Report

I4/I6 SCIENCE COMBINER DESIGNS

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Contents

Chapter 1

Overview of the focal plane design

This report presents an overview of the focal plane design for the I4 and I6 combiners, at low and medium resolutions (R=30 and R=300).

1.1 The anamorphosis factor in the spectrograph

Beam combination and spectrography are simultaneous in focal plane combiners, which means both these aspects are optimised at the same time.

Let's consider the Focal Plane Array (FPA) and define the x axis as the axis perpendicular to fringes, while y axis is parallel to fringe direction and is the axis along which spectral dispersion occurs. Let's call f_x and f_y the focal lengths equivalent to the entire combiner (from afocal beams to the FPA, without dispersion), p the pixel size of the FPA, D the diameter of a input beam, and B the length of the maximum baseline of the combiner input pupil.

The focal plane combiner should be comply with both these requirements :

- the fringe sampling requirement : at least 4 pixels per fringe for all fringes, which translates into 4 pixels on the longest baseline.

- the spectral sampling requirement : the size of the undispersed spot on the FPA corresponding to one resolution element should be small enough not to impact the measurement on another one. We will assume that choosing one pixel per resolution element means that the diameter of the first black ring of the Airy pattern of one beam should be less than one pixel.

Thus two sets of equations :

$$\frac{\lambda}{B} f_x \geq 4p \Rightarrow f_x \geq \frac{4pB}{\lambda_{\text{min}}} \tag{1.1}$$

$$\frac{2.44\lambda}{D} f_y \leq 1p \Rightarrow f_y \leq \frac{pD}{2.44\lambda_{\text{max}}} \tag{1.2}$$

Supposing equalities are realized for both equations, the ratio f_x/f_y, called the anamorphosis factor, is :

$$\frac{fx}{fy} = 9.76 \frac{\lambda_{\text{max}}}{\lambda_{\text{min}}} \frac{B}{D} \tag{1.3}$$

The wavelength ratio includes all bands (as the same optics is used), $\lambda_{\text{max}} = 2.42\mu$m and $\lambda_{\text{min}} = 1.13\mu$m, so that $\lambda_{\text{max}}/\lambda_{\text{min}} = 2.14$.

The B/D ratio is determined by the beam configuration. The beam diameter for MRAO combiners is fixed at 13 mm. The maximum baselines for the linear non-redundant layouts have been determined for both cases (see Julien Coyne's report number 14 for I4 and upcoming reports for I6) :

- for I4 combiner : $B = 191.5$ mm, so $B/D \simeq 15$ and $f_x/f_y \simeq 310$;

- for I6 combiner : $B = 408.0$ mm, so $B/D \simeq 31$ and $f_x/f_y \simeq 656$;

Note that the ratio f_x/f_y only represents the theoretical maximum anamorphosis, and not the actual lower anamorphosis in a given waveband.

1.2 I4 and I6 optical design

The optical design has been fully realized with Zemax, while some optical calculations were done using IDL and MAPLE.

1.2.1 Step 1 : 1D model with IDL/MAPLE simulations

The conventional solution to implement an anamorphosis is to use an afocal combination of two cylindrical mirrors with the ratio of their focal lengths equal to the anamorphosis ratio. While this works perfectly for 3 beams recombination in a single band (AMBER concept study by example) for which the anamorphosis ratio is about 10, a more complex design is required here. Thus a 3 mirror design has been chosen, as a compromise between simplicity, cost (only one more mirror) and compactness.

The first mirror is outside the dewar and allows all beams to converge to the dewar pinhole. The mirror surface is not fully used as the beams in linear configuration are distributed along the x axis. Thus it would be possible to replace this mirror with several smaller mirrors (each reflecting a beam) if judged more practical during actual implementation.

The second and third mirrors are placed in combination with the first so as to focus the beams onto the detector with the desired anamorphism factor. A possible drawback to this approach is the absence of a pupil plane inside the dewar, which may make initial alignment more difficult, but this drawback is compensated by the fact no fourth mirror (and subsequent alignments) is required. The absence of a pupil plane inside the Dewar means in particular that no cold pupil plane stop (at least no conventional one) would be used.

There were virtually very few difference between I4 and I6 simulations. I6 is a more extreme version of I4, but the fundamental design remains the same.

An IDL program was written to derive all focal lengths sets that would be compliant with all conjugation relations for 3 aligned mirrors without relative angles. Reasonable boundaries were imposed on focal lengths and F/D so that each optical element would not depart from realistic specifications :

- only parabolic and cylindric mirrors were used ;
- focal lengths not smaller than 10 cm ;
- distances between mirrors, and the distance from last mirror to detector have to be large enough (>10 cm) ;

To compensate for the lack of angle modelization, and other possible sources of errors, calculations were done on 5% more demanding specifications (i.e. slightly more that 4 pixels per fringes, and less than one pixel per spectral resolution element). A pixel size of 40μm has been assumed, as this seems currently the most probable choice. Table 1.1 presents the results of this study.

During this process, it appeared that both cylindrical mirrors could be chosen to have the same focal length without constraining to much the rest of the layout, which could potentially reduce manufacturing costs of such custom mirrors. Additional MAPLE computations shew it was even easier to get a good output (= set of focal lengths) by imposing this condition, which was finally done.

All these simple specifications already allowed to select designs down to only a few possible layouts. The choice of focal lengths was further constrained by the need for a dewar as small as possible, therefore the most compact design of all remaining sets was chosen for each combiner (I4 and I6).

Once the choice of focal lengths is fixed, main characteristics of the layout can be derived, as table 1.2 shows. Most noteworthy is the fact that I4 in the K band and I6 in general would require more than 256 pixels to sample the whole fringe set.

	I4	I6
Equivalent focal lengths (mm)	28363.6 - 85.8	59642.2 - 85.8
Anamorphism fx/fy	330.6	695.2

Table 1.1: Theoretical I4/I6 specifications for 1D model. For actual specifications, see table 1.4.

	J1	J2	H1	H2	K1	K2
Nmax (I4)	145	183	194	234	267	310
Nmax (I6)	308	390	412	49 9	569	661
Nmin (I4)	20	25	26	32	36	42
Nmin (I6)	42	52	55	67	76	88
Ny	0.44	0.56	0.59	0.72	0.82	0.95
Nspec @R=300	79	79	63	63	49	49

Table 1.2: I4 and I6 on the CCD. For each band, the values at minimum and maximum wavelengths are given. All values are in pixels. Nspec is the size of the waveband along the spectral dispersion axis y. Ny is the diameter of the PSF (till the first black ring) along the y axis. Nmax is the width along the x axis necessary to sample all fringes. Nmin is the width required to sample at least one fastest fringe. Note that I4 and I6 share the same Ny and Nspec values as their equivalent focal length along the y axis are the same.

1.2.2 Step 2 : Zemax design

After IDL calculations a 1D layout – all angles between optical elements were null – was first realized under Zemax. Despite all previous IDL optimisations, the footprint was still larger than 3 meters along the beam propagation direction, so the diffractive element position and an additional folding mirror were placed in optimal positions to reduce it to one third (see final layouts in section 1.3).

Angles and translations of optical elements that are necessary for clearance reason were then introduced. Slight adjustments to the theoretical values of distances and focal lengths were necessary to reduce the impact (fine adjustments were done in the final optimisation step).

1.2.3 Step 3 : Other components/parameters

Diffracting element

There are several possibilities of diffracting components for the spectrograph. The final choice is subject to confirmation of availability in a manufacturer's catalog and best efficiency/ease of use ratio.

Here are the different solutions :

- a blazed reflective grating. While this is the most simple solution for mid to high resolution modes, throughput may be a problem. However compared to what is technically achievable in the state of the art optics, the spectral resolution requirements are far from demanding, allowing to put manufacturing efforts on blazing efficiency.
- a direct vision prism : adequate solution for low resolution mode (the grating equivalent would have only a dozen grooves per mm), less aberrations than a grating, no flux loss by multiple orders.
- a grism : chromatic coma aberrations originating from the grating are corrected, multiple orders but flux loss is reduced.

Currently the Zemax designs implement reflective gratings. Table 1.3 shows the current characteristics of the gratings in each case.

	J (R=300)	H (R=300)	K (R=300)
I4	98	74	53
I6	120	85	68

Table 1.3: Diffractive elements specifications in lines/mm for R=300 (R=30 ones are 1/10th of these).

Pinhole

Pinhole characteristics/filtering are currently TBD. Consequently the effects of a pinhole have not been taken into account so far in Zemax modelling.

Beam shape

The beam was supposed to have a top hat shape, and to be 13 mm wide. The influence of a more realistic beam shape on performance will have to be evaluated in the future.

1.2.4 Step 4 : Optimizations and tolerancing

When switching the waveband or the spectral resolution, positions and angles must be adjusted for :

- the dispersing element : both the number of lines per mm and its angle in the layout plane do change. The position of the filter/resolution wheel cannot change but it can be assumed the position of the grism itself inside the wheel can differ from a few tenth of mm from element to element (however we did not have to adjust this parameter).
- the last mirror : major constraint is that it should form the image outside the incoming ray zone ;
- the Focal Plane Array ;

Angles are the main variables to be optimized, though it is possible to slightly alter the focal lengths of the mirror within the imposed range determined when doing Zemax tolerancing. Table 1.4 shows the final values retained.

	Parabolic mirror	Cylindrical 1	Cylindrical 2
I4	1562.2	150.0	150.0
I6	4524.5	120.0	120.0

Table 1.4: Final focal lengths of the mirrors in millimeters

The optimization process aims at increasing visibility amplitudes, while the tolerancing aims at determining which conditions make the visibilities drop below the specification threshold. Obtaining the visibilities from the image plane is a three step process. First the Physical Optics Propagation mode (under Zemax) is used to compute the irradiance on the detector. Then irradiance data on the FPA are exported to a text file, used as input to an IDL routine which computes the Optical Transfer Function and its modulus, giving a result as presented on figure 1.1.

Each visibility amplitude is computed as the ratio of two values : the maximum of the satellite peak (of the corresponding baseline) and the maximum of the central peak. The central peak is very acute, therefore the sampling has to be chosen carefully to achieve satisfying precision on its maximum value.

Note that the use of a χ^2 fit of the data with the theoretical transfer function is possible to enhance the visibility evaluation by determining the precise scale factor (in the FPA, along the x axis) between the theoretical perfect (unaberrated) OTF and the design's one (as shown on figure 1.2).

Overall visibility losses are shown in table 1.5. For the I4 they are about $3 - 9\%$. I6 unfortunately achieve worse performance, with $4 - 18\%$ losses. This is mainly due to increased off-axis aberrations : the diameter of the pupil itself is twice as large, and more apertures in the pupil configuration are located far from the optical axis.

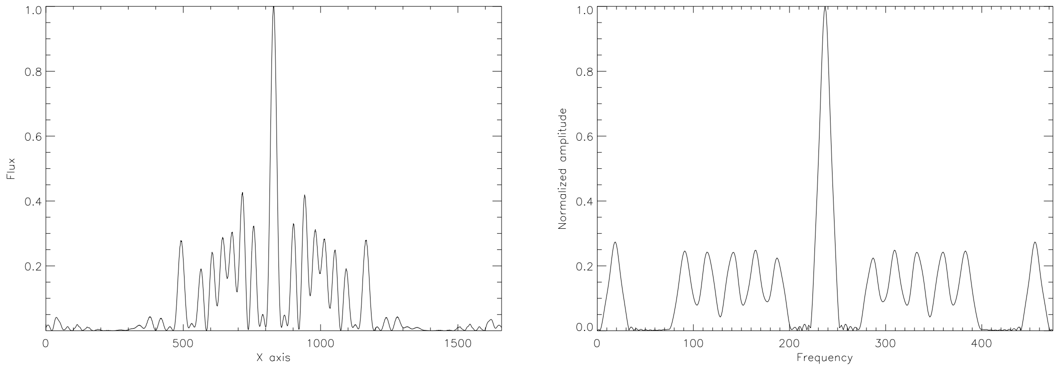

Figure 1.1: Point spread function (from Zemax) and modulus transfer function (computed by IDL) along the x axis for I4 layout. The six satellite peaks on each side of the central peak are well defined.

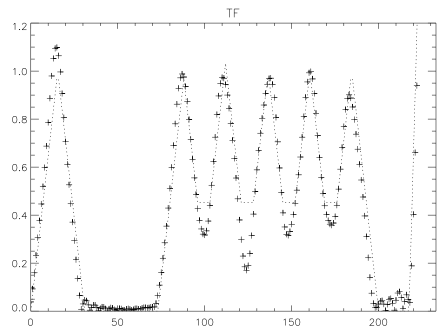

Figure 1.2: χ^2 fit of the aberrated MTF by the theoretical unaberrated MTF. This fit allows the retrieval of the exact sampling rate along the X axis.

From these visibilities considered as starting points, tolerancing has been conducted on each element, calculating the resulting visibility loss for relevant positioning errors. This is currently (11/08/06) a work in progress. Current results for 1% and 5% losses are shown in table 1.6 for I4, and table 1.7 for I6.

Another important property of our final layouts is the flux leakage of a spectral line (= one range of pixels) to its two adjacents ones. All layouts are optimized so that the spectral lines are as thin as possible on the whole range of the waveband (obviously, the spot sizes at extremum wavelength values are generally coarser). Table 1.8 presents the results of the corresponding study.

1.3 Final layouts

In the next pages are presented the final layouts I4 and I6 for R=300 and J band seen from the side (*yz* plane) and rotated along the *y* axis (other layouts are not included – for now – as they do not differ much visually). One can see a remaining problem is the possible lack of space for the detector : if it proves to be large, it may intercept the beam travelling from the grating to the mirror. This could be addressed but not without severe alteration of the design (and then probably more important visibility losses).

The final footprint of the dewar is about 16000 cm^3 (length,width,height = 100 cm $\times 8$ cm $\times 20$ cm) for I4, and 33000 cm^3 (110 cm $\times 10$ cm $\times 30$ cm) for I6.

1.4 Work in progress

Due to Zemax inherent limitations (poor scripting, monochromatic calculations in POP mode, slow algorithms, sampling problems), tolerancing of the focal plane design is slow and tedious. Consequently exporting the current design information under other softwares (Matlab) for easier computation is strongly considered.

Currently the full modeling of the effects of the pinhole, of the eventual cold stop inside the Dewar and of the detector constitutes the next goal of the focal plane study.

	J (R=30)	H (R=30)	K (R=30)	J (R=300)	H (R=300)	K (R=300)
I4	3.8 - 8.1	3.3 - 7.5	2.6 - 6.7	4.5 - 8.9	3.5 - 7.7	4.1 - 7.0
I6	4.8 - 18.0	4.9 - 13.5	5.0 - 9.8	4.8 - 18.8	4.3 - 13.7	4.9 - 10.7

Table 1.5: Optimization results. Minimum and maximum visibility loss percentages at central wavelength for each band and each spectral resolution, obtained by oversampled DFT. Losses are solely due to aberrations (off-axis, tilted components, grating induced, etc.).

Component	θ_x	θ_y	θ_z	x	y	z	f
Parabolic mirror	0.05 / 0.1	0.05 / 0.08	$\times$	0.5 / 1.5	1.0 / 3.0	0.1 / 0.2	0.2 / 0.5
Cylindric mirror 1	0.1 / 0.3	0.2 / 0.3	0.02 / 0.05	0.8 / 1.5	$\times$	1.0 / 3.0	0.12 / 0.15
Folding mirror	0.1/ 0.5	0.08 / 0.1	$\times$	$\times$	$\times$	$\times$	$\times$
Grating	0.1 / 0.2	0.2 / 0.3	0.3 / 0.5	$\times$	$\times$	$\times$	$\times$
Cylindric mirror 2	0.2 / 0.5	0.2 / 0.4	0.01 / 0.03	$\times$	0.2 / 0.5	0.01 / 0.02	0.1 / 0.2

Table 1.6: Tolerancing results for I4. Given angle (in degrees), position (in mm along x, y and z axes) and focal length (in mm) accuracies correspond to 1% and 5% visibility losses.

Component	θ_x	θ_y	θ_z	x	y	z	f
Parabolic mirror	0.02 / 0.5	0.02 / 0.05	$\times$	0.3 / 1.	0.5 / 1.0	0.1 / 0.2	0.1 / 0.4
Cylindric mirror 1	0.05 / 0.2	0.1 / 0.2	0.01 / 0.03	0.3 / 0.8	$\times$	0.5 / 1.0	0.05 / 0.1
Folding mirror	0.1/ 0.2	0.05 / 0.08	$\times$	$\times$	$\times$	$\times$	$\times$
Grating	0.08 / 0.1	0.1 / 0.2	0.2 / 0.4	$\times$	$\times$	$\times$	$\times$
Cylindric mirror 2	0.1 / 0.3	0.1 / 0.2	0.01 / 0.02	$\times$	0.15 / 0.4	0.01 / 0.02	0.08 / 0.15

Table 1.7: Tolerancing results for I6. Given angle (in degrees), position (in mm along x, y and z axes) and focal length (in mm) accuracies correspond to 1% and 5% visibility losses.

	J (R=30)	H (R=30)	K (R=30)	J (R=300)	H (R=300)	K (R=300)
I4	4.1	2.7	2.6	<0.1	3.3	0.8
I6	1.0	2.0	0.3	<0.1	<0.1	0.3

Table 1.8: Percentage of leaked flux (flux outside the 40μm width) for a spectral line. Calculations were done at the central wavelength.

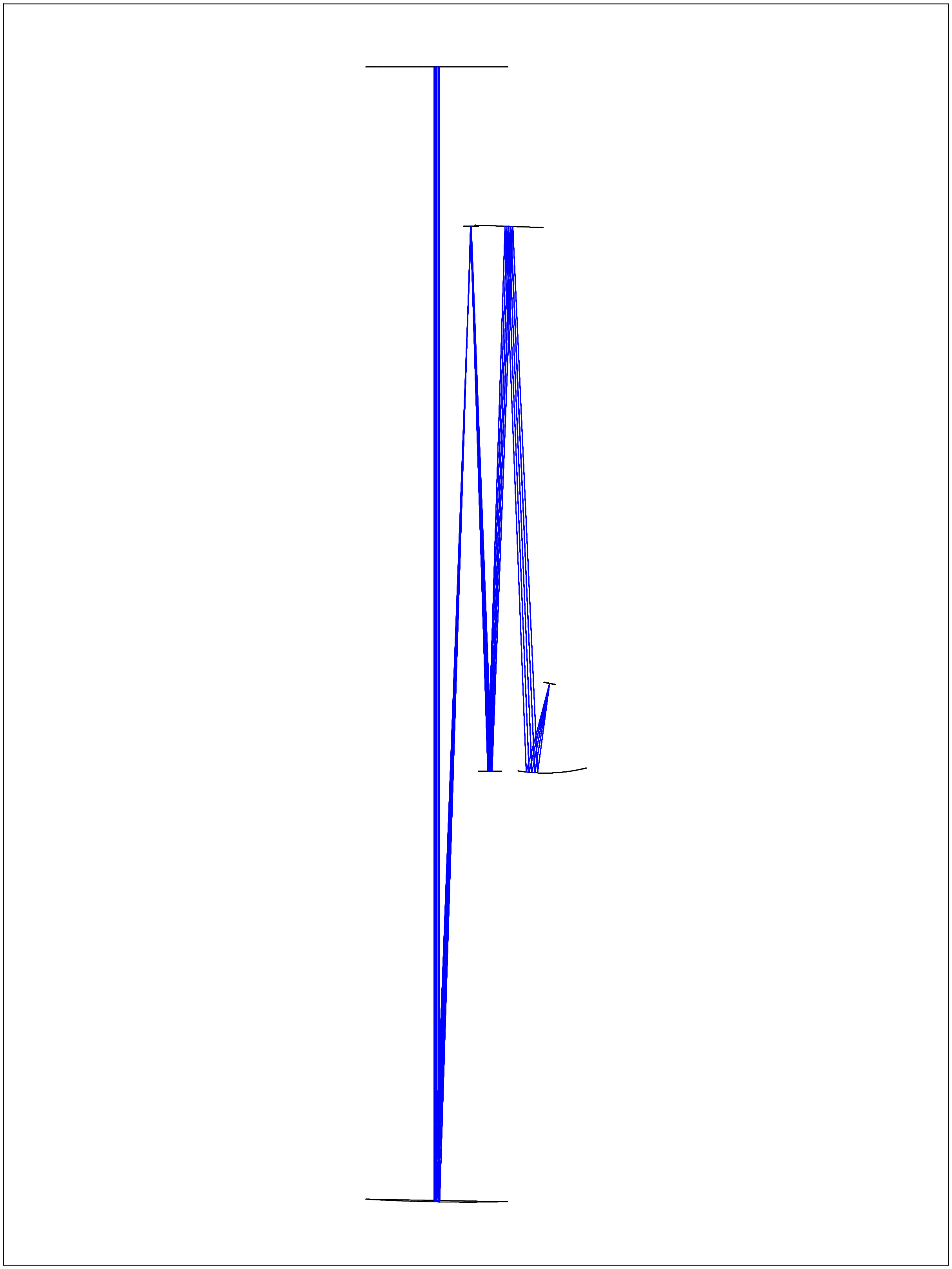

Figure 1.3: View of the I4 design seen in the yz plane.

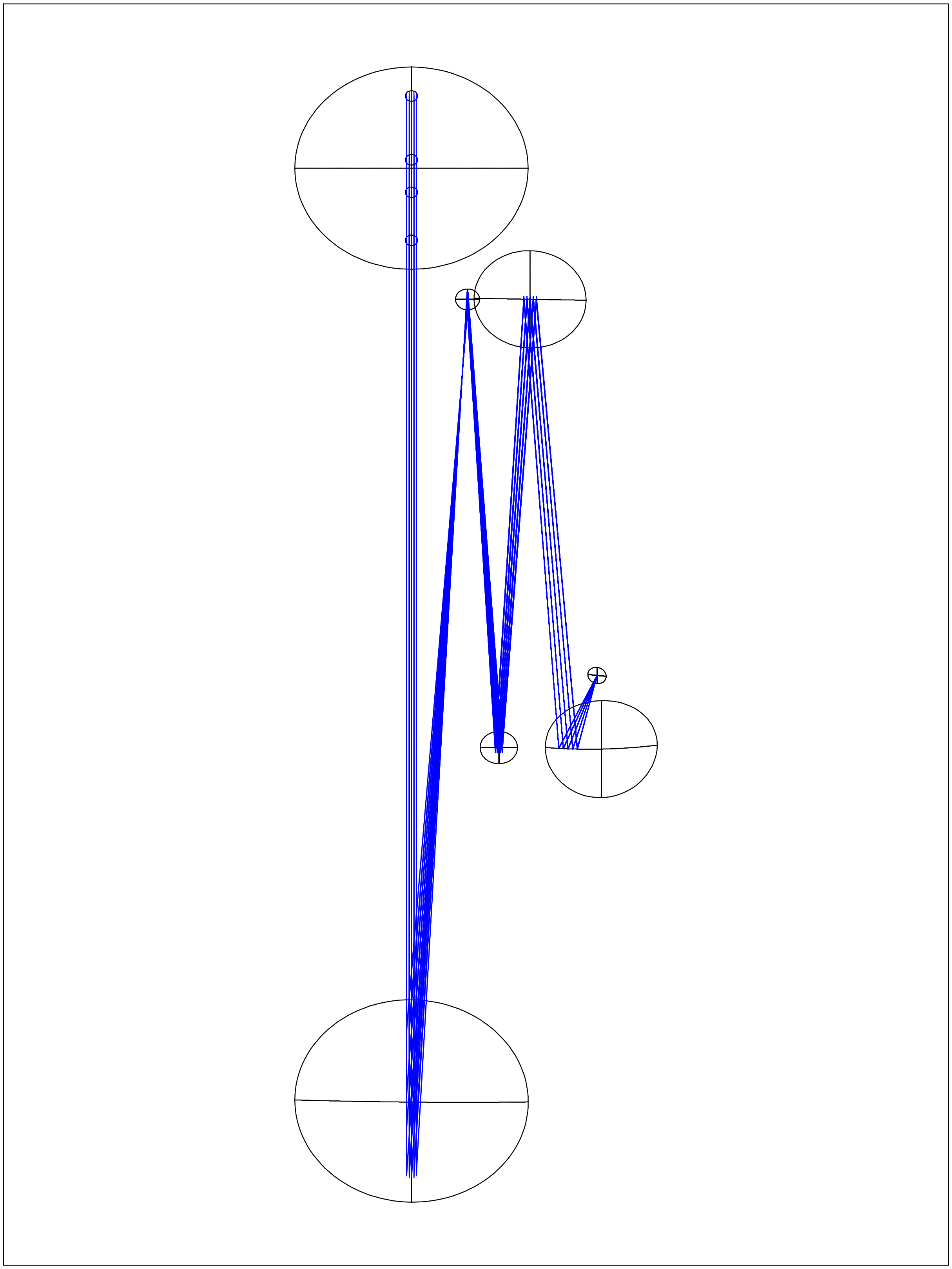

Figure 1.4: View of the rotated I4 design.

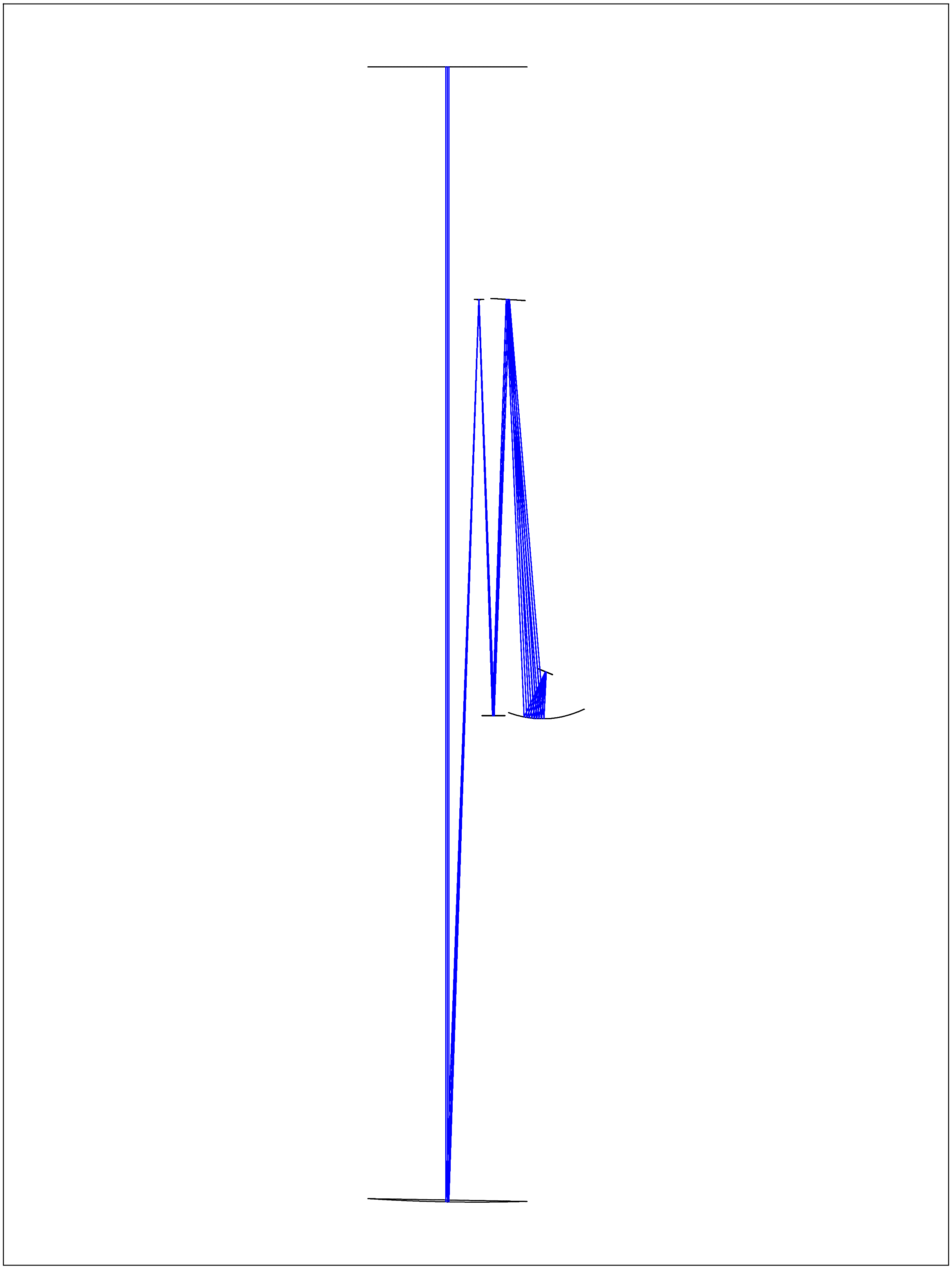

Figure 1.5: View of the I6 design seen in the yz plane.

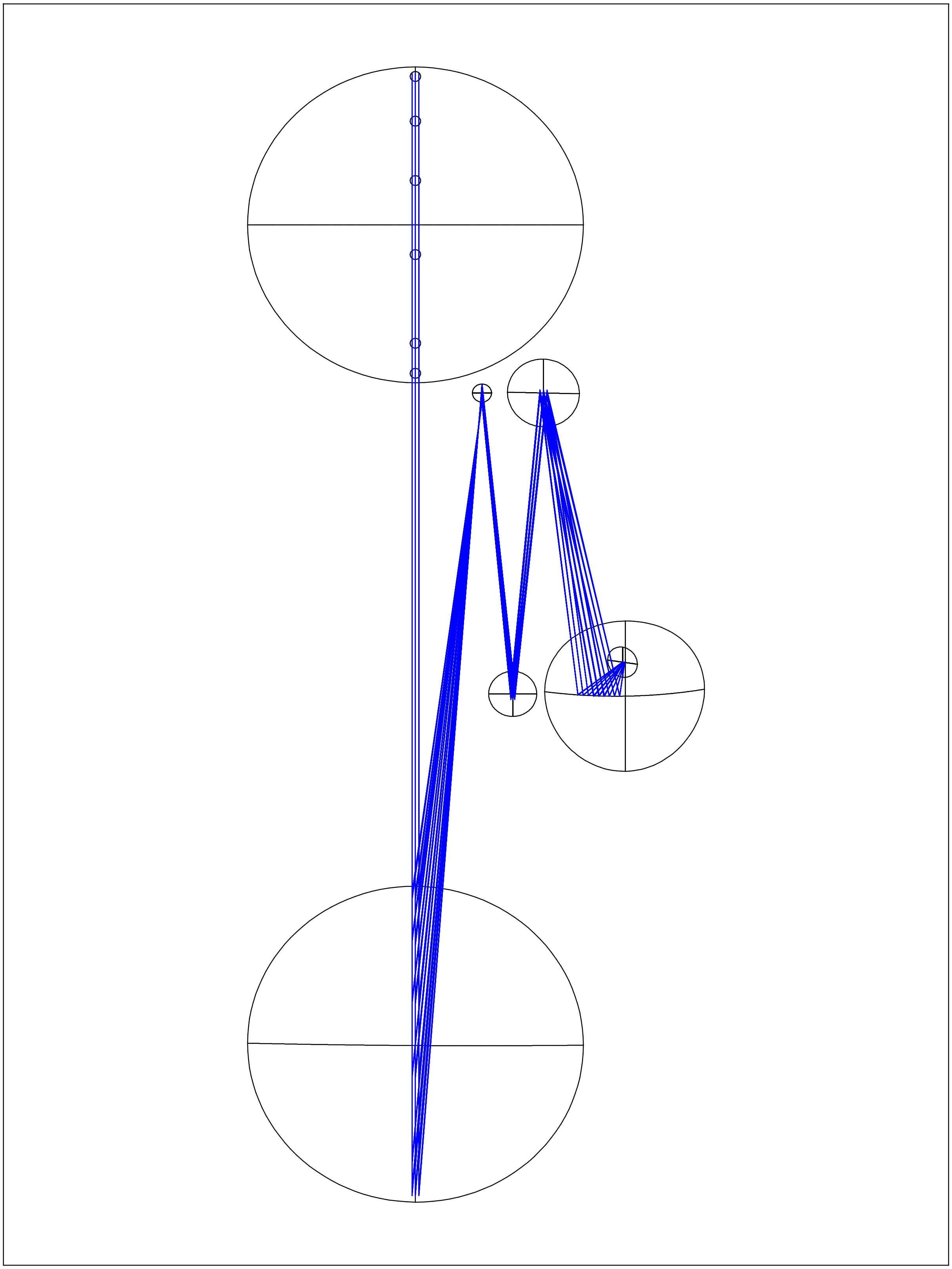

Figure 1.6: View of the rotated I6 design.