

# X-ray tomography on CICC conductors and joints

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# TS 2019

Deliverable(s) of this task:

D01 Outcomes of CT examination of CICC conductors and joints samples and associated analyses:

- Structural integrity characterization
- Local void statistics
- Strand trajectory reconstruction
- Development of an XCT protocol for CICC joints

Annual report on XCT analysis of CICC cables and joints.

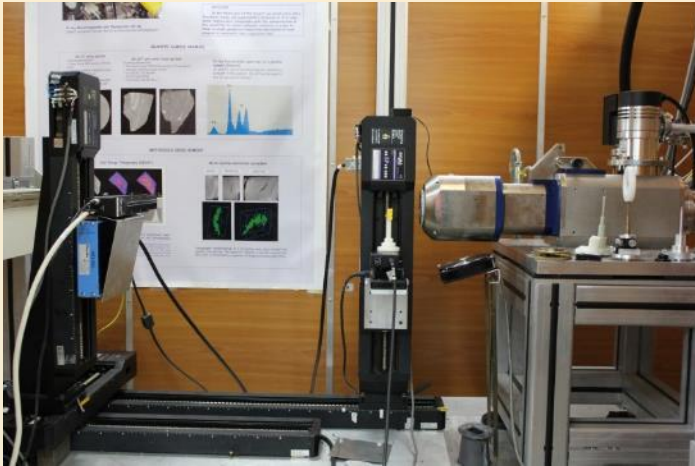
Real costs (excluding overheads) Total 0.1+0.3 ppy & 5 kEuro HW

# OUTLINE

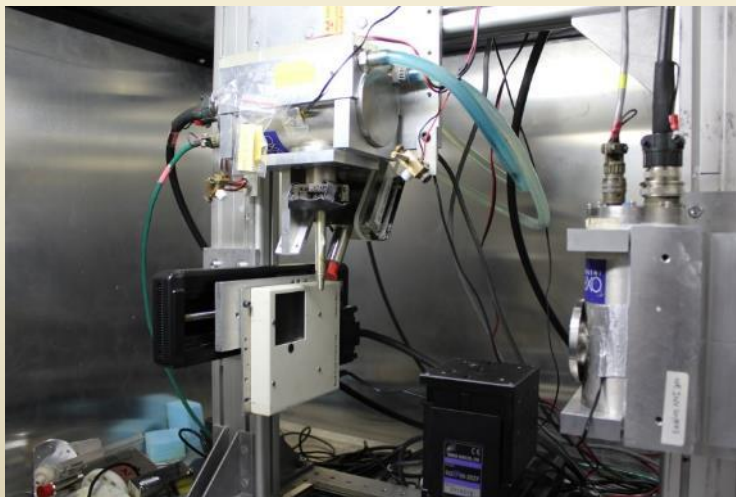
- Application of X-ray tomography on a HTS CICC prototype
  - Scanning configuration optimization
  - Room vs. liquid nitrogen comparison
  - Reconstruction of a relevant fragment of HTS cable
  - Quantitative analysis of the HTS cable components
- Tomography analysis of microstructural integrity of joints of HTS tapes
- Micro-tomography vs micro-laminography scanning configurations
- Additional work: refining of high resolution tomography on advanced SC strands

# Center for Advanced X-ray Imaging

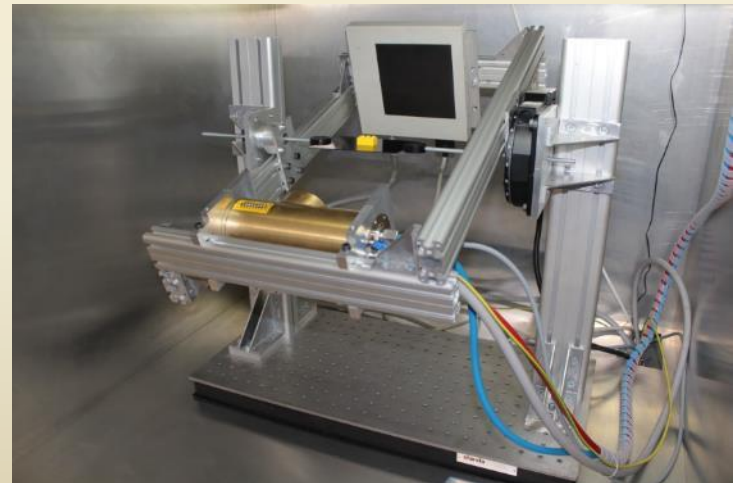
## Sub-micron resolution tomograph



## Industrial tomograph (high energy)

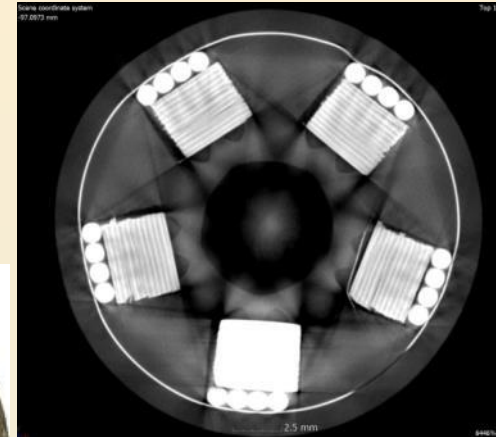
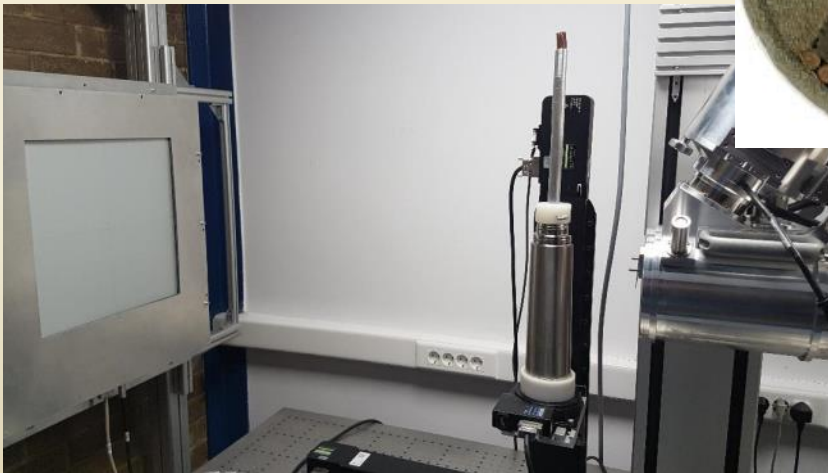


## 3D tomography & composition mapping - material science

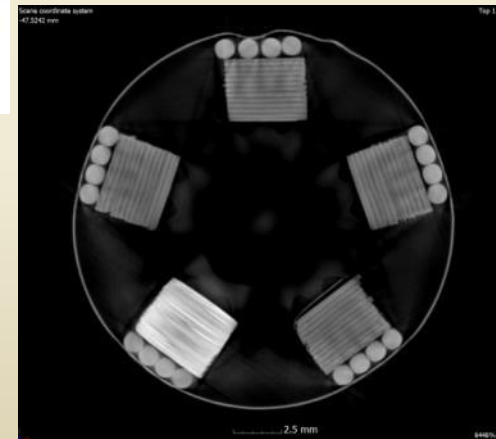


## Gantry tomograph: bio-applications

# X-ray tomography analysis of an ENEA HTS prototype



CT section rough image



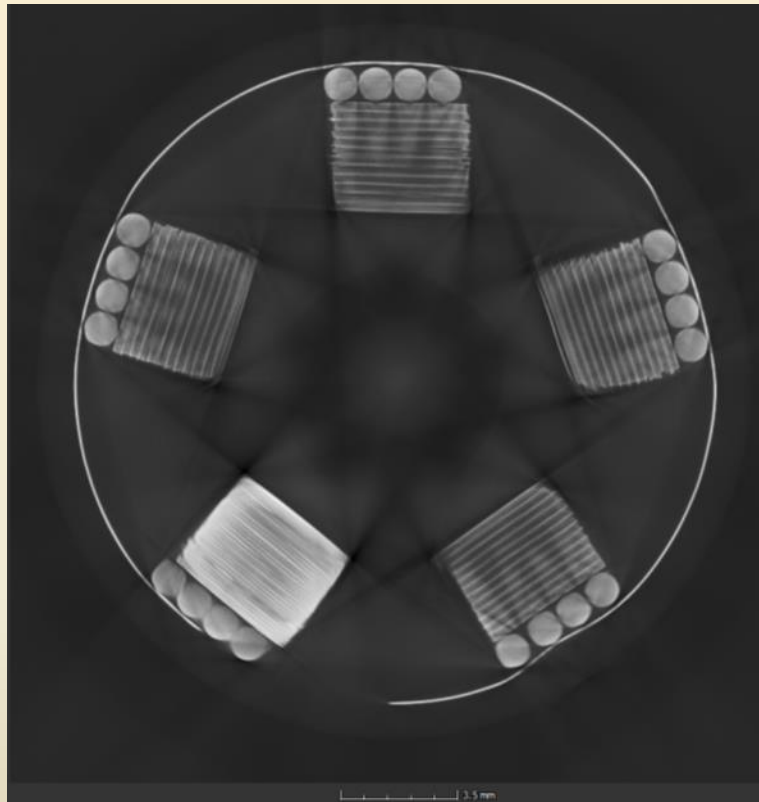
CT section filtered image

CT on HTS CICC at RT & LN

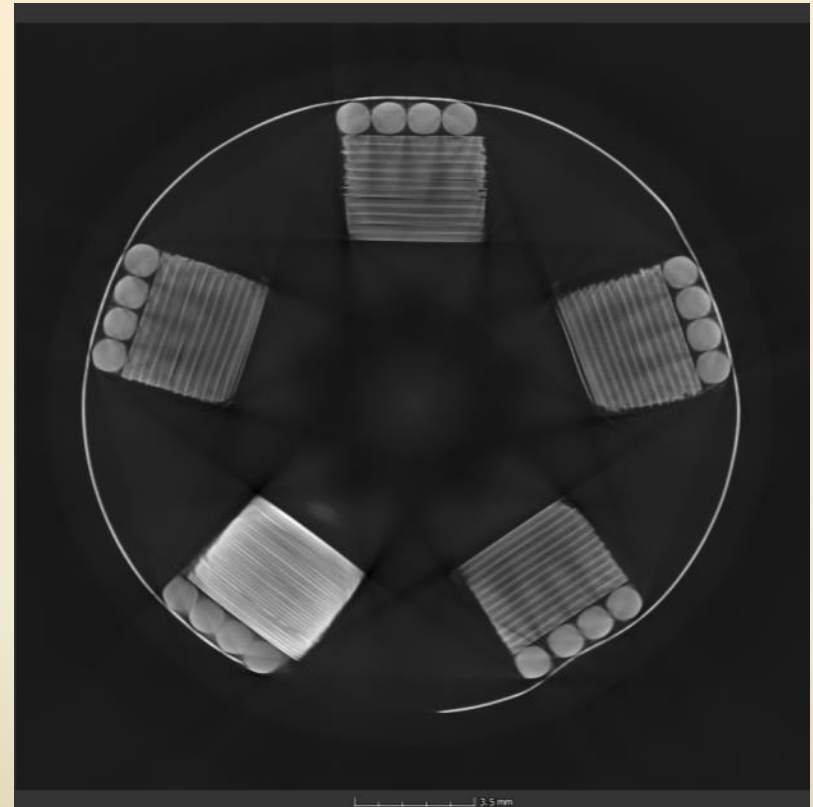
# ENEA HTS DEMO Prototype

180kV, 10 microns/voxel

Room temperature

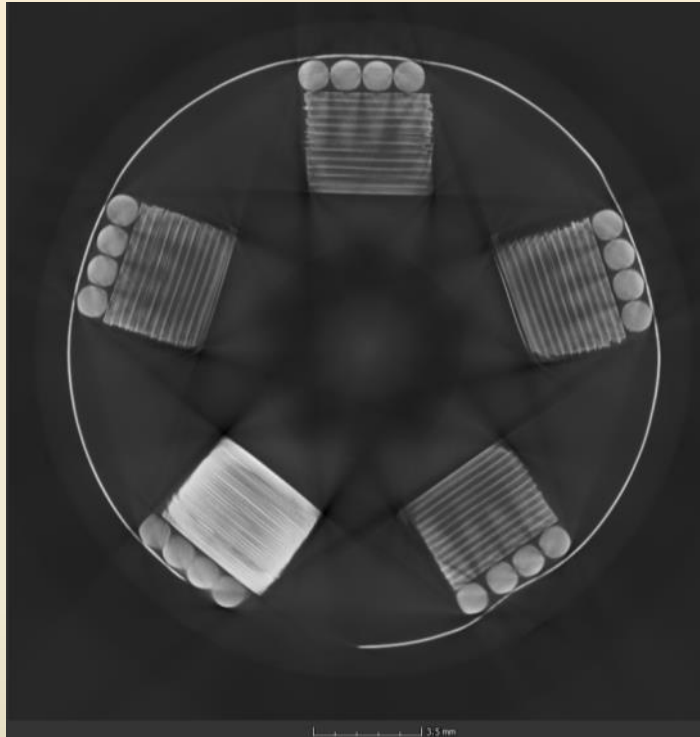


Liquid nitrogen

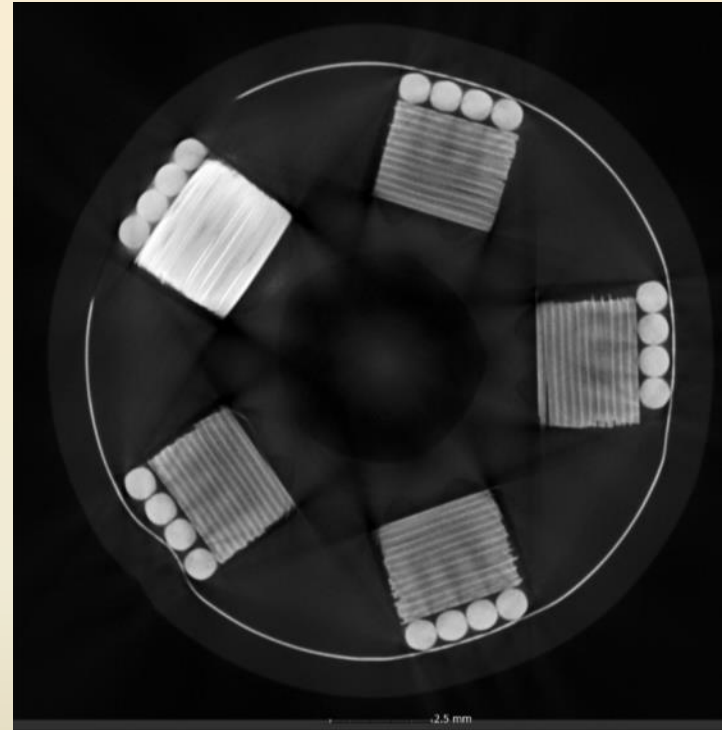


# XCT cross-sections 180 kV vs 250 kV

180kV



250 kV



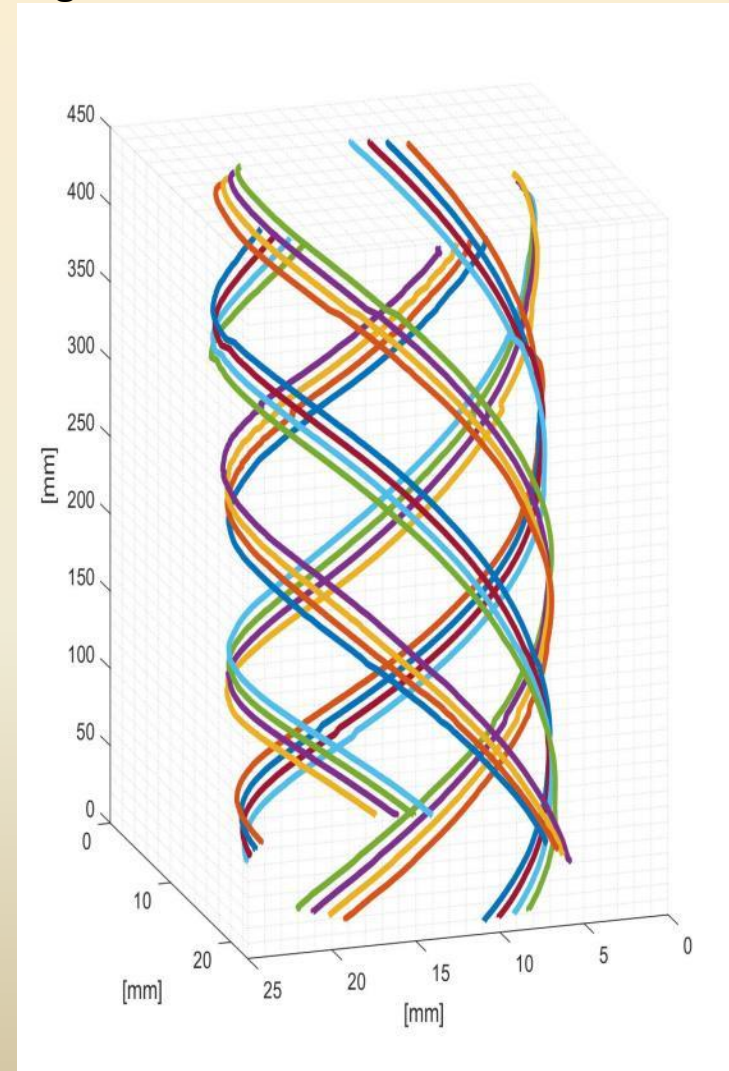
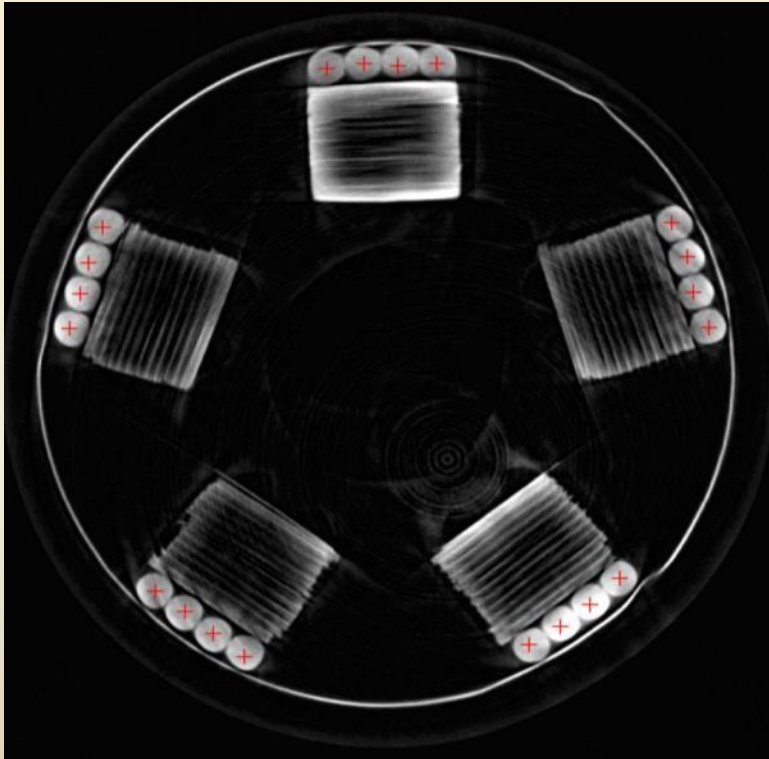
High penetration power XCT system is better suited for HTS CICCs tomography analysis

**2D & 3D movies of HTS CICC tomography images**

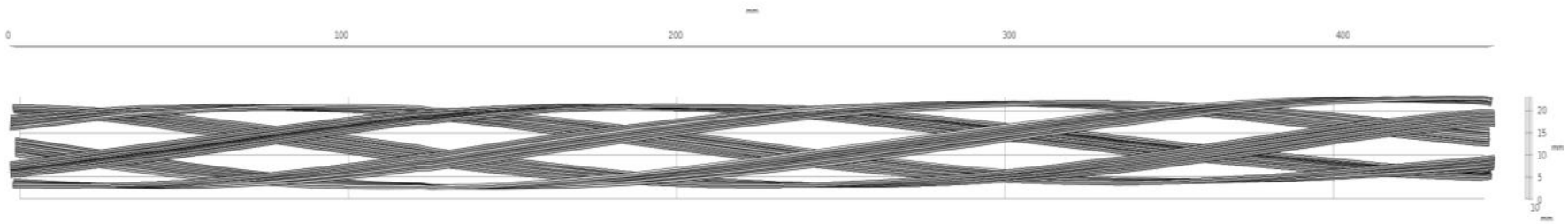


## Cu wires trajectory reconstruction

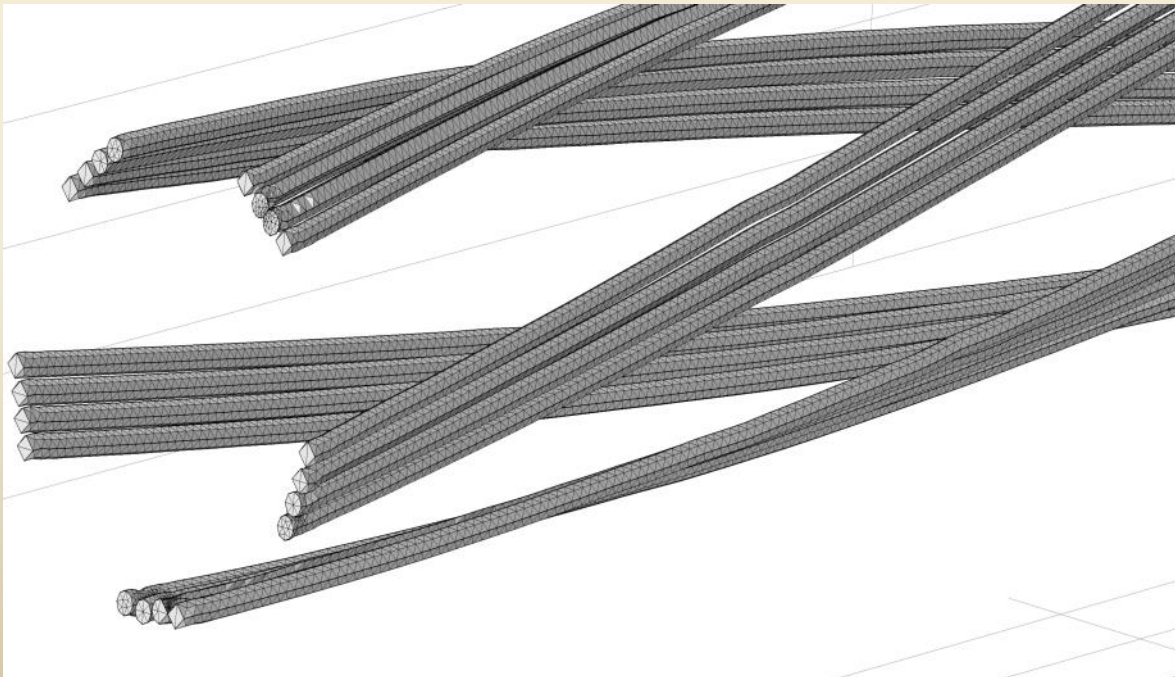
- It is used Circle Hough Transform (CHT) - slicewise
- After connecting all the centroids of adjacent slices, the resulted trajectory is smoothed using Savitzky-Golay algorithm



# Image processing towards finite element discretization for Multiphysics simulations.



Cu wires trajectory reconstruction on a ~400 mm section

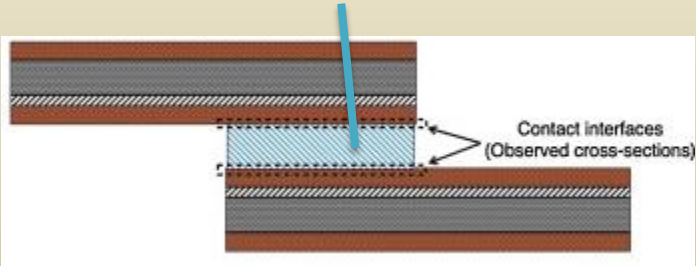
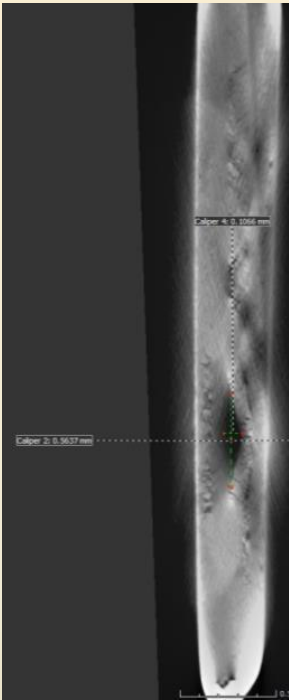
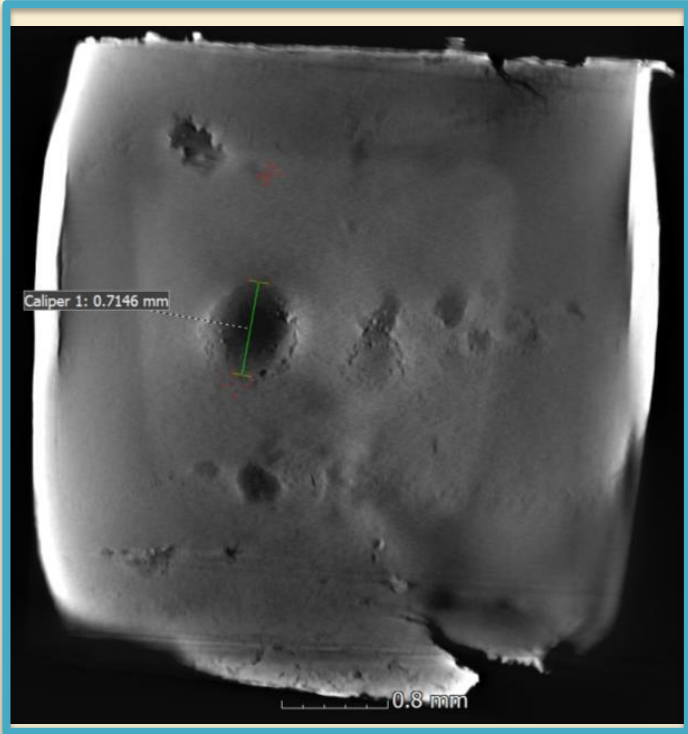


finite element discretization

HTS tape joints  
analysis of microstructural integrity  
by tomography analysis

# HTS tape joints - tomography analysis

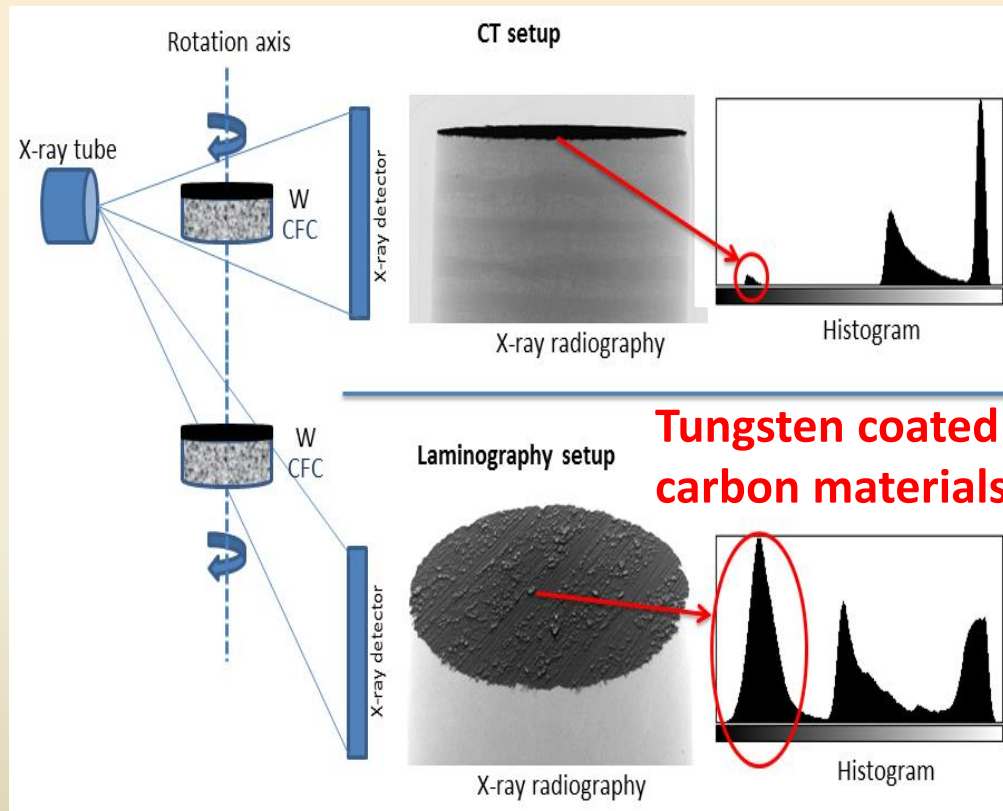
The sample consists of two 4-mm-wide copper-stabilized REBCO tapes joined in a Spark Plasma Sintering (SPS) machine. A thin layer of bulk HTS material was added.



It is possible to evaluate the contact resistance based on the actual contact area determined from tomography measurements

# X-ray micro-laminography ( $\mu$ XCL)

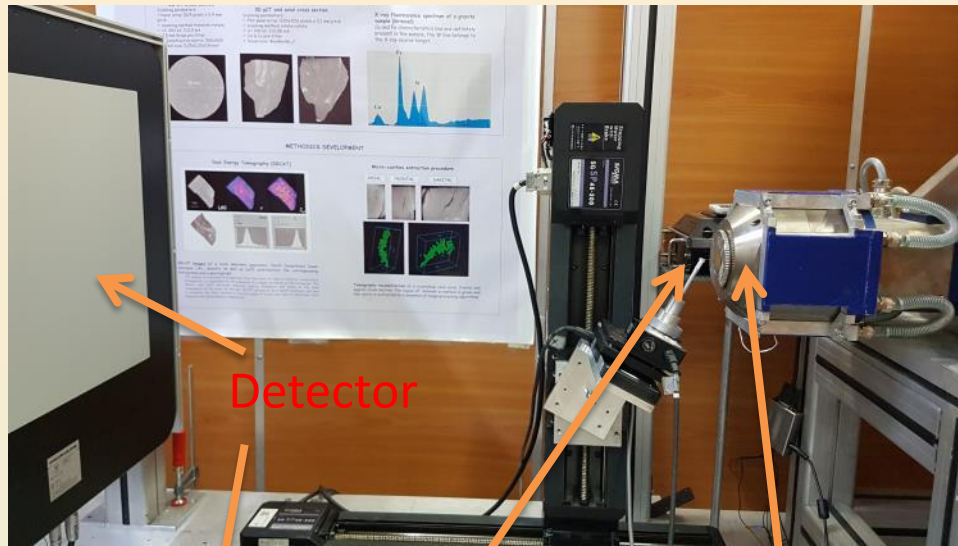
- generalization of  $\mu$ XCT that permits the inspection of planar objects
- $\mu$ XCL avoids using projections from angles closest to the sample coated surface leading thus to reconstructions with fewer artefacts.



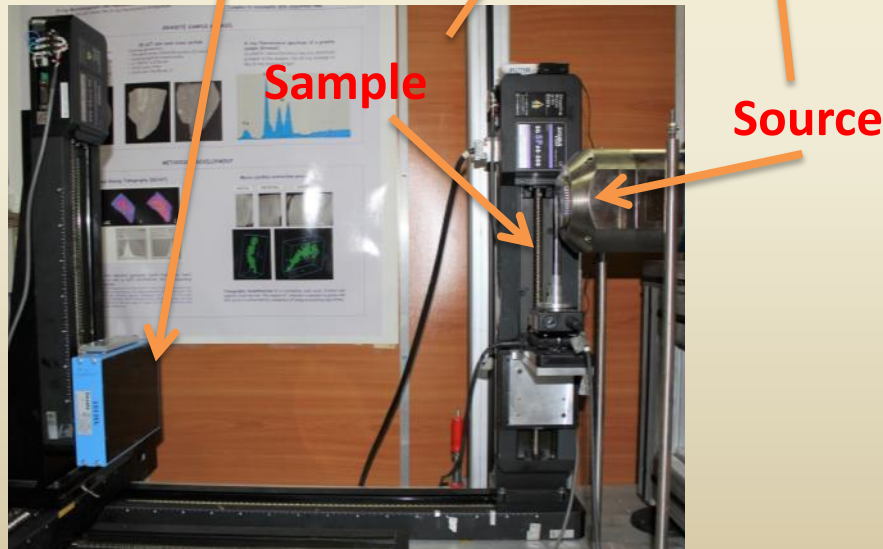
Increased contribution of the information containing X-ray interaction with the W coating as seen in the overall grey level histogram as depicted in the red circles.

**3D micro-tomography versus X-ray micro-laminography scanning configurations**

# X-ray micro-laminography alternative configurations



Sample placed  
on a tilt rotation  
axis

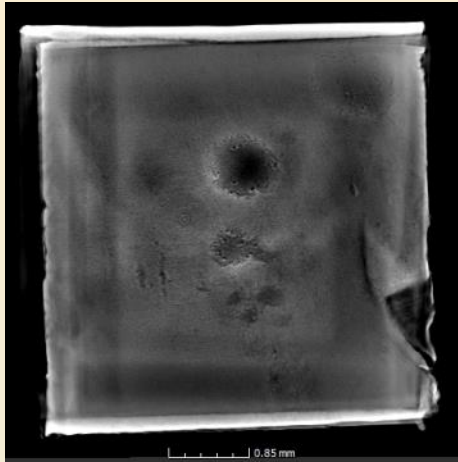
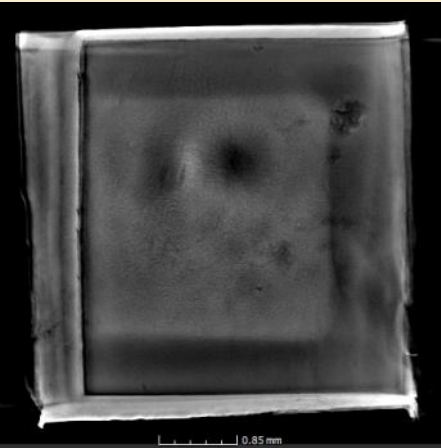
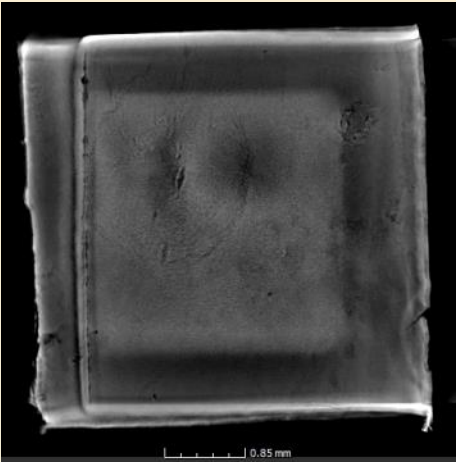


Sample placed on a  
vertical rotation axis  
but with an offset of  
the detector

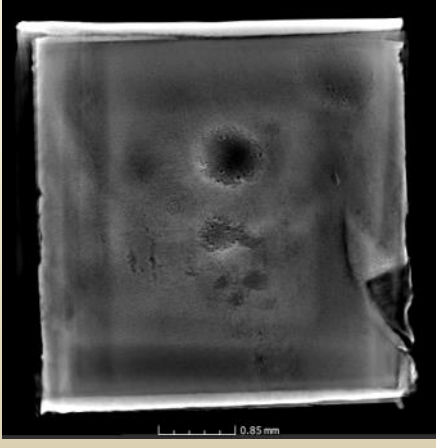
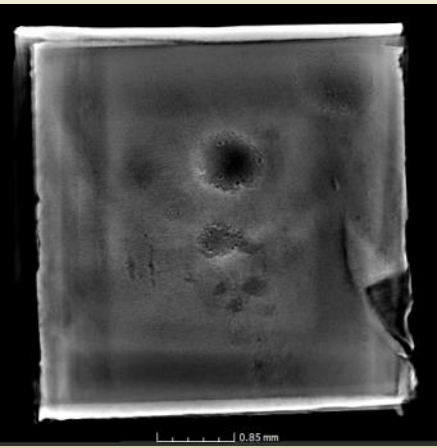
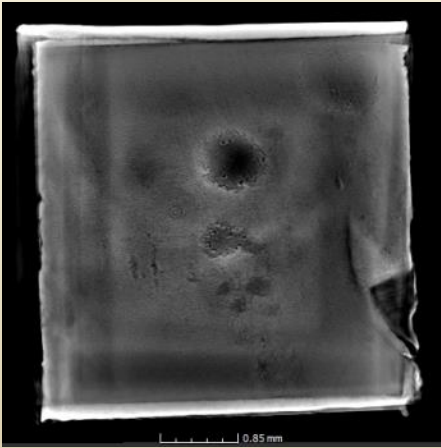
# HTS tape joints - laminography analysis

Laminography cross-sections showing discontinuities in the tape-bulk material interfaces

Top interface



Bottom interface



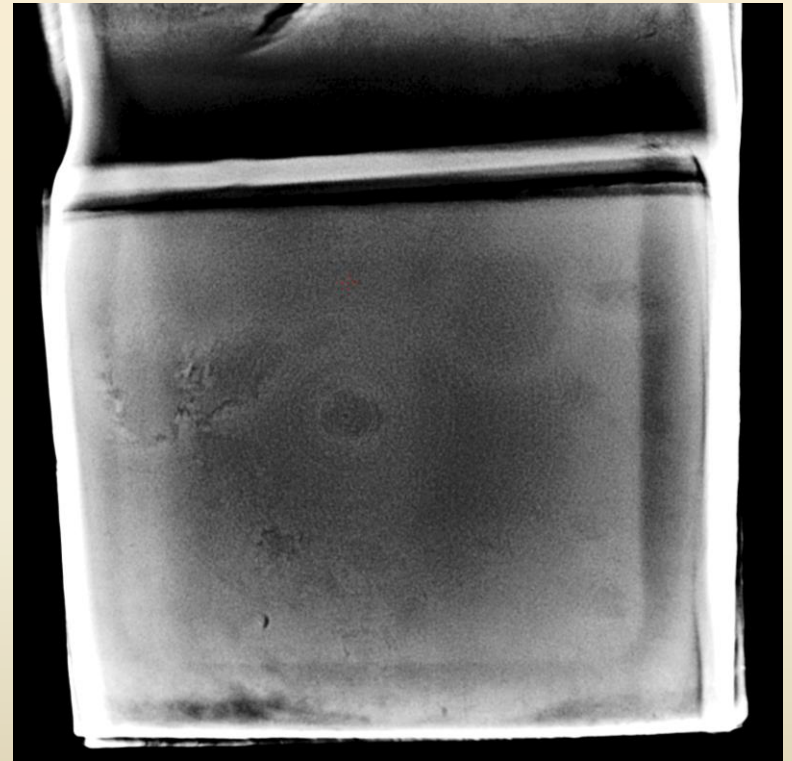
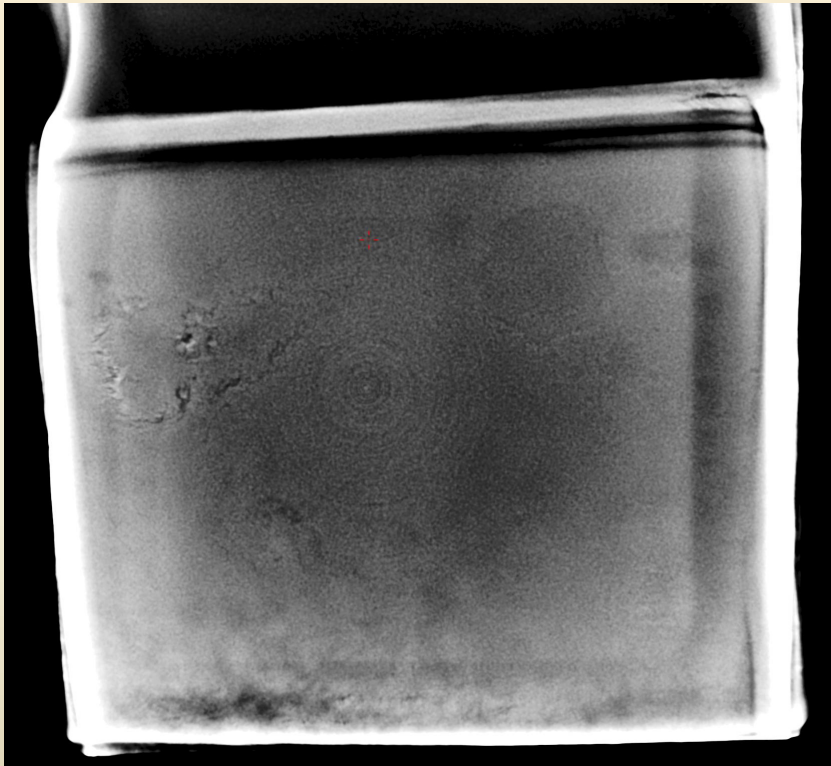
**2D movie of HTS tape joints laminography images**



Highly space resolved  
tomography on advanced  
Bronze(Cu-Sn) strands

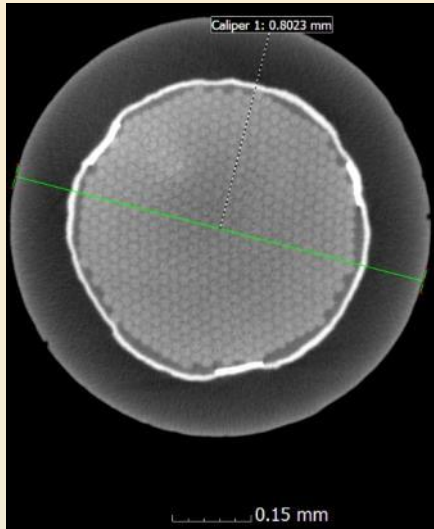
# HTS tape joints - laminography analysis

Laminography cross-sections showing discontinuities in the tape-bulk material interface

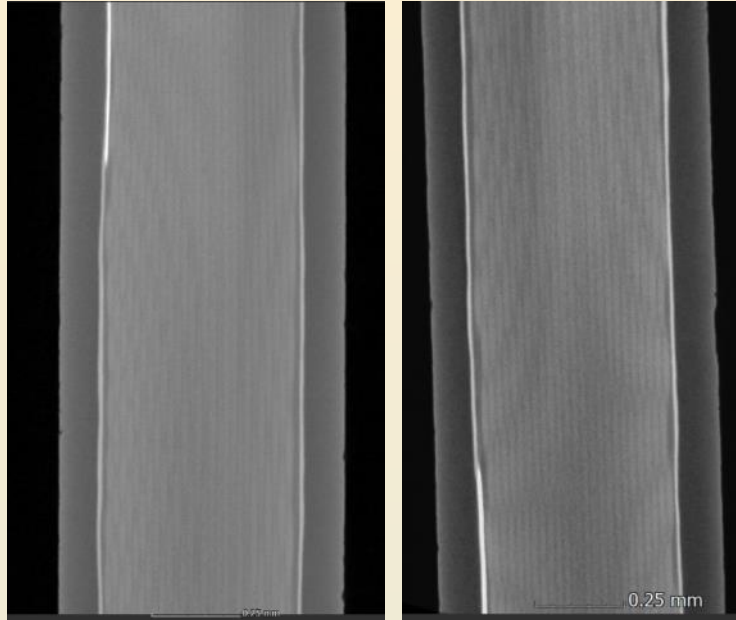


The sample consists of two HTS tapes with a thicker bulk HTS layer in between. Joining was done in a Spark Plasma Sintering (SPS) machine

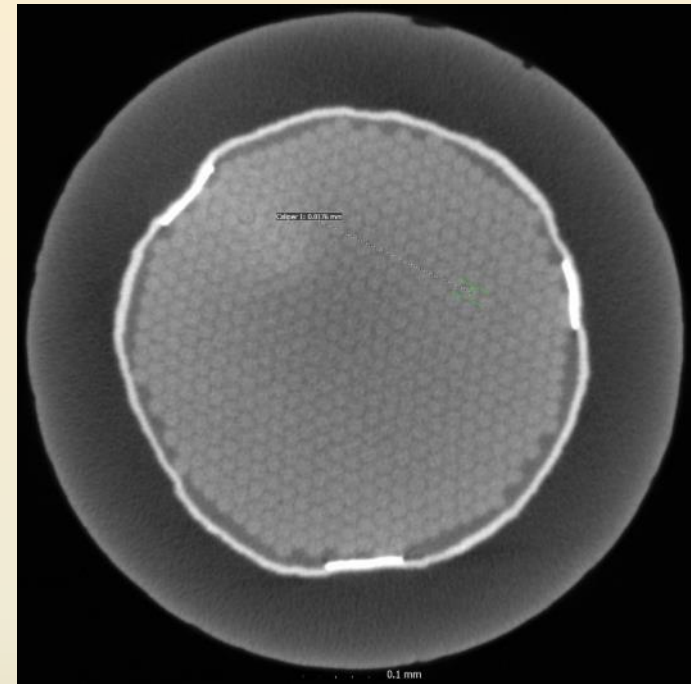
# Bronze filaments (before heat treatment)



Top View with  
filament diameter  
measurement

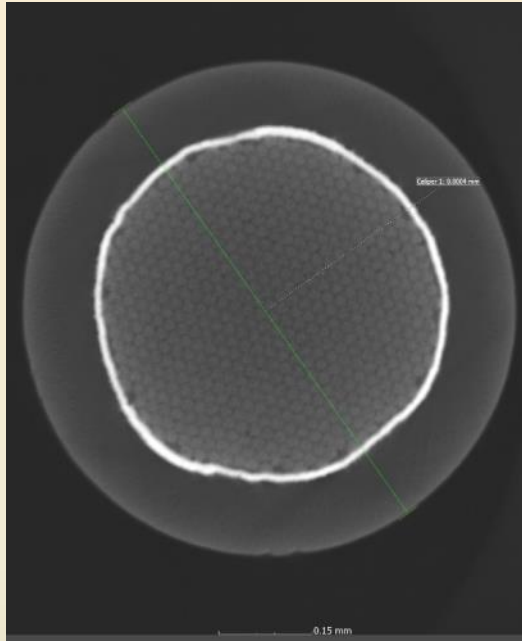


Front and Right View

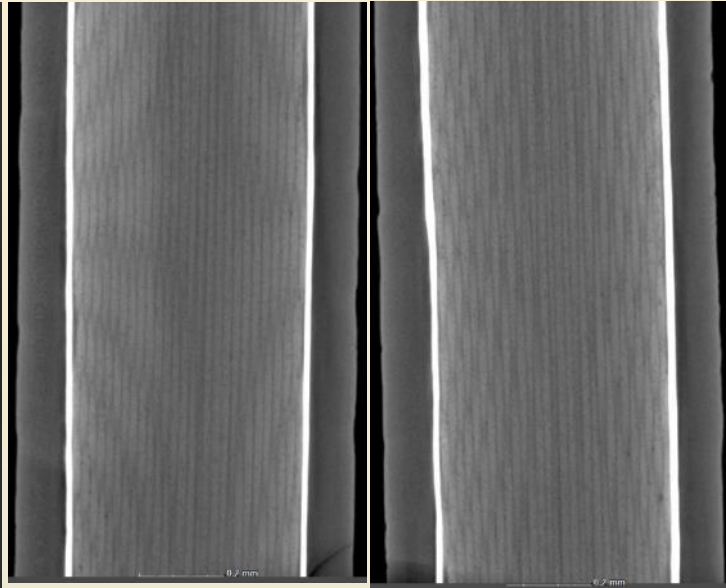


Top View with Nb<sub>3</sub>Sn cores  
measurements

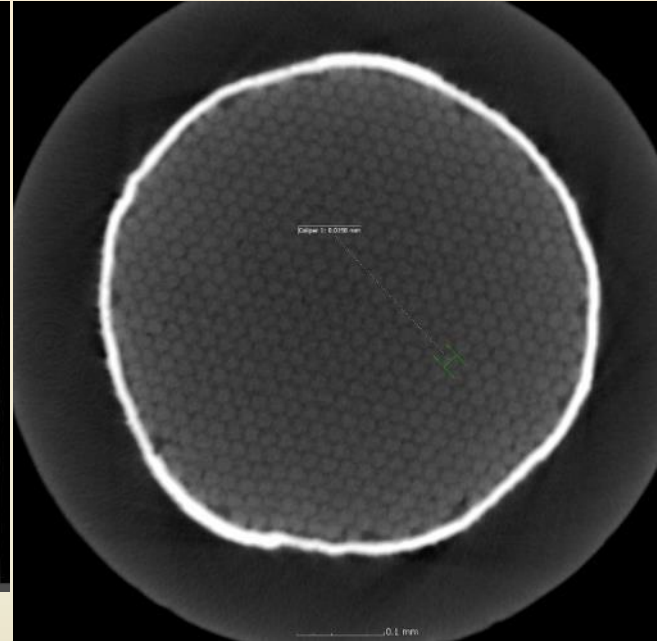
# Bronze filaments (after heat treatment)



Top View with filament diameter measurement

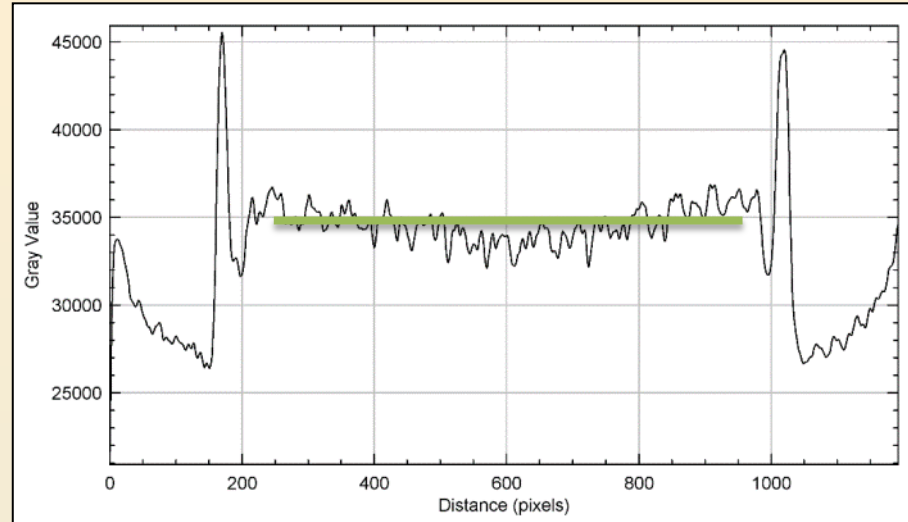
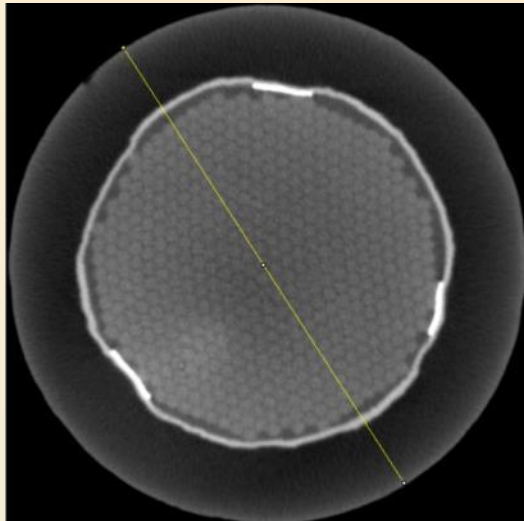


Front and Right View

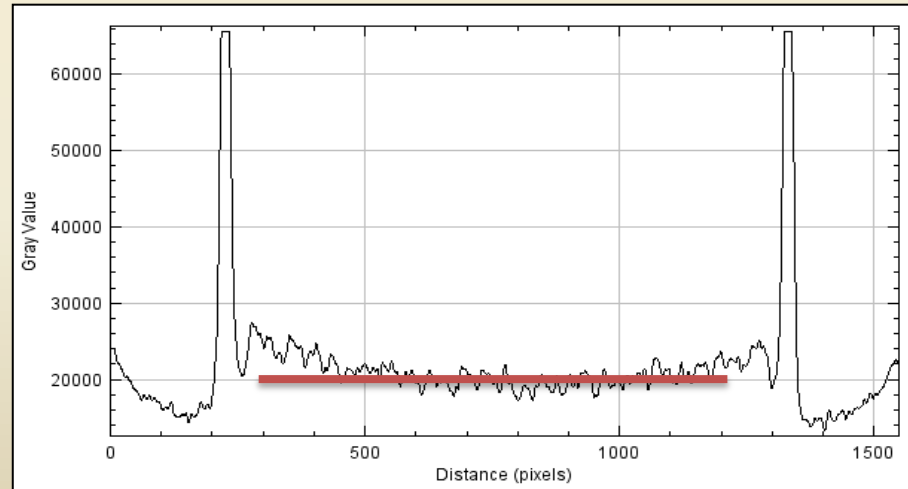
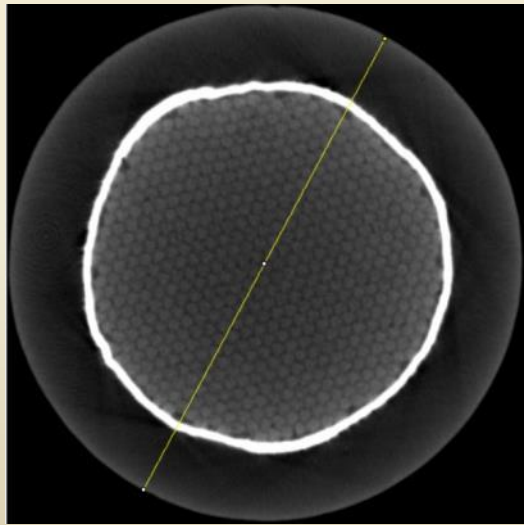


Top View with Nb<sub>3</sub>Sn cores measurements

# Comparison of before & after heat treatment



before HT



after HT

SC alloy has a reduced effective X-ray attenuation factor

# TS 2020

## Proposed tasks

In 2020 we will conduct X-ray tomography (XCT) analysis on CICC conductors and joints relevant for the DEMO magnet system. New samples are already provided by ENEA and CEA, respectively. It is planned that other samples will be provided within the EU-CN cooperation.

ENEA DEMO prototypes:

- Tomography analysis of sample(s) of low-field type (higher ratio of Cu vs Nb<sub>3</sub>Sn than in the already XCT scanned sample).

CEA DEMO prototypes:

- Study of contact mapping dependence on compaction
- XCT analysis of joint structures relevant for DEMO magnet system.

Thank you for attention!