An engineering perspective on high field superconducting magnets

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Past, present and future of high field s/c magnets

- NMR ‘requirements prototyping’
  - Low drift magnets & minimal quenching up to 22 Tesla
- High field ‘outsert’ developments using LTS conductors
  - Increasing energy density with high critical current wires
- High field magnet developments using HTS superconductors
  - The challenge of strain and quench management

Challenge of high field magnets :- size and stored energy of NMR magnets

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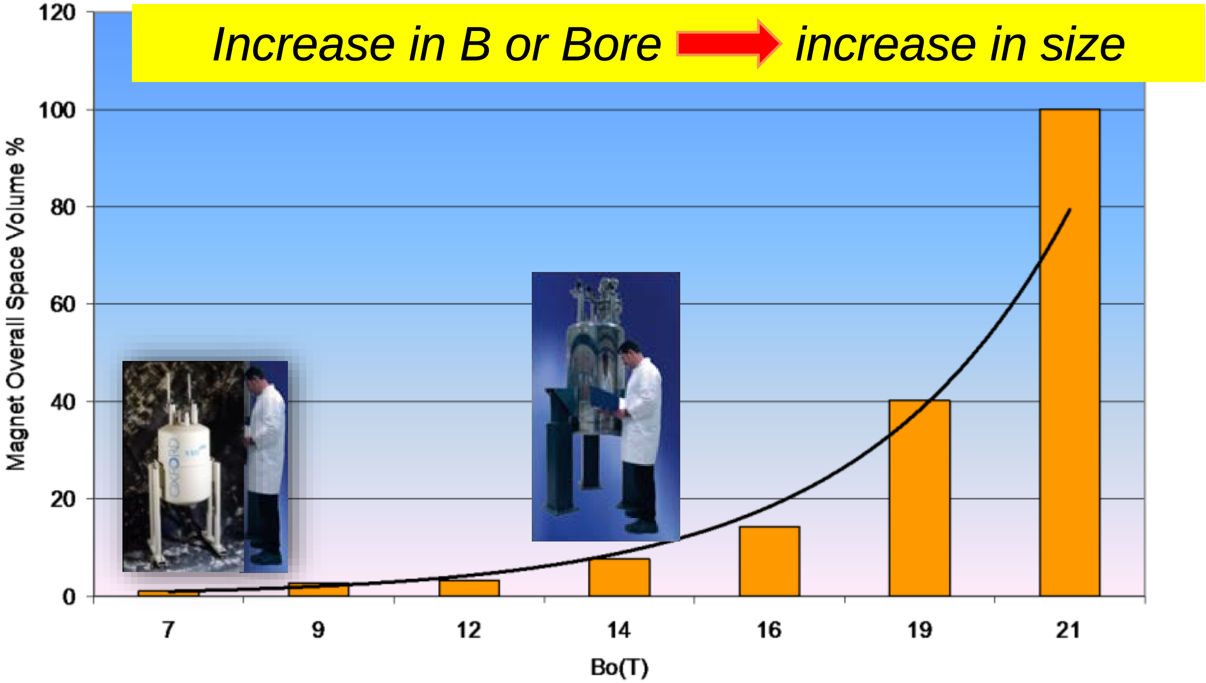
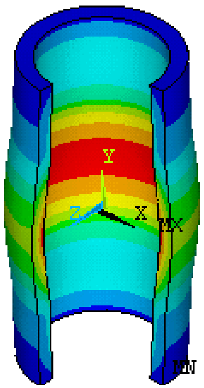


Stored energy of a 7 Tesla (400 MHz)
0.22 MJ

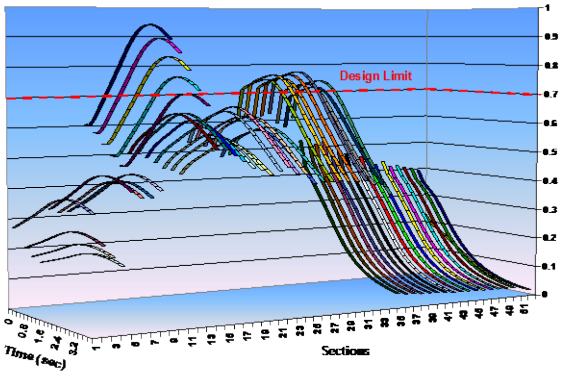
Stored energy of a 22 Tesla (950 MHz)
21 MJ

Two main high field design challenges :



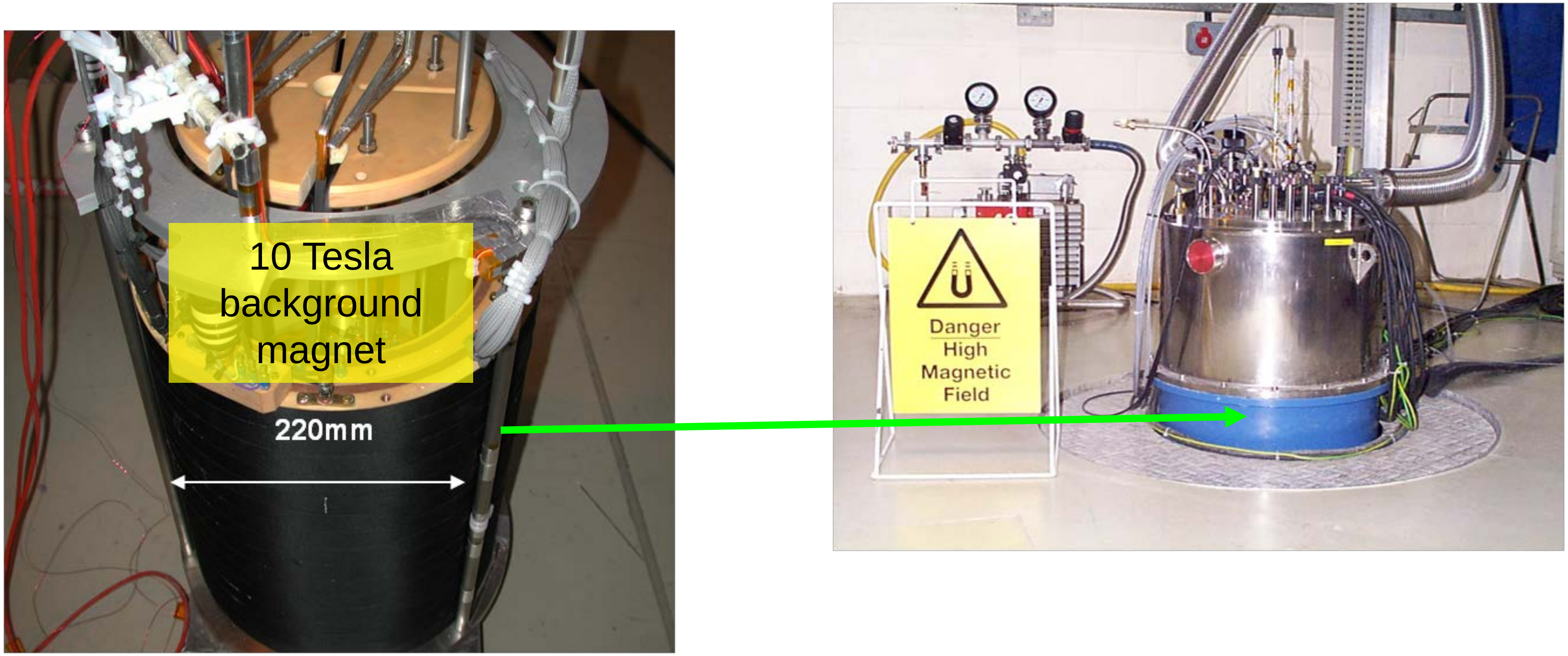
Pseudo static stresses

&



Quench transients

Requirements prototyping identified as the best technique to develop high field magnets

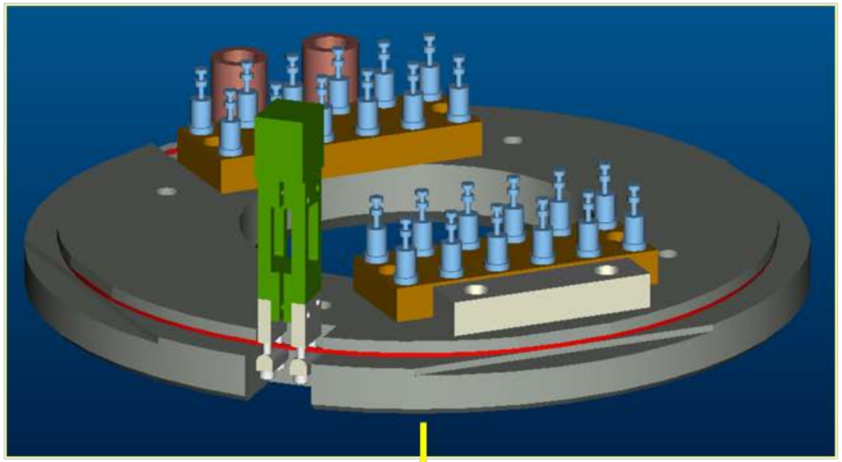


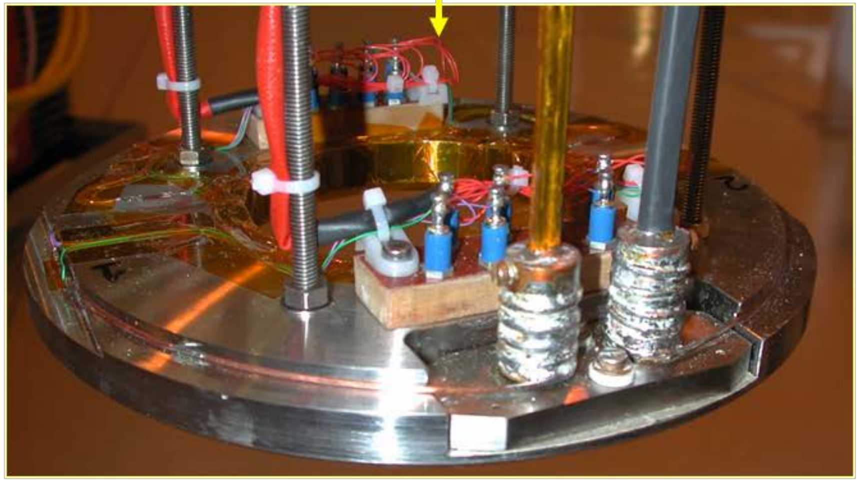
Running prototype coils and wires in a 10 Tesla background field magnet :-

The stresses are now due to Lorentz forces

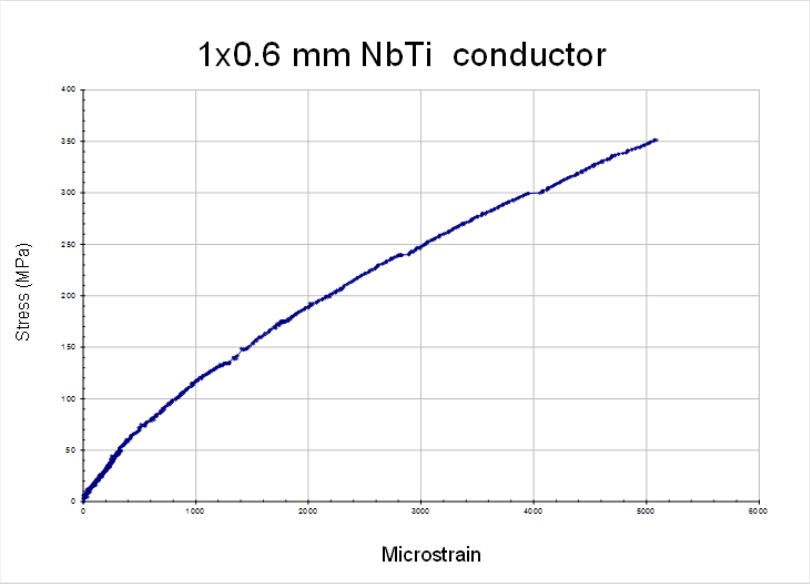
i.e. A TRULY REPRESENTATIVE MAGNET TEST

Wire strain and quench characterisation





Provides Stress/Strain curves for superconducting wires at 4.2K background fields up to 10 Tesla.



Also make preliminary assessment of the short sample performance (SSP) & quench behaviour of new wires before their use in prototype magnets!

NMR @ 22T, requirements prototyping NbTi coils

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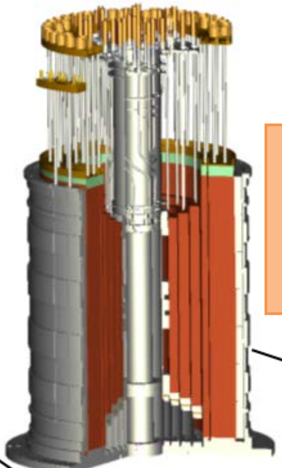
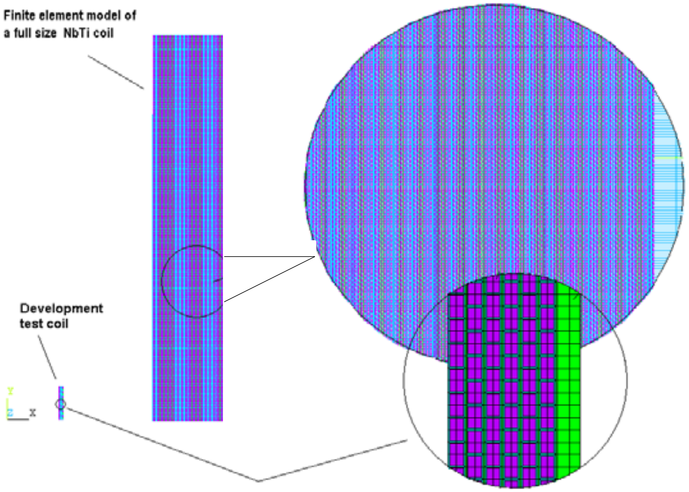
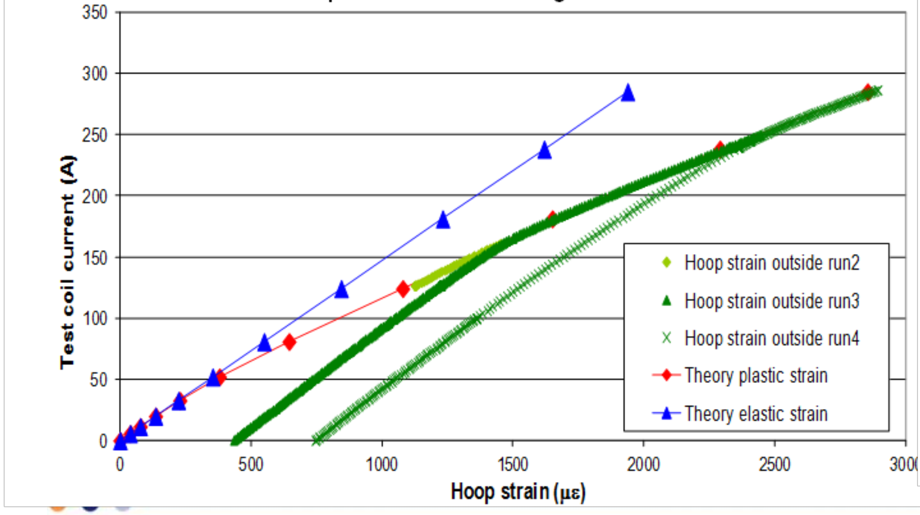


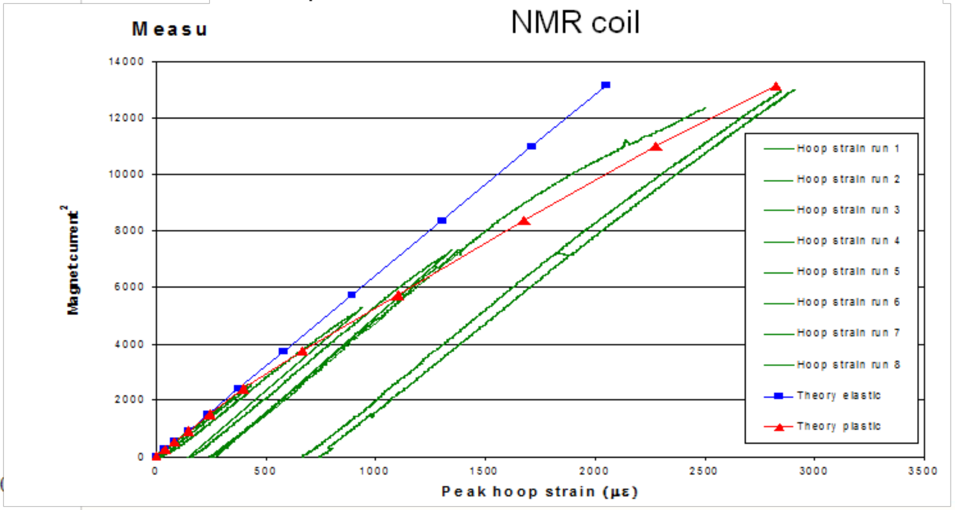
Finite element analysis techniques



Hoop strain on the outer diameter of a NbTi test coil running up in an 8.5T background field



Hoop strain on the outer diameter of a 21 MHz NMR coil



A theoretical model predicting strain is good but designing zero quench coils is the aim.

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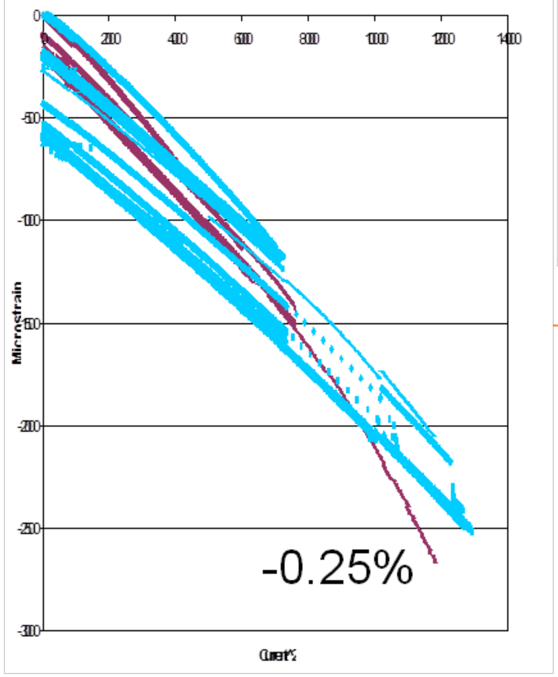
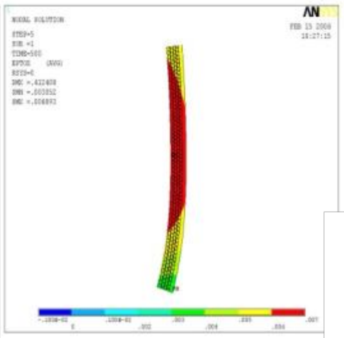
Axial compression at the mid height of a 21 Tesla NMR outer NbTi coil



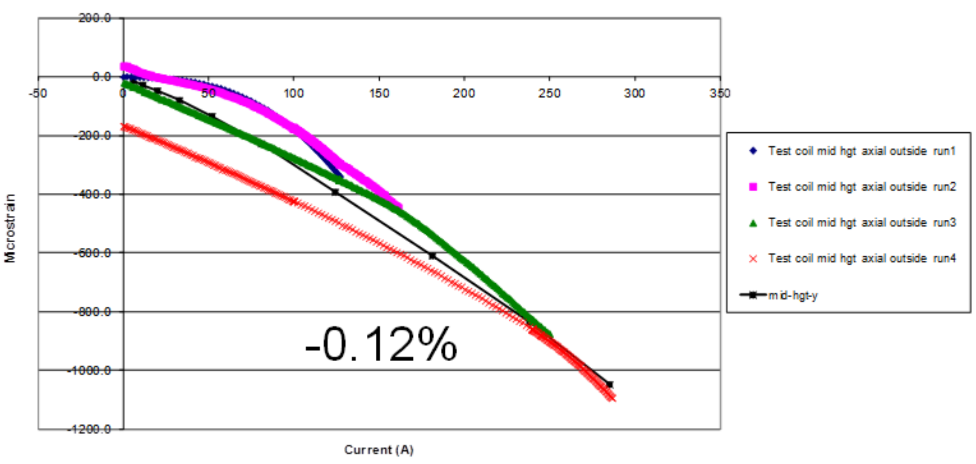
-0.25%



& the measured strains

Finite element detailed models show the Von Mises and axial stresses differ :

Axial compression at the mid height of a 120mm diameter NbTi test coil



-0.12%

Is this still a representative test with respect to coil quench behaviour?

Can the magnet engineer replicate the tensile stresses on a unit cell of composite to best investigate it's quench behaviour at the micro Joule level?

Quench performance of NbTi test coils compared to 21 Tesla NbTi NMR coils

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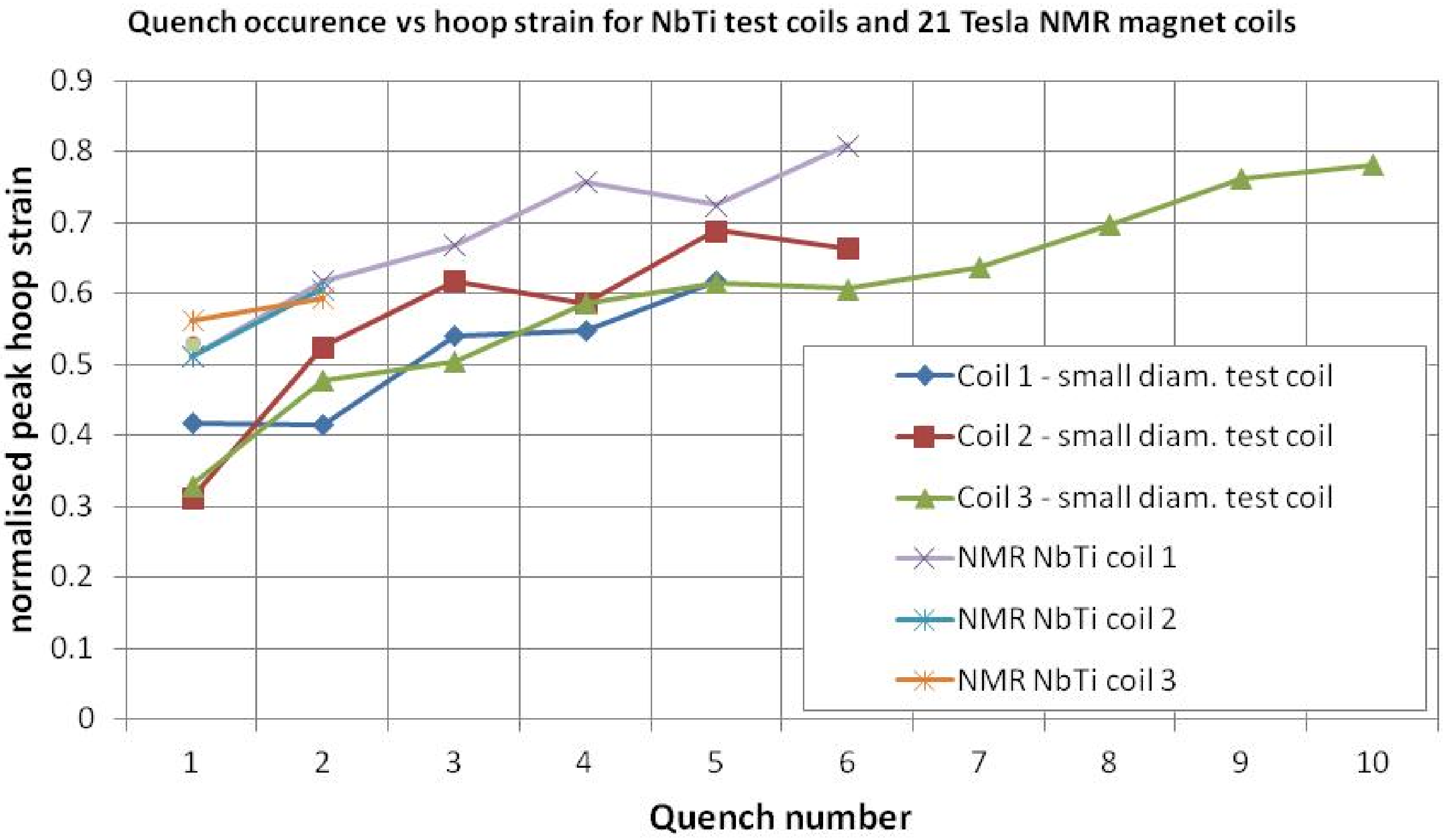
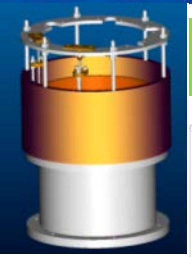
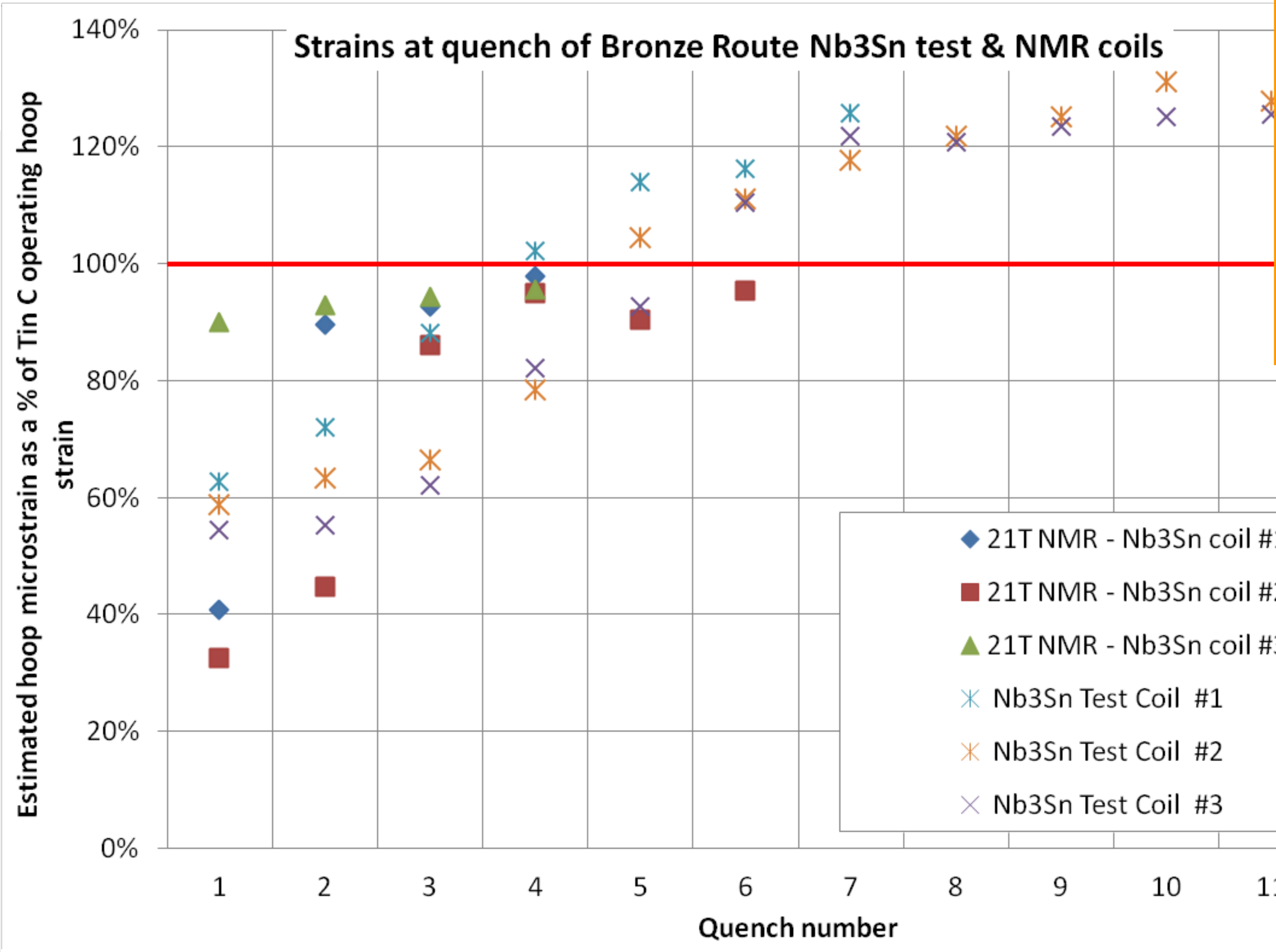
Quench performance similar within B field & SSP constraints

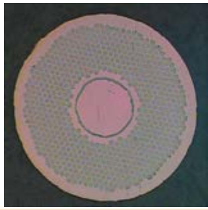


Quench performance bronze route Nb3Sn test coils and 21 Tesla magnet NMR coils

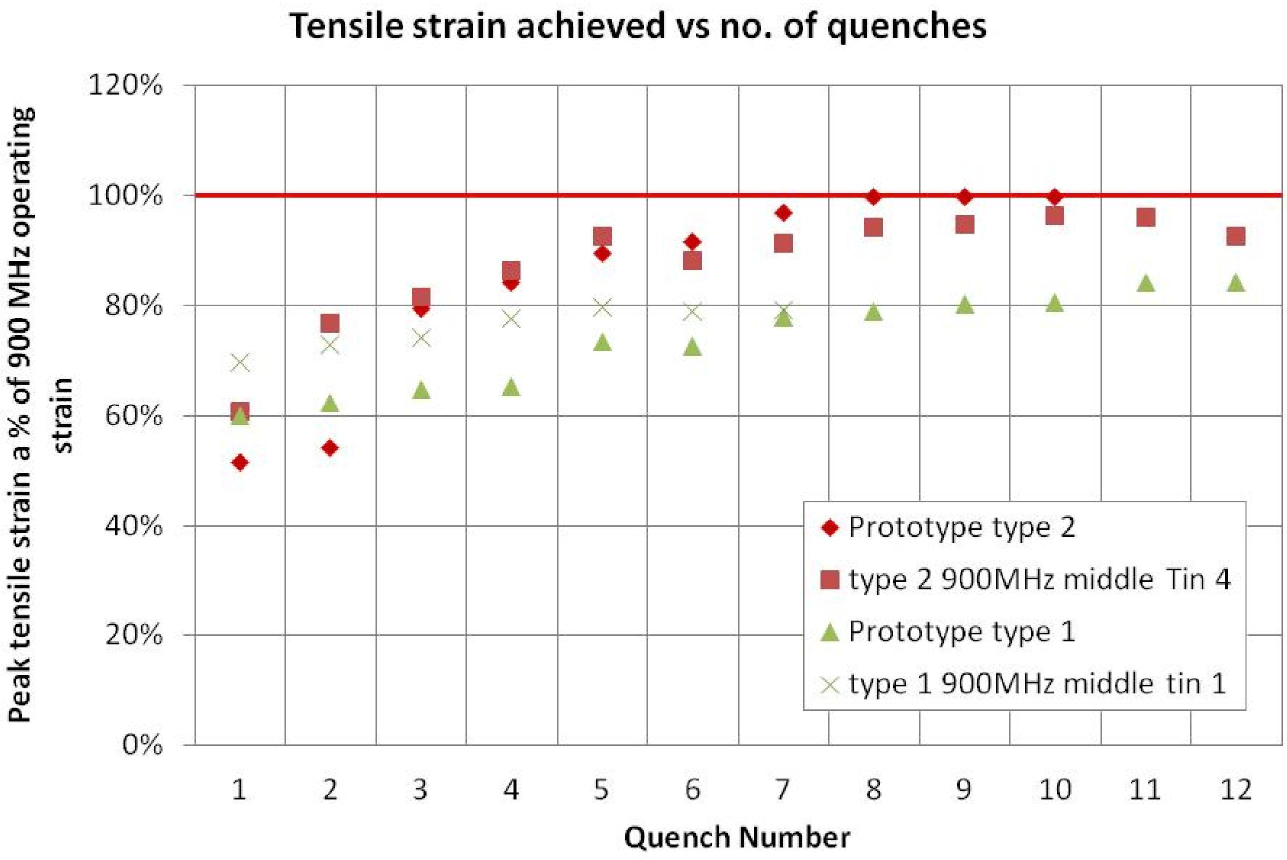


Different B fields and SSP, but similar quench characteristics





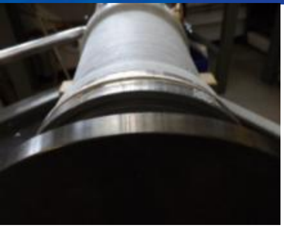
Requirement prototype coils give the engineer a new perspective on different coil structures.



Coil quench behaviour is ‘a little more predictable’. Look to new materials.

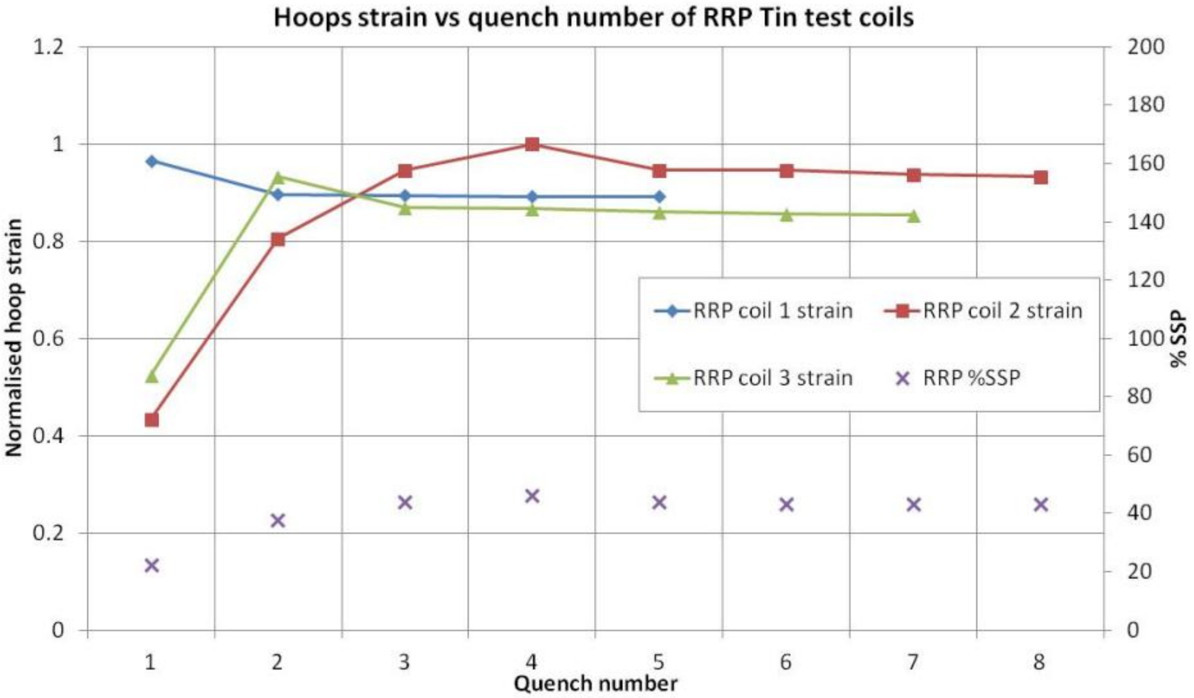
An example of two different coil constuctions tested at > $1,000 per quench in full NMR magnet and $10 per quench in test coils.

Restack rod process (RRP) wires : new coil structures, lower quench probability



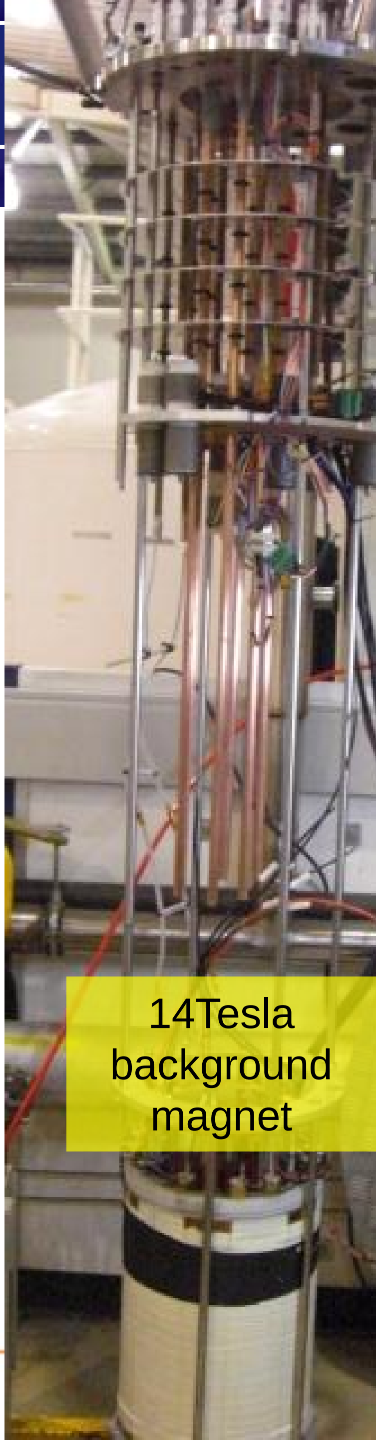
Magnet test coil ramped up in background field with strain gauges fitted :-

(1 to 4) quenches before the Nb_3Sn strain limit is reached!



Next challenge

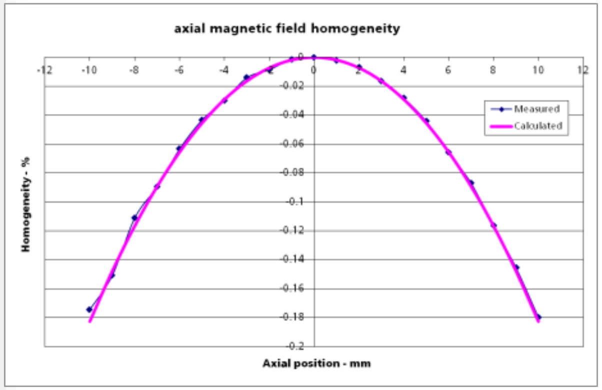
Quench dynamics modelling and experiment. Again done using requirement prototype coils with both voltage monitoring & fibre optics.



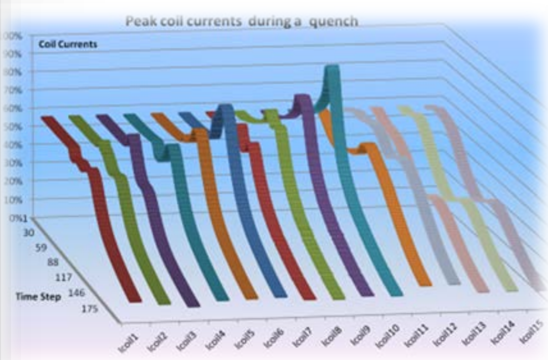
14Tesla background magnet

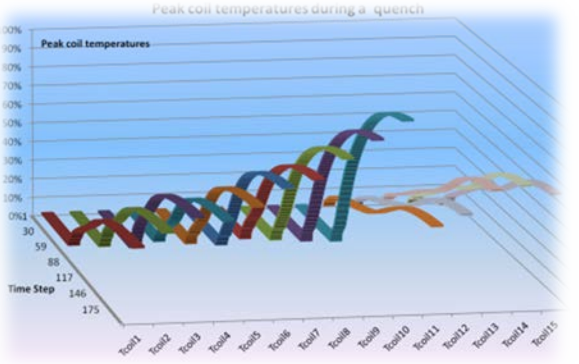
All this work led to a new class of ‘compact’ high field magnets for research

Compact
22T/52 mm (2.2K)
20 T/52 mm(4.2K)
for
Research Applications



15T_160mm system - LTS @ 4.2K
Prof Wang, IEE, China
used for HTS inserts





Further development brought a new class of ‘outsert’ magnets for high field research

15T_250mm @ T = 4.2K LTS - NHMFL

Requirements	Specifications	Actual
Flux density homogeneity	< 0.0143 over a 10 mm DSV	0.0144 over a 10 mm DSV
Energisation rate	< 1 hours	59.55 min
Stored energy	7.3 Mjoule nominal	6.95 MJoule
Static Helium Boil off (No insert coil)	< 3.2 L / hour	1.2 L / hour
Helium Capacity	300 L nominal	313 L

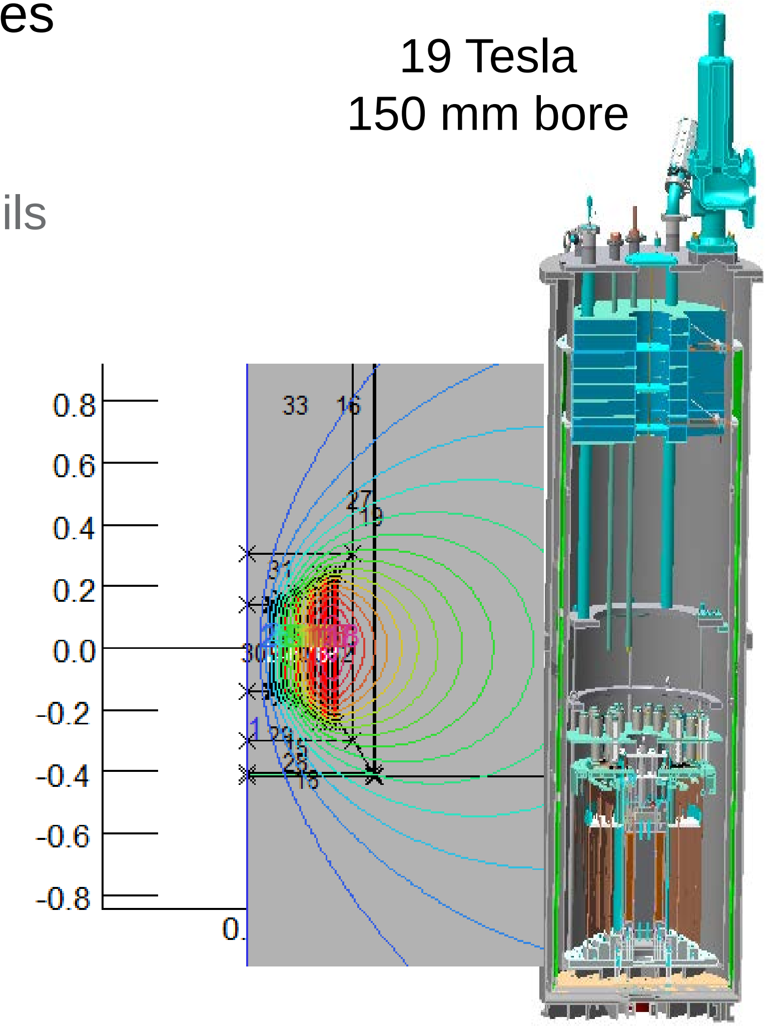
19T_150mm @ T = 4.2K LTS - HLD

Requirements	Specifications	Actual
Flux density homogeneity	< 0.04 % over a 10 mm DSV	< 0.04 % over a 10 mm DSV
Energisation rate	< 2 hours	< 2 hours
Stored energy	5.7 MJoule	5.7 MJoule
Static Helium Boil off (No insert coil)	< 3.2 L / hour	0.86 L / hour
Helium Capacity	240 L	240 L

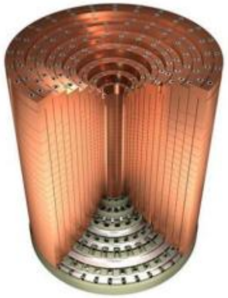
Further engineering modelling is required for these large magnet systems

- Key requirements achieved & unique features
  - Low vibration – No nitrogen shield
  - Top loading magnet support system for flexibility in mounting & exchanging insert coils
  - Low loss magnet current leads
  - Fully integrated magnet protection system

- Complex mechanical interactions defined & modelled for cryostat mechanical design:
  - Vacuum load (internal/external)
  - Internal pressure (helium evaporation/Q)
  - Magnet mass (~750Kg)
  - System mass (~1495Kg)
  - Quench eddy current forces


19 Tesla
150 mm bore

A new type of Ultra High-Field Magnet >30T



- Three primary approaches for high-field electromagnets
  1) **Non superconducting;**
     - RT copper magnets. No inherent upper-field limit – only more power & cooling required (i.e. need to be close to a power static & a lake)
     - Stronger materials enabling current record: 33T (~35MW) at NHMFL.
     - For special applications only – pulsed fields (100 T) also done

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  2) **Hybrid-combination of 1) and 3);**
     - A copper magnet (inner section) combined with a superconducting magnet (outer section).
     - Current record: 45T (30Cu/15SC)T, at NHMFL.

The future?

  3) **All Superconducting;**
     - Low-temperature superconductors (LTS) 4K-20K
     - High-temperature superconductors (HTS) 40K-100K

Engineering Current Density (J_e) limitations dictate conductor selection

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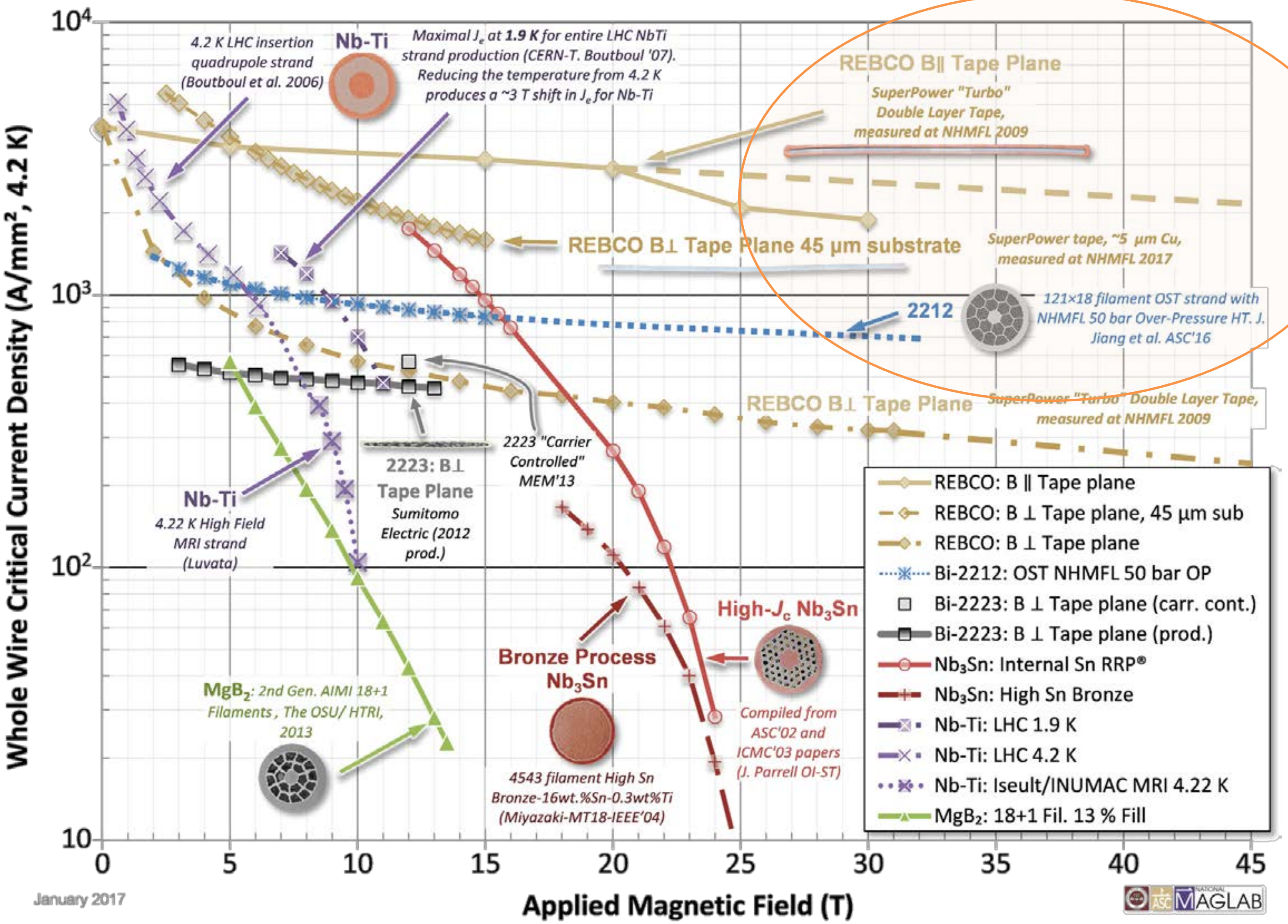


Two high potential ultra-high field conductors

LTS practical engineering limit 23-24T

HTS practical engineering limit ?40-50T?

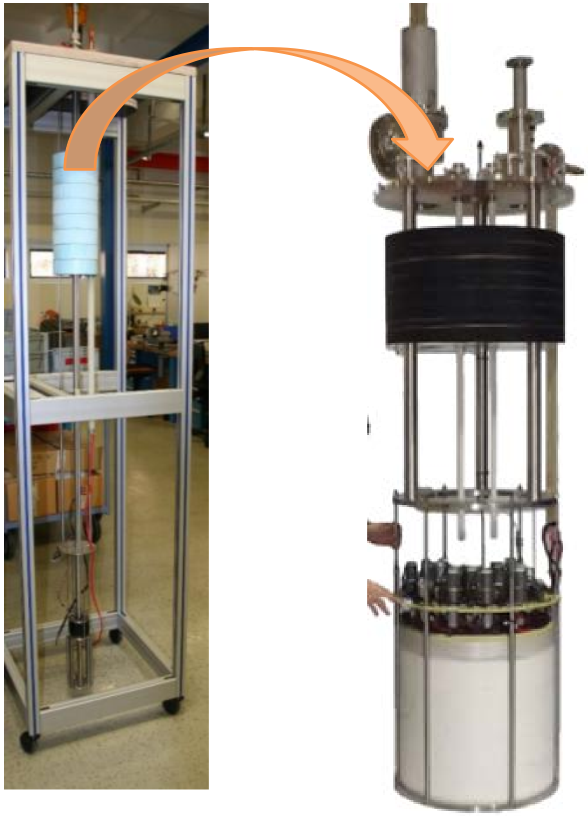
BSSCO coils of various diameters are under test at 19 Tesla at HLD Dresden

Coil#1 fabrication & test at Low B field

Successfully tested to high short sample at 19T




Small and large diameter coils at HLD, reactions at B-OST and NHMFL

The next generation of requirement prototype coils (the best route to 30T and beyond?)

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