

# Investing in Superconductivity: The Industry of Science



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# Outline



1. About Bruker
2. Products and markets
  - Superconductors
  - NMR magnets
  - Selected Big Science projects (ITER, XFEL, ...)
3. Vision and R&D for future superconducting products
  - R&D towards 1.2 GHz NMR magnets
  - Future Big Science projects

# About Bruker

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# Bruker at a Glance

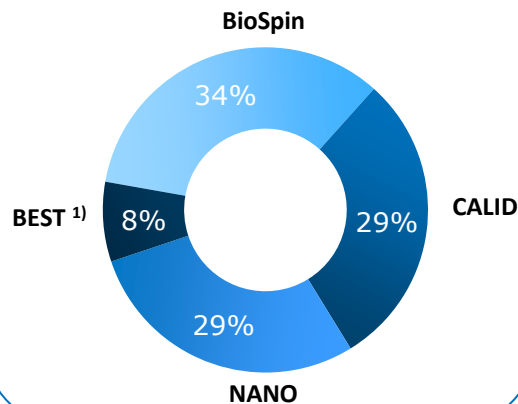


Bruker is one of the world's leading analytical instrumentation companies.

*"Our high-performance scientific instruments and high-value analytical and diagnostic solutions enable scientists to explore life and materials at molecular, cellular and microscopic levels."*



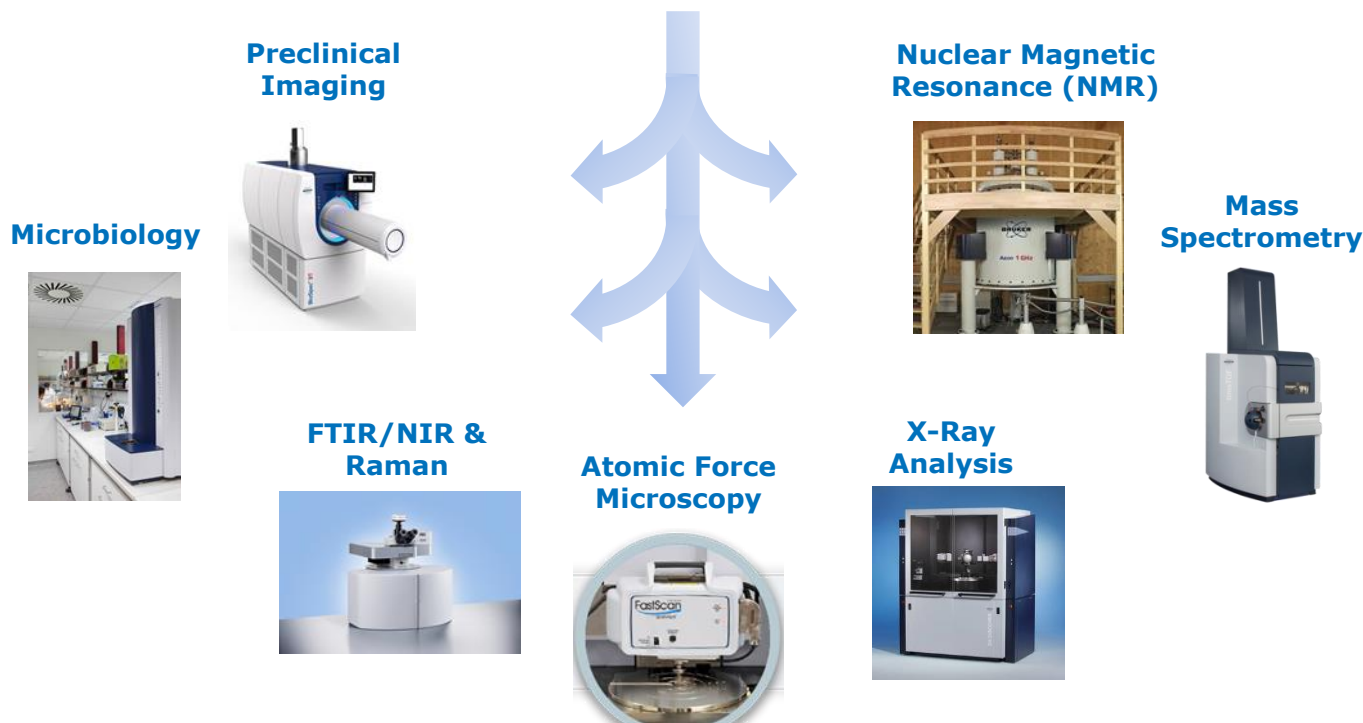
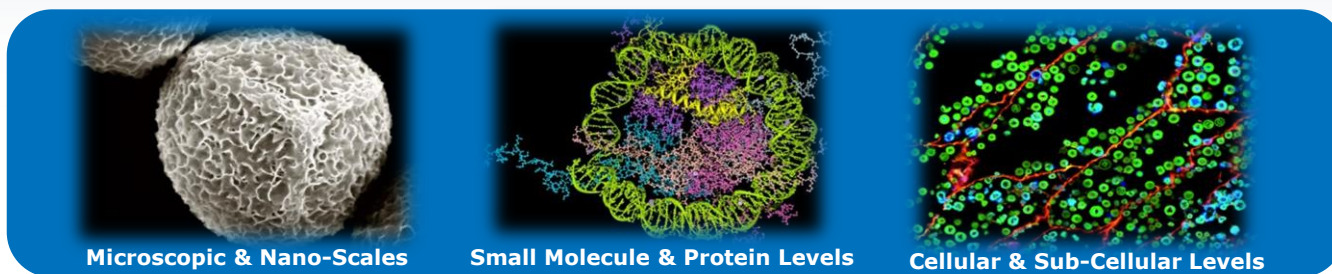
**2016 Revenue Distribution:**



- **Founded in 1960**
- **~6,000 employees worldwide, with over 90 locations on all continents**
- **2016 revenue: ~\$1.6 billion**
- **R&D investment: ~10% of revenue**
- **~75% of revenue from scientific and diagnostic instruments**
- **A public company (NASDAQ: BRKR) with headquarters in Billerica, MA**

1) Prior to Bruker OST acquisition. In 2017 BEST is expected to contribute approx. 11% of total revenue

# "High-Performance Scientific Instruments Enable Our Customers to Explore Life and Materials"



# Superconductivity at Bruker, a core competence and technology portfolio

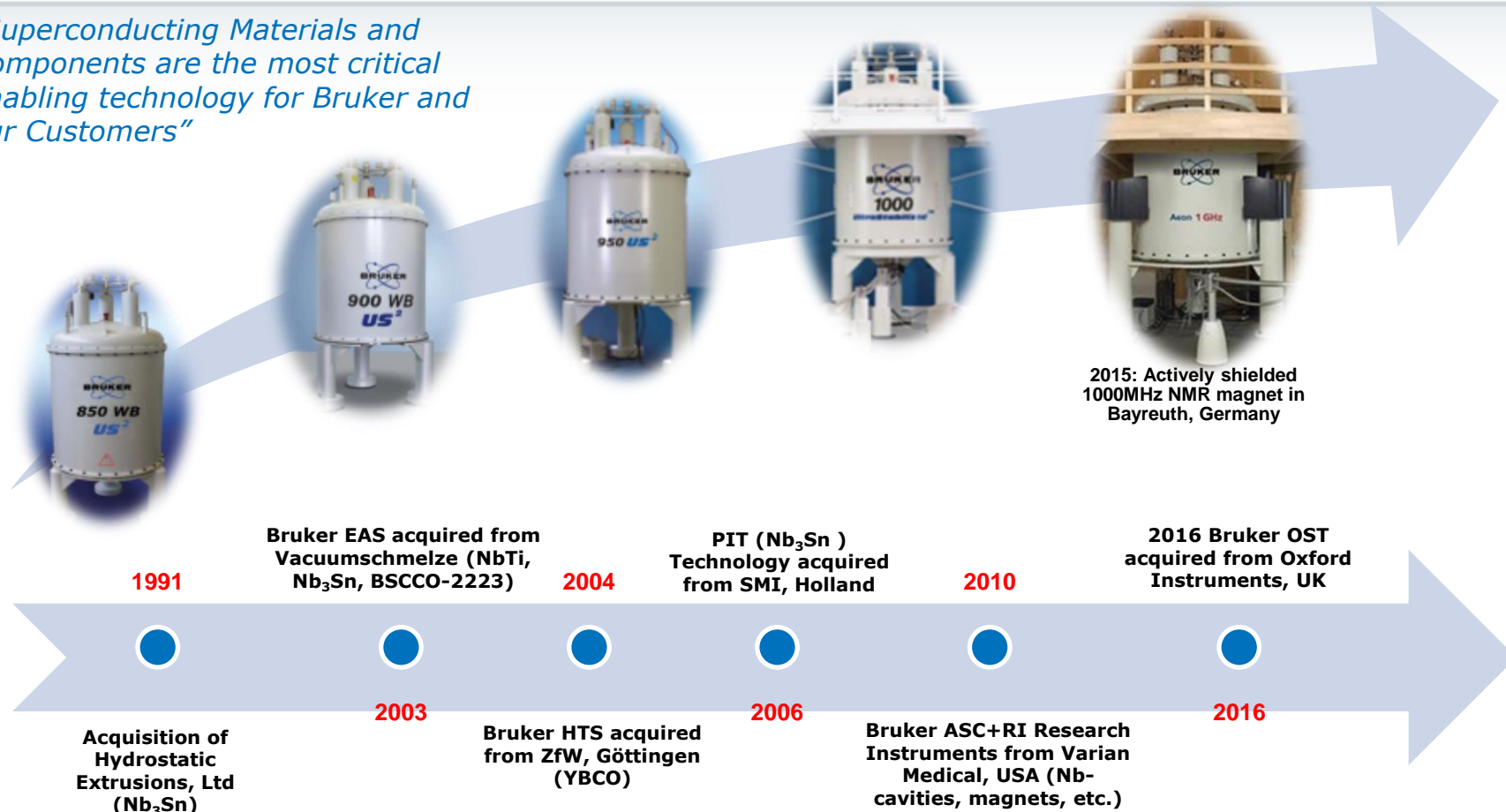


- Bruker is an instruments & services company that designs and manufactures
  - superconducting **magnets** for internal use in NMR, EPR, MRI, FTMS, DNP instrumentation
  - superconducting **wires & tapes** for MRI and HEP, plus for internal supply
  - superconducting **rf cavities** for accelerators
- More than 1,000 people at Bruker are directly involved with superconducting products

# Bruker NMR magnet progress and superconductors go hand in hand



*"Superconducting Materials and Components are the most critical enabling technology for Bruker and our Customers"*



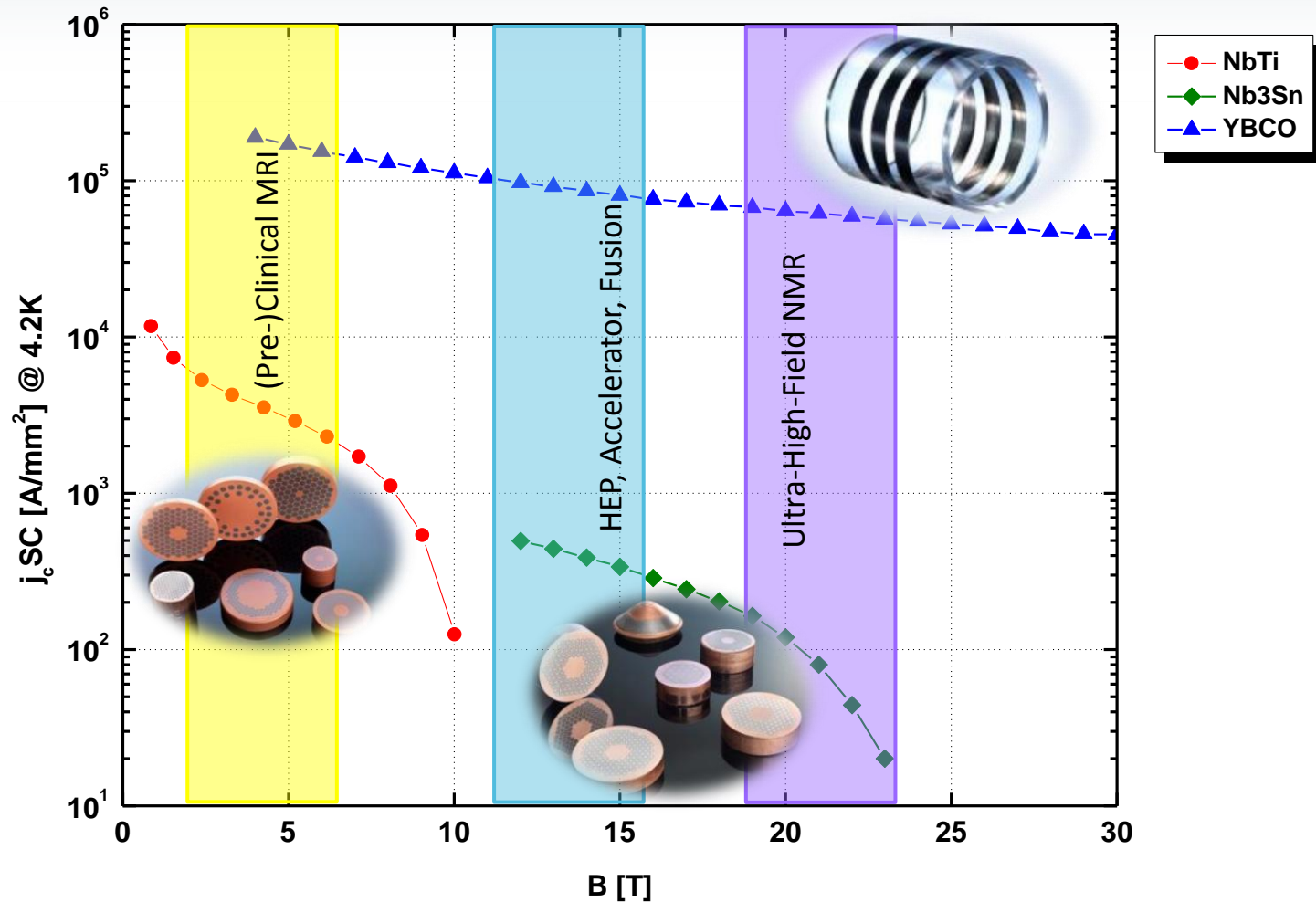
- World leading magnet innovation requires world leading superconductor innovation
- Bruker continues to invest in world-class superconductor technologies for MRI and NMR

# Products and markets

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# Performance & Application of Different Types of Superconducting Materials



# Bruker Superconductors

## The BEST Supercon Product Range



Nb-based



Nb rf cavities

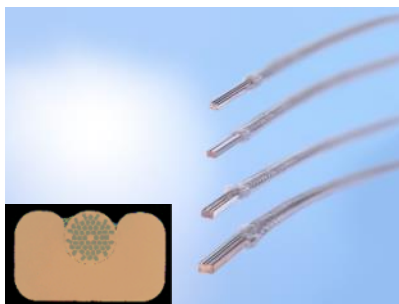


Nb rf accelerator moduls

NbTi-based



NbTi (Niobium-Titanium)



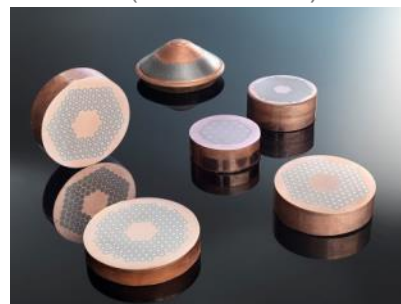
NbTi Wire in Channel (WIC)

$B < 9.5 \text{ T}$

$\text{Nb}_3\text{Sn}$ -based



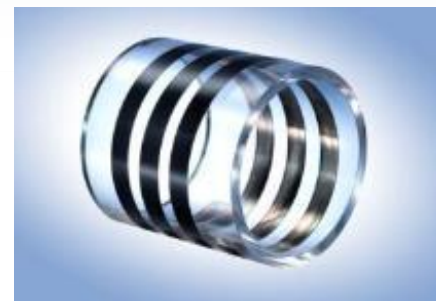
$\text{Nb}_3\text{Sn}$  Bronze route  
(Niobium-Tin)



$\text{Nb}_3\text{Sn}$  RRP® / PIT (Niobium-Tin)

$B > 10 \text{ T}$

HTS-based



YBCO



Bi-2212

$B > 20 \text{ T}$   
or  $T >> 4.2 \text{ K}$

# Wire progress $\Rightarrow$ Magnet progress



Unshielded  
1 GHz (2009)



System Properties	
Ceiling Height	
5.9 m	4.9 m
Stray Field Diameter	
24 m	7.2 m
Mass	
< 15 t	< 8 t
Helium Hold Time	
> 60 d	> 1 yr

Aeon 1 GHz  
Actively Shielded  
(2015)



# Wire progress $\Rightarrow$ Magnet progress



800 MHz 2K



Operational Ceiling Height: 3660 mm  
Mass: 3500 kg  
Helium Consumption: < 140 ml/h

800 MHz 4.2K



Operational Ceiling Height: 3250 mm  
Mass: 2100 kg  
Helium Consumption: < 47 ml/h

# Superconductors for ,Big Science`: Fusion and High-Energy Physics (HEP)



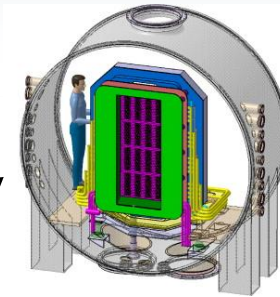
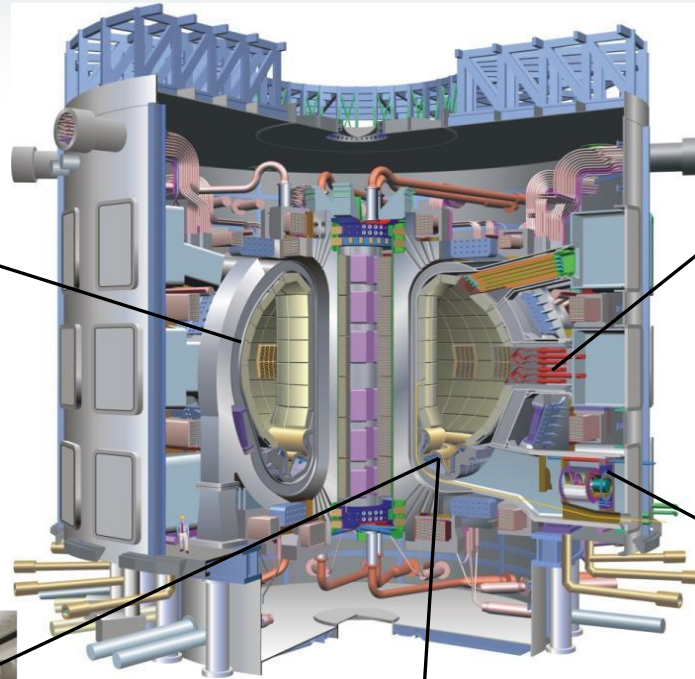
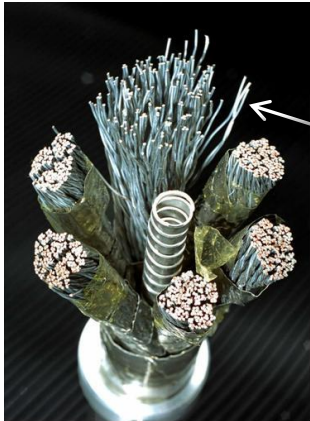
- Bruker broadly supports Big Science projects with a large variety of superconducting solutions with world leading technical performance and reliability.
- Fusion projects (selected examples):
  - ITER (Nb3Sn strand, cryopump, inner vertical target, superconducting magnet for plasma wall interaction research)
  - JT60 (Stacks of BiAgAu-2223 for Current Leads)
  - Wendelstein W-7X (NbTi cable-in-conduit conductor, Stacks of BiAgAu-2223 for Current Leads)
- HEP accelerator projects (selected examples):
  - CERN LHC (NbTi strand for dipoles and quadrupoles and cable for ATLAS, 50% of BiAgAu-2223 tapes for HTS current leads, plus >400 quadrupole magnets from predecessor company)
  - XFEL (420 superconducting rf cavities)



# Previous and Potential Bruker Contributions to ITER

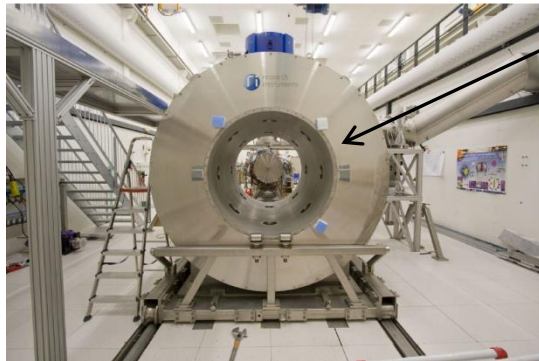


Nb3Sn strand for TF coil cable  
(BEST, ~23%)

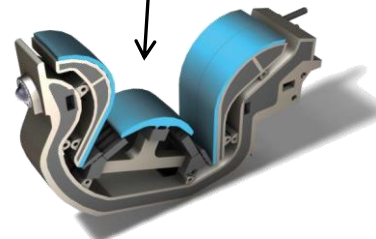


Grids for  
diagnostic beam  
source [DNB] (RI)

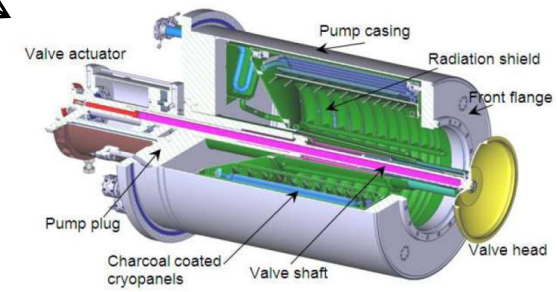
Participating in design and potentially assembly  
of IFMIF, a superconducting accelerator for  
irradiation testing of ITER material (RI)



Superconducting magnet system for  
testing plasma wall interactions at DIFFER



Inner vertical target mock-ups  
of the divertor (RI)



Pre-production cryopump (RI)

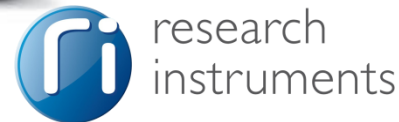
**~€100M over  
several years**

# TESLA-type SRF cavity production



Order for 420 supercon rf cavities received in 2010 from DESY (XFEL project), project finished in 2015. Total XFEL contract including couplers ~ 10M€ p.a.

Order for 181 SRF cavities received in 2015 from US JLAB (for LCLS-II project at SLAC)



## Scope:

- Mechanical manufacturing of SRF cavity, respecting the pressure vessel code
- Complete surface preparation and helium vessel welding , including N2 doping for LCLS-II

All R&D is project based and externally financed.

# RI (Research Instruments GmbH, a 51% BEST subsidiary) Cleanroom for XFEL SRF Cavities





# RI Infrastructure for SRF Surface Preparation

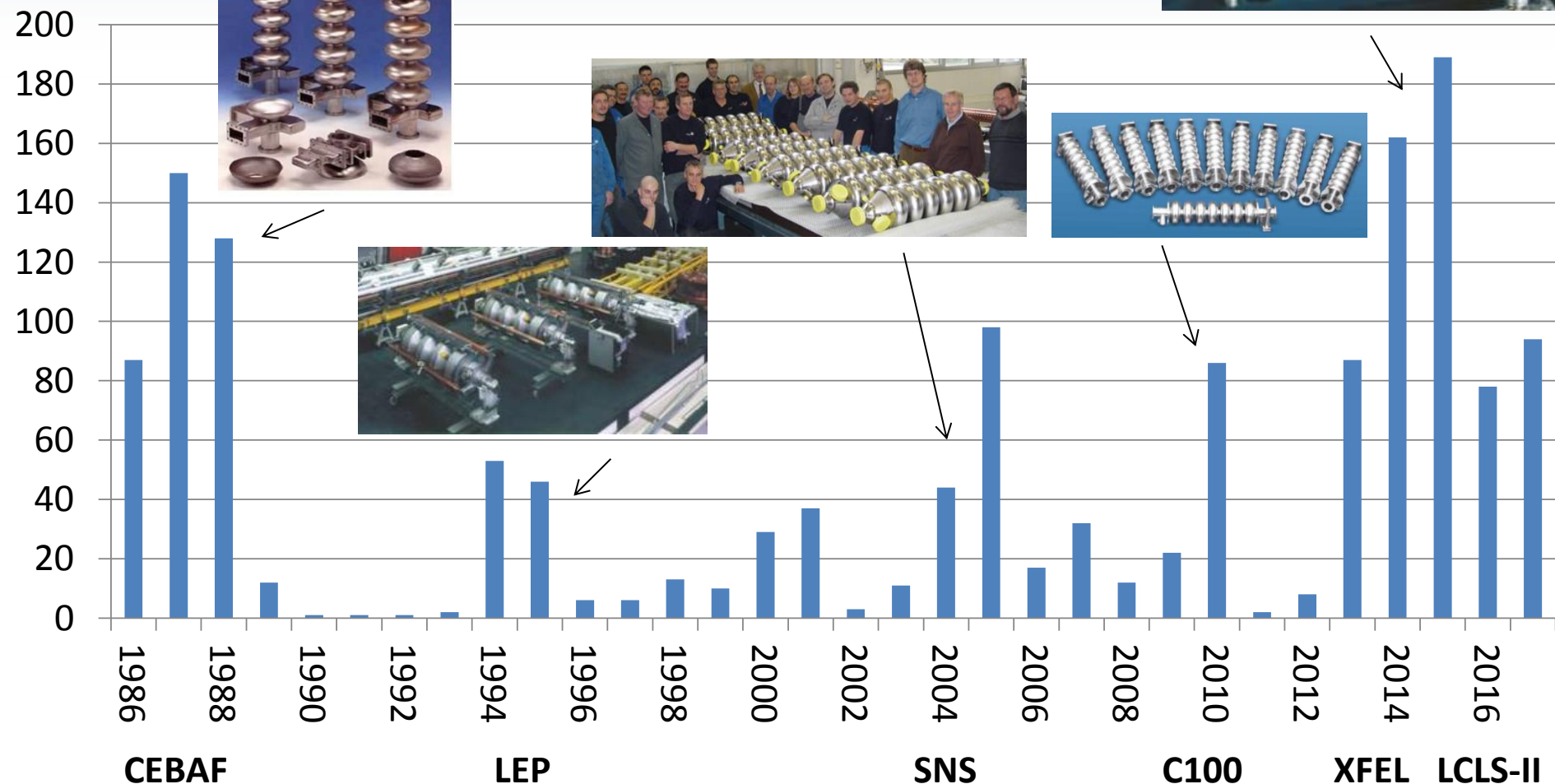


- Electro-polishing plant
- Buffered chemical polishing plant
- 800 C annealing furnace
- 120 C baking station
- TIG welding and pressure testing of titanium helium vessel
- 120 m<sup>2</sup> ISO 4 clean room with high pressure water rinsing stations, special vacuum pumping system



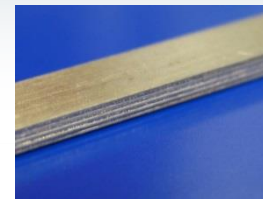
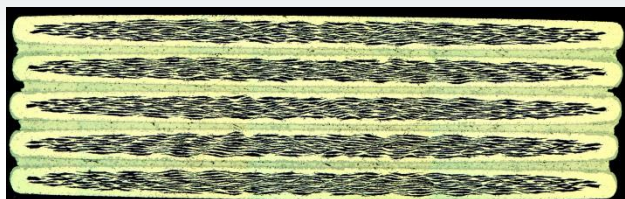
Investment for cleanroom and related infrastructure was included in XFEL contract.

# SRF Cavities Delivered by RI



In total, more than 1,500 SRF cavities produced at RI within the last 30 years.

# Post-project Considerations: Example Bi-2223 HTS



- Bruker supplied 2,850 stacks of BiAgAu-2223 tapes for current leads in Wendelstein W-7X and JT-60SA



R. Heller, KIT

- After completion of these 2 contracts, no follow-up contract was on the horizon.
- Industry cannot keep idle resources for potential follow-up projects years later.

⇒ **Bi-2223 personnel was assigned to other areas and Bi-2223 production was discontinued in 2011, in favor of high-field YBCO tape R&D and production.**

# Bruker Achievements in Superconductivity

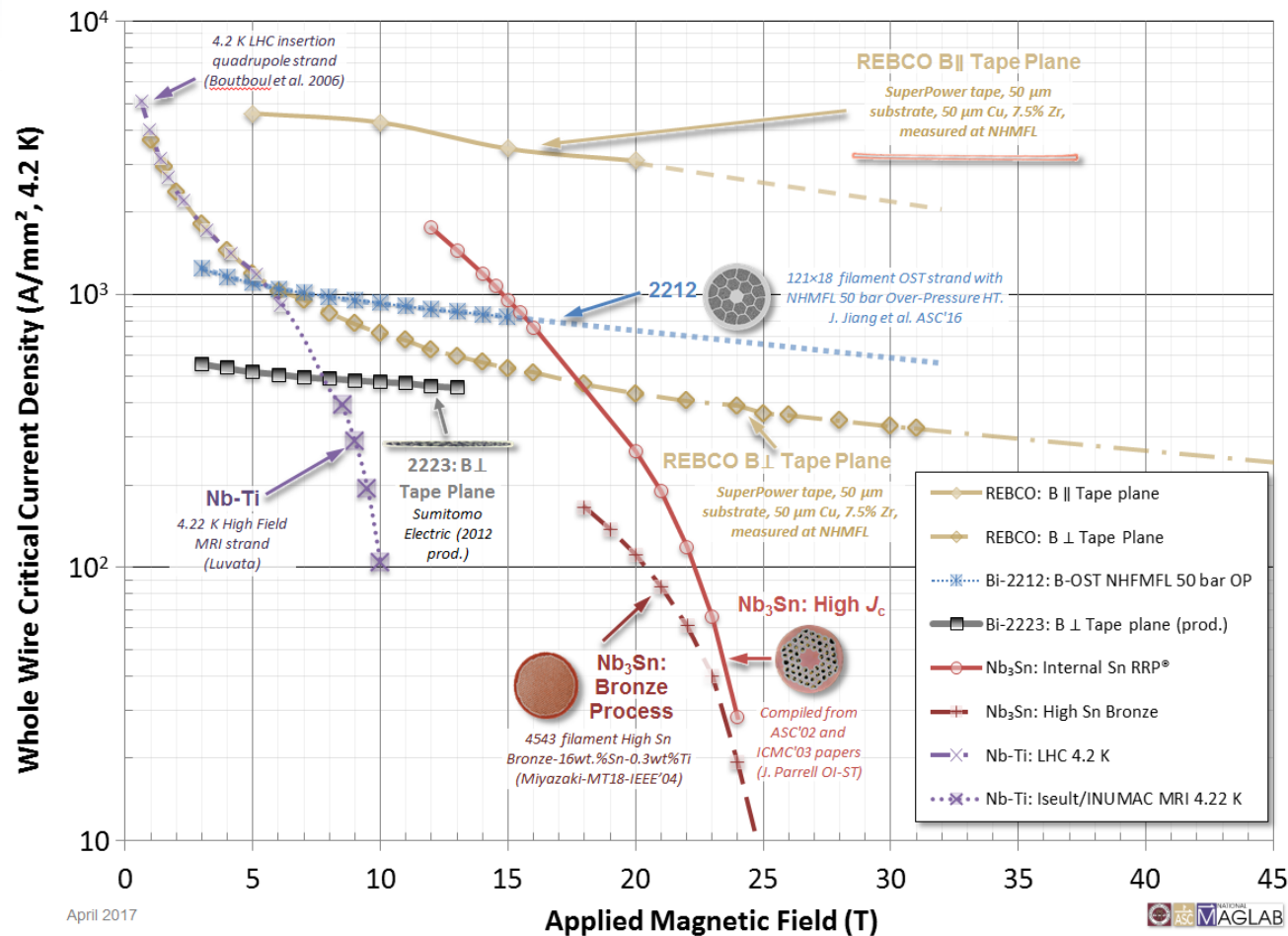


- Highest performance high resolution Bruker NMR, EPR, preclinical MRI, FTMS and DNP gyrotron superconducting magnets
- Broadest superconductor materials, wire and tape portfolio at BEST
- BEST RRP and PIT highest performing Nb<sub>3</sub>Sn conductors at industrial scale
- BEST YBCO tape: highest in-field performance with tape length up to 600m
- World-renown track record for highest reliability, quality and flexibility in NbTi supply to healthcare industry (MRI, particle therapy) with LTS conductors, magnets and accelerator components
- World-leading performance superconducting rf cavities from RI

# **Vision and R&D for future Superconducting Products**



# The Potential of High Temperature Superconductors (HTS)



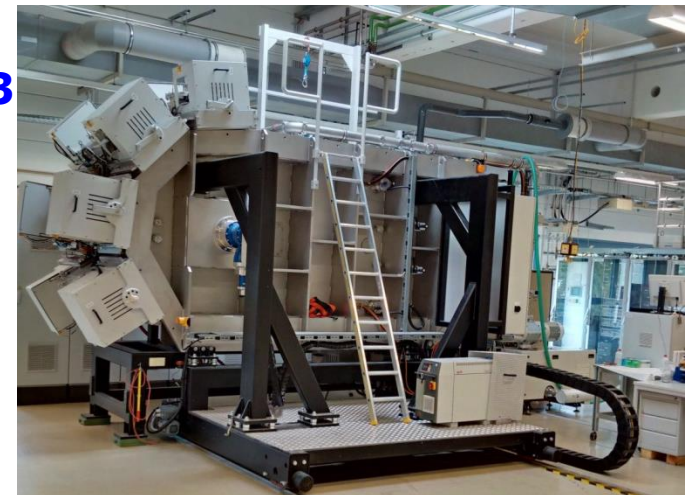
Credit:

Peter Lee /  
NHMFL

# BEST YBCO Coated Conductors (Tape)



- YBCO tapes are manufactured by thin film deposition in clean, controlled atmosphere
- Several process steps are necessary
- Optimized for highest performance in ultra-high magnetic fields
- 4mm tapes with up to 600m lengths, sufficient for NMR, at a few km per year
- Requires dedicated, expensive equipment



**PLD600**



**ABAD3**

# Towards 1.2 GHz High-Resolution NMR Magnets with HTS Inserts



At Bruker, we have conducted numerous tests of tape properties and of solenoid windings in LTS high-field outsert magnets to clarify:

- ✓ Electrical YBCO tape properties & mechanical strength, but production yield and throughput still low
- ✓ Jointing
- ✓ Homogeneity (for high-resolution NMR)
- ✓ HTS Quench-Protection
- ✓ Extremely low drift for NMR
- ✓ Winding Technique



YBCO Test coil solenoid winding



28 layers



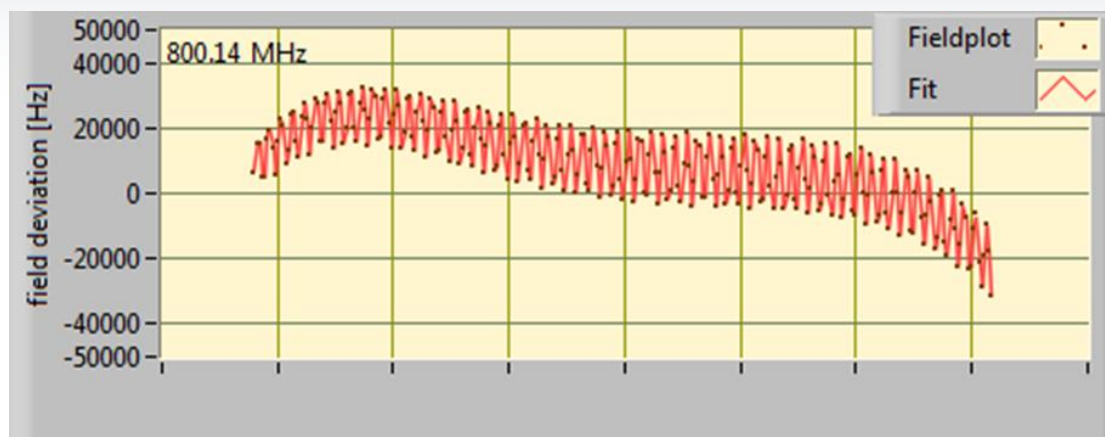
12 layers



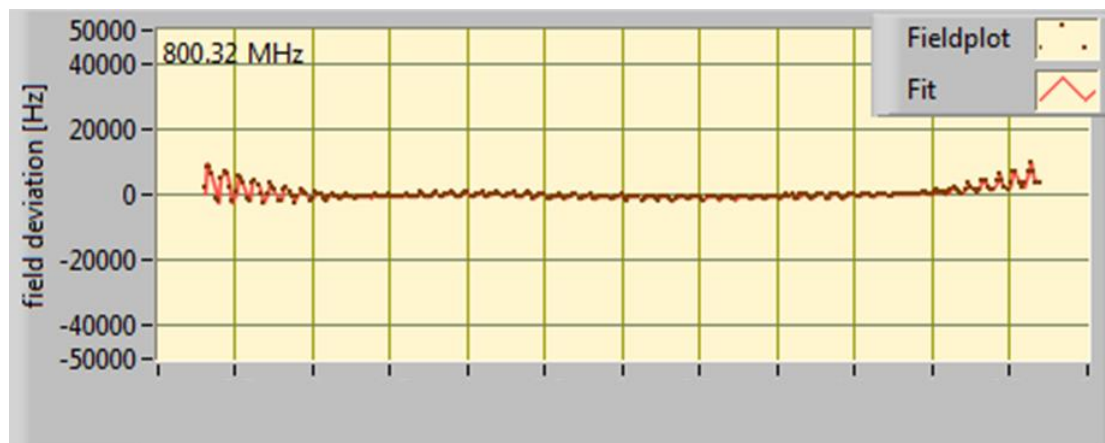
# Homogenization of HTS Magnets



Homogeneity of a „raw“  
HTS magnet:

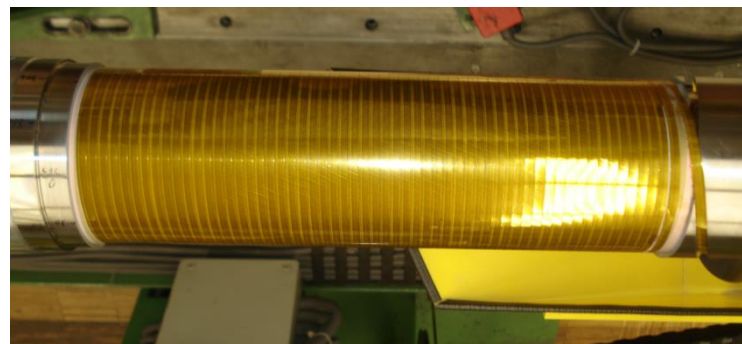


Homogeneity of a HTS  
magnet with cryoshims  
and homogenization  
module:



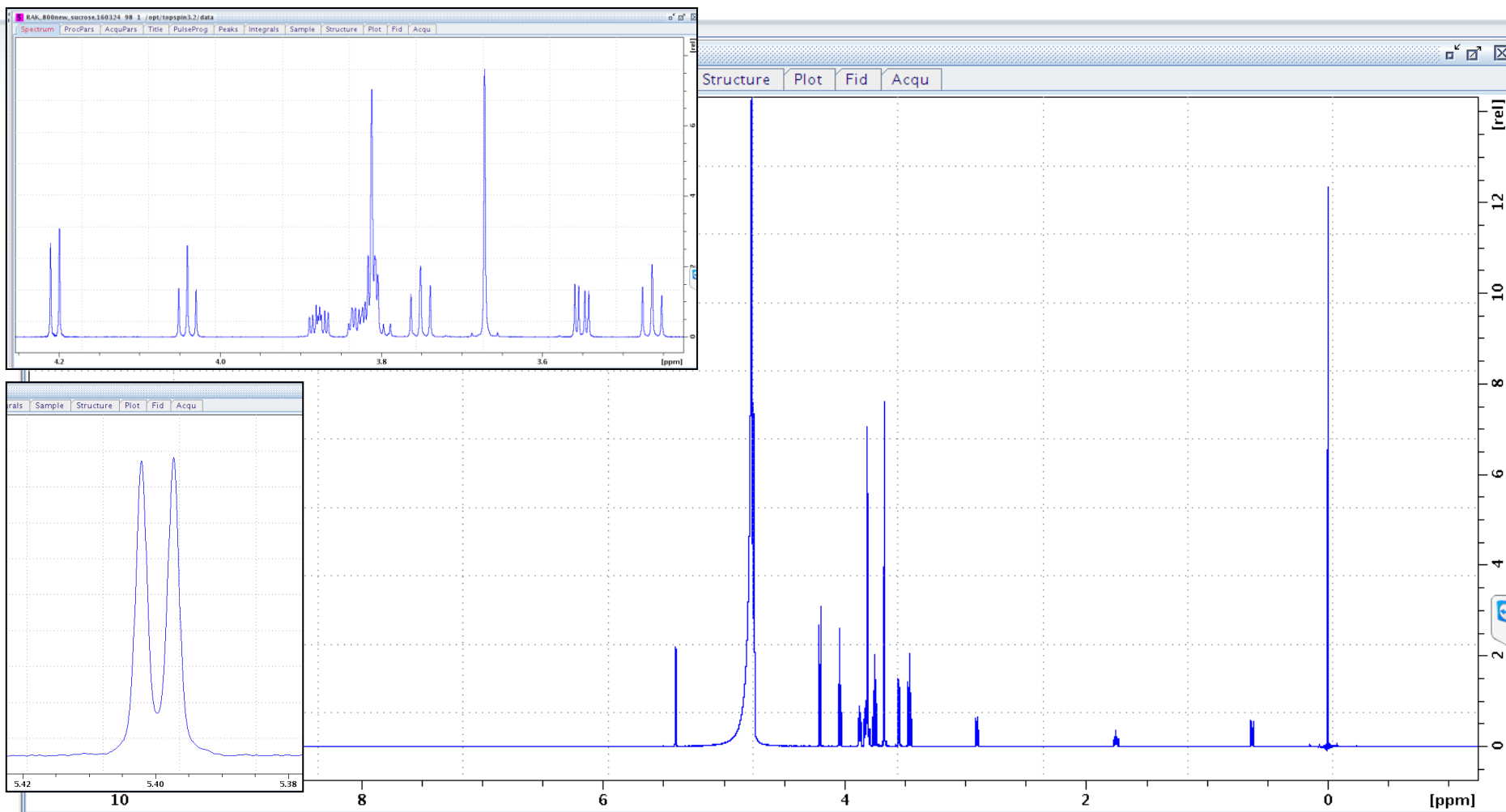
Homogeneity now comparable to classical LTS magnets!

# Bruker: 800 MHz LTS outsert + HTS insert



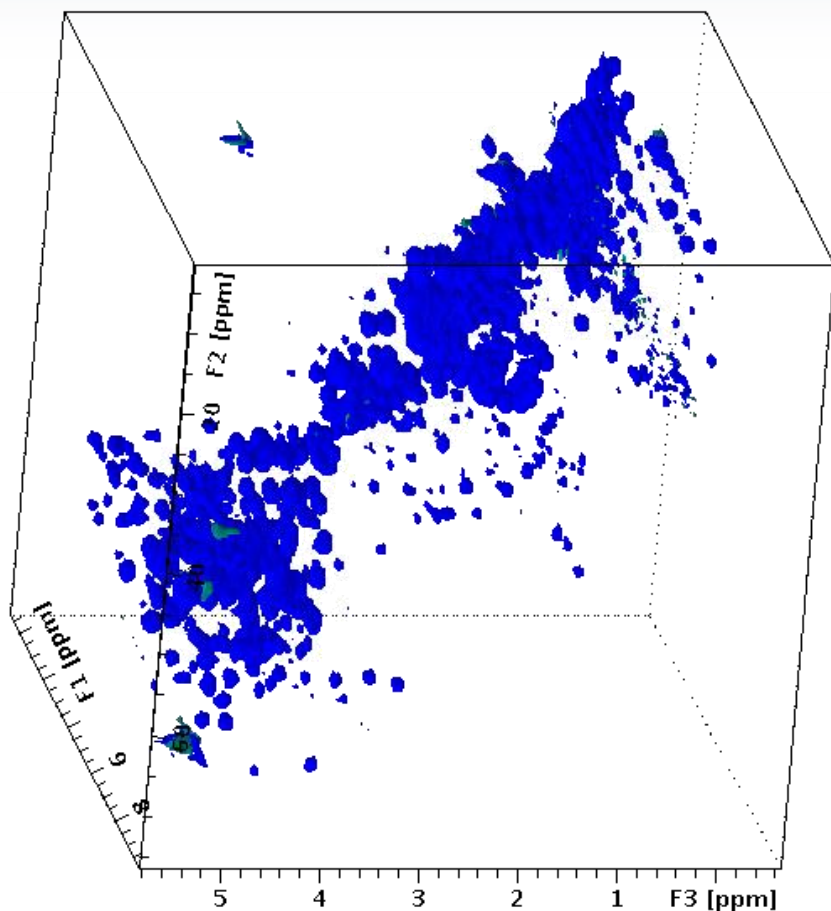
- 800 MHz persistent NMR magnet with good homogeneity
- $^1\text{H}$  NMR Drift < 5 Hz/hr
- In operation for >250 days

# Bruker: 800 MHz LTS + HTS NMR Data: Excellent Lineshape & Water Suppression with 5mm triple-resonance NMR probe

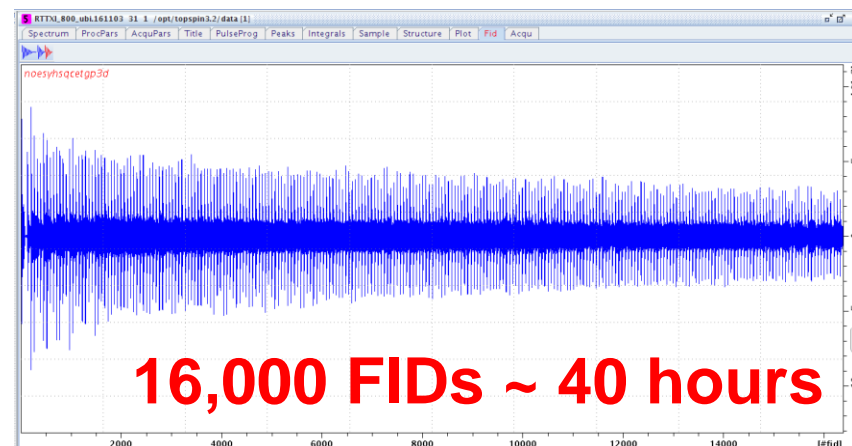
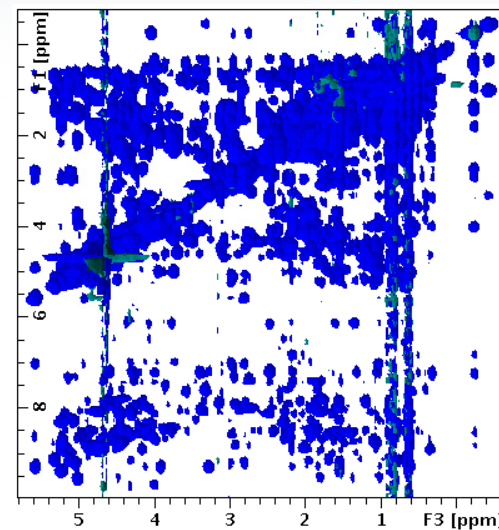
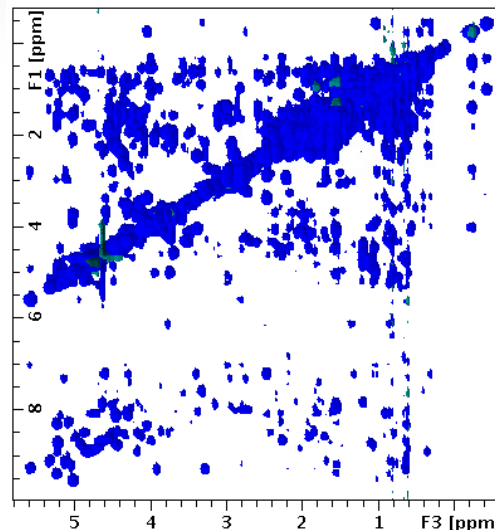


Presat 1D1H 2mM Sucrose in H2O:D2O 90:10

# Bruker: 800 MHz LTS + HTS Structural Biology NMR: excellent 3D NOESY-HSQC ( $^{13}\text{C}$ edited), 5mm RT TXI probe



1mM Ubiquitin  $^{13}\text{C}/^{15}\text{N}$  labeled



**16,000 FIDs ~ 40 hours**

# Plan: 1.1 GHz and 1.2 GHz Persistent, High-Resolution NMR Magnets



- Magnets will be reasonably sized, only slightly larger than 1 GHz
- Magnets will be actively-shielded and ultra-stabilized
- Operation in persistent mode
- Magnets will meet the standard drift specifications required for high-resolution NMR
- Stray field (5 G): < 4.3 m radial
- Minimum ceiling height: < 6.5 m
- No other special siting requirements

# Bruker Vision for Superconductivity in Big Science/HEP



- ILC (International Linear Collider) would need ~16,000 Niobium SRF cavities
- FCC (2 versions) need 3,000 – 9,000 tons  $\text{Nb}_3\text{Sn}$  with improved performance (R&D and capacity required), and/or 700–2,000 tons of HTS (Bruker opinion: not feasible within next decade); **Q: Feasibility of hybrid with highest  $I_c$   $\text{Nb}_3\text{Sn}$  outsert with YBCO insert?**
- DEMO (different versions published) for fusion would need similar superconductor quantities as ITER but higher performance
- Production timeline for these projects is far out, but **R&D and planning can't wait**
- Today's capacities for SRF cavities,  $\text{Nb}_3\text{Sn}$  or HTS production would meet only a fraction of required demand ➔ **Need initial capacity ramp soon to test scale up** (similar to semiconductor or pharma industries!)
- Bruker has a strong commitment to science and medicine, and can contribute technical, production and quality expertise to develop and produce many highest performance superconducting materials and components for HEP and Fusion.
- As a public company, Bruker is not in a position to finance the necessary R&D and production scale-up. **MRI and NMR now have different SC requirements from HEP.**



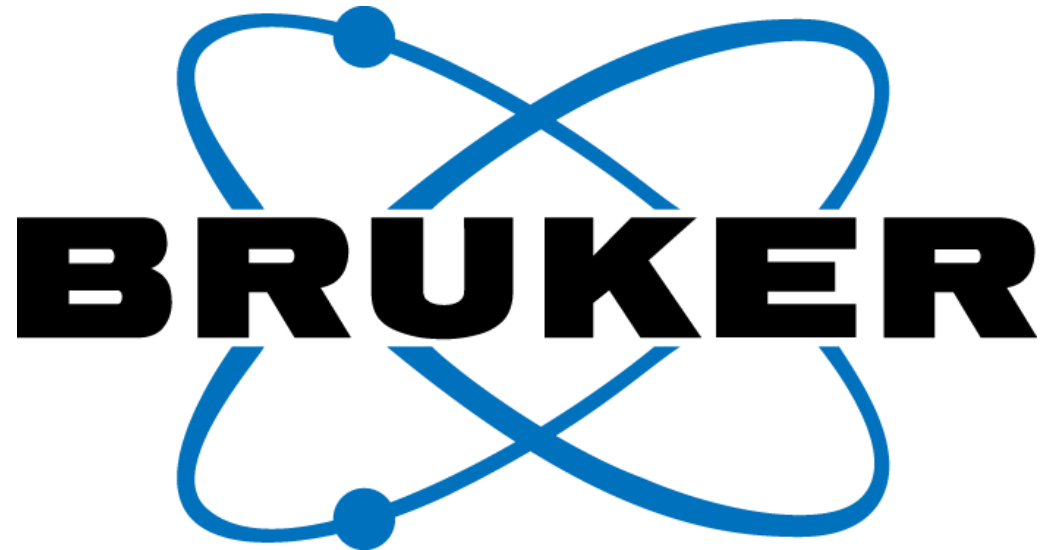
# Bruker business requirements and Big Science project requirements



- Bruker will continue to develop superconductors for its own scientific instruments portfolio. This means superconductors with specific requirements for ultra-stable, ultra-homogeneous and ultra-high performance magnets (1.2 GHz and beyond) to be produced in small quantities.
- We continue to invest in superconductor manufacturing for our large MRI magnet OEM customers and our own systems portfolio. This includes very large quantities of high-quality, cost-effective NbTi, high performance Nb<sub>3</sub>Sn and HTS for NMR.
- The Big Science HEP and Fusion communities need to consider long-term funded Innovation & Stewardship programs to attain their own long term goals in superconductivity: How to secure the **development** of technically very different highest performance superconductors, that can be scaled up and validated, and eventually produced at affordable cost in the large quantities, if and when FCC, and/or ILC, and/or DEMO are funded? Long gaps in R&D or production funding, and the resulting reduced competencies through attrition or redeployment are a major concern, and will greatly increase time-lines and cost later.
- Big Science HEP and Fusion communities face the biggest challenge, now that their requirements can no longer be derived from MRI or NMR. How to estimate technical specifications, novel design concepts and **production needs** and the required investments for possibly the biggest projects yet - but in 10-20 years time? Maintain innovation & capabilities + monitor and continuously assess future cost and production requirements, establish and validate the scale up, and eventually hopefully convince global decision makers to fund the next very large projects, even beyond LHC and ITER.

- Investing in superconductivity has made Bruker the leader in NMR, EPR, FTMS, preclinical MRI, and SRFs.
- Healthcare OEM customers (big MRI companies, PT) require very high volumes of low-margin NbTi only.
- Big Science (HEP) and Fusion projects with needs for high-performing superconducting materials or SRFs will face new issues, as SC materials for MRI (NbTi), NMR (existing Nb<sub>3</sub>Sn and HTS are fine) and the future SC needs of HEP (e.g. CERN FCC) have diverged.





Innovation with Integrity