MECHANICAL DESIGN OPTIMIZATION OF AN RFQ (PARTICLE) ACCELERATOR PROTOTYPE MADE BY ADDITIVE MANUFACTURING

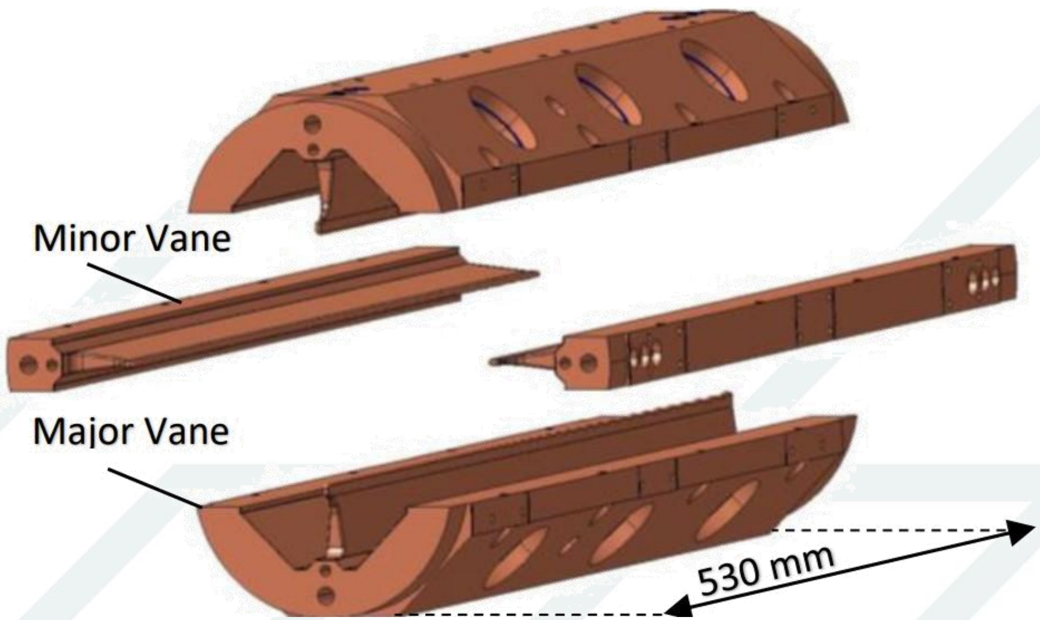
3rd CERN Baltic Conference

G.Pikurs
Supervised by:
Dr phys.M.Vretenar,
Prof. T.Torims

11/10/2023

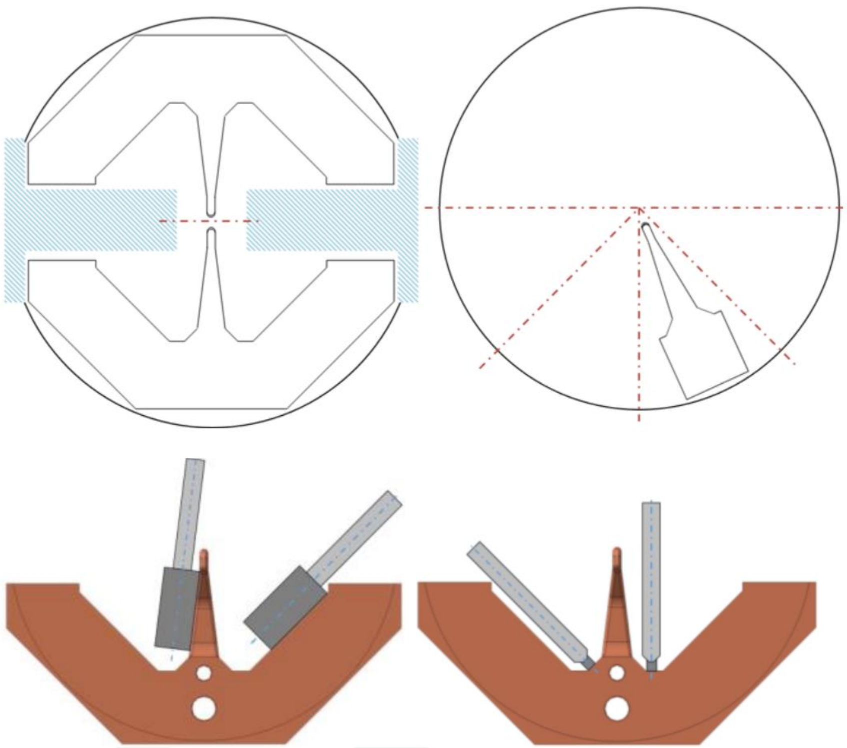
Objective of research

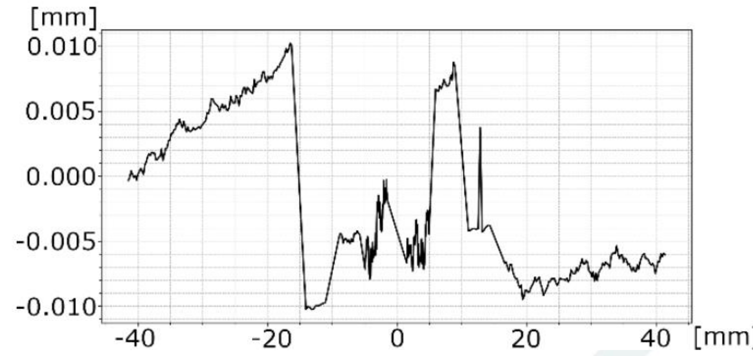
The aim is to develop a technology of RFQ manufacturing for AM-based design to improve overall performance and cost efficiency with respect to conventional technology.

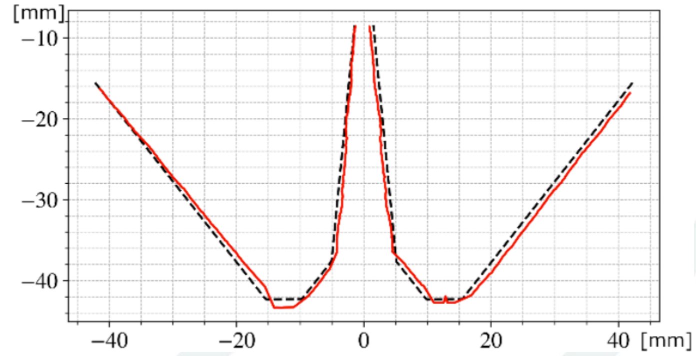


K.Scibor et.al. PIXE-RFQ modulation and cavity machining. EUSPEN20

Conventional machining approach







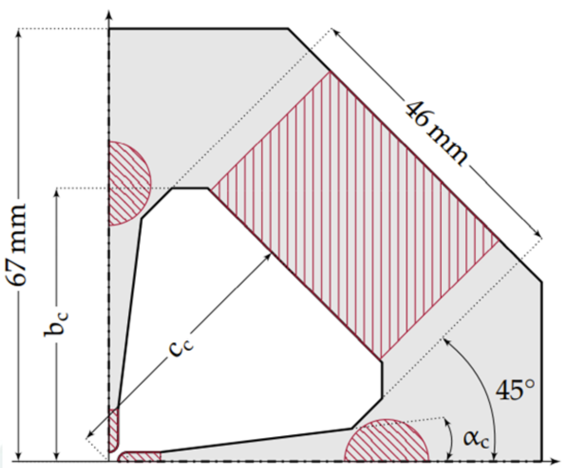
K. Scibor, S.Mathot, et.al. PIXE-RFQ modulation and cavity machining. CERN EN-MME

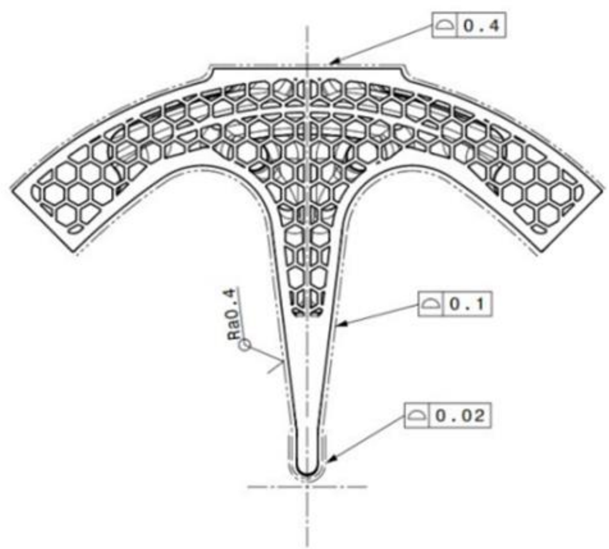
Manufacturing time for PIXE ~16months
Includes several machining, stress relief, metrology and brazing processes, in total more than 52 manufacturing steps

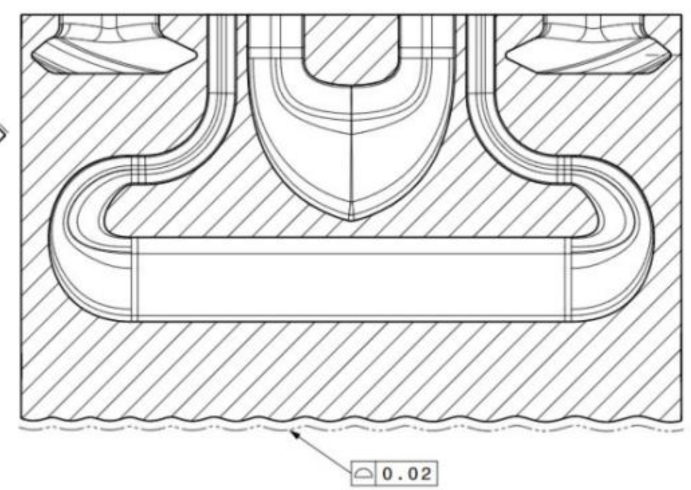
Targets set for AM RFQ

Challenge	Target
Geometrical accuracy	20μm on vane tip, 100μm elsewhere
Surface roughness	R_a=0.4μm for all inner surfaces
Cavity Quality factor	>90% Q_0
Cooling improvement	$\Delta L<2\mu$m
Limit pressure*	10^{-7}mbar
Electrical conductivity*	95% of pure copper IACS
Peak electric field on surface*	~40MV/m

* - within scope of PhD thesis

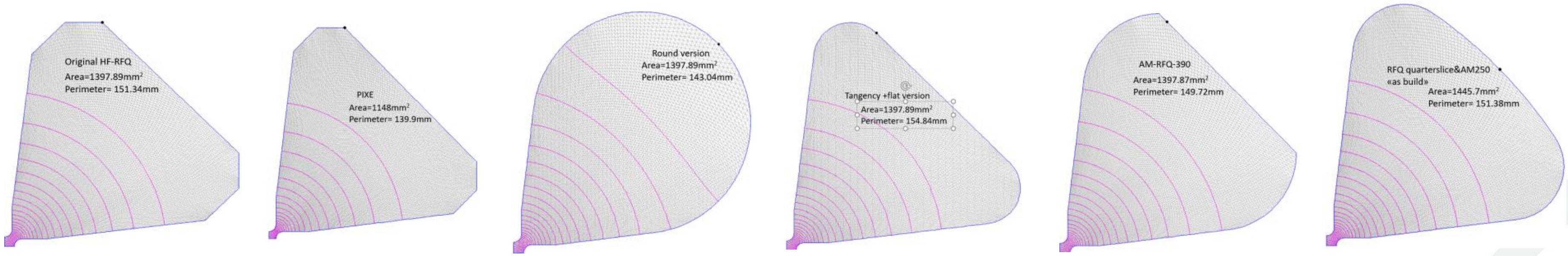






[H.Pommerenke 2020]

RFQ cavity 2D design study



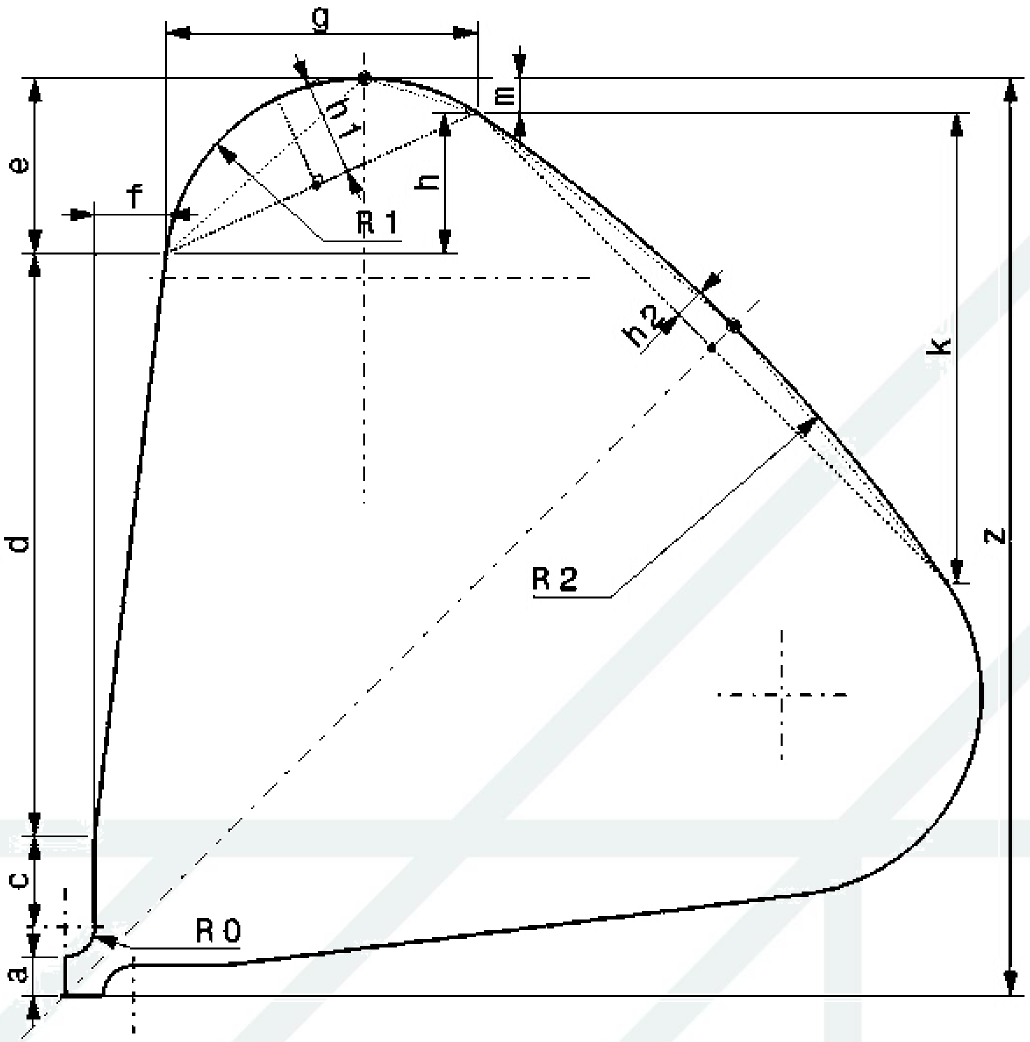
Design name	Perimeter, mm	Area, mm^2	Area/ Peri meter	R. Frequency, MHz	$Q_{0,2D}$ value	Tip R, mm	Aper ture R, mm	Shunt impendance, MΩ/m	Stored energy $x10^{-5}$J/cm
HF-RFQ	151.34	1397.89	9.237	716.56	**8028.51**	1.504	1.935	6303.89	6.8775
PIXE	139.9	1148	8.206	728.97	**7156.49**	1.439	1.439	6286.239	6.87484
Carbon	142.15	1202	8.456	709.78	**7273.45**	1.411	1.411	6620.685	6.87443
RoundDesign	143.04	1397.89	9.773	714.75	**8608.20**	1504	1.935	6737.561	6.91407
Tangency+F	154.84	1397.89	9.028	716.59	**7811.74**	1.504	1.935	6133.634	6.90091
AM390	149.72	1397.87	9.337	716.44	**8138.77**	1.504	1.935	6388.894	7.55072
AM 1/4 RFQ	**151.38**	**1445.7**	**9.550**	**703.25**	**8254.51**	**1.504**	**1.935**	**6578.903**	**6.90091**
AM250-200 µm	152.1	1475.2	9.699	736.70	**8569.27**	1.304	2.135	6574.460	4.36554

Alternative 2D quality factor model

$$Q_{0,2\mathrm{D}} = \frac{S}{L}\kappa$$

The quality factor Q is a ratio of the energy stored in the cavity to the energy dissipated in the walls per RF cycle.

$$Q_0 = \frac{\omega_0 W_0}{P_0}$$



Q-factor calculation

$$S = z^2 - (a + R_0 + c + d + e)^2 - \frac{1}{2}\pi {R_0}^2 - 2R_0c - 2R_0d - df - 2R_0ef - 2(eg - (gh + {R_1}^2 cos^{-1}(\frac{R_1 - h_1}{R_1}))) - (R_1 - h_1)\sqrt{2R_1h_1 - {h_1}^2} - 2(k + \frac{l}{2})m - (k^2 - (\frac{1}{2}k^2 + {R_2}^2 cos^{-1}(\frac{R_2 - h_2}{R_2})) - (R_2 - h_2)\sqrt{2R_2h_2 - {h_2}^2}$$

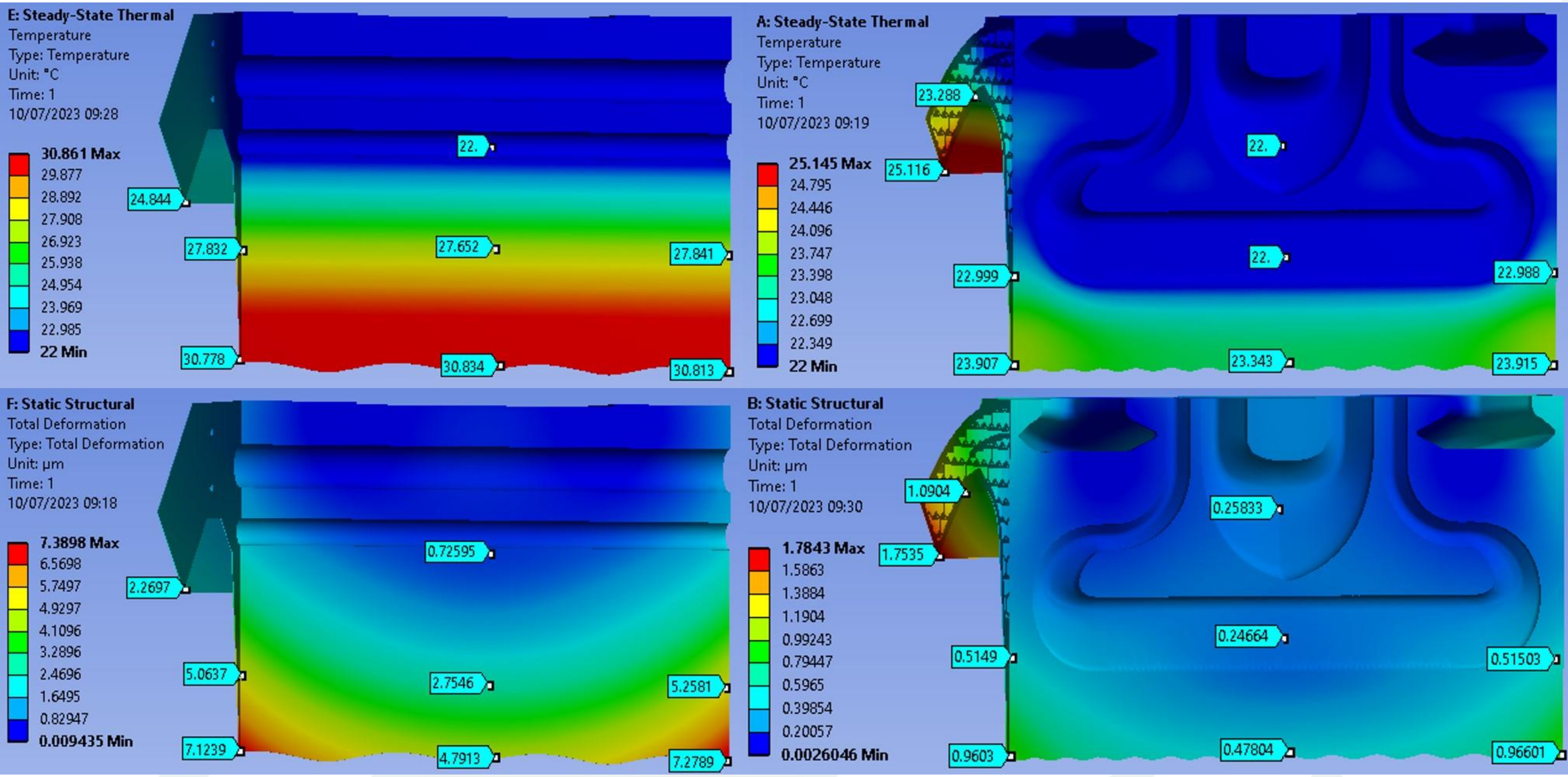
$$L = a + \frac{\pi R_0}{2} + c + \sqrt{d^2 + f^2} + 2R_1 cos^{-1}(\frac{R_1 - h_1}{R_1}) + R_2 cos^{-1}(\frac{R_2 - h_2}{R_2})$$

κ - Q factor coeficient adopted for 750MHz RFQ design line κ=890.9

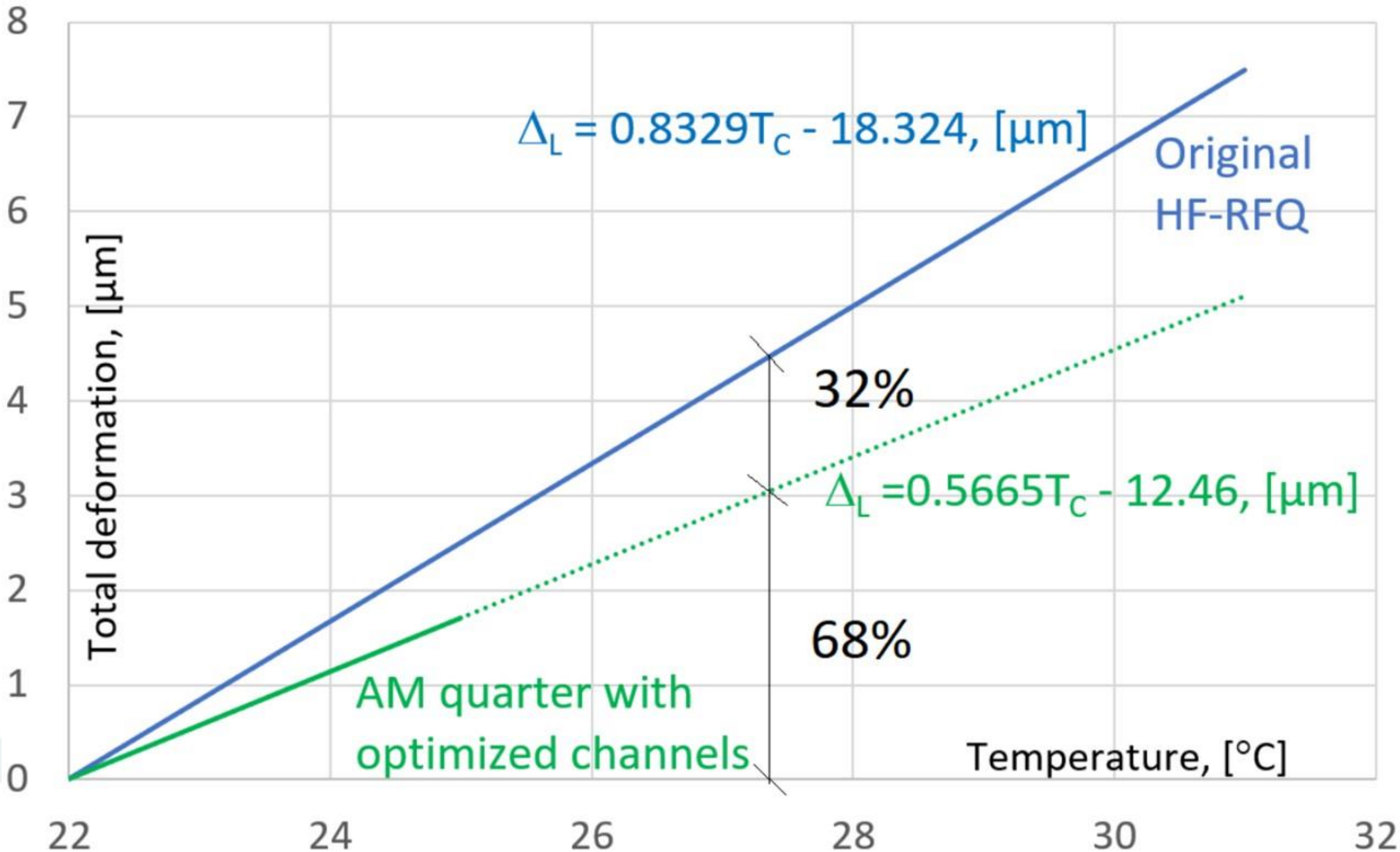
Alternative math model results

	Mathmodel				SUPERFISH				
Design name	Perimeter, mm	Area, mm^2	Area/ Peri meter	$Q_{0,2D}$ value	R. Frequency, MHz	$Q_{0,2D}$ value	Tip R, mm	Aperture R, mm	Q value deviation %
HF-RFQ	151.34	1397.89	9.237	8044.26	716.56	8028.51	1.504	1.935	0.19
PIXE	139.9	1148	8.206	7146.45	728.97	7156.49	1.439	1.439	-0.14
Carbon	142.15	1202	8.456	7364.17	709.78	7273.45	1.411	1.411	1.25
RoundDesign	143.04	1397.89	9.773	8511.03	714.75	8608.20	1504	1.935	-1.13
Tangency+F	154.84	1397.89	9.028	7862.43	716.59	7811.74	1.504	1.935	0.65
AM390	149.72	1397.87	9.337	8131.18	716.44	8138.77	1.504	1.935	-0.09
AM 1/4 RFQ	151.38	1445.7	9.550	**8317.19**	703.25	**8254.51**	1.504	1.935	**0.76**
AM250-200 µm	152.1	1475.2	9.699	8446.73	736.70	8569.27	1.304	2.135	-1.43

Temperature distribution and Max total deformation for design versions(SteadyState Thermal +Static Structural)

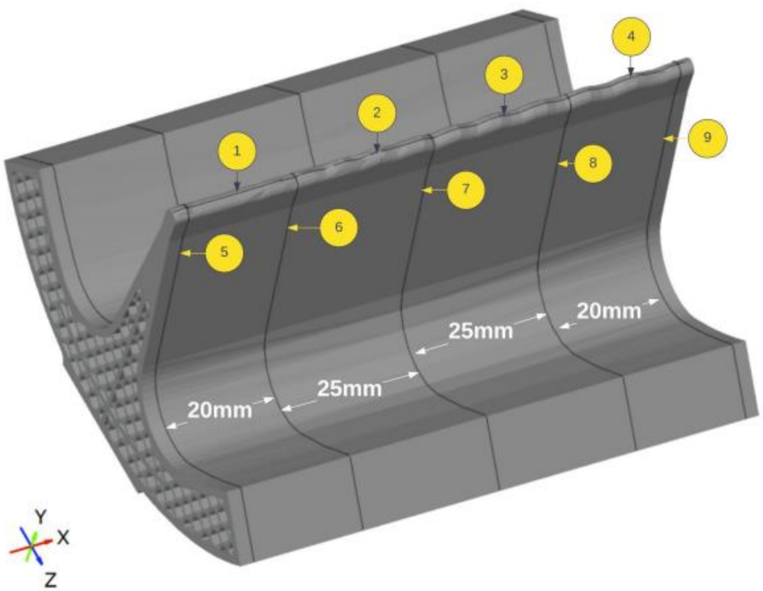


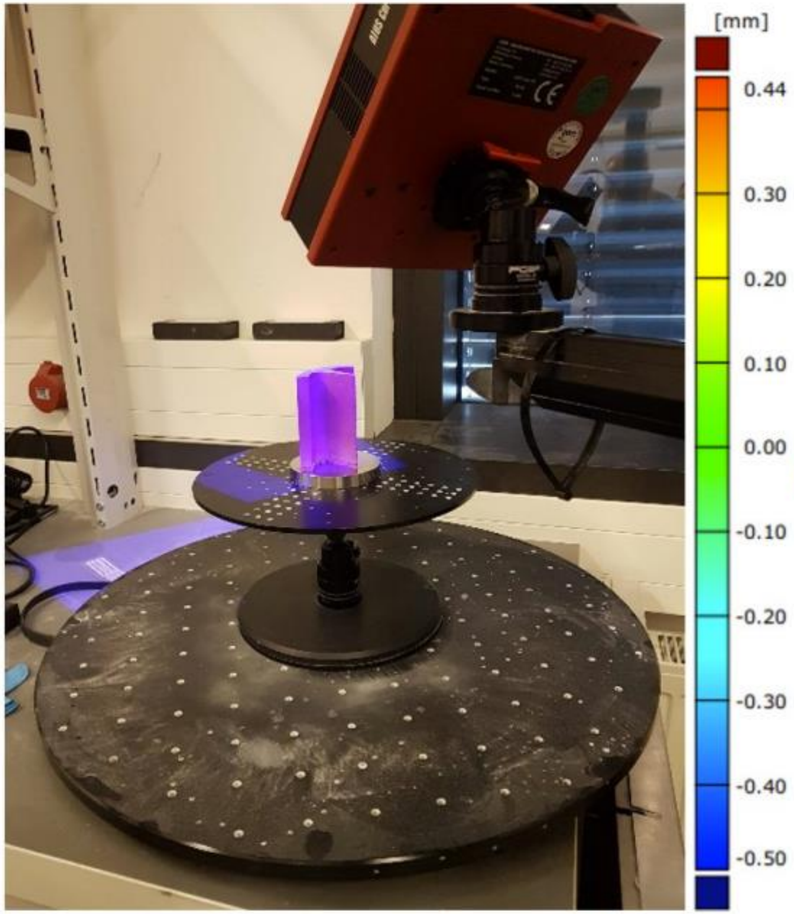
Max total deformation as function from temperature



Metrological inspections

- CMM
- Optical



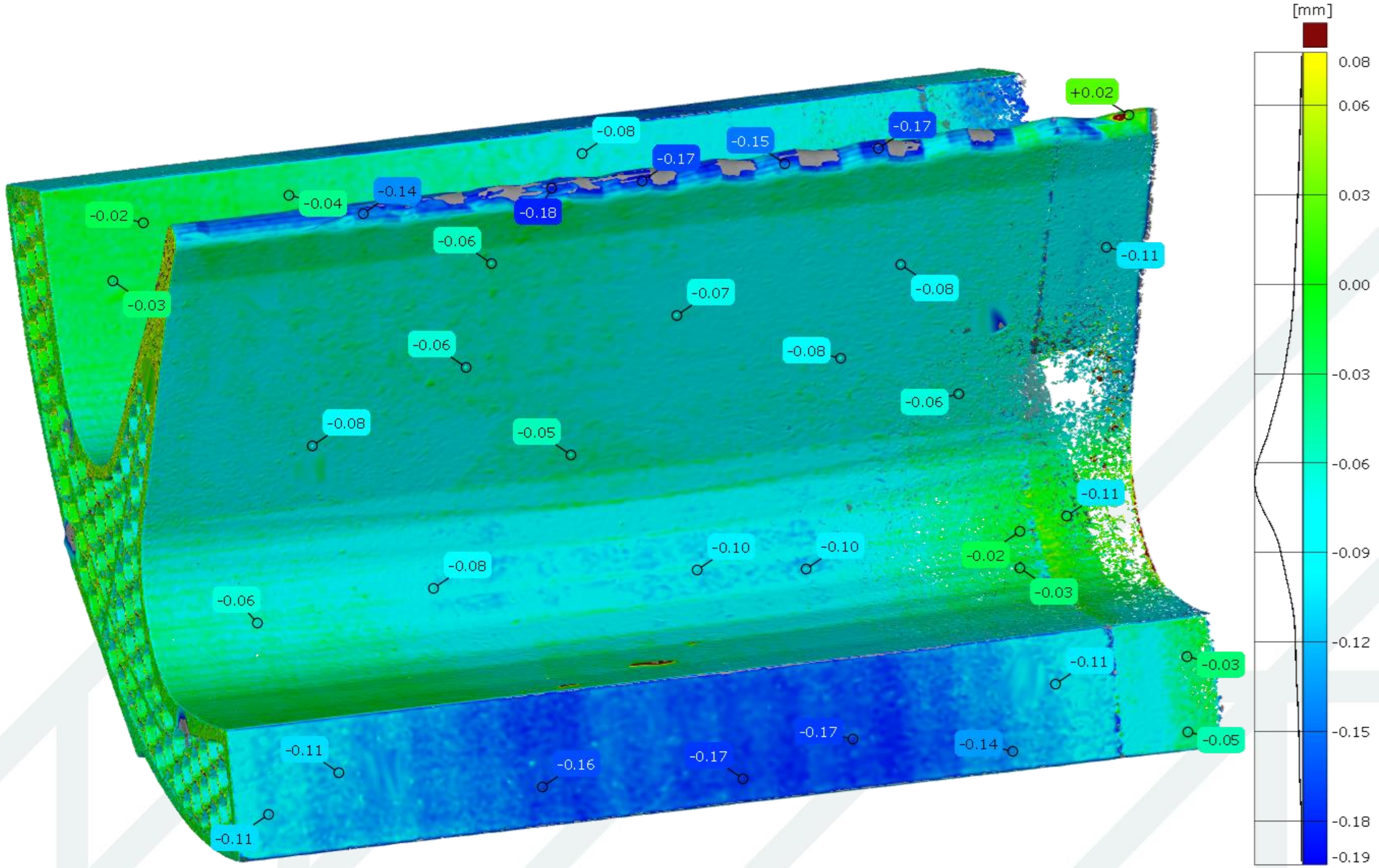


Postprocessing

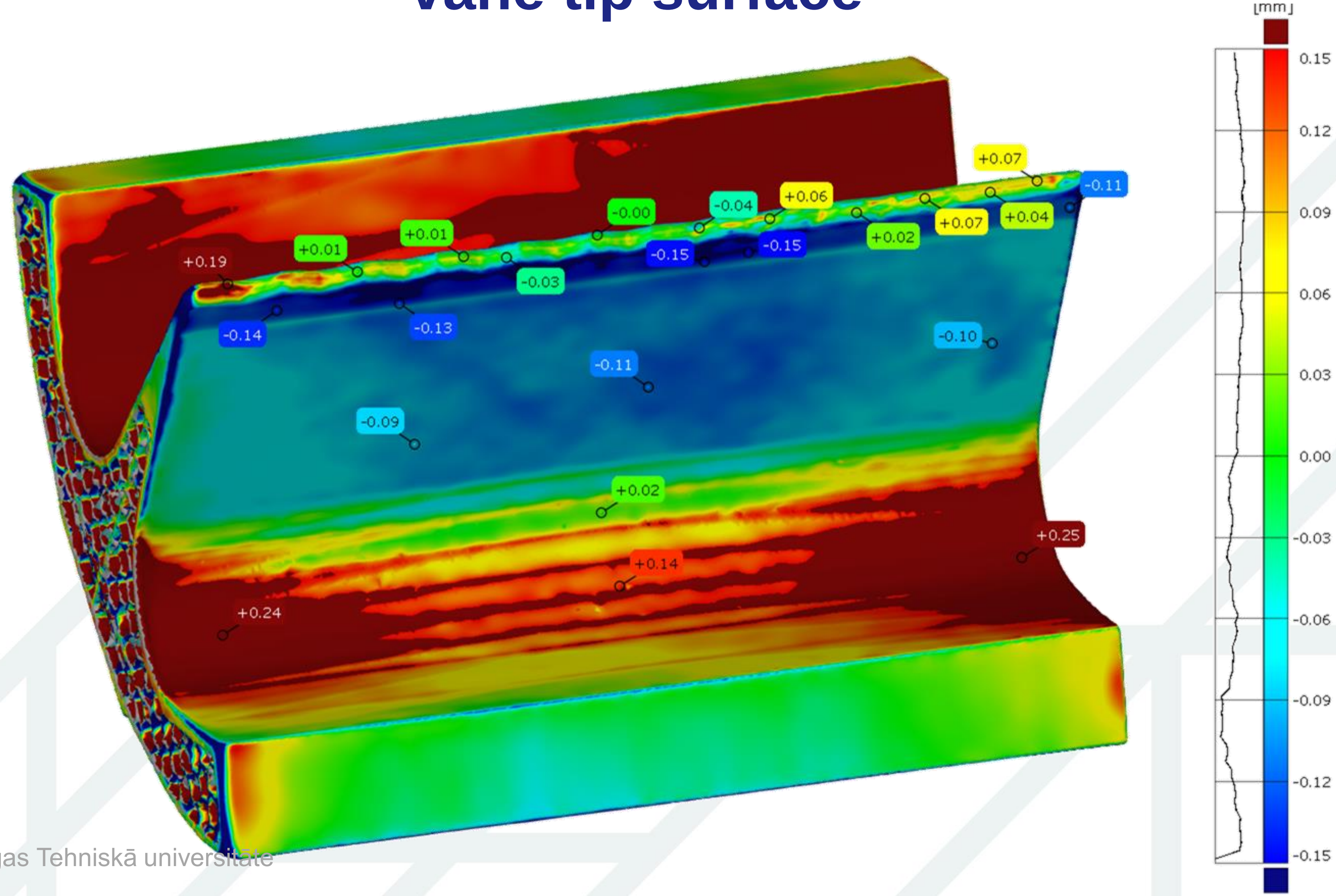
- Mass finishing at Rosler Italiana
- MMP technology® by BINC industries

-Initial surface roughness for «as built» part average profile roughness value Ra15
-Average surface profile roughness after treatment Ra0.2

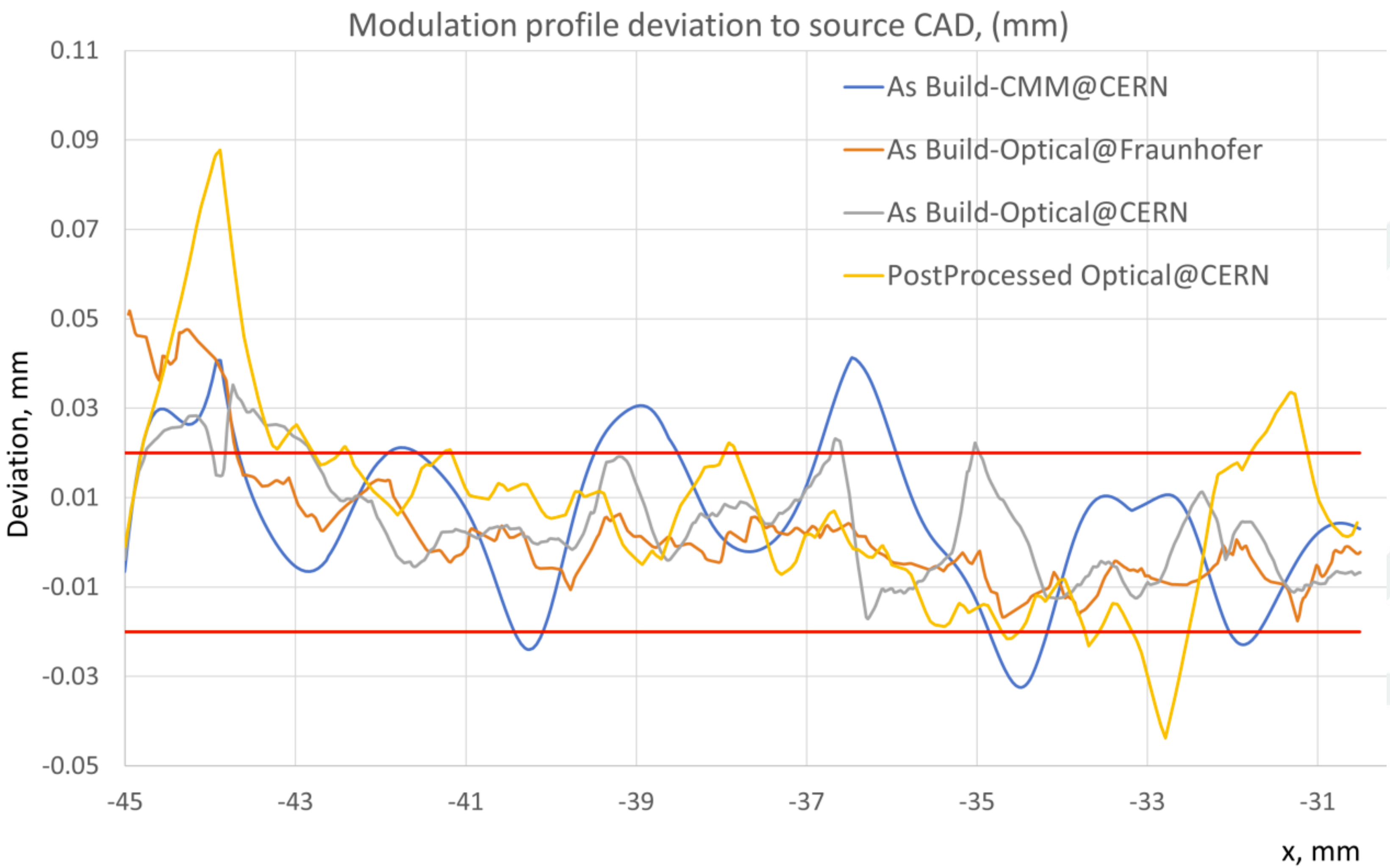
Pointcloud and CAD global «best fit» alignment for «as build» part



Postprocessed by MMP technology AM-RFQ pointcloud vs CAD model local «best fit» on vane tip surface



Vane tip modulation deviation



AM vs conventional technology

Parameter	Conventional	AM	Reduction, %
Manufacturing time, months	16*	4**	75
Material waste, %	41.2	2.5	39.7
Number of manufacturing substeps	52***	15	71
Weight****, kg/m	175	55	68.6
Geometric accuracy	excellent	acceptable	-10
Cooling performance by Δ_L, μm	$0.8329T_C$-18.324	$0.5665T_C$-12.46	32
Quality factor Q_{2D}	8028.51	8254.51	2.6

* - value from ELISA project for PIXE RFQ;

** - estimated values based on IFAST WP10 activities and assumptions;

*** - PIXE technology;

**** - weight calculation for full RFQ sector/brazed unit

Conclusions

- AM is a highly progressing technology and it is well suited for the complex geomeries of accelerator components.
- AM allows improvement of the shape and routing of the RFQ cooling channels, improving heat removal and thermal distortions significantly.
- Surface postprocessing for AM parts are critical and compensation methods must be applied.

Thank you for attention!