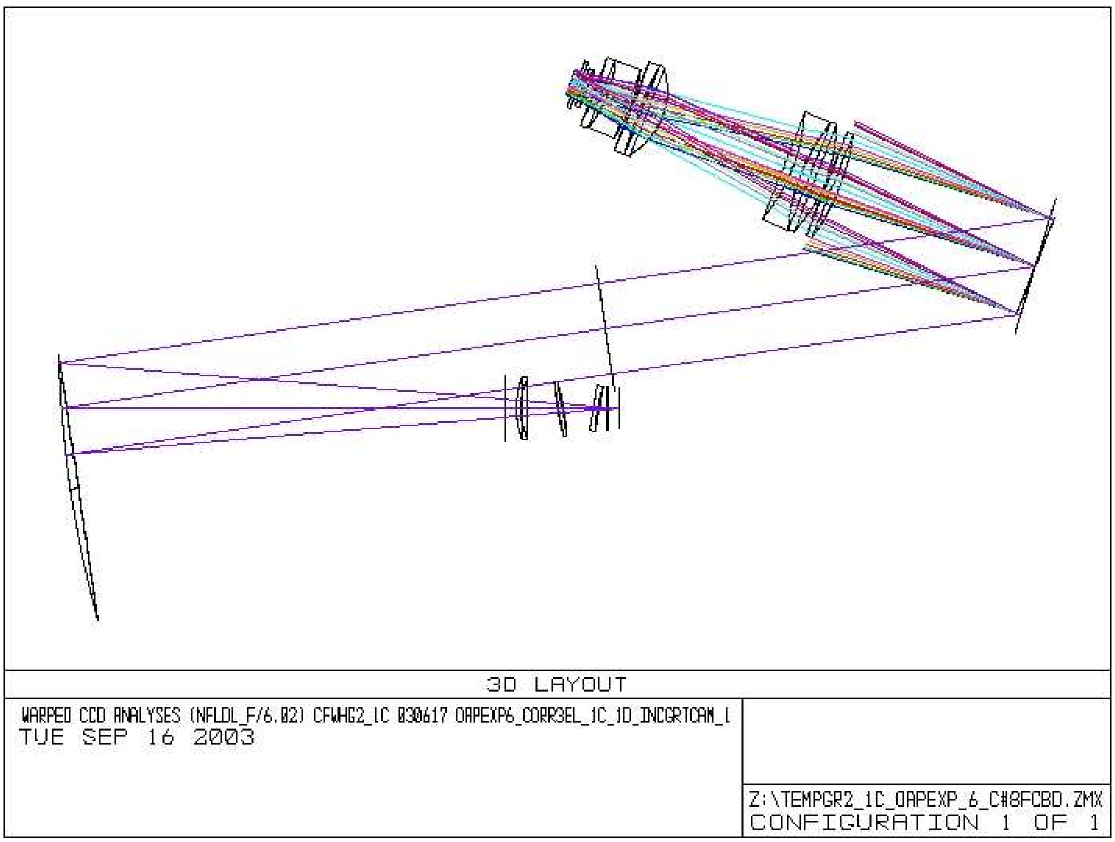



Fig. 6.— Proof-of-concept off-axis collimator system for low-order grating same orientation as Figure 2 – color coding is by wavelength). Note reduced grating-camera for the larger camera-collimator angle of 30°. [Credit: C. Harmer, private communication.]

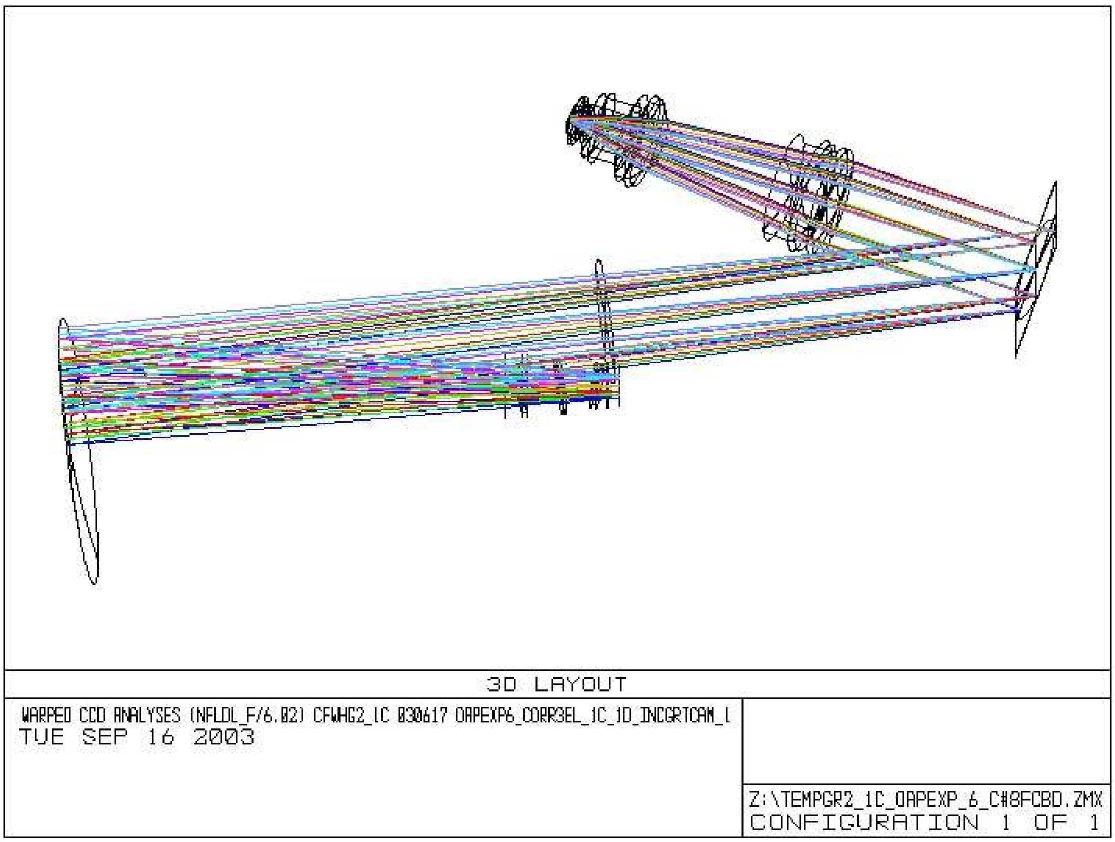



Fig. 7.— Proof-of-concept off-axis collimator system for low-order grating (same orientation as Figure 3 – color coding is by field). Note location of pupil at the grating. [Credit: C. Harmer, private communication.]

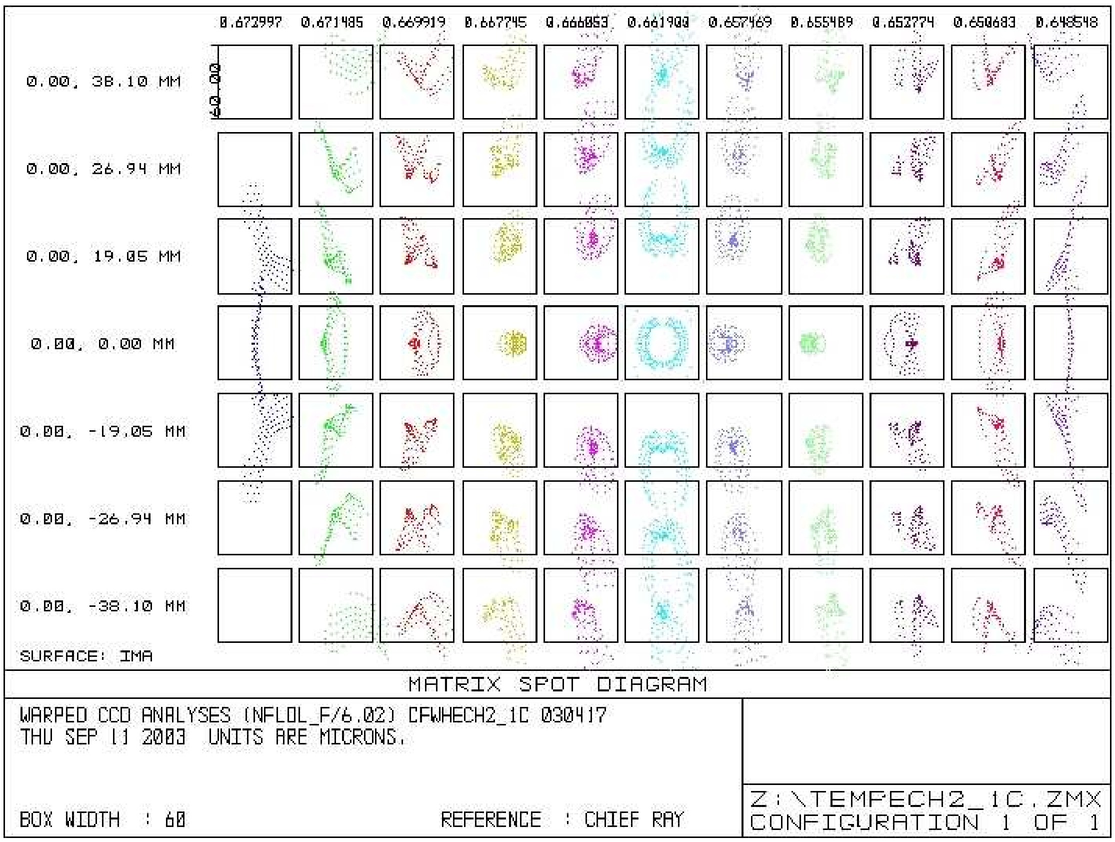



Fig. 8.— Matrix spot diagrams for existing system for the echelle order 8 centered at 669nm. Boxes are 60 microns (2.5 pixels for the current CCD). The x-axis is in the dispersion dimension, with wavelengths listed in microns at the top. The y-axis is the spatial dimension, with offset from the slit center listed in mm. [Credit: C. Harmer, private communication.]

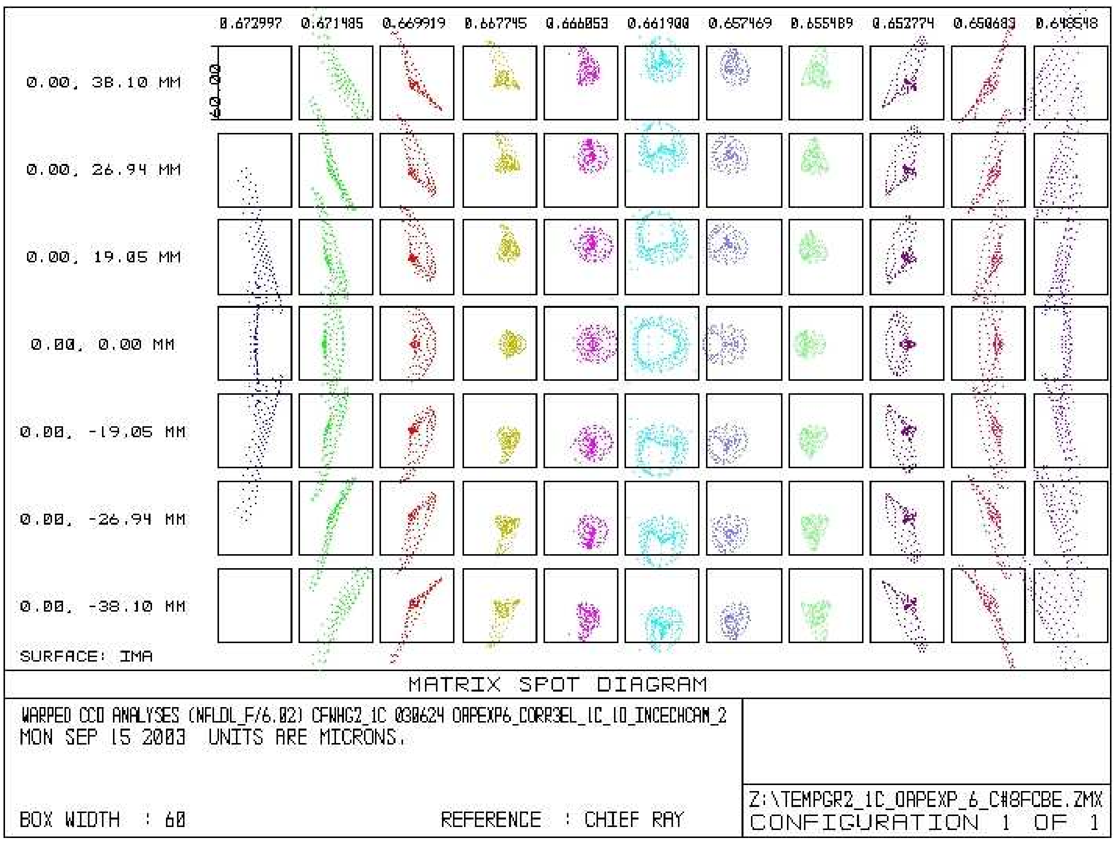



Fig. 9.— Matrix spot diagrams for off-axis system for the echelle order 8 centered at 669nm. Boxes are 60 microns (2.5 pixels). Note image quality is better in the off-axis system because of the added surfaces from the corrector. [Credit: C. Harmer, private communication.]

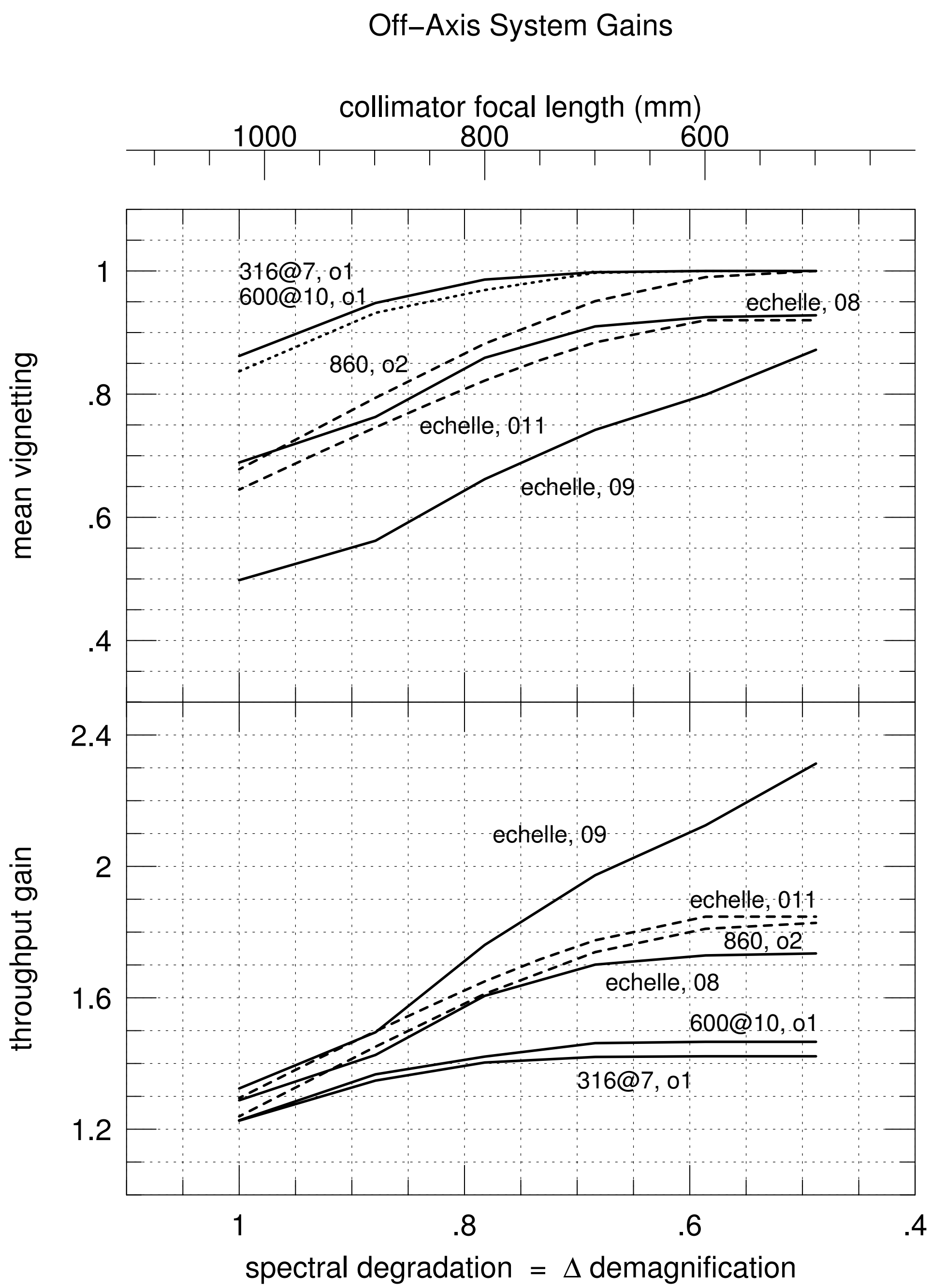



Fig. 10.— Mean vignetting along slit for the WIYN Bench Spectrograph and an off-axis collimator as a function of collimator focal-length (top scale), or demagnification (bottom scale). The demagnification is normalized to the current collimator focal-length of 1023mm. The bottom panel shows the mean vignetting for the off-axis collimator normalized by the mean vignetting for the current, on-axis collimator. Results are shown for a variety of spectrograph setups (labeled). The echelle order 11, 850 order 2, and 316 order 1 setups are close to on-order. The echelle order 8 and 9 are at the blue and red half-order points respectively (both are roughly at order 8.5).

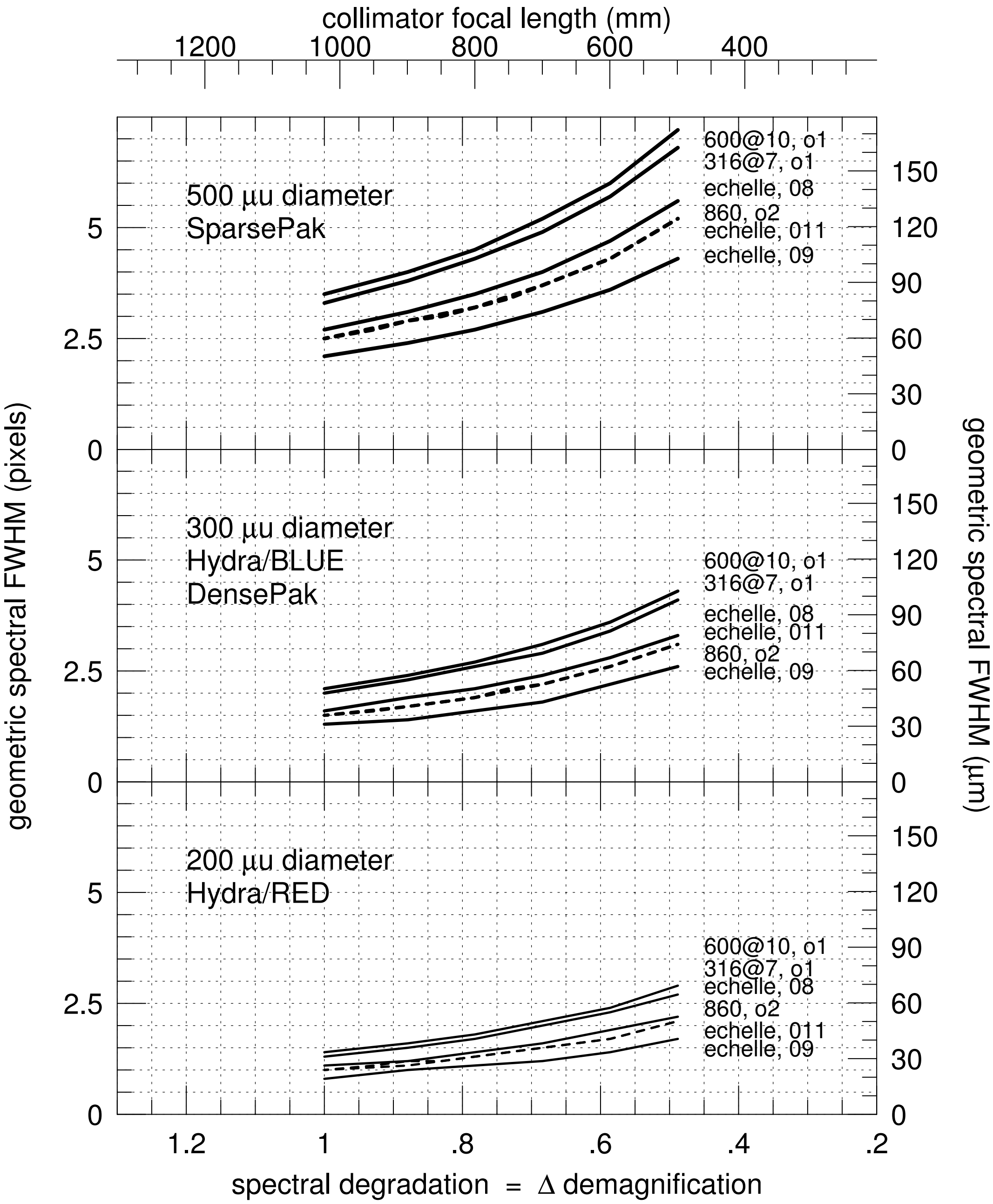



Fig. 11.— Geometric spectral FWHM for the WIYN Bench Spectrograph as a function of collimator focal-length (top scale), or demagnification (bottom scale). The demagnification is normalized to the current collimator focal-length of 1023mm. The FWHM is shown for 3 fiber sizes: 200 um (Hydra Red), 300 um (Hydra Blue and DensePak), and 500 um (SparsePak).

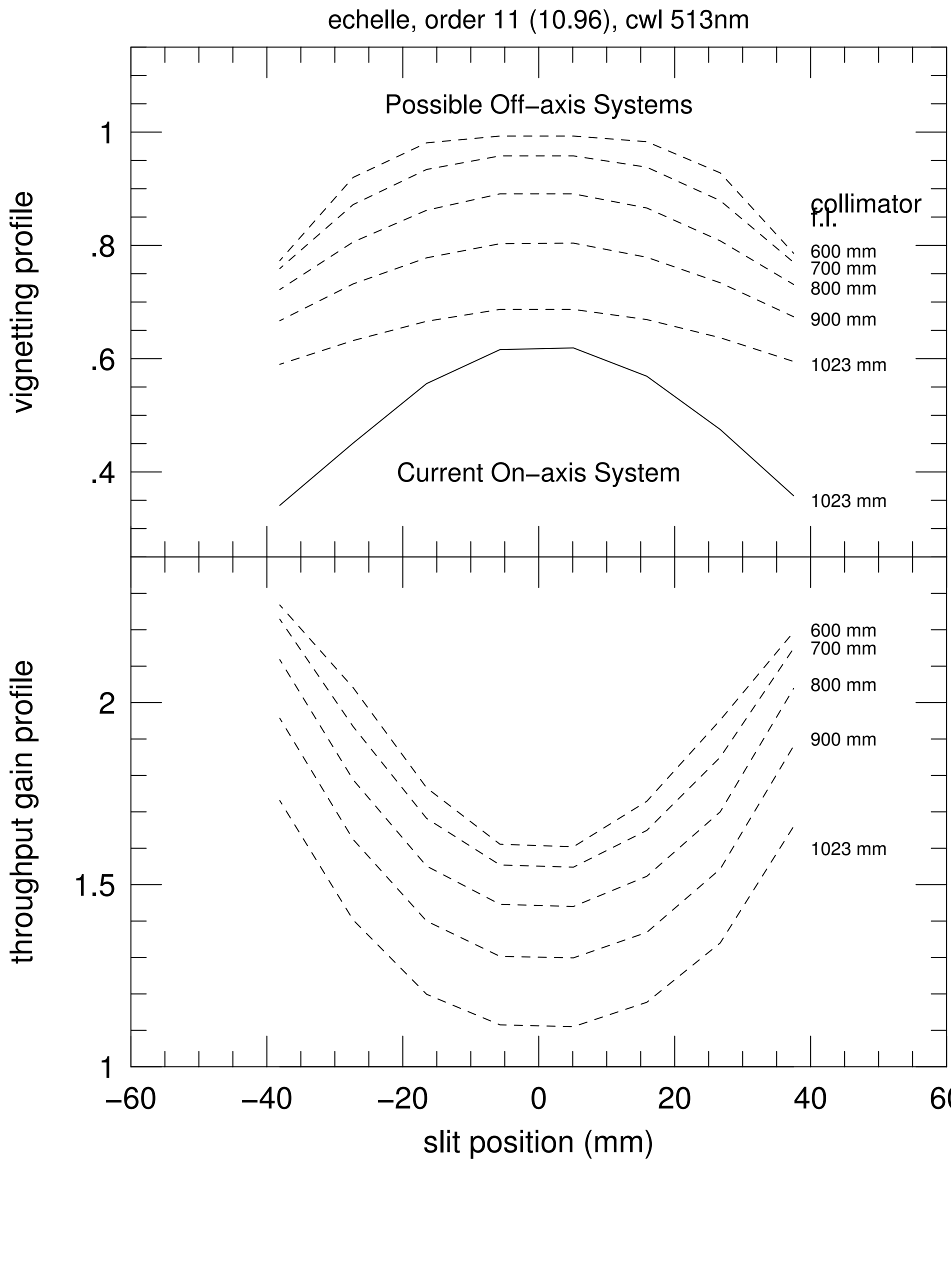



Fig. 12.— Slit functions for one of six setups: echelle, order 11 (10.96), cwl 513 nm: "on-order" setup. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

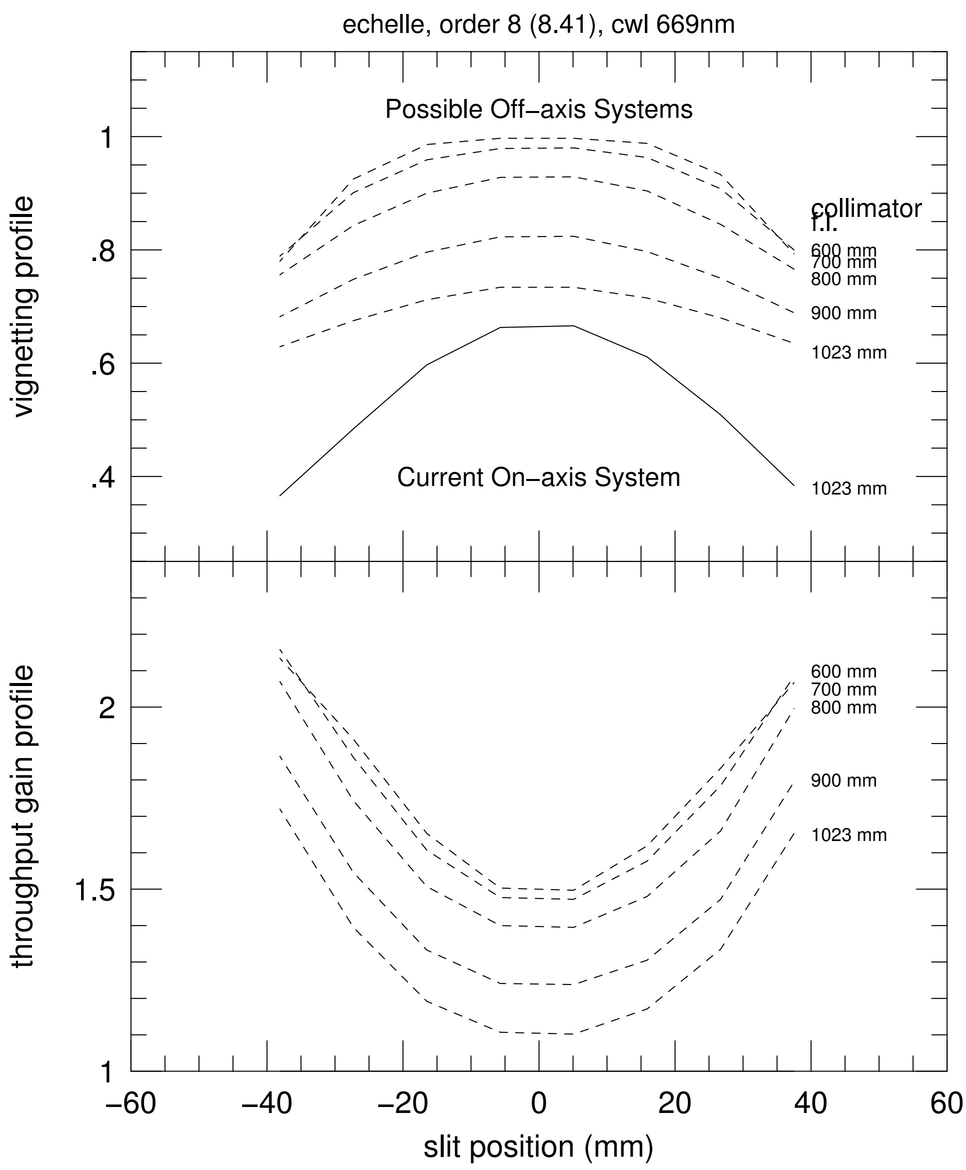



Fig. 13.— Slit functions for one of six setups: echelle, order 8 (8.41), cwl 669 nm: "off-order" setup up - blue. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

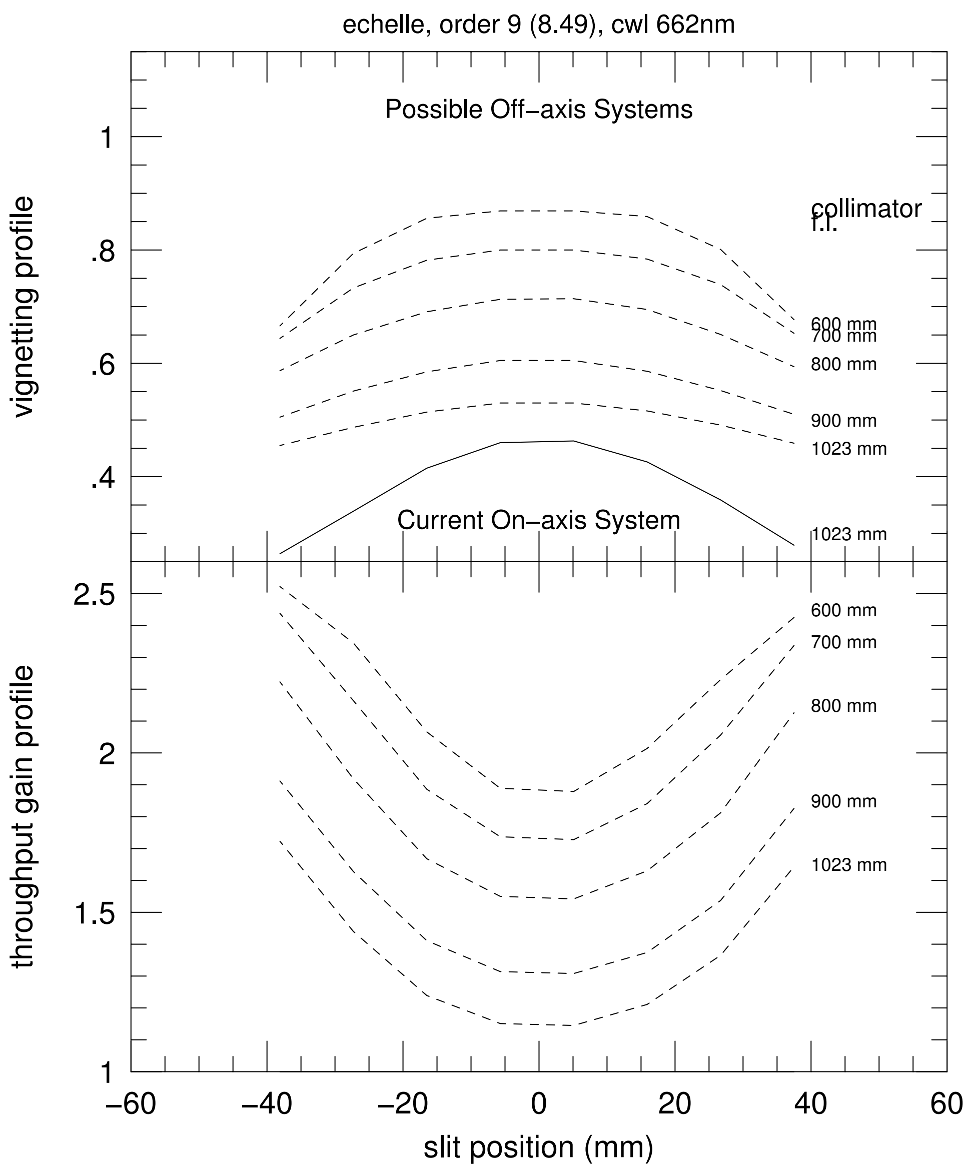



Fig. 14.— Slit functions for one of six setups: echelle, order 9 (8.49), cwl 662 nm: "off-order" setup up - red. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

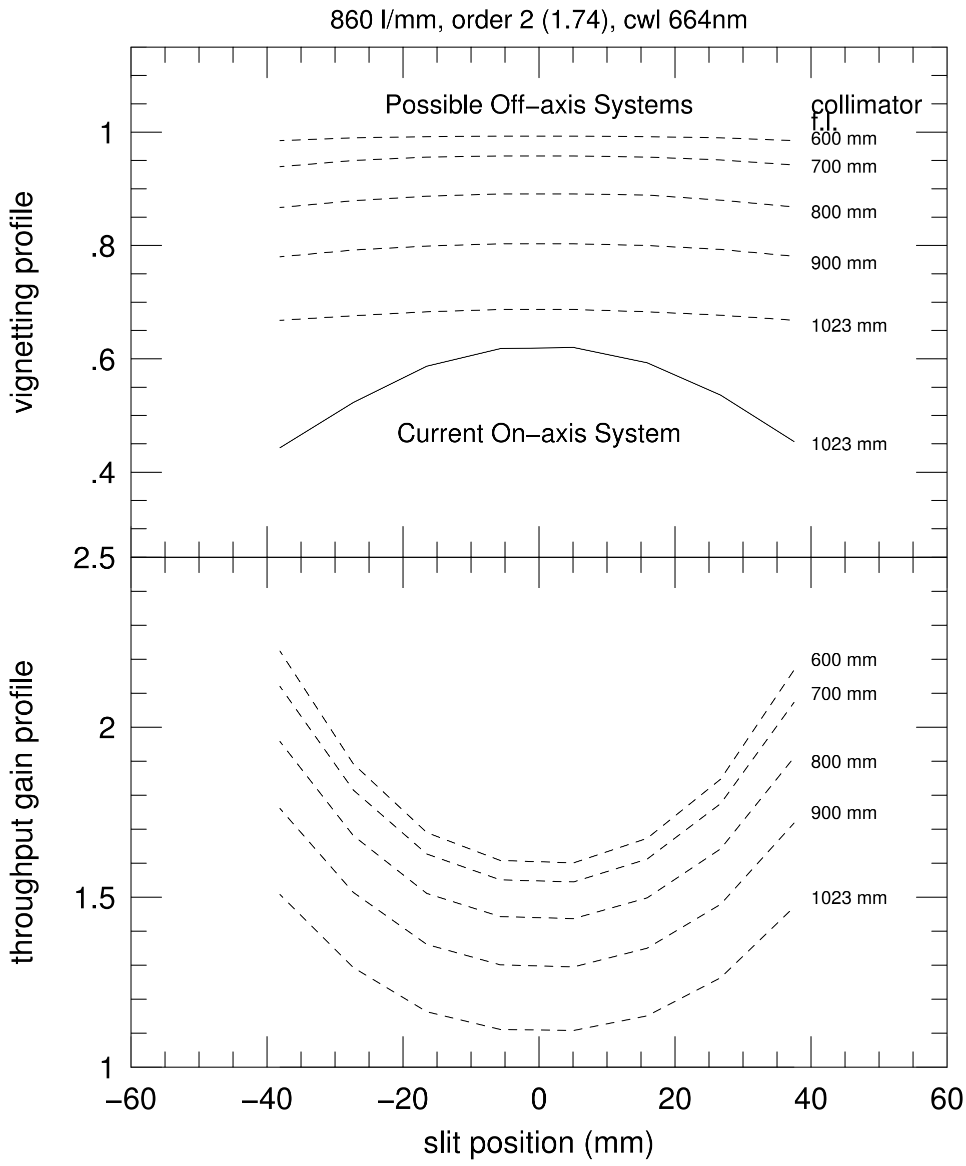



Fig. 15.— Slit functions for one of six setups: 860@30.9, order 2 (1.74), cwl 664 nm: "on-order" setup. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

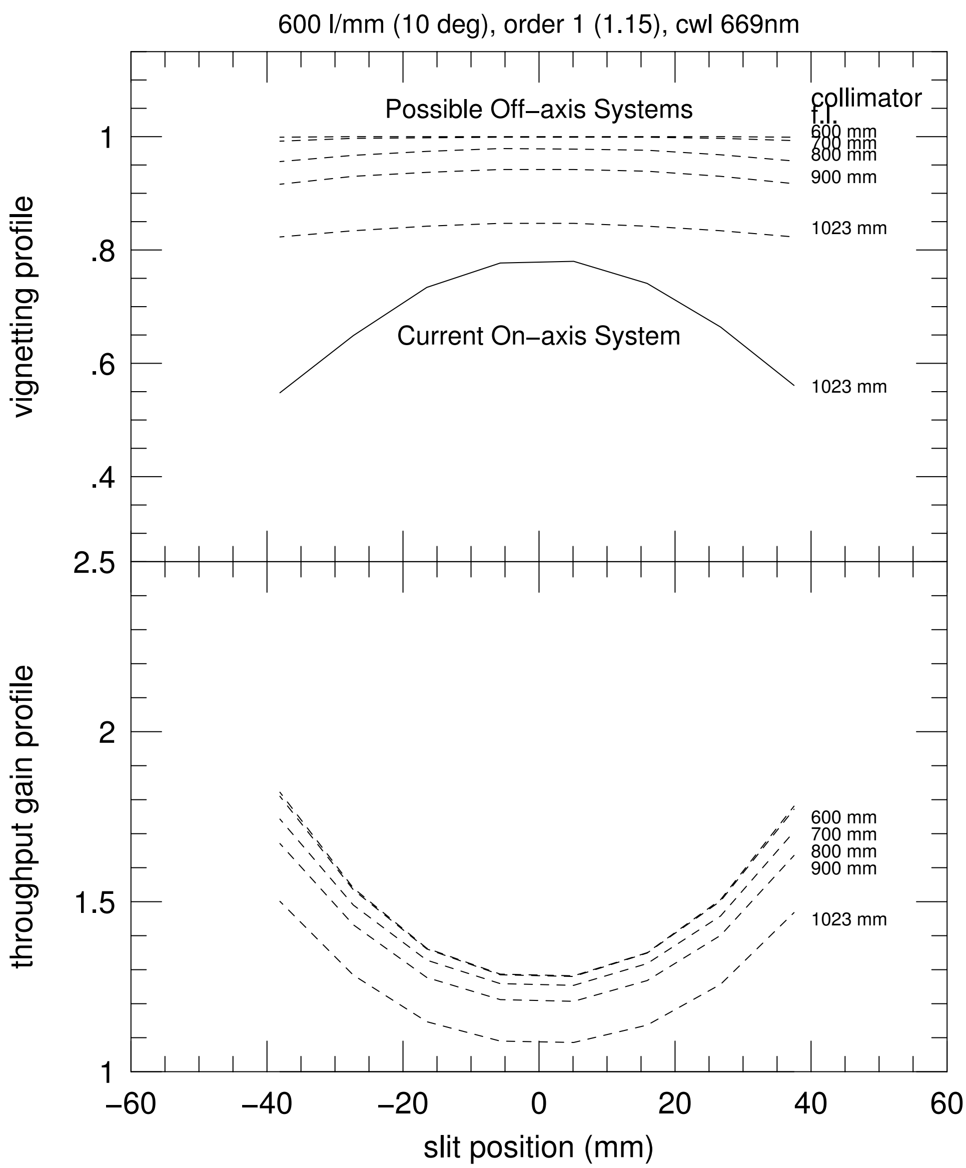



Fig. 16.— Slit functions for one of six setups: 600@10, order 1 (1.74), cwl 664 nm: "on-order" setup. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

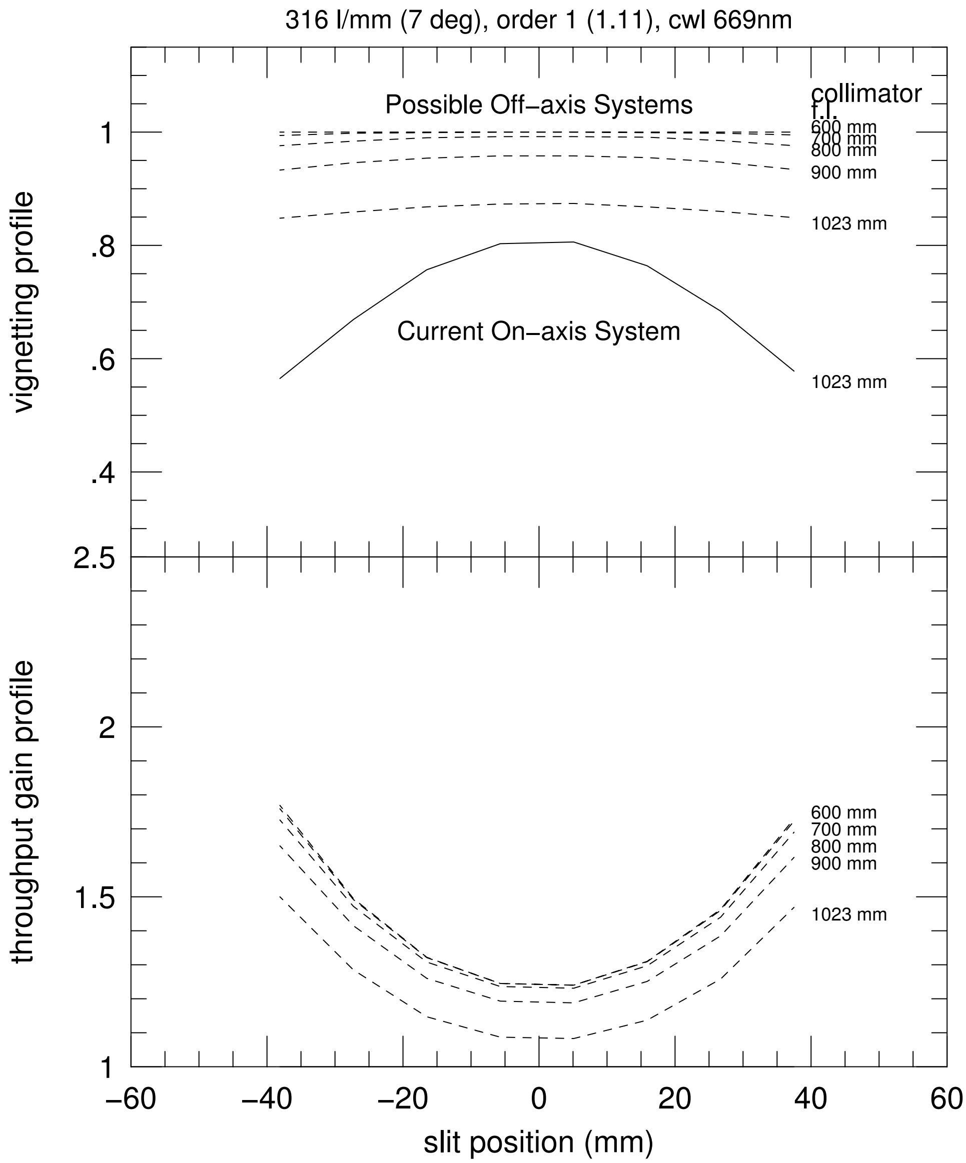



Fig. 17.— Slit functions for one of six setups: 316@7, order 1 (1.11), cwl 669 nm: "on-order" setup. For each setup the slit function is shown for the current collimator (f.l. 1023 mm), and for 5 off-axis collimators with f.l. of 1023, 900, 800, 700, and 600 mm.

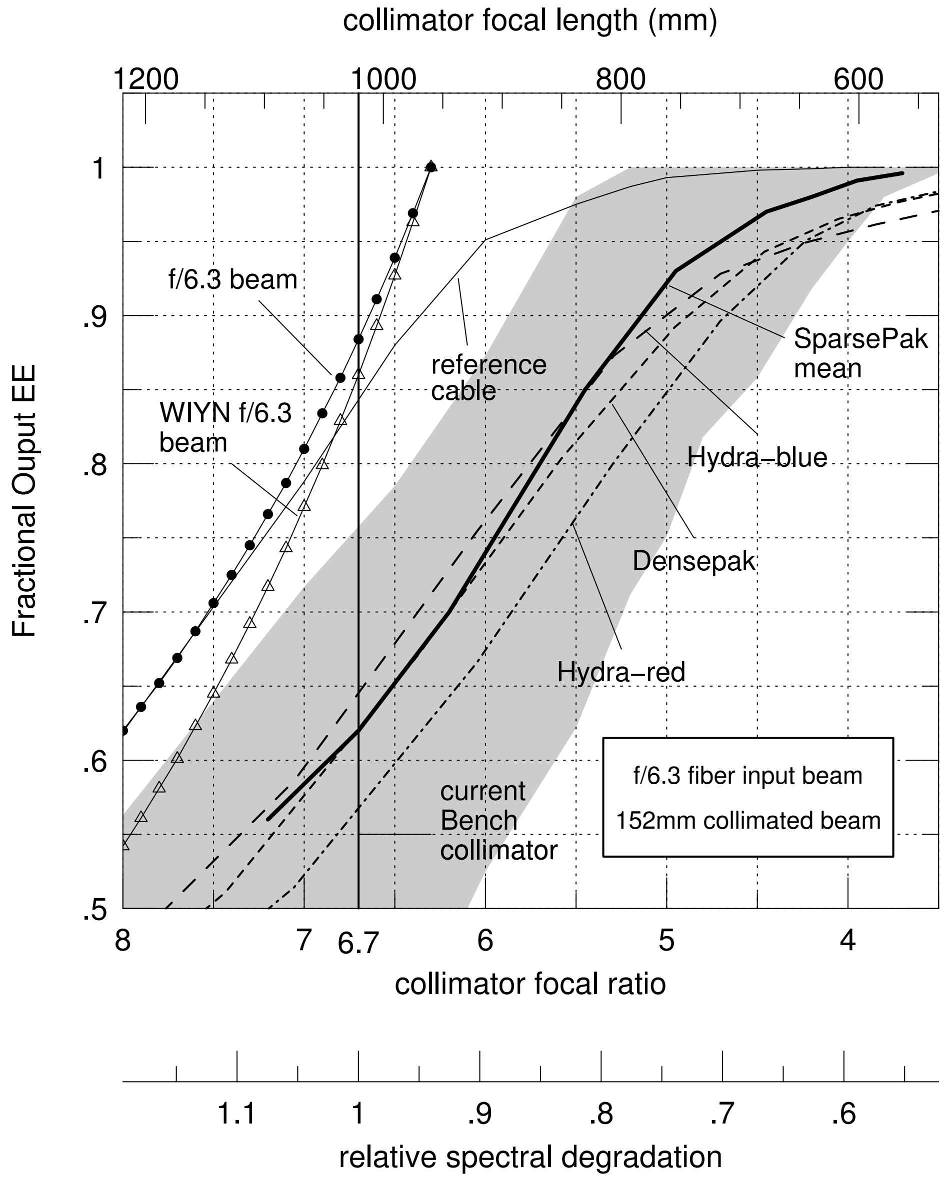



Fig. 18.— Fractional output encircled energy (EE) from fibers as a function of WIYN Bench Spectrograph collimator focal ratio (bottom axis) or collimator focal length (top axis). This assumes a 152mm collimated beam diameter and that all fibers are fed with a f/6.3 beam. The mean SparsePak beam profile (thick, solid line) the range for the 13 measured SparsePak fibers (grey shaded area), and reference cable (thin solid curve) are based on laboratory measurements using the f/6.3 input beam shown as a thin solid curve with solid circles. Comparable curves, as measured *on the telescope* for Densepak (300$\mu$m fibers), and the two Hydra cables (with "blue," 310$\mu$m and "red," 200$\mu$m fibers), are shown for comparison (private communication, P. Smith & C. Conselice). These measurements use the WIYN f/6.3 beam (accounting for the central obstruction), shown as the thin solid curve with open triangles. The very bottom scale (relative spectral degradation) indicates how the spectral resolution of the Bench would alter (worst case) due to changes in system demagnification as a function of changes in the collimator focal length at fixed camera focal length. The current Bench has a f/6.7 collimator for a 152mm collimated beam. This figure illustrates the effects of FRD on light losses for the Bench Spectrograph, and how optimization trades might be made between throughput and spectral resolution for redesign of the Bench Spectrograph collimator. [Credit: reprinted from Bershady et al. 2003.]

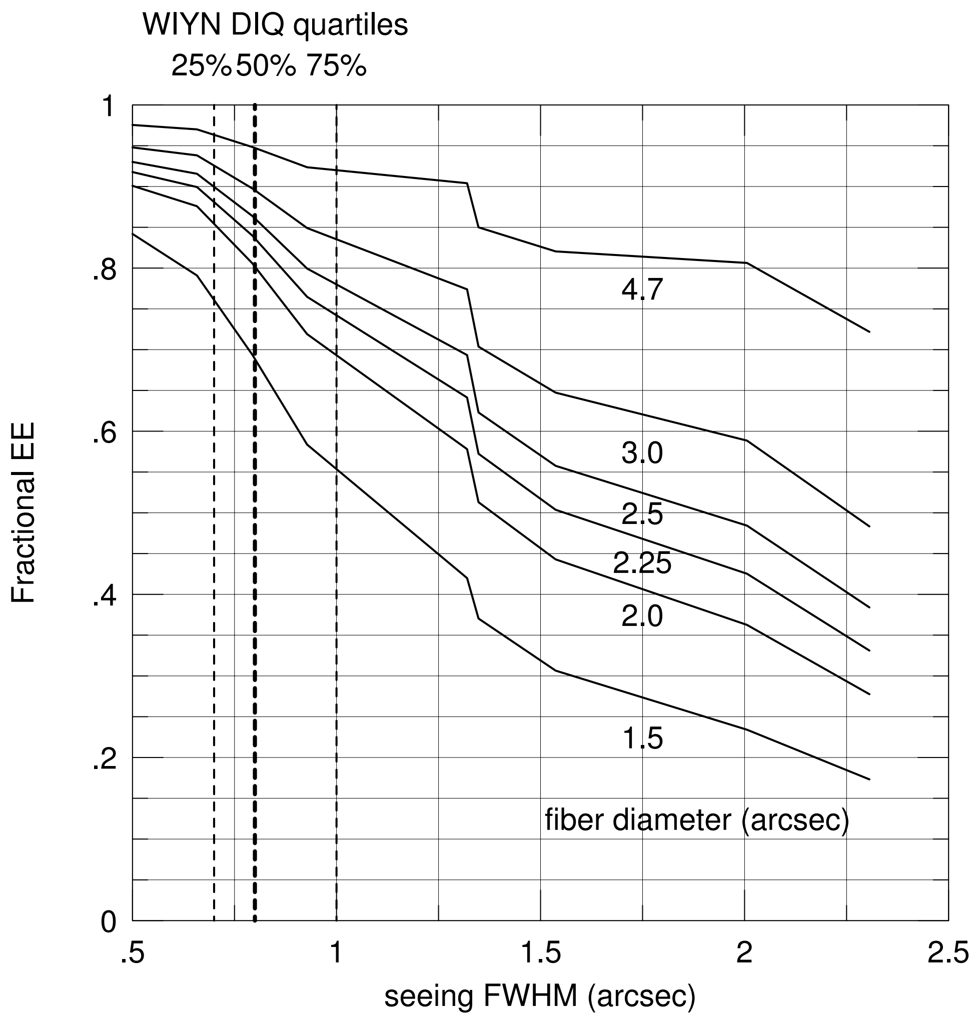



Fig. 19.— Encircled energy (EE) as a function of seeing FWHM for fibers of different diameters. Curves used measured PSFs from MiniMo data. Labeled are median and quartile DIQ over the past year (courtesy C. Corson). Note the small difference in EE (10-15%) for 200 and 300 $\mu$m fibers over typical seeing values.

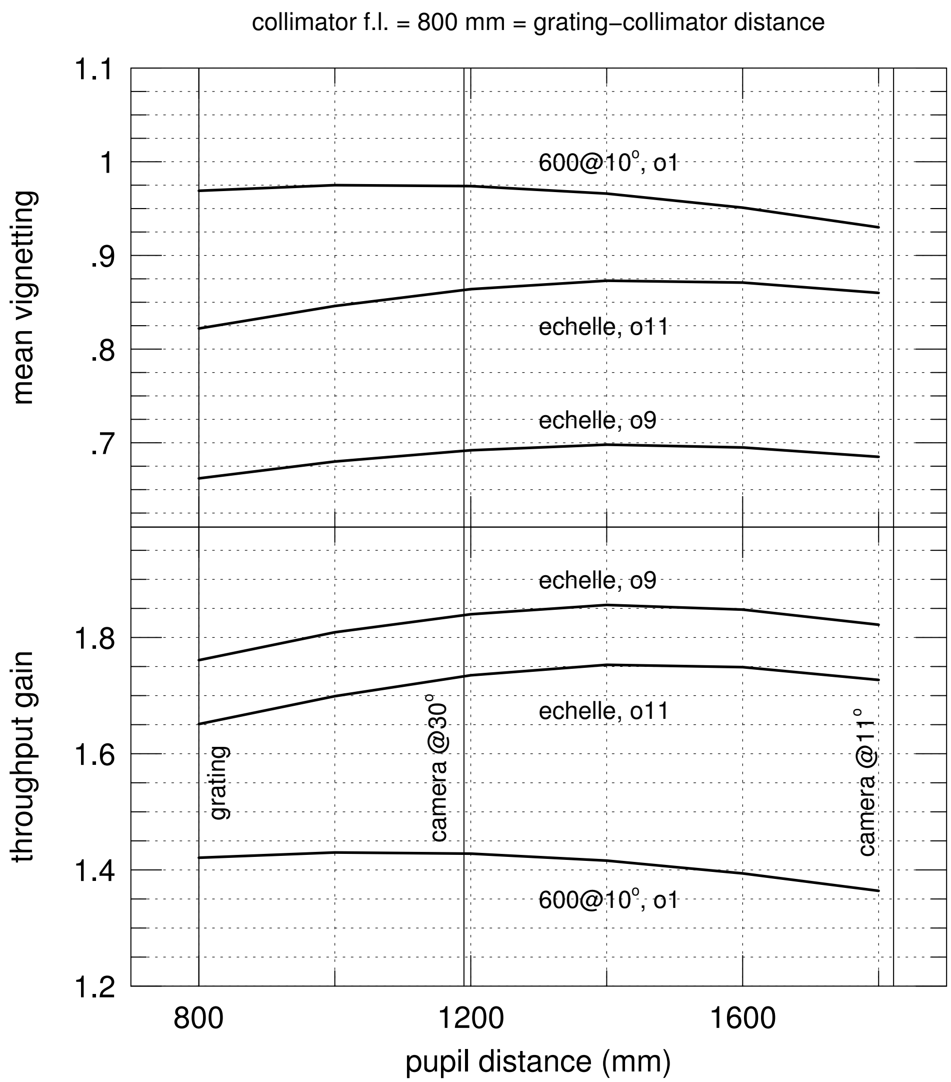



Fig. 20.— Mean vignetting and throughput gain as a function of pupil distance (from the collimator) for an off-axis system with an 800mm f.l. collimator and the grating placed at this distance from the collimator. Vignetting and throughput gains are calculated for on-order and off-order echelle configurations ($\theta_{cc} = 11°$) as well as a low-order grating configuration ($\theta_{cc} = 30°$) with different grating-camera distances. Peak gains, which are small, are had at intermediate distances between grating and camera distance in the echelle configuration. For these gratings a pupil distance of about 1250mm is a suitable compromise.

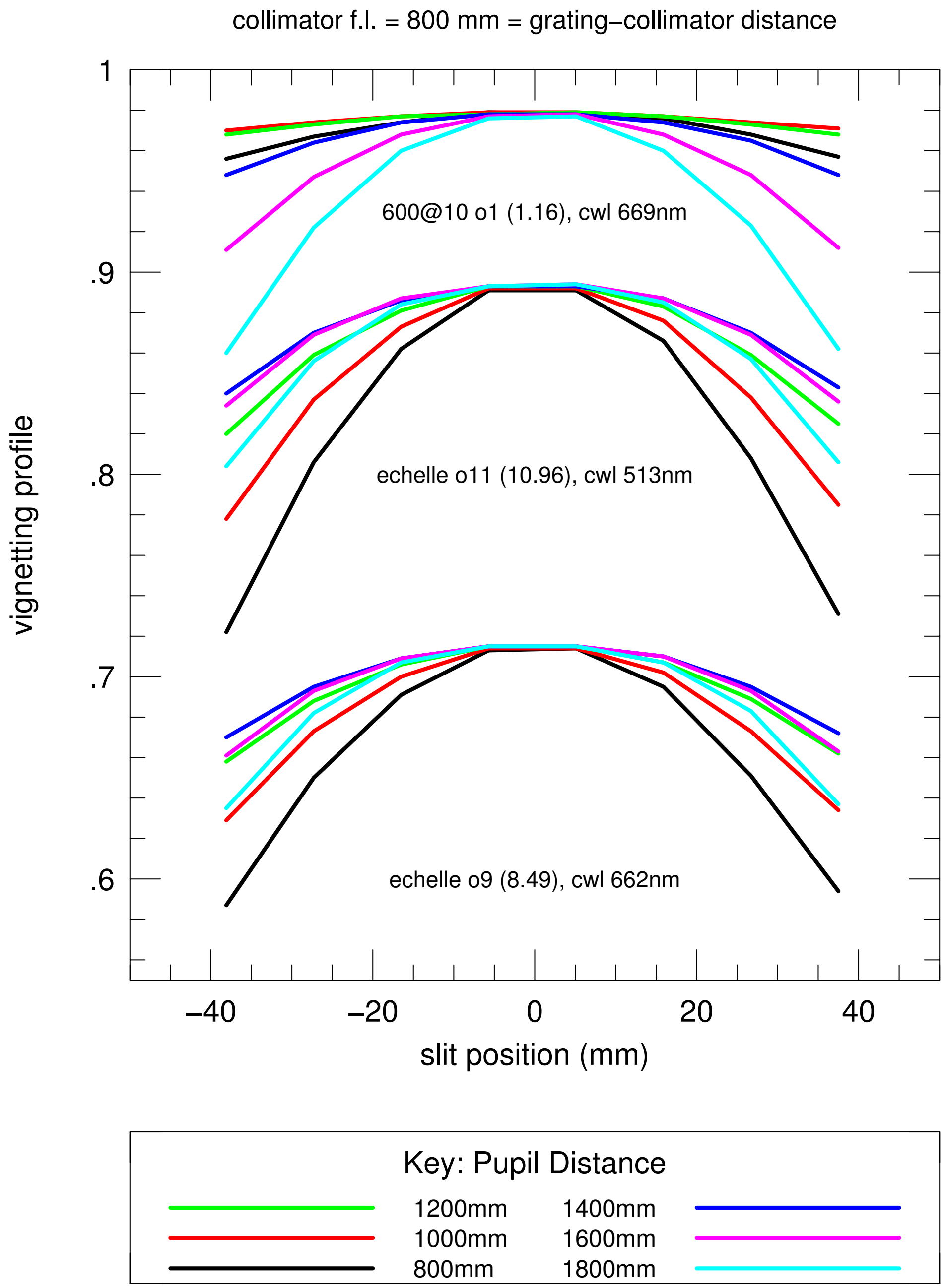



Fig. 21.— Vignetting profiles for the same grating configurations in Figure 20 as a function of pupil distance. The optimum compromise pupil distance is between the green and blue curves. Significant gains in vignetting can be made by adjusting the pupil distance, but these gains are second order compared to adjustments in the collimator focal length (cf. Figures 10,12-17).

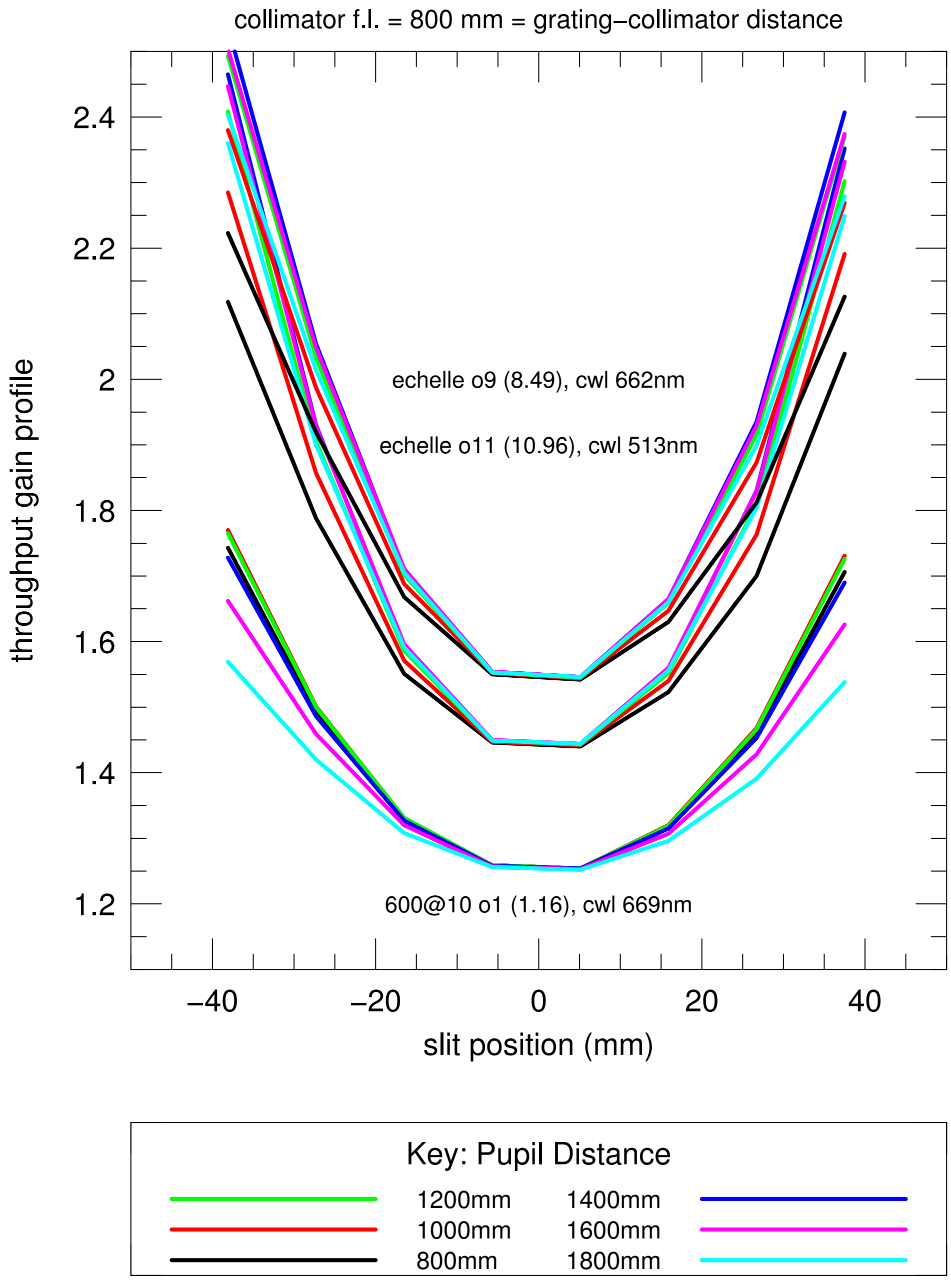



Fig. 22.— Throughput gain profiles for the same grating configurations in Figure 20 as a function of pupil distance. The optimum compromise pupil distance is between the green and blue curves. Significant gains in vignetting can be made by adjusting the pupil distance, but these gains are second order compared to adjustments in the collimator focal length (cf. Figures 10,12-17).

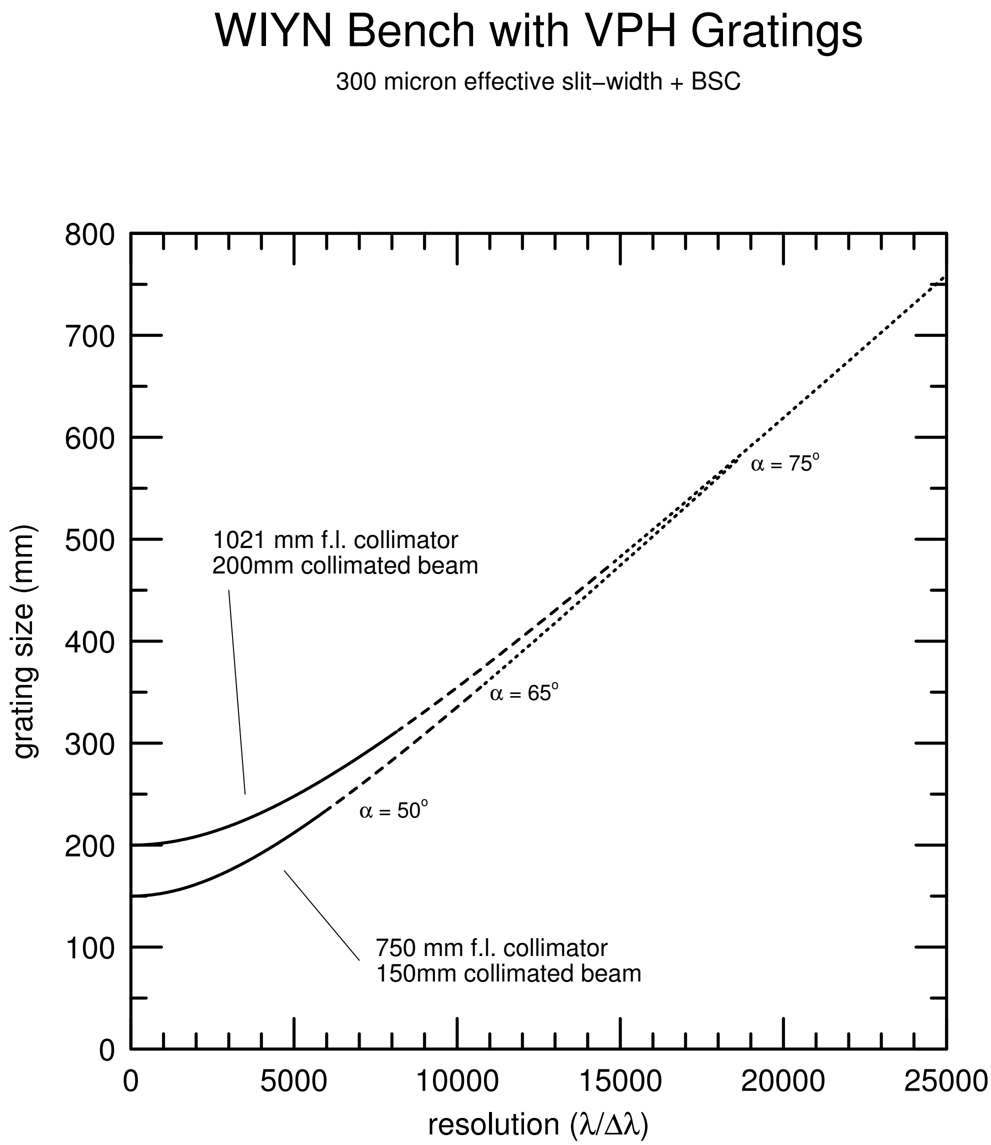



Fig. 23.— Required grating size in dispersion dimension for the Bench Spectrograph to reach a given spectral resolution with VPH gratings (or any grating used near Littrow). Incidence angles, $\alpha$, are indicated by line type. The relation is given for two assumed beam diameters of 200mm, which encloses 90% EE for the current collimator f.l. of 1021mm; or 150mm which encloses 90% EE for a collimator f.l. of 750mm. Despite the decrease in demagnification for a shorter collimator f.l., the ability to achieve larger $\alpha$ w/o vignetting a grating of a given size makes higher spectral resolutions easier to achieve with a shorter collimator f.l. *if* VPH gratings can be made efficient at these angles.

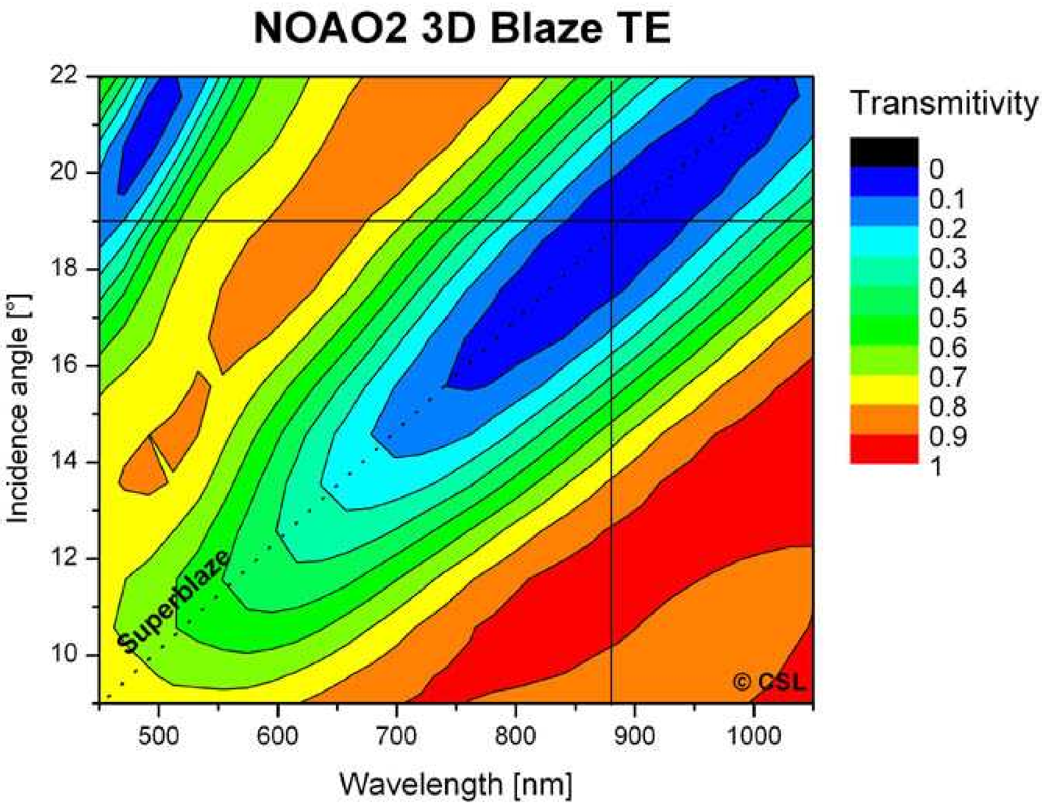



Fig. 24.— The throughput of the 740 l/mm VPH grating as a function of wavelength and grating angle as measured by the manufacturer, CSL, prior to substrate post-polishing and coating. Note high throughput of both 1st and 2nd order peaks. [Credit: S. Barden, private communication.]

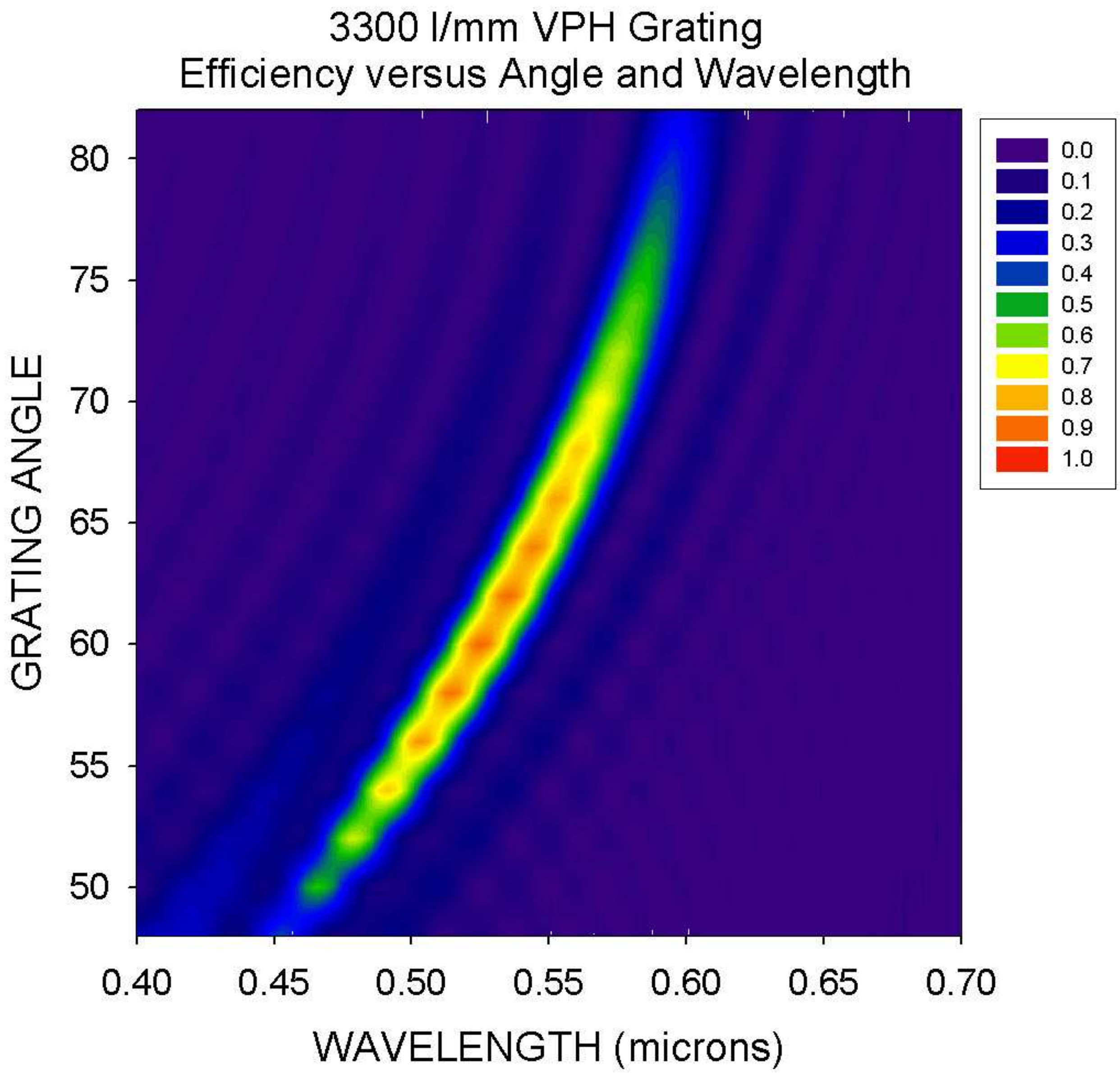



Fig. 25.— The predicted throughput of the 3300 l/mm VPH grating in first order as a function of wavelength and grating angle (S. Barden). Note the high throughput (>80%) achievable over ∼50nm at grating angles of 55 to 70 degrees. At these angles the delivered spectral resolution for 300 $\mu$m fibers is between 8,000 and 18,000. [Credit: S. Barden, private communication.]

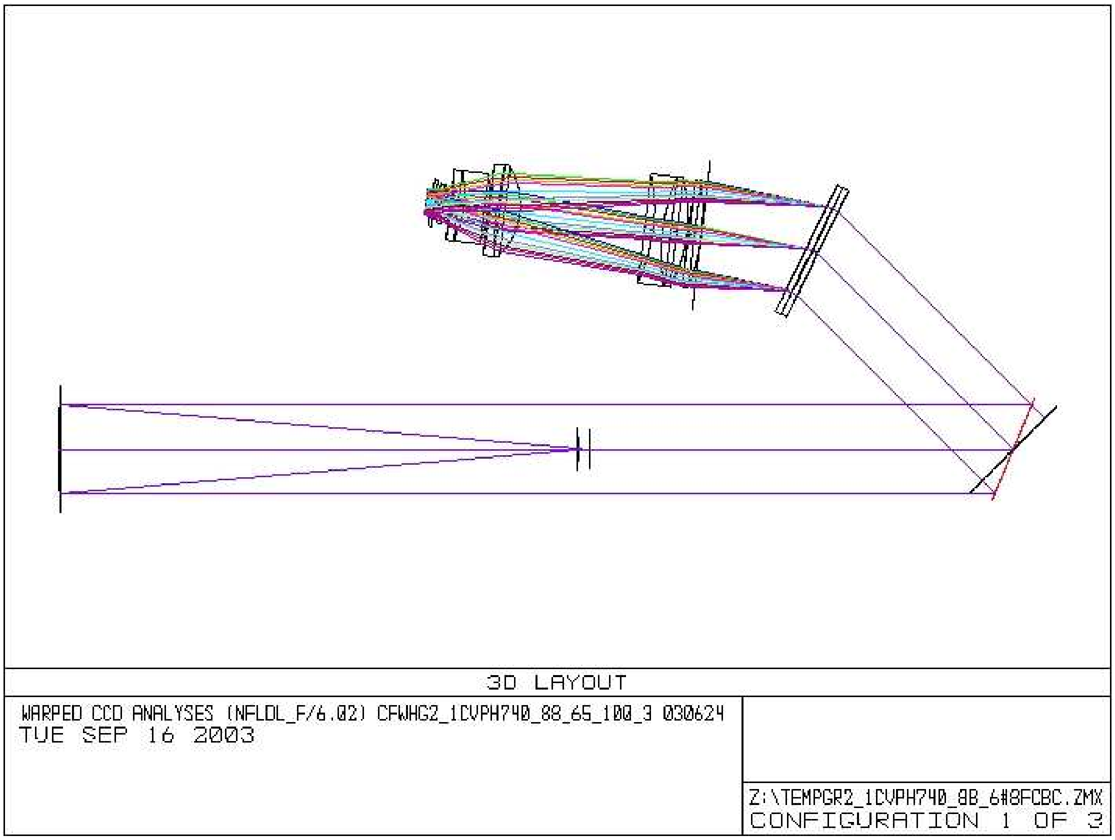



Fig. 26.— Layout for testing 740 l/mm VPH grating on existing Bench Spectrograph as viewed from above the bench (color coding is by wavelength). Note the location of the fold mirror at the location used for existing gratings, and then the location of the VPH grating close to the camera objective. This setup will yield little vignetting in wavelength but larger vignetting in field compared to existing low-order grating setups. [Credit: D. Harmer and C. Harmer, private communication.]

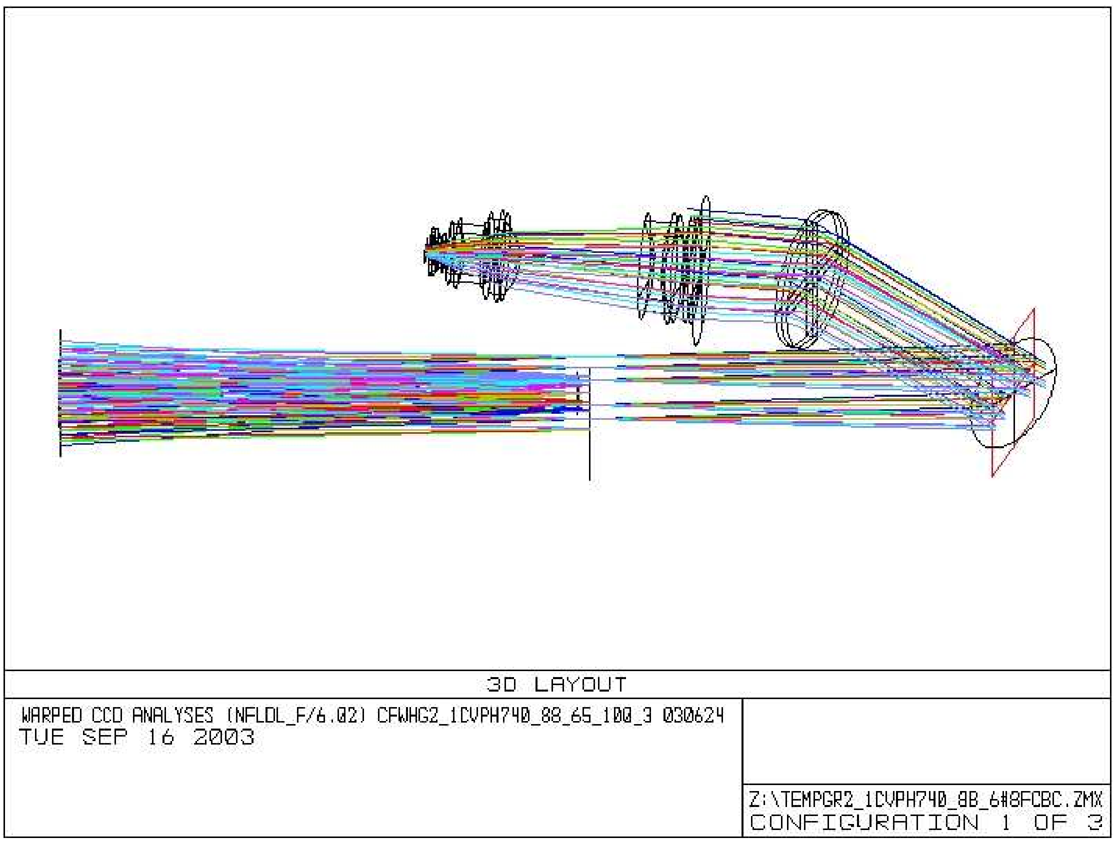



Fig. 27.— Layout for testing 740 l/mm VPH grating on existing Bench Spectrograph as viewed across the bench (color coding is by field). Note location of pupil is still at the fiber feed since this *test* setup uses the existing collimator. [Credit: D. Harmer and C. Harmer, private communication.]

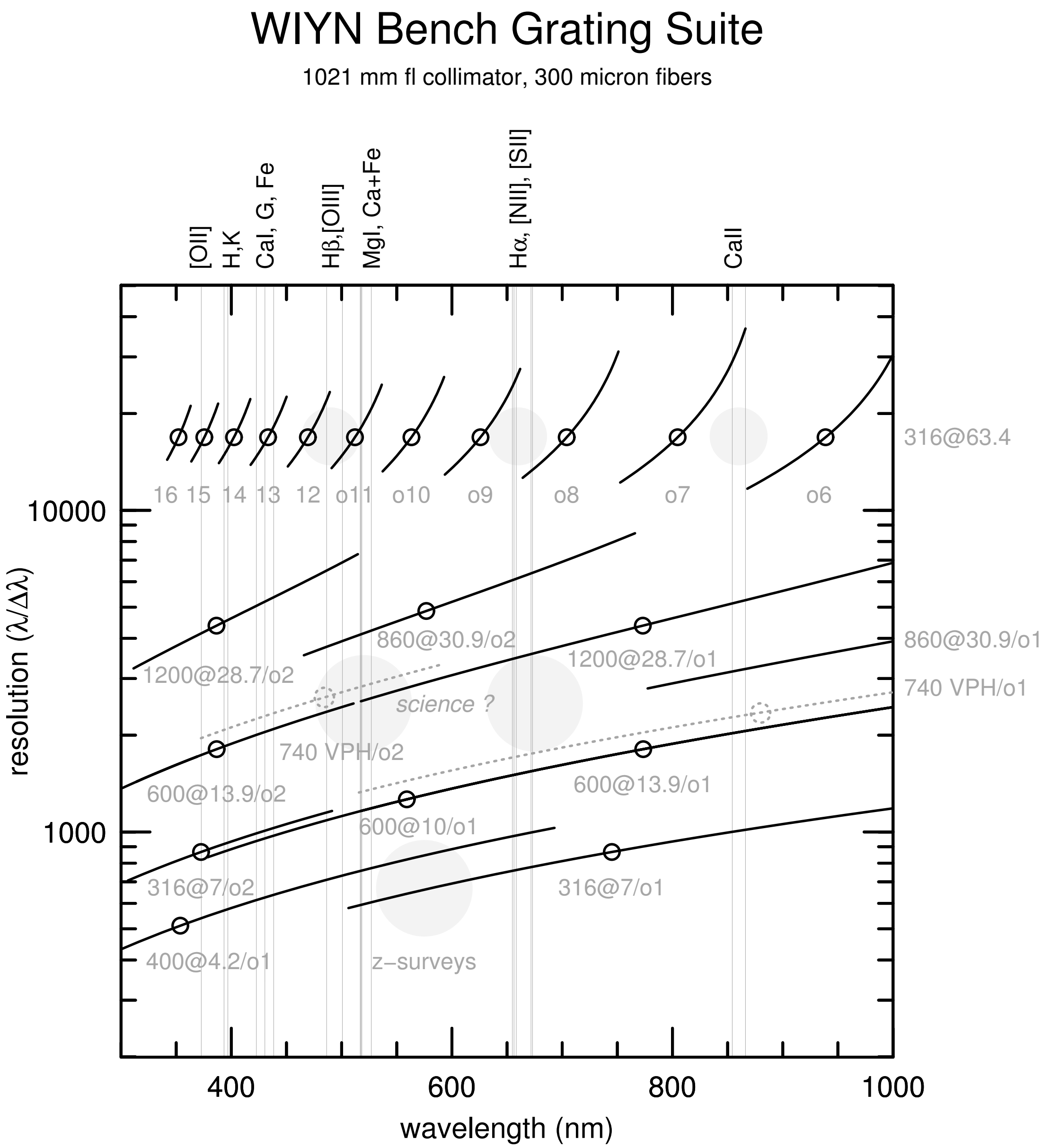
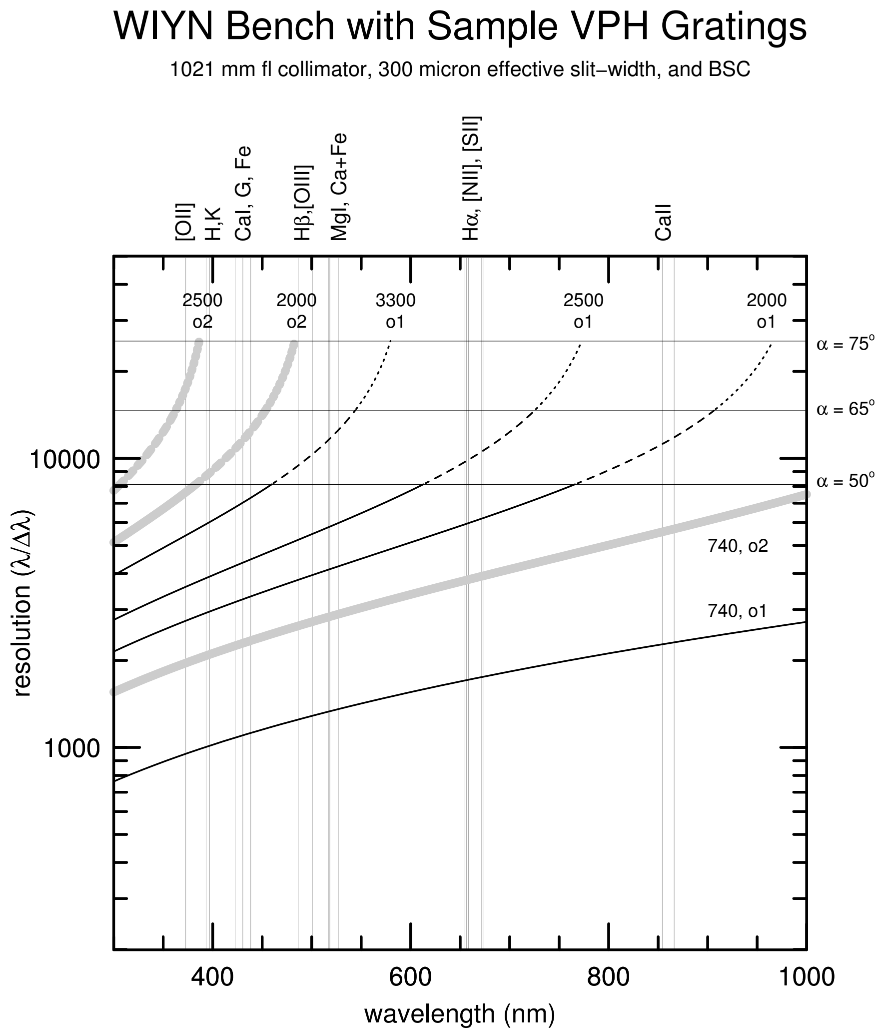



Fig. 28.— Achievable wavelength-resolution space for the Bench Spectrograph and the existing grating suite assuming a 300 $\mu$m fiber and existing spectrograph system with the Bench Camera. Gratings and their orders are labeled in grey. Open circles indicate blaze wavelength assuming a camera-collimator angle of 30°. The 740 l/mm VPH grating is also shown as grey dotted lines. Large, light-grey filled circles indicates some regions in wavelength-resolution space which are not well covered by the existing grating suite. Some of these voids may be scientifically compelling to fill.




| α (deg) | $D_{beam}$ (mm) | $D_{grating}$ (mm) | α (deg) | $D_{beam}$ (mm) | $D_{grating}$ (mm) |
|---|---|---|---|---|---|
| 50 | 150 | 233 | 50 | 200 | 311 |
| 65 | 150 | 355 | 65 | 200 | 473 |
| 75 | 150 | 580 | 75 | 200 | 773 |

Fig. 29.— Achievable wavelength-resolution space for the Bench Spectrograph and several possible VPH gratings in 1st and 2nd order assuming a 300 $\mu$m fiber and existing spectrograph system with the Bench Camera. The superblaze peaks are not indicated, but refer to Figures 24 and 25 for the 740 and 3300 l/mm gratings. *Note that these peaks can be selected in the grating design.* The relation between resolution, wavelength and grating incidence angle, $\alpha$ is indicated by line type. Note the very high resolutions which are achievable at optical wavelengths with high-density gratings for $\alpha > 50°$. To achieve these large angles and not vignette the gratings must be large, as indicated in the table at the bottom of the plot for two different beam sizes. For reference, the Bench Spectrograph is designed to have a 150mm collimated beam but at the current collimator focal length 90% EE is enclosed in a 200mm beam. Hence a shorter collimator focal length is desirable to achieve higher spectral resolutions even taking into account changes in demagnificantion (refer to Figure 23.)