KAGRA End Bench Telescope
Zemax simulations

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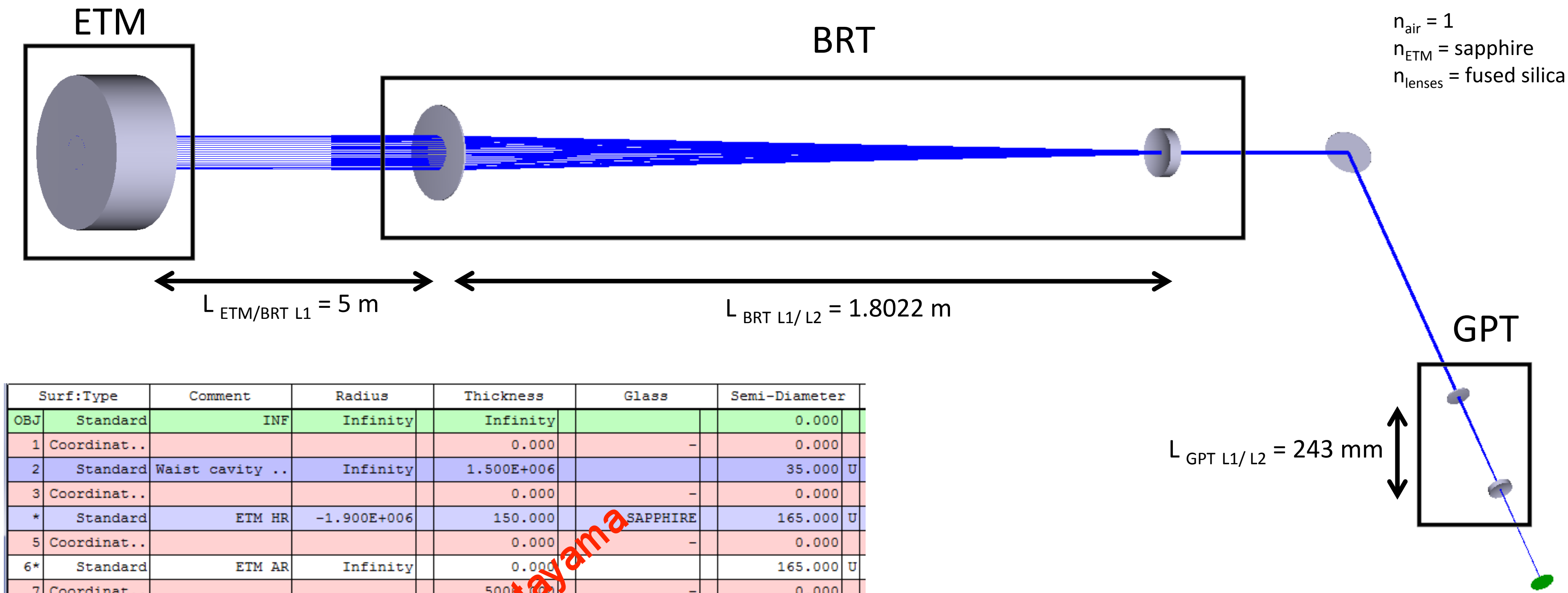
OUTLINE

- Optical design
  - layout
  - gaussian parameters
  - aberrations

- Tolerancing
  - definition
  - results

OPTICAL DESIGN: LAYOUT



Surf:Type		Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard	INF	Infinity		Infinity				0.000	
1	Coordinat..				0.000			-	0.000	
2	Standard	Waist cavity ..	Infinity		1.500E+006				35.000	U
3	Coordinat..				0.000			-	0.000	
*	Standard	ETM HR	-1.900E+006		150.000		SAPPHIRE		165.000	U
5	Coordinat..				0.000			-	0.000	
6*	Standard	ETM AR	Infinity		0.000				165.000	U
7	Coordinat..				5000.000			-	0.000	
8	Coordinat..				0.000			-	0.000	
9*	Standard	L1_a	1776.614		10.000		F_SILICA		100.000	U
10*	Standard	L1_b	-1776.614	P	0.000				100.000	U
11	Coordinat..				1801.400			-	0.000	
12*	Standard	L2_a	-158.894		10.000		F_SILICA		50.800	U
13*	Standard	L2_b	158.894	P	0.000				50.800	U
14	Coordinat..				650.000			-	0.000	
15*	Standard		Infinity		0.000		MIRROR		50.800	U
16	Coordinat..				-650.000			-	0.000	
17*	Standard	L3	-308.500	V	-5.000		F_SILICA		25.400	U
18*	Standard		308.500	P	0.000				25.400	U
19	Coordinat..				-243.000			-	0.000	
20*	Standard	L3	103.850	V	-5.000		F_SILICA		25.400	U
21*	Standard		-103.850	P	0.000				25.400	U
22	Coordinat..				-303.657			-	0.000	
IMA	Standard	Lens position	Infinity		-				25.400	U

Input from Junko Katayama

ETM 1st side / RoC = 1900 m

ETM 2nd side / RoC = infinity

e_{ETM}= 150 mm / wedge = 0.2°

BRT L1 / bi-convex / RoC = 1776.614 mm

BRT L2 / bi-concave / RoC = (-) 158.894 mm

GPT L1 / bi-convex / RoC = 308.5 mm / f = 343.6 mm

GPT L2 / bi-concave / RoC = (-) 103.85 mm / f = (-) 114.5 mm

e_{lenses}= 5 mm

OPTICAL DESIGN: GAUSSIAN PARAMETERS

Specifications/Parameters	EBT
Distance waist in the cavity – ETM first side	1500 m
Waist size in the cavity	16.197 mm
Wavelength	1064 nm

Y-Direction Fundamental Mode Results:

Sur	Size	Waist	Position	Radius	Divergence	Rayleigh
2	1.61970E+001	1.61970E+001	6.00000E+001	1.00000E+010	2.09102E-005	7.74597E+005
3	3.53016E+001	1.61970E+001	1.50006E+006	1.90004E+006	2.09102E-005	7.74597E+005
STO	3.53016E+001	9.96681E+000	1.74857E+006	1.90003E+006	1.93675E-005	5.14616E+005
5	3.53044E+001	9.96681E+000	1.74872E+006	1.90016E+006	1.93675E-005	5.14616E+005
6	3.53044E+001	9.96681E+000	9.96685E+005	1.08300E+006	3.39809E-005	2.93306E+005
7	3.53044E+001	9.96681E+000	9.96685E+005	1.08300E+006	3.39809E-005	2.93306E+005
8	3.54674E+001	9.96681E+000	1.00168E+006	1.08757E+006	3.39809E-005	2.93306E+005
9	3.54674E+001	3.78686E-002	-5.74875E+003	-5.74876E+003	6.16950E-003	6.13795E+000
10	3.54057E+001	1.89163E-002	-1.97751E+003	-1.97751E+003	1.79023E-002	1.05653E+000
11	3.54057E+001	1.89163E-002	-1.97751E+003	-1.97751E+003	1.79023E-002	1.05653E+000
12	3.13866E+000	3.75358E-002	-5.04226E+002	-5.04298E+002	6.22418E-003	6.03057E+000
13	3.07642E+000	1.01022E+000	-8.66753E+003	-9.71512E+003	3.35254E-004	3.01331E+003
14	3.22322E+000	1.01022E+000	-9.12985E+003	-1.01244E+004	3.35254E-004	3.01331E+003
15	2.93129E+000	1.01022E+000	8.20783E+003	9.31410E+003	3.35254E-004	3.01331E+003
16	2.93067E+000	1.01022E+000	8.20586E+003	9.31239E+003	3.35254E-004	3.01331E+003
17	2.72714E+000	7.89844E-002	9.21579E+002	9.22353E+002	2.95795E-003	2.67023E+001
18	2.71236E+000	4.11007E-002	3.29120E+002	3.29196E+002	8.24010E-003	4.98777E+000
19	2.71236E+000	4.11007E-002	3.29120E+002	3.29196E+002	8.24010E-003	4.98777E+000
20	7.10837E-001	6.54984E-002	1.98433E+002	2.00133E+002	3.56699E-003	1.83623E+001
21	6.93079E-001	1.53818E-001	3.06924E+002	3.22825E+002	2.20183E-003	6.98593E+001
22	6.93079E-001	1.53818E-001	3.06924E+002	3.22825E+002	2.20183E-003	6.98593E+001
IMA	1.53986E-001	1.53818E-001	3.26598E+000	1.49756E+003	2.20183E-003	6.98593E+001

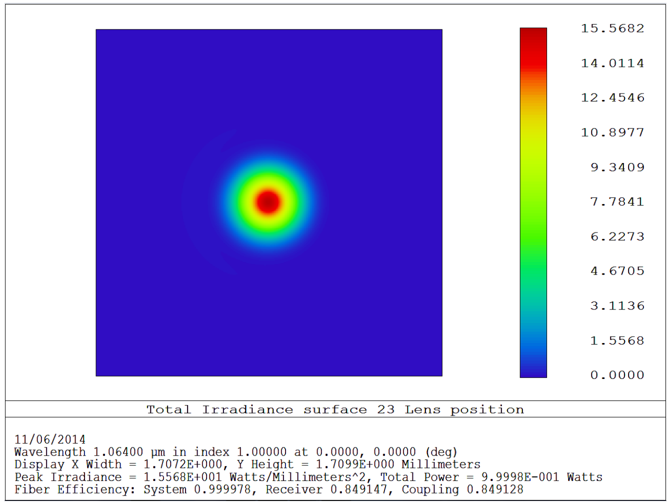
X-Direction Fundamental Mode Results:

Sur	Size	Waist	Position	Radius	Divergence	Rayleigh
2	1.61970E+001	1.61970E+001	6.00000E+001	1.00000E+010	2.09102E-005	7.74597E+005
3	3.53016E+001	1.61970E+001	1.50006E+006	1.90004E+006	2.09102E-005	7.74597E+005
STO	3.53016E+001	9.96681E+000	1.74857E+006	1.90003E+006	1.93675E-005	5.14616E+005
5	3.53044E+001	9.96681E+000	1.74872E+006	1.90016E+006	1.93675E-005	5.14616E+005
6	3.53046E+001	9.96669E+000	9.96660E+005	1.08297E+006	3.39814E-005	2.93298E+005
7	3.53039E+001	9.96669E+000	9.96660E+005	1.08297E+006	3.39814E-005	2.93298E+005
8	3.54670E+001	9.96669E+000	1.00166E+006	1.08754E+006	3.39814E-005	2.93298E+005
9	3.54671E+001	3.78688E-002	-5.74873E+003	-5.74874E+003	6.16945E-003	6.13804E+000
10	3.54054E+001	1.89164E-002	-1.97749E+003	-1.97749E+003	1.79022E-002	1.05654E+000
11	3.54053E+001	1.89164E-002	-1.97749E+003	-1.97749E+003	1.79022E-002	1.05654E+000
12	3.13840E+000	3.75334E-002	-5.04151E+002	-5.04223E+002	6.22459E-003	6.02978E+000
13	3.07617E+000	1.00657E+000	-8.63911E+003	-9.67504E+003	3.36470E-004	2.99157E+003
14	3.22354E+000	1.00657E+000	-9.10143E+003	-1.00847E+004	3.36470E-004	2.99157E+003
15	4.15676E+000	1.00657E+000	8.17941E+003	9.27356E+003	3.36470E-004	2.99157E+003
16	2.92980E+000	1.00657E+000	8.17744E+003	9.27185E+003	3.36470E-004	2.99157E+003
17	2.72546E+000	7.90060E-002	9.21258E+002	9.22033E+002	2.95715E-003	2.67169E+001
18	2.71068E+000	4.11186E-002	3.29058E+002	3.29134E+002	8.23651E-003	4.99213E+000
19	2.71066E+000	4.11186E-002	3.29058E+002	3.29134E+002	8.23651E-003	4.99213E+000
20	7.10021E-001	6.54994E-002	1.98206E+002	1.99907E+002	3.56694E-003	1.83629E+001
21	6.92263E-001	1.53578E-001	3.06089E+002	3.21934E+002	2.20527E-003	6.96414E+001
22	6.92261E-001	1.53578E-001	3.06089E+002	3.21934E+002	2.20527E-003	6.96414E+001
IMA	1.53672E-001	1.53578E-001	2.43091E+000	1.99754E+003	2.20527E-003	6.96414E+001

- Gaussian beam propagation
- Weak astigmatism due to the wedge of ETM (tilted beam on BRT)
- Optics after ETM centered along the optical axis (not tilted)
- Surface number related to the lens data editor (previous slide)
- Waist size at the output (after GPT L2) = 153 µm
- Waist position at the output (after GPT L2) = 306 mm

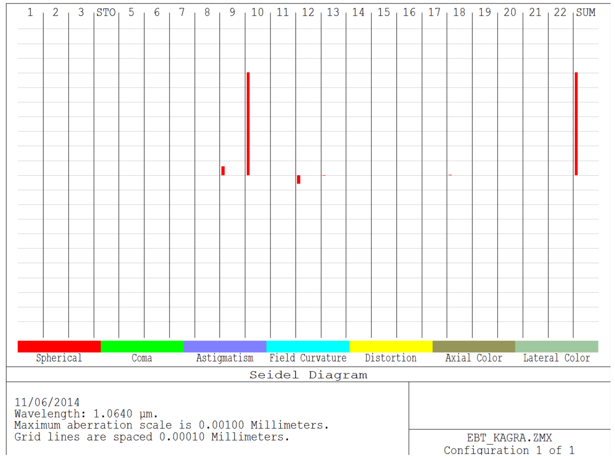
Weak difference between Zemax and the parameters (size of the beam on the optics) from Junko Katyama: maybe due to the refractive index value, , the definition of the GPT lenses the calculation method (Junko ABCD matrix?Optocad?)

OPTICAL DESIGN: ABERRATIONS (1)



- Coupling efficiency at the output of the telescope (waist position) = 85%
- Spherical aberrations: located mainly on the second side of BRT L1

Seidel diagram

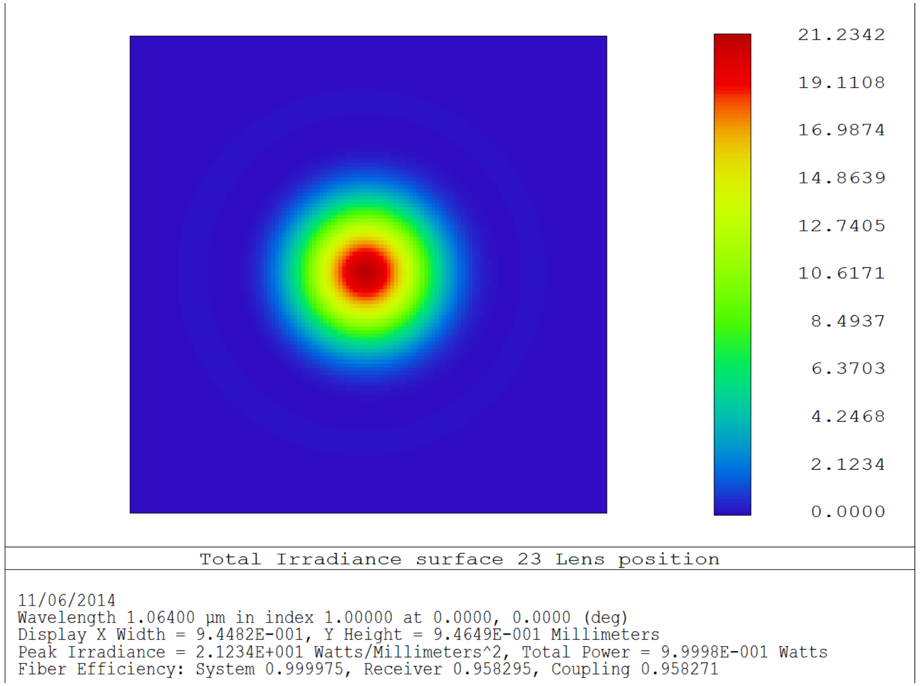


Zernike coefficients

Z	1	0.17395913 :	1
Z	2	0.00609593 :	4^(1/2) (p) * COS (A)
Z	3	0.00000000 :	4^(1/2) (p) * SIN (A)
Z	4	0.10845566 :	3^(1/2) (2p^2 - 1)
Z	5	0.00000000 :	6^(1/2) (p^2) * SIN (2A)
Z	6	0.00040738 :	6^(1/2) (p^2) * COS (2A)
Z	7	0.00000000 :	8^(1/2) (3p^3 - 2p) * SIN (A)
Z	8	0.00215895 :	8^(1/2) (3p^3 - 2p) * COS (A)
Z	9	0.00000000 :	8^(1/2) (p^3) * SIN (3A)
Z	10	0.00000001 :	8^(1/2) (p^3) * COS (3A)
Z	11	0.00621803 :	5^(1/2) (6p^4 - 6p^2 + 1)
Z	12	0.00000025 :	10^(1/2) (4p^4 - 3p^2) * COS (2A)
Z	13	0.00000000 :	10^(1/2) (4p^4 - 3p^2) * SIN (2A)
Z	14	0.00000000 :	10^(1/2) (p^4) * COS (4A)
Z	15	0.00000000 :	10^(1/2) (p^4) * SIN (4A)
Z	16	0.00000201 :	12^(1/2) (10p^5 - 12p^3 + 3p) * COS (A)
Z	17	0.00000000 :	12^(1/2) (10p^5 - 12p^3 + 3p) * SIN (A)
Z	18	0.00000000 :	12^(1/2) (5p^5 - 4p^3) * COS (3A)
Z	19	0.00000000 :	12^(1/2) (5p^5 - 4p^3) * SIN (3A)
Z	20	0.00000000 :	12^(1/2) (p^5) * COS (5A)
Z	21	0.00000000 :	12^(1/2) (p^5) * SIN (5A)
Z	22	0.00000465 :	7^(1/2) (20p^6 - 30p^4 + 12p^2 - 1)
Z	23	0.00000000 :	14^(1/2) (15p^6 - 20p^4 + 6p^2) * SIN (2A)
Z	24	0.00000000 :	14^(1/2) (15p^6 - 20p^4 + 6p^2) * COS (2A)
Z	25	0.00000000 :	14^(1/2) (6p^6 - 5p^4) * SIN (4A)
Z	26	0.00000000 :	14^(1/2) (6p^6 - 5p^4) * COS (4A)
Z	27	0.00000000 :	14^(1/2) (p^6) * SIN (6A)
Z	28	0.00000000 :	14^(1/2) (p^6) * COS (6A)
Z	29	0.00000000 :	16^(1/2) (35p^7 - 60p^5 + 30p^3 - 4p) * SIN (A)
Z	30	0.00000000 :	16^(1/2) (35p^7 - 60p^5 + 30p^3 - 4p) * COS (A)
Z	31	0.00000000 :	16^(1/2) (21p^7 - 30p^5 + 10p^3) * SIN (3A)
Z	32	0.00000000 :	16^(1/2) (21p^7 - 30p^5 + 10p^3) * COS (3A)
Z	33	0.00000000 :	16^(1/2) (7p^7 - 6p^5) * SIN (5A)
Z	34	0.00000000 :	16^(1/2) (7p^7 - 6p^5) * COS (5A)
Z	35	0.00000000 :	16^(1/2) (p^7) * SIN (7A)
Z	36	0.00000000 :	16^(1/2) (p^7) * COS (7A)
Z	37	0.00000000 :	9^(1/2) (70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)

Z4: focus aberration
Z6: astigmatism
Z8: coma
Z11:spherical aberration

OPTICAL DESIGN: ABERRATIONS (2)



- Merit function: spherical aberrations, coma, astigmatism, waist size
- Optimization of the distance BRT_L1 / BRT_L2: 1802.2mm -> 1801.4 mm
- Coupling efficiency at the output of the telescope (waist position) ~ 85%
- Spherical aberrations still located mainly on the second side of BRT L1
- Waist size at the output (after GPT L2) = 168 µm
- Waist position at the output (after GPT L2) = 356 mm

TOLERANCING

• The tolerancing study was performed using the Zemax software through a Monte Carlo simulation.

• The aim is to find the most critical parameters of the optical system that contribute to the system performances worsening

• Define the good compensators to recover optimal performances.

• This analysis is powerful and useful because all the tolerances can be considered at once. Every parameter is randomly perturbed using appropriate statistical models, all compensators are adjusted and the entire system is evaluated with all defects considered.

• First, we define a merit function that describe the coupling efficiency. This function is built considering errors on beam waist with respect to the ideal size, error on beam position with respect to ideal position and the remaining aberrations such as spherical aberrations, coma and astigmatism. The ideal configuration gives a coupling efficiency of 85%.

TOLERANCING: RoCs ERRORS

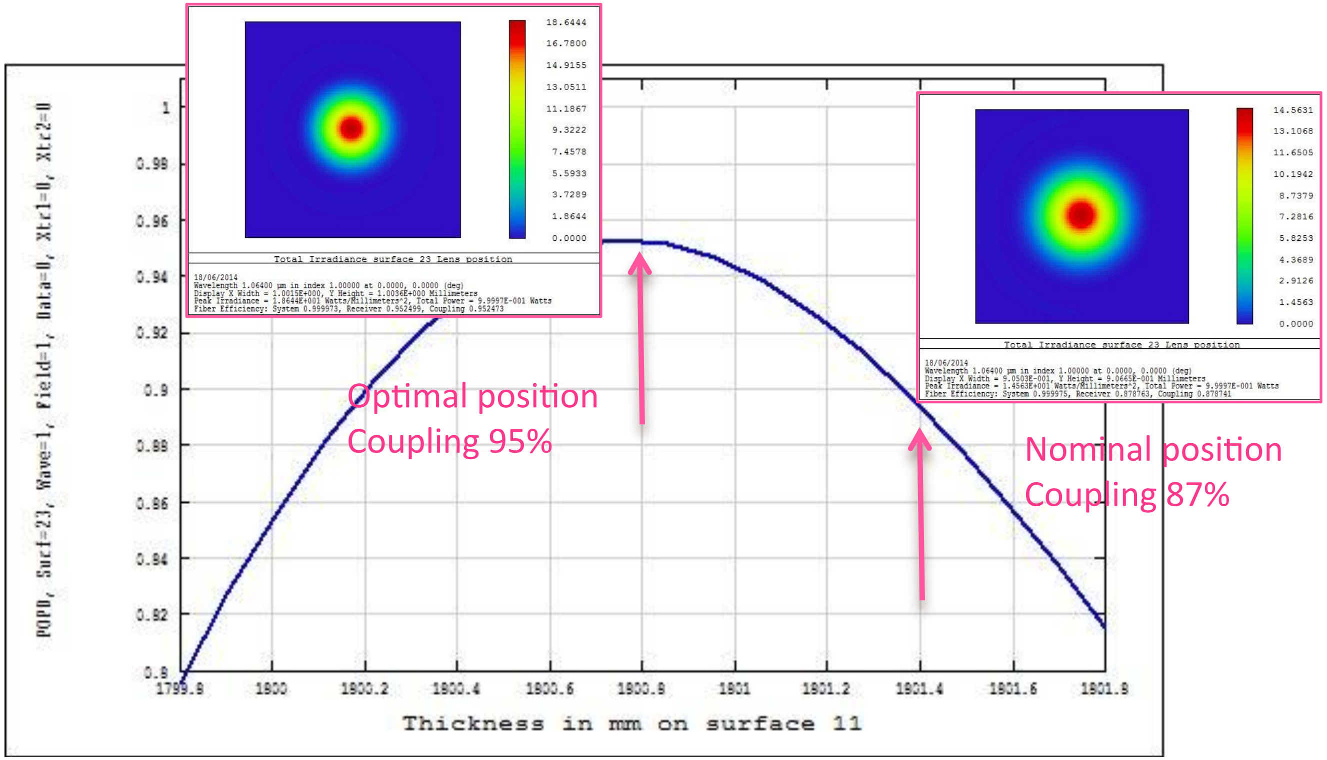
Tolerancing study: ranges needed to compensate 1% RoC errors (typical manufacturer error)
Goal: have a waist size of 168 µm and a matching ~ 85%

Optics	Distance BRT_L1 / BRT_L2 (moving BRT_L2)	Distance GPT_L1 / GPT_L2 (moving GPT_L2)
BRT_L1 side 1	+/- 10 mm	
BRT_L1 side 2	+/- 10 mm	
BRT_L2 side 1	+/- 1 mm	
BRT_L2 side 2	+/- 1 mm	
GPT_L1 side 1		+/- 3.5 mm
GPT_L1 side 2		+/- 3.5 mm
GPT_L2 side 1		+/- 1 mm
GPT_L2 side 2		+/- 1 mm

A matching higher than 85% can be recovered by using the two handles (distance between BRT lenses and the distance between GPT lenses) when there is an error on the radius of curvature. The range of the compensators are realistic and viable for the setup.

TOLERANCING: INPUT BEAM ERRORS

Tolerancing study: the input beam coming from the ITF could present errors on the waist size (~ 10%) and on the waist position (~ 50 meters)



At the nominal position, the coupling is 87% (better than 85%) because the waist size and position are changed (input beam errors), and the coupling is 87% at 356mm from GPT_L2 (not at the waist position). At the waist position (which is 374 mm), the coupling is 84%.

Idem for the optimal position: the coupling is 95% at 356mm from GPT_L2, but at the waist position (which is 434 mm in this case), the coupling is 83%.

A matching higher than 80% can be recovered by using the two handles (distance between BRT lenses and the distance between GPT lenses) when there is an error on the input beam (ITF beam).

TOLERANCING: TILT AND DECENTER

Tolerancing study: a tilt or a decenter of the optics of the telescope will induce coma, spherical aberrations and astigmatism on the beam. To respect an optimal configuration (coupling efficiency higher than 85%), we computed the maximum tilt and decenter allowed on the optics mounts of the EBT (during the alignment phase)

Optics	Tilt	Decenter
BRT_L1	+/- 1°	+/- 6 mm
BRT_L2	+/- 0.9°	+/- 2.5 mm
GPT_L1	+/- 4°	+/- 10 mm
GPT_L2	+/- 3°	+/- 10 mm

These values give the requirements on the optical mount actuators/picomotors.

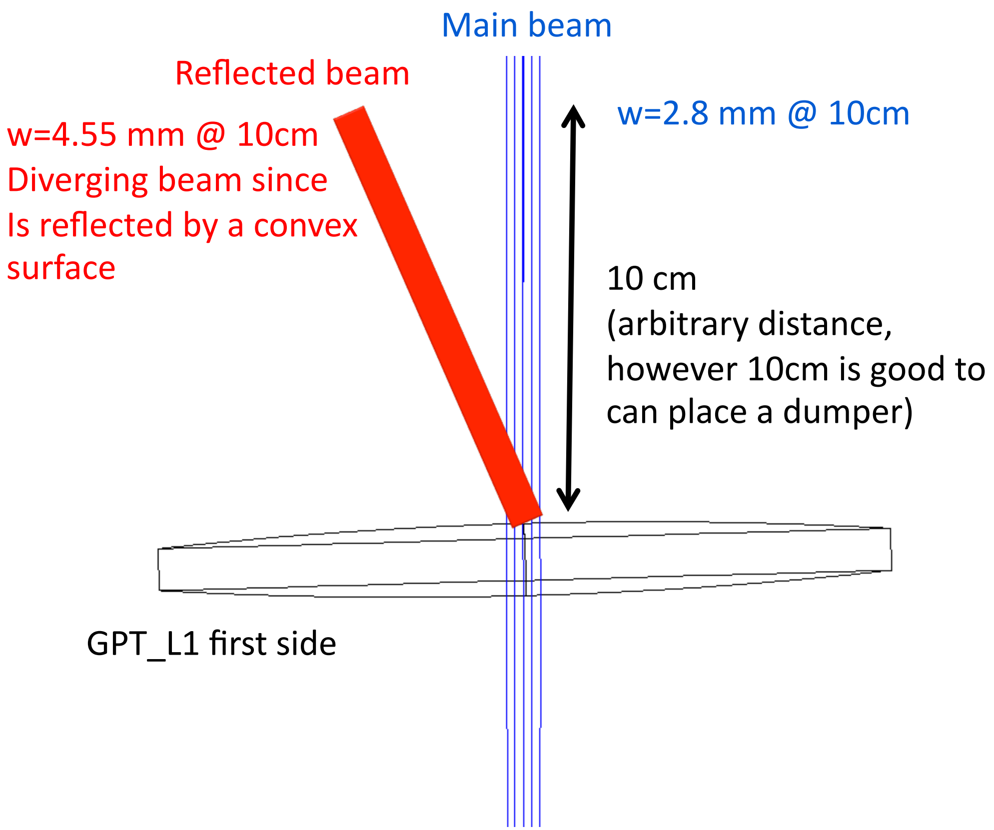
REFLECTED LIGHT BY THE GPT LENSES

The reflected light by the sides of the GPT lenses has been computed (using matlab script).

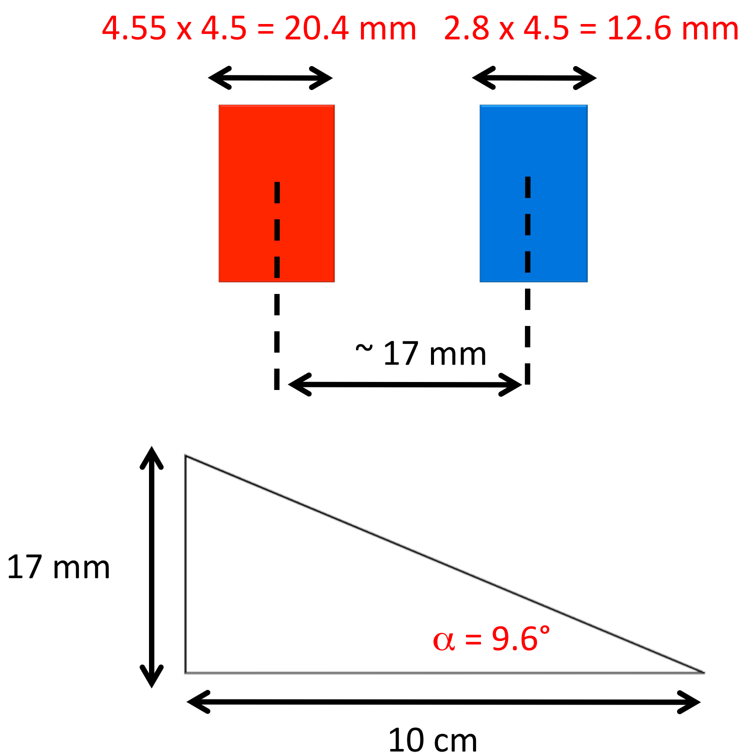
The needed angle to separe correctly the main beam and the reflected beam has been computed.

The coupling (the aberrations) induced by this angle has been simulated using Zemax.

REFLECTED LIGHT BY GPT_L1 FIRST SIDE

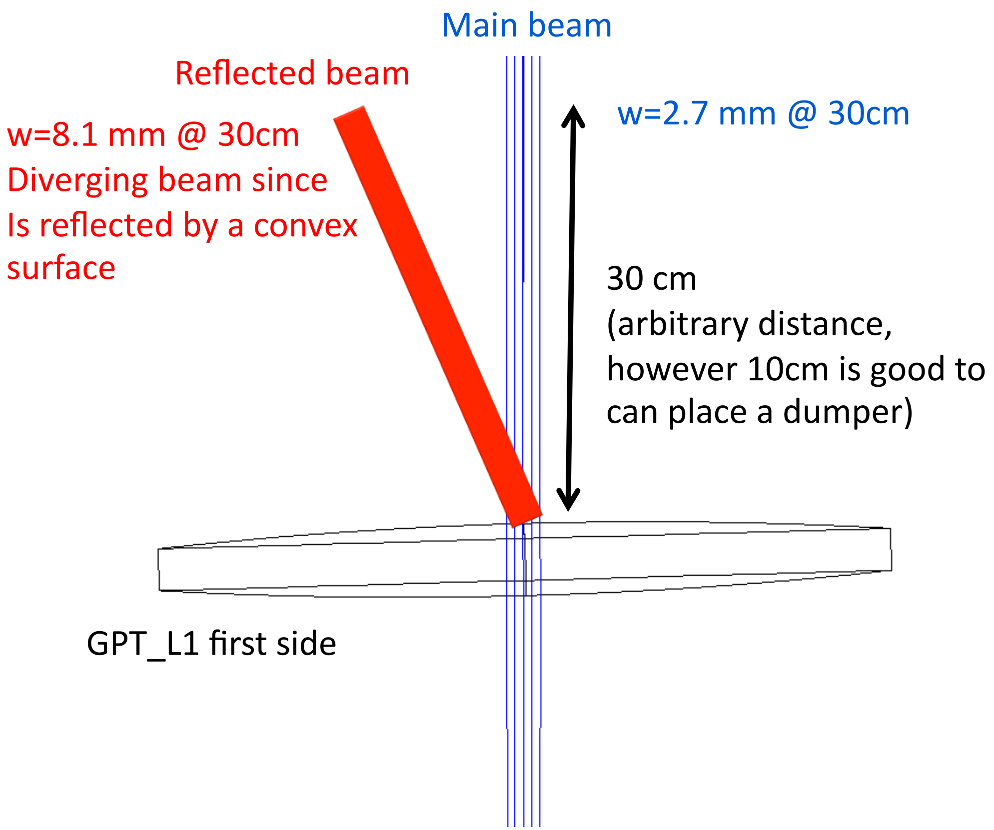


To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size

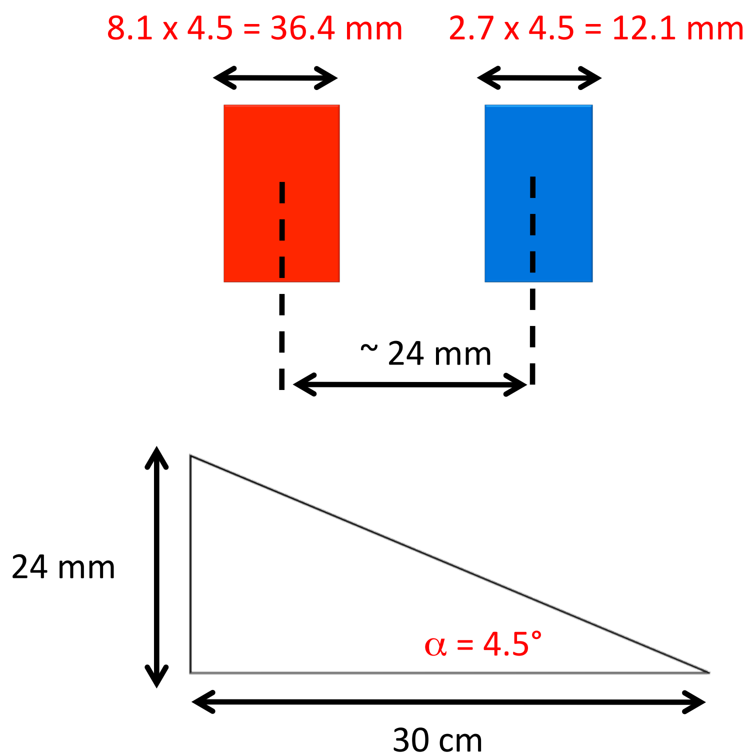


If GPT_L1 is tilted by 9.6°, the coupling efficiency is 52%.

Reflected light by GPT_L1 first side (@ 30cm)



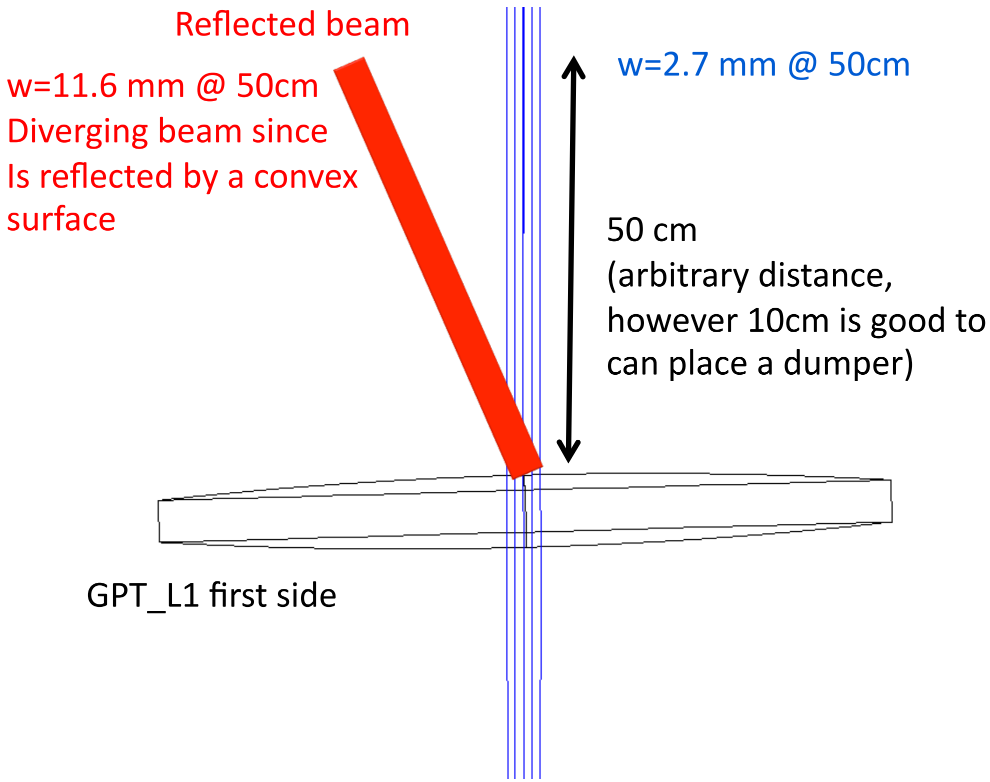
To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



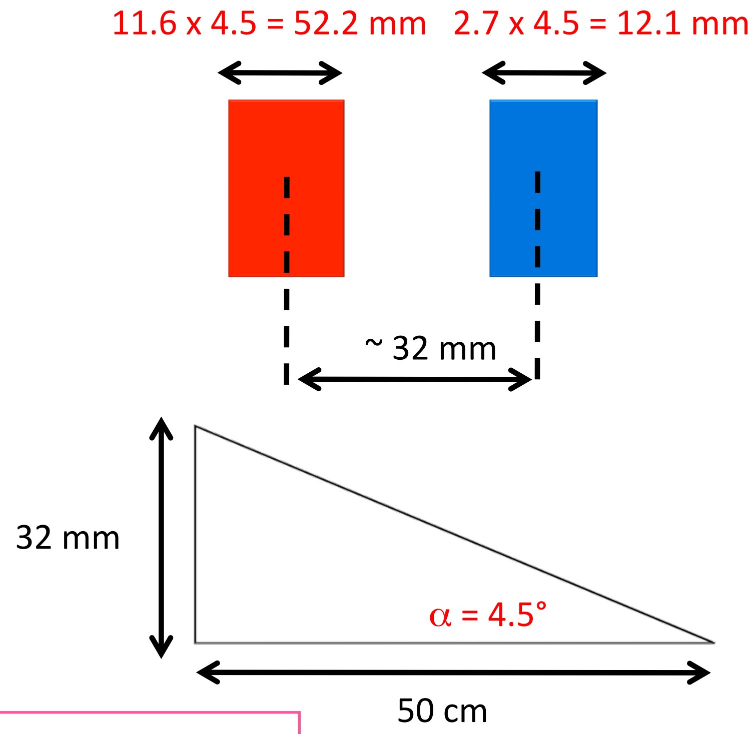
If GPT_L1 is tilted by 4.5°, the coupling efficiency is still higher than 85%.

But 2.4cm is still not enough to separe the two beams

REFLECTED LIGHT BY GPT_L1 FIRST SIDE (@ 50CM)



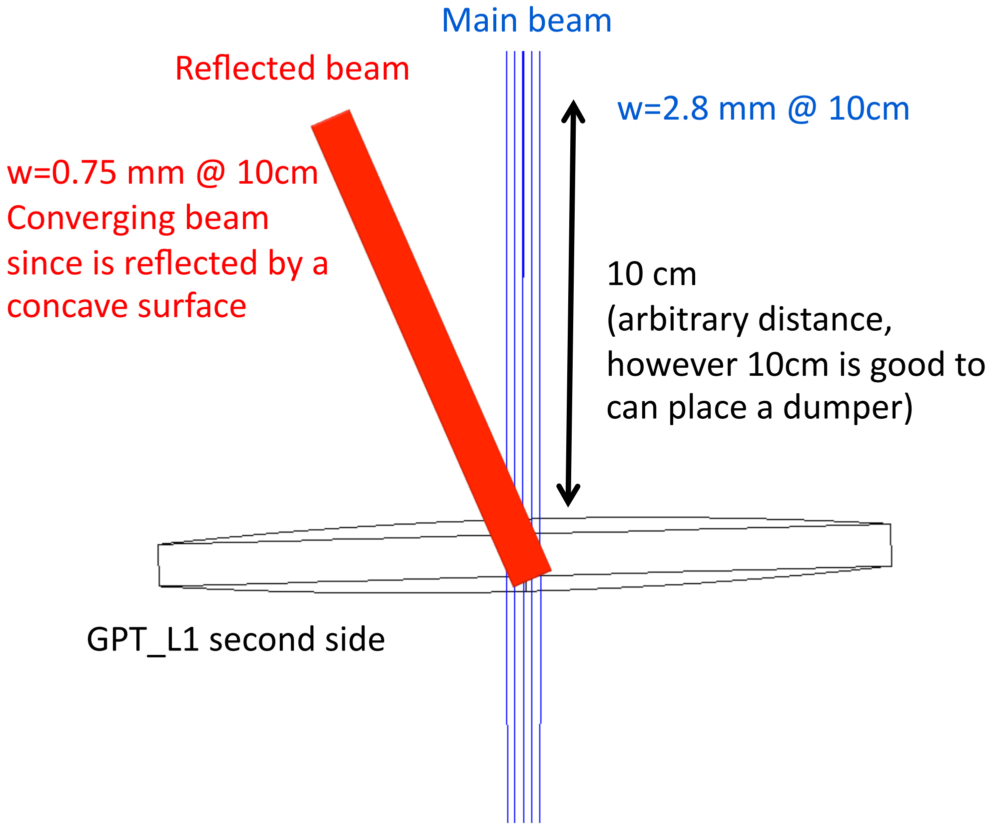
To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



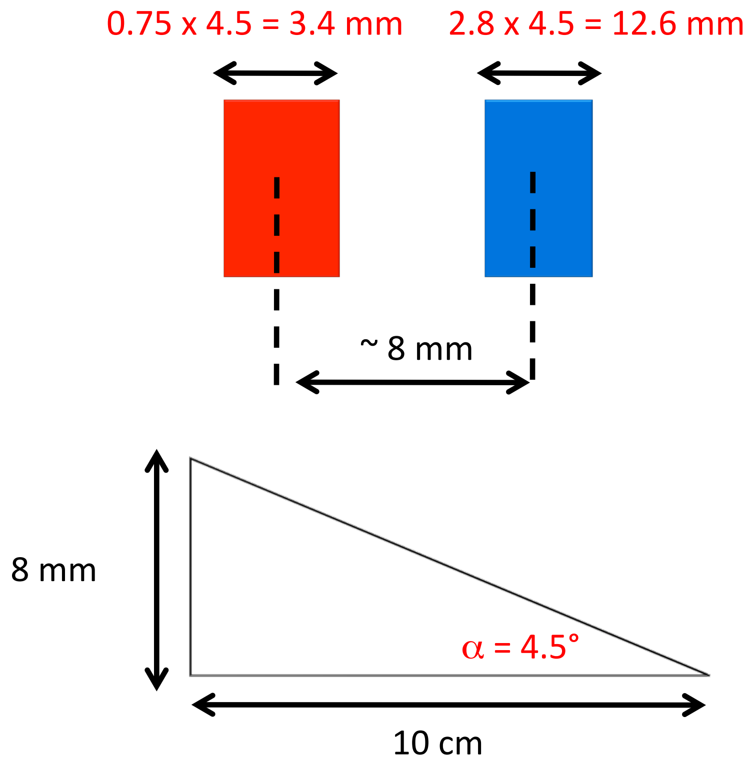
If GPT_L1 is tilted by 3.6°, the coupling efficiency is still higher than 85%.

But 3.2cm is enough to separe the two beams? Maybe yes!
Note that the maximum angle allowed for GPT_L1 to keep a coupling > 85% is 4.5°. So the beams need to be sepratead at least at 30cm from GPT_L1.

Reflected light by GPT_L1 second side



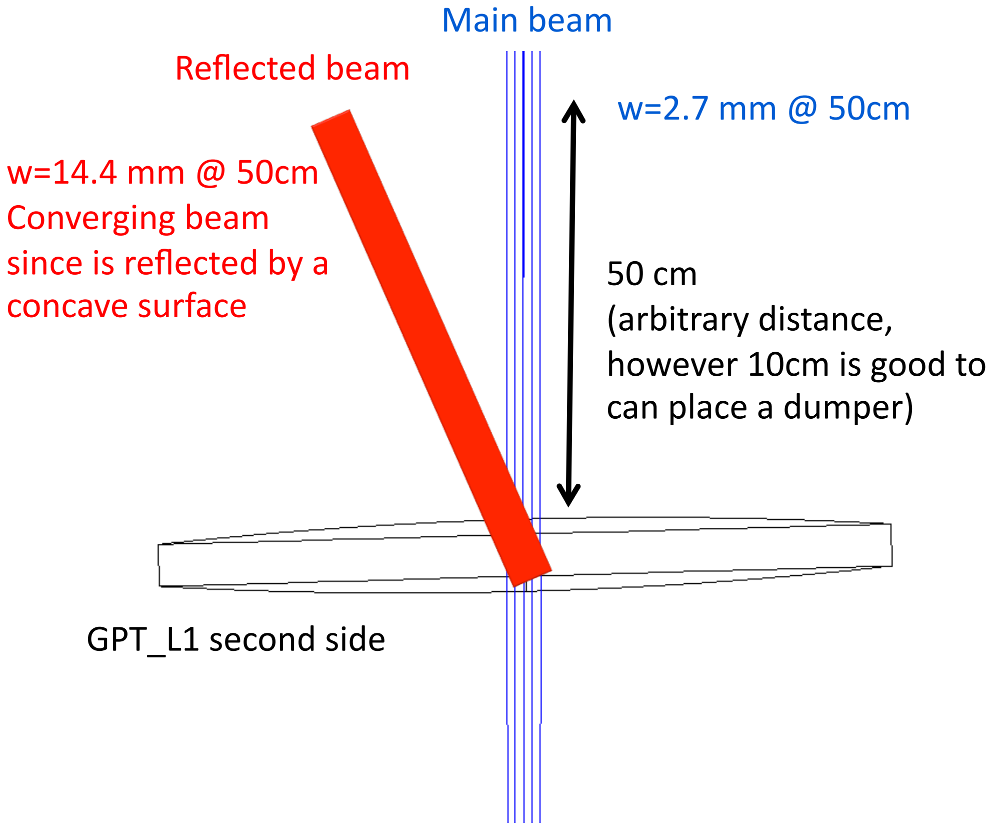
To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



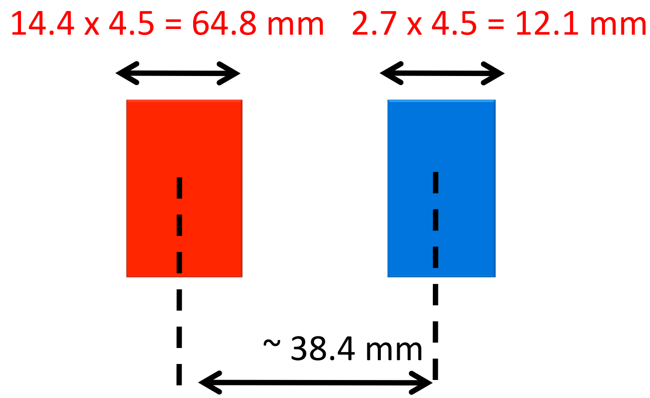
If GPT_L1 is tilted by 4.5°, the coupling efficiency is still higher than 85%.

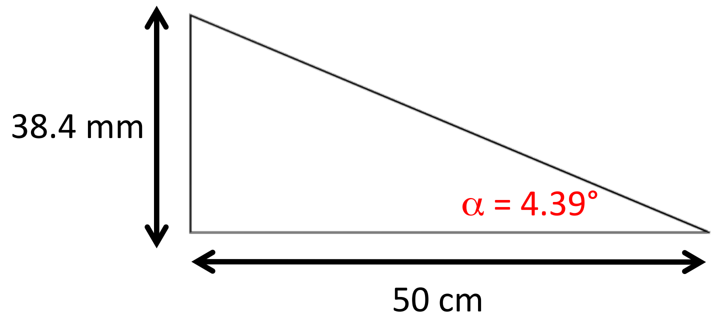
But 0.8cm is not enough to separe the two beams.

REFLECTED LIGHT BY GPT_L1 SECOND SIDE (@50CM)



To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size





If GPT_L1 is tilted by 4.39°, the coupling efficiency is still higher than 85%.

But 3.8cm is not enough to separe the two beams? Maybe yes!

REFLECTED LIGHT BY GPT_L1

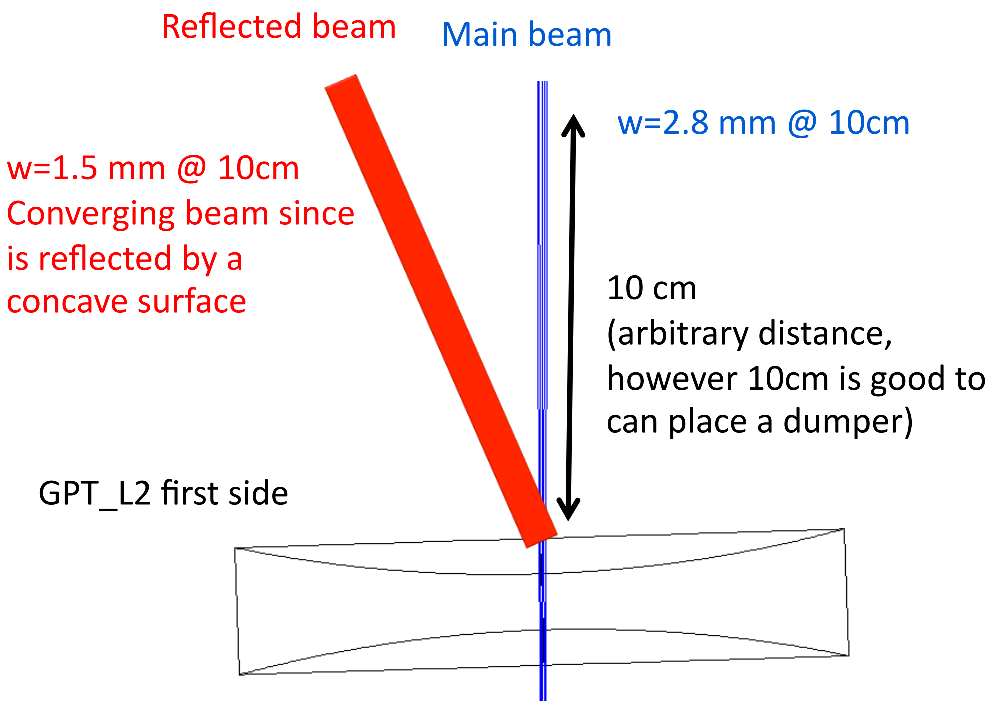
The maximum angle of tilt for GPT_L1 is 4.5° (to keep a coupling > 85%)

For the side 1, if the lens is tilted by 4.5°, the 2 beams are seprated by 3.2cm at 50cm

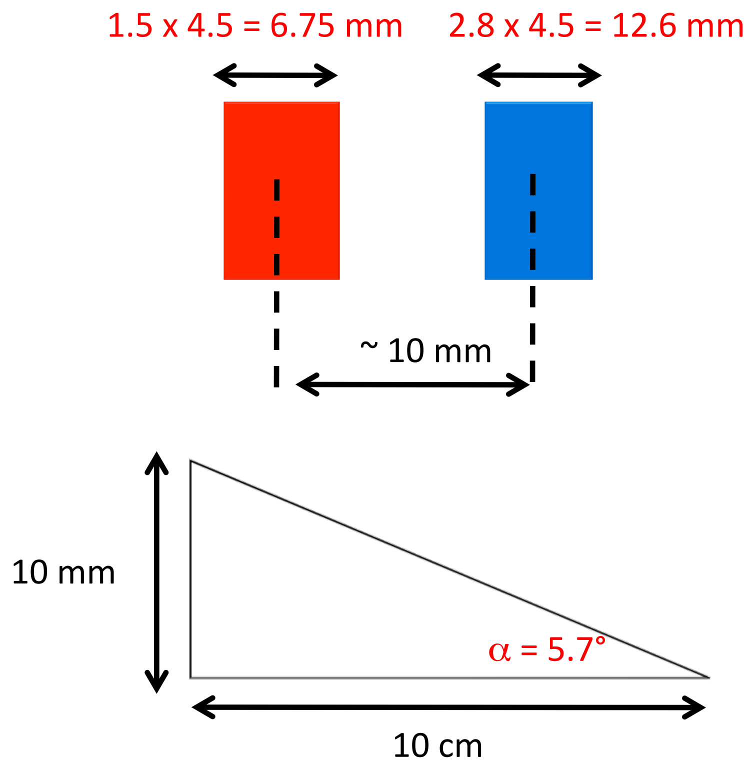
For the side 2, if the lens is tilted by 4.5°, the 2 beams are seprated by 3.8cm at 50cm

Is 3.2cm and 3.8cm enough?

REFLECTED LIGHT BY GPT_L2 FIRST SIDE



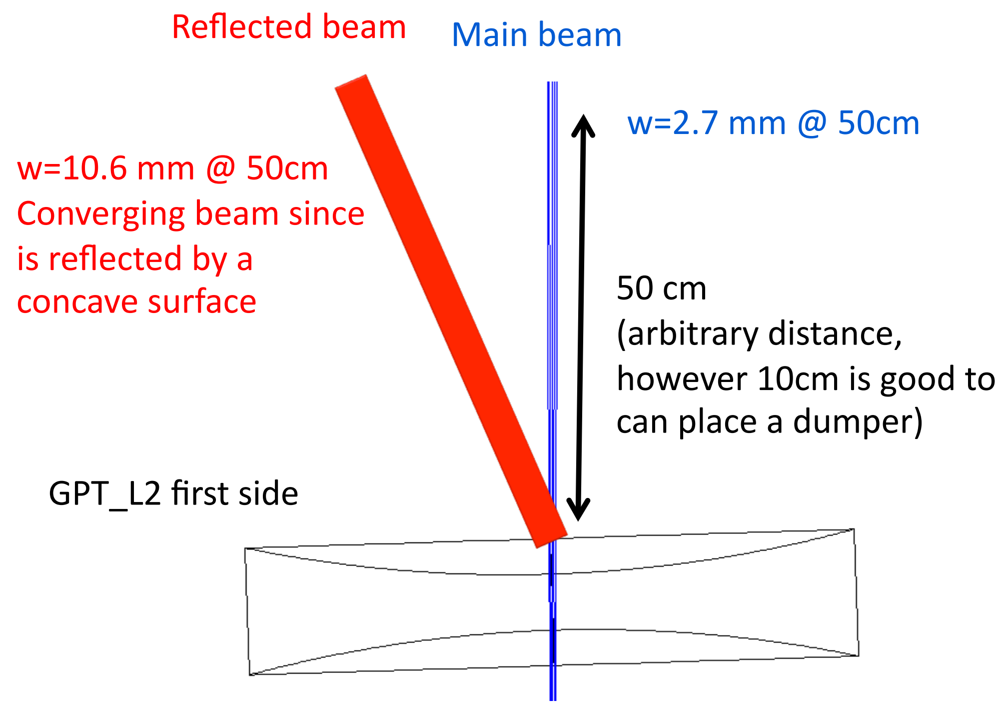
To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



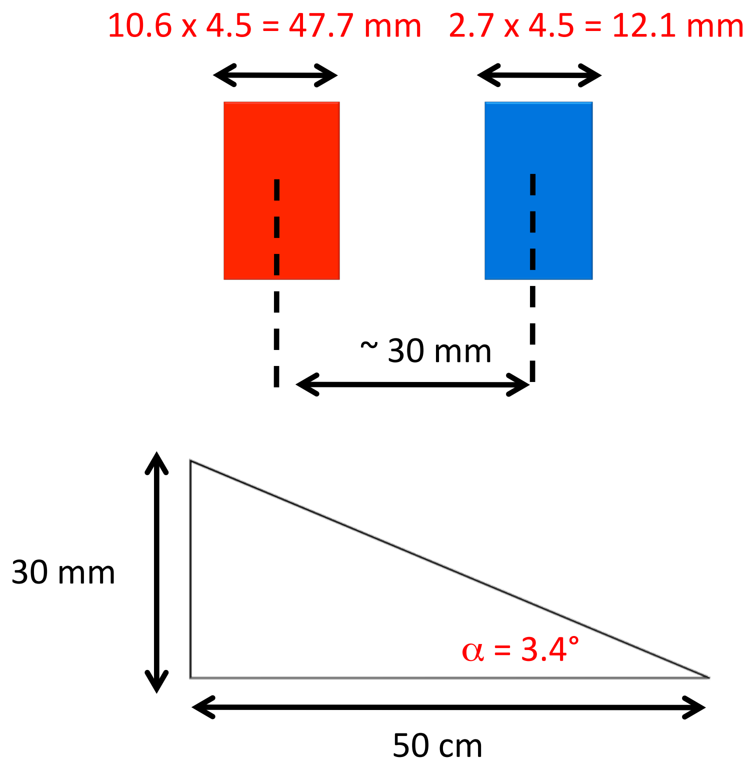
If GPT_L1 is tilted by 5.7°, the coupling efficiency is still higher than 85%.

But 1cm is not enough to separe the two beams.

Reflected light by GPT_L2 first side (@50cm)



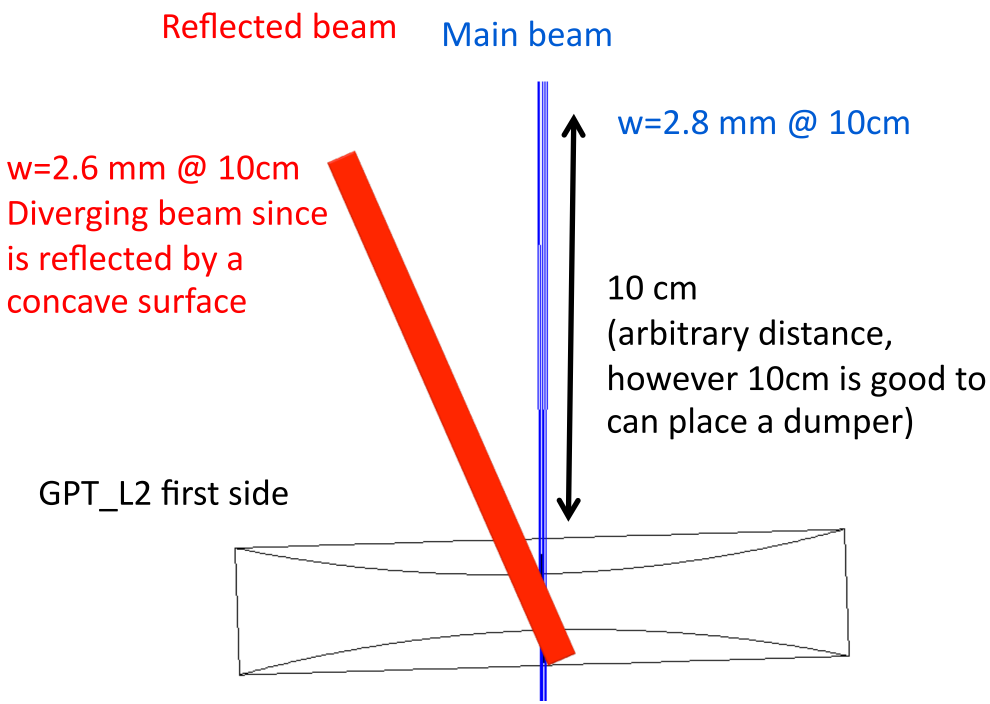
To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



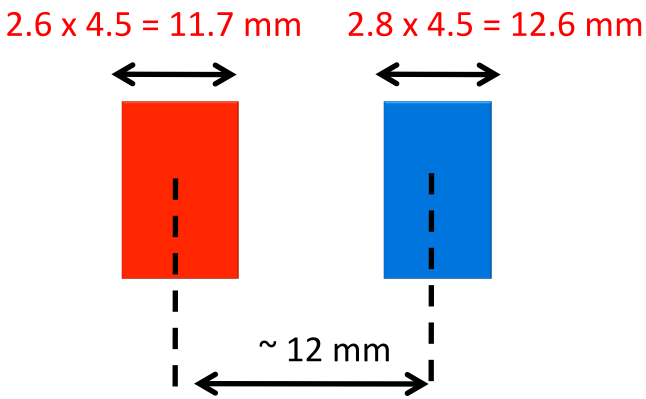
If GPT_L1 is tilted by 3.4°, the coupling efficiency is still higher than 85%.

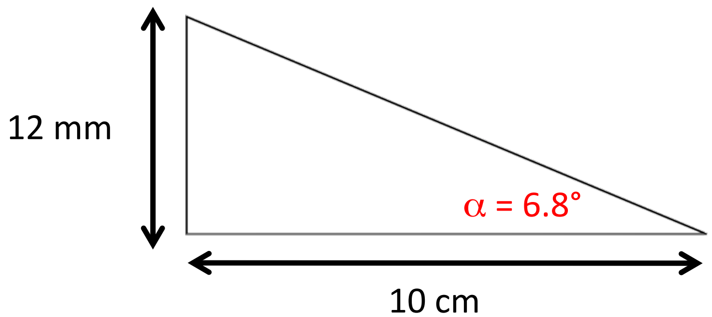
But 3cm is not enough to separe the two beams? Maybe yes!

REFLECTED LIGHT BY GPT_L2 SECOND SIDE



To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size

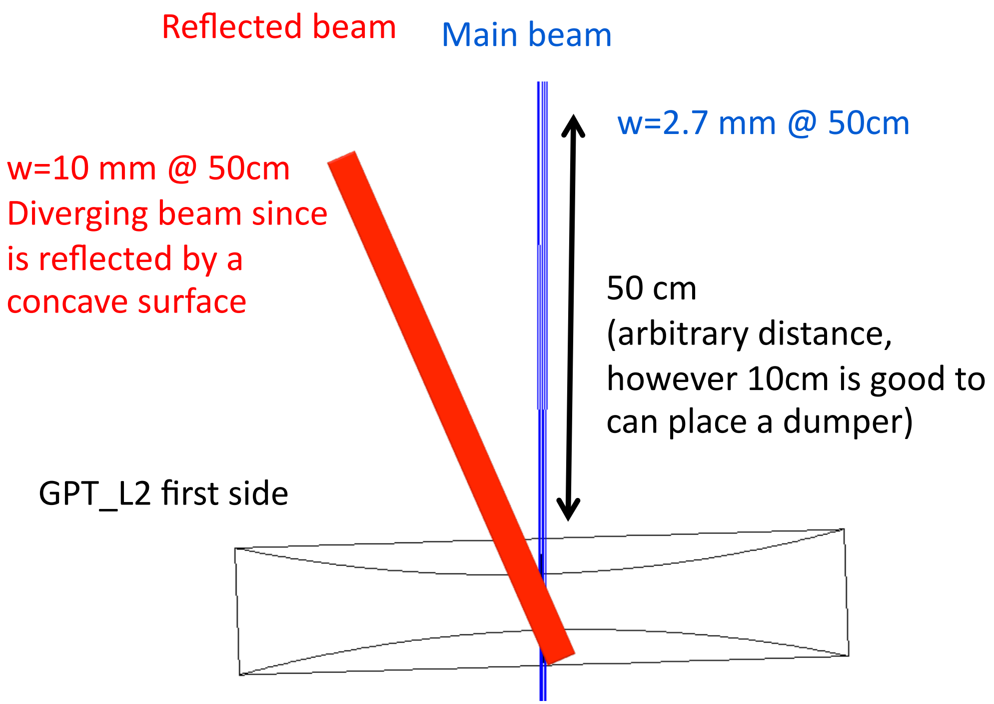




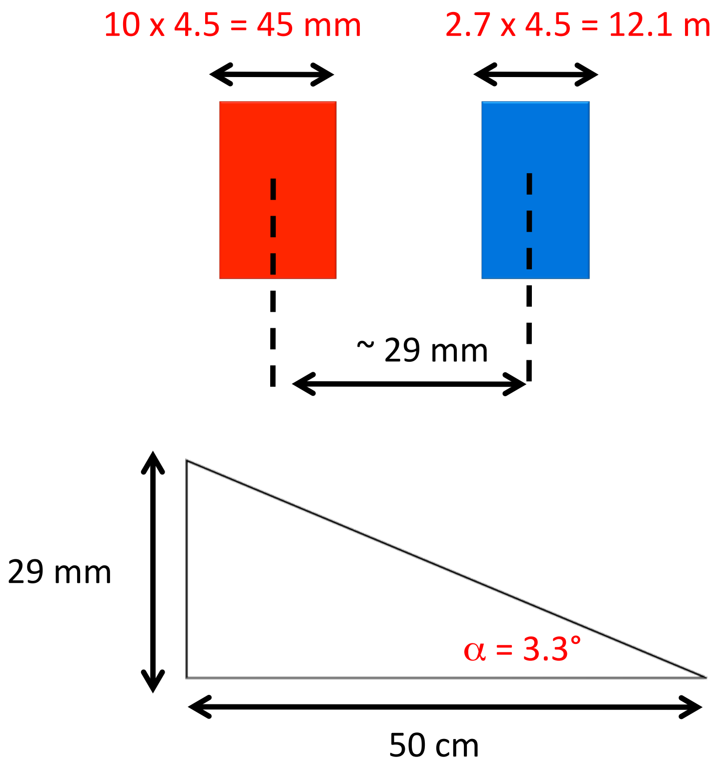
If GPT_L1 is tilted by 6.8°, the coupling efficiency is still higher than 85%.

But 1.2cm is not enough to separe the two beams.

Reflected light by GPT_L2 second side (@50cm)



To avoid the clipping losses and easily separate the beams, we have to consider 4.5 times the beam size



If GPT_L1 is tilted by 3.3°, the coupling efficiency is still higher than 85%.

But 3cm is not enough to separe the two beams? Maybe yes!

REFLECTED LIGHT BY GPT_L2

The maximum angle of tilt for GPT_L1 is 5° (to keep a coupling > 85%)

For the side 1, if the lens is tilted by 3.4°, the 2 beams are seprated by 3cm at 50cm

For the side 2, if the lens is tilted by 3.3°, the 2 beams are seprated by 3cm at 50cm

Is 3cm enough?

Note that if we tilt the lens by 5°, the beams are seprated by 4.5cm, which seems enough

CONCLUSION

- Zemax simulation for the lens configuration

- Coupling efficiency of 85%

- RoC errors and input beam errors can be easily compensate by the distance between the optics

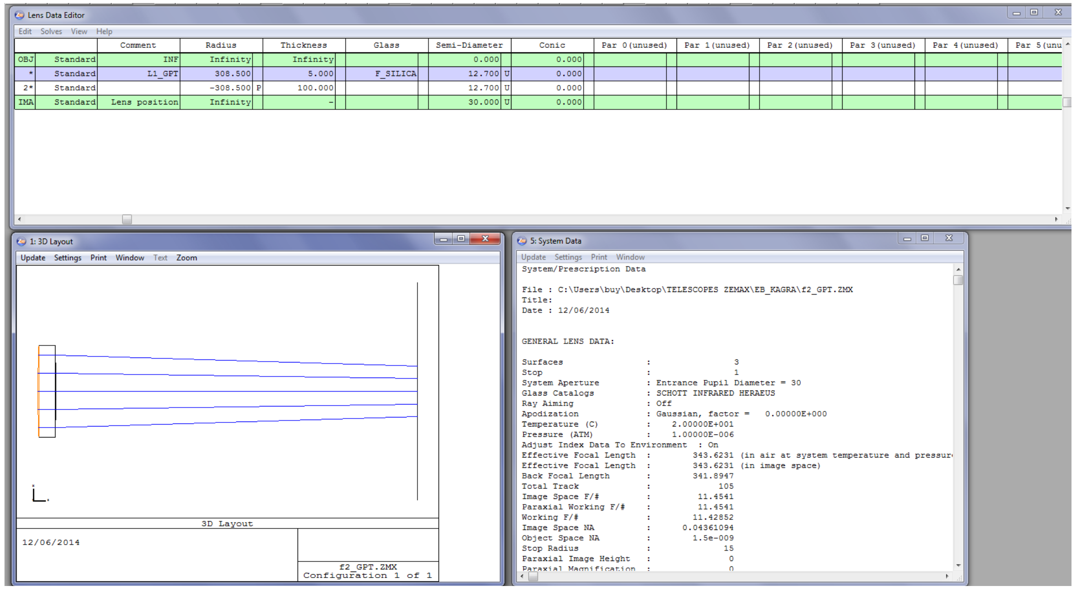
- Tilt and decenter allowed for the optics give requirements on the actuators/picomotors

- The GPT lenses can easily be tilted to dump the back-reflected light (and keep a coupling higher than 85%)

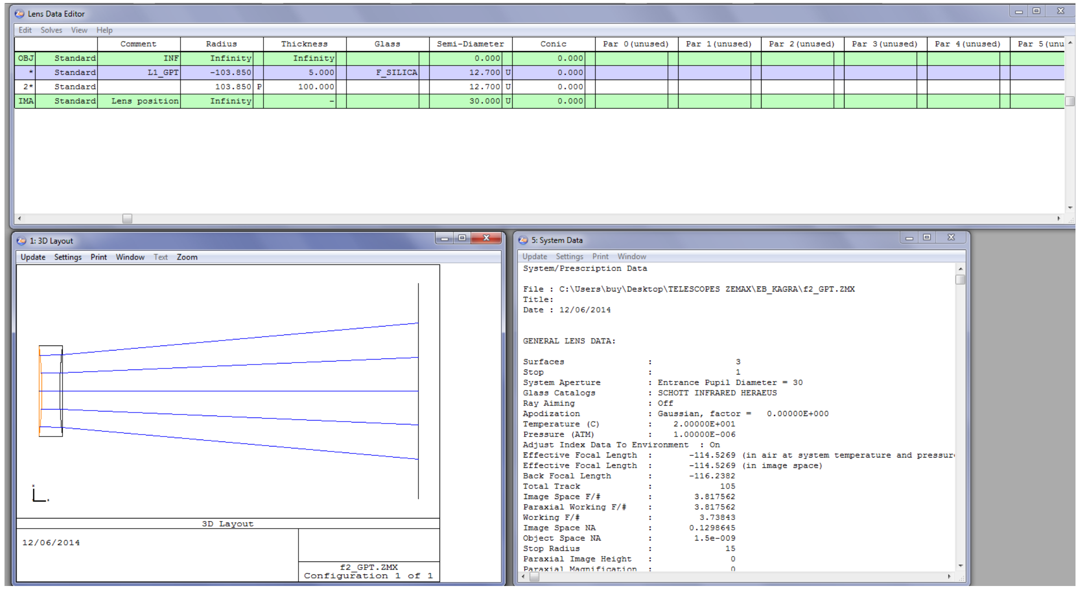
SPARE SLIDES

RoC of GPT_L1 and GPT_L2

Zemax simulation
Material: fused silica
Thickness: 5 mm

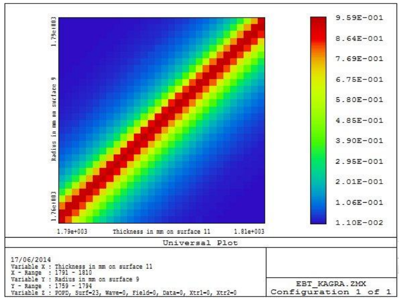


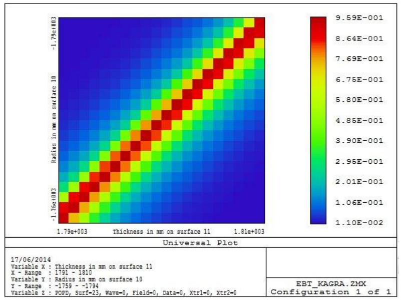
GPT_L1
Focal length: 343.6 mm
RoC value: 308.5 mm

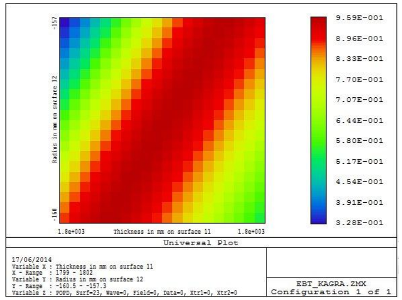


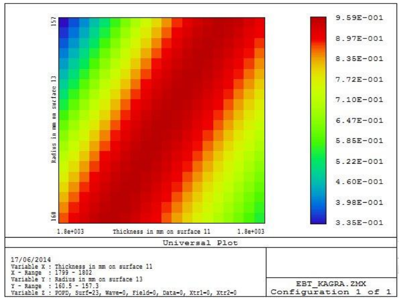
GPT_L2
Focal length: (-) 114.5 mm
RoC value: (-) 103.85 mm

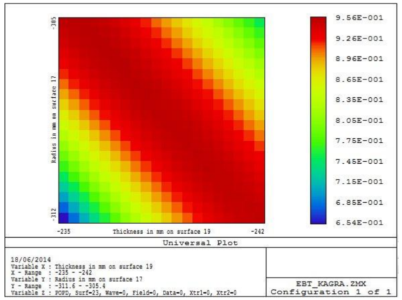
TOLERANCING: ROCS ERRORS

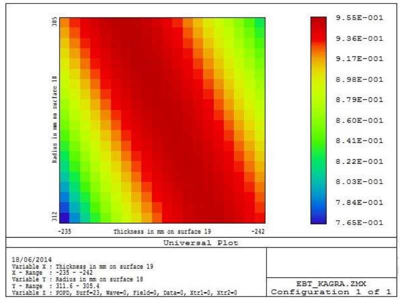

RoC error on BRT_L1 side 1
Thickness BRT_L1 / BRT_L2

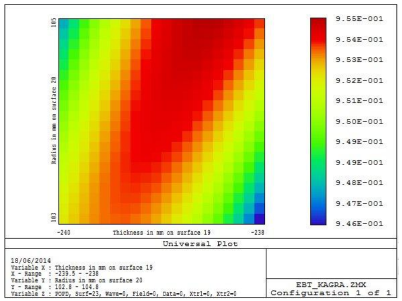

RoC error on BRT_L1 side 2
Thickness BRT_L1 / BRT_L2

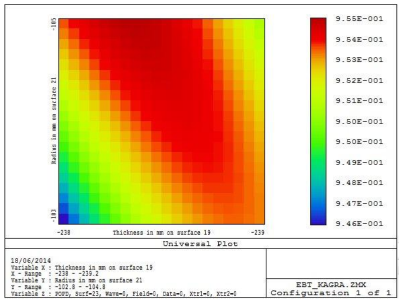

RoC error on BRT_L2 side 1
Thickness BRT_L1 / BRT_L2


RoC error on BRT_L2 side 2
Thickness BRT_L1 / BRT_L2


RoC error on GPT_L1 side 1
Thickness GPT_L1 / GPT_L2

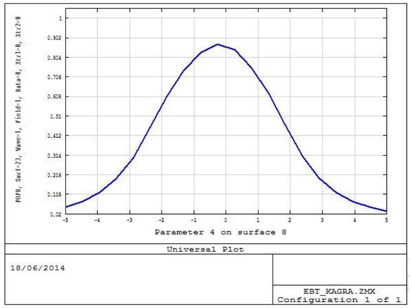

RoC error on GPT_L1 side 2
Thickness GPT_L1 / GPT_L2


RoC error on GPT_L2 side 1
Thickness GPT_L1 / GPT_L2


RoC error on GPT_L2 side 2
Thickness GPT_L1 / GPT_L2

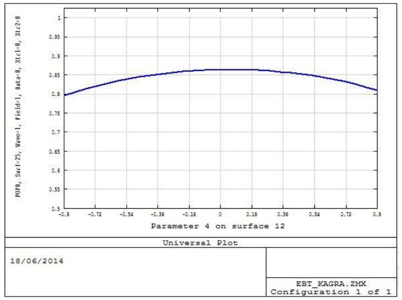
TOLERANCING: TILT AND DECENTER

Coupling efficiency



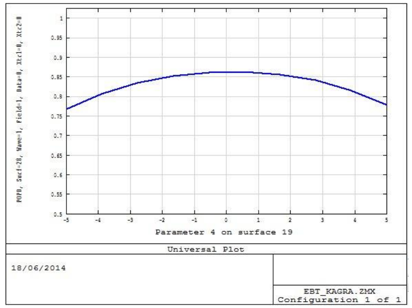
Tilt BRT_L1

Coupling efficiency



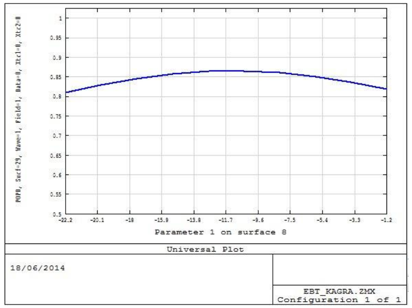
Tilt BRT_L2

Coupling efficiency



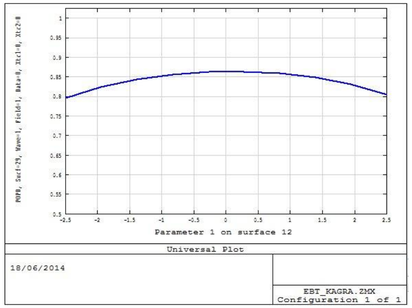
Tilt GPT_L1

Coupling efficiency



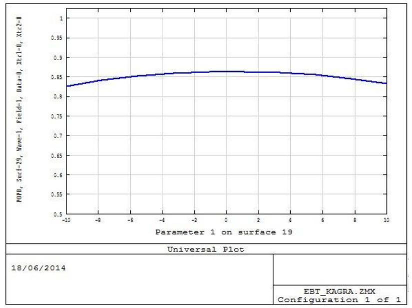
Decenter BRT_L1

Coupling efficiency



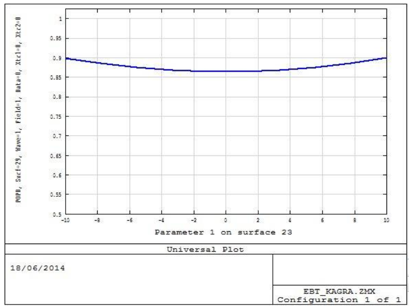
Decenter BRT_L2

Coupling efficiency



Decenter GPT_L1

Coupling efficiency



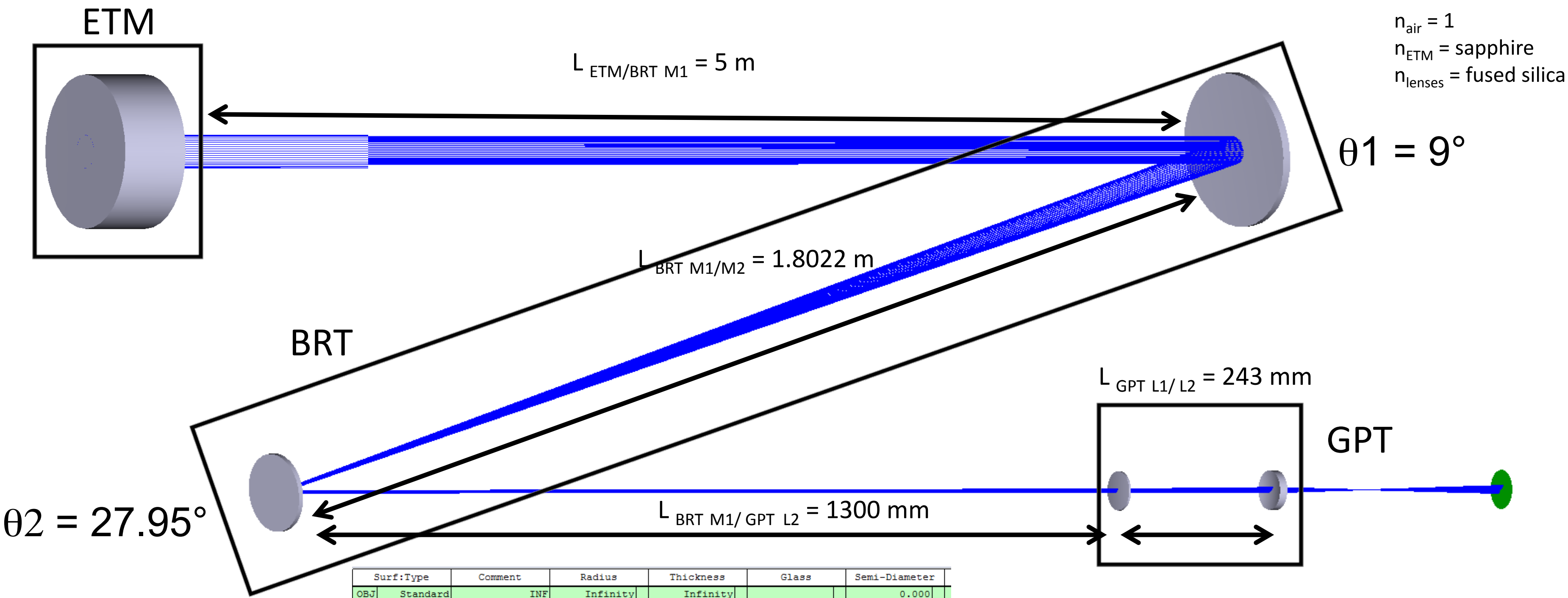
Decenter GPT_L2

Configuration with mirrors

OUTLINE

- Optical design
  - layout
  - gaussian parameters
  - aberrations
- Tolerancing
  - results

OPTICAL DESIGN: LAYOUT



	Surf:Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard	INF	Infinity		Infinity				0.000	
1	Coordinat..				0.000		-		0.000	
2	Standard	Waist cavity ..	Infinity		1.500E+006				35.000	U
3	Coordinat..				0.000		-		0.000	
*	Standard	ETM HR	-1.900E+006		150.000		SAPPHIRE		165.000	U
5	Coordinat..				0.000		-		0.000	
6*	Standard	ETM AR	Infinity		0.000				165.000	U
7	Coordinat..				5000.000		-		0.000	
8	Coordinat..				0.000		-		0.000	
9*	Standard	M1	-4000.000	V	0.000		MIRROR		100.000	U
10	Coordinat..				-1802.200	V	-		0.000	
11	Coordinat..				0.000		-		0.000	
12*	Standard	M2	-400.000		0.000		MIRROR		50.800	U
13	Coordinat..				0.000		-		0.000	
14	Coordinat..				1300.000		-		0.000	
15*	Standard	L3	308.500		5.000		F_SILICA		25.400	U
16*	Standard		-308.500		0.000				25.400	U
17	Coordinat..				0.000		-		0.000	
18	Coordinat..				243.000		-		0.000	
19*	Standard	L3	-103.850		5.000		F_SILICA		25.400	U
20*	Standard		103.850		0.000				25.400	U
21	Coordinat..				0.000		-		0.000	
22	Coordinat..				300.000		-		0.000	
IMA	Standard	Lens position	Infinity		-				25.400	U

Input from Junko Katayama

ETM 1st side / RoC = 1900 m

ETM 2nd side / RoC = infinity

e_{ETM}= 150 mm / wedge = 0.2°

BRT M1 / concave / RoC = 4000 mm

BRT M2 / convex / RoC = (-) 400 mm

GPT L1 / bi-convex / RoC = 308.5 mm / f = 343.6 mm

GPT L2 / bi-concave / RoC = (-) 103.85 mm / f = (-) 114.5 mm

e_{lenses}= 5 mm

OPTICAL DESIGN: GAUSSIAN PARAMETERS

Specifications/Parameters	EBT
Distance waist in the cavity – ETM first side	1500 m
Waist size in the cavity	16.197 mm
Wavelength	1064 nm

Y-Direction Fundamental Mode Results:

Sur	Size	Waist	Position	Radius	Divergence	Rayleigh
2	1.61970E+001	1.61970E+001	6.00000E+001	1.00000E+010	2.09102E-005	7.74597E+005
3	3.53016E+001	1.61970E+001	1.50006E+006	1.90004E+006	2.09102E-005	7.74597E+005
STO	3.53016E+001	9.96681E+000	1.74857E+006	1.90003E+006	1.93675E-005	5.14616E+005
5	3.53044E+001	9.96681E+000	1.74872E+006	1.90016E+006	1.93675E-005	5.14616E+005
6	3.53044E+001	9.96681E+000	9.96685E+005	1.08300E+006	3.39809E-005	2.93306E+005
7	3.53044E+001	9.96681E+000	9.96685E+005	1.08300E+006	3.39809E-005	2.93306E+005
8	3.54674E+001	9.96681E+000	1.00168E+006	1.08757E+006	3.39809E-005	2.93306E+005
9	3.54674E+001	1.93804E-002	2.02955E+003	2.02955E+003	1.74737E-002	1.10900E+000
10	3.54679E+001	1.93804E-002	2.02957E+003	2.02958E+003	1.74737E-002	1.10900E+000
11	3.97565E+000	1.93804E-002	2.27496E+002	2.27501E+002	1.74737E-002	1.10900E+000
12	3.97565E+000	3.12826E+000	2.26622E+004	5.95028E+004	1.08265E-004	2.88944E+004
13	3.97566E+000	3.12826E+000	2.26623E+004	5.95027E+004	1.08265E-004	2.88944E+004
14	3.97566E+000	3.12826E+000	2.26623E+004	5.95027E+004	1.08265E-004	2.88944E+004
15	4.06403E+000	5.78478E-002	-1.00616E+003	-1.00636E+003	4.03873E-003	1.43232E+001
16	4.04384E+000	2.88282E-002	-3.44199E+002	-3.44217E+002	1.17477E-002	2.45383E+000
17	4.04383E+000	2.88282E-002	-3.44198E+002	-3.44216E+002	1.17477E-002	2.45383E+000
18	4.04383E+000	2.88282E-002	-3.44198E+002	-3.44216E+002	1.17477E-002	2.45383E+000
19	1.18926E+000	5.13006E-002	-2.60892E+002	-2.61378E+002	4.55416E-003	1.12645E+001
20	1.16649E+000	2.15483E-001	-7.29399E+002	-7.55168E+002	1.57173E-003	1.37099E+002
21	1.16650E+000	2.15483E-001	-7.29400E+002	-7.55170E+002	1.57173E-003	1.37099E+002
22	1.16650E+000	2.15483E-001	-7.29400E+002	-7.55170E+002	1.57173E-003	1.37099E+002
IMA	7.08451E-001	2.15483E-001	-4.29390E+002	-4.73164E+002	1.57173E-003	1.37099E+002

X-Direction Fundamental Mode Results:

Sur	Size	Waist	Position	Radius	Divergence	Rayleigh
2	1.61970E+001	1.61970E+001	6.00000E+001	1.00000E+010	2.09102E-005	7.74597E+005
3	3.53016E+001	1.61970E+001	1.50006E+006	1.90004E+006	2.09102E-005	7.74597E+005
STO	3.53016E+001	9.96681E+000	1.74857E+006	1.90003E+006	1.93675E-005	5.14616E+005
5	3.53044E+001	9.96681E+000	1.74872E+006	1.90016E+006	1.93675E-005	5.14616E+005
6	3.53046E+001	9.96669E+000	9.96660E+005	1.08297E+006	3.39814E-005	2.93298E+005
7	3.53039E+001	9.96669E+000	9.96660E+005	1.08297E+006	3.39814E-005	2.93298E+005
8	3.54670E+001	9.96669E+000	1.00166E+006	1.08754E+006	3.39814E-005	2.93298E+005
9	3.59239E+001	1.88898E-002	1.97815E+003	1.97815E+003	1.79274E-002	1.05357E+000
10	3.54674E+001	1.88898E-002	1.97818E+003	1.97818E+003	1.79274E-002	1.05357E+000
11	3.15738E+000	1.88898E-002	1.76098E+002	1.76104E+002	1.79274E-002	1.05357E+000
12	3.57786E+000	2.96068E+000	-9.58980E+003	-7.94406E+004	1.14393E-004	2.58816E+004
13	3.15737E+000	2.96068E+000	-9.58968E+003	-7.94414E+004	1.14393E-004	2.58816E+004
14	3.15737E+000	2.96068E+000	-9.58968E+003	-7.94414E+004	1.14393E-004	2.58816E+004
15	3.10884E+000	7.41545E-002	-9.86455E+002	-9.87016E+002	3.15062E-003	2.35364E+001
16	3.09311E+000	3.73208E-002	-3.40814E+002	-3.40864E+002	9.07462E-003	4.11255E+000
17	3.09306E+000	3.73208E-002	-3.40813E+002	-3.40863E+002	9.07462E-003	4.11255E+000
18	3.09306E+000	3.73208E-002	-3.40813E+002	-3.40863E+002	9.07462E-003	4.11255E+000
19	8.88434E-001	6.47061E-002	-2.45404E+002	-2.46712E+002	3.61066E-003	1.79208E+001
20	8.70458E-001	2.25513E-001	-5.59748E+002	-6.00030E+002	1.50183E-003	1.50159E+002
21	8.70371E-001	2.25513E-001	-5.59750E+002	-6.00032E+002	1.50183E-003	1.50159E+002
22	8.70371E-001	2.25513E-001	-5.59750E+002	-6.00032E+002	1.50183E-003	1.50159E+002
IMA	4.50595E-001	2.25513E-001	-2.59739E+002	-3.46548E+002	1.50183E-003	1.50159E+002

- Gaussian beam propagation

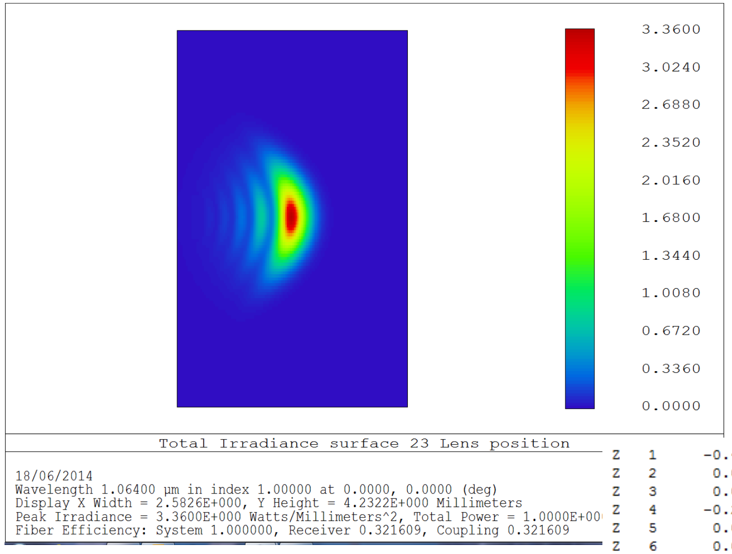
- Astigmatism due to the wedge of ETM (tilted beam on BRT) and the two spherical mirrors

- Surface number related to the lens data editor (previous slide)

- Waist size at the output (after GPT L2) ~ 220 µm
- Waist position at the output (after GPT L2) ~ 600 mm

Important difference betwen Zemax' paramaters and Junko's parameters

OPTICAL DESIGN: ABERRATIONS (1)



- Coupling efficiency at the output of the telescope (300mm after GPT_L2) = 32%
- Spherical aberrations, coma and astigmatism

Zernike coefficients

```
Z  1   -0.44379876 :   1
Z  2    0.00962481 :    4^(1/2) (p) * COS (A)
Z  3    0.00000000 :    4^(1/2) (p) * SIN (A)
Z  4   -0.26076263 :    3^(1/2) (2p^2 - 1)
Z  5    0.00000000 :    6^(1/2) (p^2) * SIN (2A)
Z  6    0.09912746 :    6^(1/2) (p^2) * COS (2A)
Z  7    0.00000000 :    8^(1/2) (3p^3 - 2p) * SIN (A)
Z  8    0.00391946 :    8^(1/2) (3p^3 - 2p) * COS (A)
Z  9    0.00000000 :    8^(1/2) (p^3) * SIN (3A)
Z 10   -0.00000258 :    8^(1/2) (p^3) * COS (3A)
Z 11   -0.00352628 :    5^(1/2) (6p^4 - 6p^2 + 1)
Z 12    0.00227375 :   10^(1/2) (4p^4 - 3p^2) * COS (2A)
Z 13    0.00000000 :   10^(1/2) (4p^4 - 3p^2) * SIN (2A)
Z 14   -0.00069611 :   10^(1/2) (p^4) * COS (4A)
Z 15    0.00000000 :   10^(1/2) (p^4) * SIN (4A)
Z 16    0.00028180 :   12^(1/2) (10p^5 - 12p^3 + 3p) * COS (A)
Z 17    0.00000000 :   12^(1/2) (10p^5 - 12p^3 + 3p) * SIN (A)
Z 18   -0.00012035 :   12^(1/2) (5p^5 - 4p^3) * COS (3A)
Z 19    0.00000000 :   12^(1/2) (5p^5 - 4p^3) * SIN (3A)
Z 20    0.00001322 :   12^(1/2) (p^5) * COS (5A)
Z 21    0.00000000 :   12^(1/2) (p^5) * SIN (5A)
Z 22   -0.00001122 :    7^(1/2) (20p^6 - 30p^4 + 12p^2 - 1)
Z 23    0.00000000 :   14^(1/2) (15p^6 - 20p^4 + 6p^2) * SIN (2A)
Z 24   -0.00000683 :   14^(1/2) (15p^6 - 20p^4 + 6p^2) * COS (2A)
Z 25    0.00000000 :   14^(1/2) (6p^6 - 5p^4) * SIN (4A)
Z 26    0.00000100 :   14^(1/2) (6p^6 - 5p^4) * COS (4A)
Z 27    0.00000000 :   14^(1/2) (p^6) * SIN (6A)
Z 28    0.00000054 :   14^(1/2) (p^6) * COS (6A)
Z 29    0.00000000 :   16^(1/2) (35p^7 - 60p^5 + 30p^3 - 4p) * SIN (A)
Z 30    0.00000040 :   16^(1/2) (35p^7 - 60p^5 + 30p^3 - 4p) * COS (A)
Z 31    0.00000000 :   16^(1/2) (21p^7 - 30p^5 + 10p^3) * SIN (3A)
Z 32   -0.00000004 :   16^(1/2) (21p^7 - 30p^5 + 10p^3) * COS (3A)
Z 33    0.00000000 :   16^(1/2) (7p^7 - 6p^5) * SIN (5A)
Z 34    0.00000007 :   16^(1/2) (7p^7 - 6p^5) * COS (5A)
Z 35    0.00000000 :   16^(1/2) (p^7) * SIN (7A)
Z 36   -0.00000001 :   16^(1/2) (p^7) * COS (7A)
Z 37   -0.00000002 :    9^(1/2) (70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)
```

Z4: focus aberration
Z6: astigmatism
Z8: coma
Z11:spherical aberration
Z12: astigmatism secondaire
Z16: coma secondaire

OPTICAL DESIGN: ABERRATIONS (2)

Design of a low-loss off-axis beam expander

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(to be published as a Technical Note in Applied Optics)

Abstract : A recipe is given in order to built up simple off-axis beam expanders for gaussian beams with low aberrations; especially, it is shown that it is possible to correct exactly the astigmatism in such a system. A realistic example is finally given.

- Reduce the astigmatism by adjusting the angle of incidence (« Design of a low-loss off-axis beam expander »)
- Optimization of the distance BRT_M1 / BRT_M2, and maybe the RoC of BRT_M1 and BRT_M2
- Try to have a coupling efficiency ~ 80%
- Have a waist size at the output (after GPT L2) ~ 168 µm

OPTICAL DESIGN: ABERRATION COMPENSATION (1)

Design of a low-loss off-axis beam expander

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- Two configurations described in the note:
  - z1 (waist position at the input of the telescope) >> b1 (Rayleigh range of the input telescope beam)
  - z1 << b1

- For the KAGRA telescope:
  - z1 = 10^3
  - b1 = 3.10^2
  - z1 not really >> b1

- However, I tried to used the compensation assuming z1 >> b1, and for θ1=9° I obtained θ2=5.16° (the formul used is described in detailed in the note)

- I integrated this angle values in Zemax, but the astigmatism was not compensated (as expected)

OPTICAL DESIGN: ABERRATION COMPENSATION (2)

- I create a merit function in Zemax, in order to compensate the astigmatism directly in the simulation
  - waist position X = waist position Y
  - astigmatism = 0
  - coma = 0
  - spherical aberration = 0
  - waist size W = waist size Y = 2.6 mm on GPT L1

- I put some variable in the simulation:
  - angle of tilt of BRT M2
  - distance between BRT M1 and BRT M2

- The results obtained are not realistic for the moment:
  - $\theta 2$=1000° (??)
  - BRT_M1 / BRT_M2 = few meters
  - the astigmatism not compensated

- I compared to what was studied for Advanced Virgo:
  - a spherical configuration has been studied
  - the minimum RoC for M1 was 8m (not less than 8m otherwise the aberrations were to strong)
  - this configuration was discarded due to the space constraints

First conclusions

• It seems difficult to compensate the aberration for the choosen configuration

• It seems that the RoC of BRT_M1 has to be increased if we want to decrease the astigmatism

• The space constraints will be a potential problem