

Perspective in NMR: REBCO coated conductors in the Bruker Ultra-High-Field NMR Magnets

Nikolay Mineev

On behalf of the Bruker UHF team

Perspective in NMR: REBCO coated conductors in the Bruker Ultra-High-Field NMR Magnets

01 Requirements for an NMR magnet

02 Bruker NMR magnets and the UHF program

03 1.3 GHz prototype NMR Magnet

04 Magnet technology

05 Coated Conductors requirements for NMR applications

Requirements for an NMR magnet

Requirements for an NMR magnet

NMR measurements requirements:

- **Very high homogeneity** of the magnetic field in the sample space for high-resolution NMR
 - Requirement: $\delta B/B \leq 10^{-9}$ in the sample volume (~20 mm long cylinder, \varnothing 5 mm)
- **Very time-stable magnetic field** (very small field drift)
 - Requirement: **10 ppb/h** (loss of 1% of field in ~ 110 years)
- Higher fields lead to:
 - **higher resolution** (dispersion), i.e. better peak separation
 - **higher signal to noise ratio** (SNR) – the signals are genuinely small

Product related requirements:

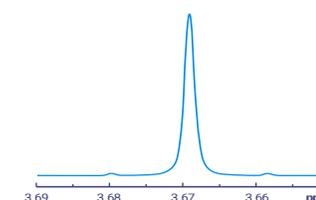
- **System size**: required lab space and transportability;
- **Cryogen consumption** during operation;
- **Price** for the system.

Field in z-direction:

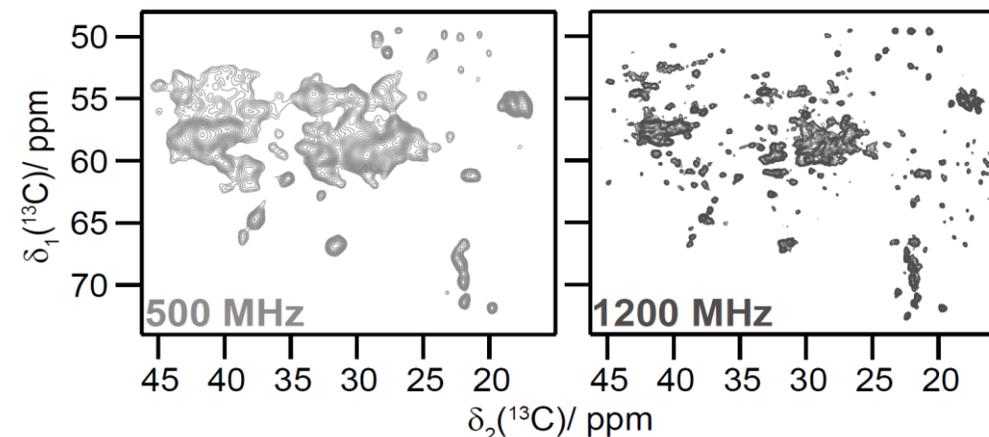
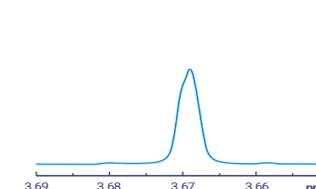
homogeneous:



Spectral peak:



with z-gradient:



20 ms DARR spectra of the DnaB helicase from *Helicobacter pylori*, recorded at 500 MHz (11.7 T) and at 1.2 GHz (28.2 T). Source: doi.org/10.1101/2021.03.31.437892

Bruker NMR magnets and the UHF program

Bruker Magnetic Resonance solutions

Bruker Magnetic Resonance (BioSpin Group) systems production is spread among 3 locations in Europe:



Bruker Switzerland,
Fällanden, Zürich area



Bruker France,
Wissembourg, Bas-Rhin region



Bruker Ettlingen,
Ettlingen, Baden-Württemberg

Bruker NMR magnets

Standard RT bore – 54 mm
Wide bore – 89 mm
Super wide bore – 154 mm



Bruker BioSpin has an active portfolio of NMR spectrometers with base frequency from 80 MHz (1.88 T benchtop) up to 1.2 GHz (28.2 T). The lower field magnets have also wide bore and a super-wide-bore versions. The total production capacity exceeds 500 magnets per year.



Bruker NMR magnets

Bruker BioSpin uses all the conventional superconductors in its magnets including NbTi, Nb₃Sn and HTS.



NbTi

everywhere

Nb₃Sn

systems above 10 T

HTS

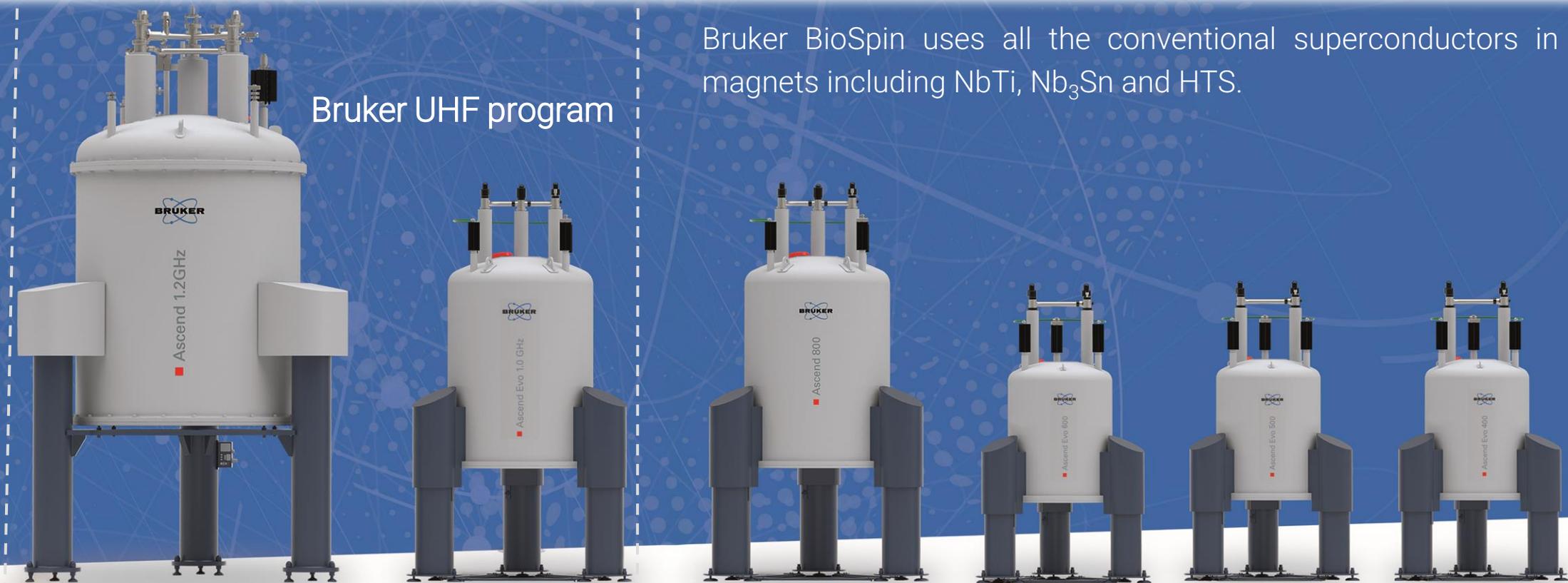
systems above 23 T

(In case of standard bore magnets)

Bruker NMR magnets

Bruker UHF program

Bruker BioSpin uses all the conventional superconductors in its magnets including NbTi, Nb₃Sn and HTS.



| | |
|--------------------|--------------------|
| NbTi | everywhere |
| Nb ₃ Sn | systems above 10 T |
| HTS | systems above 23 T |

(In case of standard bore magnets)

Bruker Ultra-High-Field program

Within the [Bruker UHF Program](#) the successful implementation of REBCO conductors enabled the highest field commercially available NMR spectrometer at the time:

[1.1 GHz and 1.2 GHz Ascend spectrometers \(2 K\).](#)

■ 2019



Ascend 1.1 GHz:
HTS/LTS hybrid, 2 K (25.9 T)

■ 2020



Ascend 1.2 GHz:
HTS/LTS hybrid, 2 K (28.2 T)

Bruker Ultra-High-Field program

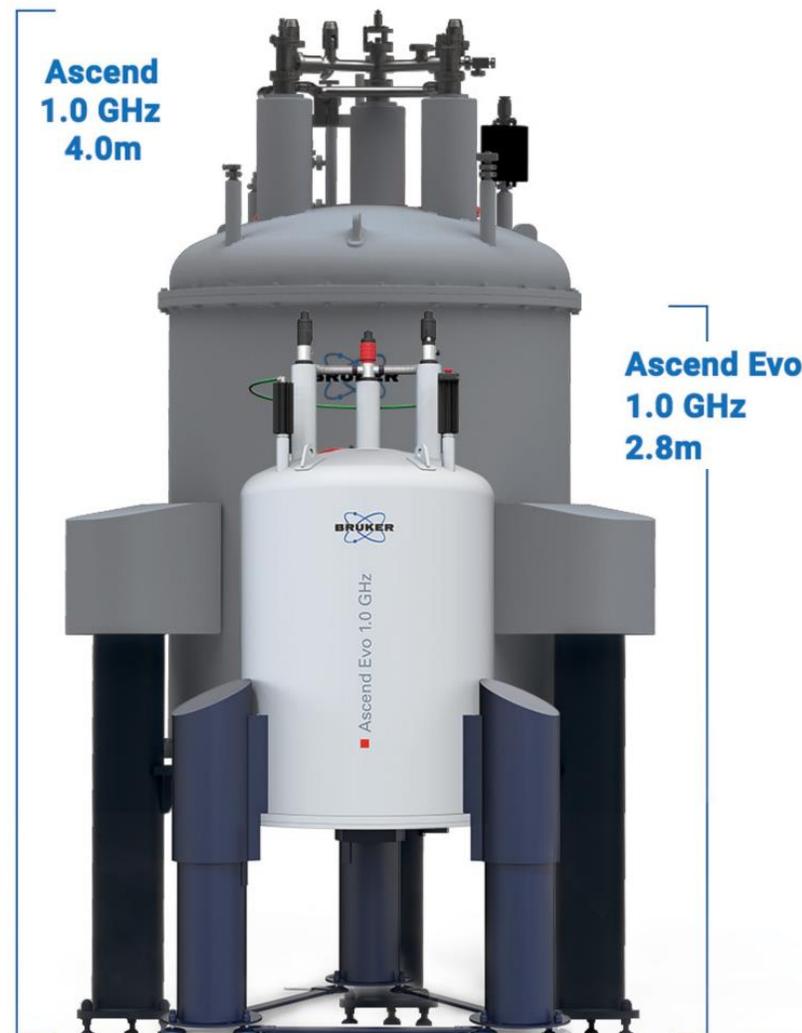
The use of REBCO conductors can not only increase the field strength of the magnets, but for lower field magnets also enables a step in a size reduction and a step in the operation temperature (4.2 K vs 2 K):

Ascend Evo 1.0 GHz (2023):

1.0 GHz (23.5 T) for single-story standard laboratories:

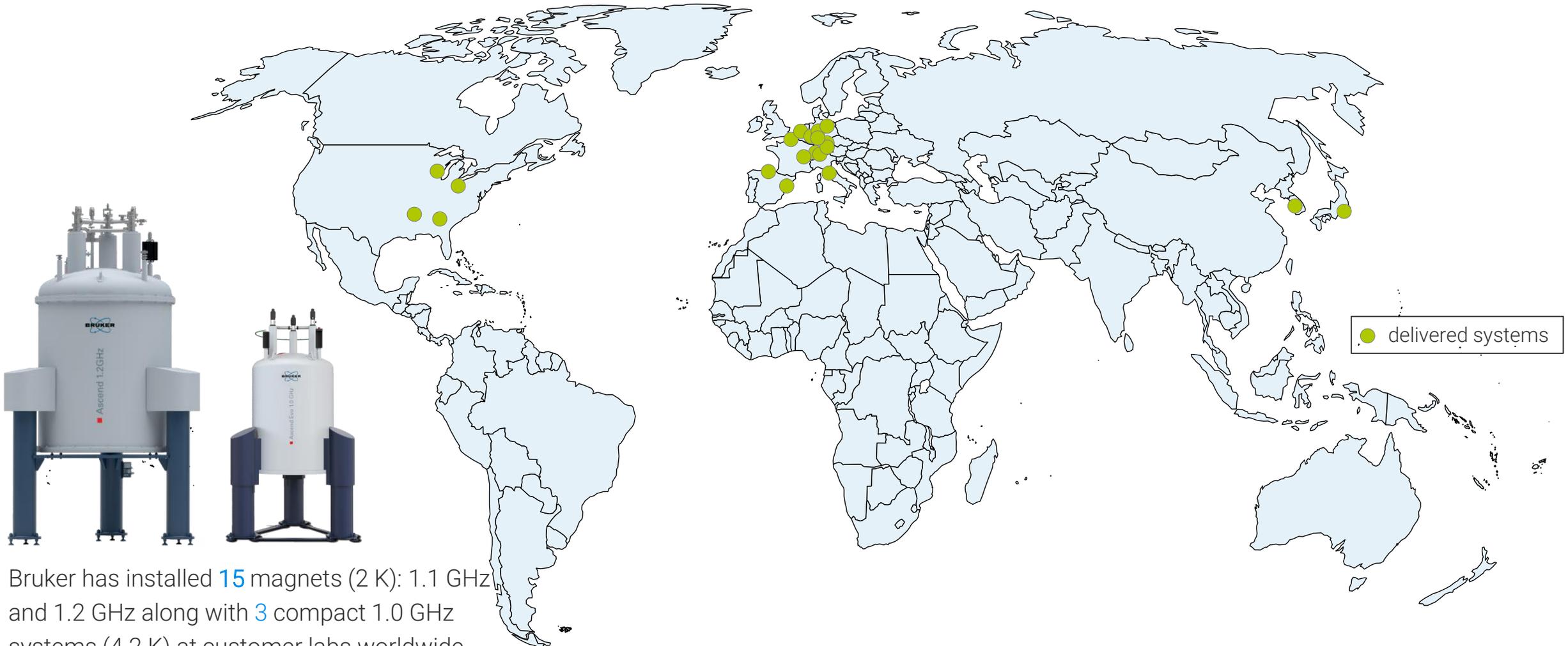
Easier siting with significantly reduced footprint, weight and stray field:

- Total weight: < 1/3 compared to Ascend 1.0 GHz
- Helium boil-off: < 1/3 compared to Ascend 1.0 GHz
- He hold time: 2 x compared to Ascend 1.0 GHz
- Stray field 5 Gauss containing surface (1.9 m radial x 2.7 m axial): roughly 1/4 compared to Ascend 1 GHz
- Minimum ceiling height: 3.25 m (single-story lab)



Size comparison of Ascend 1.0 GHz (LTS only, 2K) and Ascend Evo 1.0 GHz (HTS/LTS hybrid, 4.2 K)

1.1 GHz, 1.2 GHz and compact 1.0 GHz systems installed worldwide



Bruker has installed **15** magnets (2 K): 1.1 GHz and 1.2 GHz along with **3** compact 1.0 GHz systems (4.2 K) at customer labs worldwide.

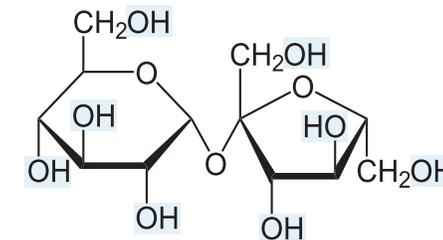
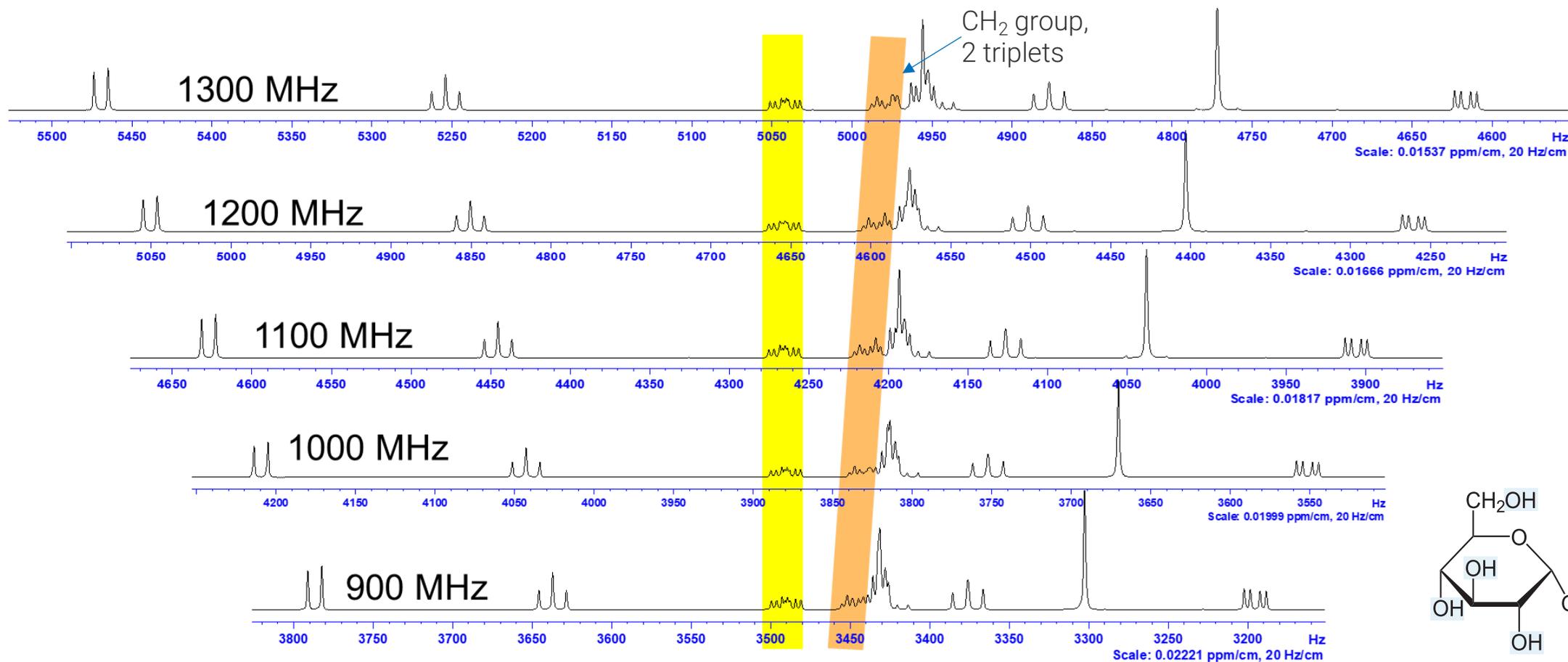
1.3 GHz Magnet (30.55 T)

- In 2024 Bruker has built and tested a prototype of a 1.3 GHz (30.55 T) spectrometer for high-resolution NMR.
- The 1.3 GHz HTS/LTS hybrid magnet is entirely superconducting and operates in persistent mode, with the NMR-class homogeneity marking a new world-record.
- The 1.3 GHz magnet follows the design solutions of the 1.2 GHz magnet, fits into the same cryostat and has the same helium/nitrogen consumption as a Bruker 1.2 GHz magnet, with only a slightly larger (+ 5%) stray field radius.



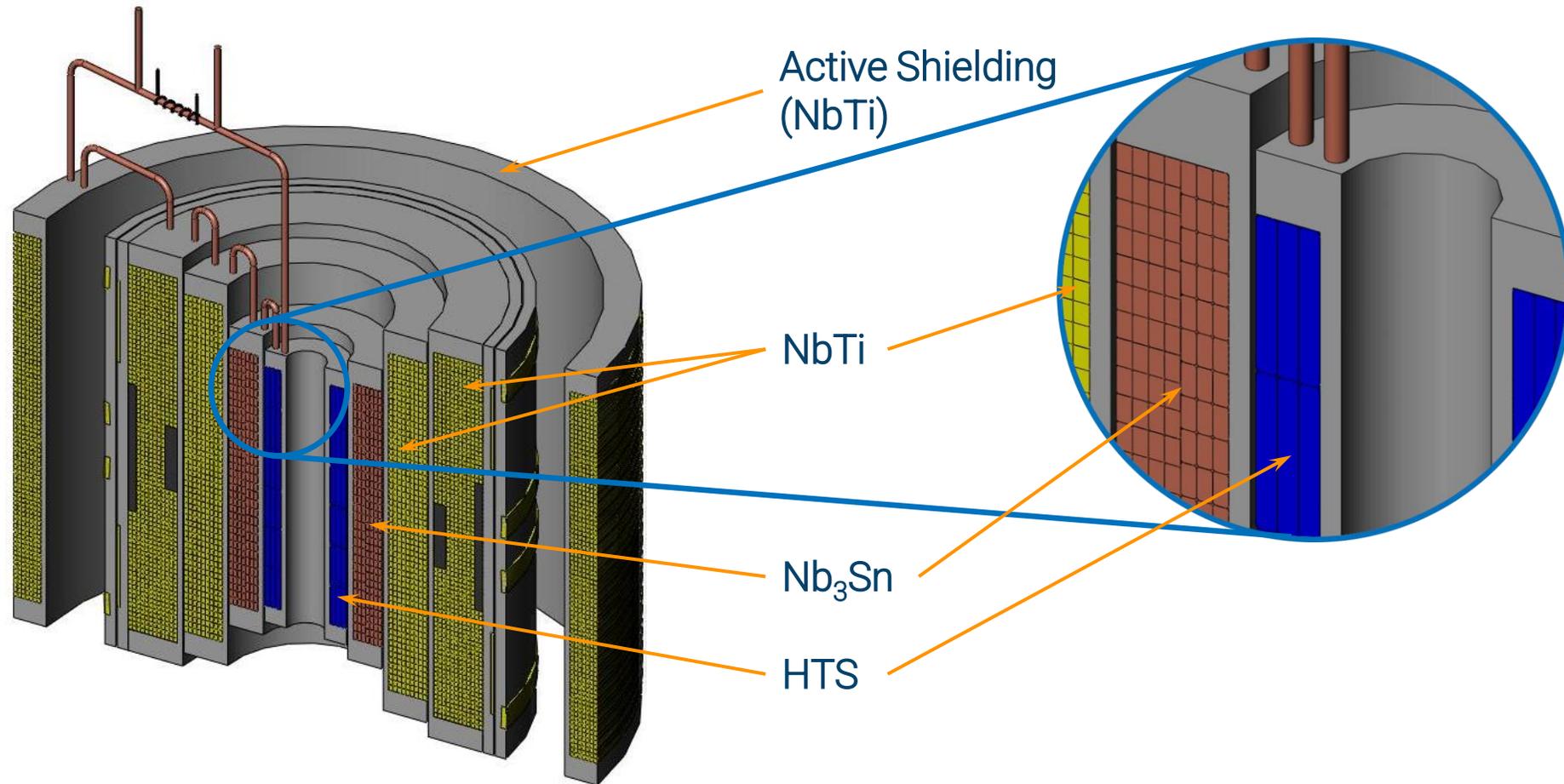
1.3 GHz Magnet (30.55 T), NMR benefits

Sugar signals of 2mM Sucrose in H₂O:D₂O (9:1) illustrate the dispersion gain with increasing field strength:



The UHF magnet technology

Design of the UHF HTS-LTS hybrid magnets



Artistic impression of the 1.x GHz magnet design

Bruker's 1.x GHz HTS-LTS hybrid NMR magnets

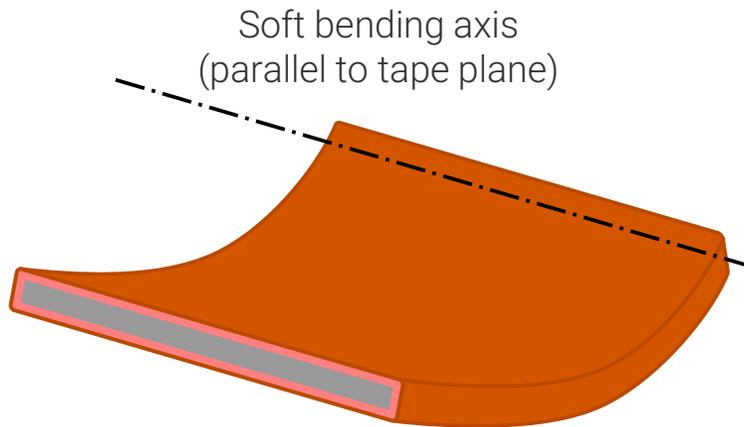
- More than 15 years ago: The [availability forecast of ReBCO coated conductors](#) lead to the start of UHF HTS-LTS hybrid magnet program.
- Design choices based on [test and prototype coils](#):
 - [Layer-wound HTS coils](#):
 - minimum number of joints;
 - compact and homogeneous winding pack;
 - allows [force management](#) for hoop stresses and axial pressures.
 - [Insulated ReBCO coated conductors tapes](#):
 - defined current path during energization and quenches;
 - less time to settle at reached field.



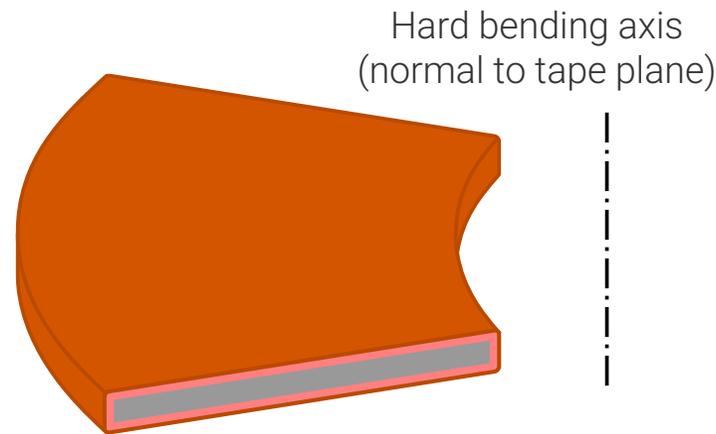
Layer-wound HTS

Winding Coated Conductor tapes

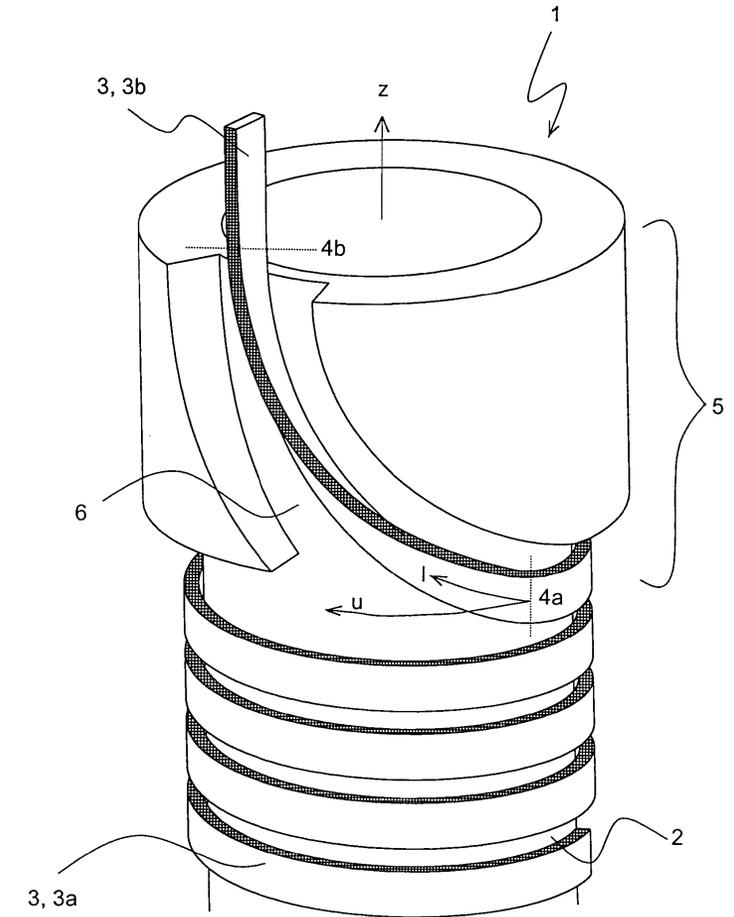
- Attempt to wind with a **minimum of hard bending** everywhere,
- including the region around the **entry to and the exit from the main winding pack**.



Soft-bending a CC tape



Hard-bending a CC tape

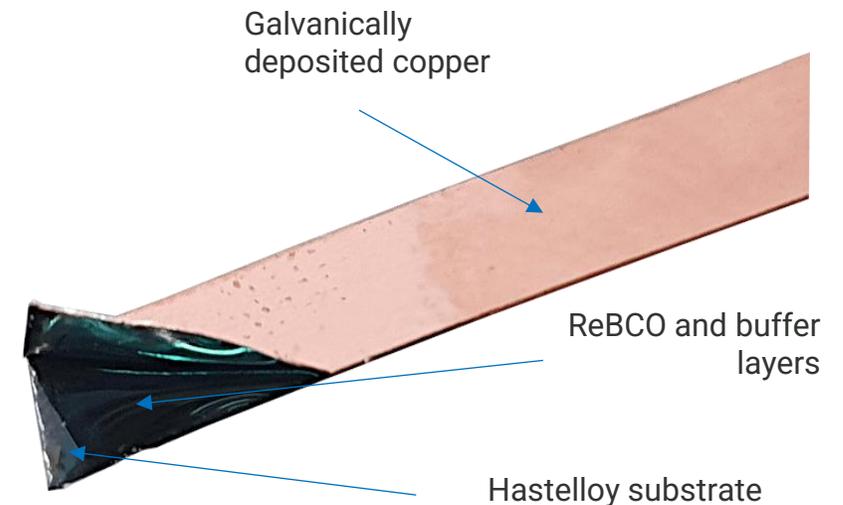


Bruker Patent US 7,215,230 B2

Requirements to REBCO coated conductors for UHF NMR applications

Performance and commercial requirements

- Key technical requirements to ReBCO coated conductors for UHF NMR magnets:
 - Uniform properties along entire piece lengths (I_c , copper, insulation,...),
 - Long piece lengths (typically 300 m to 900 m) without I_c drop-outs (I_c dips),
 - High I_c values at high magnetic fields and low temperatures (I_c at 4 K and 10 T $B_{||c}$: ~350 A to >500 A for 4 mm width),
 - Excellent mechanical properties (Hastelloy substrate,...).
- Commercial requirements:
 - Steady and reliable supply,
 - Pricing.



REBCO tapes insulation requirements

- Tape Insulation:
 - The ReBCO tape insulation shall:
 - **insulate well**: withstand high voltages,
 - be **thin** and **mechanically strong**,
 - **easy to remove** at the tape **ends**.

Good compromise not obvious.

- Insulation options:
 - Wrapping **Polyimide tape**, with or without glue;
 - **Polyimide varnish** insulation is interesting.

Types of Polyimide-tape insulation

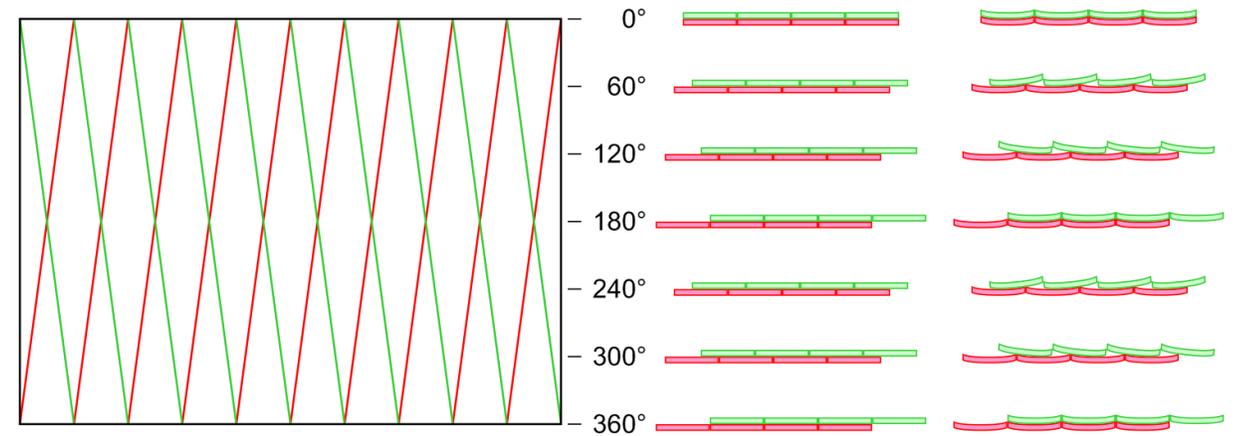


Coated insulation

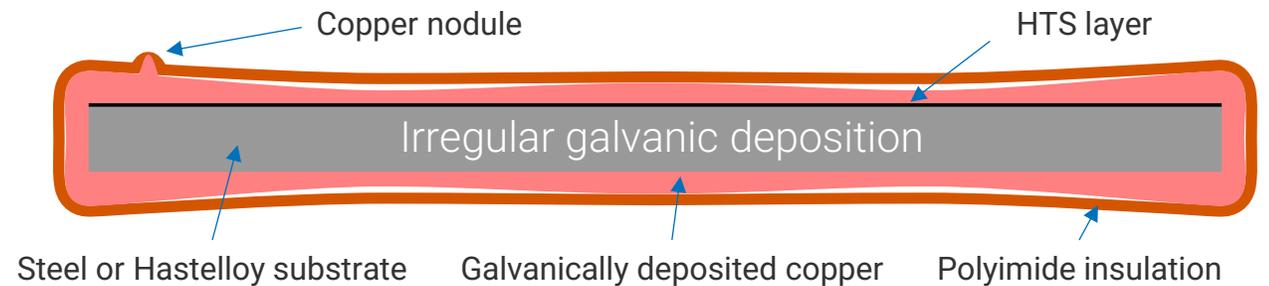


REBCO tapes geometrical requirements

- The goal is a compact winding pack with a minimal void fraction.
- The tape cross section should be as rectangular as possible, irregularities lead to voids.
 - Example curved tapes (“C-bow”): difficult to wind, gaps in winding pack.
 - Example of non-regular galvanic deposition of copper (dog-boning, copper nodules): voids in winding pack, insulation problems.
 - Example of a non-regular substrate thickness.

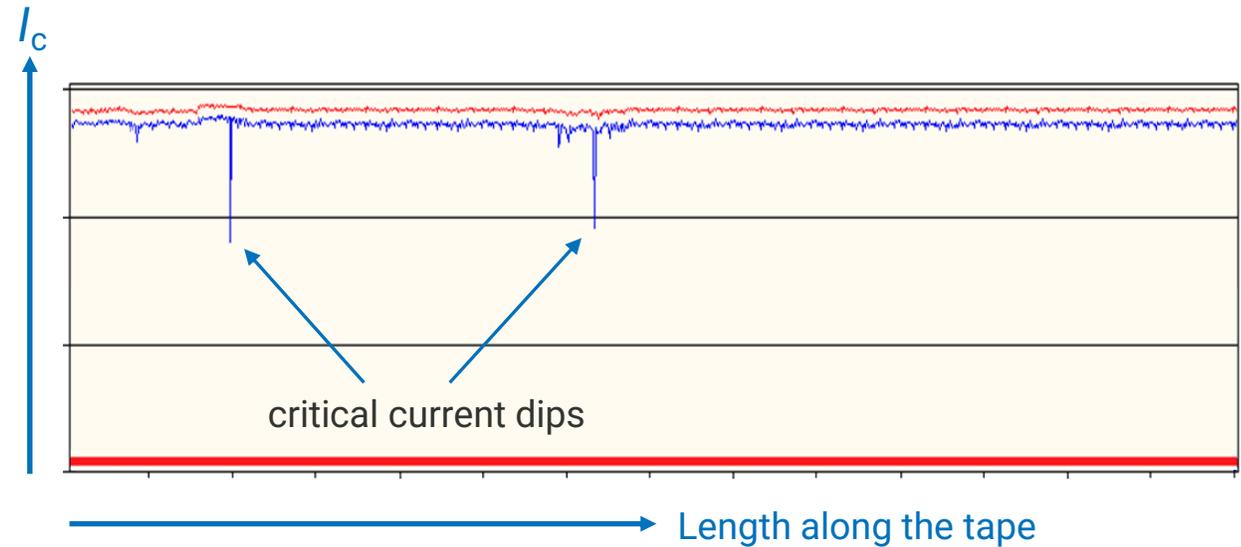


Winding of curved tape



REBCO tapes quality assurance and quality control

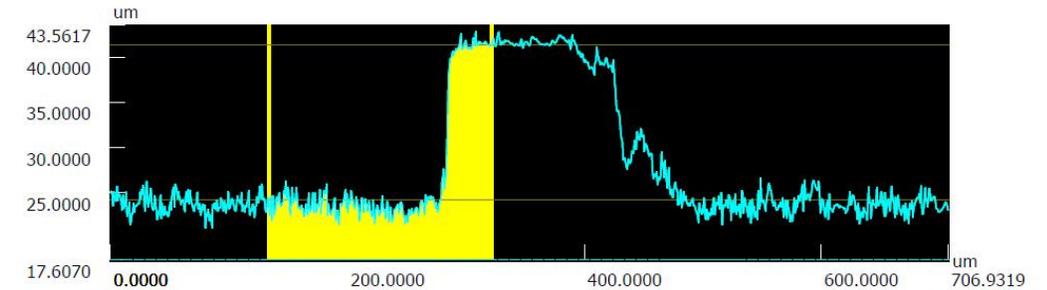
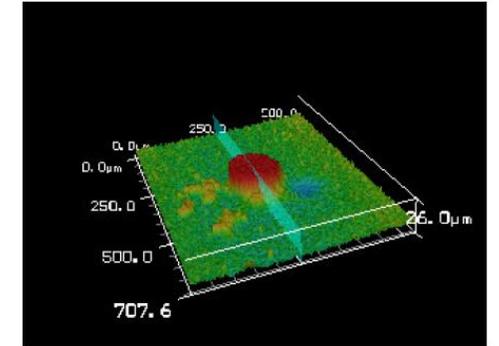
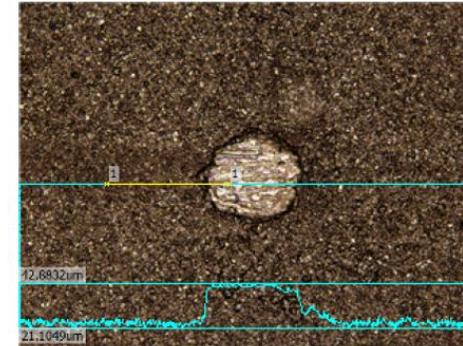
- For the procurement of long **insulated** ReBCO coated conductors, Bruker strongly relies on **the quality assurance and quality control processes** at the ReBCO tape **production sites**.
- Typically, the acceptance of ReBCO coated conductors is based on:
 - magnetic TapeStar™ measurements
 - and transport I_c measurement at 77 K, self-field along the **whole length** of the tapes.



TapeStar™ measurement (symbolic data)

REBCO tapes quality assurance and quality control

- Quality control at Bruker on the ReBCO coated conductors:
 - I_c (@ 4.2 K, 10 T, H||c),
 - micrographs of cross-sections,
 - copper surface analysis with the confocal microscope .

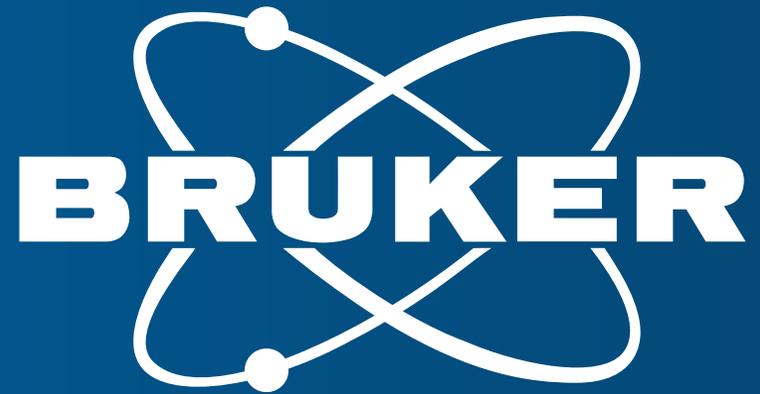


Confocal laser microscope analysis (example of a copper nodule on an HTS tape)

Thank you!

Nikolay Mineev
On behalf of the Bruker UHF team

Geneva
Zürich



Innovation with Integrity