INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

NEW OPTICAL POLISHING TECHNIQUES FOR ASPHERICAL AND FREE FORM LENSES

ESA CONTRACT NO 4000134543/21/NL/AR

FINAL PRESENTATION
PTAF-TOP-HO-002_REV.1.0

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PRESENTATION OUTLINE

- Project objectives and organization,
- Asphere manufacturing process development,
- HW3; HW4 realization + lessons learned,
- Free form manufacturing process development,
- HW5; HW6 realization + lessons learned,
- Vision of the future / Way forward / Business perspective / New market,
- Conclusion.

PROJECT OBJECTIVES

- develop the technologies and the processes for the production of highly aspheric and free form lenses
- surface roughness and shape accuracies suitable for high performance optical systems operating in visible and ultraviolet spectral range

	Fused Silica		CaF_2 (crystal orientation <111>)	
Specification	asphere	freeform	asphere	freeform
SE (nm RMS)	40 (25)	150 (40)	40 (25)	150 (40)
SaD ISO 10110-7	1x0.1	1x0.1	1x0.1; each ø 25 mm	1x0.1; each ø 25 mm
Microroughness (nm RMS)	0.5 (0.3)*	0.6 (0.3)*	0.7 (0.5)*	1.0 (0.5*)
Diameter (mm)	>= 80	>= 80	>= 80	>= 80
Curvature radius (mm)	<= 80	<= 80	<= 80	<= 80
Slope (mrad)	>1	>1	>1	>1
Departure from BSF (mm)	> 0.045	> 0.045	> 0.045	> 0.045

( ) represent project target value defined in SoW

* target value defined in SoW will be retained as long as possible

PROJECT TEAM AND RESPONSIBILITIES

- Toptec – elements design, freeform processes development

  Radek Melich – project management, elements design
  František Procháska – experiment coordination, freeform polishing
  David Tomka – freeform grinding
  Markéta Paprčková – measurement procedures
  Kamila Hortová – project PA

- asphericon – CaF_2 microroughness polishing process development, asphere processes development

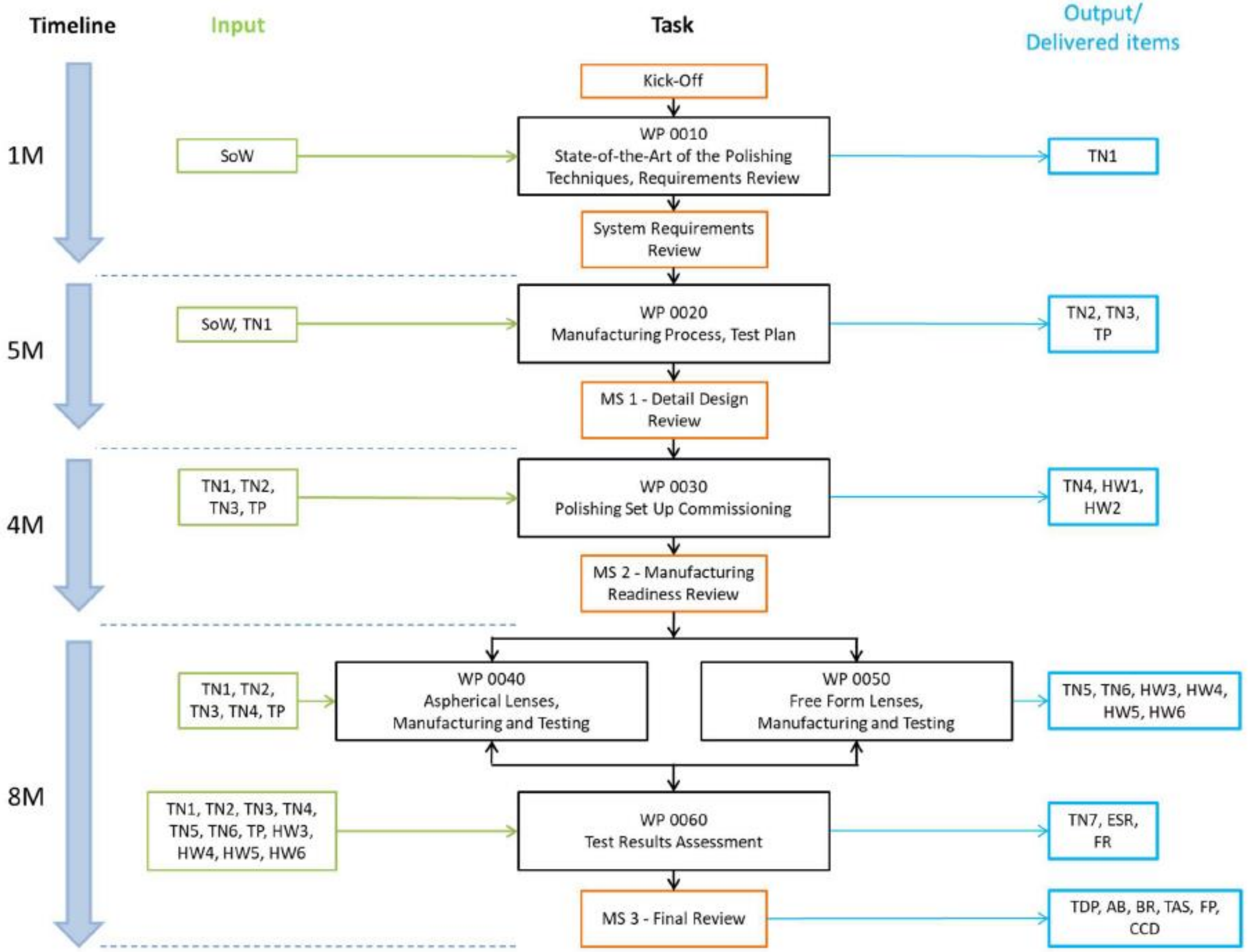
  Ondřej Matoušek - experiment coordination, aspheres polishing, measurement procedures
  Karolína Sedláčková – CaF_2 polishing, measurement procedures

- ESA – project management

  Emilie Lhome – project management, acceptance of all deliverable items

PROJECT WORK LOGIC

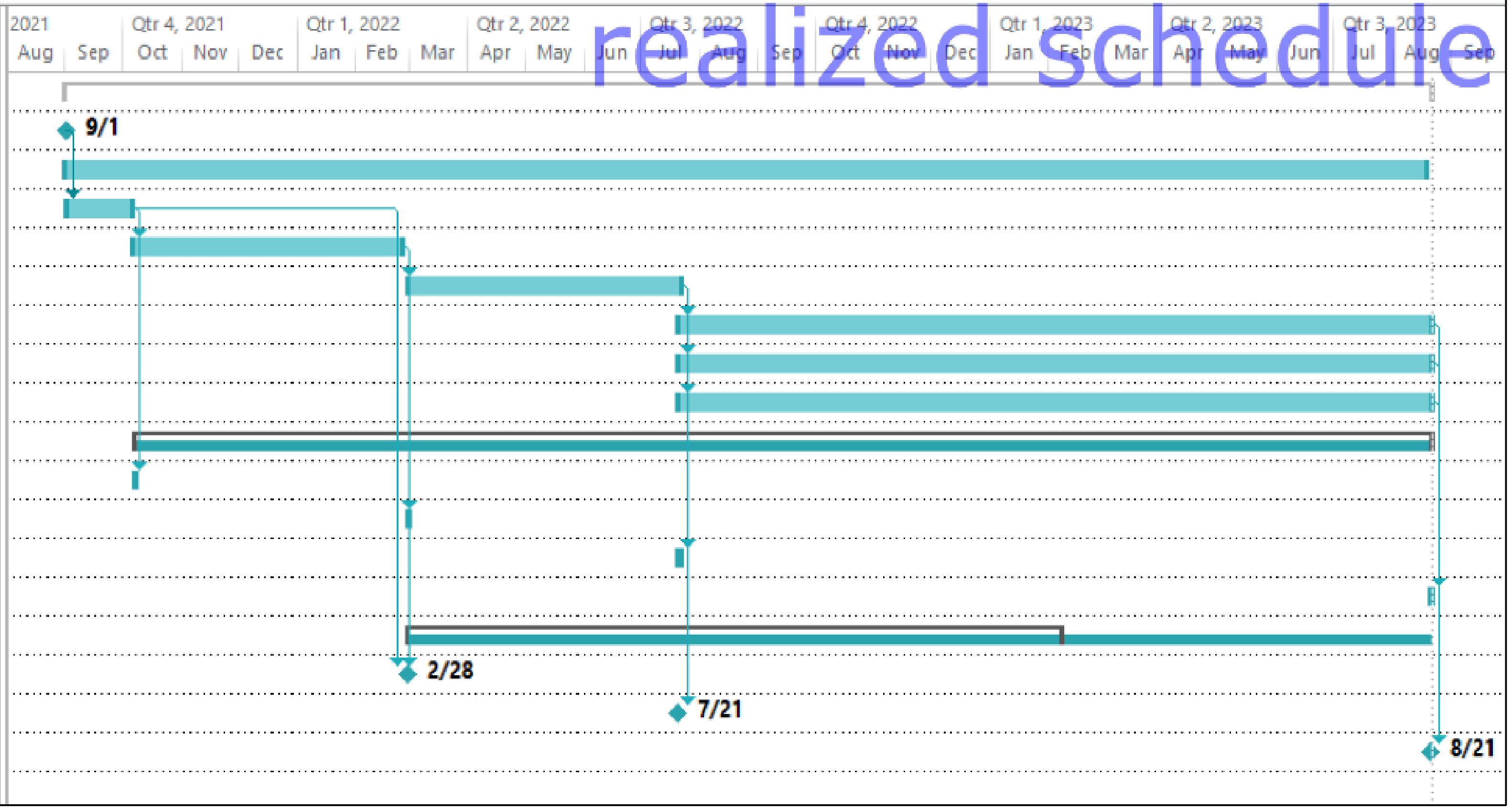
- Six work packages
- Three milestones
- Detail project documentation (TN1 – TN7; TP…)
- Progress meetings on a three weeks basis (MoMs)
- HW1 – HW6 delivered to ESA



PROJECT TIME SCHEDULE

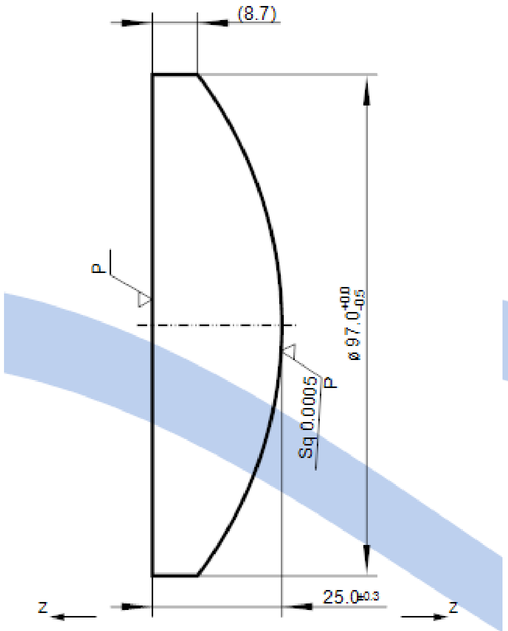
GANTT CHART

	Task Name	Duration
0	**TPTC-New Polishing Techniques**	**486.88 days**
1	T0 - kick-off	0 days
2	WP0000 - Project management	24.3 mons
3	WP0010 - State-of-the-Art of the Polishing Techniques	1.2 mons
4	WP0020 - Manufacturing Process	4.75 mons
5	WP0030 - Polishing Setup Commissioning	5 mons
6	WP0040 - Aspherical Lenses Manufacturing and Testing	13.45 mons
7	WP0050 - Free Form Lenses Manufacturing and Testing	13.45 mons
8	WP0060 - Test Results Assessment	13.45 mons
9	**Consortium Milestones and need dates**	**462 days**
10	SRR	1 day
11	DDR	1 day
12	MRR	1 day
13	Final Review	1 day
14	**TOPTEC Milestones**	**235.13 days**
15	MS-1	0 days
16	MS-2	0 days
17	MS-3	0 days

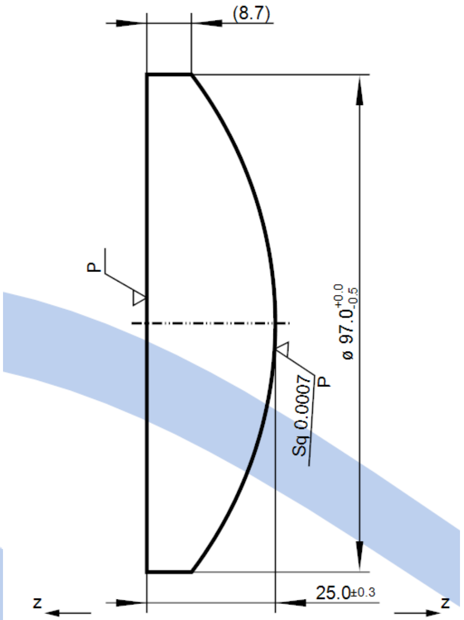


ASPHERE ELEMENTS DESIGN

- Fused Silica; CaF2
- First side – plano
- Second side – asphere



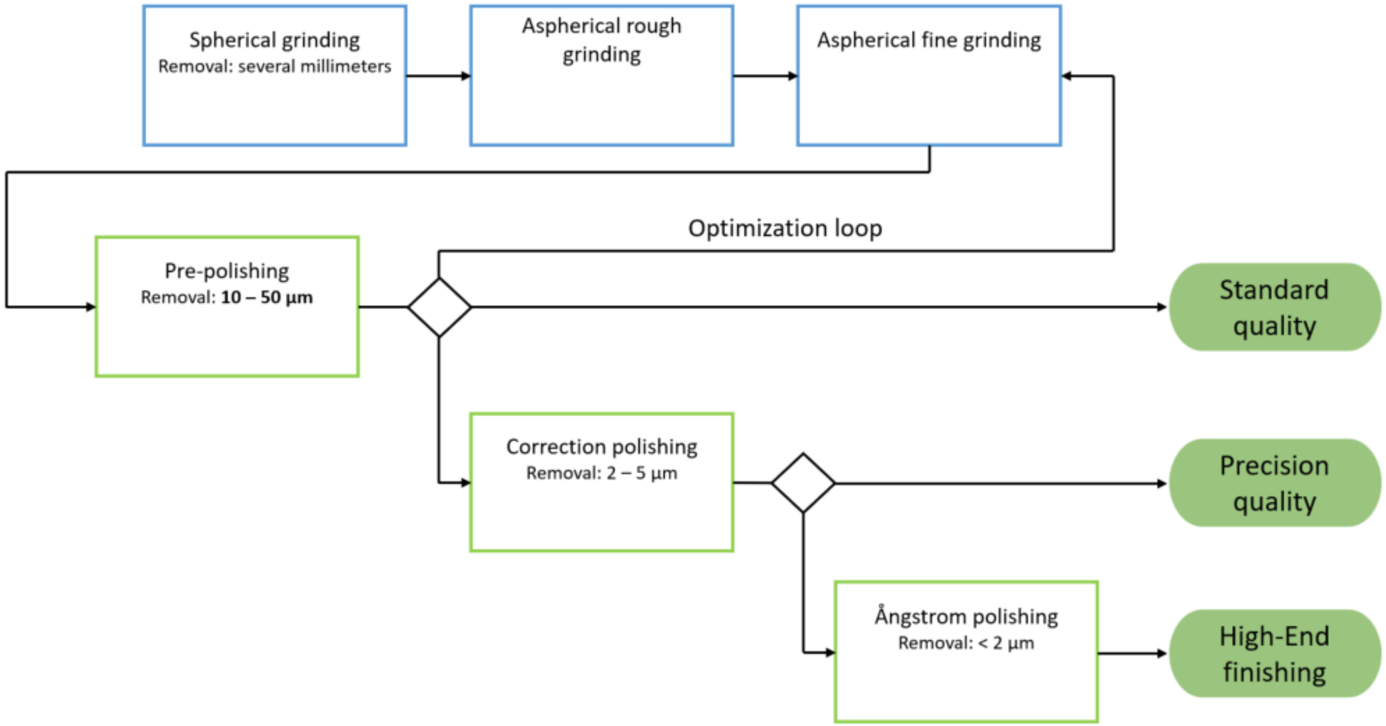
Drawing of HW3



Drawing of HW4

Material	CaF_2 , Fused Silica
Diameter D [mm]	97
Vertex shape	Convex
Vertex radius R [mm]	80 ± 0.015
Curvature C = 1/R [mm-1]	0.0125
Conic constant K [-]	0
Aspheric coefficient A6 [mm-6]	-5e-12
RMSi [nm]	≤ 40

FUSED SILICA ASPHERE MANUFACTURING PROCESS SETUP



FS ASPHERE CNC GRINDING

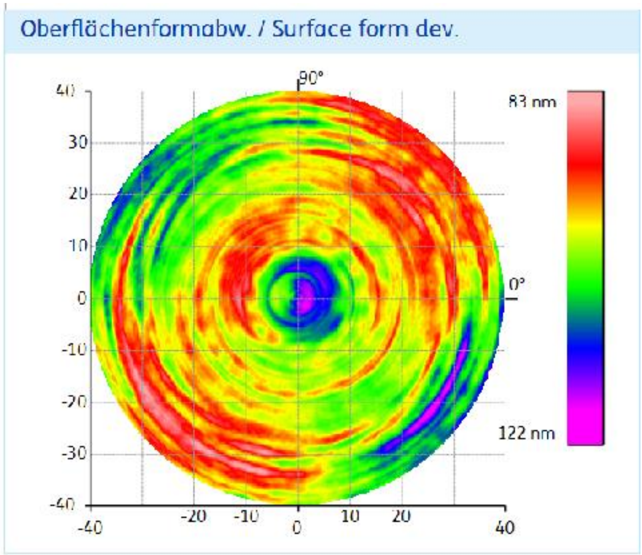
- Machine ASM100
- Tool D91 for rough grinding and D30 for fine grinding

FS ASPHERE CNC POLISHING

- Polishing was performed on machine ASP200-B
- Pre-polishing done with tool with polyurethane pad LP26 and cerium oxide-based slurry AUERPOL PZ110
- 2D correction was done with finer slurry - cerium oxide-based Hastilite FIN
- For microroughness suppression asphericon's Angstrom polishing process was used with the same slurry

- Resulting form deviation was 30 nm RMSi and microroughness 0.411 nm Sq

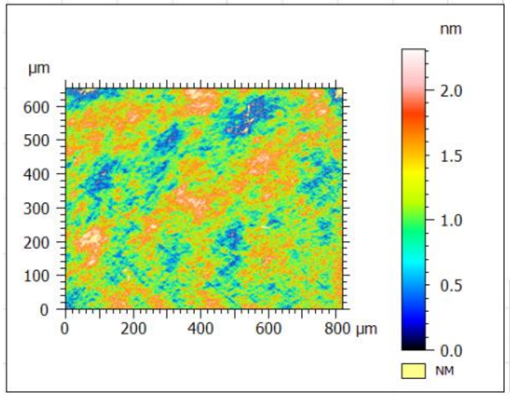
FS ASPHERE RESULTS



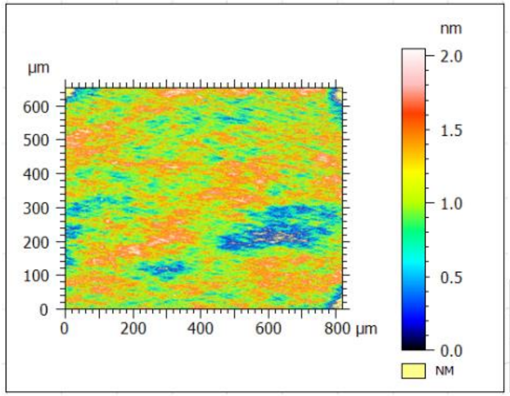
ISO Formabweichung / Deviations

A	----	RMSt	0.030 µm
B	0.205 µm	RMSi	30 nm
C	0.067 µm	RMSa	0.028 µm
PV	0.205 µm		

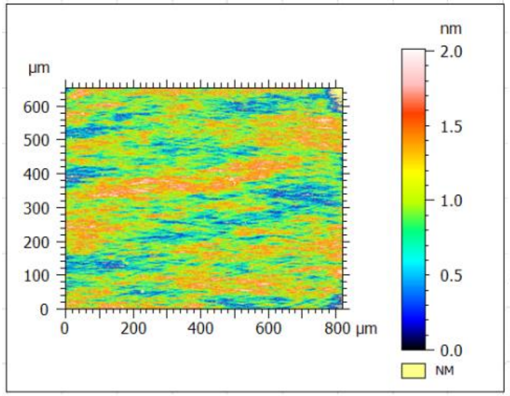
Surface form of the HW3



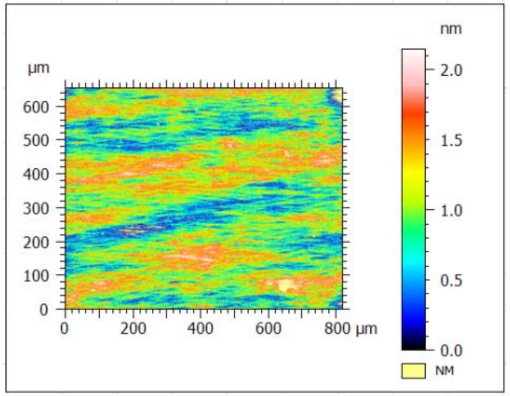
ISO 25178		
Height Parameters		
Sa	0.3620	nm
Sq	0.4484	nm



ISO 25178		
Height Parameters		
Sa	0.3030	nm
Sq	0.3789	nm



ISO 25178		
Height Parameters		
Sa	0.3190	nm
Sq	0.3937	nm



ISO 25178		
Height Parameters		
Sa	0.3482	nm
Sq	0.4275	nm

Surface microrougness of the HW3, measured with magnification 20x, measured on vertex, 10° from vertex, 20° from vertex and 26° from vertex

FS ASPHERE RESULTS

	Target / Goal	Result
Surface form error CX (rms)	40 nm	30 nm
Surface radius error CX (rms)	± 15 µm	0.72 µm
Microroughness CX (rms) (20x)	0.5 nm	0.37 – 0.45 nm
Cleanliness	1 x 0.1	OK
Edge Chips	0.1 mm	OK
Central thickness	± 0.3 mm	-0.07

Summary of the reached parameters on Fused Silica aspherical lens #3 (HW3)

Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	0.448	0.379	0.394	0.428	0.411

Summary of the reached microroughness on the (HW3), magnification 20X < 1.22, 780> mm-1

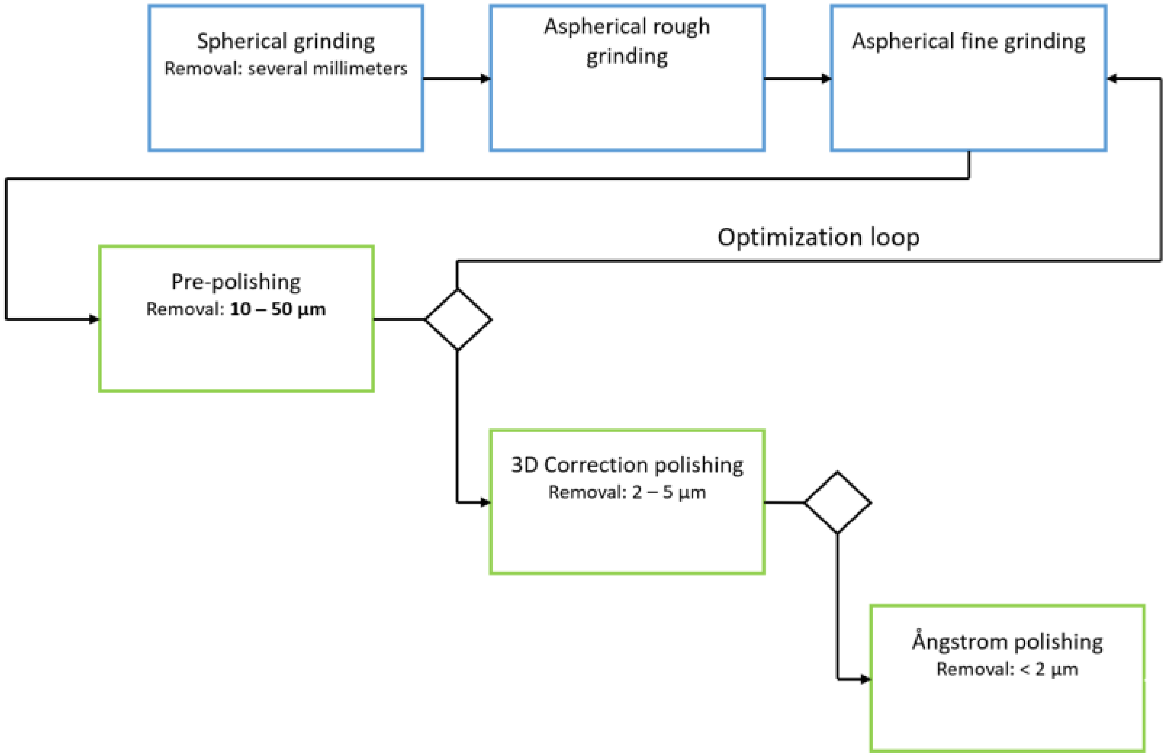
Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	1.103	0.4293	0.5906	0.8598	0.725

Summary of the reached microroughness on the Fused Silica aspherical lens #3 (HW3), magnification 10X, spatial frequency range <1, 398> mm-1

Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	0.541	0.35	0.3797	0.3626	0.371

Summary of the reached microroughness on the Fused Silica aspherical lens #3 (HW3), magnification 50X, spatial frequency range <3.05, 1000> mm-1

CALCIUM FLUORIDE ASPHERE MANUFACTURING PROCESS SETUP

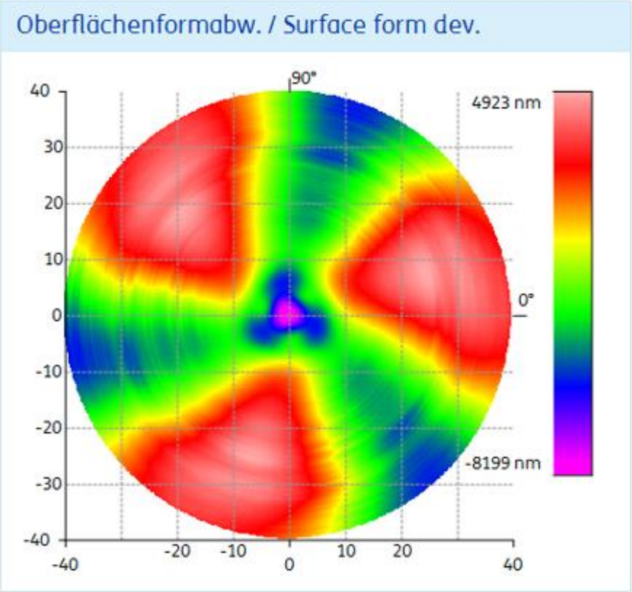


CALCIUM FLUORIDE ASPHERE CNC GRINDING

- Machine ASM100
- Tool D91 for rough grinding and D20 for fine grinding

CALCIUM FLUORIDE ASPHERE CNC PRE-POLISHING

- During polishing of CaF_2 its cubic crystalline structure forms on the surface -> goal is to reduce the forming and surface microroughness
- Polishing was performed on machine ASP200-B
- Pre-polishing with tool with polyurethane pad LP-46 and diamond-based slurry Pureon OPW - 86/10 DP 0.75 – 1 µm

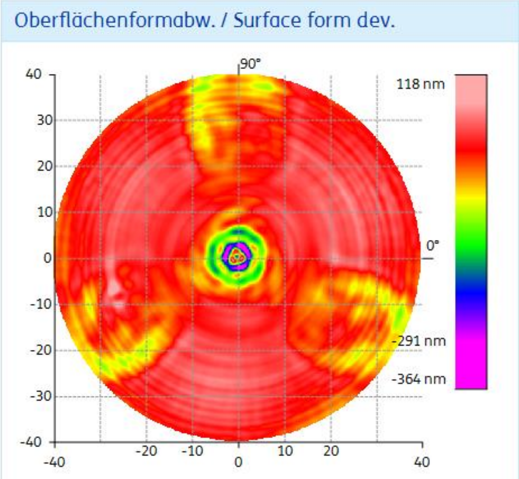


ISO Formabweichung / Deviations

A	----	RMSt	2.919 µm
B	13.122 µm	RMSi	2919 nm
C	4.711 µm	RMSa	2.765 µm
PV	13.122 µm		

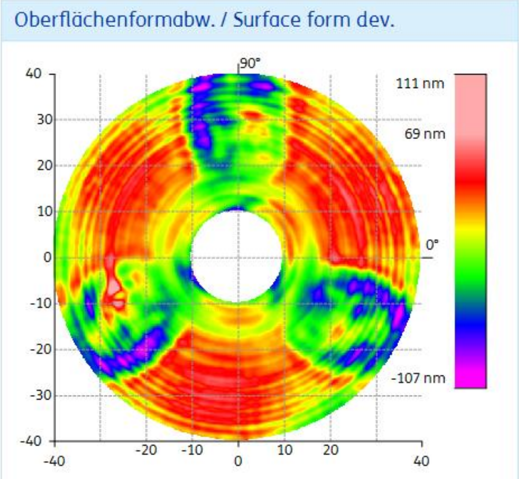
CALCIUM FLUORIDE ASPHERE CNC CORRECTION POLISHING

- 3D Polishing was performed on machine ASP200-B and integrated software PolyCam
- 3D polishing with tool with polyurethane pad LP-46 and diamond-based slurry Pureon OPW - 86/10 DP 0. 5 – 1 µm
- 3D correction removed trefoil structure, it only remained in the center of the surface



ISO Formabweichung / Deviations

A	----	RMSt	0.040 µm
B	0.482 µm	RMSi	40 nm
C	0.141 µm	RMSa	0.033 µm
PV	0.482 µm		

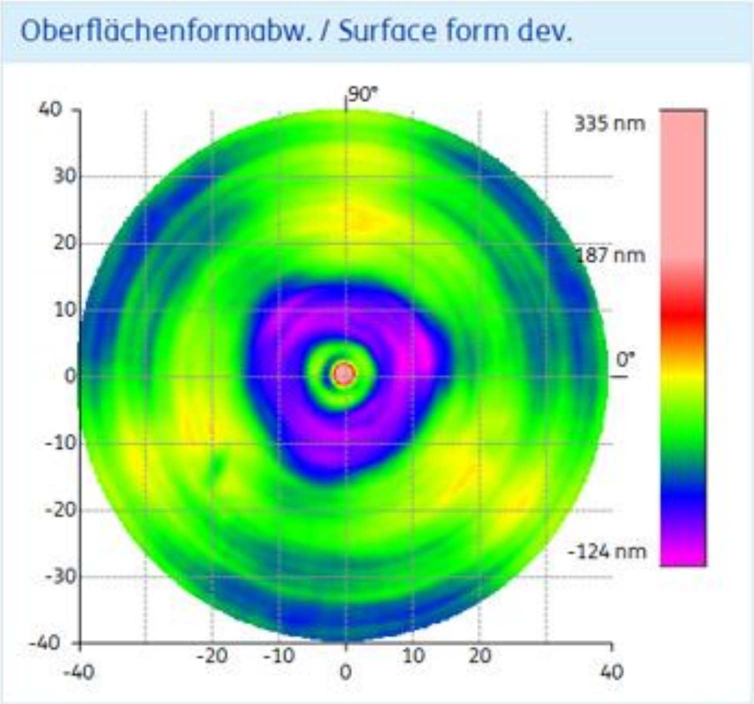


ISO Formabweichung / Deviations

A	----	RMSt	0.031 µm
B	0.218 µm	RMSi	31 nm
C	0.021 µm	RMSa	0.030 µm
PV	0.218 µm		

CALCIUM FLUORIDE ASPHERE CNC ANGSTROM POLISHING

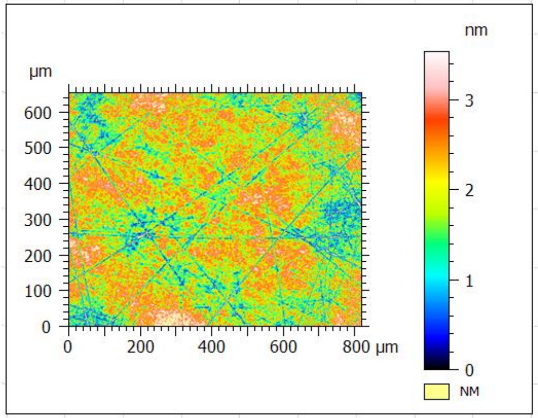
- Improves surface quality in lateral frequencies microroughness in lateral frequencies in the range of microroughness and mid-spatial frequencies
- First test – Angstrom polishing tool and slurry OPW - 86/10 DP 0.5 – 1.0 -> resulting microroughness 1.5 nm RMS
- Second test - Angstrom polishing tool and slurry OPW - 10/20 DP 0 – 0.2 GAF -> resulting microroughness 0.7 nm RMS
- Necessary to control the influence of rpm to prevent trefoil reappearance



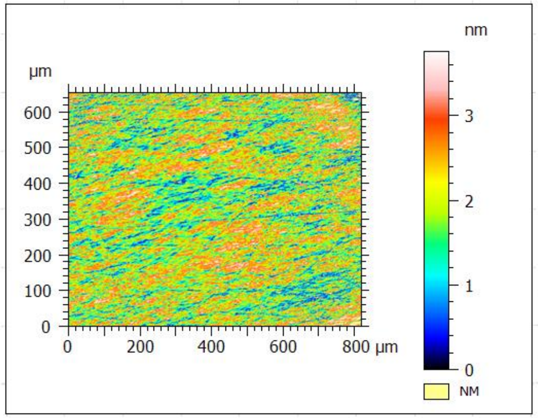
ISO Formabweichung / Deviations

A	----	RMSt	0.040 µm
B	0.461 µm	RMSi	40 nm
C	0.085 µm	RMSa	0.031 µm
PV	0.461 µm		

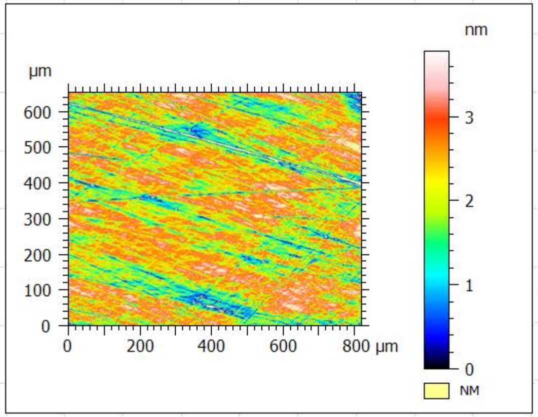
CALCIUM FLUORIDE ASPHERE MICROROUGHNESS RESULTS



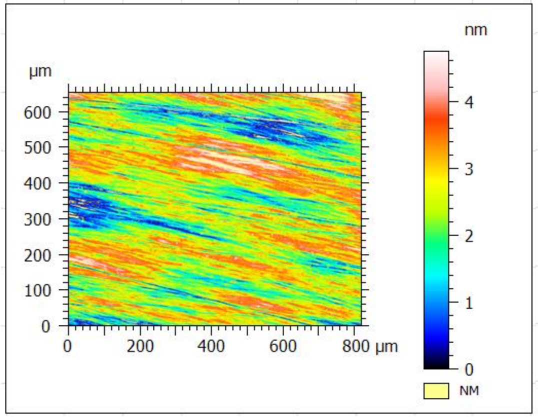
ISO 25178		
Height Parameters		
Sa	0.5294	nm
Sq	0.6603	nm



ISO 25178		
Height Parameters		
Sa	0.6045	nm
Sq	0.7449	nm



ISO 25178		
Height Parameters		
Sa	0.5578	nm
Sq	0.6973	nm



ISO 25178		
Height Parameters		
Sa	0.7091	nm
Sq	0.8903	nm

Surface microrougness of the HW4, measured with magnification 20x, measured on vertex, 10° from vertex, 20° from vertex and 26° from vertex

CALCIUM FLUORIDE ASPHERE RESULTS

	Target / Goal	Result
Surface form error CX (rms)	40 nm	40 nm
Surface radius error CX	± 15 µm	8.22 µm
Microroughness CX (rms) (20x)	0.7 nm	0.66 – 0.89 nm
Cleanlines	1 x 0.1 (at each Ø 25 mm)	OK
Edge Chips	0.1 mm	OK
Central thickness	± 0.3 mm	-0.02

Summary of the reached parameters on the HW4

Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	0.660	0.745	0.697	0.890	0.721

Summary of the reached microroughness on the HW4, magnification 20X, spatial frequency range <1.22, 780> mm-1

Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	2.371	1.174	0.9862	0.890	1.0801

Summary of the reached microroughness on the HW4, magnification 10X, spatial frequency range <1.398> mm-1

Position	0°	10°	20°	26°	median
Microroughness RMS [nm]	0.660	0.8679	0.6978	0.827	0.7624

Summary of the reached microroughness on the HW4, magnification 50X, spatial frequency range <3.05, 1000> mm-1

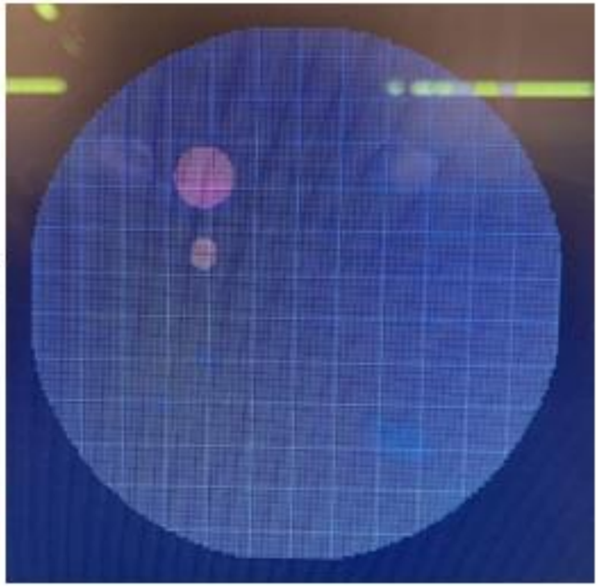
OVERVIEW OF MANUFACTURING PROCESSES

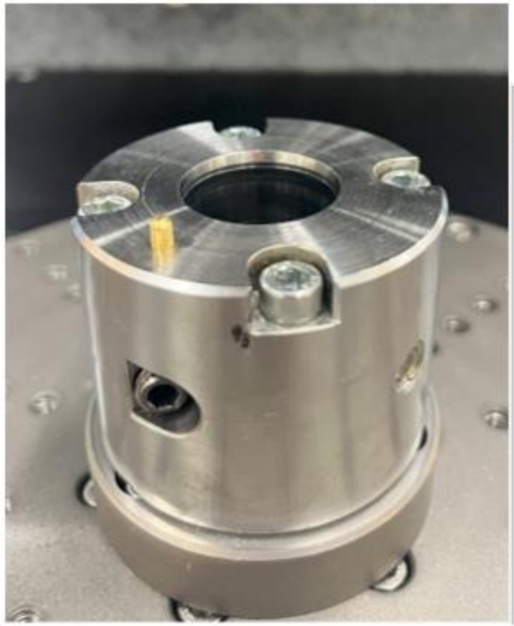
	1st side	Grinding	Pre-polishing	2D correction	3D correction	Angstrom polishing	Summary
HW3 (FS)	Approx. 45 min on crank arm polishing machine	1 cycle – 40 minutes	2 cycles - 60 minutes	10 cycles – 90 minutes	N/A	17 cycles – 100 minutes	30 cycles – 290 minutes
HW4 (CaF_2)	Approx. 25 min on crank arm polishing machine	4 cycles – 15 minutes	2 cycle – 10 minutes	3 cycles – 50 minutes	25 cycles - > 360 minutes	16 cycles - > 360 minutes	50 cycles - > 800 min

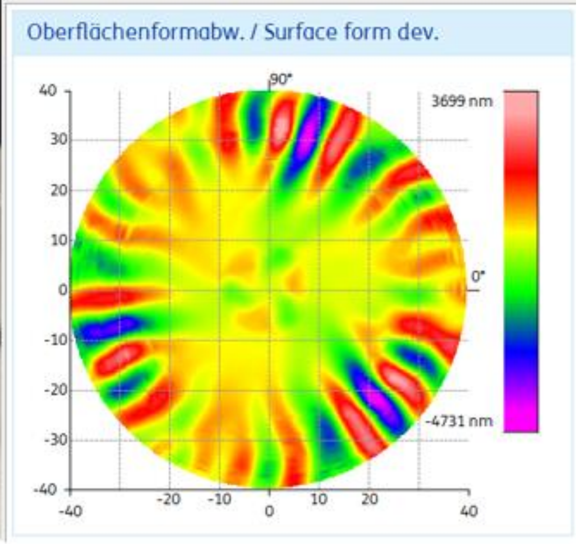
HW3 - fused silica asphere

HW4 - CaF2 asphere

ASPHERES LESSONS LEARNED







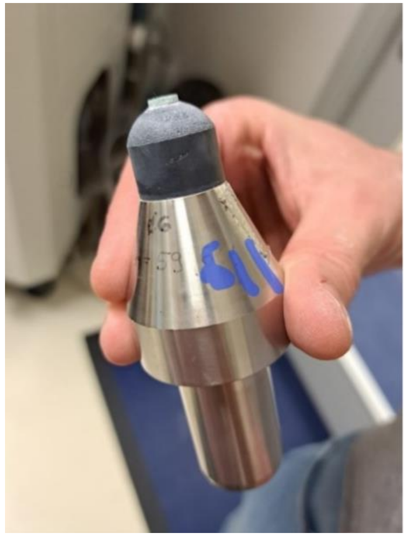
Data handling for 3D correction

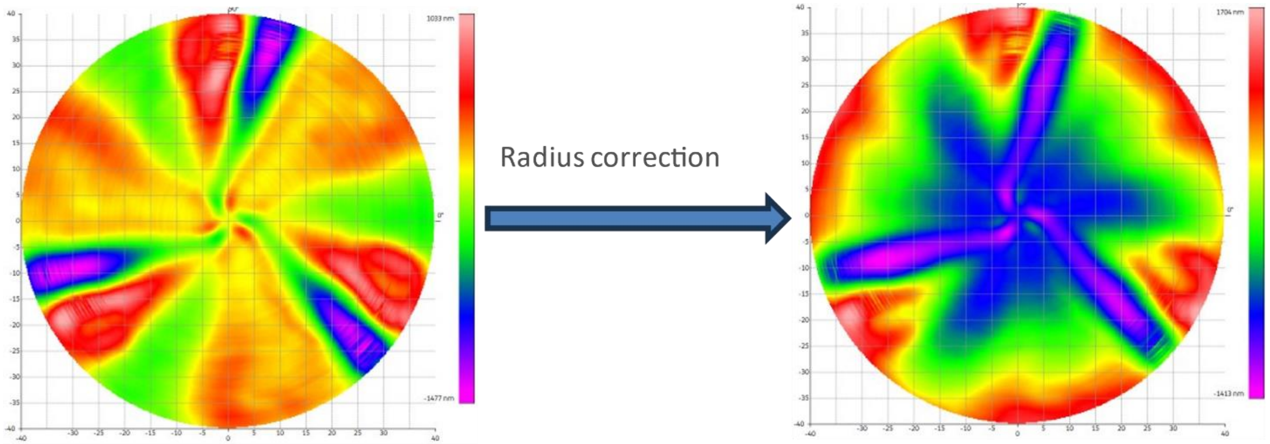
- Proper 3D correction depends on proper data handling
- Finding correct orientation of the CNC machine

Angular calibration

- Angular offset of the workpiece position between measurement and polishing cause structure generation with a period corresponding to the angular offset
- Necessary step was to guarantee repeatibility – developement of new calibration procedure for angular correction

ASPHERES LESSONS LEARNED





Tooling for 3D correction

- Necessary to find compromise between a tool speed and diameter of the tool
- Solution was to used radial tool covered with polyurethane

Central defect issue

- With incorrect settings in 3D correction polishing parasitic periodical structure appear
- Solution was to reduce correction polishing in central part - filter imported data and move correction to the edges of the lens

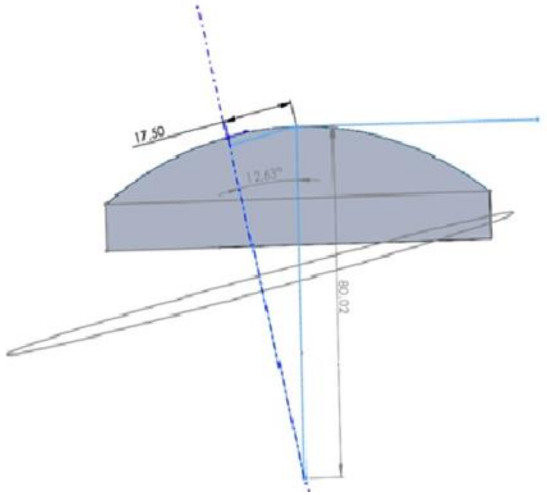
IPP toptec

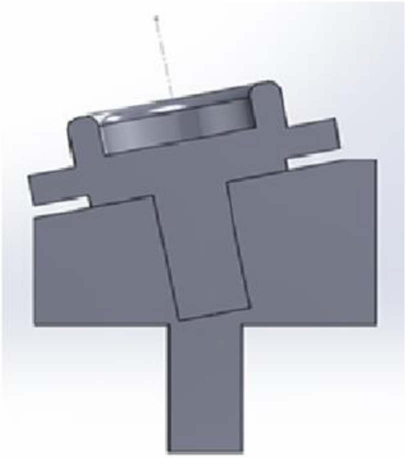
ASPHERE MACHINING CONCLUSION

- **Realization of the parts HW3 – Fused Silica and HW4 – CaF_2 <1,1,1> validate the manufacturing processes on a laboratory scale, which corresponds with TRL4.**
- **Both aspherical elements were successfully realized and reached the goal of the project as regards the surface form error to be smaller than 40 nm RMS.**
- **Regarding the surface micro-roughness, the goal to reach values under 0.5 nm on Fused Silica was met when asphericon reached 0.4 nm. The production process is very stable and can be used even for volume production.**
- **The micro-roughness level requirement of the CaF_2 was set to 0.7 nm. The required value was very tightly met but the microroughness around 0.7 nm is very on the edge of the developed process and is suitable for single-piece production or very small series.**
- **During the project, asphericon developed several new polishing processes. Asphericon gained plenty of experience with new polishing slurries, with the 3D correction polishing process, and handling non-constant removal rates on crystalline materials.**

FREE FORM ELEMENTS DESIGN

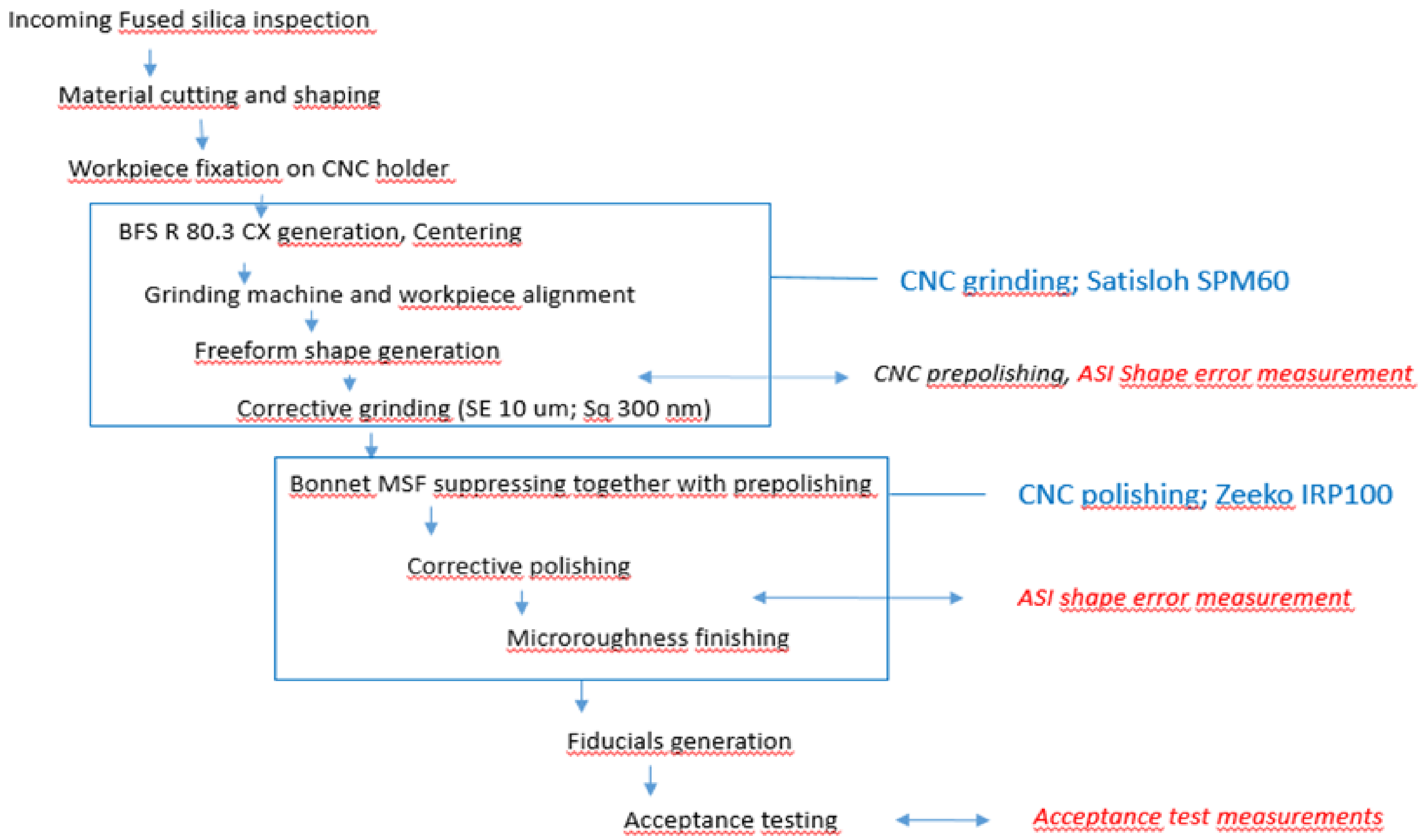
- S-BSL7; Fused Silica; CaF2 materials
- off-axis part of the asphere, distance between mechanical and optical axes 17.5 mm
- non rotary symmetry
- measurable on QED ASI





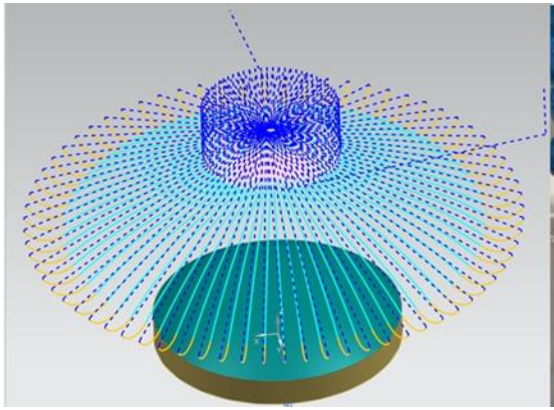
Material	S-BSL7 glass, CaF_2 , Fused Silica
Maternal diameter D [mm]	132
Vertex shape	Convex
Vertex radius R [mm]	80 ± 0.015
Curvature C = 1/R [mm-1]	0.0125
Conic constant K [-]	0
Aspheric coefficient A6 [mm-6]	-5e-12
Sag check point at ρ = 50 mm Z(50) [mm]	17.472
SE specification (nm RMS)	150 (40)
Microroughness (nm RMS)	FS:0.6 (0.3); CaF2 1.0 (0.5)

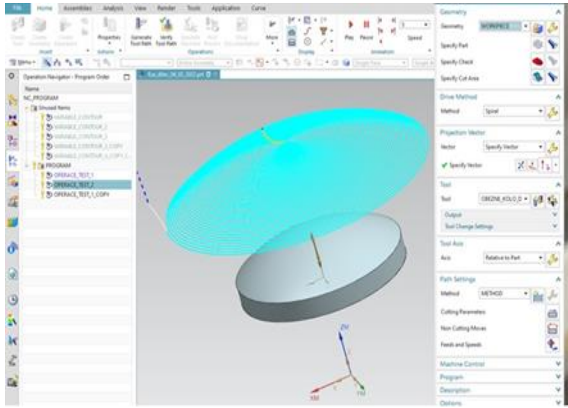
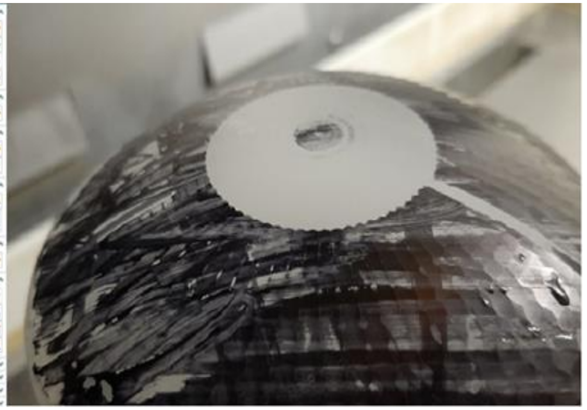
FUSED SILICA FREE FORM MANUFACTURING PROCESS SETUP



FS FREE FORM CNC GRINDING

- Satisloh SPM 60 machine with customized post-processor; SolidWorks CAD SW for 3D model construction; Siemens NX CAD-CAM SW for 5 axis machining
- Radial Zig Variable Contour process kinematics for rough grinding; Spiral kinematics for fine grinding

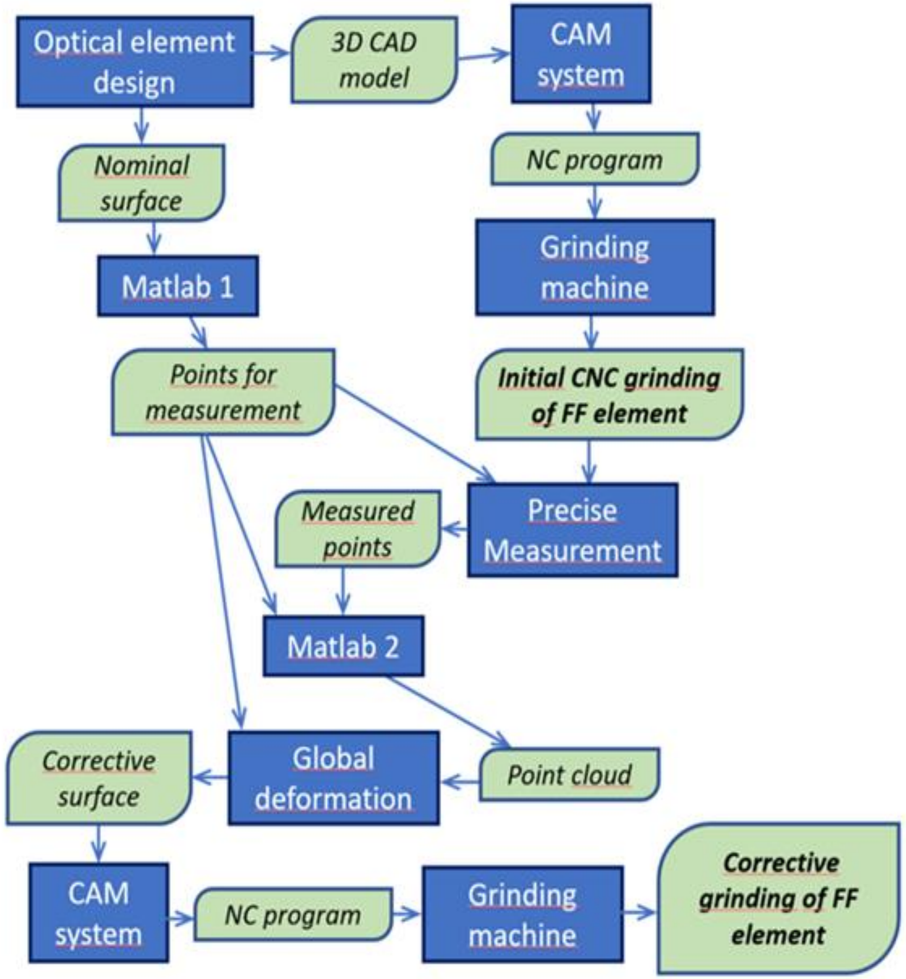


- cup tool D90 for best-fit radius generation; wheel tool D90 and D38 for free form shaping
- surface with an SFE < 15 um PV or SFE < 3 um RMS

FS FREE FORM CNC CORRECTIVE GRINDING

- corrective grinding process based on the correction of the tool path calculated from the deviation of ground and nominal surface
- using of the Global Deformation Function of Siemens NX SW
- surface with SFE < 10 um PV or SFE < 1.9 um RMS after 1st step
- surface with SFE < 7 um PV or SFE < 1.3 um RMS after 2st subseqent step
- **resulting SE fully acceptable for polishing**



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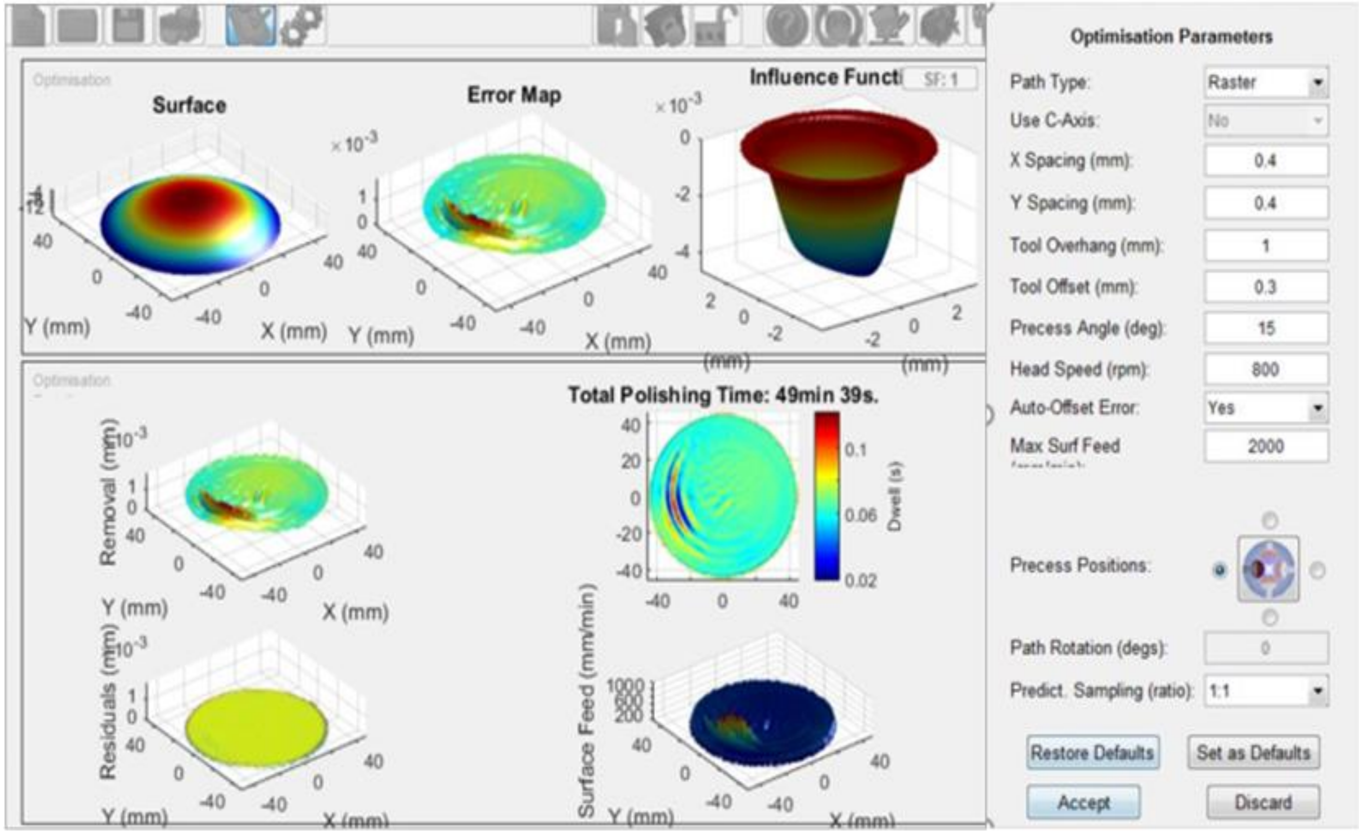
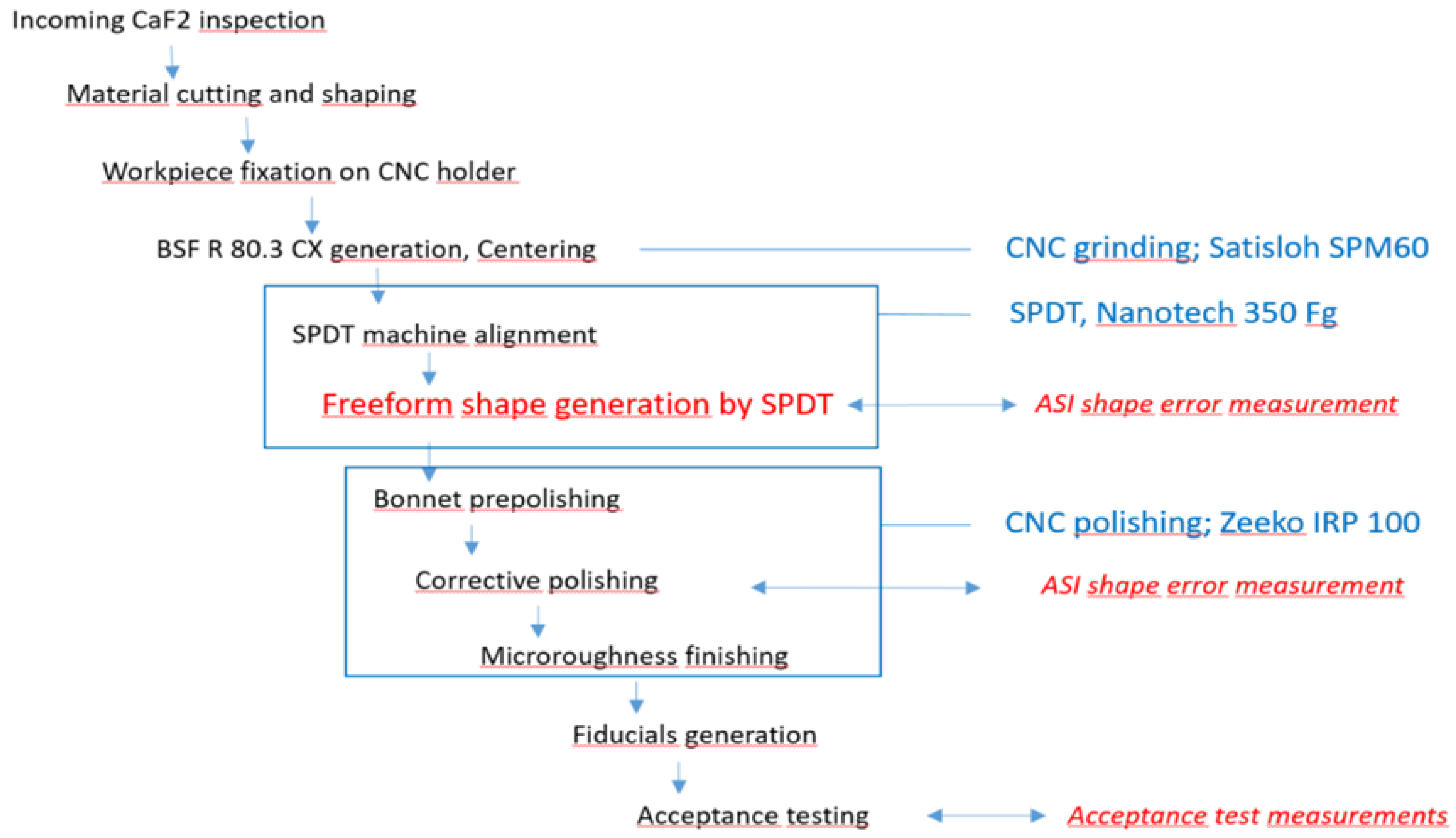
FREE FORM CNC POLISHING

- all polishing processes realized on Zeeko IRP1OO machine using of the raster kinematics
- prepolishing integrated with MSF suppressing into one process by FEM polyurethane polishing tool
- Corrective polishing based on Dwell time calculation from SE map measured by ASI and from the Tool influent function
- Microroughness pitch polishing for surface finishing



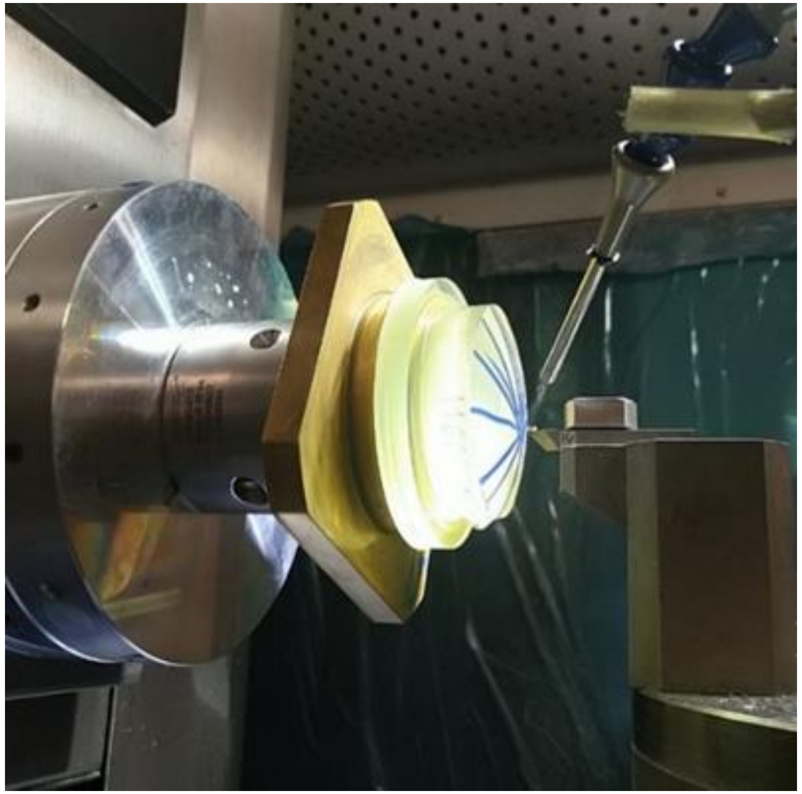
CALCIUM FLUORIDE FREE FORM MANUFACTURING PROCESS SETUP



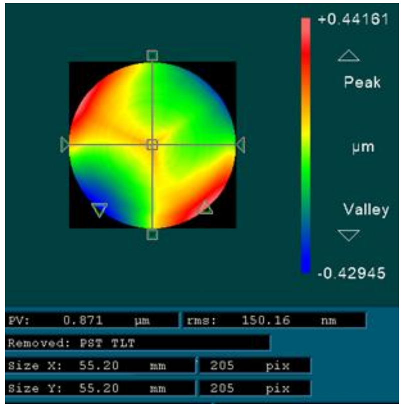
CALCIUM FLUORIDE FREE FORM SPDT MACHINING

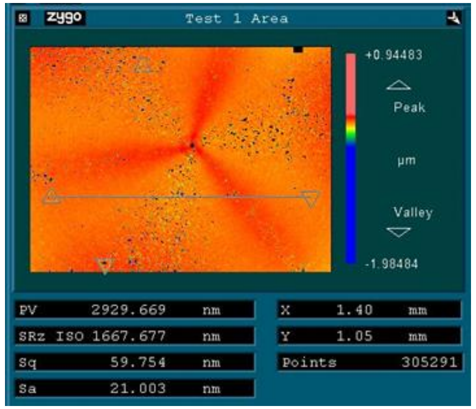
- SPDT machining performed on 5 axis Moore Nanotech 350 FG machine

SPDT mode	Slow side servo
WP spindle rotation (1/min)	22 - 150
Radial feed (mm/rev)	0.01
Penetration depth (µm)	5 x 30; 20; 5; 2
Tool radius (mm)	0.7



- Surface from SPDT fully acceptable for polishing

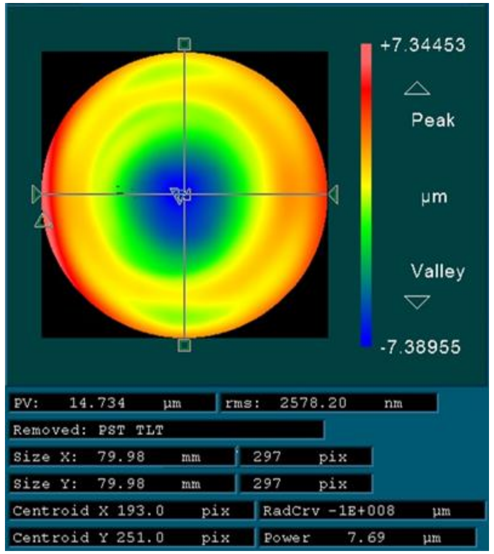




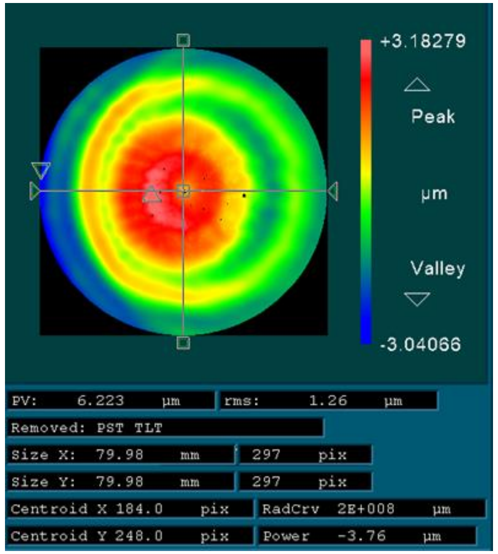
FREE FORM MACHINING PROCESS TEST

- Process chain CNC grinding – CNC Corrective grinding – CNC polishing tested on glass S-BSL7 (FF2 element)

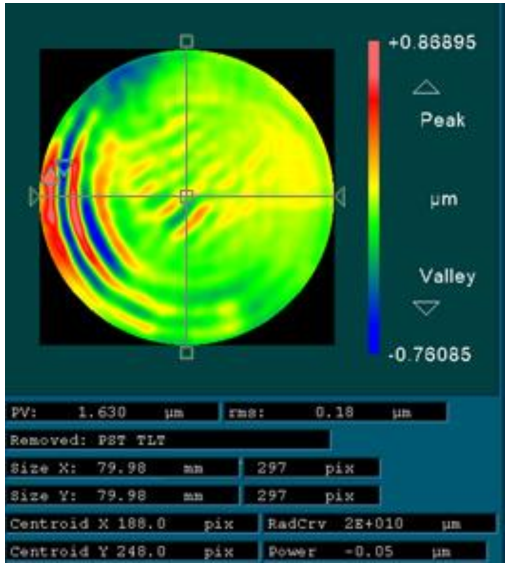
- SE after CNC grinding 15 um PV; after 1st iteration of Corrective grinding 9 um PV and after 2 nd iteration 6 um PV
    - reduction of the freeform surface radius error (SAG)
    - also reduction of surface curvature and residual error (IRR; RSI)



CNC grinding



2st iteration CG



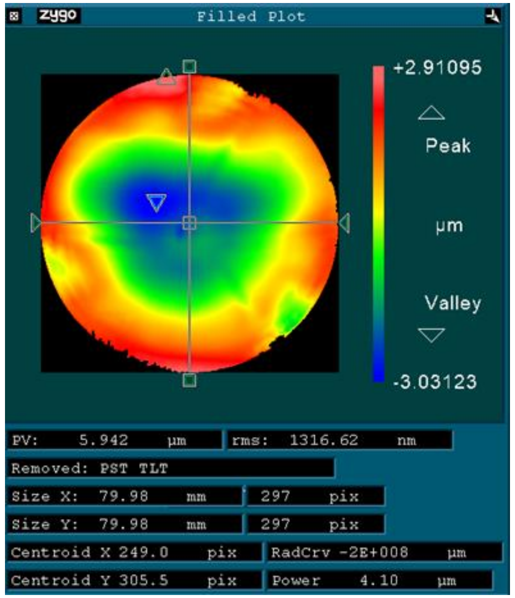
Corrective polishing

- SE after polishing process (Prepolishing + Corrective polishing) 1.6 um PV – **Machining process ready for skip to Fused silica material**

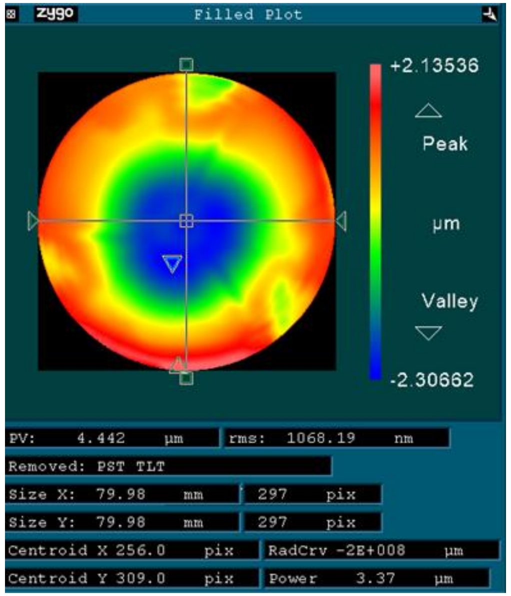
FREE FORM MACHINING PROCESS TEST

- process chain SPDT – CNC polishing tested on 1;1;1 oriented monocristalline CaF2 (CaF FF1 element)

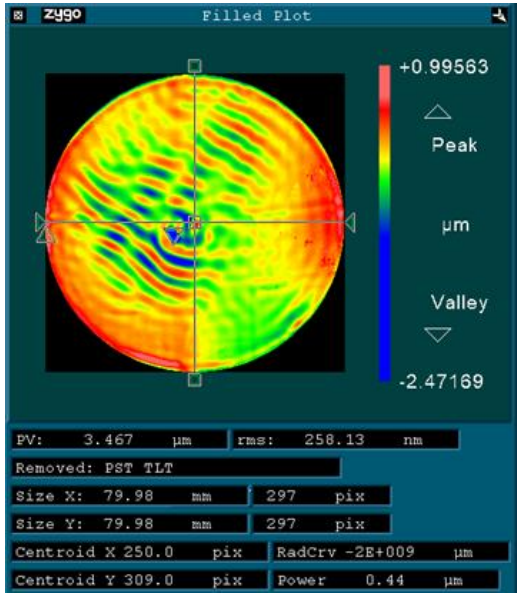
- SE after SPDT 6 um PV;
  after prepolishing 4.5 um PV
  and after Corrective
  polishing 3.5 um PV
  - reduction of the low frequencies, but developing of MSF limiting specification fulfilment



SPDT



Prepolishing

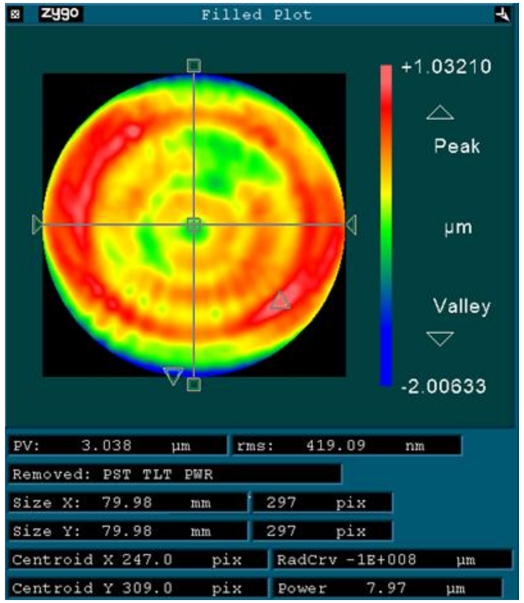


Corrective polishing

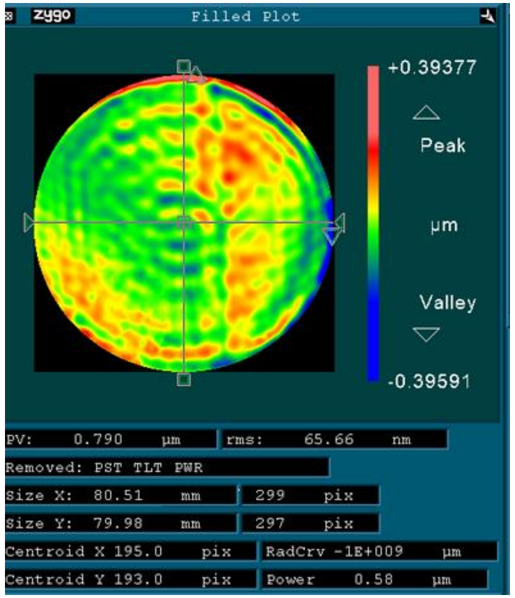
- ***Machining process ready for skip to CaF2 material after Zeeko Non linear correction implementation***

FREE FORM HW5 REALIZATION

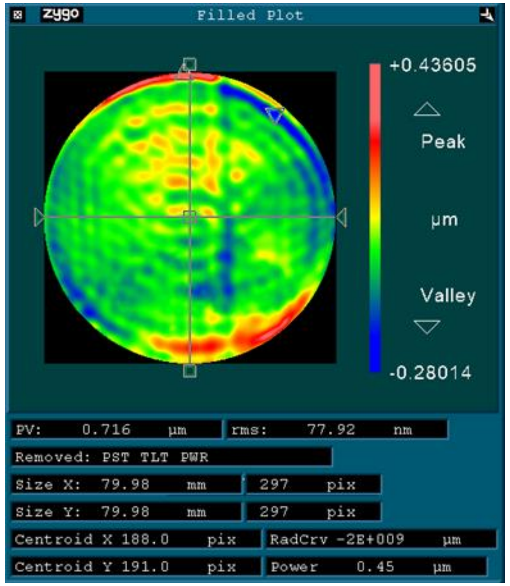
- HW5 (Free form element FS FF4) realized with process settings tested on S-BSL7
- CNC polishing involved: Prepolishing, Corrective polishing, Polishing for microroughness
- HW5 machining process results (with Power removing):



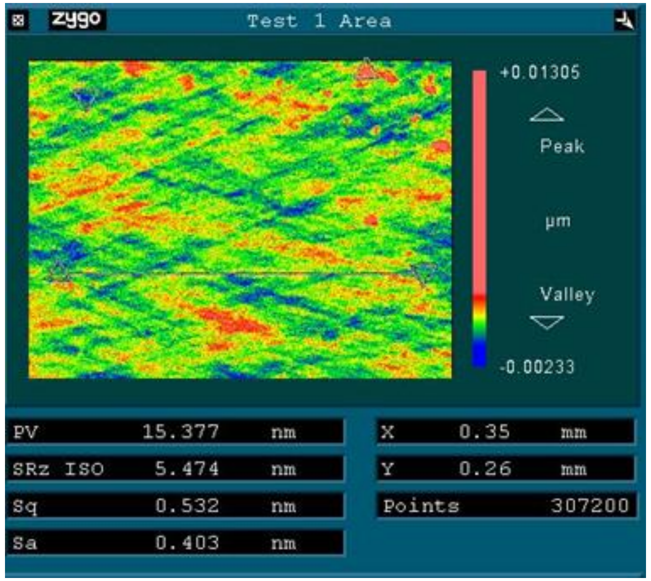
Corrective grinding



Corrective polishing



Microroughness polishing



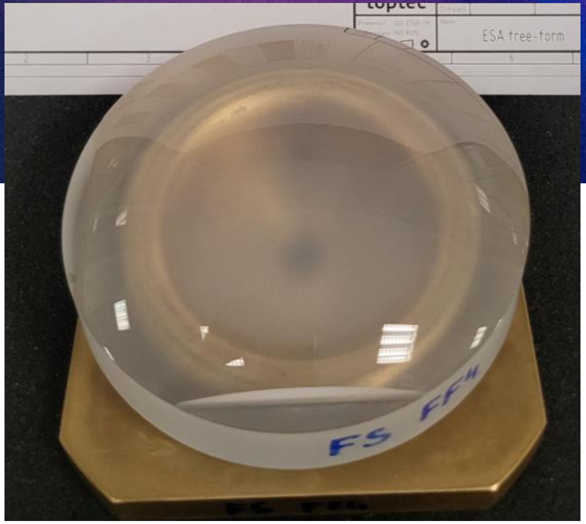
WLI 20x microroughness

FREE FORM HW5 REALIZATION

- HW5 results – ISO 10110 analysis

ISO 101 10-5 parameter	PV	RMS
SAG; RMSt (µm)	0.53	0.18
IRR; RMSi (µm)	0.83	0.09
RSI; RMSa (µm)	0.14	0.09
Microroughness Sq (nm) 5x	-	0.96 (remaining MSF)
Microroughness Sq (nm) 20x	-	0.49
Microroughness Sq (nm) 50x	-	0.51

FreeForm FS	Form deviation ⌀80 mm (ISO 10110-5) [nm]	Surface radius	Microroughness rms [nm]	Cleanliness (ISO)
Tolerances	RMSi < 150	80 +/- 0.015 mm	< 0.6	1x0.1; E0.5
Results	RMSi 77.915	80.0013 mm +0.0016%	0.5	0x0.1

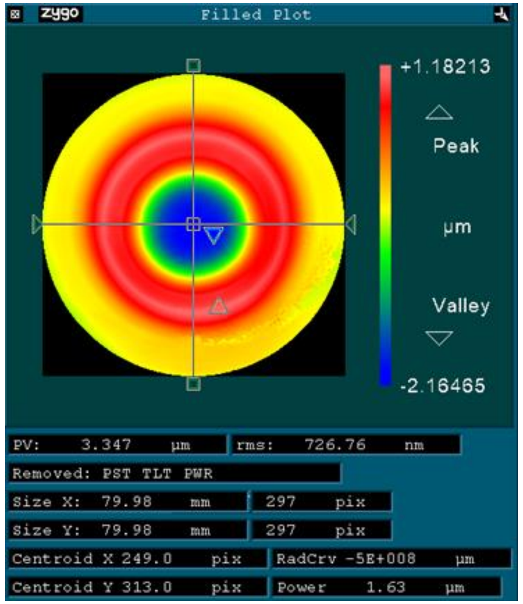


- Process time estimation

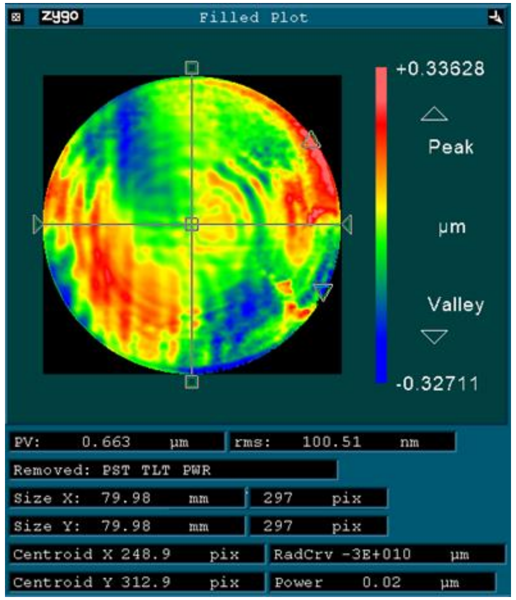
	No. of Cycles	Time sum/1 cycle .[min]
BFS generation	1	120/120
CNC free-form grinding	15	1410/94
SFE measurement	1	60/60
CNC free-form corrective grinding	7	658/94
SFE measurement	1	60/60
Prepolishing and MSF correction	10	360/36
SFE measurement	10	600/60
Corrective polishing	8	660/82.5
SFE measurement	8	480/60
Microroughness polishing	4	120/30
SFE and WLI measurement	4	360/90
SUM of all time		4648

FREE FORM HW6 REALIZATION

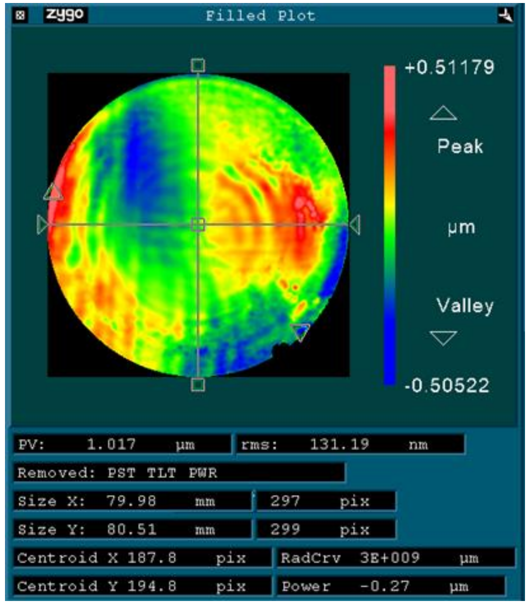
- HW6 - Free form element CaF_2 FF2 realized by process connected SPDT and CNC polishing
- CNC polishing involved: Prepolishing, Corrective polishing, Polishing for microroughness
- HW6 machining process results (with Power removing):



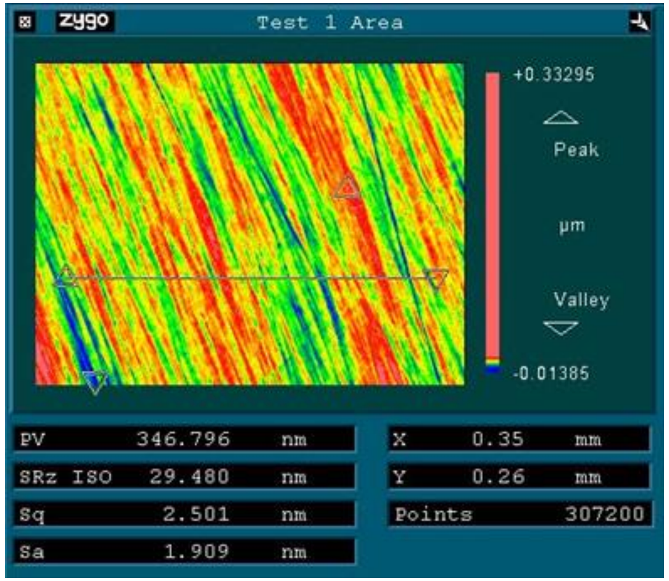
SPDT



Corrective polishing



Microroughness polishing



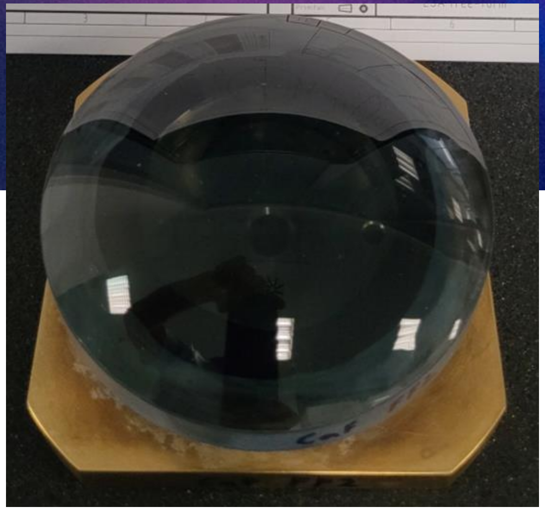
WLI 20x microroughness

FREE FORM HW6 REALIZATION

- HW6 results – ISO 10110 analysis

ISO 101 10-5 parameter	PV	RMS
SAG; RMSt (µm)	0.31	0.18
IRR; RMSi (µm)	1.18	0.15
RSI; RMSa (µm)	0.03	0.15
Microroughness Sq (nm) 5x	-	5.21 (remaining MSF)
Microroughness Sq (nm) 20x	-	2.3
Microroughness Sq (nm) 50x	-	2.6

FreeForm CaF2	Form deviation ø80 mm (ISO 10110-5) [nm]	Surface radius	Microroughness rms [nm]	Cleanliness (ISO)
Tolerances	RMSi < 150	80 +/- 0.015 mm	< 1	1 x 0.1 (at each subaperture of ø25 mm); E0.5
Results	RMSi 131.190	79.9963 mm -0.0046%	2.3	0x0.1



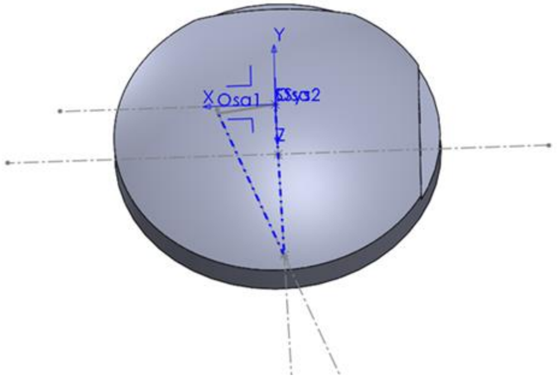
- Process time estimation

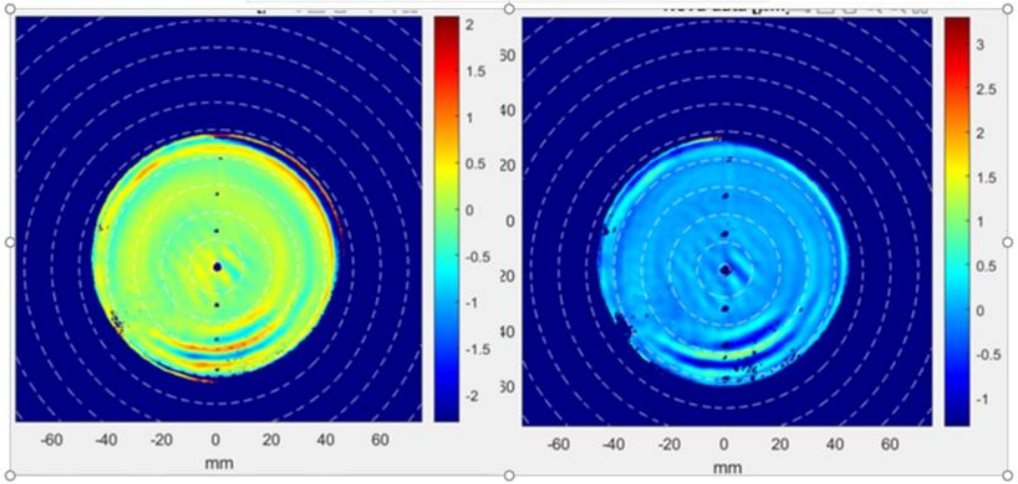
	No. of Cycles	Time sum/1 cycle .[min]
BFS generation	1	95/95
SPDT free-form surface generation	8	420/52.5
SFE measurement	1	60/60
Prepolishing and MSF suppression	8	248/31
SFE measurement	8	480/60
Corrective polishing	4	284/71
SFE measurement	4	240/60
Microroughness polishing	4	120/30
SFE and WLI measurement	4	360/90
SUM of all time		2307

fine micro-scratches formation on CaF2 by the pitch tool and diamond slurry interaction

FREE FORM MACHINING – LESSONS LEARNED

- Toptec was able to overcome and solve several difficulties to achieve project requirements:
  - Free form 3D model with detail construction steps description
  - Data handling through process chain (data format transformation, data resolution, axis orientation etc.) – applications programming in MatLab necessary
  - ASI surface error measurement data lateral calibration and recalculation





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FREE FORM MACHINING

- **Technology progress**
  - process combines a mechanical engineering approach based on Computer Aided Design and Computer Aided Manufacturing software and an optical engineering approach using specific devices
  - integration of the prepolishing steps with the Mid spatial suppression steps thanks to using the developed FEM polyurethane tool
- **Business perspective**
  - ability to produce free form elements, or optical systems with these optical elements, in very high quality
  - ability to produce TMA as part of the TRUTHS and Sboc mission or the optical system for the QUVIK satellite of the Czech Ambitious Mission under the patronage of ESA
- **Future vision**
  - usage of SPDT technology with laser assistance for other than CaF2 material
  - minimisation of the microroughness on CaF2

FREE FORM MACHINING CONCLUSION

- The ESA project 4000134543/21/NL/AR named "New Optical Polishing Techniques for Aspherical and Free-form Lenses" summarizes manufacturing and measurement techniques that enable high performance elements to be made of two main materials – crystalline CaF2 with <1,1,1> orientation and Fused Silica - those suits to both VIS and UV application as well as for space applications.
- Realization of the parts HW5 and HW6 validate the manufacturing processes on a laboratory scale, which corresponds with TRL4.
- Realized free form elements successfully reach the goal of the project as regards the surface form error to be smaller than 150 nm RMS.
- Regarding the surface micro-roughness, the goal to reach values smaller than 0.6 nm on Fused Silica was met when Toptec reached 0.51 nm.
- However, the micro-roughness level requirement of the CaF2 to be smaller than 1.0 nm. was not met due to fine micro-scratches formation.
- Toptec was able to overcome and solve several difficulties connected to the right data handling and data processing.

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THANK YOU FOR YOUR ATTENTION