Lecture 16

Thermal Analysis

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What is Thermal Analysis?

Optical systems are used in a variety of environments.
Therefore, it is required to model effects of temperature, pressure, etc, in an optical system design.

Modelling of temperature effects on optical system is known as **Thermal Analysis**

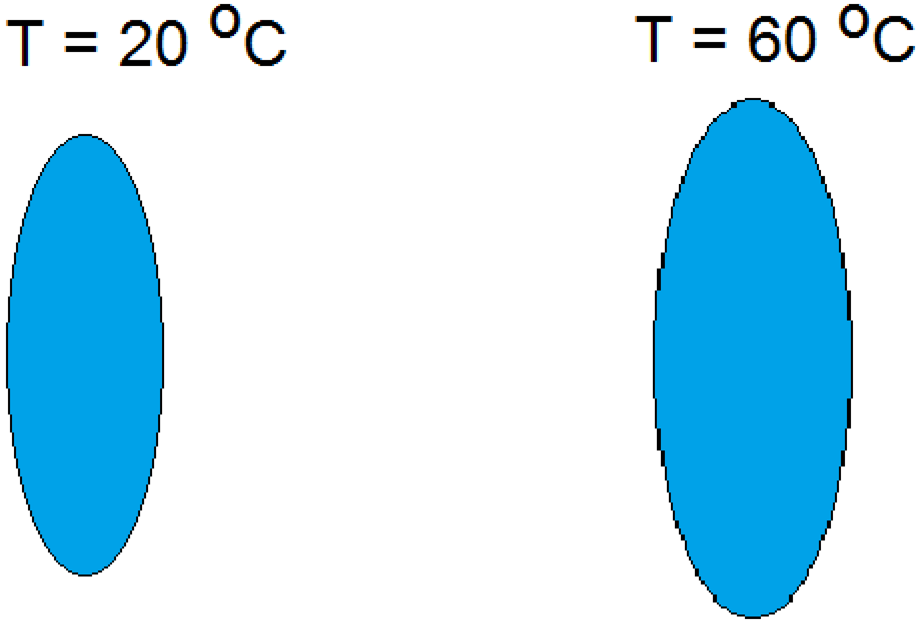
It is important to include temperature effects, if temperature change is more than 40 degrees since

- Glass expands / contracts
- Mechanical holders expands / contracts

In military applications, we may use effect of temperature changes in the range ±50 ^{o}C.

Temperature and Lens Geometry

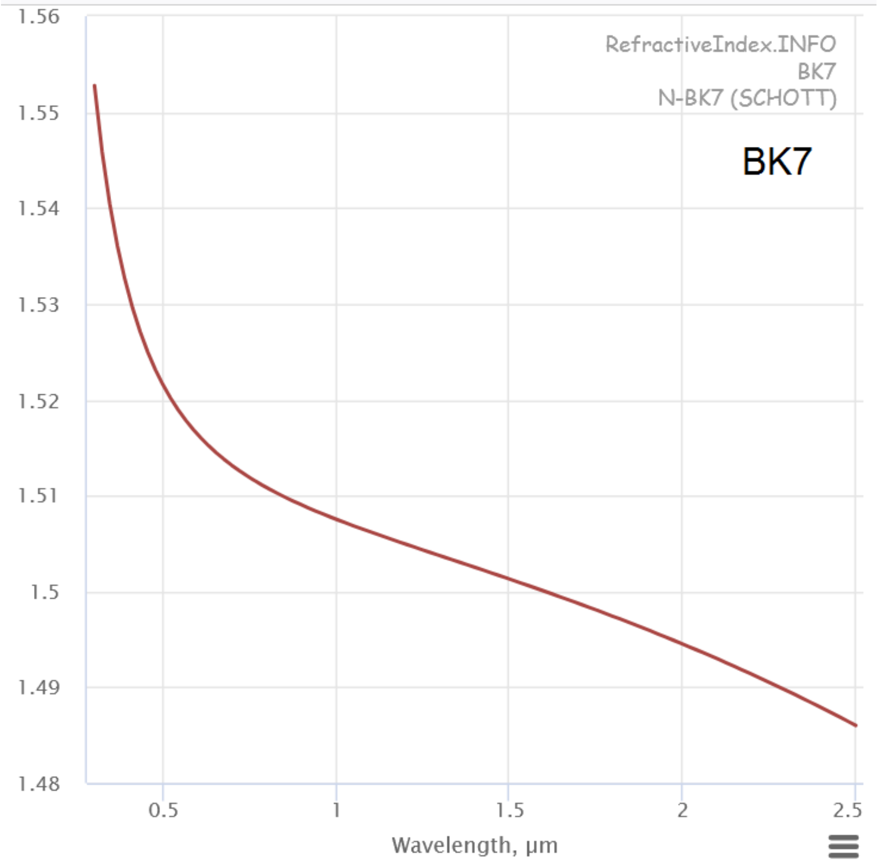
- Glass expands isotropically (uniformly in all directions).
- That is radii and thickness expand at the same rate.



Exaggerated thermal expansion of a lens

Temperature, Pressure and Index of Ref.

- For many optical materials the refractive index decreases as the wavelength increases.in optical region.
- Refractive index
  - of a glass decreases as the temperature of medium increases.
  - of air increases as the pressure of the medium increases.
- Hence, the designer should take these factors into account when making the analysis.



Temperature and Focal Length of a Lens

Considering the simple case of a single element thin lens, the change in focal length (Δf) of the lens with temperature is given by:

$$\Delta f = -\gamma f \Delta T = -\left(\frac{dn/dT}{n-1} - \alpha_L\right) f \Delta T$$

γ = thermo-optical coefficient of the lens
dn/dT = refractive index change with temperature
n = refractive index of the lens
α_L = thermal expansion coefficient (TCE) of the lens
f = focal length of the lens
ΔT = temperature change

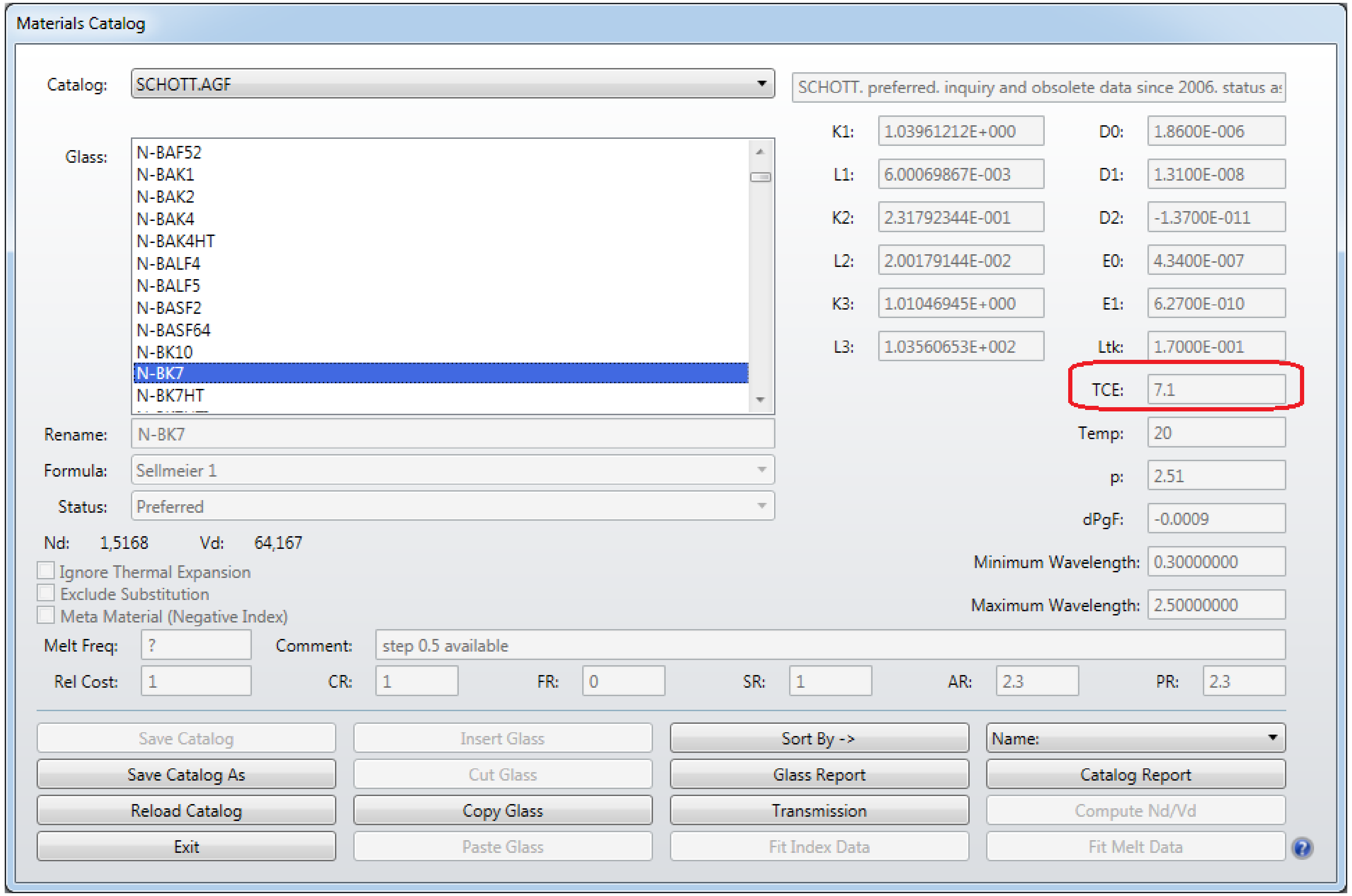
Thermal effects are espeically very important in IR applications. Assume that we have a 75-mm-diameter $f/1.5$ Germanium lens with a focal length of 112.5 mm

Depth of focus: δ = 0.046 mm
Change in Focal length: Δf = 0.599 mm (for ΔT = 40 ^{o}C)

The difference is very large. Therefore, relatively large temperature change is a very serious problem in thermal infrared systems.

TCE of Some Materials

Glass	TCE (1/°C)
N-BK7	7.1×10^{-6}
N-SF2	7.1×10^{-6}
N-SF5	7.9×10^{-6}
N-F2	6.7×10^{-6}
N-LAF35	5.3×10^{-6}
POLYCARB	60.0×10^{-6}
Germanium	5.7×10^{-6}
ZnSe	7.2×10^{-6}



Lens Holder	TCE (1/°C)
Steel	9×10^{-6}
Iron	11×10^{-6}
Aluminum	23×10^{-6}
Brass	188×10^{-6}

Material	Refractive Index at 4 µm	Refractive Index at 10 µm	$dn/dt/°C$	Comments
Germanium	4.0243	4.0032	0.000396	Expensive, large *dn/dt*
Silicon	3.4255	3.4179*	0.000150	Large *dn/dt*
Zinc sulfide, CVD	2.2520	2.2005	0.0000433	
Zinc selenide, CVD	2.4331	2.4065	0.000060	Expensive, very low absorption
AMTIR I (Ge/As/SE:33/12/55)	2.5141	2.4976	0.000072	
Magnesium fluoride	1.3526	†	0.000020	Low cost, no ctg required
Sapphire	1.6753	†	0.000010	Very hard, low emissivity at high temperature

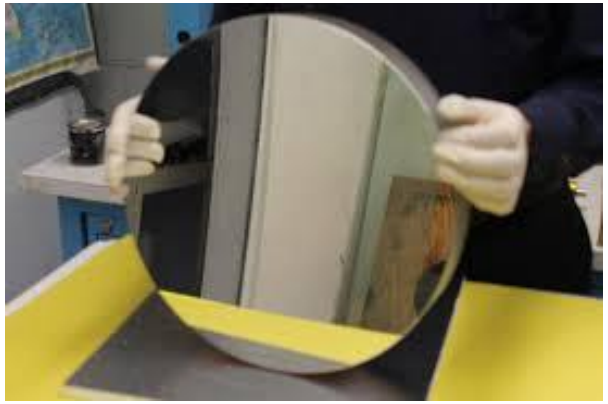
Zerodur Glass

Zerodur is extremely low expansion glass ceramic from Schott Company. It is used in high-tech applications:

- IC (Integrated Circuit)
- FPD (Flat Panel Display)
- Lithography
- High-precision metrology
- Astronomy (as mirror material)

CTE Grades	CTE (0 °C; 50 °C)*
ZERODUR® Expansion Class 2	0 ± 0.100 · 10^{-6}/K
ZERODUR® Expansion Class 1	0 ± 0.050 · 10^{-6}/K
ZERODUR® Expansion Class 0	0 ± 0.020 · 10^{-6}/K
ZERODUR® Expansion Class 0 **SPECIAL**	0 ± 0.010 · 10^{-6}/K
ZERODUR® Expansion Class 0 **EXTREME**	0 ± 0.007 · 10^{-6}/K
ZERODUR® **TAILORED**	TAILORED ± 0.020 · 10^{-6}/K (± 0.010 · 10^{-6}/K upon request) Optimized for application temperature profile

CTE is TCE in Zemax



Athermalization

ChatGPT says:

Athermalization is the process of designing a system or device in such a way that it <u>remains insensitive to changes in temperature</u>.

This can be achieved by various means, such as
- using materials with low thermal expansion coefficients,
- incorporating compensating elements in the design, or
- using active control systems to regulate the temperature.

Athermalization is particularly important in precision instruments, such as **optical systems** and **electronic circuits**, where changes in temperature can cause drift or changes in performance. By designing these systems to be athermal, their performance can be maintained over a wide temperature range.

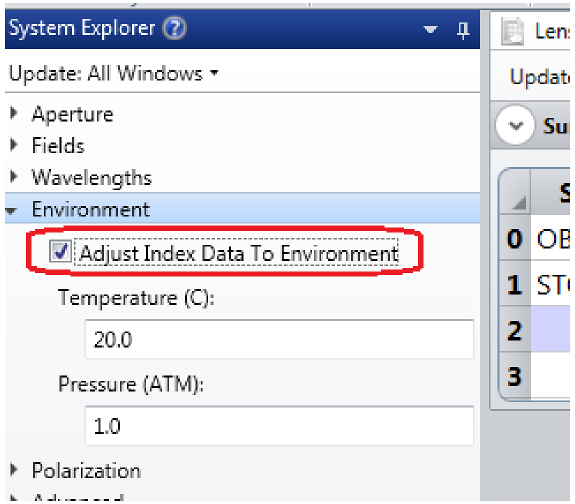
It is clear that, in design process, the optical system must be optimized to operate at different temperatures.

Thermal Analysis in Zemax

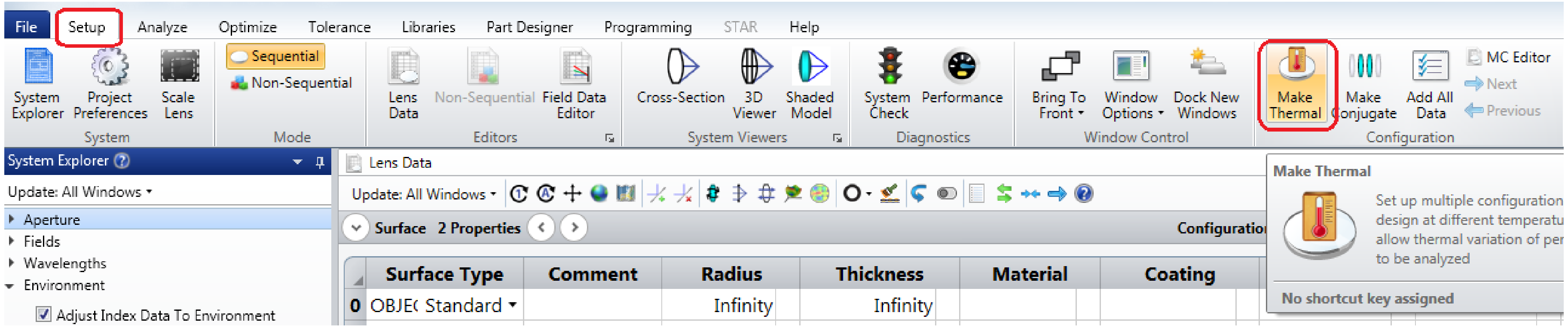
Zemax OpticStudio has thermal modeling capability.

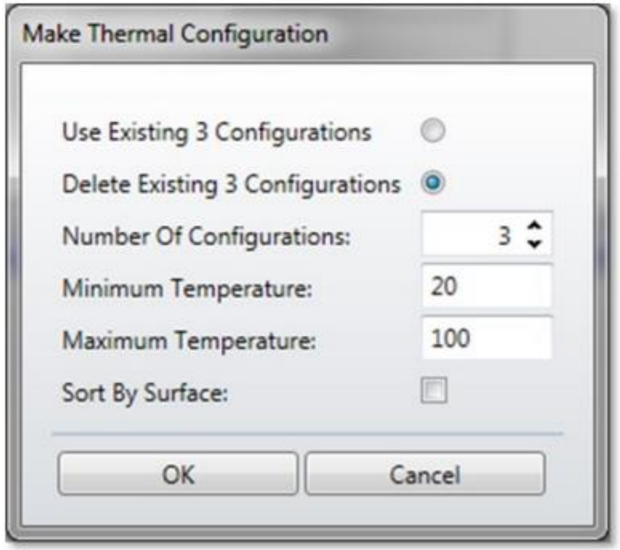
Before starting thermal analysis, you need to check

“Adjust Index Data To Environment” option in System Explorer window.



In Zemax, **Make Thermal** Tool provides modelling thermal effects via MCE





- All parameters that are affected by temperature have to be listed in the Multiple Configuration Editor (MCE).

- Thermal pickups are used for the parameters in the MCE so that those values are automatically computed by Zemax.

- **Make Thermal** tool provides convenient way to insert all operands in the MCE with thermal pickups.

Example1: Single Lens

Consider the lens

Glass:	BK7
Object:	at infinity
R_1:	+250 mm
R_2:	-300 mm
ct:	6 mm
ENPD:	20 mm
TCE:	7.1e-6 / ^oC
Wavelength:	d-line

Investigate the temperature effects on the spot diagram and EFFL.

Use 4 different temperature configurations and let

$T_{min} = -20\ ^oC$

$T_{max} = +60\ ^oC$

Example1: LDE

Initial LDE before Thermal Analysis:

Lens Data

Update: All Windows

Surface 4 Properties | Configuration 1/1

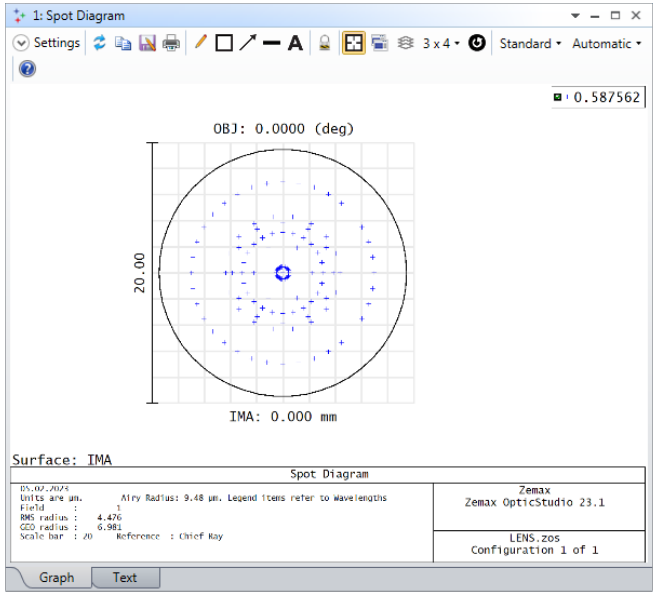
	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			0.000		0.000	0.000	0.0...	0.000
1	STOP	Standard		Infinity	0.000			10.000	U	0.000	10.000	0.0...	0.000
2	(aper)	Standard		250.000	6.000	BK7		11.000	U	0.000	11.000	0.0...	-
3	(aper)	Standard		-300.000	262.311			11.000	U	0.000	11.000	0.0...	0.000
4	IMAGE	Standard		Infinity	-			6.981E-03		0.000	6.981E-03	0.0...	0.000

After **Quick Focus** we have

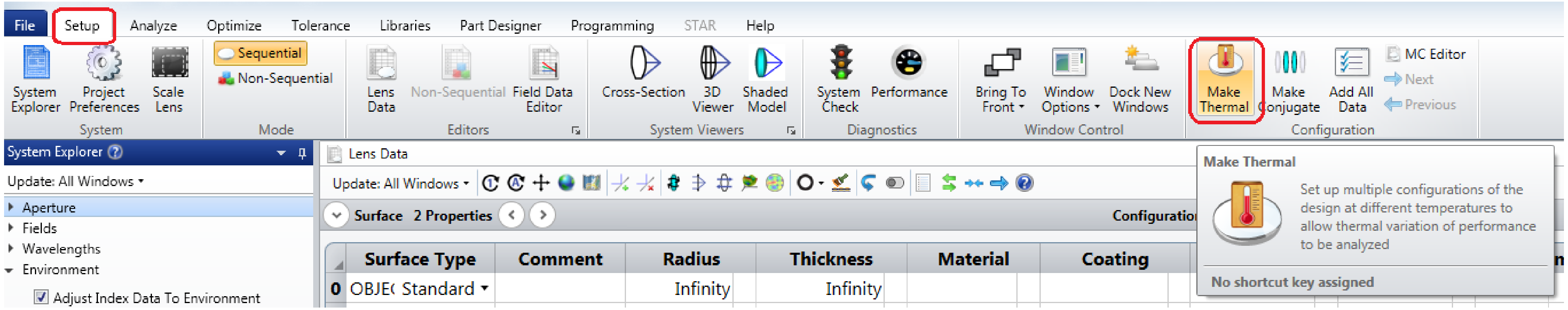
EFFL = 264.8459 mm

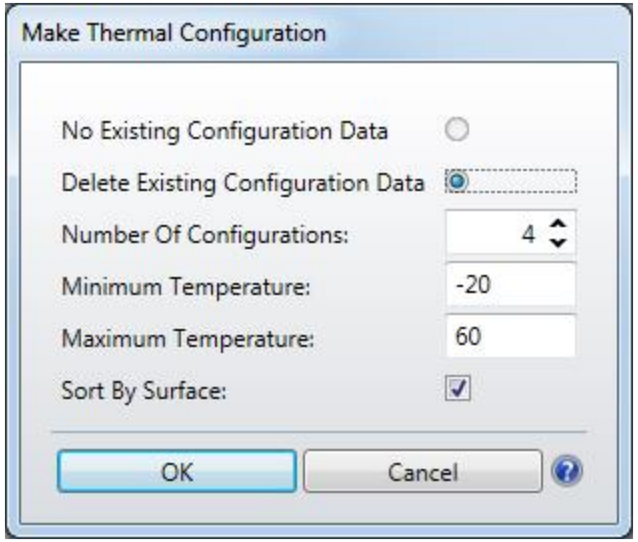
RMS Spot Radius = 4.76 um

Airy Disk Radius = 9.48 um



Example1: Make Thermal

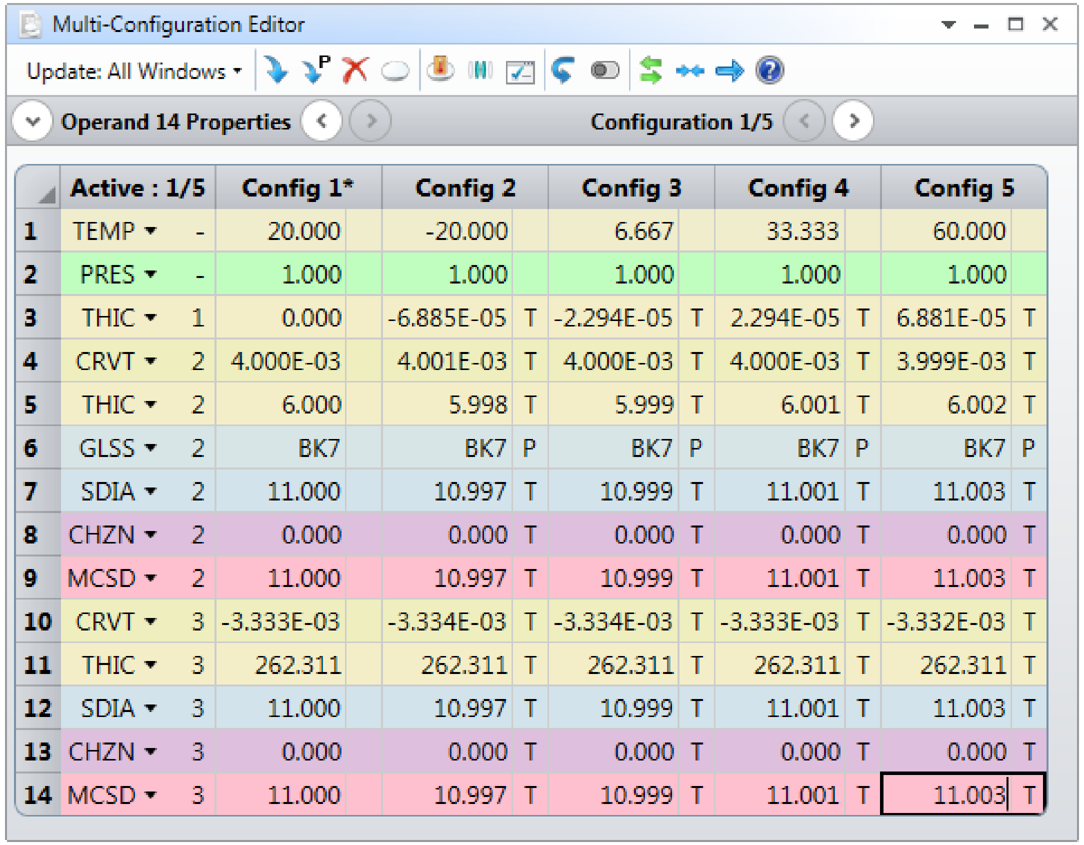




Example1: MCE Result of Analysis

TEMP: Temperature
PRES: Pressure
THIC: Thickness
CRVT: Curvature
GLSS: Glass
SDIA: SemiDiameter
CHZN: ChipZone
MCSD: Mech. SemiDiameter

T	EFFL	SPOT
-20.0	264.83	4.69
6.6	264.84	4.54
20.0	264.84	4.76
33.3	264.85	4.42
60.0	264.86	4.33



	Active : 1/5		Config 1*	Config 2	Config 3	Config 4	Config 5
1	TEMP	-	20.000	-20.000	6.667	33.333	60.000
2	PRES	-	1.000	1.000	1.000	1.000	1.000
3	THIC	1	0.000	-6.885E-05 T	-2.294E-05 T	2.294E-05 T	6.881E-05 T
4	CRVT	2	4.000E-03	4.001E-03 T	4.000E-03 T	4.000E-03 T	3.999E-03 T
5	THIC	2	6.000	5.998 T	5.999 T	6.001 T	6.002 T
6	GLSS	2	BK7	BK7 P	BK7 P	BK7 P	BK7 P
7	SDIA	2	11.000	10.997 T	10.999 T	11.001 T	11.003 T
8	CHZN	2	0.000	0.000 T	0.000 T	0.000 T	0.000 T
9	MCSD	2	11.000	10.997 T	10.999 T	11.001 T	11.003 T
10	CRVT	3	-3.333E-03	-3.334E-03 T	-3.334E-03 T	-3.333E-03 T	-3.332E-03 T
11	THIC	3	262.311	262.311 T	262.311 T	262.311 T	262.311 T
12	SDIA	3	11.000	10.997 T	10.999 T	11.001 T	11.003 T
13	CHZN	3	0.000	0.000 T	0.000 T	0.000 T	0.000 T
14	MCSD	3	11.000	10.997 T	10.999 T	11.001 T	11.003 T

Example2: Thermal Analysis of a Mirror

Consider a concave mirror made from aluminum.

|R| = 500 mm
ENPD = 100 mm
TCE = 23e-6 / ^{o}C
Conic = -1 (parabolic mirror)

Investigate the temperature effects on radius and semi-diameter,
at T = 20 ^{o}C and at T = +60 ^{o}C.

We have two configurations:

Lens Data

Update: All Windows

Surface 3 Properties — Configuration 1/1

	Surface Type		Commei	Radius	Thickness	Material	TCE x 1E-6	Conic
0	OBJECT	Standard		Infinity	Infinity		0.000	0.000
1	STOP	Standard		Infinity	300.000		0.000	0.000
2		Standard		-500.000	-250.000	MIRROR	23.000	-1.000
3	IMAGE	Standard		Infinity	-		0.000	0.000

Lens Data

Update: All Windows

Surface 3 Properties — Configuration 2/2

	Surface Type		Commei	Radius	Thickness	Material	TCE x 1E-6	Conic
0	OBJECT	Standard		Infinity	Infinity		0.000	0.000
1	STOP	Standard		Infinity	299.998 P		0.000	0.000
2	(aper)	Standard		-500.460 P	-250.230 P	MIRROR	23.000	-1.000
3	IMAGE	Standard		Infinity	-		0.000	0.000

Multi-Configuration Editor

Update: All Windows

Operand 8 Properties — Configuration 1/2

	Active : 1/2		Config 1*	Config 2	
1	TEMP	-	20.000	60.000	
2	PRES	-	1.000	1.000	
3	THIC	1	300.000	299.998	T
4	CRVT	2	-2.000E-03	-1.998E-03	T
5	THIC	2	-250.000	-250.230	T
6	SDIA	2	50.000	50.046	T
7	CHZN	2	0.000	0.000	T
8	MCSD	2	50.000	50.046	T

Example3: Thermal Analysis of a CookeTriplet

In this example, we will investigate the Cooke Triplet at:

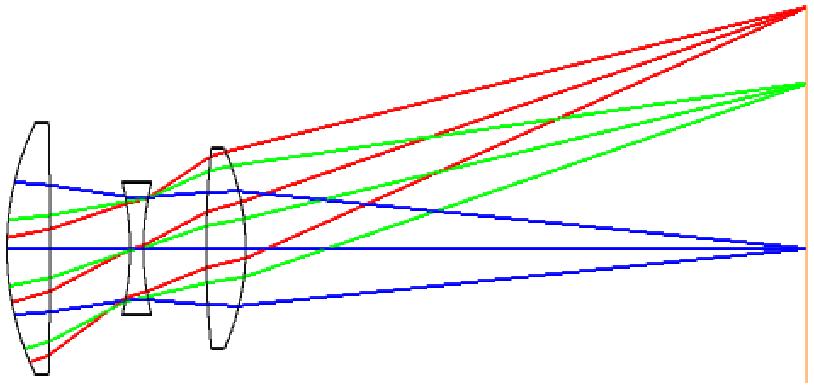
<zemax>\Samples\Sequential\Objectives\Cooke 40 degree field.zos

Lens Data

Update: All Windows

Surface 7 Properties   Configuration 1/1

	Surface Type		Com	Radius	Thickness	Material	Coating	Clear Semi-D	Chip Zone	Mech Semi-D	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000
1	(aper)	Standard		22.014 V	3.259 V	SK16 S	AR	9.500 U	0.000	9.500	0.000	-
2	(aper)	Standard		-435.760 V	6.008 V		AR	9.500 U	0.000	9.500	0.000	23.600
3	(aper)	Standard		-22.213 V	1.000 V	F2 S	AR	5.000 U	0.000	5.000	0.000	-
4	STOP (aper)	Standard		20.292 V	4.750 V		AR	5.000 U	0.000	5.000	0.000	23.600
5	(aper)	Standard		79.684 V	2.952 V	SK16 S	AR	7.500 U	0.000	7.500	0.000	-
6	(aper)	Standard		-18.395 V	42.208 V		AR	7.500 U	0.000	7.500	0.000	23.600
7	IMAGE	Standard		Infinity	-			18.173	0.000	18.173	0.000	0.000



Lens holder: Aluminum

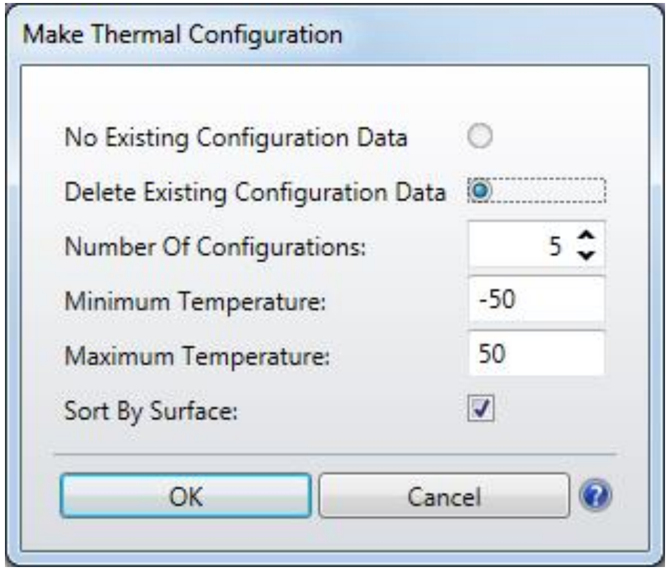
EFFL = 50 mm

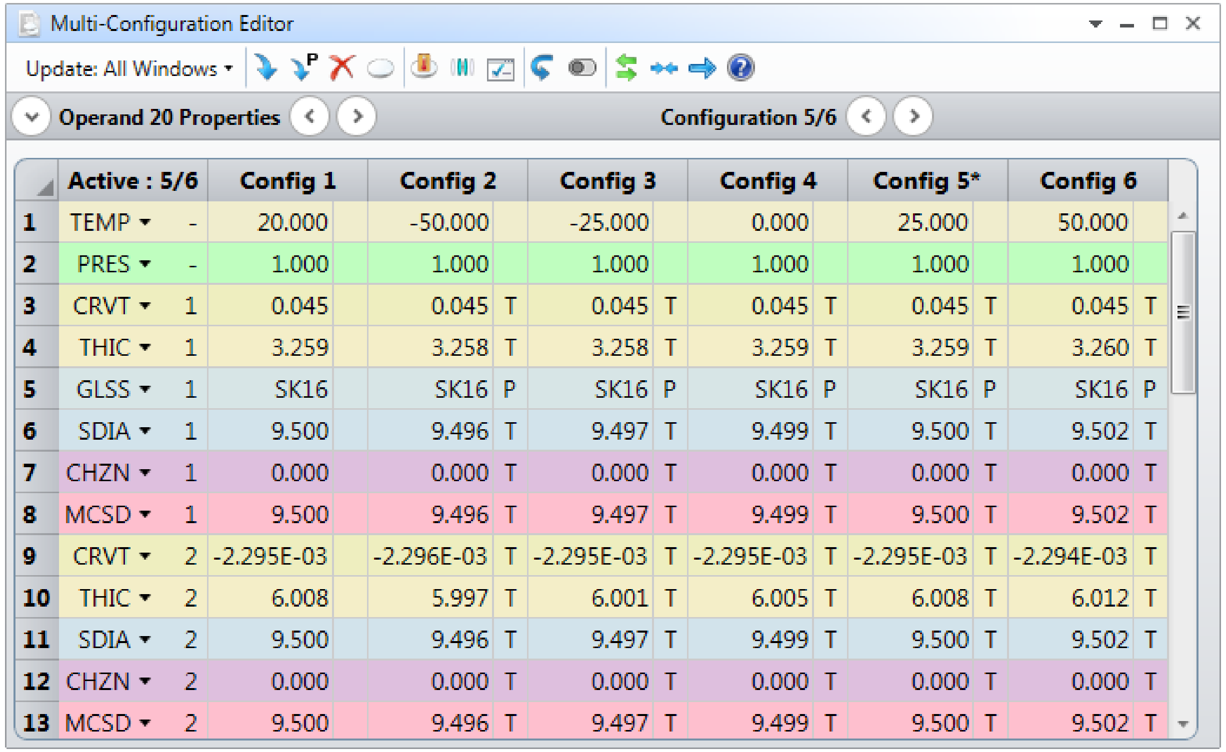
F/# = 5

FOV = 40º

λ = [0.48, 0.55, 0.65] nm

T = ±50 ^{o}C

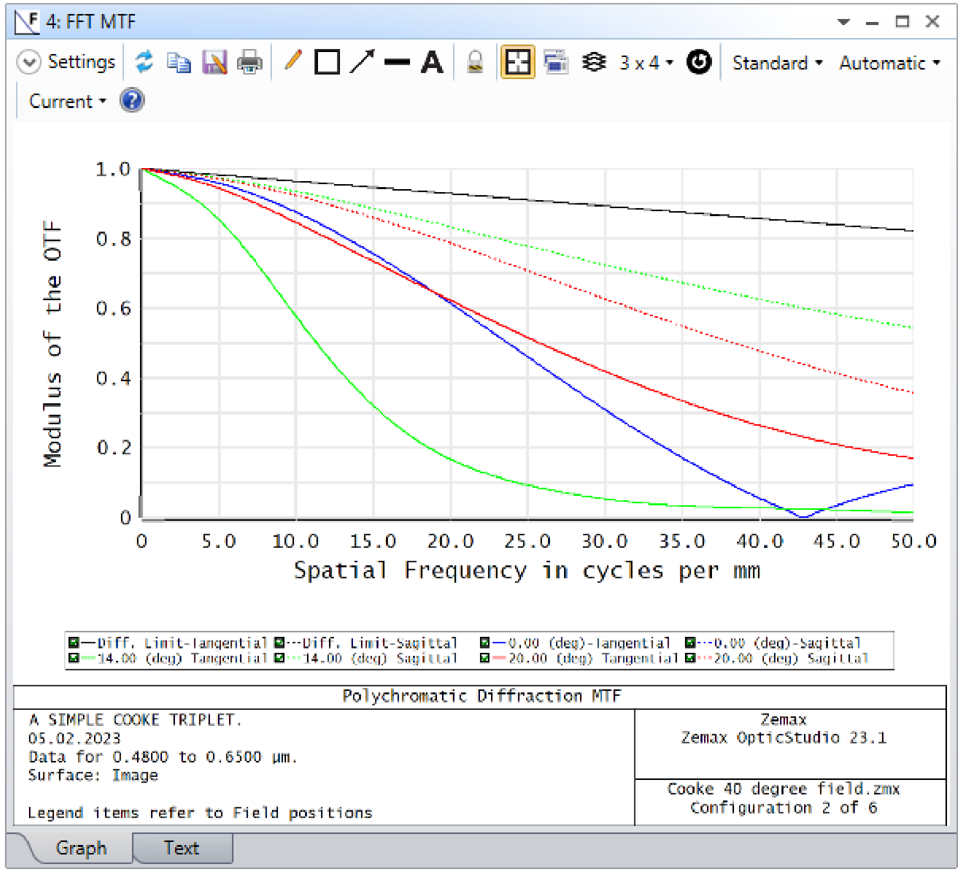


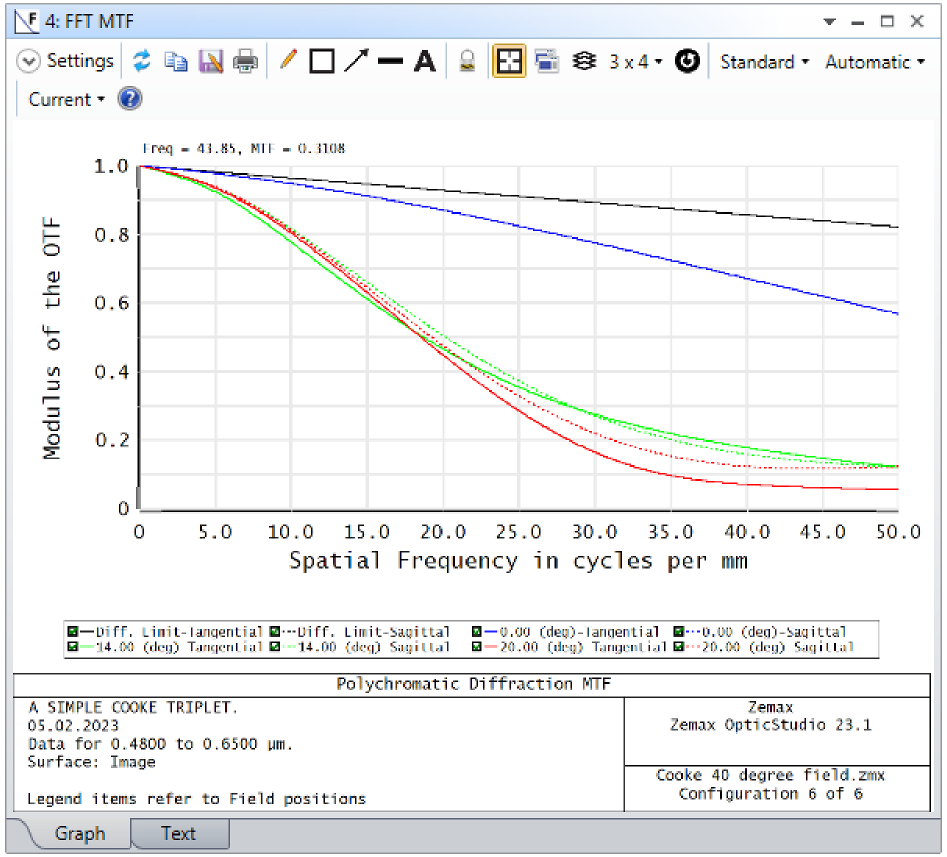


	Active : 5/6		Config 1	Config 2	Config 3	Config 4	Config 5*	Config 6
1	TEMP	-	20.000	-50.000	-25.000	0.000	25.000	50.000
2	PRES	-	1.000	1.000	1.000	1.000	1.000	1.000
3	CRVT	1	0.045	0.045 T	0.045 T	0.045 T	0.045 T	0.045 T
4	THIC	1	3.259	3.258 T	3.258 T	3.259 T	3.259 T	3.260 T
5	GLSS	1	SK16	SK16 P	SK16 P	SK16 P	SK16 P	SK16 P
6	SDIA	1	9.500	9.496 T	9.497 T	9.499 T	9.500 T	9.502 T
7	CHZN	1	0.000	0.000 T	0.000 T	0.000 T	0.000 T	0.000 T
8	MCSD	1	9.500	9.496 T	9.497 T	9.499 T	9.500 T	9.502 T
9	CRVT	2	-2.295E-03	-2.296E-03 T	-2.295E-03 T	-2.295E-03 T	-2.295E-03 T	-2.294E-03 T
10	THIC	2	6.008	5.997 T	6.001 T	6.005 T	6.008 T	6.012 T
11	SDIA	2	9.500	9.496 T	9.497 T	9.499 T	9.500 T	9.502 T
12	CHZN	2	0.000	0.000 T	0.000 T	0.000 T	0.000 T	0.000 T
13	MCSD	2	9.500	9.496 T	9.497 T	9.499 T	9.500 T	9.502 T

Look into MTF, OPD, RMS vs Field, RMS vs Wavelength, Ray Fan plots.

You will see effects temperature on the design clearly.





Example3: Athermalization

To Make system athermal,

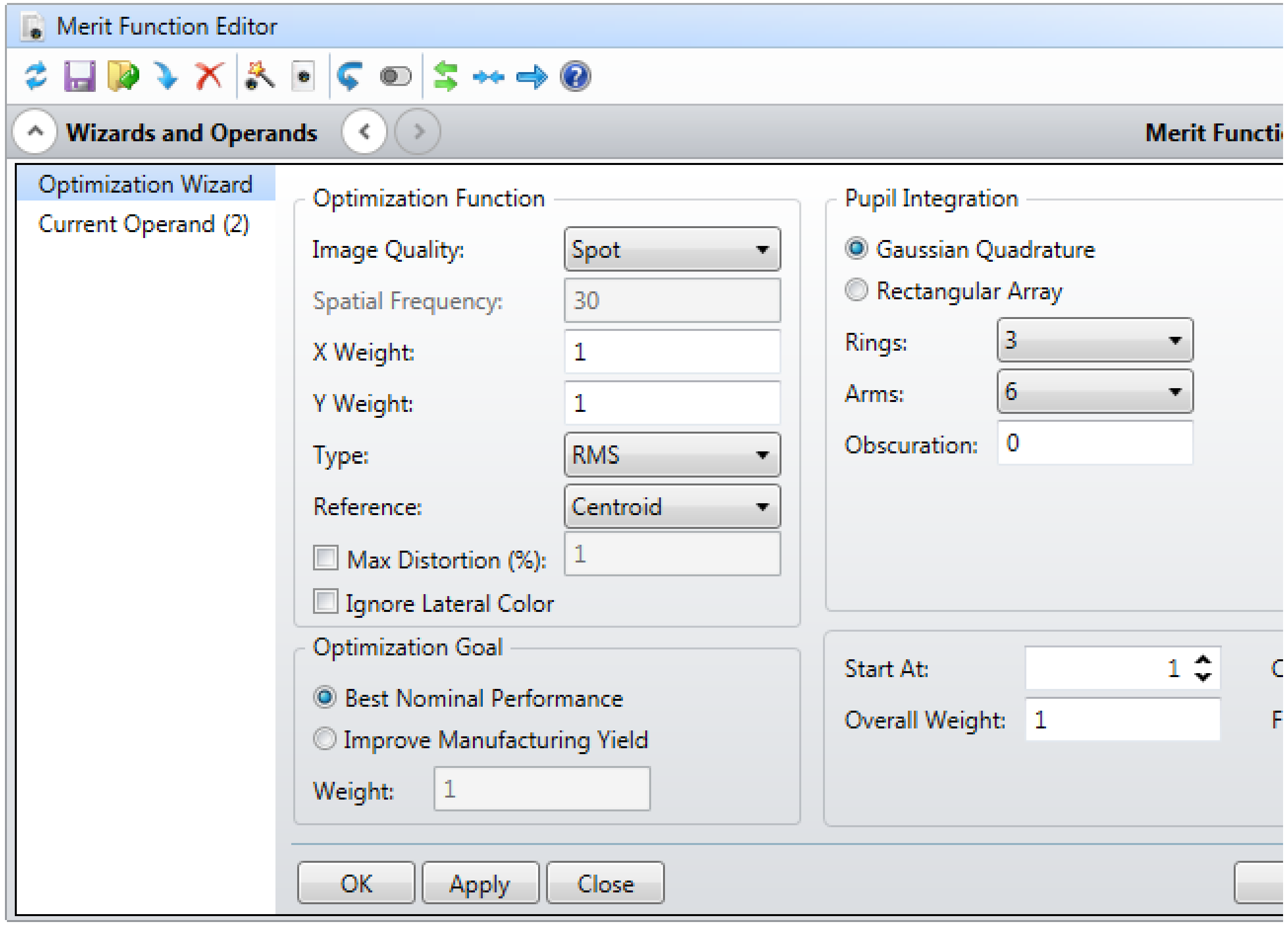
1. Setup all CRVT ve GLSS operand as variable in Config 1.

2. For all configurations, at surface 6, all THIC operands must be variable. This is required to get minimum spot radius for all configurations.

	Active : 1/6		Config 1*		Config 2		Config 3		Config 4		Config 5		Config 6	
1	TEMP	-	20.000		-50.000		-25.000		0.000		25.000		50.000	
2	PRES	-	1.000		1.000		1.000		1.000		1.000		1.000	
3	CRVT	1	0.045	V	0.045	T	0.045	T	0.045	T	0.045	T	0.045	T
4	THIC	1	3.259		3.258	T	3.258	T	3.259	T	3.259	T	3.260	T
5	GLSS	1	SK16		SK16	P	SK16	P	SK16	P	SK16	P	SK16	P
6	SDIA	1	9.500		9.496	T	9.497	T	9.499	T	9.500	T	9.502	T
7	CHZN	1	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
8	MCSD	1	9.500		9.496	T	9.497	T	9.499	T	9.500	T	9.502	T
9	CRVT	2	-2.295E-03	V	-2.296E-03	T	-2.295E-03	T	-2.295E-03	T	-2.295E-03	T	-2.294E-03	T
10	THIC	2	6.008		5.997	T	6.001	T	6.005	T	6.008	T	6.012	T
11	SDIA	2	9.500		9.496	T	9.497	T	9.499	T	9.500	T	9.502	T
12	CHZN	2	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
13	MCSD	2	9.500		9.496	T	9.497	T	9.499	T	9.500	T	9.502	T
14	CRVT	3	-0.045	V	-0.045	T	-0.045	T	-0.045	T	-0.045	T	-0.045	T
15	THIC	3	1.000		0.999	T	1.000	T	1.000	T	1.000	T	1.000	T
16	GLSS	3	F2		F2	P	F2	P	F2	P	F2	P	F2	P
17	SDIA	3	5.000		4.997	T	4.998	T	4.999	T	5.000	T	5.001	T
18	CHZN	3	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
19	MCSD	3	5.000		4.997	T	4.998	T	4.999	T	5.000	T	5.001	T
20	CRVT	4	0.049	V	0.049	T	0.049	T	0.049	T	0.049	T	0.049	T
21	THIC	4	4.750		4.742	T	4.745	T	4.748	T	4.751	T	4.754	T
22	SDIA	4	5.000		4.997	T	4.998	T	4.999	T	5.000	T	5.001	T
23	CHZN	4	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
24	MCSD	4	5.000		4.997	T	4.998	T	4.999	T	5.000	T	5.001	T
25	CRVT	5	0.013	V	0.013	T	0.013	T	0.013	T	0.013	T	0.013	T
26	THIC	5	2.952		2.951	T	2.951	T	2.952	T	2.952	T	2.953	T
27	GLSS	5	SK16		SK16	P	SK16	P	SK16	P	SK16	P	SK16	P
28	SDIA	5	7.500		7.497	T	7.498	T	7.499	T	7.500	T	7.501	T
29	CHZN	5	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
30	MCSD	5	7.500		7.497	T	7.498	T	7.499	T	7.500	T	7.501	T
31	CRVT	6	-0.054	V	-0.054	T	-0.054	T	-0.054	T	-0.054	T	-0.054	T
32	THIC	6	42.208	V	42.140	V	42.164	V	42.188	V	42.213	V	42.237	V
33	SDIA	6	7.500		7.497	T	7.498	T	7.499	T	7.500	T	7.501	T
34	CHZN	6	0.000		0.000	T	0.000	T	0.000	T	0.000	T	0.000	T
35	MCSD	6	7.500		7.497	T	7.498	T	7.499	T	7.500	T	7.501	T

Example3: MFE

Select Spot for Image Quality and press **OK.**



Set EFFL = 50 mm.

Merit Function Editor

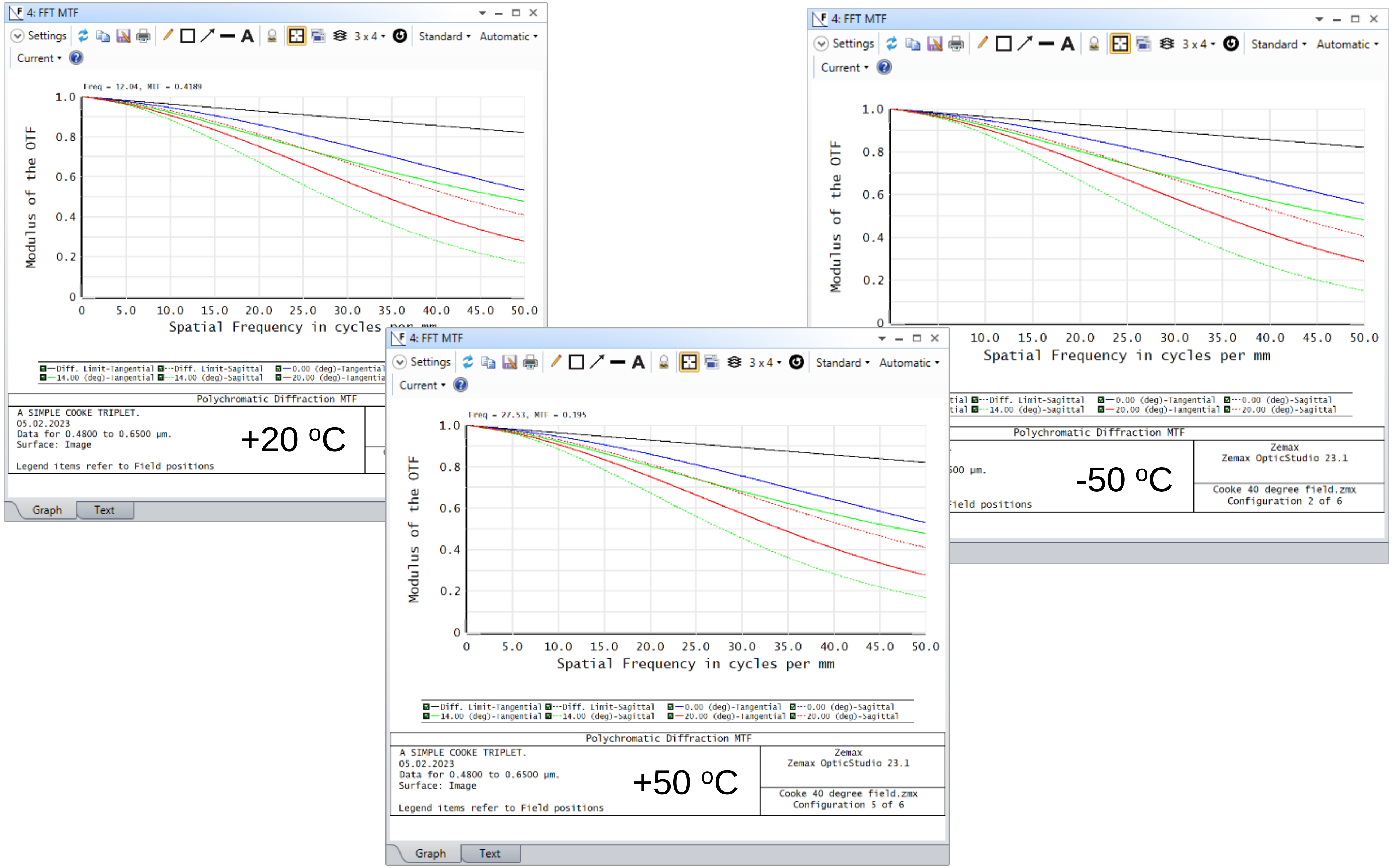
Wizards and Operands   Merit Function: 0.00838464725379272

	Type		Wave							Target	Weight	Value	% Contrib
1	CONF	1											
2	EFFL		2				[redacted]			50.000	1.000	0.000	0.000
3	DMFS												
4	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 a											
5	CONF	1											
6	BLNK	No air or glass constraints.											
7	BLNK	Operands for field 1.											
8	TRCX		1	0.000	0.000	0.336	0.000			0.000	0.078	5.434E-03	0.100
9	TRCY		1	0.000	0.000	0.336	0.000			0.000	0.078	0.000	0.000
10	TRCX		1	0.000	0.000	0.707	0.000			0.000	0.124	4.222E-03	0.096
11	TRCY		1	0.000	0.000	0.707	0.000			0.000	0.124	0.000	0.000
12	TRCX		1	0.000	0.000	0.942	0.000			0.000	0.078	-8.163E-04	2.250E-03
13	TRCY		1	0.000	0.000	0.942	0.000			0.000	0.078	0.000	0.000
14	TRCX		2	0.000	0.000	0.336	0.000			0.000	0.097	5.685E-03	0.136

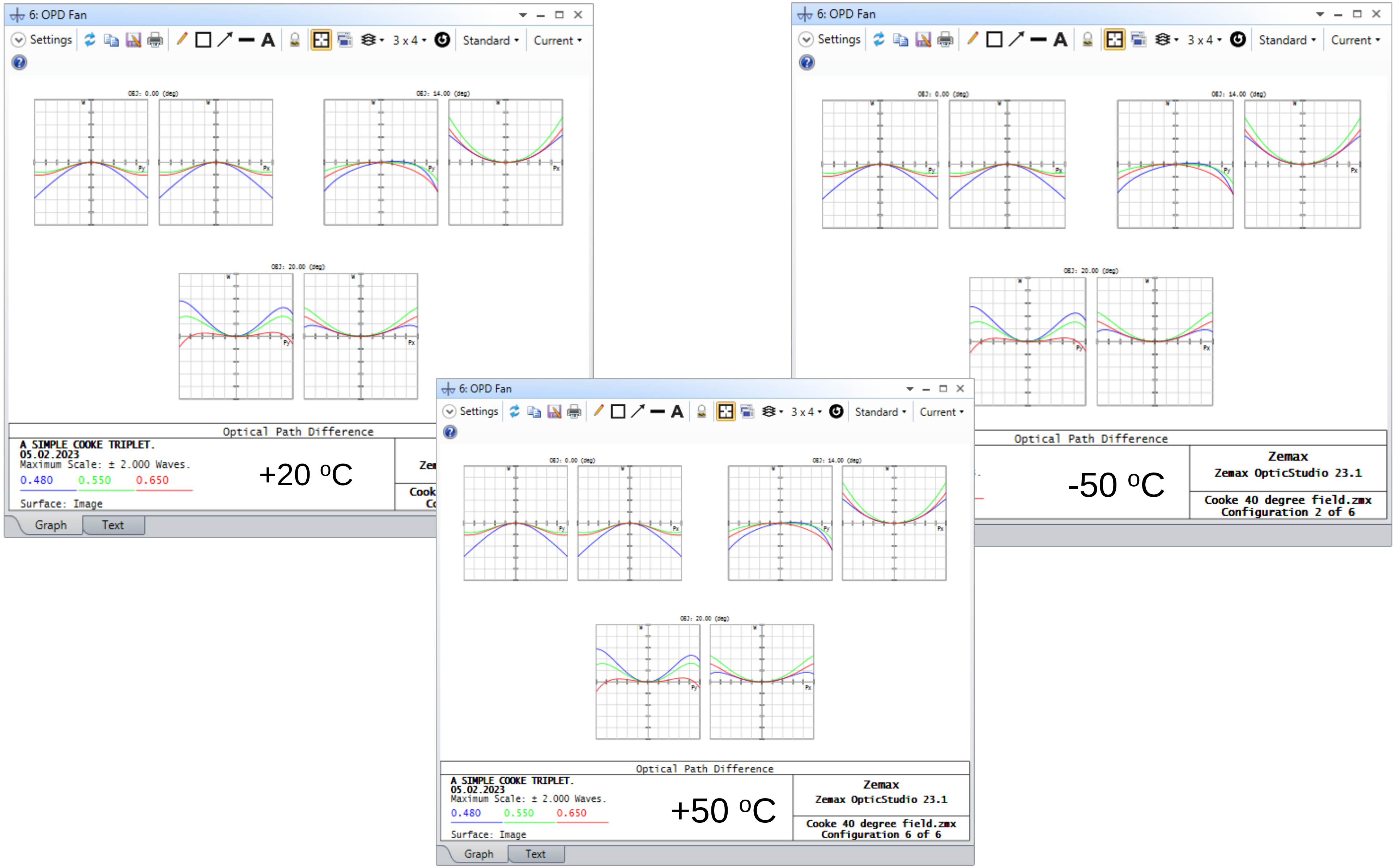
In **Optimize** Tab, click on **Hammer Current** and wait a few minutes.

You will see the decrease of thermal effects on the system.

Example3: Athermalization (MTF plot)



Example3: Athermalization (OPD)



Example3: Athermalization (Result)

T	EFFL (mm)	TOTR (mm)
-50	50.06	60.64
-25	50.04	60.61
0	50.02	60.59
+20	50.00	60.58
+25	50.00	60.57
+50	49.97	60.55
	Δf=90 μm	ΔL=90 μm

At 20 ^{o}C, depth of focus is δ = ± 27.5 μm.

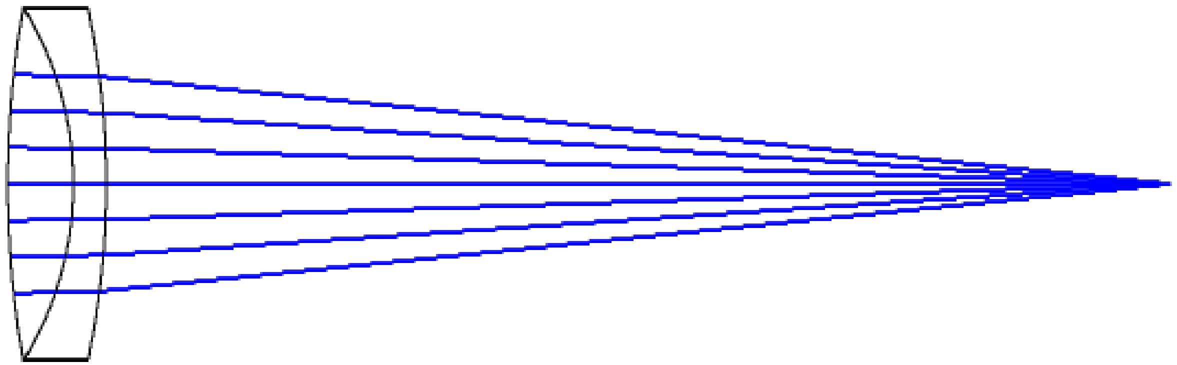
Since ΔL/2 > δ, we may need manual or auto focus system.

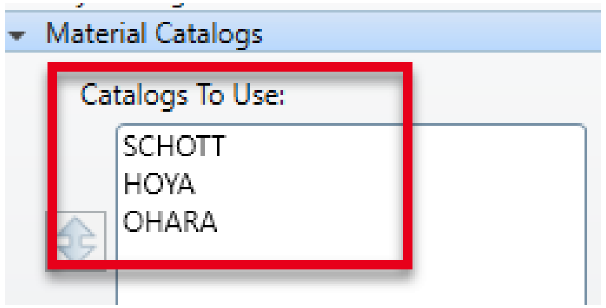
Remember, one way to make a system athermal is to translate (move) lens elements by a greater or lesser amount depending on the magnification.

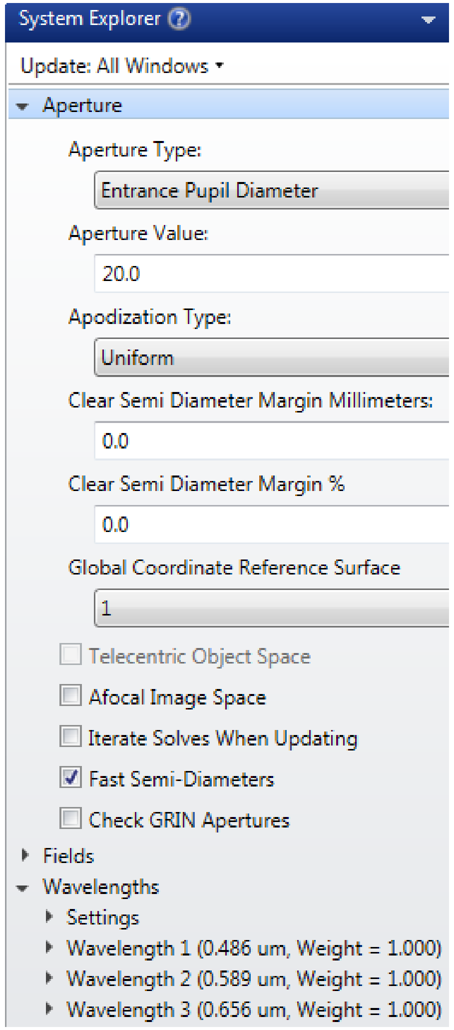
Example4: Athermal Doublet Design

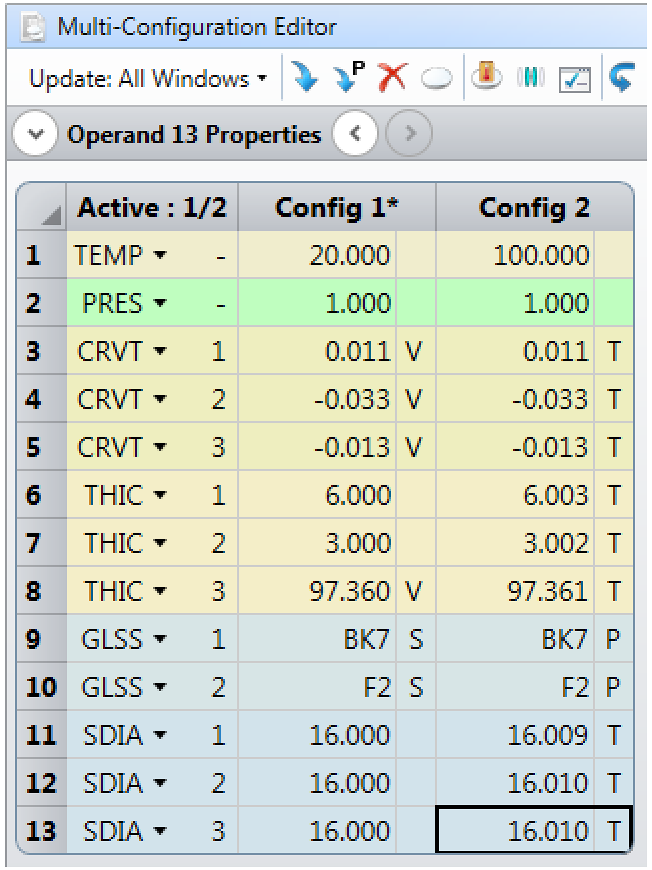
In this example we will design an athermal doublet whose LDE is as follows at 20 ºC.
We want to design it such that the optical performases are almost the same at 20 ºC and 100 ºC.

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-D
0	OI Standard		Infinity	Infinity			0.000
1	ST Standard		92.847 V	6.000	BK7 S		16.000 U
2	(a Standard		-30.716 V	3.000	F2 S		16.000 U
3	(a Standard		-78.197 V	97.360 V			16.000 U
4	IN Standard		Infinity	-			0.010

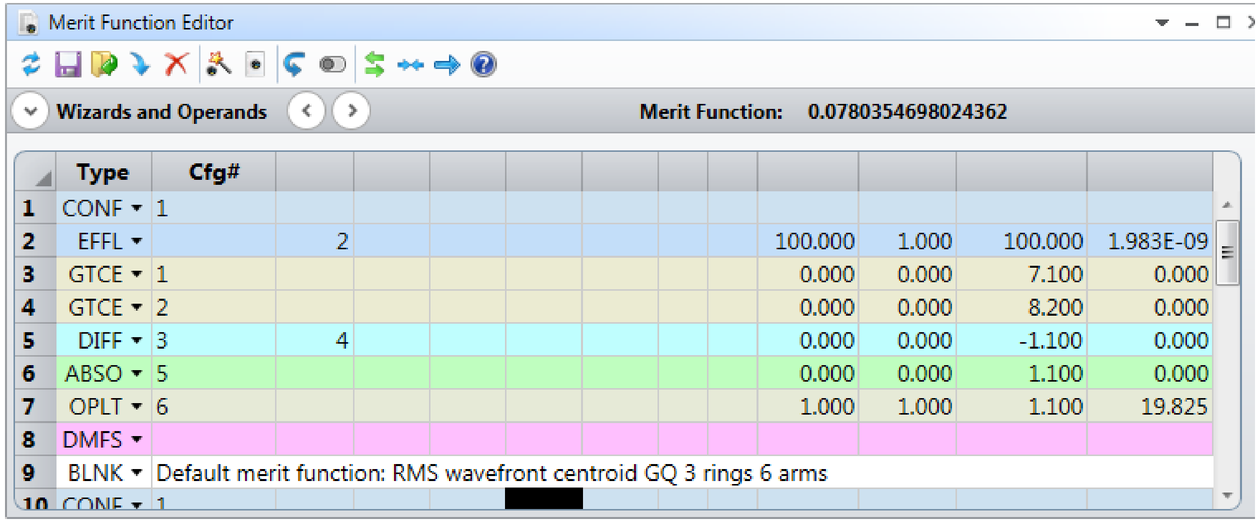








	Active : 1/2		Config 1*		Config 2	
1	TEMP	-	20.000		100.000	
2	PRES	-	1.000		1.000	
3	CRVT	1	0.011	V	0.011	T
4	CRVT	2	-0.033	V	-0.033	T
5	CRVT	3	-0.013	V	-0.013	T
6	THIC	1	6.000		6.003	T
7	THIC	2	3.000		3.002	T
8	THIC	3	97.360	V	97.361	T
9	GLSS	1	BK7	S	BK7	P
10	GLSS	2	F2	S	F2	P
11	SDIA	1	16.000		16.009	T
12	SDIA	2	16.000		16.010	T
13	SDIA	3	16.000		16.010	T

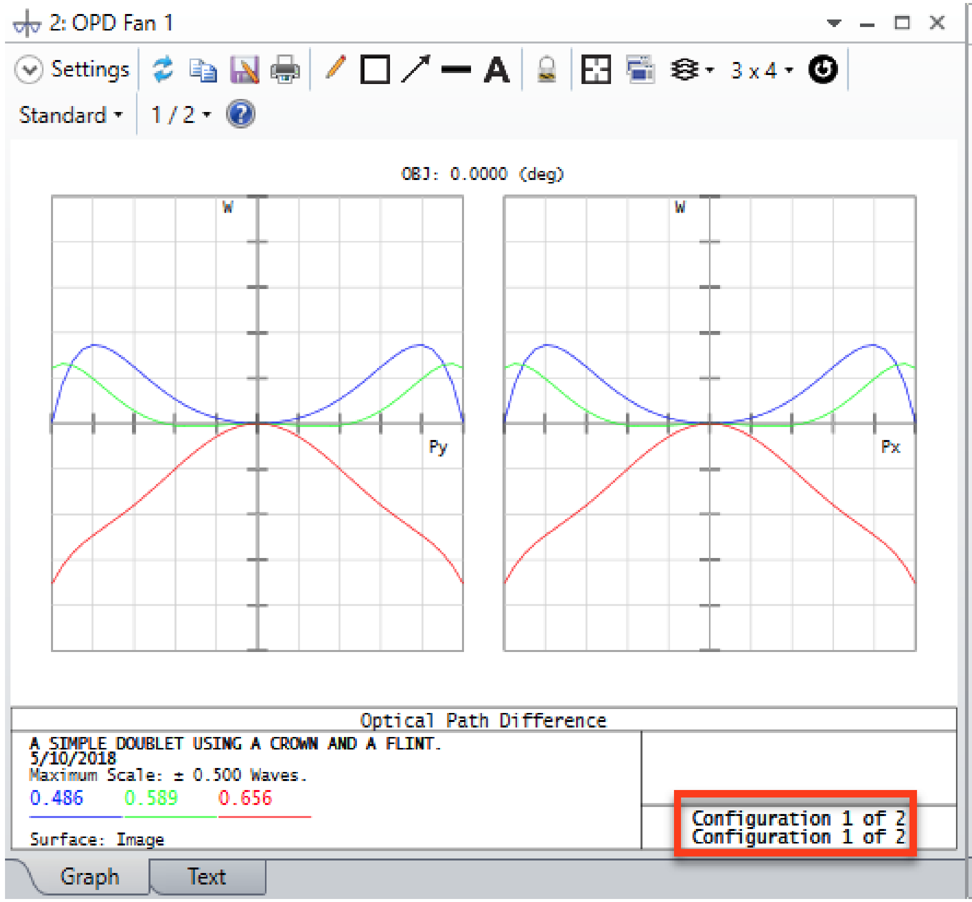


	Type	Cfg#									
1	CONF	1									
2	EFFL		2					100.000	1.000	100.000	1.983E-09
3	GTCE	1						0.000	0.000	7.100	0.000
4	GTCE	2						0.000	0.000	8.200	0.000
5	DIFF	3	4					0.000	0.000	-1.100	0.000
6	ABSO	5						0.000	0.000	1.100	0.000
7	OPLT	6						1.000	1.000	1.100	19.825
8	DMFS										
9	BLNK	Default merit function: RMS wavefront centroid GQ 3 rings 6 arms									
10	CONF	1									

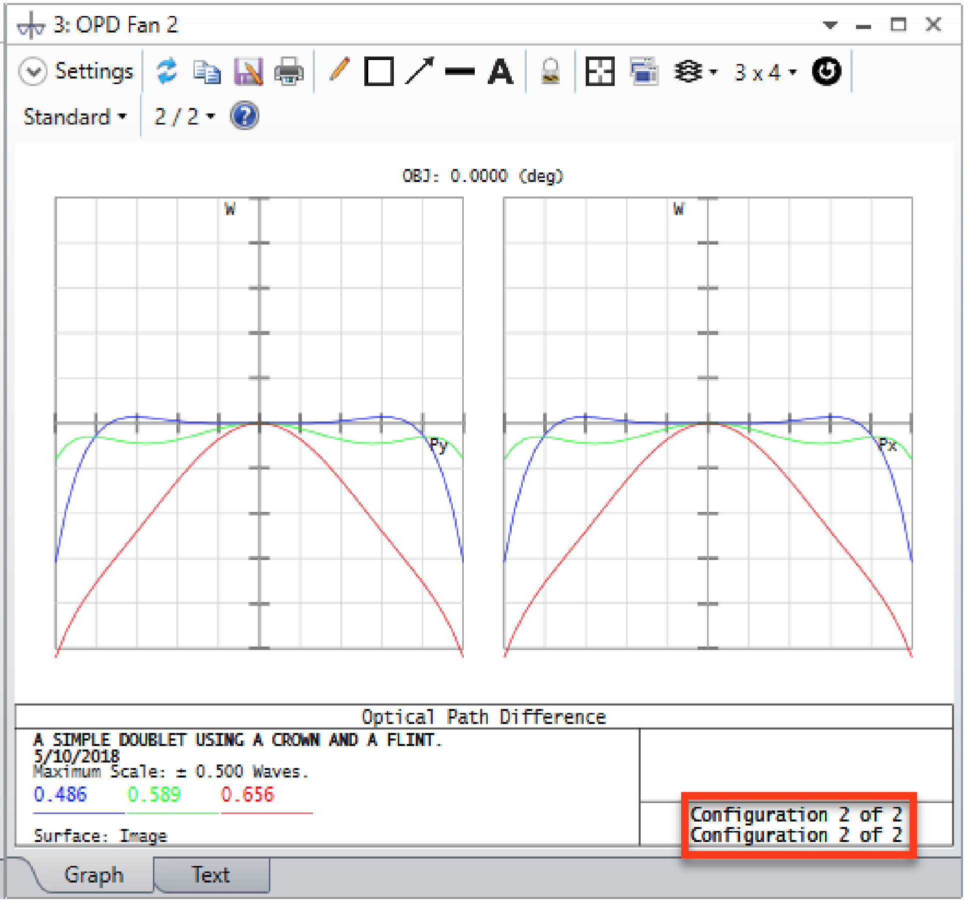
EFFL: Effective Focal Length
GTCE: Glass TCE value
DIFF: Difference between operands
ABSO: Absoute Value
OPLT: Operand Less Than

Example4: OPD Before Optimization

T = 20 ^oC



T=100 ^oC



Example4: OPD After Optimization

T = 20 ^oC T=100 ^oC