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ReBCO coated conductors for Ultra-High-Field NMR magnets

Patrik Vonlanthen on behalf of Bruker's UHF NMR team

26 October 2022

IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2023.
Submitted October, 2022; Selected October, 2022. Presentation given at Applied Superconductivity Conference, Honolulu, HI, USA, October 26 2022.

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ReBCO coated conductors for Ultra-High-Field NMR magnets

01 ReBCO coated conductors – enabling technology for 1.x GHz magnets

02 Bruker's 1.2 GHz HTS-LTS hybrid NMR magnet program

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07 1.x GHz HTS-LTS hybrid NMR magnets delivered and ordered

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ReBCO coated conductors – enabling technology for 1.x GHz magnets

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ReBCO coated conductors – enabling technology for 1.x GHz NMR magnets

- ReBCO coated conductors, the enabling technology for the new Ultra-High-Field (UHF) magnets
  - Ascend 1.2 GHz (28.2 T, HTS/LTS hybrid, 2 K):
    - highest field commercially available NMR spectrometer.
  - Ascend Evo 1.0 GHz (23.5 T, HTS/LTS hybrid, 4.2 K):
    - GHz-class NMR spectrometer with very compact magnet size.

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

Ascend Evo 1.0 GHz
(HTS/LTS hybrid, 4.2 K)

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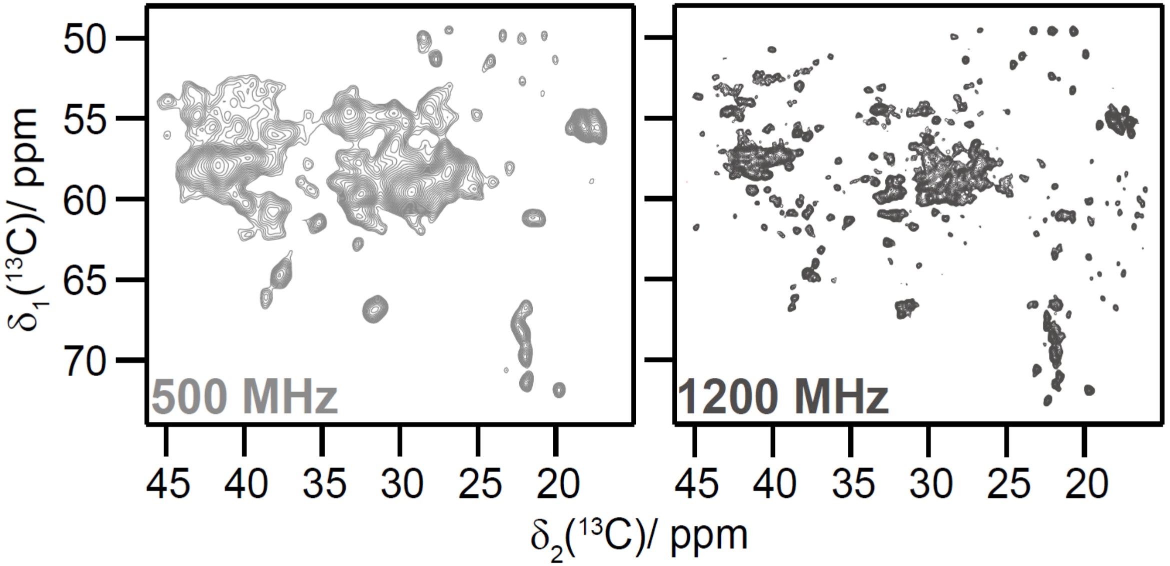
ReBCO coated conductors – enabling technology for 1.x GHz NMR magnets

- Higher fields: ReBCO coated conductors enable magnetic fields beyond the limit of LTS conductors (~1.0 GHz / 23.5 T) with decisive advantages regarding
  - resolution (dispersion), i.e. better peak separation
    - In higher dimension NMR experiments $\propto B_0^n$
  - better signal to noise ratio
    - Bigger energy split between up and down spin states leads to a stronger occupation difference → stronger NMR signal from sample



20 ms DARR spectra of the DnaB helicase from Helico-bacter pylori, recorded at 500 MHz (11.7 T) and at 1.2 GHz (28.2 T). The increase in resolution is clearly visible.
Source: https://doi.org/10.1101/2021.03.31.437892

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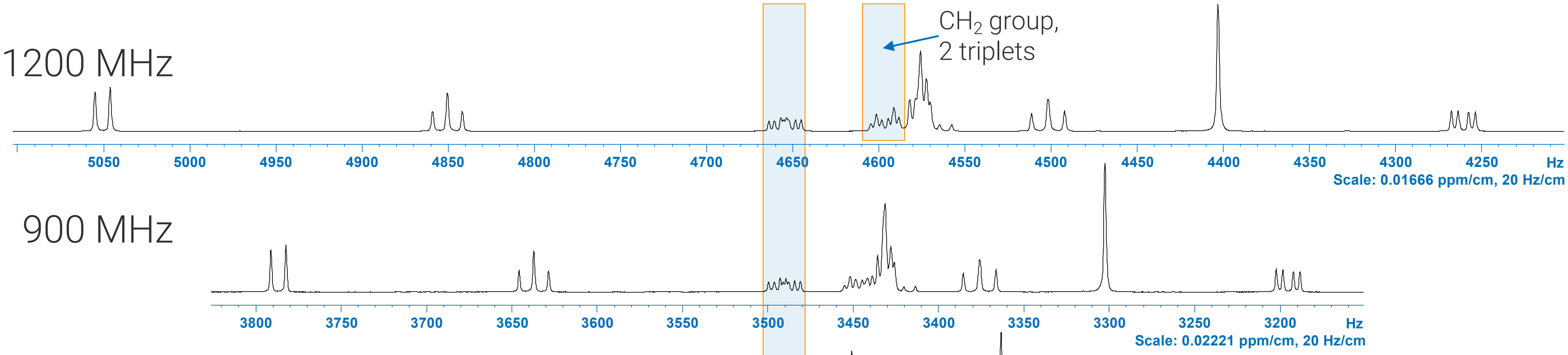
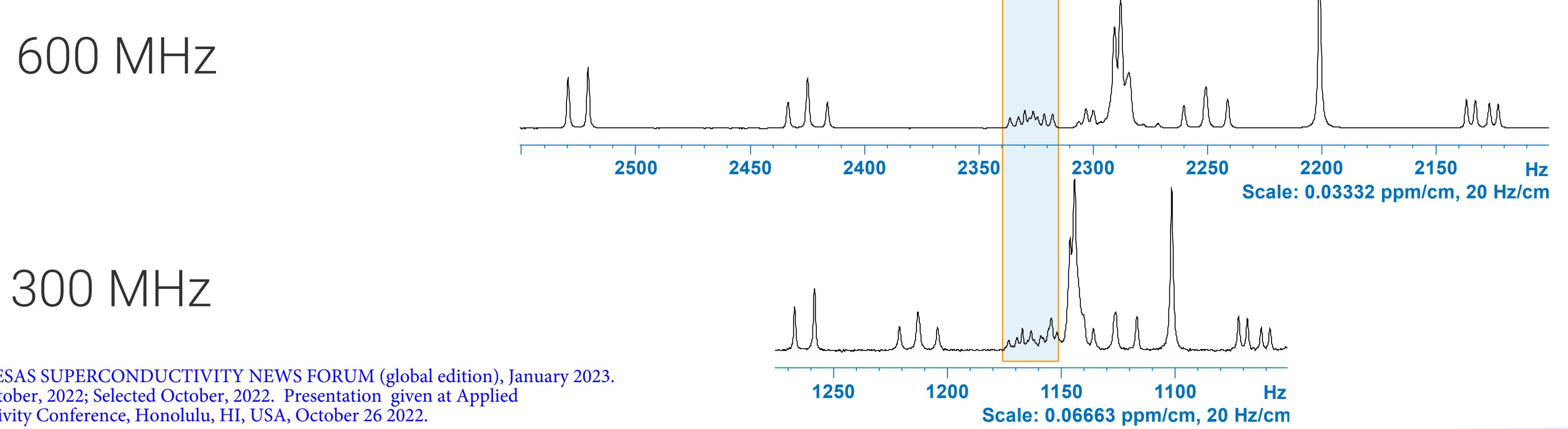
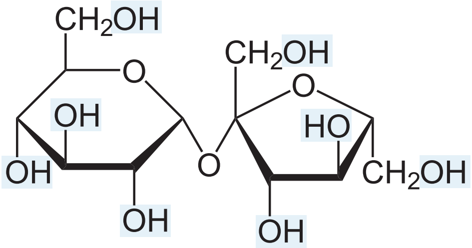
Dispersion at Ultra High Fields

Sugar signals of 2 mM Sucrose in H_2O:D_2O (9:1) illustrate the dispersion gain with increasing field strength







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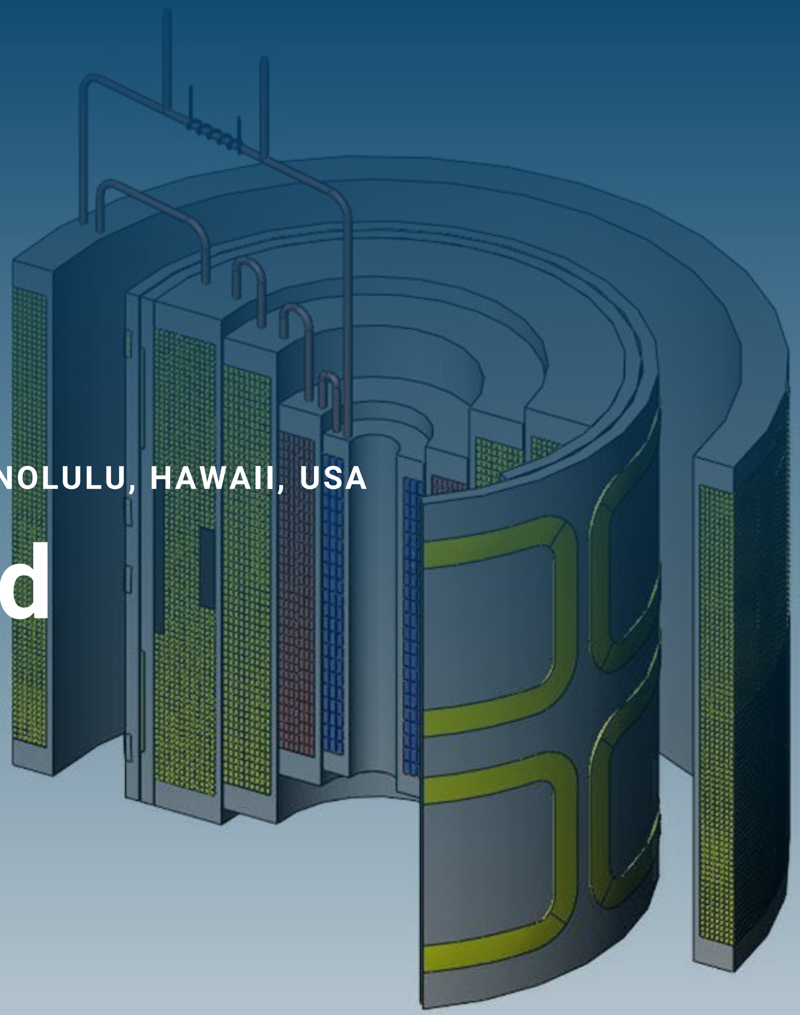
Bruker’s 1.2 GHz HTS-LTS hybrid NMR magnet program



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Bruker's 1.2 GHz HTS-LTS hybrid NMR magnet program

- More than 10 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

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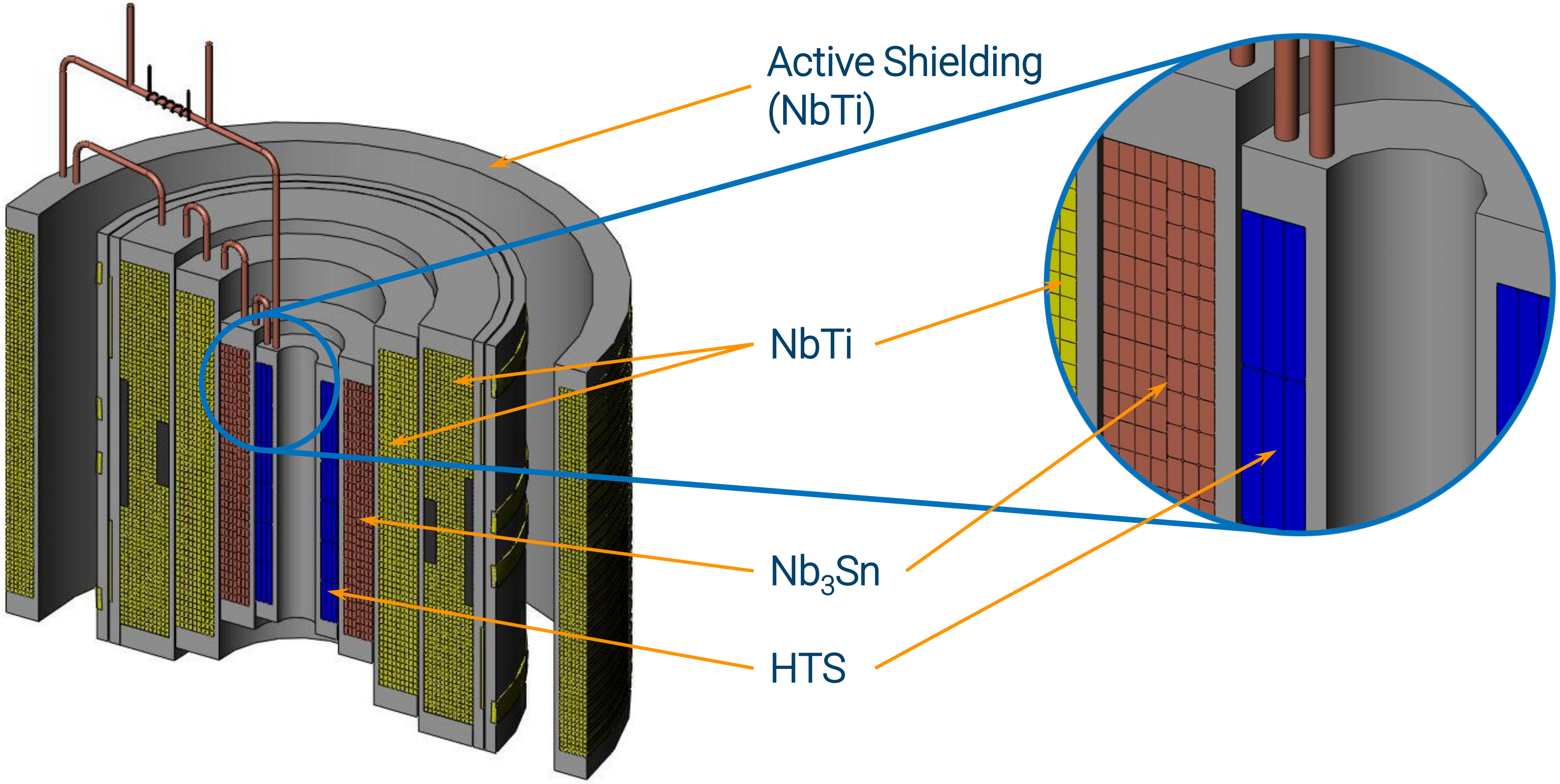
Design of the UHF HTS-LTS hybrid magnets



Artistic impression of the 1.2 GHz magnet design

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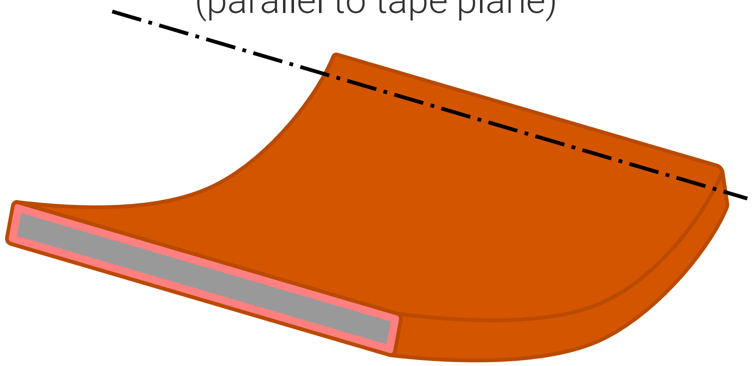
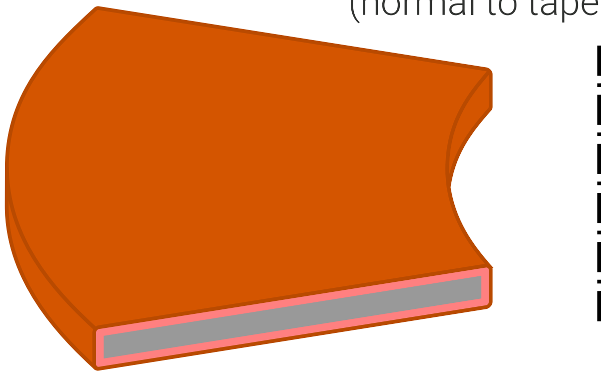
Winding Coated Conductor tapes

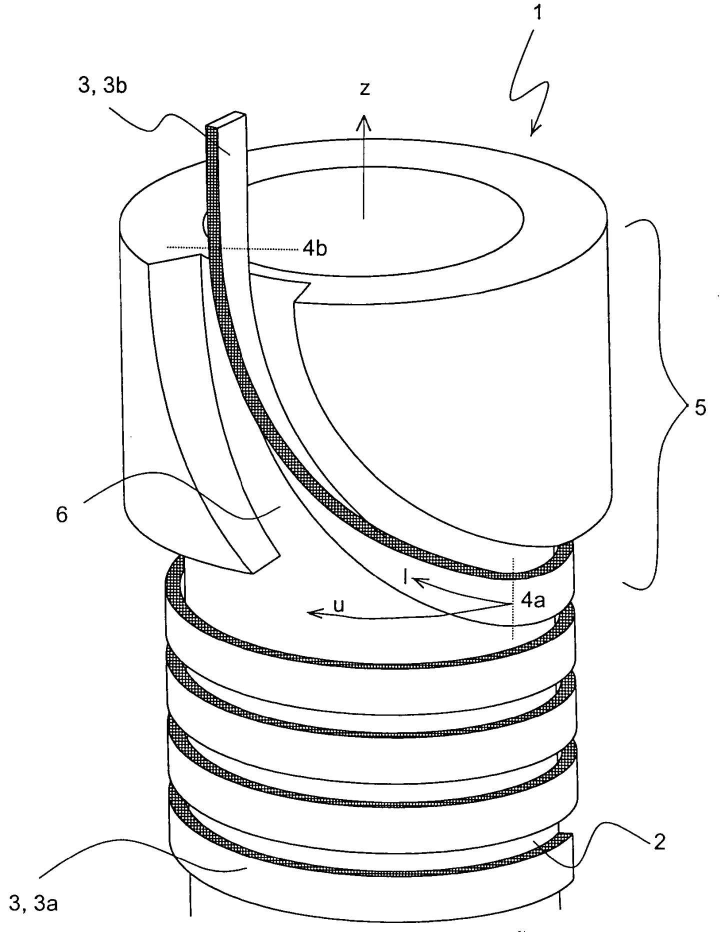
- Attempt to wind with a minimum of hard bending everywhere,
- including the region around the entry to and the exit from the main winding pack.



Soft-bending a CC tape



Hard-bending a CC tape



Bruker Patent US 7,215,230 B2

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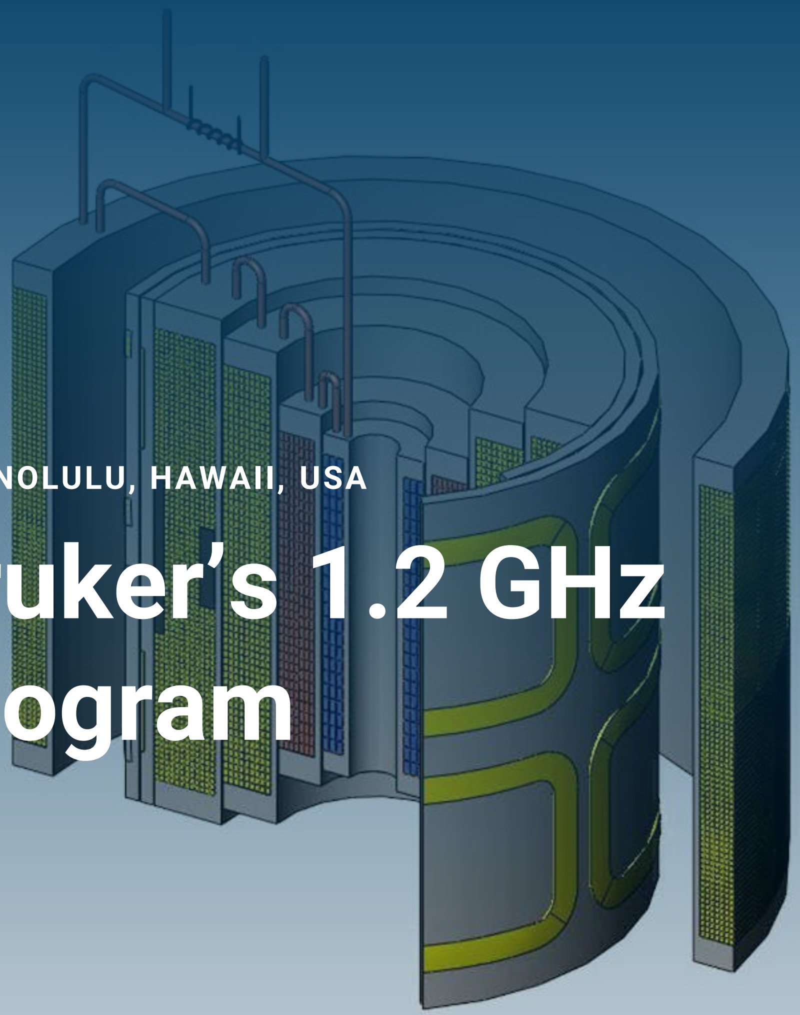
Experience gained so far with Bruker’s 1.2 GHz HTS-LTS hybrid NMR magnet program



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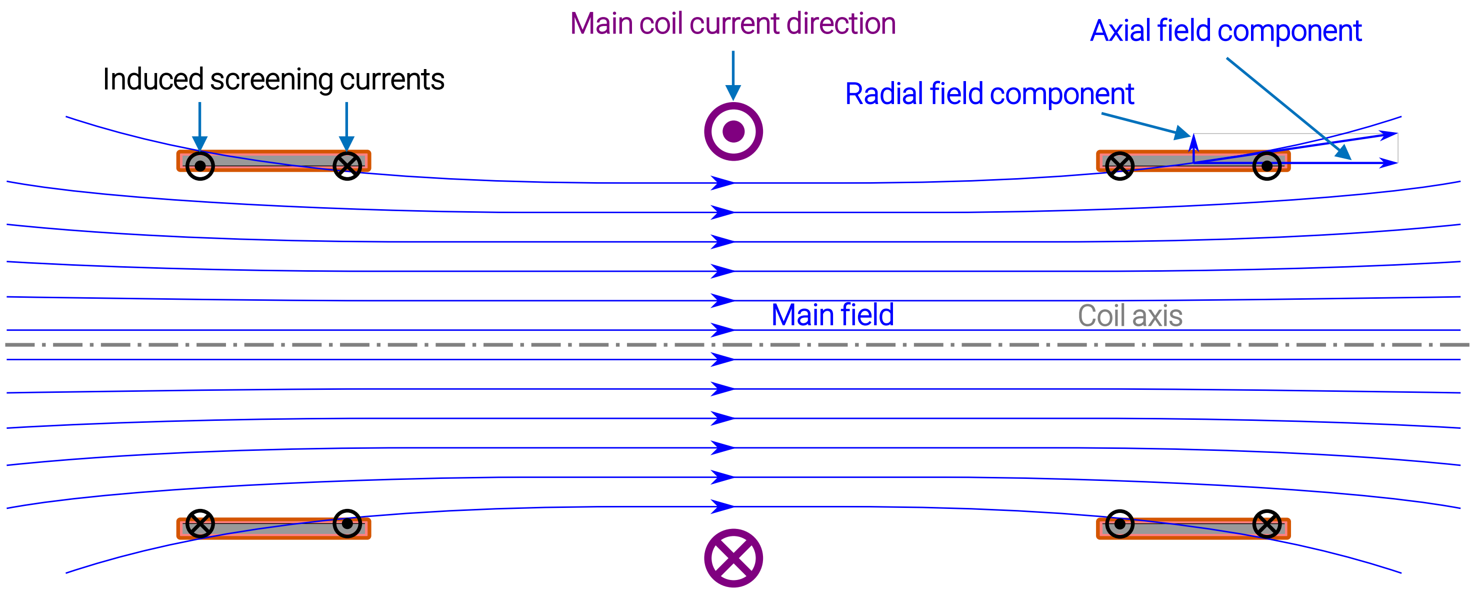
The homogeneity of HTS-LTS hybrid magnets – screening currents

- HTS screening currents strongly influence the magnet's homogeneity
  - The 4 mm wide tapes offer a big area to induce loop currents, which tend to screen the magnetic field.
  - At the centre of a solenoid the screening currents mainly generate
    - an additional negative field (reducing the total field)
    - a z^2 gradient.



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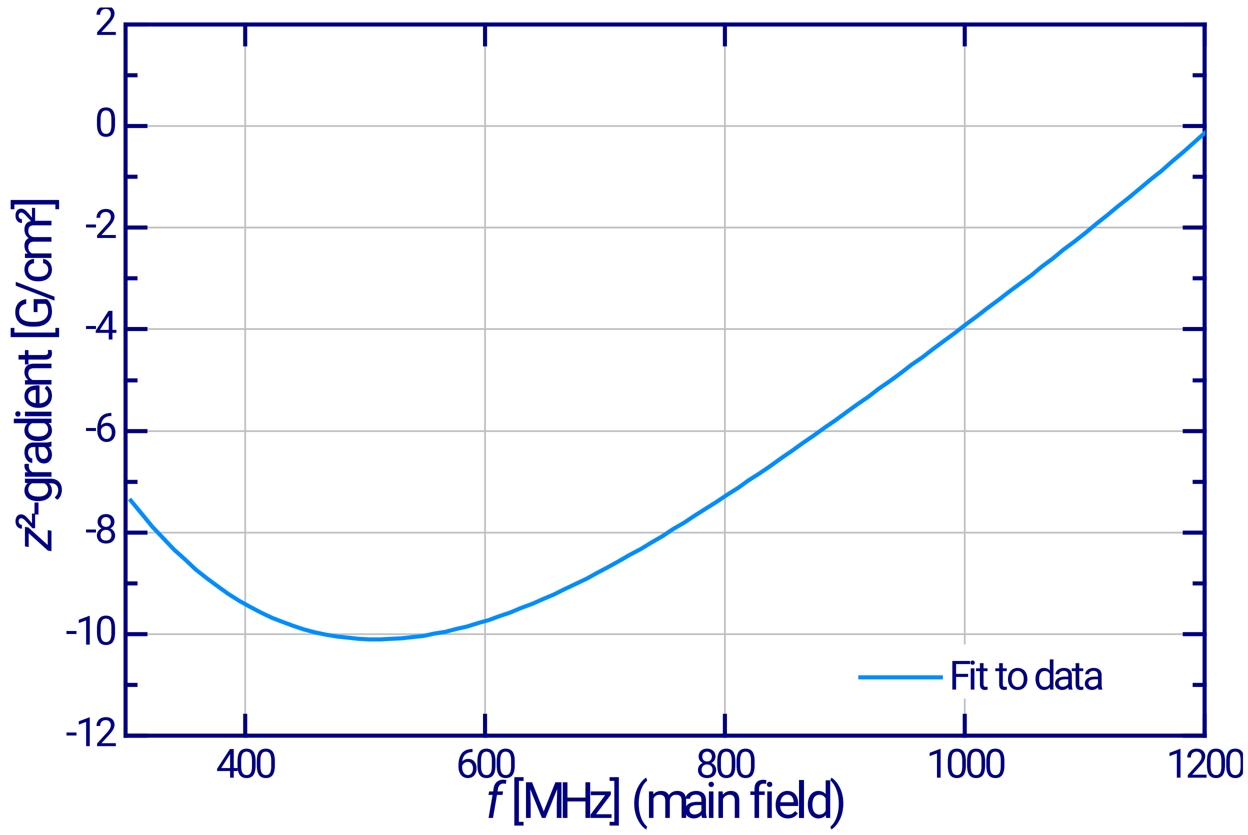
z^2 gradient of HTS-LTS hybrid magnets during energization

- The z^2 gradient varies considerably during magnet energization.
- The goal is to get zero z^2 gradient at the target field.
  - This effect must be considered in the magnet homogenization.



z^2 gradient of a 1.2 GHz magnet during energization

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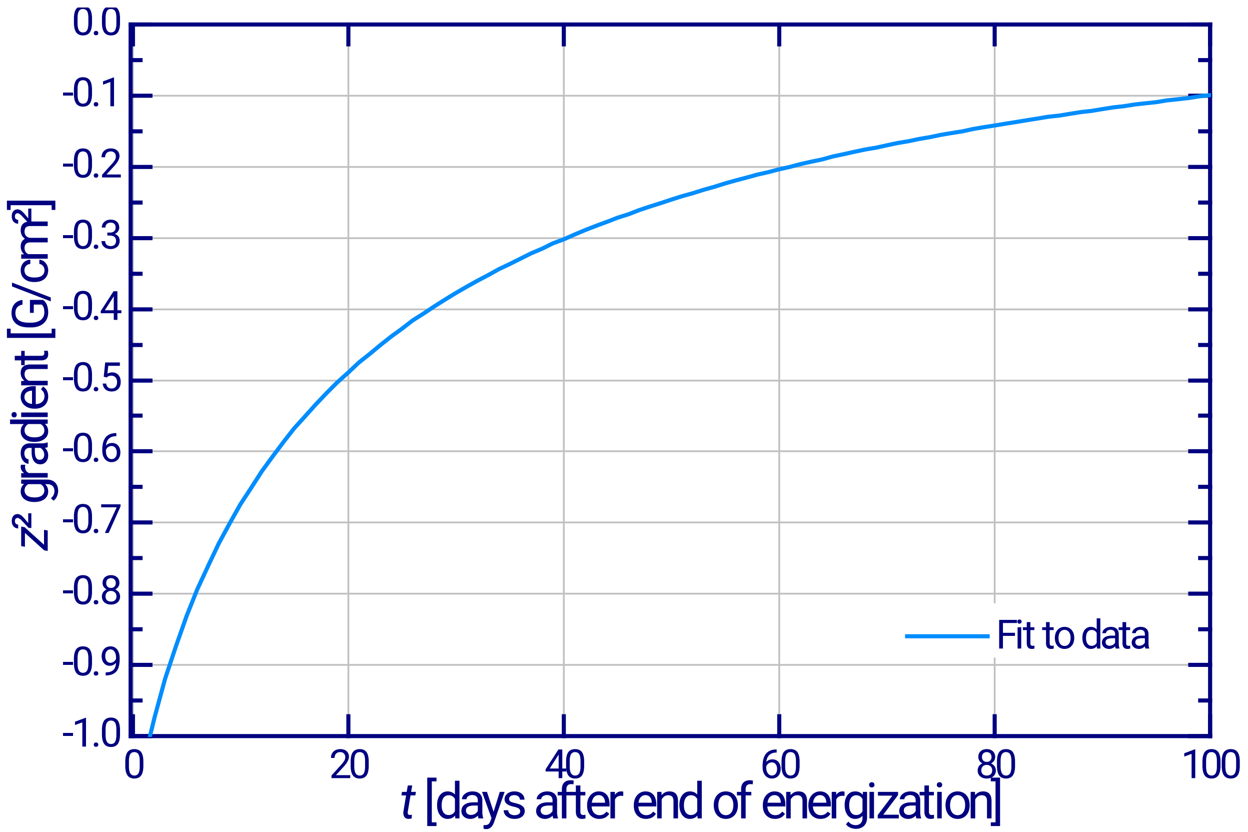
Initial drift of the z² gradient of HTS-LTS hybrid magnets

- The relaxation of the screening currents also leads to an initial increase of the z² gradient.
  - This effect must be considered in the homogenization process.
- The z² gradient stabilizes after several weeks.



Initial drift of the z² gradient of a 1.2 GHz magnet after reaching full field

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Next step: Ascend Evo 1.0 GHz – single-story 1.0 GHz 4K NMR magnet

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Next step: Ascend Evo 1.0 GHz – single-story 1.0 GHz 4K NMR magnet

- Ascend Evo 1.0 GHz:
  - Taking advantage of the high current density at high magnetic fields of ReBCO coated conductors, a compact HTS/LTS hybrid 1.0 GHz (23.5 T) single-story NMR magnet, operating at 4.2 Kelvin, has been developed.
  - Provides many more structural biology and drug discovery researchers access to the sensitivity and resolution of GHz NMR.

Ascend Evo 1.0 GHz (HTS/LTS hybrid, 4.2 K)

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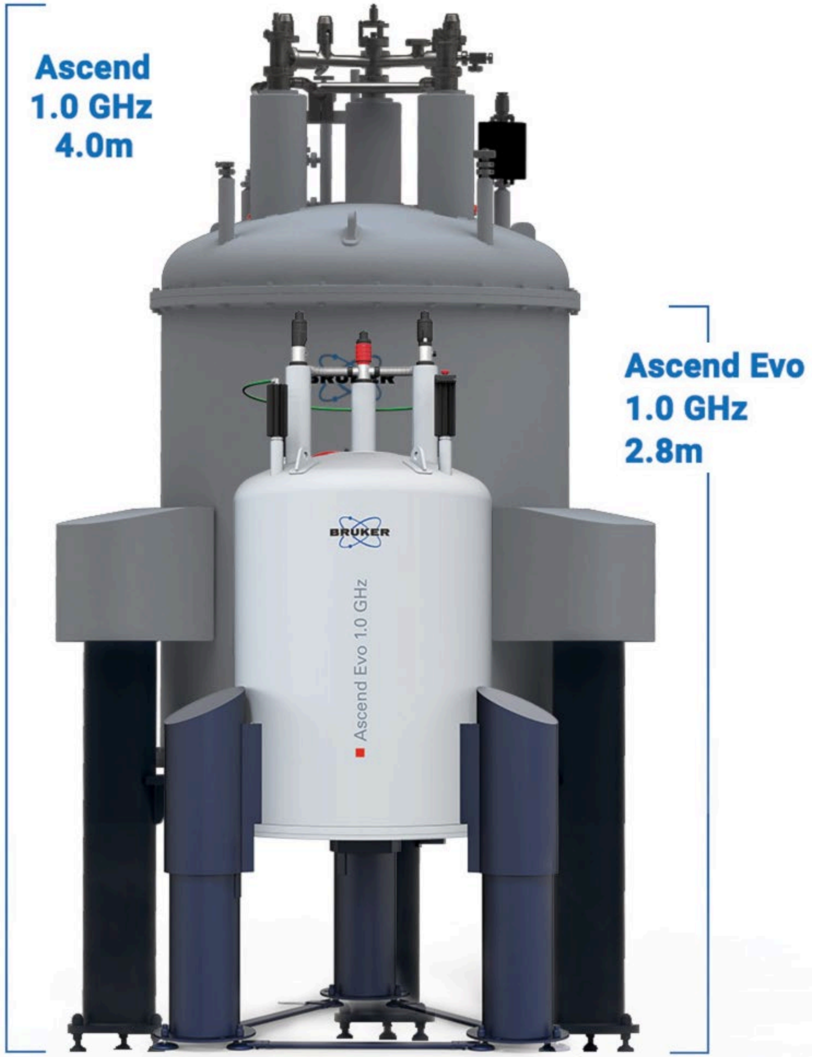
Ascend Evo 1.0 GHz – Ascend 1.0 GHz comparison

- Ascend Evo 1.0 GHz:
  - 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)

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Requirements to REBCO coated conductors for UHF NMR applications

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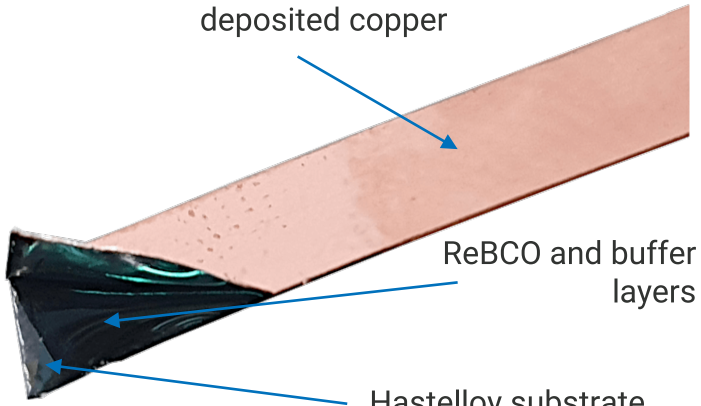
Requirements to ReBCO coated conductors for UHF NMR application

- Key technical requirements to ReBCO coated conductors for UHF NMR magnets:
  - Uniform properties along entire piece lengths (Ic, copper, insulation,…)
  - Long piece lengths (typically 300 m to 900 m) without Ic drop-outs (I_C dips)
  - High Ic 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



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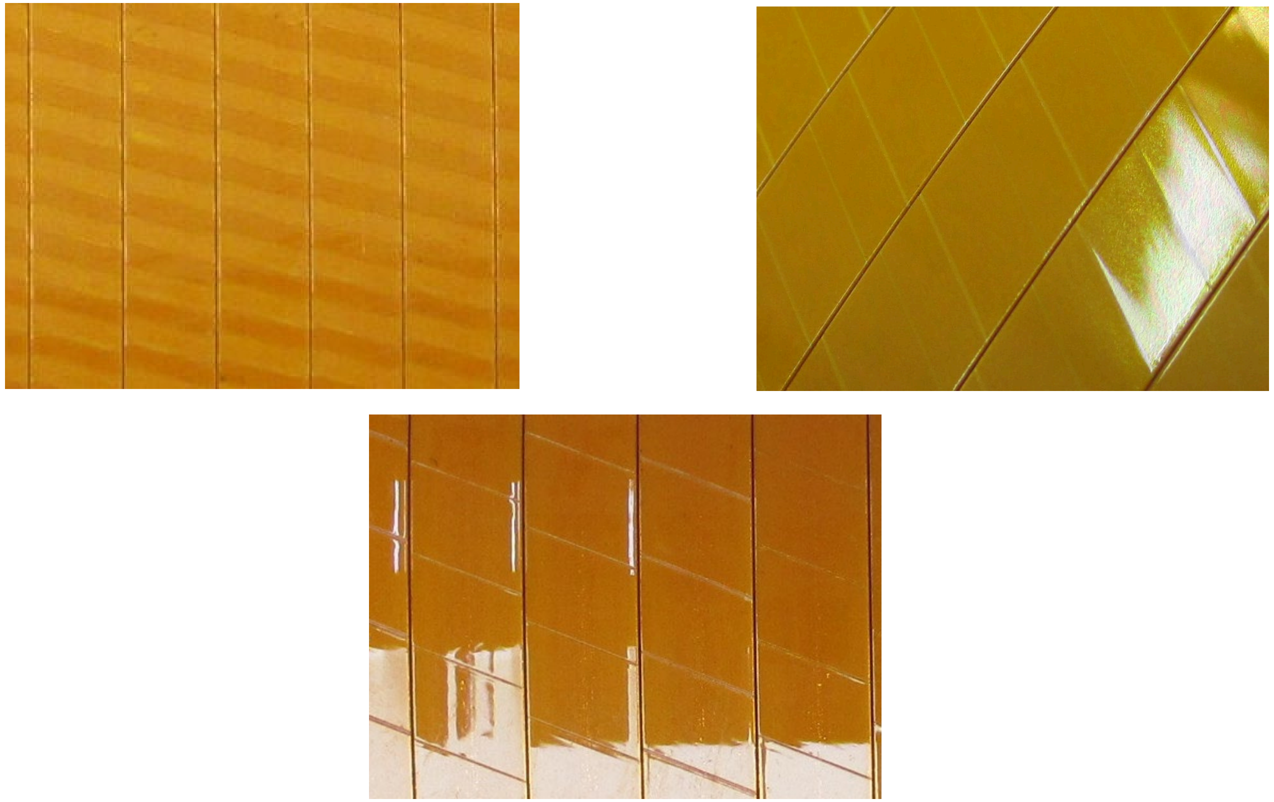
Requirements to ReBCO coated conductors for UHF NMR application

- 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
    - Application of Polyimide varnish interesting



Types of Polyimide-tape insulation

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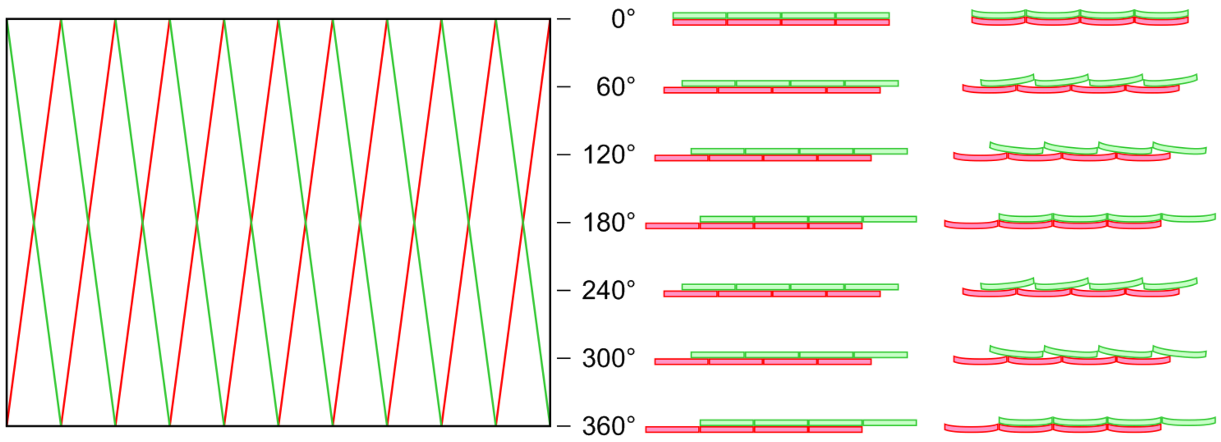
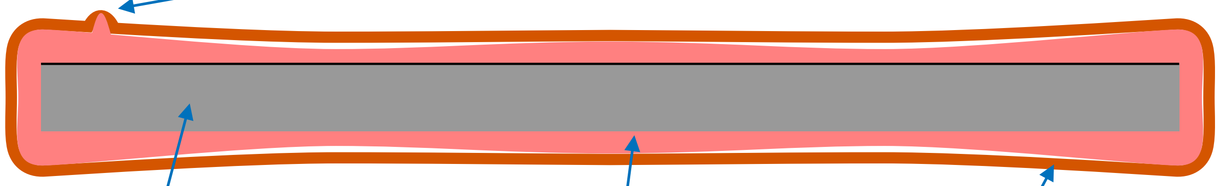
Requirements to ReBCO coated conductors for UHF NMR application

- 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.



Winding of curved tape



Irregular galvanic deposition

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ReBCO coated conductors quality assurance and quality control processes

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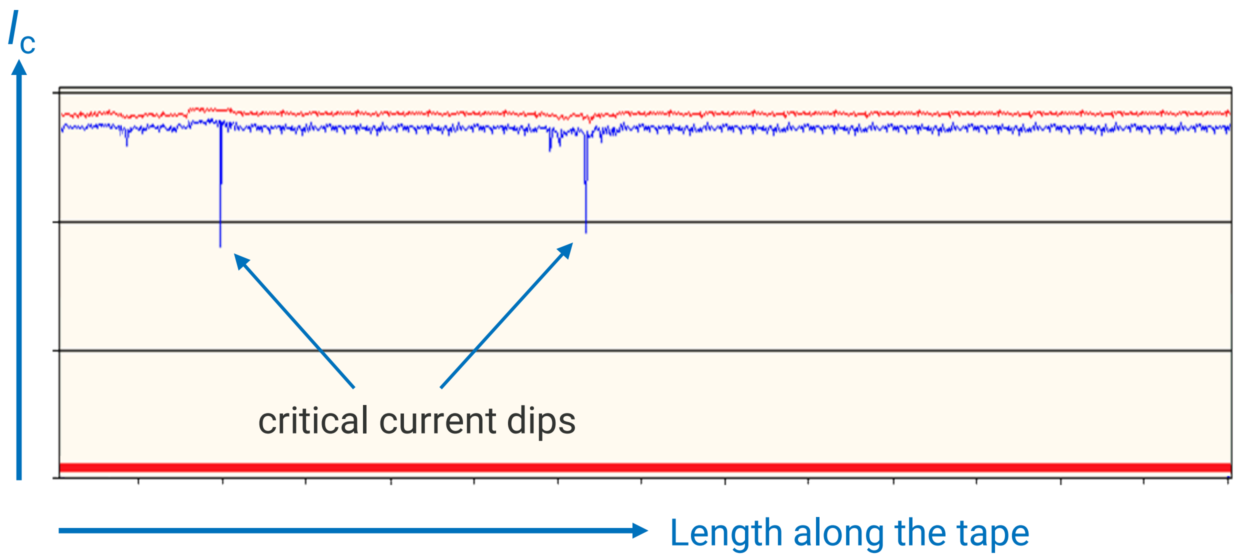
ReBCO coated conductors quality assurance and quality control processes

- 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[TM] measurements
  - and transport Ic measurement at 77 K, self-field,

along the whole length of the tapes.



Tapestar[TM] measurement (symbolic data)

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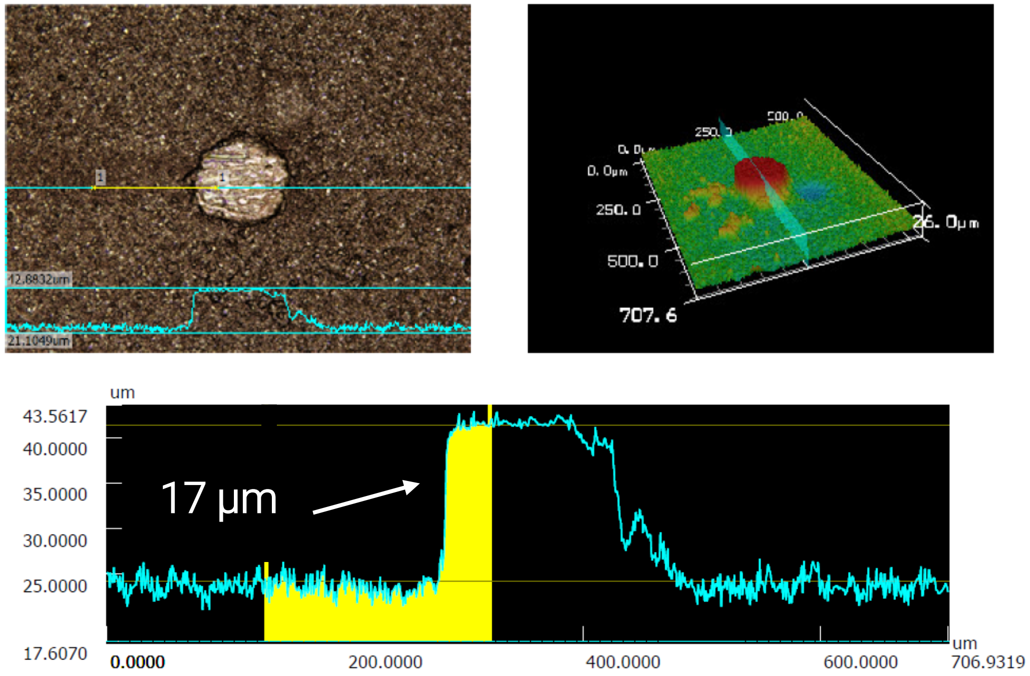
ReBCO coated conductors quality assurance and quality control processes

- Quality control at Bruker on the ReBCO coated conductors:
  - tests on short samples (~1m) from both ends of the long, already insulated, tapes and includes:
    - Ic (@ 4.2 K, 10 T),
    - micrographs of cross-sections, and
    - confocal microscope analysis of the copper surface.



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

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1.x GHz HTS-LTS hybrid NMR magnets delivered and ordered

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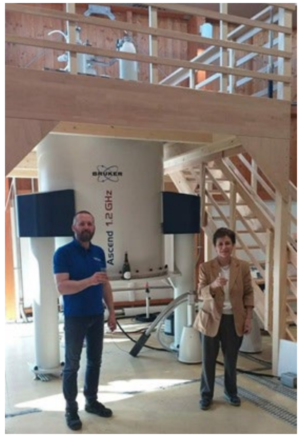
Installed 1.2 GHz NMR Systems



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ETH Zurich, CH

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FZ Jülich, DE

Utrecht University, NL

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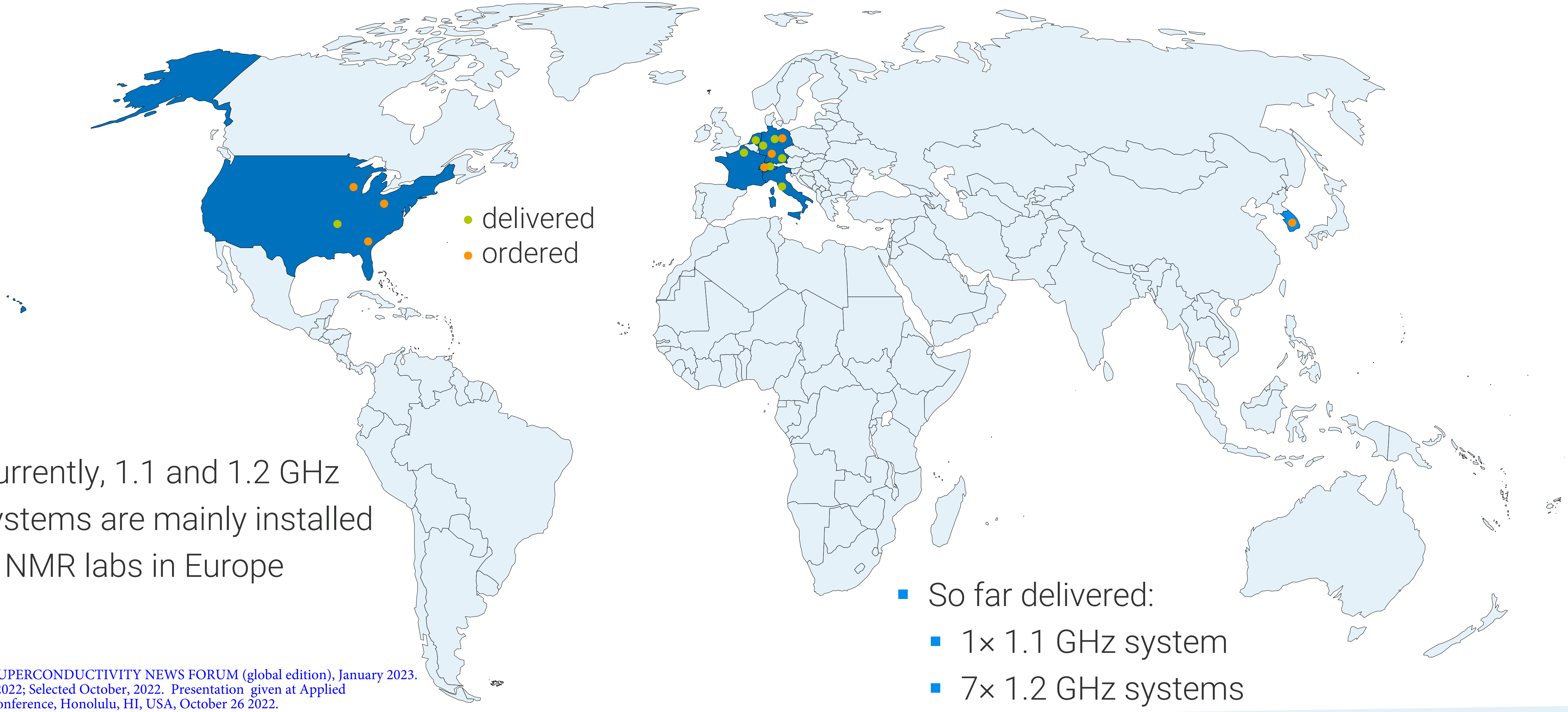
1.1 and 1.2 GHz NMR systems using ReBCO coated conductors ordered or delivered worldwide (October 2022)



- Currently, 1.1 and 1.2 GHz systems are mainly installed in NMR labs in Europe

- So far delivered:
  - 1× 1.1 GHz system
  - 7× 1.2 GHz systems

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Ascend Evo 1.0 GHz systems using ReBCO coated conductors worldwide (October 2022)

- The first three Ascend Evo 1.0 GHz will be delivered to sites in Japan and Spain

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Thank you!

The UHF NMR Team
Bruker Switzerland AG

Innovation with Integrity

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