Microstructural parameters for modelling of superconducting foams

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Abstract Modelling the mechanical and superconducting properties of superconducting, open-cell foam samples requires a proper description of their specific microstructure. A large superconducting $YBa_2Cu_3O_x$ (YBCO) foam (dimensions 5 x 2 x 2 cm^3) sample prepared at RWTH Aachen [1,2] was investigated using optical microscopy, AFM, SEM (EBSD) and x-ray tomography, enabling to identify the parameters important for modelling.

Why superconducting foams?

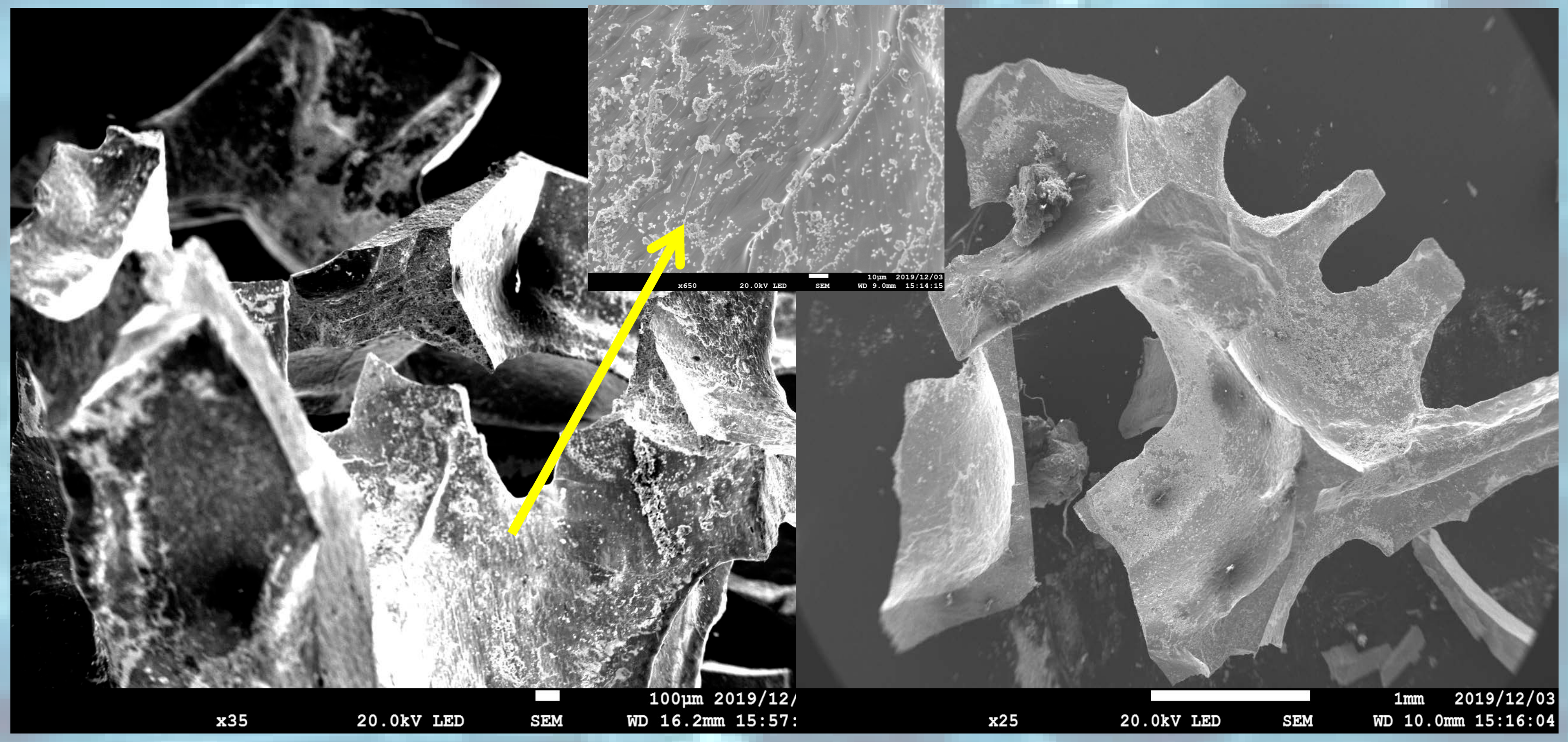
The foams may be applied as **ultra-light trapped field (TF) magnets** whereever the weight and the cooling efficiency counts, e.g., in space.
High cooling efficiency (coolant can pass through the sample).
Straightforward **scalability of the sample size** (limited only by furnace size).

How are foams prepared?

(1)Polyurethane foam as base material
(2)Covering this foam by a slurry of Y-211 and PVA
(3)Heat treatment to burn off the polymer → „green“ Y-211 foam
(4)IG-process to convert Y-211 into 123 phase, including a seed crystal
→ the overall foam sample shows a texture like a bulk sample.

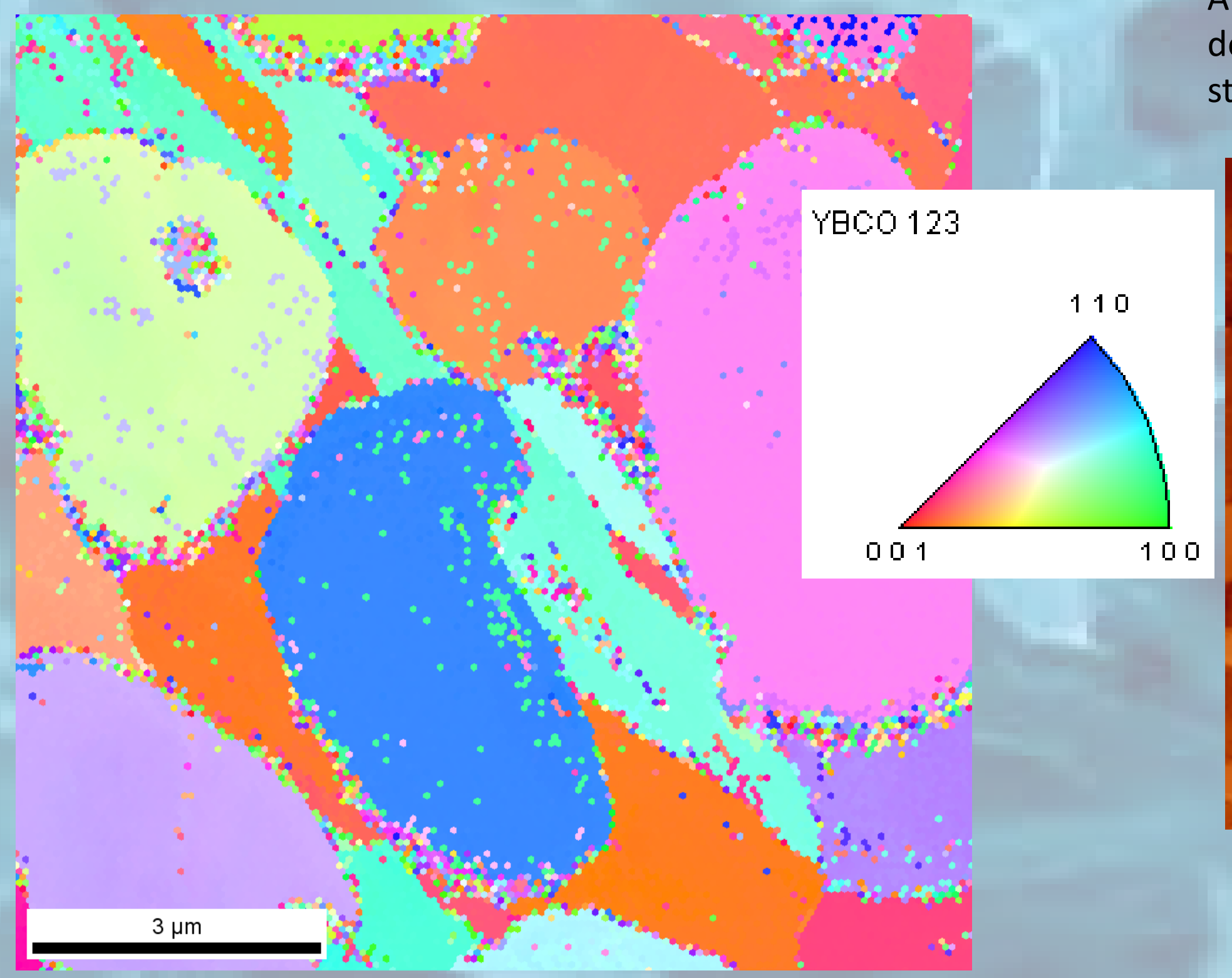
SEM imaging

Gives information on strut arrangement and details of the strut surfaces. High magnification reveals liquid phase particles.



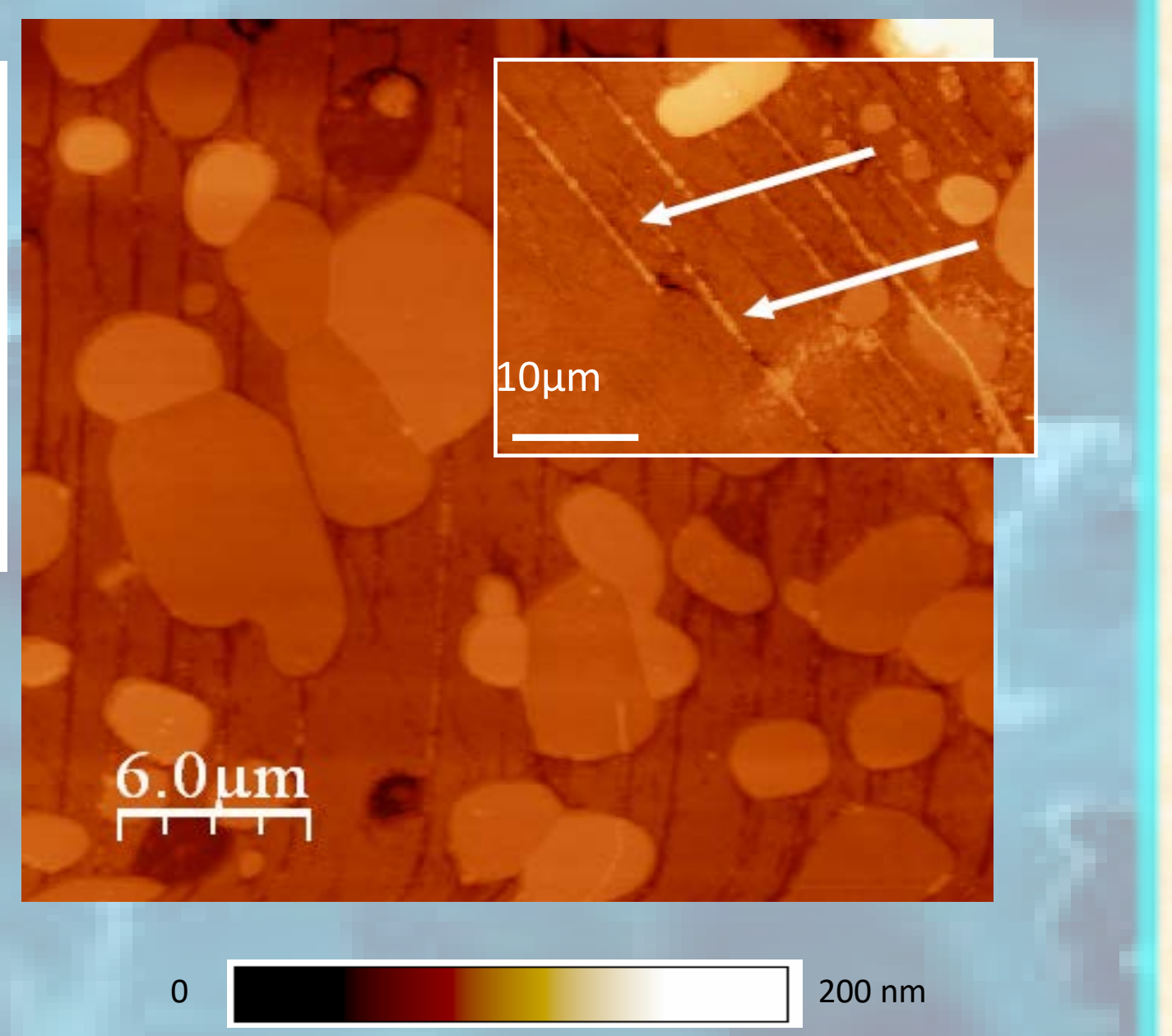
EBSD orientation imaging

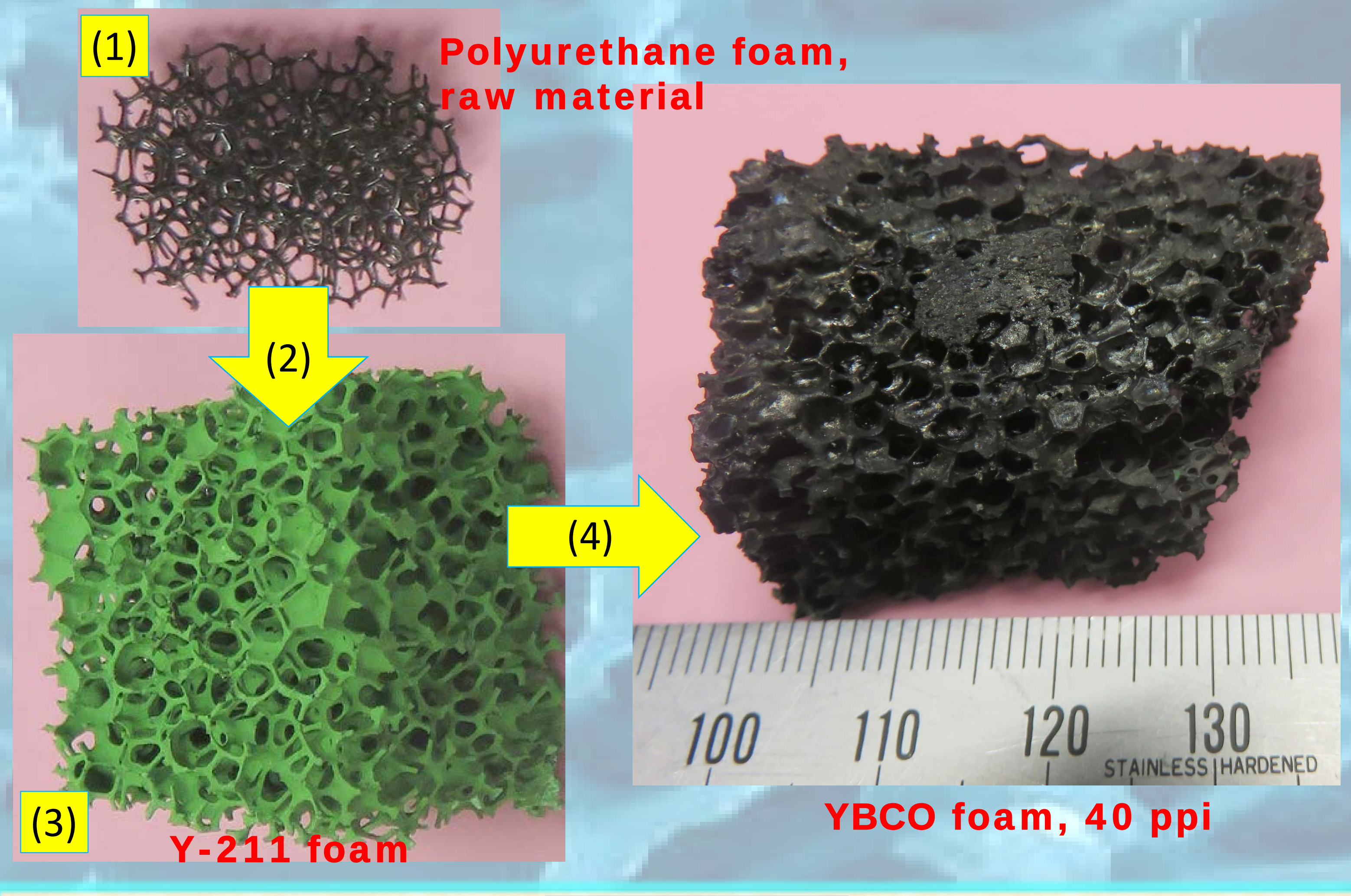
Yields the crystallographic orientation and phase distribution



AFM topography

AFM reveals the height profile (after polishing) and details of the sample growth like the characteristic stripes filled with tiny Y-211 particles



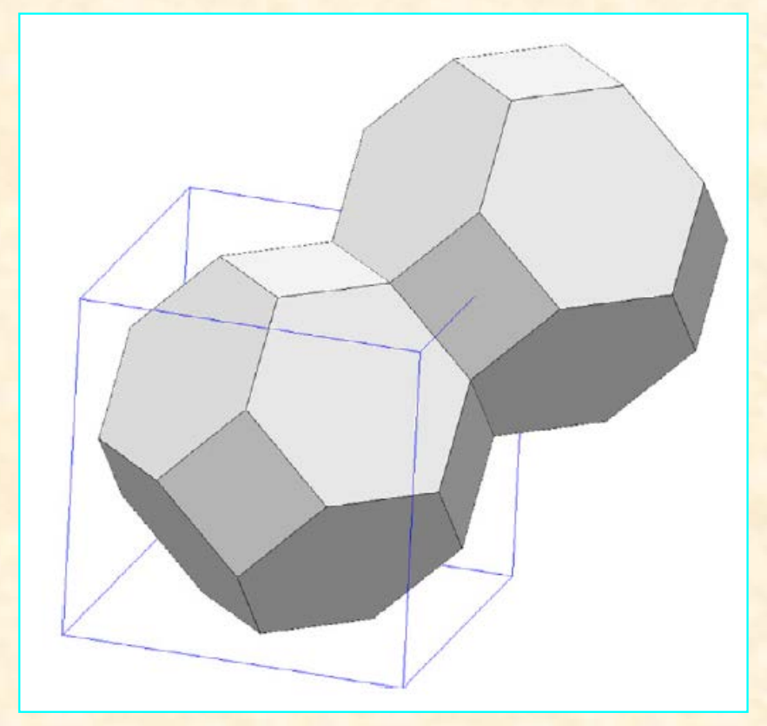


Polyurethane foam, raw material

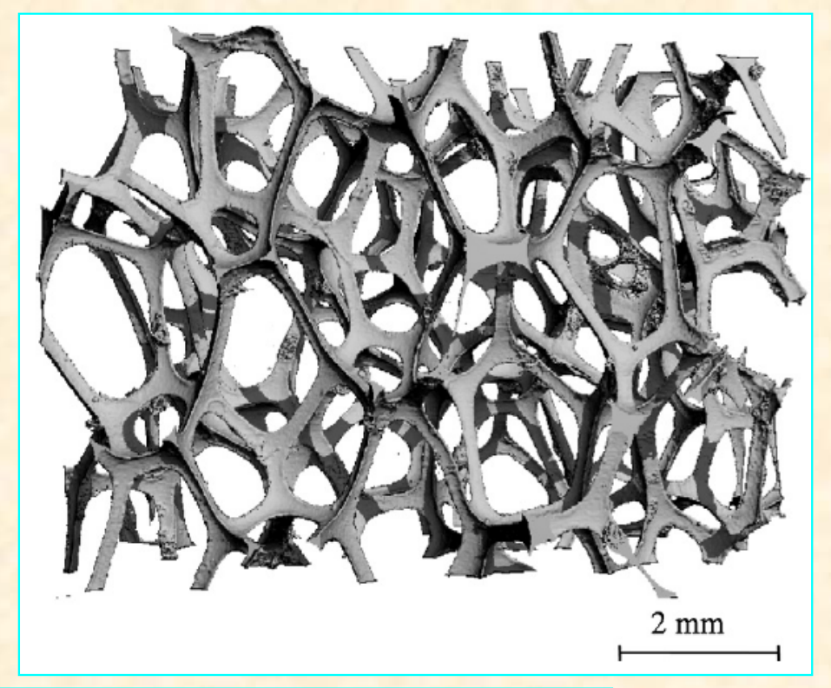
Y-211 foam

YBCO foam, 40 ppi

Numerical modelling of foam sample

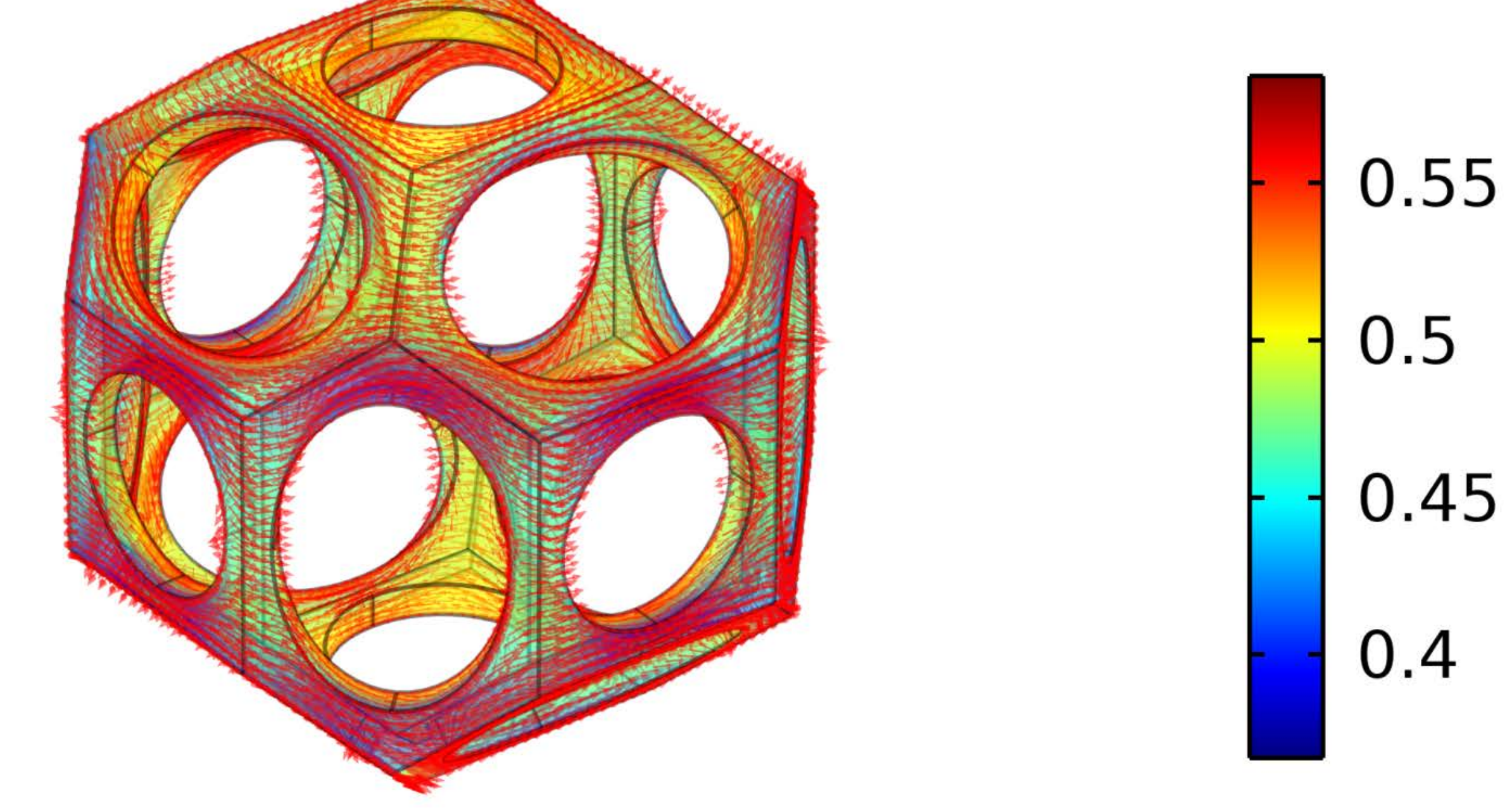


2 Kelvin cells, drawn by Surface Evolver



„real“ foam structure,
20 ppi polyurethane foam

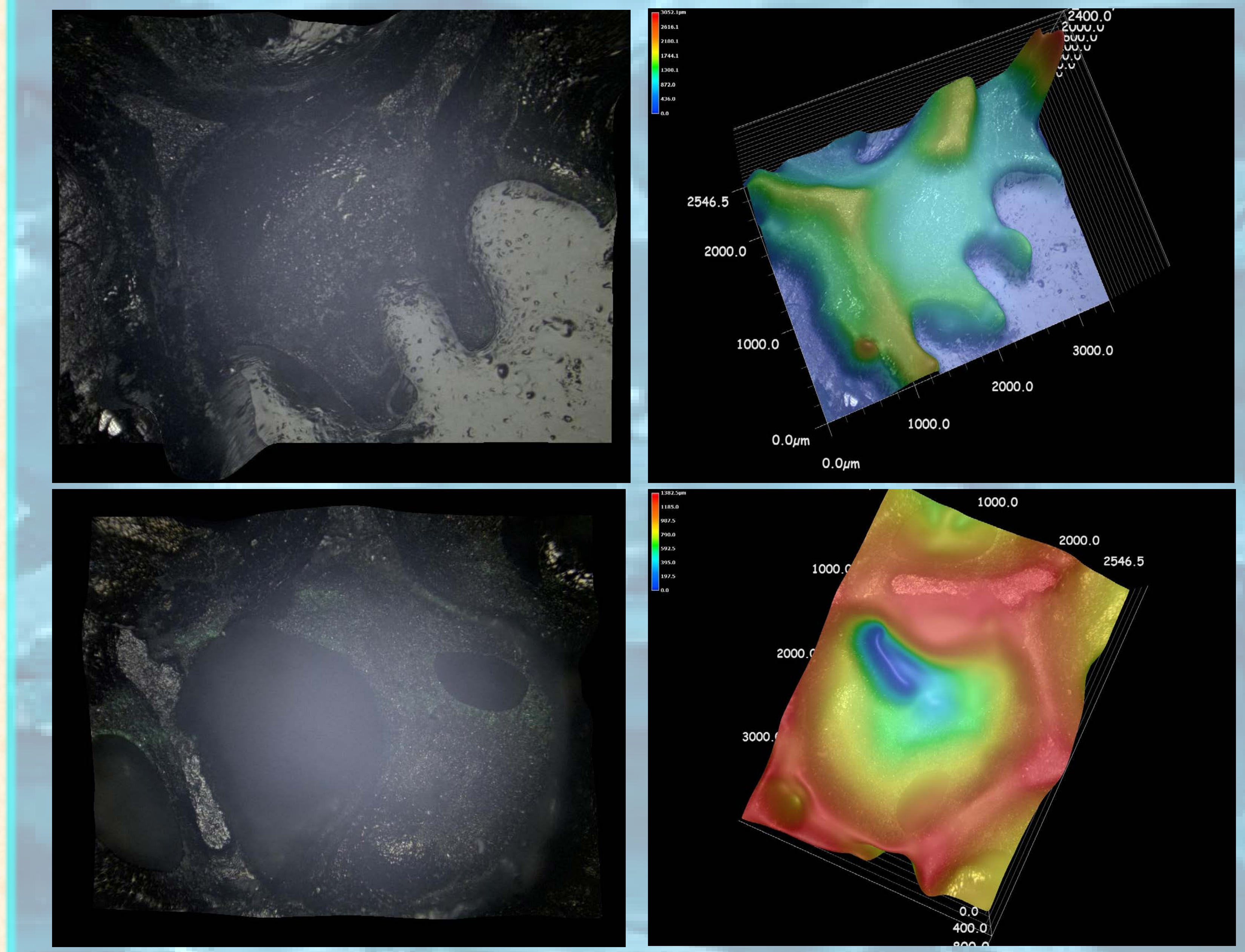
Modeling trapped fields



Microstructure considerations

The foam microstructure is relatively complicated due to the 3D-arrangement of the foam struts. The overall sample has (001)-orientation due to the seed crystal, but for a given strut, the position in the original sample determines the orientation. Thus, EBSD measurements reveal only pointed information, but gives details on the arrangement of Y-211 particles and the YBCO matrix.

The Kelvin cell geometry has been used by many researchers to represent foam structures. This geometry consists out of six square and eight hexagonal faces and is capable to partition the space into identical equal-volume units with minimal surface energy. However, we see that in this model all foam struts are identical, and the nodes, where the struts interconnect, are quite simplified. Although such Kelvin cell models have proven to be useful to model the mechanical response of cellular materials, the geometry of the Kelvin cell does not comply with a real foam topology. The cells of real foams are irregular polyhedra with anywhere from 9 to 17 faces in nearly monodisperse foams [5-8]. The material is concentrated in the nearly straight ligaments and in the nodes where they intersect. Thus, the mechanical properties of foams depend strongly on the microstructure realized, and on the basic properties of the base material. The specific part of the microstructure, which is relevant for the mechanical properties of the foam, is the shape and geometry of the various nodes. Thus, it is essential to determine the relevant parameters (cell size, cell anisotropy, ligament length) of the superconducting foam samples, requiring 3D-imaging of the foam structure.



3D optical images (Keyence VHX 5000)

Using 3D microscopy, the pore structure of the foam can be investigated in detail. From a large number of such images, we can deduce the variation of the pore size and the dimensions of the foam struts throughout the foam sample. Together with X-ray tomography, this will yield a full picture of a given foam sample.

Current flow The flow of the superconducting currents in a foam sample is manifold: (i) There is a current flow in the entire sample perimeter, which can be visualized by trapped field measurements [9]. (ii) Currents can flow in small circles around a given pore. This current flow gives rise to the sharp peaks seen in the trapped field measurements. (iii) Currents can branch up at the nodes in the structure. (iv) Currents flowing within the foam struts face the variation of orientation of the superconducting material, depending on the location within the foam sample. We have to note that there is a specific structure of the foam struts: The tiny Y-211 particles are located mostly in groove-like channels within the YBCO matrix [3], and the strut surface exhibits the presence of $Ba_3Cu_5O_8$-particles stemming form the liquid source in the IG-processing, which may contribute to the flux pinning. All these details do not play a role for the mechanical properties, but are essential for the superconducting performance. Thus, the final model must consider all these specific details of the foam microstructure.

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