Institute of Applied Physics
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Lens Design I

Lecture 11: Correction I

2024-06-27

Yueqian Zhang

Preliminary Schedule - Lens Design I 2024

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1	04.04.	Basics	Zhang	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, coordinates, System description, 3D geometry, aperture, field, wavelength
2	18.04.	Properties of optical systems I	Tang	Diameters, stop and pupil, vignetting, layouts, materials, glass catalogs, raytrace, ray fans and sampling, footprints
3	25.04.	Properties of optical systems II	Tang	Types of surfaces, cardinal elements, lens properties, Imaging, magnification, paraxial approximation and modelling, telecentricity, infinity object distance and afocal image, local/global coordinates
4	02.05.	Properties of optical systems III	Tang	Component reversal, system insertion, scaling of systems, aspheres, gratings and diffractive surfaces, gradient media, solves
5	16.05.	Advanced handling I	Tang	Miscellaneous, fold mirror, universal plot, slider, multiconfiguration, lens catalogs
6	23.05.	Aberrations I	Zhang	Representation of geometrical aberrations, spot diagram, transverse aberration diagrams, aberration expansions, primary aberrations
7	30.05.	Aberrations II	Zhang	Wave aberrations, Zernike polynomials, measurement of quality
8	06.06.	Aberrations III	Tang	Point spread function, optical transfer function
9	13.06.	Optimization I	Tang	Principles of nonlinear optimization, optimization in optical design, general process, optimization in Zemax
10	20.06.	Optimization II	Zhang	Initial systems, special issues, sensitivity of variables in optical systems, global optimization methods
11	27.06.	Correction I	Zhang	Symmetry principle, lens bending, correcting spherical aberration, coma, astigmatism, field curvature, chromatical correction
12	04.07.	Correction II	Zhang	Field lenses, stop position influence, retrofocus and telephoto setup, aspheres and higher orders, freeform systems, miscellaneous

Contents

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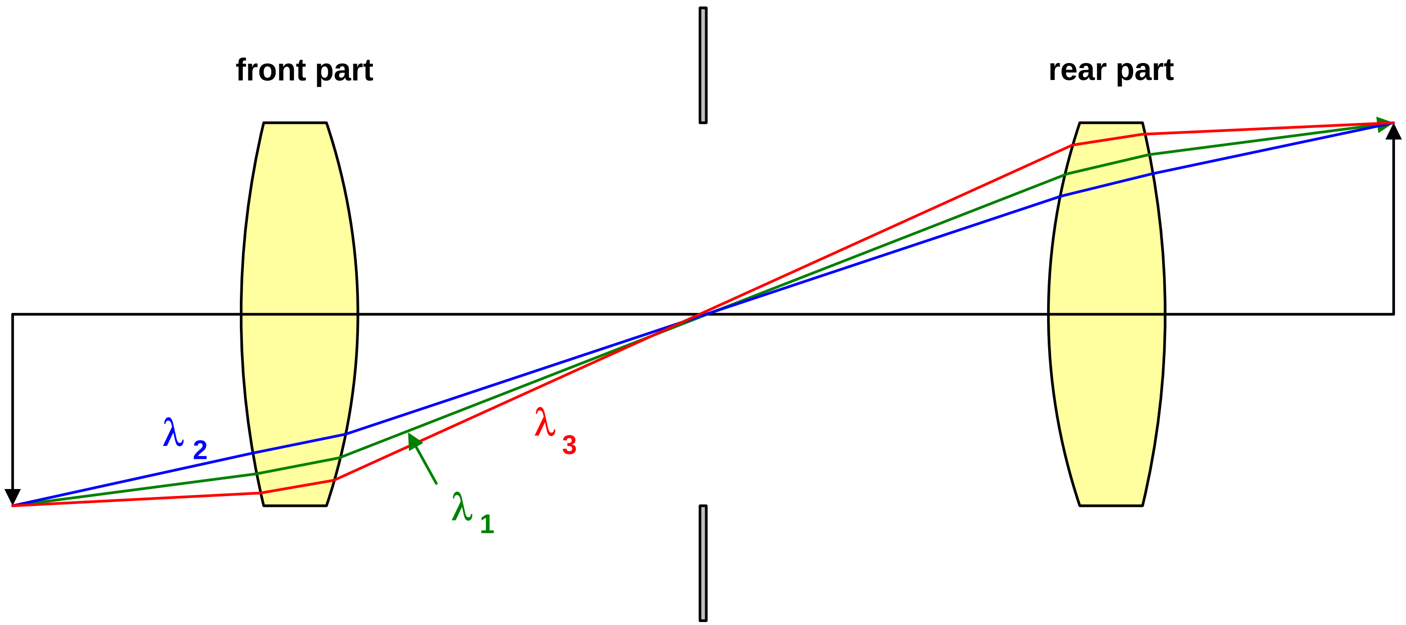
Principle of Symmetry

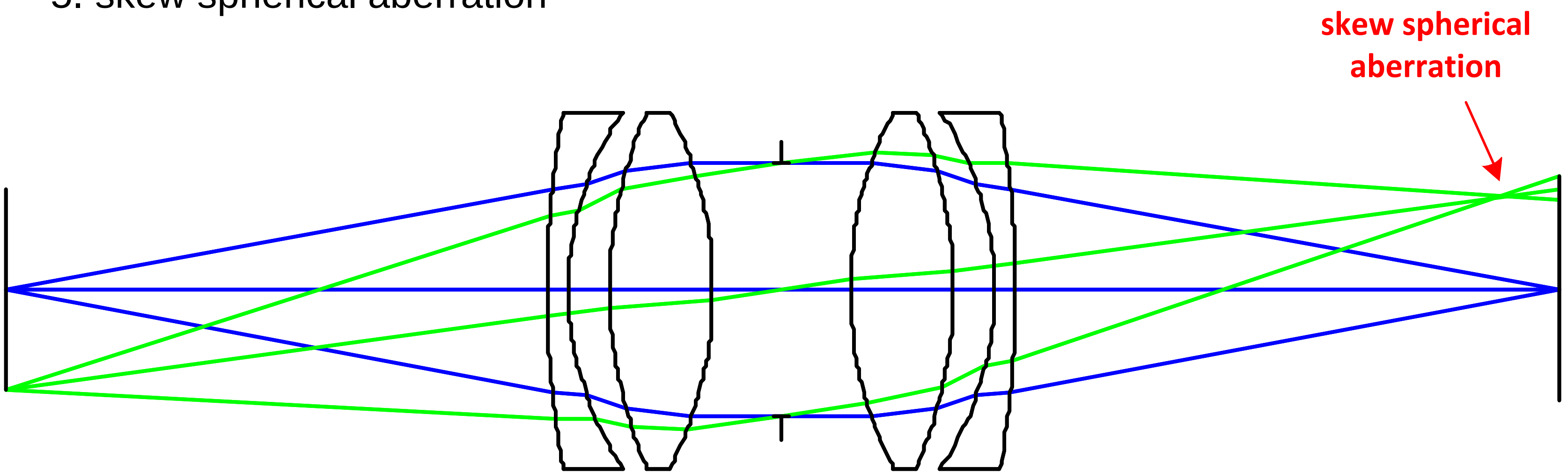
- Perfect symmetrical system: magnification m = -1
- Stop in centre of symmetry
- Symmetrical contributions of wave aberrations are doubled (spherical)
- Asymmetrical contributions of wave aberration vanishes W(-x) = -W(x)
- Easy correction of:
  coma, distortion, chromatical change of magnification



Symmetrical Systems

Ideal symmetrical systems:

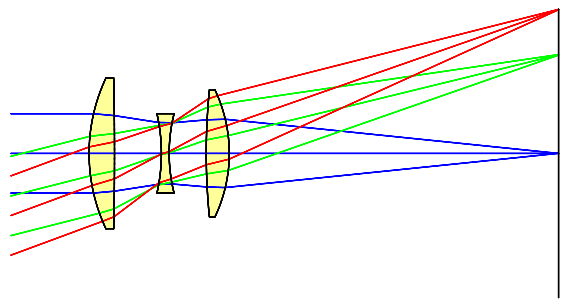
- Vanishing coma, distortion, lateral color aberration
- Remaining residual aberrations:
  1. spherical aberration
  2. astigmatism
  3. field curvature
  4. axial chromatical aberration
  5. skew spherical aberration



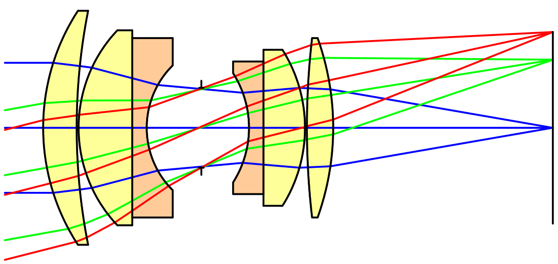
Symmetry Principle

- Application of symmetry principle: photographic lenses
- Especially field dominant aberrations can be corrected
- Also approximate fulfillment of symmetry condition helps significantly: quasi symmetry
- Realization of quasi-symmetric setups in nearly all photographic systems

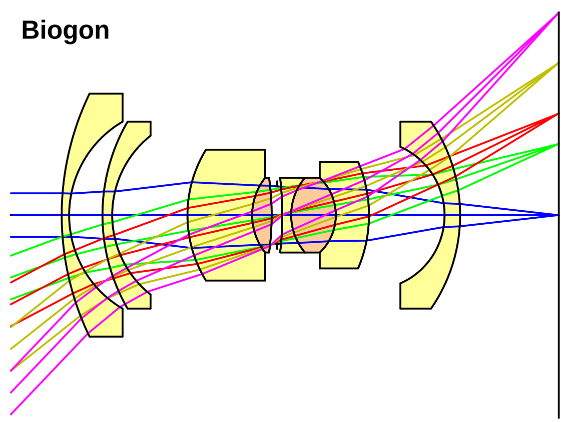
Triplet



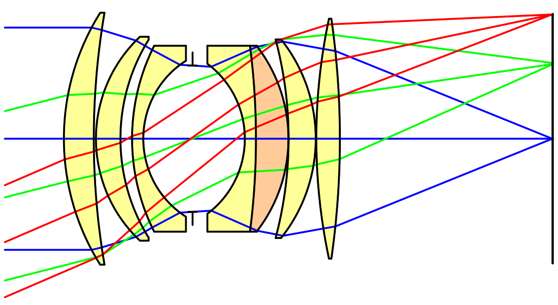
Double Gauss (6 elements)



Biogon



Double Gauss (7 elements)



Ref : H. Zügge

Coma Correction: Symmetry Principle

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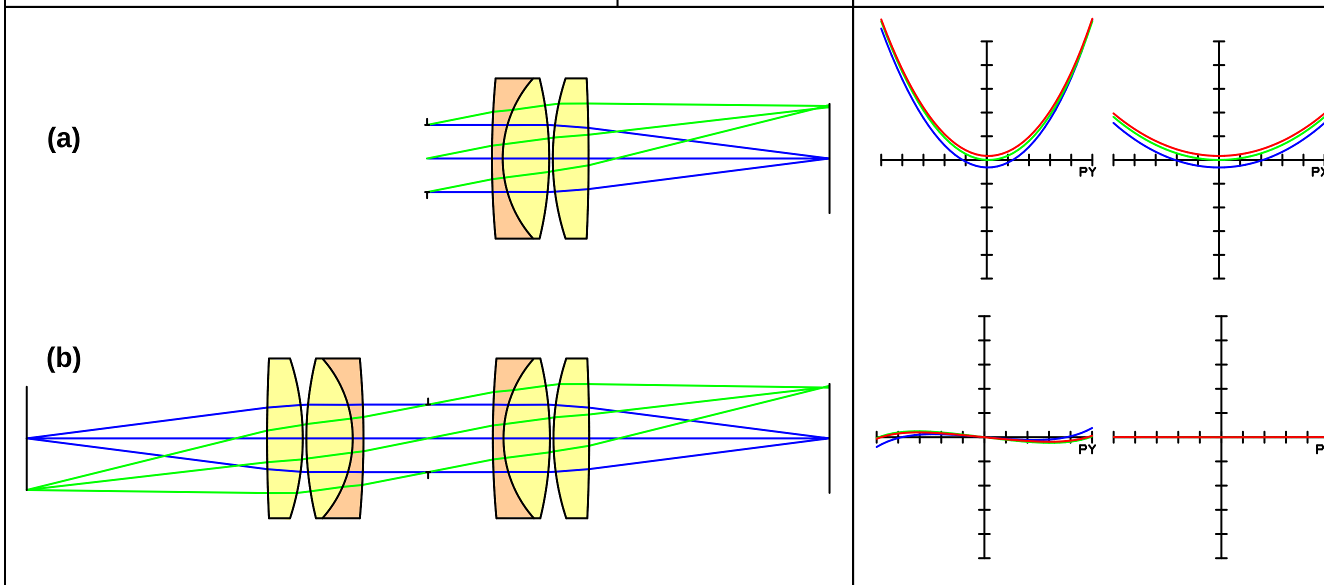
- Perfect coma correction in the case of symmetry
- But magnification m = -1 not useful in most practical cases

Symmetry principle	**Image height:**	**y' = 19 mm**	
	Pupil section:	**meridional**	**sagittal**
	Transverse Aberration:	$\Delta y'$ **0.5 mm**	$\Delta y'$ **0.5 mm**



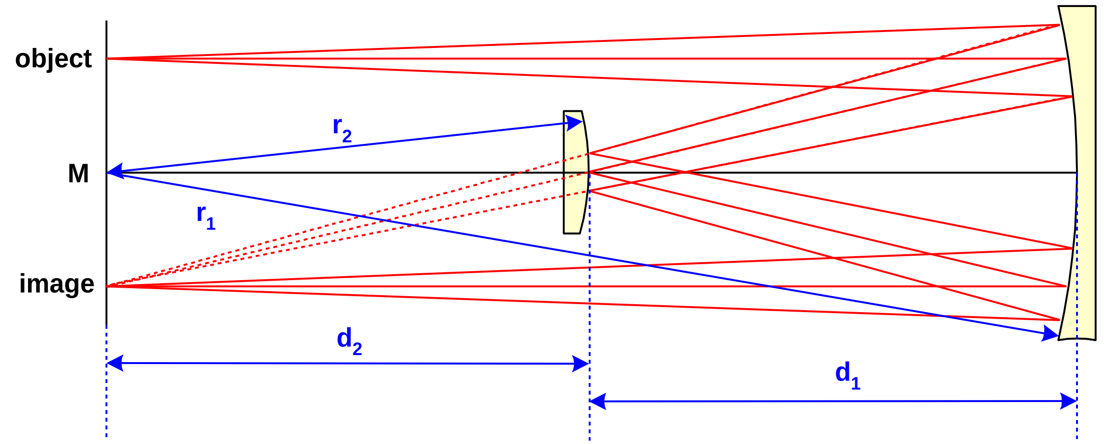
From : H. Zügge

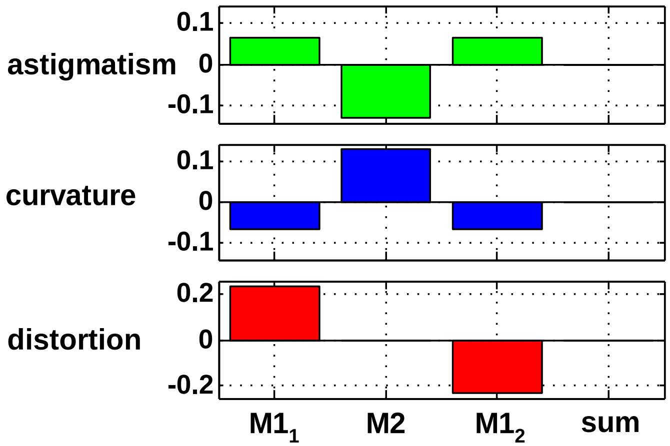
Offner-System

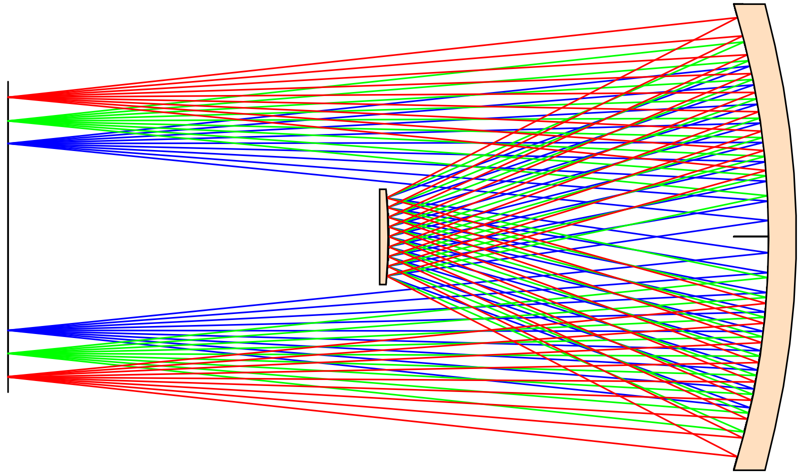
- Concentric system of Offner: relation

$$d_1 = d_2 = \frac{r_1}{2} = r_2$$

- Due to symmetry:
  Perfect correction of field aberrations in third order







Dyson-System

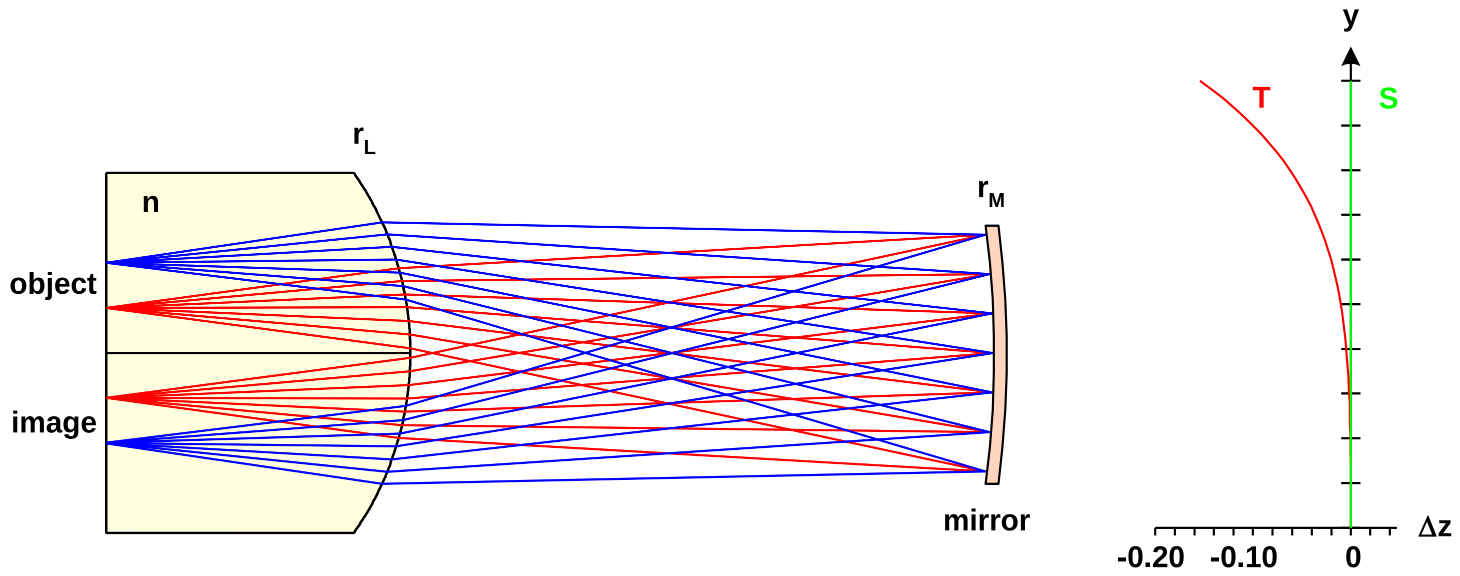
- Catadioptric system with m = -1 according Dyson

  Advantage : flat field

  Application: lithography and projection
- Relation:

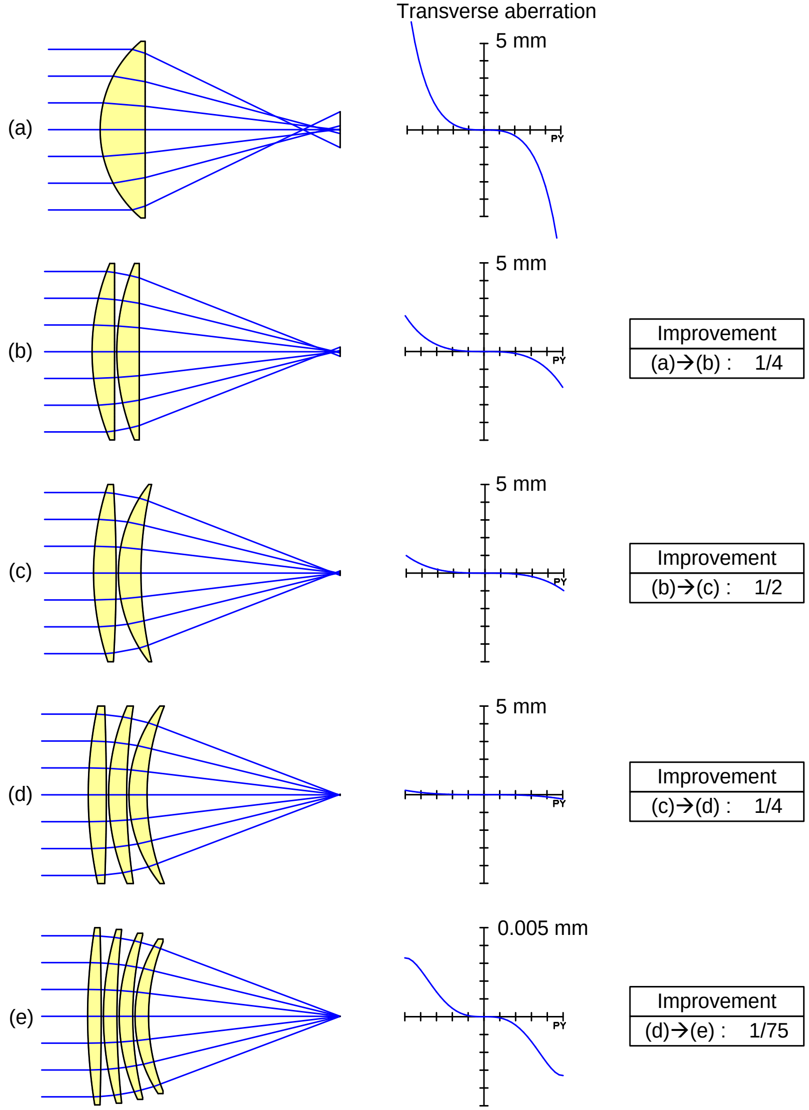
$$r_L = \frac{n-1}{n} \cdot r_M$$

- Residual aberration : astigmatism



Correcting Spherical Aberration: Lens Splitting

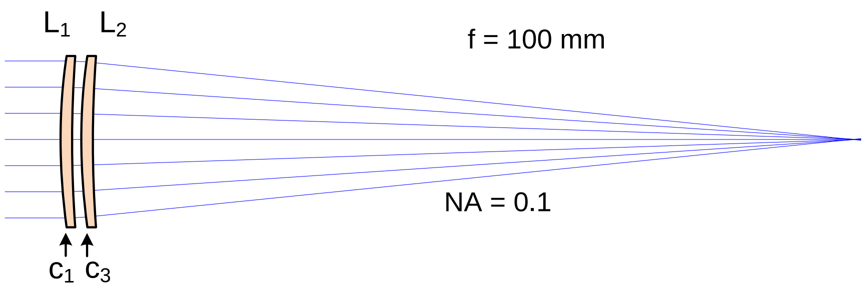
- Correction of spherical aberration: Splitting of lenses
- Distribution of ray bending on several surfaces:
  - smaller incidence angles reduces the effect of nonlinearity
  - decreasing of contributions at every surface, but same sign
- Last example (e): one surface with compensating effect



Ref : H. Zügge

Spherical Correction of a Dublet

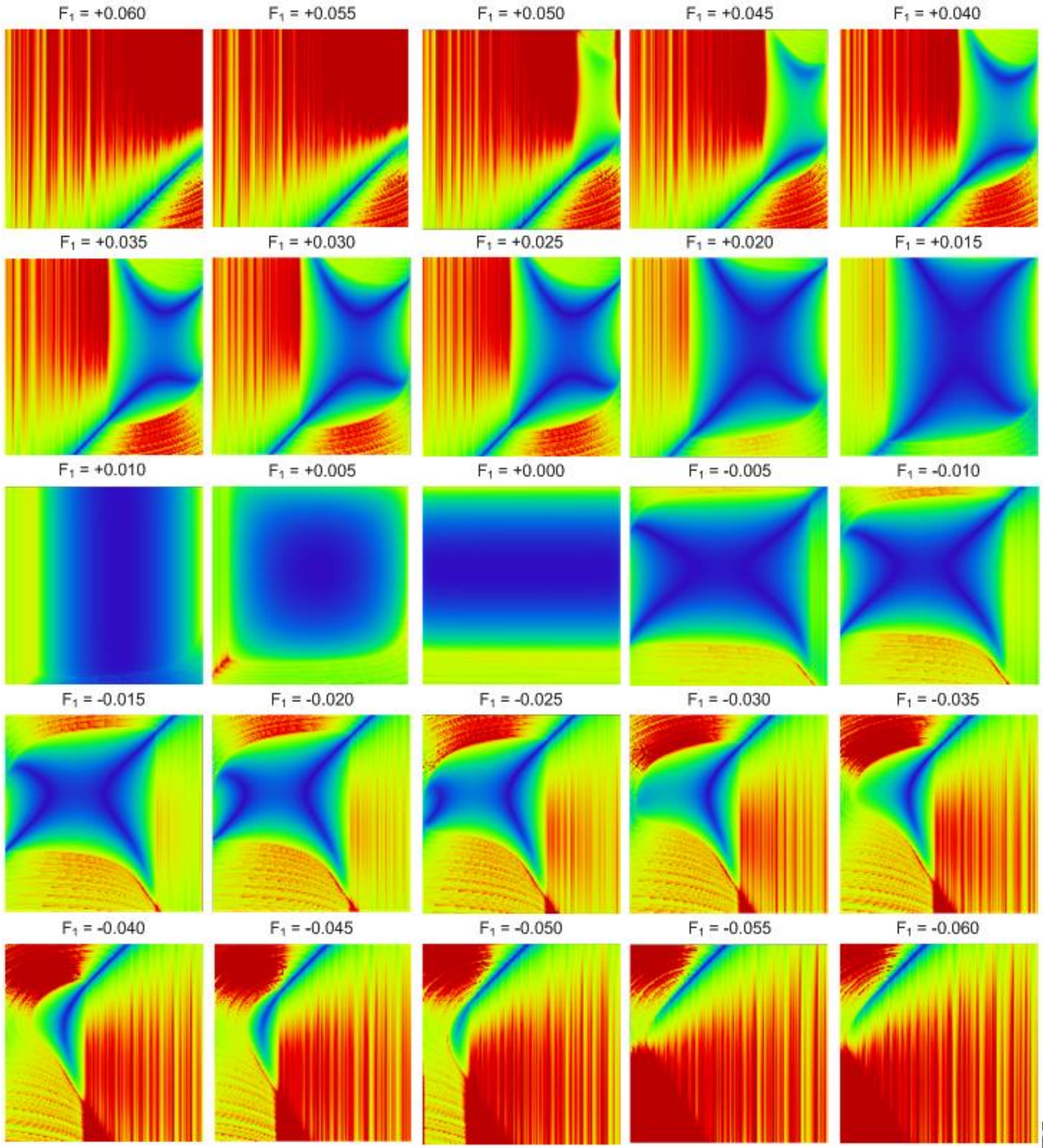
- Only spherical correction by bending only
- Fixed focal length
- 3 degrees of freedom
  F_1, c_1, c_3



- Correction of spherical aberration by one counterbended surface
- Every of the 4 surfaces can serve as corrector
- The lens with the corrector surface must have negative power with virtual imaging impact
  Spherical correction of a single lens only for M>>1 or M << -1 (parabolic behavior)
- First lens corrector: retro focus type setup
- Second lens corrector: tele setup
- In any case long branch of solutions with changing bending of the other lens,
- Best solution: positive lenses have bending with the same spherical contributions

Spherical Correction of a Dublet

- Numerical solution
- F_1 varied
- Parameter every chart:
  horizontal: c_1 = -0.1...+0.1
  vertical: c_3 = -0.1...+0.1



Spherical Correction of a Dublet

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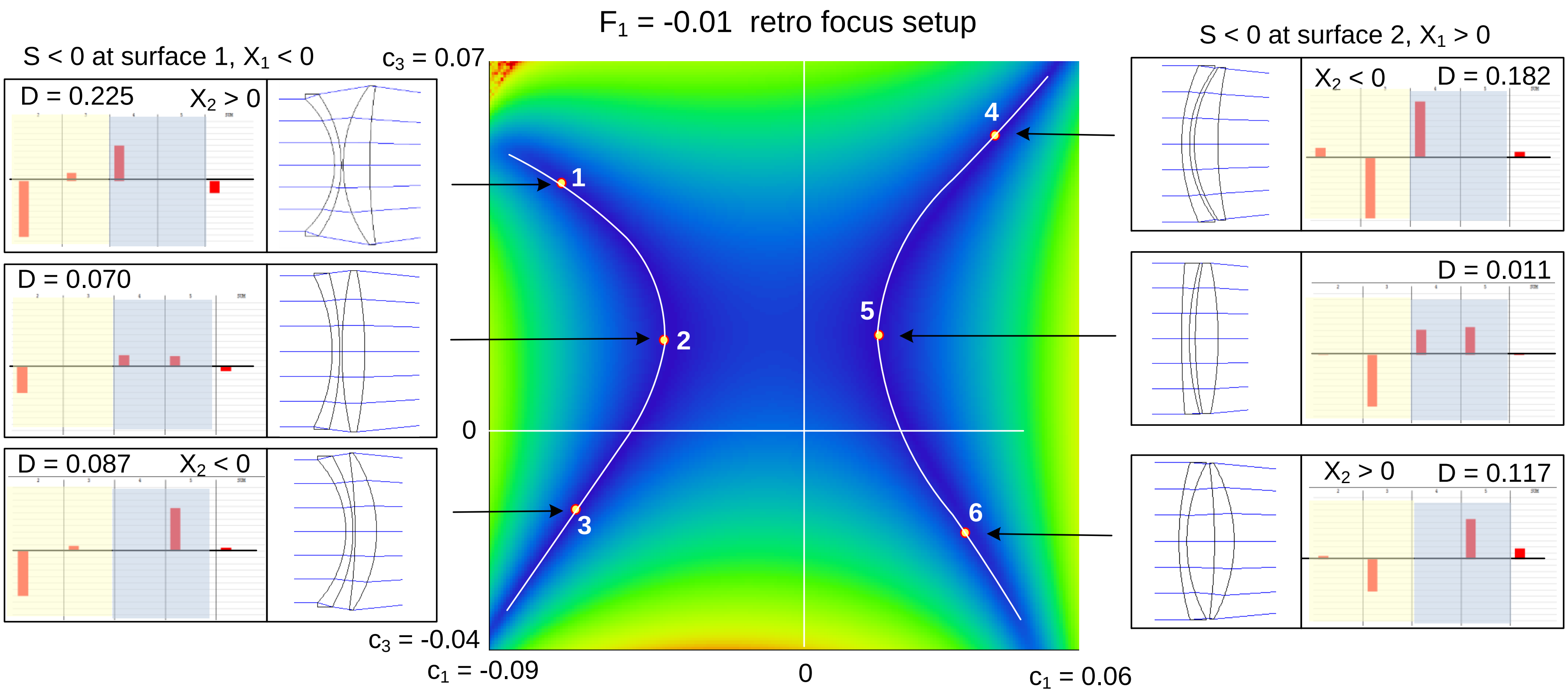
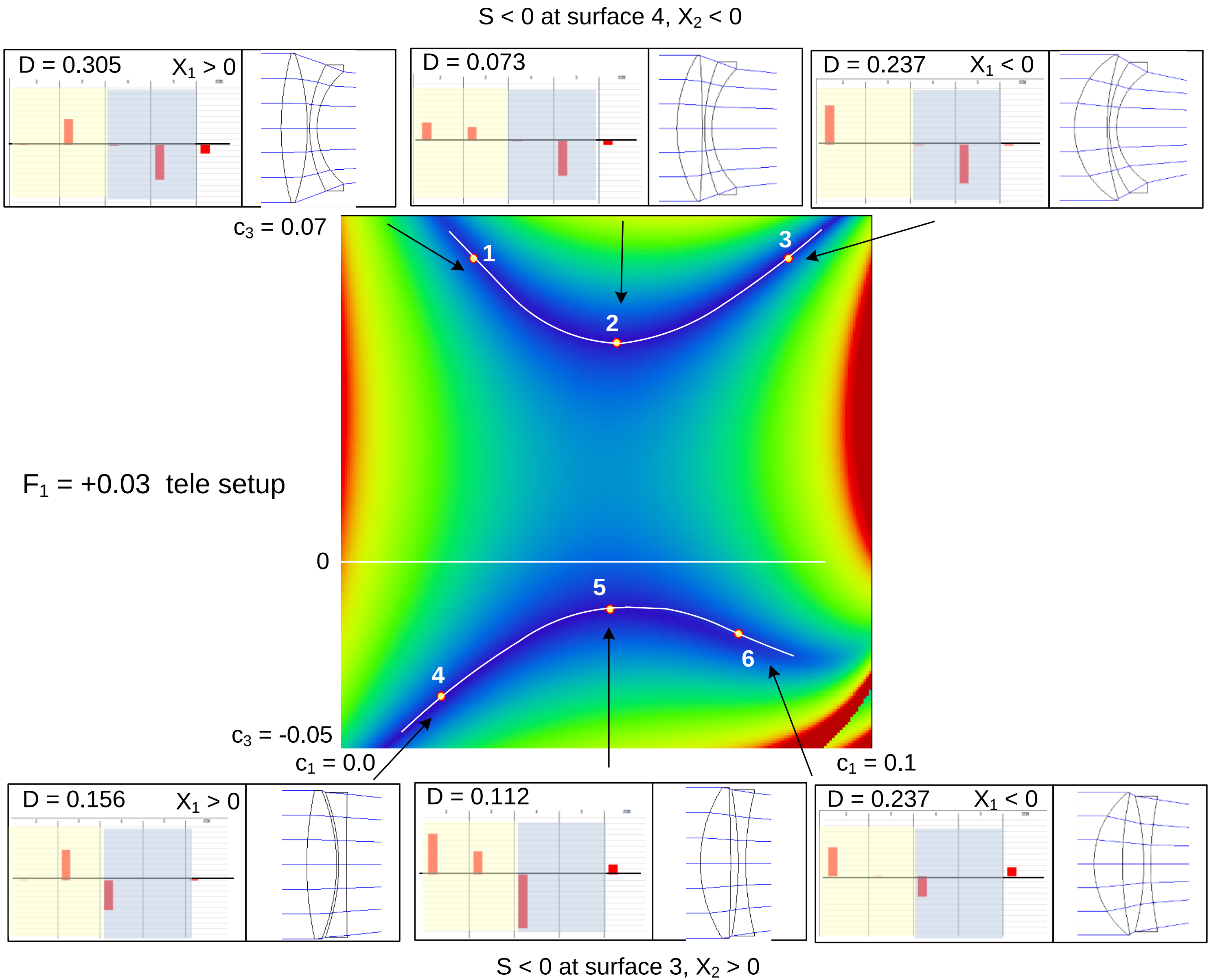
- Case of correcting first lens
  Seidel bars not to scale



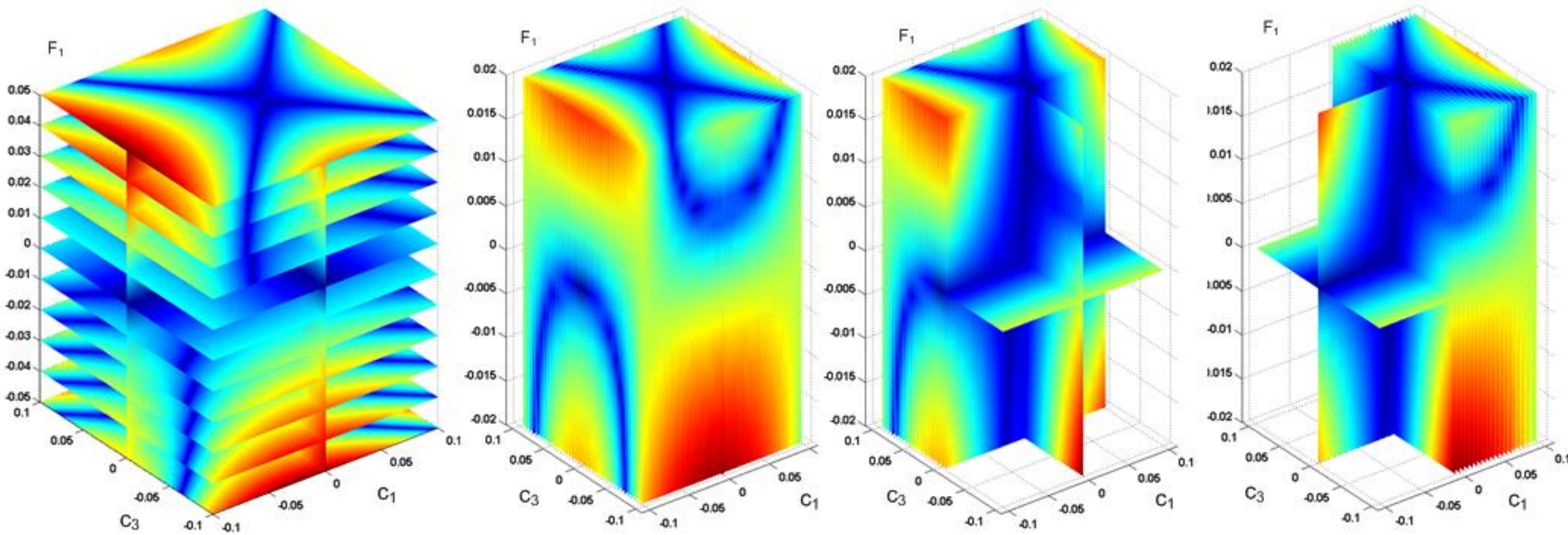
Spherical Correction of a Dublet

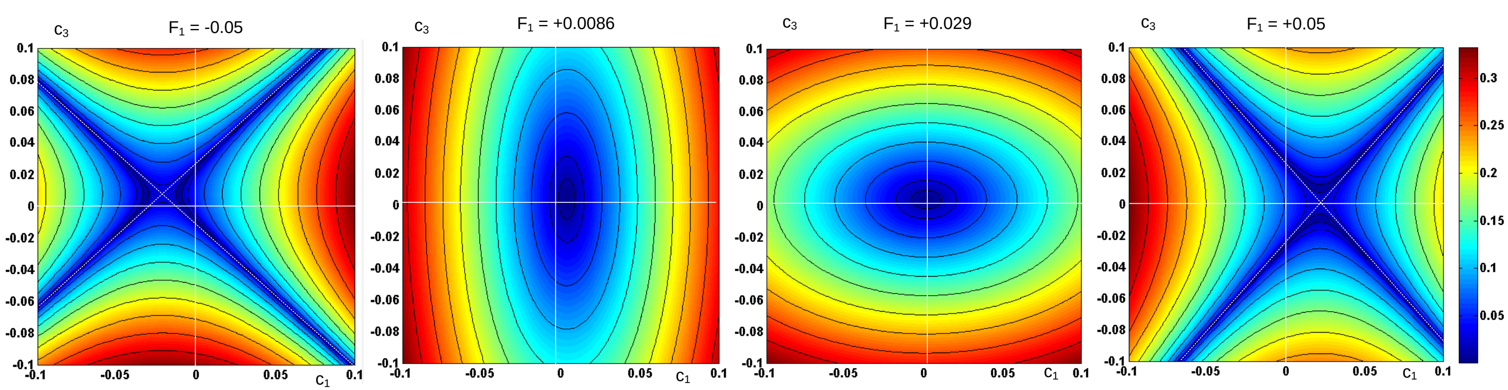
- Case of correcting 2nd lens



Spherical Correction of a Dublet

- Analytical solution with Seidel theory
- Use of formula $S^* = F^3 \left[A \cdot M^2 + B \cdot MX + C \cdot X^2 + D \right]$





Coma Correction: Stop Position and Aspheres

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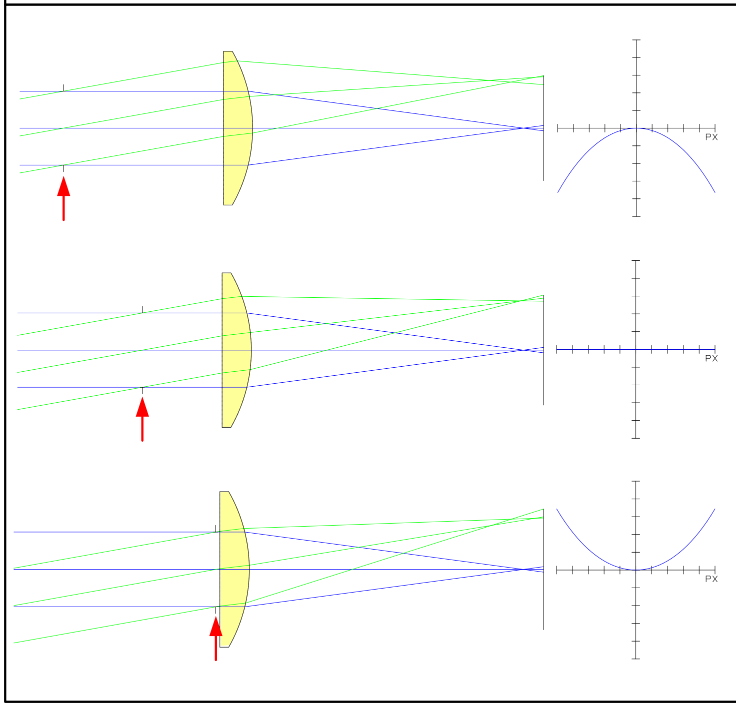
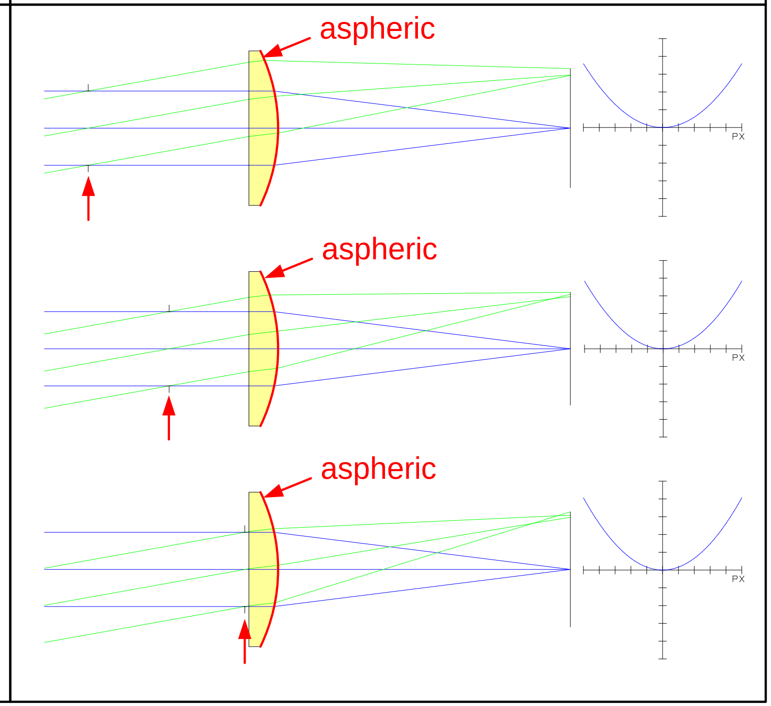
- Combined effect, aspherical case prevent correction

Plano-convex element exhibits spherical aberration	Sagittal coma $\Delta y'$ 0.5 mm	Spherical aberration corrected with aspheric surface	Sagittal coma $\Delta y'$ 0.5 mm
			

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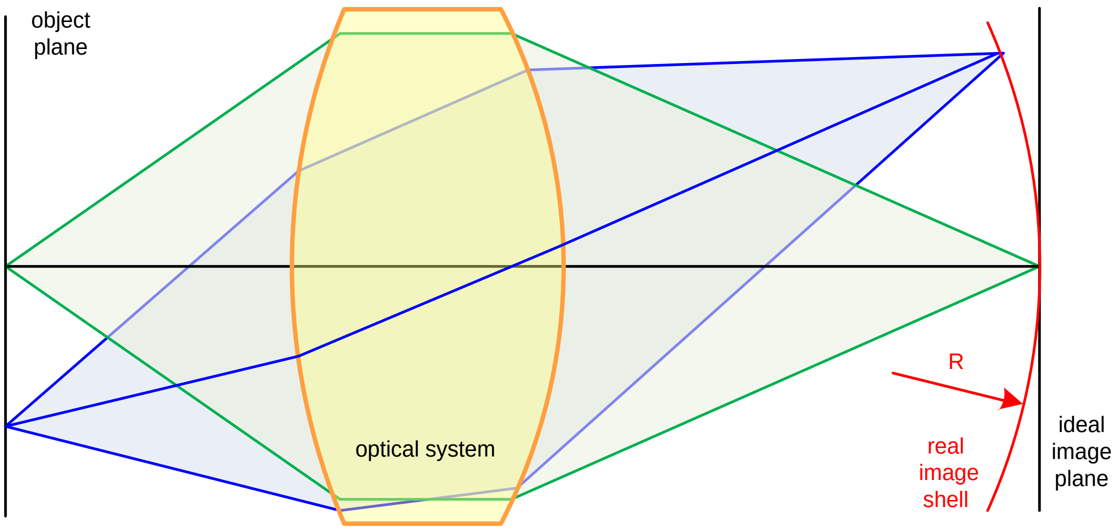
Petzval Theorem for Field Curvature

- Petzval theorem for field curvature:
  1. formulation for surfaces
  $$\frac{1}{R_{ptz}} = -n_m' \sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k}$$
  2. formulation for thin lenses (in air)
  $$\frac{1}{R_{ptz}} = -\sum_j \frac{1}{n_j \cdot f_j}$$
- Important: no dependence on bending
- Natural behavior: image curved towards system
- Problem: collecting systems with f > 0:
  If only positive lenses:
  R_{ptz} always negative



Petzval Theorem for Field Curvature

- Goal: vanishing Petzval curvature
$$\frac{1}{R_{ptz}} = -\sum_j \frac{1}{n_j \cdot f_j}$$
  and positive total refractive power
$$\frac{1}{f} = \sum_j \frac{h_j}{h_1} \cdot \frac{1}{f}$$
  for multi-component systems

- Solution:
  General principle for correction of curvature of image field:
  1. Positive lenses with:
     - high refractive index
     - large marginal ray heights
     - gives large contribution to power and low weighting in Petzval sum
  2. Negative lenses with:
     - low refractive index
     - samll marginal ray heights
     - gives small negative contribution to power and high weighting in Petzval sum

Flattening Meniscus Lenses

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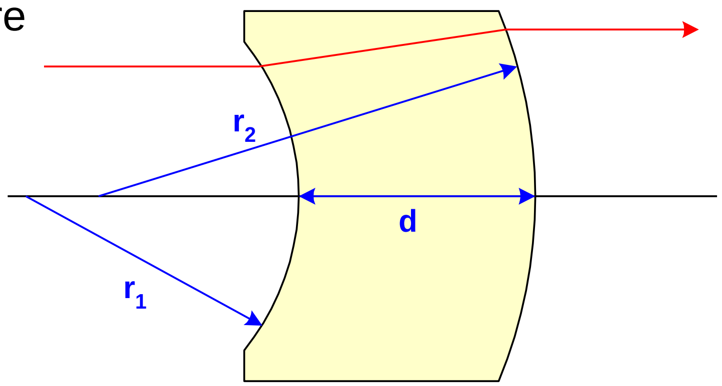
- Possible lenses / lens groups for correcting field curvature
- Interesting candidates: thick mensiscus shaped lenses



$$\frac{1}{R_{ptz}} = -\sum_k \frac{n_k' - n_k}{n_k \cdot n_k' \cdot r_k} = -\frac{1}{n \cdot f} + \left(\frac{n-1}{n}\right)^2 \cdot \frac{d}{r_1 r_2}$$

1. Hoeghs mensicus: identical radii
   - Petzval sum zero
   - remaining positive refractive power

$$F' = \frac{(n-1)^2 d}{n \cdot r^2}$$

2. Concentric meniscus,
   - Petzval sum negative
   - weak negative focal length
   - refractive power for thickness d:

$$r_2 = r_1 - d$$

$$\frac{1}{R_{ptz}} = \frac{(n-1) \cdot d}{n r_1 \cdot (r_1 - d)}$$

$$F' = -\frac{(n-1)d}{n r_1 (r_1 - d)}$$

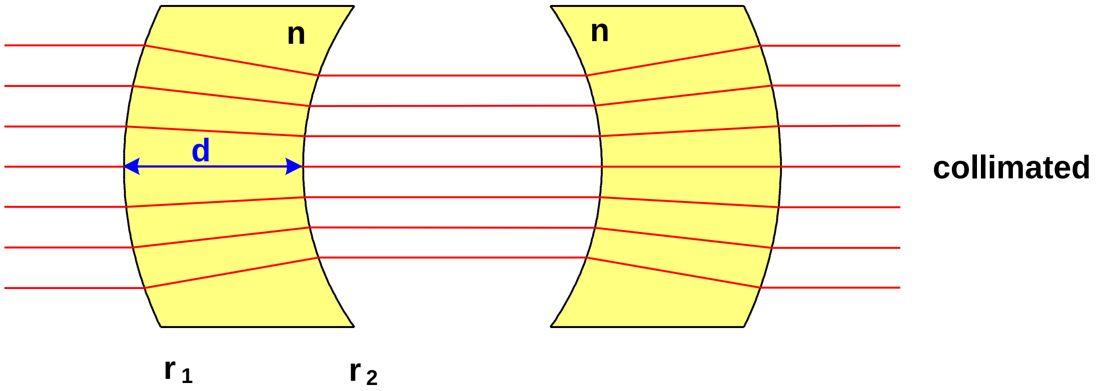
3. Thick meniscus without refractive power
   Relation between radii

$$r_2 = r_1 - d \cdot \frac{n-1}{n}$$

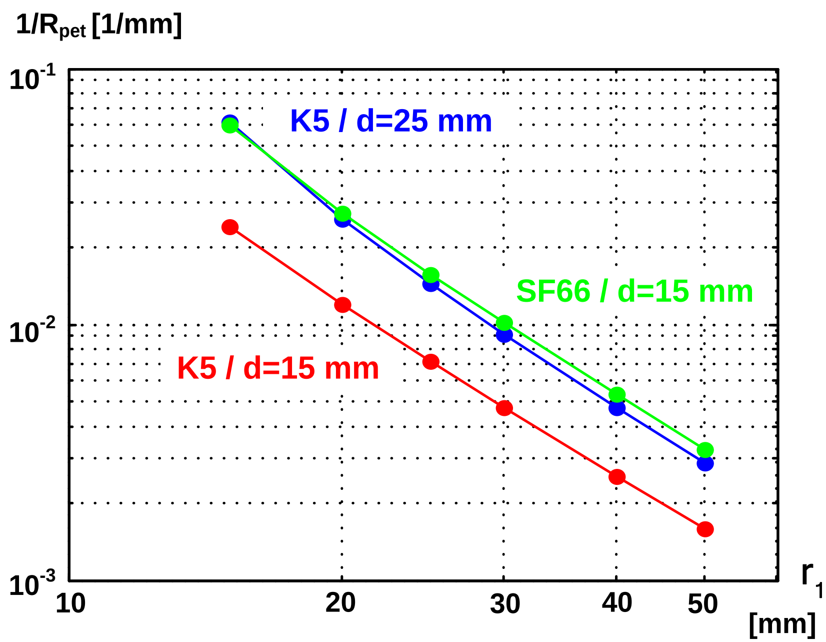
$$\frac{1}{R_{ptz}} = \frac{(n-1)^2 \cdot d}{n r_1 \cdot [n r_1 - d \cdot (n-1)]} > 0$$

Correcting Petzval Curvature

- Group of meniscus lenses

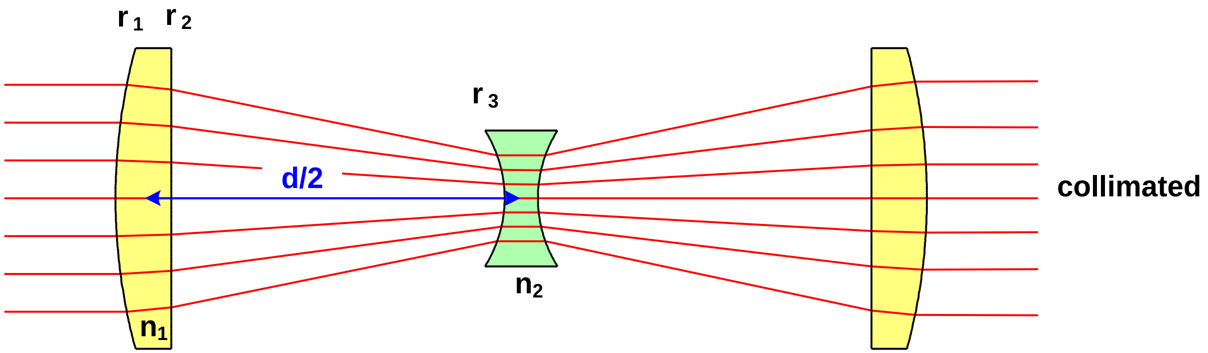


- Effect of distance and refractive indices

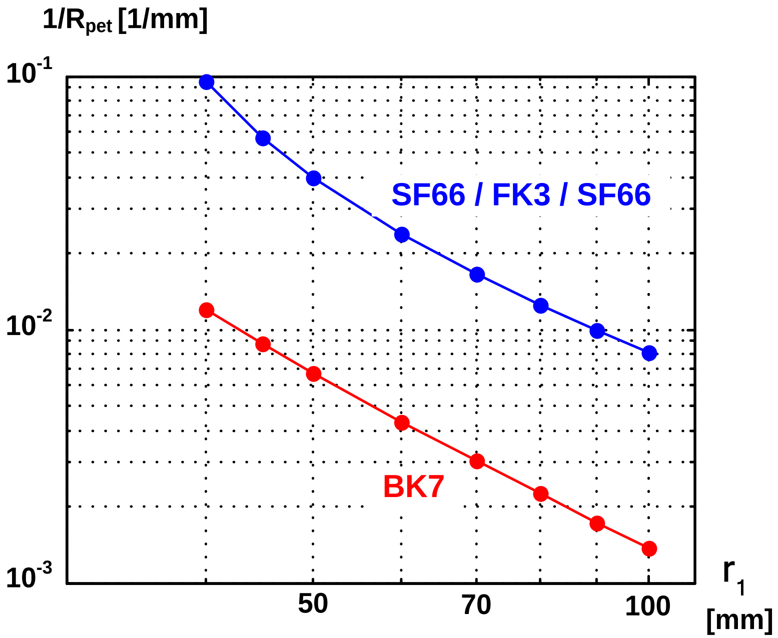


Correcting Petzval Curvature

- Triplet group with + - +



- Effect of distance and refractive indices



Field Curvature

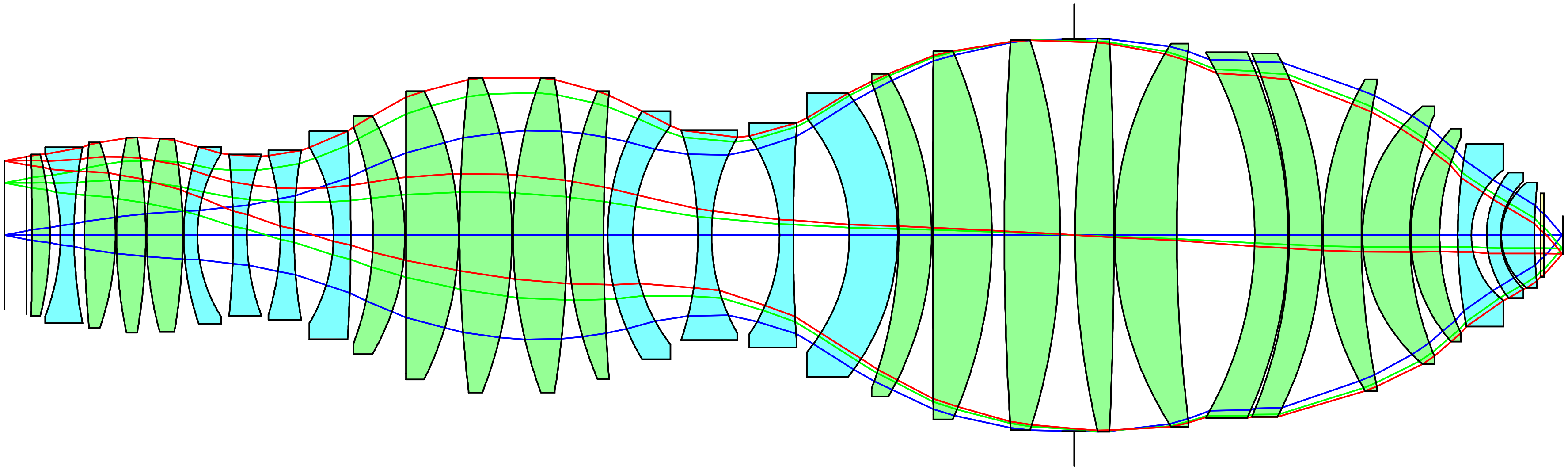
- Correction of Petzval field curvature in lithographic lens for flat wafer

$$\frac{1}{R} = -\sum_j \frac{F_j}{n_j}$$

- Positive lenses: Green h_j large
- Negative lenses : Blue h_j small

$$F = \sum_j \frac{h_j}{h_1} \cdot F_j$$

- Correction principle: certain number of bulges

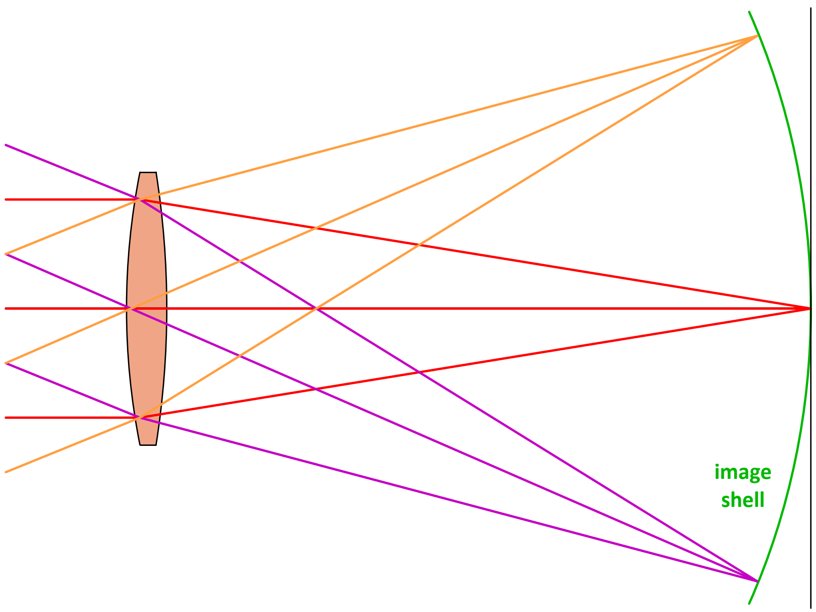


Flattening Field Lens

Effect of a field lens for flattening the image surface

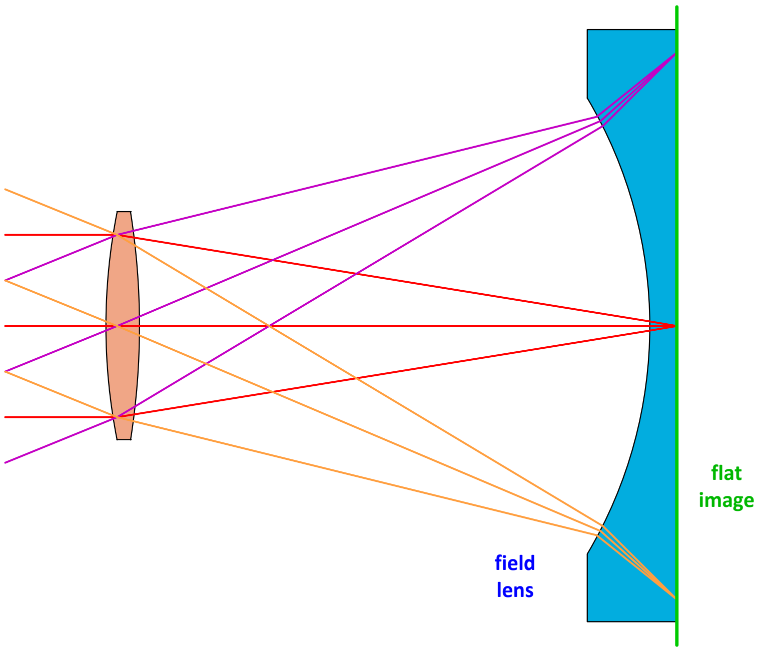
1. Without field lens

curved image surface



2. With field lens

image plane



Achromate : Basic Formulas

- Idea:
  1. Two thin lenses close together with different materials
  2. Total power

$$F = F_1 + F_2$$

  3. Achromatic correction condition

$$\frac{F_1}{\nu_1} + \frac{F_2}{\nu_2} = 0$$

- Individual power values

$$F_1 = \frac{1}{1 - \frac{\nu_2}{\nu_1}} \cdot F \qquad F_2 = \frac{1}{1 - \frac{\nu_1}{\nu_2}} \cdot F$$

- Properties:
  1. One positive and one negative lens necessary
  2. Two different sequences of plus (crown) / minus (flint)
  3. Large ν-difference relaxes the bendings
  4. Achromatic correction indipendent from bending
  5. Bending corrects spherical aberration at the margin
  6. Aplanatic coma correction for special glass choices
  7. Further optimization of materials reduces the spherical zonal aberration

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Achromate: Correction

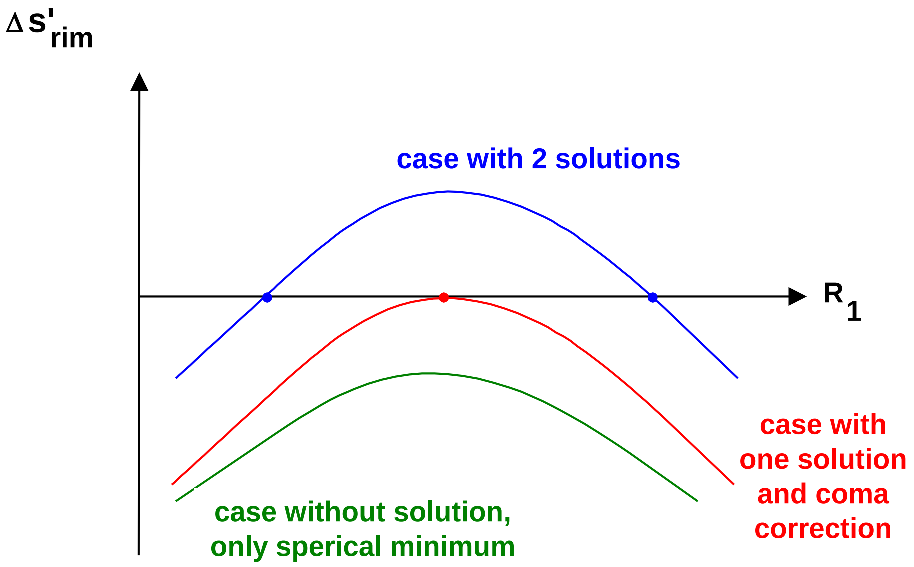
- Cemented achromate:
  6 degrees of freedom:
  3 radii, 2 indices, ratio ν_1/ν_2

- Correction of spherical aberration:
  diverging cemented surface with positive spherical contribution for $n_{neg} > n_{pos}$

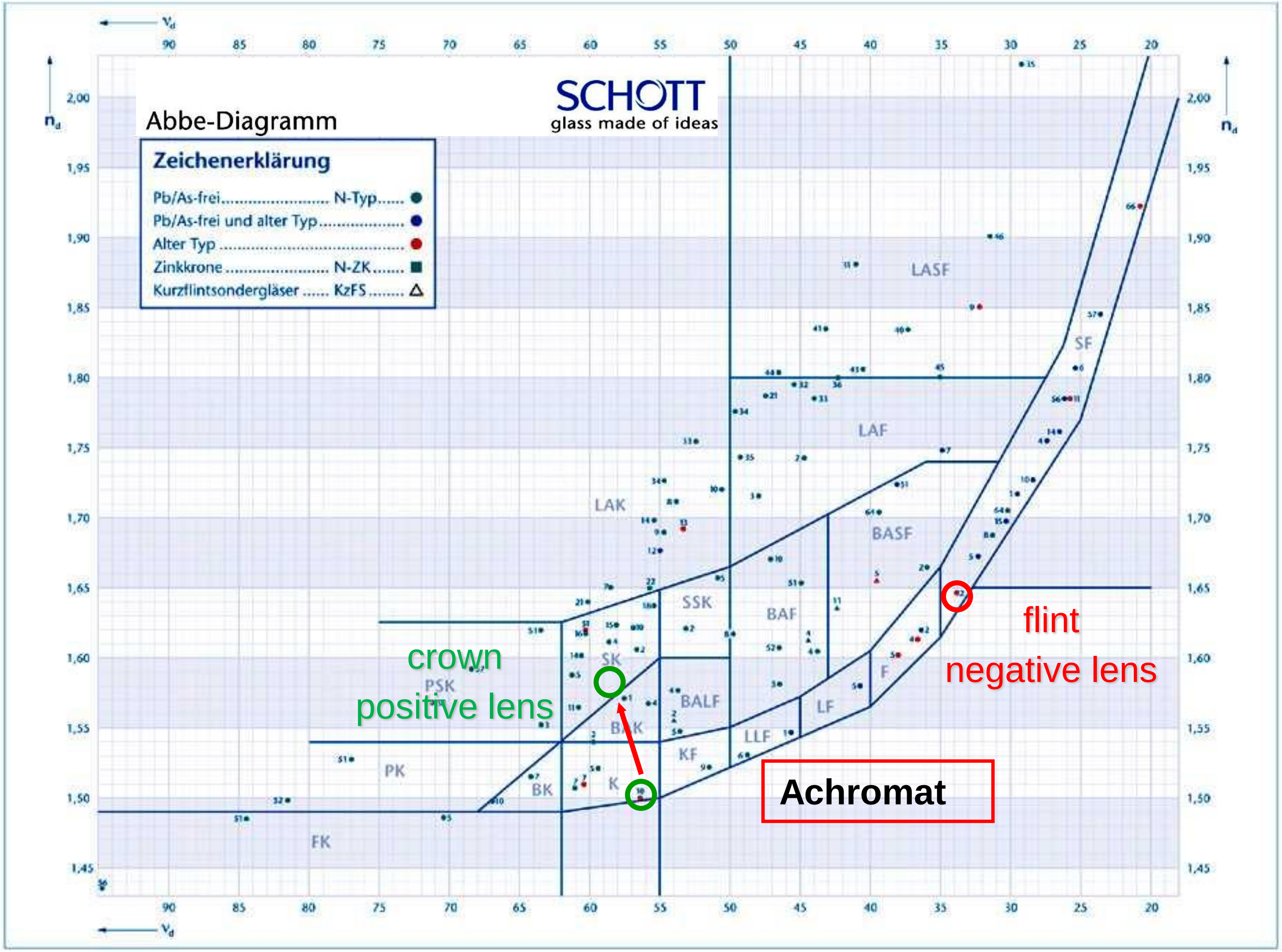
- Choice of glass: possible goals
  1. aplanatic coma correction
  2. minimization of spherochromatism
  3. minimization of secondary spectrum

- Bending has no impact on chromatical correction:
  is used to correct spherical aberration at the edge

- Three solution regions for bending
  1. no spherical correction
  2. two equivalent solutions
  3. one aplanatic solution, very stable

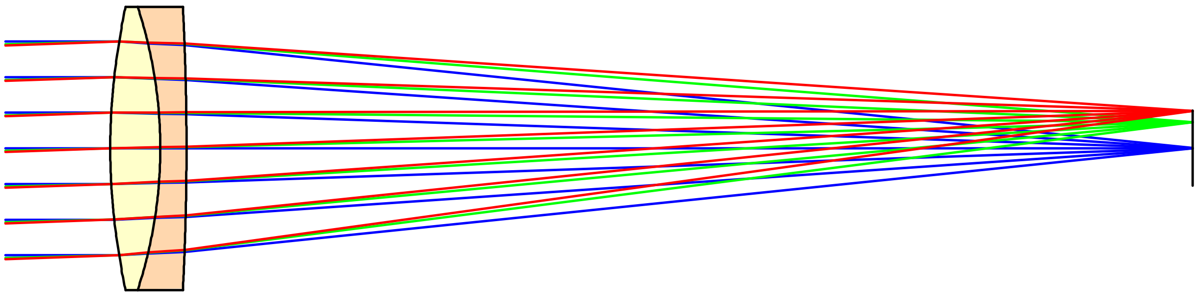


Achomatic solutions in the Glass Diagram

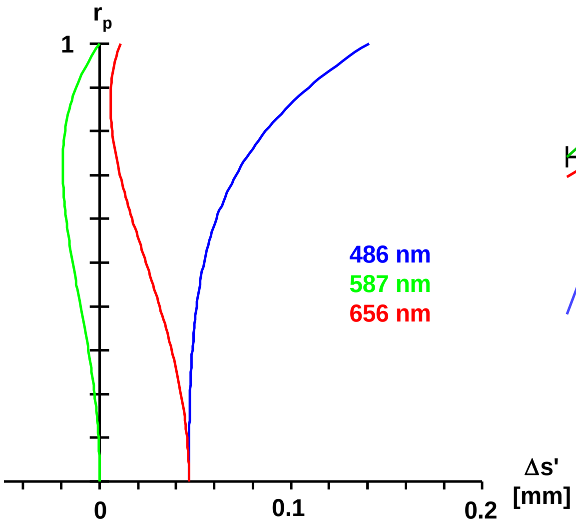


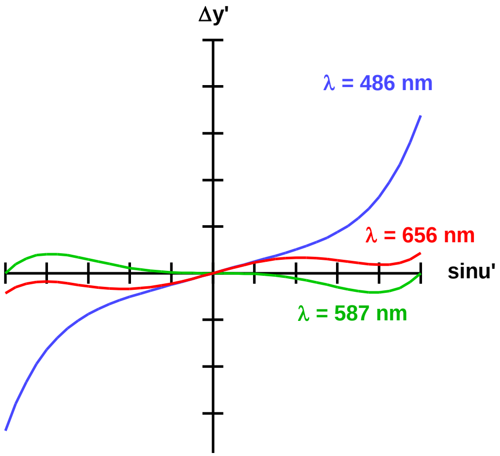
Achromate

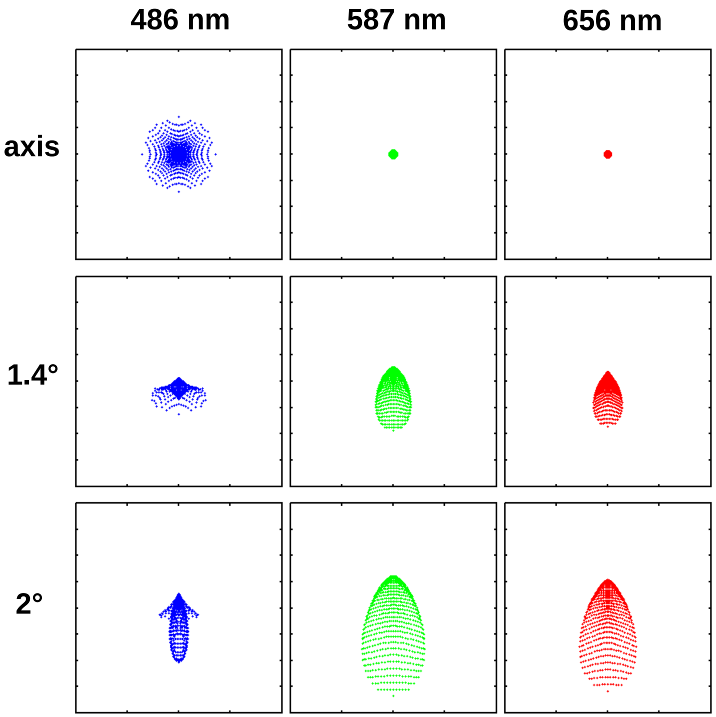
- Achromate



- Longitudinal aberration
- Transverse aberration
- Spot diagram







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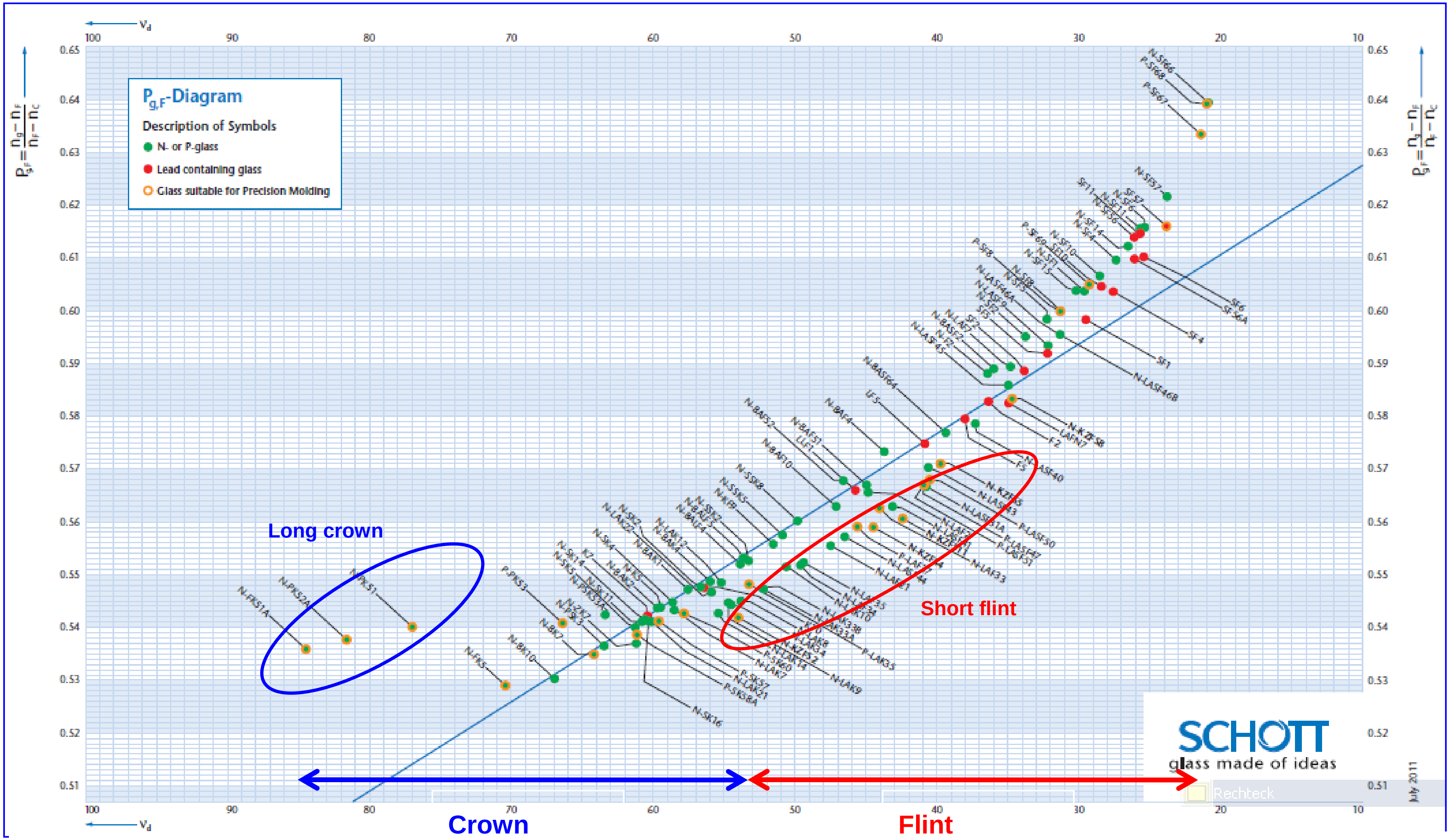
Relative Partial Dispersion

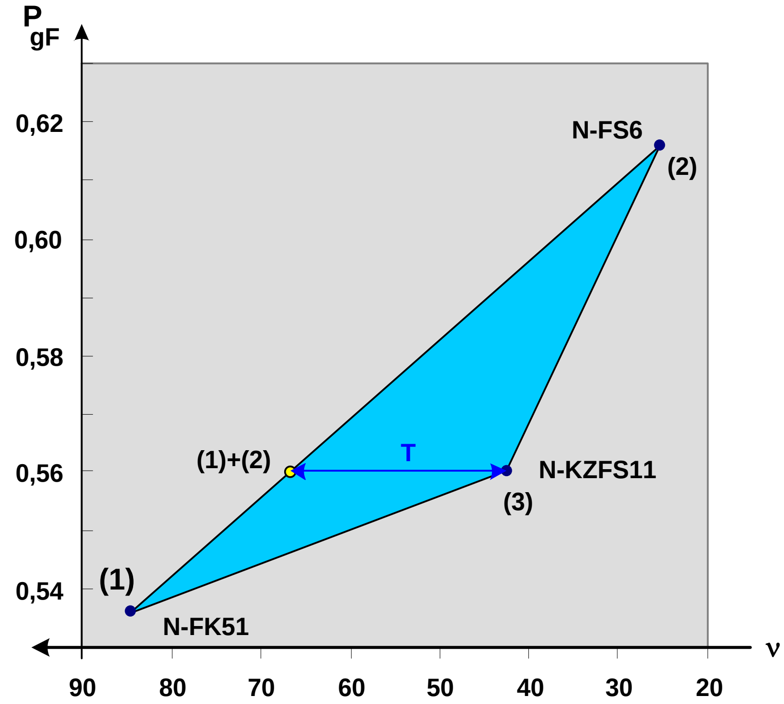
- Long crown and short flint as special realizations of large P

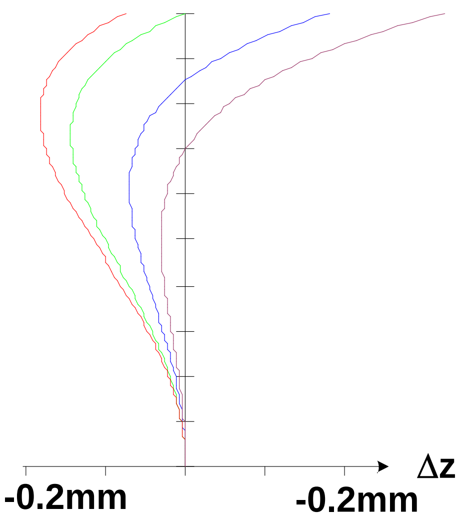


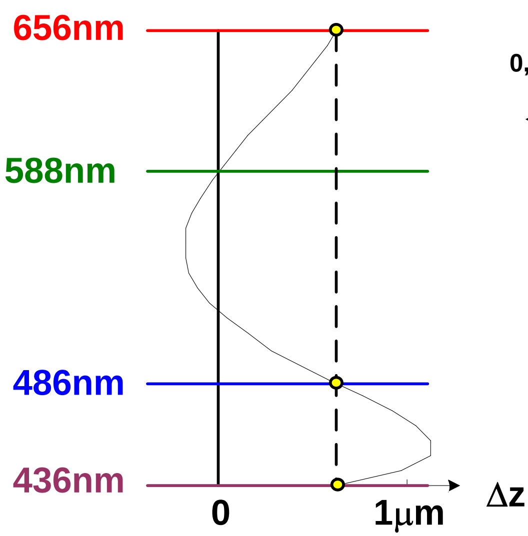
Ref.:H. Zuegge

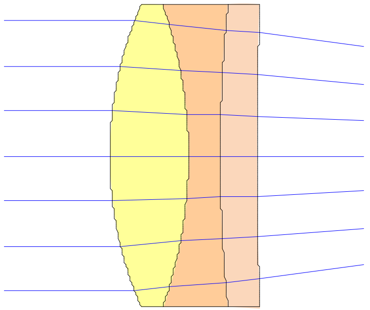
Axial Colour : Apochromate

- Choice of at least one special glass
- Correction of secondary spectrum: anomalous partial dispersion
- At least one glass should deviate significantly form the normal glass line









Apochromate

- Focal power condition

$$F = F_1 + F_2 + F_3$$

- Achromatic condition

$$\frac{F_1}{\nu_1} + \frac{F_2}{\nu_2} + \frac{F_3}{\nu_3} = 0$$

- Secondary spectrum

$$\frac{P_1 \cdot F_1}{\nu_1} + \frac{P_2 \cdot F_2}{\nu_2} + \frac{P_3 \cdot F_3}{\nu_3} = 0$$

- Curvatures of lenses

$$c = \frac{1}{r_1} - \frac{1}{r_2}$$

$$c_a = \frac{1}{f \cdot E \cdot (\nu_a - \nu_c)} \cdot \frac{P_b - P_c}{n_{a,\lambda 1} - n_{a,\lambda 3}}$$

$$c_b = \frac{1}{f \cdot E \cdot (\nu_a - \nu_c)} \cdot \frac{P_c - P_a}{n_{b,\lambda 1} - n_{b,\lambda 3}}$$

$$c_c = \frac{1}{f \cdot E \cdot (\nu_a - \nu_c)} \cdot \frac{P_a - P_b}{n_{c,\lambda 1} - n_{c,\lambda 3}}$$

- Parameter E

$$E = \frac{1}{\nu_a - \nu_c} \cdot \left[\nu_a \cdot (P_b - P_c) + \nu_b \cdot (P_c - P_a) + \nu_c \cdot (P_a - P_b)\right]$$

- The 3 materials are not allowed to be on the normal line
- The triangle of the 3 points should be large: small c_j give relaxed design

Buried Surface

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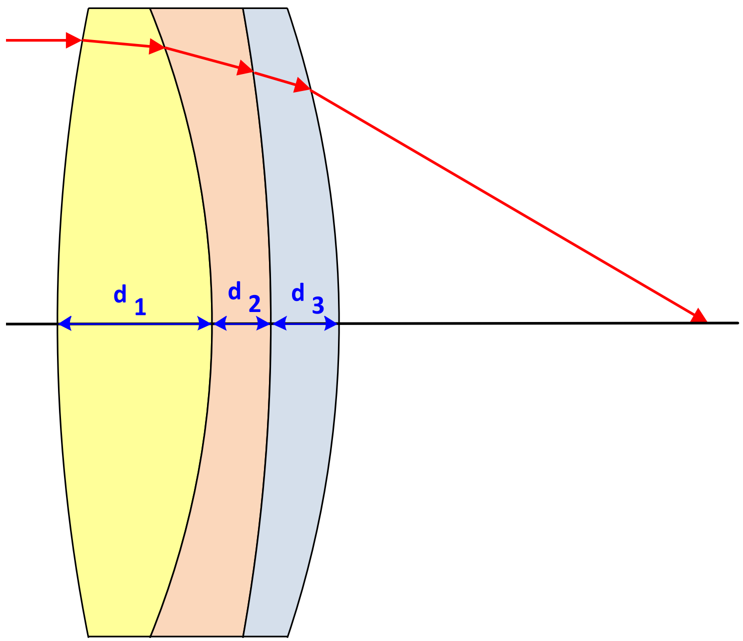
- Cemented surface with perfect refrcative index match
- No impact on monochromatic aberrations
- Only influence on chromatical aberrations
- Especially 3-fold cemented components are advantages
- Can serve as a starting setup for chromatical correction with fulfilled monochromatic correction
- Special glass combinations with nearly perfect parameters

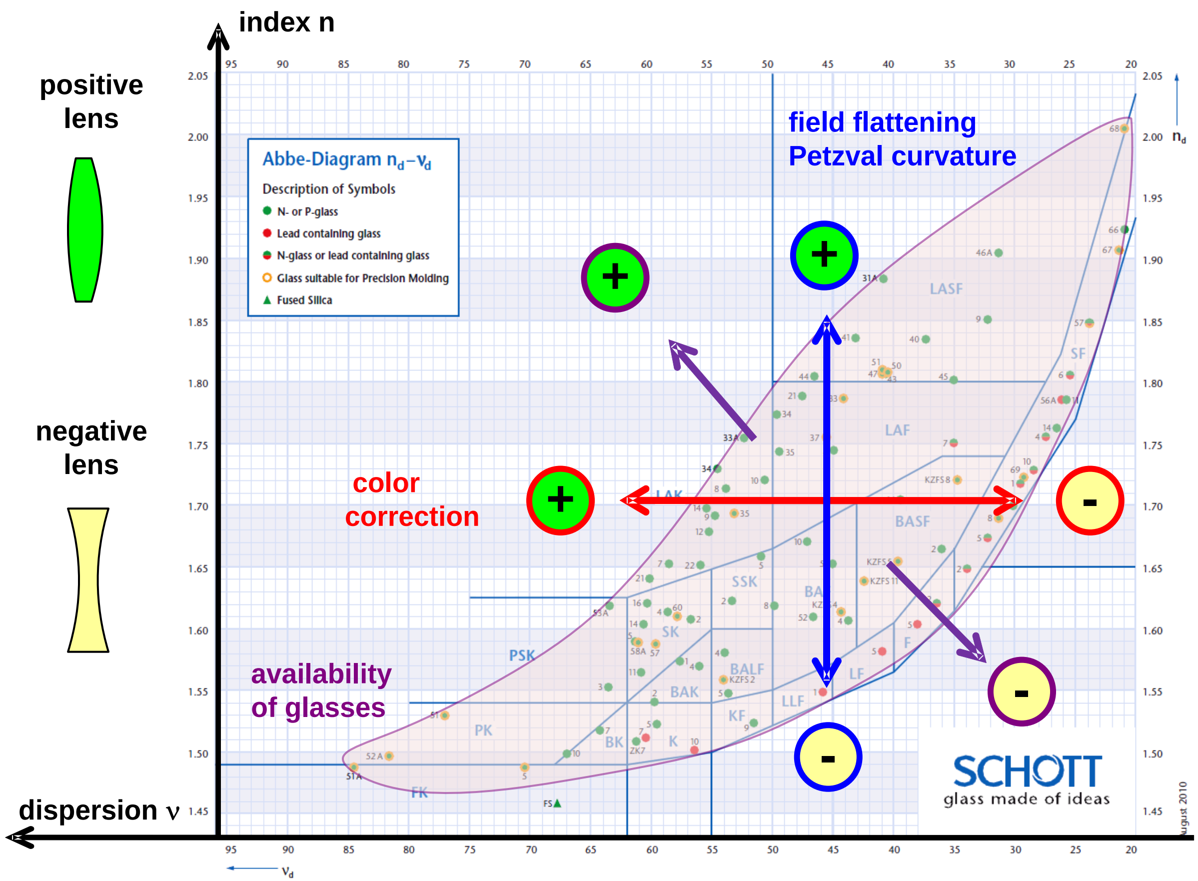
Nr	Glas	n_d	Δn_d	ν_d	$\Delta\nu_d$
1	SK16	1.62031	0.00001	60.28	22.32
	F9	1.62030		37.96	
2	SK5	1.58905	0.00003	61.23	20.26
	LF2	1.58908		40.97	
3	SSK2	1.62218	0.00004	53.13	17.06
	F13	1.62222		36.07	
4	SK7	1.60720	0.00002	59.47	10.23
	BaF5	1.60718		49.24	



Principles of Glass Selection in Optimization

- Design Rules for glass selection

- Different design goals:
  1. Color correction:
     large dispersion difference desired
  2. Field flattening:
     large index difference desired



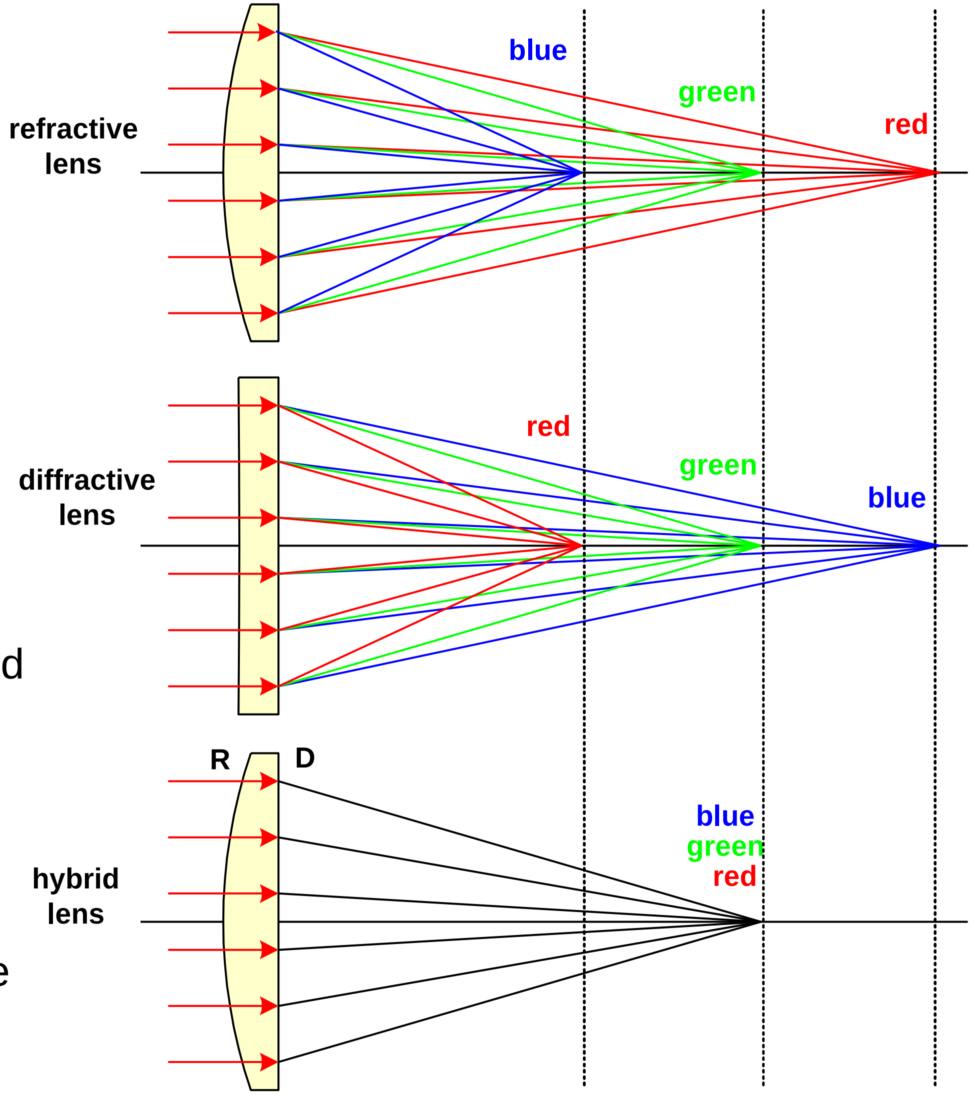
Ref : H. Zügge

Achromatic Hybrid Lens

- Lens with diffractive structured surface: hybrid lens
- Refractive lens: dispersion with Abbe number ν = 25...90
- Diffractive lens: equivalent Abbe number

$$\nu_d = \frac{\lambda_d}{\lambda_F - \lambda_C} = -\,3.453$$

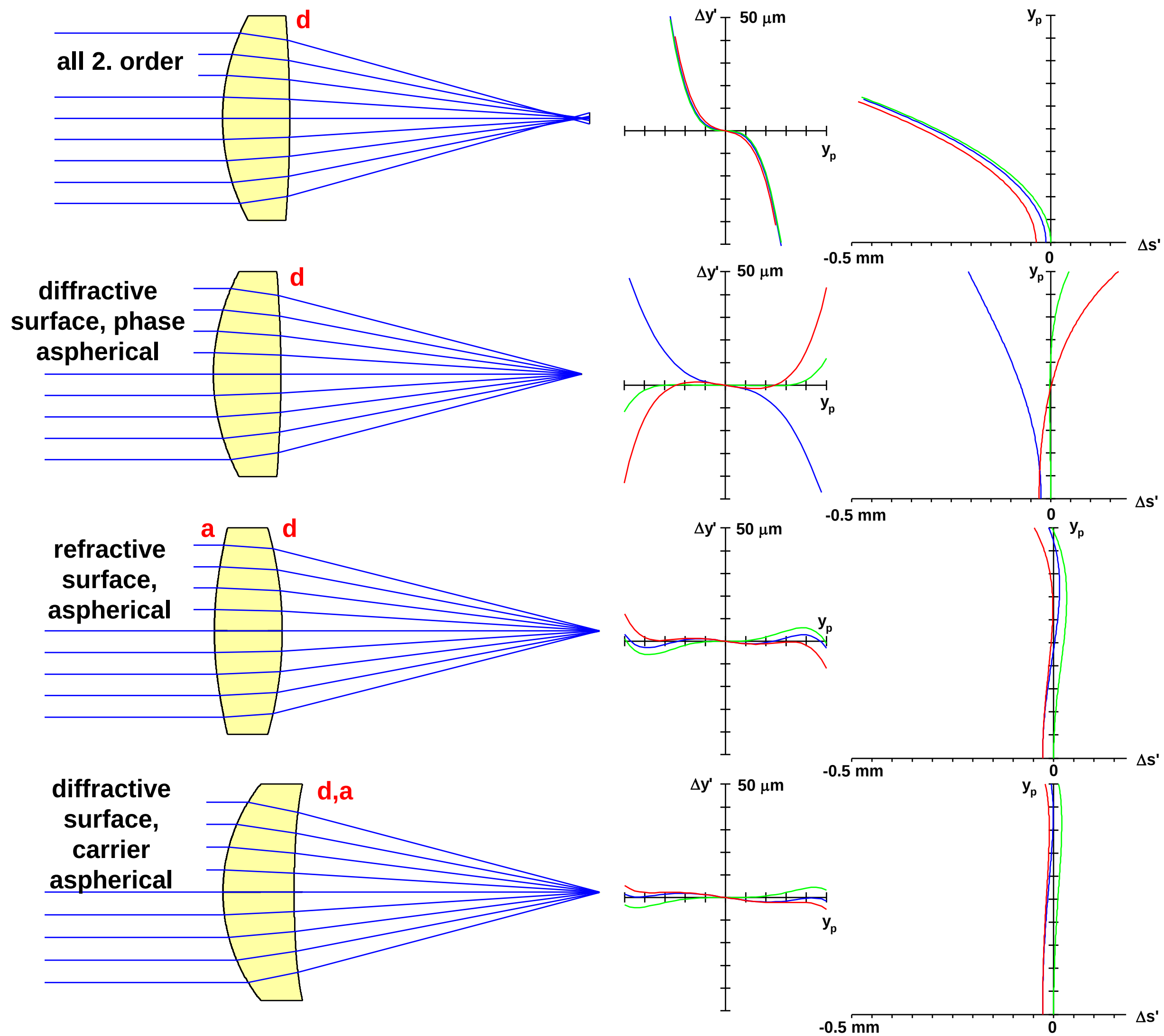
- Combination of refractive and diffractive surfaces: achromatic correction for compensated dispersion
- Usually remains a residual high secondary spectrum
- Broadband color correction is possible but complicated



Diffractive Optics: Singlet Solutions

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- Combination of DOE and aspherical carrier



Exercise: Symmetric system

In a symmetric system, all odd aberrations are completely corrected. This is demonstrated in this exercise.

a) Establish an incoming collimated beam with wavelength 500 nm and 10 mm diameter with the field angles 0°, 7° and 10°. It is focussed by two lenses with material SF6, thickness 5 mm and distance 10 mm. The image is located in a distance of 100 mm, the stop lies 5 mm before the first lens vertex. Optimize the system by changing only the radii of curvature. Inspect the quality by calculating the spots, the Seidel aberration contributions, the distortion and the Zernike coefficients for the outer field point.

b) Now double the system perfectly symmetric. Exchange the field definition from angle to the equivalent finite object height. What is the correction now ? Change the position of the stop only by a slider option. What kind of changes are seen ? Prepare a universal plot to see the change in coma as a function of the stop location between 0 and 10 mm.

c) Now re-optimize the system preserving the symmetry. Is the system now diffraction limited ?