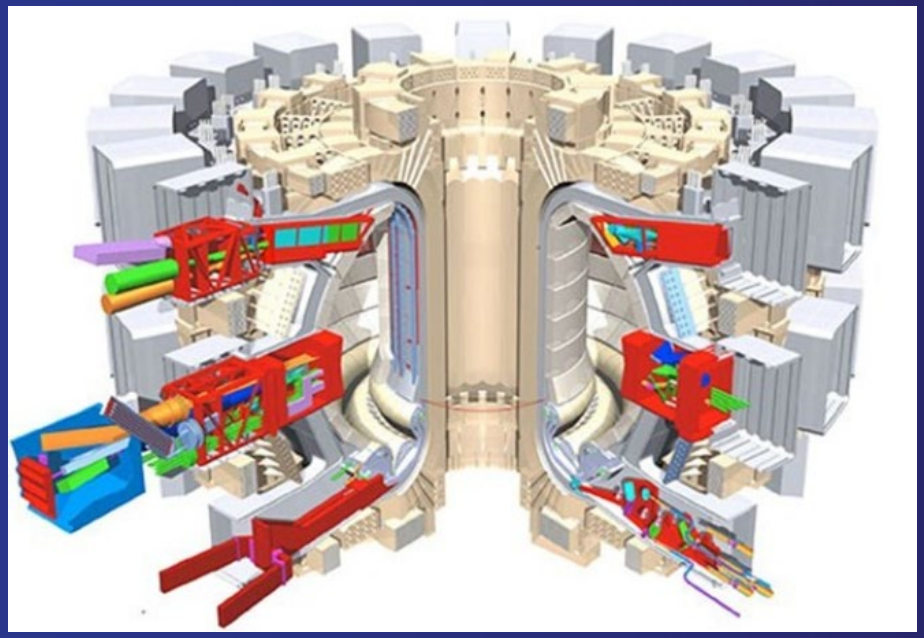
UWAVS Active Alignment

Overview and implementation of active alignment

2024-02-26
Version 1.2



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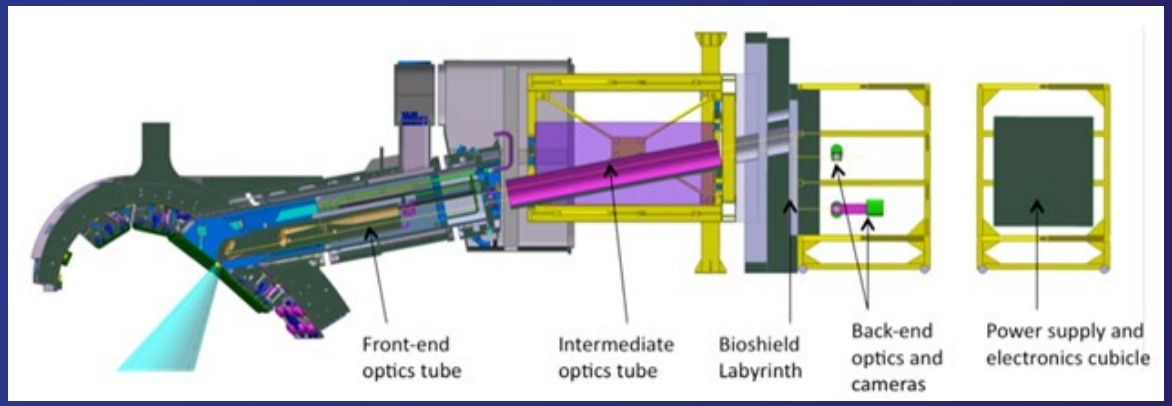


Change log

- **Version 1**
  - Initial version for 2017 UWAVS design
- **Version 1.1**
  - Updated for 2023 design
  - Complete compensator range assessment
- **For the version 1.2**
  - Latest mirror sizes applied
  - Footprints on mirrors updated
  - Vacuum vessel thermal deformations updated as defined in "ITER_Vacuum_Vessel_Load_Specification_2F52JY_v3_4.pdf"
  - Zemax diagrams updated to the latest design
  - Typos fixed
  - Explanations and conclusions added
  - I&C inputs added
  - Total required actuator ranges updated including tolerances and thermal deformations

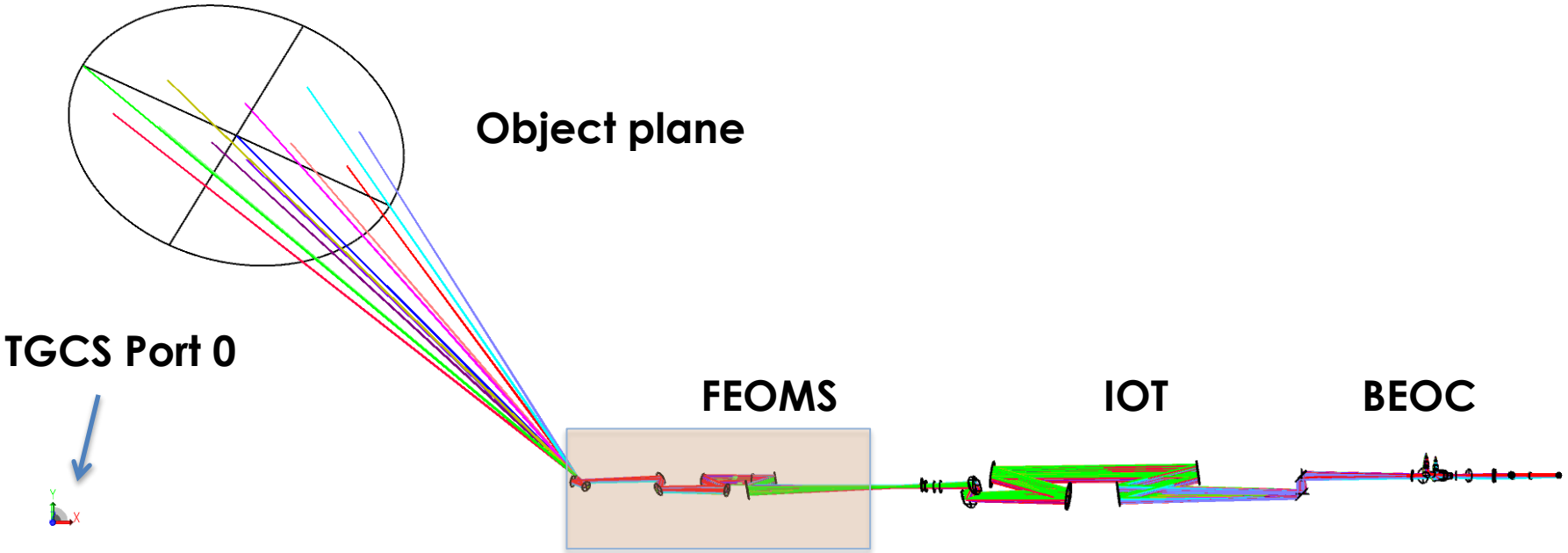
Approach

- **Optical design and analysis**
  - UWAVS system layout
  - Model build-up

  (Reference CAD Model: 0000168113_IOT_SUBSYS_REV_A144_20231117.stp)
- **Targeted outcome of the analysis**
  - Compensators for Active alignment
    - A40 mirrors compensate vessel deformation
    - Visible camera focusing compensate differences visible & IR
  - Footprint on A40 mirrors
- **Applied cases for analysis**
  1. Mechanical Tolerances
  2. Operational thermal deformations (FEOMS-70C,IOT-52C, BEOC-37C)
  3. Vacuum Vessel Thermal deformation
  4. Rotation point of A40 actuators effect
  5. Thermal expansion of ISS and PCSS included in thermal analysis. (vertical expansions are not included only expansion in TGCS port 0 x-direction;)
- **Conclusion**

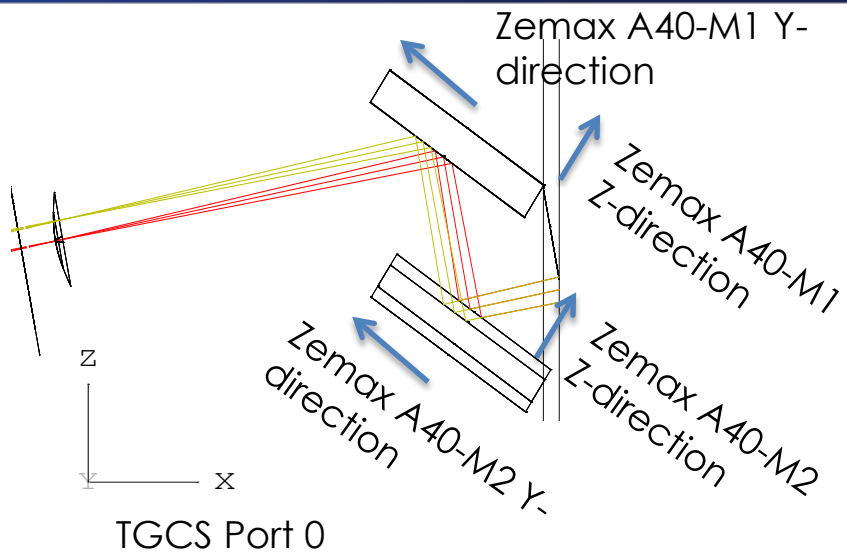
WAVS System Description & analysis

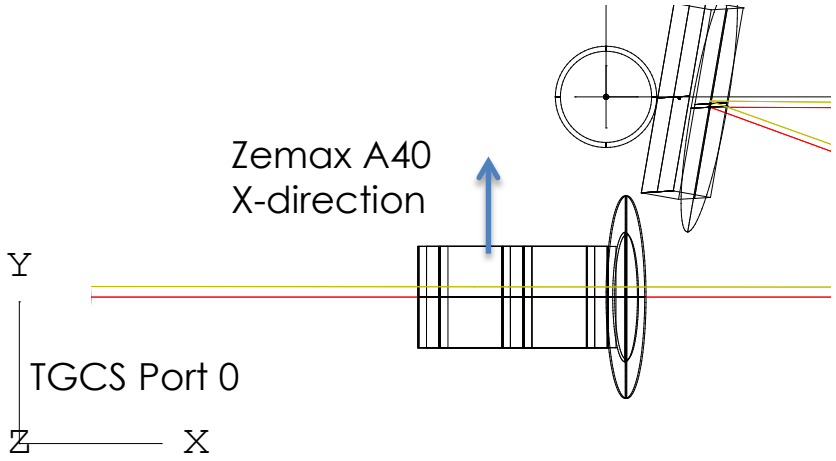
- **Total WAVS system from tokomak to detectors | Top View**



Coordinate systems

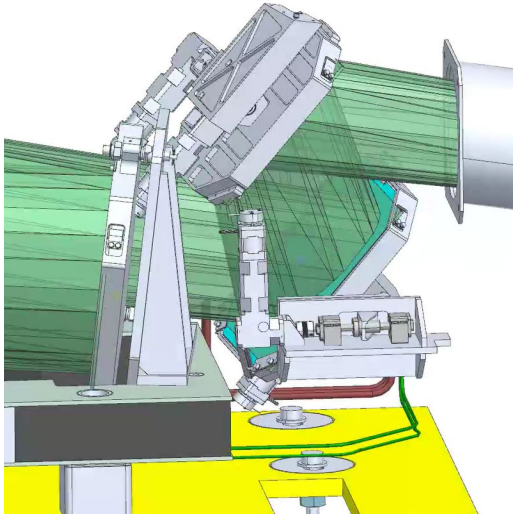
- **ITER coordinates**
  - X: radial outwards
  - Y: Tangential
  - Z: Up
- **Footprint diagrams**
  - X: ITER Y-direction
  - Y: Combined up and Radial inward (-X+Z)
  - Z: Out of plane

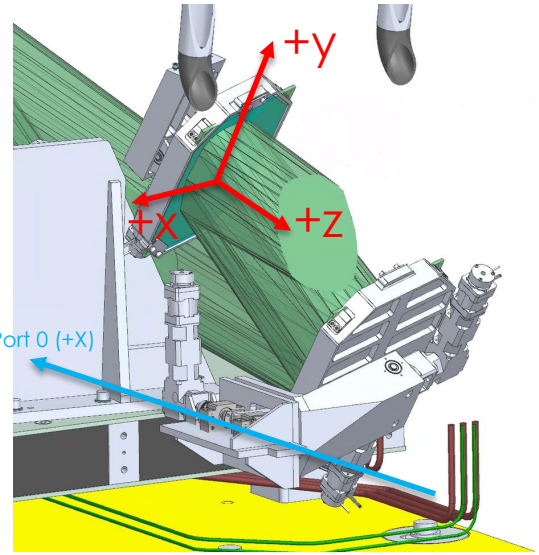




Active alignment system (A40)

- **A40-M1**
  - 2 rotational actuator for tip-tilt
- **A40-M2**
  - 2 rotational actuator for tip-tilt and a piston for focus
- **Input for alignment**
  - Object recognition
  - Contrast measurement
  - Focus adjustment requires focus variation
- **Bandwidth ~1Hz maximum**
  - Thermal deformation
  - Mechanical additional deformation ➔ requires image processing





Outputs

- **Actuator Range, Resolution**
- **Footprints on mirror**
  - (Image spot size)
- **Input for I & C**
- **Analysis considers**
  - **Tolerances**
    - Updated optical analysis 'ITER_Modules_Tolerance_Simulations.pptx (26feb2024)' is implemented.
  - Thermal Loads
    - In Vessel-STOP Analysis (FEOMS-70°C)
    - Ex-Vessel-Zemax Thermal Analysis (IOT-52°C, BEOC-37°C)
    - Vacuum Vessel Deformation
    - ISS and PCSS translational thermal expansions
  - Actuator Rotation Axis Position Effect

Tolerance Analysis

- **Tolerance Analysis**
  - Both versions 'UWAVS-2 Tolerance simulations results 220719_TNO_DanielPerez.pptx'and 'ITER final tolerance analysis_ 12.02.2024' are included
- **Impact on actuation ranges**
  - There is sufficient ROM of A40-M1 X-tilt, A40-M2 X-tilt, A40-M2 Y-tilt, A40-M2 piston actuators (see slide 18)
- **Impact on foot print shift A40**
  - No vignetting on footprints

Tolerance Impact on Actuator Ranges

Compensator		Units	Min	98% low	Max	98% high	mean	stdv	Available range
	Y tilt	degrees	**-1.3254**	0.004223	**2.546236**	1.854753	0.588114	0.6546553	5.22
A40-M1	**X tilt**	degrees	**-1.9845**	-0.68276	**2.604715**	1.443777	-0.06407	0.7304201	3.7
	Piston	mm	**-6.08791**	-0.96438	**7.742676**	4.697364	0.876701	2.01205952	15
	X tilt	degrees	**-2.81835**	-0.69501	**2.901408**	1.788263	0.027606	0.87297941	3.14
A40-M2	**Y tilt**	degrees	**-1.8338**	0.075292	**2.821218**	2.209903	0.730273	0.74945417	4.69
	Y tilt	degrees	**-0.16629**	-0.05589	**0.160833**	0.106592	-0.00295	0.05853455	1.94
A50-M1	**X tilt**	degrees	**-0.10829**	-0.03328	**0.118552**	0.082719	0.002184	0.03978978	1.33
	Y tilt	degrees	**-0.15355**	-0.04594	**0.151834**	0.113235	0.004145	0.05677884	1.94
A50-M2	**X tilt**	degrees	**-0.09606**	-0.03016	**0.094479**	0.067514	-0.00155	0.0342215	1.3
	Y tilt	degrees	**-0.10939**	-0.04549	**0.1208**	0.092831	-0.00143	0.04666847	1.84
A50-M3	**X tilt**	degrees	**-0.08337**	-0.03242	**0.099714**	0.072985	-0.00211	0.03604686	1.43
	Y tilt	degrees	**-1.26972**	-0.70777	**1.319753**	1.173318	0.007774	0.69968484	1.8
A50-M4	**X tilt**	degrees	**-0.82323**	-0.41693	**0.866937**	0.808432	0.065798	0.46284538	1.4
	Y tilt	degrees	**-2.48614**	-0.6575	**2.887421**	1.978848	0.058014	0.86801671	9.0
A60-M1	**X tilt**	degrees	**-2.39919**	-0.91542	**1.66649**	1.217556	-0.30318	0.71162183	7.0
	Y tilt	degrees	**-2.55201**	-0.67461	**3.120407**	2.067978	0.087887	0.90843898	9.0
	X tilt	degrees	**-2.60459**	-0.98266	**1.981503**	1.369765	-0.30993	0.80677767	7.0
A60-M2	**Z piston**	mm	**-15.1979**	-6.09967	**8.484126**	4.718663	-3.1014	3.63725338	NA
Camera	**focus**	mm	**-0.03916**	-0.03733	**-0.03489**	-0.0359	-0.03691	0.00055142	NA

Tolerance Impact on A40 Mirrors Footprints

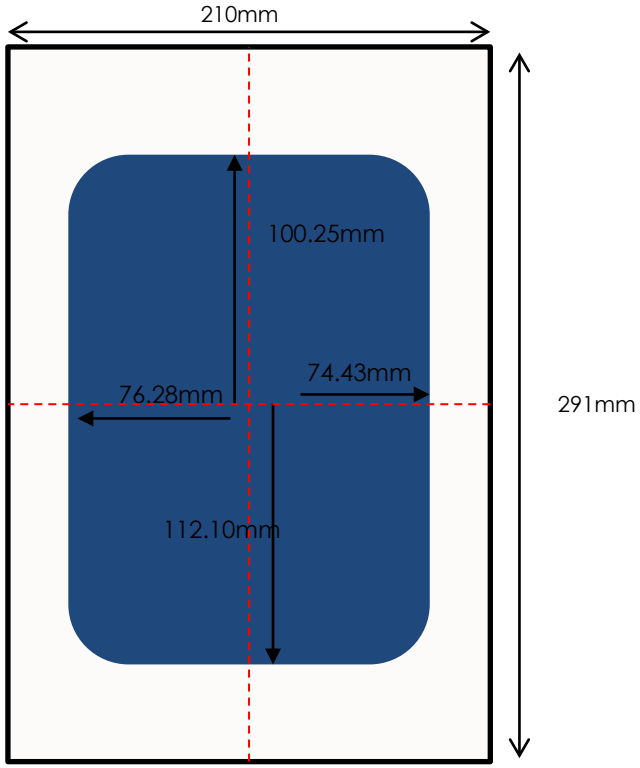
- On MC simulations for the system, the footprints on the A40 mirrors have been measured.
- The procedure is to use the merit function to find the extreme rays positions on the A40-M1 and A40-M2 and compare them with the nominal.

	A40-M1				A40-M2				
	X max	X min	Y max	Y min	X max	X min	Y max	Y min	Units
Nominal	74.43	-76.28	100.25	-112.10	86.84	-89.73	114.09	-125.21	mm
Full	93.021	-85.868	105.22	-117.85	91.175	-114.52	117.37	-145.11	mm

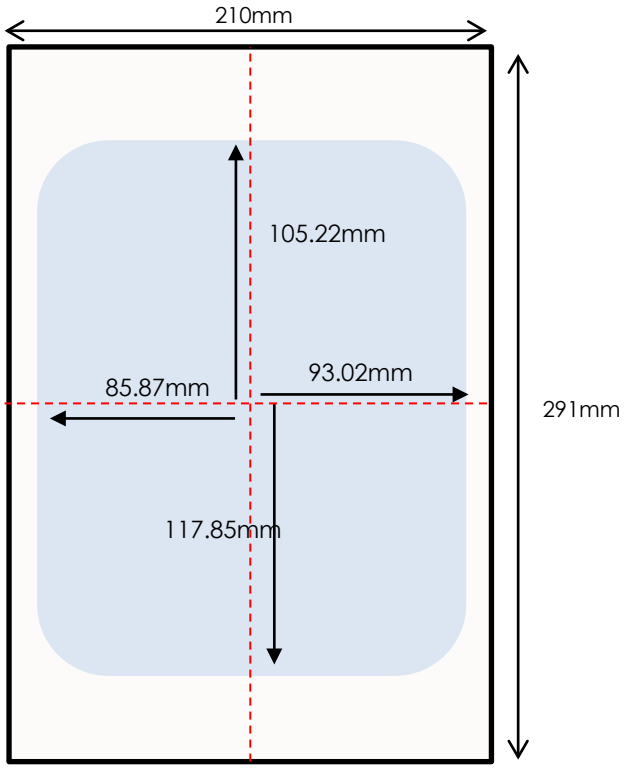
Tolerance Impact on A40 Footprint-Graphical results

A40-M1

Nominal footprint on A40-M1



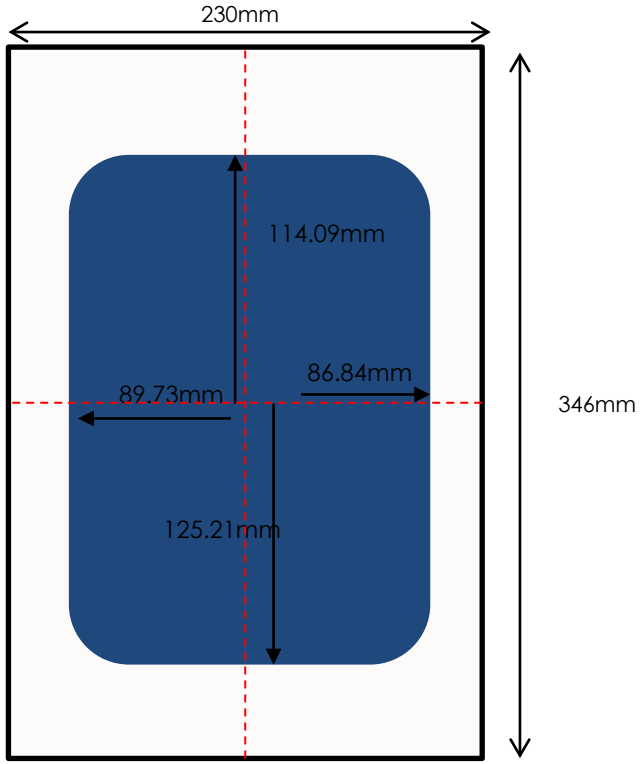
Max. footprint on A40-M1 after tolerances



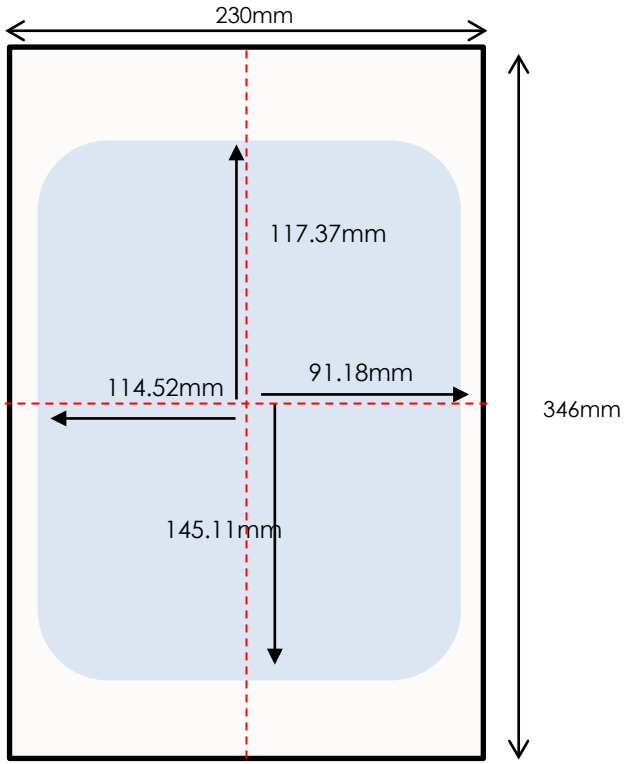
Tolerance Impact on A40 Footprint-Graphical results

A40-M2

Nominal footprint on A40-M2



Max. footprint on A40-M2 after tolerances

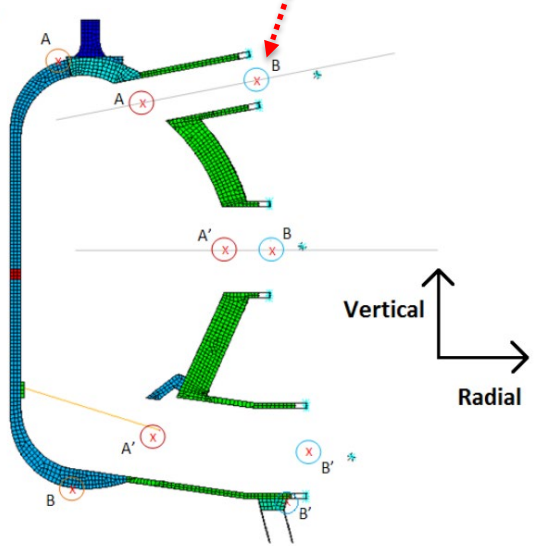


Thermal Loads-Overview

- **The following element thermal and mechanical deformations have been simulated:**
  - Effect of Vessel expansion on UPP position
  - Thermal and mechanical deformations of the FEOMS from the STOP analysis
  - Simple Thermal simulations of IOT. IOT at 52°C
  - Simple Thermal simulations of BEOC. BEOC at 37°C
- **The following elements are not considered:**
  - ISS and PCSS thermal expansion (in z-direction, upwards)
  - Full STOP analysis of IOT and BEOC
- **Simulations were performed for IR-1 channel**
- **Output of the simulations are:**
  - Image quality for complete system
  - A40-M1 & A40-M2 tip/tilt compensation range
  - A40-M2 focal compensation range

Thermal Loads-Vessel displacement

- **Deformation of the vessel induces the following displacements of the UP-B point:**
  - Radial: 14,8 mm
  - Vertical: 21,9 mm
- **All results are for the IR-1 channel**
- **Vessel deformation is simulated by displacements of all the optical elements after the FEOMS in radial and vertical directions according to the ITER system of reference.**



[34] VV_360°_Global_Thermal-Structural_Analys_6VWFN3_v1_5.pdf

11.8.2 ***Relative Displacements***

Table 11-36 Relative displacements [mm] at the upper, equatorial and lower cryostat bellows due to different load cases, note the effect of gravity is not considered in all load cases (relative to the interface VV Gravity Support/Cryostat Pedestal ring).

Load case	Port level	u_{rad}	u_{tor}	u_{vert}
Normal Operating* @ 100°C (from [34])	Lower	16.82	0	7.04
	Equatorial	15.40	0	15.06
	Upper	14.8	0	21.9
Baking* @ 200°C (from [34])	Lower	39.48	0	17.61
	Equatorial	36.16	0	36.46
	Upper	34.58	0	52.48
VDEII† (from [19] with scaling factor VDEII=0.54*VDEIII)	Lower	±9.17	±5.22	±2.54
	Equatorial	±11.29	±9.53	±7.85
	Upper	±12.96	±11.74	±4.16
VDEIII† (from [19])	Lower	±16.96	±9.65	±4.68
	Equatorial	±20.88	±17.61	±14.51
	Upper	±24	±21.73	±7.69
SL-2‡ (from [3])	Lower	±6.53	±3.83	±1.97
	Equatorial	±6.05	±5.6	±10.13
	Upper	±7.87	±5.75	±11.17
SMHV‡ (from [3])	Lower	±4.78	±2.8	±1.44
	Equatorial	±4.43	±4.1	±7.4
	Upper	±5.75	±4.2	±8.15
SL-1‡ (from [3])	Lower	±2.23	±1.32	±0.68
	Equatorial	±2.07	±1.92	±3.45
	Upper	±2.68	±1.97	±3.8

* Note that the specified values are calculated in [34] and increased with an analysis uncertainty factor of 1.2 and does not take into account the probable thermal expansion from port extensions and connecting ducts.
† Note that the specified values are calculated in [19] and increased with an analysis uncertainty factor of 1.2 combined with a factor of 1.5 in order to obtain design values.
‡ Note that the factor of 1.25 to take into account the possible changes on the Building and Tokamak design is applied.

ITER_Vacuum_Vessel_Load_Specification_2F52JY_v3_4.pdf

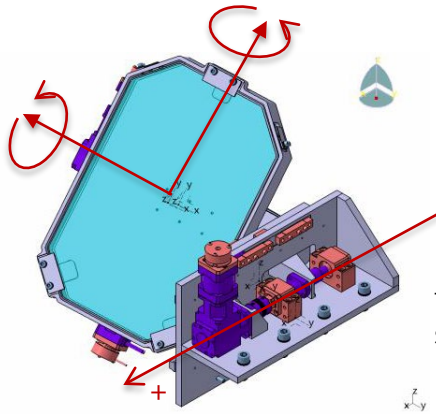
Thermal Loads-Overview: STOP and thermal analysis

- **STOP analysis data uses the data provided by GA.**
  - It is limited to the FEOMS
- **For the IOT and BEOC, Zemax thermal analysis was implemented.**
  - It assumes uniform elements deformation for uniform temperatures
  - With respect to the front of the ISS/PCSS
  - No vertical mechanical deformations were considered for IOT and BEOC.
    - This might reduce the required actuator focus range by ~1mm
    - This might reduce the required A40-M1 y-dimension by ~1.4mm

Thermal Loads-Compensation

- **Compensation is for the following performance elements:**
  - Central field spot position on sensor
  - Full field spot size
- **Compensators are:**
  - Tip/tilt of A40-M1 & A40-M2 with respect its optical surface
  - A40-M2 focal displacement with respect a plane located on the ITER system of reference horizontal (TGCS Port 0)

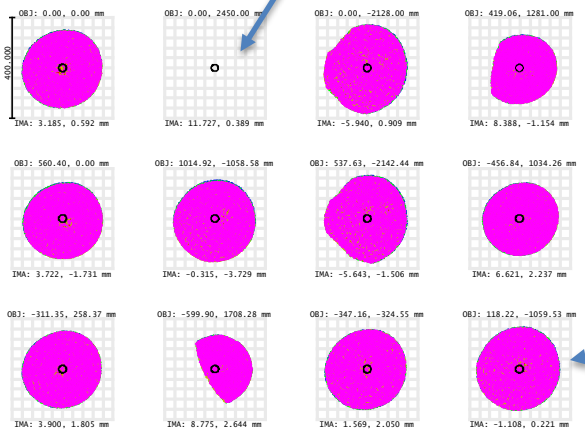
Tip/tilt rotation axis

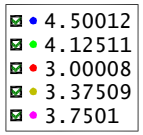


Focus compensation (zemax axis direction, TGCS-port 0 has opposite sign)

Thermal Loads-Image displacement and spot size
no compensation

Spot lost/vignetted





Spot sizes increases

Central field spot displacement	IR-1 channel
Spot X position (on camera)	2.87mm
Spot Y position (on camera)	0.36mm

Surface: IMA

Spot Diagram

SS.CA UWAVS, 19/12/2023
Units are µm. Airy Radius: 15.149µm. Legend items refer to Wavelengths

Field	1	2	3	4	5	6	7	8	9	10	11	12
RMS radius :	109.908	0.000	118.840	95.906	108.372	113.312	116.338	103.108	108.427	94.569	112.240	115.576
GEO radius :	161.937	0.000	178.376	147.246	159.627	170.873	175.657	153.276	160.338	145.152	167.601	169.424
Scale bar :	400.000	Reference : Chief Ray										

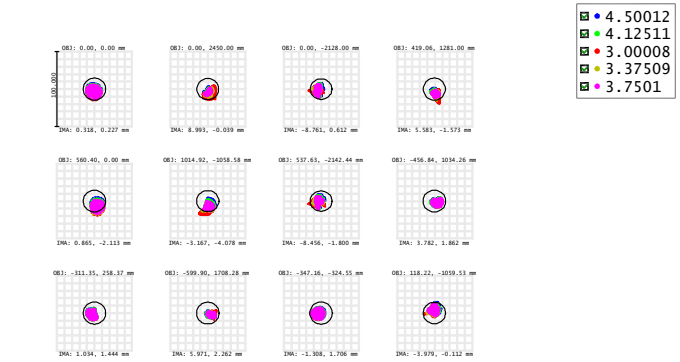
Zemax
Zemax OpticStudio 22.2

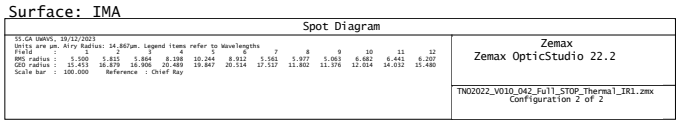
TNO2022_V010_042_Full_STOP_Thermal_IR1.zmx
Configuration 2 of 2

Spot sizes on vis 1 camera for Important defocus on the system

Without alignment compensation imaging resolution is degraded too much

Thermal Loads-Image displacement and spot size
Compensation





Spot size and positions have the same values as the ones with the system without displacement

Light that crosses the Vacuum window. 99.94% light crosses. **This value will be reduced after tolerances**

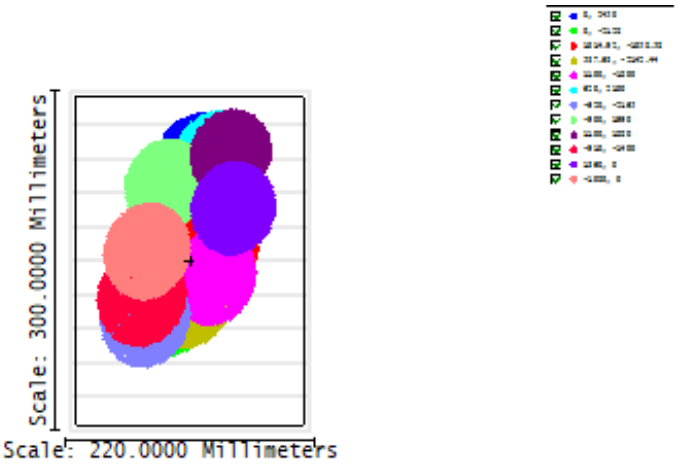
	Mirror coord. (tilt) TGCS x direction (focus)		Actuator movement	
Compensator	Value		Value	
	degrees	mrad	degrees	mrad
A40-M1 X tilt	-0,0177	-0,31	-0,0177	-0,31
A40-M1 Y tilt	-1,338	-23,35	-1,338	-23,35
A40-M2 X tilt	0,0133	0,23	0,0133	0,23
A40-M2 Y tilt	-1,249	-21,80	-1,249	-21,80
A40-M2 focus	-19,20 mm		-19,20 mm	

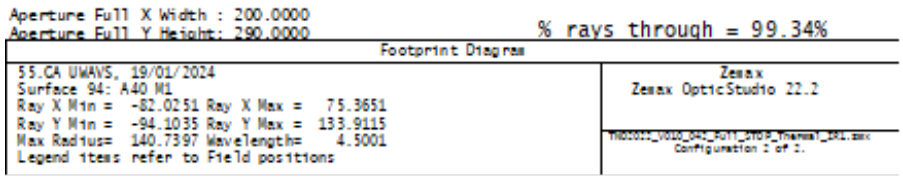
Actuator tip & tilt coordinates are aligned with Zemax local coordinates to simplify data interpretation

Actuator-Range of motions	Rx (mrad)	Ry (mrad)	Dz (mm)
A40-M1	+/- 31	+/- 46	+/- 15
A40-M2	+/- 27	+/- 41	

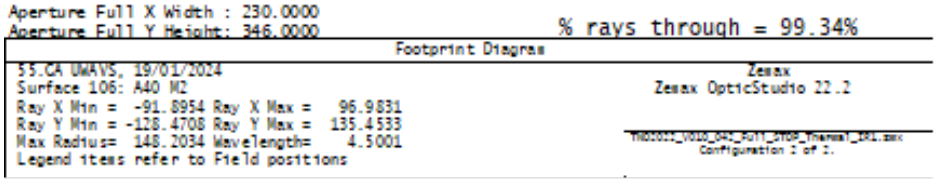
- Not enough range for focus compensation to start from the center of the adjustment range (ROM (-/+ 15 mm),-19,20 is needed
- Tilt actuators has sufficient ROM

Thermal Loads-Footprint on A40 mirrors-updated





A40-M1 footprint

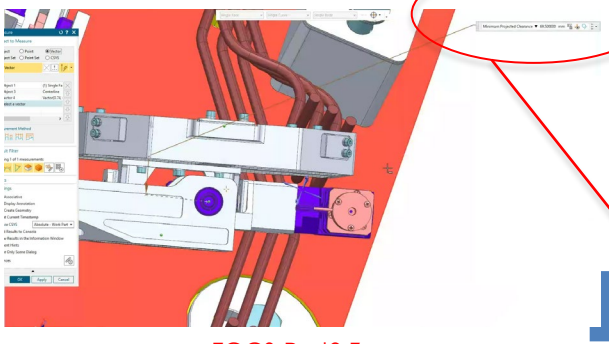


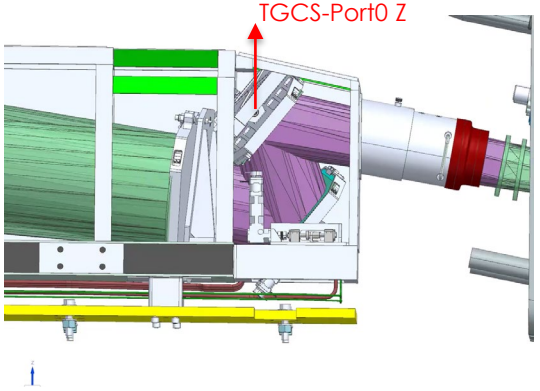
A40-M2 footprint

No vignetting due to load induced beam shifts

Mirror dimensions reference: A40 Mirror Size Notes 20240111.pptx

Tip/tilt actuators Rotation axis





Tip tilt of A40-M1/M2:

- rotation point is ~69,5 mm behind mirror,
- the mirrors shift downwards (along –Z direction)
- Piston shift is negligible

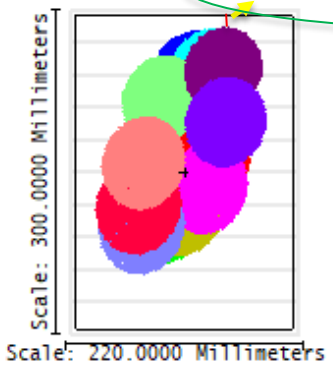
Rotation axis position effect

	Distance to rotation axis (mm)	max. ROM-actuator (rad)	Distance dz (mm) (TGCS-port0)
A40-M1	69,5	0,046	3,20
A40-M2	69,5	0,041	2,85

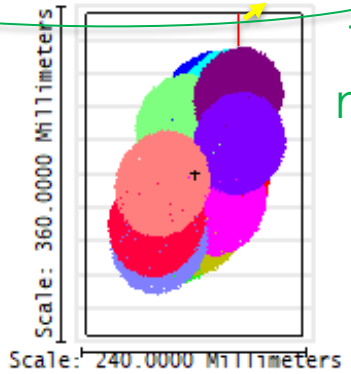
Margin needed in the upper side of footprints of the mirrors

16,09 mm

44,55 mm



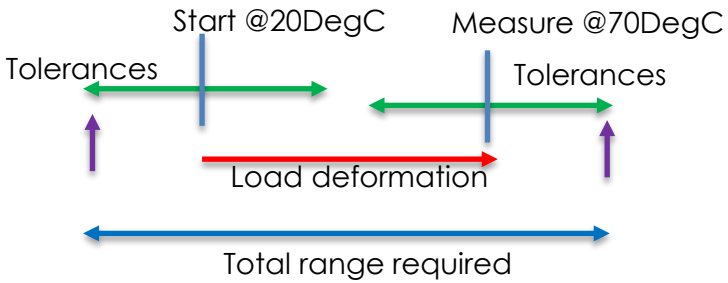
A40-M1 footprint



A40-M2 footprint

There is sufficient margin on mirrror size

Actuator Range summary



Overview	A40-M1		A40-M2		
Cooordinates	ZLCS	ZLCS	TGCS Port 0	ZLCS	ZLCS
	Rx (mrad)	Ry (mrad)	dz (mm)	Rx (mrad)	Ry (mrad)
STOP IOT-zemax temp analysis (52 C) BEOC-zemax temp analysis (37 C) Vacuum vessel deformation	-0,31	-23,35	-19,20	0,23	-21,80
Tolerances (-)direction (UWAVS-2 Tolerance simulations results 220719_TNO_DanielPerez.pptx)	-14,24	-18,45	no piston in the old design	-9,69	-4,38
Tolerances (+)direction (UWAVS-2 Tolerance simulations results 220719_TNO_DanielPerez.pptx)	10,68	11,66		11,52	7,28
Tolerances (-)direction, %98 (55.GA UWAVS final tolerance analysis_Feb2024)	-25,20	-32,37	-4,70	-31,21	-38,57
Tolerances (+) direction, %98 (55.GA UWAVS final tolerance analysis_Feb2024)	25,20	32,37	4,70	31,21	38,57
Total range required : Thermal + tolerances (55.GA UWAVS final tolerance analysis_Feb2024)	50,71	88,10	28,60	62,65	98,94
TOTAL Range provided by A40 actuators	128,00	182,00	30,00	108,00	162,00

Red indicates there is not sufficient ROM in one direction
Green indicates there is sufficient ROM in one direction

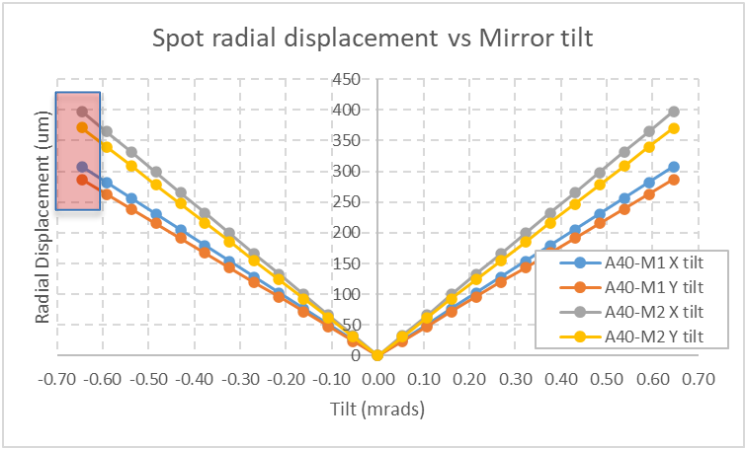
A40 mirrors tilt resolution analysis

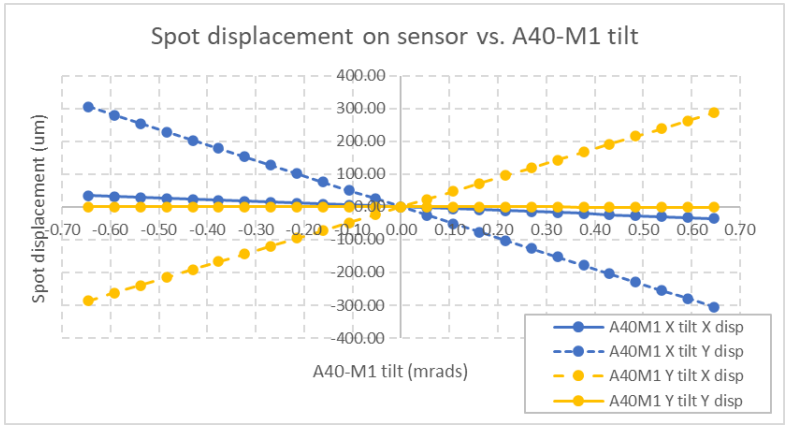
- **Simulations on the tip-tilt A40 alignment mirrors resolution**
  - Performance evaluated in channel vis-1
  - Nominal resolution is defined as +/-0.65 mrads
- **Impact**
  - Spot size is not affected significantly
  - Large impact on image location on sensor (~74pixels shift)
- **Recommendation**
  - Reduce A40 tip-tilt adjustment resolution to improve image position control on the camera

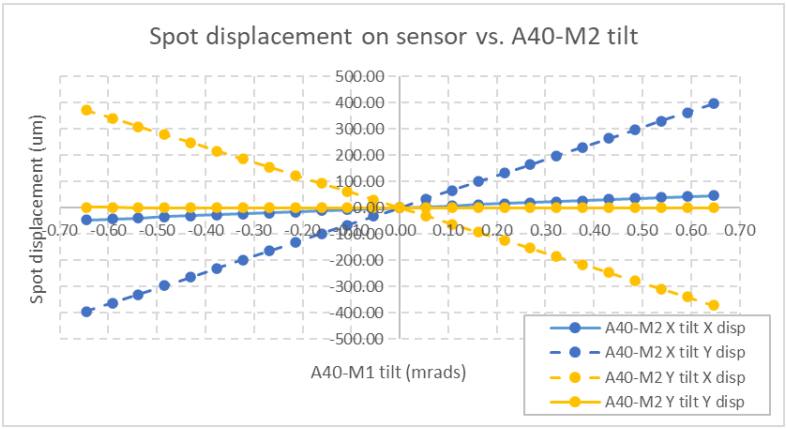
A40 mirrors sensitivity to tip/tilt resolution

- **Tip/tilt on A40 components causes a spot displacement of 270-400 microns. That implies 74 pixels displacement for a single mirror resolution (on vis-1)**

Better resolution is needed in order to have subpixel displacement



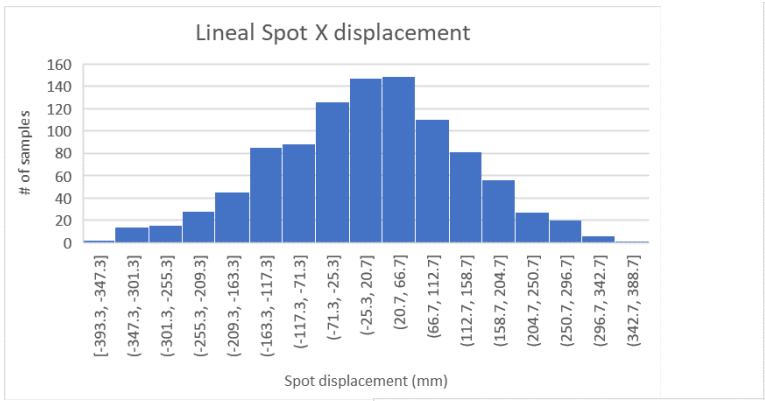


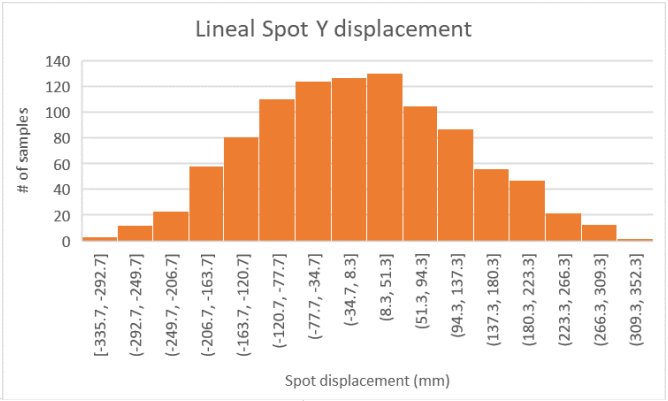


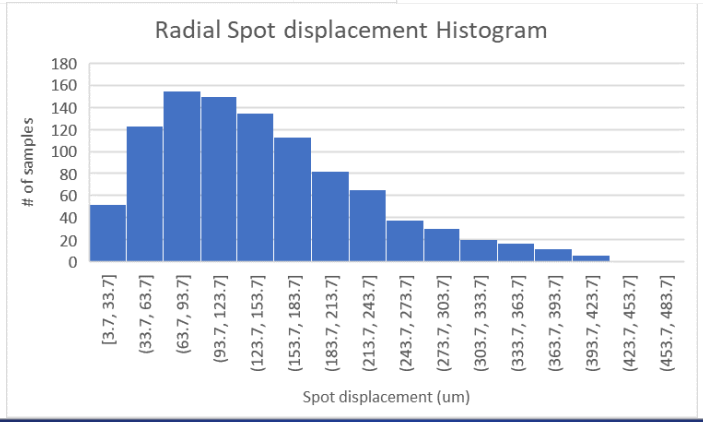
Targeted resolutions for A40 actuators	
Tilt actuators	<0,008 mrad
Piston	<0,045 mm

A40 mirrors resolution – Impact of adjustment on imaging resolution

- **Large adjustment steps in A40 adjustment result in sub-optimal imaging quality**
- **Analysis performed:**
  - Monte Carlo simulations have been performed to evaluate the effect of the combined tilt on the image position
  - Outcome of the simulations is the spot displacement on X and Y axis.
  - For 95% of the cases, combination of tilts causes a radial spot displacement of 320 microns or less.







Input for I &C -Active Alignment Process Flow

- Active alignment takes place during the operation
- Active alignment process needs some inputs from previous alignment & integration and calibration steps
- **These inputs are :**
  - As-built position of mirrors (Integration and alignment)
  - Lookup tables (T_{20} and T_{70} temperature alignment)
  - As-built position of A40 mirrors (T_{20} and T_{70} temperature alignment)
  - Tokamak map (model)
  - Wall to Pixel mapping (calibration)

Input for I &C -Active Alignment Process Flow

Alignment and Integration

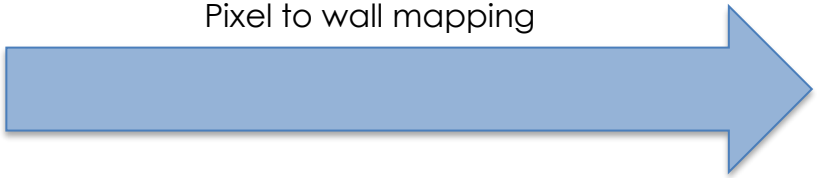
- Factory
- PIF
- Port Cell

Alignment

- T_{20} alignment
- Pupil alignment
- T_{70} alignment

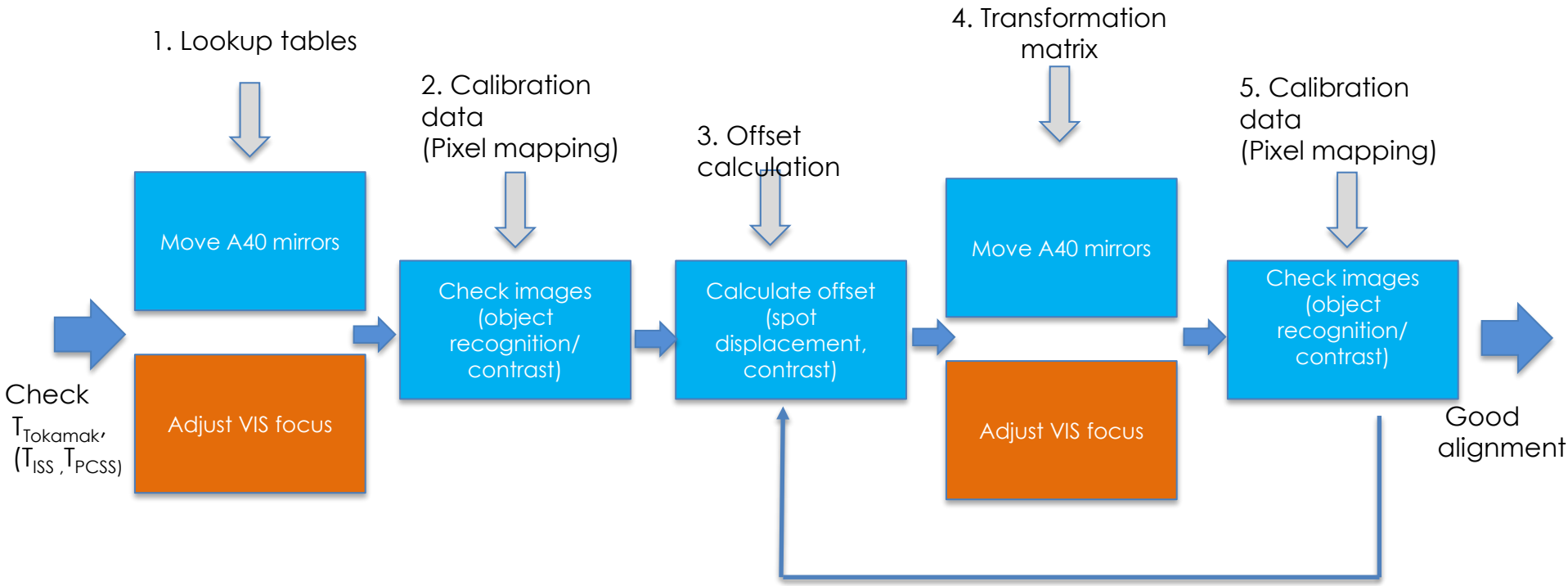
Calibration

As-built position of mirrors
Look up tables (for different Ts)
Tokamak map
Pixel to wall mapping



Active Alignment Process Flow

Input for I &C -Active Alignment Process Flow



Active Alignment Process Flow

- **1. Lookup tables-examples**

	Actuator movement	
Compensator_ As build tolerances	Value	
	degrees	mrad
A40-M1 X tilt		
A40-M1 Y tilt		
A40-M2 X tilt		
A40-M2 Y tilt		
A40-M2 focus		
Visible actuator	Nominal after alignment	

As-built values

T-alignment&integration
(as-built values)
Nominal values after alignment

	Actuator movement	
Compensator_ Toperation	Value	
	degrees	mrad
A40-M1 X tilt	-0,0177	-0,31
A40-M1 Y tilt	-1,338	-23,35
A40-M2 X tilt	0,0133	0,23
A40-M2 Y tilt	-1,249	-21,80
A40-M2 focus	-19,20 mm	
Visible actuator	TBD	

T-high temperature operation
From thermal analysis

Temperature vs compensator value graphs needs interpolation for Wide range of temperature

Active Alignment Process Flow

- **2. Calibration data (Pixel mapping)**
  - Calibration provides pixel to wall map using tokamak model in steps:
    - Combined CAD and zemax model map
    - Landmark identification
    - Extra image distortion determination

- **3. Offset calculation**
  - Software is needed to calculate offset (spot displacement, contrast) in 3 steps:
    1. Contrast enhancement
    2. Landmark identification
    3. Offset calculation

Active Alignment Process Flow

- **4. Transformation matrix**
  - Describes relation between A40-actuators to image position movement
  - Can be inverted to get image to actuator data

$$\begin{pmatrix} dx_{spot}\ (\mu m) \\ dy_{spot}\ (\mu m) \\ Rx_{spot}\ (mrad) \\ Ry_{spot}\ (mrad) \\ Focus\ (\mu m) \end{pmatrix} = \begin{pmatrix} -0{,}093488158 & -0{,}083858448 & -3{,}995000553 & -4{,}87169445 & 0{,}289840363 \\ -0{,}162486746 & -0{,}175771313 & -6{,}660566191 & -10{,}18753731 & 0{,}56560828 \\ 0{,}005978034 & 0{,}00535456 & 0{,}18961868 & 0{,}252727578 & -0{,}019607271 \\ -0{,}014842635 & 0{,}015303927 & -0{,}75603112 & 0{,}705472959 & -0{,}013665458 \\ -0{,}035642772 & -0{,}783668571 & -79{,}61784777 & -12{,}12289654 & -19{,}81530518 \end{pmatrix} \cdot \begin{pmatrix} dRx_{M1}\ (mrad) \\ dRy_{M1}\ (mrad) \\ dRx_{M2}\ (mrad) \\ dRy_{M2}\ (mrad) \\ dZ_{M2}\ (\mu m) \end{pmatrix}$$

Active Alignment Process Flow

- **5. Calibration data (Pixel mapping)**
  - Calibration provides pixel to wall map using tokamak model in steps:
    - Combined CAD and zemax model map
    - Landmark identification
    - Extra image distortion determination
  - Is the same process as step 2, but resulting shifts should be way smaller

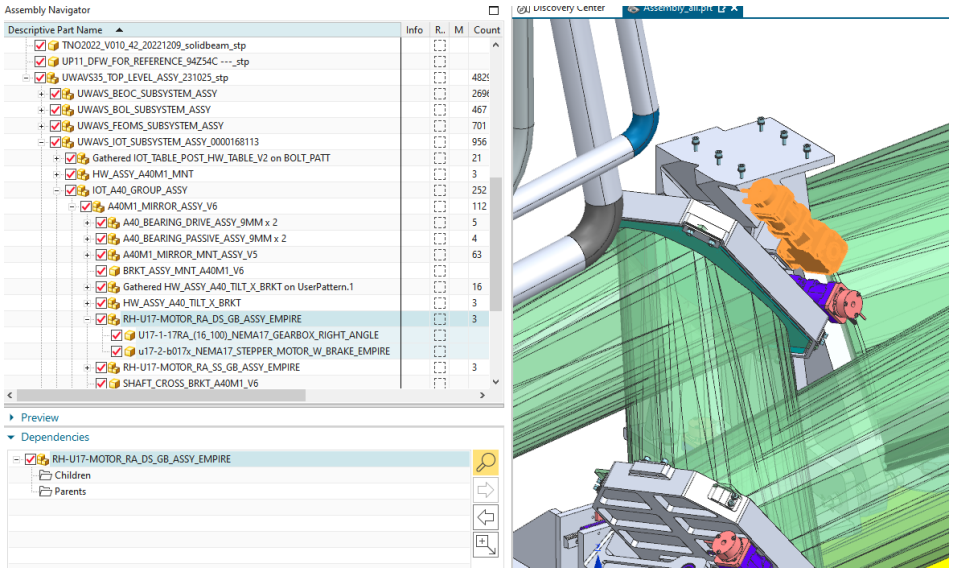
Conclusion

- **Actuator range of motion:**
  - A40: Not enough range for focus compensation to start from the center of the adjustment range (ROM (-/+ 15 mm),-19,20 is needed
- **No vignetting on the footprints after compensation**
- **Better resolution of tilt (<0,008 mrad) and focus (<0,045 mm) actuators is needed**
- **Active alignment Process Flow as an input for I&C provided**
- **Limitations of analysis**
  - Simplified ex-vessel thermal analysis: ISS and PCSS vertical thermal expansions are not included

Back up slides

A40 mirrors tilt Actuator Specifications

Optic ID	Optic Alignment Type (1, 2)	Alignment Performance												Notes
		4. Current Performance Net Total												
		+/-DX [mm]		+/-DY [mm]		+/-DZ [mm]		+/-RX [mrad]		+/-RY [mrad]		+/-RZ [mrad]		
		ROM	Res	ROM	Res	ROM	Res	ROM	Res	ROM	Res	ROM	Res	
A40M1	Active	0.00	?	0.00	?	0.00	?	31.00	0.65	46.00	0.65	0.00	?	Active alignment for VV thermal displacements
A40M2	Active	0.00	?	0.00	?	15.00	0.06	27.00	0.65	41.00	0.65	0.00	?	Active alignment for VV thermal displacements



- **Gearbox effect on resolution needs to be checked**

A40 mirrors tilt Actuator Specifications-updated (20.02.24-email-Tyler)

Optic ID	Alignment Type	Realizable Alignment Specifications*						
		+/-DZ [mm]		+/-RX [mrad]		+/-RY [mrad]		
		ROM	Res	ROM	Res	ROM	Res	
A40-M1	Active	-	-	64.00	0.650	91.00	0.650	
A40-M2	Active	15.00	0.001	54.00	0.650	81.00	0.650	

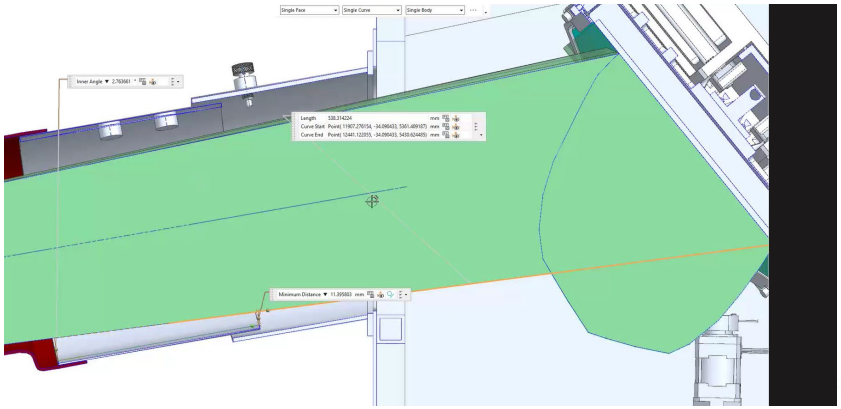
Table Notes:

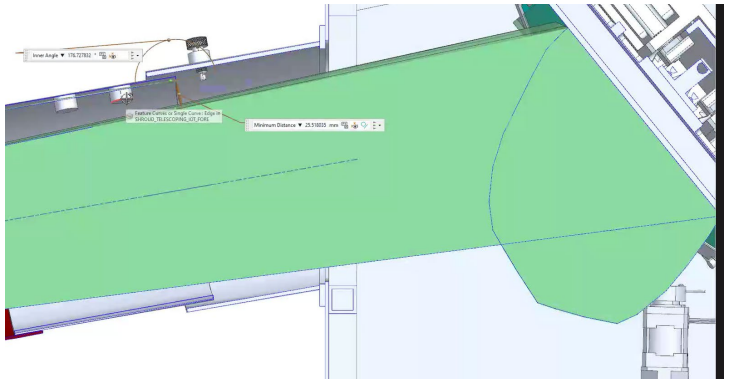
ROM = Range of Motion; Res = Resolution

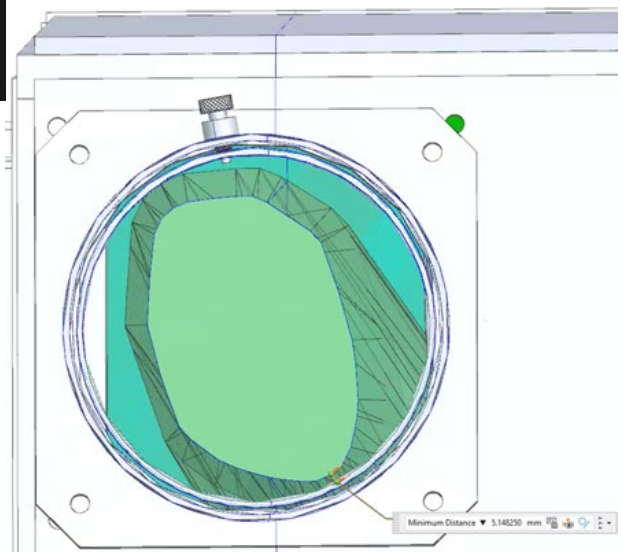
* Preliminary realizable alignment specifications (to be revised)

Margins in the CAD model

- **Margins for the footprint (nominal@20°on the mirror M1, 25.518 mm available for top side, 11.396 mm for bottom side and the minimum distance where the footprint is close to edge 5.148 mm**







WAVS System Description & analysis

- **Total WAVS system from tokomak to detectors | Top View**