VIRUS-W: an integral field unit spectrograph dedicated to the study of spiral galaxy bulges

Maximilian H. Fabricius[a,b], Stuart Barnes[c], Ralf Bender[a,b], Niv Drory[a], Frank Grupp[b], Gary J. Hill[c], Ulrich Hopp[a,b], Phillip J. MacQueen[c]

[a]University Observatory of the Ludwig-Maximilians University (LMU), Munich, Germany;
[b]Max-Planck Institute for Extraterrestrial Physics (MPE), Munich, Germany;
[c]McDonald Observatory and Department of Astronomy, University of Texas at Austin, USA

ABSTRACT

We present the design, layout and performance estimates for a fiber based Integral Field Unit spectrograph. This instrument is built for flexible use at different telescopes, and in particular for the new 2 m telescope on Mount Wendelstein in the Bavarian Alps. Based on the VIRUS spectrograph for the HETDEX experiment, the proposed instrument will have a fiber head consisting of 267 optical fibers. The large angular field of view of 150×75 arcseconds will allow full coverage of the bulge regions of most local late type galaxies in one or two pointings. Realized by the usage of VPH gratings, a $R \simeq 2500$ and a $R \simeq 6800$ mode with 850 Å and 515 Å wavelength coverage will be dedicated to the study of stellar populations and kinematics of late type galaxy bulges.

Keywords: galaxy bulges, stellar populations, dynamics, integral field unit, IFU, optical fibers, spectrograph, Wendelstein

1. INTRODUCTION

In the past years Integral Field Unit (IFU) spectrographs gained increasing popularity within the astrophysical community and an increasing number of telescopes are equipped with such an instrument. They allow the acquisition of spectroscopic information not only for a single point or a one-dimensional slit in the image plane but rather for a whole two-dimensional field. Possible applications reach from detailed kinematical and chemical studies of subregions of individual galaxies to cosmological surveys.

Also over the last years the advance of knowledge in the field of optical fibers allows them to be manufactured to a wide range of specifications at relatively low cost and high and stable quality. As arranging a number of fibers into an IFU head in the focal plane and into a slit-like configuration at the side of the spectrograph is straightforward, their usage in the construction of IFU instruments is very convenient.

The University Observatory in Munich is currently building a new 2 m telescope on top of the mountain Wendelstein in Bavaria, Germany[1]. Parallel to the construction of the telescope a number of instruments are developed[2] – one of them being an IFU spectrograph. While being developed as part of the Wendelstein 2 m instrumentation efforts, the instrument is designed for flexible use at different telescopes as well. The design is heavily based on the VIRUS spectrograph proposed for the HETDEX experiment (see [5] to [8]). A prototype of this instrument is already in operation.

The spectrograph will have two different modes of spectral resolution: A $R \simeq 2500$ mode for stellar populations studies of galaxy bulges, and a $R \simeq 6800$ mode to resolve the velocity dispersions which are expected in kinematically cold bulges like pseudobulges of spiral galaxies. A large angular field of view of 150×75 arcseconds will give full coverage of the bulge regions of most local late type galaxies in one or two pointings with a fill factor of 1/3. Alternatively a dithering mode will give close to 100 % spatial coverage in three pointings per field.

The combination of relatively high spectral resolution and large field coverage places it into a yet very sparsly populated reagion in the resolution vs. field coverage plane of already existing IFUs. Given an about eight times

Further author information: (Send correspondence to Maximilian H. Fabricius)
Maximilian H. Fabricius: E-mail: mxhf@mpe.mpg.de, Telephone: +49 (0)89 30000 3694

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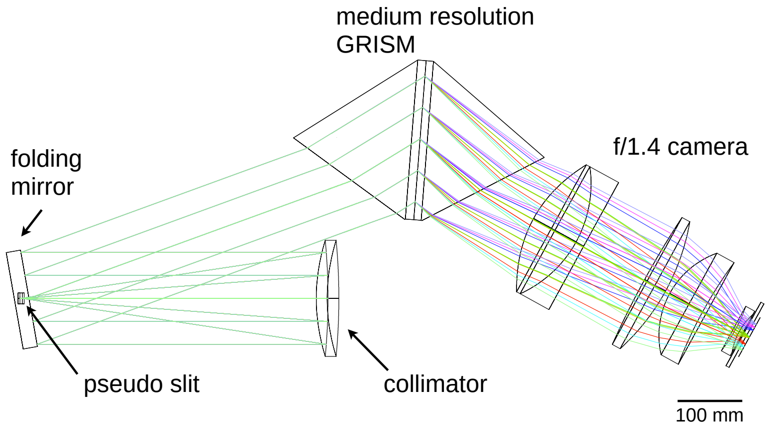

Figure 1. Schematic view of the spectrograph's optical layout in the medium resolution mode (R$\simeq$6800) configuration. The 267 150$\,\mu$m core optical fibers are arrayed into a fan-like pseudo slit. The slit is located inside the folding mirror to the left of the figure (pointing out of the image plane). The fibers point perpendicular the surface of the collimating mirror. The collimated beam is reflected back onto the folding mirror and enters the dispersive element – in the medium resolution mode a 3300 ll/mm 220 mm $\times$ 170 mm large VPH grating sandwiched between two large prisms (GRISM). Due to the large diffraction angle the prisms are needed to avoid internal reflection at the grating plate surfaces. A large 200 mm aperture dioptric camera records the spectra.

larger spatial coverage and a spectral resolution which is higher by a factor of two, VIRUS-W will allow the extension of studies of – for example – the SAURON (see e.g. [10], [11]) spectrograph into the direction local late type and lower mass galaxies.

2. OPTICAL DESIGN

The input focal ratio of the spectrograph is $f/3.35$ and is matched to the output numerical aperture of the optical fibers. The fibers are arrayed in a pseudoslit which is located within a folding mirror. They point perpendicular to a spherical collimating mirror (see Fig. 1, 2 and 4). An anti-reflective coated cylindrical normalizer lens is attached to the fibers. The two volume phase holographic (VPH) gratings can be exchanged without having to change the position of the camera. The utilization of fibers allows the spectrograph to be placed on an optical bench inside a climatized room underneath the telescope dome. Drifts due to temperature changes or changing g vector are therefore avoided.

Medium resolution mode

The medium resolution mode with R $\simeq$ 6800 (see Fig. 1) will enable the observer to study velocity dispersions down to 20 km/s. The covered wavelength range will be 515 Å wide and reach from 4930 Å to 5445 Å. This covers the OIII lines at 4959 Å and 5007 Å and the Mg lines at 5167 Å, 5172 Å and 5183 Å up to a redshift of 0.03 (see Fig. 3). The grating is a 3300 lines per millimeter VPH grating blazed at 35.9° (inside fused silica). The grating efficiency varies from 45 % to 85 % in the covered wavelength range. Prisms will be attached to the VPH surfaces to avoid internal reflection and to keep the camera location fixed between the two resolution modes. Due to the larger angle of incidence this grating will be larger than in the low resolution case and be about 170 mm x 220 mm in size.

The prisms are manufactured by POG Przisionsoptik Gera GmbH in Gera, Germany. The VPH grating is manufactured by Kaiser Optical Systems, Inc. in Ann Arbor, Michigan, USA who will glue the prisms to the grating surfaces.

Low resolution mode

The low resolution mode with R $\simeq$ 2500 (see Fig. 2) will cover the wavelength range from 4750 Å to 5600 Å. In addition to the already mentioned spectral features this enables the observation of H_β and the Fe lines 5270 Å,

spectral coverage	4930 Å- 5445 Å
resolution ($\Delta\lambda/\lambda$)	6500 to 7080 (depending on wavelength)
resolution (σ)	20 km/s to 18 km/s
grating	3300 ll/mm VPH grating sandwiched between two prisms

Table 1. Medium resolution mode data. Spectral resolutions were calculated from the ray-traced linear dispersion and the spatial size of the spectral resolution element.

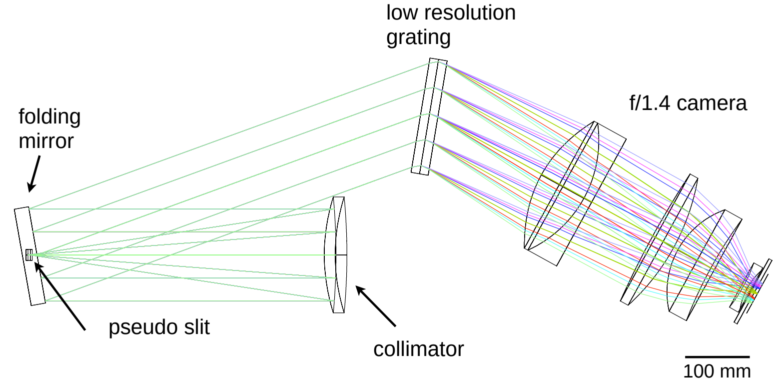

Figure 2. As figure 1. In the low resolution mode (R $\simeq$ 2500) the dispersive element is a 1900 ll/mm 160 mm $\times$ 170 mm large VPH grating. The camera position stays fixed between the two different resolutions modes.

5335 Å and 5406 Å and their corresponding Lick pseudo-continua (see e.g. [4]) up to z $\simeq$ 0.03 (see Fig. 3). The dispersive element is again a VPH grating with 1900 ll/mm blazed at 38°. The size of this grating will be 145 mm $\times$ 165 mm. Since here the diffraction angle is smaller, there is no need to attach prisms as in the medium resolution mode.

spectral coverage	4750 Å - 5600 Å
resolution ($\Delta\lambda/\lambda$)	2150 to 2780 (depending on wavelength)
resolution (σ)	59 km/s to 46 km/s
grating	1900 ll/mm VPH grating

Table 2. Low resolution mode data. Spectral resolutions were calculated from the ray-traced linear dispersion divided and the spatial size of the spectral resolution element.

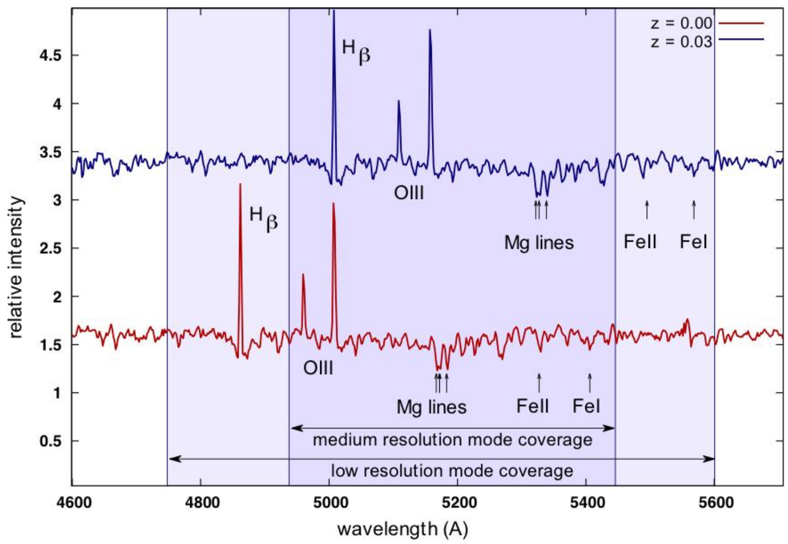

Figure 3. Shows the spectral coverage of the spectrograph. Plotted is an averaged spectrum of 29 SDSS spiral galaxies at restframe and z = 0.03. In the medium resolution mode the covered wavelength range will reach from 5070 Å to 5445 Å. This covers the OIII lines at 4959 Å and 5007 Å and the Mg lines at 5167 Å, 5172 Å and 5183 Å up to a redshift of 0.03. The low resolution mode will cover the wavelength range from 4750 Å to 5600 Å. This enables the observation of H_β and the Fe lines at 5270 Å , 5335 Å and 5406 Å and their corresponding pseudo-continua up to z ≃ 0.03.

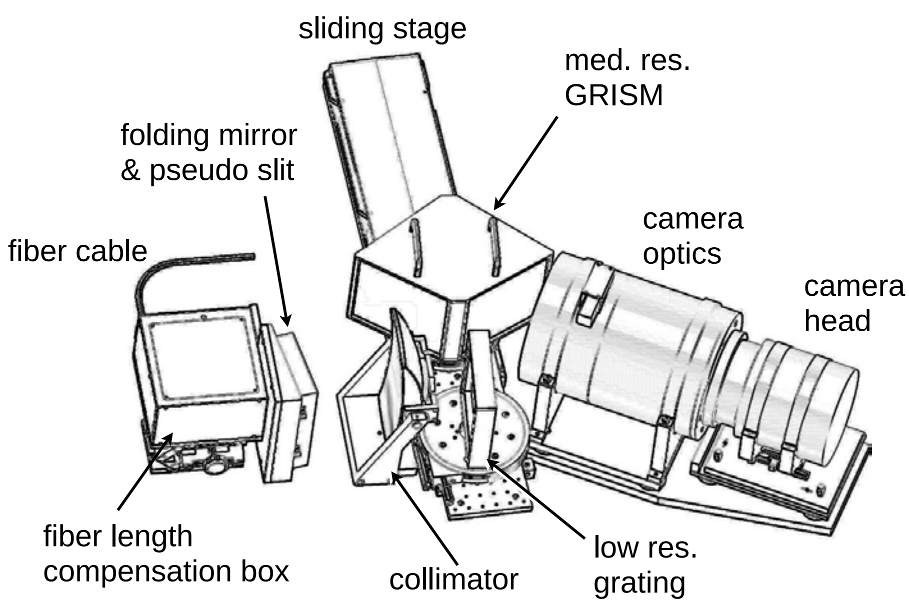

Figure 4. Rendered image of the bench-mounted VIRUS-W spectrograph. The system silt is located inside the folding mirror. A housing which is attached to the folding mirrors allows to compensate for length differences of the fibers. The medium resolution GRISM and the low resolution grating are mounted on a sliding stage for automatic exchange.

IFU

The IFU will consist of 267 individual optical fibers arrayed into a dense-packed rectangular array (see Fig. 5). To match the f-number of the new Wendelstein telescope we will use a focal reducer. To allow for focal ratio degradation in the fibers the focal reducer will produce a $f/3.65$ beam which is slightly slower than the input focal ratio of the spectrograph. The maximum fiber core diameter is given by the resolution requirements and is 150 μm. The array consists of $20/21 \times 13$ fibers with a pitch of 255 μm. This results in a head size of 5.36 mm $\times$ 2.68 mm and — given a $f/3.65$ beam — a 150×76 arcseconds field of view. The individual fibers have a diameter of 4.4 arcseconds on sky and cover an area of 14.1 arcseconds squared each.

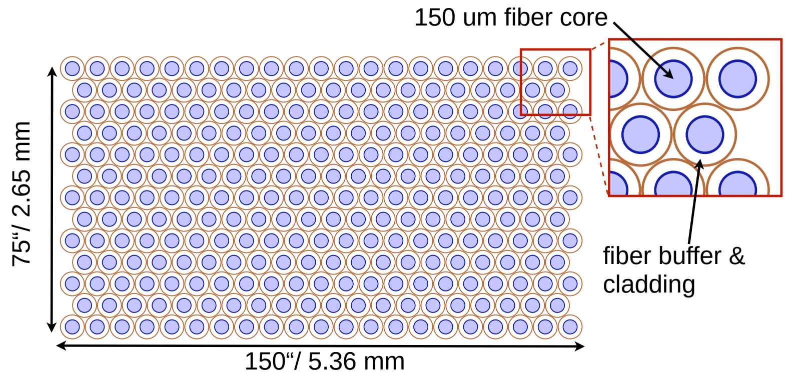

Figure 5. VIRUS-W IFU configuration. The densepack type fiber head consists of an array of 267 150 μm core fibers arranged in 13 rows of 20 and 21 fibers each with a pitch of 255 μm

As in the case of the VIRUS-P prototype manufacturers explored the usage of an array of fused silica ferrules or drilled holes for the positioning of the individual fibers. To our surprise it turned out that even these small geometries can be drilled mechanically.

Camera

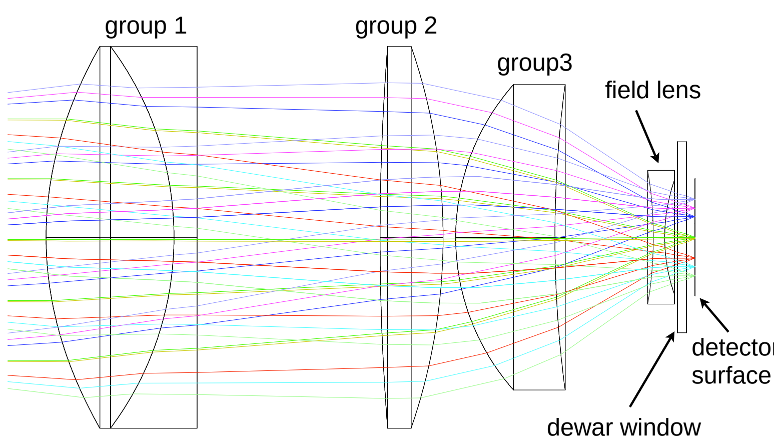

Figure 6. The VIRUS-W 200 mm aperture $f/1.4$ camera. Surface data are given in table 3. The window between the field flattener and the detector allows to mechanically decouple the cryostat from the optics housing. Otherwise the fast optical beam would have resulted in very tight tolerances for the detector position.

We replaced the Schmidt camera of the original VIRUS-P design by a $f/1.4$ dioptric camera to avoid the central obscuration of a Schmitd system (see Fig. 6). The camera design is based on the SALT telescope High Resolution Spectrograph red arm camera (see [3] and [9]) and incorporates mostly spherical components. The only aspheric surfaces are the entrance surface and the last field flattener surface (see Tab. 3). Besides avoiding central obscuration, a dioptric design has the advantage of simplifying the dewar design for the detector. Even though a close proximity of the detector to the field flattener is generally favorable, we decided to place a dewar window between the field lens and the detector. This allows to mechanically decouple the cryostat from the lens housing and to fine adjust the whole cryostat rather than the detector inside the vacuum. This simplified the cryostat design significantly.

The camera optics and its housing are being manufactured by POG Präzisionsoptik Gera GmbH in Gera, Germany. The camera head is made by Spectral Instruments, Inc. in Tucson, Arizona, USA.

Grp.	**Surf.**	**Glass**	**R of curv. (mm)**	**Diam. (mm)**	**thickness (mm)**	**Notes**
1	1	S-FSL5	179.4796	200	67.0000	asph. $c = -4.4296$, $a_4 = 7.7344 \times 10^{-8}$, $a_6 = -3.7140 \times 10^{-12}$, $a_8 = 1.7621 \times 10^{-16}$, $a_{10} = -5.3331 \times 10^{-21}$
1	2	S-TIH1	-166.2436	200	12.0000	
1	3		flat	200	96.2878	
2	1	S-BAH11	1280.2371	200	33.0000	
2	2		-305.1473	200	5.3918	
3	1	N-LAK7	121.2324	160	52.0000	
3	2		593.2538	160	52.3159	
4	1	Lithosil	-233.3127	70	6.0000	field lens, asph. $c = 0.0$, $a_4 = -4.9830 \times 10^{-7}$, $a_6 = 3.1592 \times 10^{-10}$, $a_8 = -6.9386 \times 10^{-14}$
4	2		91.5383	60	7.5556	
5	1	silica	flat	100	4.7630	dewar window
	2	vacuum	flat	100	3.5000	
	1		flat			e2v CCD44-82 2k x 4k 15 μm pixel CCD

Table 3. Surface data for the VIRUS-W camera design. The entrance surface and the first field lens' surface are aspheres. Note: These are the surface data before test plate fitting.

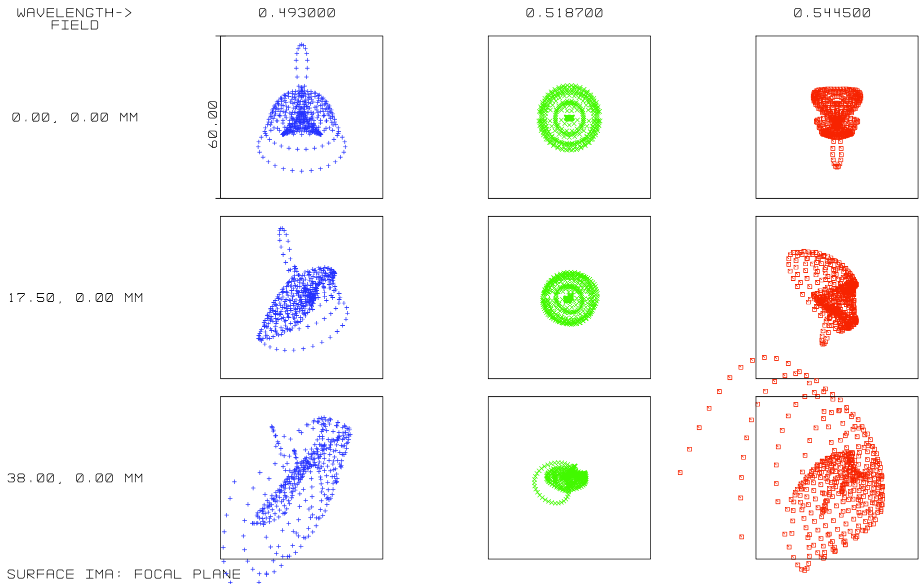

Figure 7. Medium resolution mode spot diagram: Shown are spot diagrams for the blue cutoff wavelength 4930 Å (left coloumn), the center wavelength 5187 Å (middle coloumn) and the red cutoff wavelength 5445 Å (right coloumn). The individual rows show different fiber positions along the slit. The uppermost row shows the center fiber, the middle row shows an intermediate fiber positions, the bottom row shows the outermost fiber position. The box size is 60 μm and is slightly smaller than the spatial size of the spectral resolution element of 64 μm.

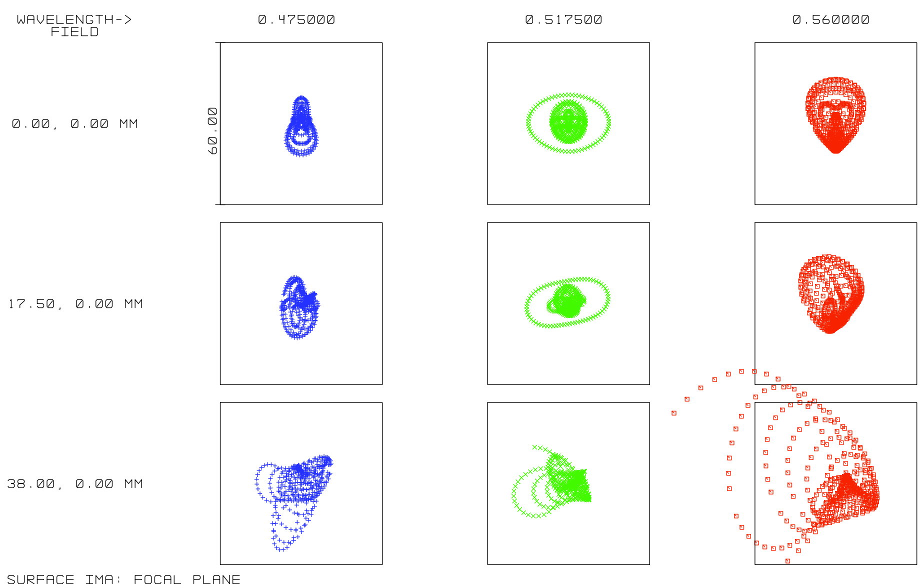

Figure 8. Low resolution mode spot diagram: As figure 7. Shown are spot diagrams for the blue cutoff wavelength 4750 Å (left coloumn), the center wavelength 5175 Å (middle coloumn) and the red cutoff wavelength 5600 Å (right coloumn).

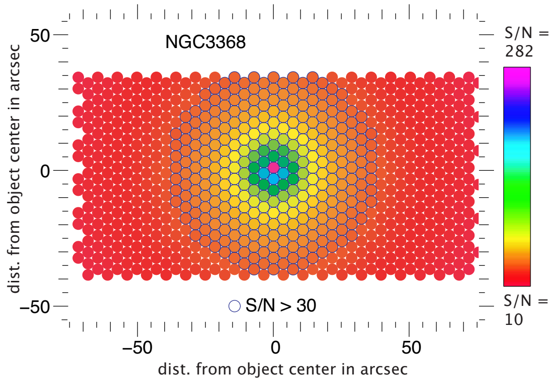

Figure 9. Signal to noise estimate per fiber for a dithered three times one hour exposure of NGC3368.

3. PERFORMANCE

Based on theoretical predictions by the grating manufacturers and the current telescope design a preliminary calculation suggests a signal to noise ratio of about 10 for the medium resolution mode, an one hour exposure and an object with a V band surface brightness of 22 (mag/arcsec^{-2}).

Simulations accompanied the optical design process. We performed Monte Carlo ray tracing simulations of the spectrograph using a custom code. Specular and diffuse reflections as well as absorption were modeled in a statistical manner which allows us to probe for artifacts such as stray light ghosts and sky concentration (see Fig. 10). Even worst case reflectivities of 5 % for each refractive surface predict stray light and ghost levels below 1.5 %. As all surfaces will be anti-reflactive coated the signal level is expected to be much lower. Simulated frames aid the development of the reduction software before the individual parts of the spectrograph are manufactured and assembled.

4. STATUS

As of April 2008 the camera optics, the camera head and the medium resolution mode grating are in production. The mirrors have been fabricated and are coated. The mechanical design for the spectrograph is completed. First mechanical parts are being manufactured. The estimated completion date of the medium resolution mode is February 2009. Since the Wendelstein 2 m telescope will not be available by then we may start observing with VIRUS-W at a different telescope – very likely the McDonald 2.7 m Harlan Smith Telescope in Texas.

5. SUMMARY

We presented the design for a new fiber based Integral Field unit spectrograph for the new 2 m Wendelstein telescope in Bavaria Germany based on the VIRUS spectrograph for the HETDEX experiment. Its large field coverage of 150×75 arcseconds and its two modes of spectral resolution of $R \simeq 2500$ and $R \simeq 6800$ are targeted at the study of stellar populations and kinematics of local late type galaxies. Most parts are in production and the instrument is expected to become available in early 2009.

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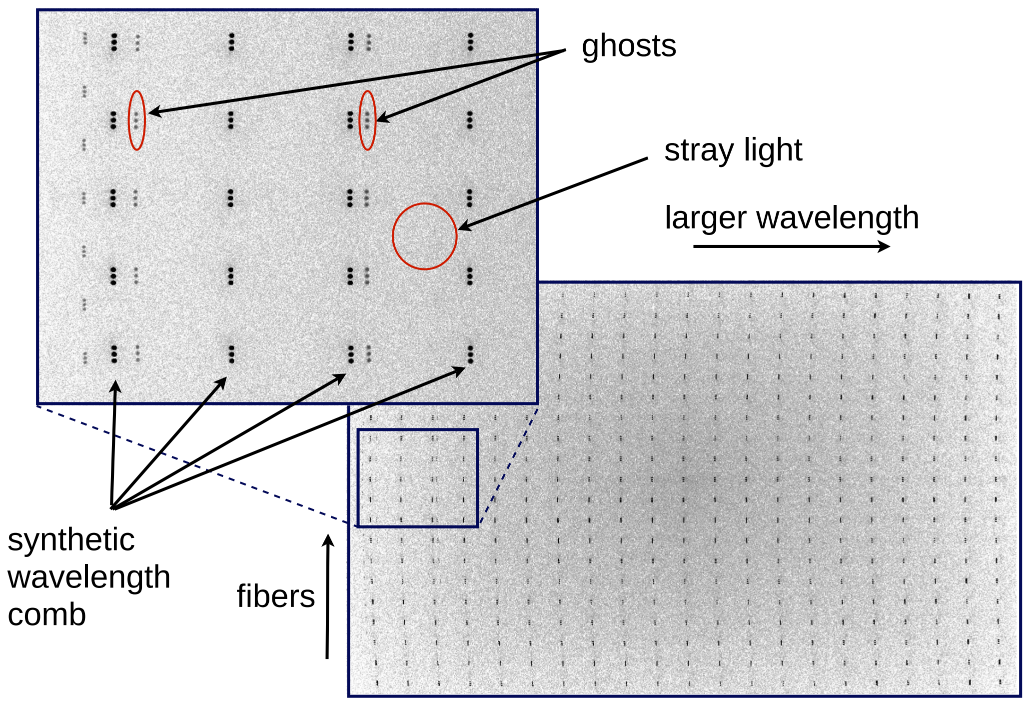

Figure 10. A simulated frame. The source was an artificial wavelength comb with peaks spaced at roughly 25 Å. Only groups of three fibers were simulated to get a clear view on the stray light between the fibers and to reduce computational cost. The image scale is logarithmic to emphasize artifacts. The magnified image region shows a portion of the simulated frame at the blue spectral end. Clearly visible are ghosts and stray light. Here the ghost signal level is below 1.5 %. The simulation was done assuming a worst case reflectivity of 5 % of all refractive surface. The actual ghost signal level is expected to be much smaller. The stray light level here is below a hundredth of a percent.

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