TECHNICAL REPORT

**OPTIMIZATION OF THE ZEMAX DESIGN OF
THE SCUBA-2 IFTS**

INO 060140 R/09

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1. INTRODUCTION AND OBJECTIVES

The University of Lethbridge develops a sub-millimetre imaging FTS for use with SCUBA-2 project on the JCMT telescope. The Zemax model needed to be optimized to maximize the FOV and efficiency.

Objectives:

1- Optical design optimization and tolerancing:

The FTS has been modelled in Zemax as a folded system of paraxial mirrors, and the optimization has been completed by INO. The mirror surfaces/positions were optimized based on a set of criteria provided by the University of Lethbridge. The paraxial mirrors were replaced by real mirrors (extended polynomials). The rooftop mirrors included in Lethbridge simulation were replaced by hollow corner cubes. An analysis of the performances of the IFTS (Imaging Fourier Transform Spectrometer) was performed, and the results are presented below. We detail performances in terms of achievable FOV (Field Of View) / spot pattern / vignetting, at ZPD and for the 2 resolution modes (±15mm and ±200mm travel). We detail the impact of the IFTS on the FOV, spot pattern and vignetting of the SCUBA-2 camera.

The full SCUBA-2 / JCMT optical model was already available at INO.

> File: \\Netdisk01\User0685\040193 - Polarimètre SCUBA-2 Phase 1 Preliminary design\simulations zemax\Fichier original télescope JCMT + caméra SCUBA-2\SC2_POL_OPT_001.ZMX
>
> File: \\Netdisk01\User0685\060140 - SCUBA-2 IFTS\Fichier Zemax JCMT\Scuba2_141105876mmwindowreoptimized.ZMX

The FTS model for one input port of the interferometer was provided by the client.

> File: \\Netdisk01\User0685\060140 - SCUBA-2 IFTS\multi-conf_test.ZMX

In this model, the optics for the second input port are identical to the first, but mirrored about the plane of the beam splitters. The model shows the approximate configuration of the mirrors, and the simplified image and pupil from the SCUBA-2 system between mirrors C3 and N1. The goal is for the FTS to reproduce the same image and pupil at the output. The model has 5 configurations. The first configuration is when the FTS corner cube mirrors are at zero path difference (ZPD) location. This is the starting point for the optimization. Configurations 2 and 3 are when the corner cube mirrors are displaced the distance required by the low-resolution mode. Configuration 4 and 5 are for the high-resolution mode.

With those files as a starting point, INO integrated the IFTS in the telescope and SCUBA-2 camera design and optimized it to obtain the best spot size and lowest possible vignetting, considering the available space inside the telescope mechanical structure.

> Final Zemax file (real mirrors model): \\Netdisk01\User0685\060140 - SCUBA-2 IFTS\IFTS draft 6_9.zmx

An IGES or STEP file (exported from Zemax) with all the optical surfaces was provided by INO to the client for him to verify that the mirrors fit into the allowed space envelope.

Final IGES file: \\Netdisk01\User0685\060140 - SCUBA-2 IFTS\IFTS draft 6_9_config0003.IGS

2- Mirrors surfaces prescription:

INO provided all the necessary information about the prescription of each mirror surface to enable the client to produce mechanical drawings for manufacturing (diamond turned aluminium). This information is included in the final IGES file delivered to the client. Additional details on mirror surfaces can be found below.

3- List of mechanical issues:

INO helped identify any other mechanical issues associated with mounting the optics in the framework. A list of mechanical issues can be found below.

The mechanical design will be performed by the client.

4- Assistance with documentation for CDR:

INO finalized the optical design for the Critical Design Review (CDR), and provided assistance to the client to produce the documentation needed for the CDR. INO delivered an optimized Zemax file with real mirrors surfaces, with each mirror surface prescription.

5- Management, monthly reports and minutes of meetings

INO provides a final status on hours done on the project, with associated costs, below.

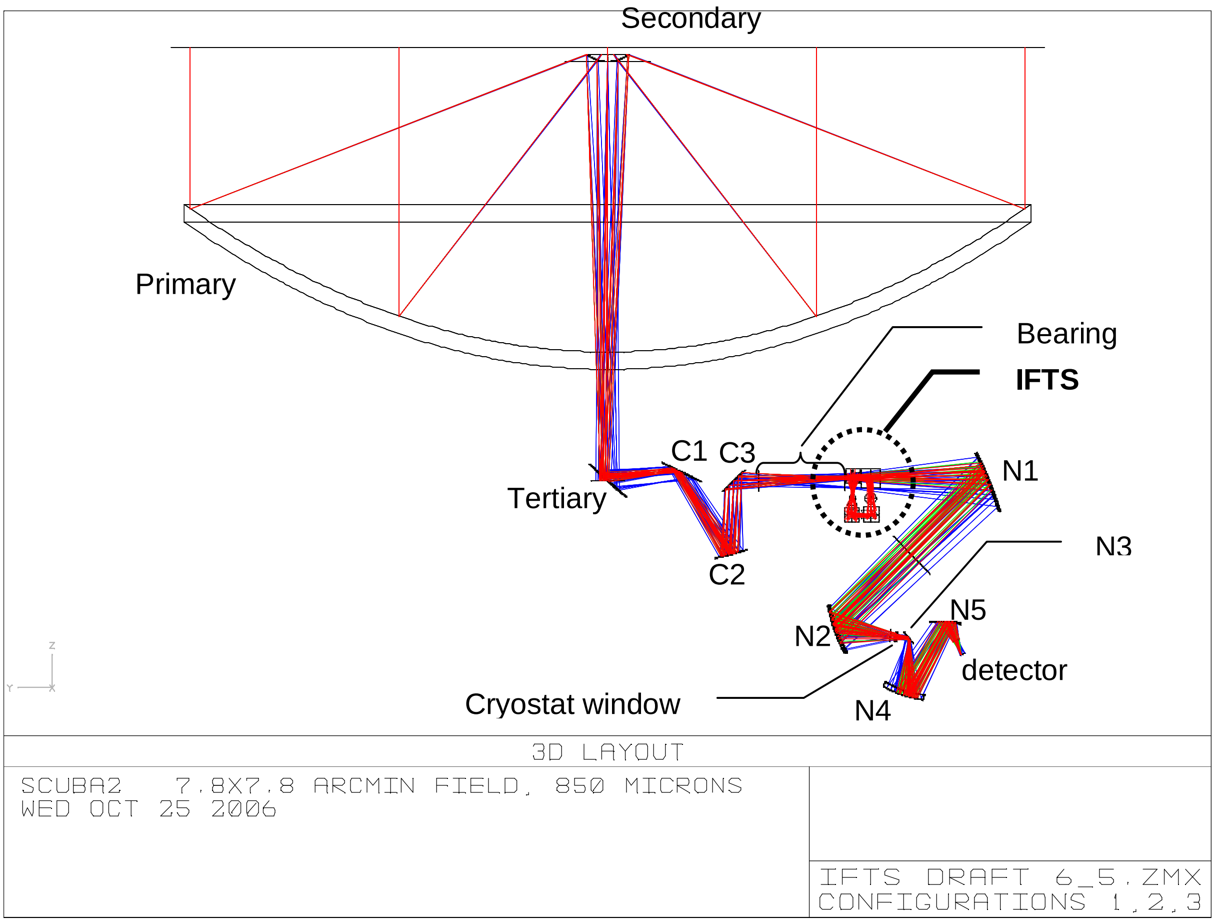
2. DELIVERABLES

1. Optical Design

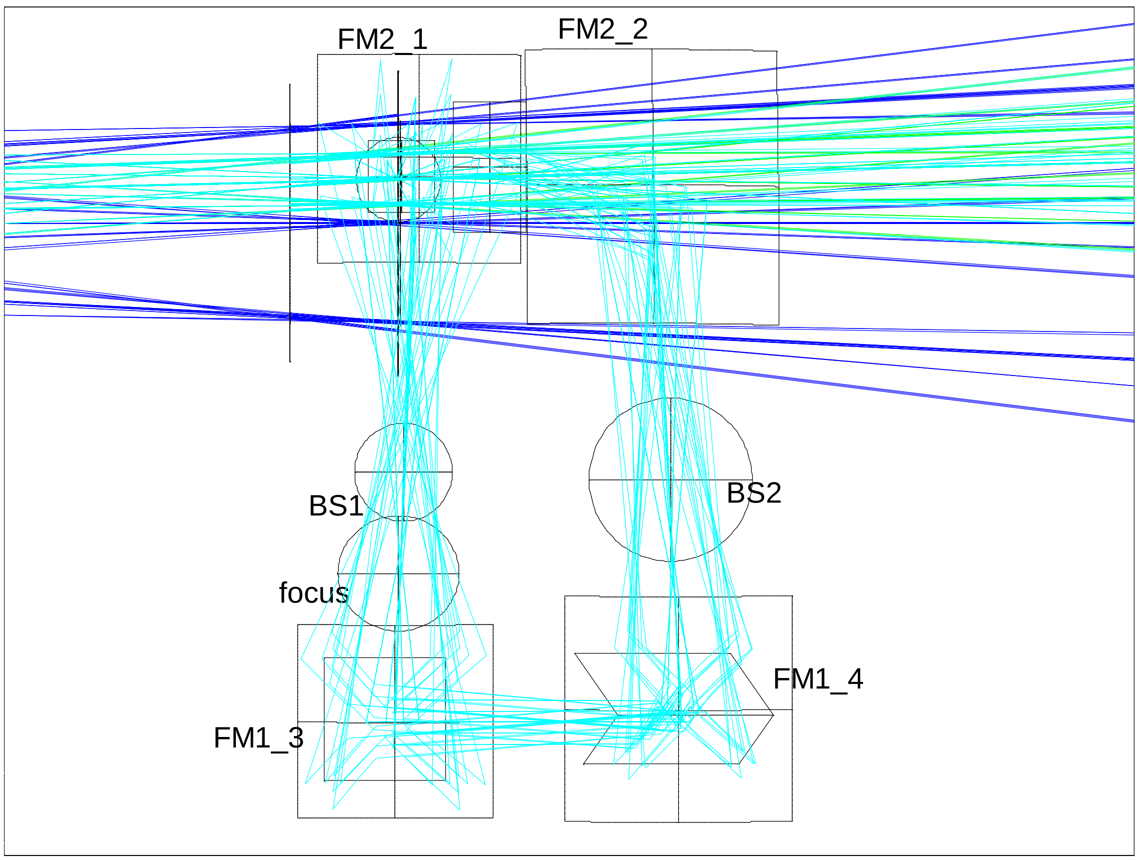
a) Zemax model

Real mirrors design: File: \\Netdisk01\User0685\060140 - SCUBA-2 IFTS\Fichier Zemax IFTS\ IFTS draft 6_9.zmx

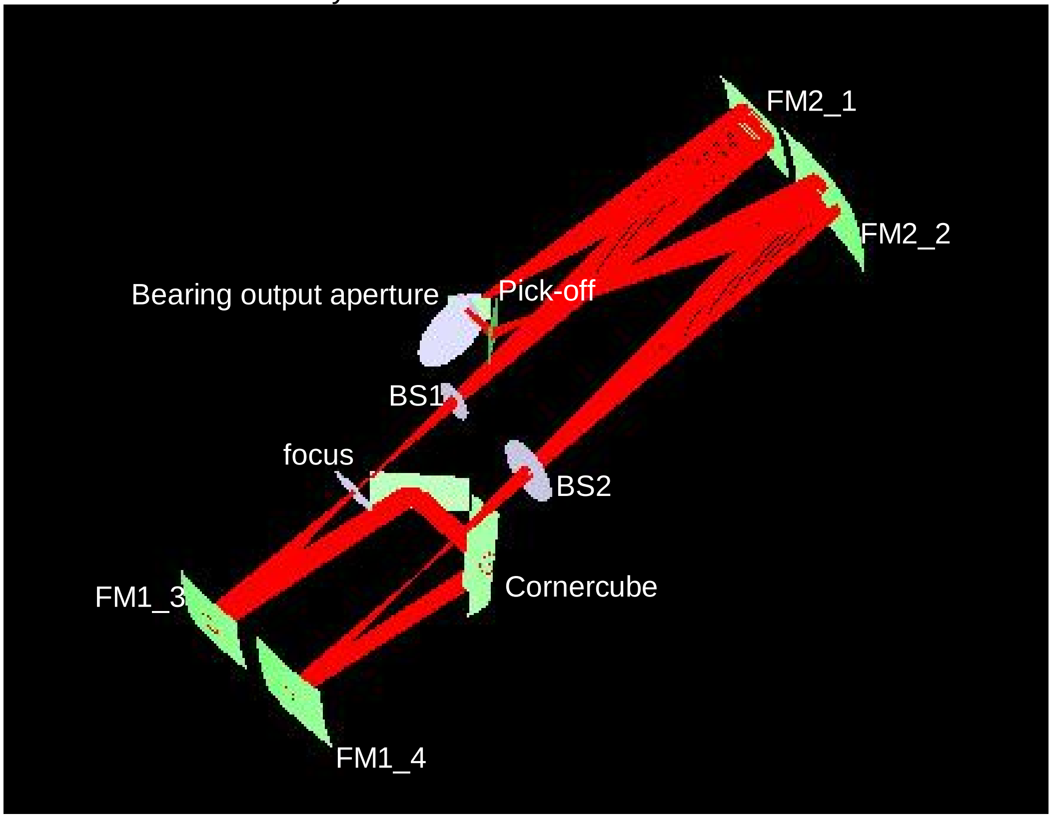
The IFTS is located at the exit of the bearing, between mirrors C3 and N1. In the following figure, the bearing length is represented by an accolade, and the IFTS location is encircled. All JCMT telescope and SCUBA-2 camera mirrors are identified, as well as the cryostat window.



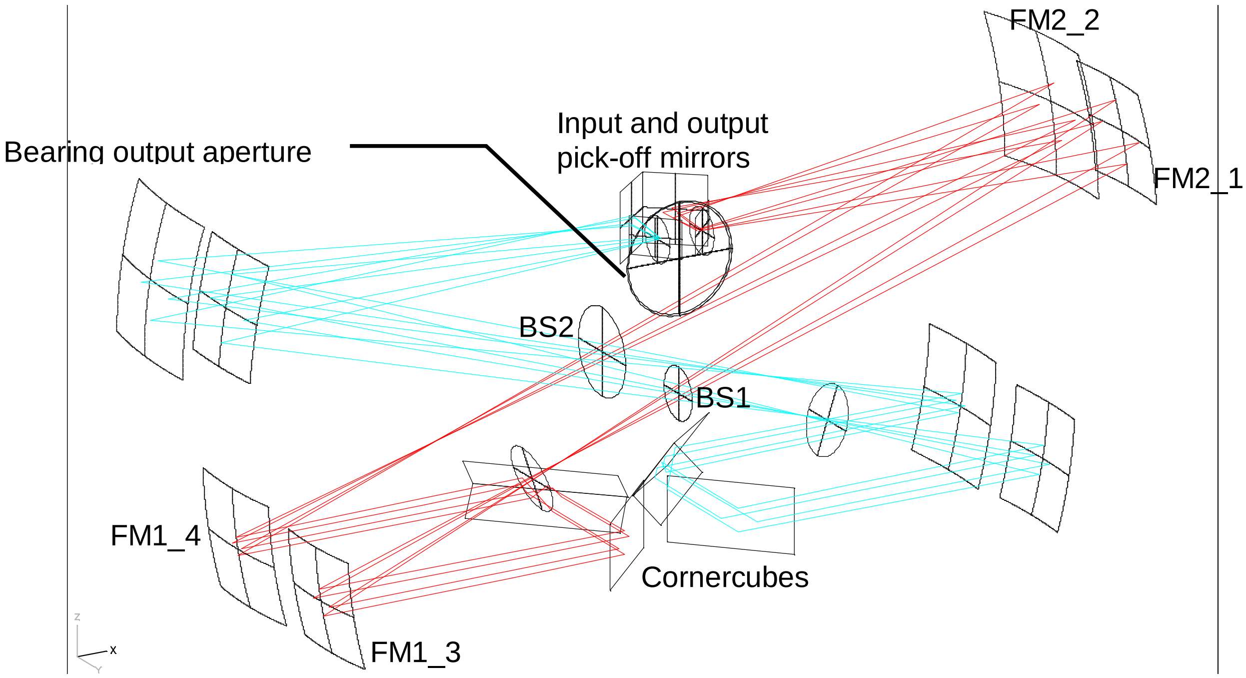
The IFTS has two symmetrical sides. The two beam splitters are located under the telescope axis, and enough clearance is given to allow for a 10 mm rim around the beam splitters (BS1 and BS2) without it vignetting the telescope beam (in blue) when the IFTS is not in use. We checked that there is no mechanical interference between mirrors FM2_1 and FM2_2, FM1_3 and FM1_4, between the different parts of the corner cube mirror, and between the different parts of the input and output pick-off mirrors. The breadboard supporting the IFTS being at 772 mm under the telescope optical axis, we checked that there was enough space under the corner cube mirrors to allow for a translating stage, and that there was no mechanical interference between the lower folding mirrors and the breadboard. Below is a side view of the IFTS, showing the clearance around the beam splitters, and the space between adjacent folding mirrors.



Below is a solid view of one of the two symmetrical sides of the IFTS.

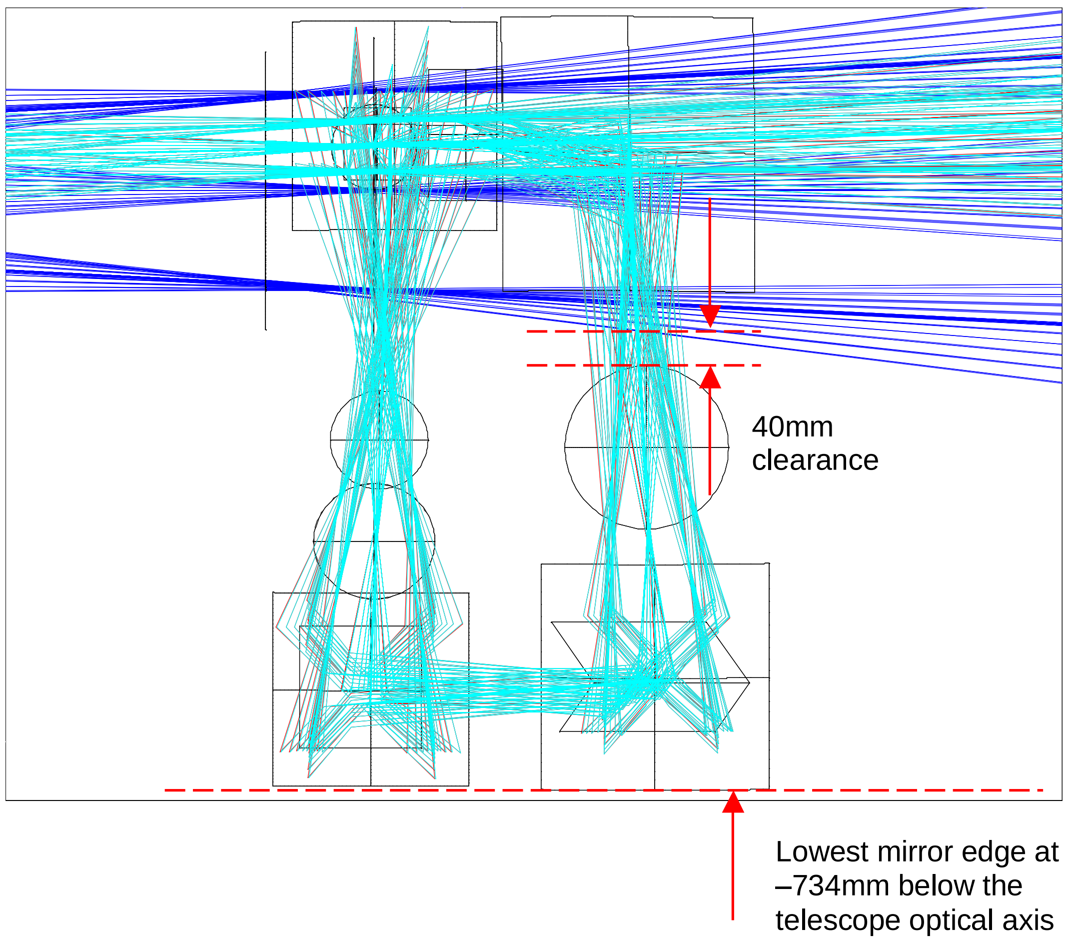


A view of the two sides of the IFTS follows.



The IFTS components relative to the telescope beam are located as not to interfere with the telescope beam when the IFTS is not in use.

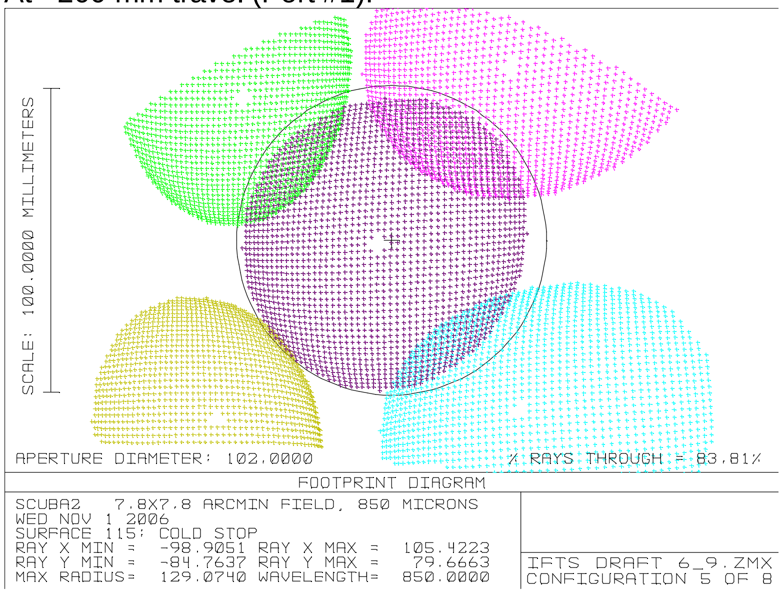
There is enough clearance below the telescope beam to accommodate the second beamsplitter mount. The beamsplitter rings will add ~10mm to the radius of the beamsplitter clear aperture. In the current design, there is 40 mm clearance to accommodate this mounting ring between the telescope beam (in blue) and the IFTS second beamsplitter. The current design also meet the requirement of available volume, limited by the baseplate positionned at –772mm below the telescope optical axis.



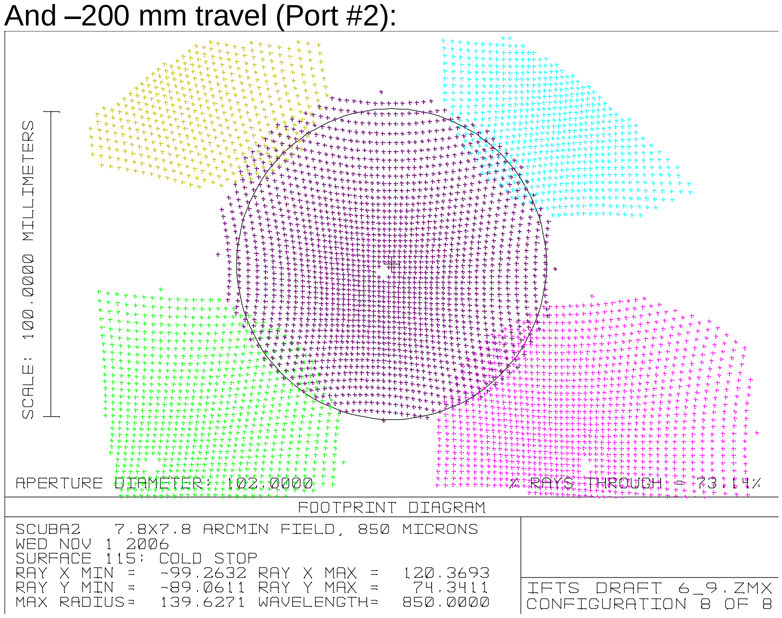
b) Performances of the IFTS with corner cubes

Spill-over: The spill-over mainly happens at the cold stop, at ±200mm travel.

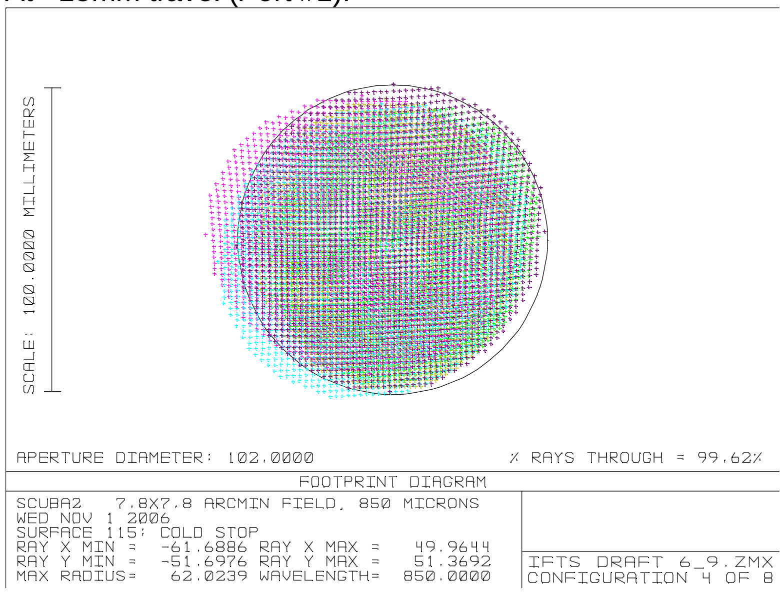
At +200 mm travel (Port #1):



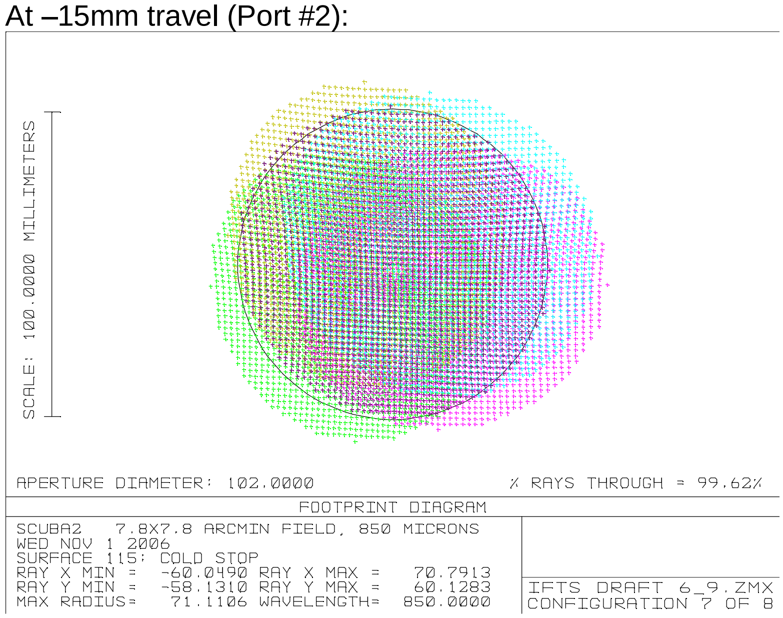
And –200 mm travel (Port #2):



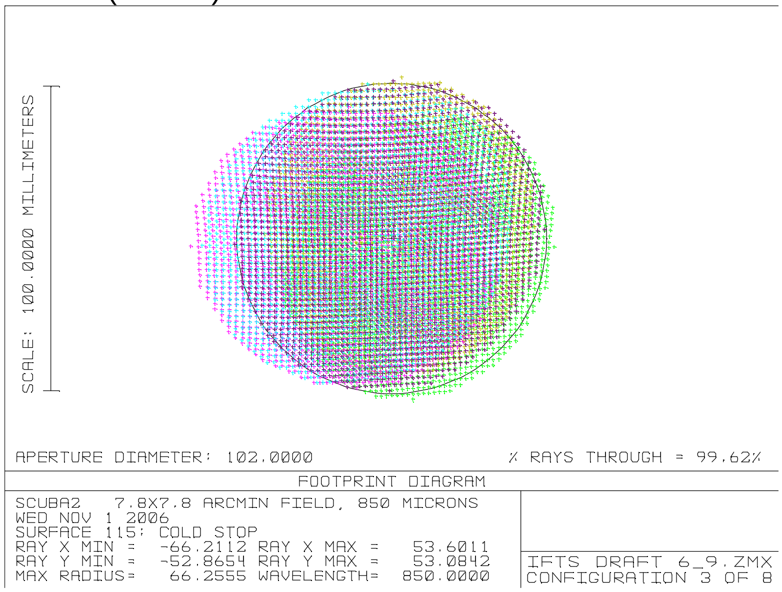
At +15mm travel (Port #1):



At –15mm travel (Port #2):



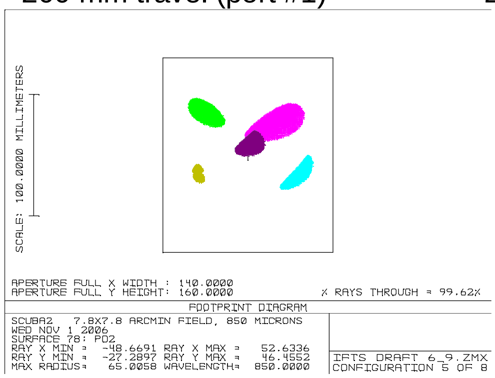
At ZPD (Port #1):

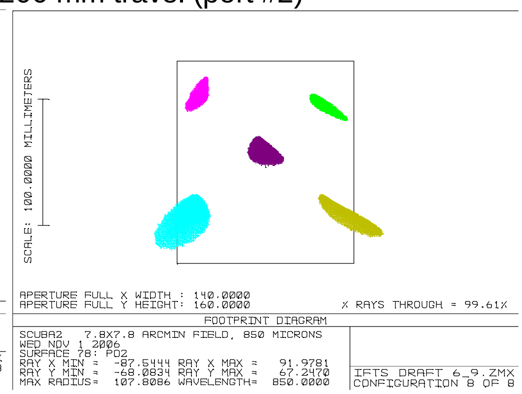


There is also spill-over at other surfaces:

Spill-over at the output pick-off mirrors:

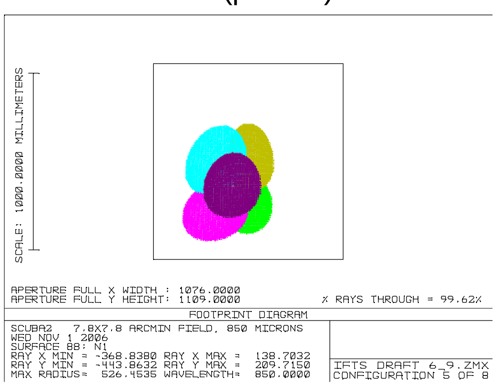
+200 mm travel (port #1) -200 mm travel (port #2)

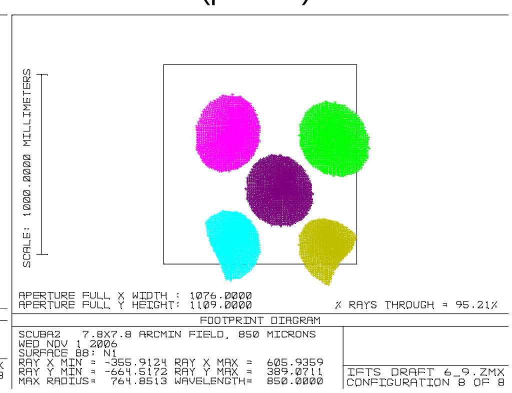




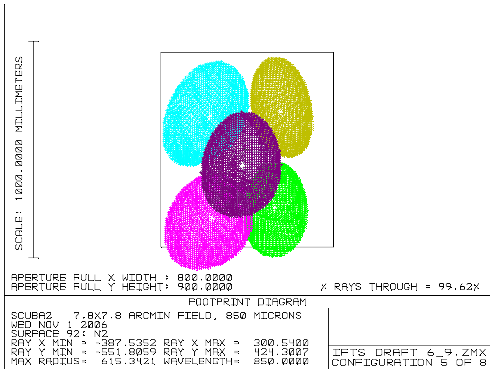
Spill-over at N1

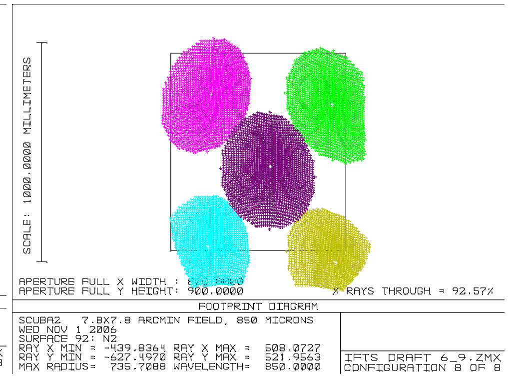
+200 mm travel (port #1) -200 mm travel (port #2)



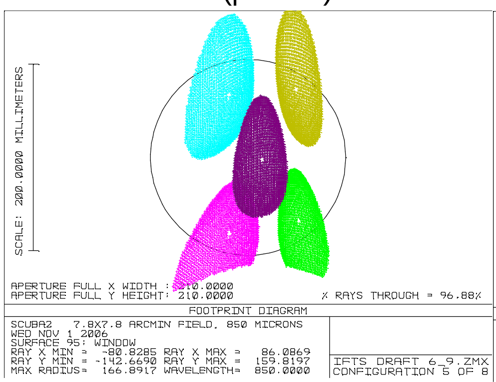


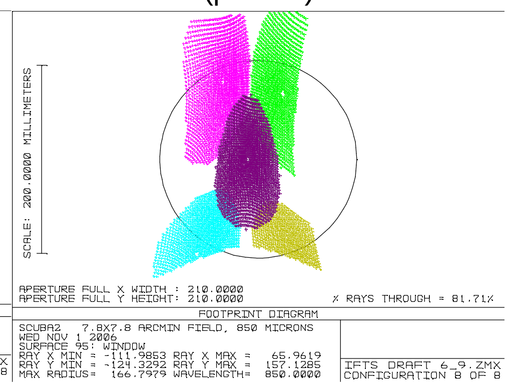
Spill-over at N2
+200 mm travel (port #1) -200 mm travel (port #2)



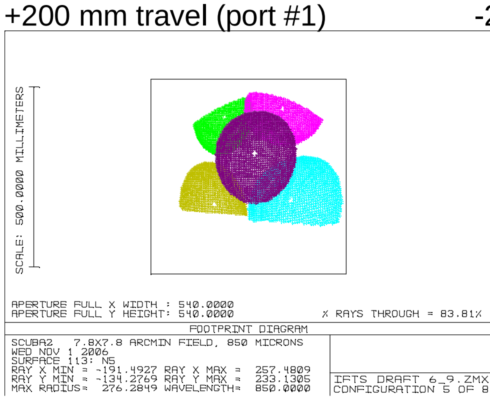


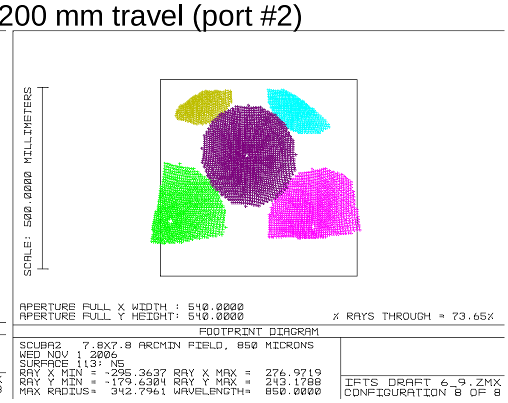
Spill-over at the cryostat window:
+200 mm travel (port #1) -200 mm travel (port #2)





Spill-over at N5:
+200 mm travel (port #1) -200 mm travel (port #2)





In the IFTS, there is no other spill-over except at the output pick-off mirror at –200mm travel, as shown above.

Vignetting: The result of spill-over at surfaces between the IFTS output pick-off mirrors and the camera cold stop is vignetting. If we consider all apertures, we obtain vignetting that increases with the travel distance.

The proportion of rays getting through to the detector with travel distance is:

Travel distance	Side with increasing travel distance	Side with decreasing travel distance
ZPD	95.09%	95.09%
±15mm	96.96%	91.34%
±30mm	96.86%	87.49%
±50mm	94.21%	82.53%
±100mm	82.99%	70.04%
±150mm	71.95%	59.18%
±200mm	62.07%	51.97%

For each field, we compared the proportion of rays getting through for each branch of the interferometer, and computed the contrast of the corresponding interferogram for increasing travel distance.

Field #3(central field), (-0.028760, 0.028760)deg.:

Travel distance	Side with increasing travel distance	Side with decreasing travel distance	Interference contrast, excluding image shift
ZPD	97.55%	97.55%	1.000
±15mm	98.01%	97.14%	0.991
±30mm	98.37%	96.89%	0.985
±50mm	98.83%	96.53%	0.977
±100mm	91.64%	94.44%	0.970
±150mm	91.64%	91.22%	0.995
±200mm	91.64%	91.69%	0.999

Field #2, (-0.012090, 0.012090)deg.:

Travel distance	Side with increasing travel distance	Side with decreasing travel distance	Interference contrast, excluding image shift
ZPD	95.41%	95.41%	1.000
±15mm	99.75%	85.67%	0.859
±30mm	99.75%	76.08%	0.763
±50mm	98.32%	64.51%	0.656
±100mm	71.44%	37.38%	0.523
±150mm	43.45%	15.76%	0.363
±200mm	19.07%	2.91%	0.153

Field #4, (-0.012090, 0.045430)deg.:

Travel distance	Side with increasing travel distance	Side with decreasing travel distance	Interference contrast, excluding image shift
ZPD	98.27%	98.27%	1.000
±15mm	99.59%	89.55%	0.899
±30mm	95.41%	79.55%	0.834
±50mm	84.19%	67.16%	0.798
±100mm	53.85%	38.25%	0.710
±150mm	26.93%	13.16%	0.489
±200mm	1.99%	0.56%	0.281

Field #5, (-0.045430, 0.012090)deg.:

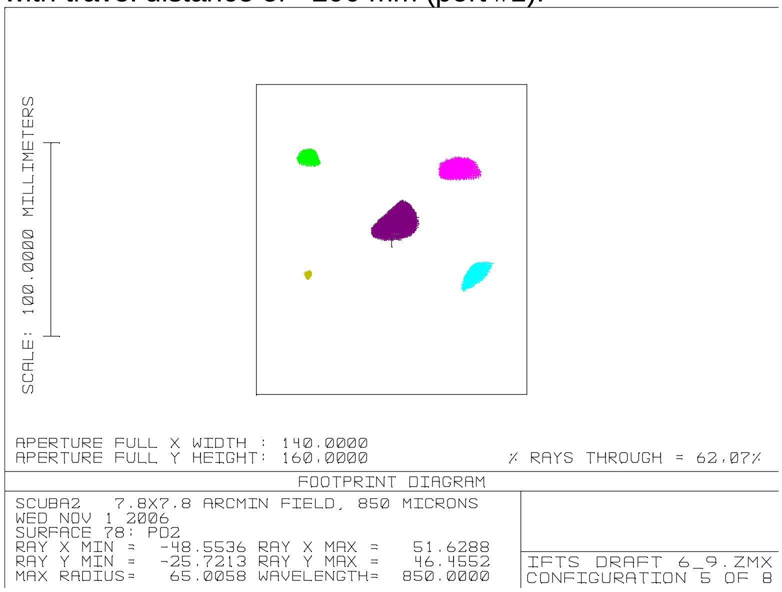
Travel distance	Side with increasing travel distance	Side with decreasing travel distance	Interference contrast, excluding image shift
ZPD	86.23%	86.23%	1.000
±15mm	91.02%	80.06%	0.880
±30mm	93.57%	73.43%	0.785
±50mm	88.73%	64.00%	0.721
±100mm	65.53%	41.05%	0.626
±150mm	42.53%	19.28%	0.453
±200mm	22.74%	4.03%	0.177

Field #6, (-0.045430, 0.045430)deg.:

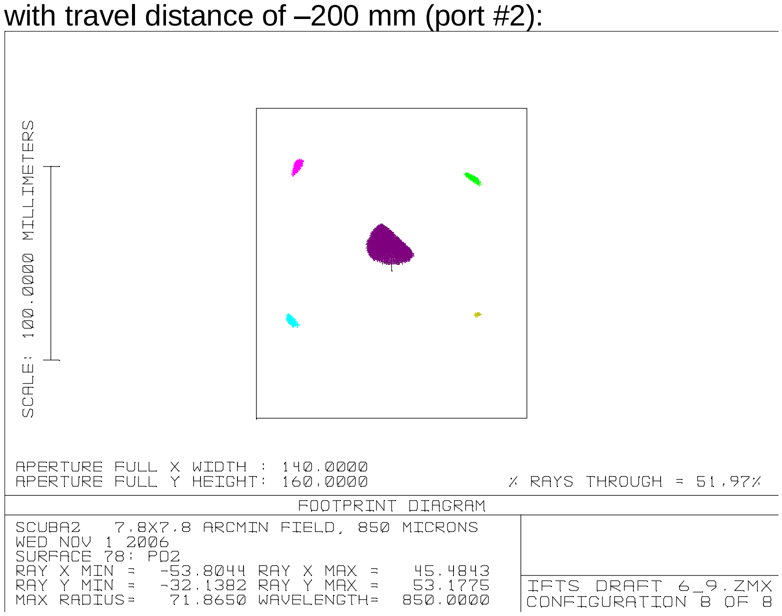
Travel distance	Side with increasing travel distance	Side with decreasing travel distance	Interference contrast, excluding image shift
ZPD	88.37%	88.37%	1.000
±15mm	92.20%	81.64%	0.885
±30mm	91.13%	74.40%	0.816
±50mm	82.56%	64.81%	0.785
±100mm	57.89%	42.02%	0.622
±150mm	36.41%	19.07%	0.524
±200mm	16.57%	2.19%	0.132

If we consider vignetting, the footprint of the beam at the output pick-off mirrors is:

with travel distance of +200 mm (port #1):

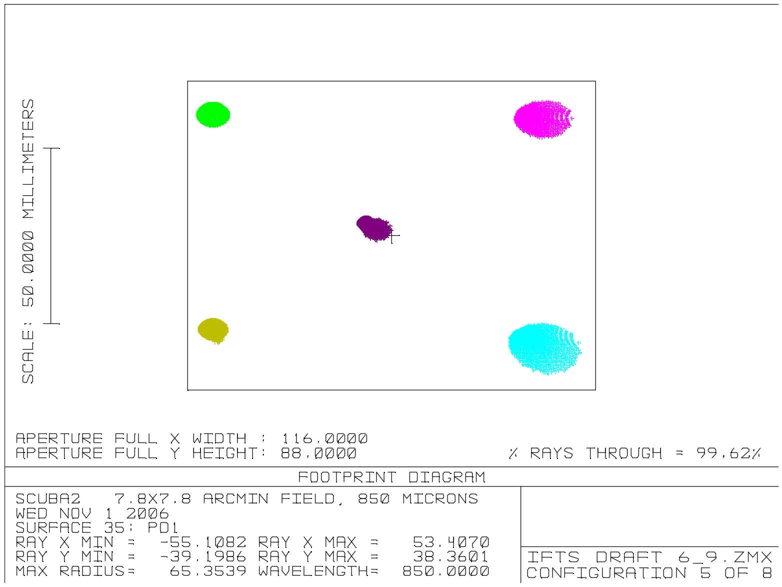


with travel distance of –200 mm (port #2):

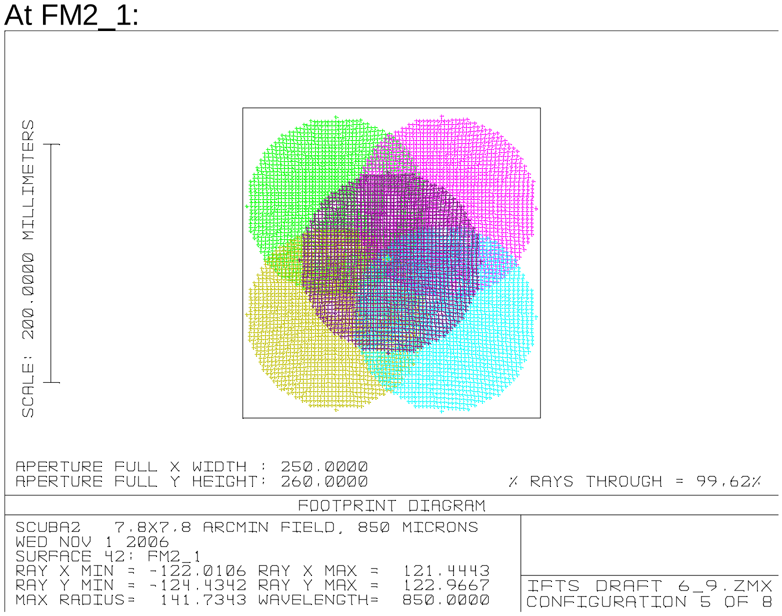


Footprint of the beam at each IFTS surface: There is no vignetting of the beam in the IFTS except at the output pick-off mirrors as shown in preceding paragraphs. The footprint of the beam at the other surfaces of the IFTS is presented in the following figures (port #1).

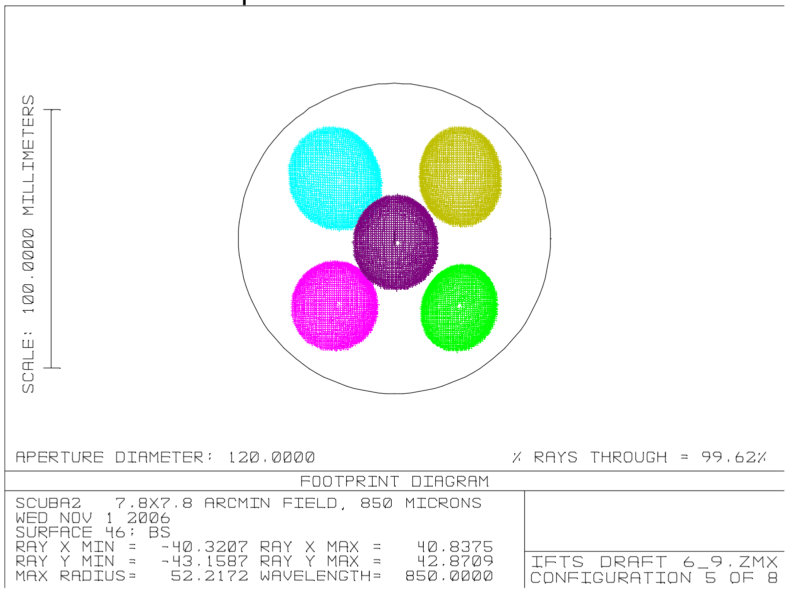
At PO1:



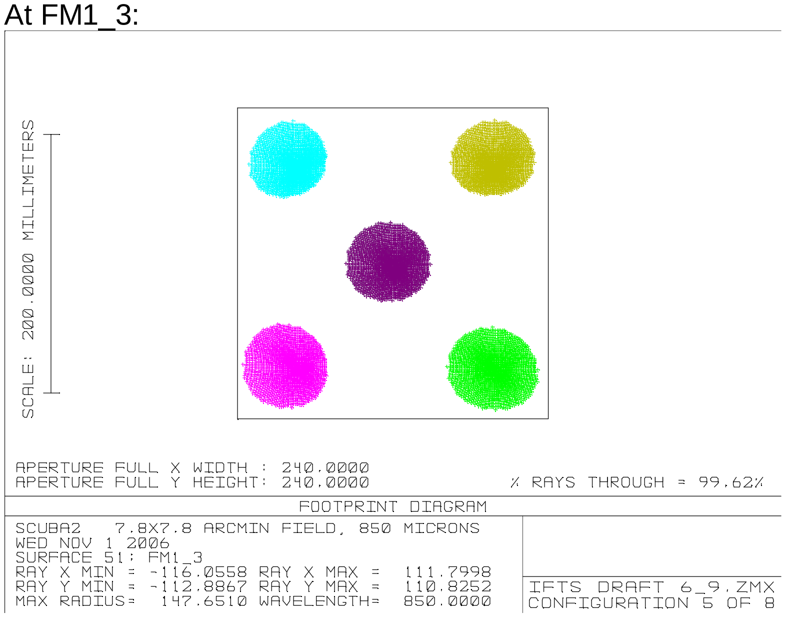
At FM2_1:



At the first beam splitter BS1:



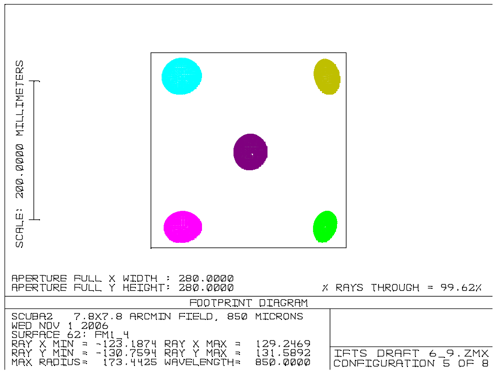
At FM1_3:



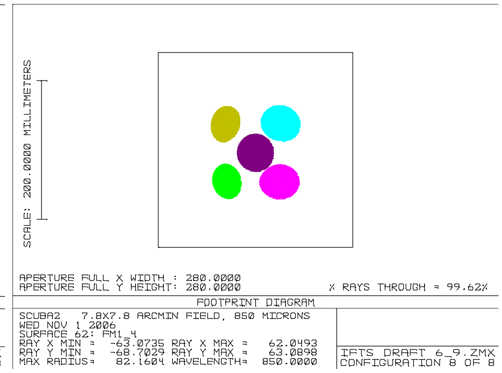
The footprint at surfaces after FM1_3 varies with the travel distance of the cornercube mirrors carriage. The footprint at each surface subsequent to FM1_3 is shown below, for various travel distances between –200mm and +200mm.

At FM1_4

At travel = +200mm (port #1)

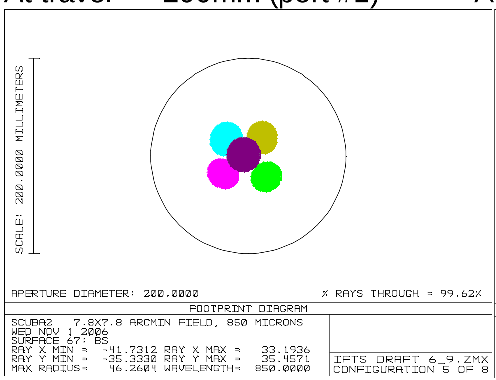


At travel = -200mm (port #2)

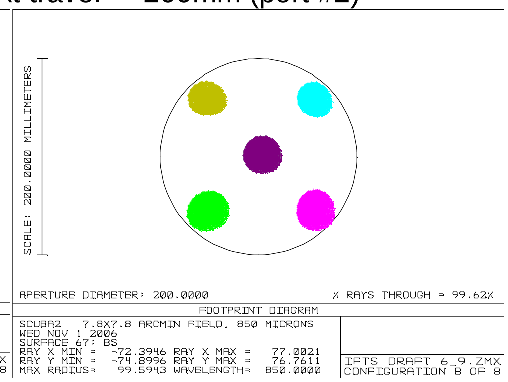


At BS2

At travel = +200mm (port #1)

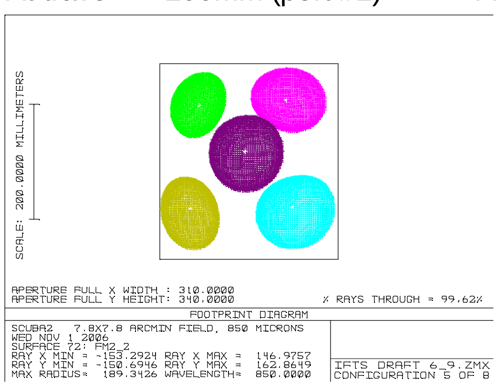


At travel = -200mm (port #2)

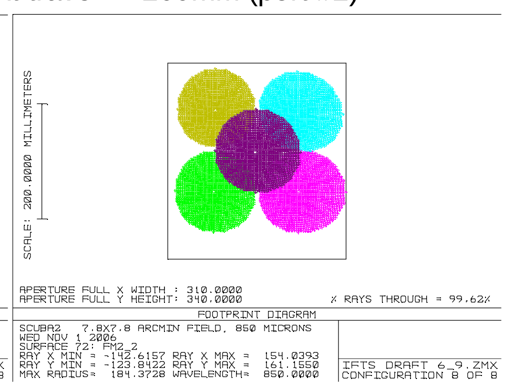


At FM2_2

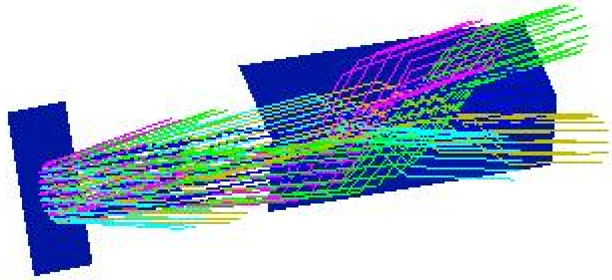
At travel = +200mm (port #1)



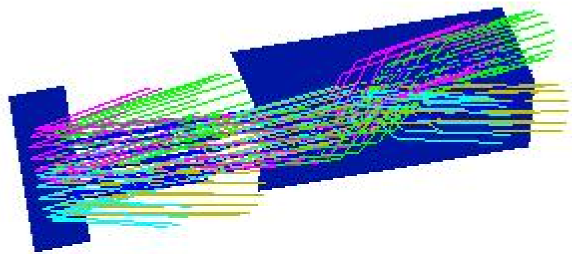
At travel = -200mm (port #2)



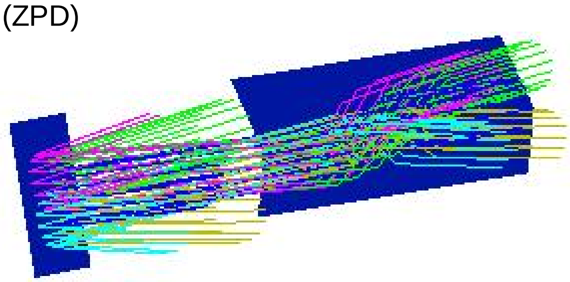
At the cornercube (for the port #1 side of the interferometer):
At travel = +200mm



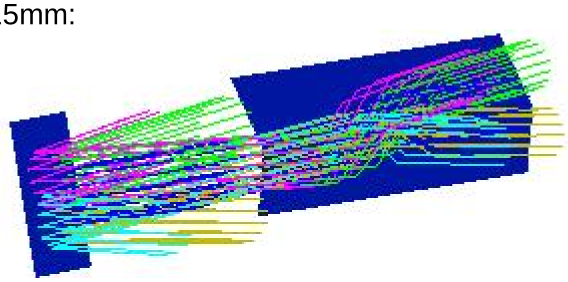
At travel = +15mm



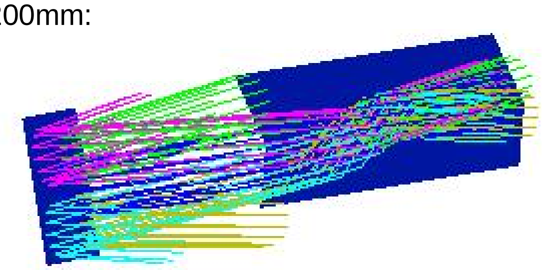
At travel = 0 (ZPD)



At travel = -15mm:



At travel = -200mm:



Spot size vs. travel distance:

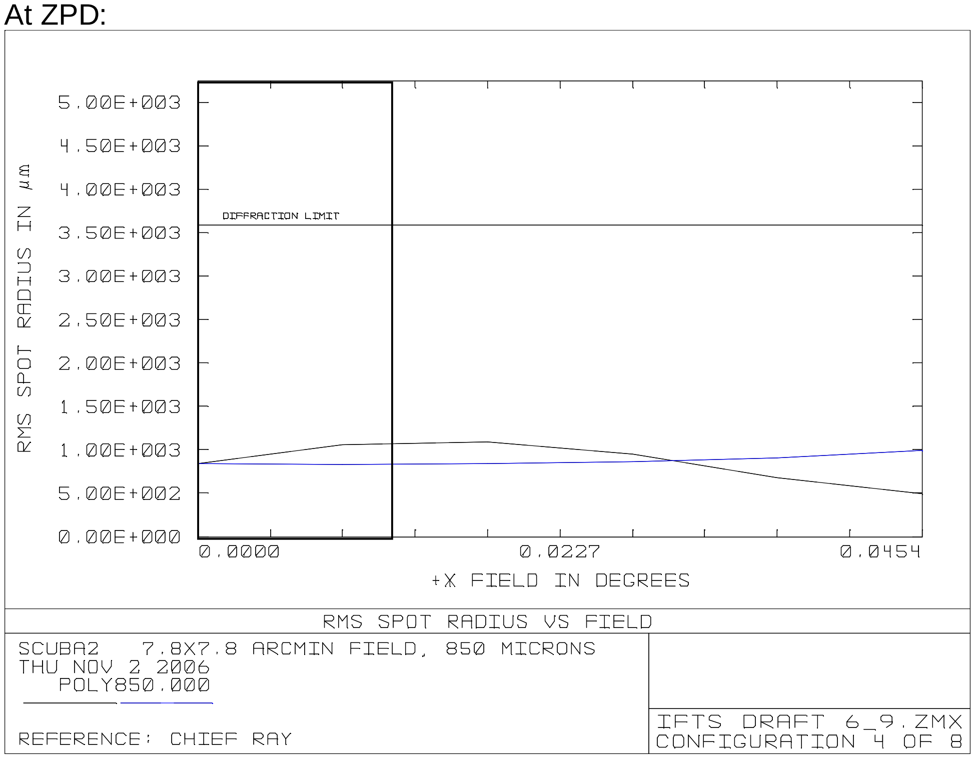
The spot size increases with travel distance. It stays under the diffraction limit for travel distances between +200mm and –100mm.

RMS Spot radius (µm) vs. field of view and travel distance

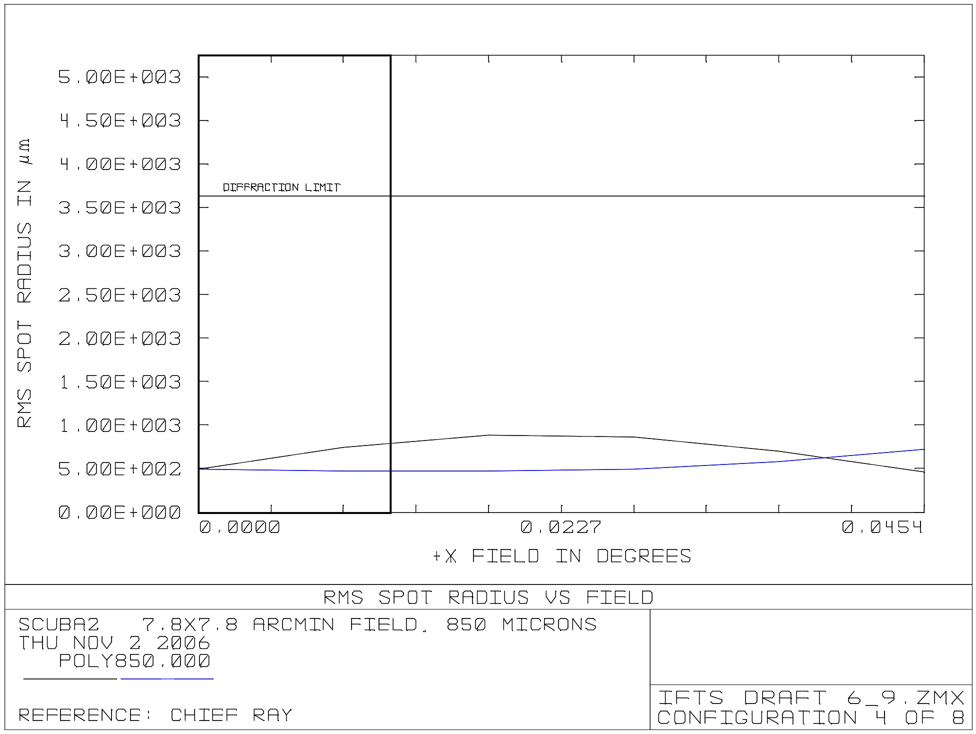
Field #	*2*	*3*	*4*	*5*	*6*	
FoV (deg.)	0.01711198	0.04072935	0.04698478	0.04698478	0.0642053	Airy Radius (µm)
Travel (mm)	RMS spot radius (µm)					
200	1278.53	763.154	1519.94	2303.04	2574.04	2914
150	806.492	779.851	996.049	1051.42	1209.62	2870
100	778.353	798.99	1052.66	1214.97	1006.35	2827
50	562.318	822.465	930.403	836.875	1129.04	3788
30	624.236	830.383	911.04	627.228	1126.54	3673
15	780.399	835.557	1016.31	562.852	1061.97	3630
0	983.13	841.091	1252.08	610.479	1089.92	3591
-15	1015.77	846.36	1436.71	714.621	1136.45	3556
-30	968.777	853.107	1506.06	797.314	1197.13	3474
-50	903.066	853.275	1575.29	857.148	1305.42	3447
-100	2184.03	855.31	2864.79	1332.28	2219.53	3403
-150	5752.9	864.648	8149.83	3570.26	5222.3	3405
-200	1.10E+04	873.98	2.10E+04	7681.65	1.10E+04	3331

In the following graphs, the RMS spot radius is plotted for fields along the X-axis (dashed line in black) and along the Y-axis (continuous line in blue). The useful portion of the graph is from field = 0.01209 deg. to field = 0.04543 deg.

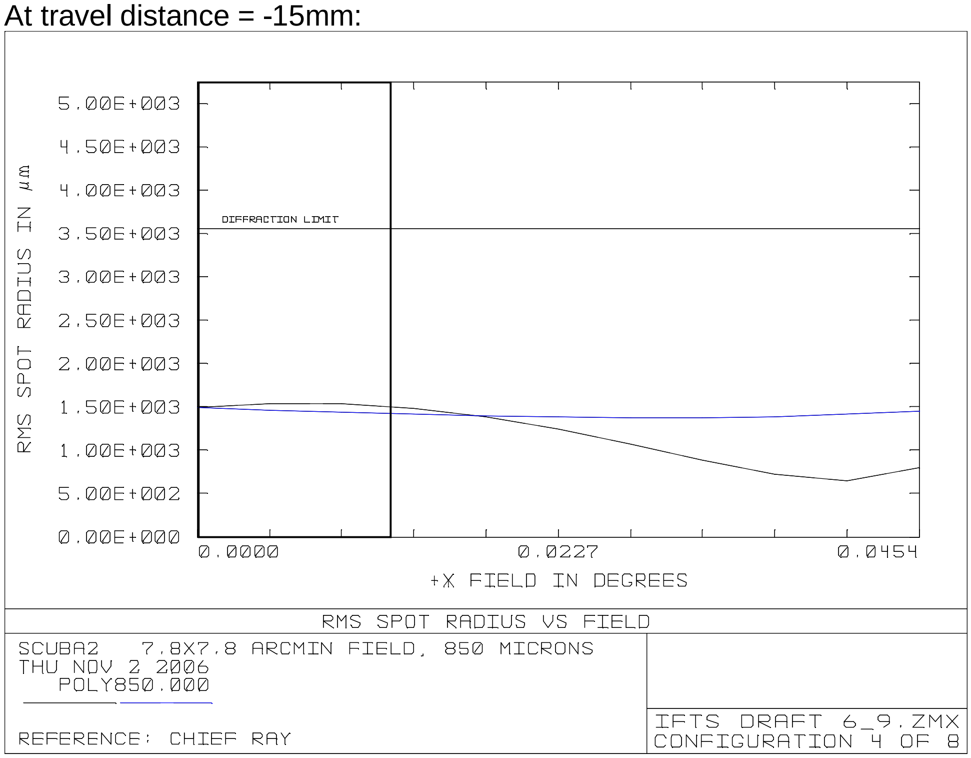
At ZPD:



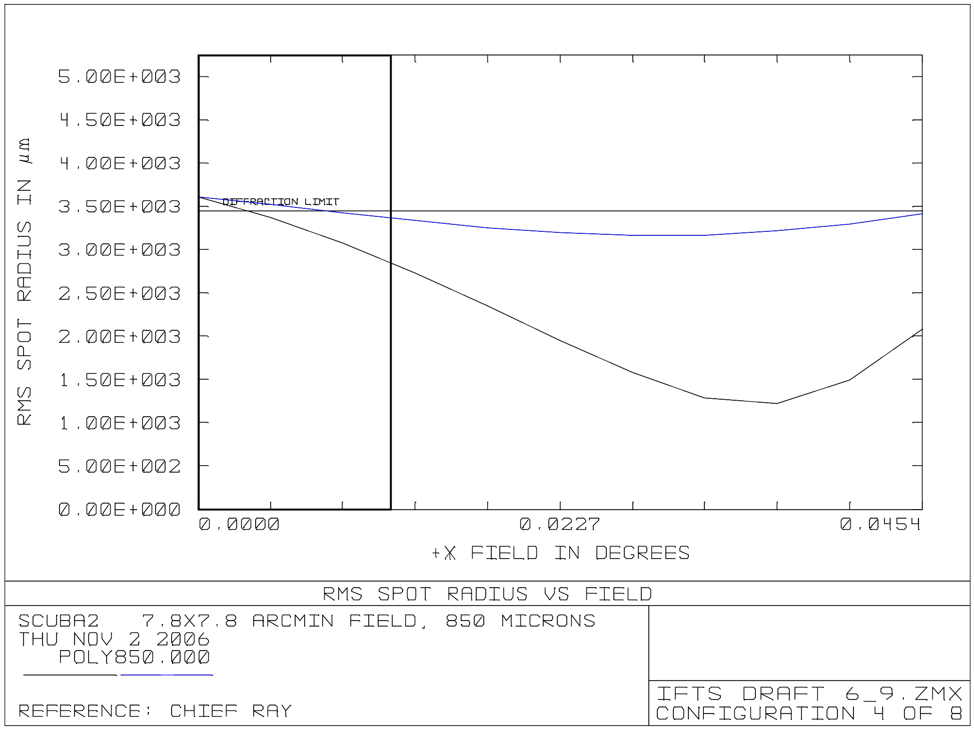
At travel distance = +15mm:



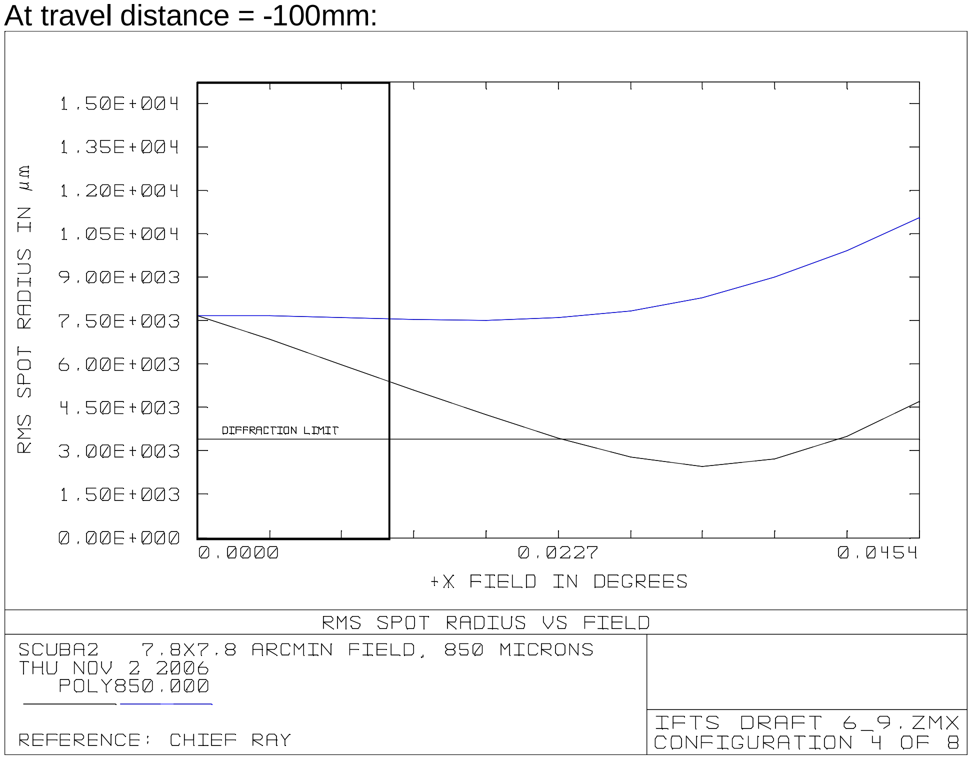
At travel distance = -15mm:



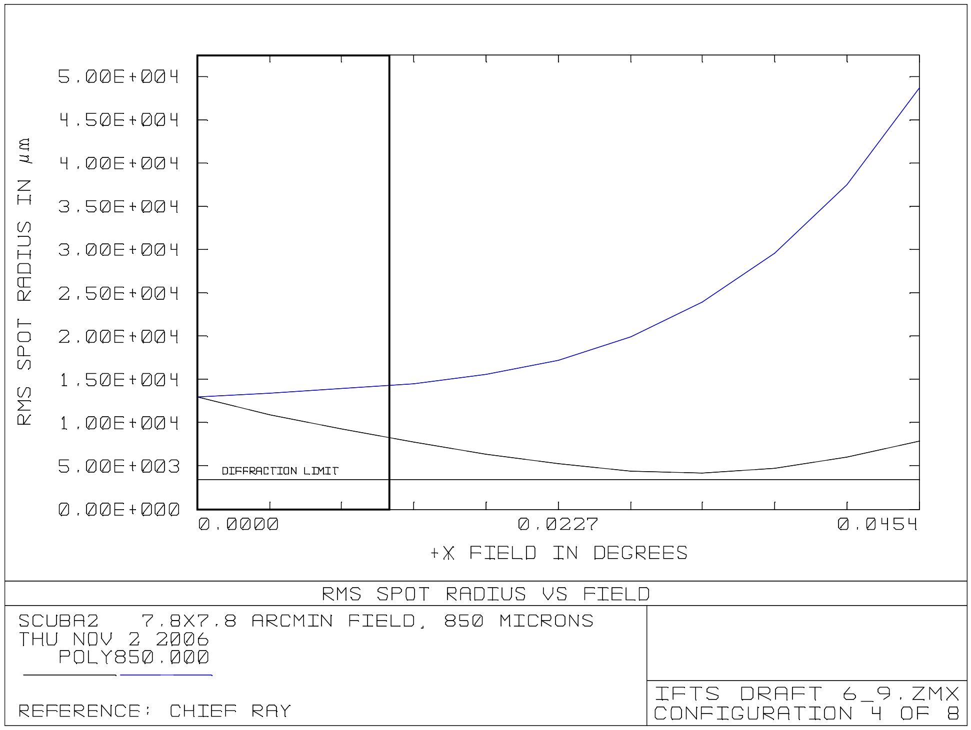
At travel distance = -50mm:



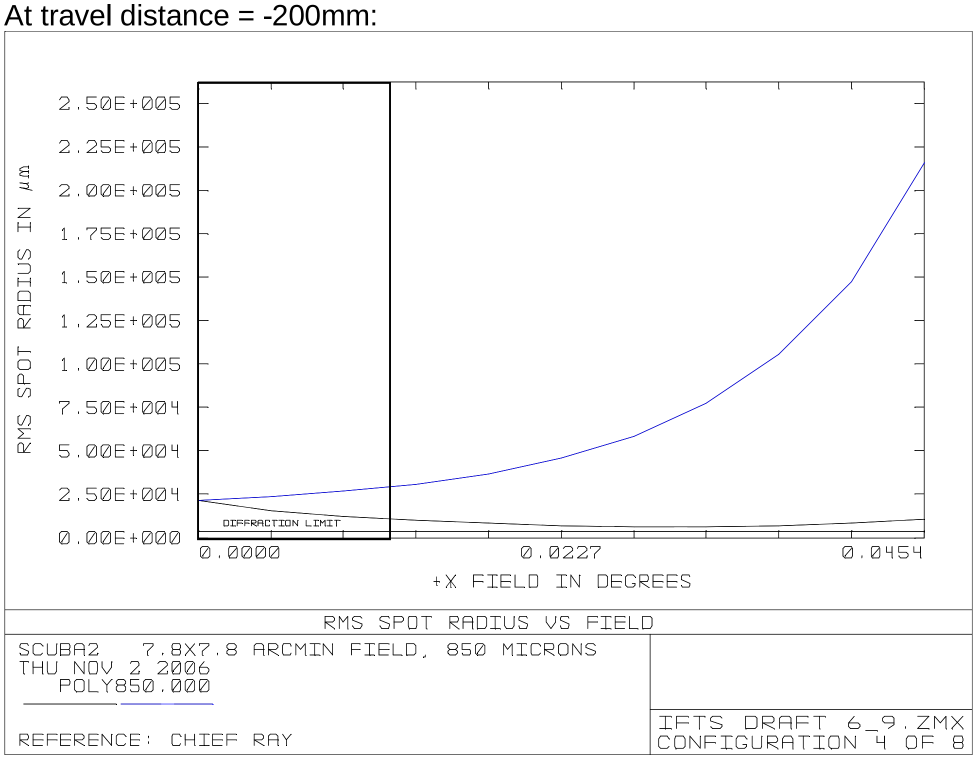
At travel distance = -100mm:



At travel distance = -150mm:



At travel distance = -200mm:



Superposition of spots from the two sides of the IFTS, vs. travel:

The coordinate transform between the non-FTS image and the FTS image is as follows.

Port 1 Angular field coordinates in Zemax

Field Point	Field number	X (degrees)	Y (degrees)
Optical axis	1	0	0
Port centre	3	-0.02876	-0.02876
Corners of 2' square around centre	2	-0.01209	-0.01209
	4	-0.01209	-0.04543
	5	-0.04543	-0.01209
	6	-0.04543	-0.04543

Port 2 Angular field coordinates in Zemax

Field Point	Field number	X (degrees)	Y (degrees)
Optical axis	1	0	0
Port centre	3	0.02876	-0.02876
Corners of 2' square around centre	2	0.01209	-0.01209
	4	0.01209	-0.04543
	5	0.04543	-0.01209
	6	0.04543	-0.04543

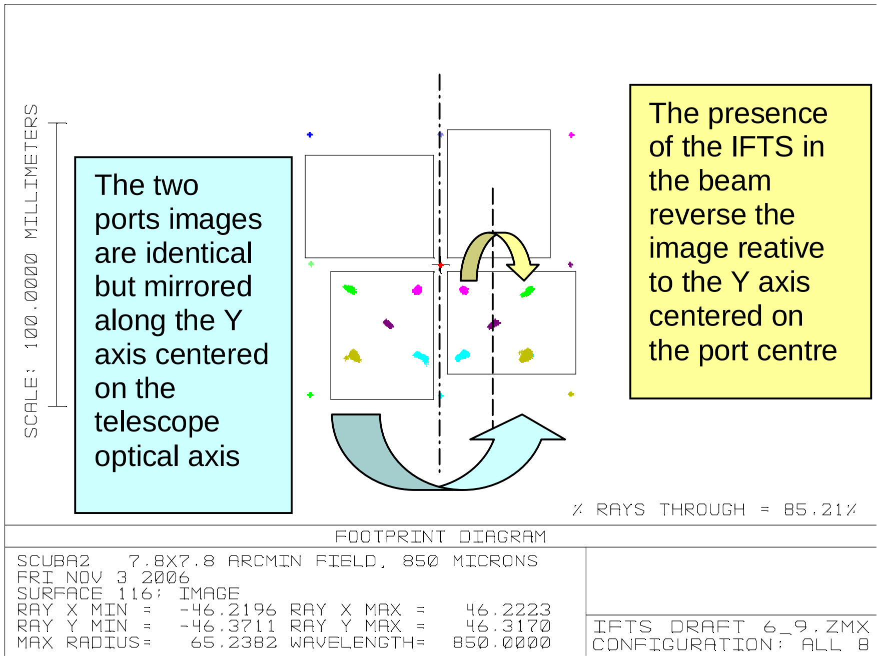
Field coordinates at the array for SCUBA-2 and corresponding field number for the IFTS port #1

Field Point	FTS-2 Field #	SCUBA-2 Field #	X (mm)	Y (mm)
Optical axis	1	1	0	0
Port centre	3	3	-20.0322947	-20.03077623
Corners of 2' square around centre	2	5	-31.7309996	-8.35864783
	4	6	-31.7105090	-32.0245799
	5	2	-8.42407491	-8.5458825
	6	4	-8.37725999	-32.2411558

Field coordinates at the array for SCUBA-2 and corresponding field number for the IFTS port #2

Field Point	FTS-2 Field #	SCUBA-2 Field #	X (mm)	Y (mm)
Optical axis	1	1	0	0
Port centre	3	3	20.0322947	-20.03077623
Corners of 2' square around centre	2	5	31.7309996	-8.35864783
	4	6	31.7105090	-32.0245799
	5	2	8.42407491	-8.5458825
	6	4	8.37725999	-32.2411558

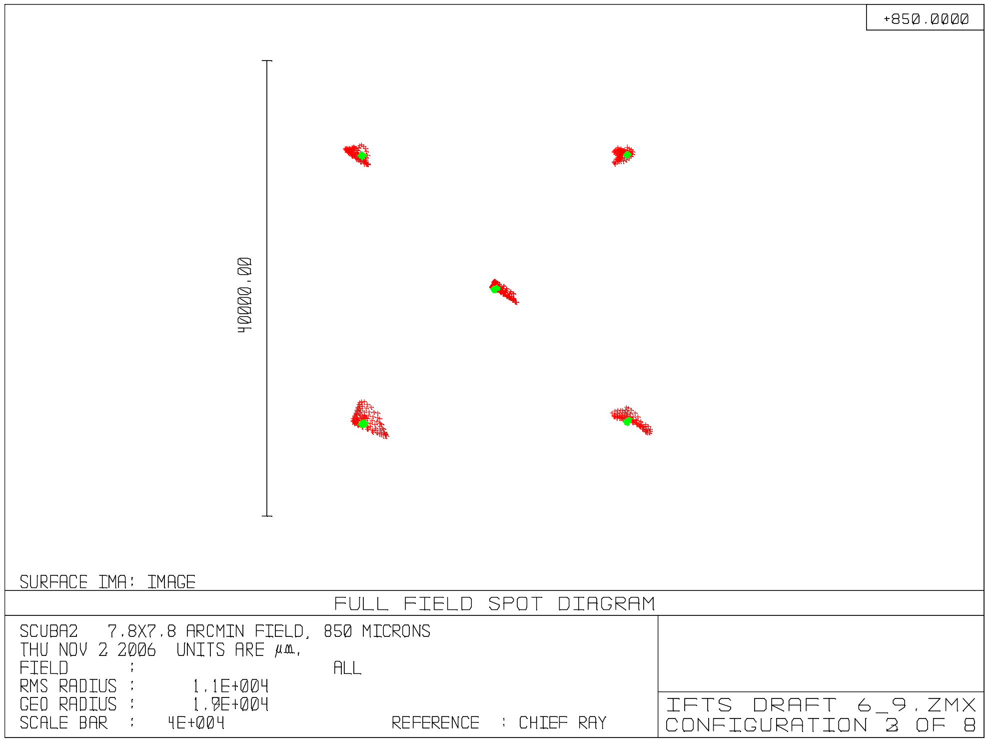
The image flip due to the presence of the IFTS is as follows.



At ZPD, the spots from the two sides of the IFTS are perfectly superimposed. The image is distorted and very slightly rotated relative to the image without the IFTS in the beam. The slight rotation is due to FM2_2 that is tilted horizontally along its Y to be able to get the output pick-off mirrors as close as possible to the input pick-off mirrors to limit the vignetting. This creates a slight rotation of the image at the image plane.

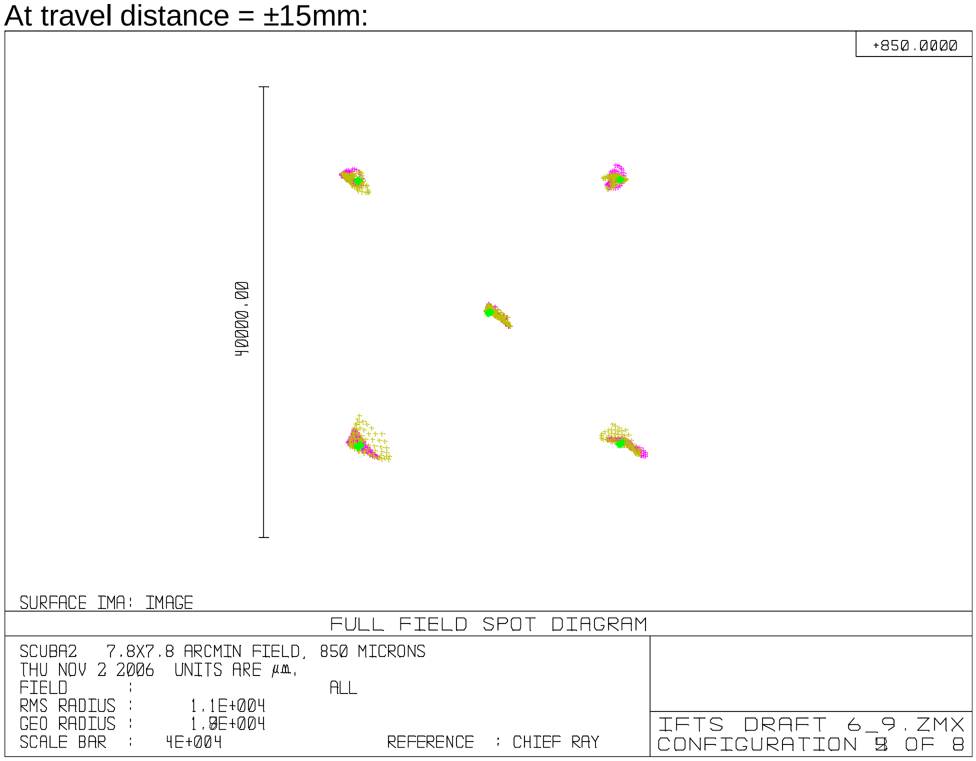
The spots without the IFTS in the beam are in light green, and the spots for the IFTS at ZPD are in red.

At ZPD:

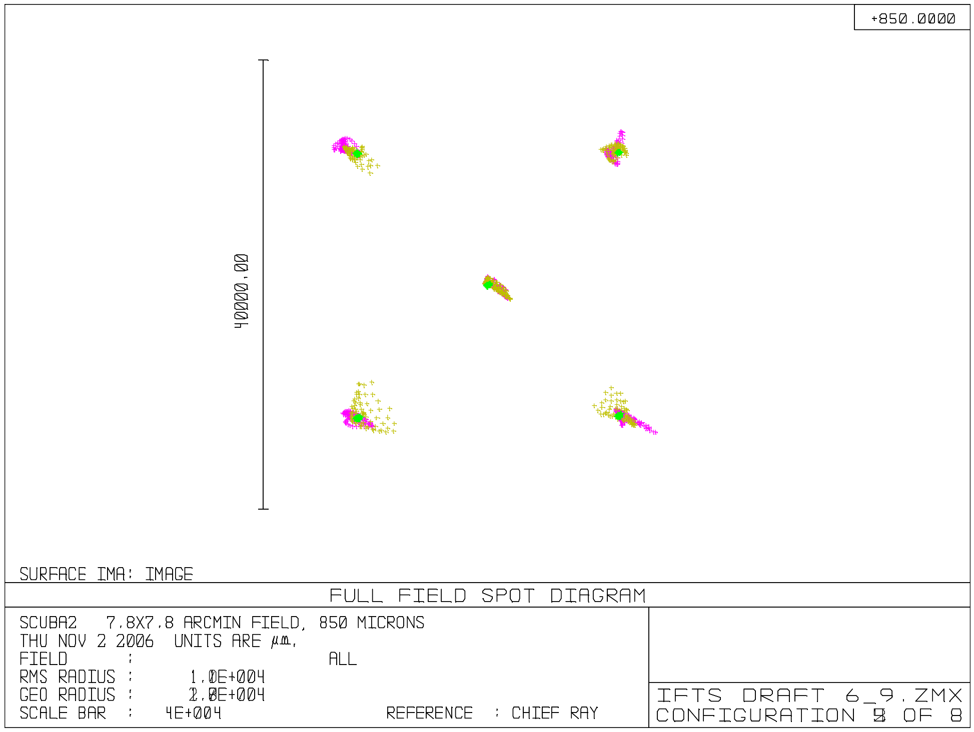


With increasing travel distance, the spots change size. The spots from the positive travel distance side of the IFTS are in pink, and those from the negative travel distance side of the IFTS are in khaki.

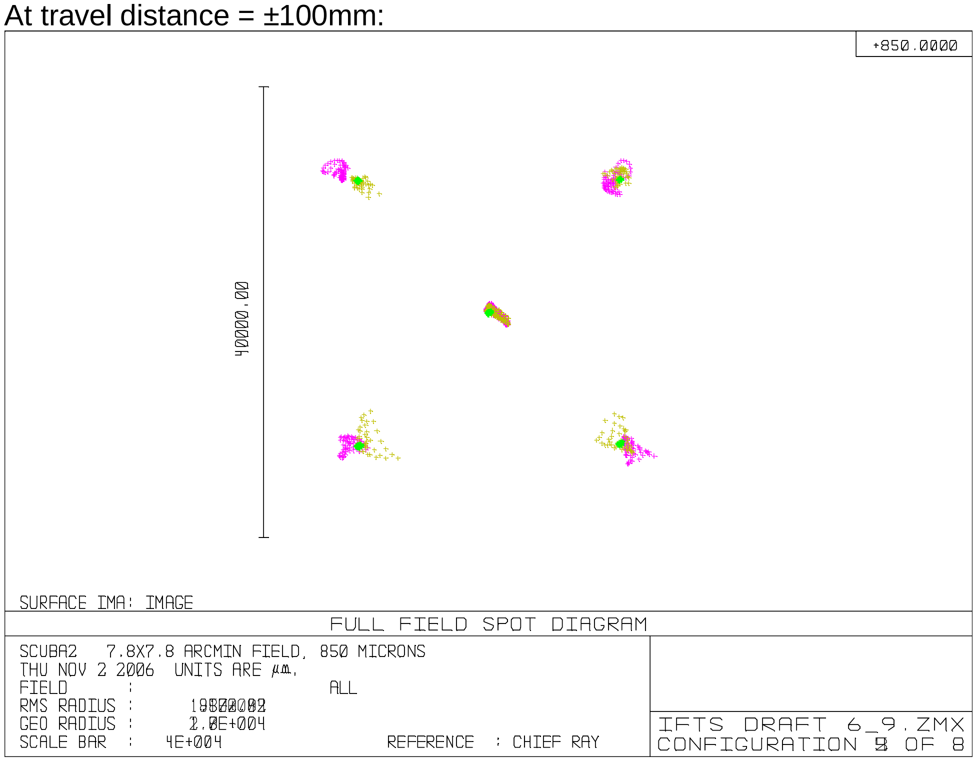
At travel distance = ±15mm:



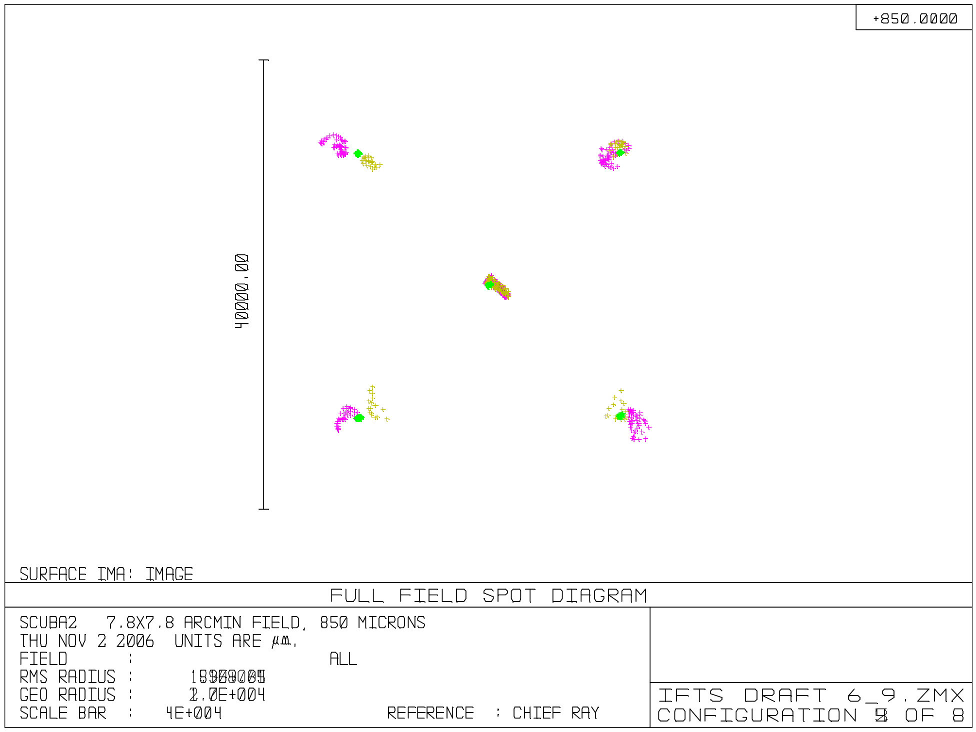
At travel distance = ±50mm:



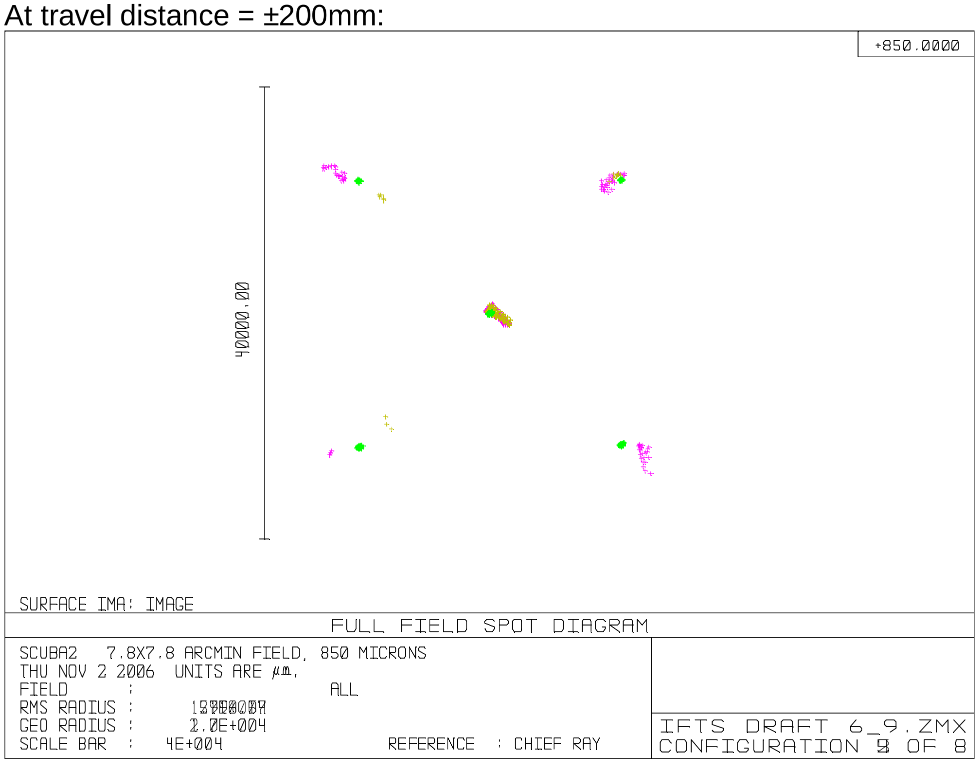
At travel distance = ±100mm:



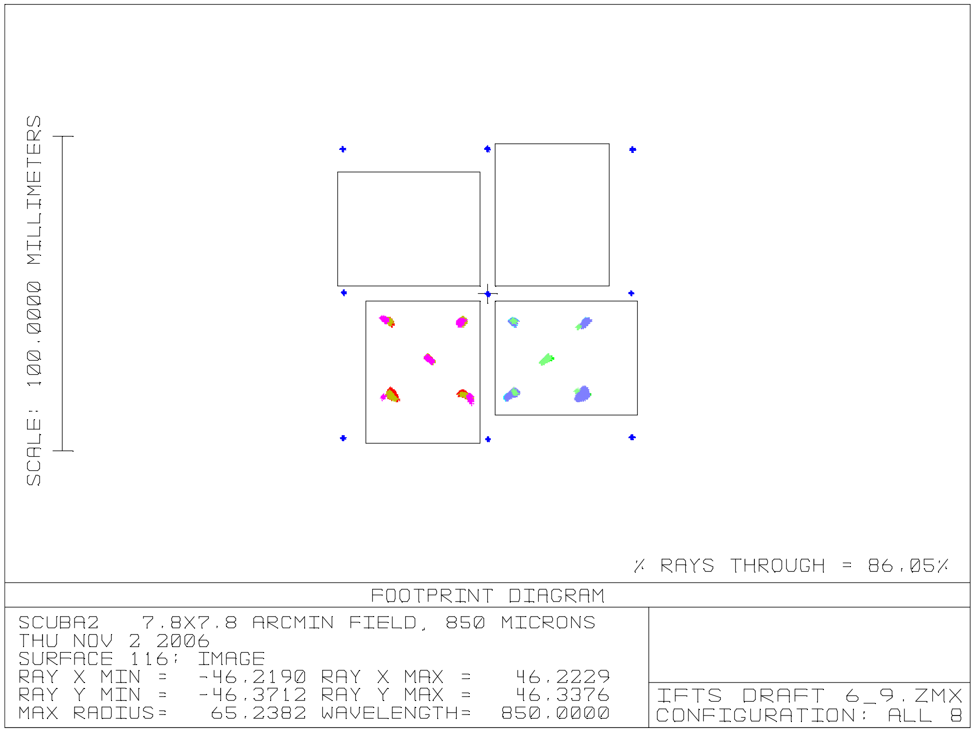
At travel distance = ±150mm:



At travel distance = ±200mm:



The total field of view of the telescope is compared with the field of view of each port of the IFTS in the graph below.



The impact is a gradual shift of the image with increasing travel distance.

Field coordinates at the array for SCUBA-2 and corresponding field number for the IFTS port #1

Field Point	FTS-2 Field #	SCUBA-2 Field #	X (mm)	Y (mm)
Optical axis	1	1	0	0
Port centre	3	3	-20.0322947	-20.03077623
Corners of 2' square around centre	2	5	-31.7309996	-8.35864783
	4	6	-31.7105090	-32.0245799
	5	2	-8.42407491	-8.5458825
	6	4	-8.37725999	-32.2411558

Field coordinates at the array for the IFTS port #1

Field (deg.)	Absolute travel distance (mm)	Shift between two interferograms (mm)	Magnification of image	Rotation of image	Coordinates of chief ray in image plane (mm)			
					Positive travel Distance		Negative travel distance	
					X	Y	X	Y
Central field #3 (-0.02876, 0.02876)	0	0.000			-19.235	-20.650	-19.235	-20.650
	15	0.005			-19.235	-20.647	-19.236	-20.652
	50	0.017			-19.233	-20.642	-19.238	-20.658
	100	0.034			-19.230	-20.634	-19.239	-20.667
	150	0.052			-19.227	-20.626	-19.240	-20.676
	200	0.069			-19.224	-20.619	-19.240	-20.686
Field #2 (-0.01209, 0.01209)	0	0.000			-32.082	-8.501	-32.082	-8.501
	15	0.311			-32.194	-8.474	-31.901	-8.579
	50	1.212			-32.257	-8.533	-31.145	-9.015
	100	3.596			-32.128	-8.664	-29.020	-10.473
	150	8.363			-32.186	-8.412	-25.337	-13.211
	200	16.664			-32.983	-7.219	-19.816	-17.433
Field #4 (-0.01209, 0.04543)	0	0.000			-31.039	-32.308	-31.039	-32.308
	15	0.822			-31.115	-32.266	-30.293	-32.292
	50	0.854			-31.227	-32.034	-30.381	-31.916
	100	3.502			-31.546	-31.723	-28.448	-30.090
	150	10.667			-32.500	-31.956	-23.893	-25.655
	200	27.854			-34.522	-33.286	-12.973	-15.637
Field #5 (-0.04543, 0.01209)	0	0.000			-8.041	-8.526	-8.041	-8.526
	15	0.380			-8.153	-8.703	-7.969	-8.371
	50	1.071			-8.505	-9.125	-8.011	-8.175
	100	0.915			-9.001	-9.458	-8.783	-8.569
	150	2.017			-9.068	-8.972	-10.680	-10.184
	200	8.713			-8.102	-6.990	-13.955	-13.444
Field #6 (-0.04543, 0.04543)	0	0.000			-7.364	-32.231	-7.364	-32.231
	15	0.209			-7.267	-32.216	-7.476	-32.216
	50	0.835			-7.042	-32.134	-7.864	-31.988
	100	2.789			-6.512	-32.150	-8.995	-30.879
	150	7.406			-5.425	-32.695	-11.341	-28.240
	200	16.554			-3.464	-34.150	-15.802	-23.113

2. Mirrors surfaces prescriptions

File : IFTS draft 5_3.zmx

Extended polynomial surfaces :

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{N} A_i E_i(x,y)$$

where : $c = \frac{1}{R}$

$E_1 = x$
$E_2 = y$
$E_3 = x^2$
$E_4 = x\,y$
$E_5 = y^2$
$E_6 = x^3$
$E_7 = x^2\,y$
$E_8 = x\,y^2$
$E_9 = y^3$

In configuration 3, on one « side » of the interferometer :

Surface #	42	51	64	74
Surface	FM2_1	FM1_3	FM1_4	FM2_2
R	-1239.387666	1135.457034	1188.090330	-1173.797759
k	-0.668826	2.379386	-2.367087	2.131911
A_1	0	0	0	0
A_2 *	0	0	0	0
A_3	-7.86e-6	5.161e-6	6.626e-6	1.945e-6
A_4 *	3.224e-6	1.407e-6	-2.32e-7	-9.79e-6
A_5	3.605e-6	-1.78e-6	8.613e-7	4.362e-6
A_6 *	3.080e-8	6.144e-8	-4.08e-9	-6.53e-8
A_7	-4.75e-8	3.706e-8	4.178e-8	-1.96e-7
A_8 *	3.608e-8	-2.47e-8	-4.99e-9	-2.22e-8
A_9	-4.48e-8	9.553e-9	1.434e-8	-2.49e-8

Pick-off mirrors and Corner cube mirrors surfaces are flat.

In configuration 6, on the other « side » of the interferometer :

Surface #	42	51	64	74
Surface	FM2_3	FM1_1	FM1_2	FM2_4
R	-1239.387666	1135.457034	1188.090330	-1173.797759
k	-0.668826	2.379386	-2.367087	2.131911
A_1	0	0	0	0
A_2 *	0	0	0	0
A_3	-7.86e-6	5.161e-6	6.626e-6	1.945e-6
A_4 *	-3.224e-6	-1.407e-6	2.32e-7	9.79e-6
A_5	3.605e-6	-1.78e-6	8.613e-7	4.362e-6
A_6 *	-3.080e-8	-6.144e-8	4.08e-9	6.53e-8
A_7	-4.75e-8	3.706e-8	4.178e-8	-1.96e-7
A_8 *	-3.608e-8	2.47e-8	4.99e-9	2.22e-8
A_9	-4.48e-8	9.553e-9	1.434e-8	-2.49e-8

* The sign is reversed for the equivalent mirror on the other side of the IFTS.

The aperture for each mirror has the following dimensions:

In configuration 3, on one « side » of the interferometer :

Surface #	Surface	Aperture size (mm)		Aperture decentre (mm)	
		Width (X)	Height (Y)	X *	Y
35	PO1	116	88	5	-4
42	FM2_1	250	260	25	-28
51	FM1_3	240	240	-4	10
57	CC1	270	106.066018		
57	CC2	270	84.569936		
57	CC3	210	150		
62	FM1_4	280	280	10	-5
72	FM2_2	310	340	-21	6
78	PO2	140	160	1	-15

Surface #	Surface	Aperture size (mm)	Aperture decentre (mm)	
		Diameter	X *	Y
46	BS1	120	6	-5
67	BS2	200	0	4

* The sign is reversed for the equivalent mirror on the other side of the IFTS.

In configuration 6, on the other « side » of the interferometer :

Surface #	Surface	Aperture size (mm)		Aperture decentre (mm)	
		Width (X)	Height (Y)	X *	Y
35	PO3	116	88	-5	-4
42	FM2_3	250	260	-25	-28
51	FM1_1	240	240	4	10
57	CC1’	270	106.066018		
57	CC2’	270	84.569936		
57	CC3’	210	150		
62	FM1_2	280	280	-10	-5
72	FM2_4	310	340	21	6
78	PO4	140	160	-1	-15

Surface #	Surface	Aperture size (mm)	Aperture decentre (mm)	
		Diameter	X *	Y
46	BS1	120	-6	-5
67	BS2	200	0	4

3. List of mechanical issues associated with mounting the optics

The choice of a cornercube instead of a rooftop will ease the alignment with the correct orientation relative to the travel direction, since it is symmetric in only one axis. If it is misaligned relative to the travel direction, the reflected beam will shift up/down with increasing travel distance.

The tolerance analysis showed that the folding mirrors tilt is a critical parameter.

4. Views and drawings of the IFTS for CDR presentation purposes

Files provided:

3. SCHEDULE

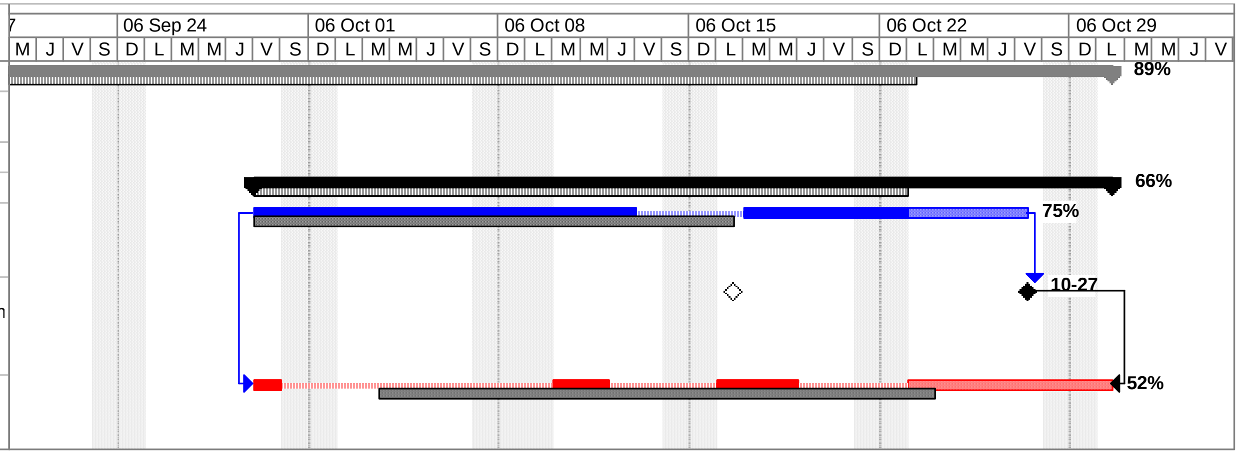
1. Project status (Total hours done / Final cost)

In the following table, we detail the time planned versus the time spent for the different tasks in the project, with associated costs.

N°		Index WBS	Etat FDT	Nom de la tâche	work (baseline)	work (done)	Cost
8		**P02**	✗	**Phase 2**	**65 hr**	**62.75 hr**	**7,404 $**
9		P02.3	✓	Simulation with hollow corner cubes	40 hr	55.75 hr	6,578 $
10		P02.2	✓	Assymetrical optimization for high resolution mode	20 hr	0 hr	0 $
11		P02.4	✓	Management / interaction with client	5 hr	7 hr	826 $

The Gantt chart below shows the baseline planning (grey) at the beginning of the project, compared with the real project calendar. Each task is listed and its realisation in time is detailed.

N°		Index WBS	Etat FDT	Nom de la tâche
0		**P**	✓	**060140.Publié**
1		P*	✗	Avis de démarrage de projet
2	✓	**P01**	✗	**Phase 1**
8		**P02**	✗	**Phase 2**
9		P02.3	✓	Simulation with hollow corner cubes
10		P02.2	✓	Assymetrical optimization for high resolution mode
11		P02.4	✓	Management / interaction with client



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INO-9000-FOR-136 ed00rev01

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