Neutron tomography as a new method for 3D structure analysis of CFC as plasma facing material

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1. Motivation

IPP performed an extensive R&D programme to develop the divertor components for Wendelstein 7-X

Aim: Investigation of Carbon Fibre Composite (CFC) morphology modifications of highly heat loaded divertor components after cyclic heat load experiments.

- Possible debonding between carbon fibres and matrix due to cyclic heat loads reduces the thermal performance of the components

- Investigation of defects of CFC bonding to explore the expected lifetime
- Extensive metallographic investigation performed – but 2D results only
- Interpretation of spatial distribution is difficult and needs new techniques

➔ Evaluation of neutron tomography as method to investigate the 3D structure in detail

performed at Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II) of Technische Universität München

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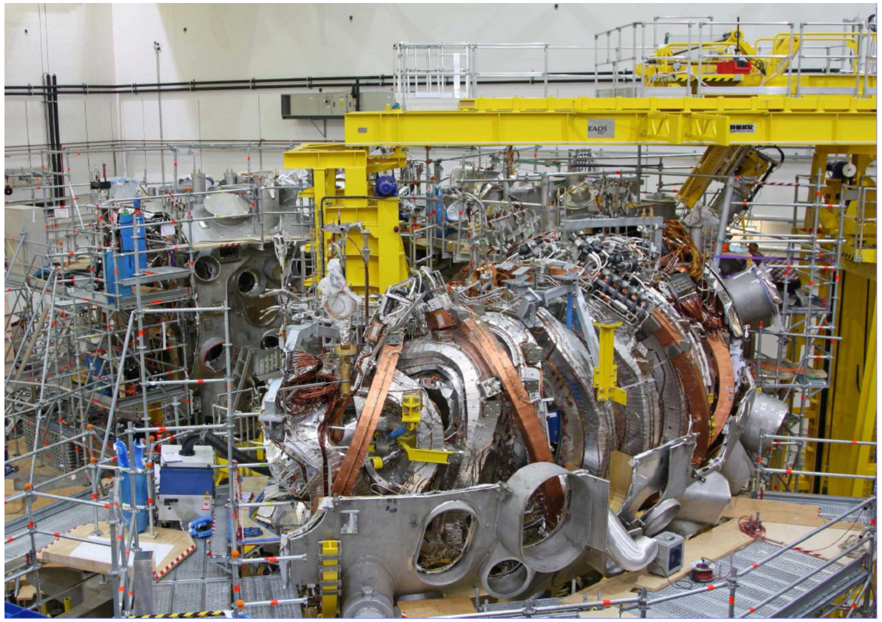
2. Introduction Wendelstein 7-X

Under construction at IPP branch Greifswald

Start of operation: 2015

- demonstrate reactor feasibility of the stellarator concept
- steady state operation (10 MW plasmas for 30 minutes)

- Divertor function:
  - direct plasma contact
  - particle and power exhaust resulted in 10 MW/m² heat flux, $T_{surface}$ ~1000°C



Construction of the device, end 2010

3/5 of the facility are at the final position

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Introduction W7-X divertor targets

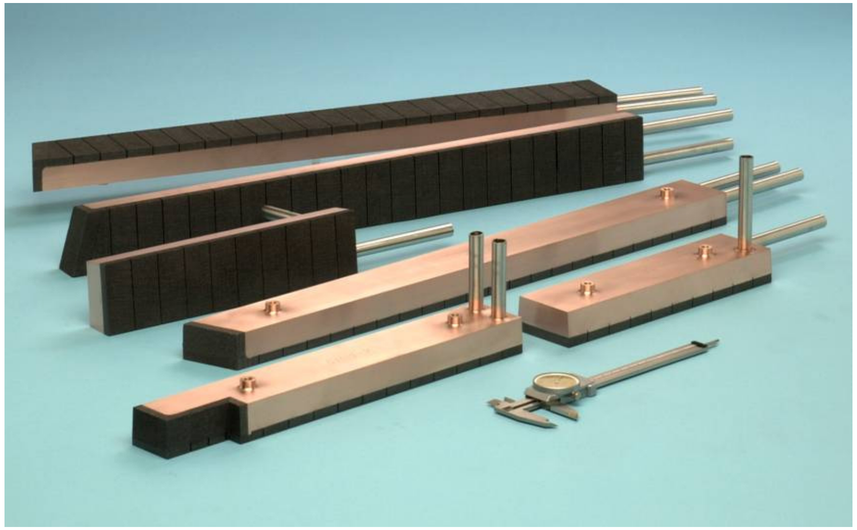
Design of divertor:

- 20 m² area, 900 water-cooled individual elements
- Designed for 10 MW/m² long pulse operation
- Industrial fabrication started in 2010

Carbon Fibre Composite (CFC) as plasma facing material, bonded on water-cooled Cu structure

- CFC: low atomic number material
- Cu: high thermal conductivity

- **Problem: strong mismatch of coefficient of thermal expansion generates high thermal stresses in the CFC/Cu interface during operation.**

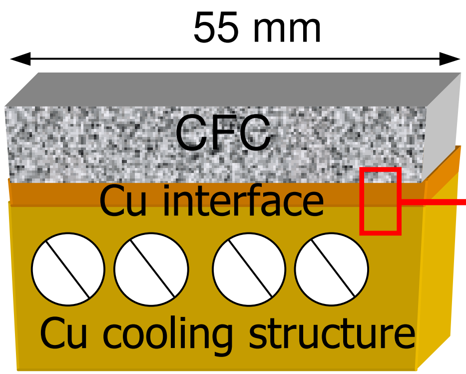


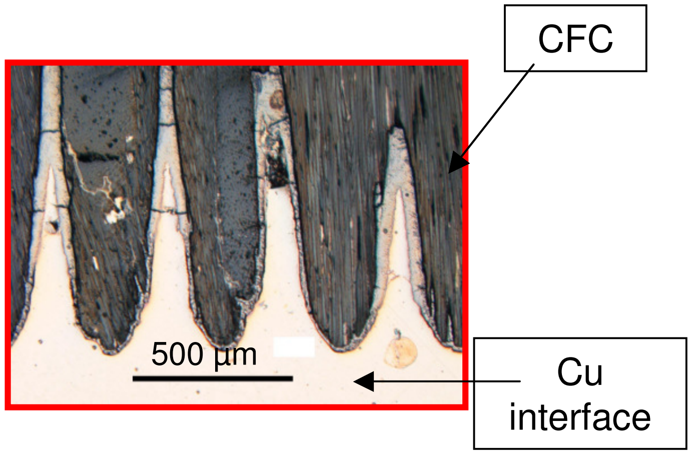
Different divertor components.
Lengths between 250 - 560 mm.

➔Neutron tomography for 3D evaluation of modifications of CFC/Cu interface after high heat flux tests up to 10,000 cycles at 10 MW/m²

Design of W7-X divertor target

Cross section of target element

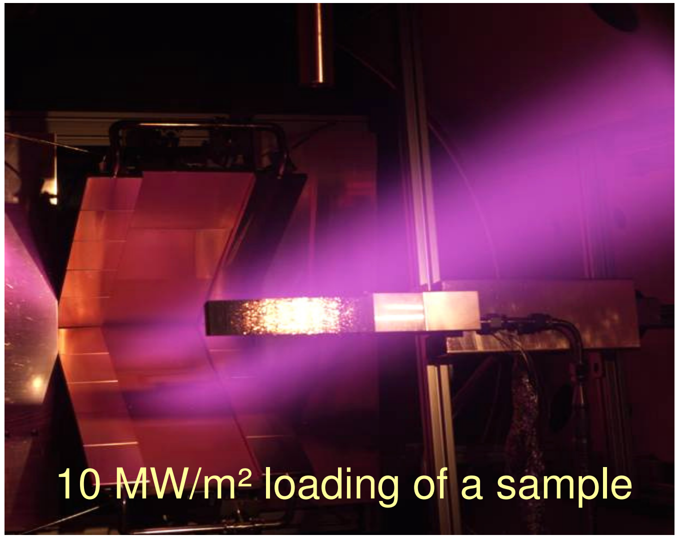




Magnification of CFC/ Cu interface

3. High heat flux tests in GLADIS (Garching Large Divertor Sample test facility)

More than 60 W7-X pre-series targets tested in GLADIS before start of production



selected samples for neutron tomography

- Reference sample, unloaded
- 5000 cycles 10 MW/m^2: study of crack propagation
- 10,000 cycl. 10 MW/m^2: lifetime of CFC bonding
- 32 MW/m^2, 30 s pulses: thermal limits

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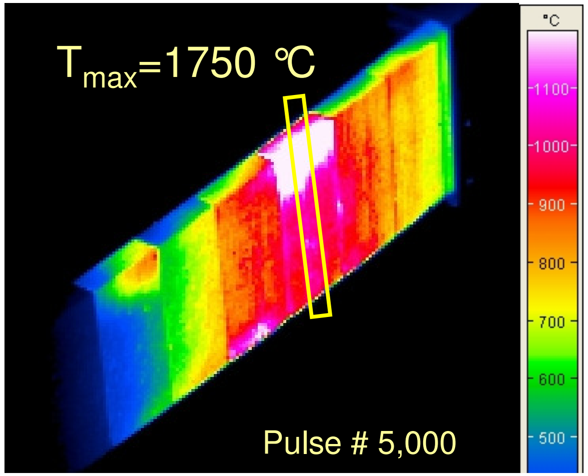
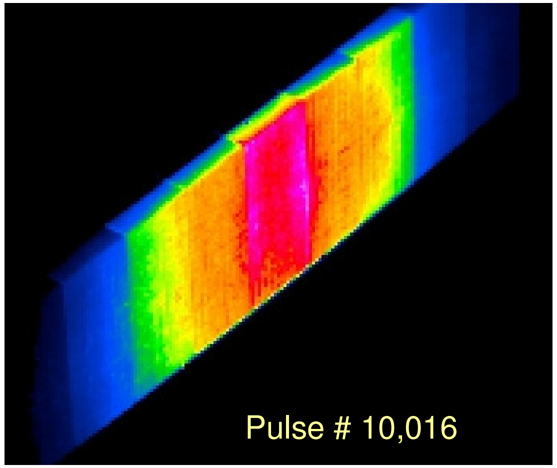
HHF test results of neutron tomography samples

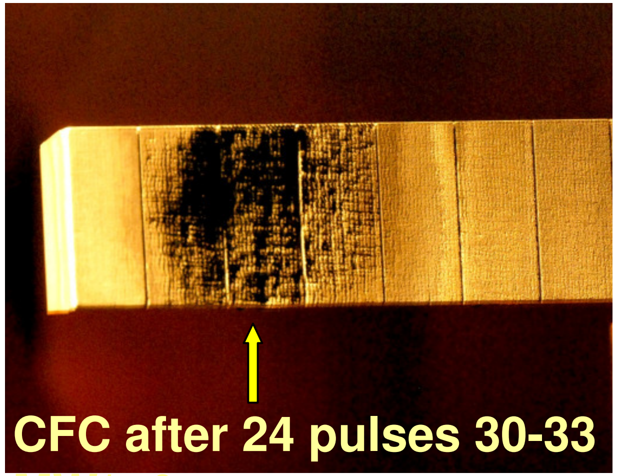
IR image of pulse 5,000



IR image of pulse 10,000



CCD image after overloading



Metallographic investigation:
large delamination of ~14 mm length, in agreement with FEM calculation

Spatial structure of the crack or of the CFC structure after loading?

Surface temperature increased from initially 1085℃ to 1125℃

Cooling structure temperature constant.

Reason: slight CFC or bonding degradation?

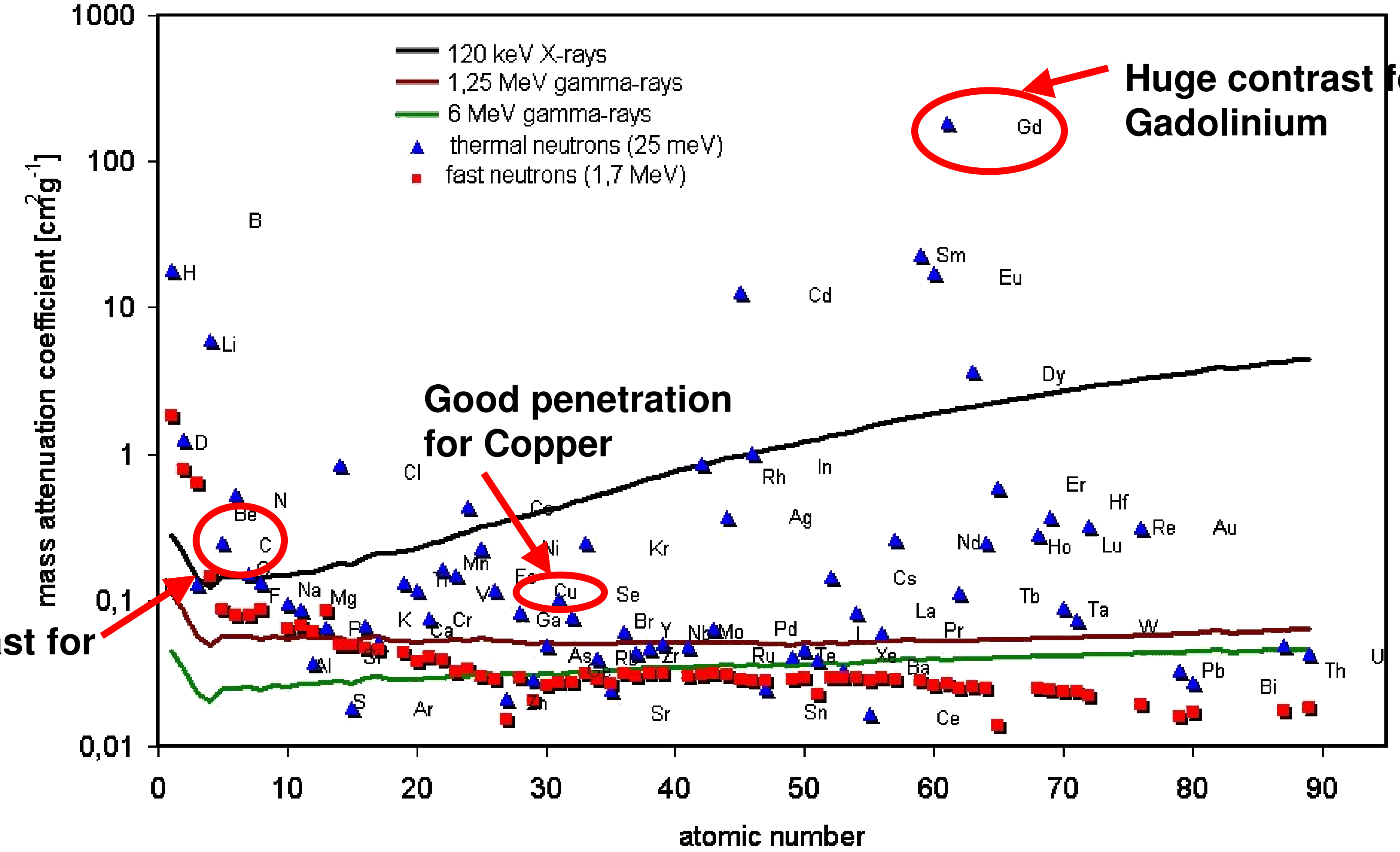
Surface temperature exceeded 2200 ℃

Strong carbon evaporation

Structure of remaining CFC?

Neutron tomography to obtain more details of 3D structural changes

4. Why tomography with neutrons?



Huge contrast for Gadolinium

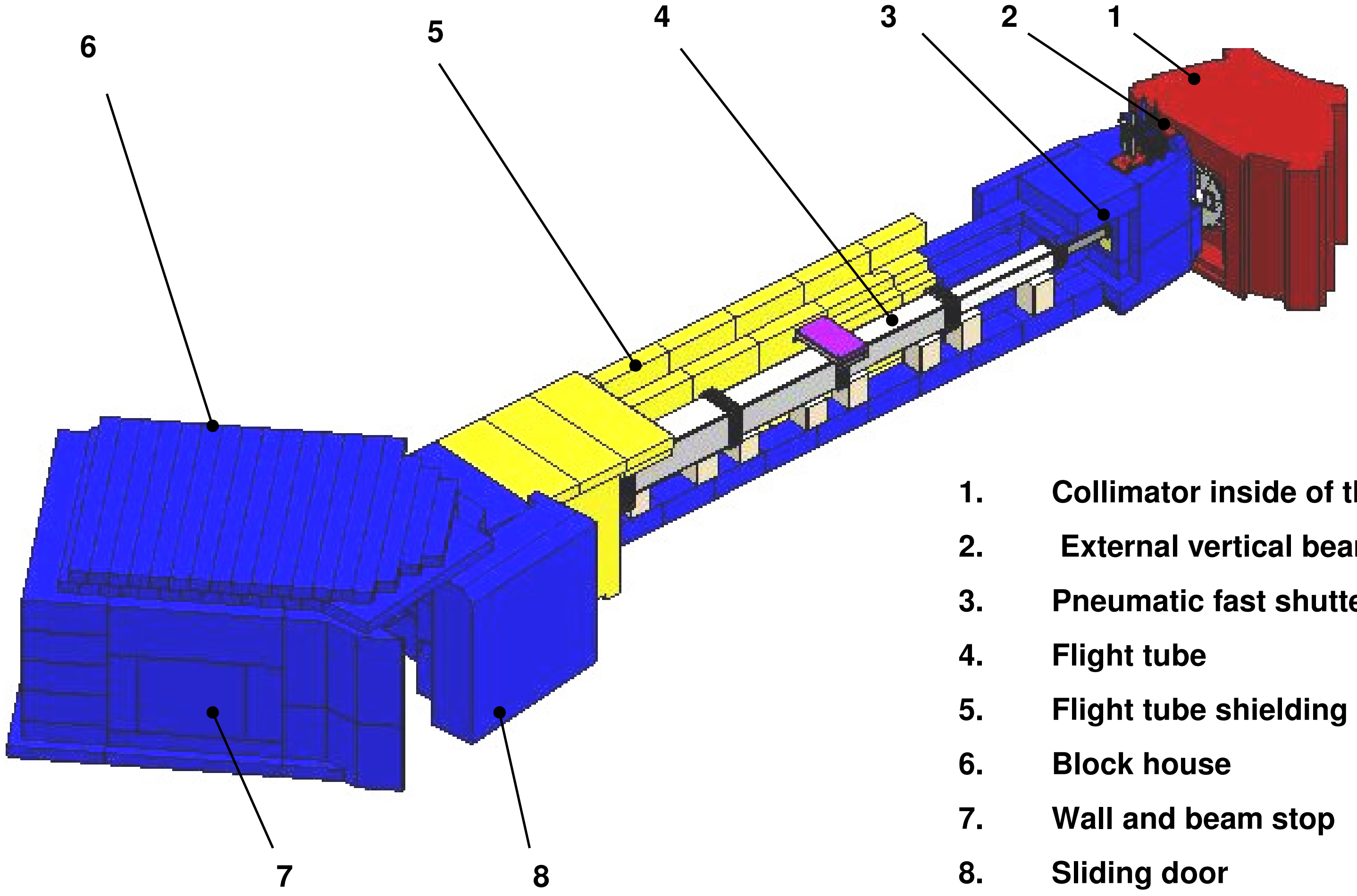
Good contrast for Carbon

Attenuation properties of elements for neutrons are quite different from those for X-rays!

Antares

Advanced **N**eutron **T**omography **A**nd **R**adiography **E**xperimental **S**ystem

Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II)
of Technische Universität München



1. **Collimator inside of the biological shielding**
2. **External vertical beam shutter**
3. **Pneumatic fast shutter**
4. **Flight tube**
5. **Flight tube shielding**
6. **Block house**
7. **Wall and beam stop**
8. **Sliding door**

Use liquid Gd contrast agent to fill the voids

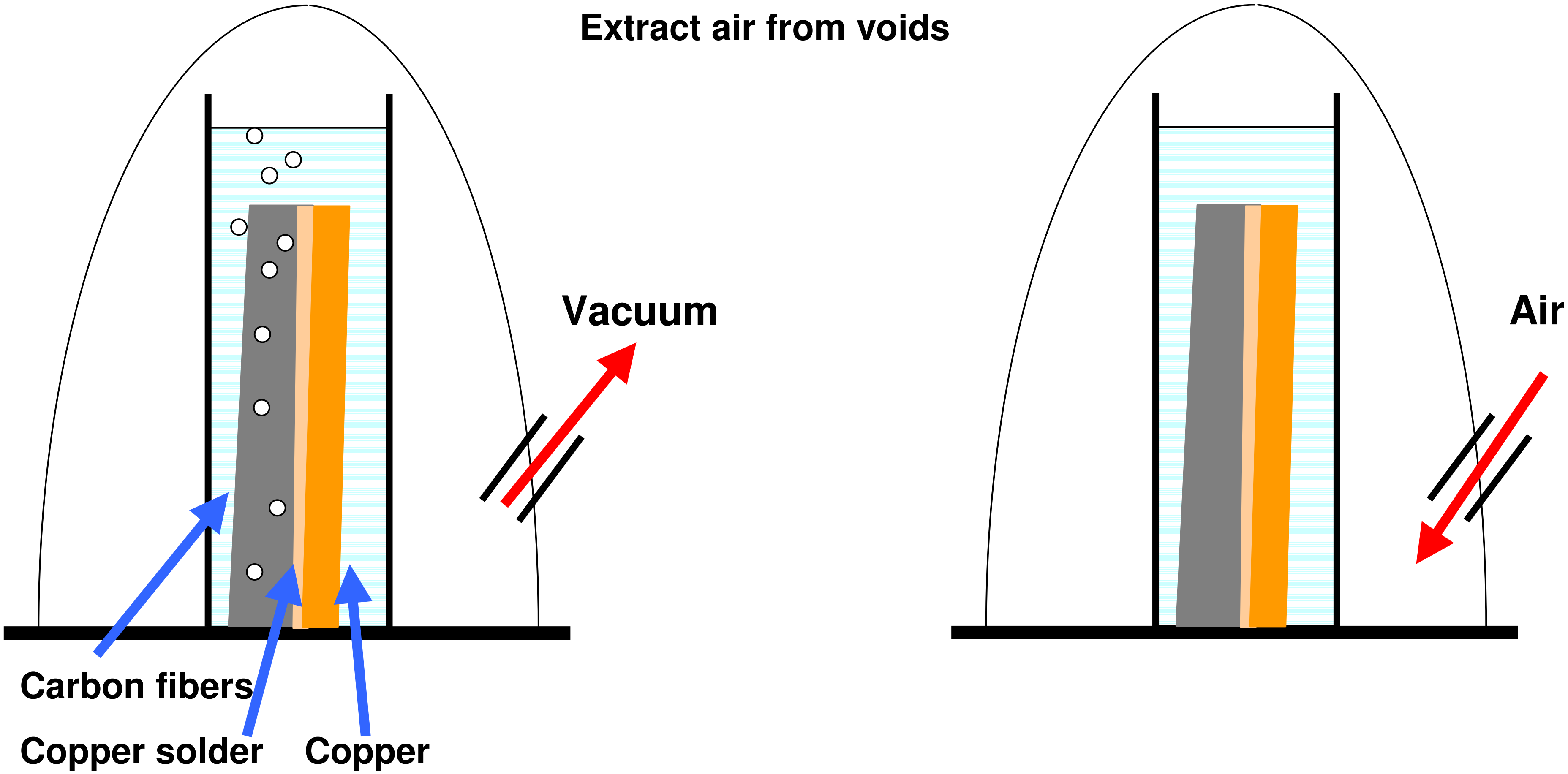
1. Submerse sample in liquid contrast agent

2. Evacuate space around liquid container:

Extract air from voids

3. Re-pressurize: External air pressure forces liquid into voids

4. Rinse in water



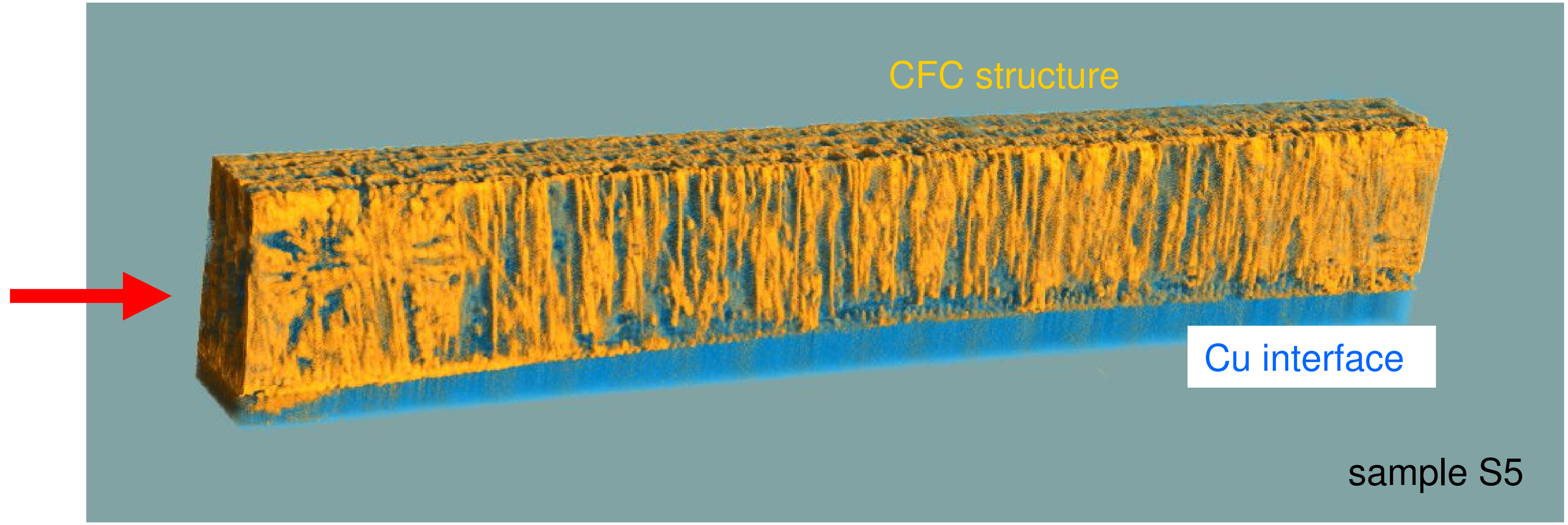
5. Results of neutron tomography

First examination:

- One practically unloaded sample S0 (only one pulse 8 MW/m²)
- One sample S5 loaded with 5,000 pulses 10 s of 10 MW/m²
  - Aim: study of crack propagation of pre-damaged CFC tiles

5. Results of neutron tomography

First 3D view: Cutout of divertor sample, with copper on bottom, carbon above - the contrast agent fills the voids, also at the interface, and gives the brightest contrast.



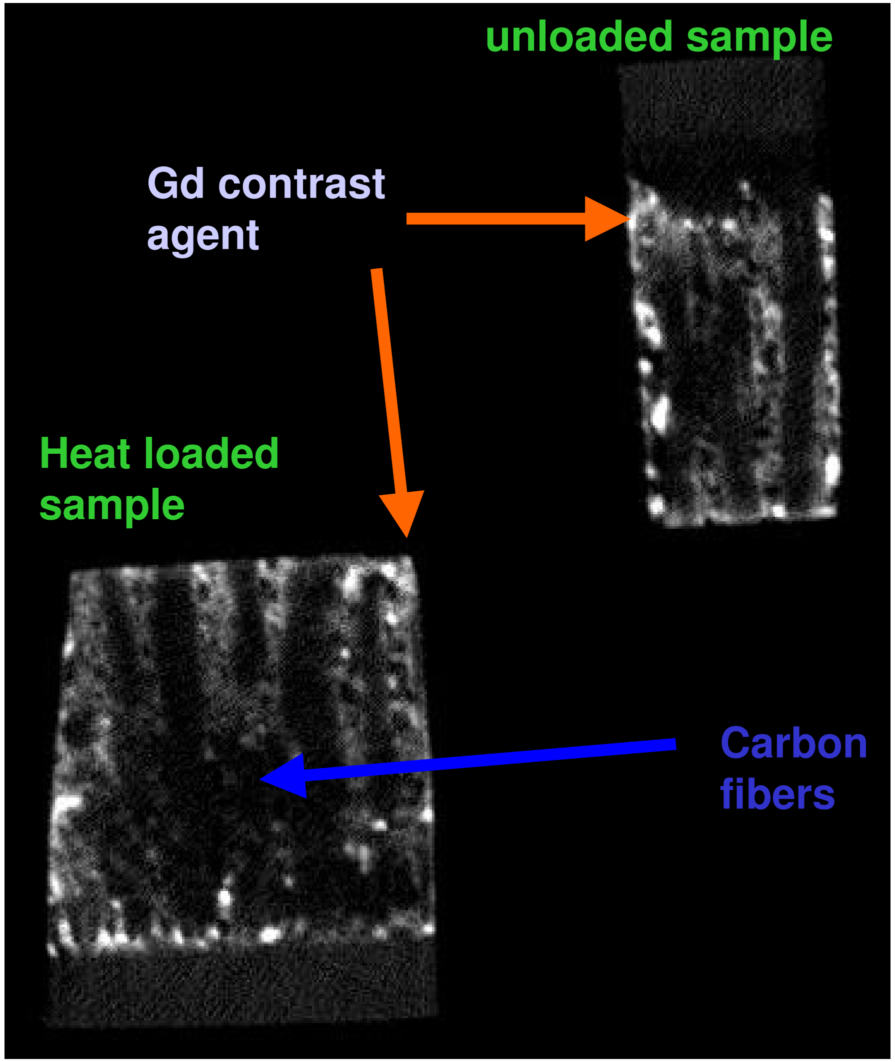
Direction of slice movie

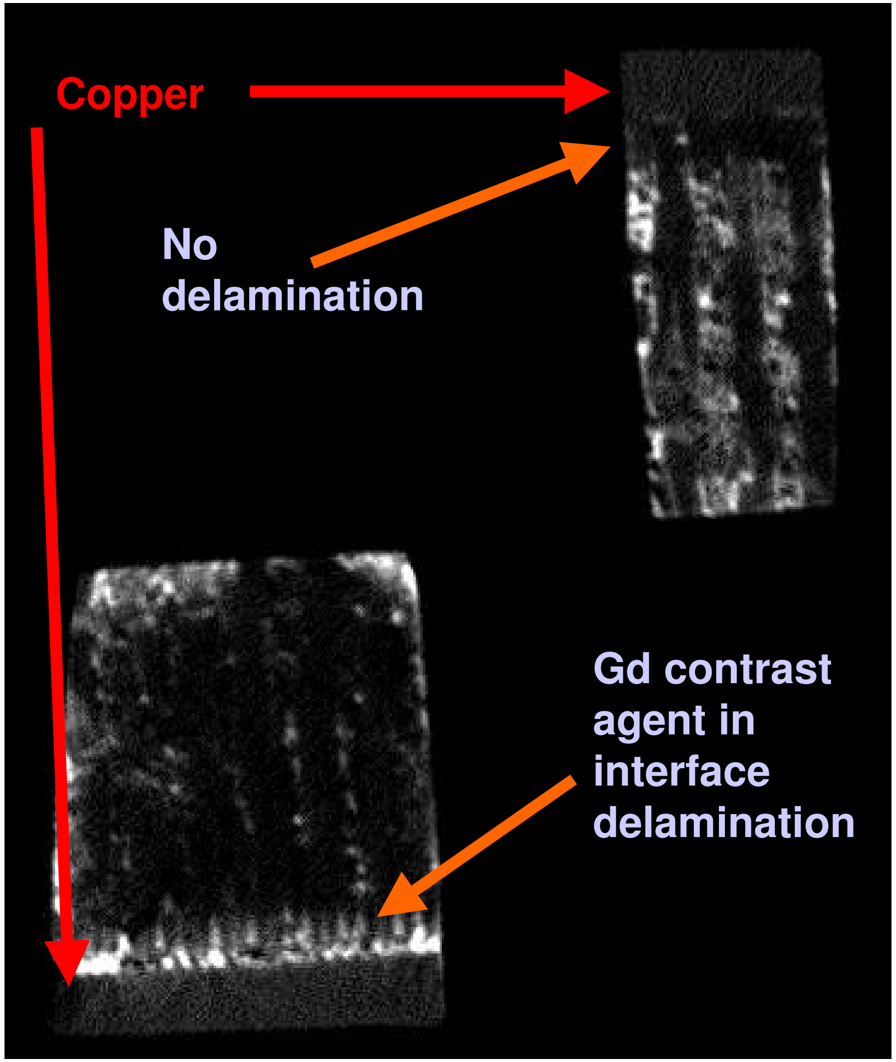
The movie on the next slide walks through the tomographic slices, starting on the left side.

The heat loaded sample is on the left (5000 pulses) and the unloaded sample on the right.

Unloaded sample

Results of neutron tomography





Results of neutron tomography

Sorry,

PowerPoint fails to recognize my video format.

Please wait while I switch to the external player.

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5. Results of neutron tomography

Second examination:

- **One sample loaded with** **10,000 pulses 10 s of 8 MW/m²**
- **Two samples overloaded with** **24 pulses 30 s of 30-33 MW/m²**

Results of neutron tomography

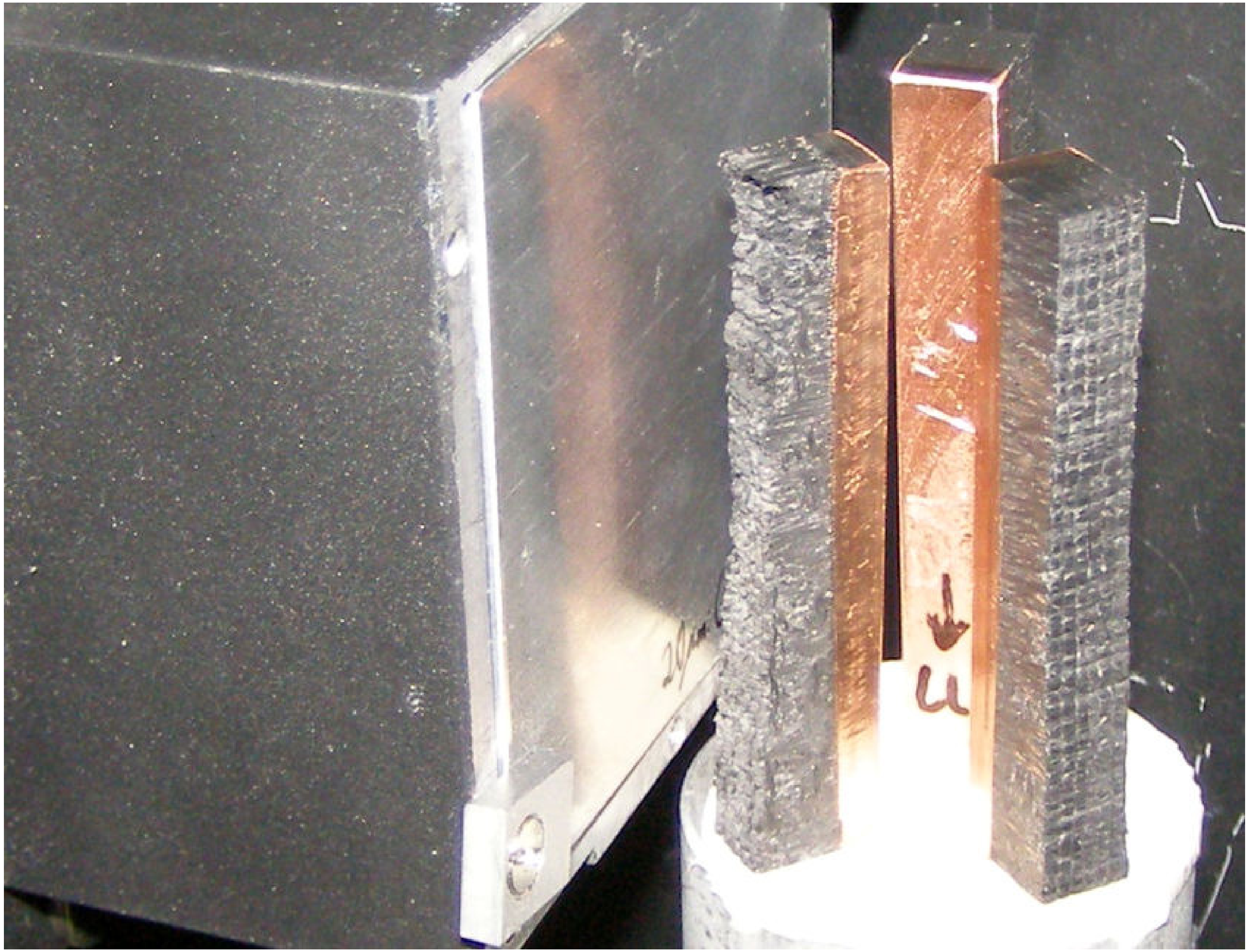
Sample arrangement on rotation table.

The cooling structure and a part of the Cu interlayer is removed.

**overloaded,
sample S 32 (left),**

**10,000 cyc.
sample S 10 (center),**

**overloaded
sample S 32 -2 (right).,**



Results of neutron tomography

One reconstructed tomographic slice at 45 mm height of above the rotation table.

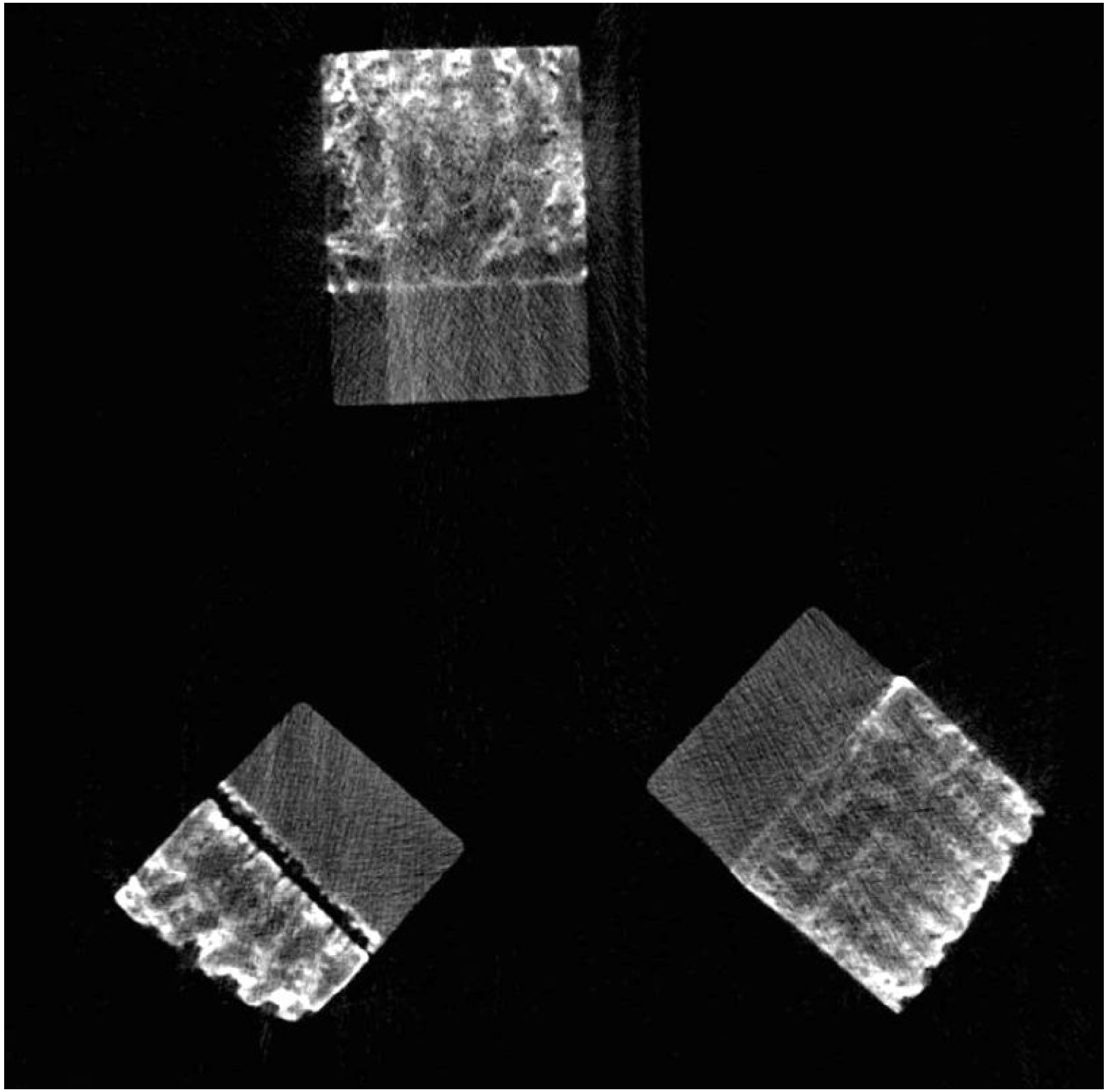
S 32 (bottom left),

S 10 (top center),

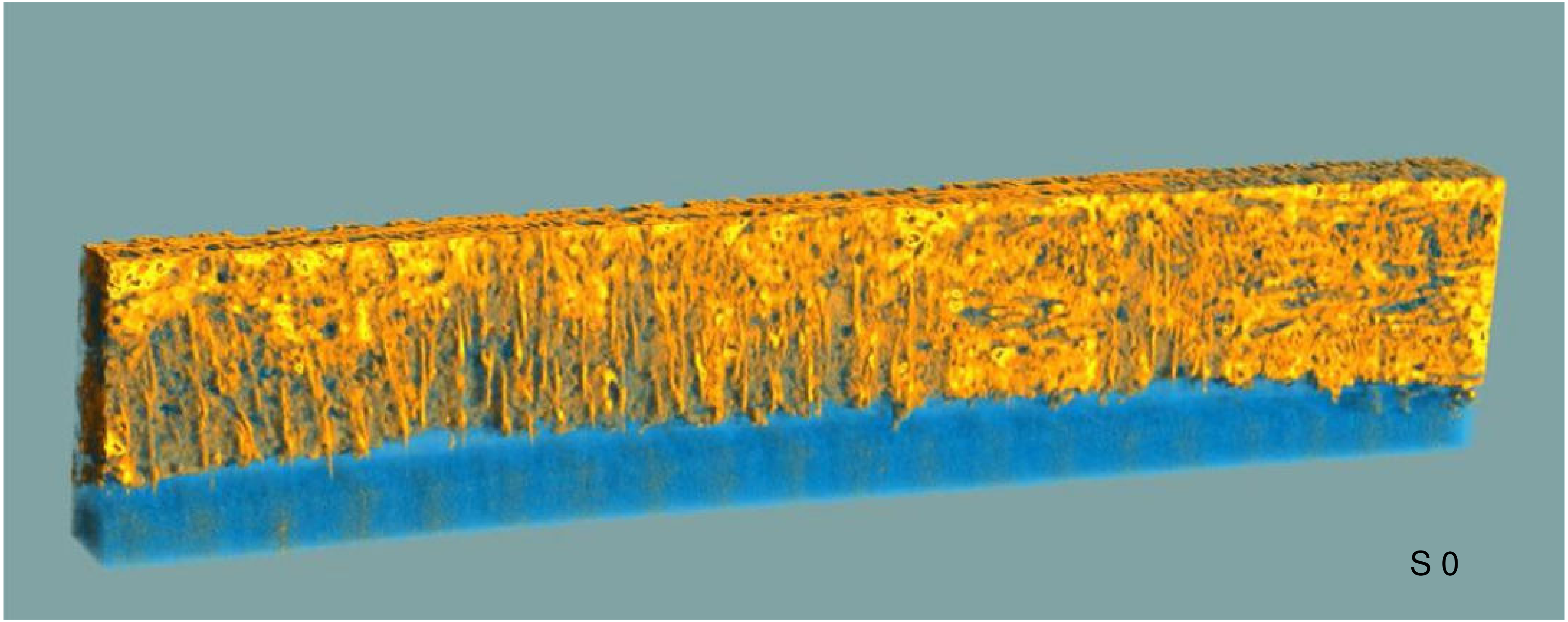
S 32-2 (bottom right).

Copper appears grey, bright parts are gadolinium contrast agent.

The large crack is not filled.



Results of neutron tomography

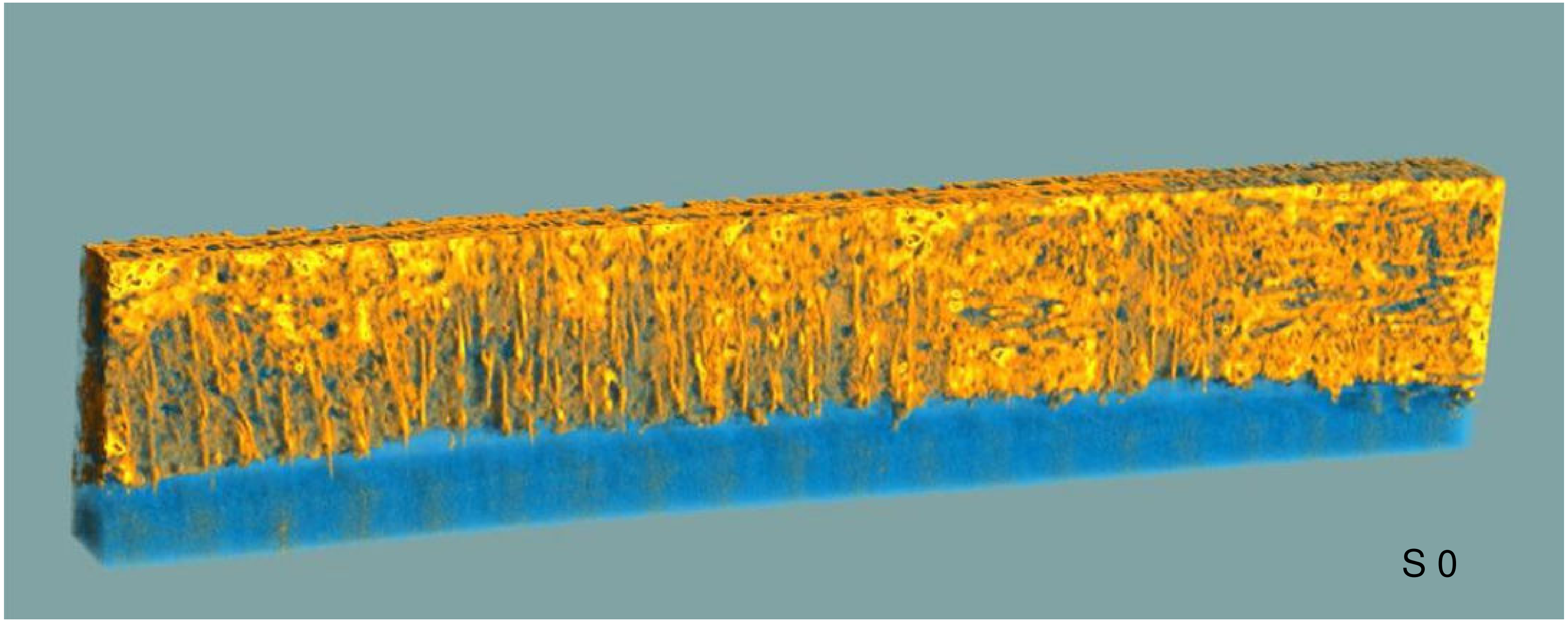


3D reconstruction of the unloaded sample.

Blue bottom: AMC/Cu. Yellow top: absorption by Gd.

The structure of the wetted CFC is well reproduced.

Results of neutron tomography

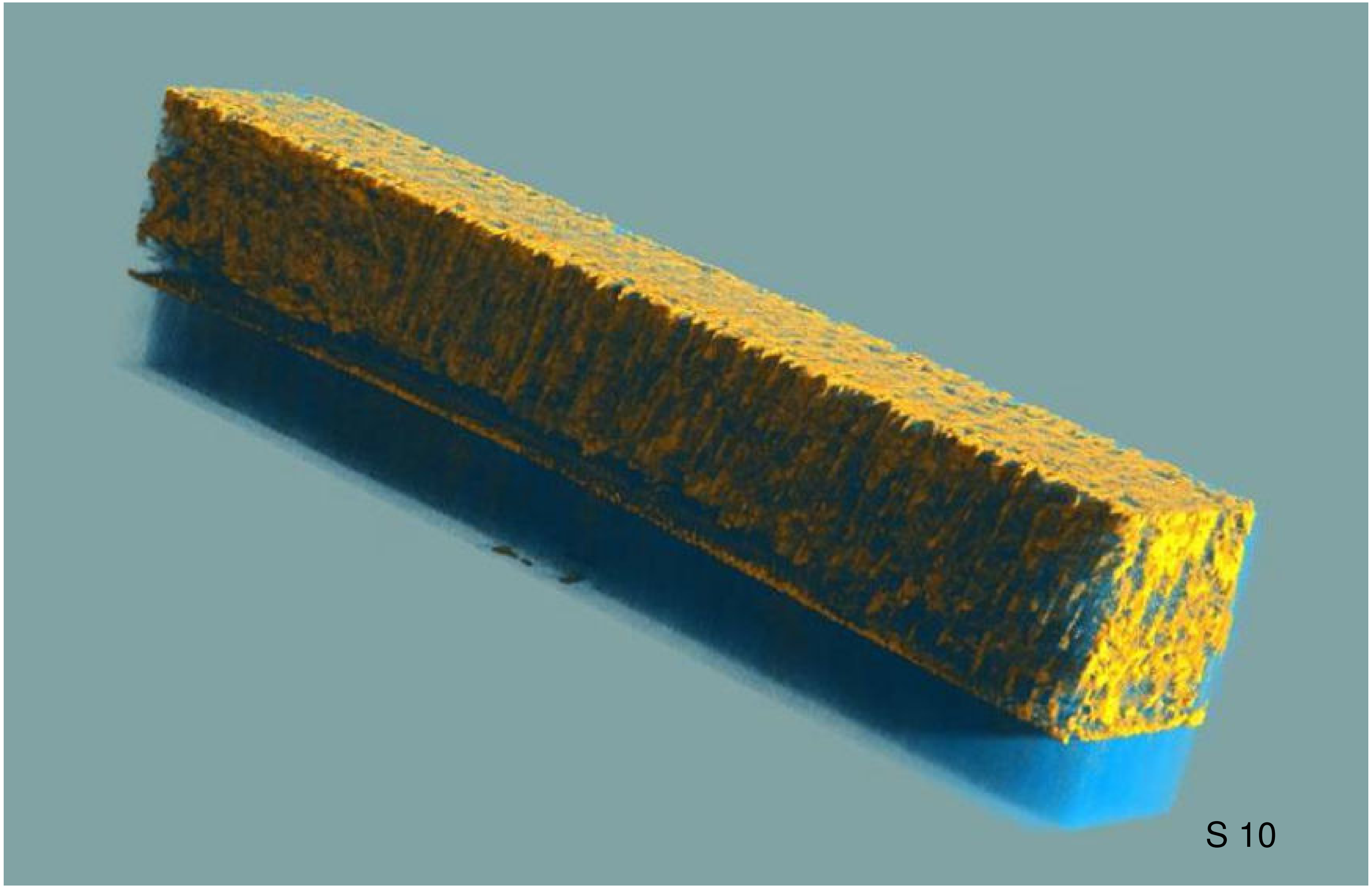


The viewing area crosses two CFC fibre planes.
The perpendicular oriented ex-pitch fibre bundles are visible in the left part, the parallel oriented ex-PAN fibrous webs are visible in the right part.
The initial CFC/Cu interface forms a barrier against the infiltration of Gd.
Only a few isolated pores in the AMC layer could be revealed.

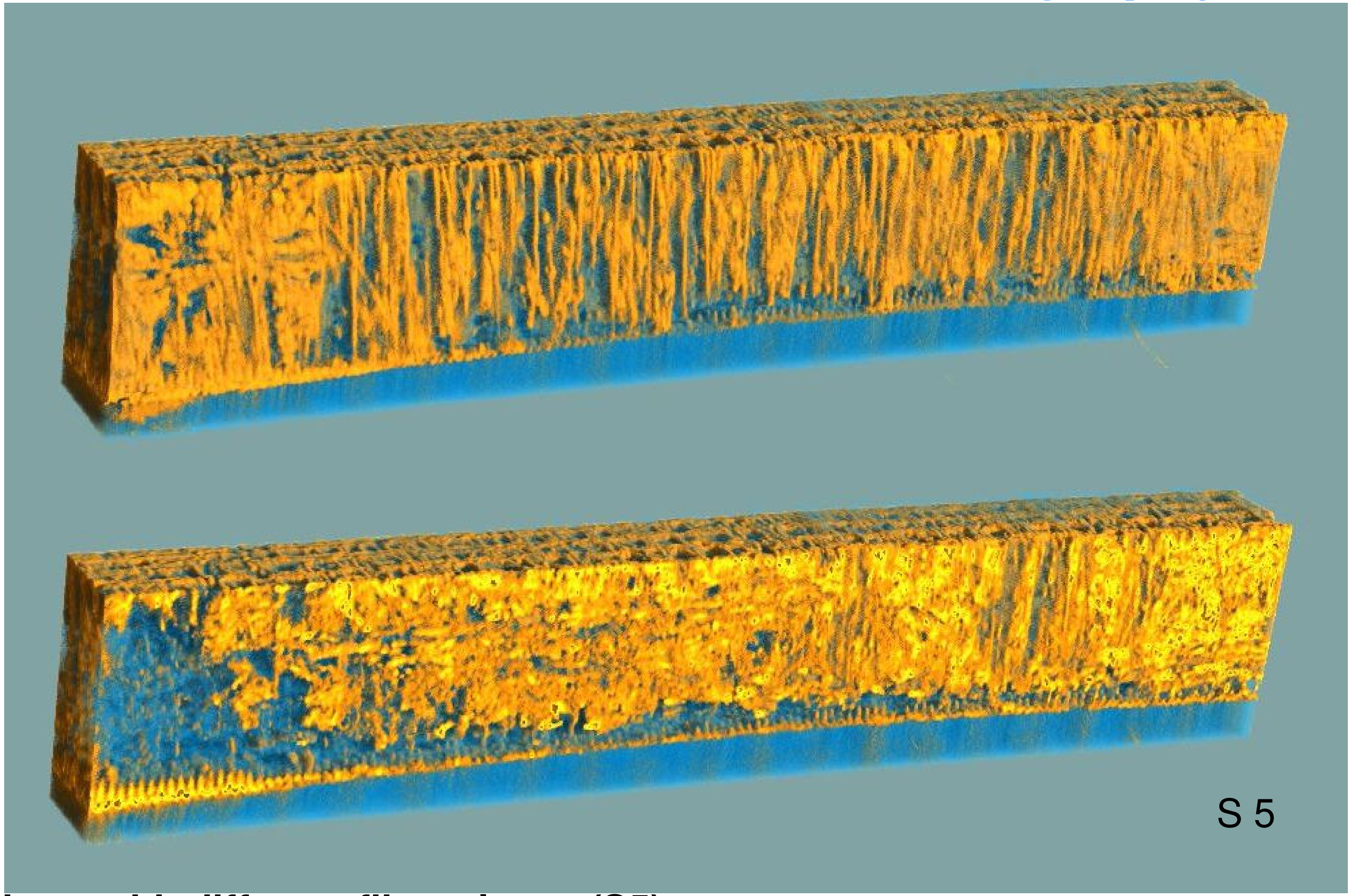
Results of neutron tomography

Image of S 10 after 10,000 cycles 10 MW/m².

The micro-fissures in the CFC/Cu interlayer are visibly filled with contrast agent.



Results of neutron tomography



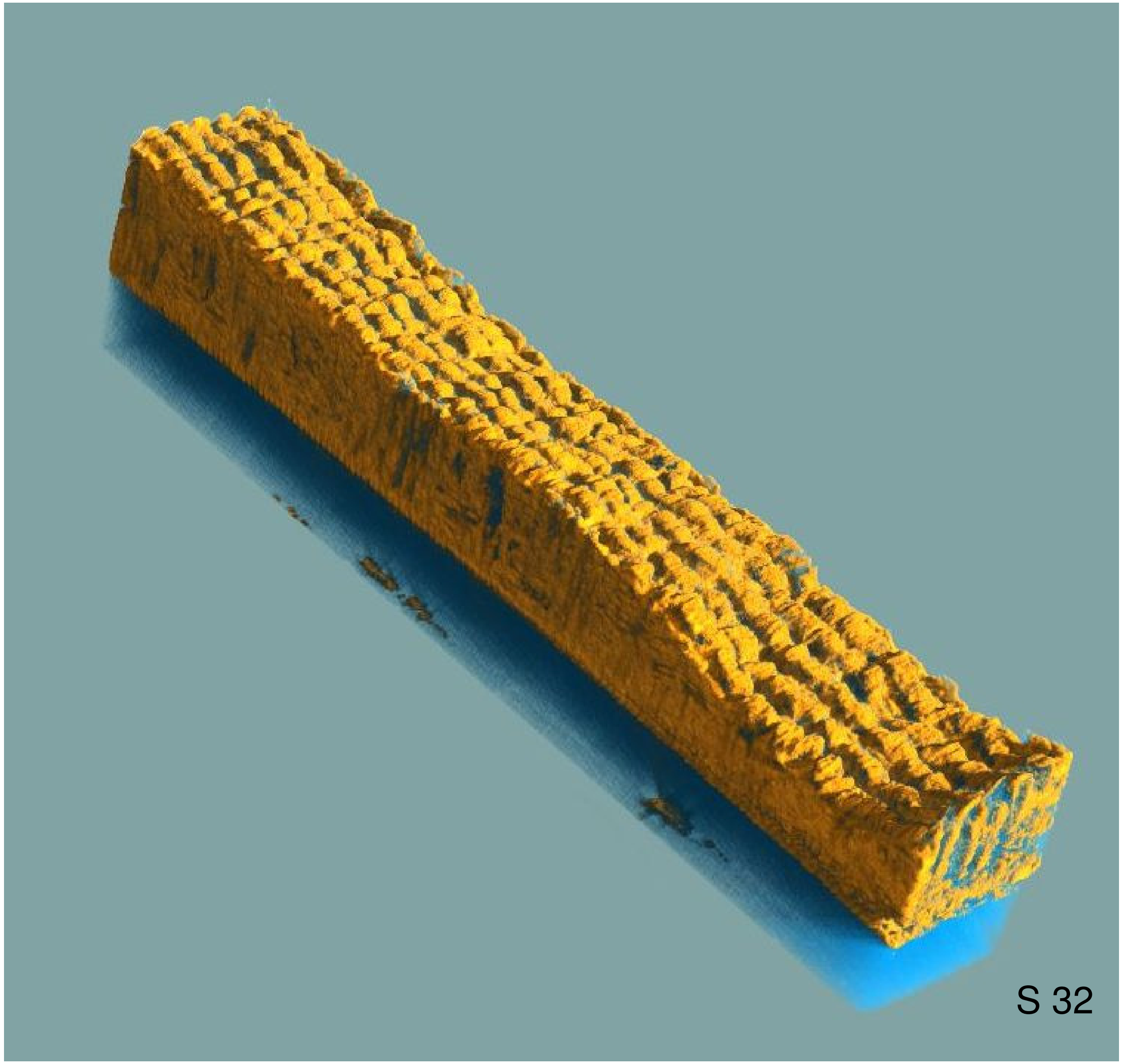
Two more views with different fibre planes (S5)

The perpendicular oriented ex-pitch fibre bundles are visible in the top image, the parallel oriented ex-PAN fibrous webs are visible in the bottom image.

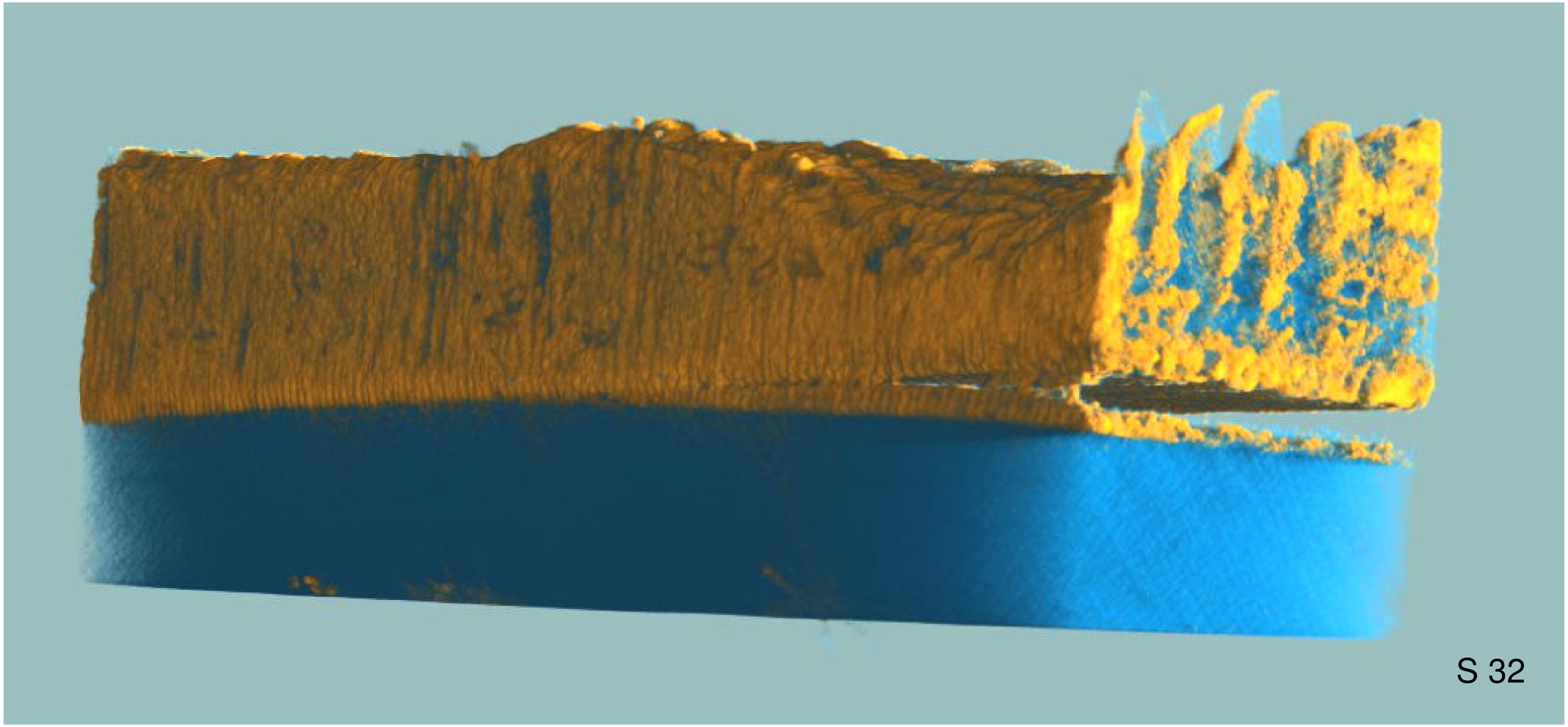
The delamination is visible filled with Gd agent.

Results of neutron tomography

Destroyed surface after 32 MW/m² heat loading.



Results of neutron tomography



View of the large delamination after 32 MW/m² heat loading.
The CFC structure is strongly damaged, but the ex-pitch fibre bundles perpendicular to the cooling structure survived. The crack is so big that the contrast agent ran out and left it empty.

6. Summary and outlook

Sample loaded with 5,000 pulses

- **There are no significant differences in the bulk carbon fiber blocks of the loaded and unloaded sample → No deterioration of the CFC block**
- **Obvious delamination between the copper and CFC block in the loaded sample, going into very fine details**
- **No delamination, not even porosity, in the interface of the unloaded sample**

6. Summary and outlook

Sample loaded with 5,000 pulses

- The extension of the microscopically identified crack could be visualized und measured.
- The 8.5 mm long total delamination moves to a partially bonded area up to 16.7 mm length.
- The central area of the loaded zone (16.7 to 25 mm) shows complete bonding. A minor infiltration of Gd in the remaining length of the sample is a sign of formation of micro-fissures in the CFC/AMC interface due to the cyclic heat loading.
- However, the IR surface temperature measurement during the loading confirmed the full heat transfer capability of the interface despite the identified partial delamination.

6. Summary and outlook

Sample loaded with 10,000 pulses

- No degradation of the CFC structure after the 10,000 cycles observed.
- No indication of a growing delamination between the different types of carbon fibres and the matrix, both for the ex-pitch, and for the ex-PAN fibres.
- Micro-fissures are visible in the CFC/Cu interlayer. This is the cause of the measured surface temperature increase.
- The heat transfer capability is slightly reduced, but the laser structured CFC surface prevents crack propagation and the formation of large failures.
- As result, no sudden loss of tiles expected.
- No irregularities revealed in the AMC/Cu bonding of the investigated samples after the extended HHF load cycles. No cracks could be identified which would give rise to an increased failure probability of the component.

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6. Summary and outlook

Thermally overloaded sample

- The results of 3D analysis along different planes through the sample explain the evaporation mechanism of CFC. The ex-pitch fibre planes essentially survived while the matrix and the ex-pan fibres are strongly damaged.
- From these observations it can be concluded that the CFC is able to withstand a limited number of overload pulses without total failure. The remaining ex-pitch fibre bundles ensure a reduced functionality of the CFC as plasma facing material.

6. Summary and outlook

- Neutron computed tomography is a unique tool to examine high-Z and low-Z materials combined.
- Contrast agents can be applied to increase contrast and mark voids even behind metallic structures.
- Neutron computed tomography is often the method of choice when X-ray tomography fails.

- The ANTARES facility for neutron imaging of the FRM II reactor of Technische Universität München is available for further examinations, together with more neutron instruments.

6. Summary and outlook

Further information on

www.frm2.tum.de

Thanks!