MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Introduction to multi-channel spectrometers

O. P. Ford

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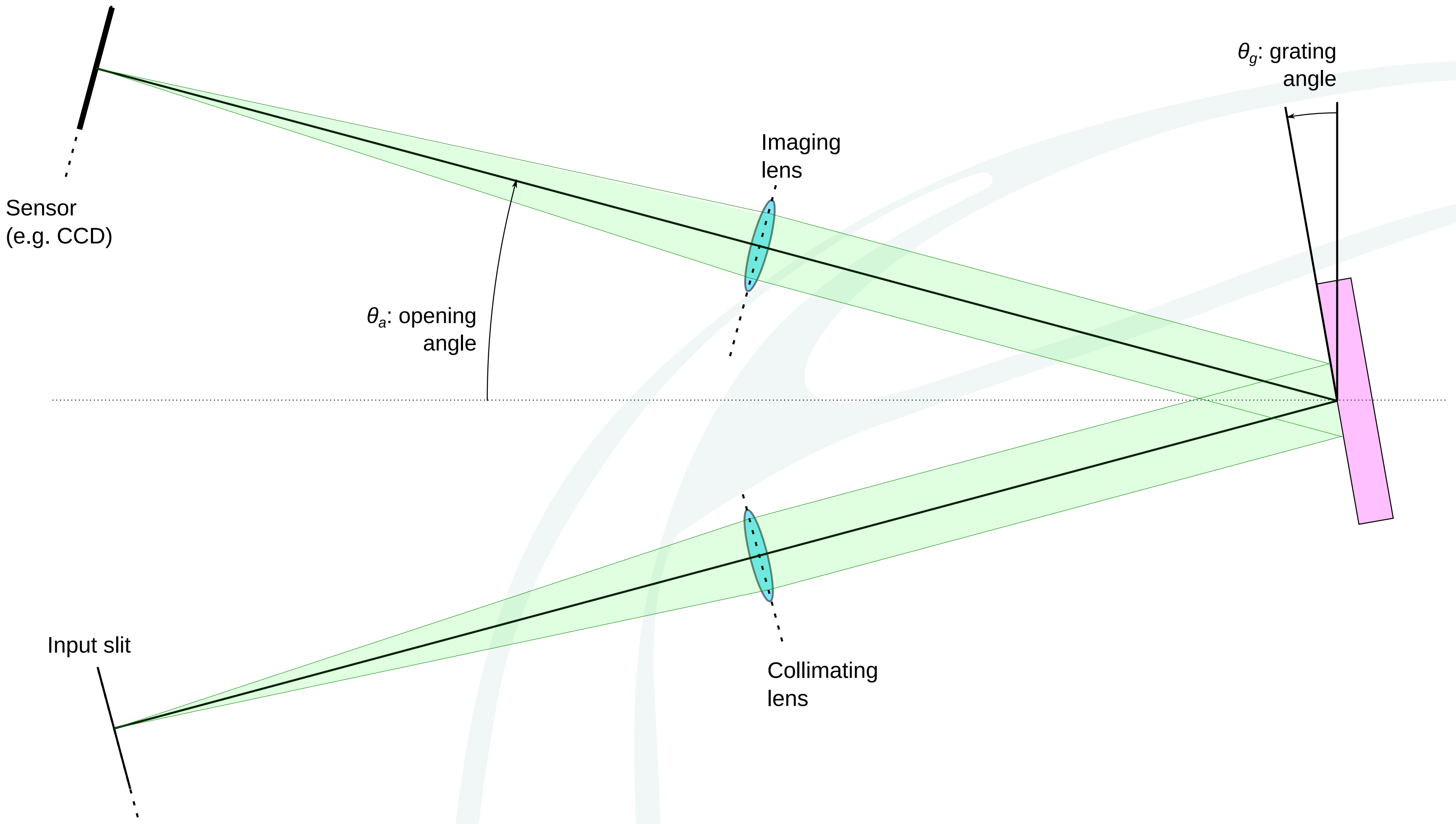
Introduction

Short introduction to multi-channel spectrometers:

- Basic principles
- Configuration and design
- Set-up
- Alignment
- Calibration

Principle

Simple spectrometers usually based on a slit and a diffraction grating.
Usually fixed input and output arms with rotating reflection grating.



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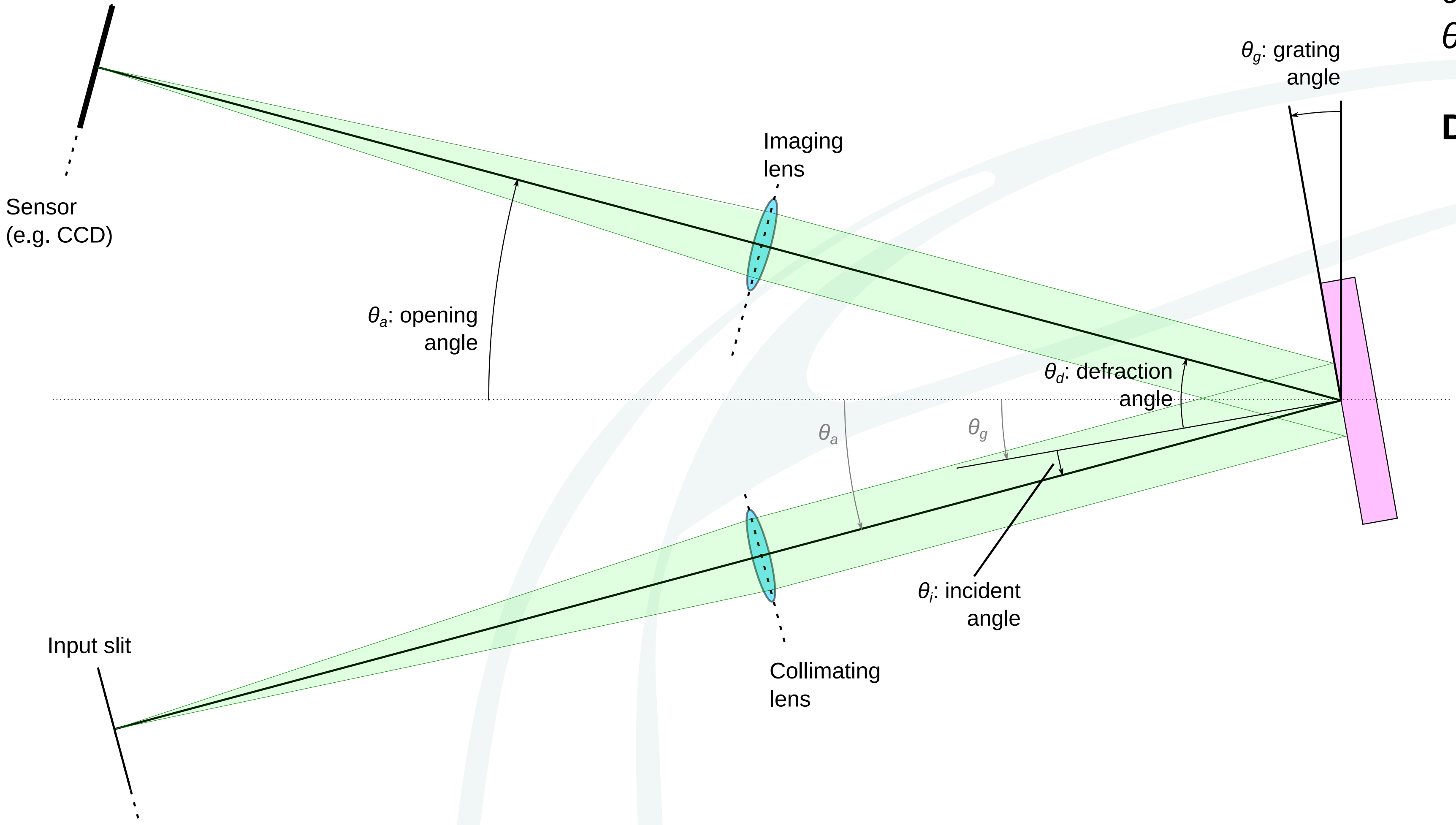

Incidence and diffration angles:

$\theta_d = \theta_a + \theta_g.$ $\theta_a = (\theta_d + \theta_i)/2$

$\theta_i = \theta_a - \theta_g.$ $\theta_g = (\theta_d - \theta_i)/2$

Diffraction equation:

$$\sin \theta_d - \sin \theta_i = k\, n\, \lambda$$

k = diffraction order
(use +1 or -1, otherwise a filter is required to select the order)
n = grating grooves [m^{-1}]
λ = wavelength [m]

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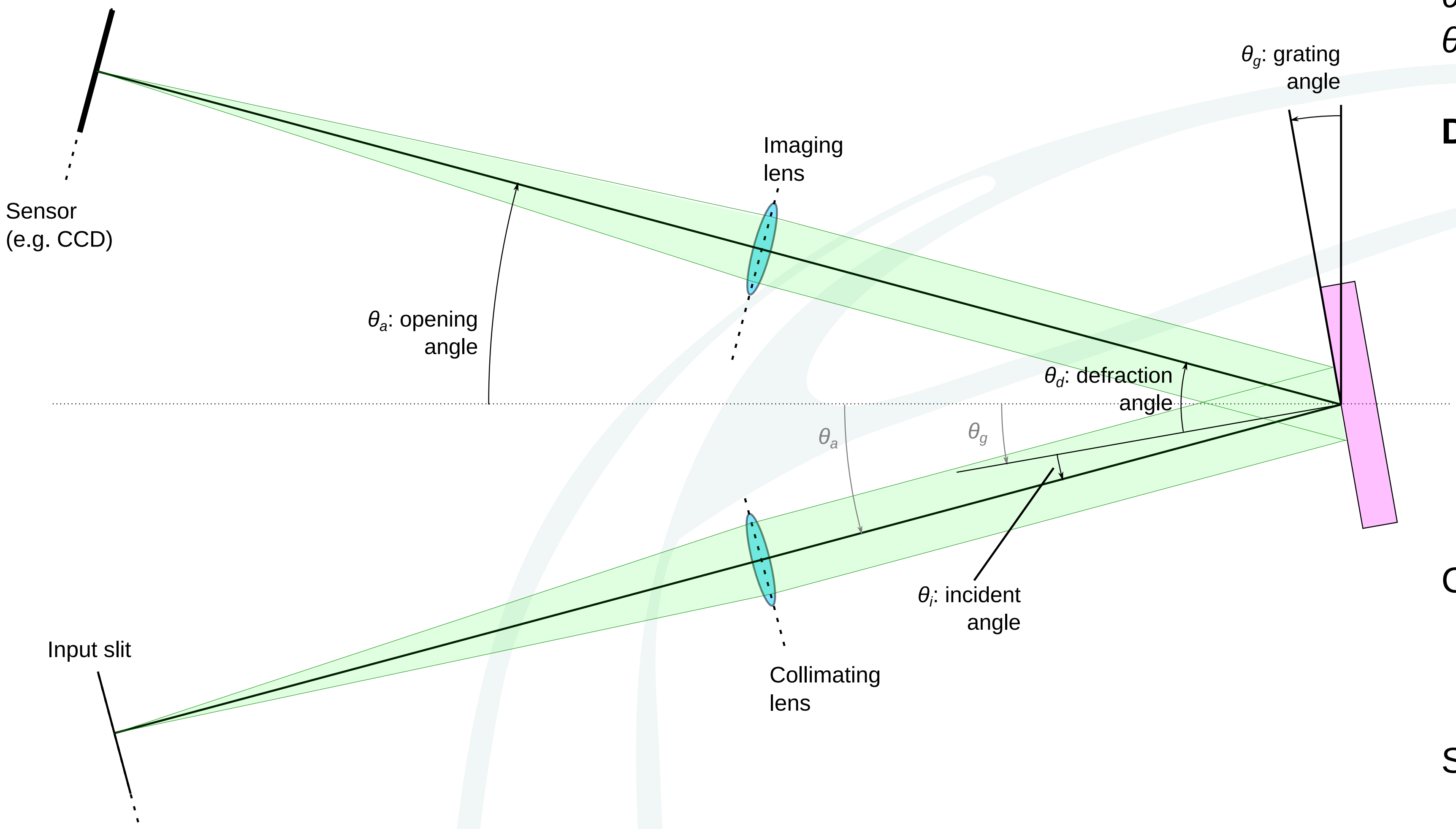

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Central wavelength:

$\sin(\theta_a + \theta_g) - \sin(\theta a - \theta g) = k\,n\,\lambda$

$\lambda = 2\cos\theta_a \sin\theta_g / k\,n$

Setting of grating for given wavelength:

$\sin\theta g = k\,n\,\lambda / (2\cos\theta a)$

Wavelength range

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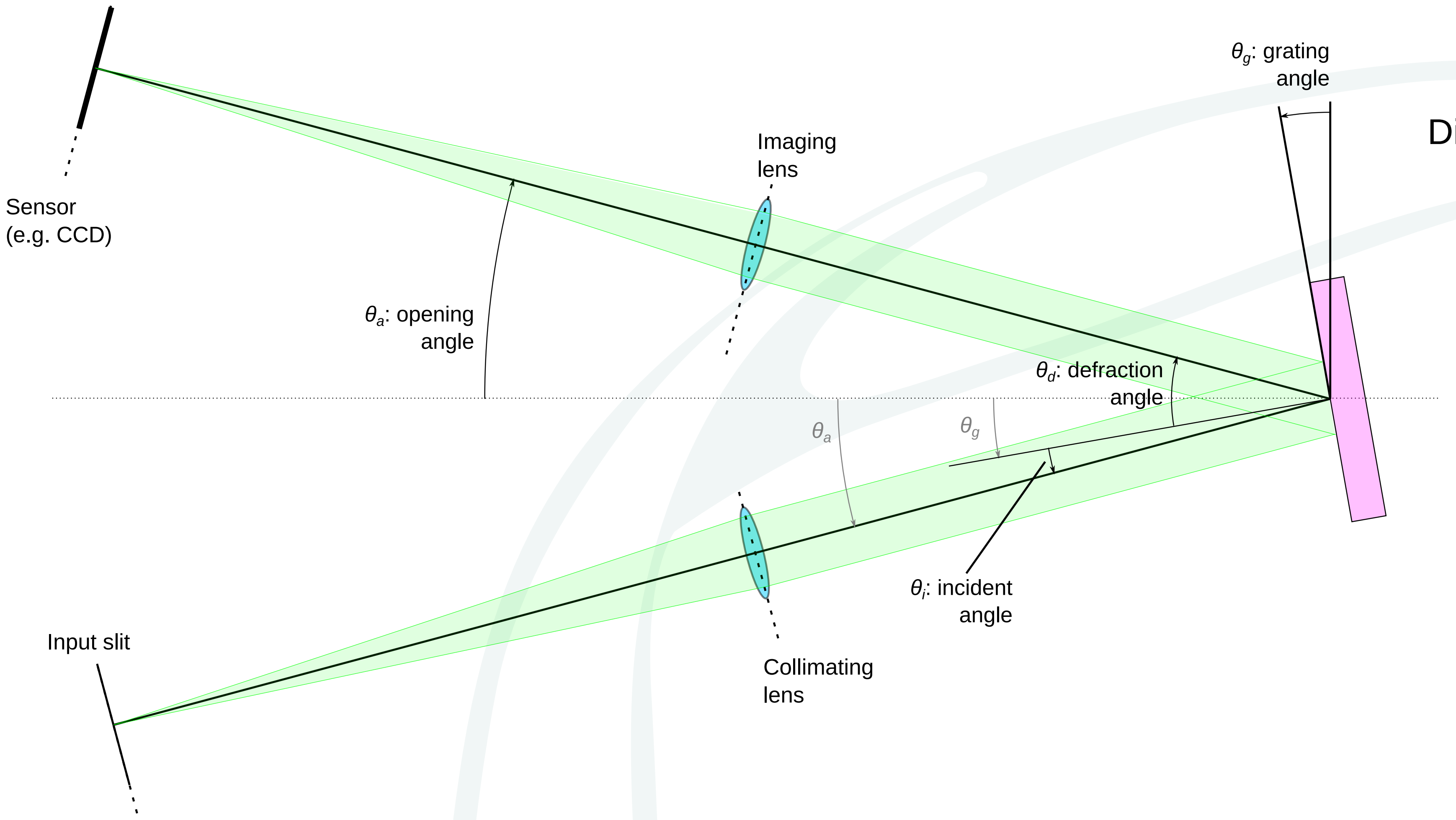

Dispersion:
$d\lambda/d\theta_d = \cos(\theta_a + \theta_g) / k\, n$

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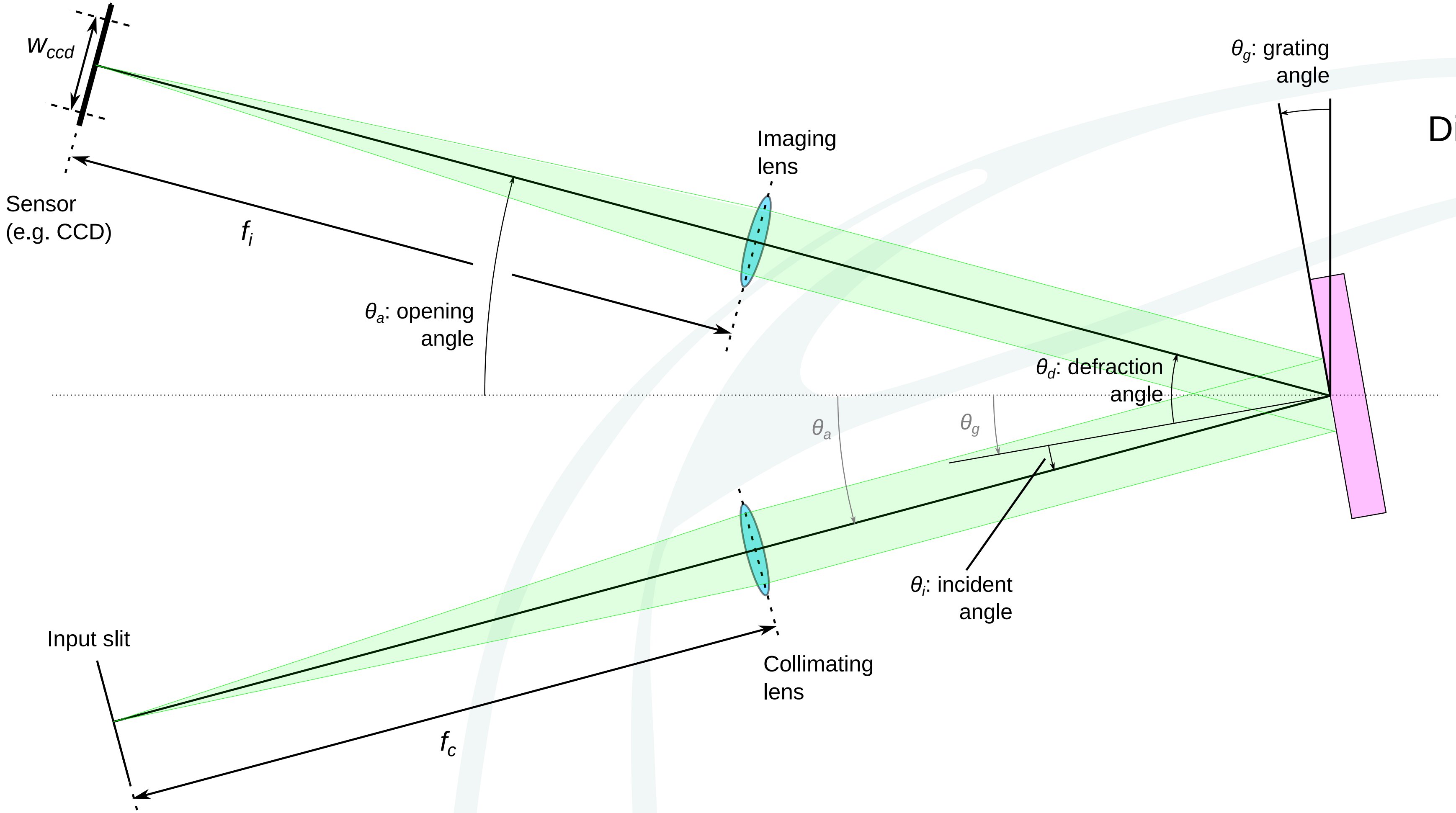

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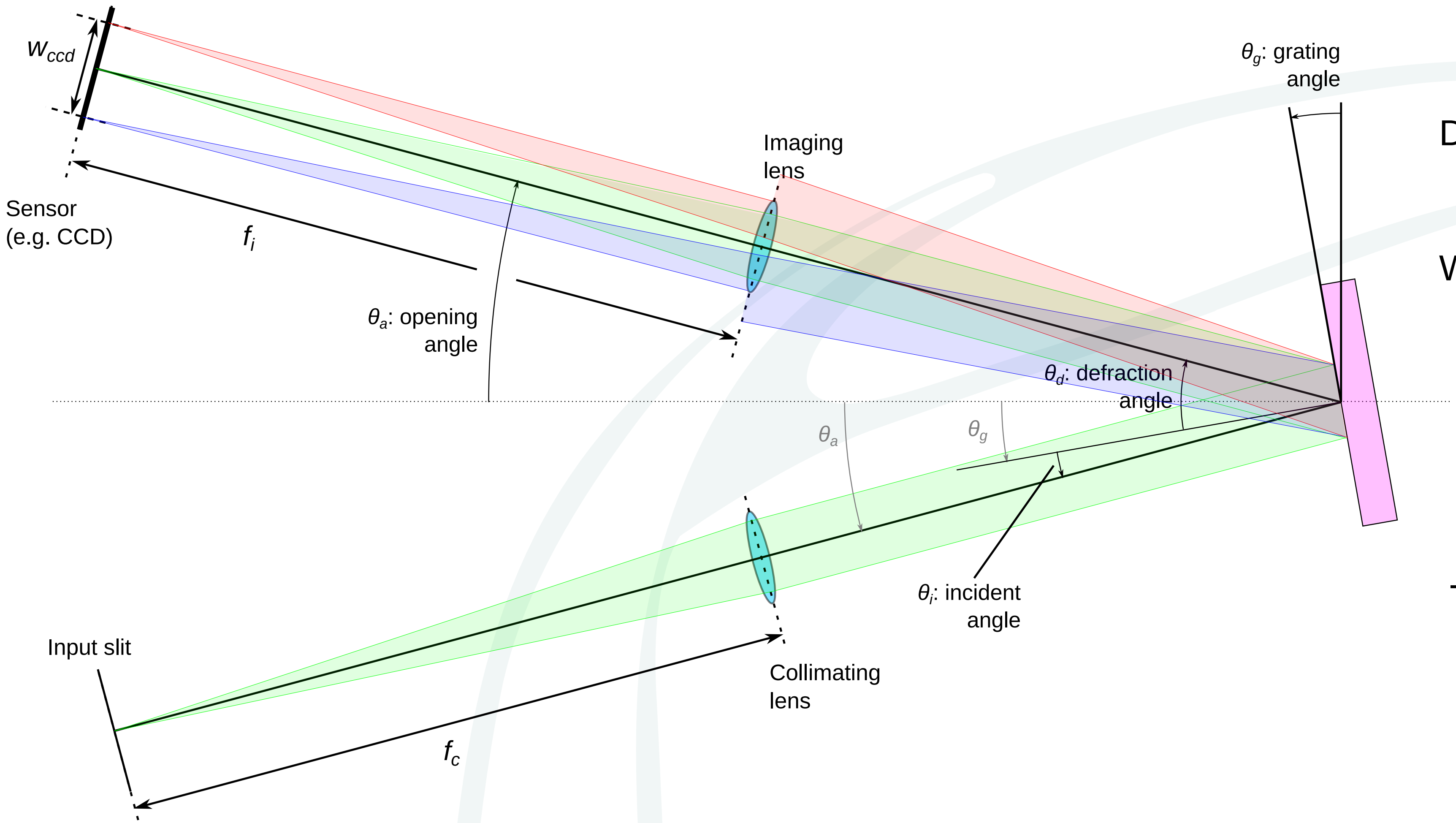

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$$\sin \theta_d - \sin \theta_i = k\, n\, \lambda$$

Dispersion:

$d\lambda/d\theta_d = \cos(\theta_a + \theta_g) / k\, n$

Wavelength range on sensor:

$\Delta\lambda = d\lambda/d\theta_d \ . \ w_{ccd} / f_i$

$= w_{ccd} / f_i \cos(\theta_a + \theta_g) / k\, n$

$= w_{ccd} / f_i \, [\ (1 - \tfrac{1}{4}k^2n^2\lambda^2)^{1/2} / kn$

$- \theta_a \tfrac{1}{2} \lambda$

$- \theta_a^2 / (kn\,(4 - k^2n^2\lambda^2)^{1/2})\ ]$

--> Weird function of θ_a and λ:

- larger θ_a
- larger λ
- larger n
- larger k

} higher resolution / less wavelength range

Wavelength range

Wavelength range on sensor:

$\Delta\lambda = \lambda\, w_s/f_i\, [\, \mathrm{sqrt}(\, 4 \cos^2 \theta_a / k^2 n^2 \lambda^2 \;-\; 1) - \tan \theta a\,] / 2$

Example: AUG1/2 with PI ProEM 1024x:
(CXRS narrow range for single line)

$k = 1$

$n = 2400\ \mathrm{mm}^{-1}$

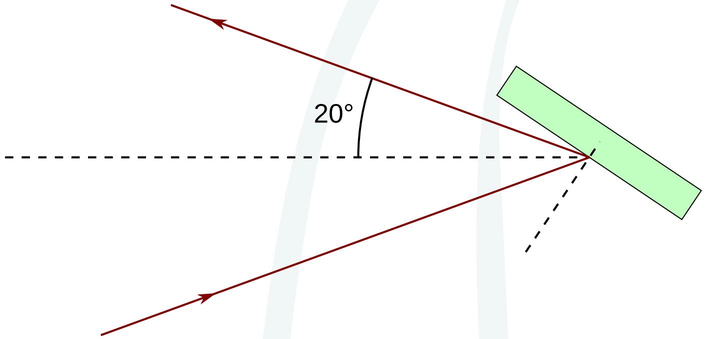
$\theta_a = 20°$

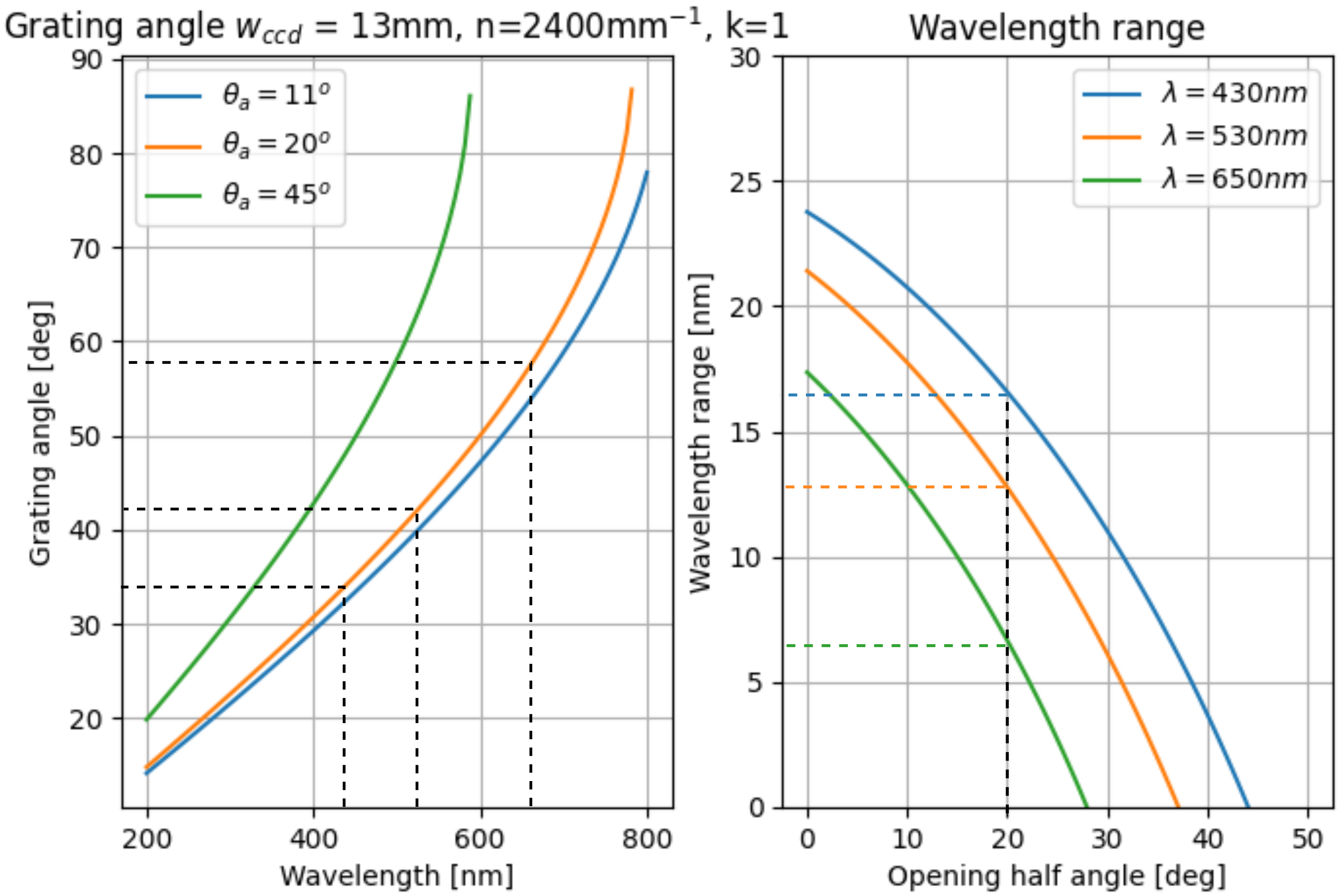
$w_{ccd} = 1024 \times 13\mu m = 13.3mm$

$f_i = 200mm$

λ [nm]	**θ_g [°]**	**Δλ [nm]**
430	33.3	16.5
530	42.6	12.8
650	56.1	6.7

(θ_i is -ve!)





Wavelength range

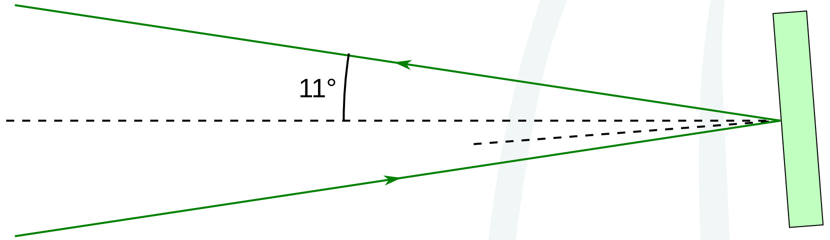
Wavelength range on sensor:

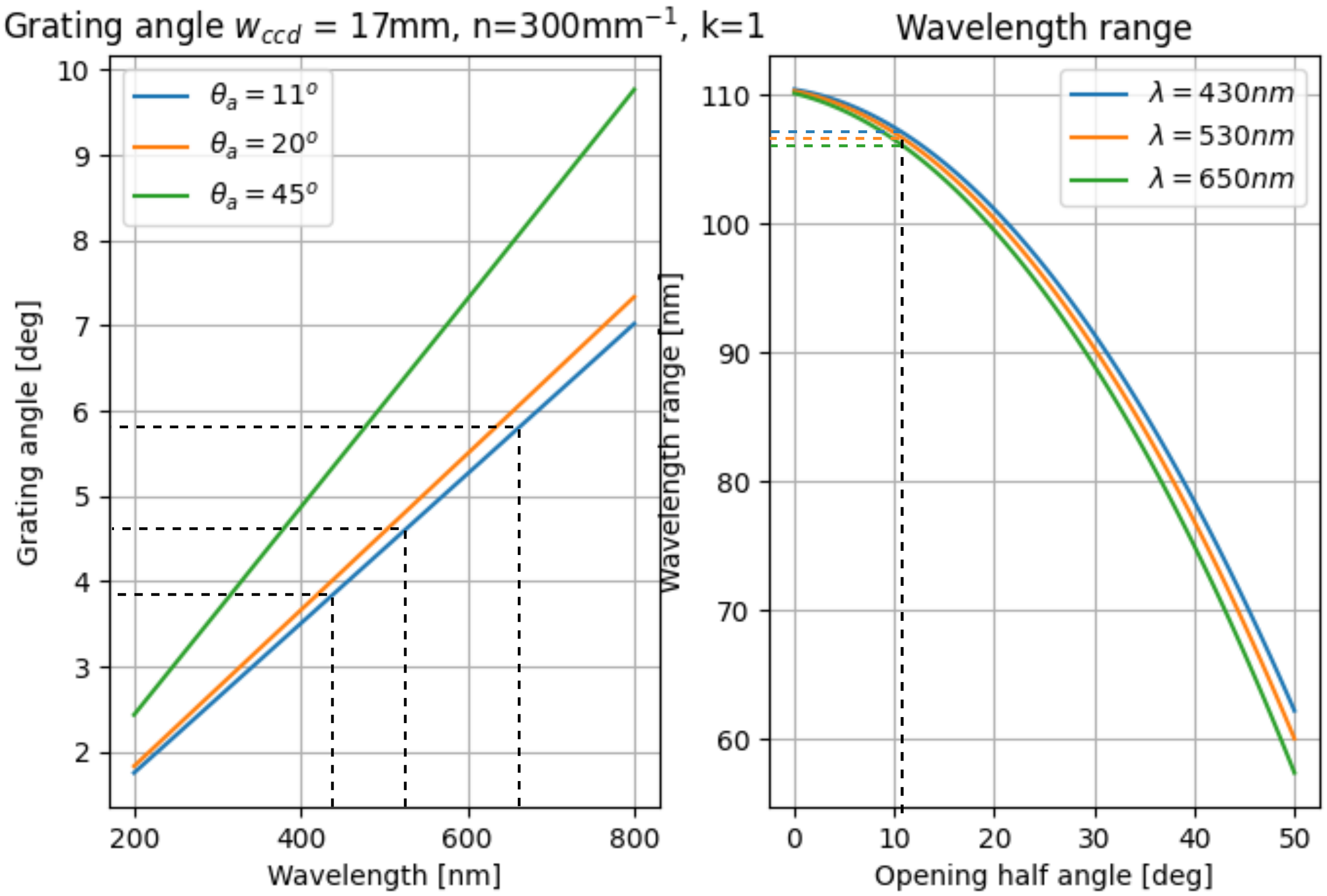
$\Delta\lambda = \lambda\, w_s/f_i\, [\, \mathrm{sqrt}(\, 4 \cos^2 \theta_a / k^2 n^2 \lambda^2 \;-\; 1) - \tan \theta a\,] / 2$

Example 2: SpexM500 with PCO Edge
for wide overview spectrum:

$k = 1$
$n = 300\ \mathrm{mm}^{-1}$
$\theta_a = 10°$
$w_{ccd} = 2560 \times 6.5\mu m = 16.6mm$
$f_i = 500mm$

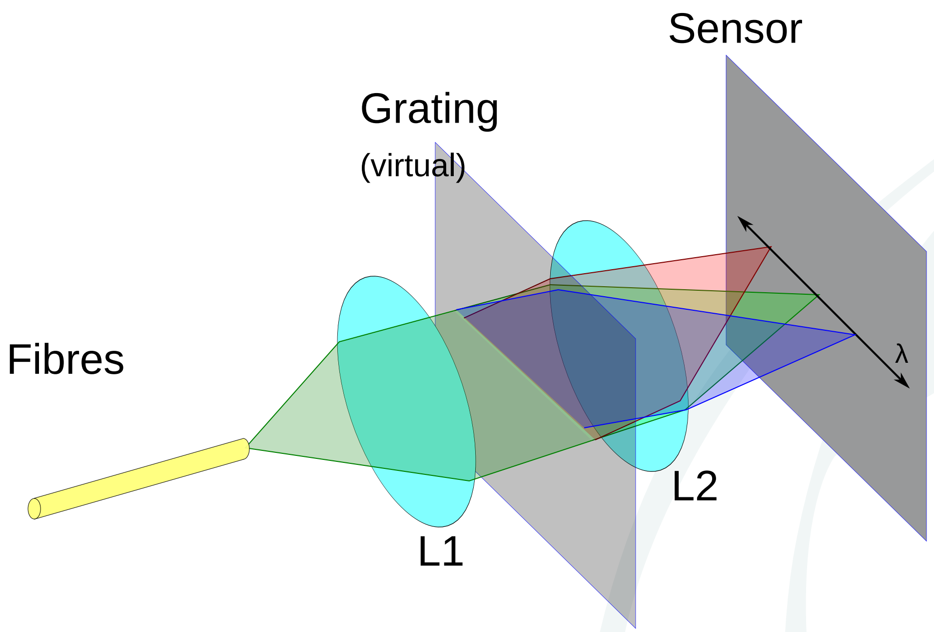
λ [nm]	**θ_g [°]**	**Δλ [nm]**
430	3.9	107
530	4.6	107
650	5.8	106





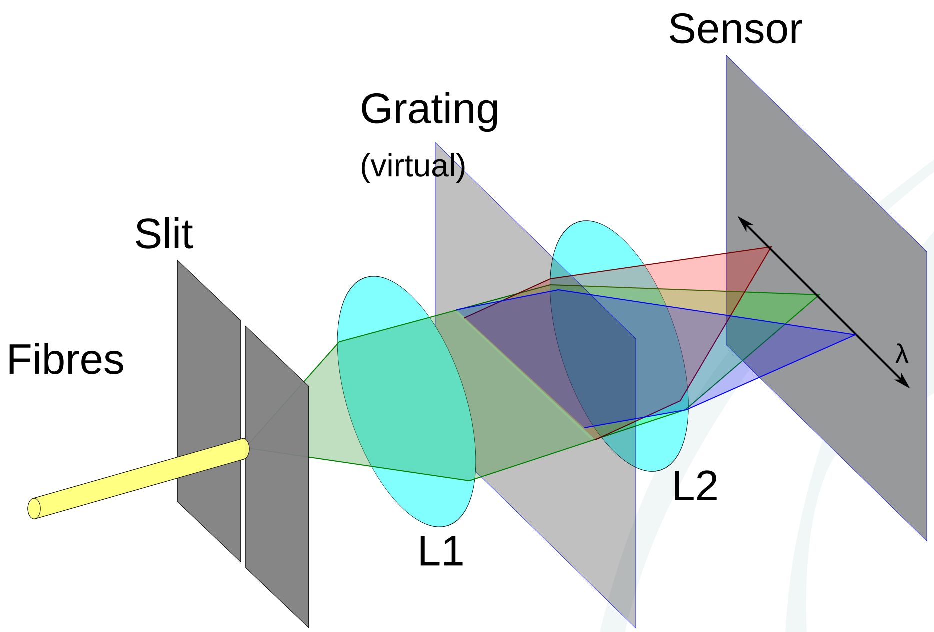
Multi-channel vertical

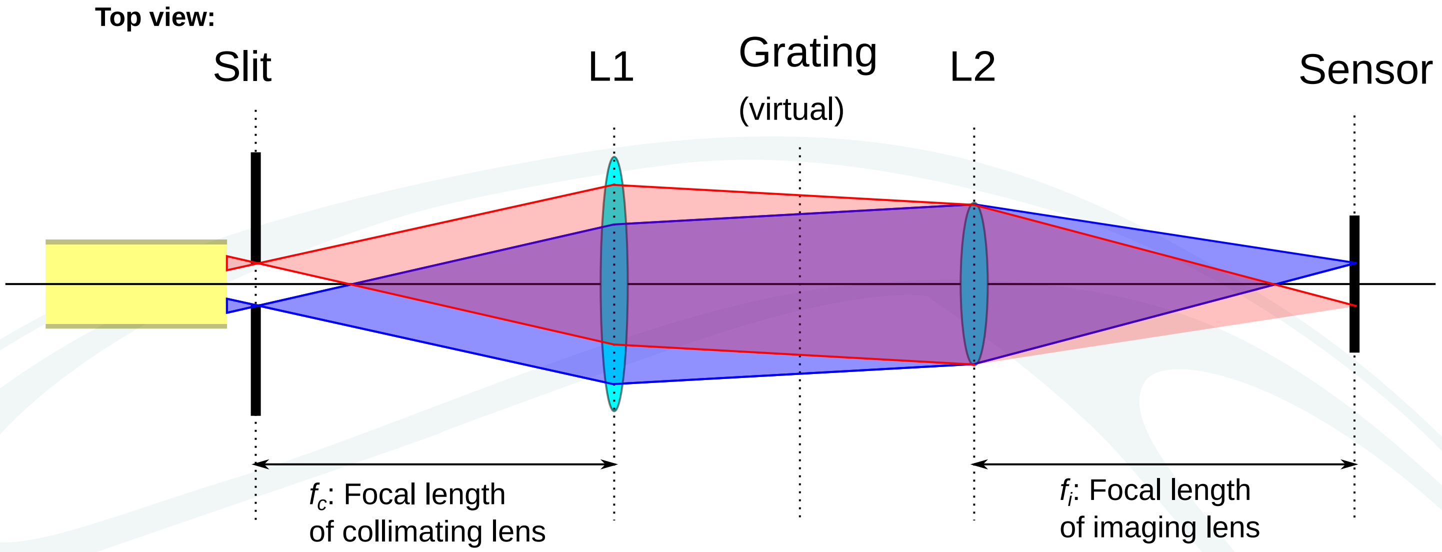
Simple multi-channel: Diffraction direction in horizontal plane.



Multi-channel vertical

Simple multi-channel: Diffraction direction in horizontal plane.
- Slit placed in front of input fibres to limit width.
- Slit imaged onto sensor in horizontal plane.

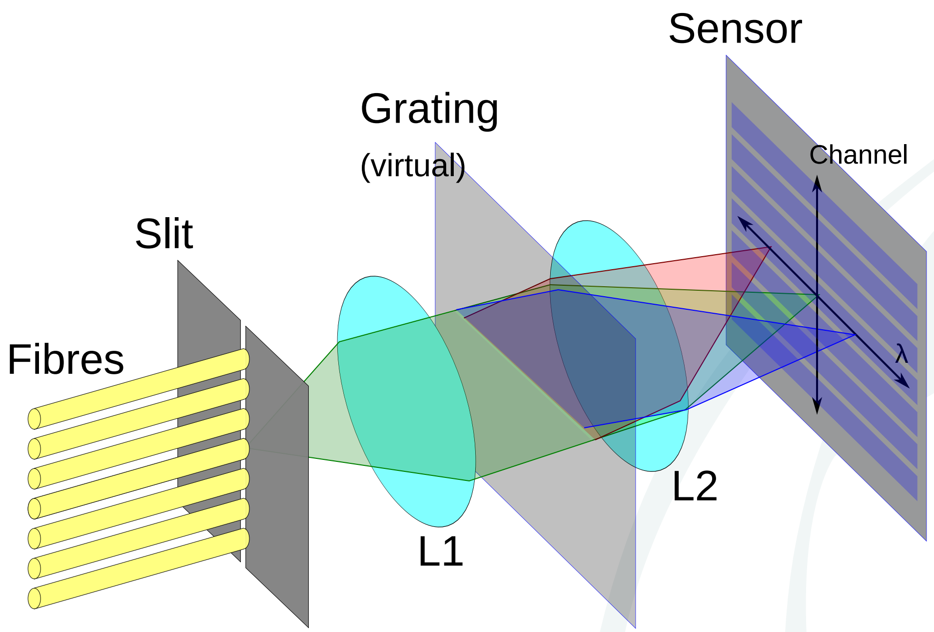


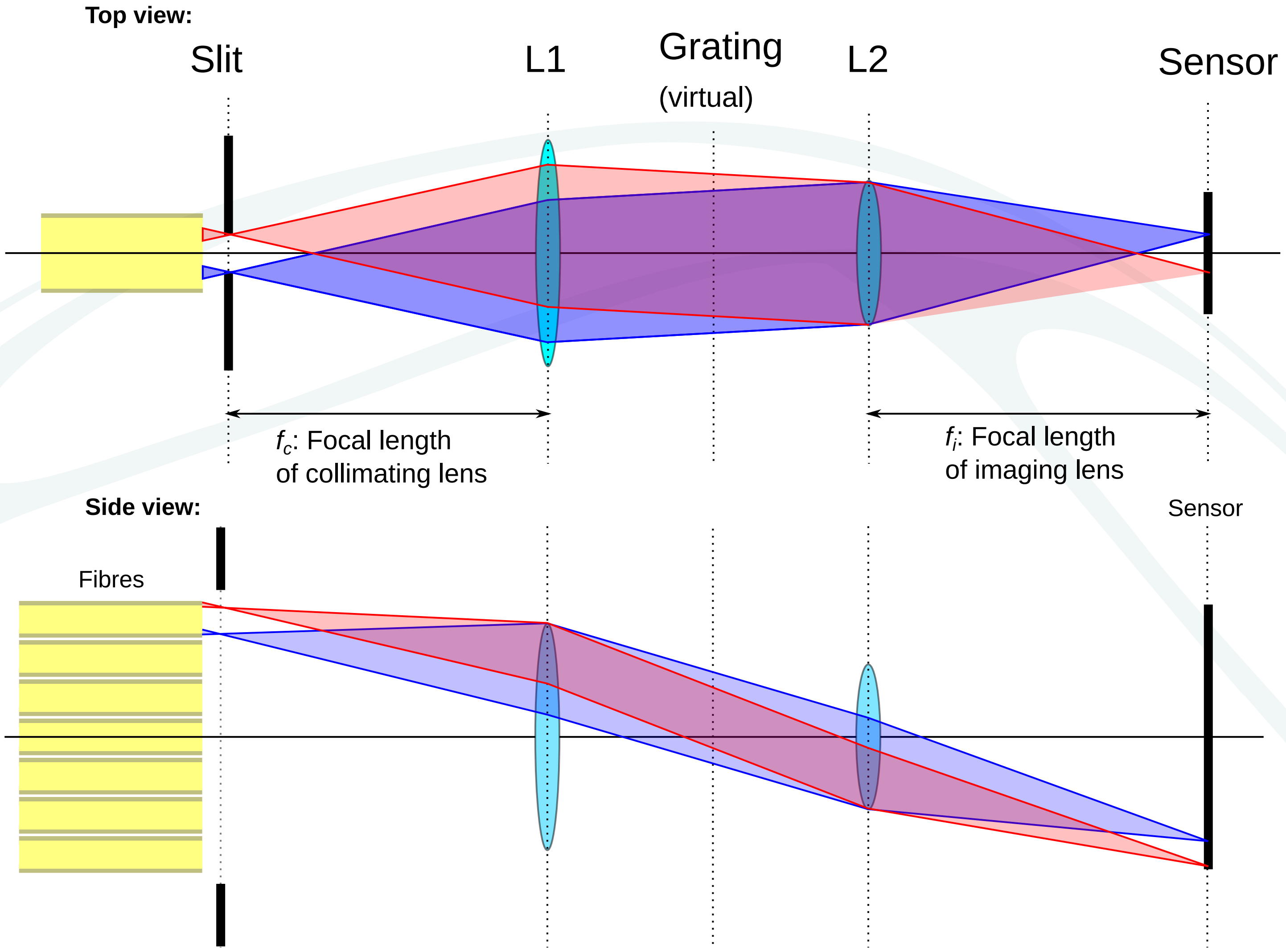


Multi-channel vertical

Simple multi-channel: Diffraction direction in horizontal plane.

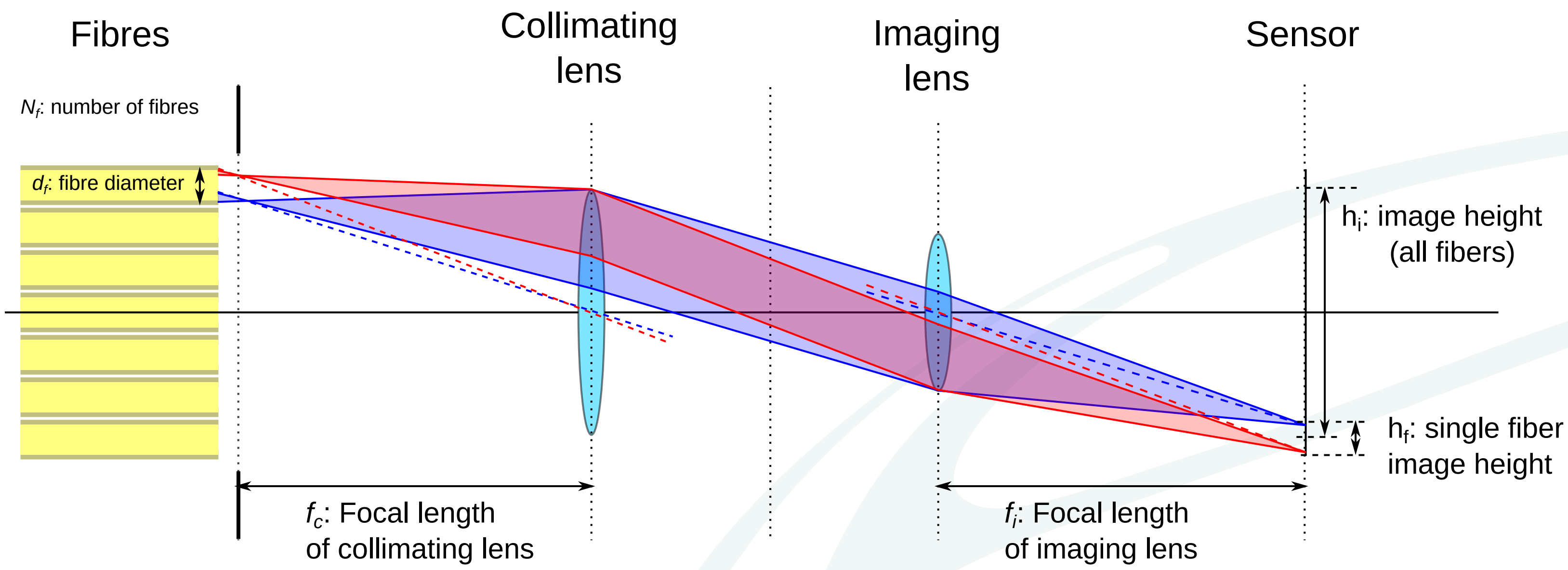
- Slit placed in front of input fibres to limit width.
- Slit imaged onto sensor in horizontal plane.
- Multiple fibres imaged onto sensor in vertical plane.





Magnification

Magnification is set by ratio of imaging and collimating lens.



Magnification: $M = f_i / f_c$
Image height: $h_i = M * (N_f * d_f)$
Fibre image size: $h_f = M * d_f$

--> Number of fibers limited by sensor height and ratio of focal lengths.

$$N_f = h_i f_c / (f_i * d_f)$$

Resolution

Magnification and slit width determine wavelength resolution:

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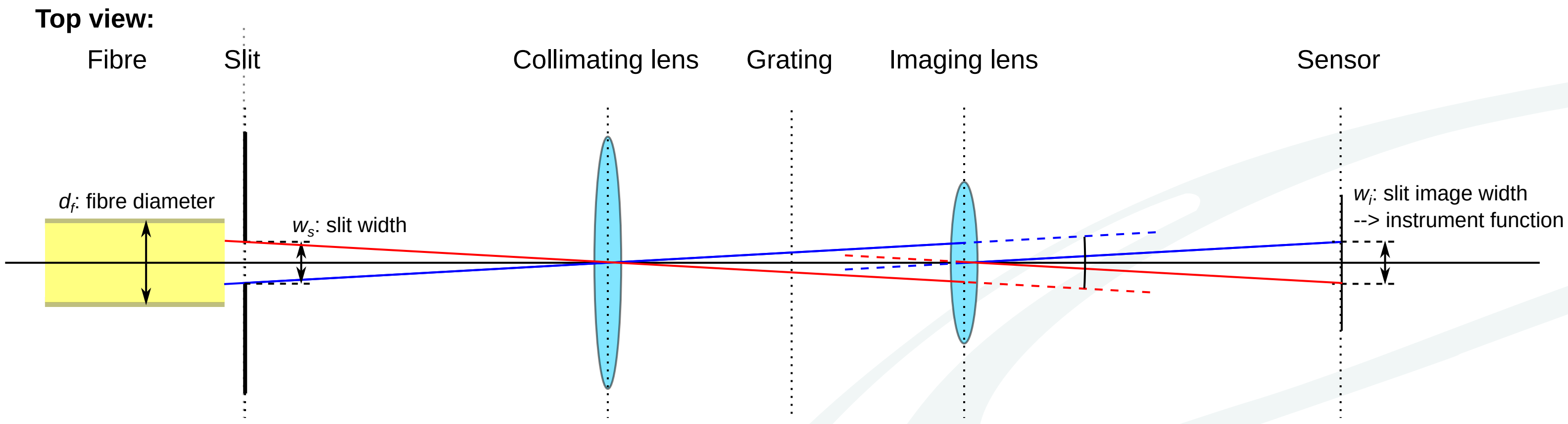


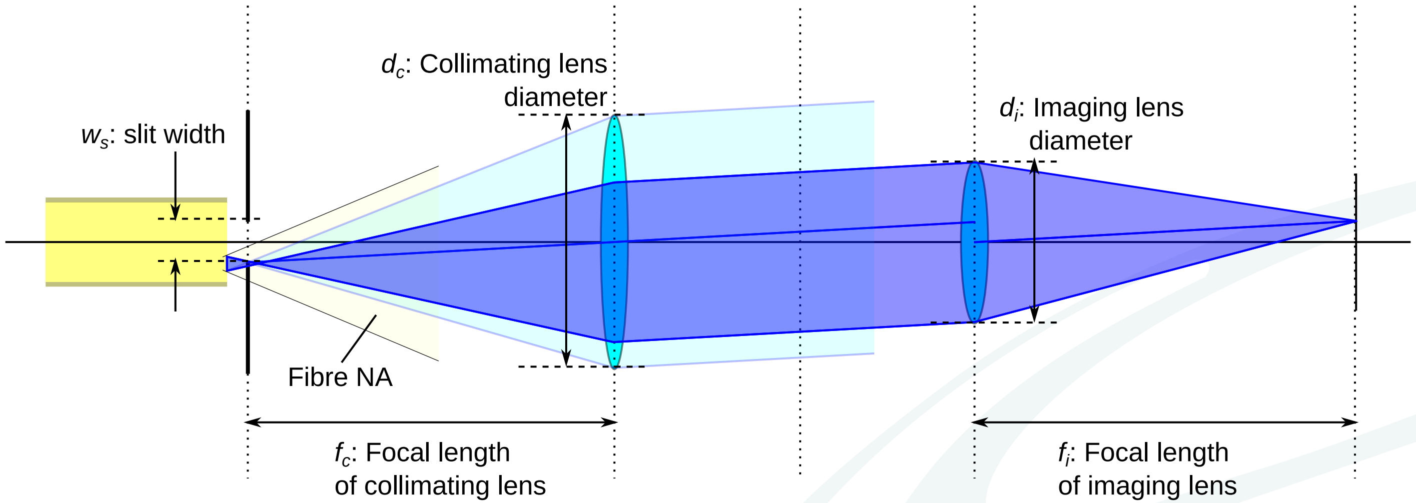
Instrument function width: $w_i = M * w_s$

As wavelength range: $\delta\lambda = cos(\theta_a + \theta_g)\ .\ w_s / (f_c\ k\ n)$

--> Wavelength resolution set by slit width and collimating lens focal length

Throughput / Étendue

Throughput is determined by lens sizes and focal lengths:



Assuming $NA > d_c / f_c$ and d_i / f_c

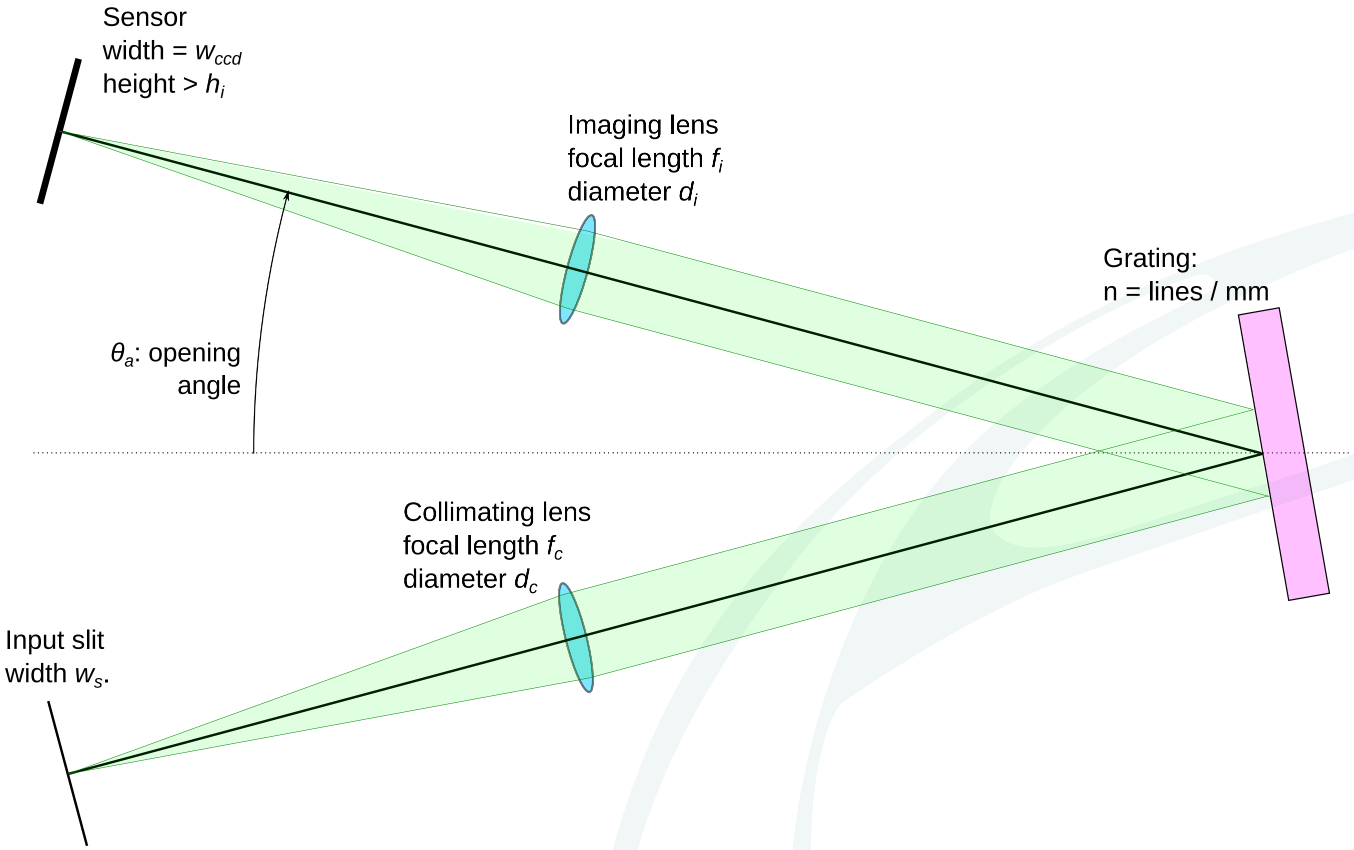
Étendue = $d_f \, . \, w_s \, . \, \min(d_c , d_i)^2 / \; f_c$

--> Best signal with short focal length collimating lens and wide slit.

Caveat: Diffraction grating efficiency usually reduces with higher n

Configuration

Complete balance of configuration parameters:



Resolution:
$\delta\lambda = A\, w_s / f_c$

Range:
$\Delta\lambda = A\, w_{ccd} / f_i$

Throughput:
$I = d_f \,.\, w_s \,.\, \min(d_c, d_i)^2 / f_c$

Channels:
$N_f = h_i\, f_c / f_i\, d_f$

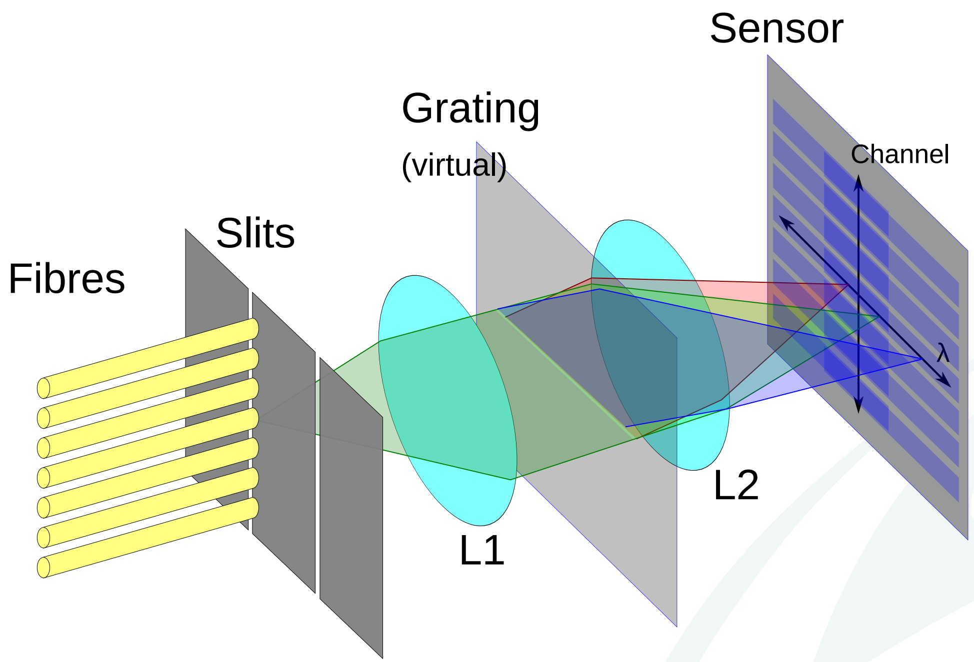
with $A(\theta_a,k,n,l) = (1 - \frac{1}{4}k^2n^2\lambda^2)^{1/2} / kn \;-\; \theta_a \,\frac{1}{2}\, \lambda \;-\; \theta_a^2 / (kn\,(4 - k^2n^2\lambda^2)^{1/2})$

Change	Resolution	Throughput	Range	Channels	Economy
Sensor ↑	–	–	↑	↑	↓
Lens Size ↑	–	↑	–	–	↓
f_i ↓ (const d_i)	–	–	↑	↑	↓
f_c ↓ (const d_c)	↓	↑	–	↓	↓
Grating n ↑	↑	–	↓	–	–
Slit width ↑	↓	↑	–	–	–

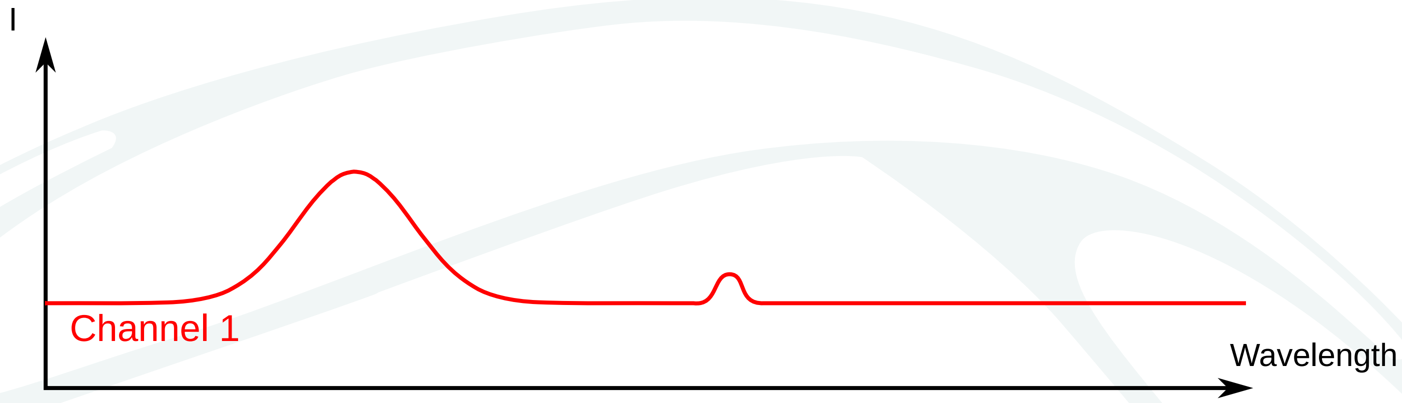
Gratings also have an efficiency that depends on wavelength, line density (n) and type.

Other Configurations

It is possible to add extra channels, overlapping in the wavelength direction:



This only works if the vicinity of the target line is free from other lines.
The spectra of overlapping channels add up, giving 2x background and hence higher noise:



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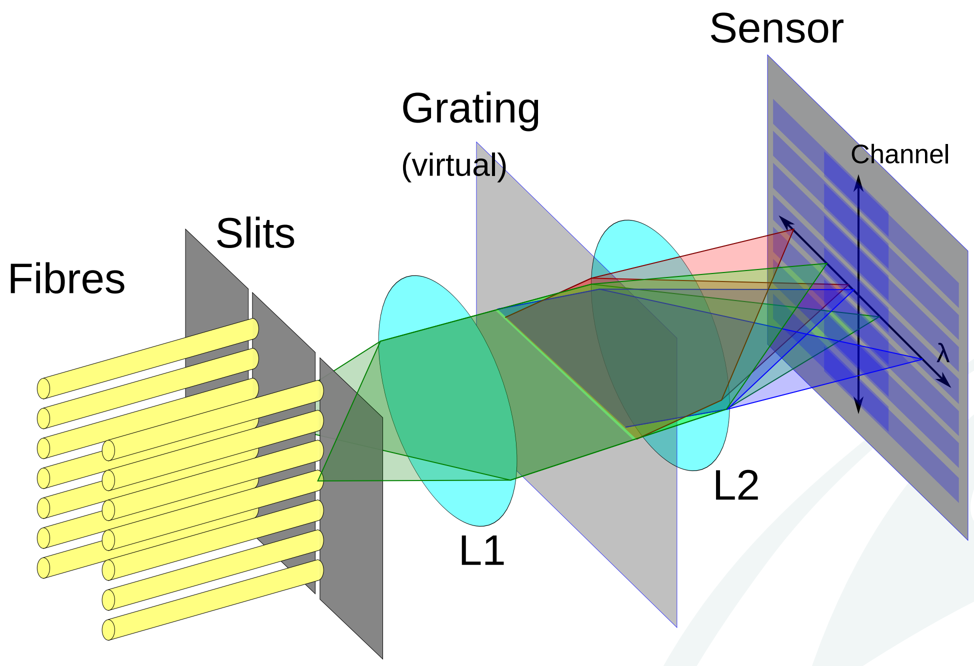

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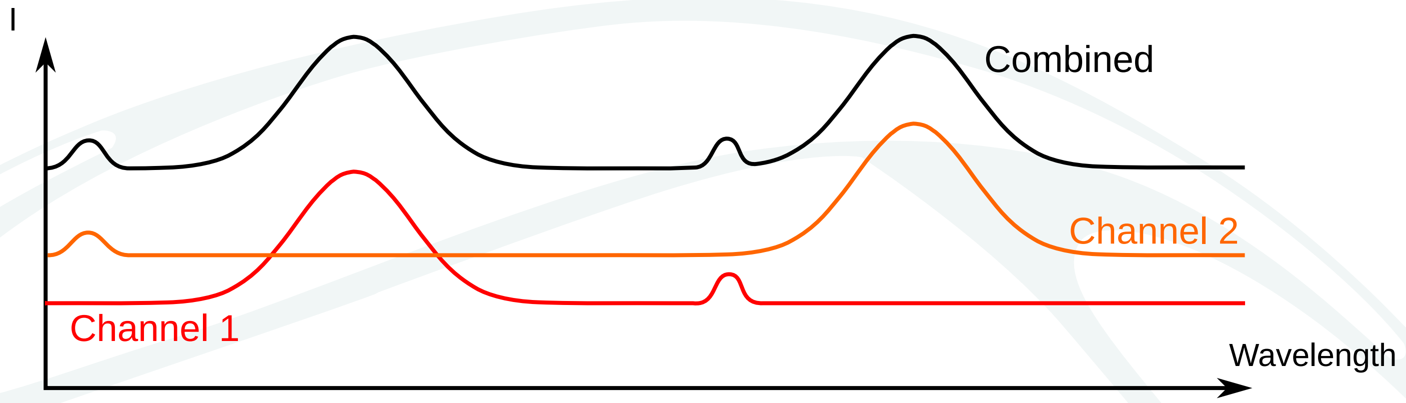

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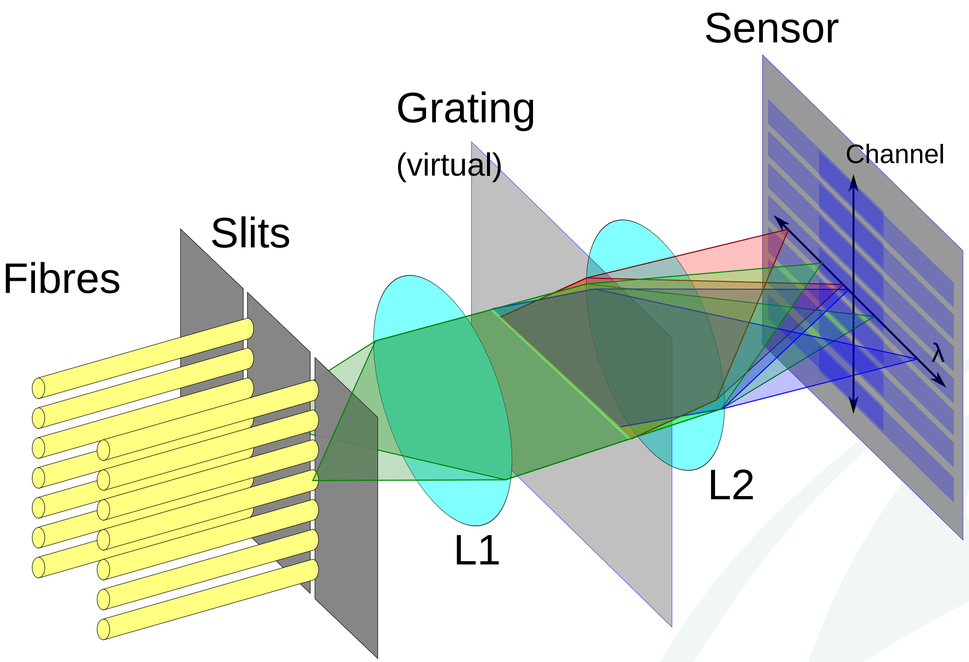

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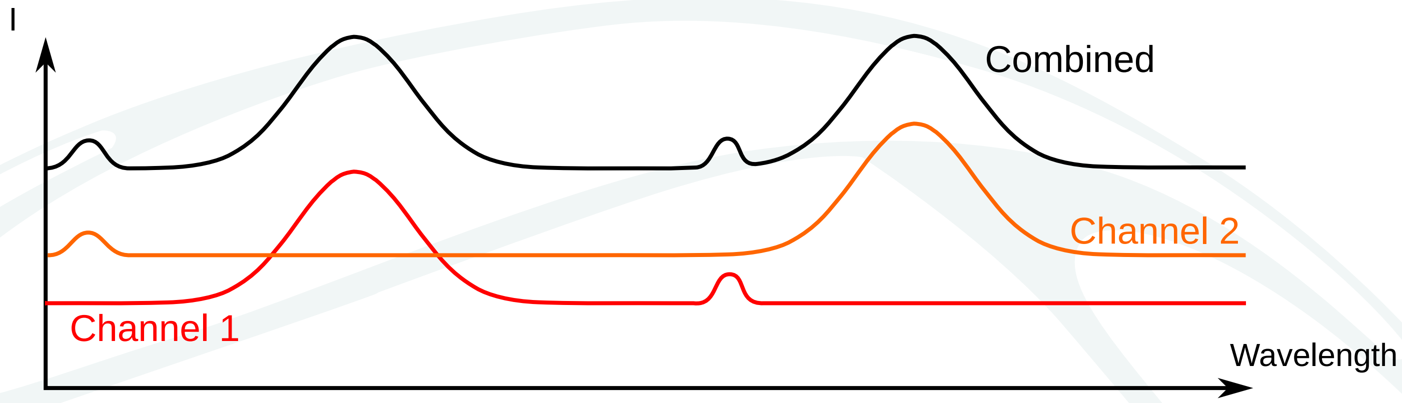
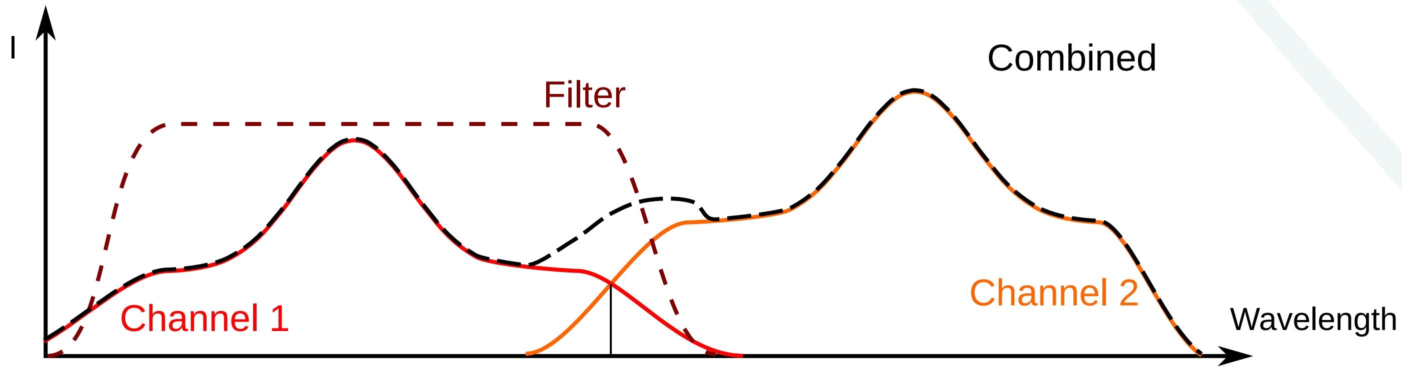


If too much contamination or noise is present, a bandpass filter can be added:



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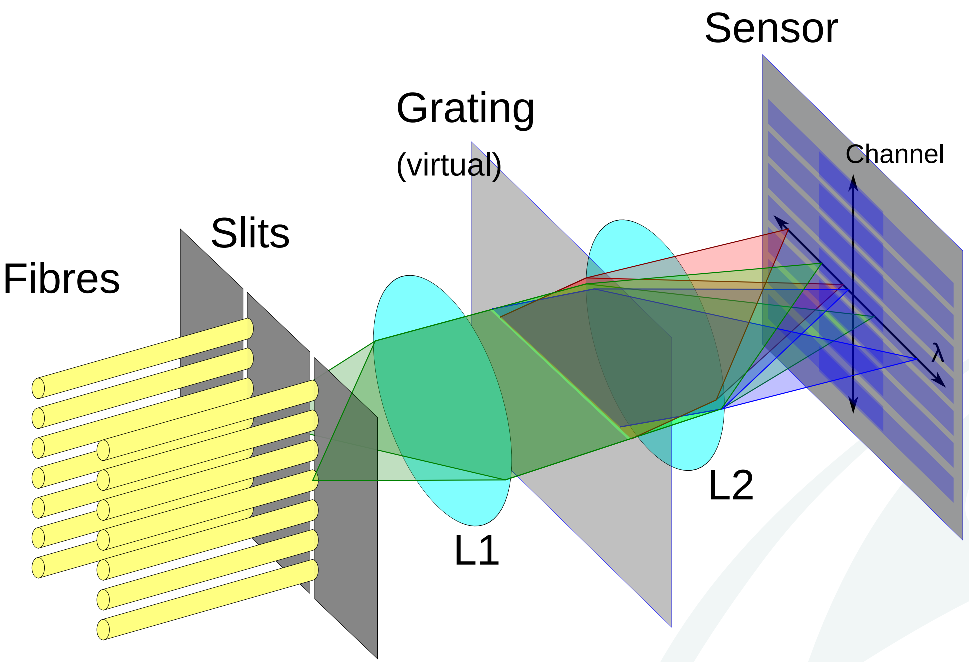

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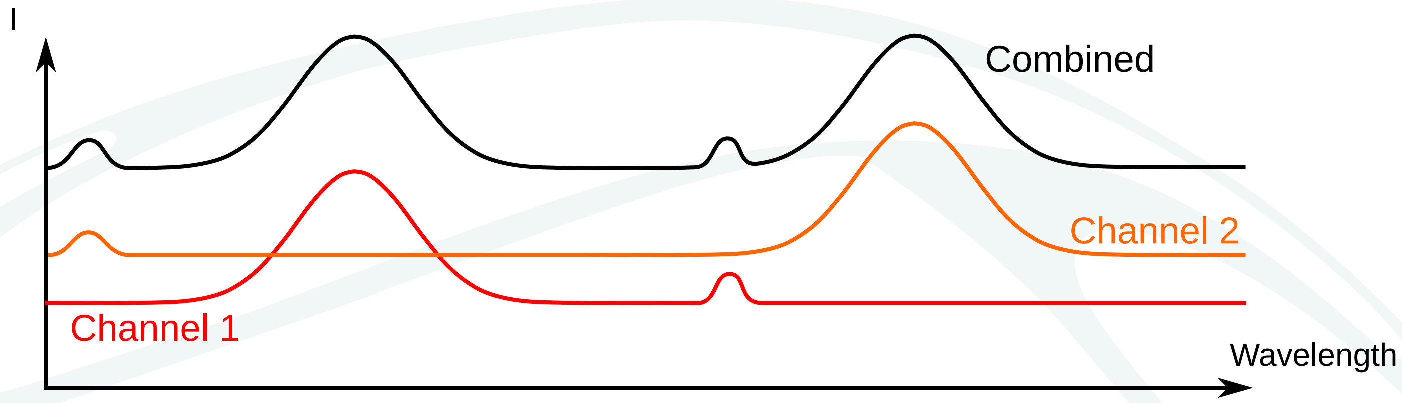

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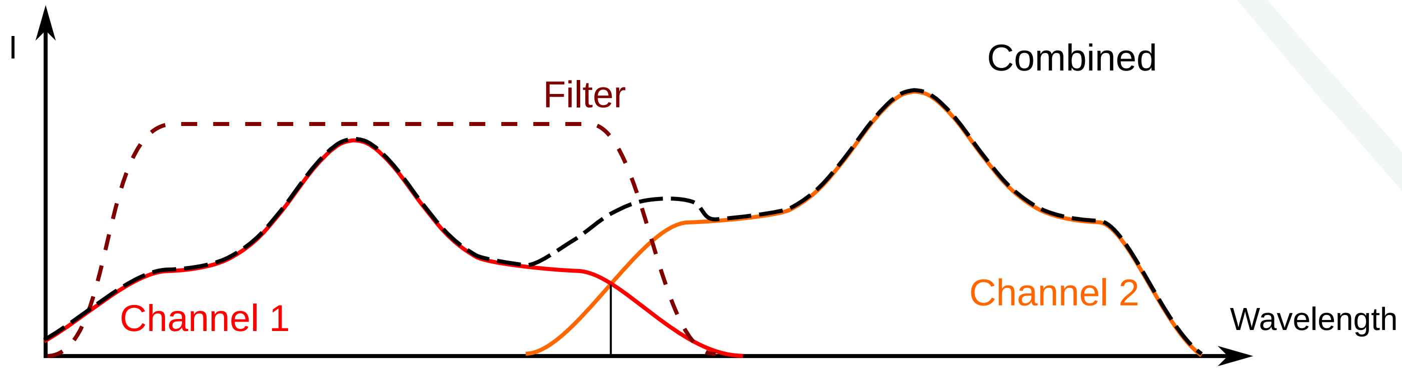
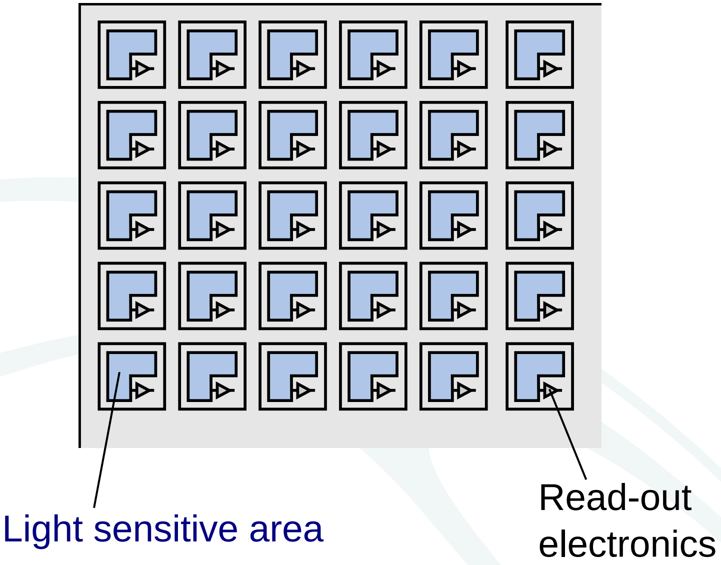


Full vertical binning:
If each column is filled with fibres from the same spatial channel and a CCD camera is used, the whole image can be binned into one row for very fast readout with a high signal level but a limited number of channels.

Sensors: CCD vs CMOS

Two types of sensor are typically used:

CMOS: *Each pixel has it's own read-out electronics.*
- Signal/noise is fixed per pixel and is not improved by binning.
- Frame rate can usually be increased by reducing vertical read-out range.
- Since each pixel has full bit-range (e.g. 16-bit), dynamic range is very high.



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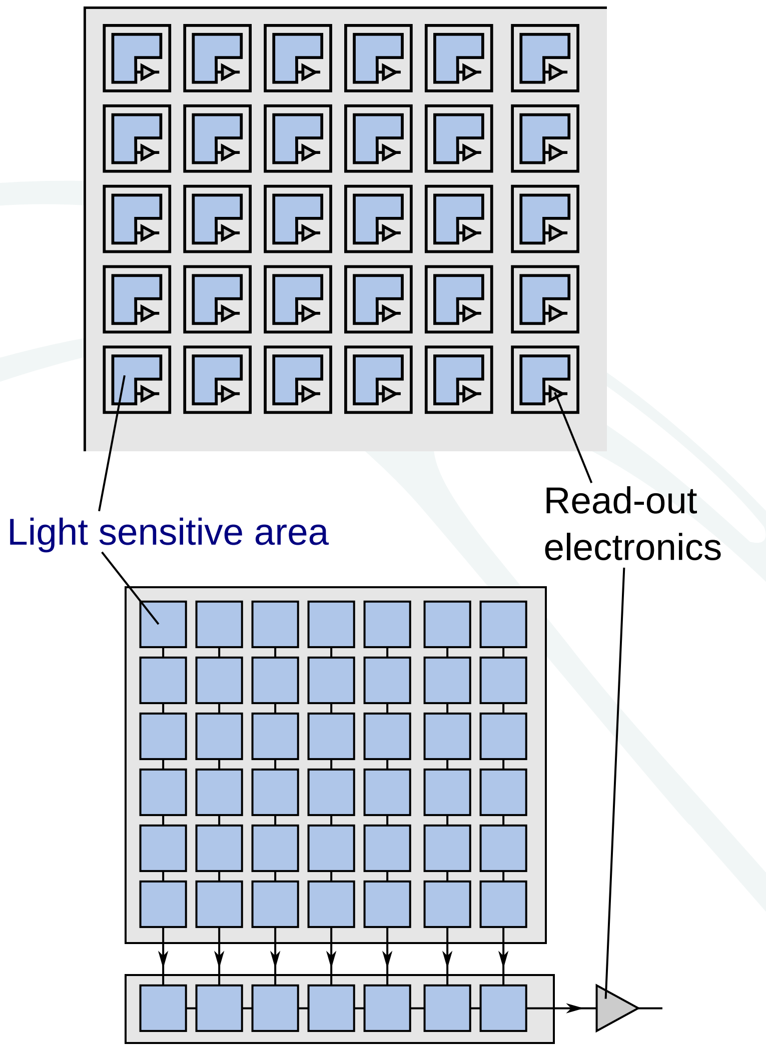


CCD: Photoelectrons are moved down sensor and read-out sequeuntially.
- Signal/noise dramatically improved by binning pixels on the chip.
- Frame rate improved by binning or by less read-out area in any direction.
- Dynamic range limited by read-out row.
- Vertical smearing can be a problem if exposure time is very low.

Set-up

Some spectrometers have few adjustments --> Less flexible but relies on machining accuracy but easier to set up.

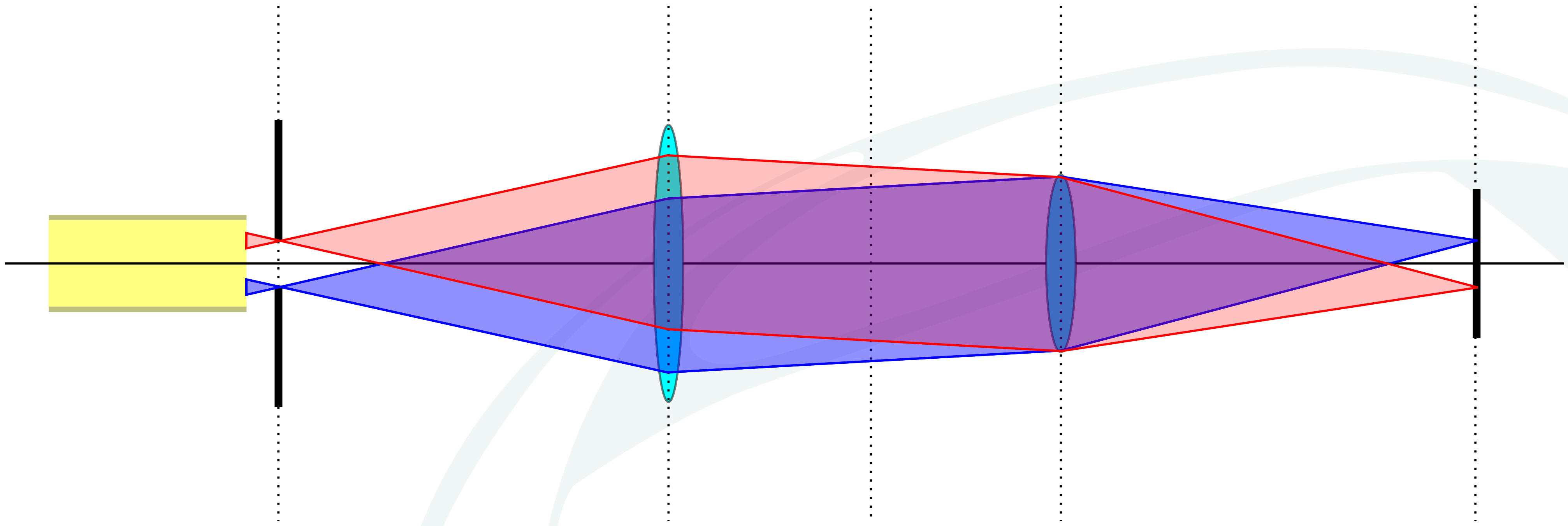
'Home-made' spectrometers or with more adjustments are very difficult to set-up initially.

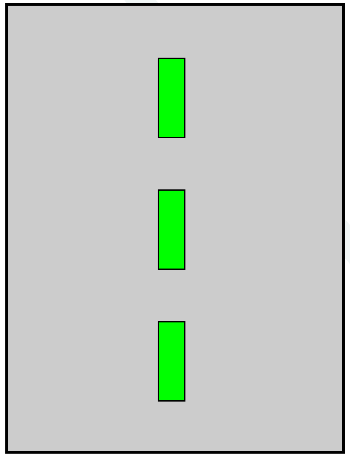
Rough method (images and explanation on later slides): **TODO: We will test and adjust this proceedure**

1) Set both lens focuses close to infinity by imaging a far distant wall/building. If already in spectrometer, use a mirror or the grating.
2) Set all optical element heights and positions roughly as designing using linear-laser.
3) Set grating as mirror ($\theta_g = 0$) and as close as possible to vertical using linear-laser back-reflection.
4) Set fibres as close as possible to back of slit. Open slit > fibres.
5) Light central fibre with a laser of known wavelength (e.g. HeNe @633nm), find grating angle motor position of that (θ_g).
6) Light all fibres with white light + neon lamp. Adjust brightnesses so stip and points are visible.
7) Set θg=0, adjust CCD to centralise image.
8) Switch between θg(λ ~ 500) and θg=0 and adjust grating lean until channel locations don't drift.
9) Adjust CCD tilt and grating tilt so that broadband lines are parallel to x on sensor.
10) Adjust both focuses to get sharp points in wavlength **and** channel directions.
11) Adjust fibre tilt to get channel column (or curve) symmetric.
12) Iterate 8-11 until no more improvement or satisfied with quality.
13) Close slit to ~1/2 width of fibres. Adjust slit tilt and left/right position to match fibres.

Focus

Both lenses have an optimal focus:

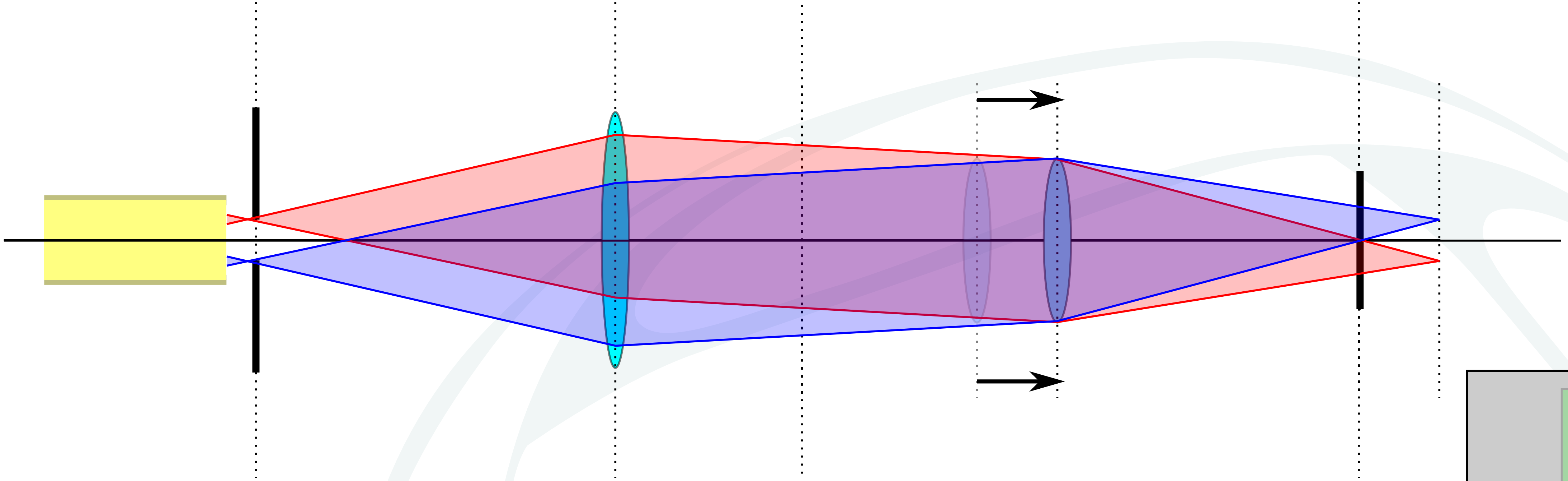




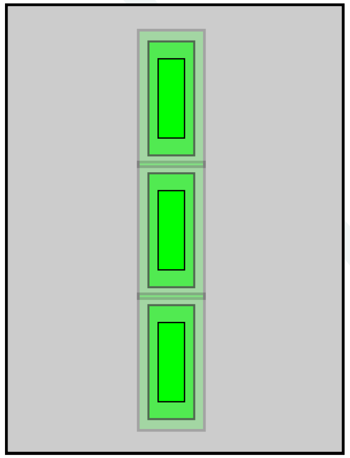
Focus

Both lenses have an optimal focus:

Focus: Defocused imaging lens:



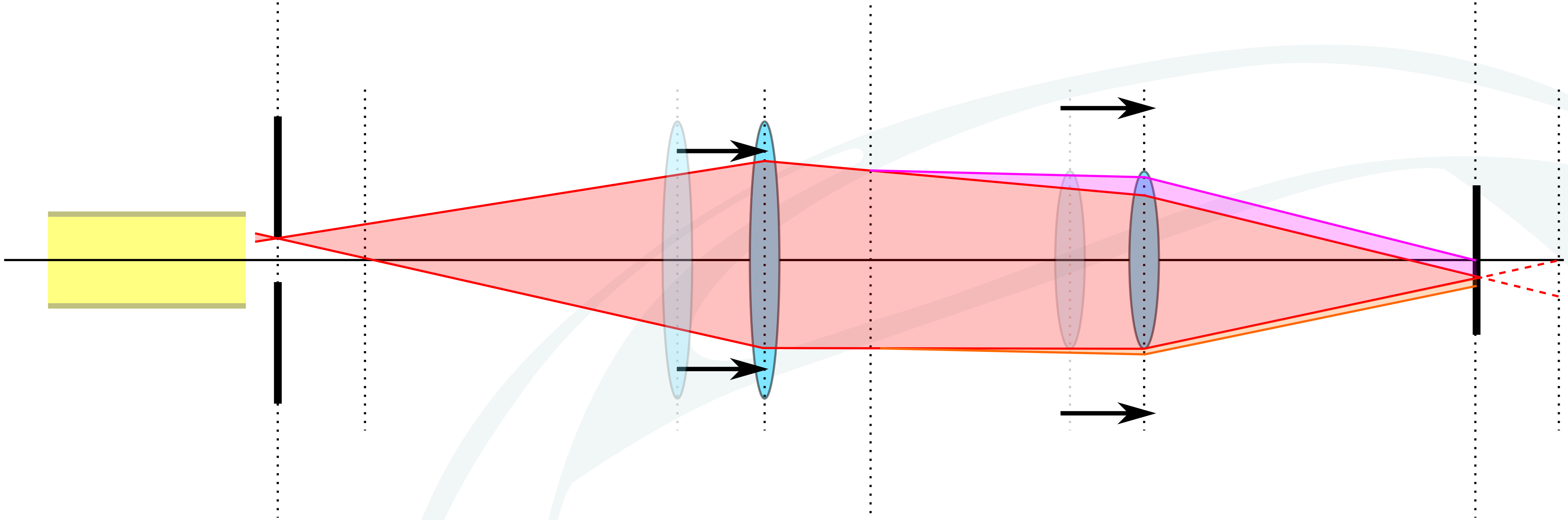
Either lens incorrect --> Blur of image in both directions



Focus

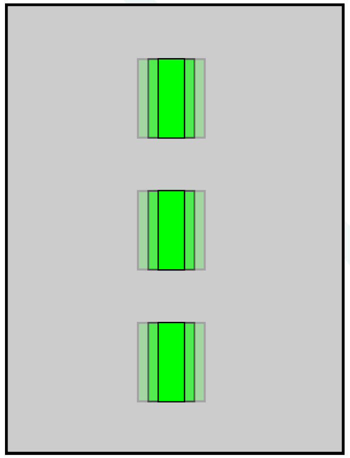
Both lenses have an optimal focus:

Focus: Compensated defocus of both lenses



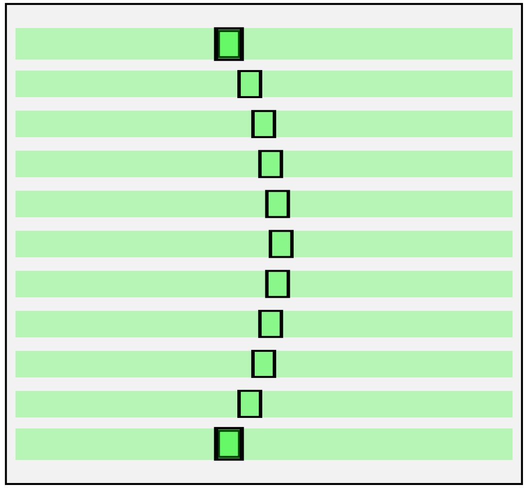
Both incorrect together --> Sharp vertical image, blurred in wavelength

(Same wavelength from same slit position sees different angles at grating)

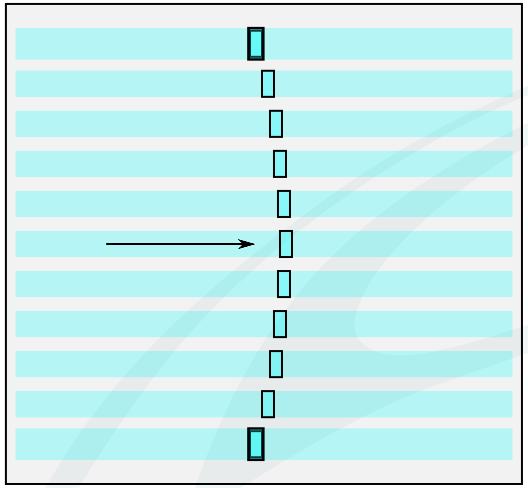


Curvature

Due to second order effects, the diffraction changes slightly with vertical angle, causing a cresent shaped image of slit:
1) Light all channels with a narrow (Neon lamp) and wideband (white LED) source.
2) Scan the grating angle (wavelength setting)
Ideal alignment and focus should look like this:



Longest wavelength



Shortest wavelength

- Straight cresent shape (top and bottom displaced the same)
- Wideband lines are straight.
- Line drift minimal with wavelength setting change.
- All points focused as best as possible in both directions.
  (extreme top+bottom might be less well focused)
- Curvature might be more at longer wavelength

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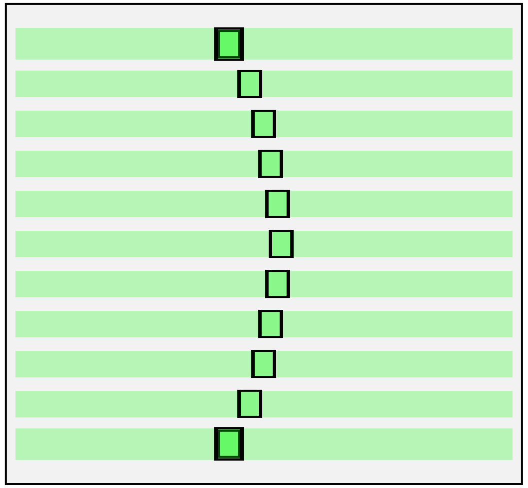
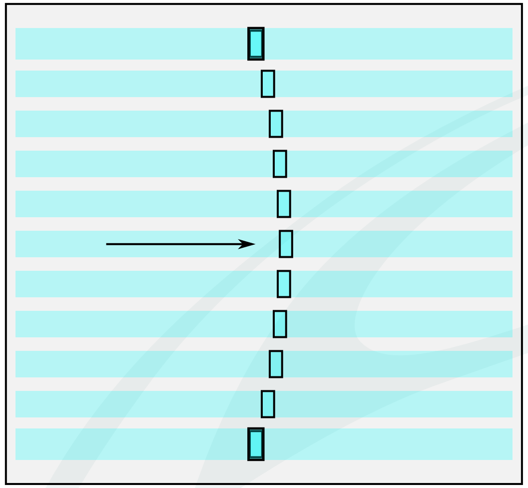


Longest wavelength

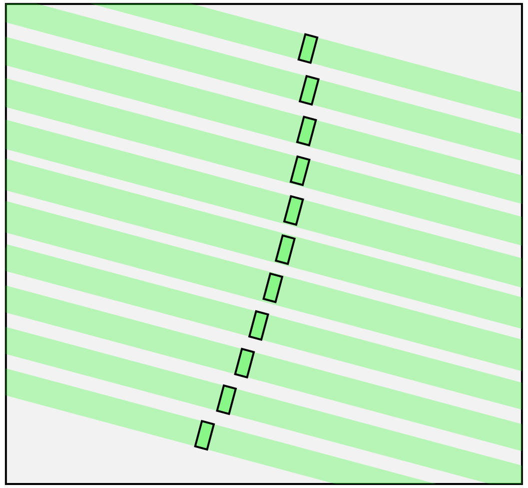


Shortest wavelength

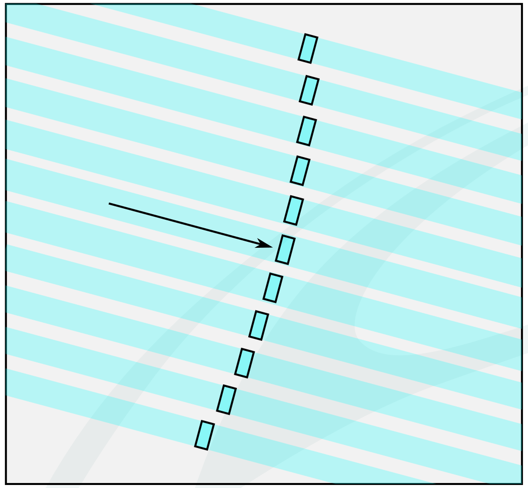
- Straight cresent shape (top and bottom displaced the same)
- Wideband lines are straight.
- Line drift minimal with wavelength setting change.
- All points focused as best as possible in both directions.
  (extreme top+bottom might be less well focused)
- Curvature might be more at longer wavelength

Alignment

Mis-alignment of each component in any axis causes combinations of effects:



Longest wavelength



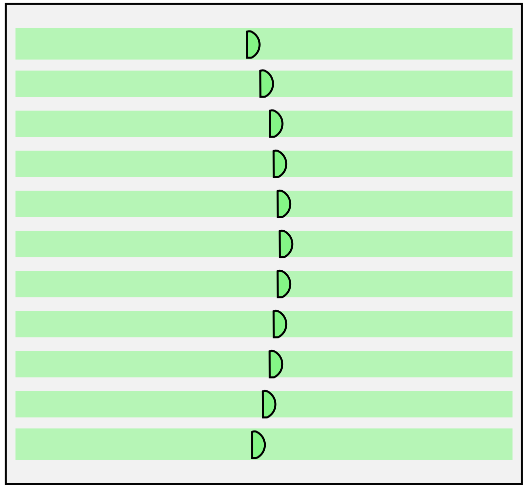
Shortest wavelength

Tilted sensor

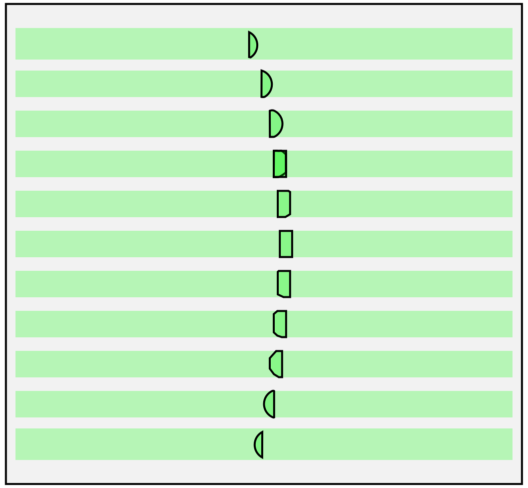
Wideband lines and crescent are both tilted, but stay in place when wavelength setting (grating angle) is changed.

Alignment

Mis-alignment of each component in any axis causes combinations of effects:



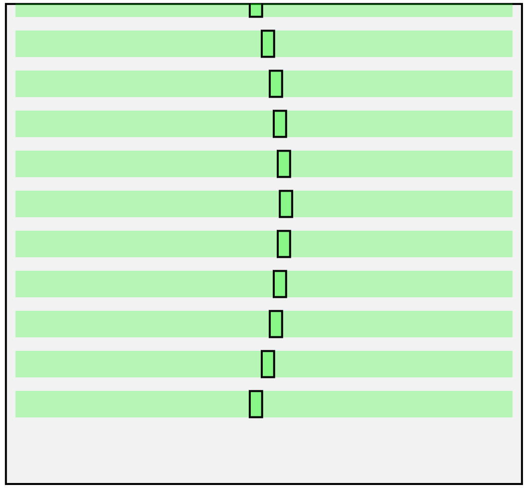
Shifted fibres relative to slit
- All fibres are out of slit in same direction

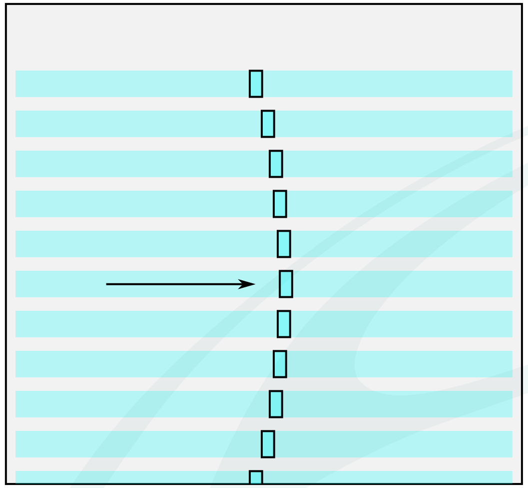


Tilted fibres
- Slit image is straight, but fibres move out of slit

Alignment

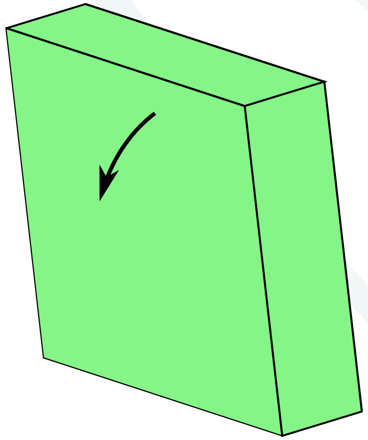
Mis-alignment of each component in any axis causes combinations of effects:





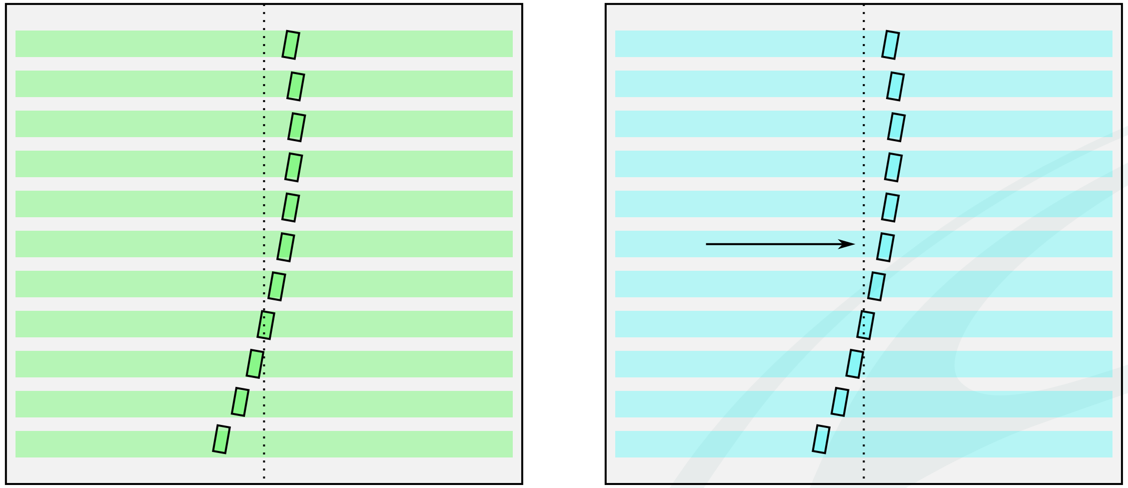
Tilted grating (forward)

- offset can be compensated at any wavelength by sensor or slit/fibre height, but will drift with wavelength (grating angle) change.



Alignment

Mis-alignment of each component in any axis causes combinations of effects:

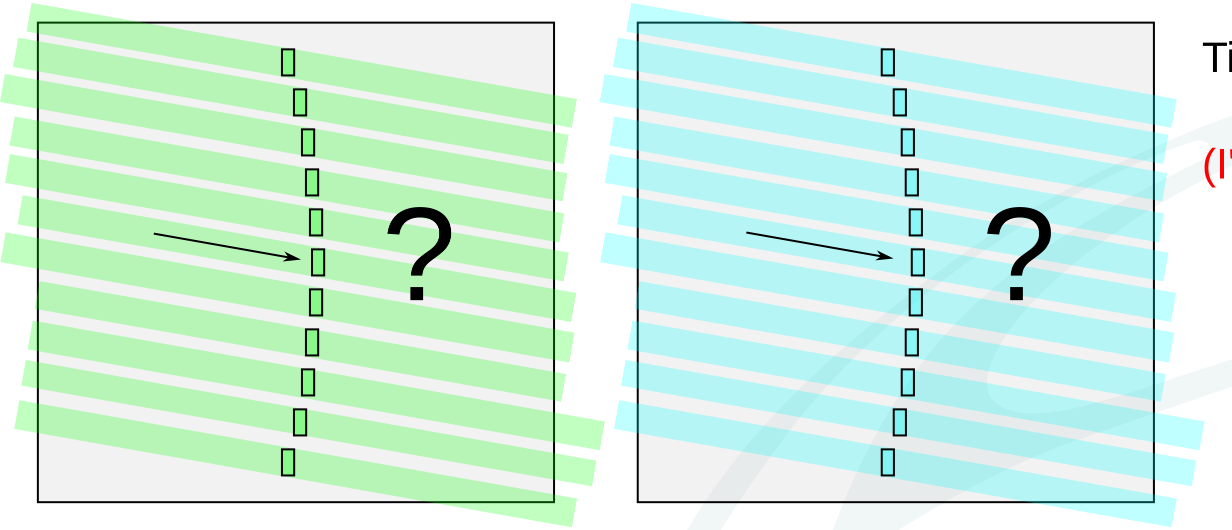


Tilted Slit/Fibers

- Cresent angle tilted but wideband lines straight.
- Everything stays in position when wavelength changed

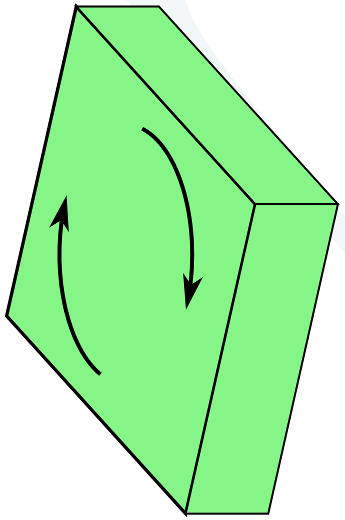
Alignment

Mis-alignment of each component in any axis causes combinations of effects:



Tilted grating (in plane)

(I'm not entirely sure about this one yet).



End

That's all folks

... at least for now ...