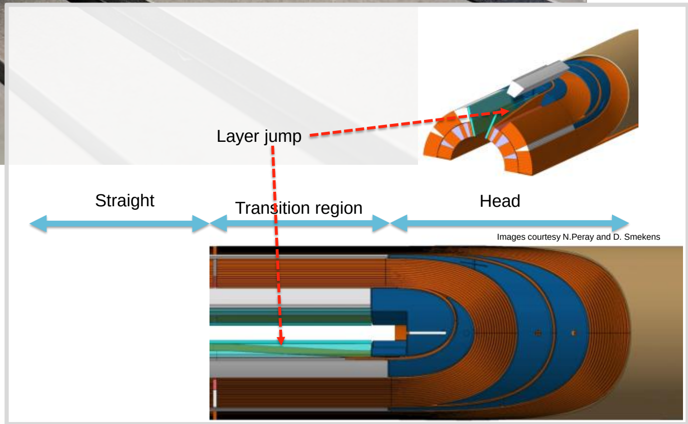
Results of preliminary NDT investigations on undamaged Coil's Head Non-connection side GE-02

Stefano Sgobba and Mariusz Dawid Jedrychowski
EN-MME-MM

12-08-2020

Coil head delivered on 06 July 2020



Segment: **Coil's Head Non-connection side.**
Coil's name: **GE-02.**
Coil's ID: **HCMBH_C005-01000002.**
Coil's geometry: **LHCMBH_C0005 Version AC.**
Cable's insulation: **LHCMBH_C0013 Version AC.**

Delete | Respond | Quick Steps | Move | Tags | Editing | Zoom

Mon 06-Jul-20 5:07 PM
Arnaud Devred
RE: Examination of Nb3 Sn coils
To Jose Luis Rudeiros Fernandez; Ignacio Aviles Santillana
Cc Stefano Sgobba; Frederic Savary

From: Jose Luis Rudeiros Fernandez <Jose.Rudeiros@cern.ch>
Sent: 06 July 2020 17:05
To: Arnaud Devred <Arnaud.Devred@cern.ch>; Ignacio Aviles Santillana <ignacio.aviles.santillana@cern.ch>
Cc: Stefano Sgobba <Stefano.Sgobba@cern.ch>; Frederic Savary <Frederic.Savary@cern.ch>
Subject: RE: Examination of Nb3 Sn coils

Dear Arnaud,

Based on the information I currently have, this is not the damaged end.
The damaged end was given to Christian Scheuerlein quite some time ago.
I believe he intended to carried out measurements by neutron diffraction of Nb_3Sn and Cu residual strain (this was communicated to me back in February).
On this point, I have already requested an update from his side and if it would be possible to recuperate the piece.

After discussing with Frédéric this morning, the part that I gave to Ignacio was proposed as a good start if there is any non-destructive examination techniques to be evaluated.

Cheers,

José Luis

⇐Undamaged

For NDT investigation purpose ⇓

Preliminary investigations

Coil head delivered on 06 July 2020

- 3D dimensional metrology of the outer envelope for reference - done
- X-Ray CT test based on internal ZEISS METROTOM 225 kV - done
- Cutting of an extremity slice and demonstration of metallographic preparation - done
- Shipping the coil head to TEC Eurolab LTD, Campogalliano /IT for a LINAC 6 MeV X-Ray CT trial – done
- LINAC 6 MeV X-Ray CT first trial results – obtained
- 3D dimensional metrology of the slice – waiting for reference drawings

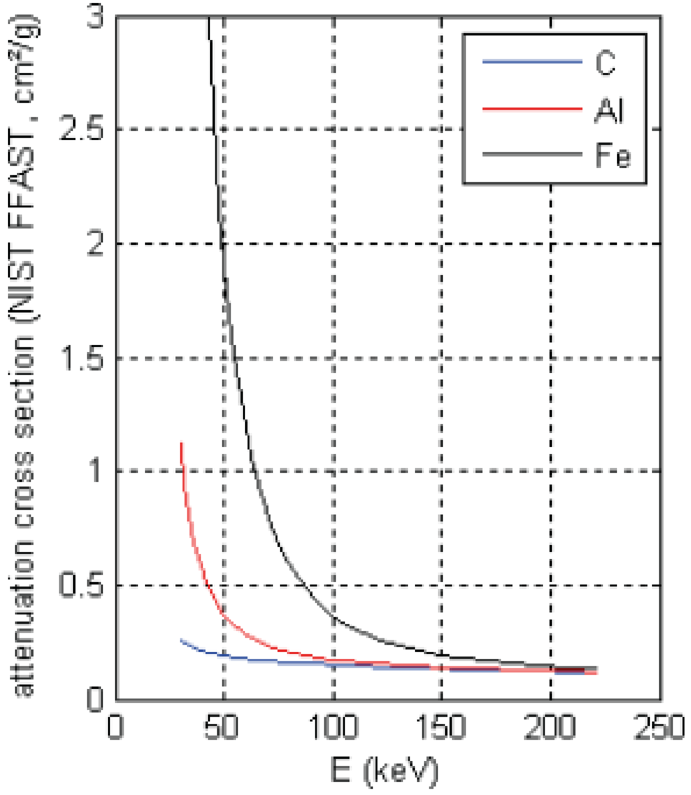
NDT preliminary results presented here (MJ)

- X-Ray CT test based on ZEISS METROTOM 225 kV available at CERN
- LINAC 6 MeV X-Ray CT - first trial results

Discussions running for additional NDT examinations, for the while with the following labs:

- LINAC 6 MeV X-Ray CT – TEC-Eurolab Modena/IT (Martina Vincetti)
- ESRF /FR – synchrotron CT – (Alexander Rack)
- PSI /CH – synchrotron CT – TOMCAT (Dr. Anne Bonnin)
- PSI /CH – neutron CT – ICON (Anders Kaestner)
- National Institute for Laser, Plasma and Radiation Physics /RO – 320 kV CT laboratory – (Ion Tiseanu)

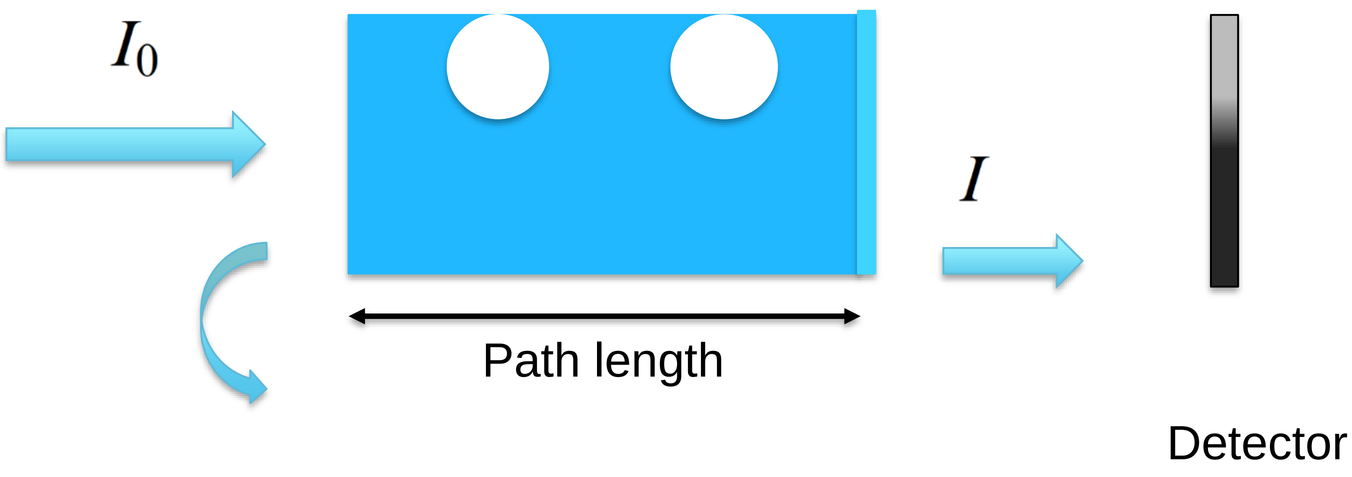
Introduction to X-Ray Computed Tomography



Beer - Lambert law

$$I = I_0 \exp\left[\sum_i (-\mu_i x_i)\right]$$

Piece
Regions with different X-ray absorption (depends on Z number)

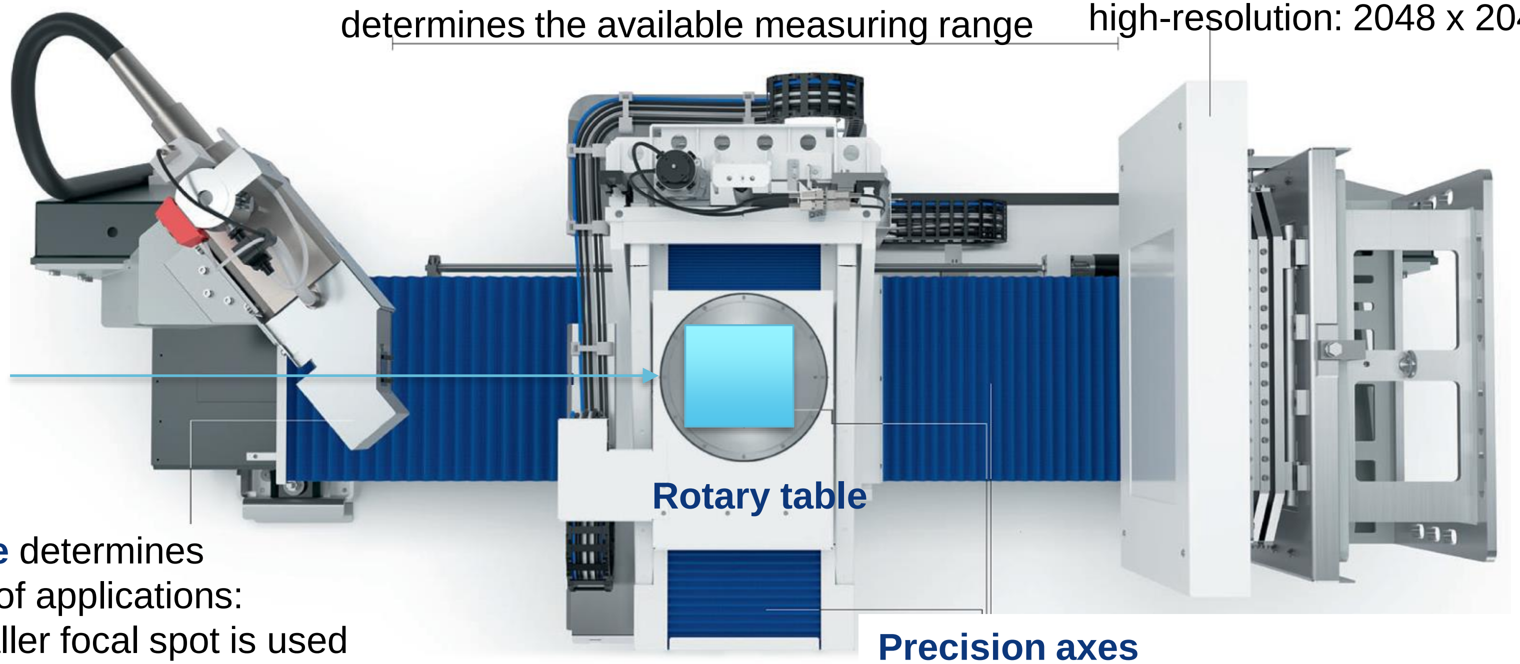


Introduction to X-Ray Computed Tomography

Tube/detector distance
determines the available measuring range

Flat image detector
high-resolution: 2048 x 2048 pixels

Piece
Regions with different
X-ray absorption



Projections
2D radiography

X-ray tube determines
the range of applications:

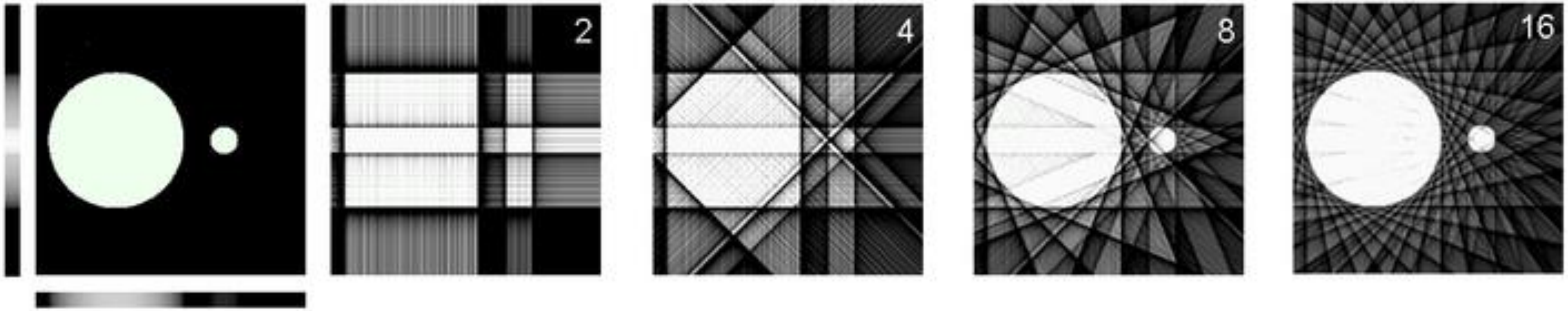
- a smaller focal spot is used for high resolution,
- a higher voltage is used for more absorbent (denser/thicker) pieces

Precision axes
The workpiece can be moved on four axes with extreme precision provided by coordinate measuring technology which, in result, allows metrology measurements.

Introduction to X-Ray Computed Tomography - Reconstruction

Large number of projections captured during rotation (0º – 360º) for each angular step → Feldkamp back-projection algorithm → 3D volume represented by grid of voxels

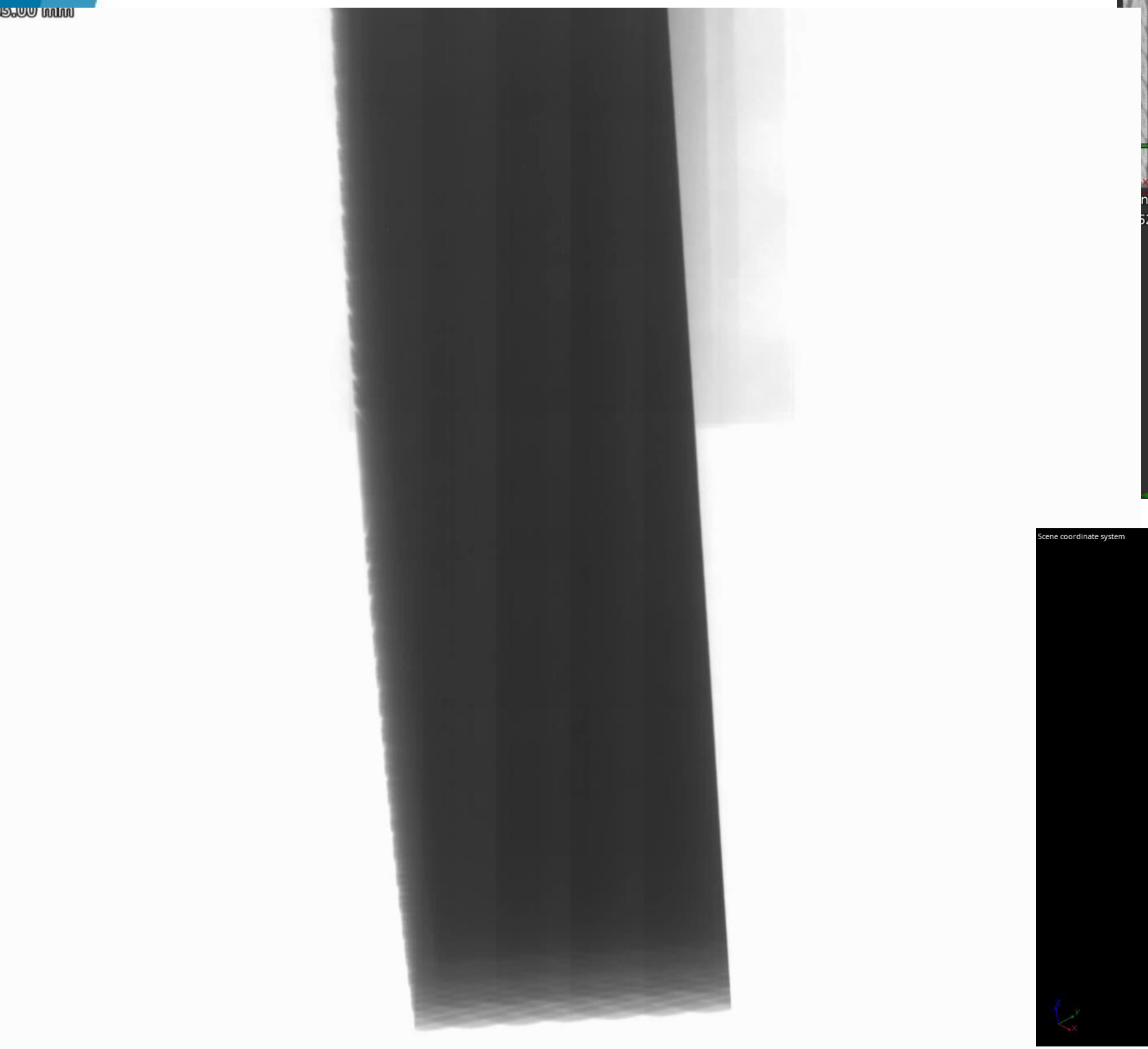
Reconstruction 2D of two circles



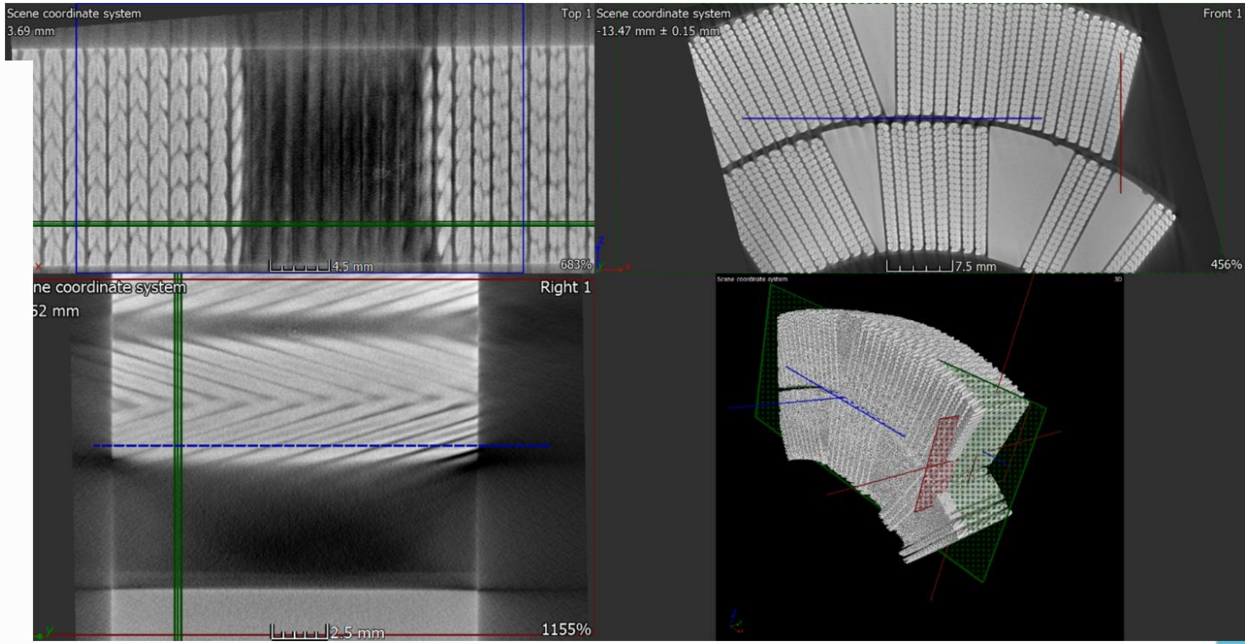
1 px line distributions – for two angles

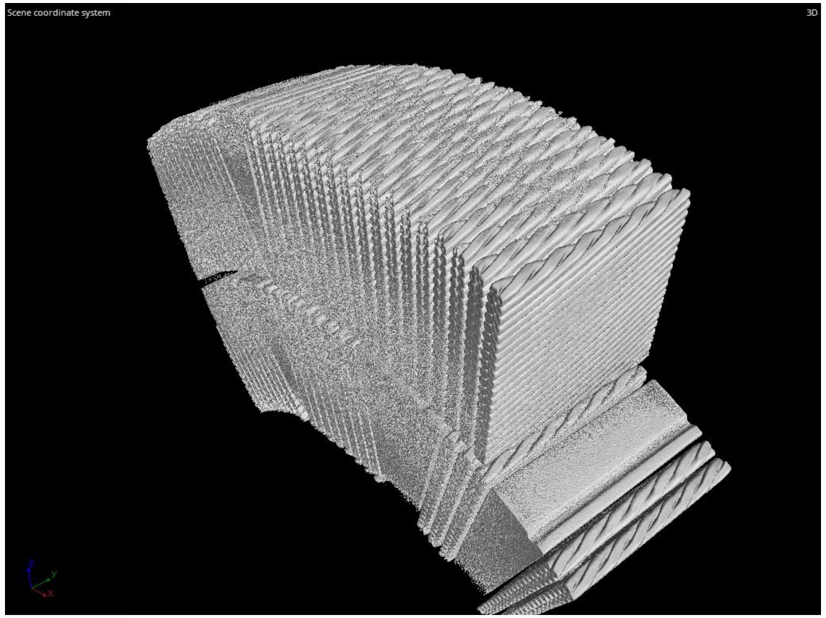
Introduction to X-Ray Computed Tomography (example of a 16 mm thick coil slice)

Projections



Reconstructed volume



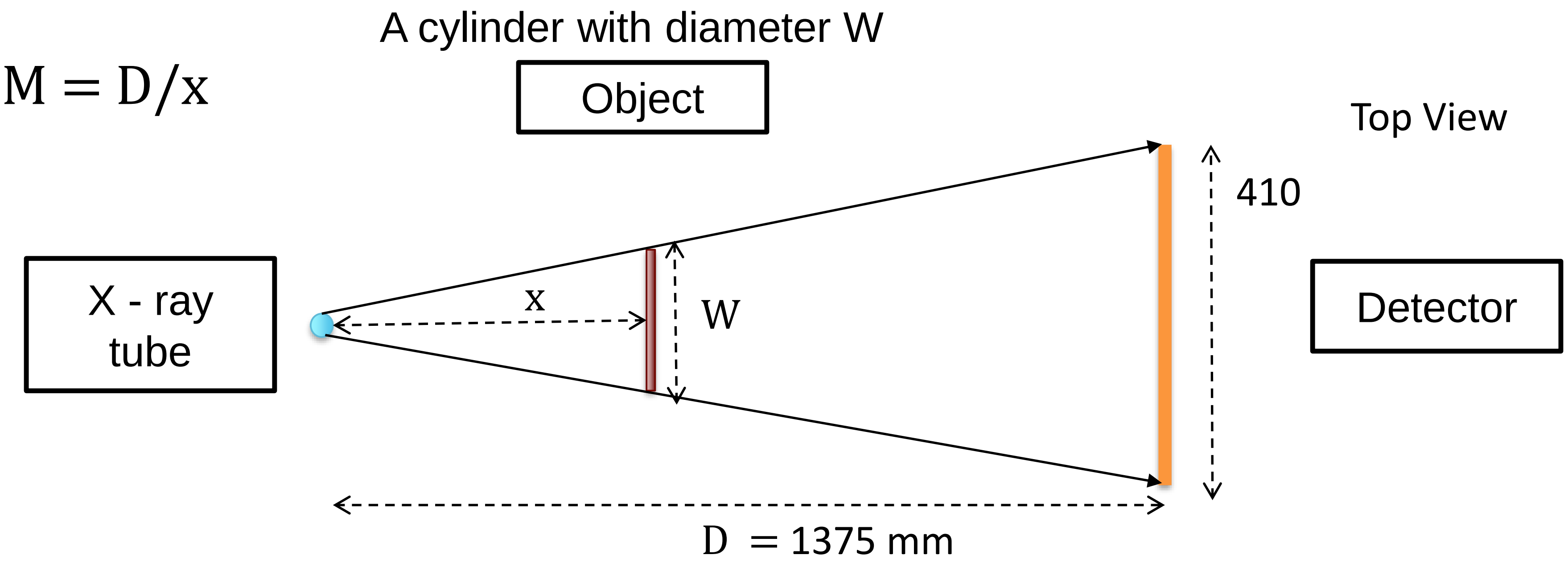


3D animation

Introduction to X-Ray Computed Tomography

Tube/piece/detector distances

magnification $\mathrm{M} = \mathrm{D}/\mathrm{x}$

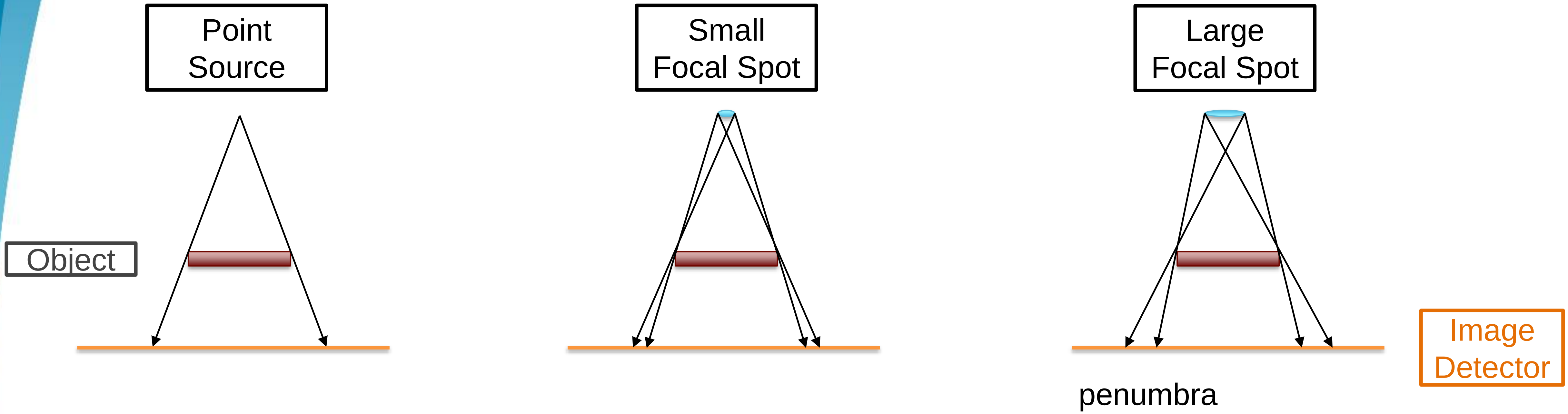


$\mathrm{W} = 2048 * \mathrm{voxel\_size}$ (assuming that detector area is fully filled in by object projection)

$\mathrm{W} / \mathrm{x} = 410\ \mathrm{mm} / \mathrm{D}$ (from Thales relation)

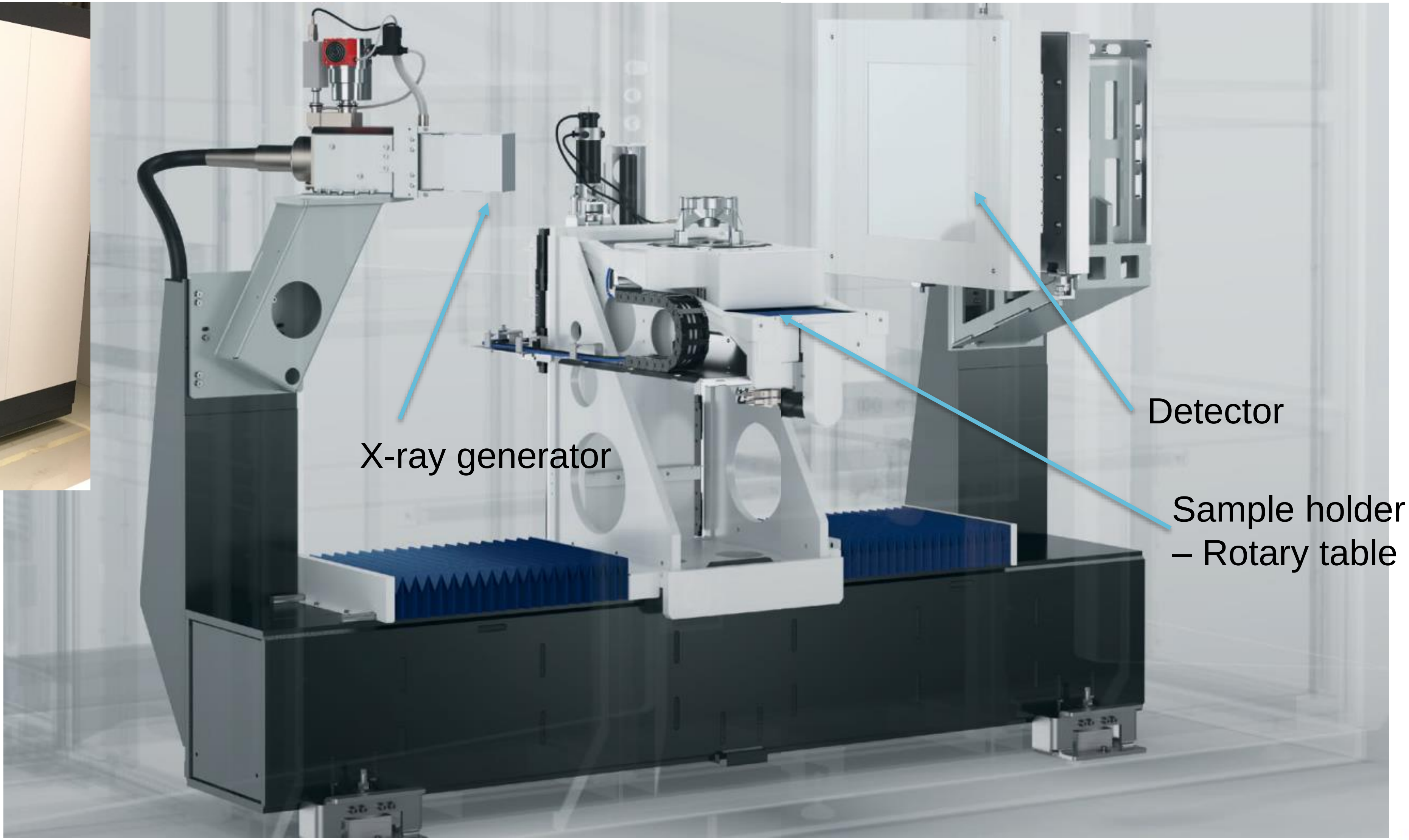
voxel_size [µm] = 410/1375 * x [µm] /2048 = 0.145 * x [mm]

Introduction to X-Ray Computed Tomography



Focal spot size has to be adjusted in respect to object size in order to avoid blurred projections

ZEISS METROTOM 225 kV available at CERN



ZEISS METROTOM 225 kV available at CERN

Specification

- Microfocus X-ray tube:

  Max. voltage 225 kV
  Max. current 3000 µA
  Max power 500 W
  Min. focal spot size **7 µm**

- High resolution flat panel imager:

  40 x 40 cm
  2048 x 2048 pixels, 16 bit

- Tube-detector distance: 1375 mm

- Max. spatial resolution: 7 µm

  Typically voxel size is **10 to 100 µm**

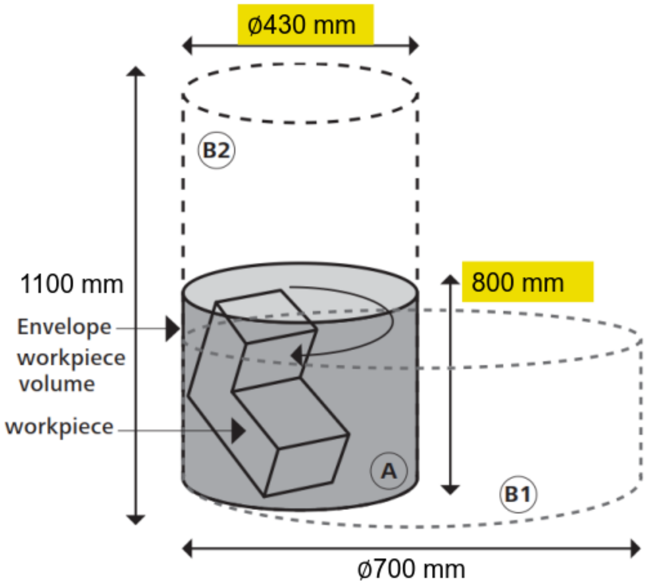
- Length measurement error [µm]:
  9 µm + L/50

Max. Measuring range:

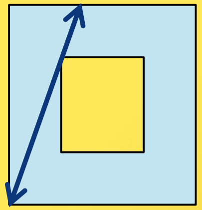
- without field extensions ø305 mm x 260 mm
- with vertical field extension ø305 mm x 655 mm
- with vertical and horizontal field extension ø570 mm x 550 mm

Workpiece size

- max. weight: 50 kg



Material	**Max. through thickness** [mm]
Polymer	> 300
Aluminium	300
Titanium	200
Steel	50
Copper	20 - 30



Max through thickness

(A) Max. workpiece size without limitation of travel range

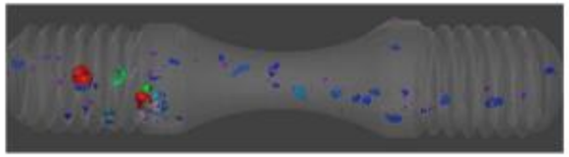
(B1) Size optimized for maximum diameter, but with restriction of measurement range; detector horizontal extension must be applied

(B2) Size optimized for maximum height, but with restriction of measurement range;

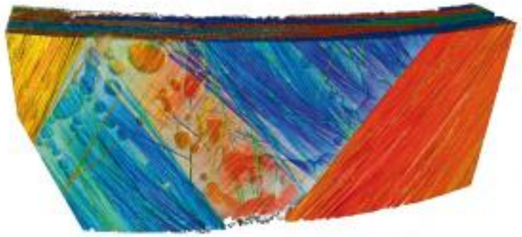
ZEISS METROTOM 225 kV available at CERN

Non destructive analyses

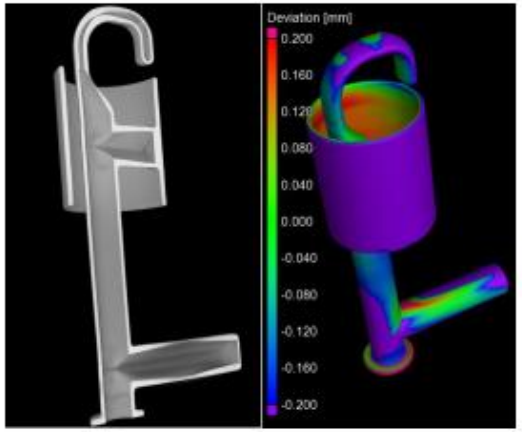
- Porosity/inclusion/crack segmentation and analysis of defects; Estimation of brazing/welding quality



- Fiber analysis



- Preparation and visualisation of 3D models
- Wall thickness analysis



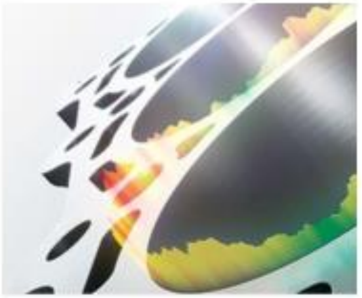
- Comparison with reference model
- Unrolled surface view

VOLUME GRAPHICS
Enabling better products

Metrology

- Advanced registration of reference system
- Comparison with CAD model
- Surface mesh – STL
- Calypso measurement
  -> excellent accuracy

ZEISS
ZEISS CALYPSO 2017



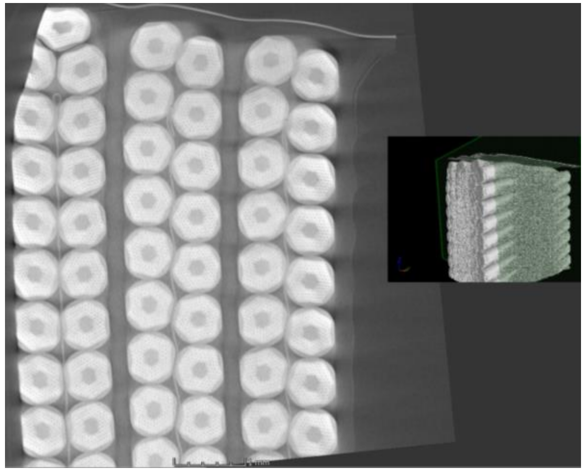
Groupe Cercle 1

Diamètre_Cercle1	30.0019	30.0000
Circularité_Cercle1	0.0377	0.0000
Distance1_X	44.9901	45.0000
Distance1_Y	35.0051	35.0000

Surface mesh

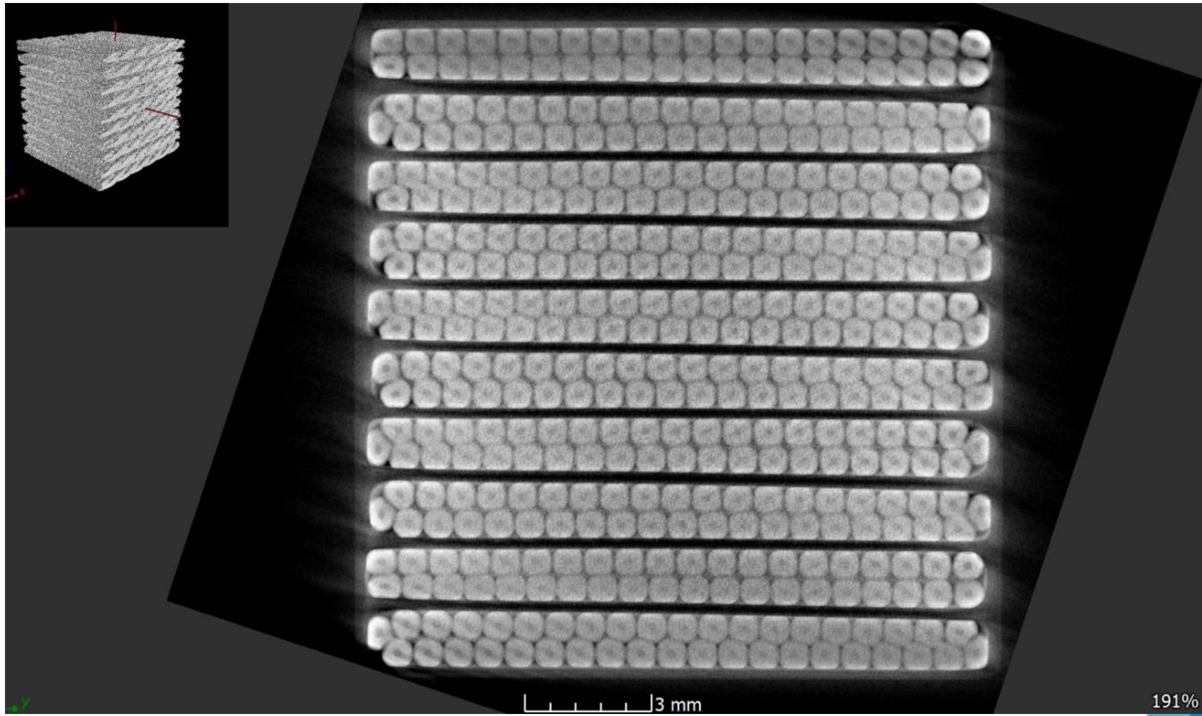
CERN
EN/MME MATERIALS & METROLOGY

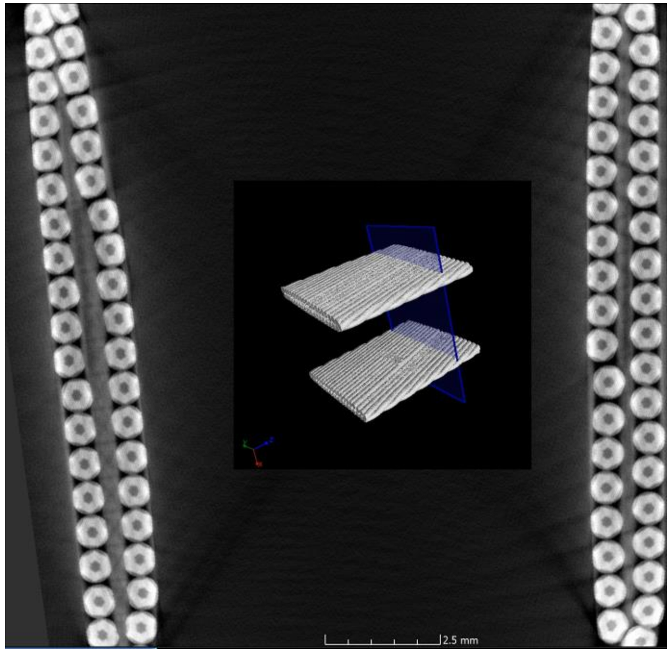
CT – CERN – 11T scale gallery



resolution **7 µm**

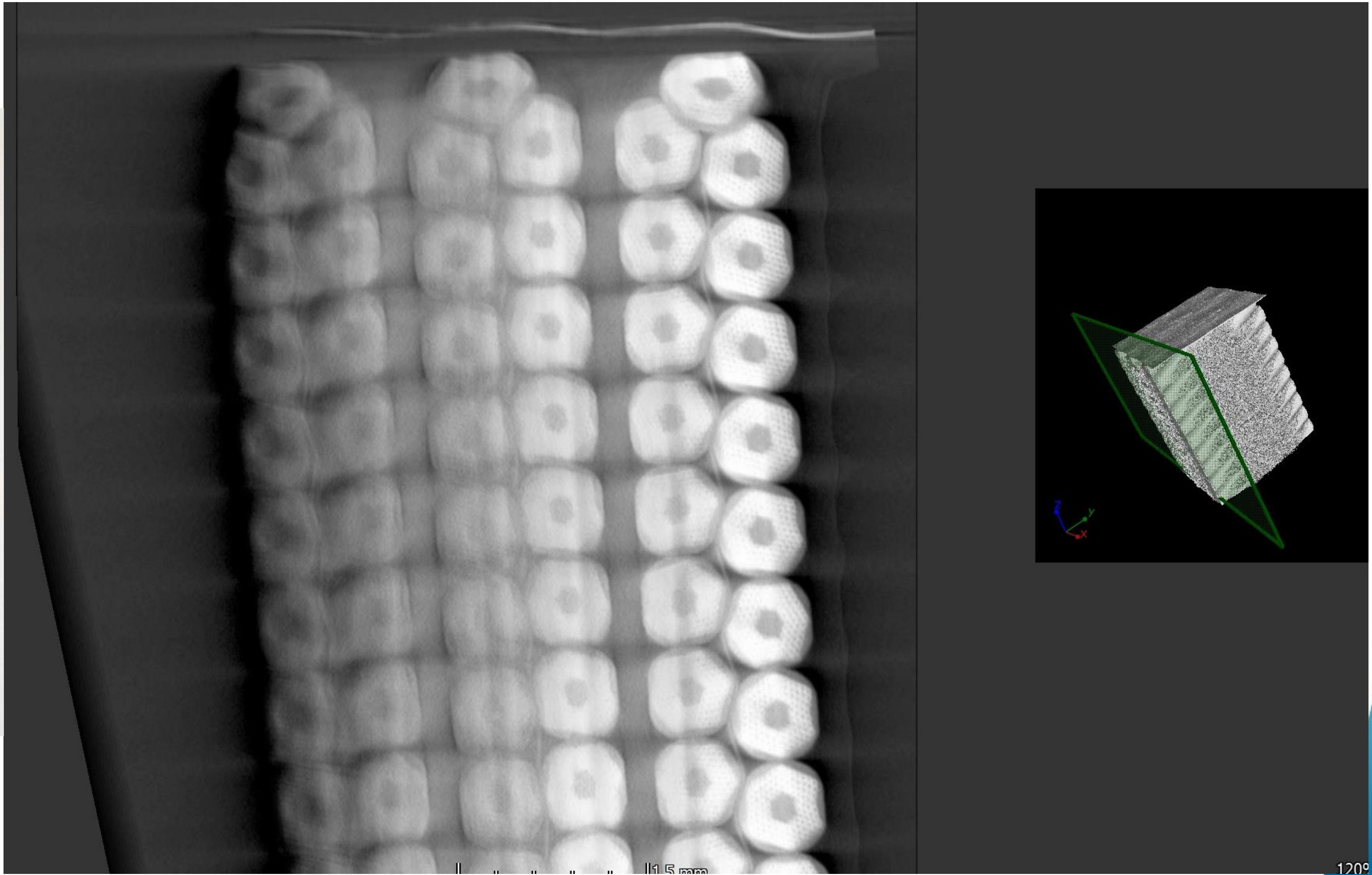
Stack of 10 Nb3Sn Cables – resolution **14 µm**





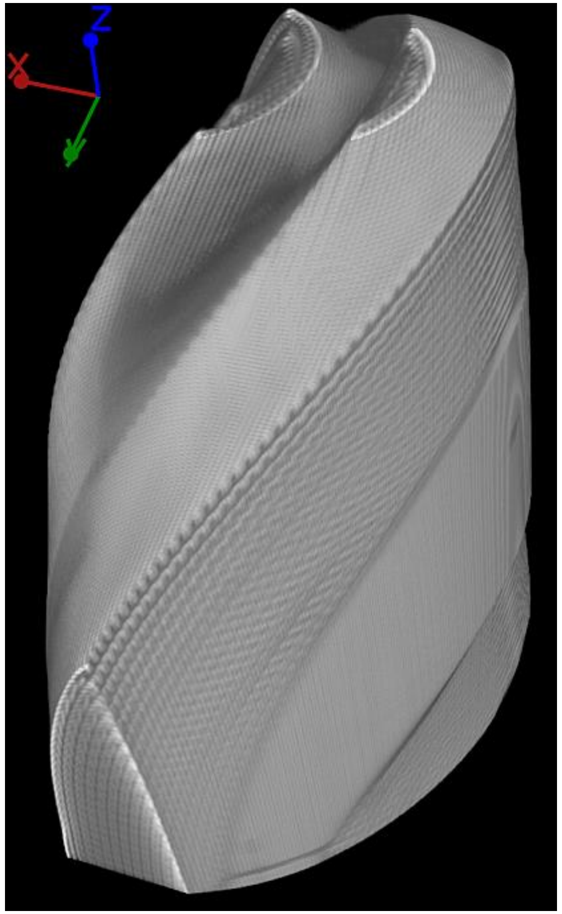
Nb3Sn Cable – resolution **10 µm**

CT – CERN – 11T scale gallery

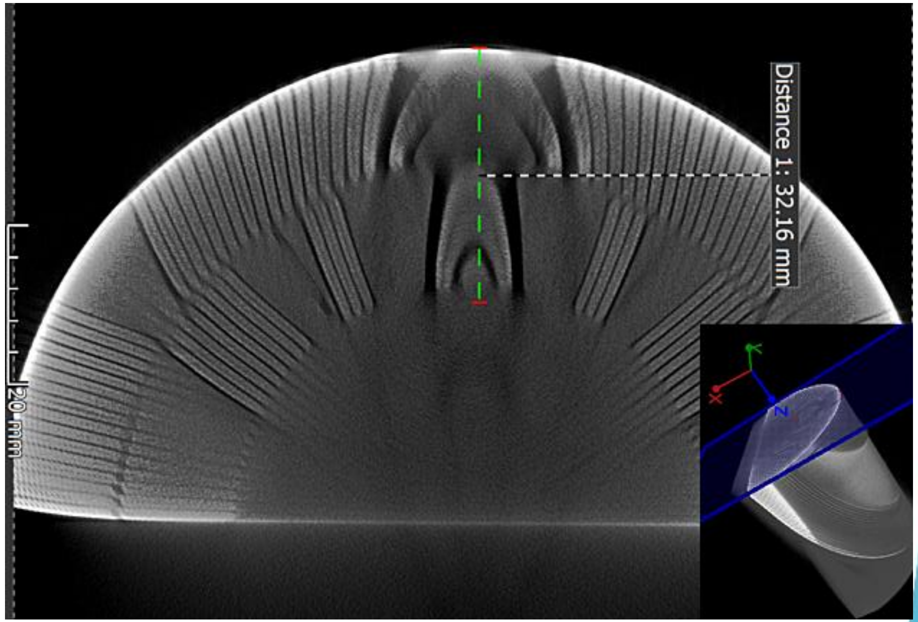


CT – CERN – 11 T scale gallery

11 T magnet coil (feasibility test, 2017)



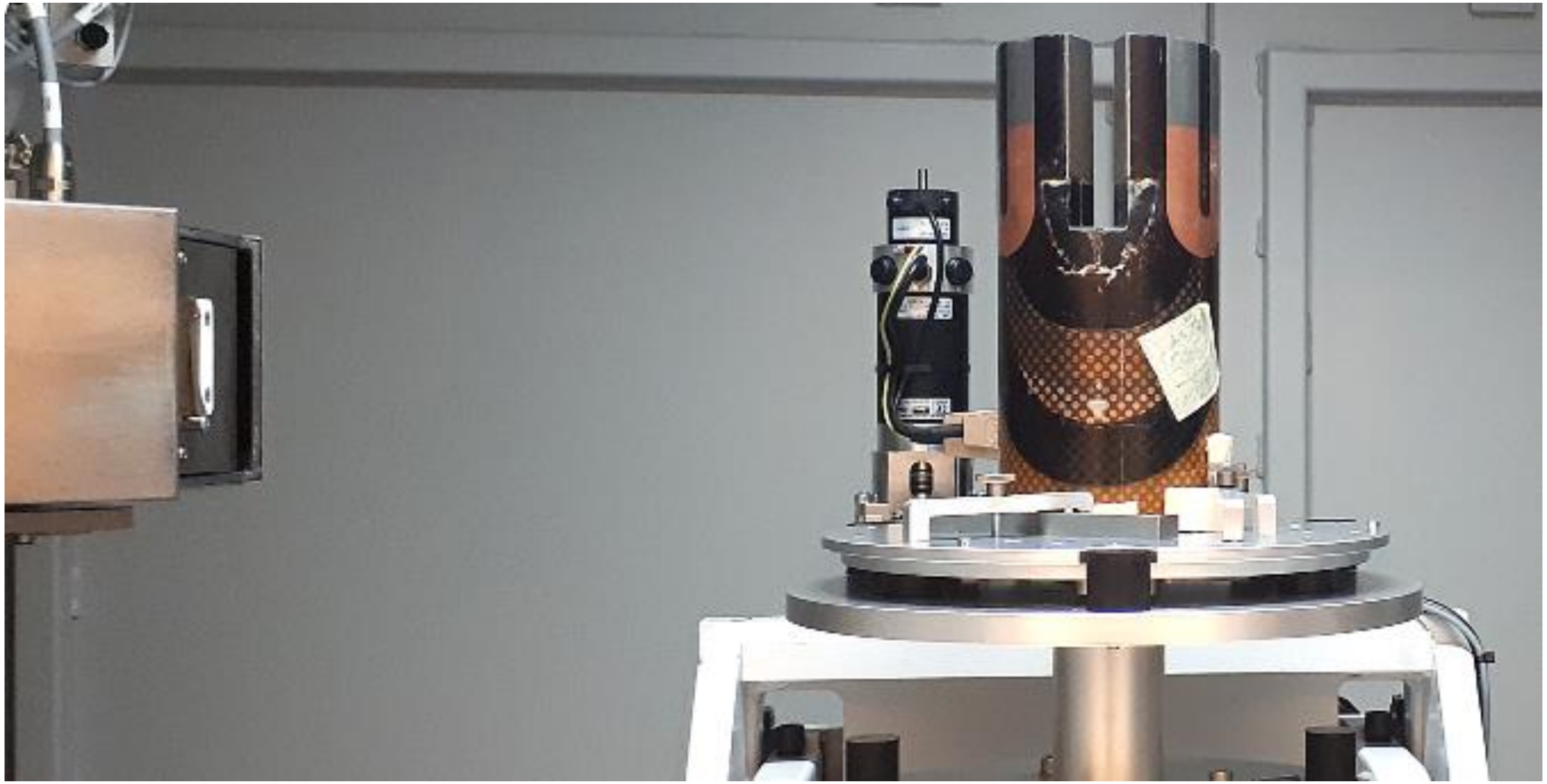
3D volume – side view



Voltage: 225 kV,
Distance: 470 mm,
Voxel size: 70 µm,
Projections: 3000,
Measurement time: 2 h

CERN EN/MME MATERIALS & METROLOGY

CT – CERN – 225 kV – 70 µm
COIL GE-02



2 scans: top part and bottom part merged

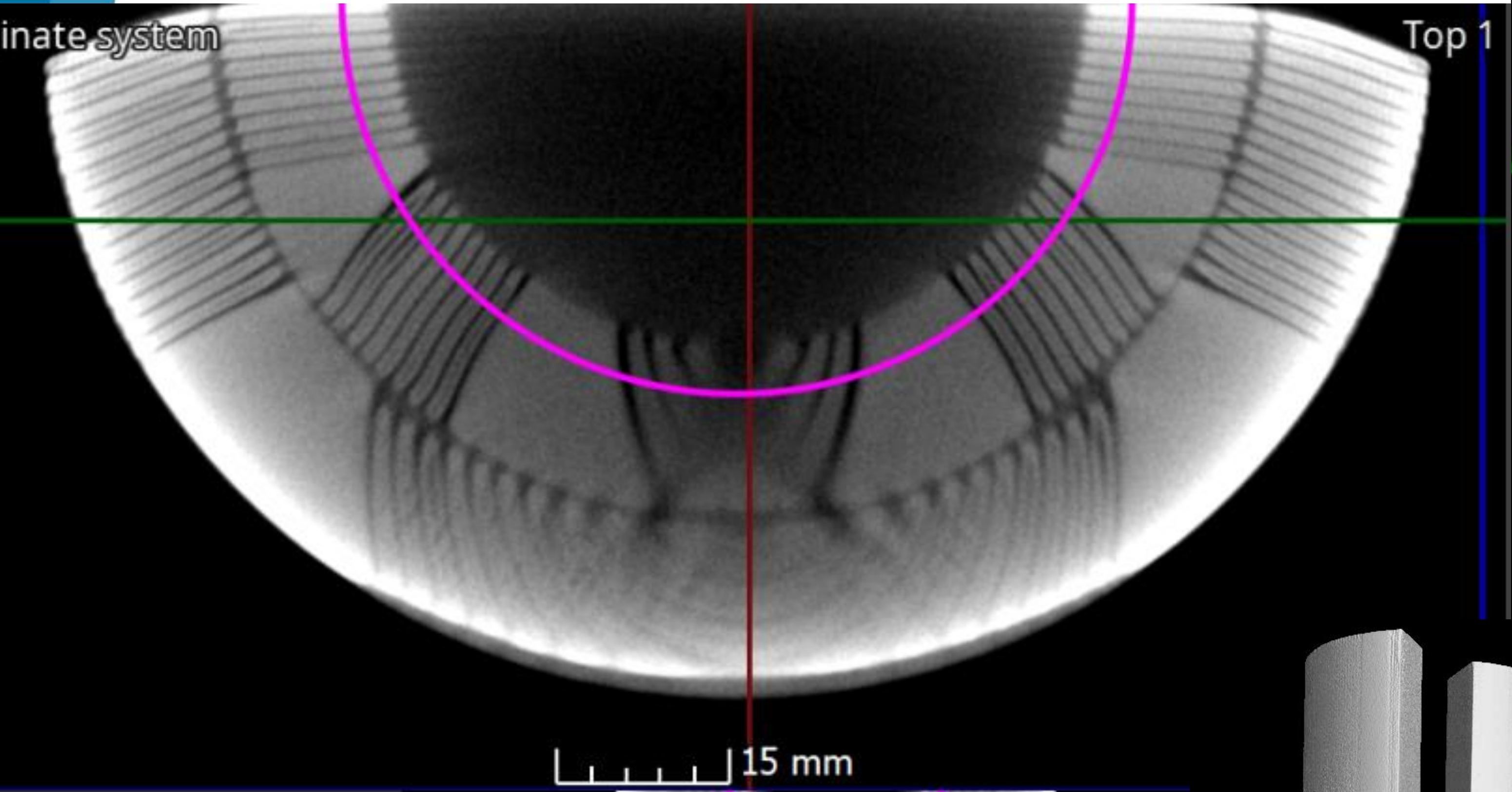
225 kV, 477 mA

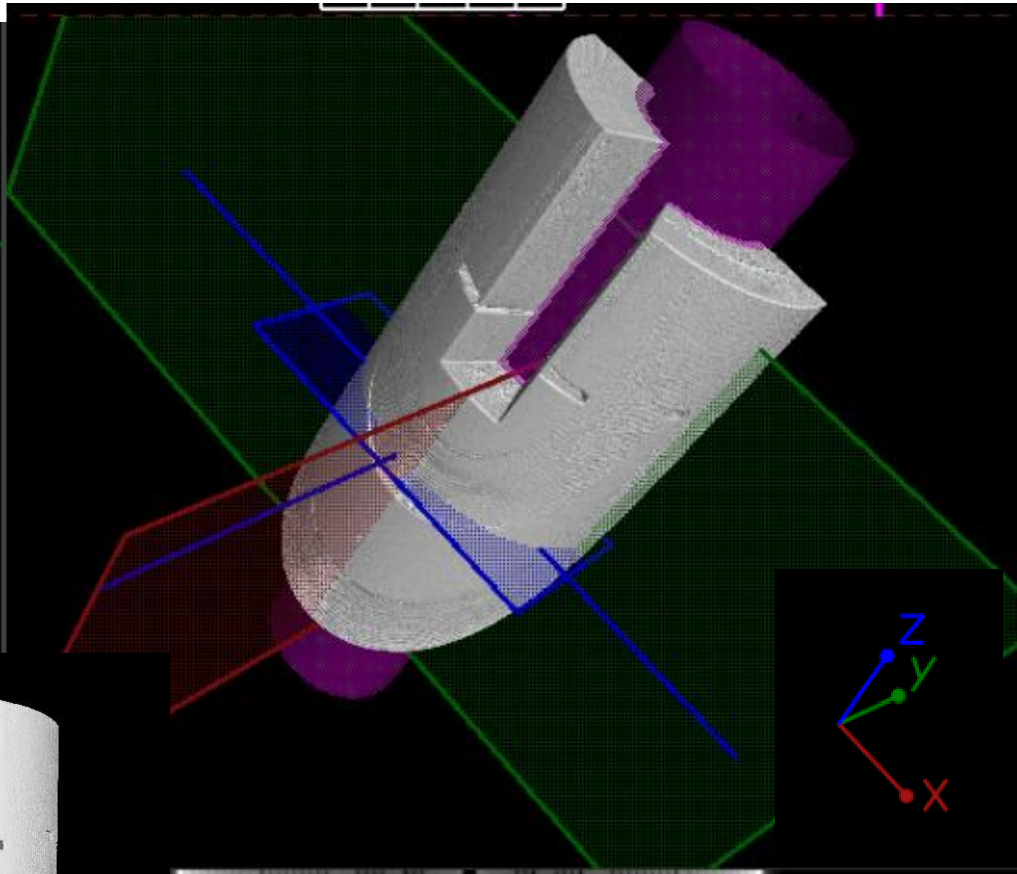
70 µm resolution

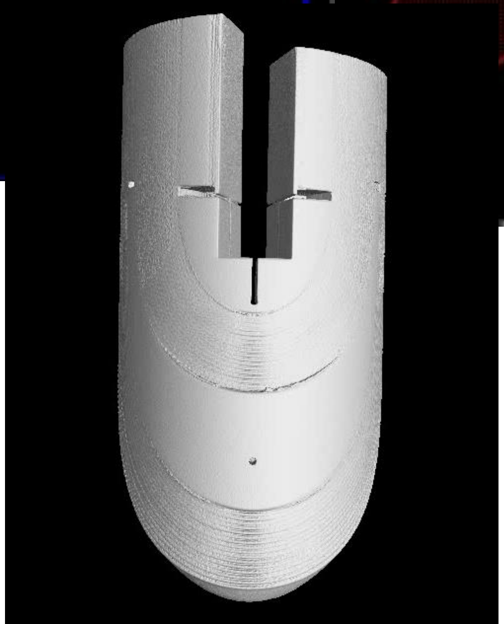
2 x 2050 projections

2 x 2.5 h of scan time

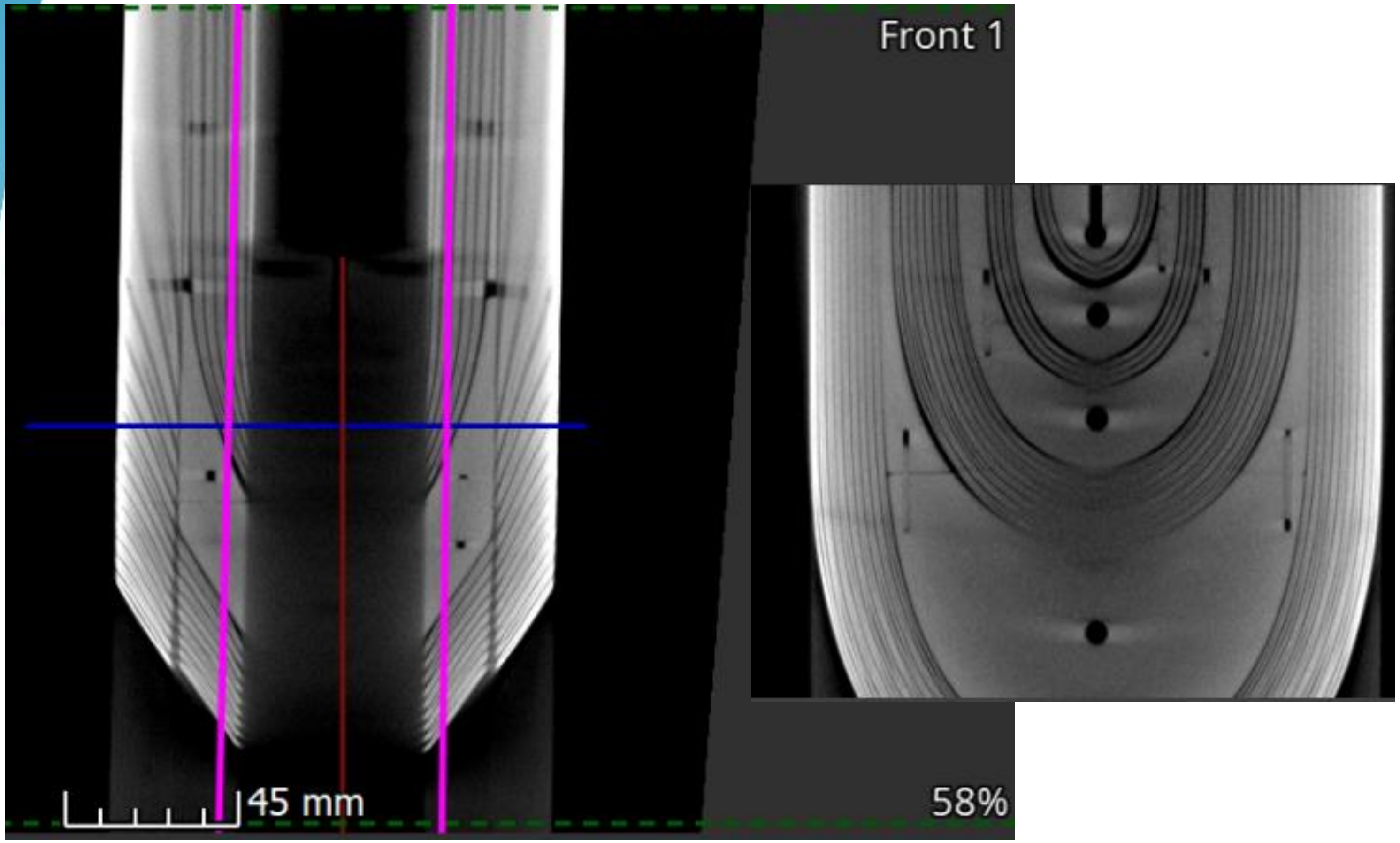
X-Ray CT: GE-02, data presentation

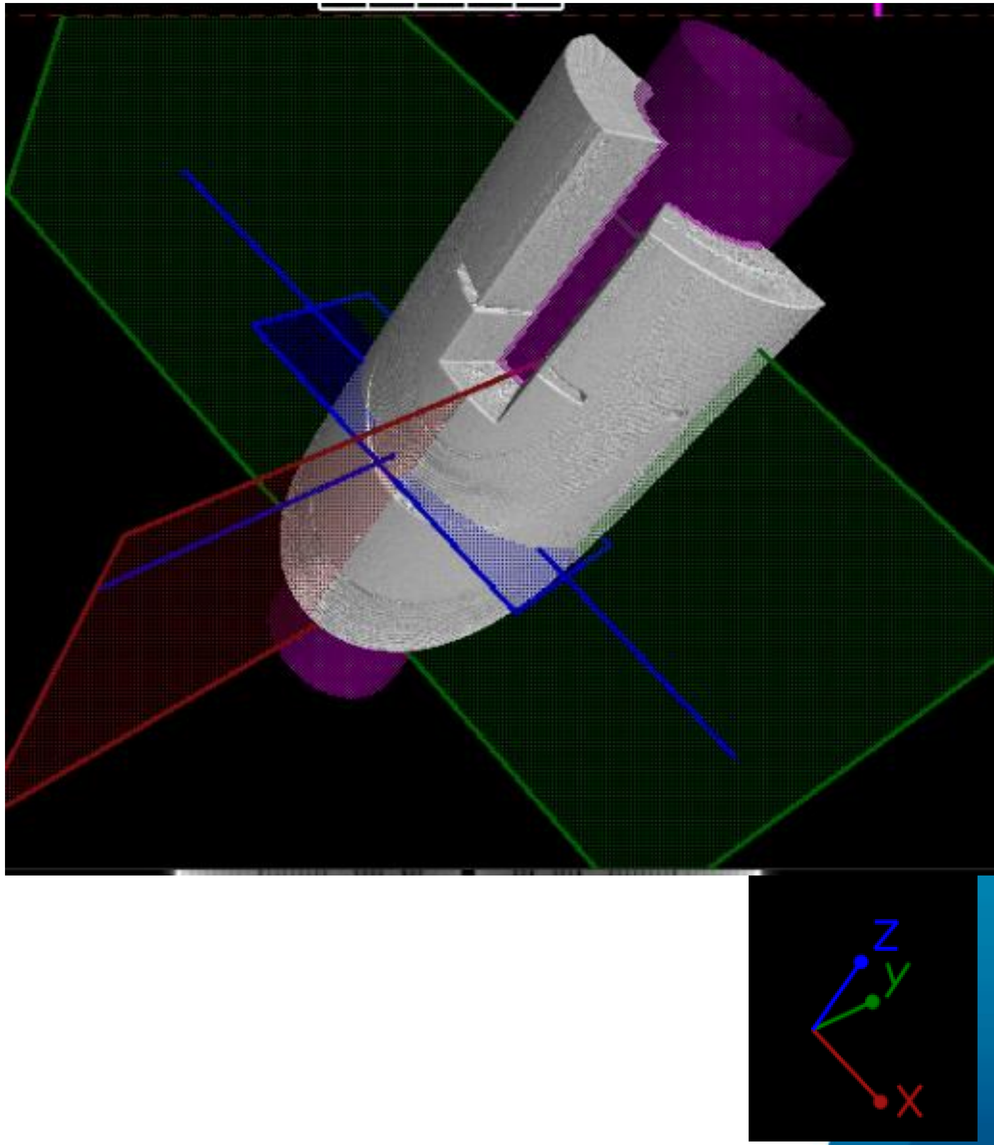




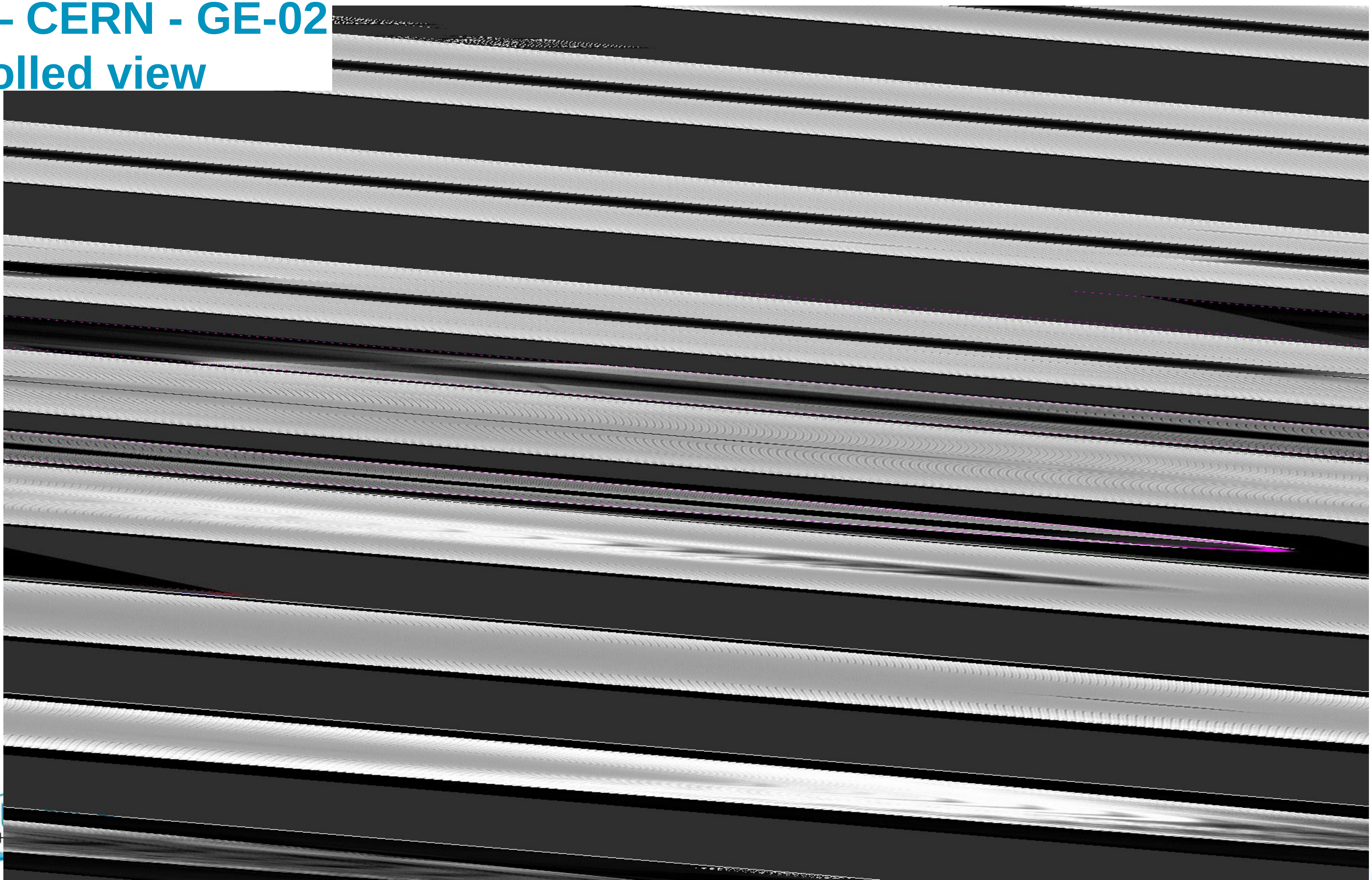


X-Ray CT: GE-02, data presentation

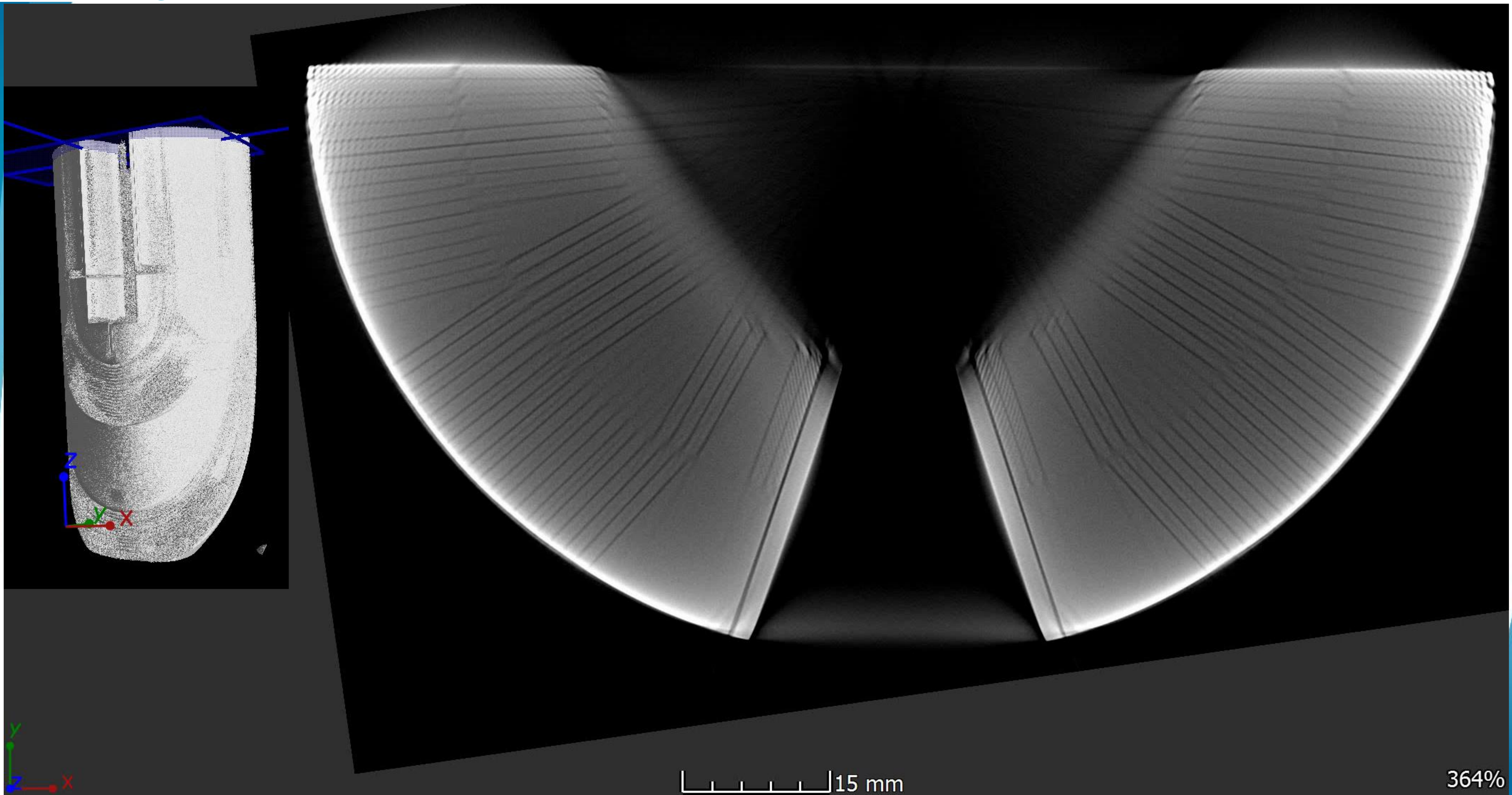




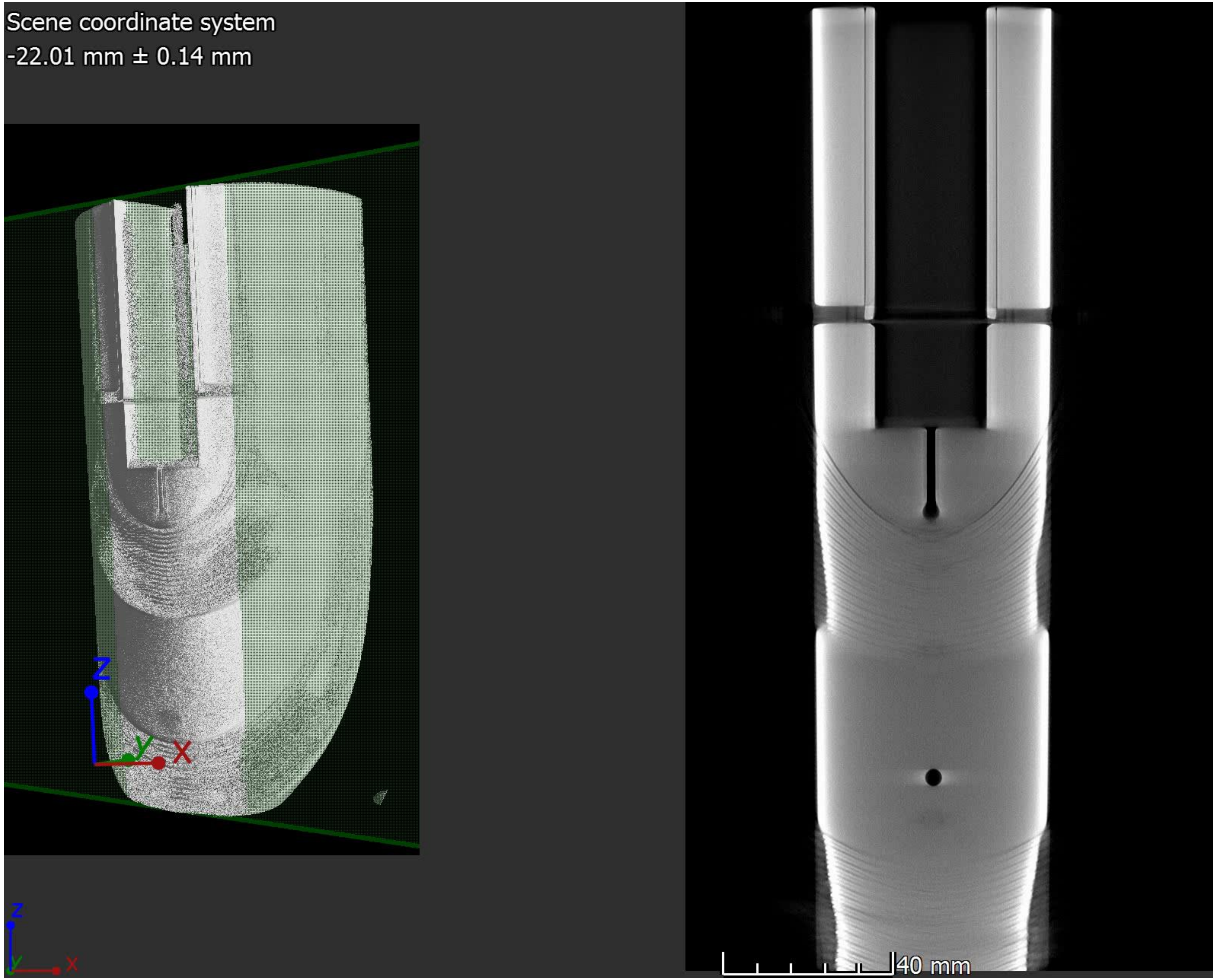
CT – CERN - GE-02 unrolled view



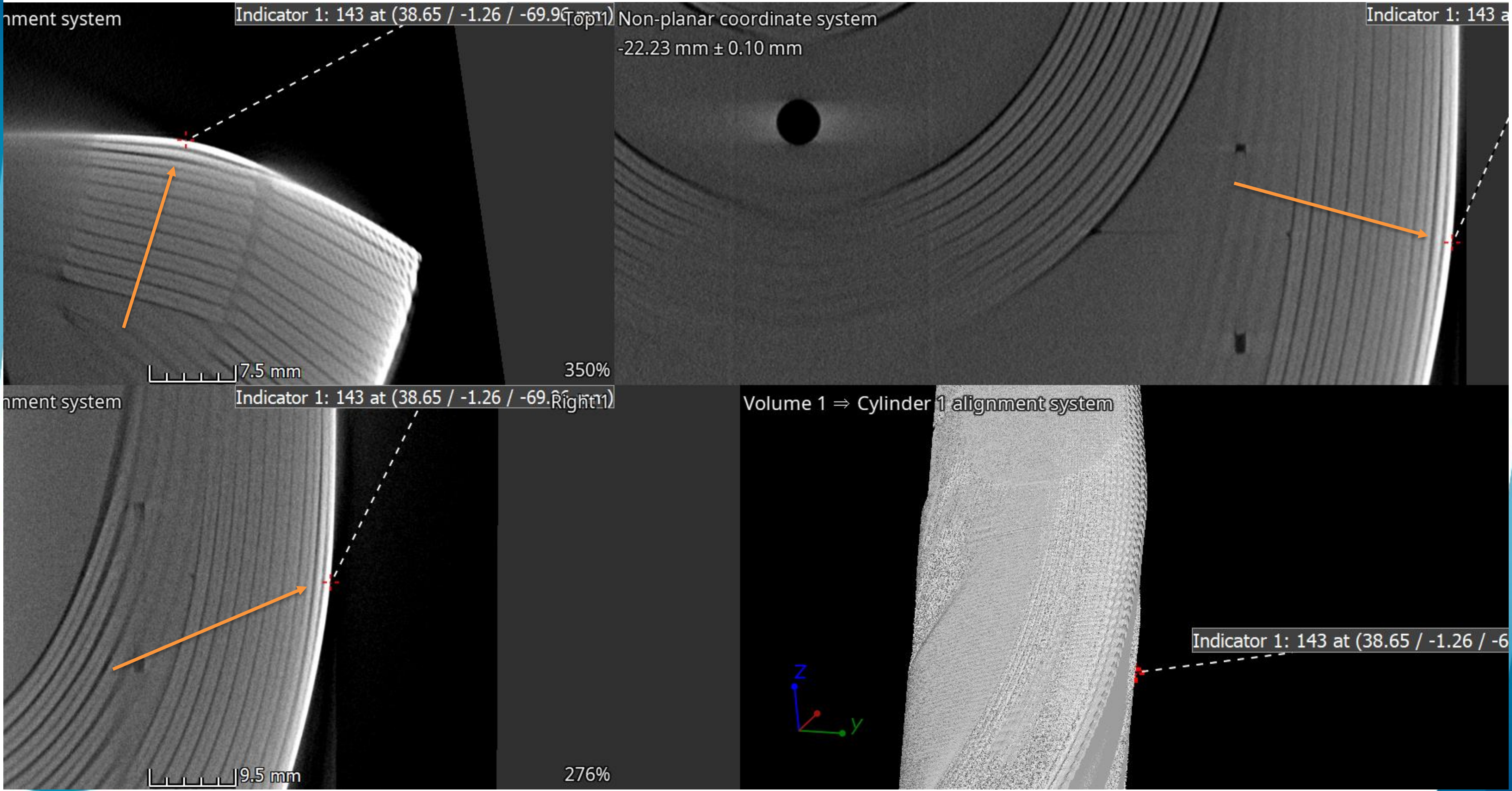
CT – CERN GE-02
z – view



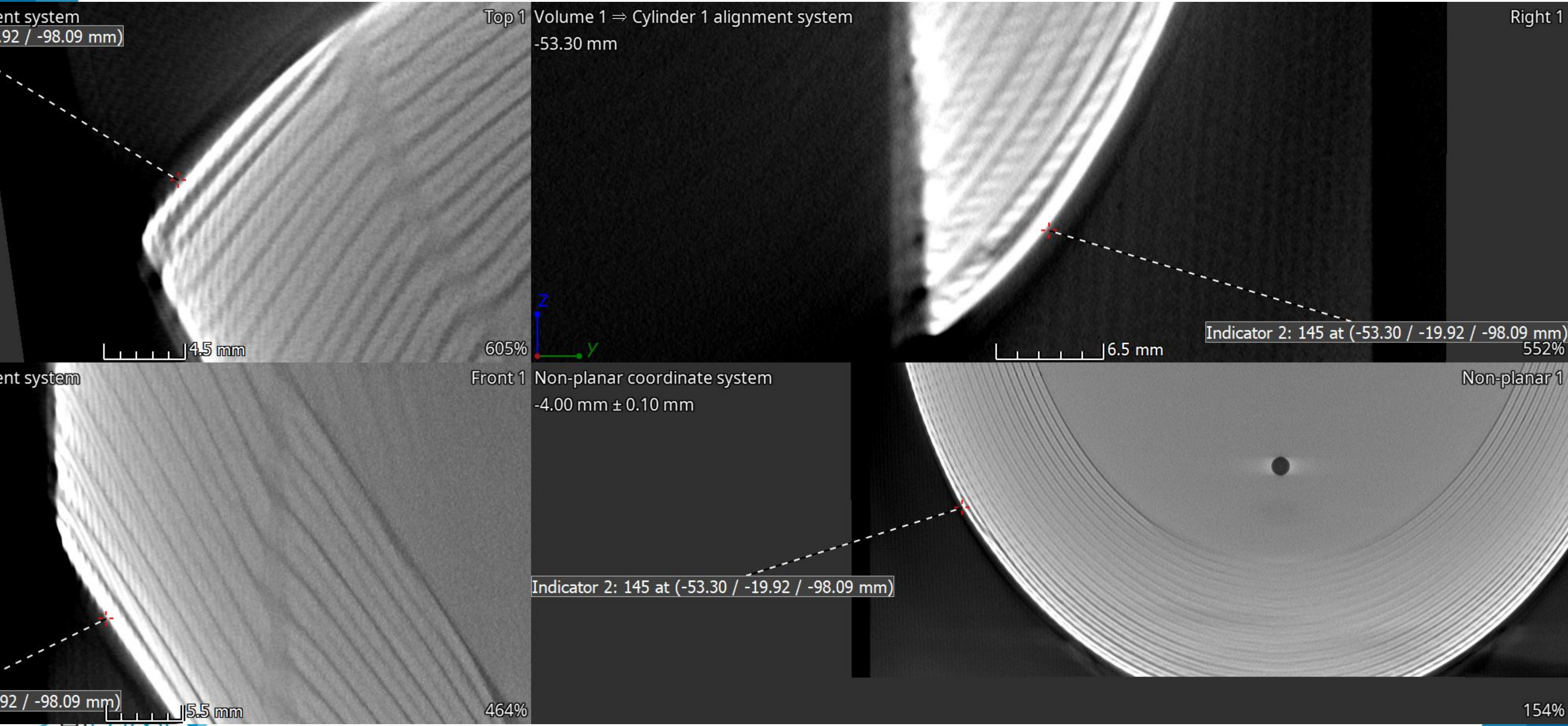
CT – CERN - GE-02
y – view



CT – CERN - GE-02


nment system
Indicator 1: 143 at (38.65 / -1.26 / -69.96 mm)
Top 1
7.5 mm
350%
Non-planar coordinate system
-22.23 mm ± 0.10 mm
Indicator 1: 143 a
nment system
Indicator 1: 143 at (38.65 / -1.26 / -69.96 mm)
Right 1
9.5 mm
276%
Volume 1 ⇒ Cylinder 1 alignment system
Indicator 1: 143 at (38.65 / -1.26 / -6
Z
y

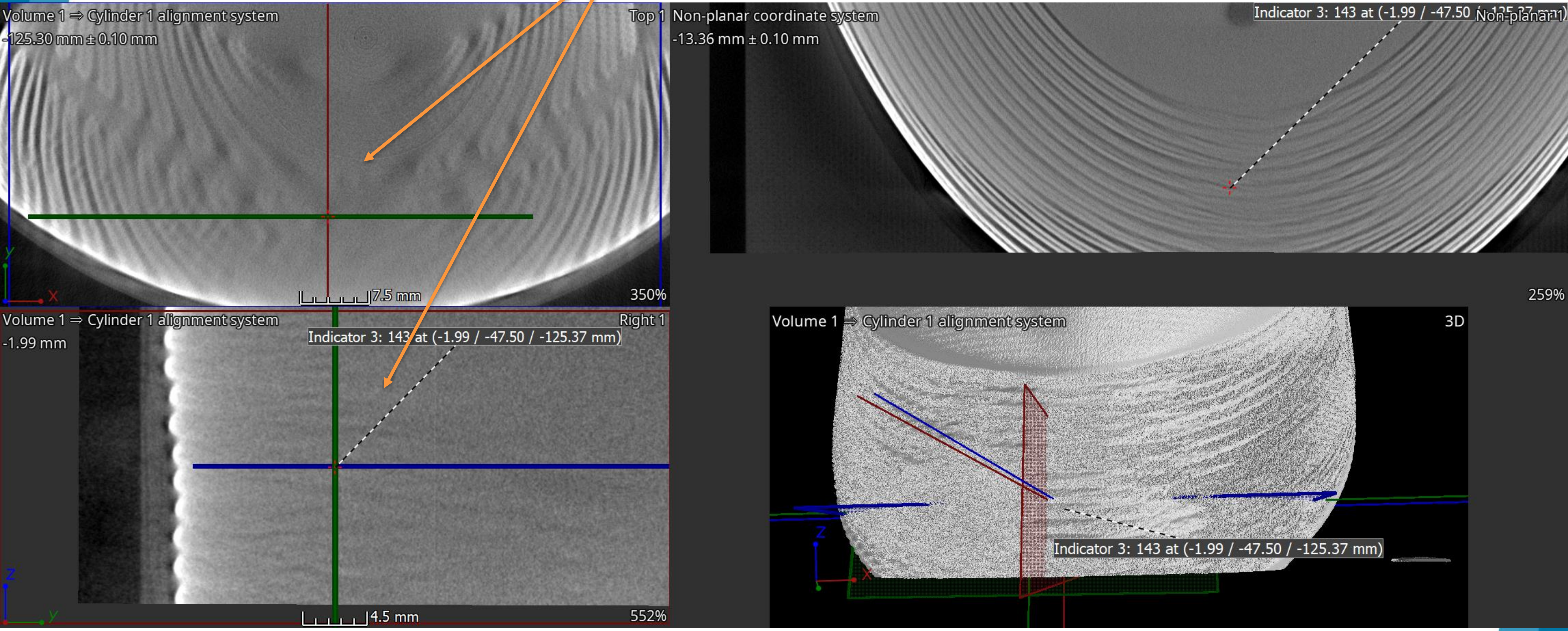
CT – CERN – GE-02



HL-LHC PROJECT

CT – CERN – GE - 02

The volume is too dense for X-rays



CT – CERN – GE-02
Summary

General views on the full coil can be provided, in particular coiling of Rutherford cables (bulging effect), but special and fine features are barely visible.

Therefore, more powerful X-ray source has to be used.

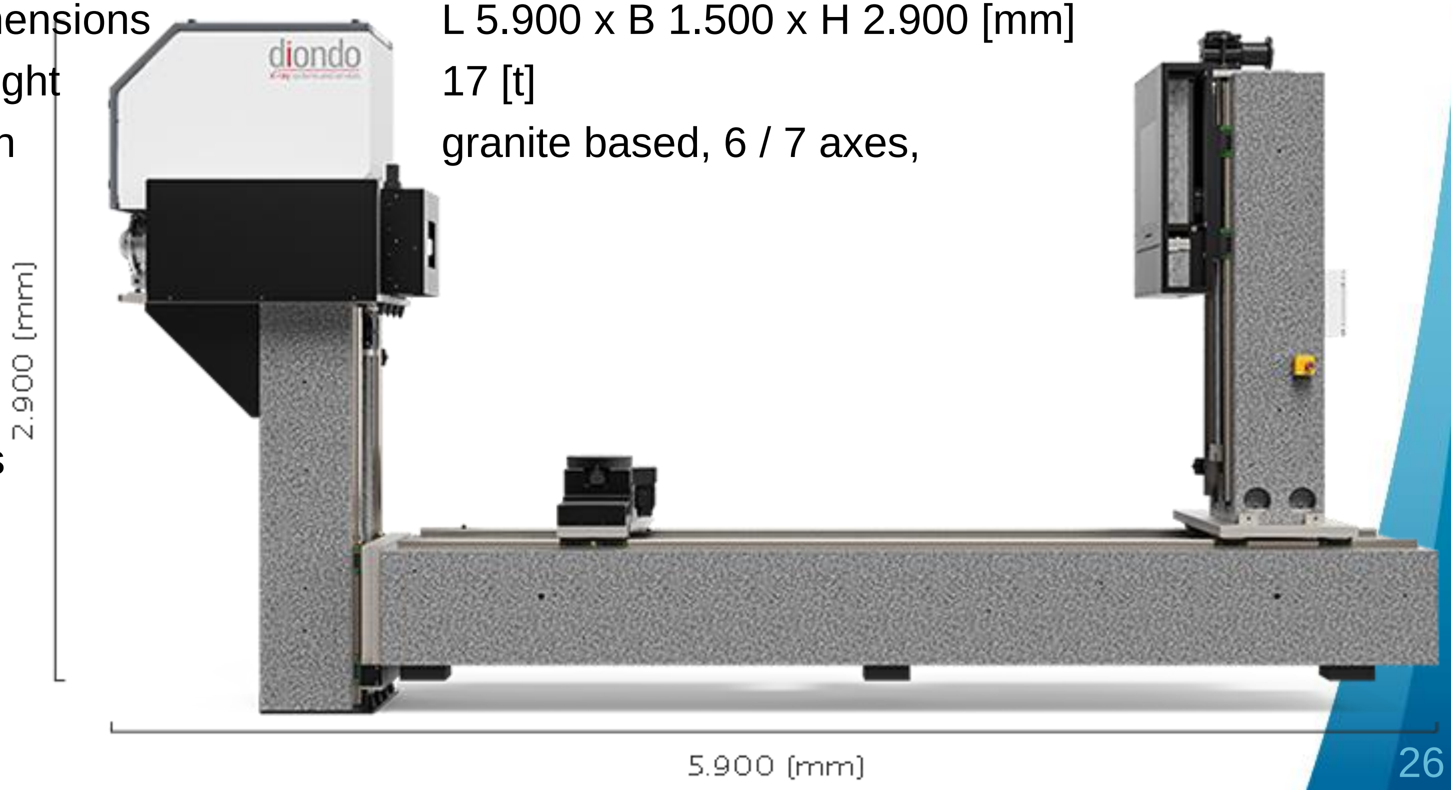
6 MeV LINAC tomography - TEC-Eurolab Modena/IT

Feasibility test:
Acquisition time: 45 minutes
Resolution: 130 µm
Spot size: 2 mm
Energy: 6 MeV

X-Ray Source	3 / 6 / 9 [MeV]
Detector	Flat Panel Detector 3.000 x 3.000 px, 140 [µm]
Scan Volume, maximum	Ø 700 x 1000 H [mm]
Focus-Detector-Distance	4000 [mm]
Sample Weight	200 [kg]
System Dimensions	L 5.900 x B 1.500 x H 2.900 [mm]
System Weight	17 [t]
Manipulation	granite based, 6 / 7 axes,

Made to accommodate 1/3/6 or 9 MeV linear accelerator x-ray sources but it can be used in a 450 Kvp bunker

The system is designed to penetrate dense bulky objects such as engine blocks, valves, truck tires and large turban blades.



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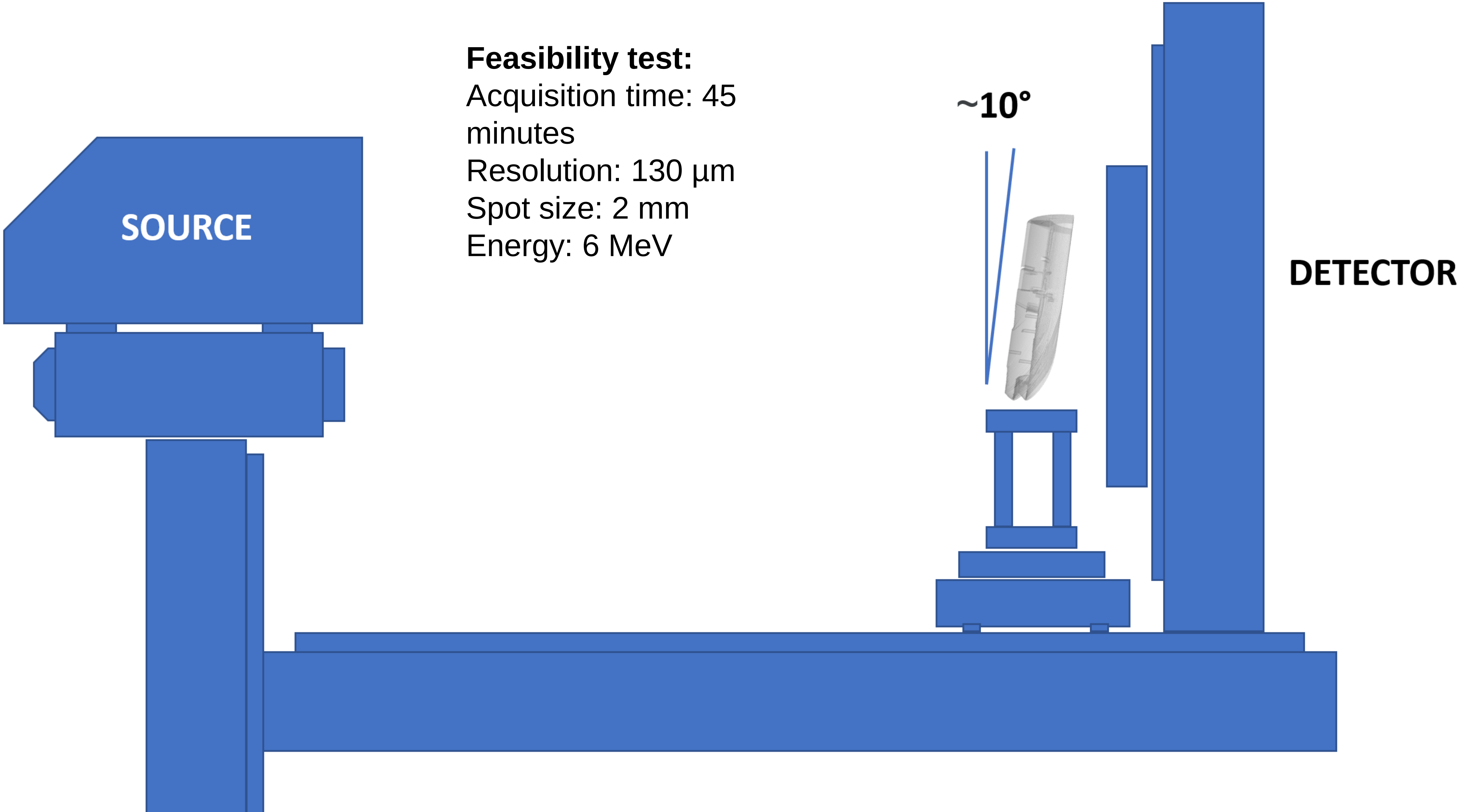
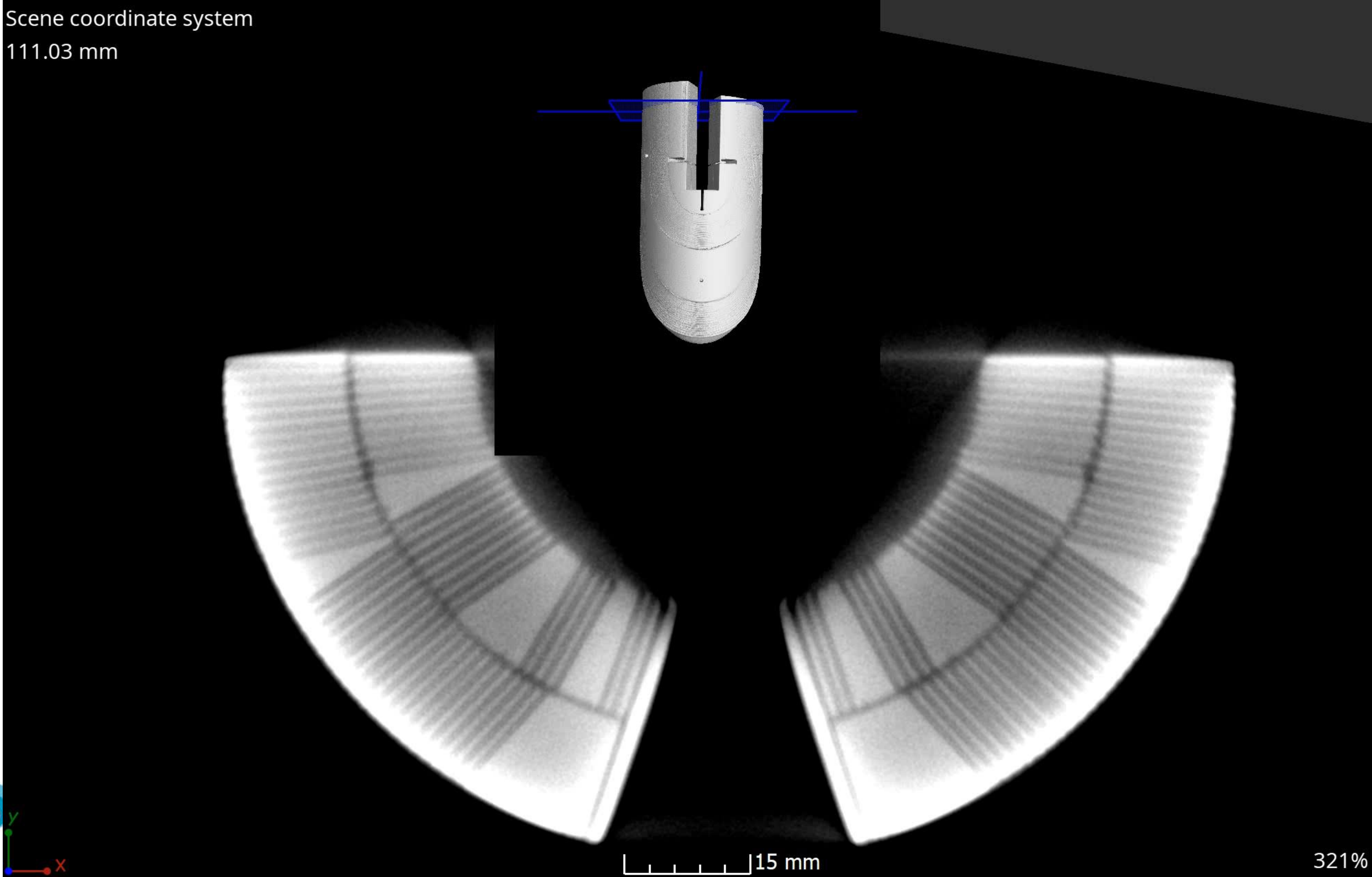
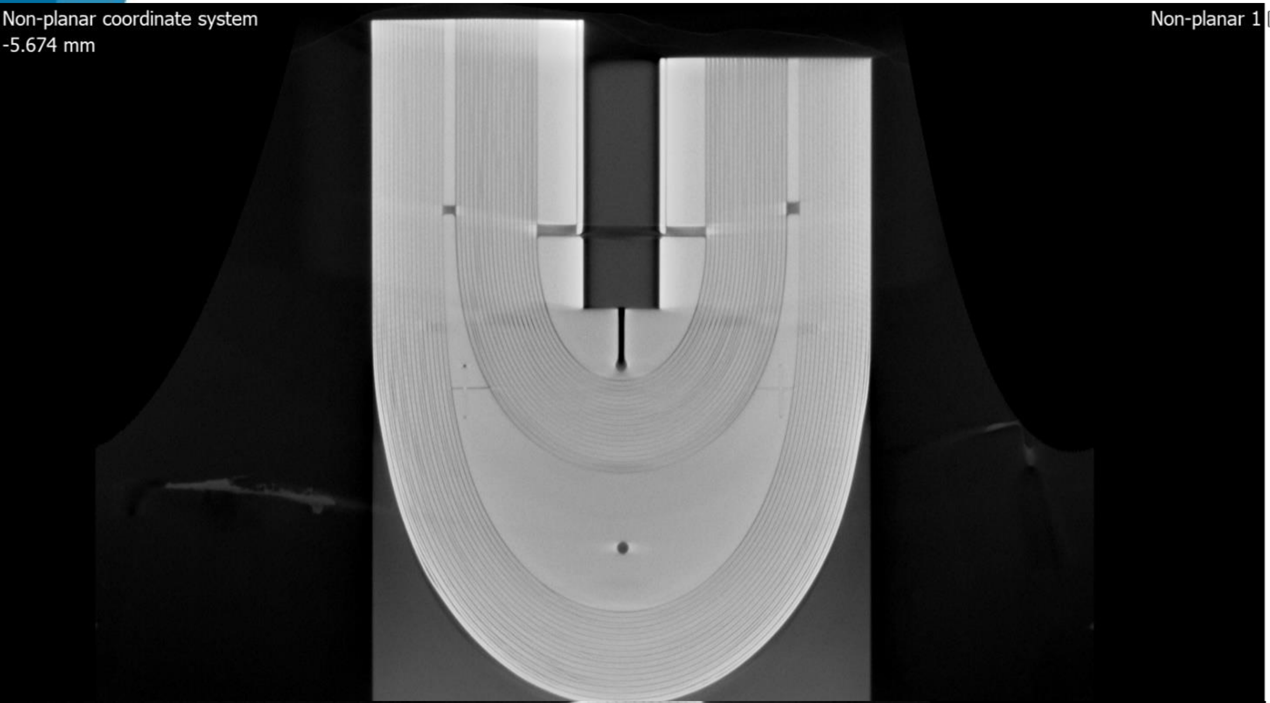


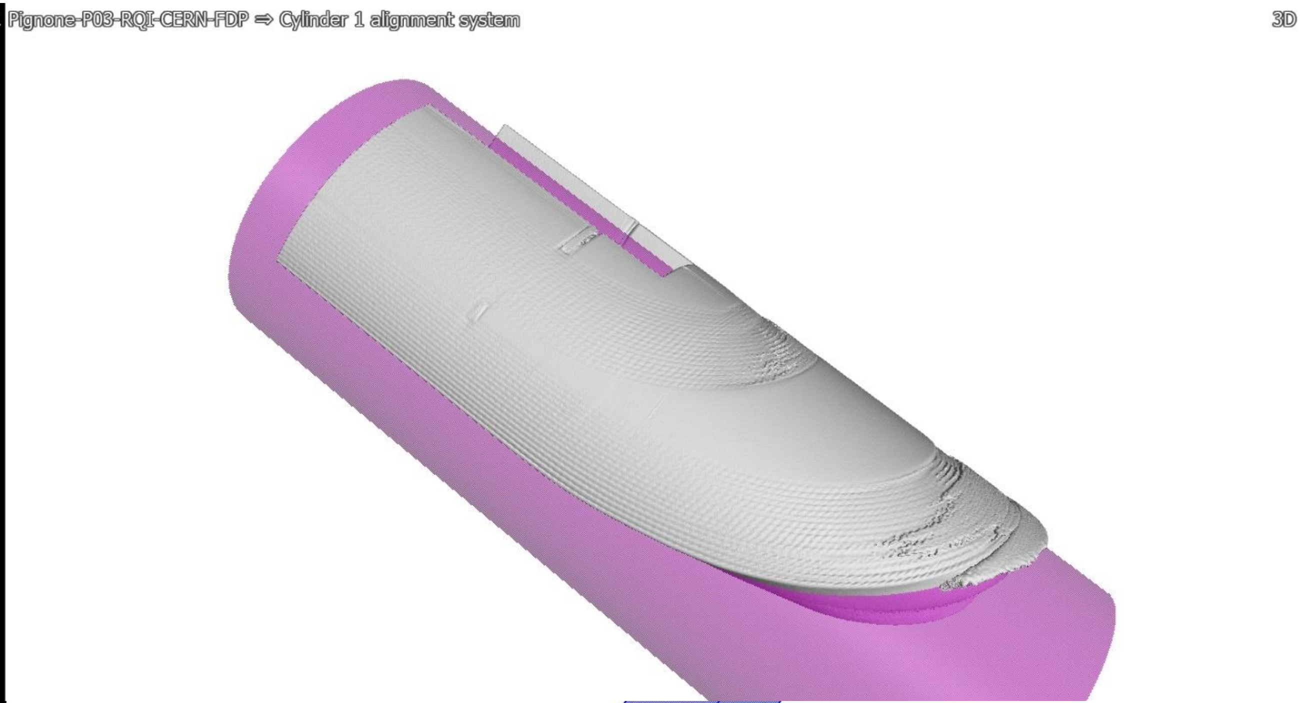
CT –
GE - 02
6 MeV

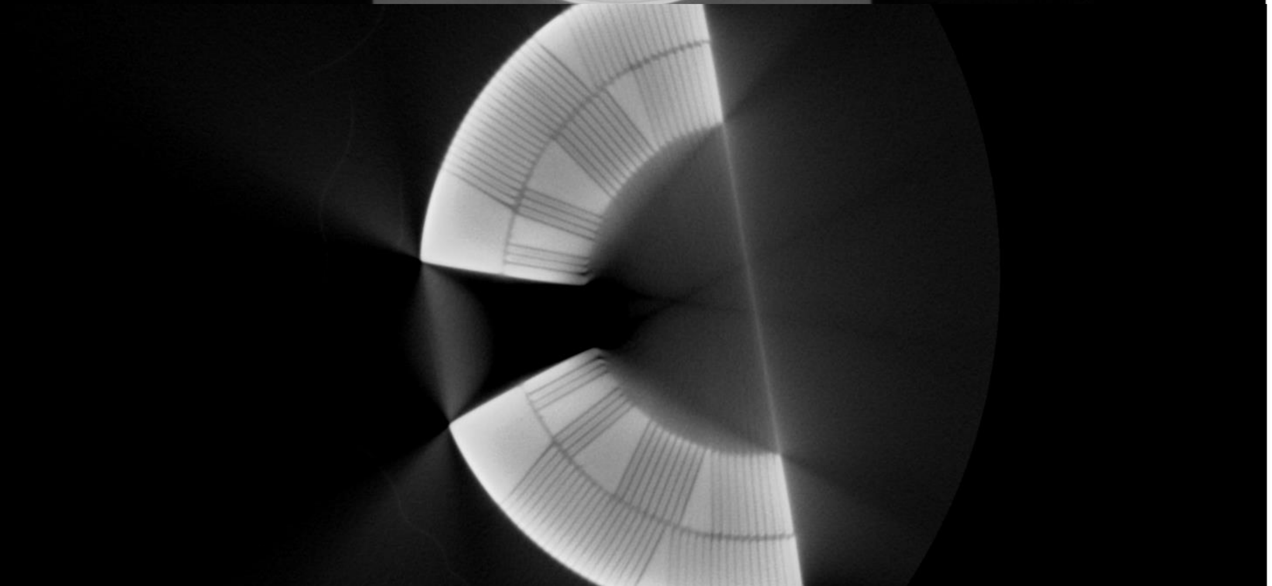
CT – GE-02 6 MeV z – view

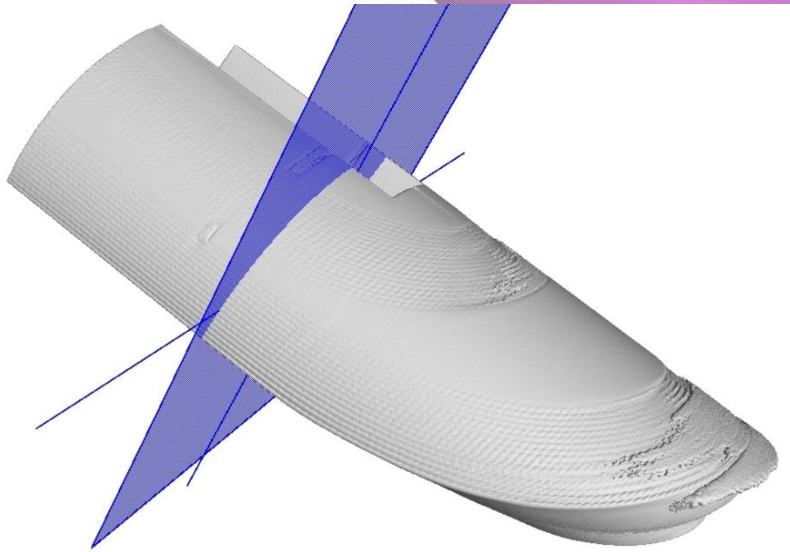


CT – GE-02 – 6 MeV – 130 µm

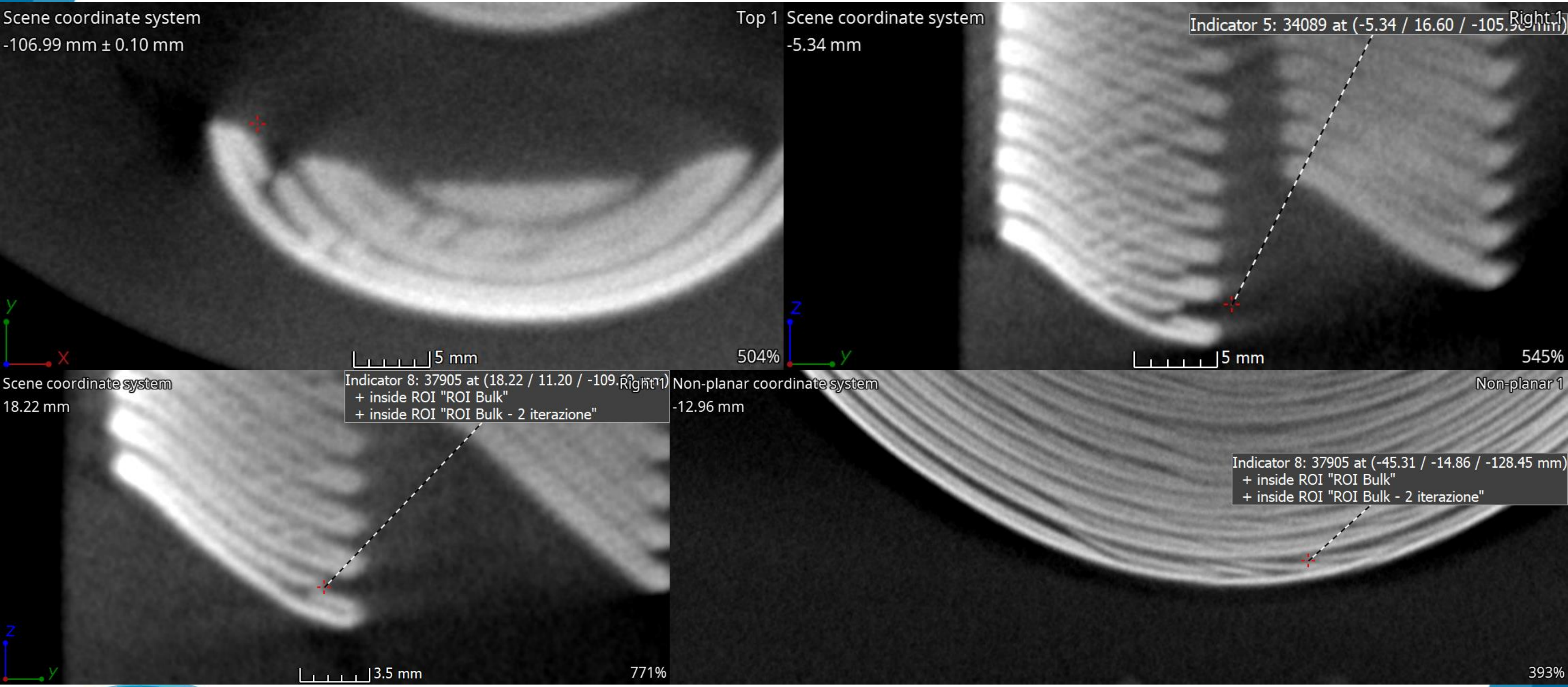




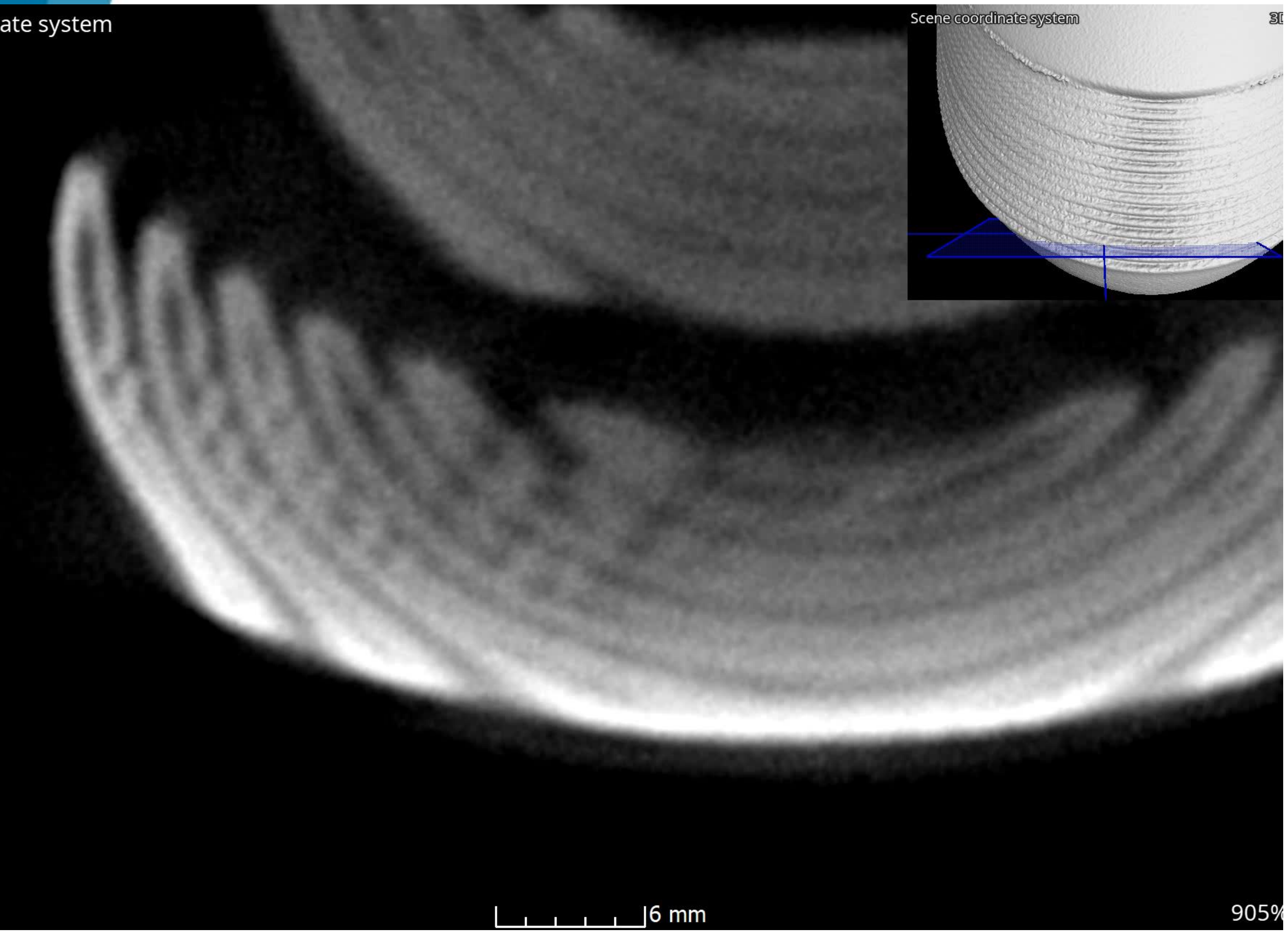


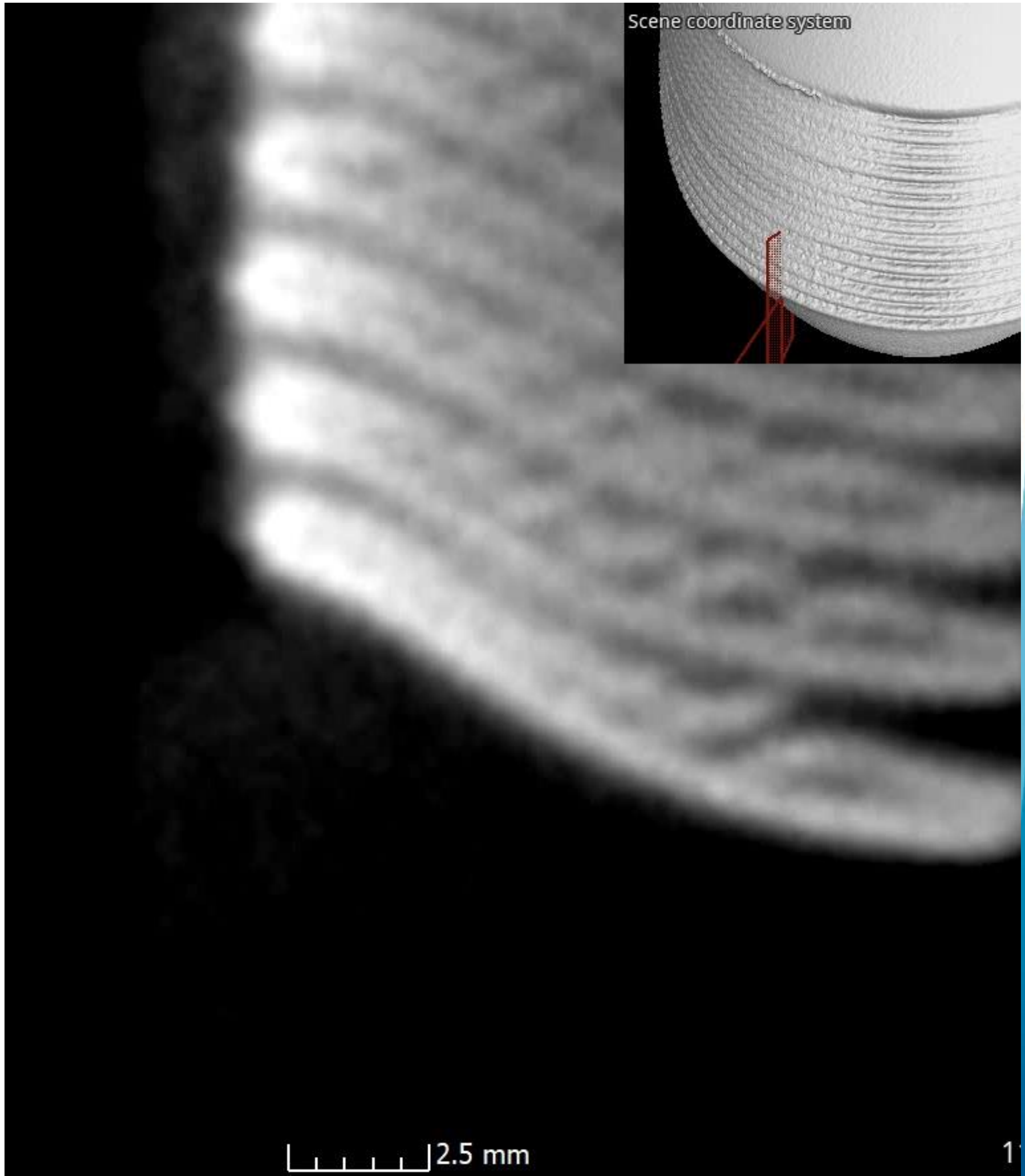


CT – GE-02 – 6 MeV – 130 µm

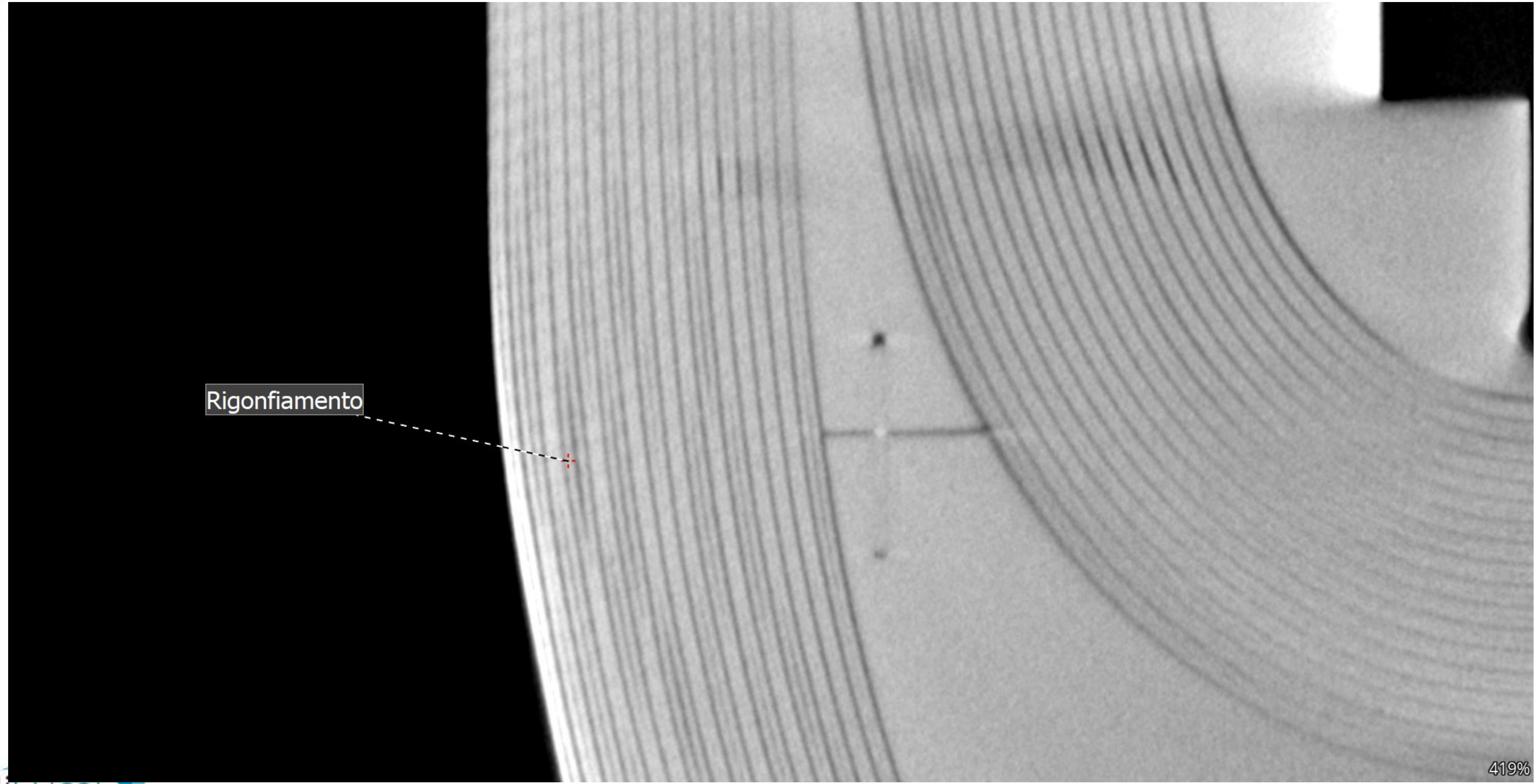


CT – GE-02 – 6 MeV – 130 µm



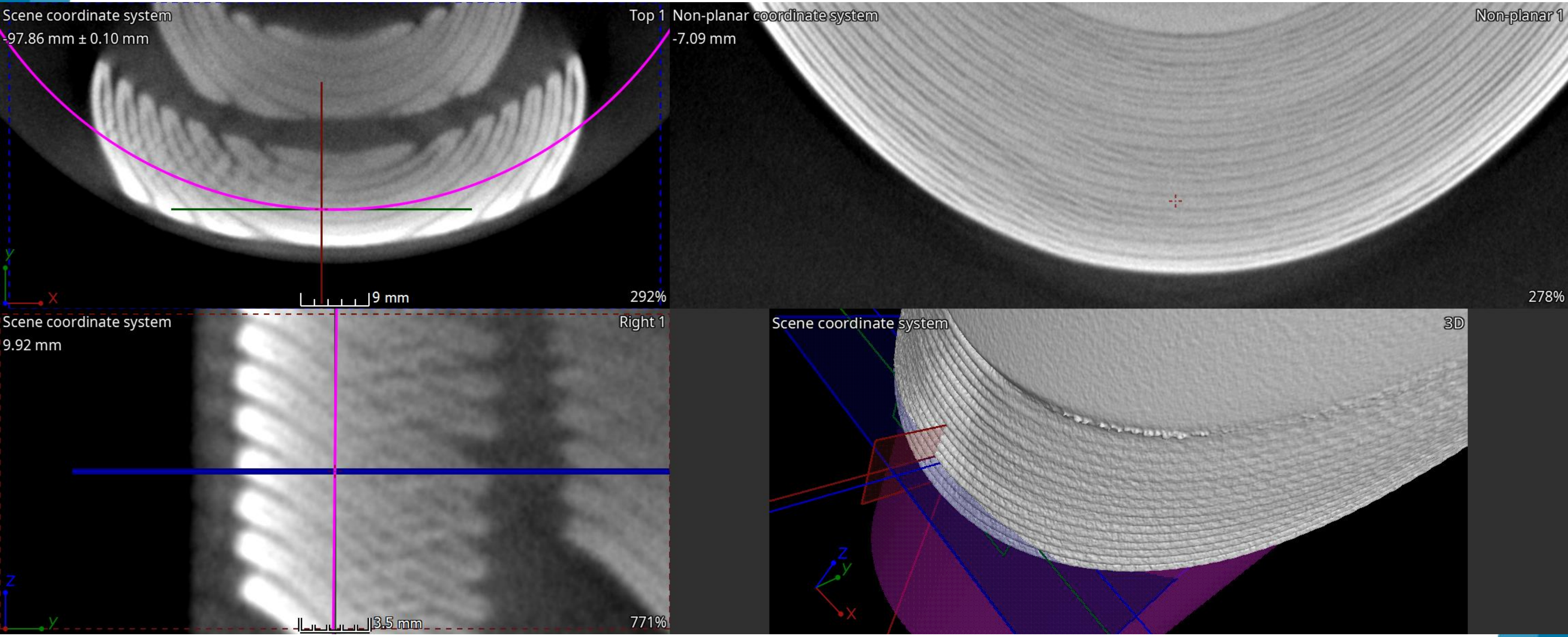


CT – GE-02 – 6 MeV – 130 μm



HiLumi HL-LHC PROJECT

CT – GE-02 – 6 MeV – 130 µm



HiLumi HL-LHC PROJECT

Summary: events and ROI

Identified events:

- Bulging
- Pop-out (or discontinuity?) of individual wires
- Geometrical events

With optimization of CT acquisition procedure it should be possible to visualize the full coil sample and analyze overall geometry as well as bulged and popped out/broken wires.

More subtle structures cannot be seen. Therefore, smaller volumes of interest (~1 cm^3 cubes) have to be cut in order to use a proper CT equipment (synchrotron facilities) and visualize internal structure of wires.

HiLumi HL-LHC PROJECT

X-Ray CT - Perspectives

6 MeV LINAC tomography at TEC-Eurolab Modena/IT

There are two ways to optimize the results:

1. Better resolution but smaller penetration potential using 3 MeV beam with filtering.
2. Special acquisition mode with additional corrections for better quality of CT data, it makes however the acquisition time 10 times longer and the resolution is not increased.

In both cases it might be necessary to focus on a specific volume of the sample (half of the coil for instance)

Other LINAC facilities being discussed (up to 9 MeV)

Empa
Materials Science and Technology

Fraunhofer
IIS

Additional techniques explored, possibilities and limitations – small samples

ESRF – ID19 synchrotron CT (~ 100 kV)

- high resolution
- more sensitive to interfaces, edges and cracks
- suitable only to small samples – less than 1 cm^3
- 5500 EUR for three scans

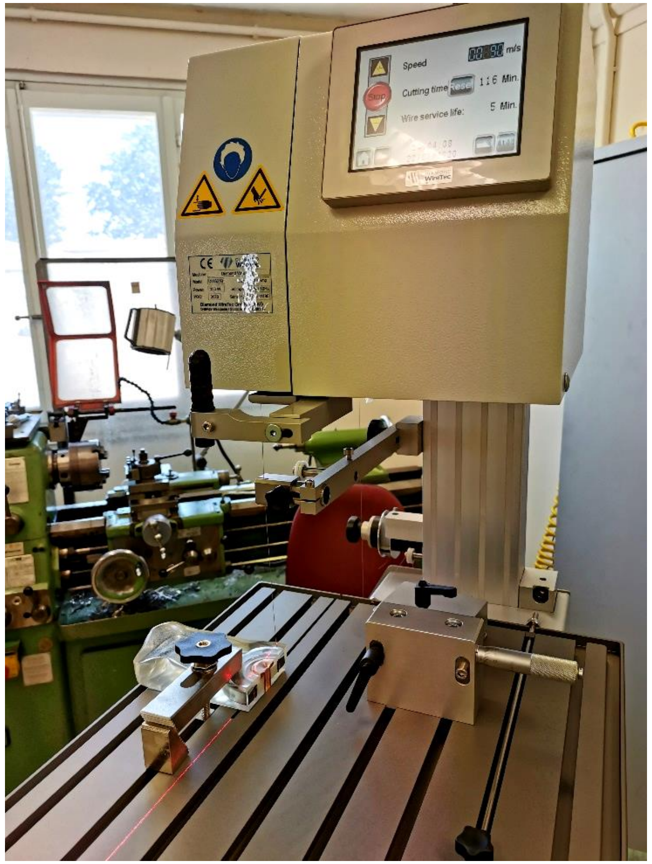
PSI – neutron CT – ICON

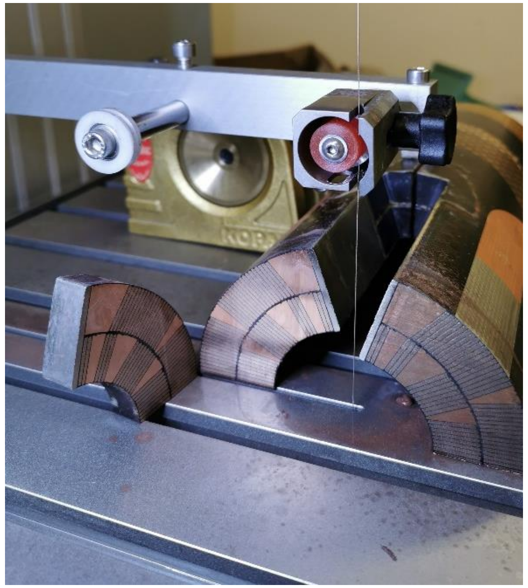
- Metals are slightly attenuating and epoxy is very attenuating (presence of H).
- Good contrasts: epoxy/metal, epoxy/void.
- Poor contrasts: metal1/metal2, metal/void.
- Samples remain active for some days-weeks depending on composition.
- Not applicable to the whole coil section or to half coil section
- open slots over fall.
- one cm-range sample per day.
- 8 kCHF/day - possible discount if publications.
- feasibility test for free

HiLumi HL-LHC PROJECT

Additional items: cutting and metallography

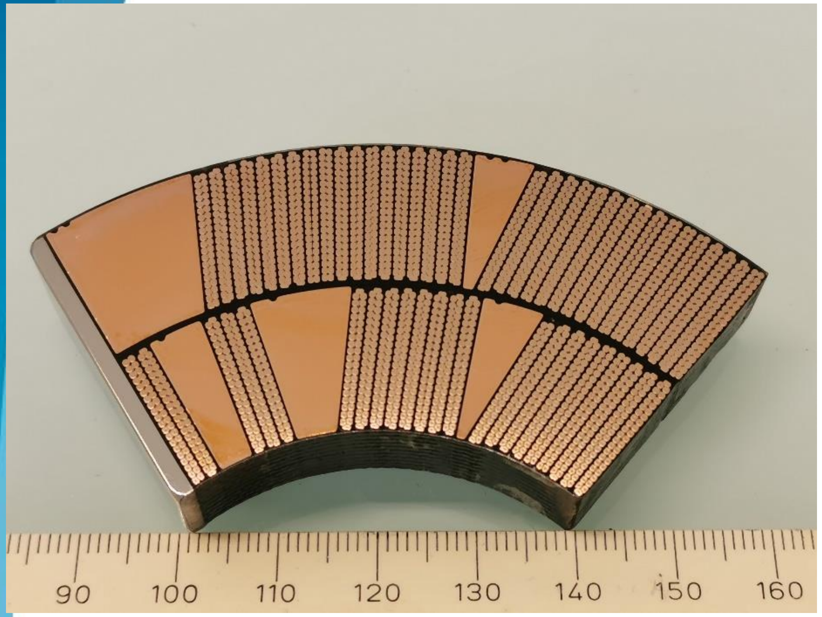
Diamond WireTec GmbH & Co. KG DWS.250 wire saw, just acquired by EN-MME-MM

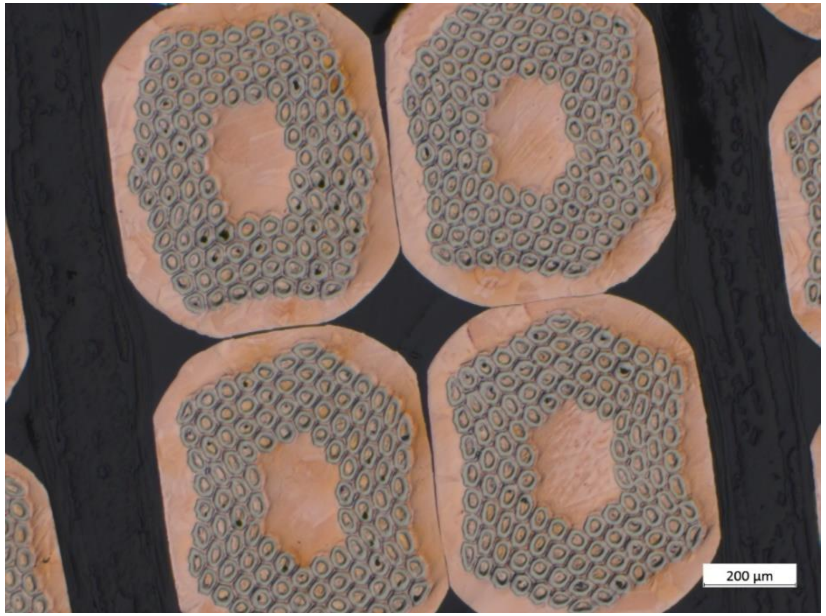


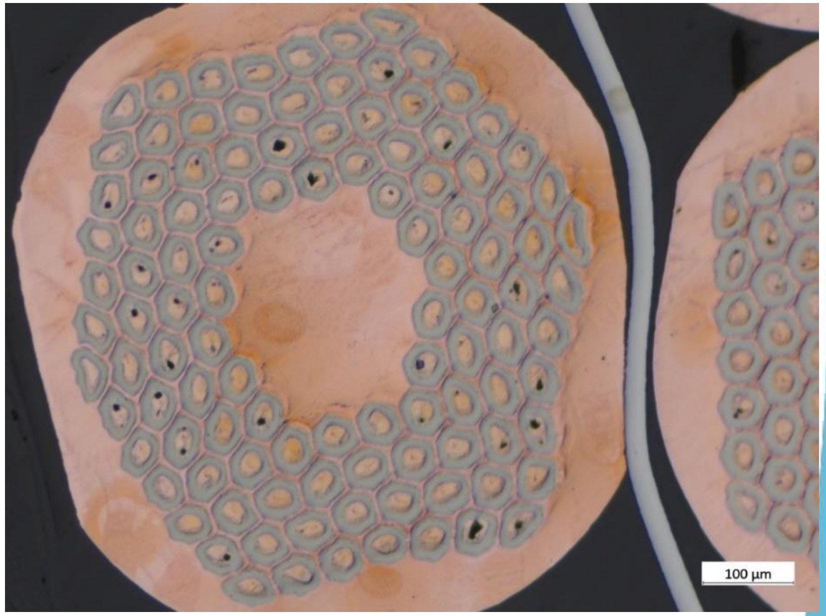


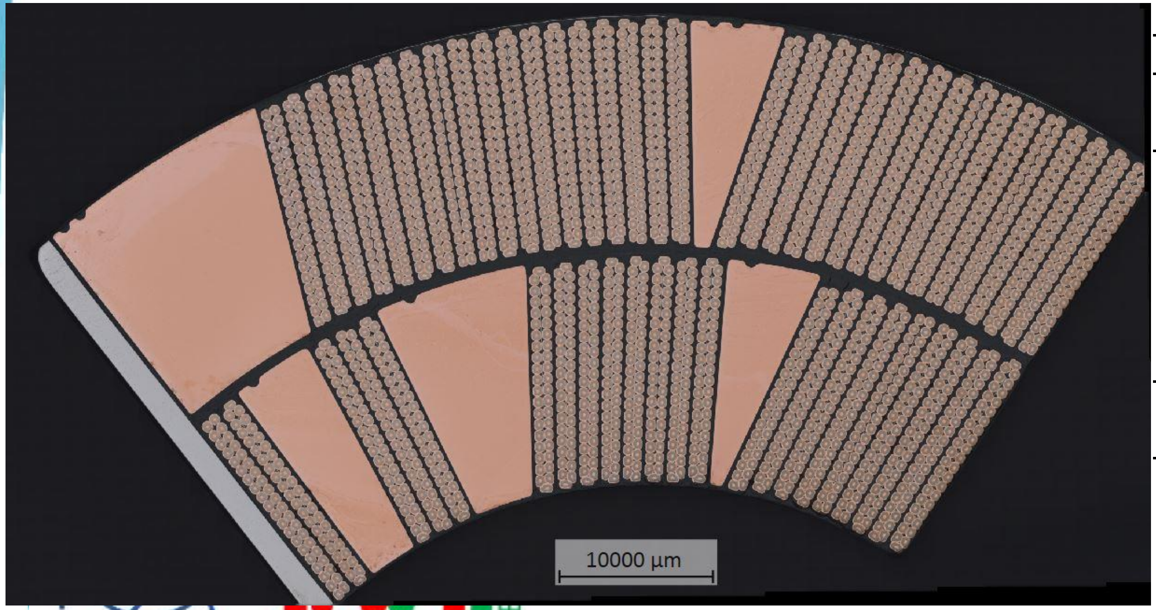
- Installation, setting up and laser alignment on the new diamond Diamond WireTec. Commissioning was carried out through difficult “multimaterial” cutting tests on brazed RF feedthroughs (Al_2O_3-Ti6Al4V-Cu) that revealed excellent surface state after cut and no induced artifacts.
- Cutting as agreed of an extremity slice of the undamaged Coil’s Head Non-connection side GE-02.

Additional items: cutting and metallography

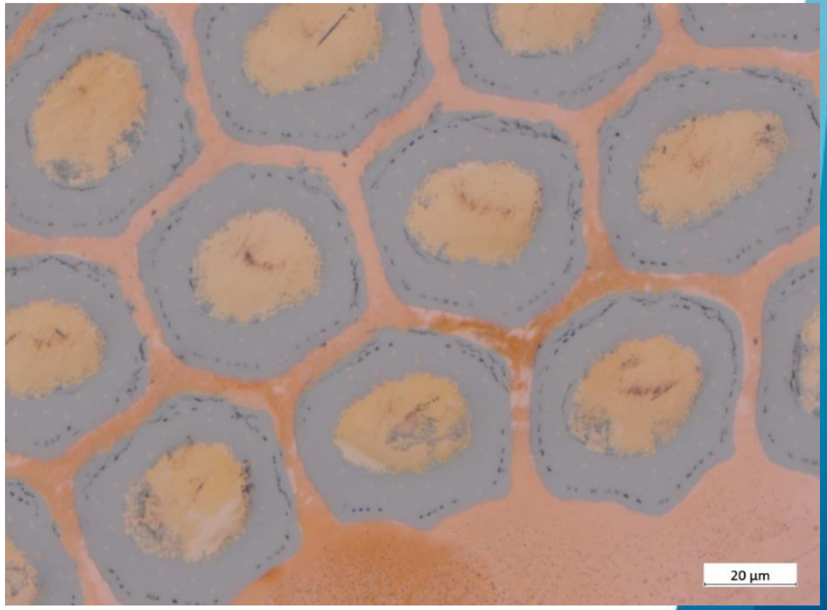








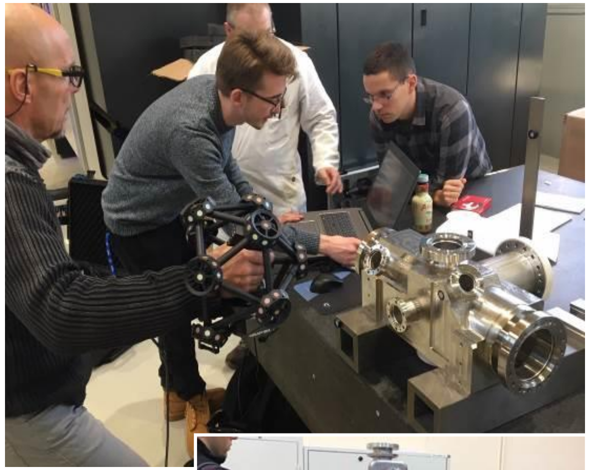
- Light grinding (600 grit)
- Polishing-etching down to 0.04 µm (colloidal silica) with very light force
- Procedure already well established in the past, demonstrated as not inducing artifacts into non-damaged filaments (see https://edms.cern.ch/document/2363700/1)
- Observable as polished: discoloration/staining very limited
- Further exploitable for FIB-SEM, including by the new Extreme EDS/SEM facility for non-conductive materials

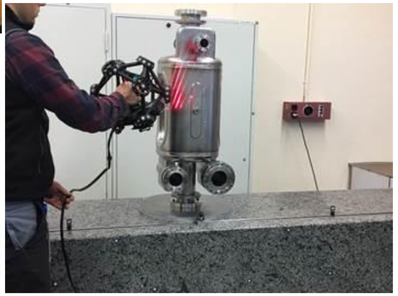


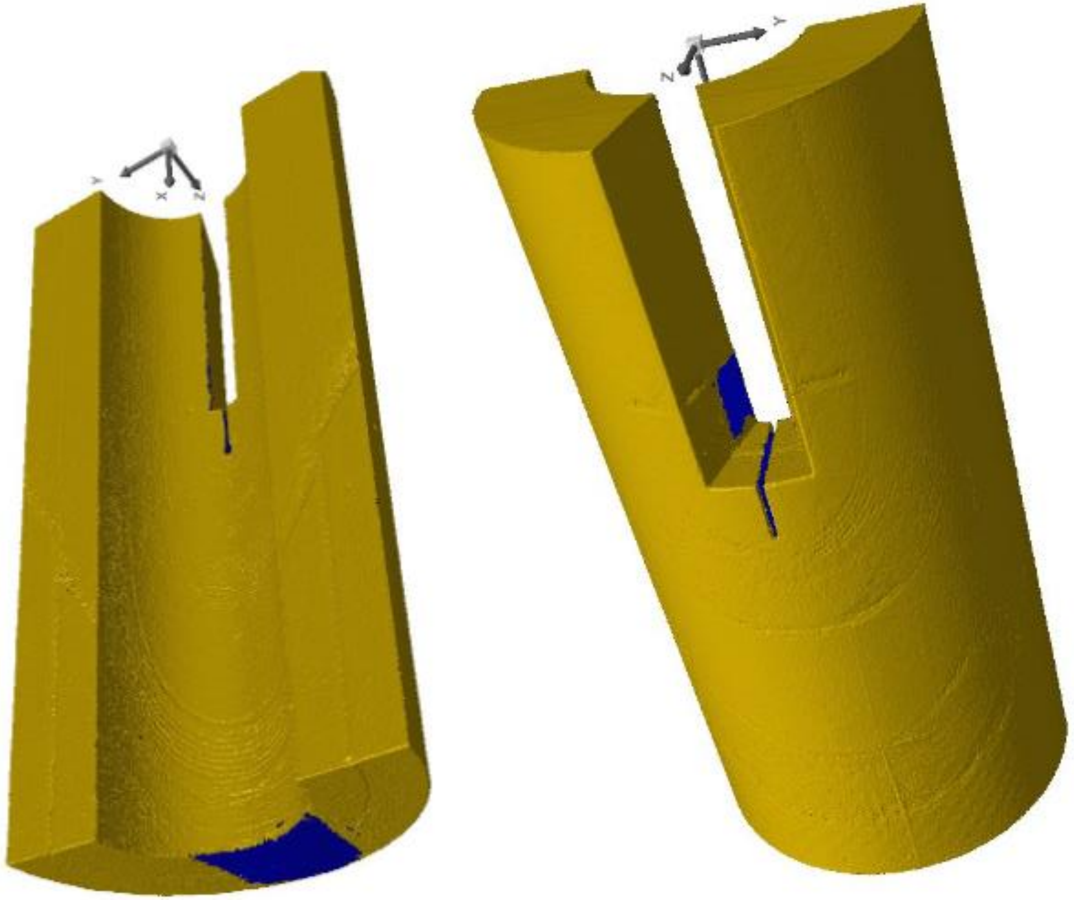
Additional items: dimensional metrology of the outer “envelope”

- MetraSCAN7503D Scanning System portable CMM
- Based on 15 laser crosses
- Acquisition of data at a frequency of 480000 measures/s
- Supplementary line improving accessibility of cavities
- Volumetric precision up to 0,064 mm in a measuring volume up to 9,1 m^3 (and 0,078 mm in 16,6 m^3)
- Metrologically accredited technique (ISO 17025, VDI/VDE 2634-3)

Measured and reconstructed envelope, EDMS 2396311

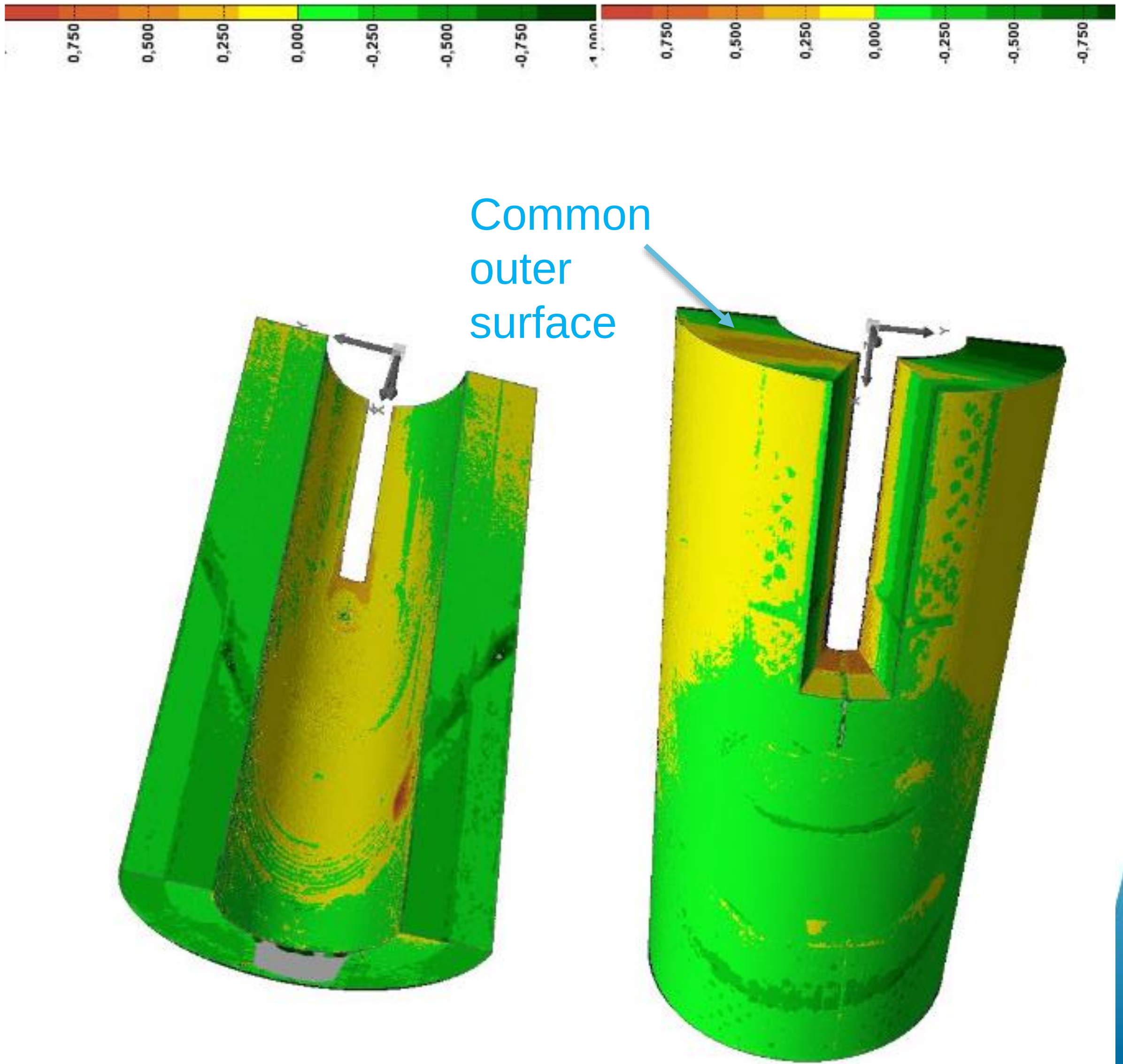




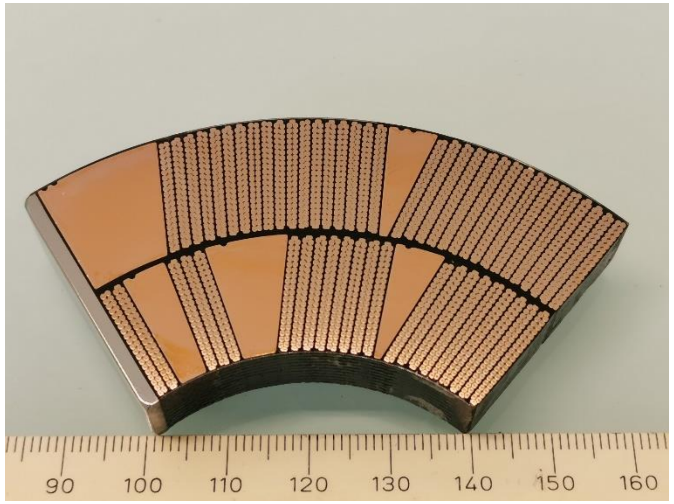


Additional items: dimensional metrology of the outer “envelope”

- Comparison with a reference envelope, while waiting for reference drawings (mail to F. Savary in date Fri 07-Aug-20 10:55 AM
- Extracted slice also waiting for dimensional metrology (optical CMM, Zeiss O-Inspect), waiting for reference drawings as above
- It will be eventually possible to refer the two measures to the same coordinate system
- Non-destructive volume metrology, see CT discussion



Common outer surface



Next steps forward

On undamaged Coil's Head Non-connection side GE-02

- Continue CT LINAC investigations
- Identify zone of interest (ZOI) and proceed with additional local CT
- Explore extent of feasibility of CT metrology based on available or eventually obtained results
- Proceed downstream with metallographic cuts in the ZOIs

- Provide drawings (action Frédéric)
- Continue with CMM dimensional metrology of extracted slice(s)

On twin sample GE-CO2, once available

- Same methodology as above, with emphasis on downstream metallographic investigation, extended to FIB-SEM and local high resolution NDT techniques (applicable on small specimens, see above) to describe the nature of the damage and identify root causes

Retrieving information from the companies for an estimation of budget and schedule including external testing