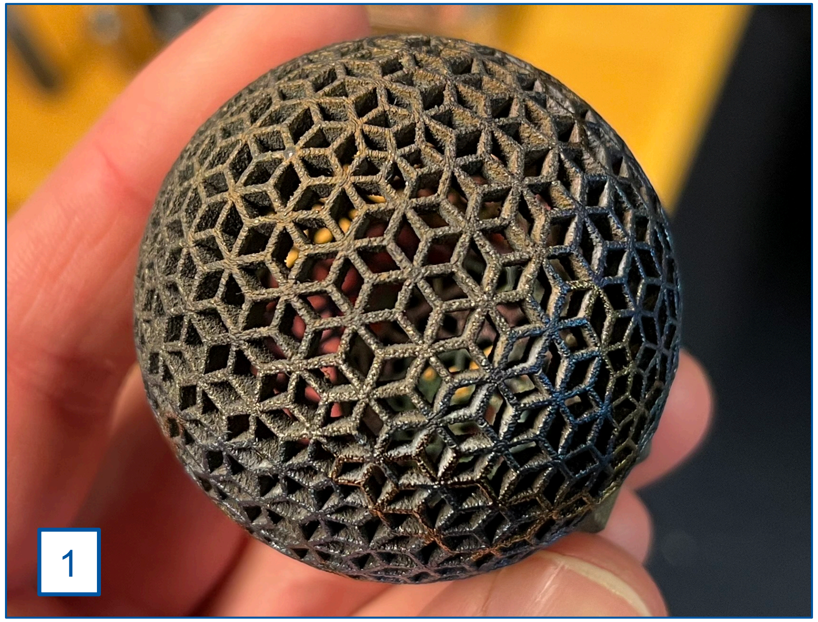
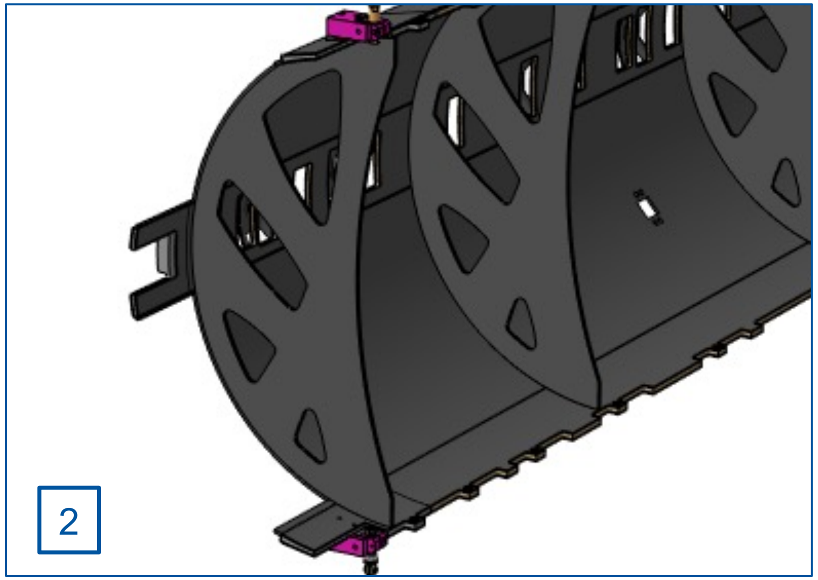
Mass optimization by additive manufacturing

Axel Filenius, 10.06.2022

Motive

- **Ideally a silicon tracking detector, like the CMS Tracker, would contain no metallic components with high-atomic number elements inside the tracking volume**
  - In reality this is simply not feasible, as some components can't be replaced by composites or plastics due to permeability, isotropicity, conductivity or compressive applications
- **As it is not possible to avoid metallic components, it is important to optimize these components to high degree**
- **An attractive path to optimization is to combine two technologies:**
  1. SLM manufacturing
  2. Computational topology optimization



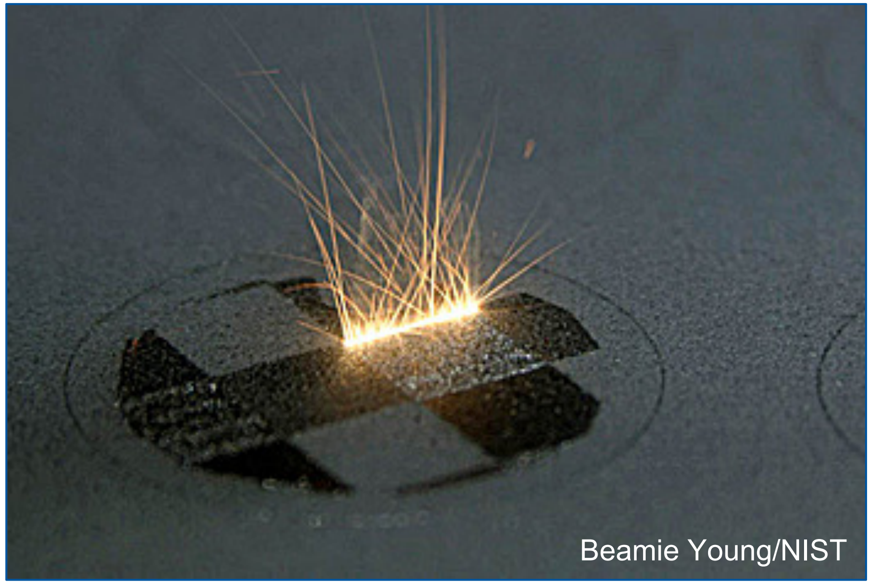


SLM Manufacturing

Basics of SLM

- **SLM (short for Selective Laser Melting), is an additive manufacturing method used for creating metallic structures additively**
  - Based on fusing small particles of chosen metal together with a focused laser beam
  - Built up layer by layer from a buildplate in a powder container
- **Wide range of possible materials:**
  - Stainless Steel 316L
  - Ti64
  - Aluminum
  - Inconel
  - Copper
  - Tool steel

Main interests for CMS Inner Tracker

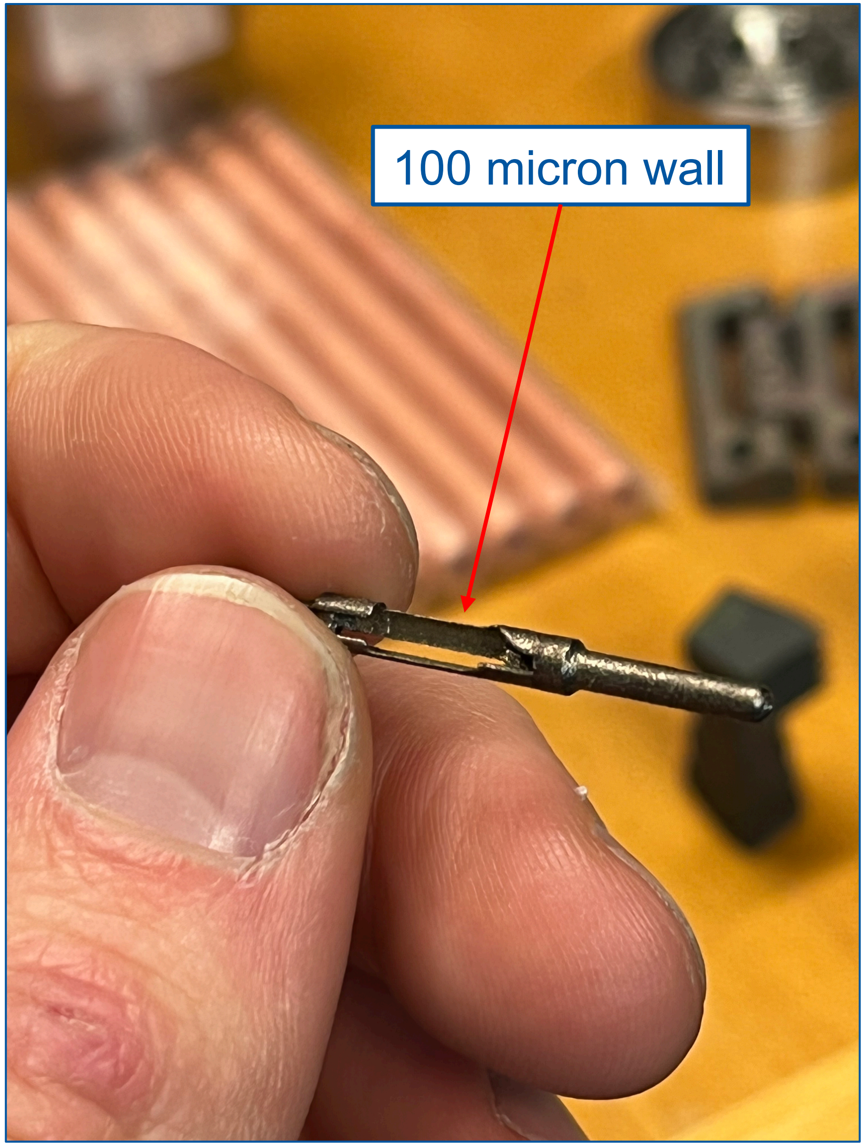


Key SLM questions (for CMS IT)

- **For our applications in the CMS Inner Tracker, there were some key questions about the SLM method that needed answering:**
  - Leak tightness of the prints (CO_2 cooling applications)
  - Material strength and stiffness variability in different planes (large anisotropicity could be problematic)
  - Weldability of the prints (CO_2 cooling applications)
  - Blockage of internal cavities (CO_2 cooling applications)
  - Leftover particles in cavities (CO_2 cooling applications)
  - Additives in the raw material (Radiation environment)
- **In order to gain understanding on these open questions, visited Delva in Finland with a prototype project proposal**
  - -> Procured prototype components in 316L Stainless Steel, more in later slides

Leak tightness

- **With EOS machines (Delva), able to achieve leak tight wall above 300microns**
  - Limited to this by the size of the laser beam and metal melt pool during the sintering process
  - Approximately 100 micron melt pool
  - 3 laser passes (infill between two outer walls) achieves good results
- **Have printed parts with 600micron wall parts capable of 680bar internal pressure**



Material properties (316L, 40µm)

System set-up	EOS M 290
EOS ParameterSet	316L 40µm FlexLine
EOSPAR name	316L_040_FlexM291_1.X
Software requirements	EOSPRINT 2.7 or newer EOSYSTEM 2.11 or newer
Powder part no.	9011-0032
Recoater blade	EOS HSS blade
Nozzle	EOS grid nozzle
Inert gas	Argon
Sieve	63 µm

Additional information	
Layer thickness	40 µm
Min. wall thickness	0.1 mm
Typical dimensional change after HT	+0.2 %
Volume rate	3.7 mm³/s

Powder chemical composition (wt.-%)

Element	Min.	Max.
Fe	Balance	
Cr	17.00	19.00
Ni	13.00	15.00
Mo	2.25	3.00
C	-	0.03
N	-	0.10

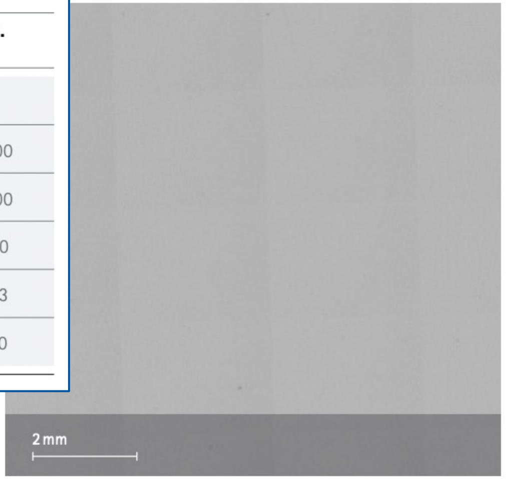
Heat Treatm

Heat treatment according to AMS 2759 is optional.

Stress relief: Hold temperature 900 °C, hold time minimum 2 h when thoroughly heated, water quenching

Solution annealing: Hold temperature 1 150 °C, hold time minimum 1.5 h when thoroughly heated, water quenching

aph of polished surface



Microstructure solution annealed
Etched with etchant Kallings 2

Defects	Result	Number of samples
Average defect percentage	0.015 %	20
Density, ISO3369	**Result**	**Number of samples**
Average density	≥ 7.97 g/cm³	20

Mechanical properties ISO6892-1

	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation at break A [%]	Number of samples
Vertical	480	570	51	105
Horizontal	540	640	40	90

Variability in material strenght/elongation in the different planes is relatively small (15%)

Expected Youngs modulus variability in the same 15% range

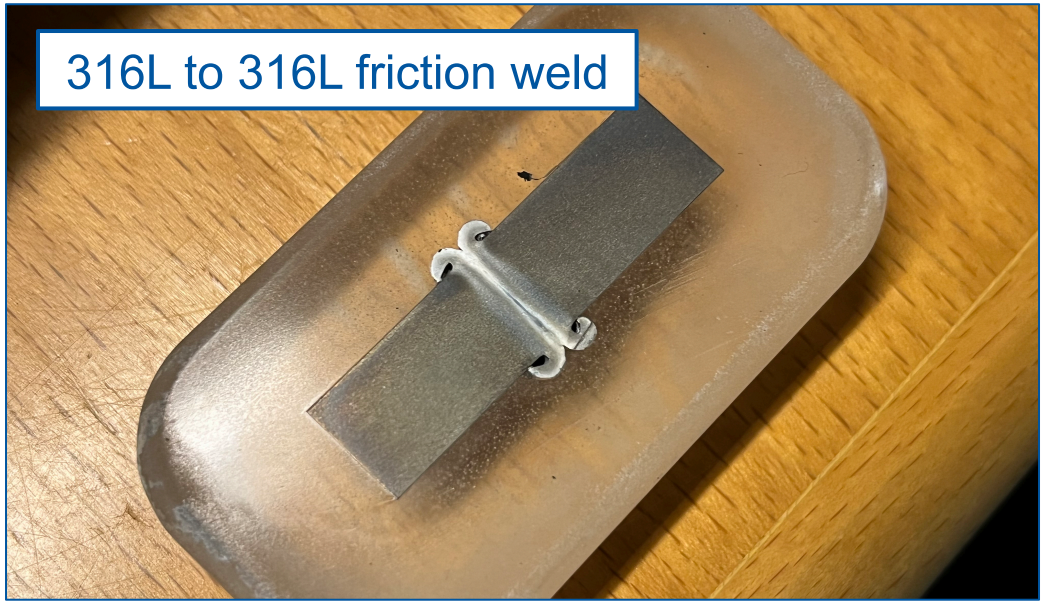
Weldability

316L SLM part welded to a standard 316L pipe

This sample cleaned by hand, welded in Argon bath

Weldability for parts incorporated in CO_2 systems studied further at Cornell University with the prototype samples ordered !

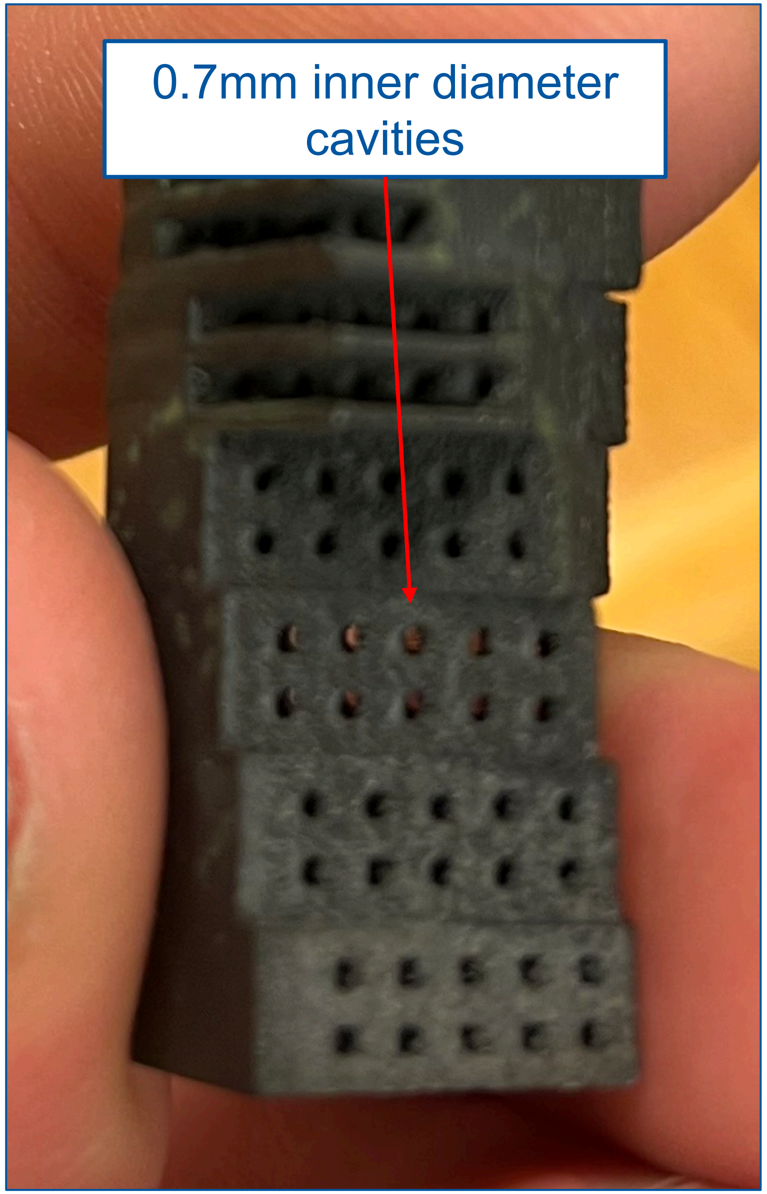
316L to 316L friction weld

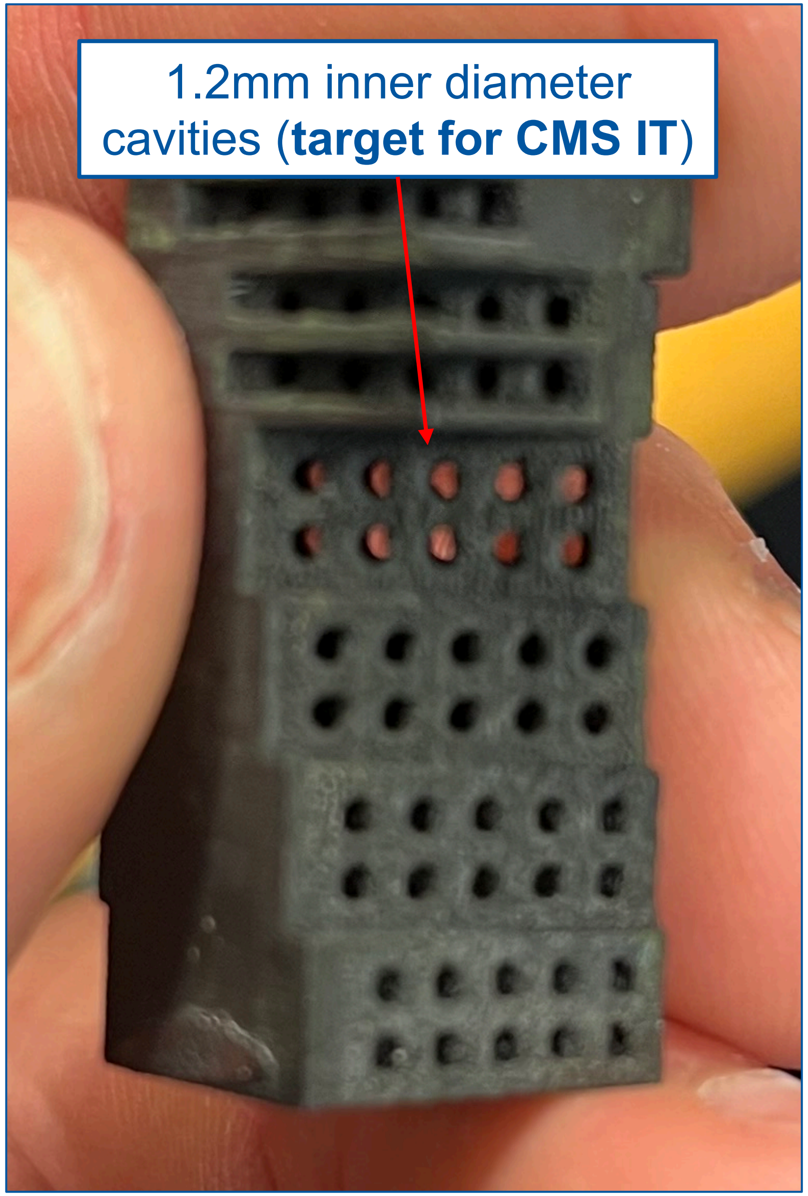


316L to Toolsteel friction weld

Cavities

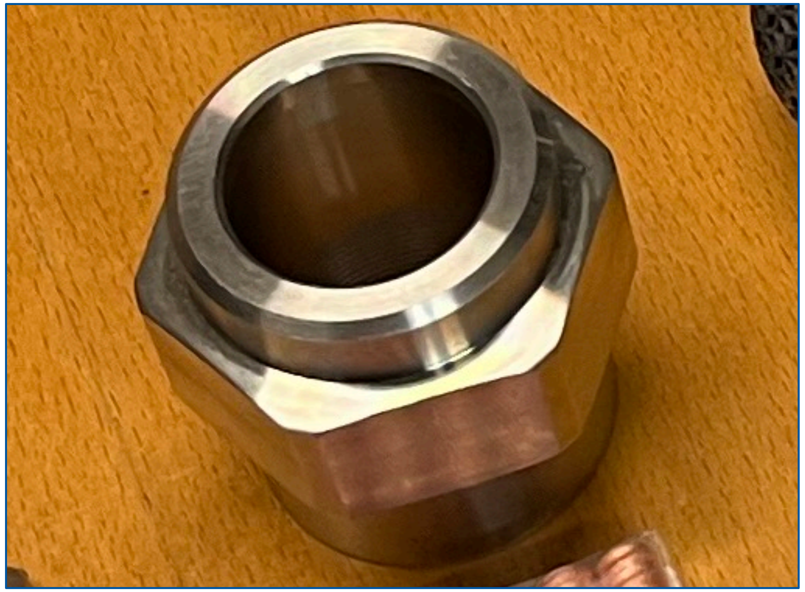
- **Able to hit CMS IT target for minimum cavity size easily**
  - 0.7mm minimum achievable ID
- **Electrochemical bath given to parts after heat-treatment**
  - Removes impurities from the heat-treatment
  - Eats away leftover particles stuck on print walls
  - Possible to also do gold-plating etc. for soldering purposes

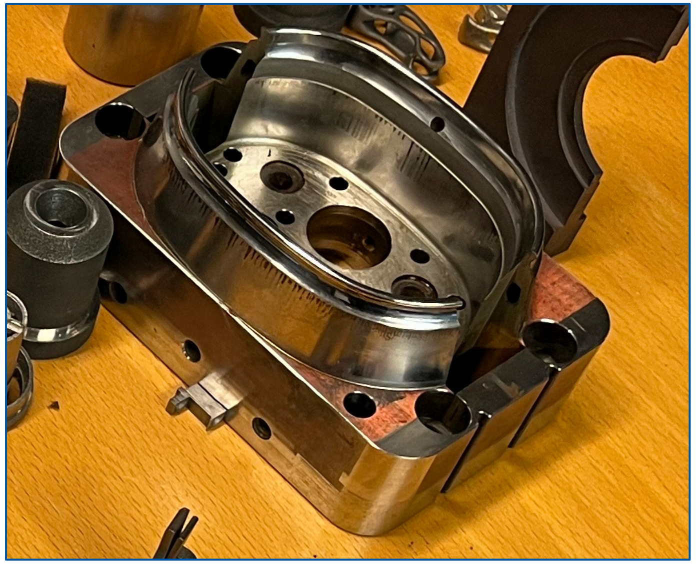




Machinability

- **SLM parts can be machined like any other metals**
  - Of course, need to adjust feed rates etc. specifically for SLM metals
- **SLM part post-processing often consists of machining/planing some reference surfaces**





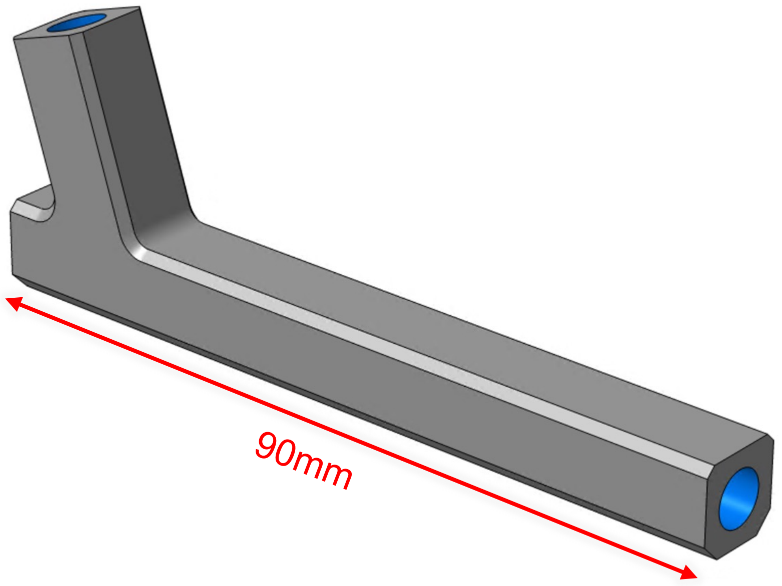

Design optimization for SLM

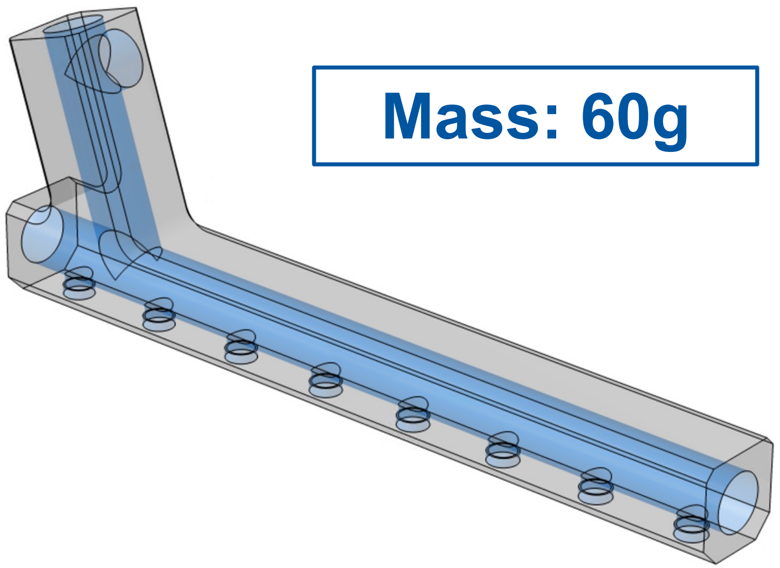
Design optimization

- **By utilizing SLM it is possible to free a part design from the constraints implied to it by subtractive manufacturing**
  - Possible to do complicated internal cavities
  - Possible to do complex surface shapes
- **Optimization of parts for SLM, in principle, just means utilizing mostly free design while taking into account the few constraints of additive manufacturing**
  - Can’t print parts in thin air without temporary supports
  - Need to support geometry during printing if exceeding 45-degree overhangs
  - With commonly available SLM printers the wall quality and integrity degrades when thickness falls below 400-300micron range
  - Limited overall size of part
  - Need to keep in mind post processing needs, like tooling jig needs for machining

TFPX return manifold, subtractive manufacturing

- **Simple Stainless Steel block machined to a T-shape**
  - Drilled in multiple operations
  - Plugged by welding caps to create closed fluid rails
- **Mass optimization of this part would require difficult machining operations, increasing cost and time**
  - Furthermore, not possible to optimize the internal fluid volume at all

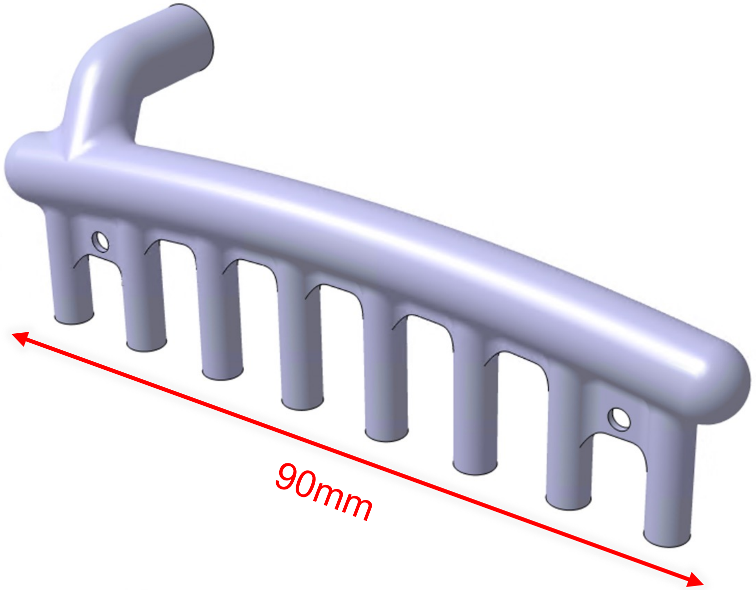




Mass: 60g

TFPX return manifold, additive manufacturing

- **When utilizing SLM manufacturing, able to optimize the design to a much higher degree even by hand**
  - Closely shrink-wrapping the part wall around the fluid volume while respecting the required wall thicknesses needed for our pressure testing to achieve minimum mass
  - Able to locally increase material where needed for strength
  - Able to have pipe stems and guides for easy welding



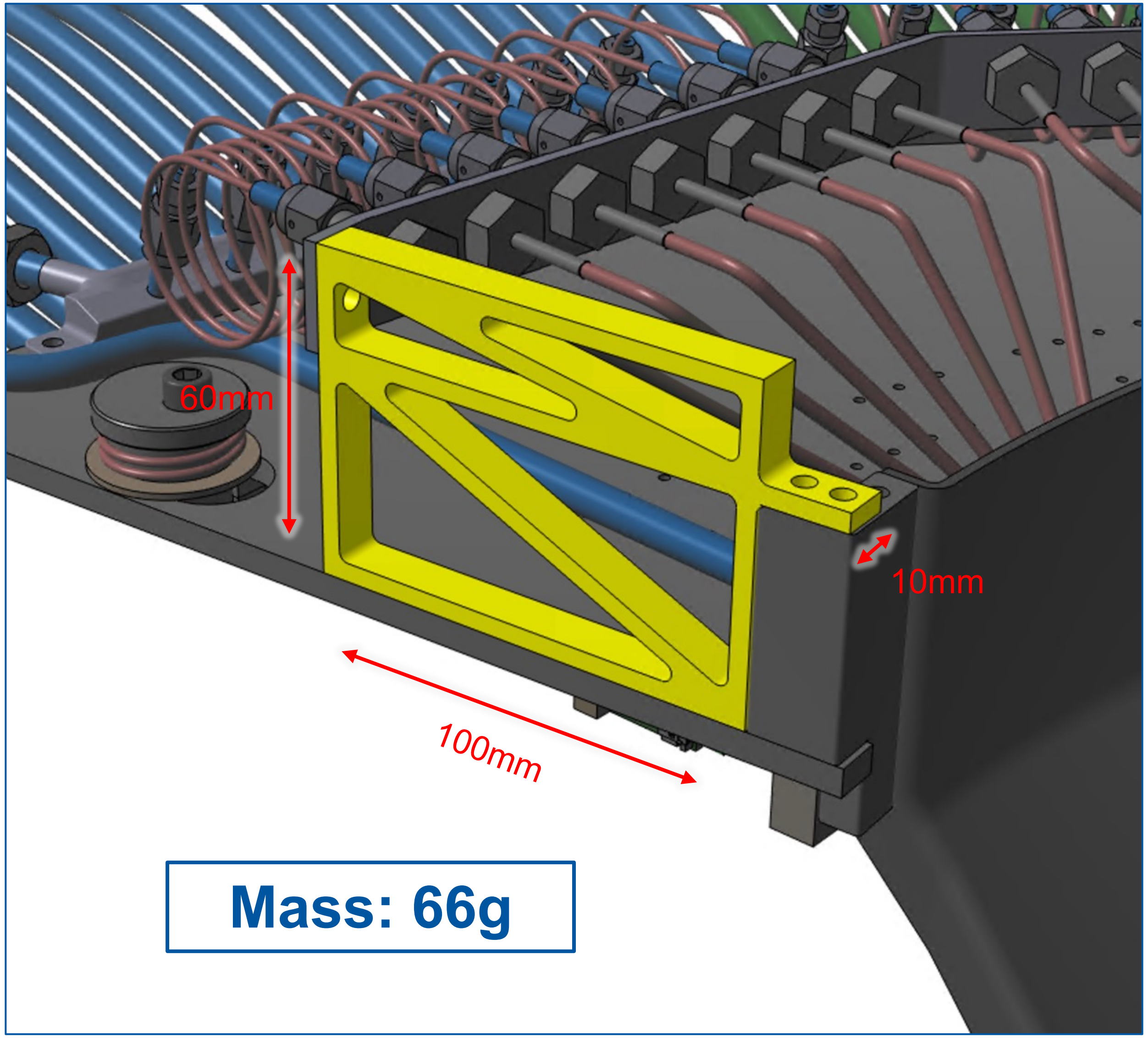
Mass estimate: 29g

Deductive optimization

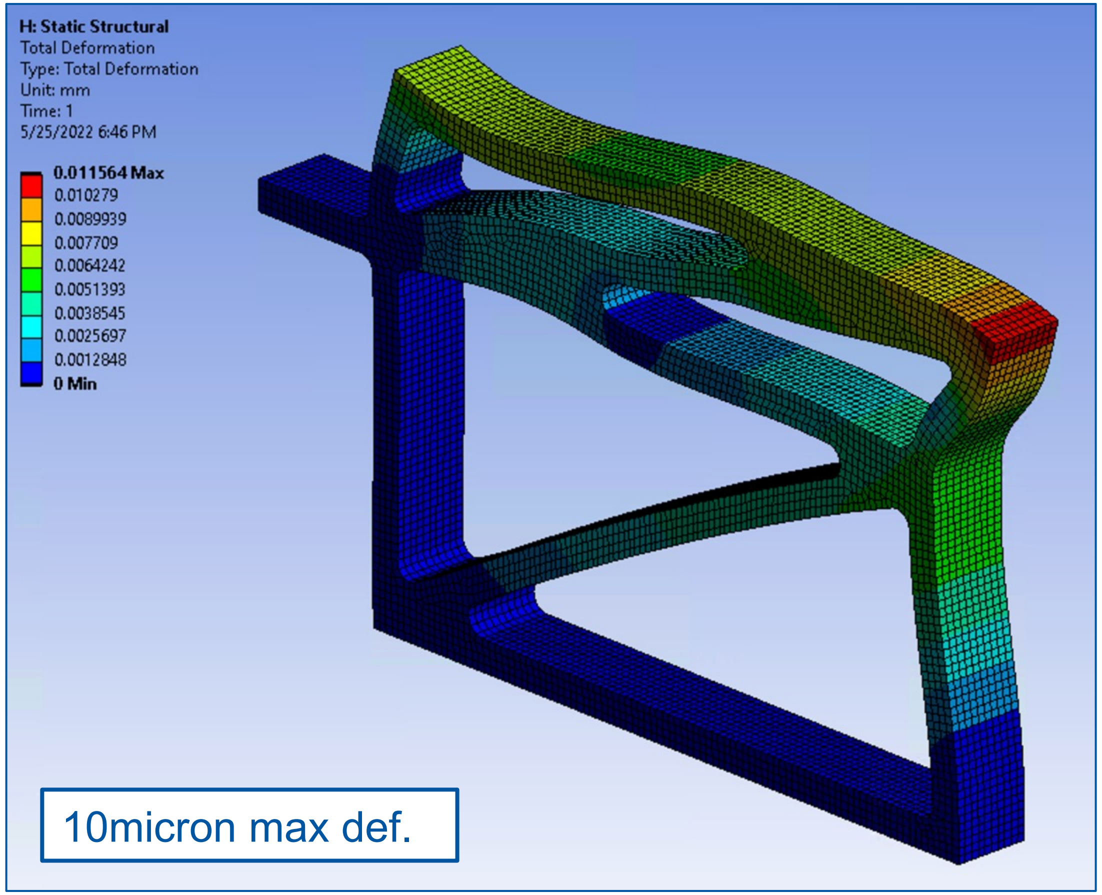
- **Deductive optimization (”Topology optimization”) is a computational optimization method working with the principle of optimizing by removal of material**
  - Can be set by the user to aim for different targets like compliance, stress, deformation or mass
- **In this automatic optimization the software is given a starting point as a region of material with supports and loads**
  - The software then iteratively calculates what regions of material can be removed while still respecting the targets set by the user
  - Sensitive to boundary conditions

TFPX Antler support, subtractive manufacturing

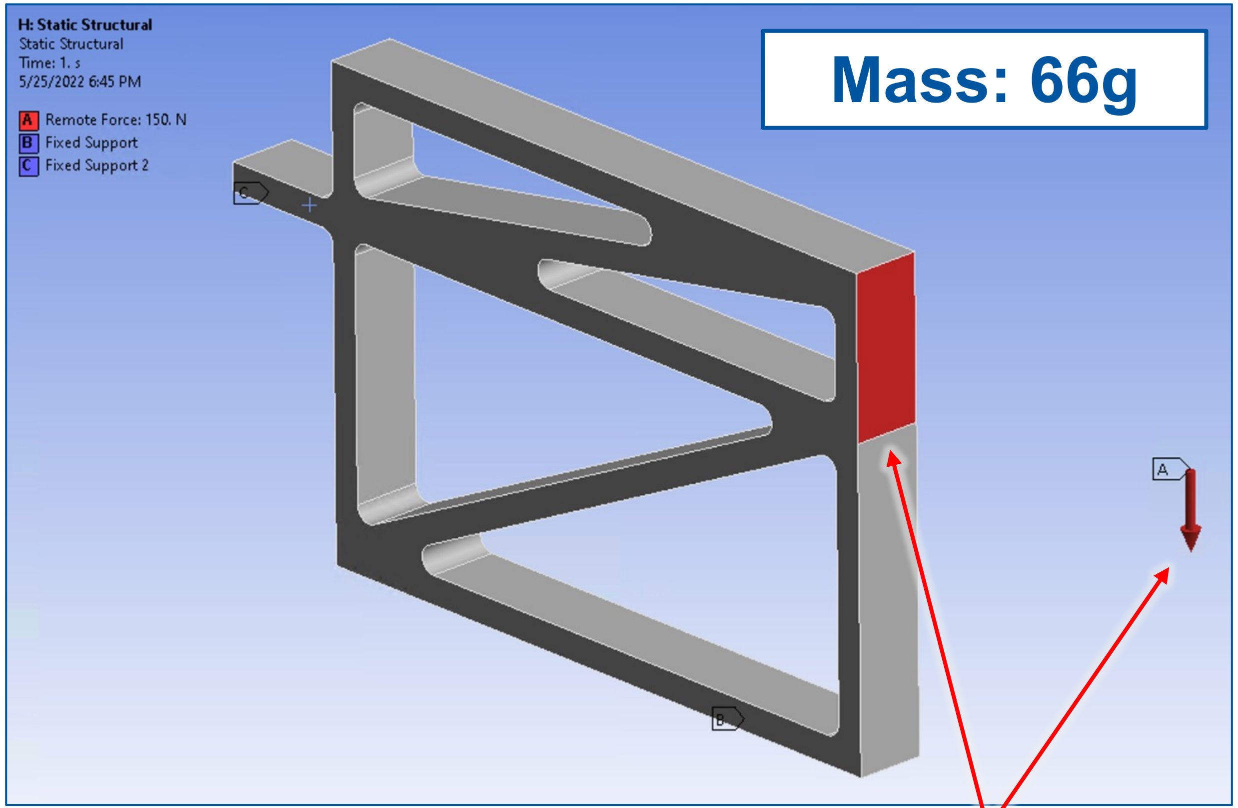
- **A fairly simple piece, easily machined with a 3-axis mill**
  - Aluminum
  - A very basic design, works sufficiently for the application



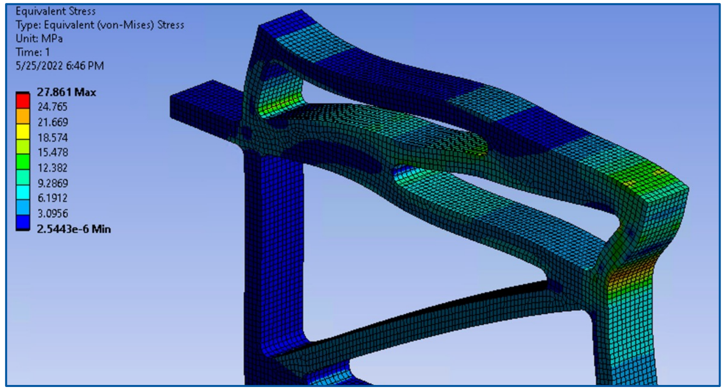
TFPX Antler support, subtractive manufacturing



10micron max def.



Mass: 66g



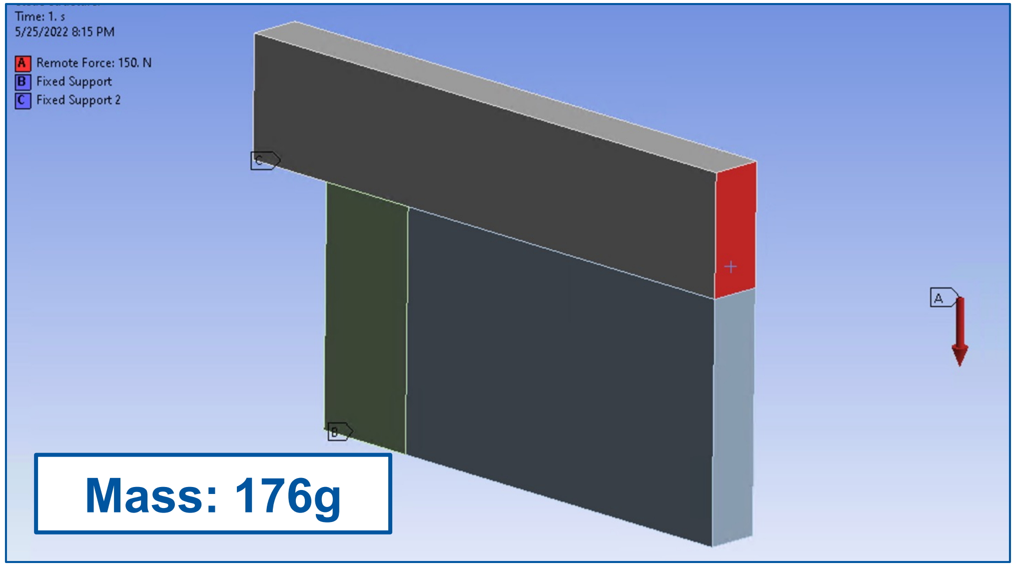
150N remote force, simulates an accidental high load while mating cooling connections

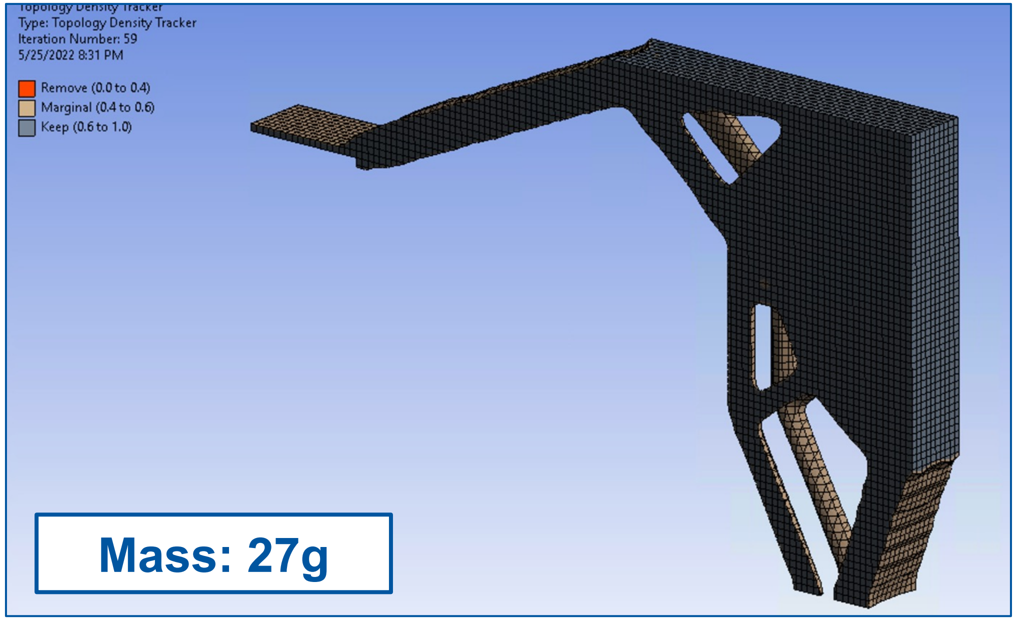
28MPa max global stress

TFPX Antler support, additive manufacturing

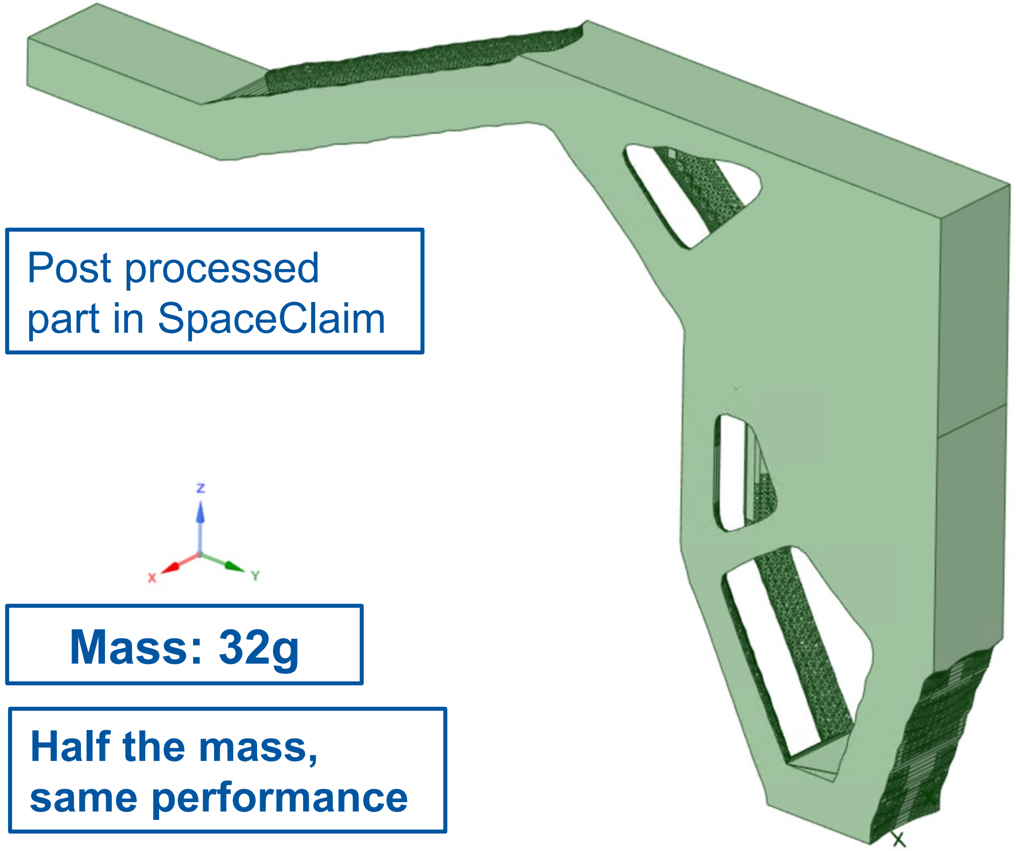
- **For topology optimizing the support, ANSYS is given a block of material with the same boundary conditions as were used for the previous simulation**
  - Starting block mass 176g
- **The topology optimization is given a compliance target with a mass requirement of 15% of the original mass**
  - Compliance target
  - Minimum member size 2mm
  - Maximum member size 10mm

Maximum global stiffness





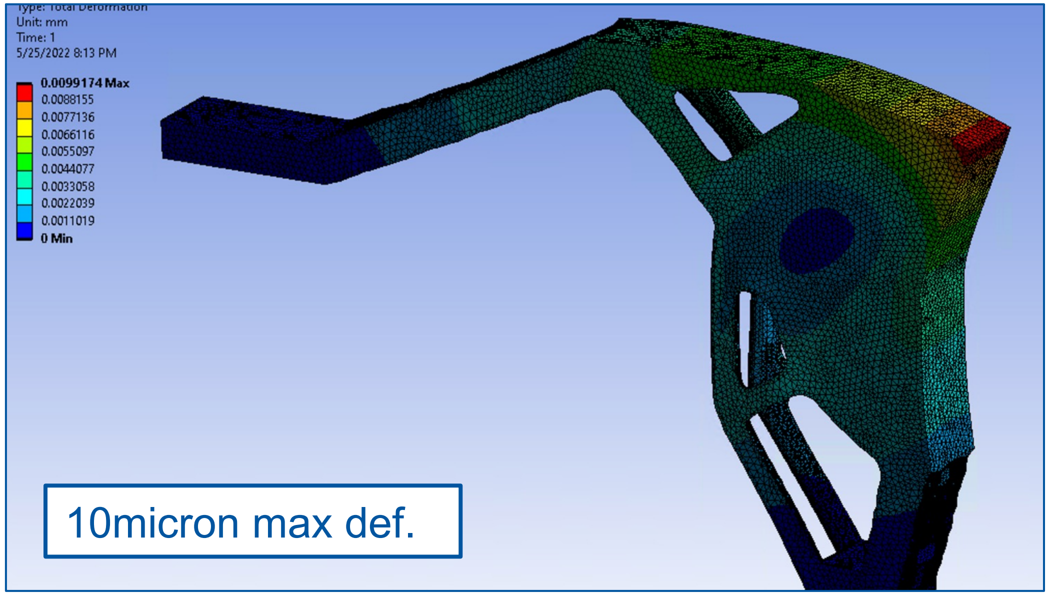
TFPX Antler support, additive manufacturing



Post processed part in SpaceClaim

Mass: 32g

Half the mass, same performance

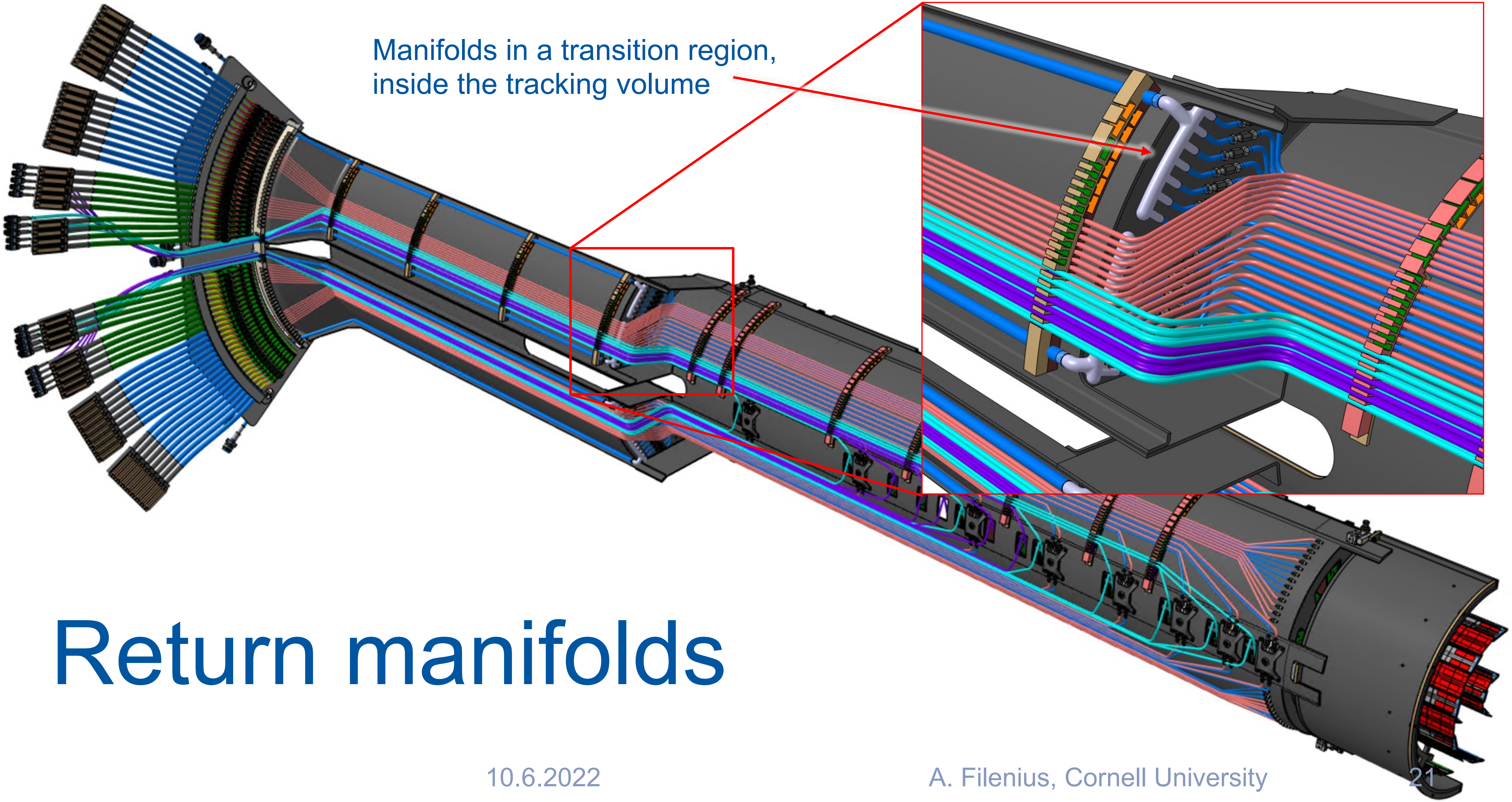


10micron max def.

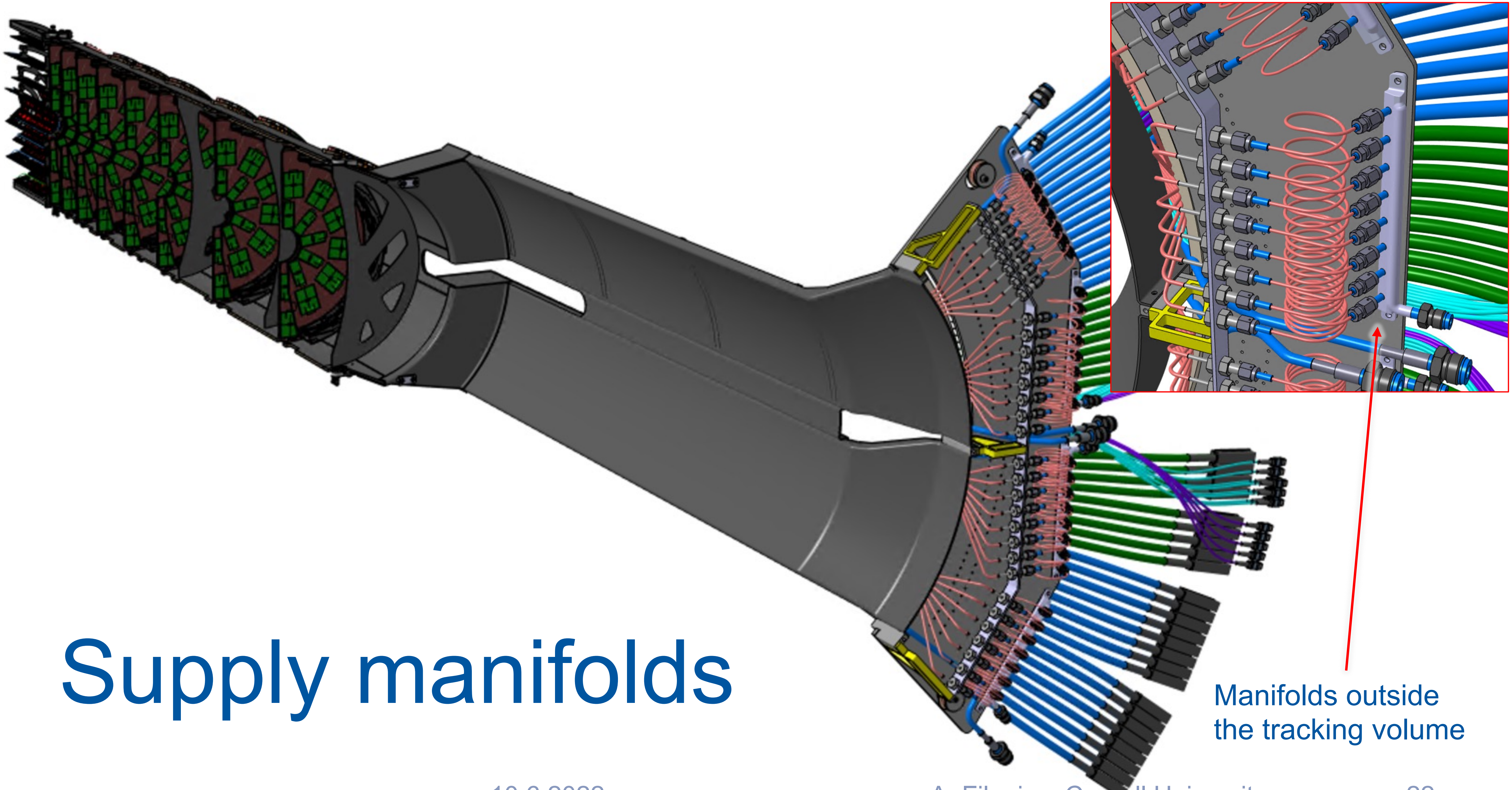
25MPa max global stress

TFPX CO_2 manifold prototypes

Return manifolds

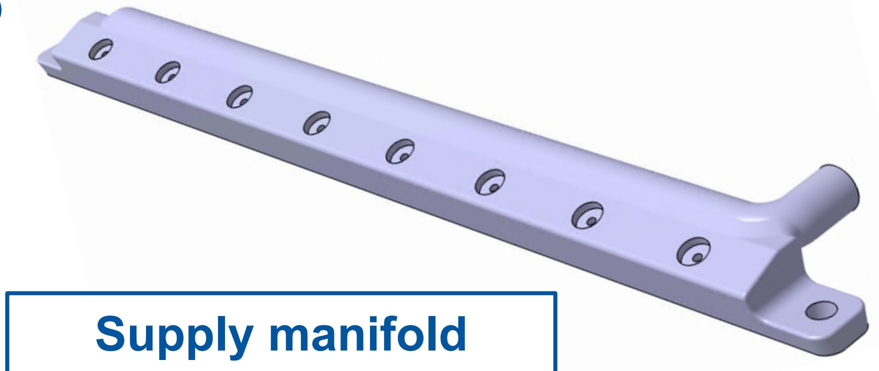


Supply manifolds

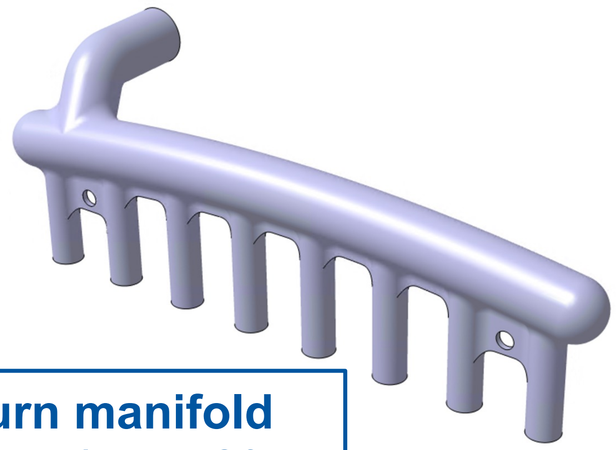


TFPX CO2 manifolds

- **To evaluate and prove the feasibility of SLM parts for use in the CMS Inner Tracker cooling system, a set of 8 CO2 manifold pairs was procured from Delva**
- **Relatively affordable:**
  - 140€ for SLM (per piece)
  - 170€ for post-processing (per piece)



Supply manifold
Mass estimate 120g
(non-mass critical area)



Return manifold
Mass estimate 29g

System's pressure ratings

Large volumes

- Cooling plant, accumulator, manifolds, main transfer lines...

Protected by safety valves

Maximum allowable pressure: **100 bar**

Tested with a safety factor of 1.43

- Test pressure at **143 bar**

Small volumes

- Detector transfer lines, on-detector piping...

Protected by burst discs

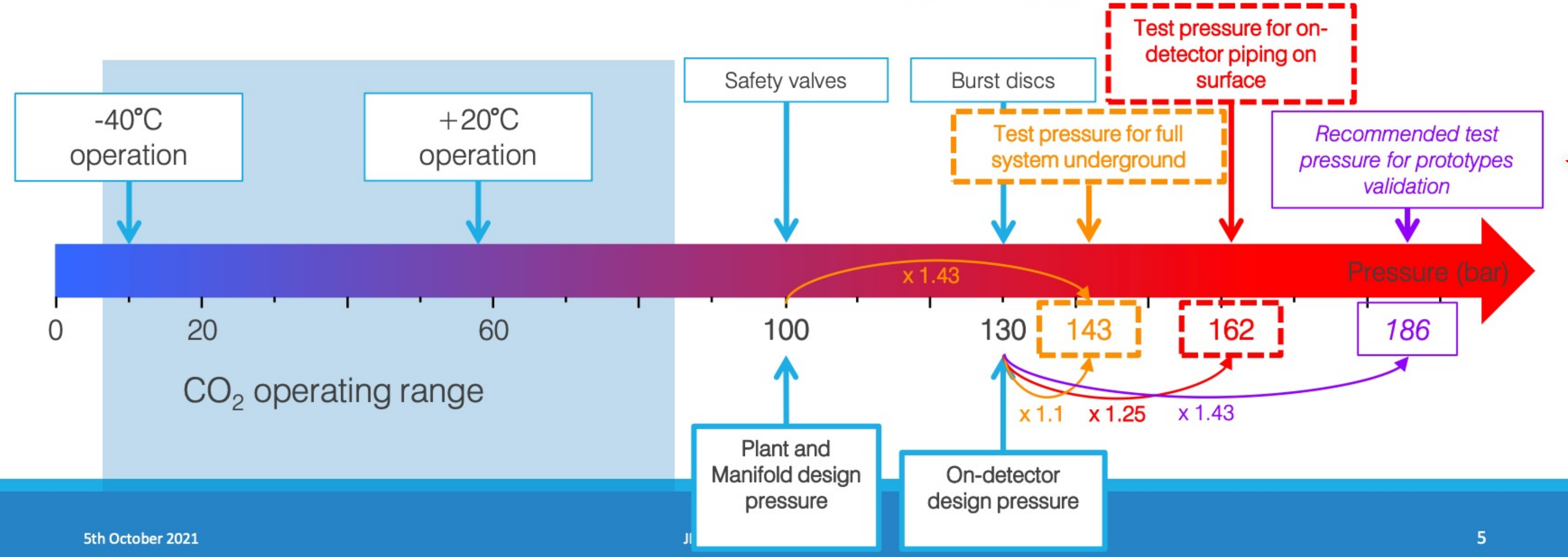
Maximum allowable pressure: **130 bar**

Tested in the factory or collaborating institute with a safety factor of 1.25

- Test pressure at **162.5 bar**

Tested in situ with a safety factor of 1.1

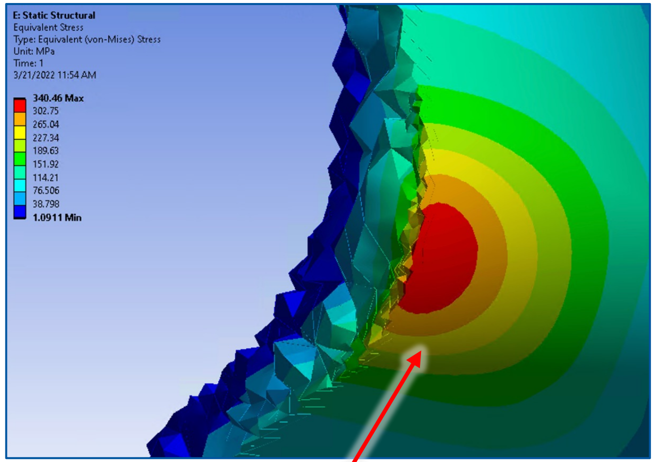
- Test pressure at **143 bar**



5th October 2021 5

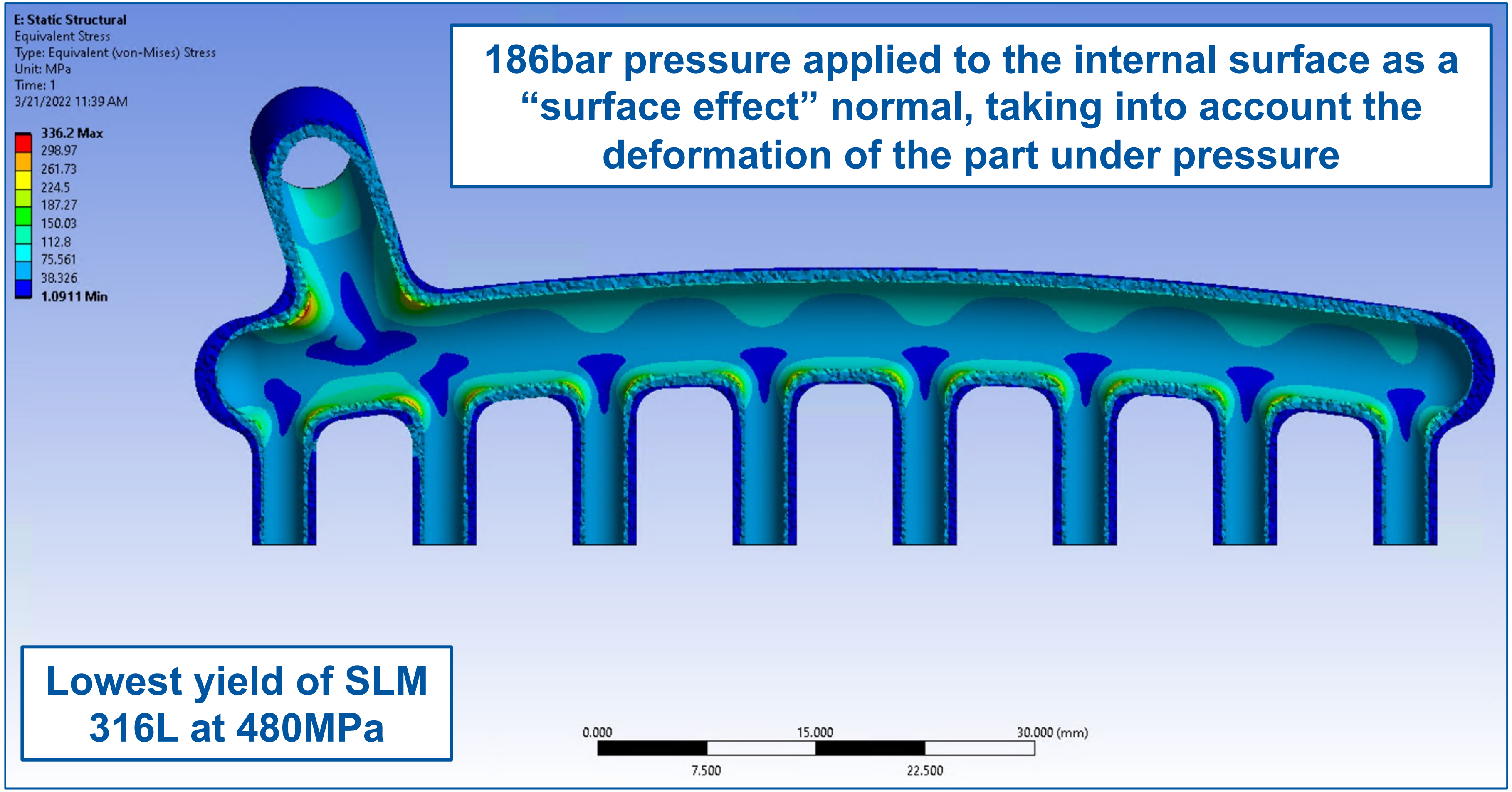
- **Pressure tests targeting the expected worst case scenario: Uncontrolled detector warm-up**
  - Liquid CO2 gasses out fully inside the detector
  - For prototyping using 186bar pressure @20C

Internal pressure FEA, return



Checked for mesh sensitivity, stabilizes around 340MPa

Used custom isotropic 316L-SLM material profile (see backup slides)



186bar pressure applied to the internal surface as a "surface effect" normal, taking into account the deformation of the part under pressure

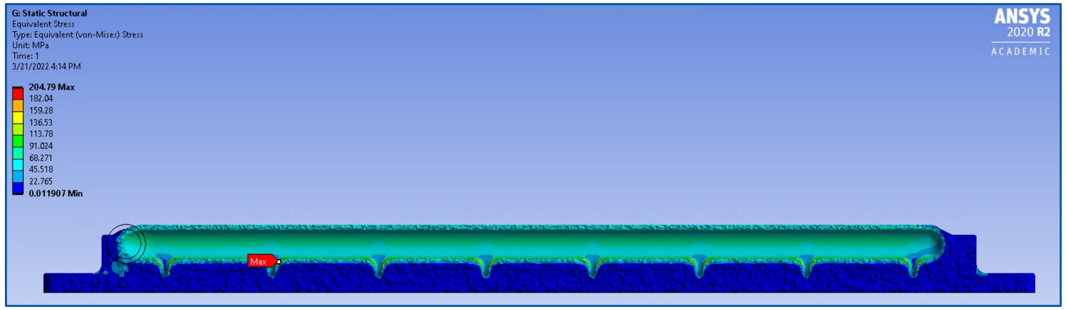
Lowest yield of SLM 316L at 480MPa

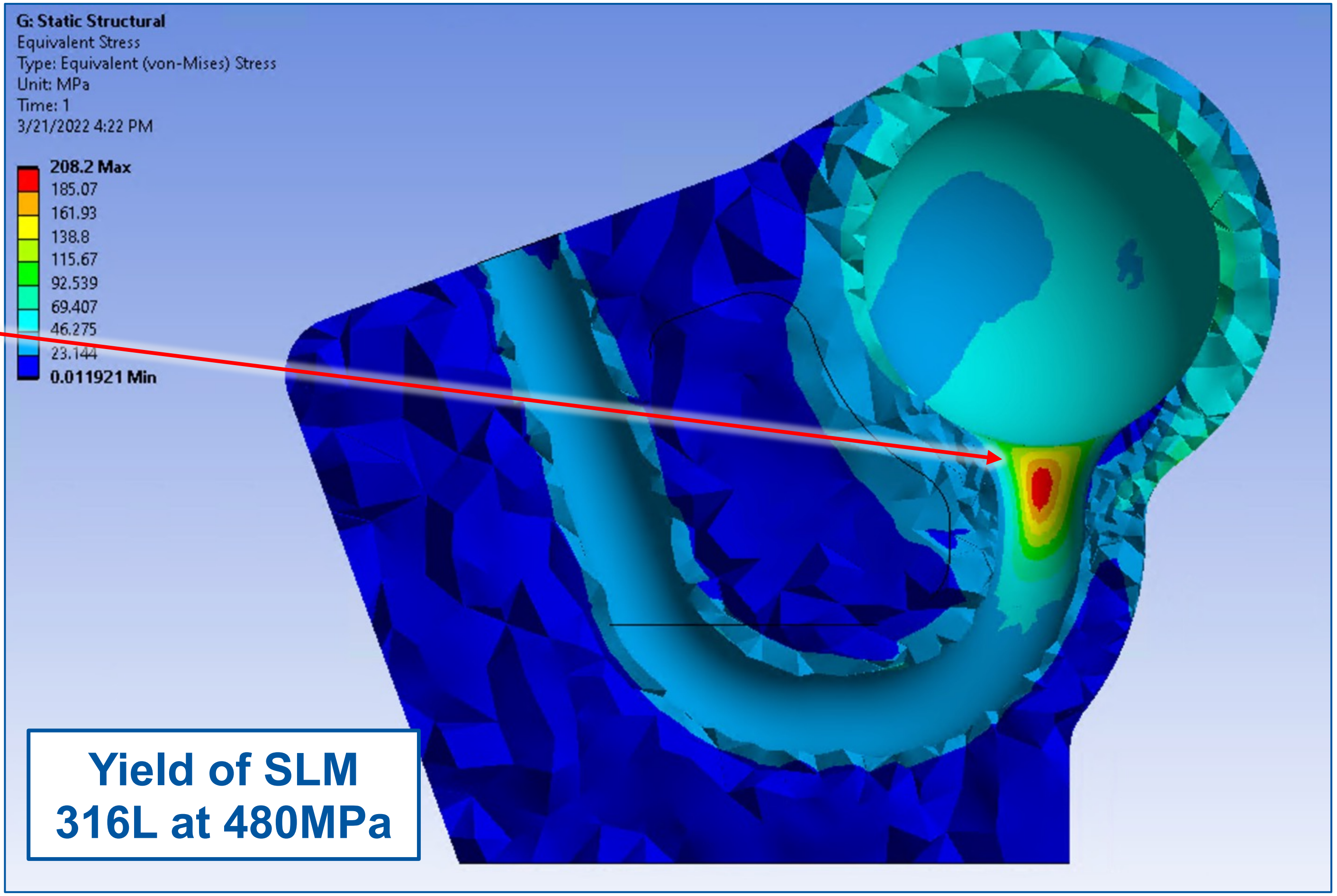
Internal pressure FEA, supply

186bar pressure applied to the internal surface as a “surface effect” normal, taking into account the deformation of the part under pressure

Checked for mesh sensitivity, stabilizes around 210MPa

Used custom isotropic 316L-SLM material profile (see backup slides)





Yield of SLM 316L at 480MPa

Internal flow FEA, supply

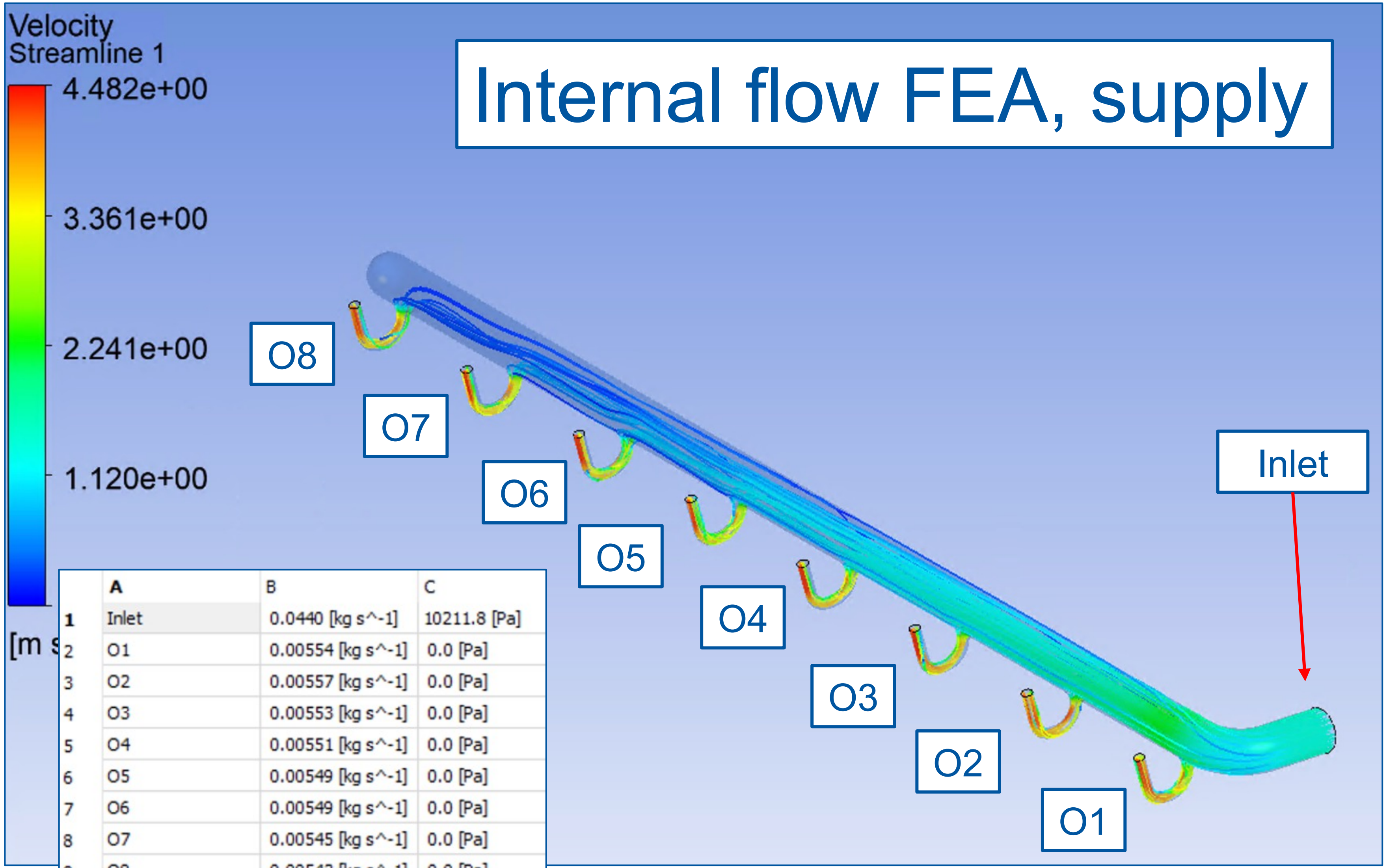
44g/s massflow inlet, 0-bar (gauge) pressure as an outlet

Equal as venting to atmosphere or individual lines providing equal resistance for the flow

K-omega SST

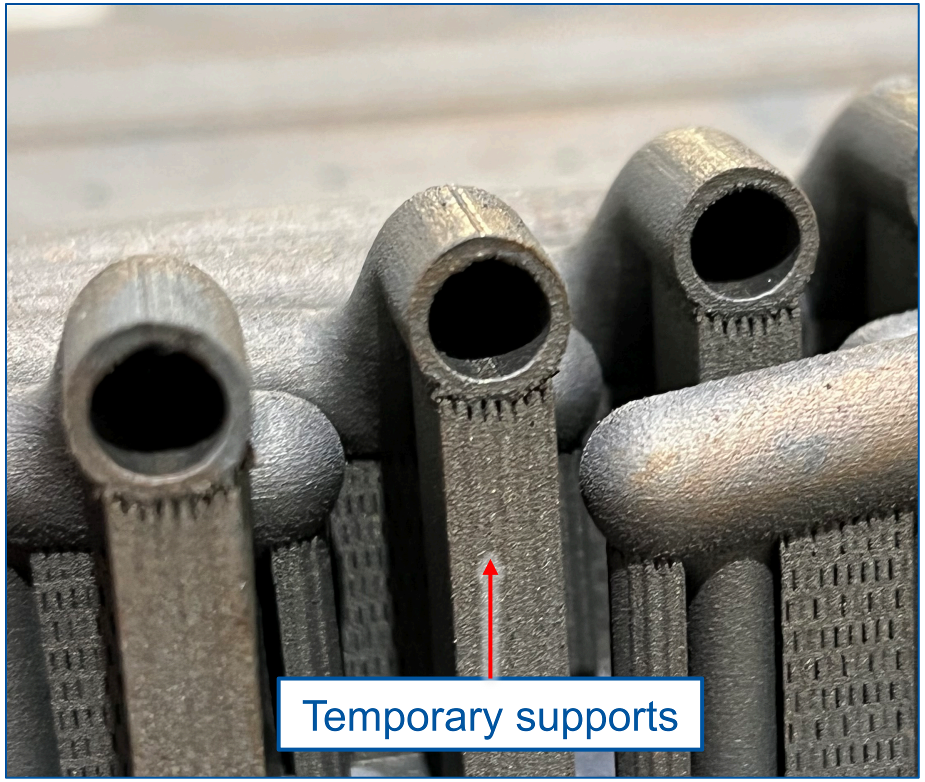
5.57g/s to 5.43 g/s massflow range in outlets from first to last, negligible difference

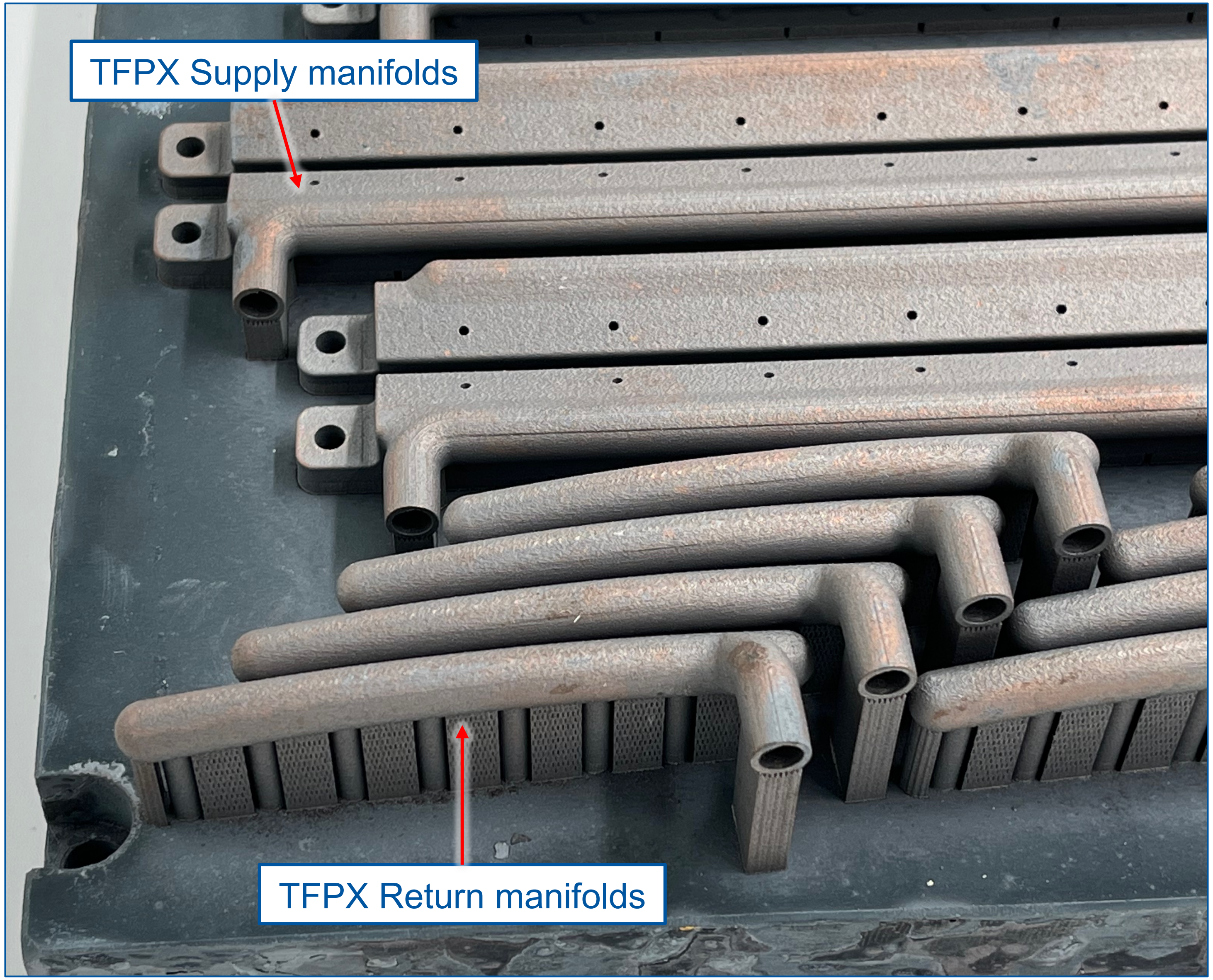
0.1bar delta pressure over the manifold



	A	B	C
1	Inlet	0.0440 [kg s^-1]	10211.8 [Pa]
2	O1	0.00554 [kg s^-1]	0.0 [Pa]
3	O2	0.00557 [kg s^-1]	0.0 [Pa]
4	O3	0.00553 [kg s^-1]	0.0 [Pa]
5	O4	0.00551 [kg s^-1]	0.0 [Pa]
6	O5	0.00549 [kg s^-1]	0.0 [Pa]
7	O6	0.00549 [kg s^-1]	0.0 [Pa]
8	O7	0.00545 [kg s^-1]	0.0 [Pa]
9	O8	0.00543 [kg s^-1]	0.0 [Pa]

SLM manifolds, after heat treatment





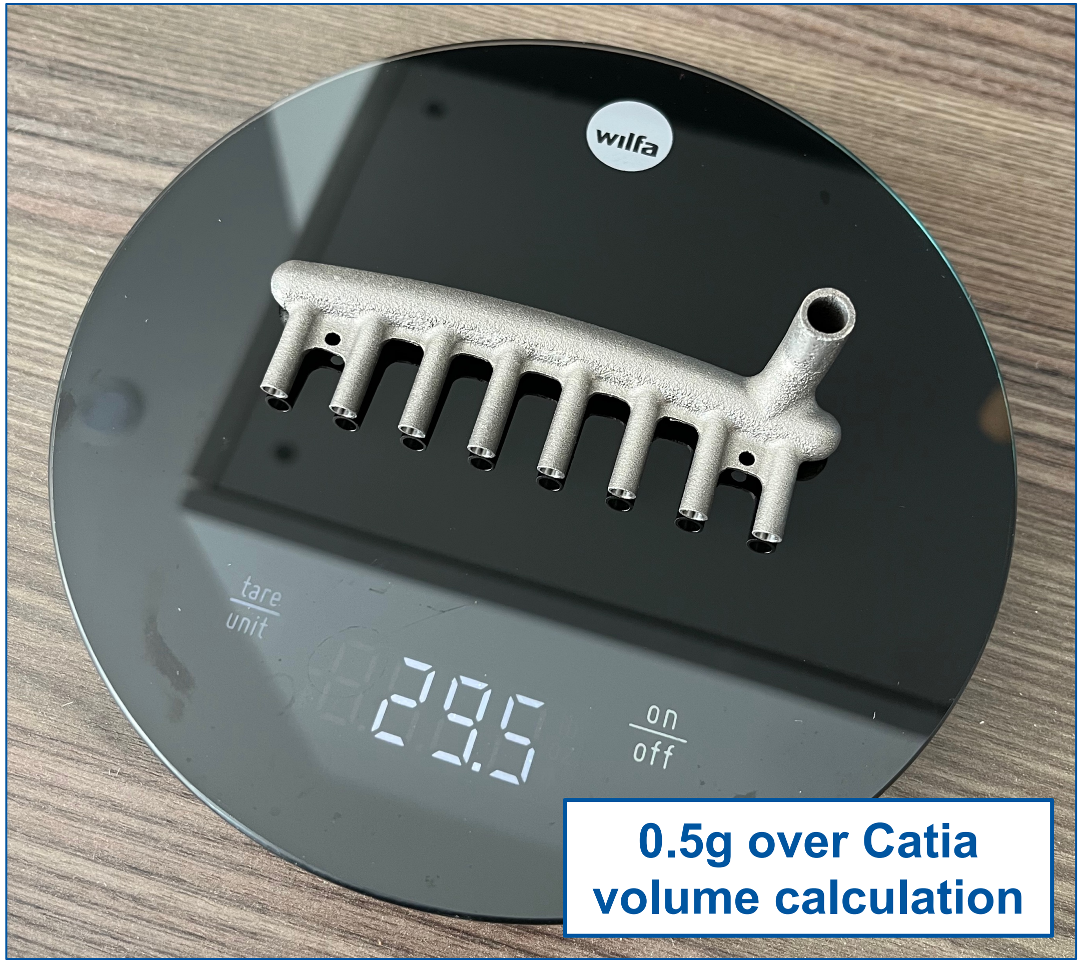
Return manifolds after post-processing

Surface roughness not as pronounced in reality

Supply manifolds after post-processing

Resulting mass

0.1g under Catia volume calculation

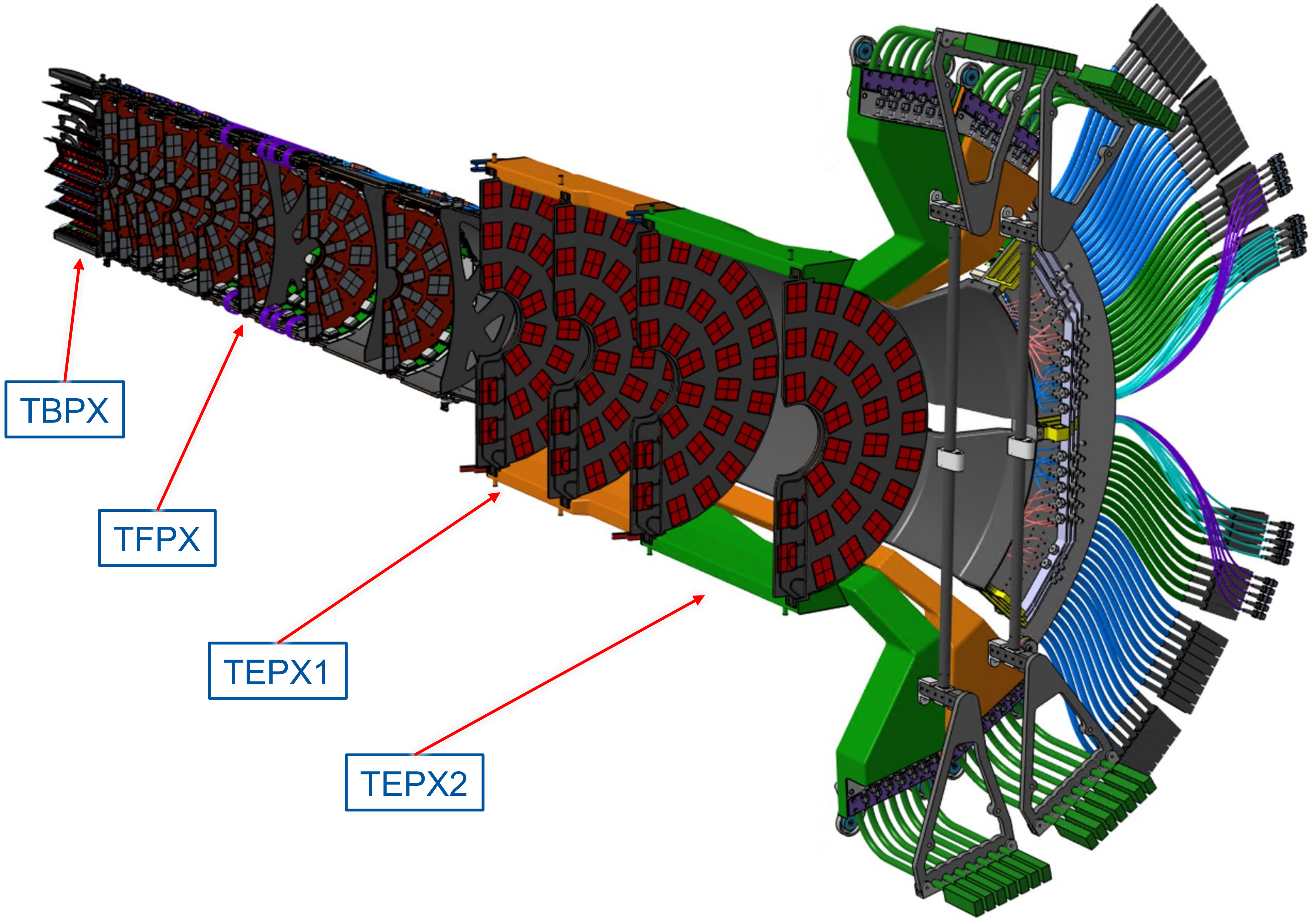


0.5g over Catia volume calculation

Conclusions (sort of)

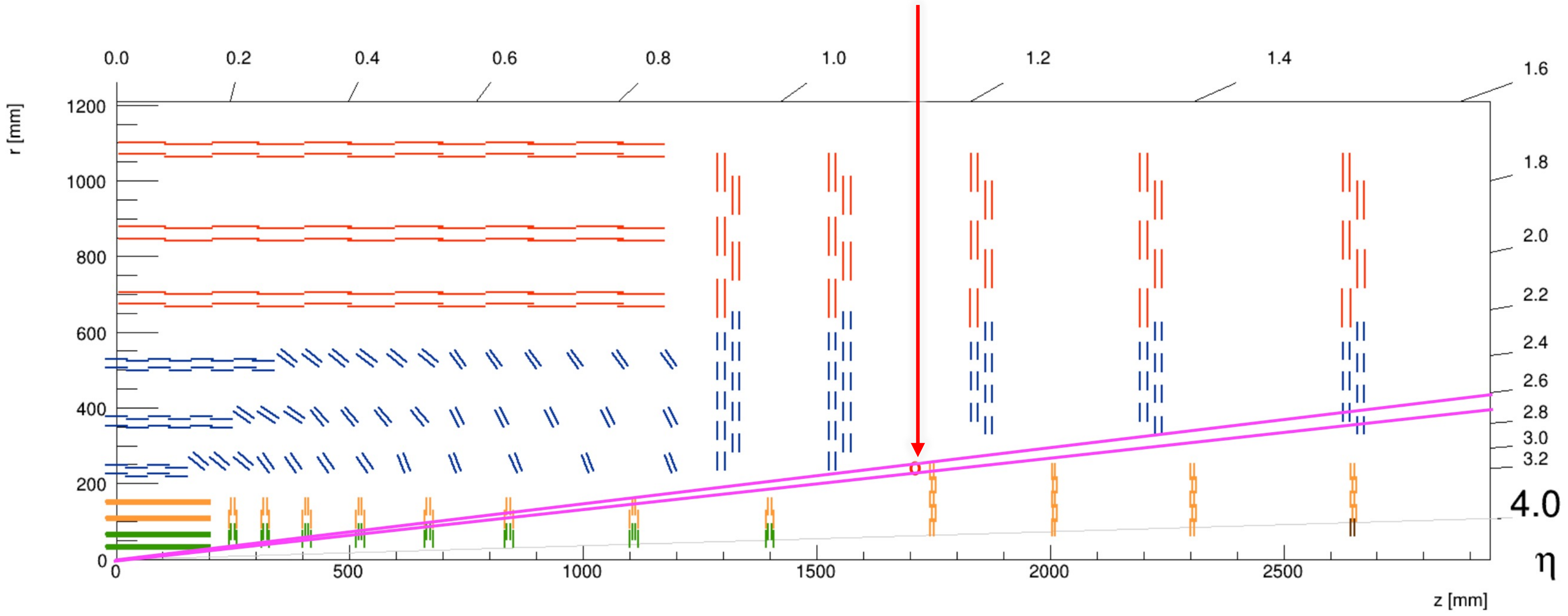
- **SLM manufacturing seems to enable the design and use of extremely low mass metallic components to replace heavier manufacturing constrained designs**
  - Unfortunately for this forum talk, still in the middle of proving the feasibility <u>specifically for CO2 cooling system application</u> (aimed to have testing data-ready, parts got stuck in mach.)
  - Past experience from Delva suggests, that we should not really expect any SLM releated failures in our CO2 application
- **Next steps:**
  - Leak, pressure and weld testing the manifolds
  - Identify all potential locations in the CMS Inner Tracker where the technology could be used to replace parts with low-mass counterparts
  - Gain access to a higher performance topology optimization software like ”Inspire” or “nTopology” for optimizing identified mechanical parts. (Able to gain testing access to Inspire through Delva)

Backup



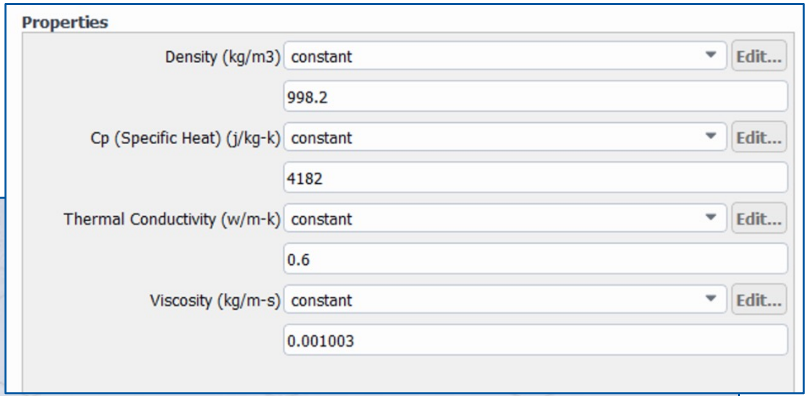
TBPX
TFPX
TEPX1
TEPX2

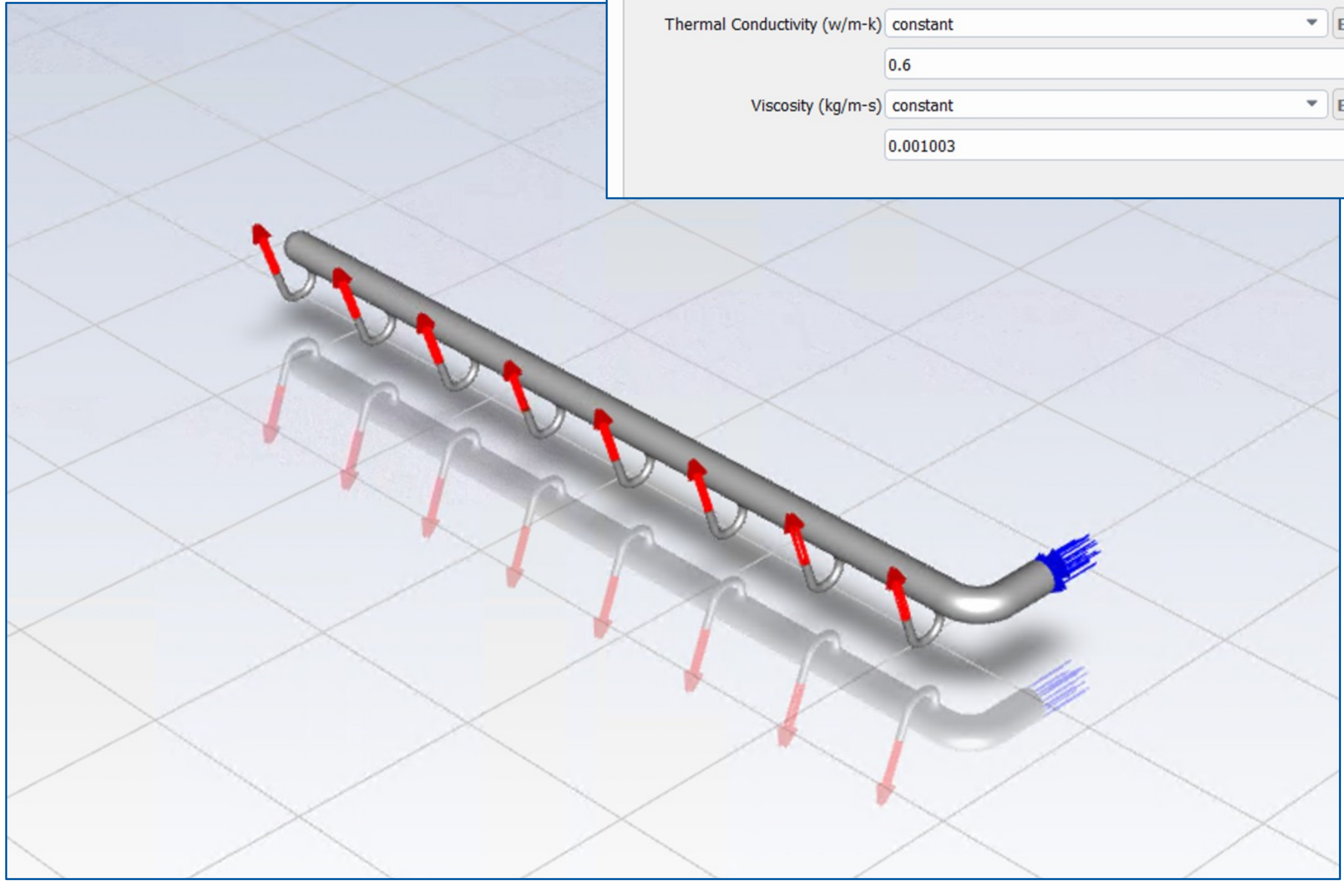
- **Return manifold location shadows approximately the ETA 2.6-2.7 region, where very few modules are present**
  - Outside of the Outer Tracker Trigger (stops at ETA 2.4)
  - Expected to span around 3 degrees in Phi per manifold, therefore quite local cones of shadow near the horizontal plane of Tracker



Fluent parameters

- **Pressure based steady state solver:**
  - K-Omega SST for turbulence formulation
  - Turbulence production limiter on
- **Convergence criterion:**
  - 1e-03 for residuals
  - 1e-06 for energy
- **Boundaries:**
  - Massflow inlet @44g/s
  - Pressure outlets at 0bar (reference)





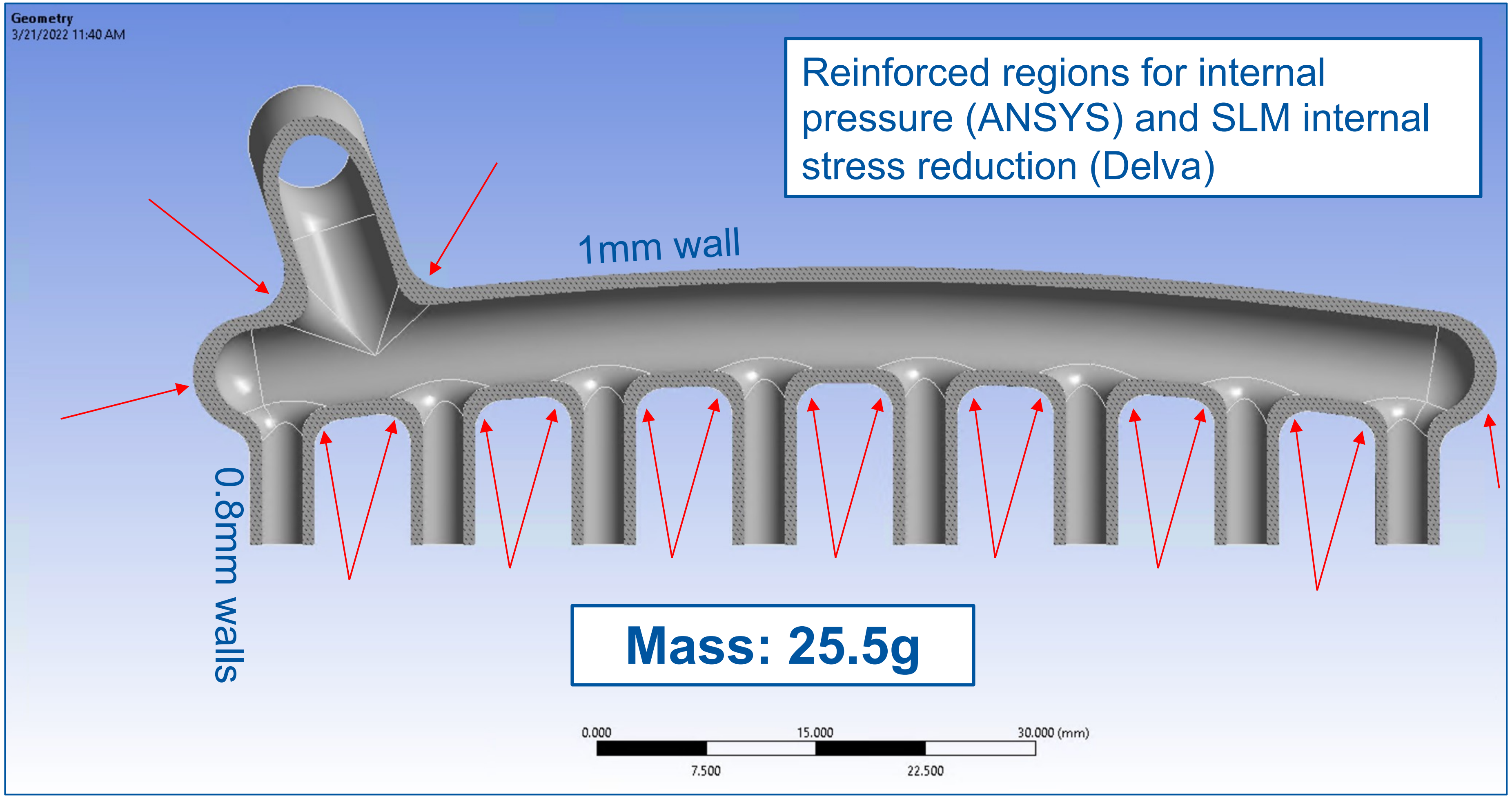
Material profile for EOS 40µm SS316L

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	7900	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
5	Coefficient of Thermal Expansion	1.7E-05	C^-1		
6	Isotropic Elasticity				
7	Derive from	Young's Modulus and Poisson...			
8	Young's Modulus	1.95E+11	Pa		
9	Poisson's Ratio	0.25			
10	Bulk Modulus	1.3E+11	Pa		
11	Shear Modulus	7.8E+10	Pa		
12	Tensile Yield Strength	480	MPa		
13	Tensile Ultimate Strength	570	MPa		
14	Isotropic Thermal Conductivity	15	J m^-1 s^-1 C^-1		
15	Specific Heat, C_p	510	J kg^-1 C^-1		
16	Isotropic Resistivity	7.07E-07	ohm m		

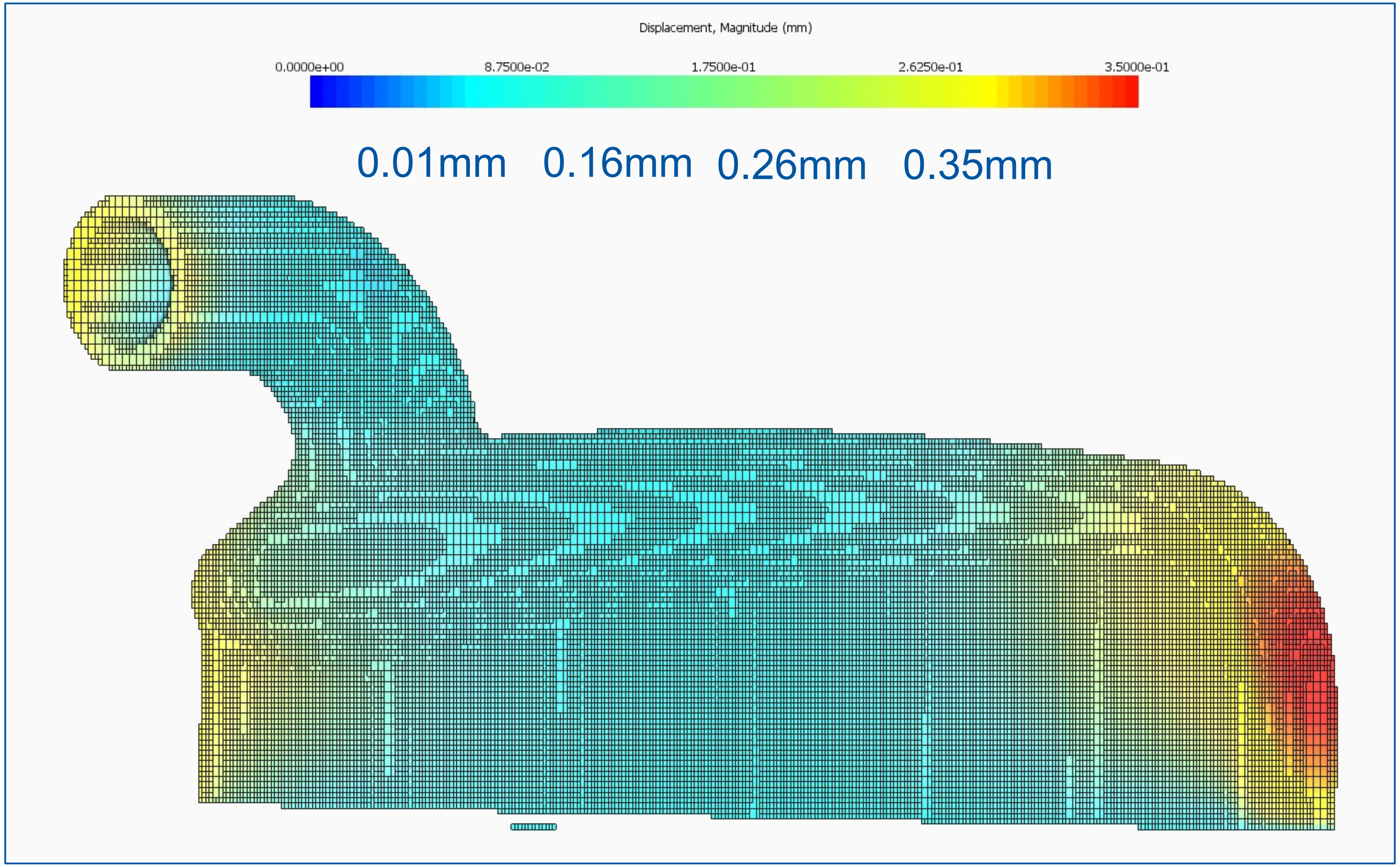
Granta materials 316L austenitic as the base

- Young's modulus and Poisson's ratio picked from ANSYS additive manufacturing library at 20C
- Yield and Tensile strength picked from EOS datasheet for 40µm SS316L

Optimized geometry

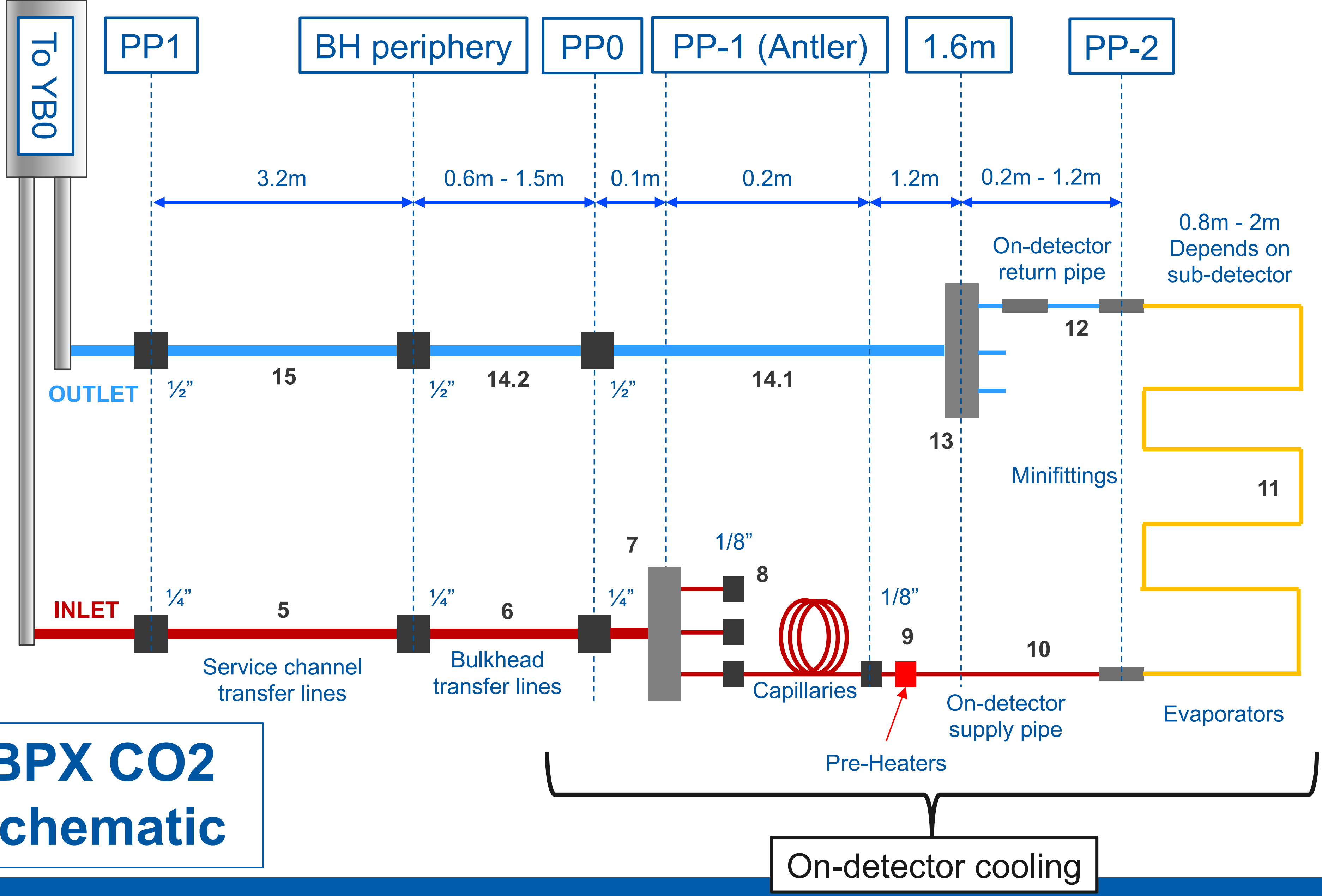


Displacement after SLM (old revision)



Delva provided some preliminary estimates on expected displacement of the part after the release of internal stresses, can be seen that the extremities of the manifold are sensitive to deformation

Adding material to these regions helps greatly with the resulting deformation, adding 0.5mm to the ends of the manifold to reduce the effect



TFPX/TBPX CO2 piping-schematic