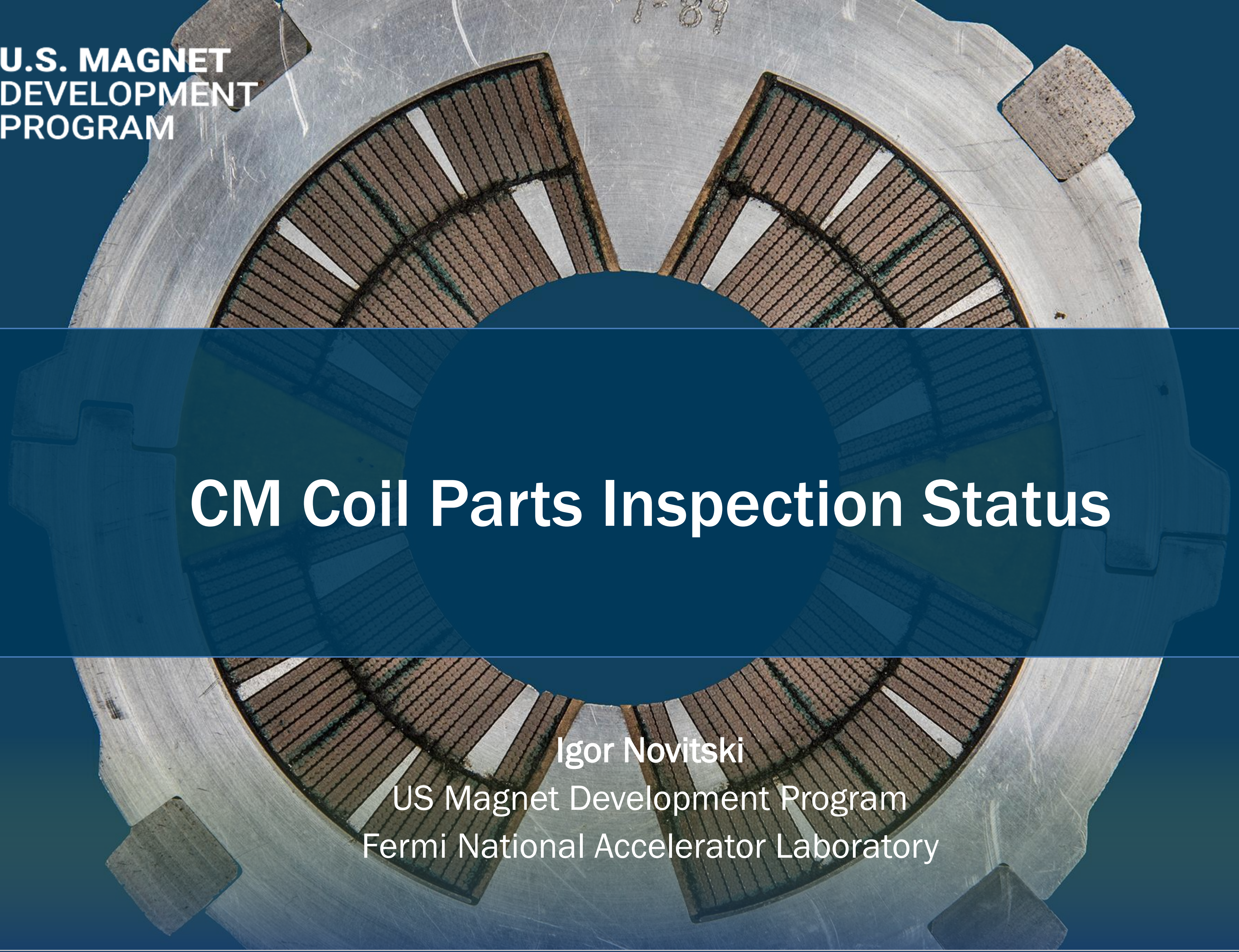
U.S. MAGNET DEVELOPMENT PROGRAM



CM Coil Parts Inspection Status

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US Magnet Development Program
Fermi National Accelerator Laboratory

SMCT Task Next Steps

FY21:

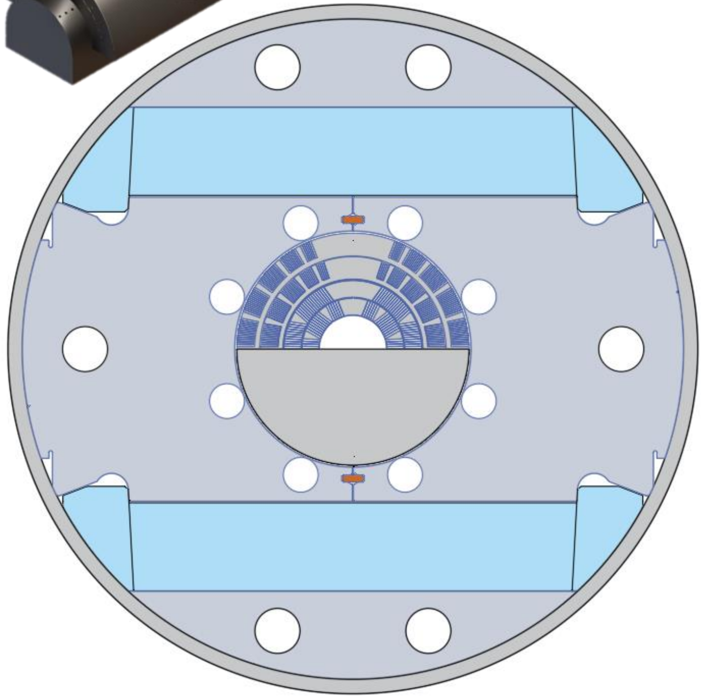
- MDPCT1 disassembly and inspection (March-April 2021)
- **SMCT coil part inspection and modification (March-April 2021)**
- SMCT coil winding/reaction/impregnation/instrumentation (May-July 2021),
- magnet structure design analysis and optimization (March-April 2021)
- Mirror block fabrication and structure part modification/inspection/instrumentation (May-July 2021)
- Mirror magnet assembly and test preparation (August-September 2021)
    - **4L mirror** will be assembled

Milestone #	Description	Target
AI-M1a	Development and test of stress management concept using a 2-layer large-aperture and 4-layer small-aperture cos-theta coils and dipole mirror structure	March 2022

FY22:

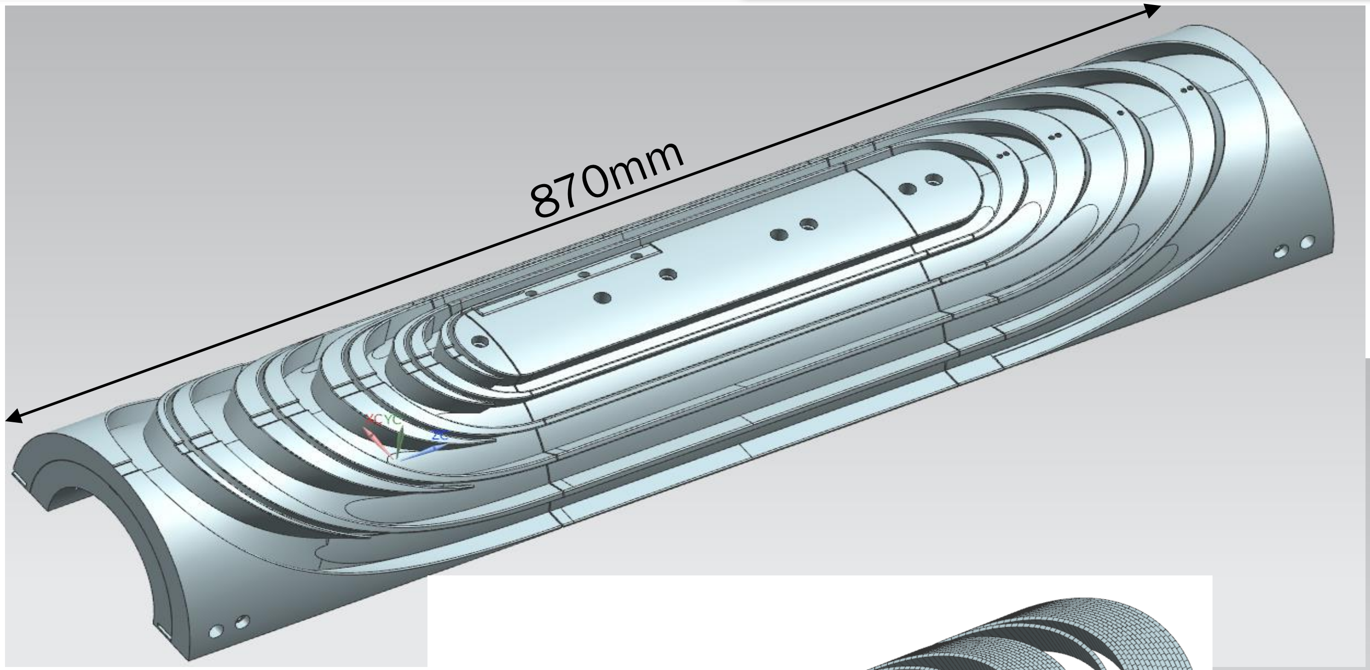
- Magnet test (October-December 2021)
    - first 120-mm SM coil will be connected to power leads and tested
    - both 60-mm and 120-mm will be connected in series and tested

SMCT coil after winding

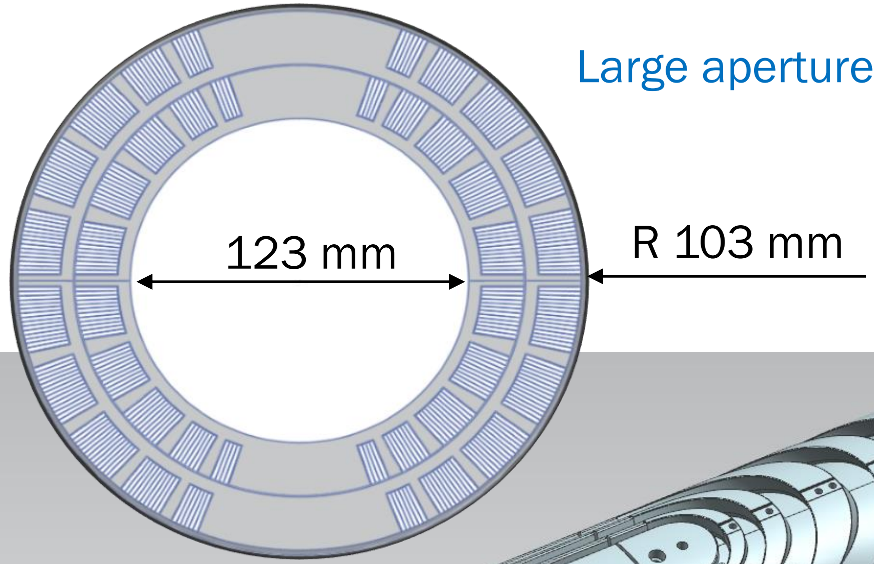


60 mm bore 4-layers Mirror Magnet

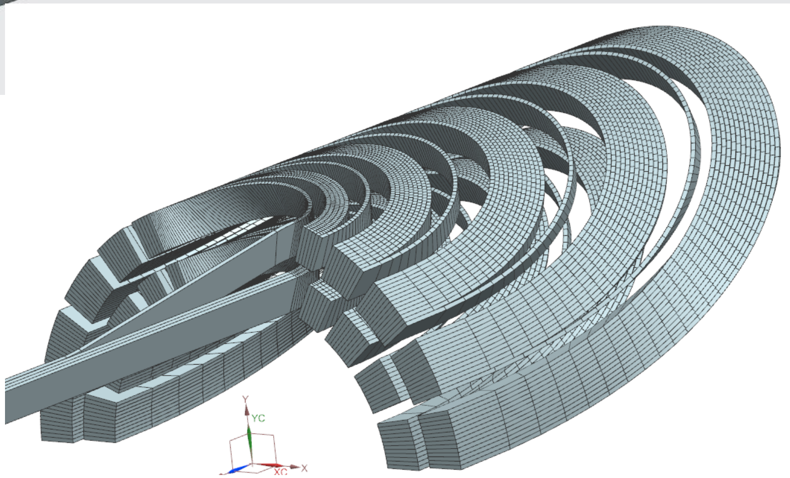
SMCT Coil Design

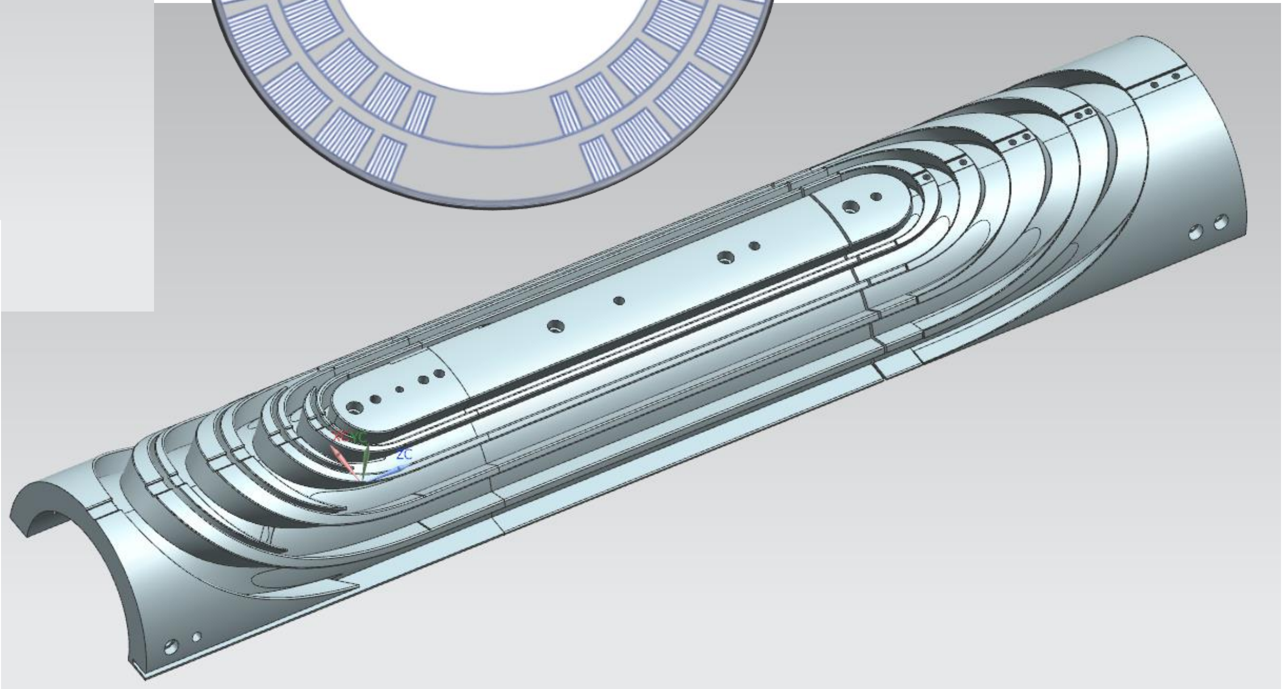


Large aperture dipole



Stress management for the whole coil





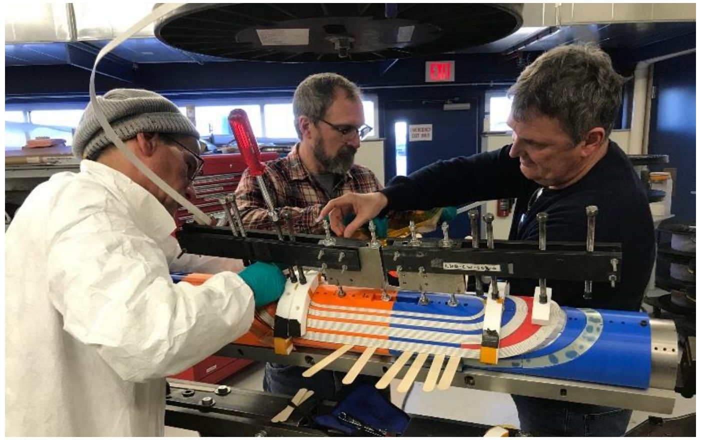
SMCT Coil Design and Technology Demonstration

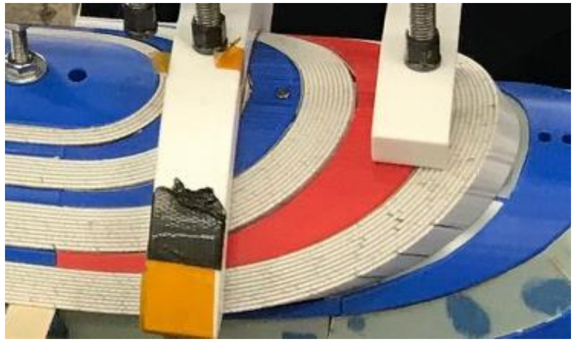
All plastic parts printed on site

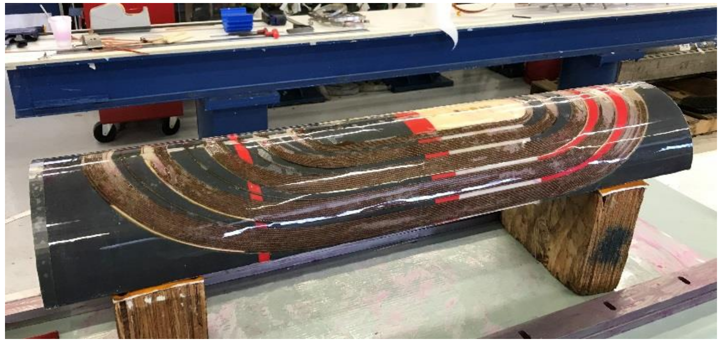
Winding in slots

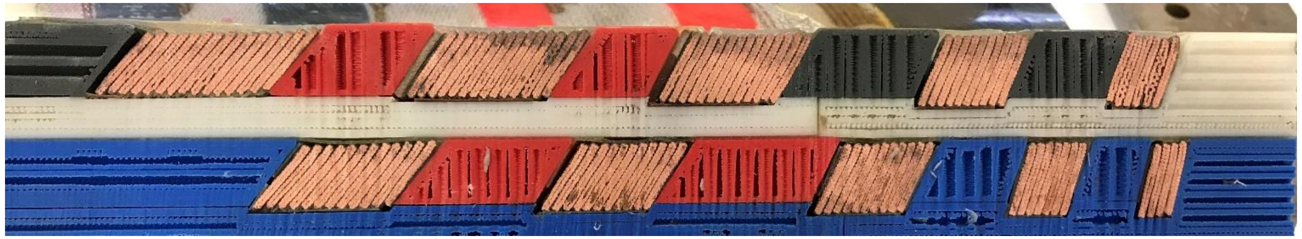
Room for cable expansion during reaction

Simplified reaction and impregnation tooling









3D Printing Approach – Learning Process

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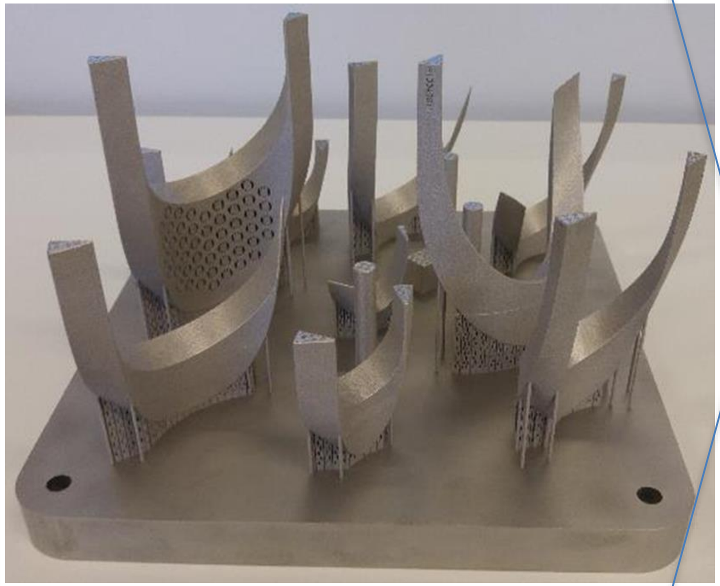
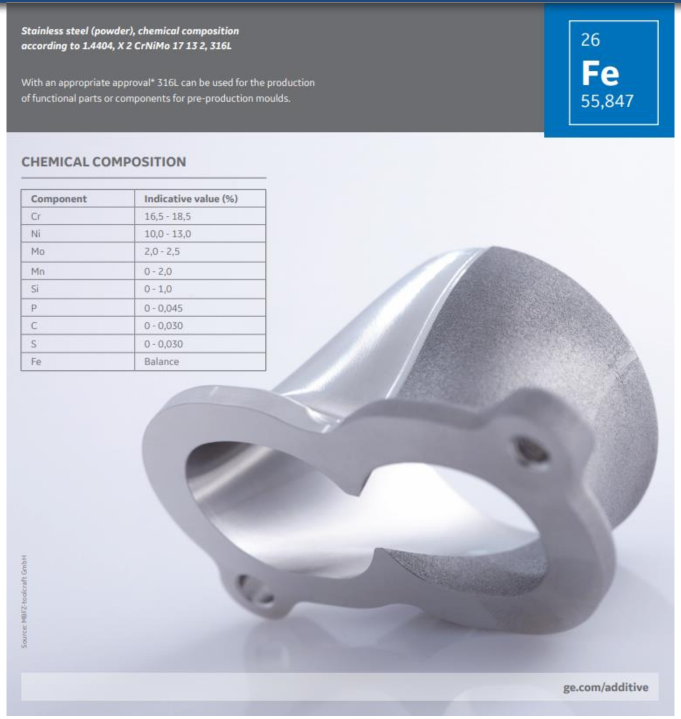


Ti-6Al-4V end parts for 15T coils printed in the EU

GE Additive equipment in USA



Stainless steel (powder), chemical composition according to 1.4404, X 2 CrNiMo 17 13 2, 316L

With an appropriate approval* 316L can be used for the production of functional parts or components for pre-production moulds.

26
Fe
55,847

CHEMICAL COMPOSITION

Component	Indicative value (%)
Cr	16,5 - 18,5
Ni	10,0 - 13,0
Mo	2,0 - 2,5
Mn	0 - 2,0
Si	0 - 1,0
P	0 - 0,045
C	0 - 0,030
S	0 - 0,030
Fe	Balance

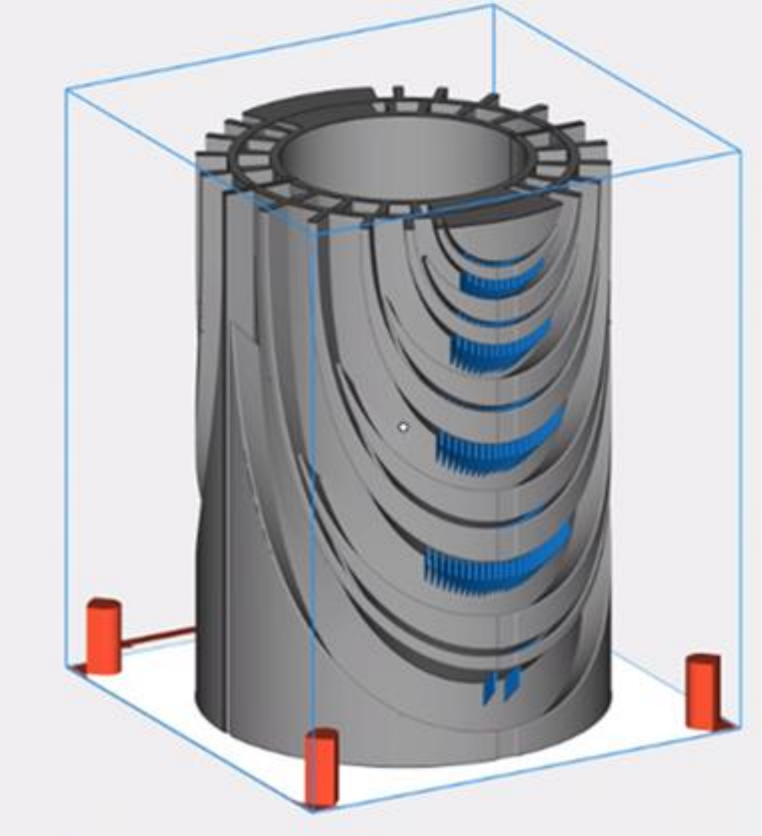
ge.com/additive

TECHNICAL DATA AFTER RECOMMENDED HEAT TREATMENT

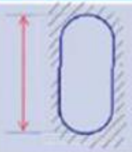
	90° (upright)	45° (polar angle)	0° (horizontal)
Yield strength $R_{p0,2}$ [1]	374 ± 5 N/mm^2	385 ± 6 N/mm^2	330 ± 8 N/mm^2
Tensile Strength R_m [1]	650 ± 5 N/mm^2	640 ± 7 N/mm^2	529 ± 8 N/mm^2
Elongation A [1,2]	65 ± 4 %	63 ± 5 %	63 ± 5 %
Young's modulus [3]	ca. $200 \cdot 10^3$ N/mm^2	ca. $200 \cdot 10^3$ N/mm^2	ca. $200 \cdot 10^3$ N/mm^2
Thermal conductivity λ [3]	ca. 15 W/mK	ca. 15 W/mK	ca. 15 W/mK
Hardness [4]	20 HRC	20 HRC	20 HRC

[1] Tensile test at 20°C according to DIN EN 50125
[2] By using a special heat treatment a higher elongation can be achieved.
[3] Specification according to the material manufacturer's data sheet.
[4] Hardness test according to DIN EN ISO 6508

Direct Metal Laser Melting (DMLM) Process Limitations

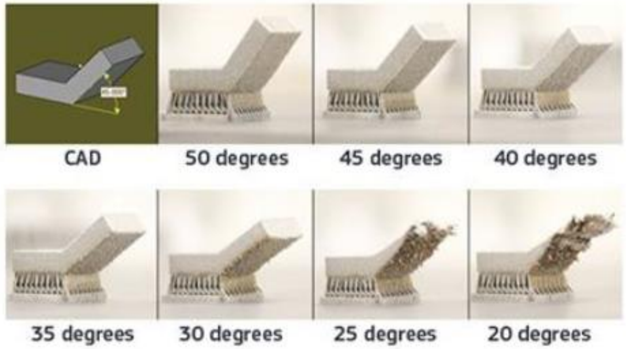


- Powder evacuation
- Stress relief heat treatment
- Plate Removal (EDM)
- Support removal and contact smoothing by hand on a best effort basis

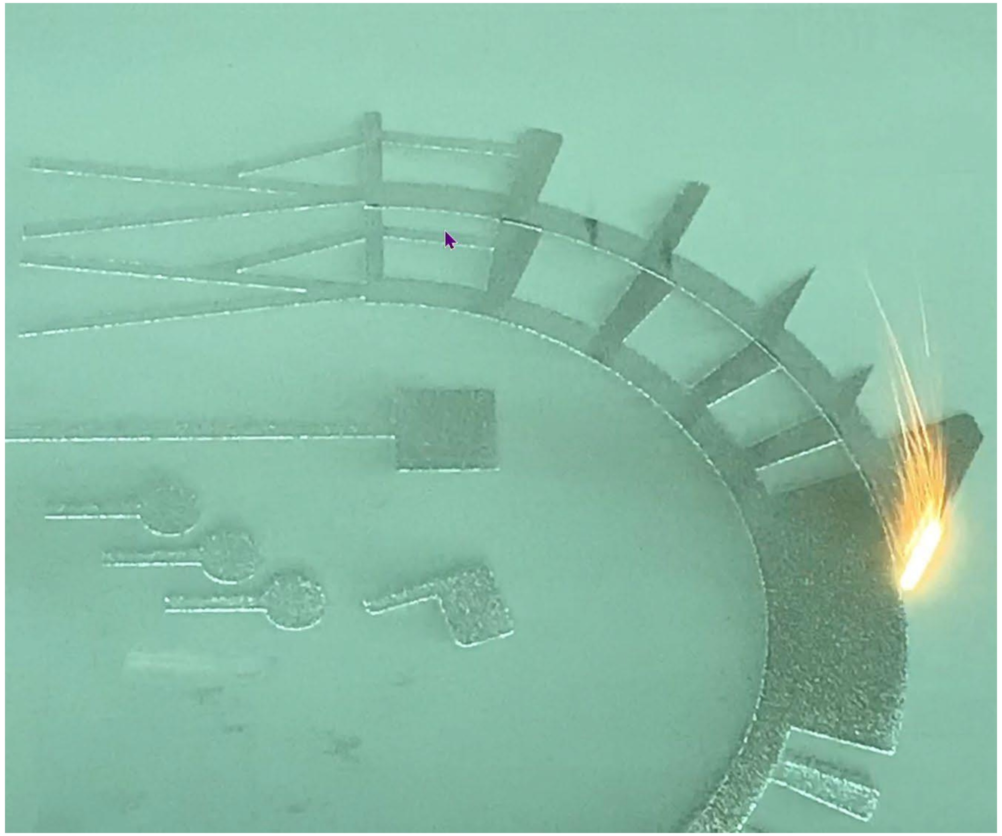
Feature	Visual Representation	Possible Tolerance
Passage Height/Width		±.002" ±0.05mm
Wall Thickness		±.002" ±0.05mm
Hole		±.005" ±0.13mm
Profile		±.010" *or more* ±0.25mm
Radius		±.005" ±0.13mm

DMLM process tolerances are material, parameter set, orientation and feature based (precision)

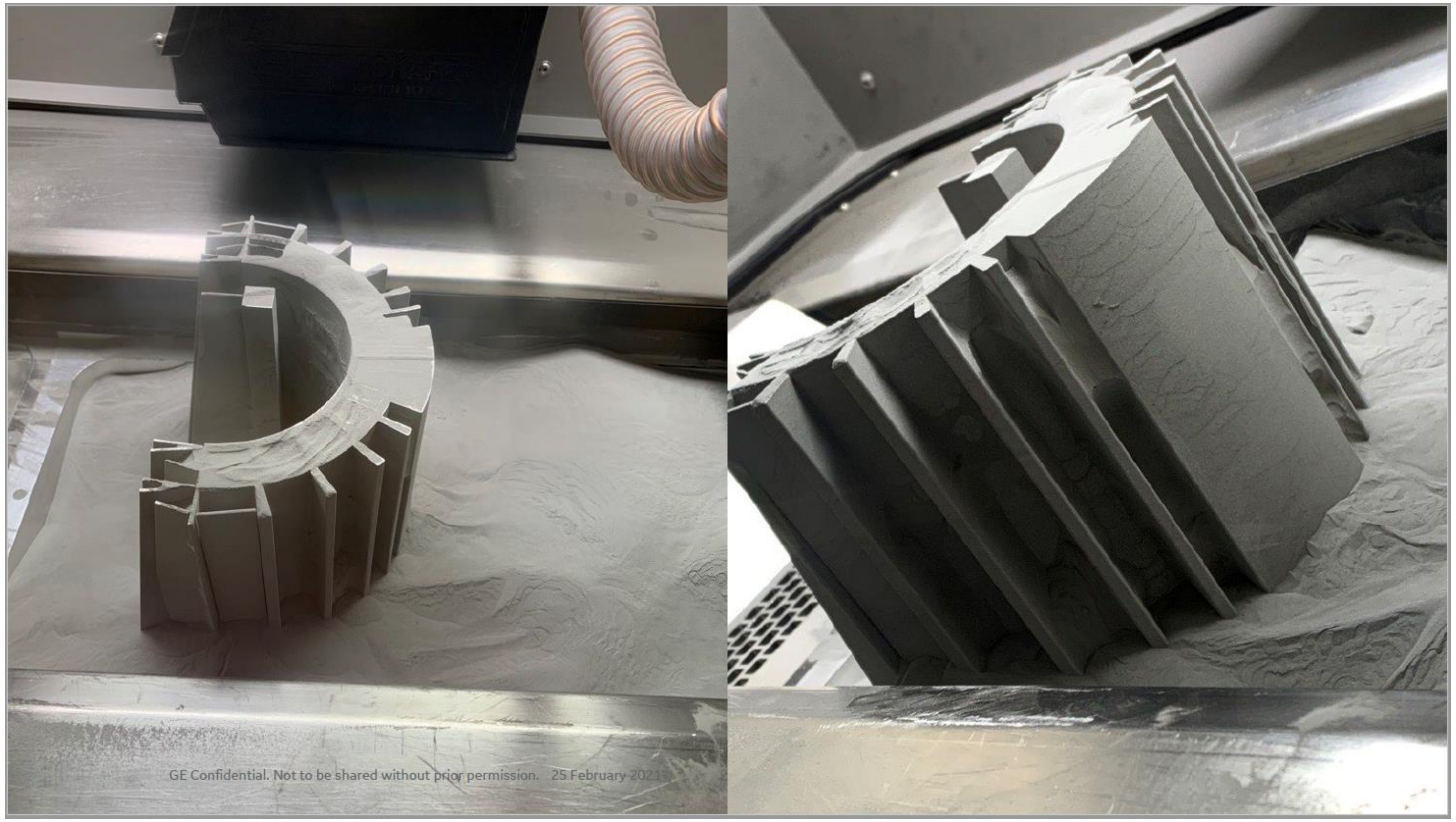
In order to achieve these tolerances relative to the entire part (datums), several "dial-in" build / inspections will be required to compensate the geometry and/or the support structures (accuracy)



SMCT Coil Parts Build by GE Additive using DMLM Technology

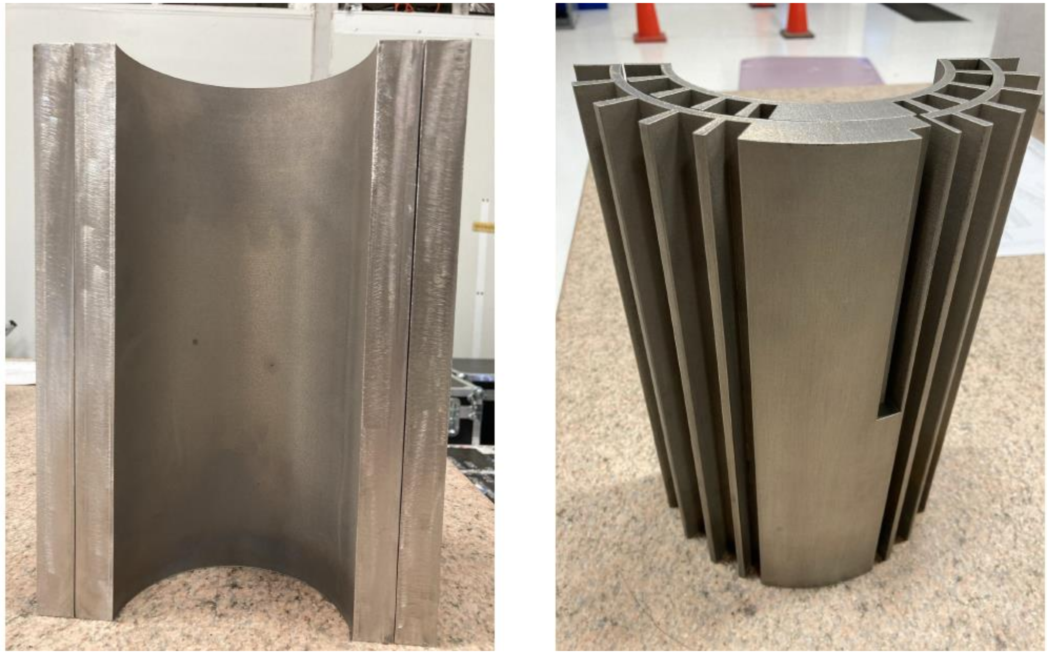


Part build process



Straight section L3 and L4 parts printing

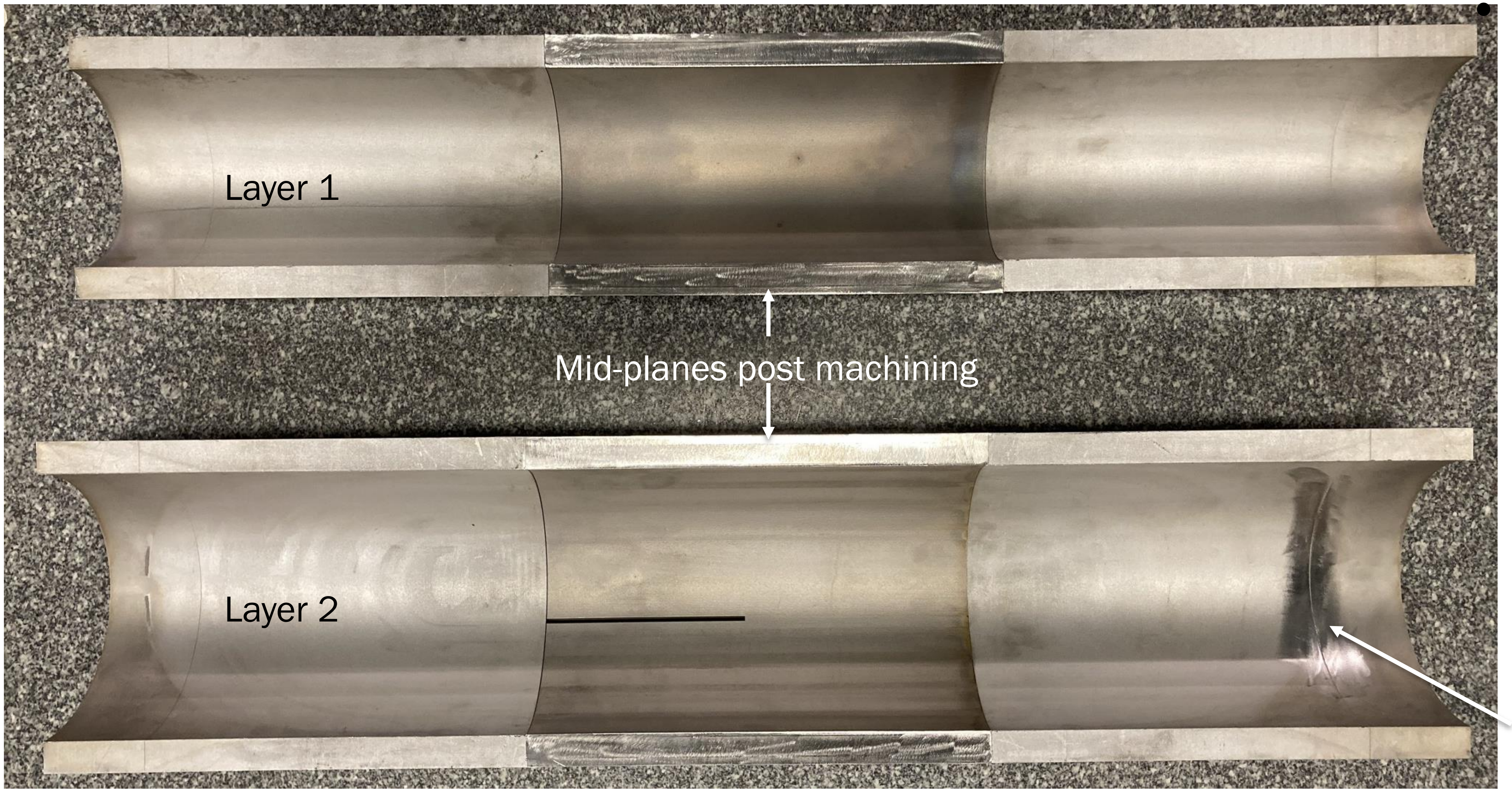
CM Coil Parts on the QC Inspection Table at Fermilab



Straight part from the build #1

End part from the build #2

CM Coil Parts, inside view



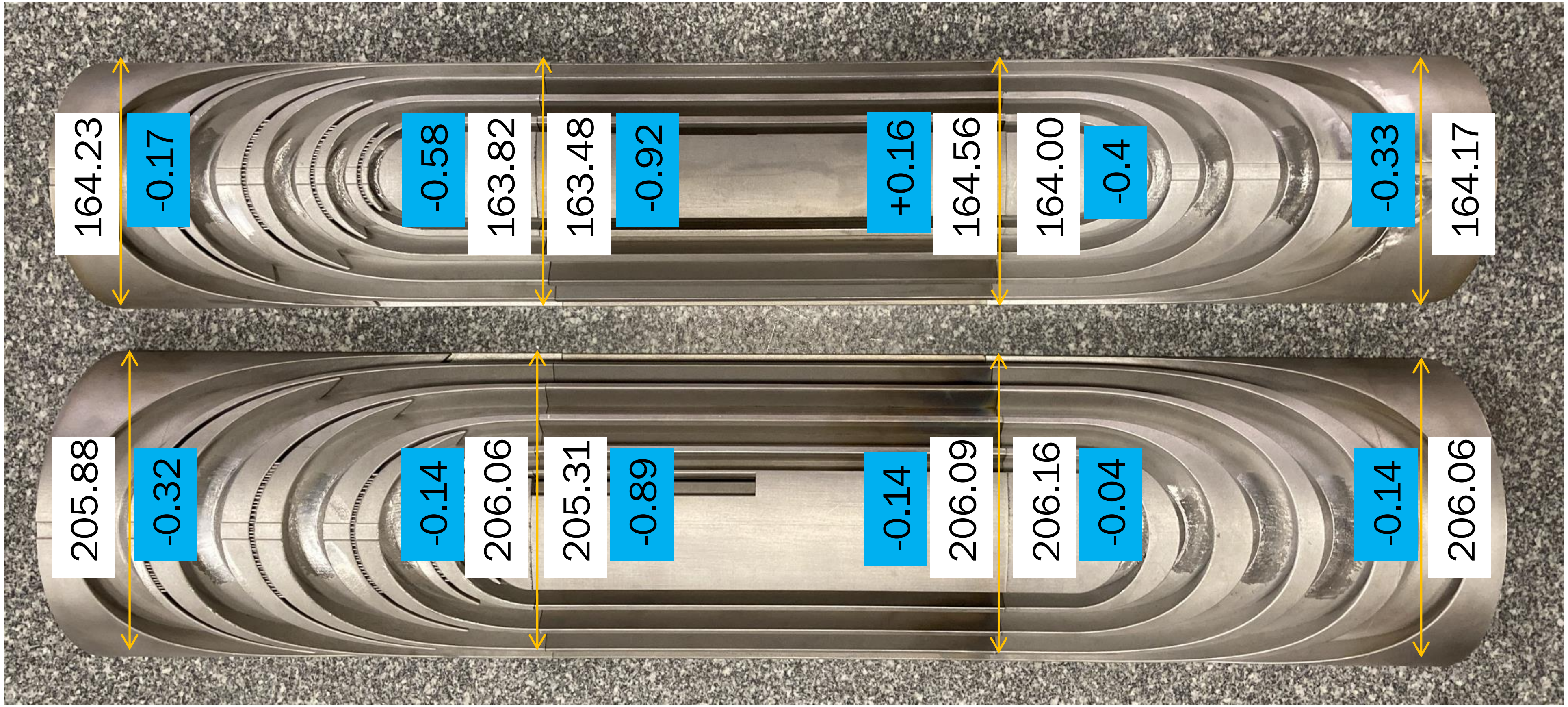
- **Discoloration**: This is standard and within limits. The variation in color of the two builds is due to the different amount of build per layer, and the subsequent cooling time for each localized Meltpool before the next layer of powder is added. The smaller the component, the shorter the layer time, the darker the overall steel component.

Sign of powder reloading

CM Coil Parts, outside view

Layer 1

Layer 2



164.4

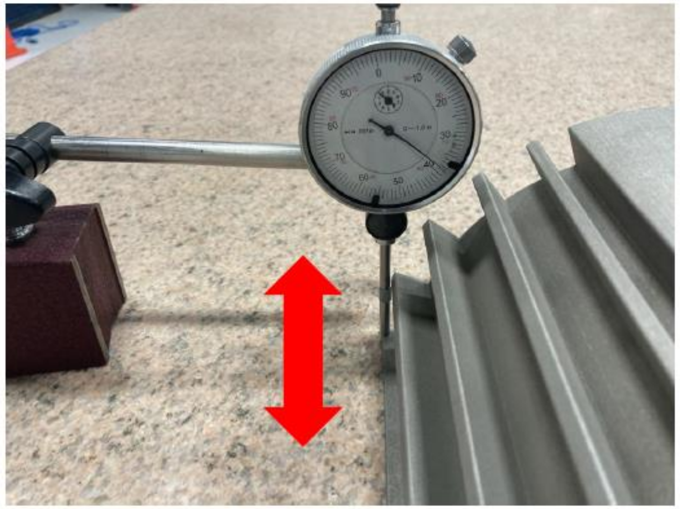
size per drawing

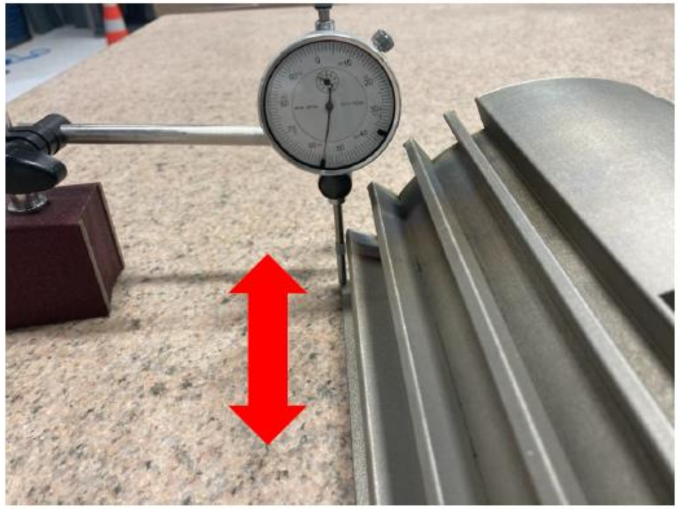
206.2

difference

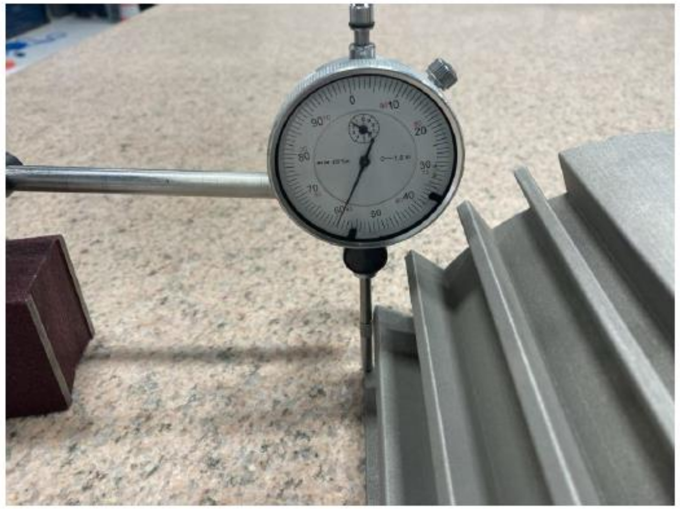
Size control by caliper measurements

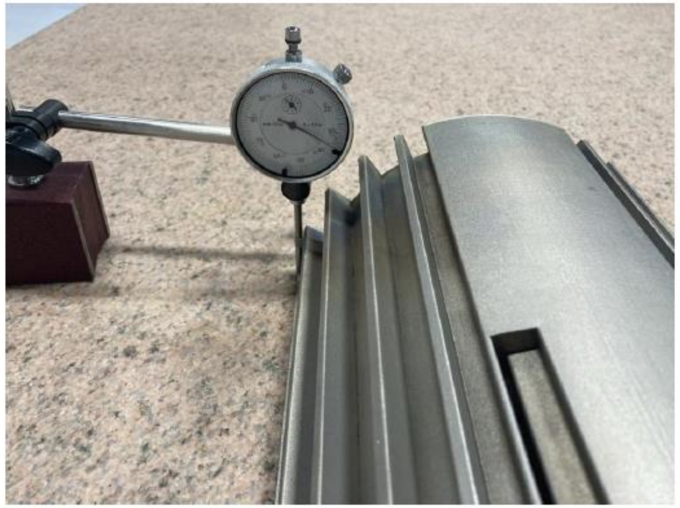
Straight Parts Twisting



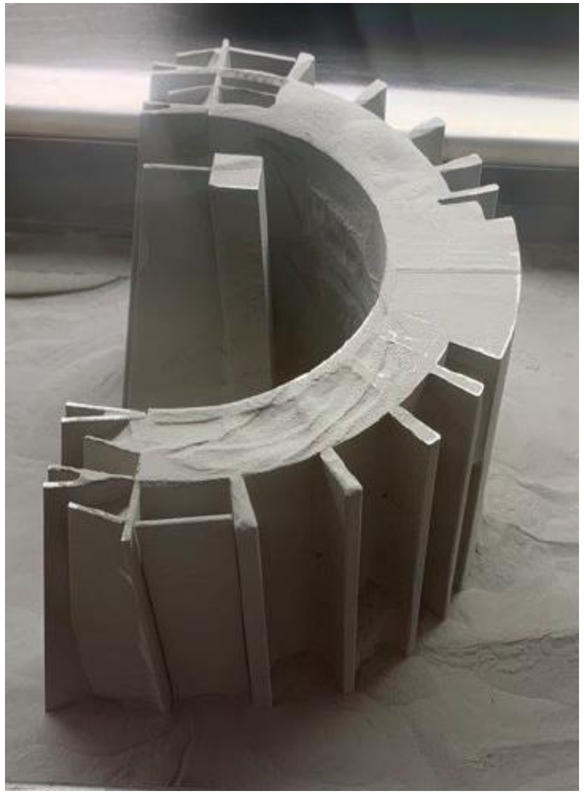


20 mils = 0.58mm
L4 rocking
Part twist



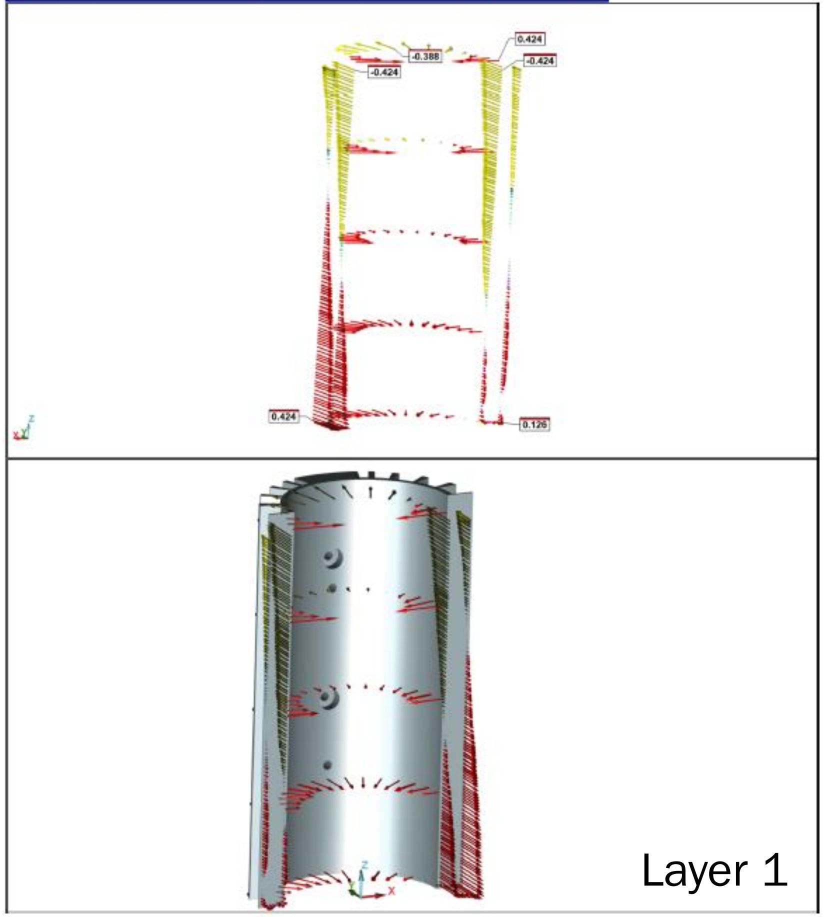


QCRs of Two Straight Parts



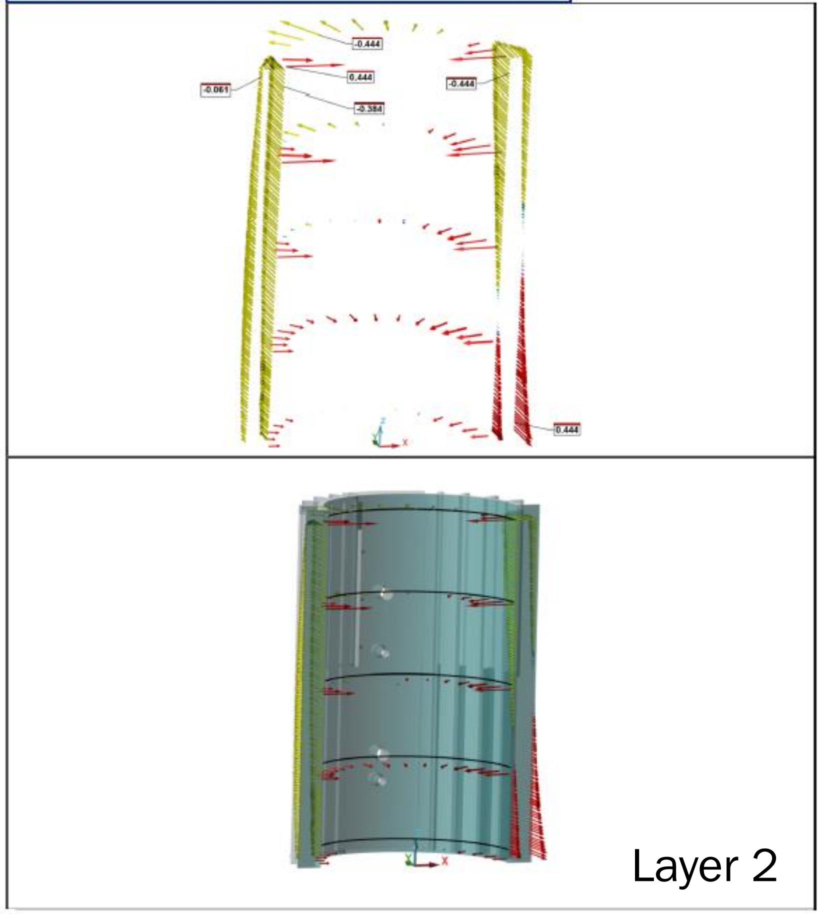
Straight parts build #1

PROFILE_FIT_TO_FLATS_AND_CYLINDER	MM	0.1	DEFAULT	ASME Y14.5
Feature	MEAS	MAX	MIN	OUTTOL
DATUM_A_POINTS	0.848	0.424	-0.388	0.748
SCN_LEFT_PLN	0.848	0.126	-0.424	0.748
SCN_RIGHT_PLN	0.848	0.424	-0.424	0.748



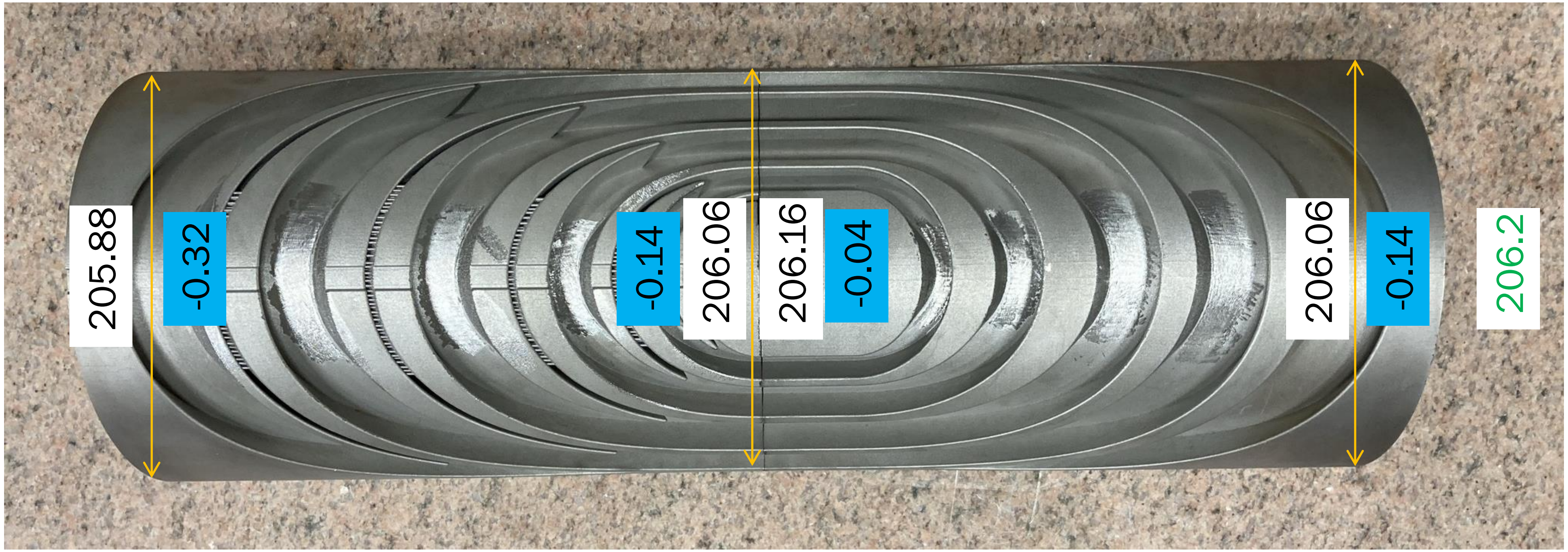
Layer 1

PROFILE_FIT_TO_FLATS_AND_CYLINDER	MM	0.1	DEFAULT	ASME Y14.5
Feature	MEAS	MAX	MIN	OUTTOL
DATUM_A_POINTS	0.889	0.444	-0.444	0.789
SCN_LEFT_PLN	0.767	-0.061	-0.384	0.667
SCN_RIGHT_PLN	0.889	0.444	-0.444	0.789



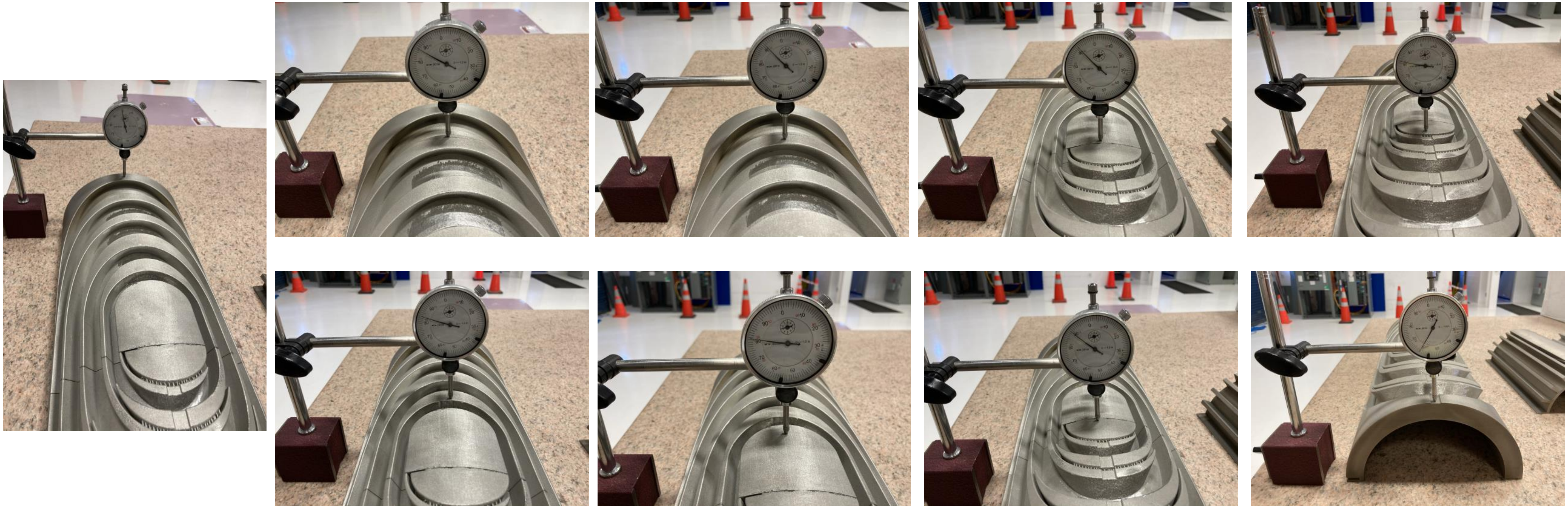
Layer 2

End Parts for Layer 2, outside view



Size control by caliper measurements

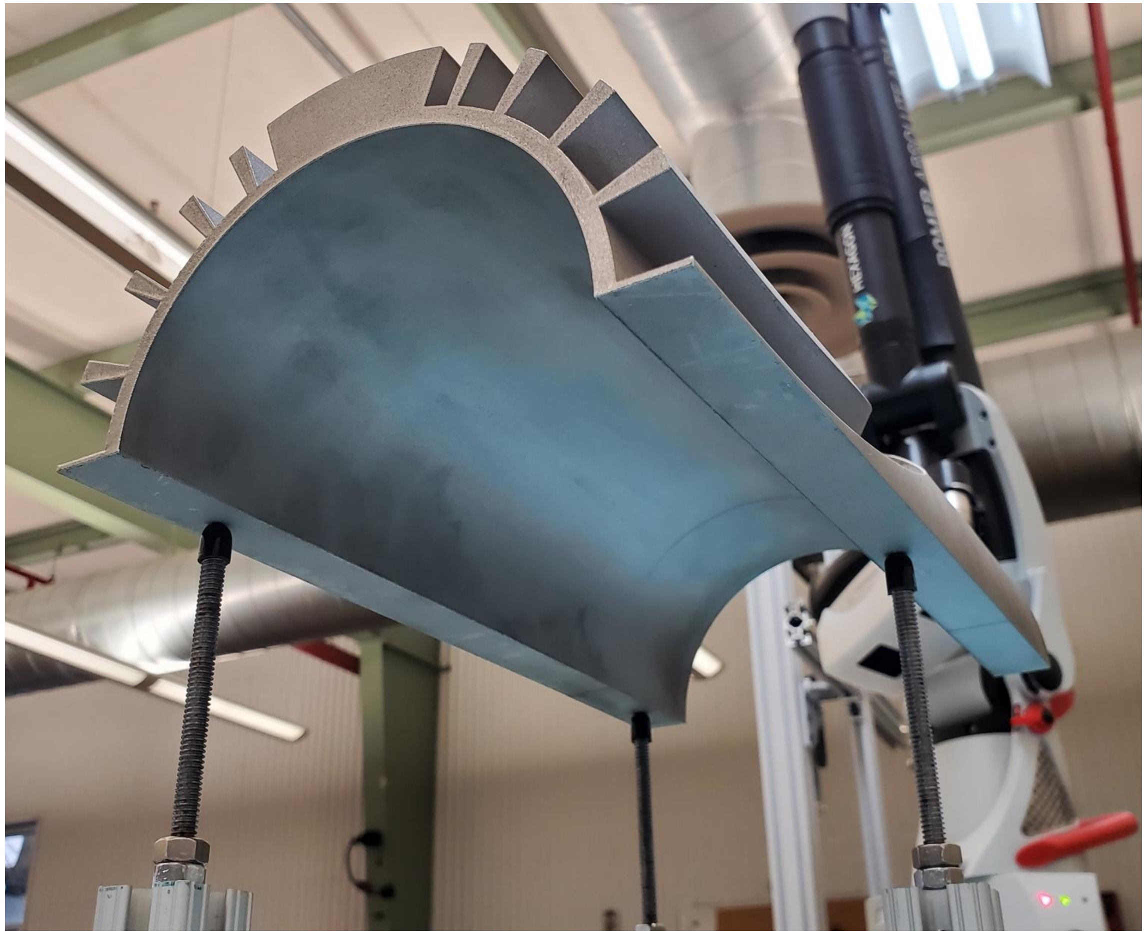
End Parts for Layer 2, outside view

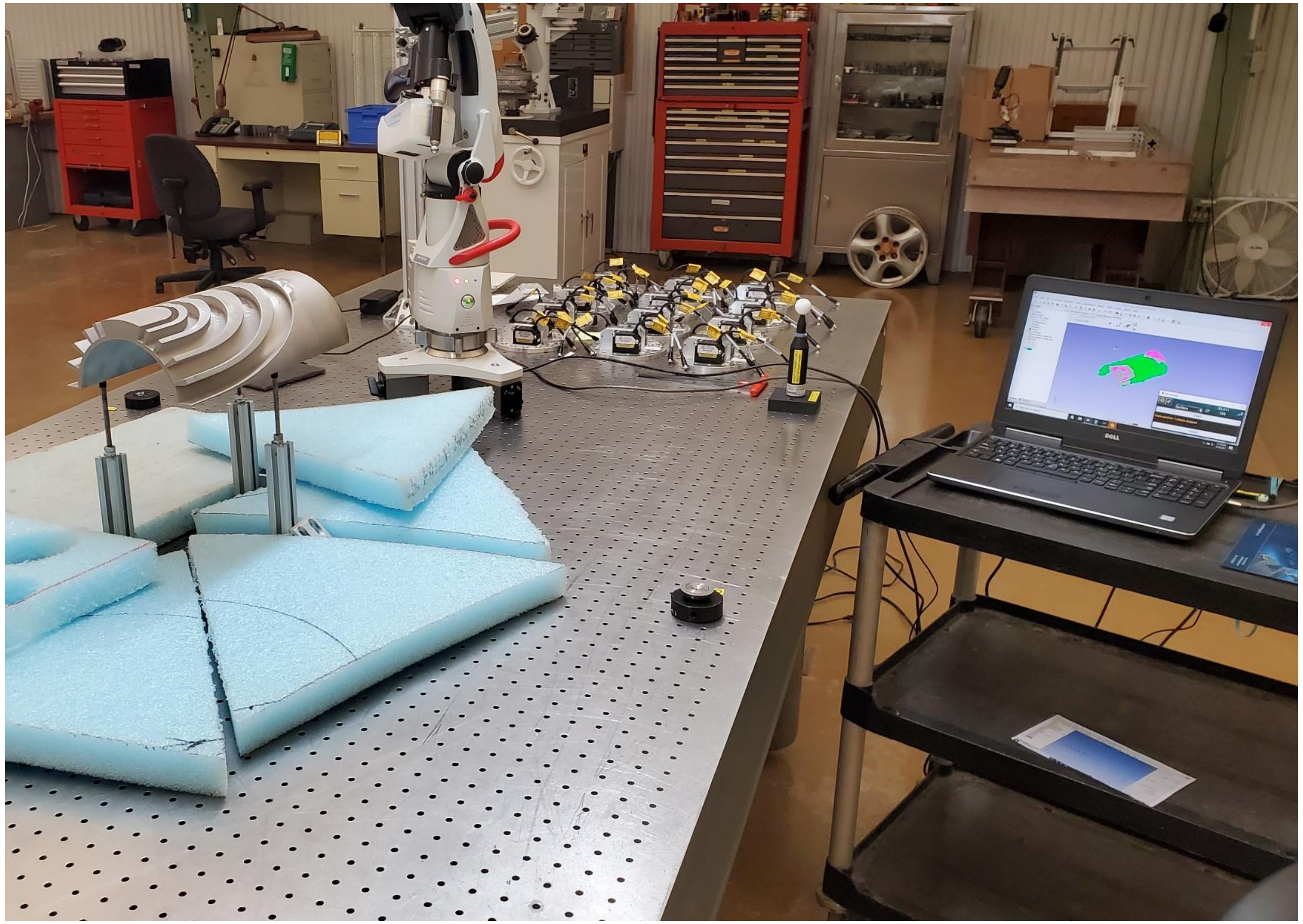


Size control by dial indicator measurements

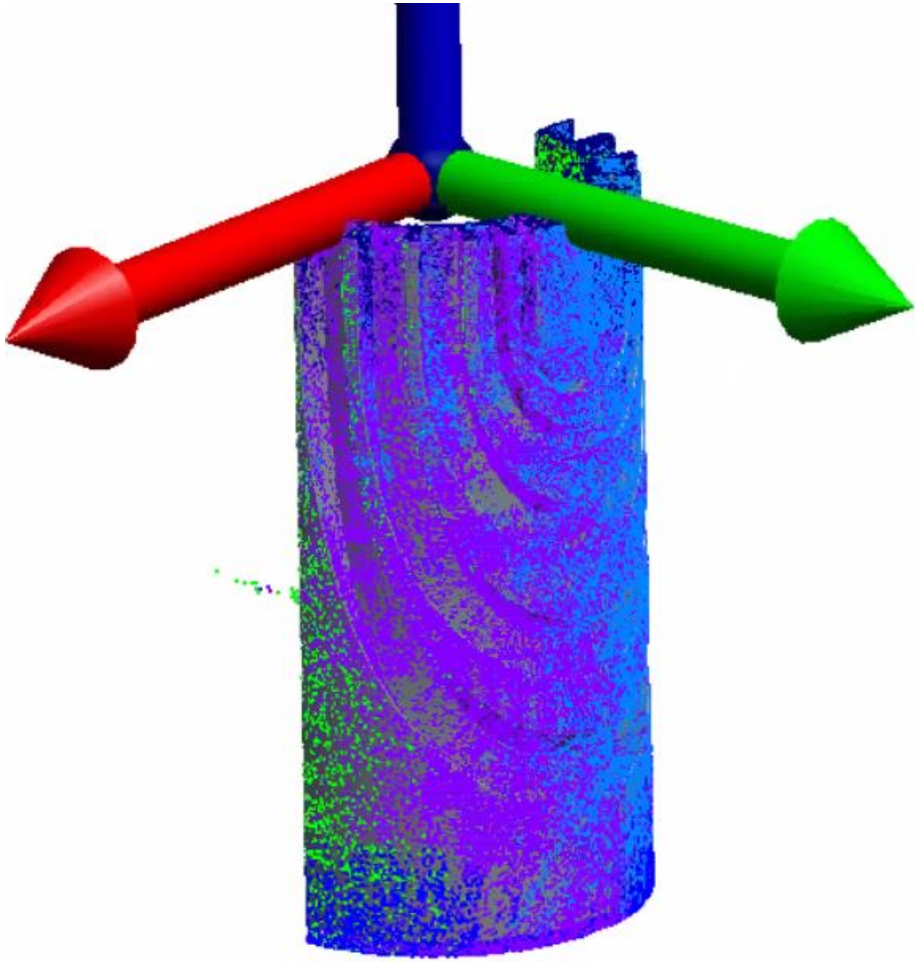
Laser Scanning by PPD Metrology Group
Part Measurement Setup

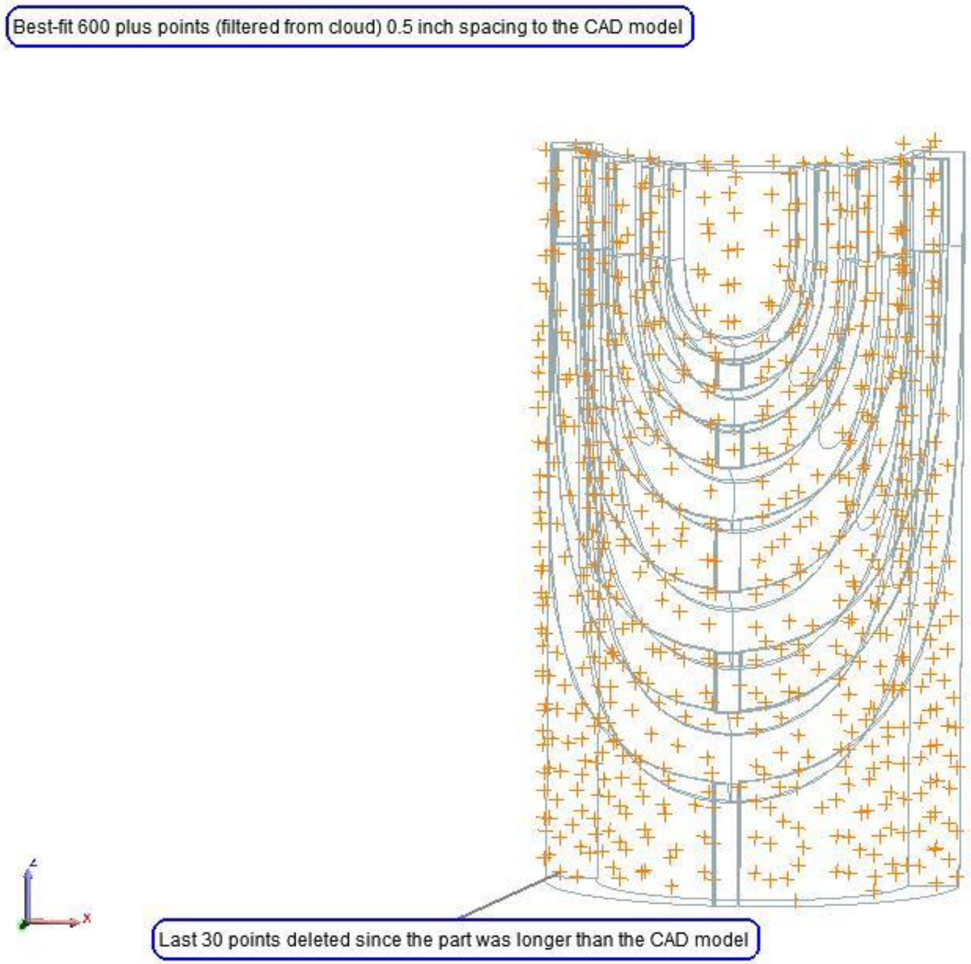
Thanks to: O’Sheg Oshinowo, Chuck Wilson, Doug Swanson, Mike Smego



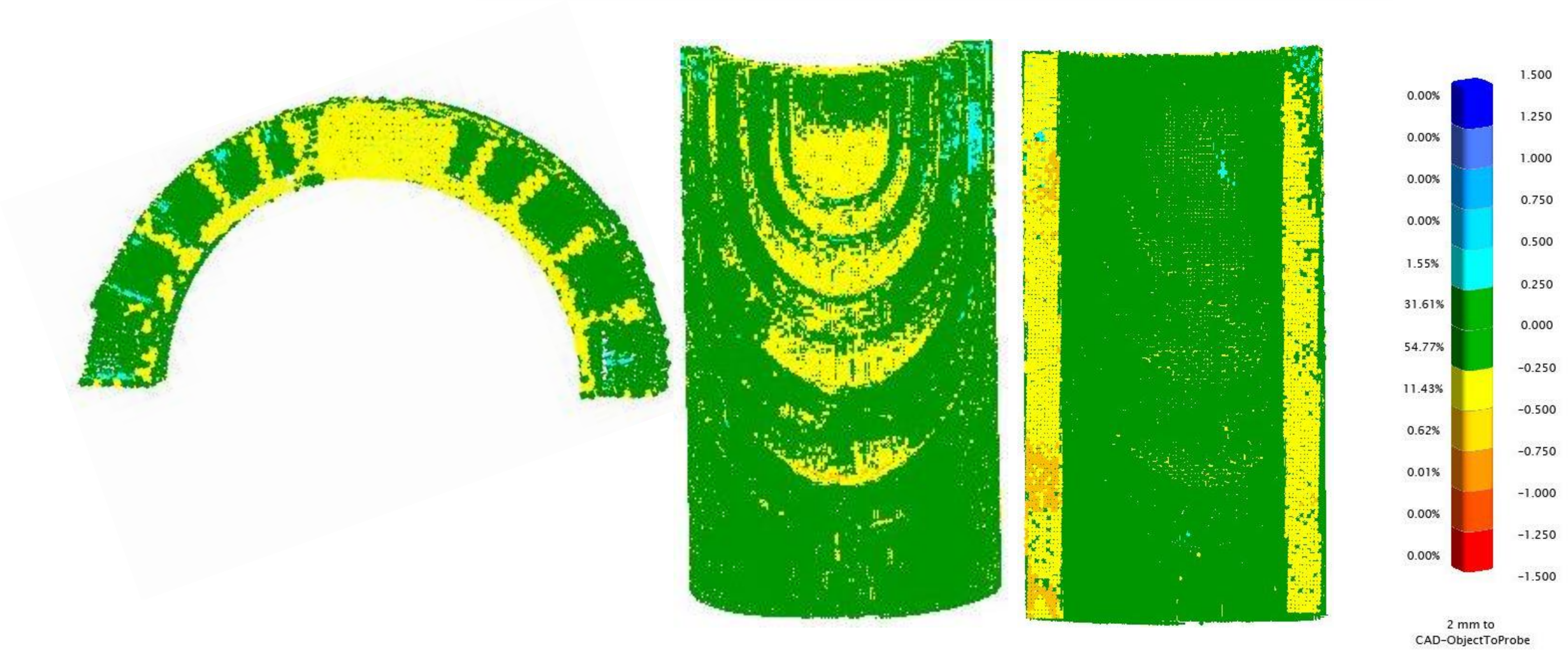


Cloud of Data Points

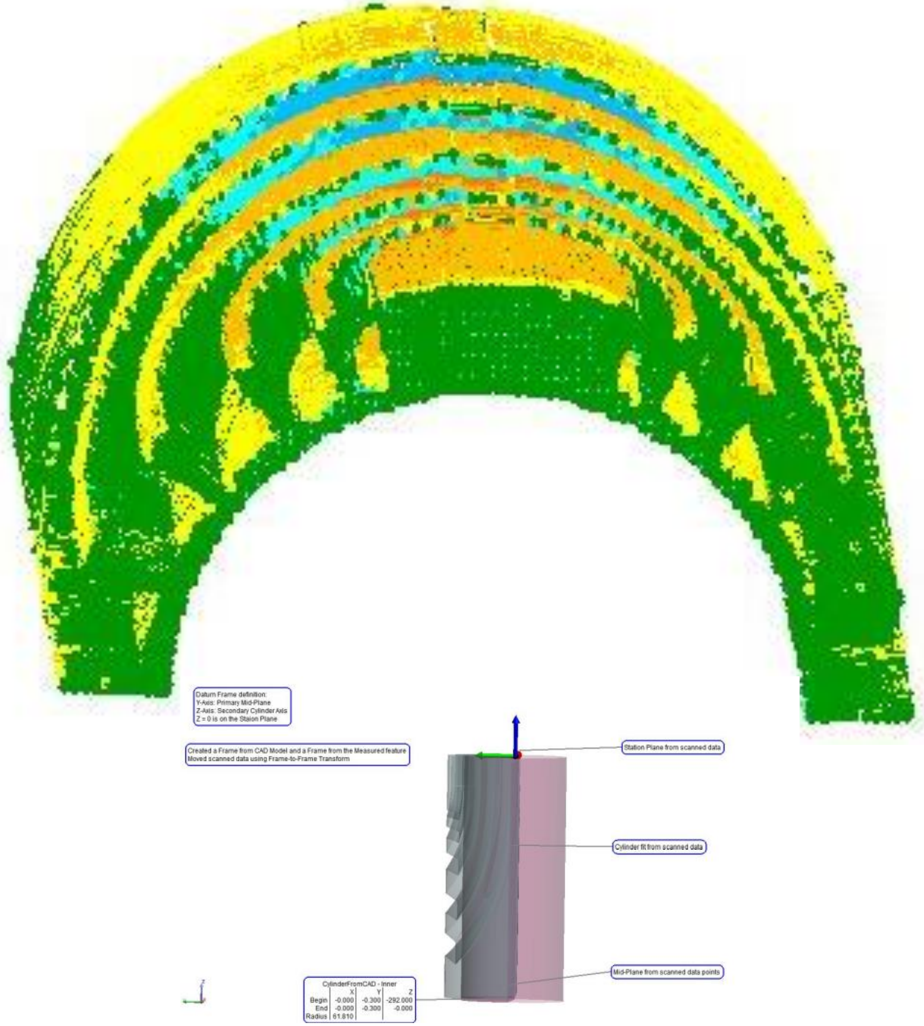


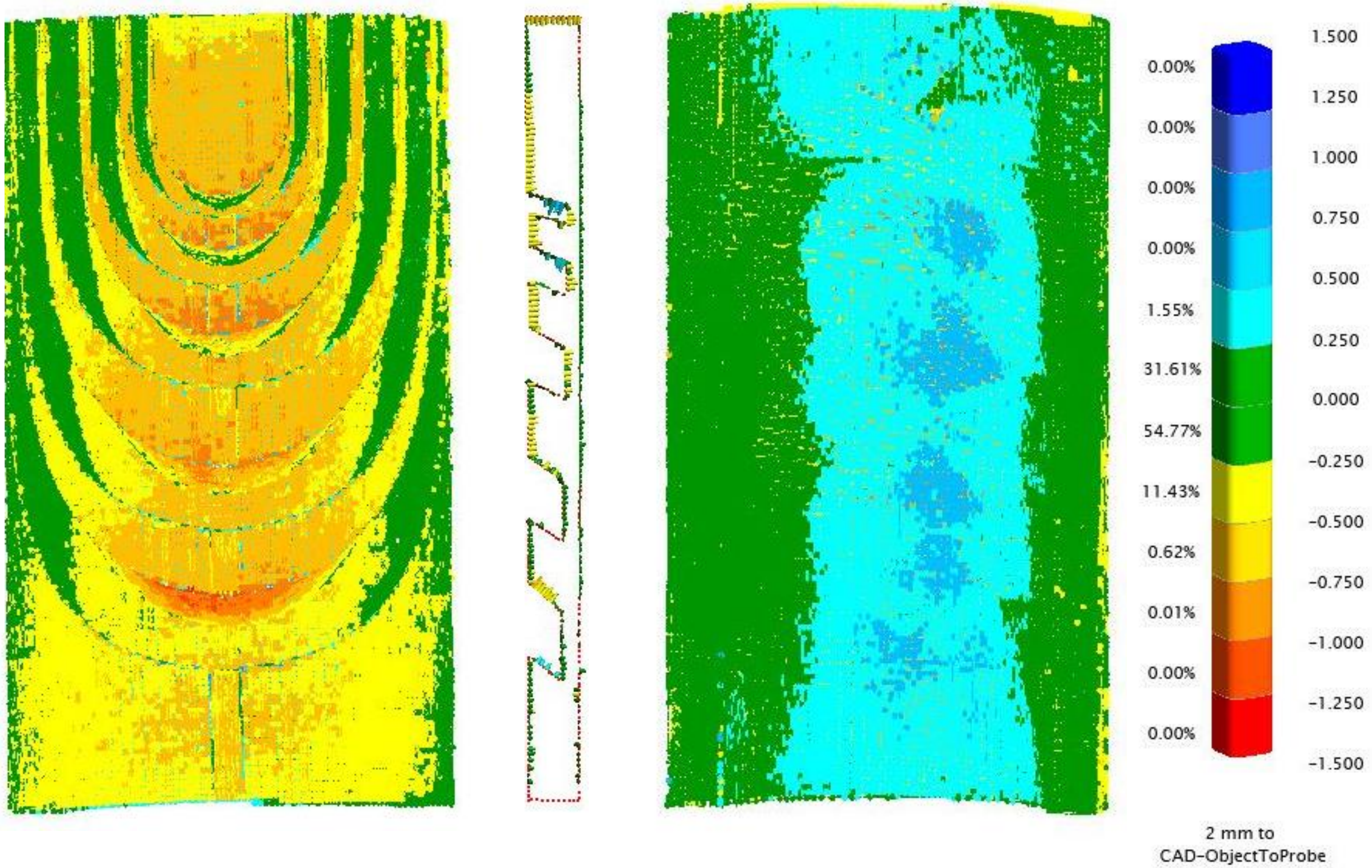


Best-Fit to CAD Model, iteration 1



Best Fit to Datum, iteration 1





Summary

- SMCT coil parts were designed and verified on the practice coil
- SMCT coil parts were built using DMLM technology in the US by GE Additive
- APC-TD QC group does not have proper equipment to inspect 3D-printed end parts for SMCT coil
- PPD metrology group has measured one end part, report is coming
- We are in a learning stage to adopt modern technology for the HF magnets