AMiquam

Multi sensor arrays for insitu electromagnetic imaging of parts during metal PBF-LB AM processing

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Metal AM: postprocessing

AMiquam

We make the testing digital

Problem:

1. Post processing: significant costs, delays
2. QC and inspection: 30-50% costs
3. Time and cost for qualification and optimisation

Major hurdle for the growth of metal AM business

Solution:

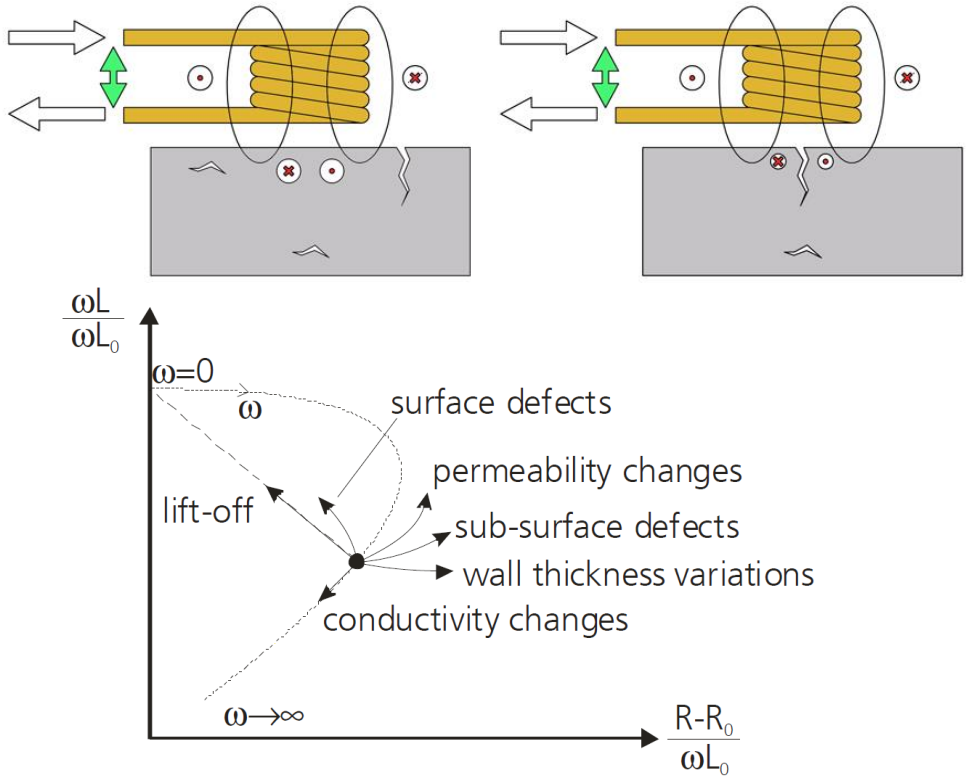
Strengthen the in-situ monitoring tools
Provide subsurface information
Integrate NDT tools in the process

LPBF offers opportunities:

Part is open and available for tests
Recoater -> scanner

Eddy currents for NDT/QC

- Normalised technique (ASNT, ISO15548, ASTM E1004-17, ASTM 3166:20, BS EN)
- Technique of choice for surface breaking crack detection in metallic components
- Useful for other applications (material properties, sub surface defects, etc…)
- Local, Simple surface preparation, no couplant

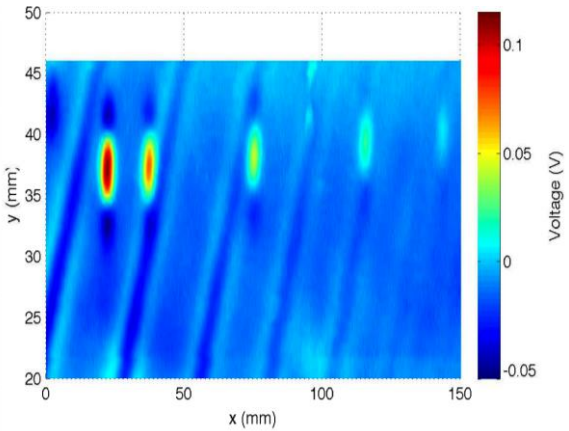


State of the art

In process material inspection (incl. process control)

Inspection of aviation Al plates ASTME 1004-02, MIL STD1537C, EN2004-1 and AMS 2772F

Detection of discontinuities



Crack detection in power blades

ASTM standard for NDE of metal AM aerospace parts E3166-20: Eddy Currents

ABLE 3 Application of NDT to Detect Additive Manufacturing Discontinuity Classes[A]

	Covered in this Guide							Not Covered in this Guide				
Discontinuity Class	CT/RT/CR/DR	ET	MET[B]	PCRT	PT	IRT	UT	AE	LT	NR	MT	VT
Surface	X[C]	X[D]	X	–	X[D]	–	–	–	–	–	–	X
Porosity	X	X[D]	–	X	X[D]	–	X	–	–	–	–	X
Cracking	X[E]	X[D]	–	X	X[D]	X	X	X	X[F]	–	X	X[G]
Lack of Fusion	X[E]	X[D]	–	X	X[D]	X	X	X	–	–	X	–
Part Dimensions	X	–	X	–	–	–	–	–	–	X[H]	–	–
Density[I]	X[J]	–	–	X	–	–	–	–	–	–	–	–
Inclusions	X[K]	X[D]	–	X	–	X	X	–	–	–	–	–
Discoloration	–	–	–	–	–	–	–	–	–	–	–	X
Residual Stress	–	X[D,L]	X	X	–	–	–	–	–	X	–	–
Hermetic Sealing	–	–	–	–	–	–	–	–	X[F]	–	–	–

[A] Abbreviations used: _ = not applicable, AE = Acoustic Emission, CR = Computed Radiography, CT = Computed Tomography, DR = Digital Radiology, ET = Eddy Current Testing, IRT = Infrared Thermography, LT = Leak Testing , MET = Metrology, MT = Magnetic Particle Testing, NR = Neutron Radiography, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, UT = Ultrasonic Testing, and VT = Visual Testing.
[B] Includes Digital Imaging.
[C] Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal features not accessible to MET, PT, or VT (including borescopy).
[D] Applicable if on surface.
[E] Radiographic methods are not optimal for detecting tight laminar features like cracking and LOF, which typically do not exhibit enough density change.
[F] If large enough to cause a leak or pressure drop across the part.
[G] Macroscopic cracks only.
[H] Conventional neutron radiography (NR) allows determination of internal and external dimensions.
[I] Pycnometry (Archimedes principle).
[J] Density variations will only show up in imaged regions having equivalent thickness.
[K] If inclusions are large enough and sufficient scattering contrast exists.
[L] Residual stress can be assessed if resulting from surface post-processing (for example, peening).

Excerpt from the Standard

”8.1 *Scope*

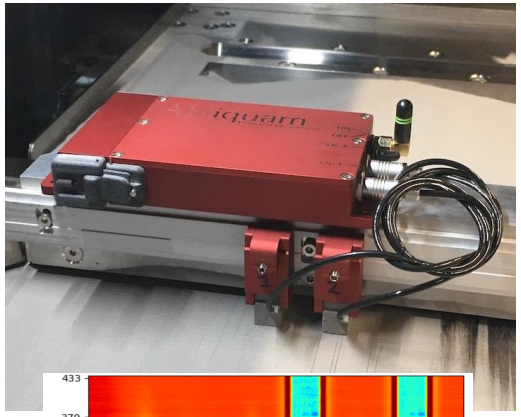
8.1.1 This section describes eddy current examination procedures commonly used in industry for quality assessment of metallic materials. These procedures are applicable to additively manufactured parts during fabrication, immediately after fabrication, after post-processing and machining, and for in-service inspection and monitoring.

8.1.2 Eddy current methods are generally most sensitive to the material surface that is proximate to the sensor. However, by selecting appropriate instrument operating parameters, the condition of both surface and near subsurface flaws can be detected. These procedures are capable of detecting surface breaking and nearby subsurface discontinuities such as cracks, porosity, voids, and inclusions as long as the flaw, discontinuity, or material condition has different electrical properties than the base material.”

AMiquam Product roadmap

From AMiquam W1 to a CaaS platform

AMiquam W1

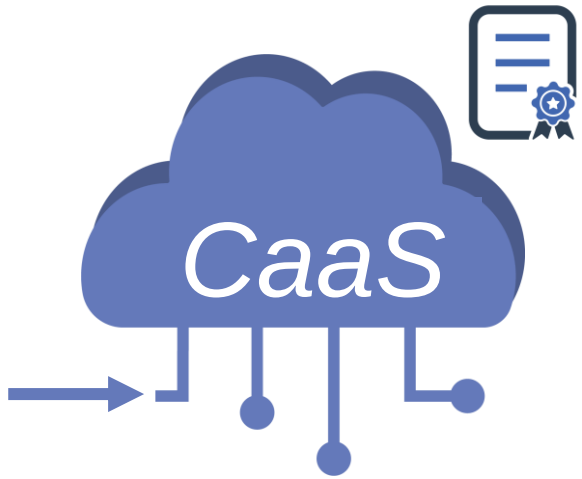


Process monitoring providing unique information on material properties

AMiquam W2 NDT

Full-volume 3D NDT enabling part certification

Certification as a Service Platform



Digital marketplace enabling certified inspectors to certify parts remotely

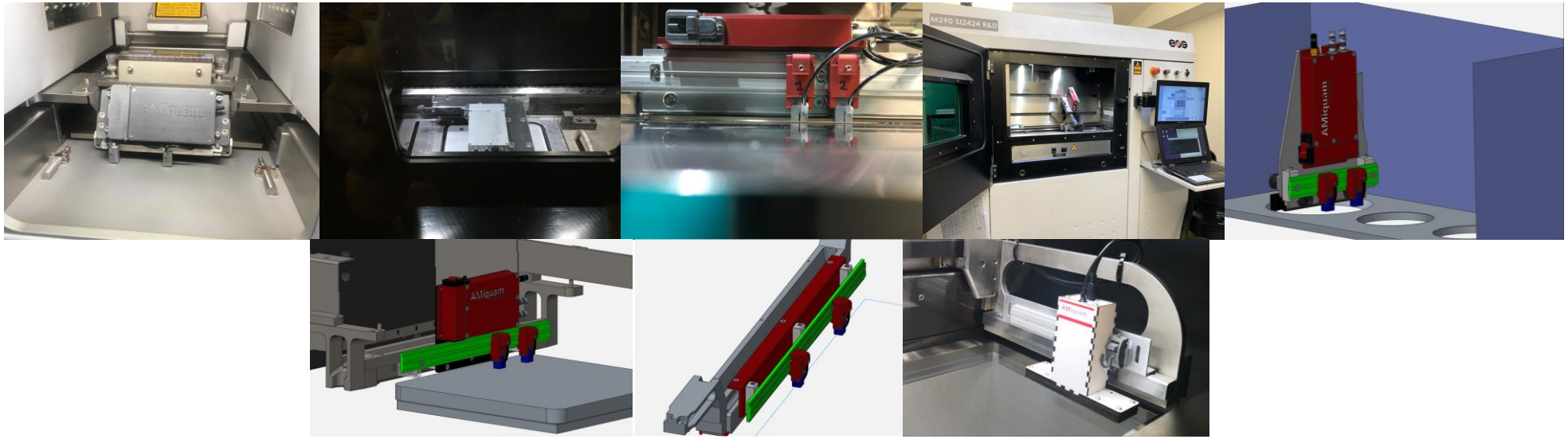
2021 → **2024** → **2025**

W1: A machine agnostic solution for LPBF

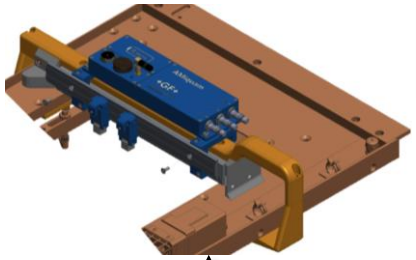
Integrable in most LPBF machines available

- Our solution can already be applied to 75% of the LPBF market and can be integrated in most of the machines on the market
- Existing concepts for other Metal AM techniques (e beam, WAAM, DED, etc..)
- Applied in pilot projects in Aerospace, Medtech, Energy, Manufacturing Industry

AMiquam technology allows **integration** in **various LPBF machines**



W1 in DMP350 machines



Machine delivered to Aviation service provider

AMiquam Inspect
Post-processing inspection
Features tagging
Thresholds settings

AMiquam Monitoring
OK/NOK for each layer
Based on features selection
OPC-UA server based

Acquisition to visualization chain

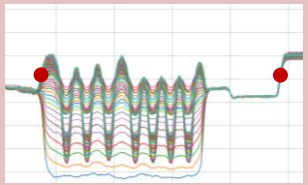
EC sensors

AMiquam Wireless W1
(*in-situ*)

Data acquisition

(AIMD)
Raw data DB

Layer-by-layer
segmentation



(AMDB)
Segmented
DB

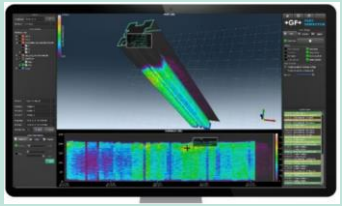
New data set available
after each recoater motion
OPC UA

Local

Digital Hub MES

AMiquam Monitor®

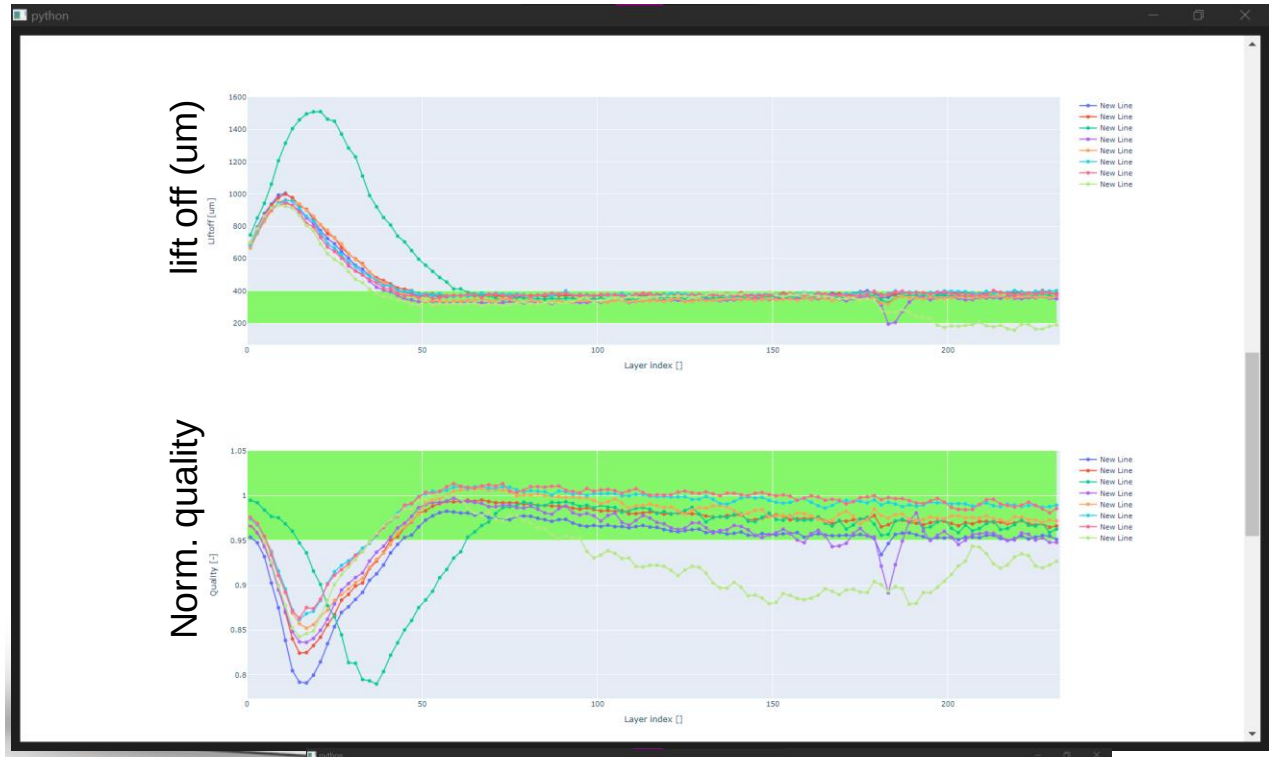
Visualization and post process software

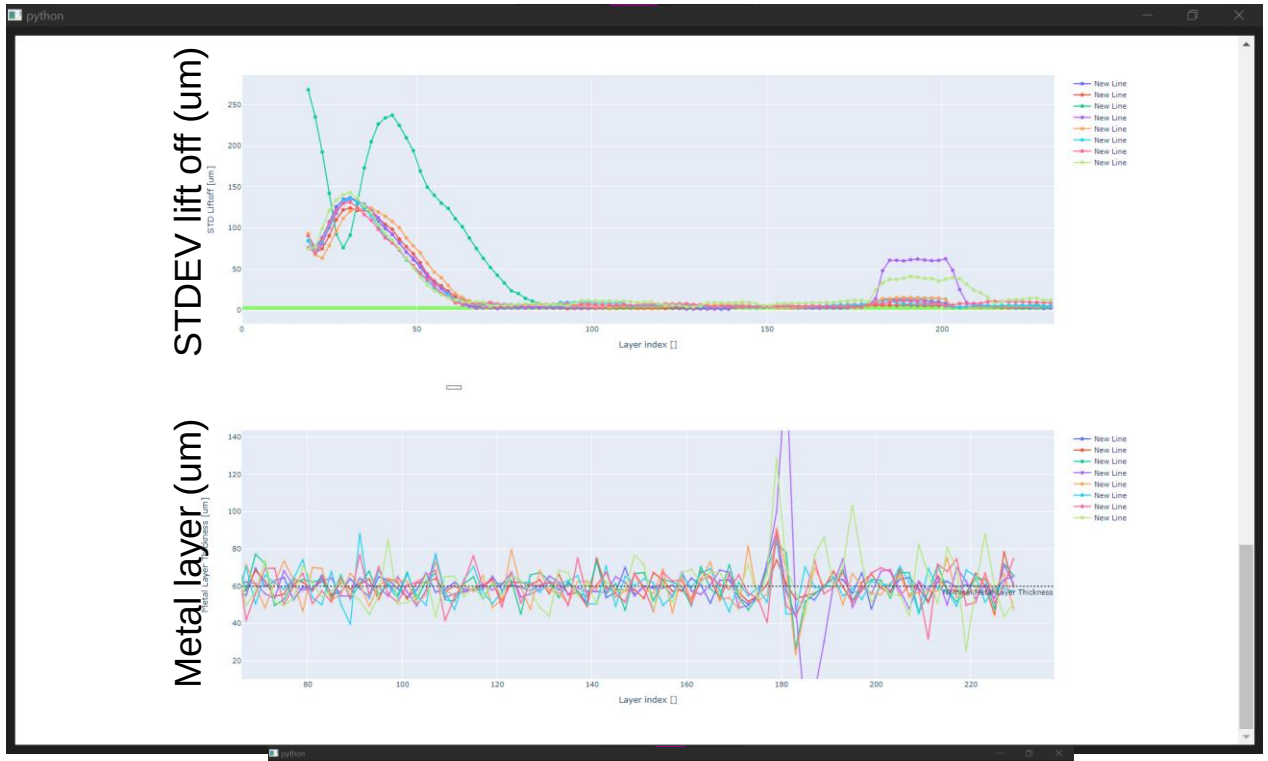


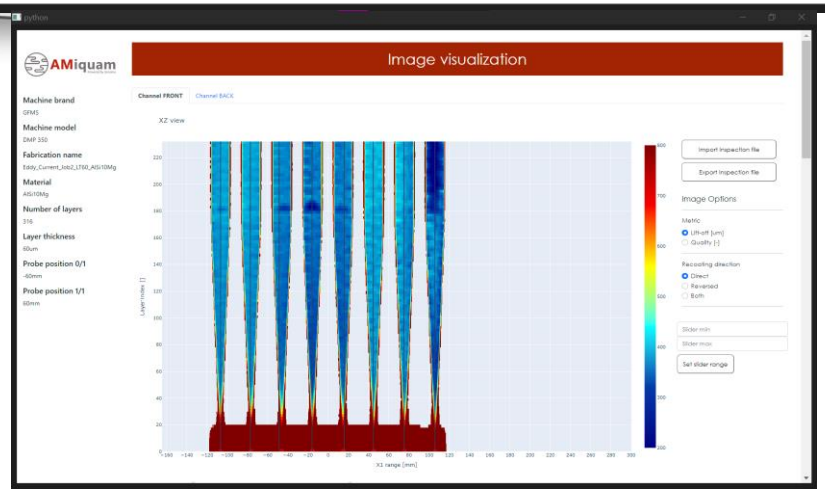
AMiquam Inspect®

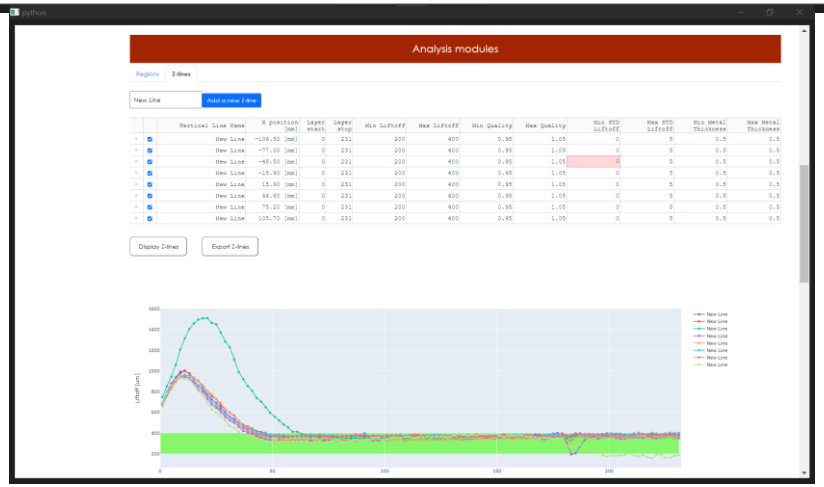
AMiquam Monitoring

Physical and statistical data ready for integration in QC documentation

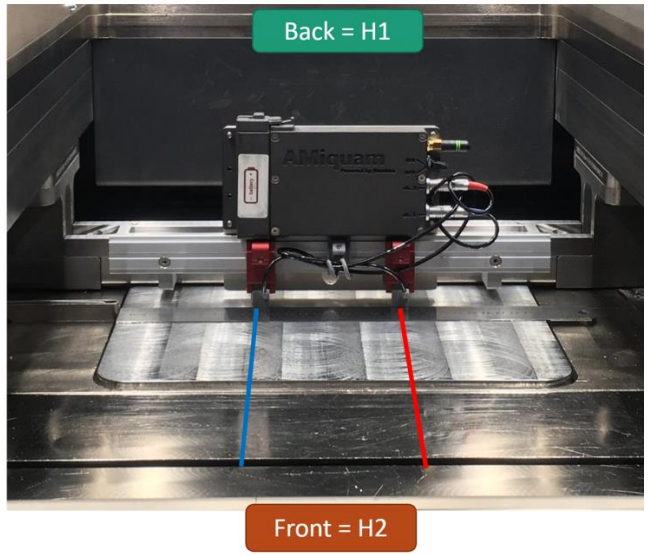




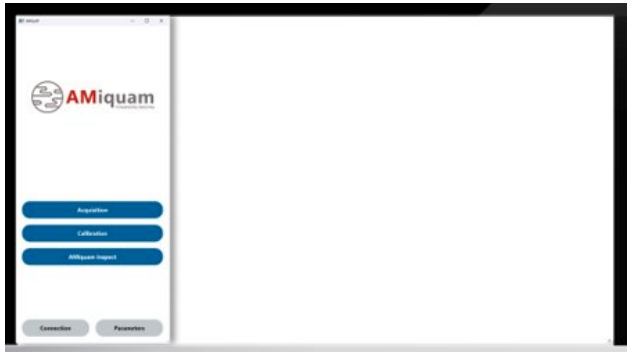




Integration of AMiquam W1 in EOS machines



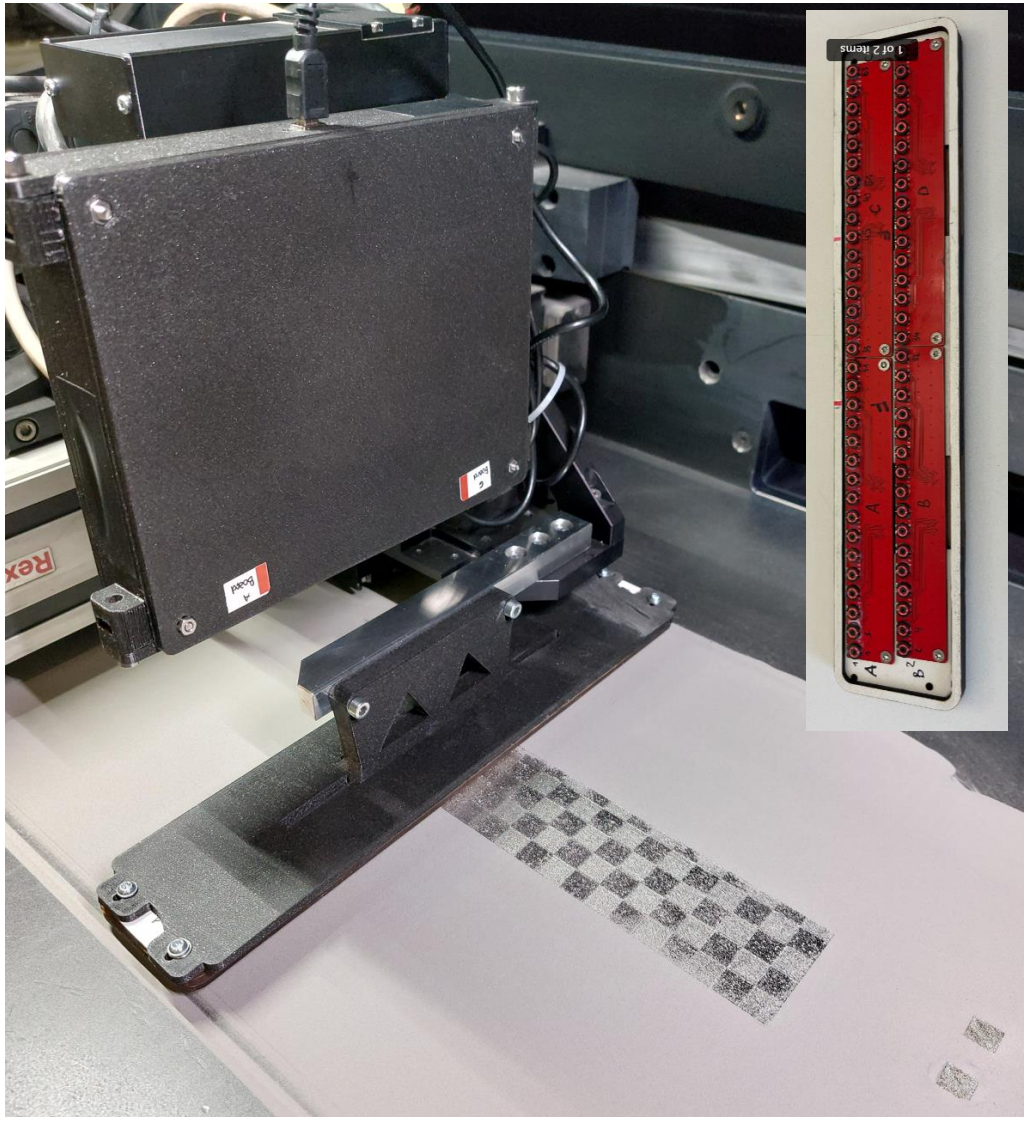
Acquisition and Calibration

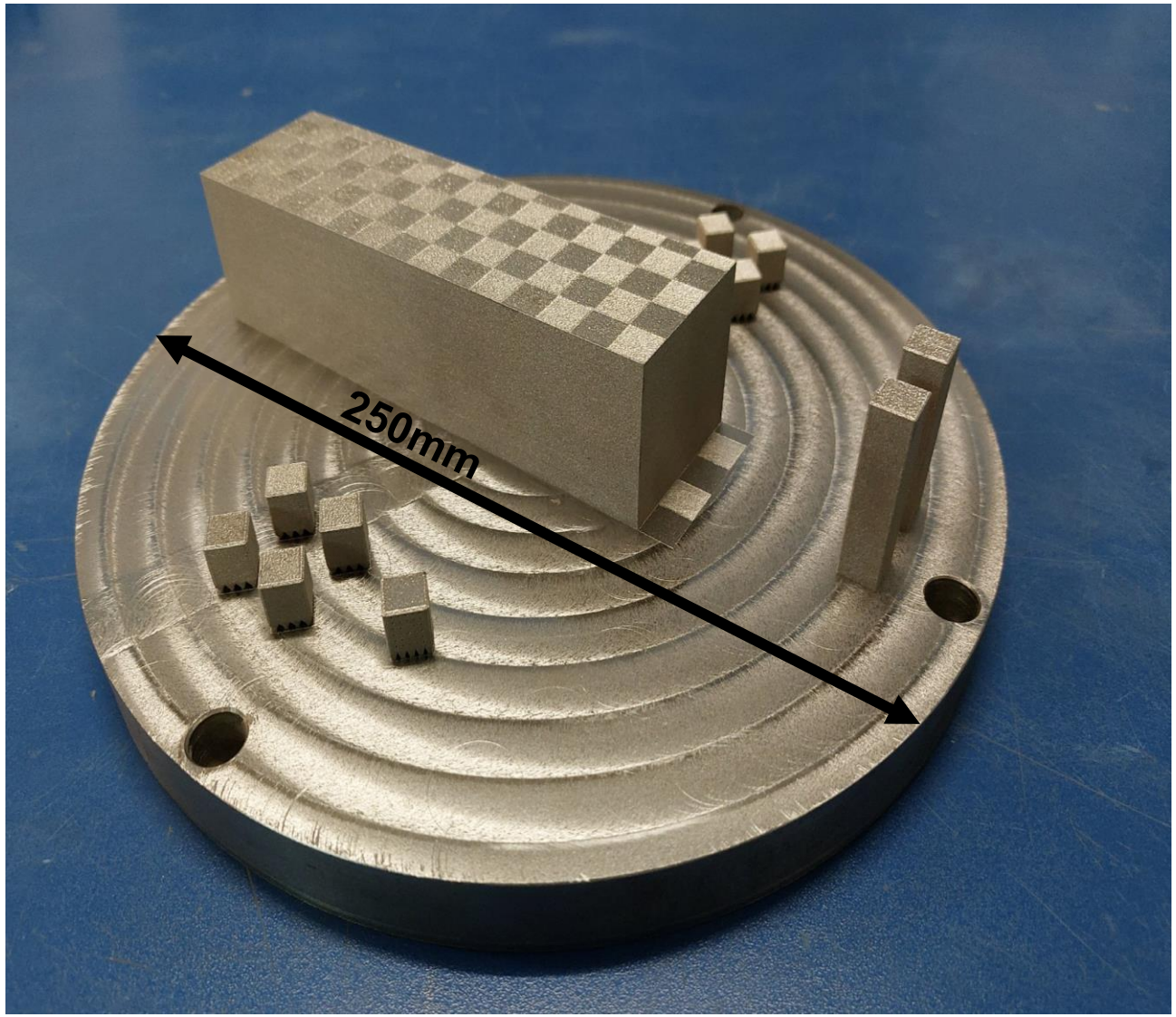


AMiquam Monitoring
OK/NOK for each layer
Based on features selection
OPC-UA server based

AMiquam Inspect
Post-processing inspection
Features tagging
Thresholds settings

W2: full build plate inspection





Fabrication example

General Build Job Details
- Material: 316L
- Machine: Aconity Midi+
- EC array: 64 coils
- Coverage: 240mm
- Sensor pitch: 3.75mm (y resolution)
- Data acquisition rate 92Hz, 1pt/0.6mm (x resolution)

Eddy current testing:
- 500µm lift-off at the start
- 200 kHz excitation frequency

Parameters:
- 30µm layer thickness – 1333 layers (40mm)
- Nominal parameter > 99.5% everywhere except where there are designed defects
- Dimension 150x38x40 (height) mm
- 100% of build plate fully inspected during fabrication with compliant NDT ET technique

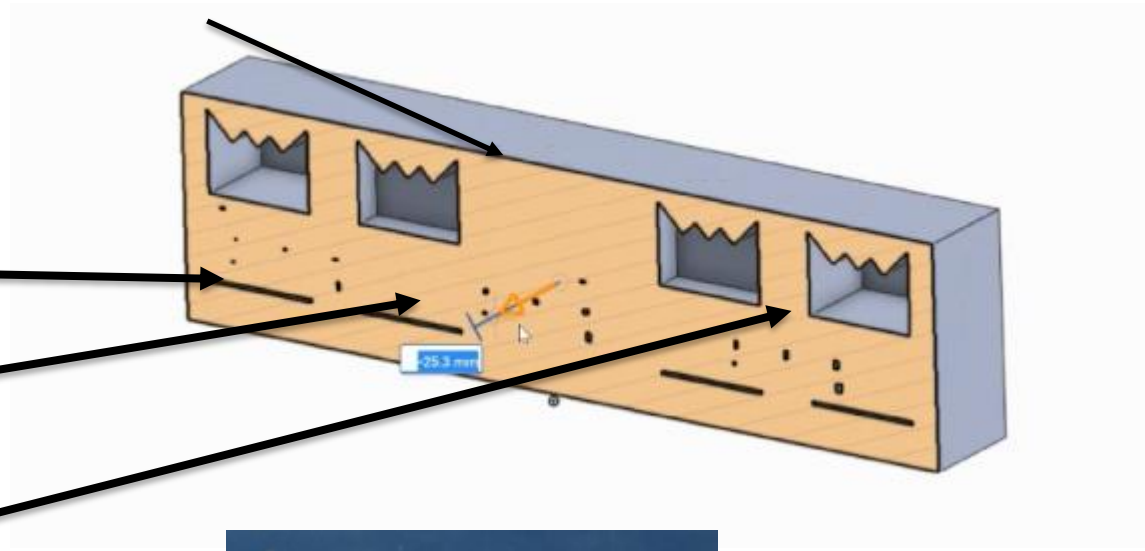
Process and Seeded Artifacts

64 independent XZ planes
10 planes crossing the part

- The first 5 mm height from build plate no defects

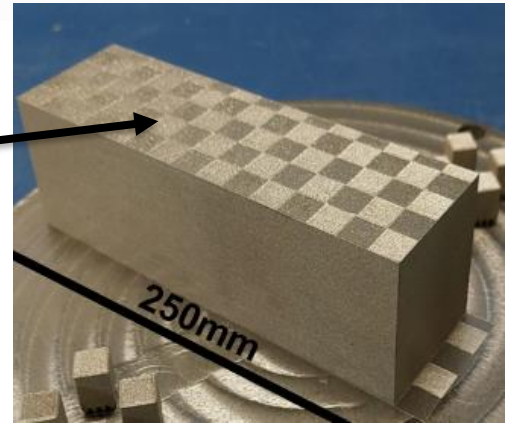
- **Porosity**
  - Full slice
  - Slices with different process parameter inducing lack of fusion

- **Localized discontinuities:**
  - “Cracks”
  - Cylindrical/Spherical cavities

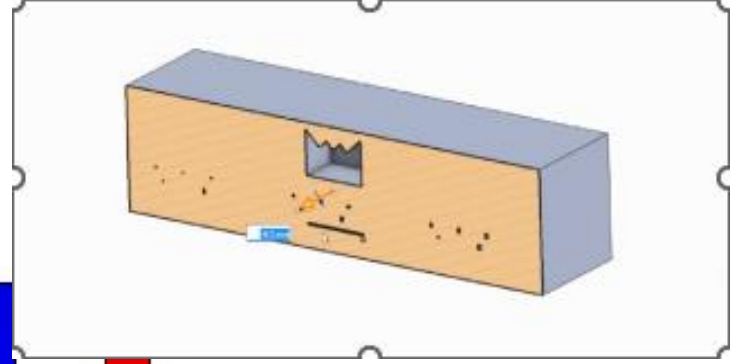


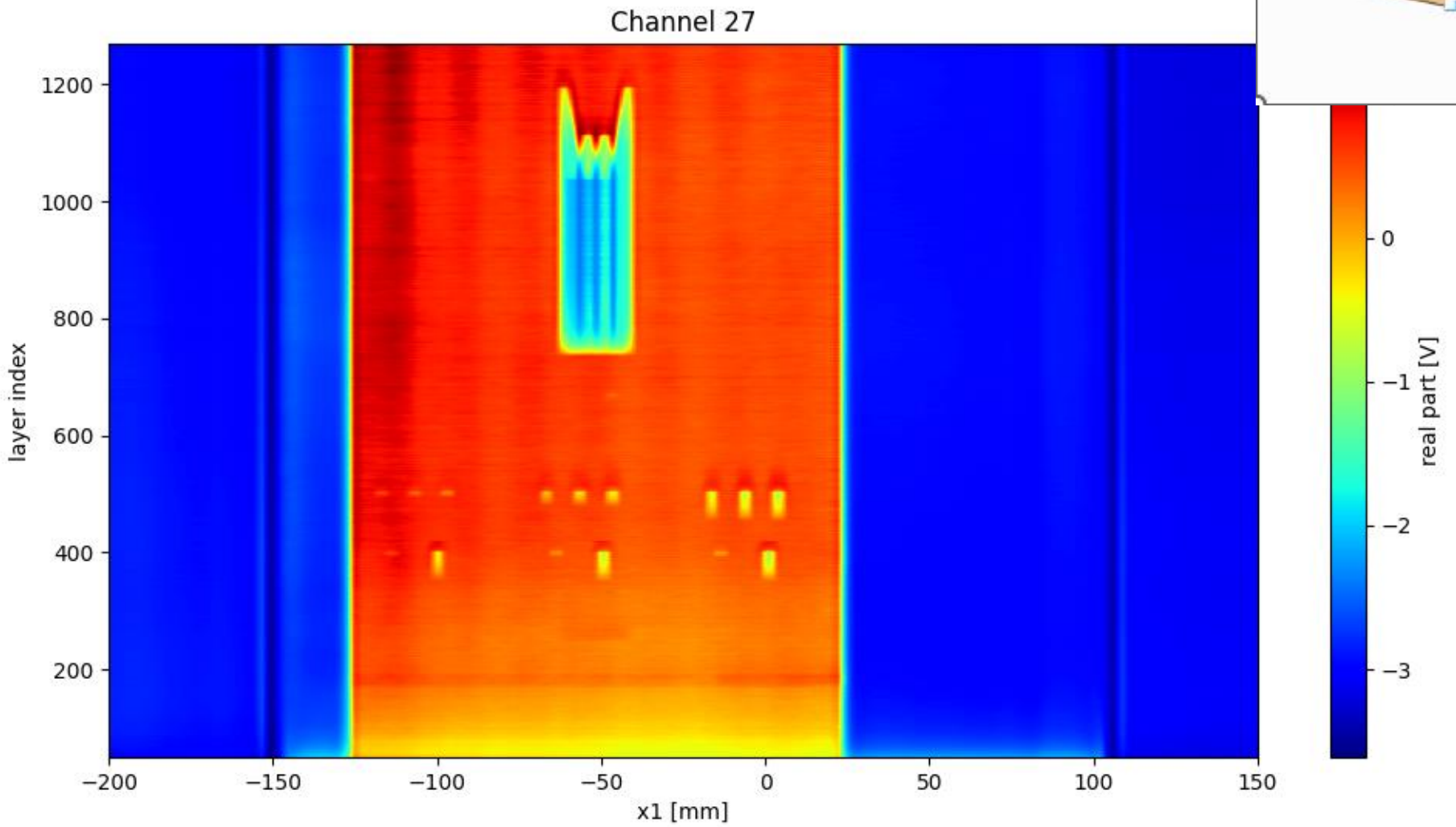
- **Empty cuboids with thin walls**

- **Effect of the chessboard patterns (90° laser trajectories) and helicity of laser trajectory angles on the EC signals**



In phase cross section plots

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real part [V]
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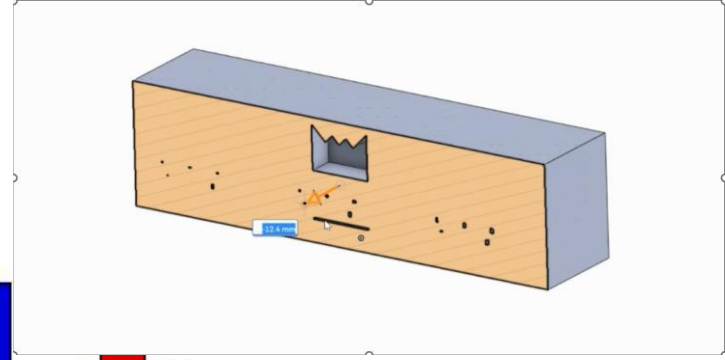

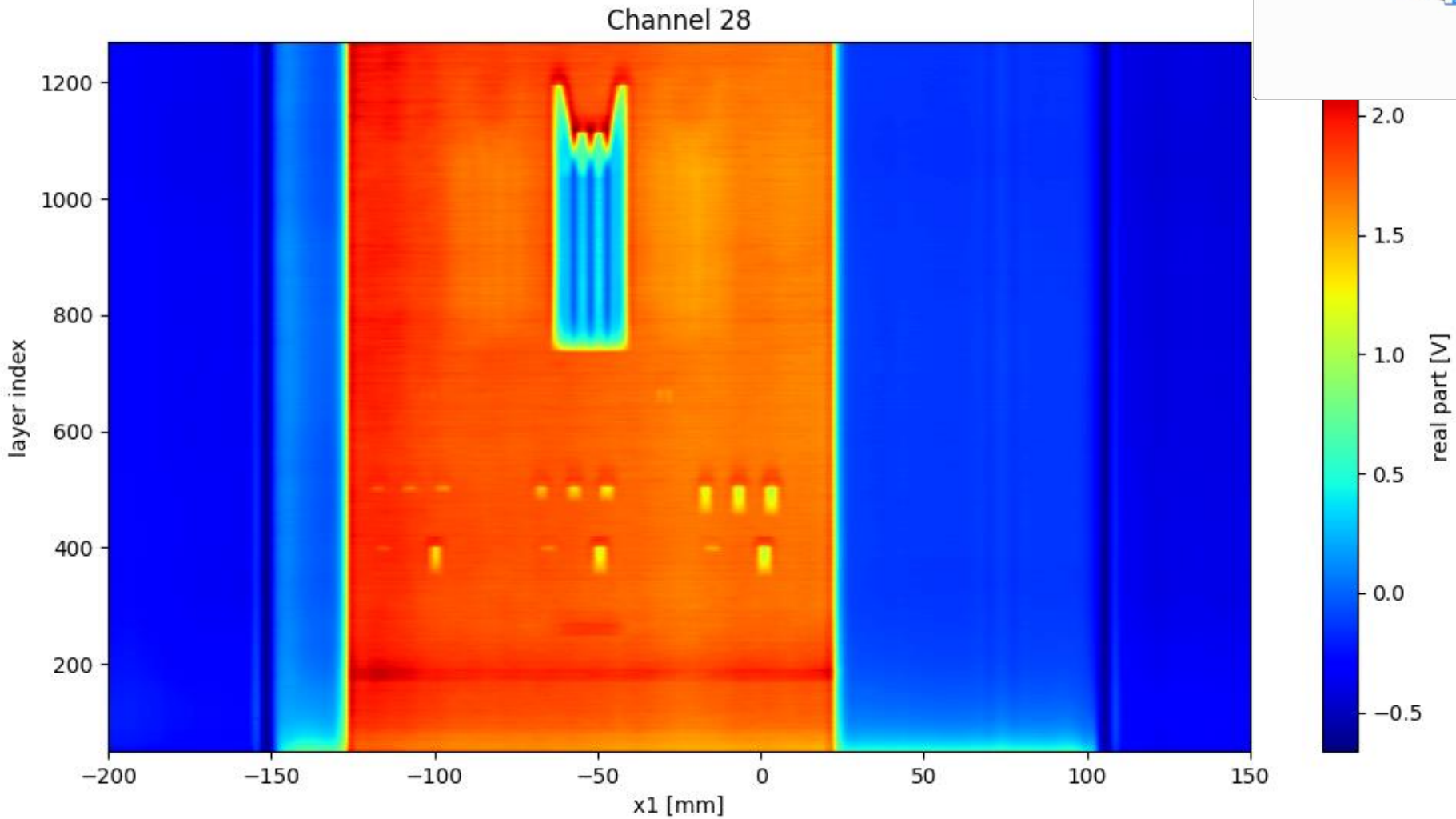
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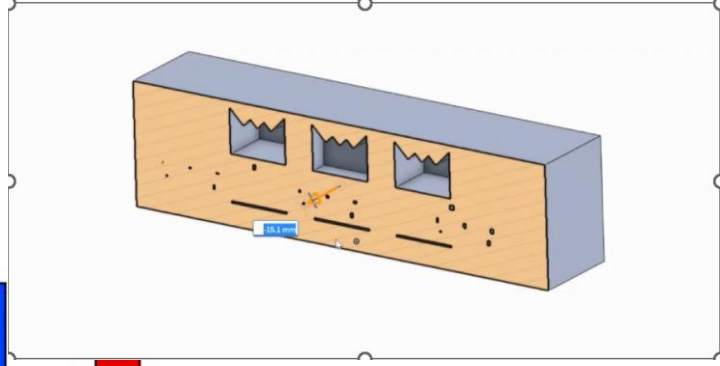

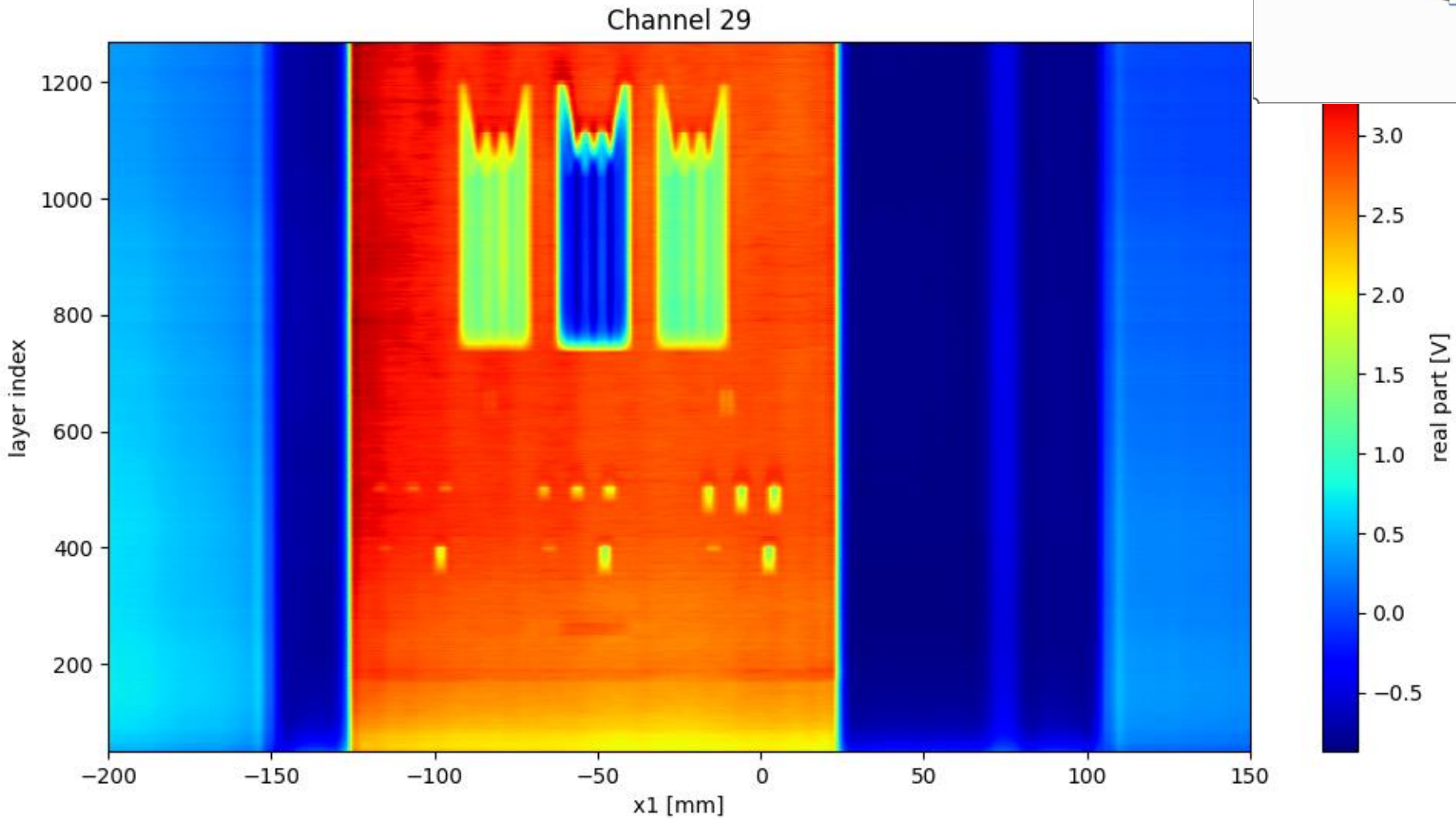
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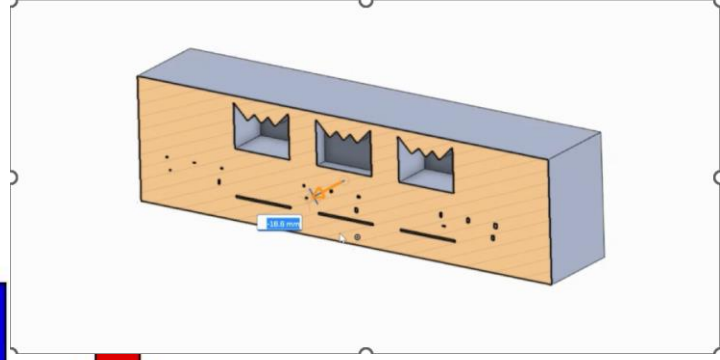

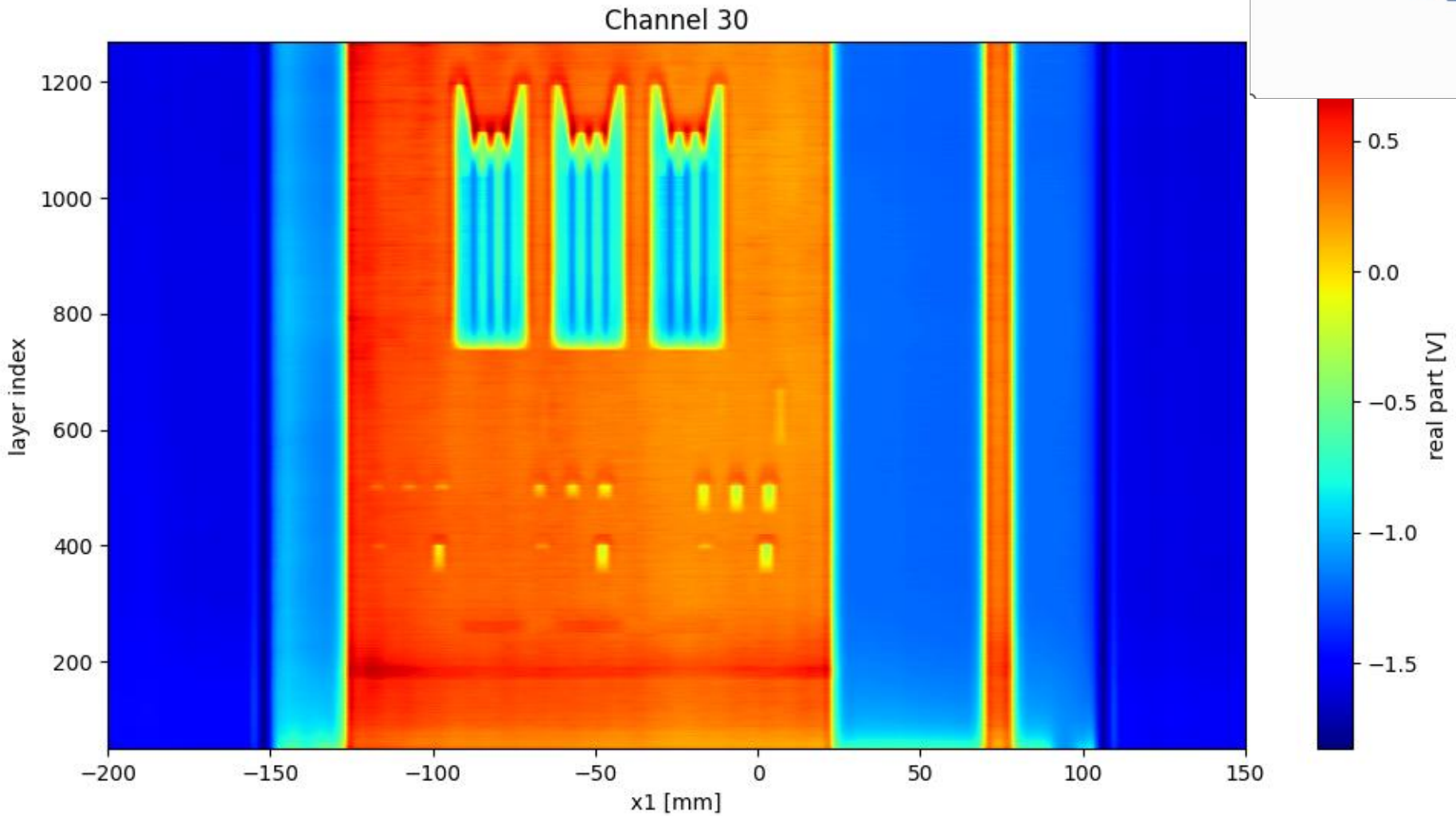
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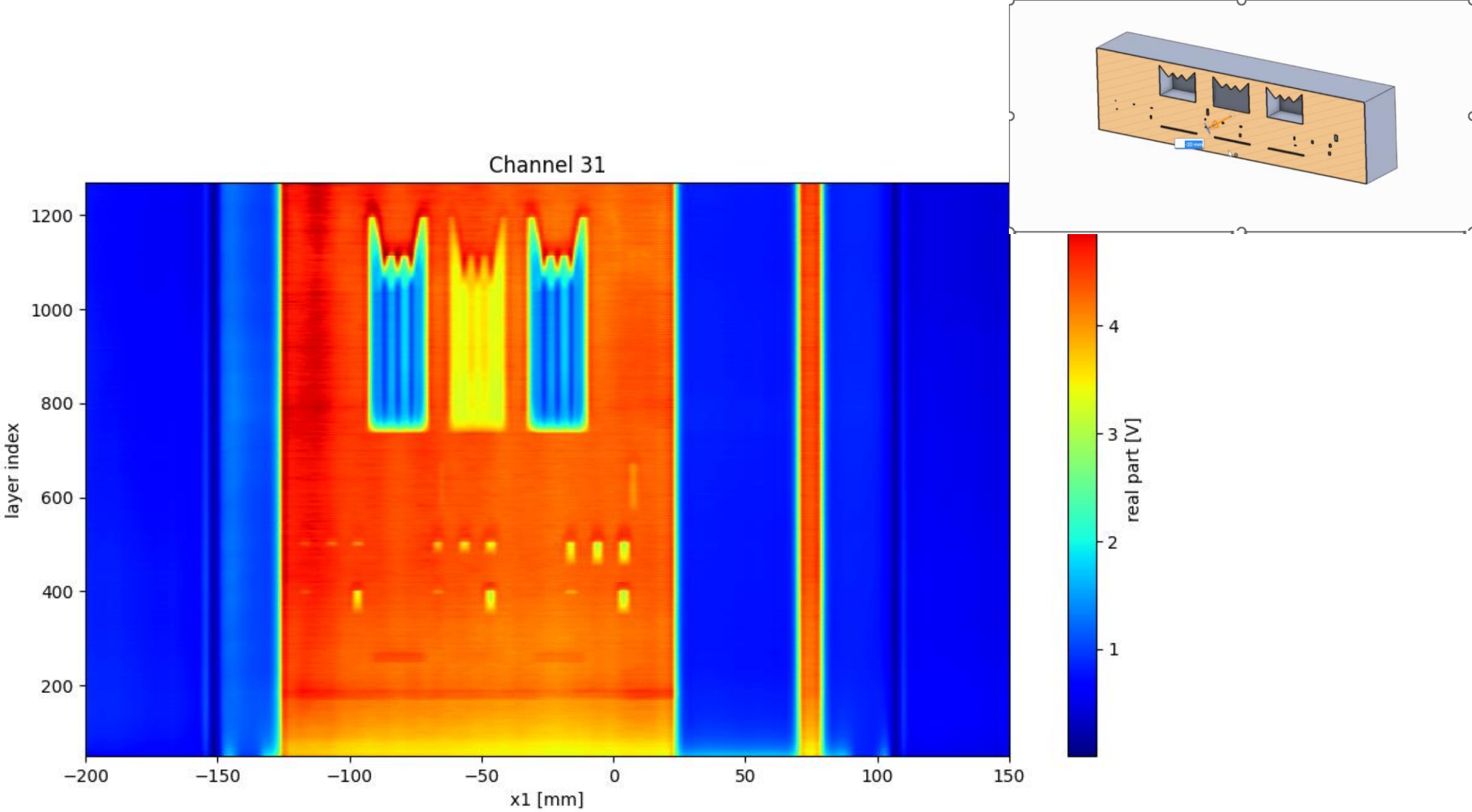
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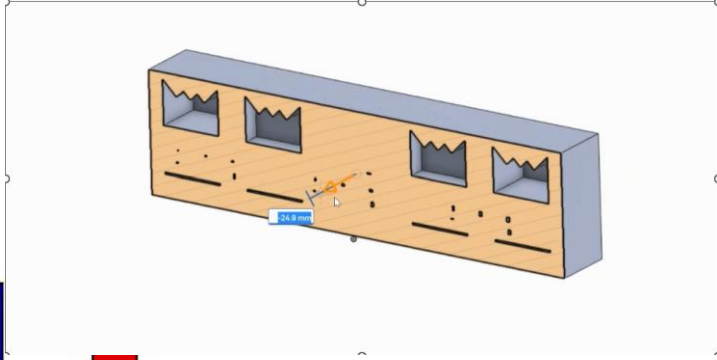

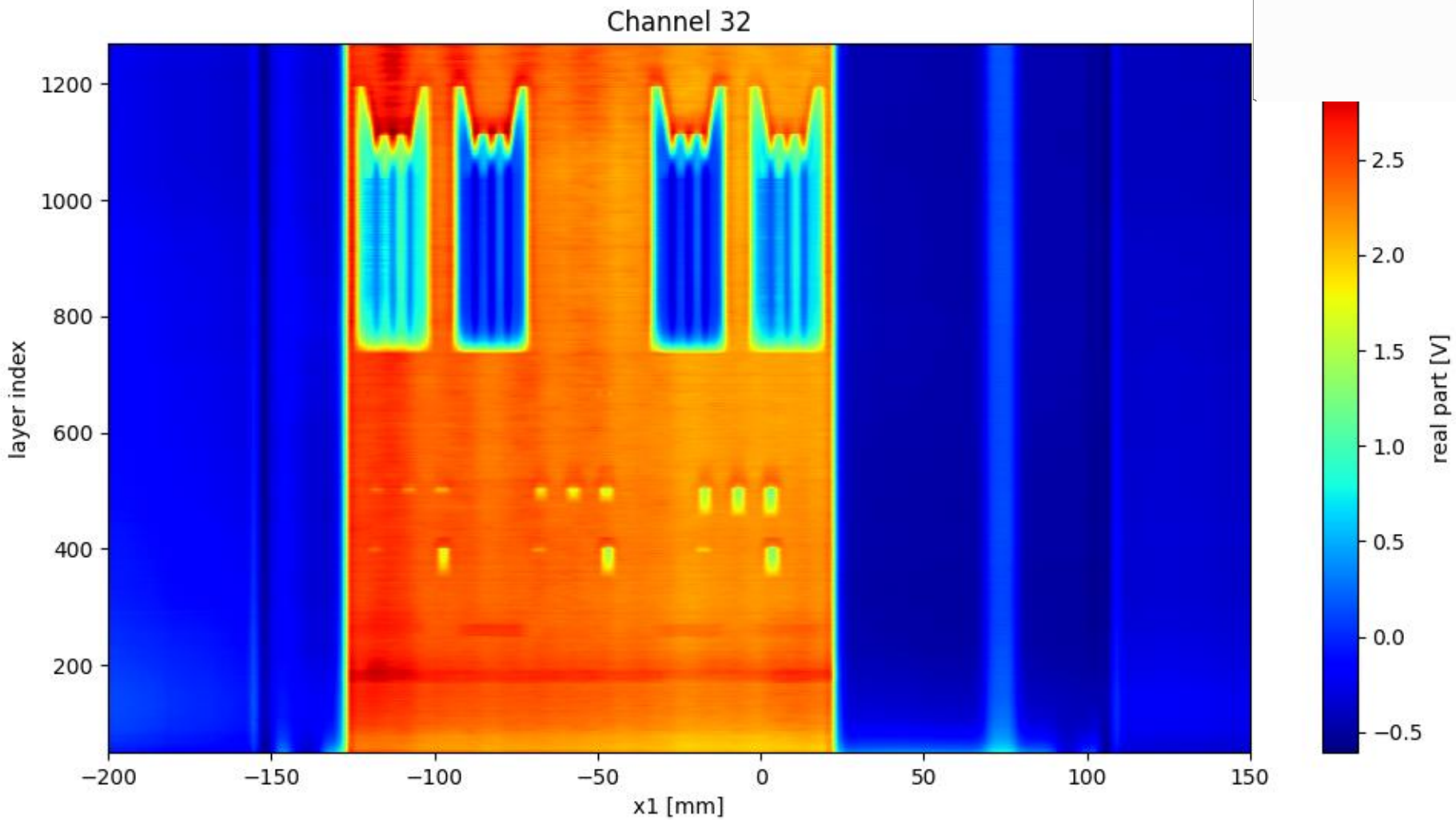
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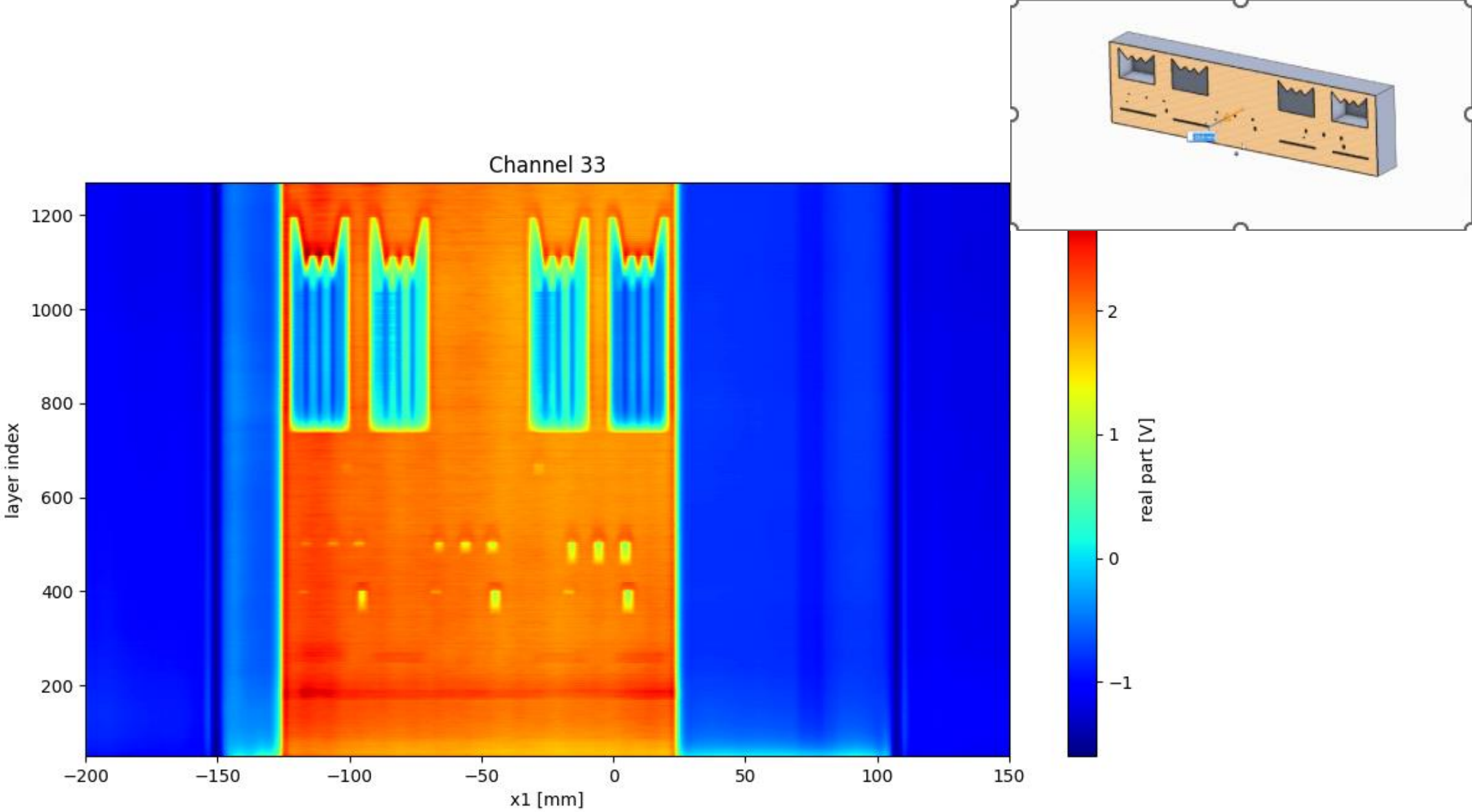
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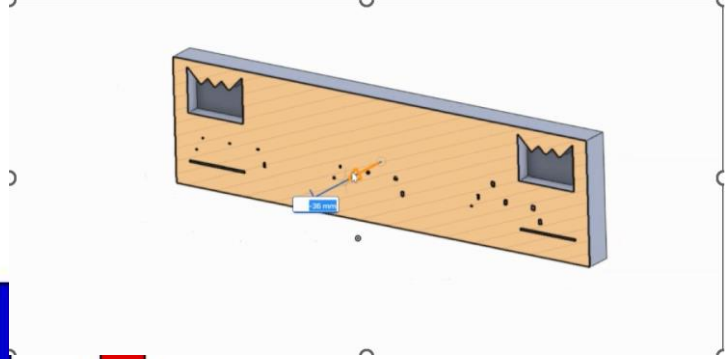

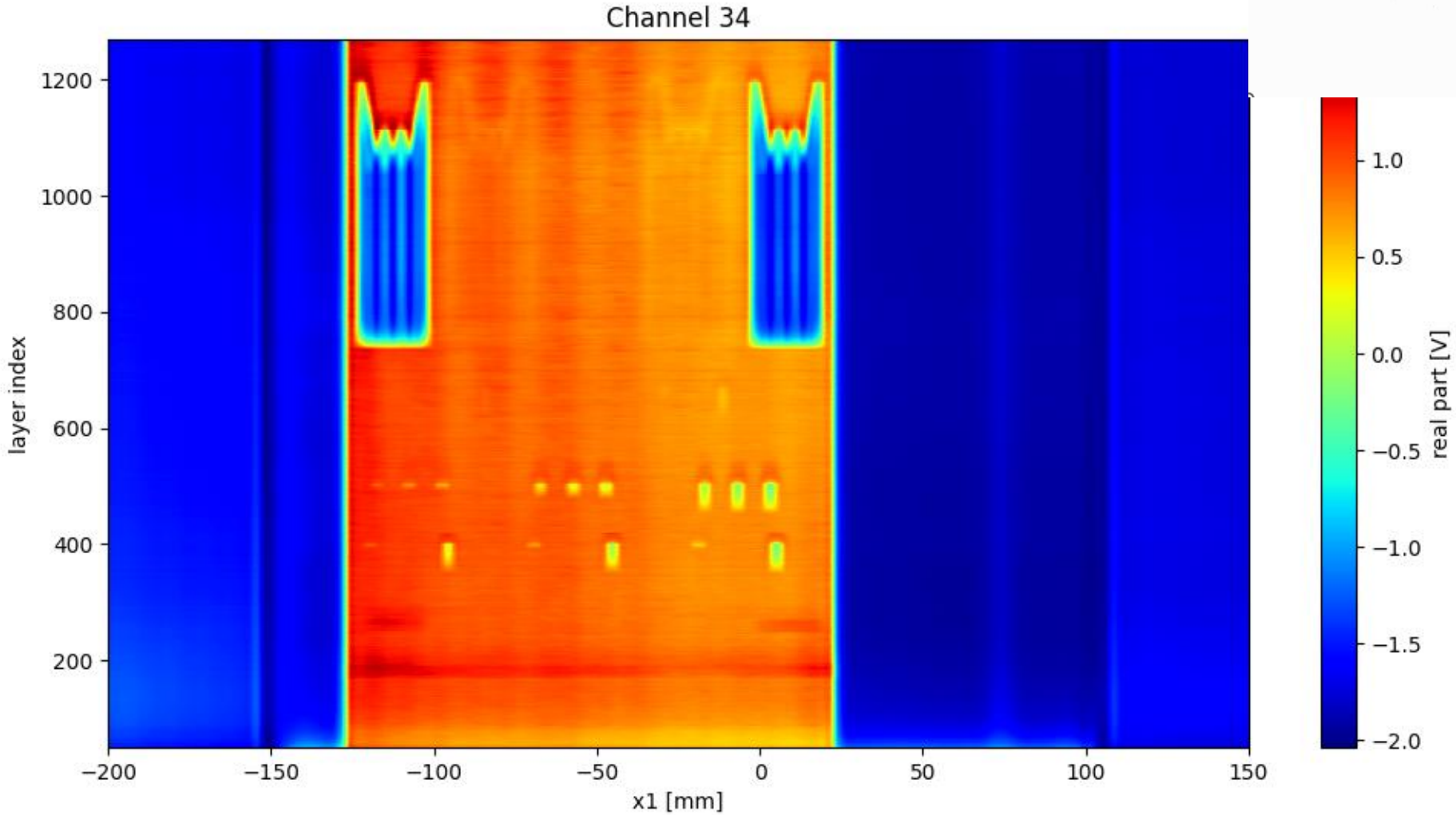
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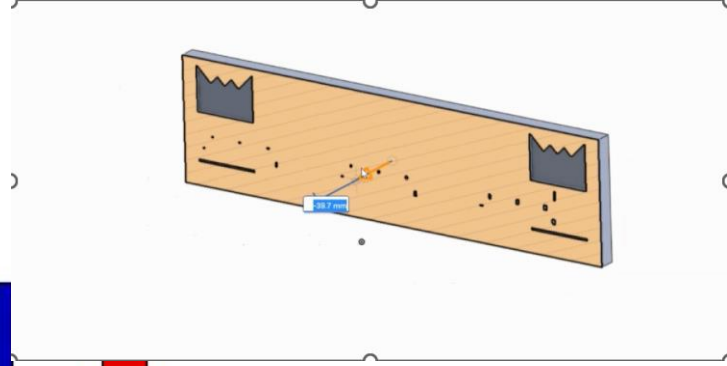
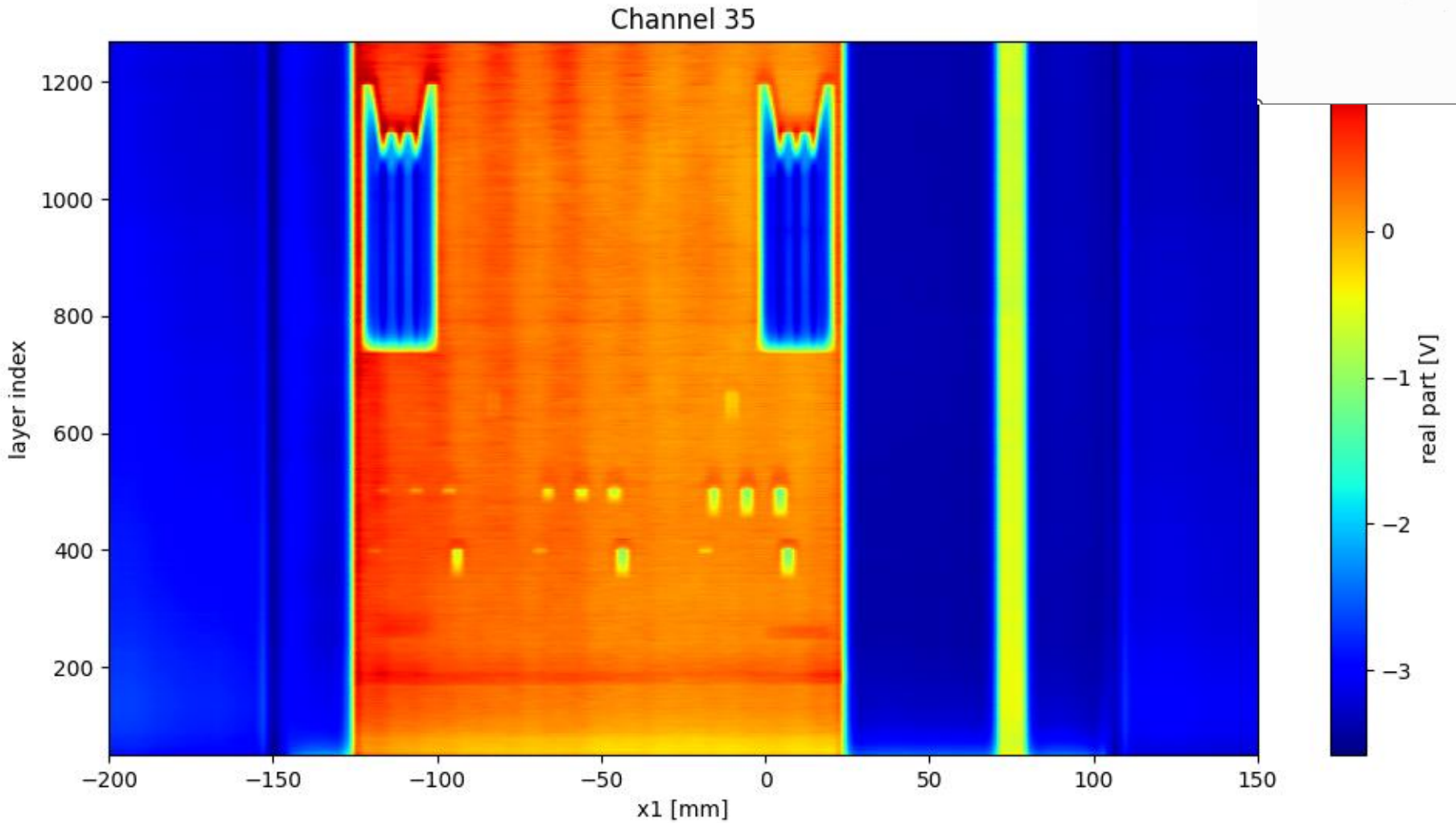
real part [V]

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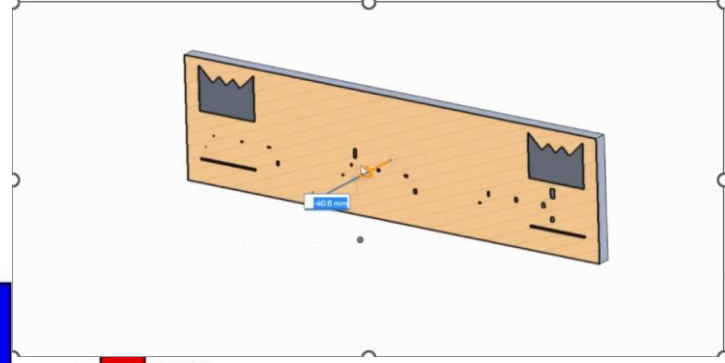

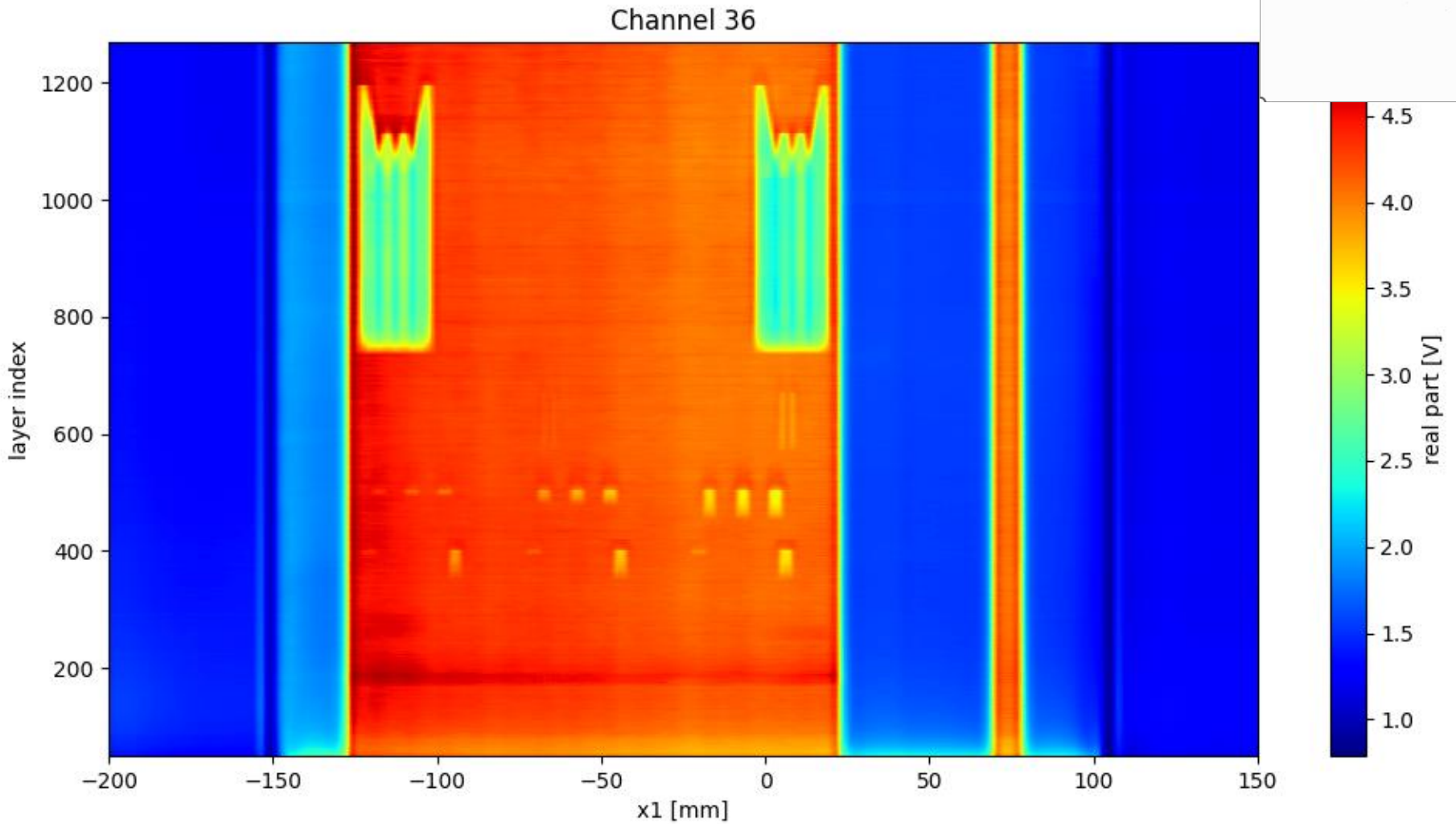
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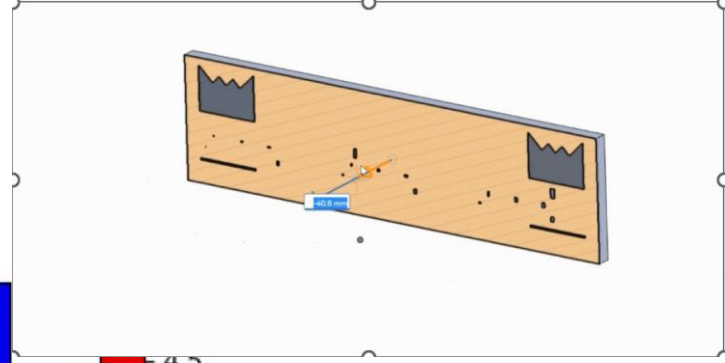
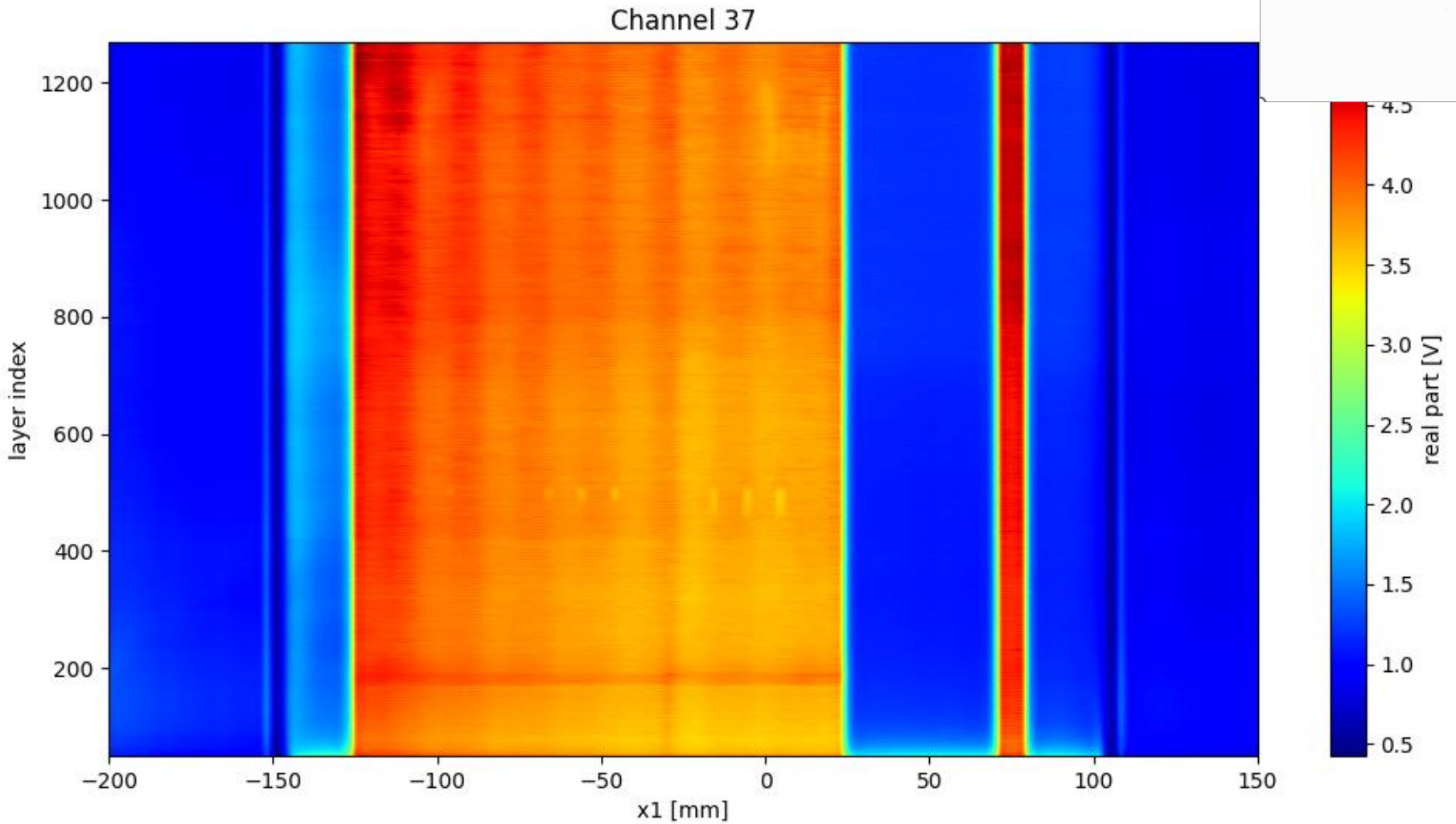
real part [V]

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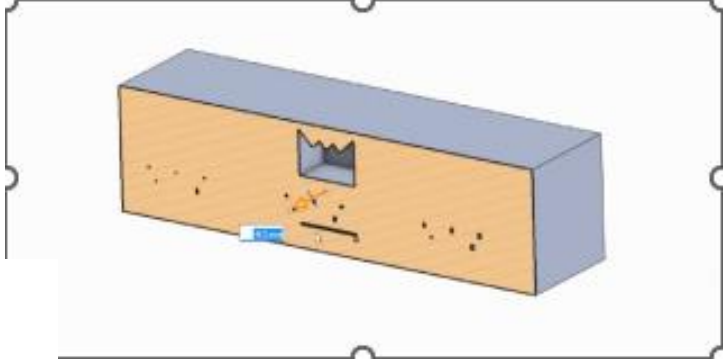
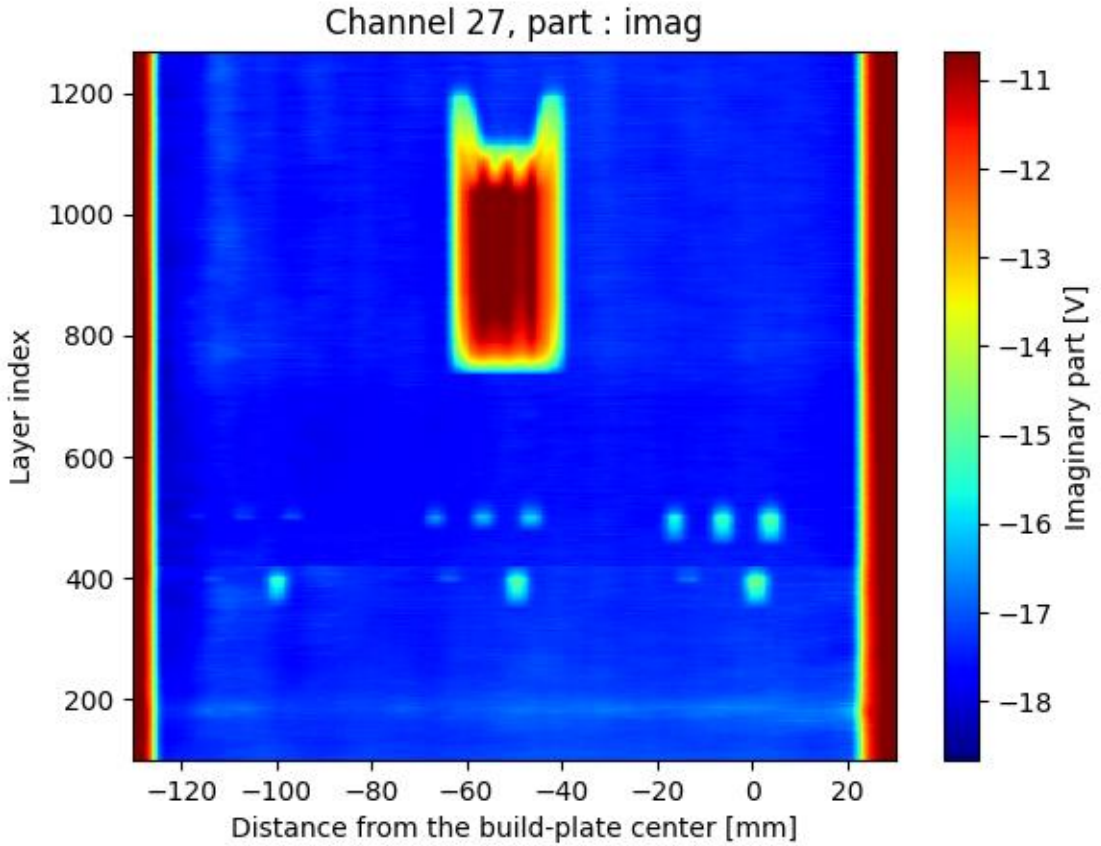
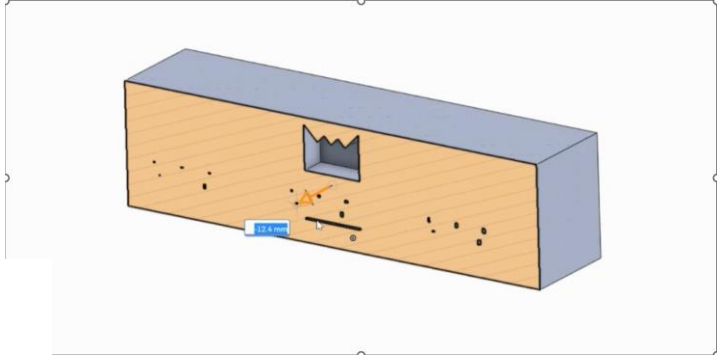
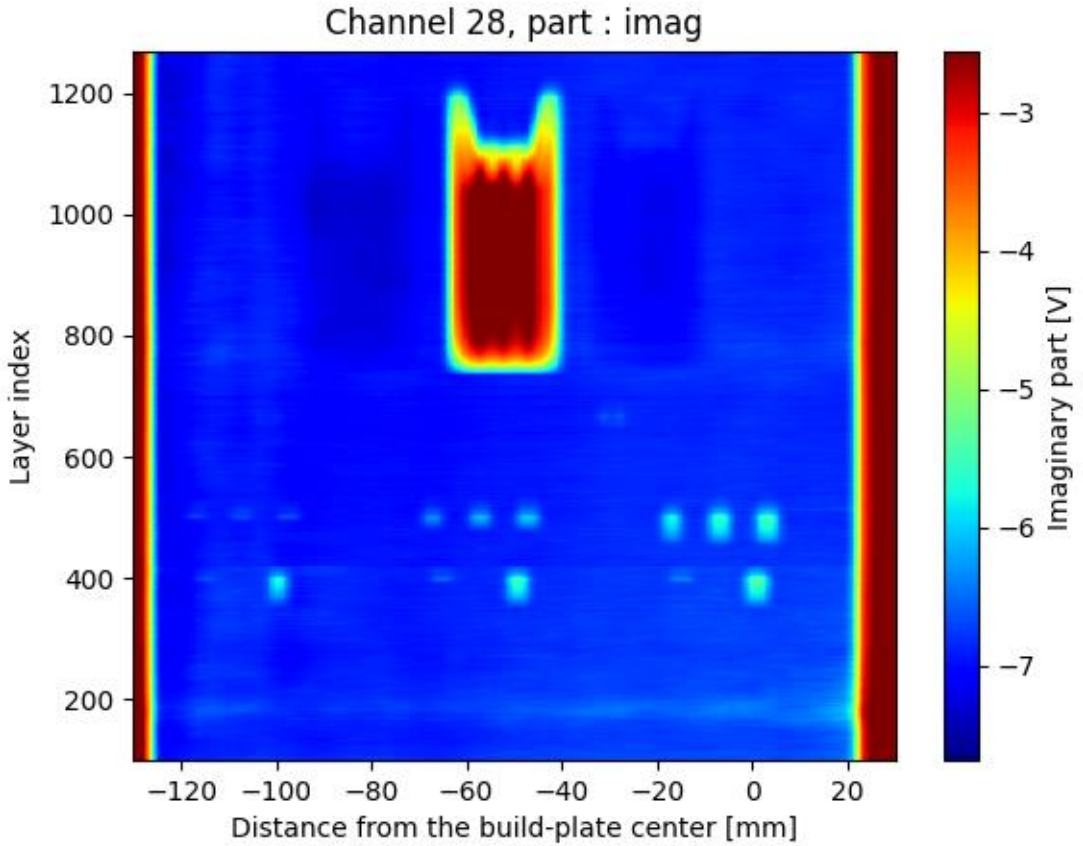
real part [V]

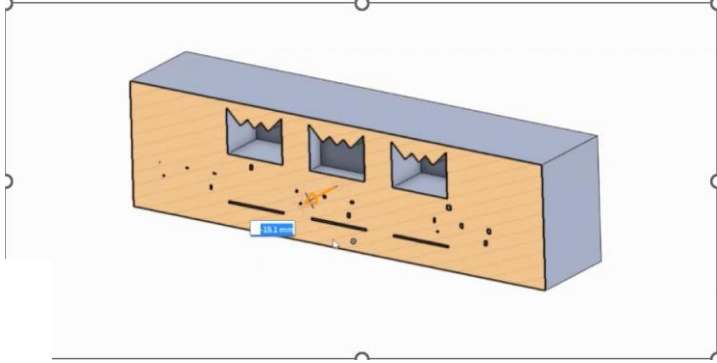
Out of phase cross section plots

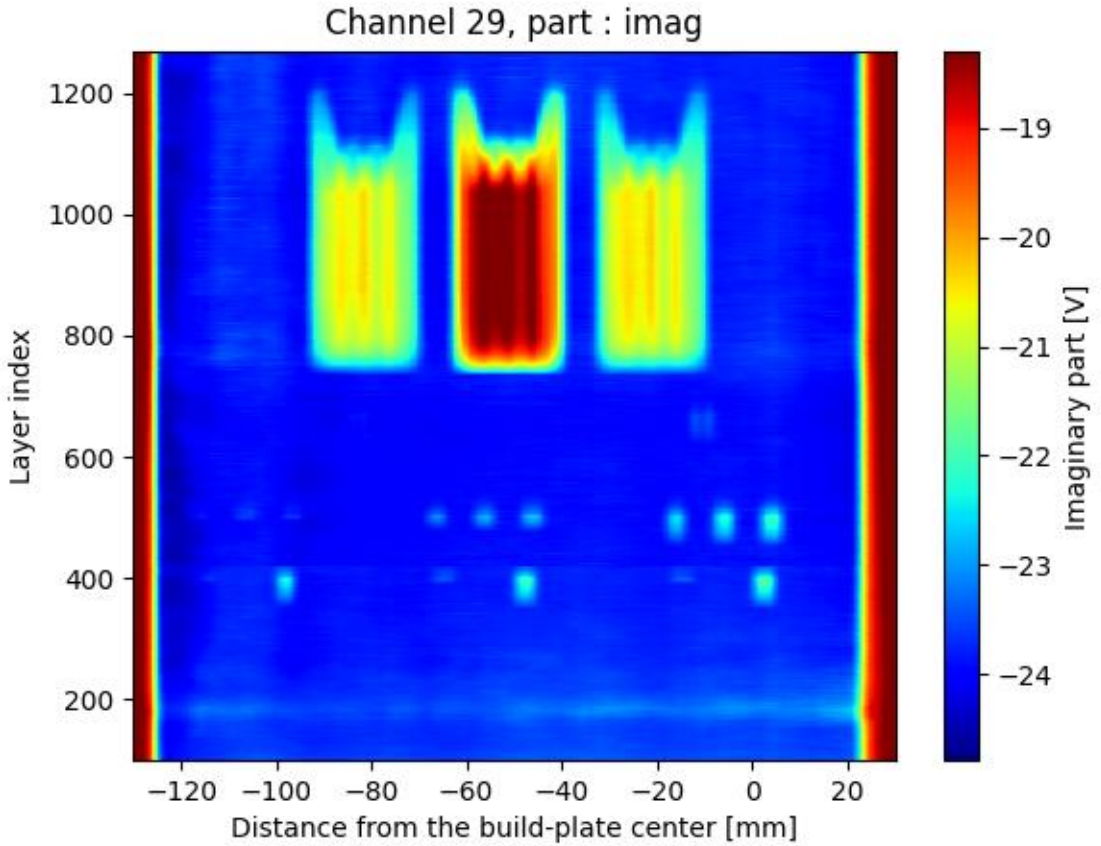


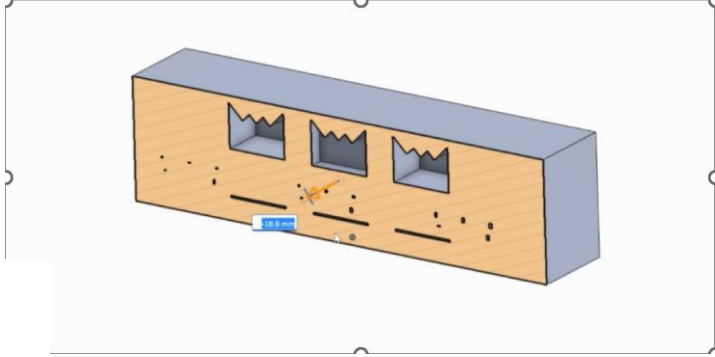

Channel 27, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−11
−12
−13
−14
−15
−16
−17
−18
Imaginary part [V]

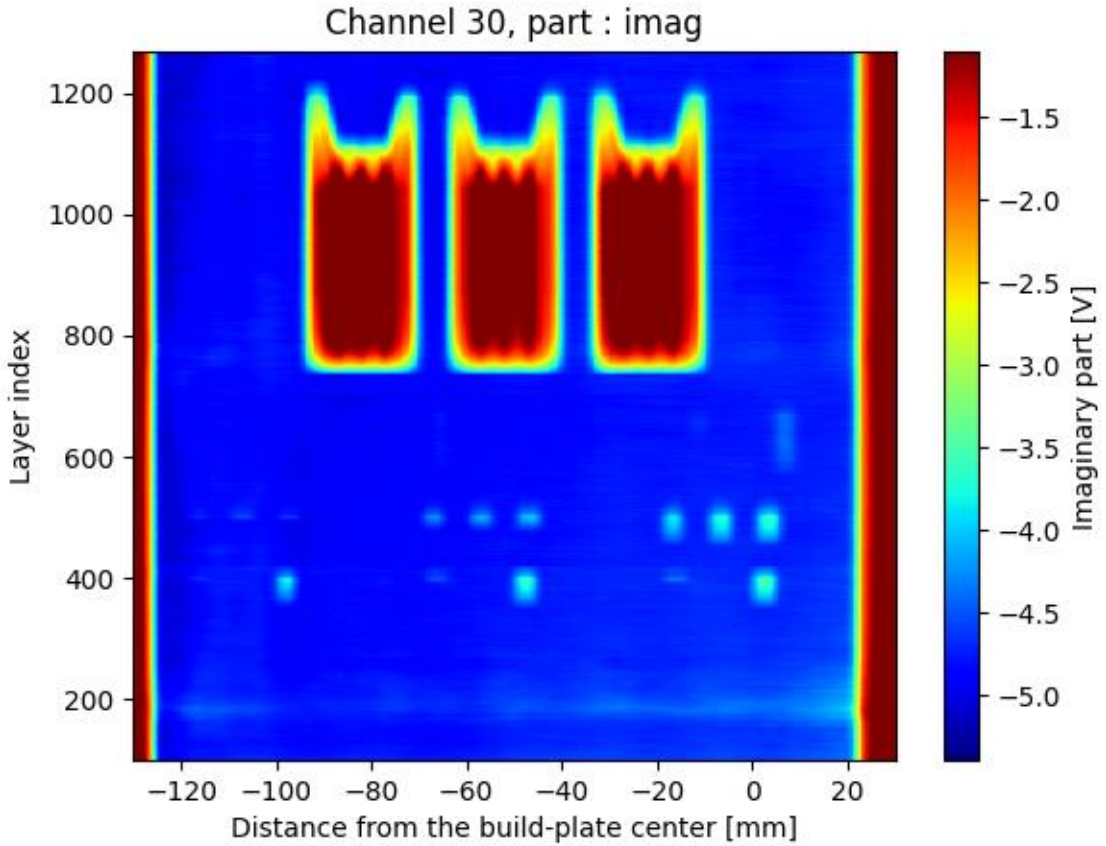


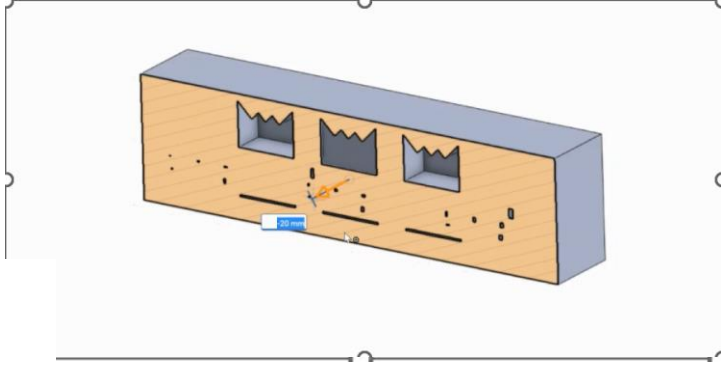

Channel 28, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−3
−4
−5
−6
−7
Imaginary part [V]

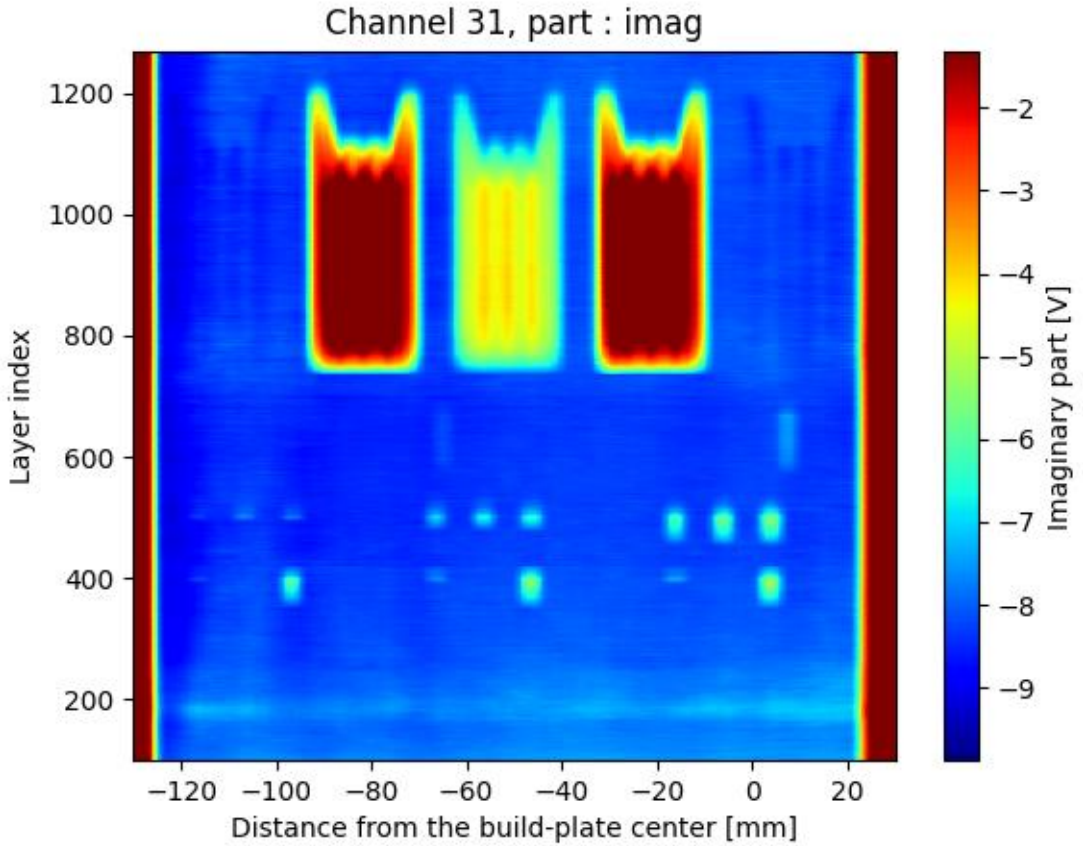


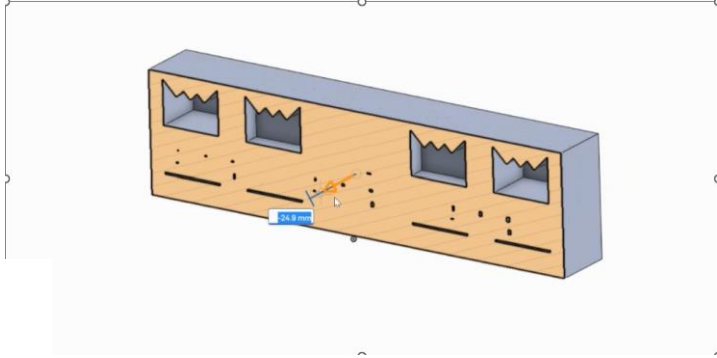

Channel 29, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−19
−20
−21
−22
−23
−24
Imaginary part [V]

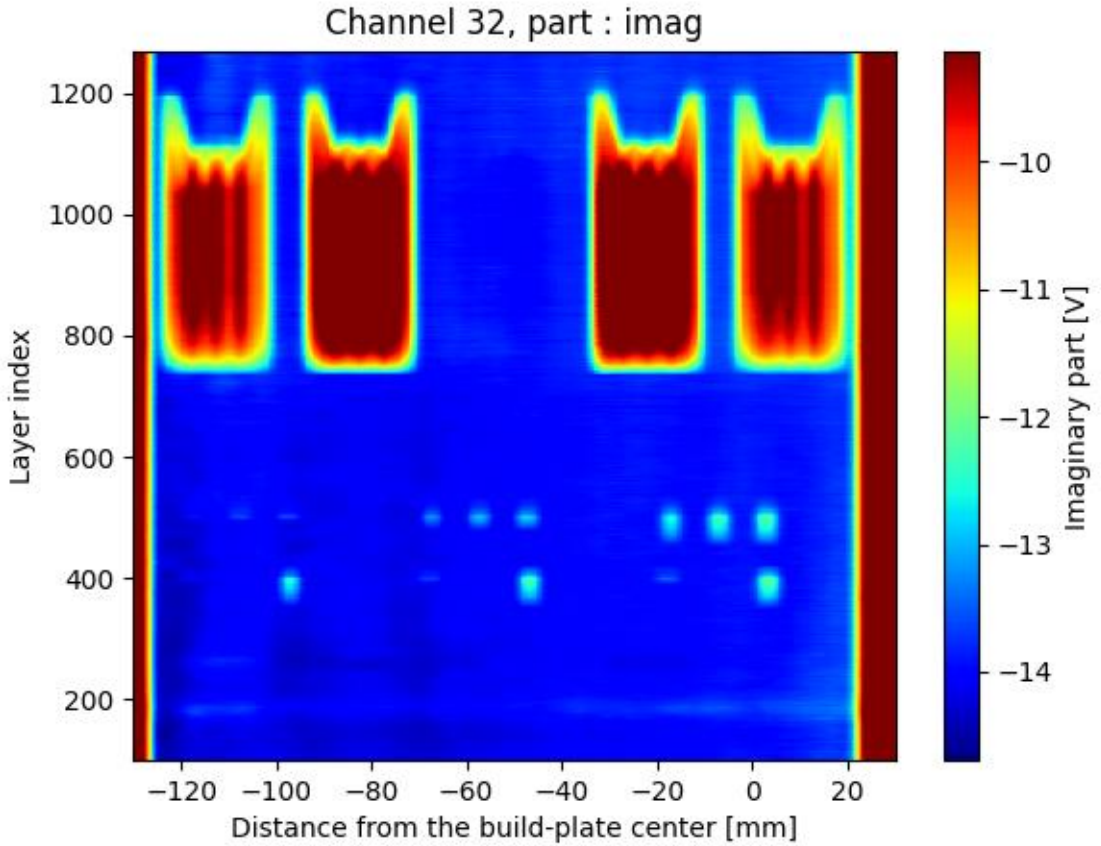


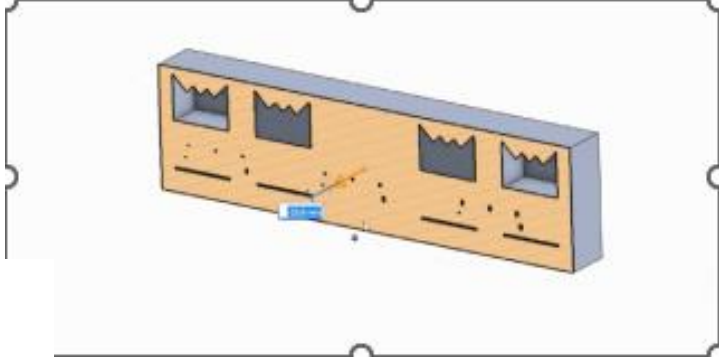

Channel 30, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
Imaginary part [V]

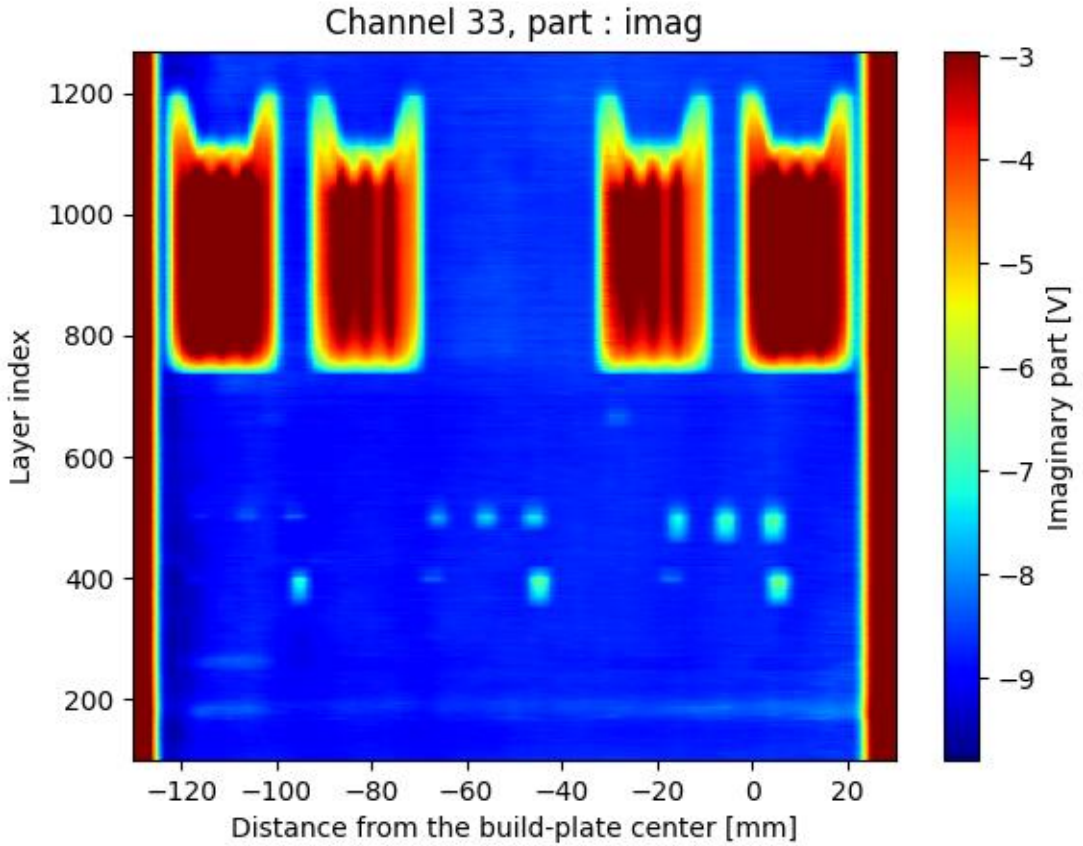


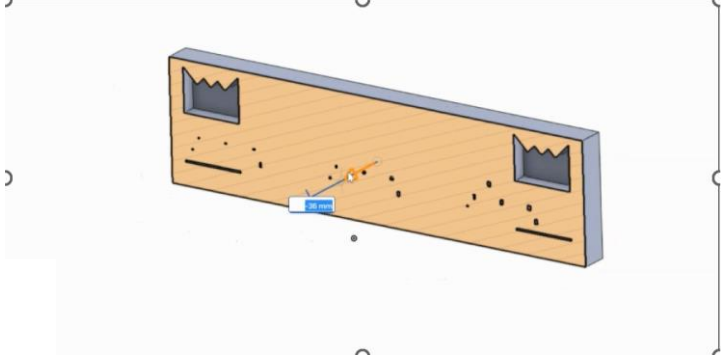

Channel 31, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−2
−3
−4
−5
−6
−7
−8
−9
Imaginary part [V]

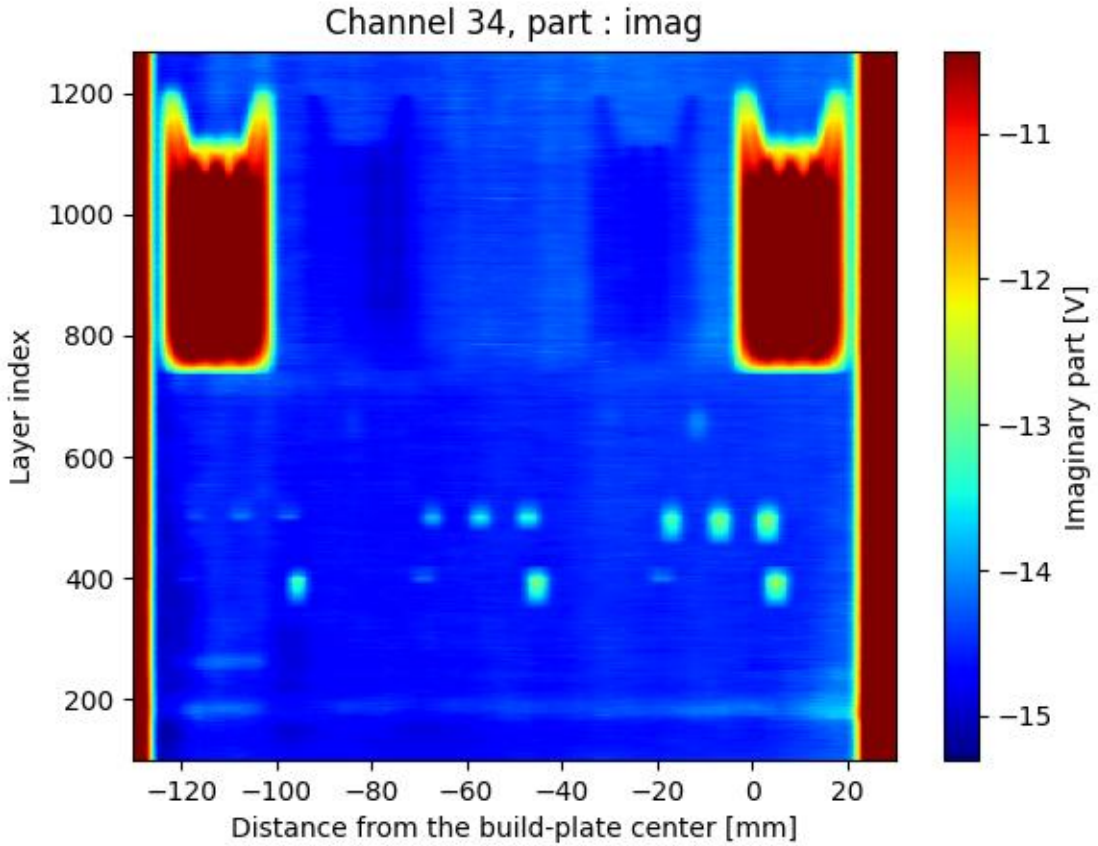


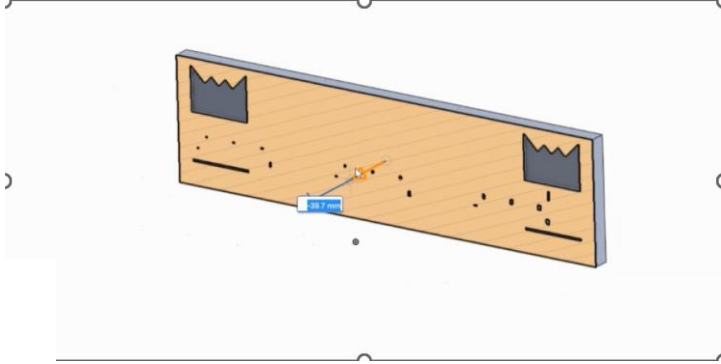

Channel 32, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−10
−11
−12
−13
−14
Imaginary part [V]

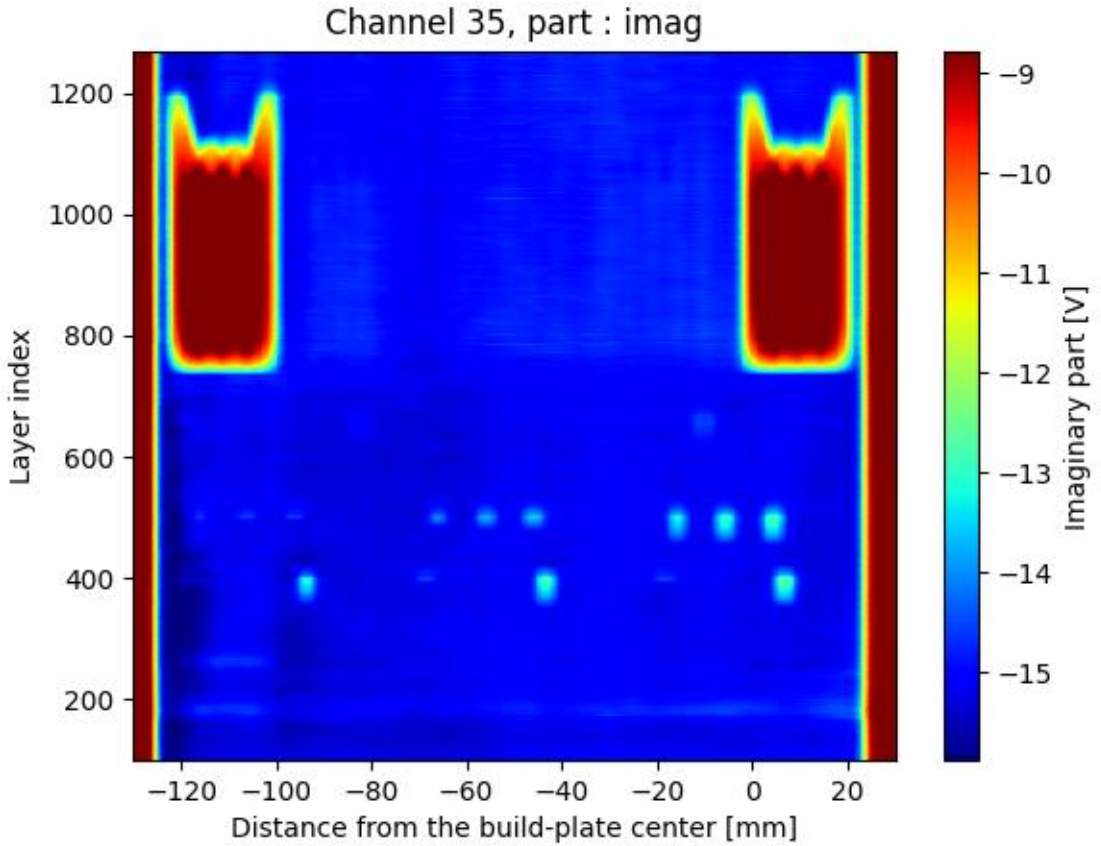


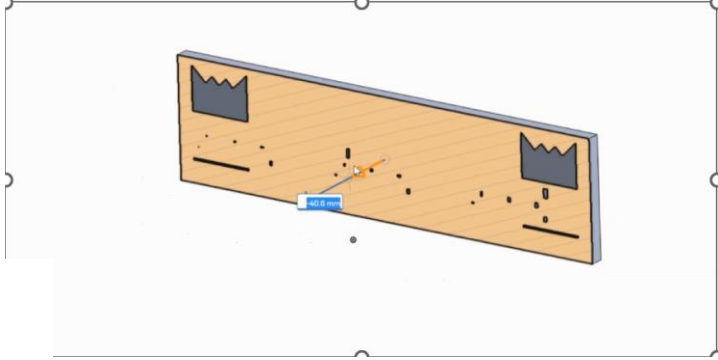

Channel 33, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−3
−4
−5
−6
−7
−8
−9
Imaginary part [V]

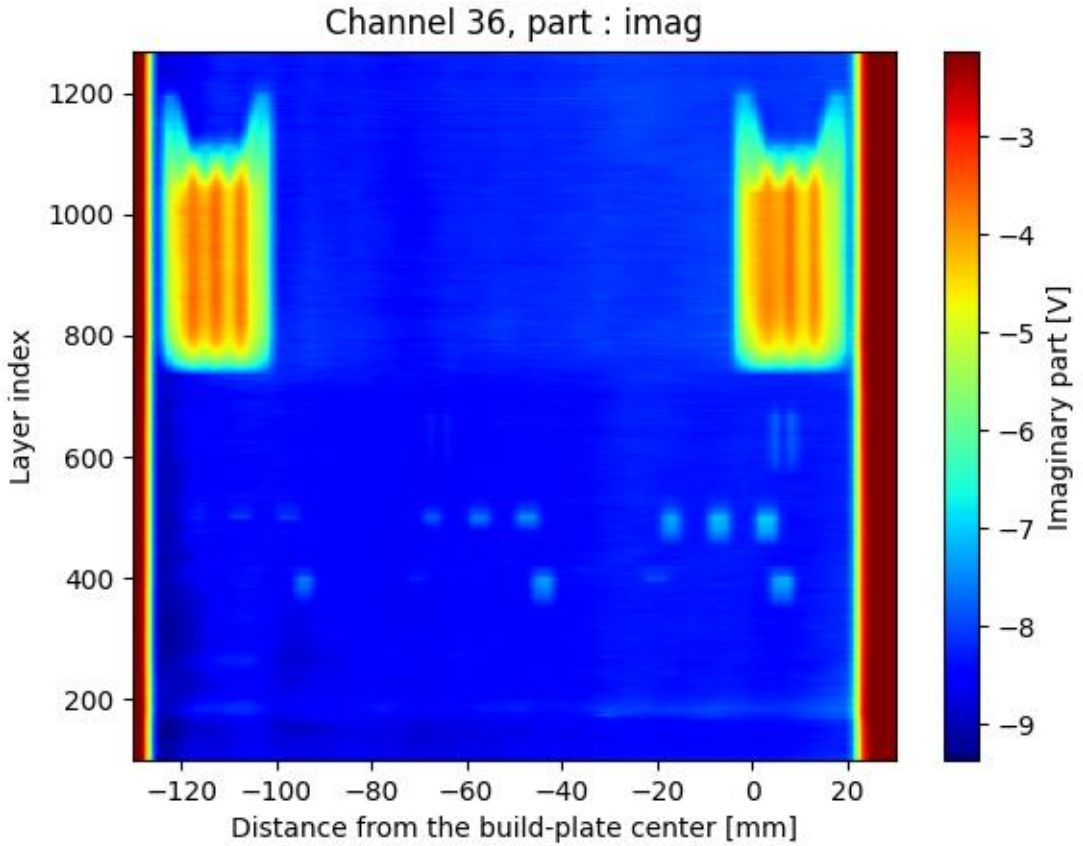



Channel 34, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−11
−12
−13
−14
−15
Imaginary part [V]




Channel 35, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−9
−10
−11
−12
−13
−14
−15
Imaginary part [V]

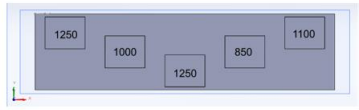


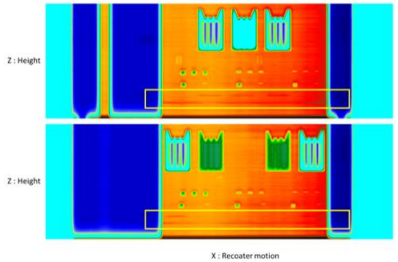

Channel 36, part : imag
Layer index
1200
1000
800
600
400
200
−120
−100
−80
−60
−40
−20
0
20
Distance from the build-plate center [mm]
−3
−4
−5
−6
−7
−8
−9
Imaginary part [V]

Report

Defect	Parameter = scan speed [mm/s]	Observed (Yes/No)
Full porosity	1250	YES
"Random" porosity	1250	YES
	1000	YES
	1250	YES
	850	YES
	1100	YES
Long crack with angle	W = 1; H = 1.5	YES
	W = 1; H = 0.3	YES
	W = 0.8; H = 1.5	YES
	W = 0.8; H = 0.3	YES
	W = 0.5; H = 1.5	YES
	W = 0.5; H = 0.3	YES
Long crack 90°	W = 1; H = 1.5	YES
	W = 1; H = 0.75	YES
	W = 1; H = 0.3	YES
	W = 0.8; H = 1.5	YES
	W = 0.8; H = 0.75	YES
	W = 0.8; H = 0.3	YES
	W = 0.5; H = 1.5	YES
	W = 0.5; H = 0.75	YES
	W = 0.5; H = 0.3	YES
Empty Cylinders Coil 1	D = 1.5; H = 3	YES
	D = 1.5; H = 1.5	YES
	D = 1.5; H = 0.75	YES
	D = 1.5; H = 0.3	N.A.
	D = 1; H = 3	YES
	D = 1; H = 1.5	YES
	D = 1; H = 0.75	YES
	D = 1; H = 0.3	N.A.
Empty Cylinders Coil 1	D = 1.5; H = 3	YES
	D = 1.5; H = 1.5	YES
	D = 1.5; H = 0.75	YES
	D = 1.5; H = 0.3	N.A.
	D = 1; H = 3	YES
	D = 1; H = 1.5	YES
	D = 1; H = 0.75	YES
	D = 1; H = 0.3	N.A.
Thin Walls Coil 1	D = 0.8	YES
	D = 0.3	NO
Thin Walls Coil 2	D = 0.5	YES
	D = 0.2	NO

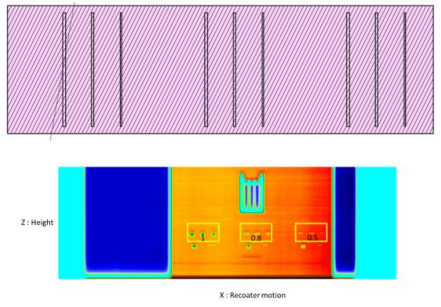
Defect	Parameter = scan speed [mm/s]	Observed (Yes/No)
Full porosity	1250	YES
"Random" porosity	1250	YES
	1000	YES
	1250	YES
	850	YES
	1100	YES



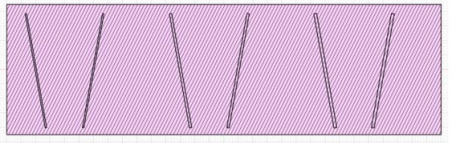


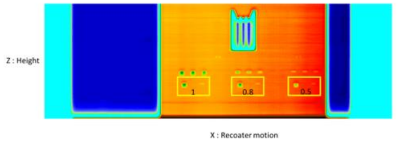
Long cracks 90°

Defect	Width (W) and Depth (H) [mm]	Observed (Yes/No)
Long crack 90°	W = 1; H = 1.5	YES
	W = 1; H = 0.75	YES
	W = 1; H = 0.3	YES
	W = 0.8; H = 1.5	YES
	W = 0.8; H = 0.75	YES
	W = 0.8; H = 0.3	YES
	W = 0.5; H = 1.5	YES
	W = 0.5; H = 0.75	YES
	W = 0.5; H = 0.3	YES



Defect	Width (W) and Depth (H) [mm]	Observed (Yes/No)
Long crack with angle	W = 1; H = 1.5	YES
	W = 1; H = 0.3	YES
	W = 0.8; H = 1.5	YES
	W = 0.8; H = 0.3	YES
	W = 0.5; H = 1.5	YES
	W = 0.5; H = 0.3	YES

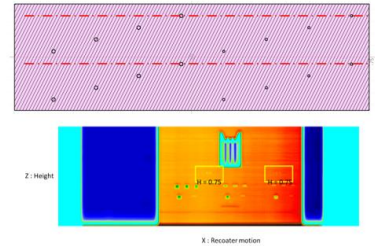




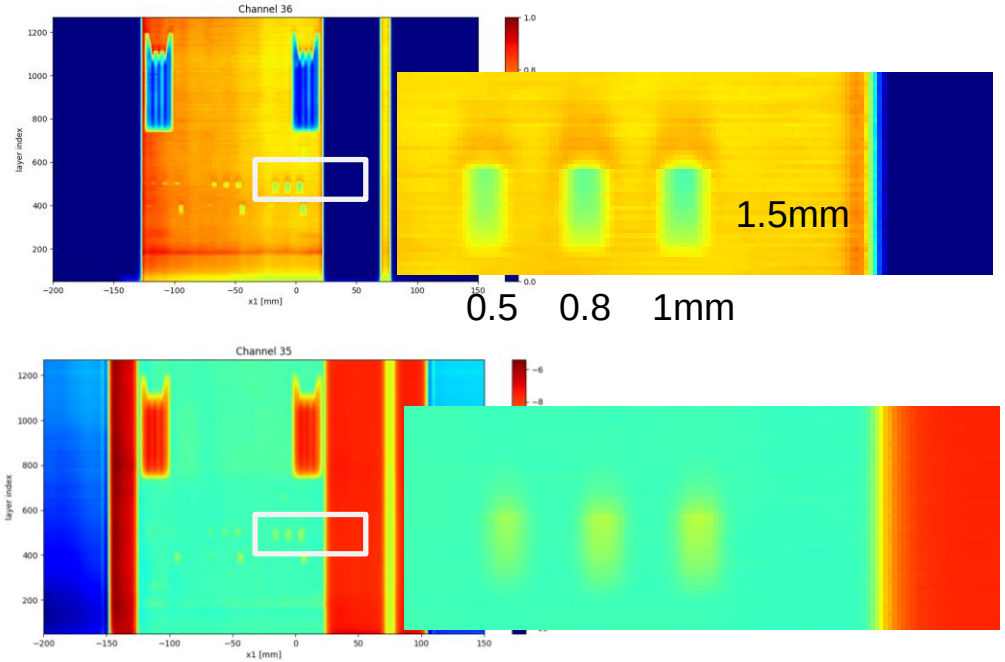
Empty Cylinders

Defect	Diam. (D) and Depth (H) [mm]	Observed (Yes/No)
Empty Cylinders Coil 1	D = 1.5; H = 3	YES
	D = 1.5; H = 1.5	YES
	D = 1.5; H = 0.75	YES
	D = 1.5; H = 0.3	N.A.
	D = 1; H = 3	YES
	D = 1; H = 1.5	YES
	D = 1; H = 0.75	YES
	D = 1; H = 0.3	N.A.
Empty Cylinders Coil 1	D = 1.5; H = 3	YES
	D = 1.5; H = 1.5	YES
	D = 1.5; H = 0.75	YES
	D = 1.5; H = 0.3	N.A.
	D = 1; H = 3	YES
	D = 1; H = 1.5	YES
	D = 1; H = 0.75	YES
	D = 1; H = 0.3	N.A.

N.A. because the coils did not monitored them:

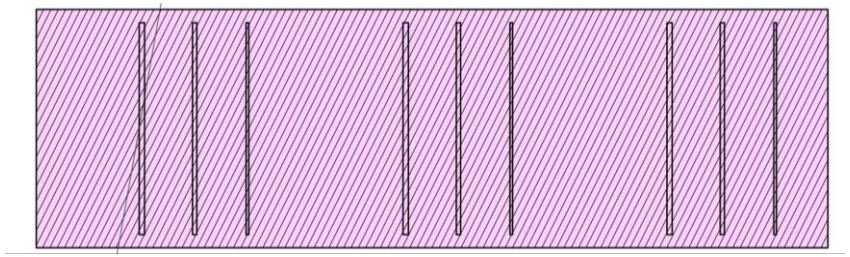


Signatures of cavities (“long cracks”)

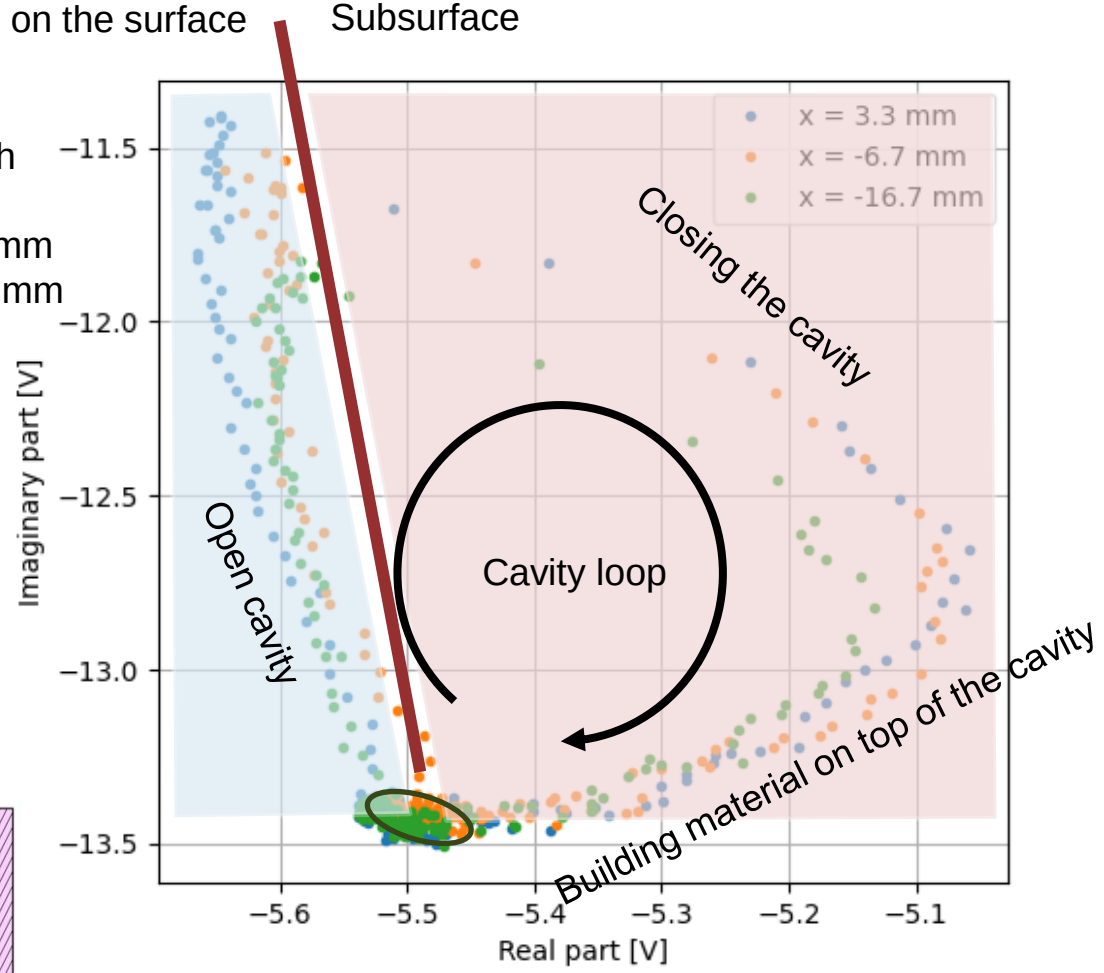


Long cracks. perpendicular:

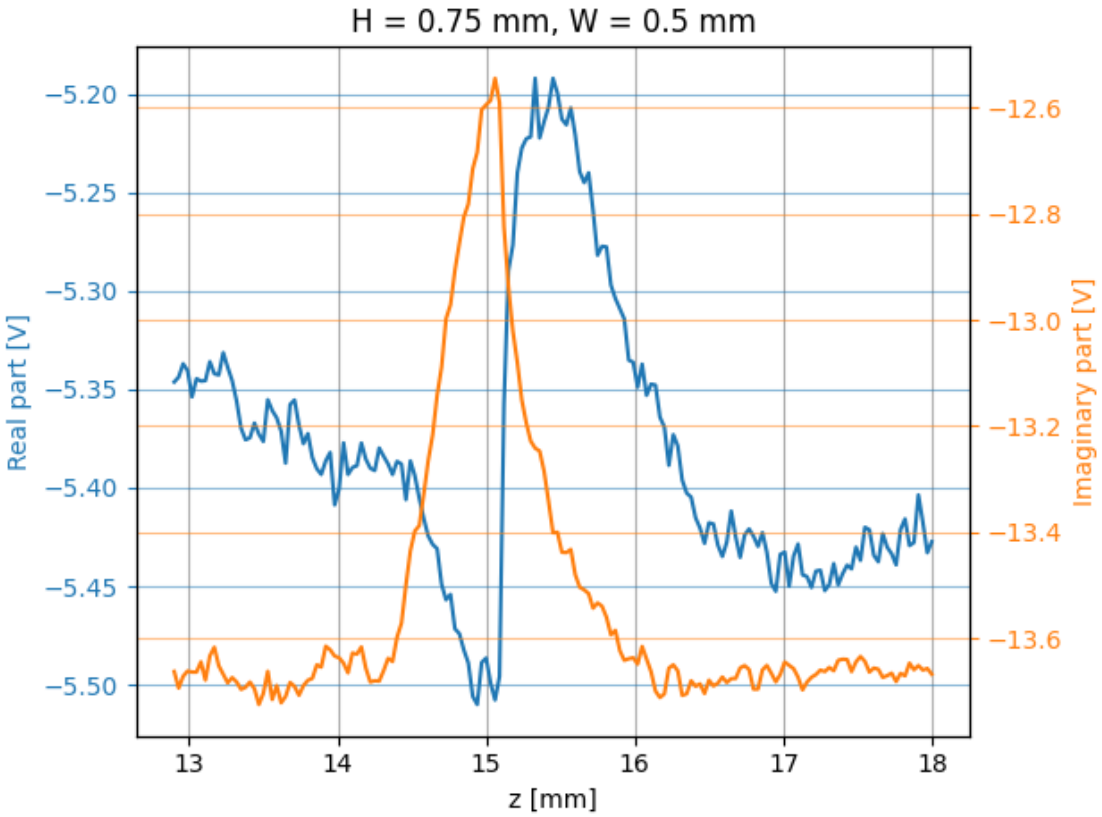
- Length = 40 mm
- Width = [0.5; 0.8; 1] mm
- Depth = [0.3; 0.75; 1.5] mm



Cavity width
Blue: 1mm
Green: 0.8mm
Orange 0.5mm



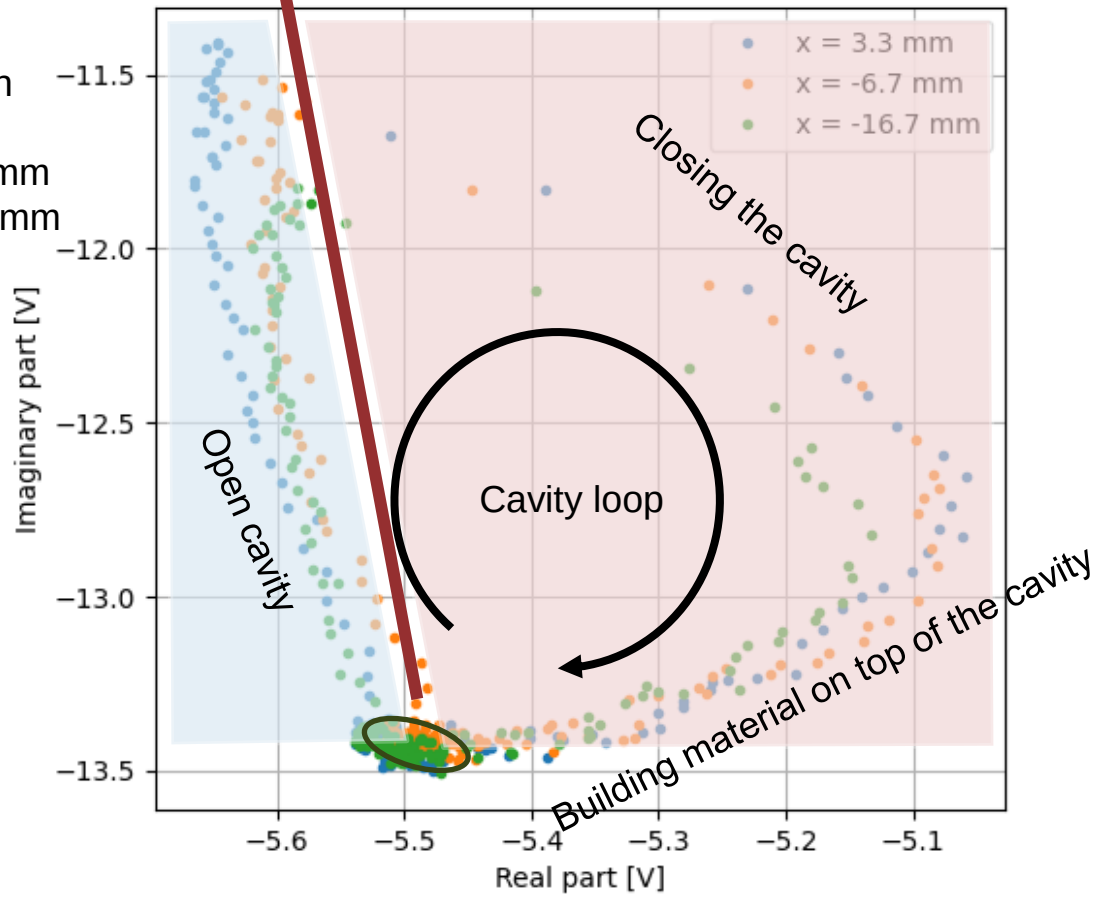
Signatures of cavities ("long cracks")



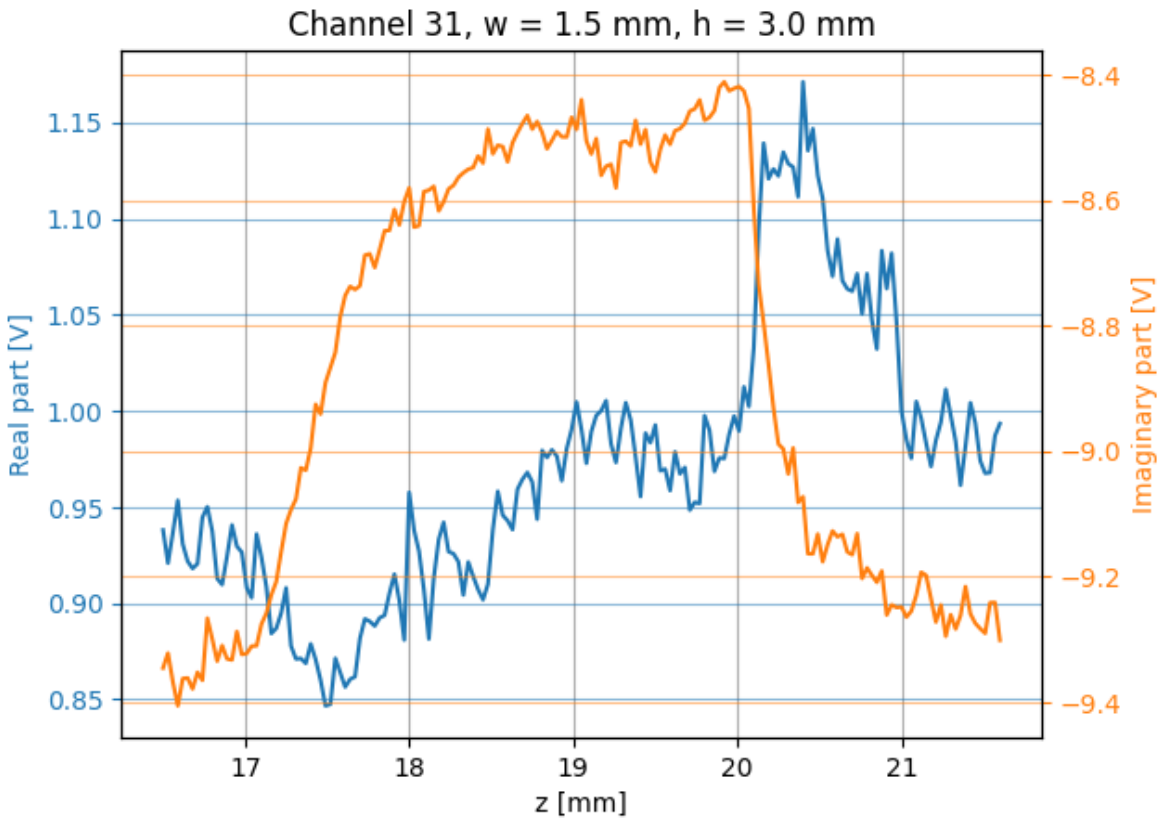
Visible on the surface

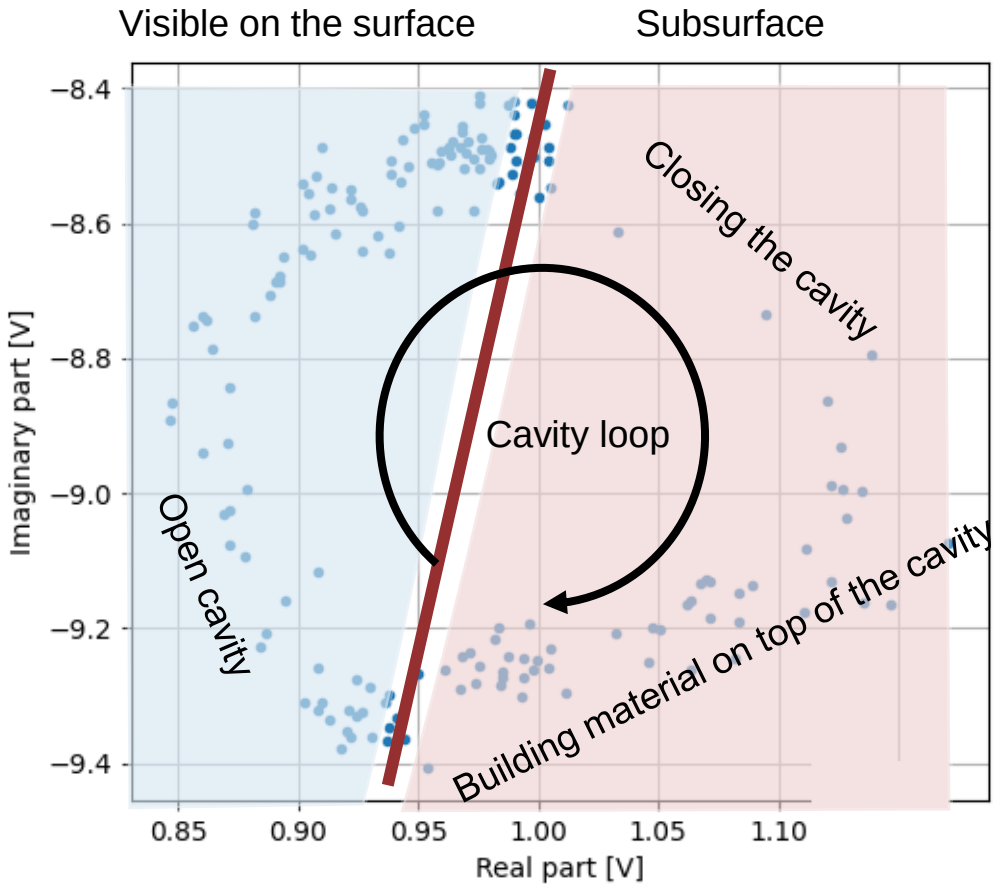
Subsurface

Cavity width
Blue: 1mm
Green: 0.8mm
Orange 0.5mm

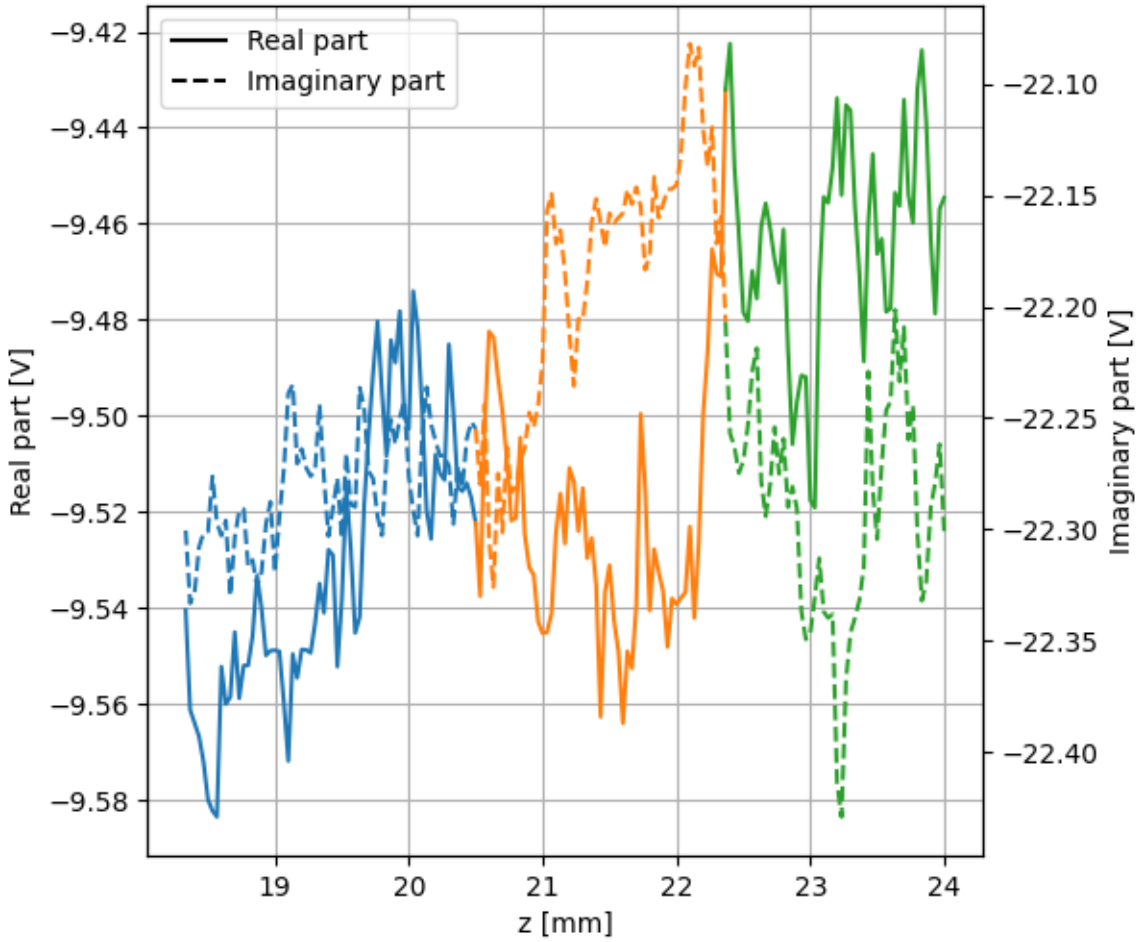


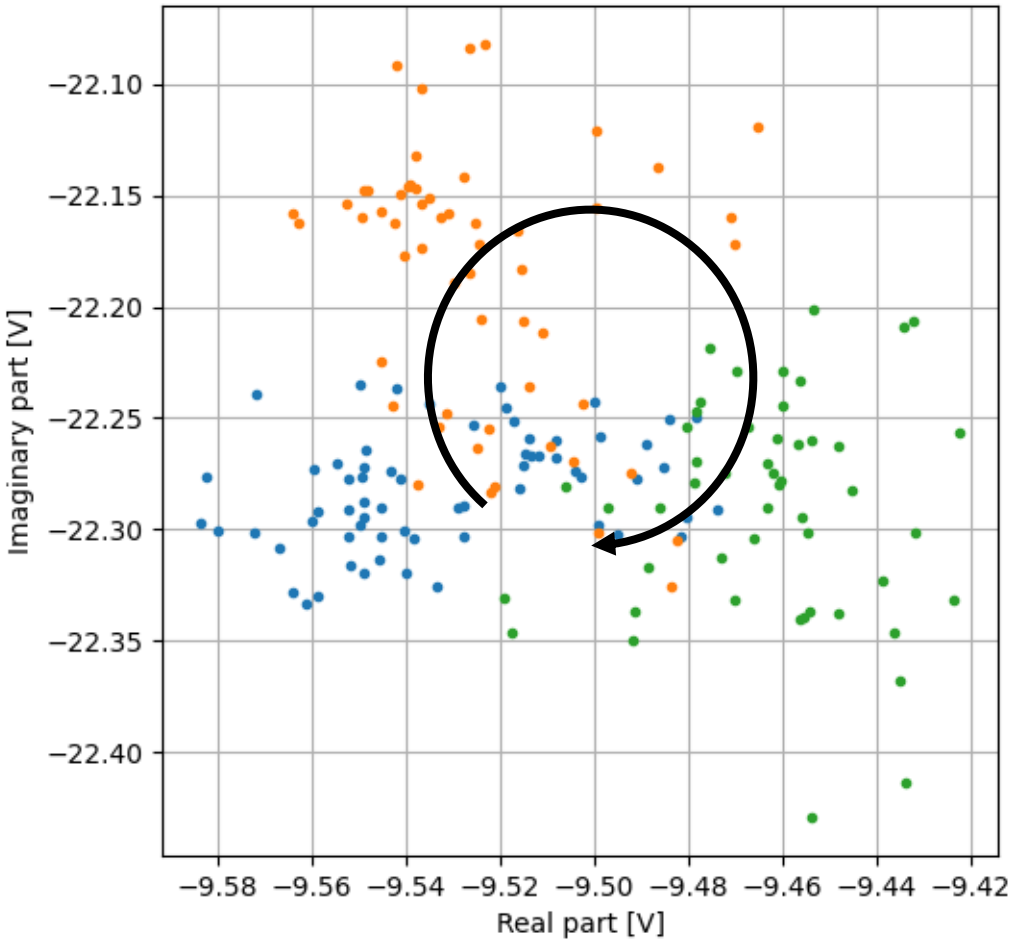
Signatures of cylinders (large)





Signatures of cylinders (medium)

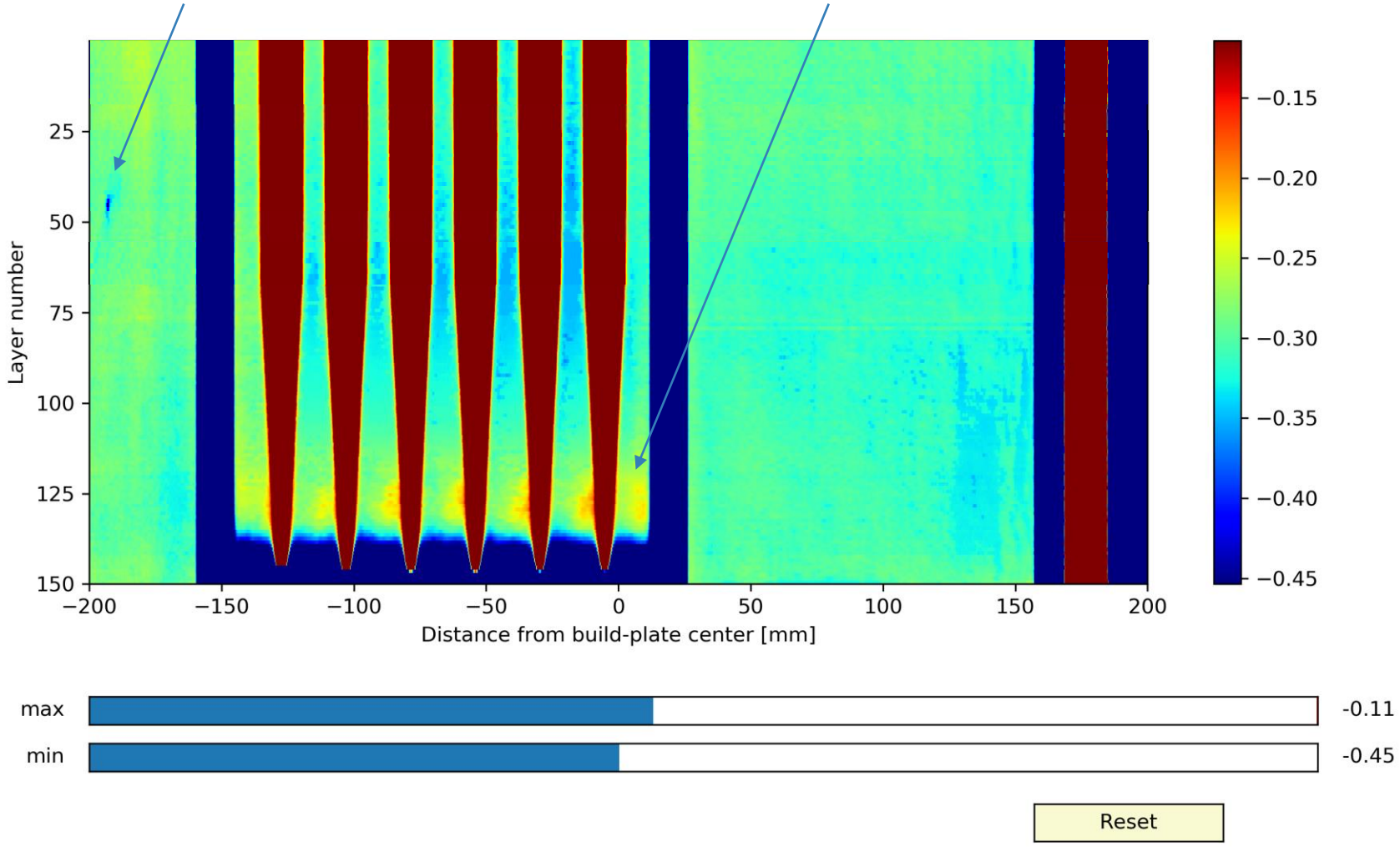




In-situ powder check

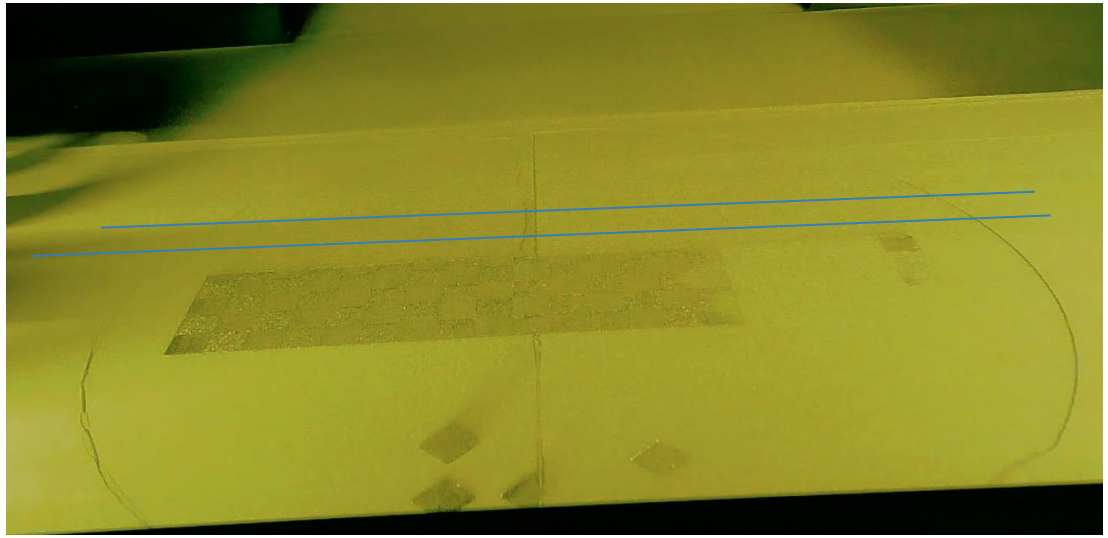
Powder application

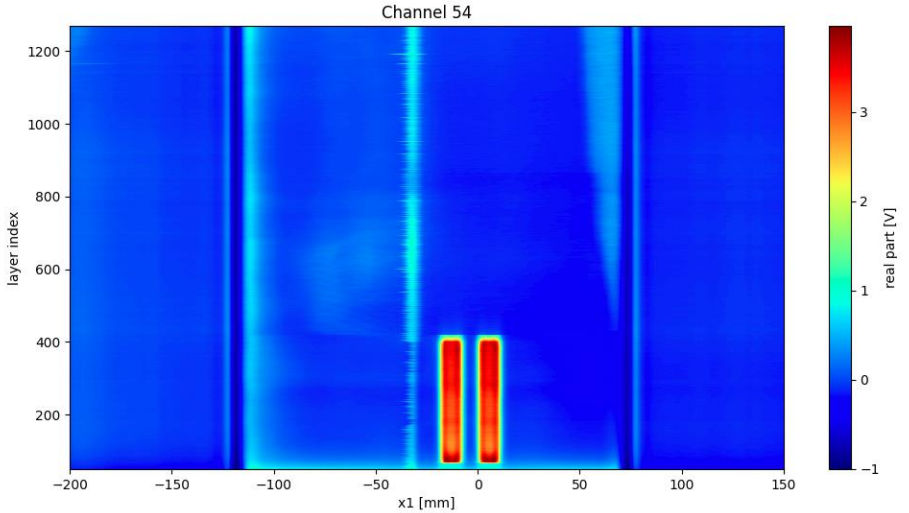
detect particles, powder bed inhomogeneities, and powder aging

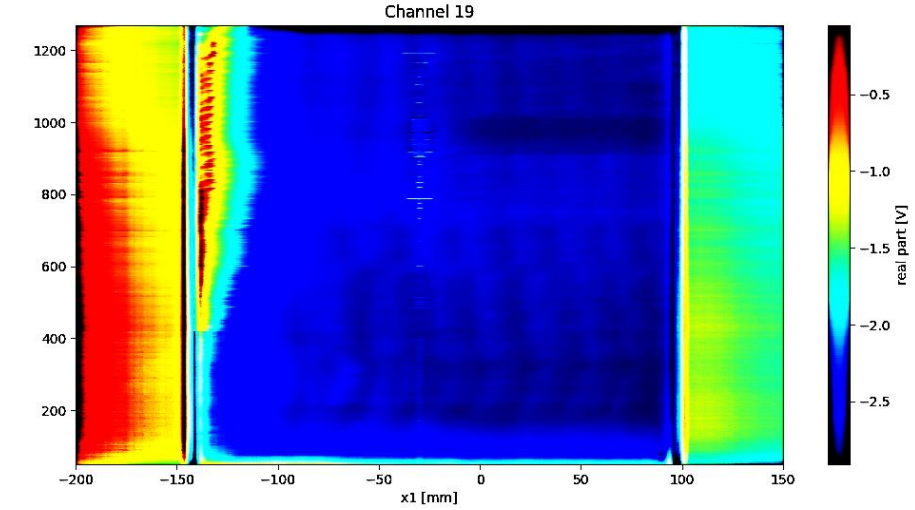


Powder bed inspection

detect particles, powder bed inhomogeneities, and powder aging





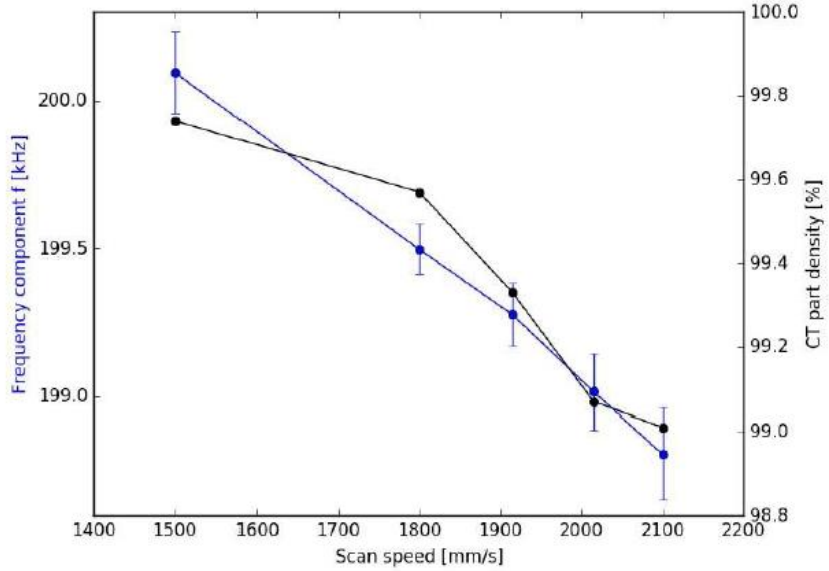


Process monitoring

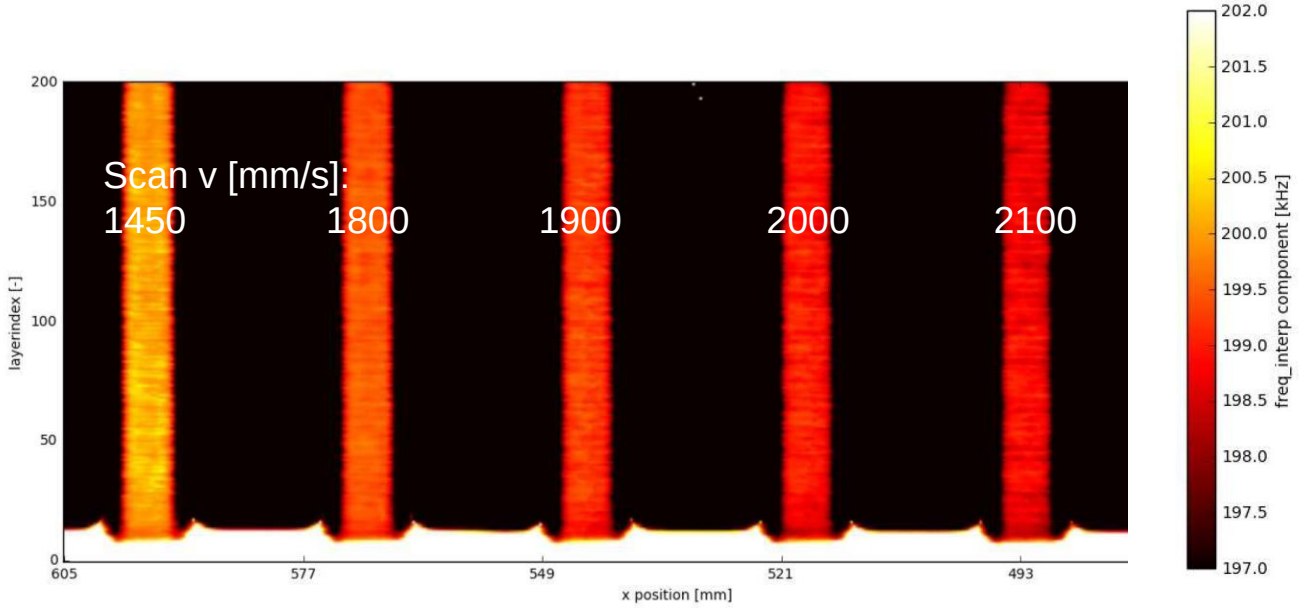
Process application

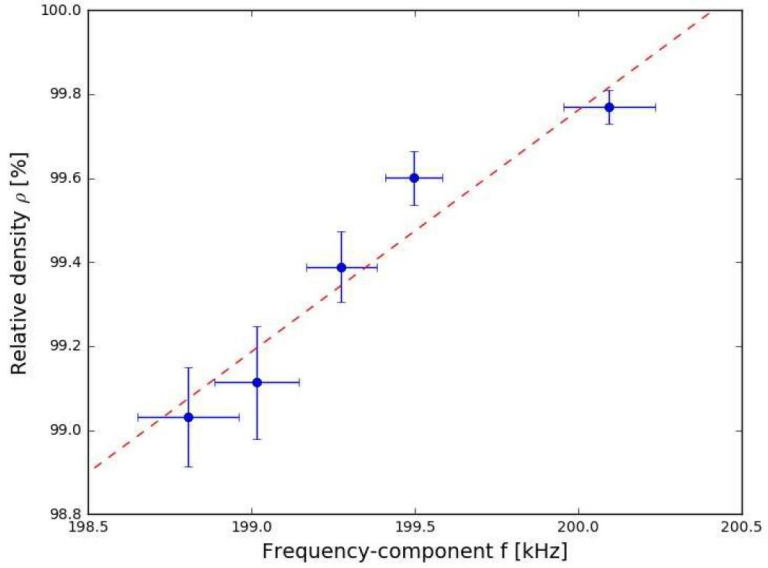
test machine health and process stability
early warning for process deviation
0.1% porosity + 2um lift off sensitivity

CT scan – EC comparison



Frequency heatmap (x-z plane)

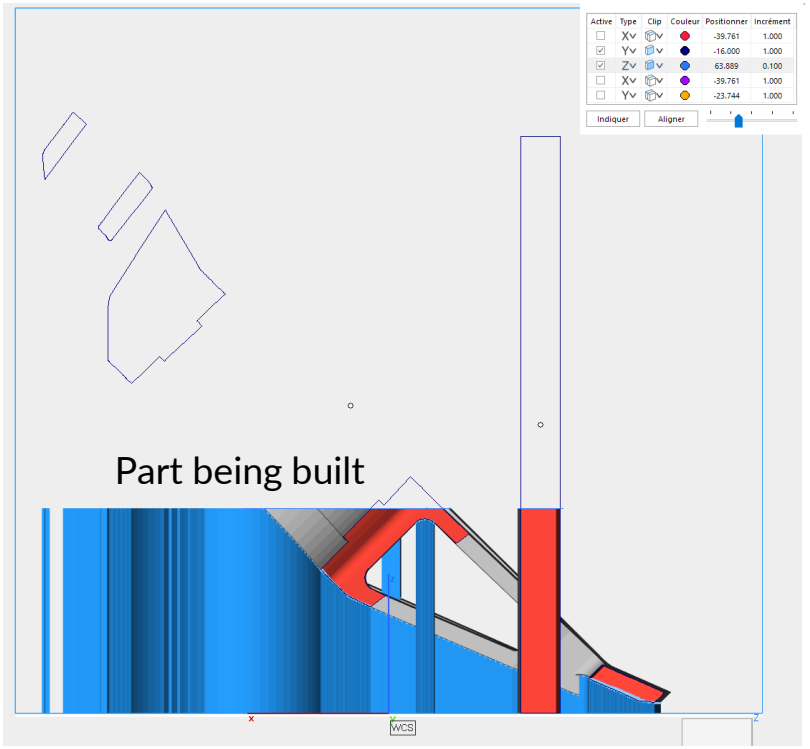




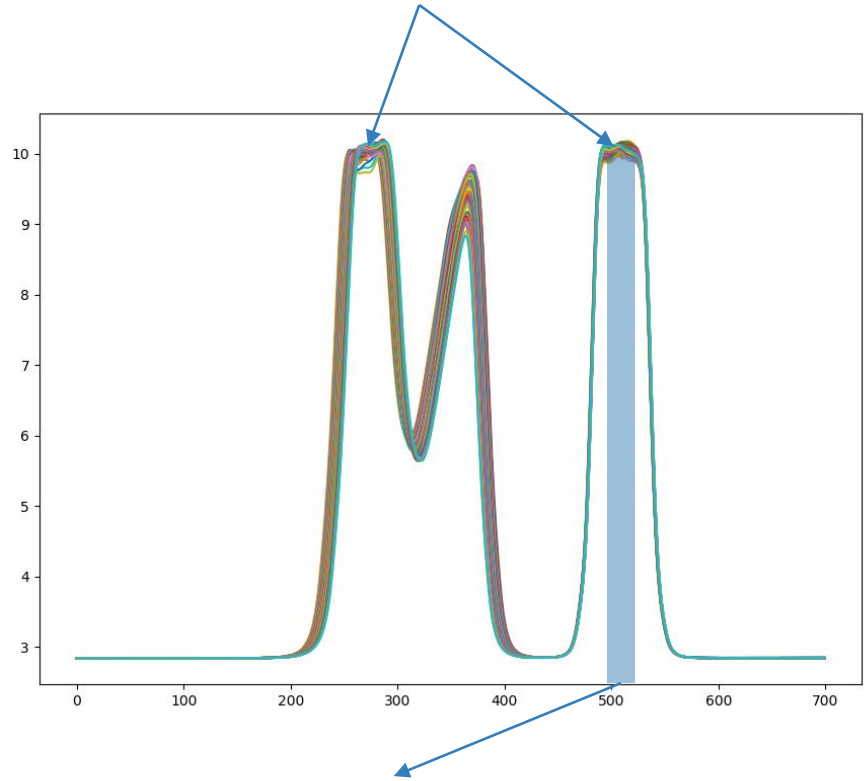
Part monitoring application

monitor your production

Integration of compliant sensors on the recoater of a Concept Laser M2 to directly monitor the quality of the parts during the powder recoating motion



Variations of the signals used to assess the regularity of the process



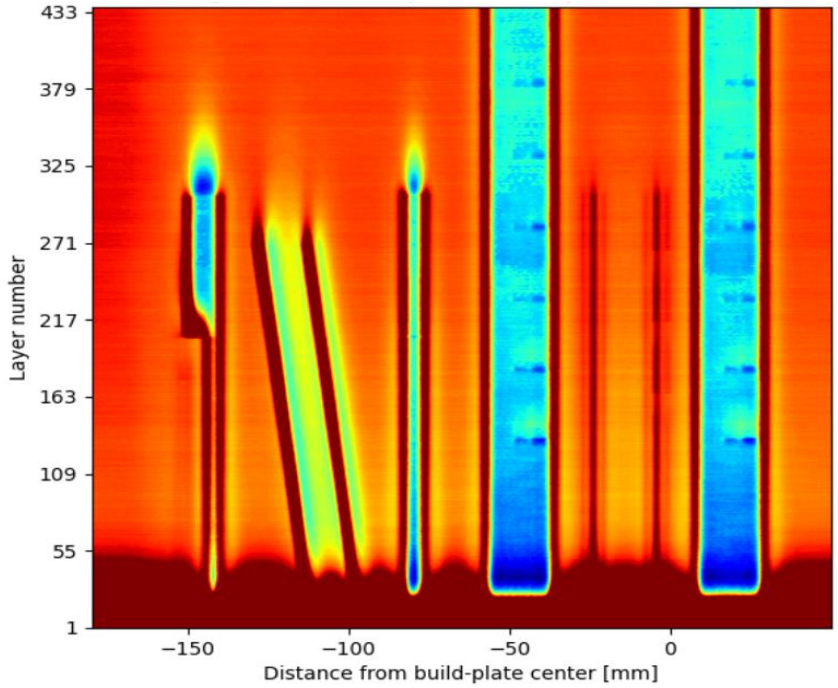
Input parameters

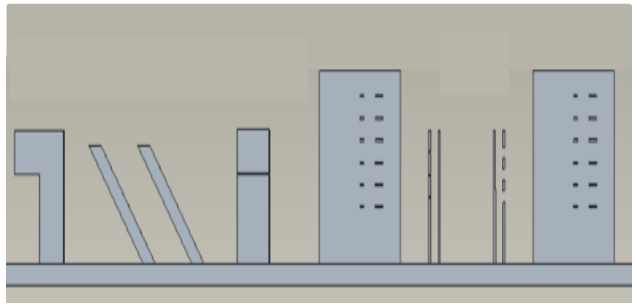
- Position, reference value, acceptable deviation
- Possibly layer dependent
- Acceptable deviation determined by performing several fabrications and extracting a standard deviation

3DPrecision collaboration

AMiquam application

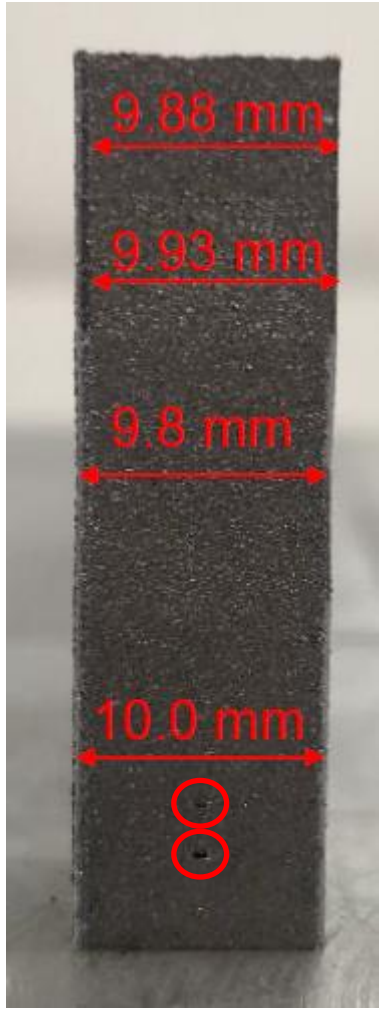
verify the presence of critical features in the part

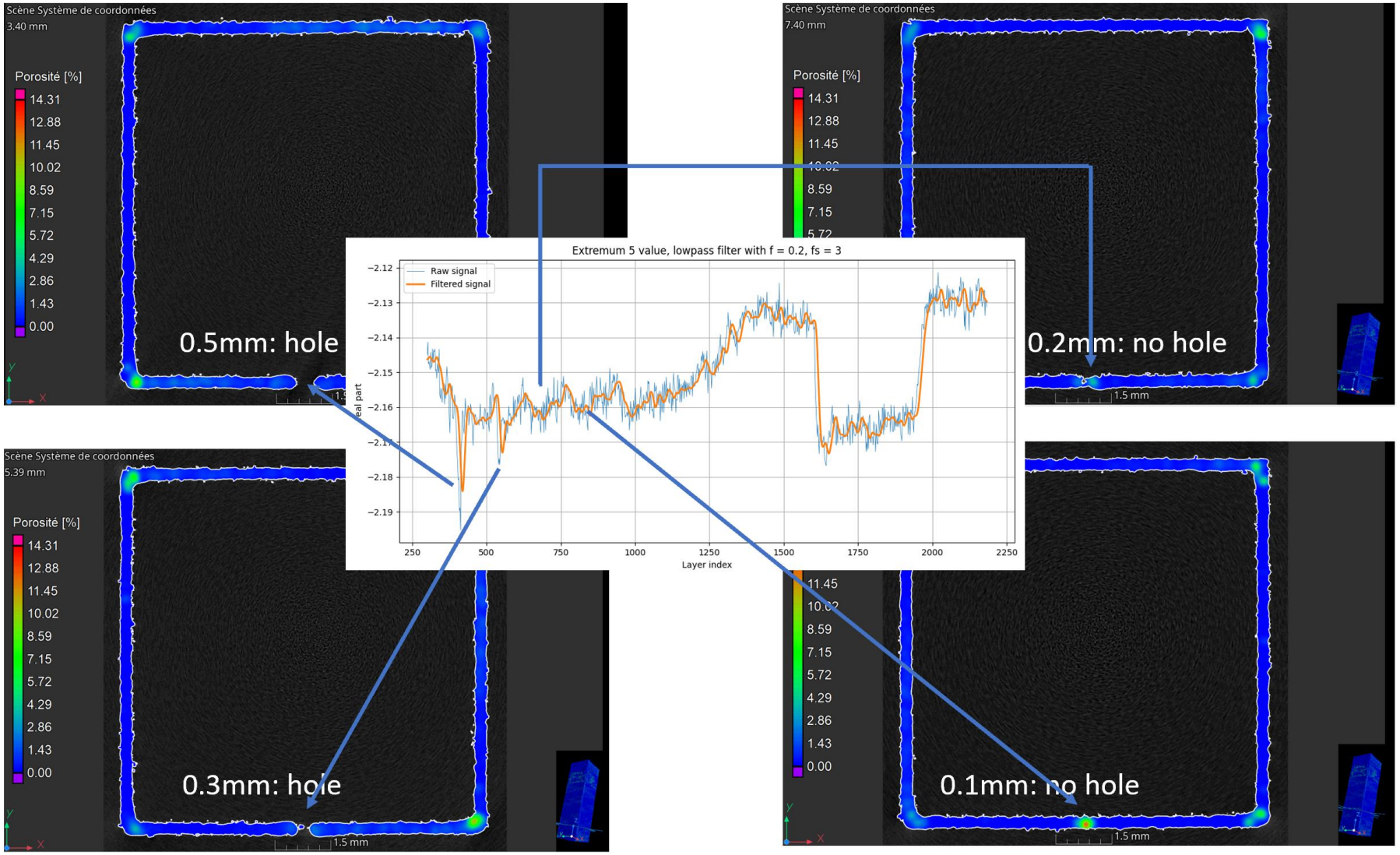




Part application

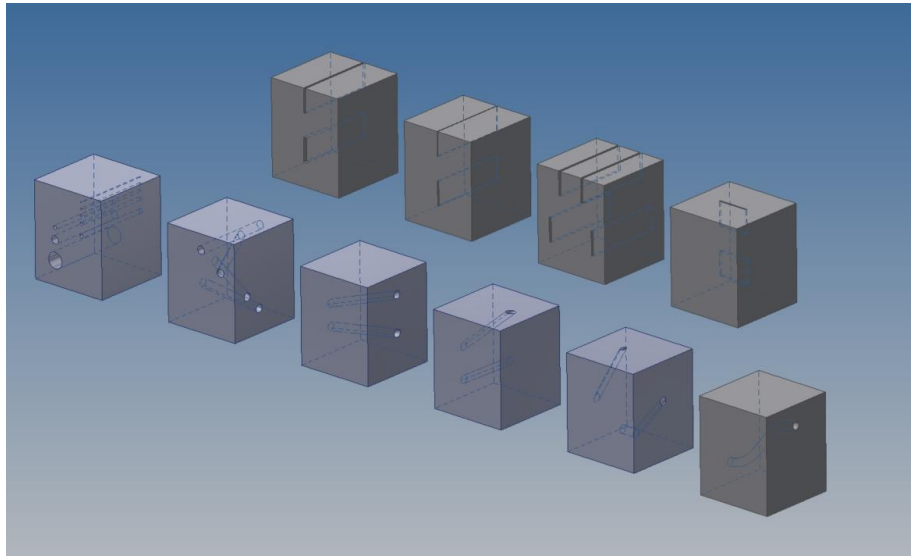
verify the presence of critical features in the part

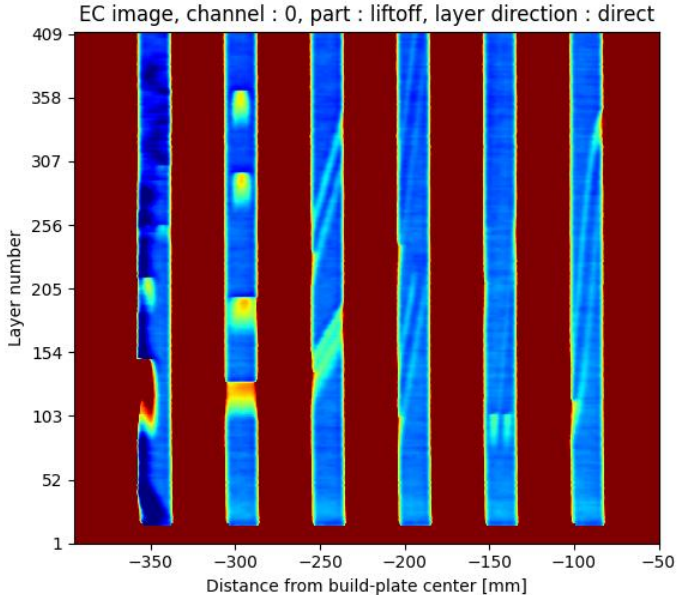


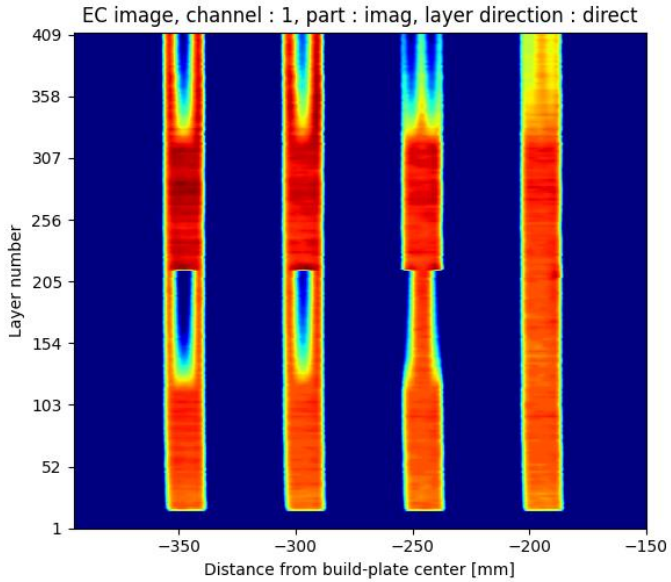


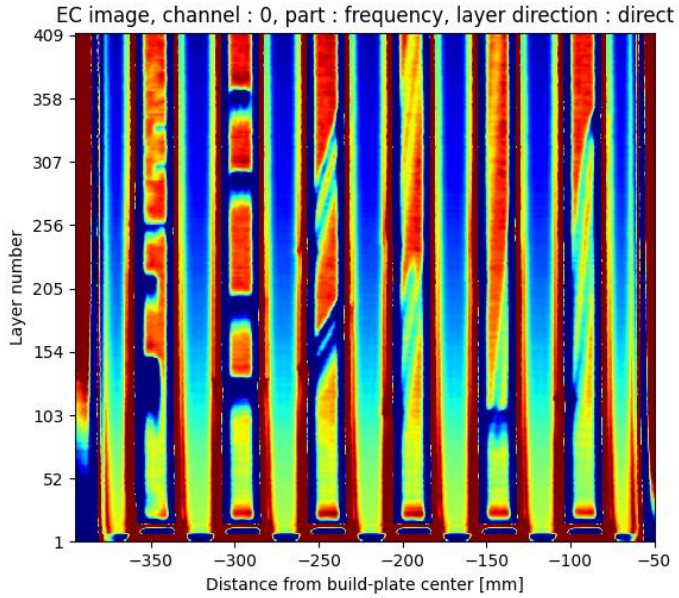
Inner structure application

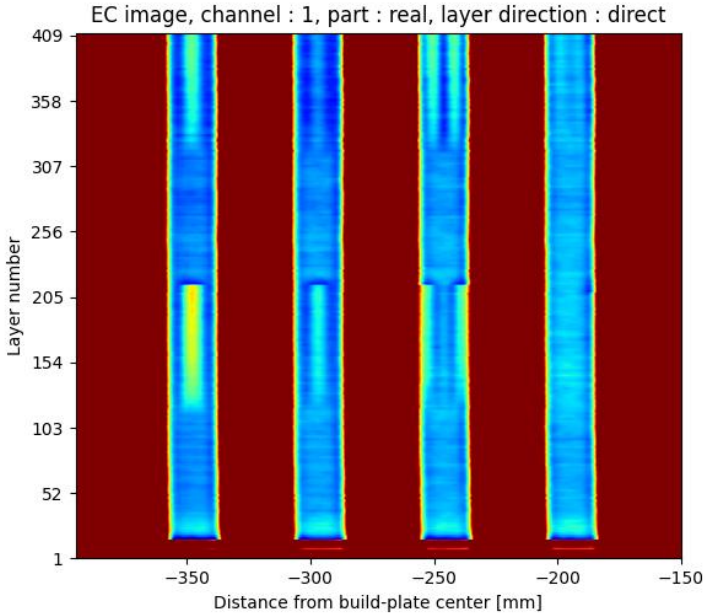
cavities







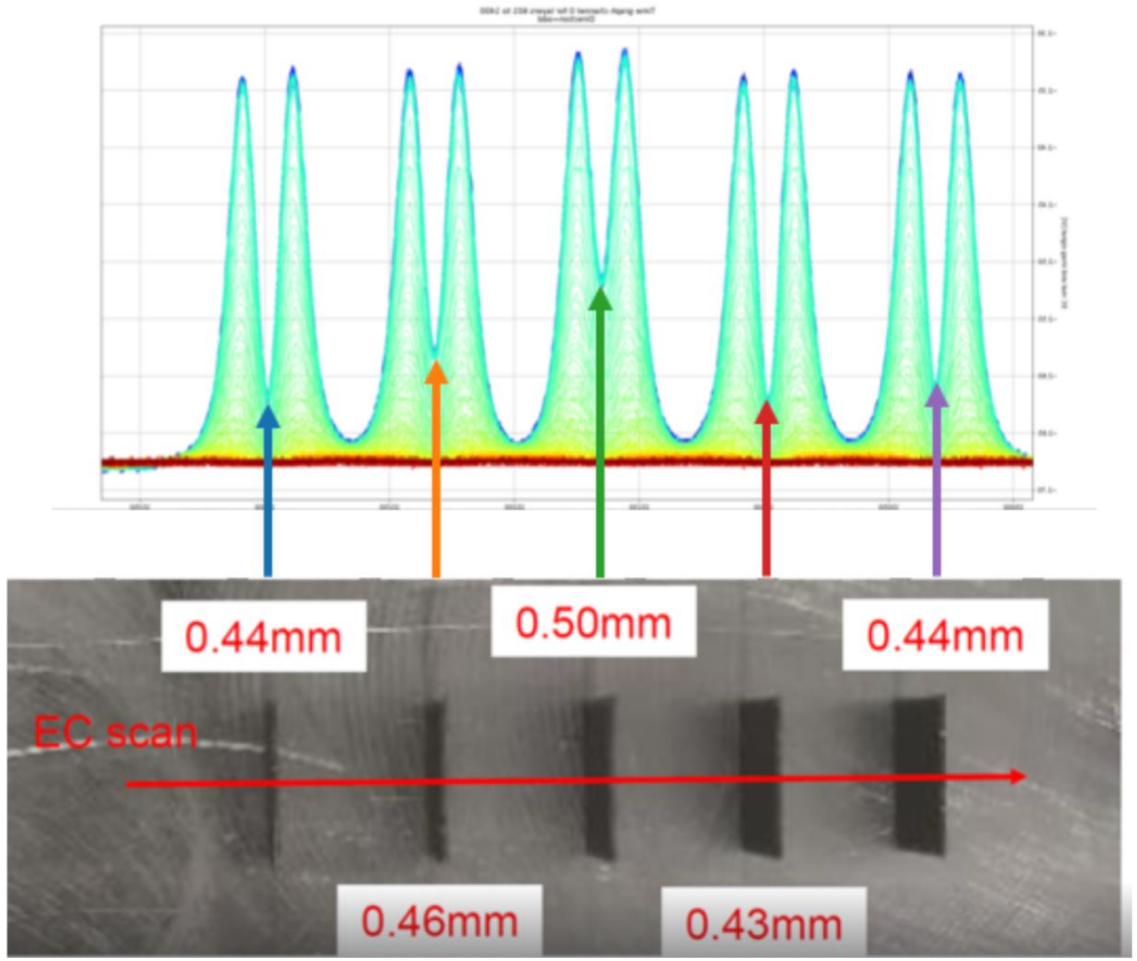


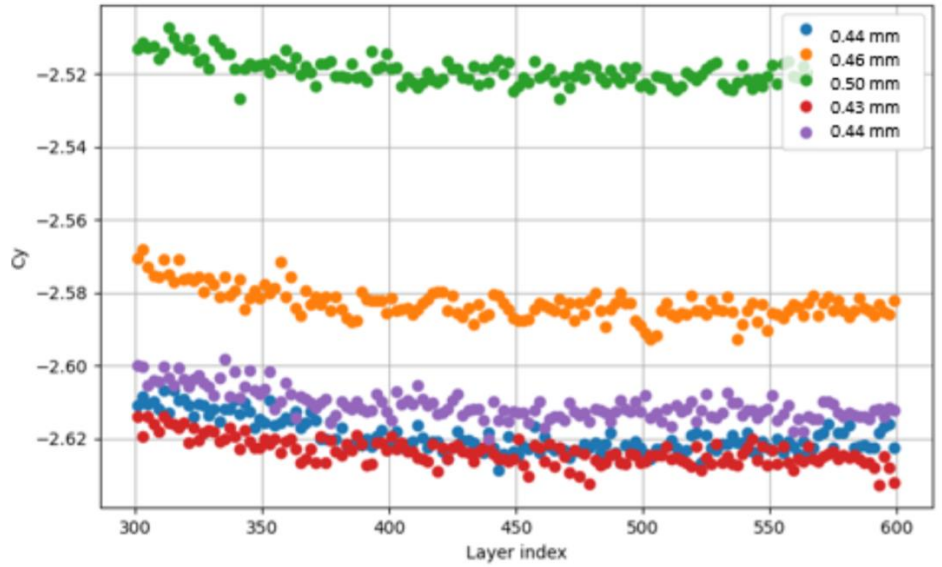


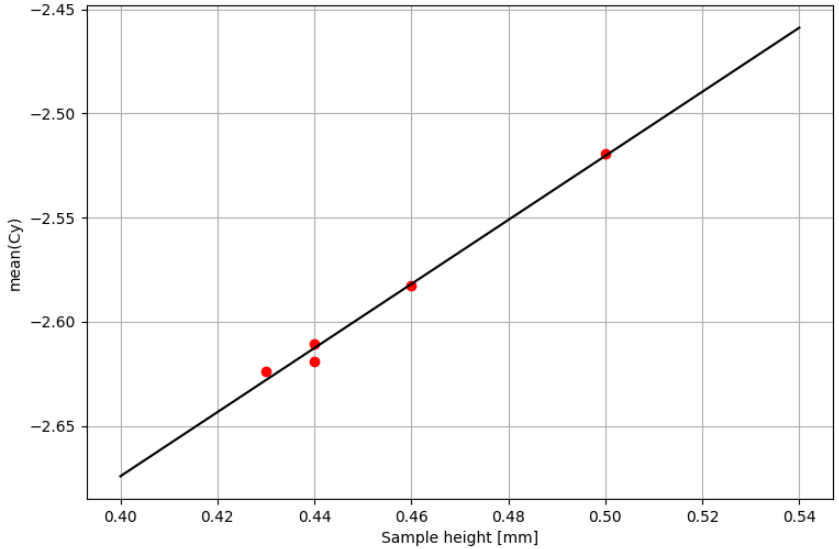
In-situ metrology and part displacement

AMiquam application

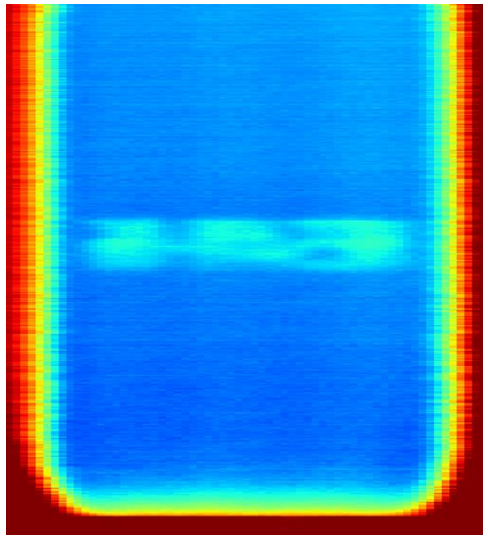
in machine metrology <10um resolution

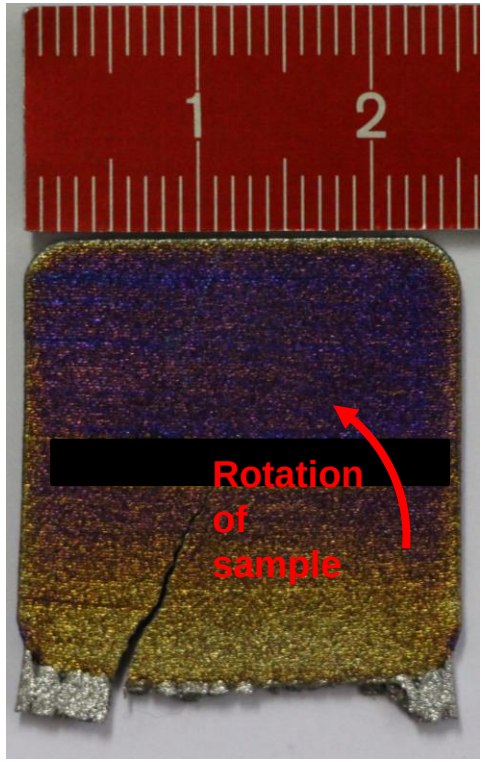




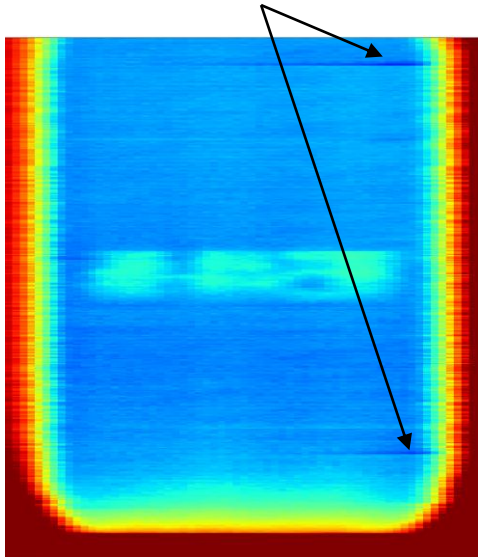


Early detection of cold cracking



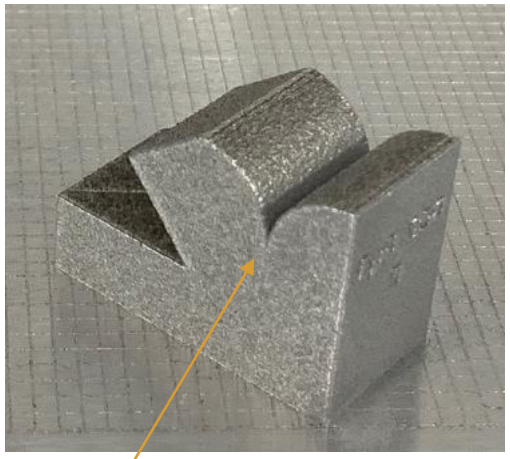


Detection of small changes in part position due to cracking
Unnoticed by the other machine monitoring tools (and without collision with recoater) the process continued

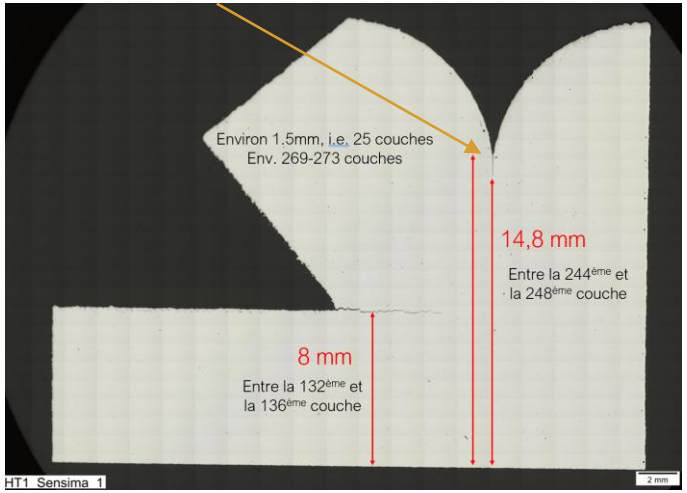


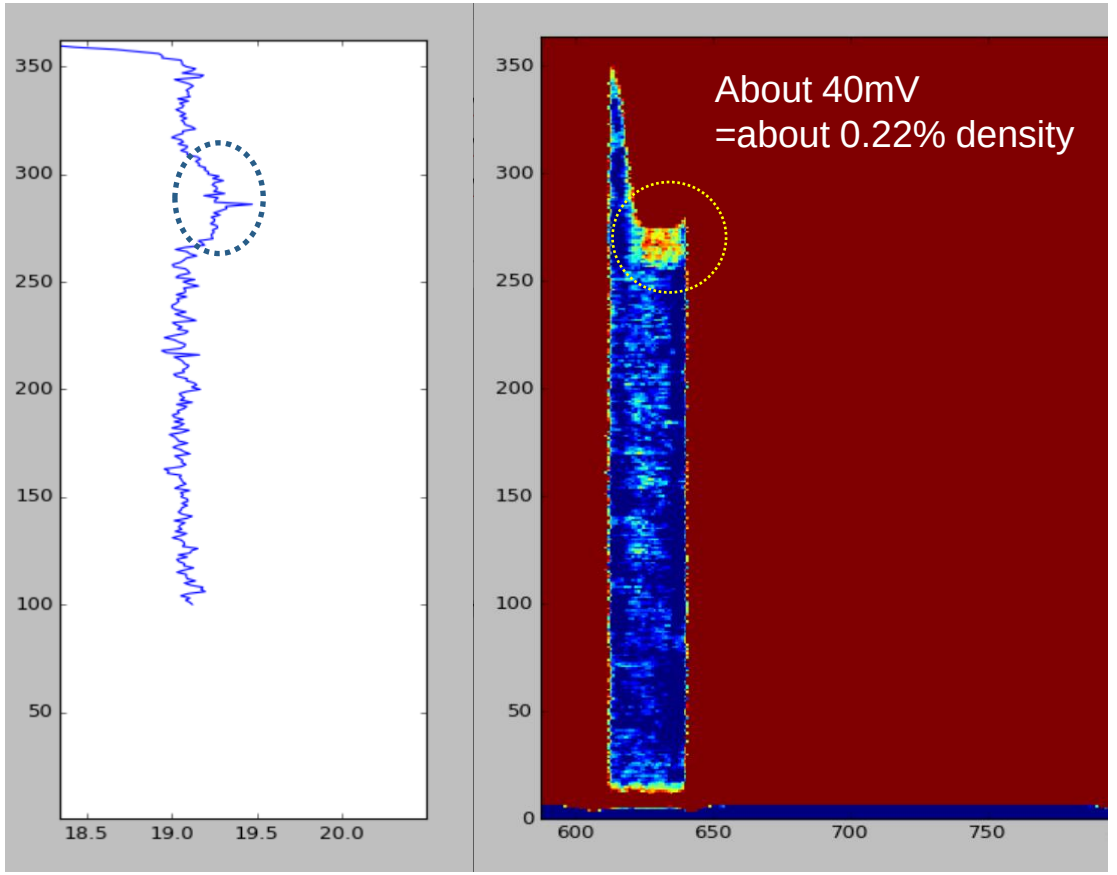
AMiquam application

detect part deformation (residual stress, cold cracking)



Crack





0.1% swelling of the part detected during fabrication
Lower density detected at the region where the crack occurs
-> these are correlated with the crack presence

Thanks!

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1196 Gland, Switzerland