HFM High Field Magnets 14-16 April 2021

Workshop State-of-the-Art in High Field Accelerator Magnets, April 14-16, 2021

MDP general meeting Wednesday, April 28

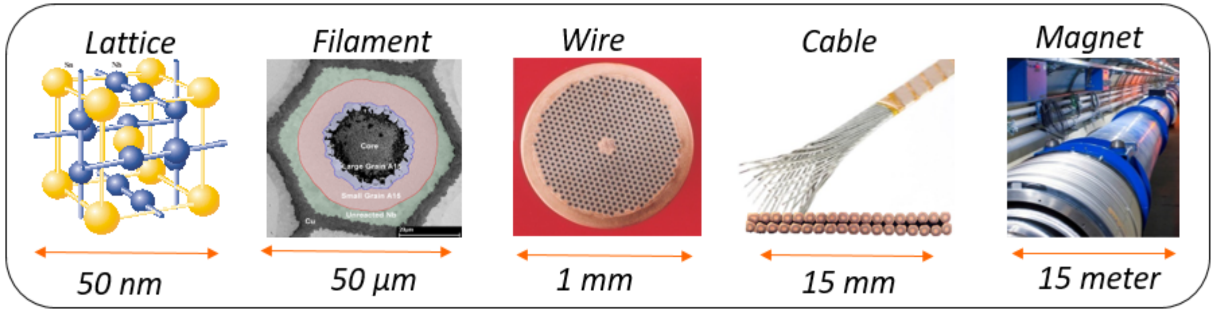
U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn Conductor Characterization

- a selection of critical issues -

Marc Dhallé & Herman ten Kate,
University of Twente

1. Focus on most critical issues…..
2. Critical current density, filaments, AC Loss
3. Strain effects on wires and cables
4. Stability, degradation, training
5. Conclusion



1. From material to a successful magnet

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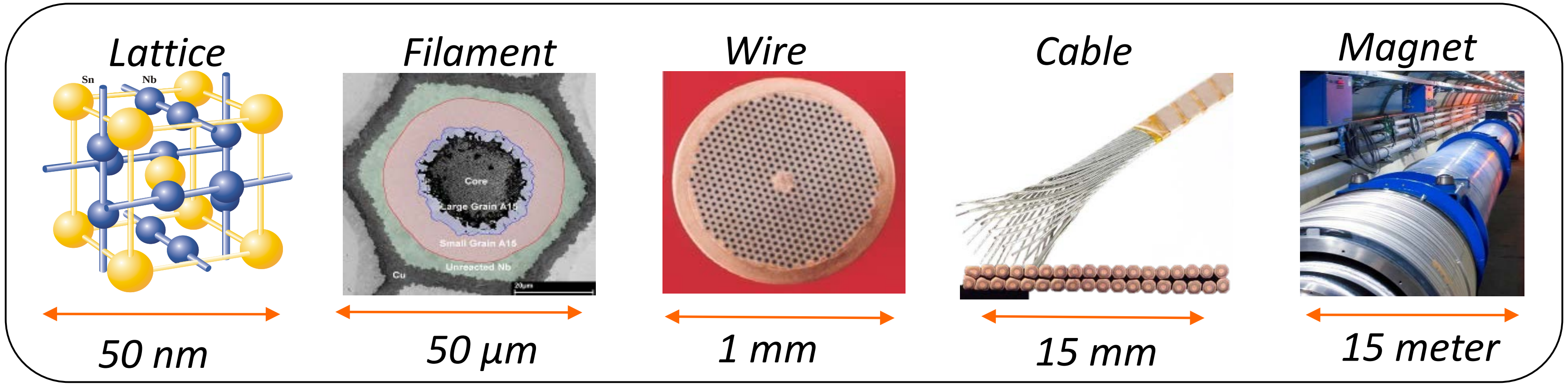
➢ **How to make cables that guarantee the accelerator magnet not to quench or degrade ?**

Key physics phenomena:

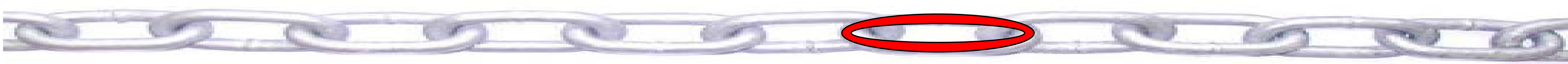
Critical current density – Magnetization & Ramp loss – Stress & Strain – Stability & Training



- Performance
- Manufacturability
- Robustness
- Reliability
- Availability
- Cost

Few key parameters:

J_c - D_{eff} - Interfilament resistance - Interstrand resistance - Wire architecture - Cooling - Specific Heat



✓ We need to understand and control the entire chain, but emphasis is on cable level….

2. J_c - D_{eff} - AC loss - status in Nb_3Sn Rutherford cables

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J_c & D_{eff}: for efficiency-cost-volume reasons the engineering current density in accelerator windings have to be at least some 400 A/mm^2 at the requested field:

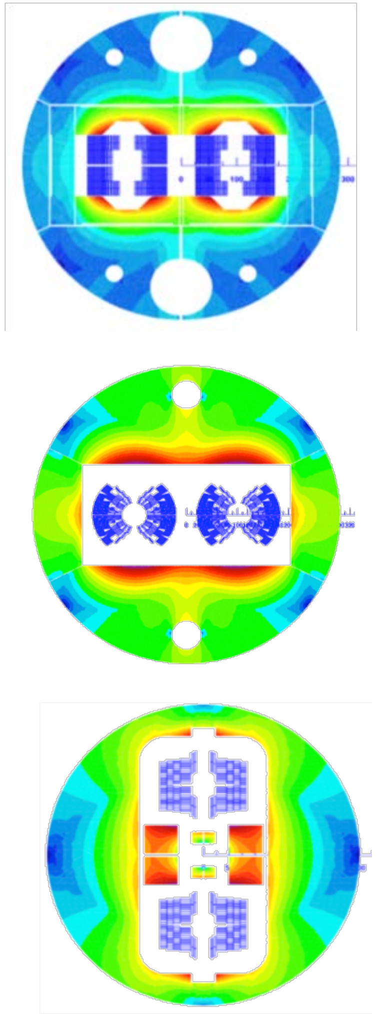
- 8 T at LHC, 11-12 T for HL-LHC, 15-16 T for FCC, 20+T for FCC+
- Non-Cu Jc increase well underway for achieving 1500 A/mm^2 in <20 µm filaments at 16T@4.2K, reached in km long wires (see previous talks[†])
- Next: further increase to some 1800 A/mm^2, for achieving margin and robustness, reduction of D_{eff} to 20 µm, and making long lengths
- A great success made possible by CERN's drive towards affordable 15-16 T.

Ramp Losses: in strands and cables sufficiently predictable provided inter-filament and inter-strand resistances are under control and filament shape is known.

Hottest issues for cables, and thus for magnet performances are:

- Sustaining Transverse Pressure on cable wide face,
- Achieving no (or little) training and stable long-term performance.
- ✓ So, we will focus on this in the next slides….

(†) Ballarino 2021, Xu 2021



Three 16T FCC designs

2. J_c - D_{eff} - AC loss - status in Nb_3Sn Rutherford cables

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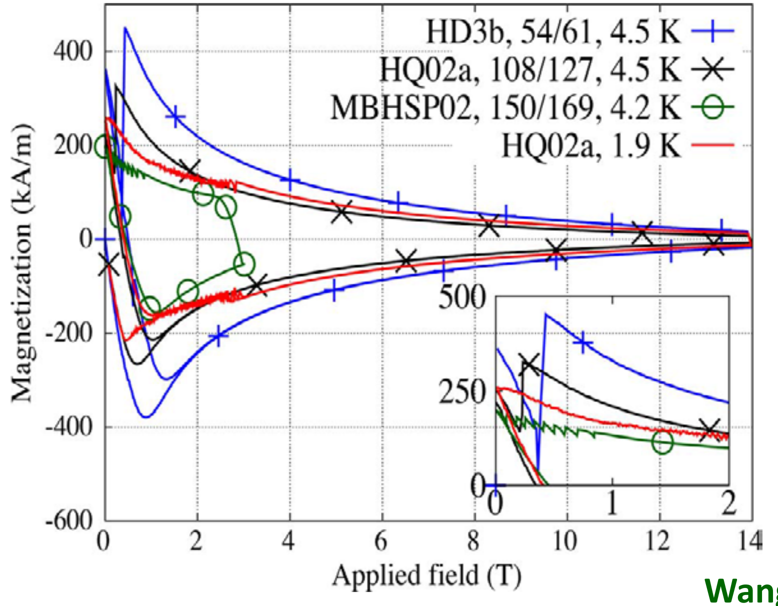
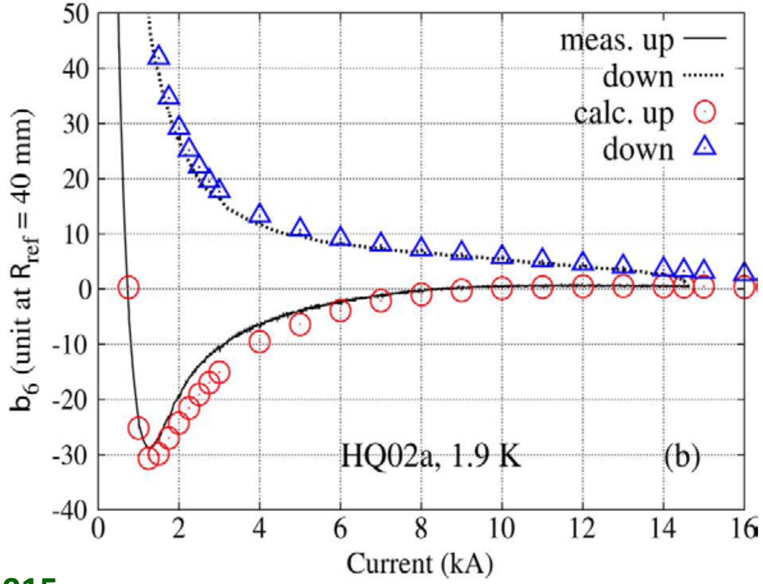
Literature survey 2015-2021(*)

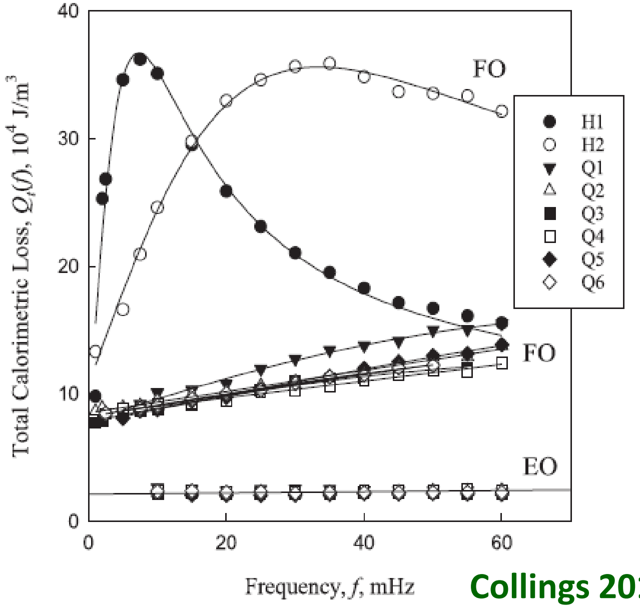


Wang 2015

Magnetization loops RRP strands



Sextupole moment HQ02 magnet



Collings 2017

Coupling losses several Rutherford cables US program

Magnetization and ramp losses well-understood when strand magnetization, R_a & R_c are known

- For Nb_3Sn not a major research issue last ~ 5 years (at least not in the public domain).

(*) The extensive body of work < 2015 is not included in this presentation.

3.1 Strain effect - Single strands

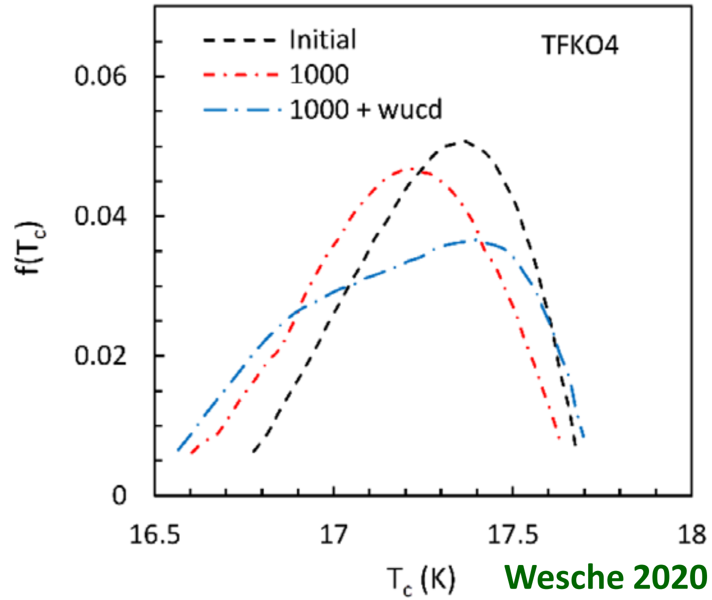
Literature survey 2015-2021$^{(*)}$

Internal stress/strain -distribution well-charted with local probes:

- n-diffraction reveals strain distribution on filament level (Scheuerlein 2017, Osamura 2019), role of thermal pre-strain (Suwa 2018), bending strain (Hemmi 2017), pre-bending (Takahashi 2015)
- X-rays reveal strain distribution matrix (Scheuerlein 2017, Jin 2017)
- Related T_c distribution evolves with mechanical / thermal cycling (Wesche 2020).

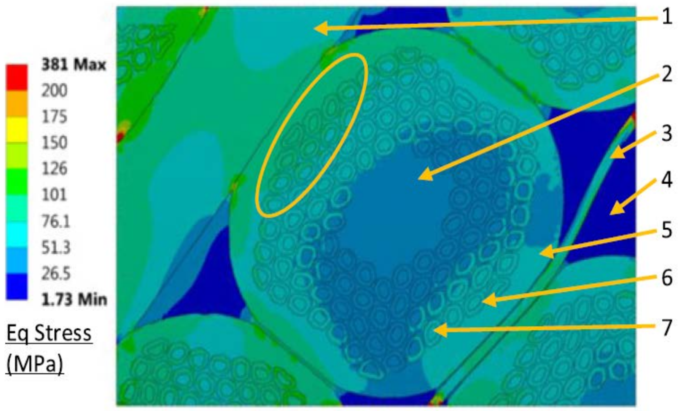
Modelling has refined to a local filament level:

- Multi-level modelling from coil all the way down to filament (Daly 2018)
- Influence of imperfections on transverse-stress concentration (Zhai 2016) and thermal pre-strain (d'Hauthuille 2017)
- Role of plastic matrix deformation (Ta 2015, Barzi 2019)
- Role of filament cracking on $\sigma(\varepsilon)$ (Wang 2016) and on J_c (Liu 2018).



Wesche 2020

Evolution T_c distribution with cycling



Stress distribution magnet strand **Daly 2018**

(*) The extensive body of work < 2015 is not included in this presentation.

3.1 Strain effect - Single strands

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Literature survey 2015-2021(*)

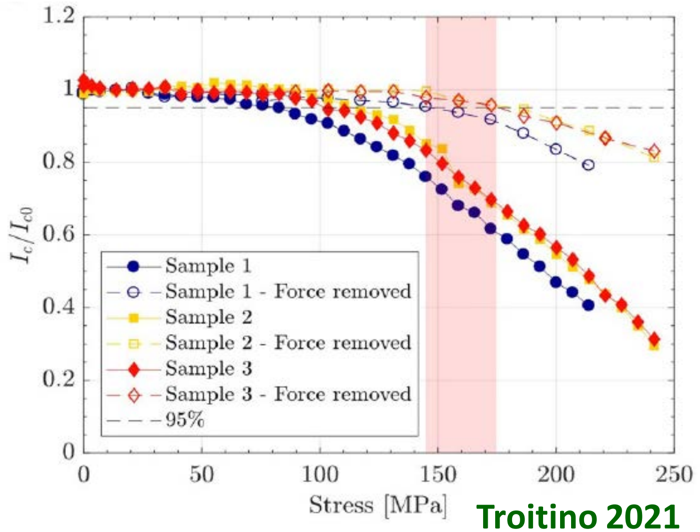
Single-strand strain response experiments have refined ....

- Axial strain response well-documented (Liu 2015), including role of factors such as voids (Barth 2018) and filament twist (Seeber 2019)
- Transverse strain response measured under magnet-relevant conditions no J_c degradation up to ~ 150 – 180 Mpa (Troitino 2021).

... and are well-understood:

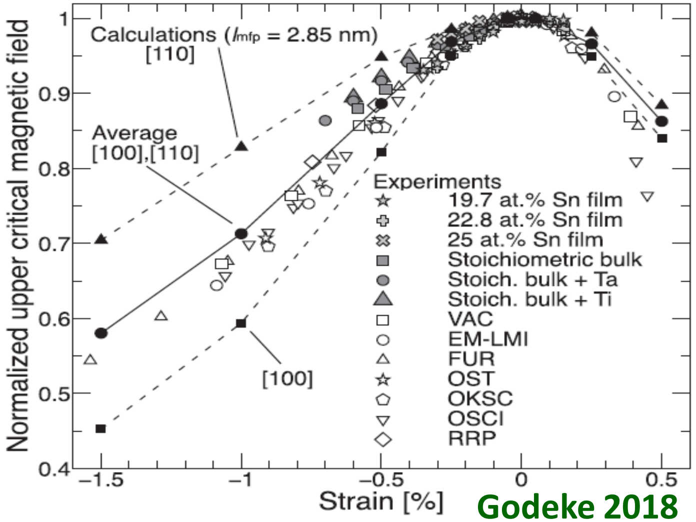
- Strain response is well-described and quite predictable (Ekin 2016)
- It is intrinsically related to the interplay between lattice disorder (Mentink 2017) and the electronic DOS (Godeke 2018, Qiao 2019)
- It can, if needed, be further 'engineered' with internal reinforcements (Sugitomo 2021, Barzi 2019, Hishinuma 2018).

Conclusion: "***The overwhelming lesson from the 30 years of Nb_3Sn development for ITER is that the issue is not the strand production, but the strand use***" (Mitchell 2020)



Troitino 2021

Transv. stress response RRP strand



Godeke 2018

A-priori axial strain response vs. data

3.2 Transverse pressure - Rutherford cables

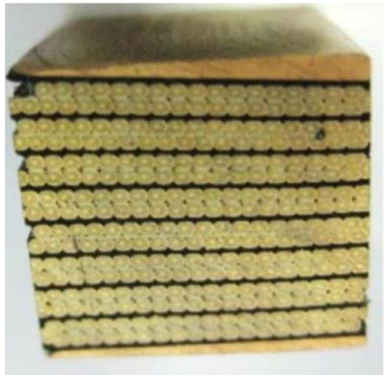
Literature survey 2015-2021(*)

Important body of data collected mechanical behavior cable stacks ...

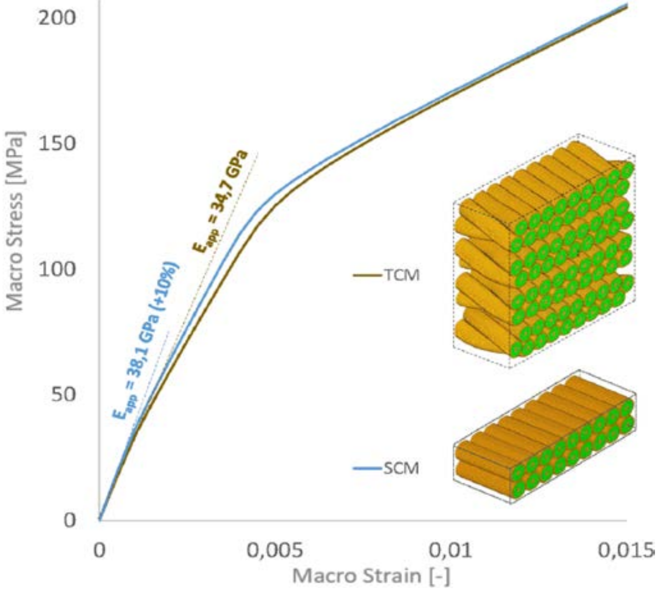
- Overall stiffness impregnated stacks (Wolf 2019a); evolution geometry during HT (Durante 2016, Rochepault 2016)
- Local probes: n-diffraction loaded stacks (Wolf 2019b); X-ray tomography & contact imaging (Wolf2018)
- Effect of RT pre-loading (Ebermann 2018) and of cable uniformity (Fleiter 2018) on critical current;

… and applied in coil modelling

- Strain distribution in impregnated stacks (Nunio 2019) and winding pack (Martins Araujo 2020)
- I_c & thermal margin prediction (Vallone 2021);
- Strain development during quench (Troitino 2020).



Wolf 2019a
Impregnated stack for RT testing



FEM modelling stack response **Nunio 2019**

(*) The extensive body of work < 2015 is not included in this presentation.

3.2 Transverse pressure - Rutherford cables

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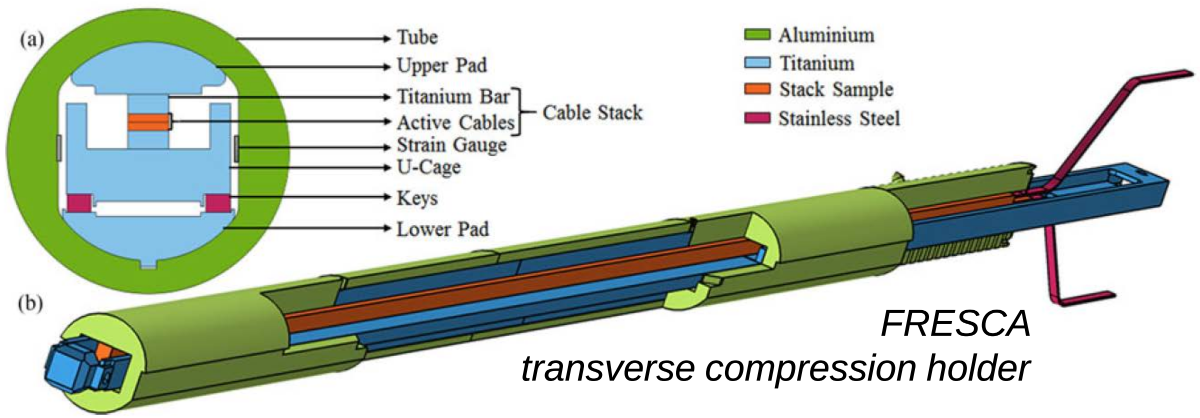
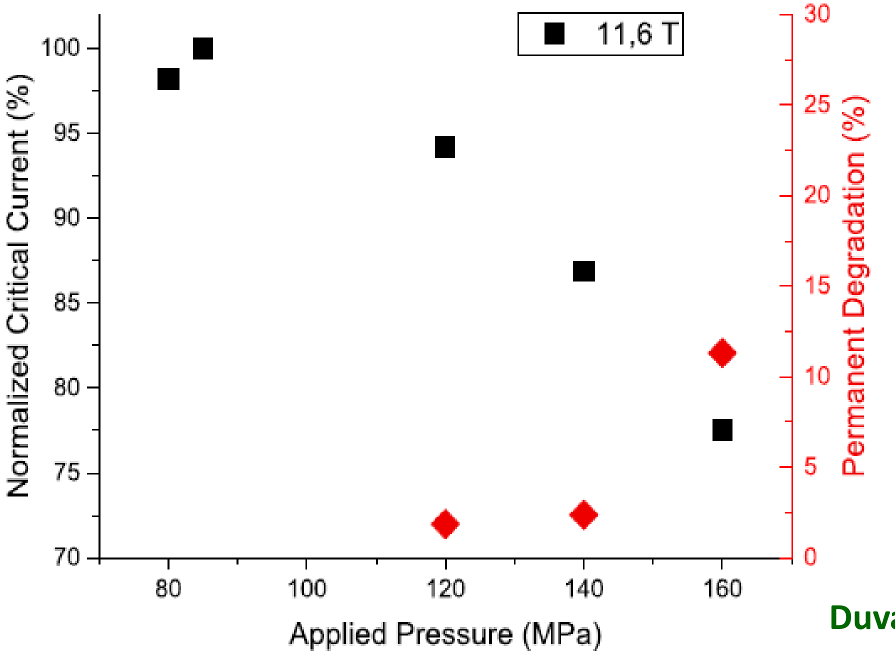


FRESCA
transverse compression holder

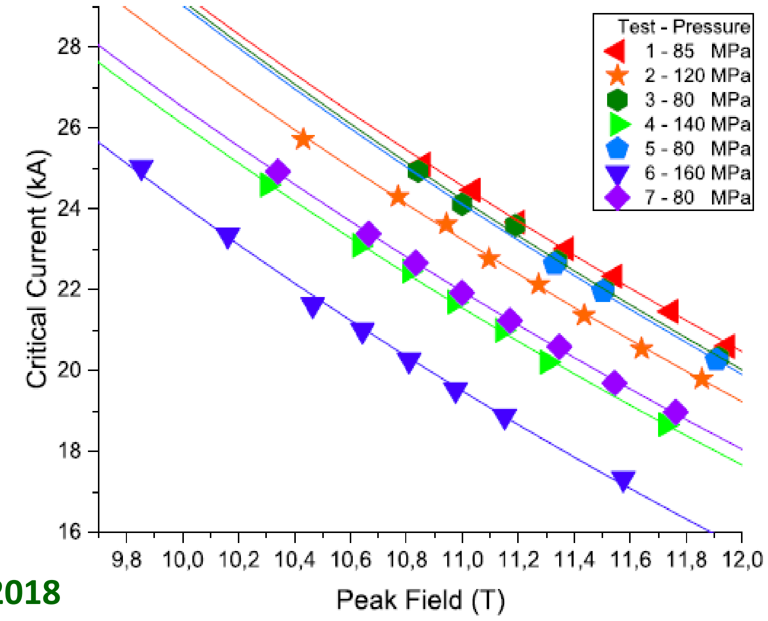
Critical current cables vs field and transverse pressure in ***FRESCA***
(Duvauchelle 2018)

- Long-sample;
- Precise $B_{c2}(\sigma)$ analysis;
- RT stress-adjustment.



I_c *response RRP cable*

Duvauchelle 2018



B_{c2} *response RRP cable*

3.2 Transverse pressure - Rutherford cables

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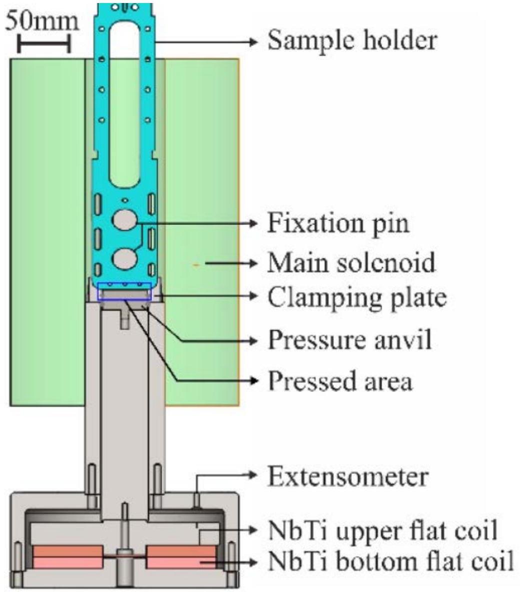
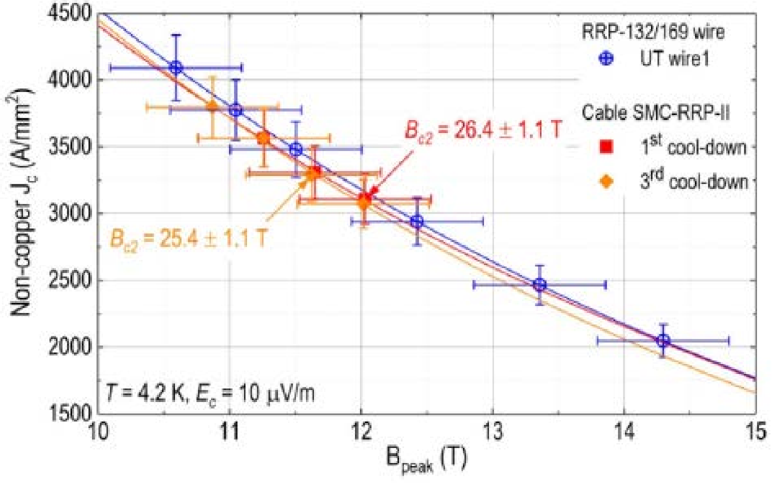
UTwente Cryopress / transformer



P. Gao PhD thesis UTwente 2019

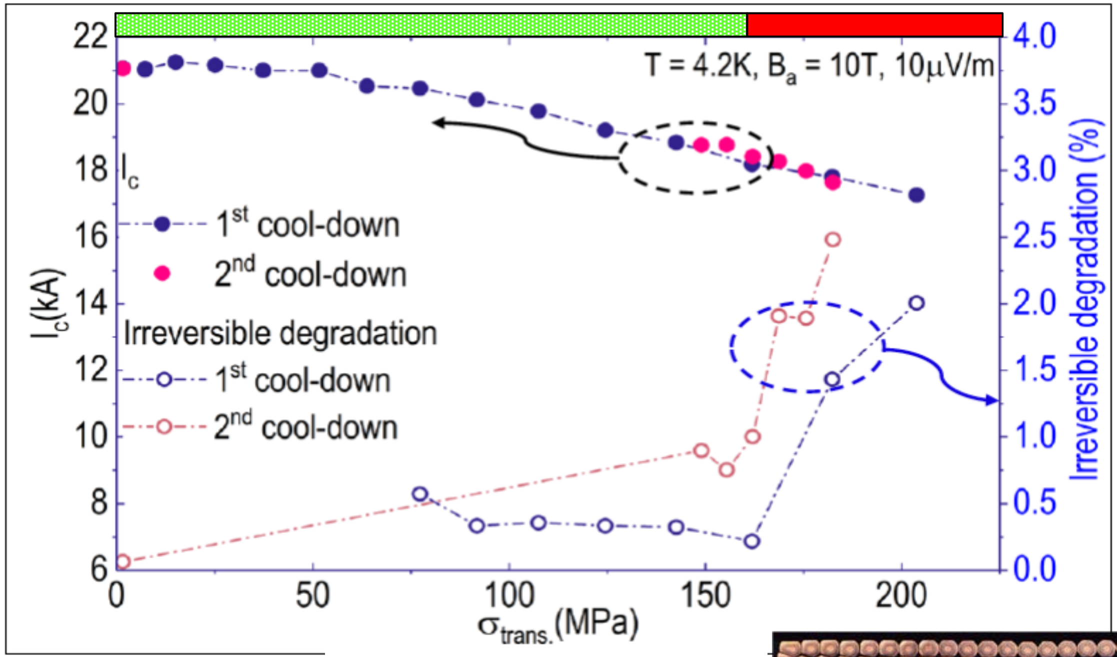


B_{c2} response RRP cable

Critical current cables vs field and transverse pressure in ***UT press*** / transformer

(Gao 2020)

- In-situ stress variation;
- Ease of mechanical and/or thermal cycling;
- Short sample.



I_c response RRP cable

3.2 Transverse pressure - Rutherford cables

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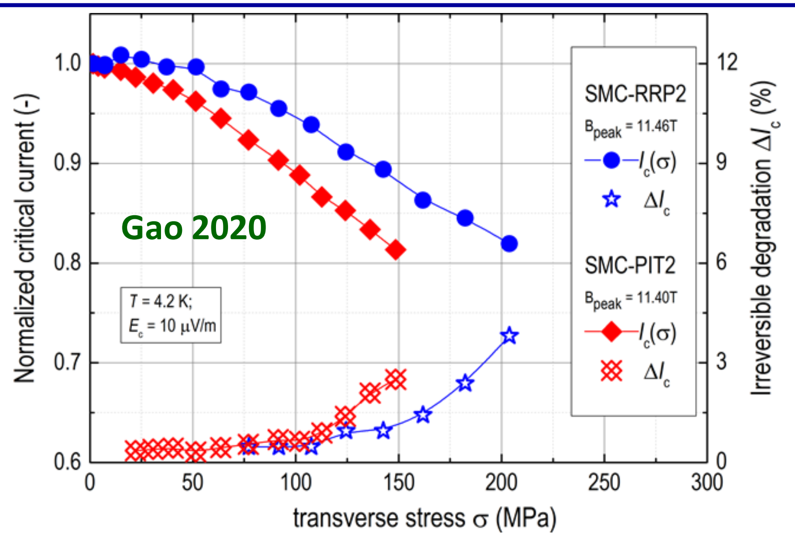
- Critical current affected by pressure
- **Reversible reduction** due to lattice deflection, some 10-20% at 150 MPa!
- **Irreversible reduction** due to copper yielding, changing Nb_3Sn pre-stress state, significant > 100 MPa
- **Irreversible damage**, filament cracking
- Starts at some 150-200 MPa.

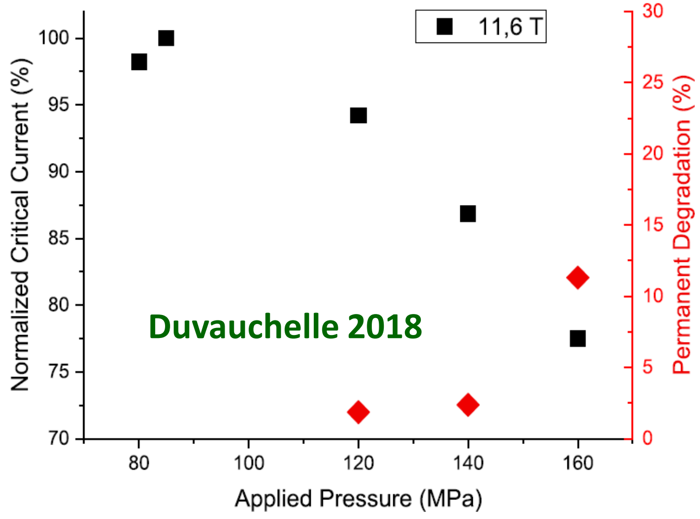
Note: measured with pressure uniformly applied, in real coil not the case, thus worse to expect.

✓ **Transverse pressure of some 150 MPa OK** in *perfectly* impregnated cables, but I_c then some 10-20% less, eating from the margin, thus reduced stability!

✓ Strand and cable mechanical optimization possible to some extend, not more, hitting a **principle limit for non-reinforced Rutherford cables** !



Benchmarking I_c response



Benchmarking I_c response

3.2 Transverse pressure - Rutherford cables

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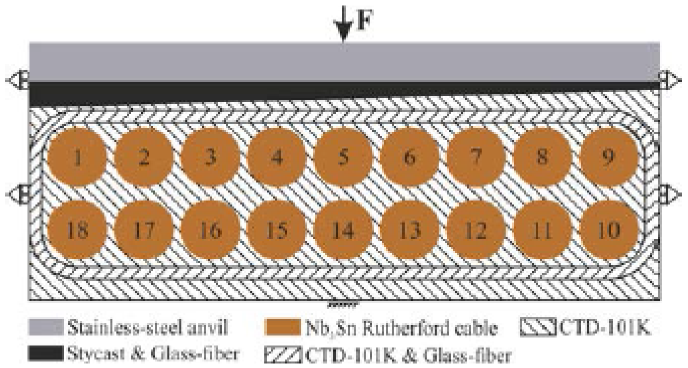
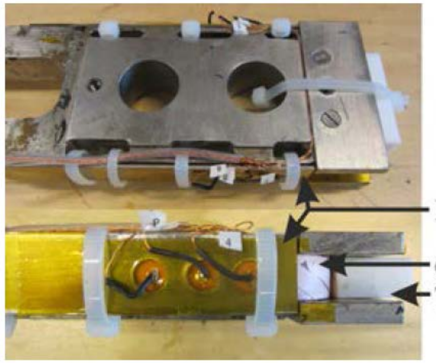
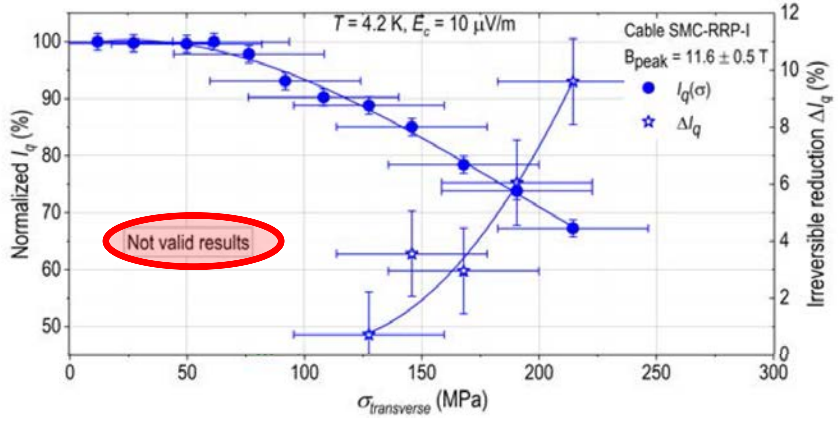
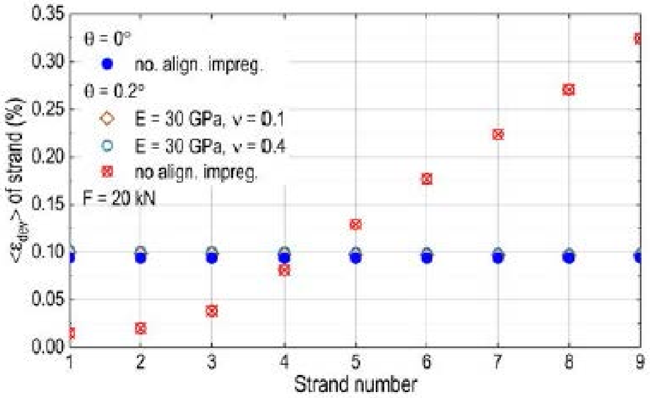
The non-ideal world in cable measurements: Imperfect parallelism (0.2°)

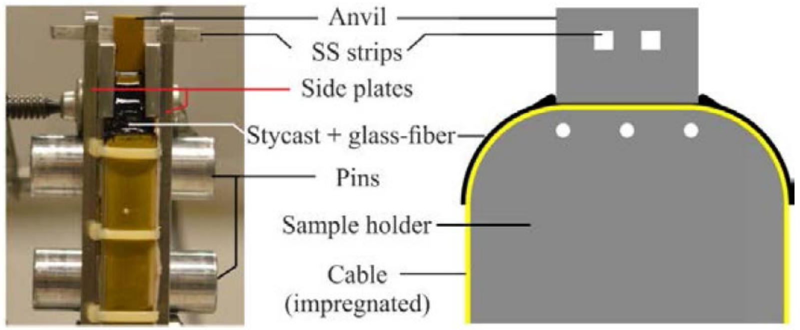


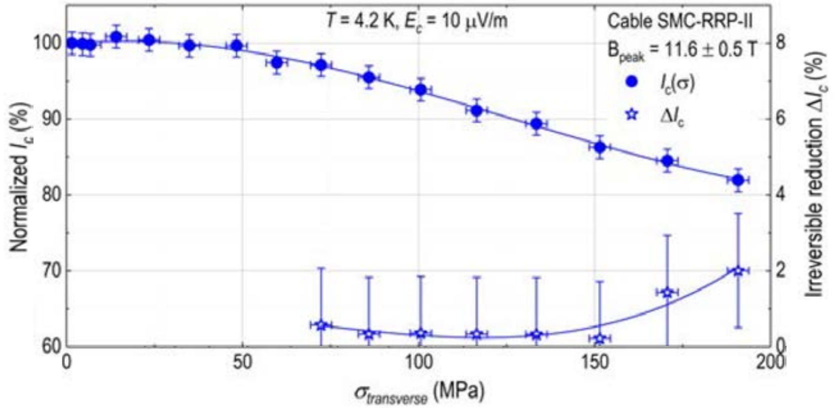




Correcting action: 2nd "alignment" impregnation



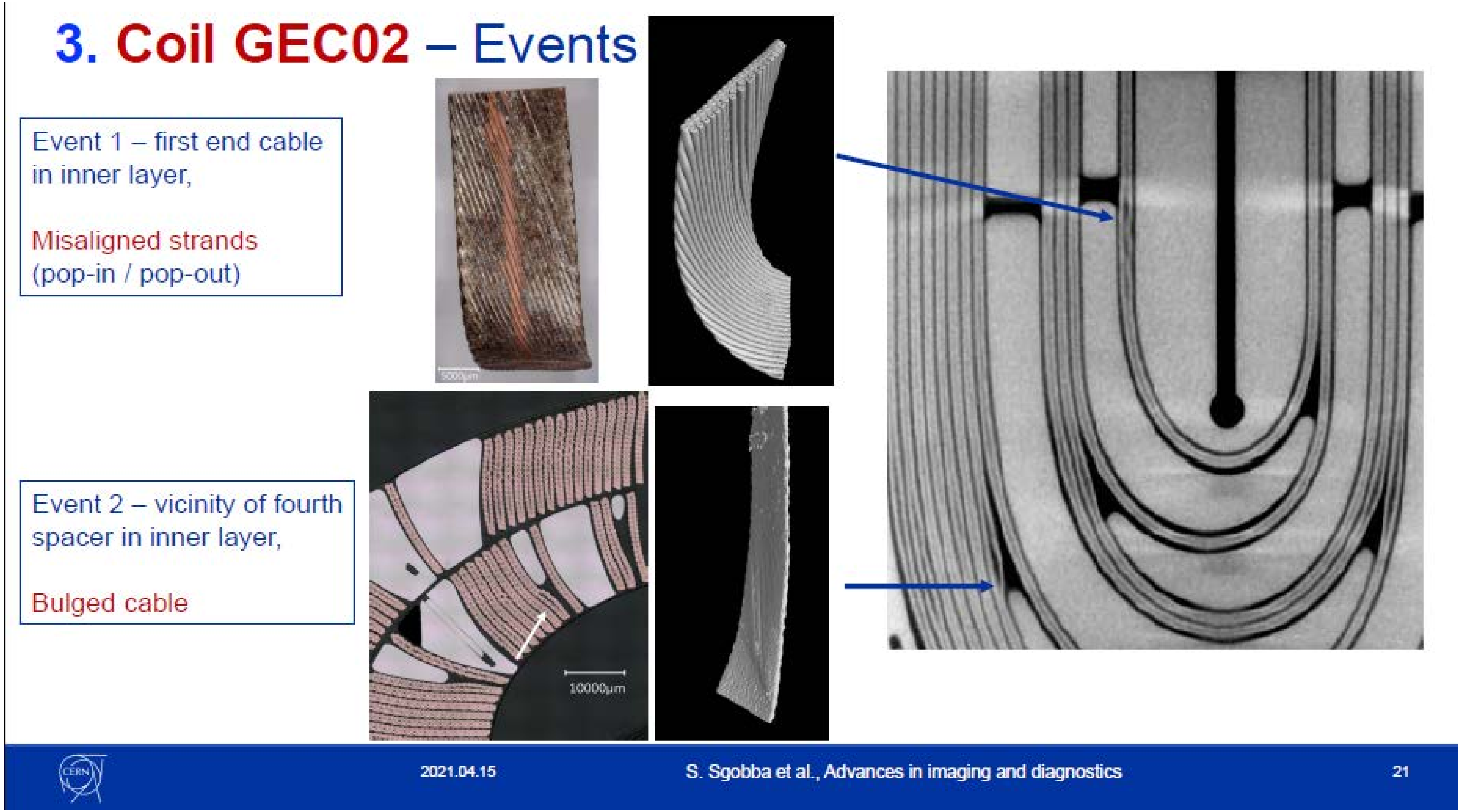




P. Gao PhD thesis UTwente 2019

3.2 Transverse pressure - Rutherford cables

The non-ideal world in magnets: post-mortem on dipole coils (Sgobba 2021)



4.1 Stability versus I/I_c – The 'stability cliff'

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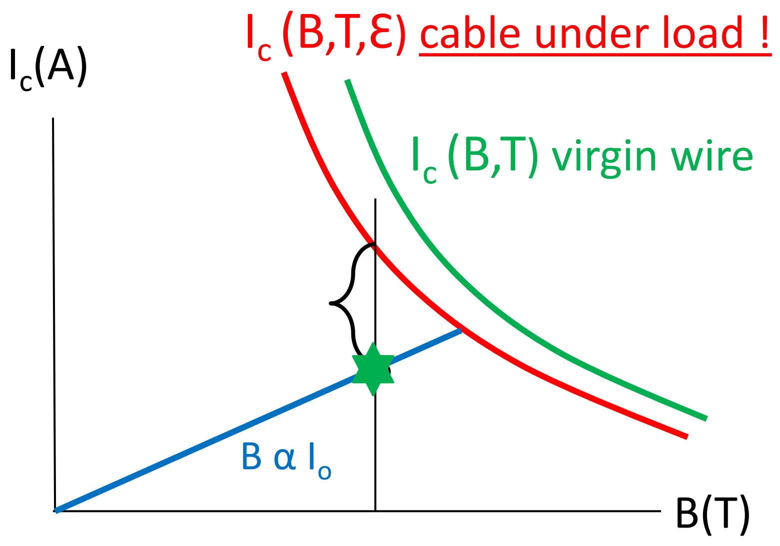
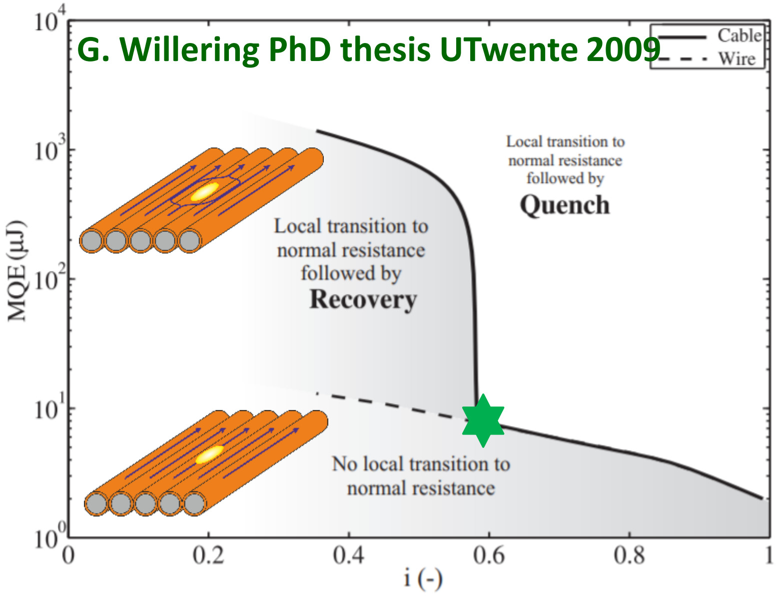
- Operate cable at operating point I/I_c not too high.
- I_c is of the cable after manufacturing (cabling degradation, may be -5%) and fully loaded at 150-200 MPa (-10 to 20%); so effectively at some 75 to 80% of the wire I_c (only).
- **To profit from *collective* strand *stability*, be on left side of the kink, to get robustness and be less susceptible to wire motion and resin cracking!**
- The transition is characterized mainly by single strand level (heat capacity) and the "kink value" of I/I_c.
- **Systematically all factors determining i_{kink} were investigated experimentally *and* verified by simulation (CUDI).**
- Key factors are **C_p** (added high C_p material or sf He in cable); **cooling** with sf He and **inter-strand contact resistances**!

We probably can't base a large series production of long magnets on a design relying on single strand stability… have to accept the consequences.





4.1 Stability versus I/I_c – The 'stability cliff'

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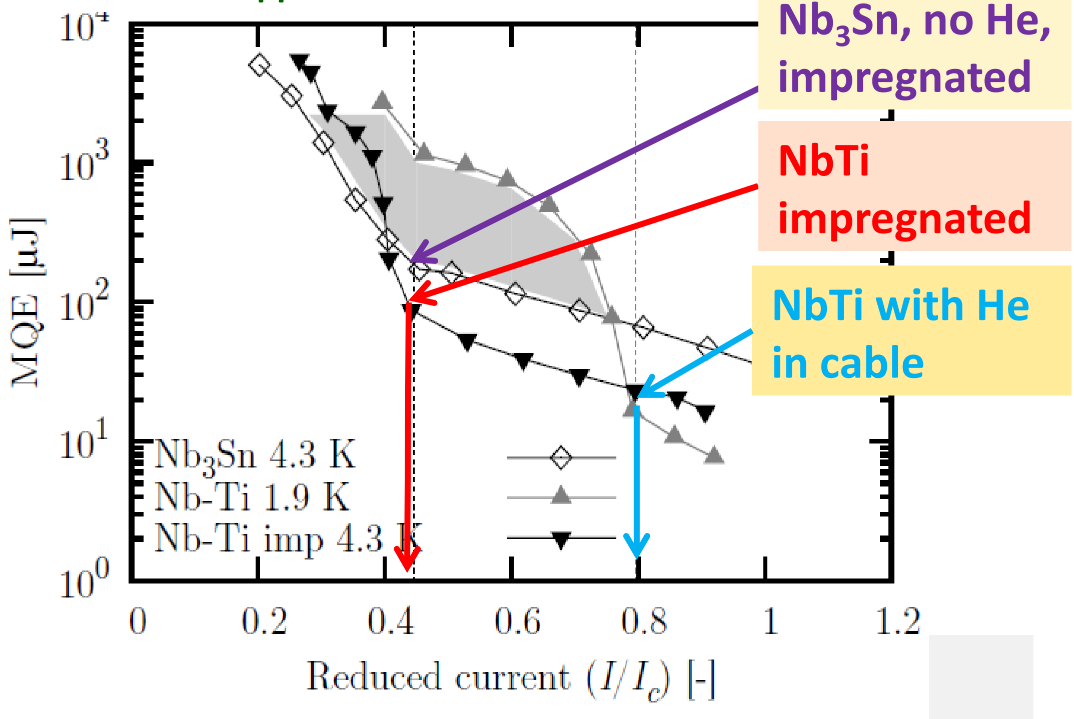
- Using collective cable stability yields a factor 10 to 50 in MQE!
- For NbTi@1.9 K, sf-He inside, ***needs margin*** to profit from collective strand stability, ---> $I/I_c<0.75$.
- **Impregnated Nb_3Sn is well in "single strand regime" when at some > 75% on load line!** Need to reduce I/Ic down to < 0.45 to profit again, and this cost €€€€.
- Convincingly, we see the same in impregnated NbTi 1.9 K, "lost" stability, need I/I_c less than some 0.45!

M. De Rapper PhD thesis UTwente 2014



Cure? what to do!

1. Keep impregnated cables, but reduce I/I_c to some 0.45; cost a lot to buy this robustness, but what else?
2. Increase heat capacity of the conductor by adding high C_p material (brings something, but not enough).
3. Bring sf He heat sink and cooling back in the conductor, make a porous cable or use a Cable-in-Conduit.
4. Drastically reduce inter-strand contact resistance, strand coating, porous metal filler, solder.
5. **A well-balanced combination of 1 to 4!**
6. **Much more cable stability tests and simulations needed to master this key problem.**

4.2 Example of enhancing stability – boosting C_p

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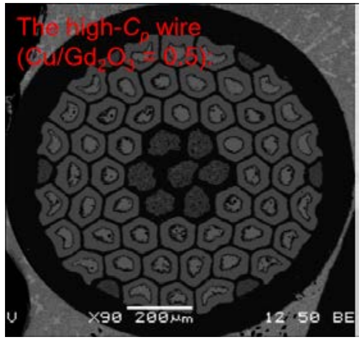
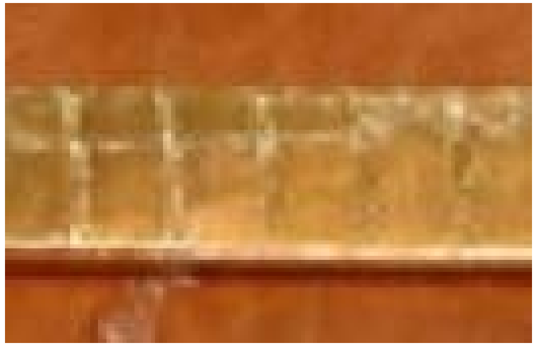
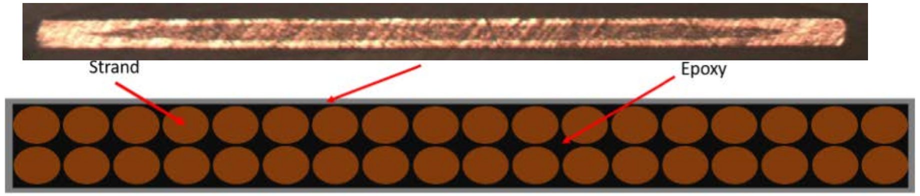
High C_p material (e.g. Gd_2O_3 or Gd_2O_2S) can be added to (Xu 2019, Barzi 2020 & 2021):

- strand (replacing filaments) or as a coating
- in the cable (core strip, wrap, replacing strands)
- in winding blocks (wedges)
- as interface to coil structure (cover sheets)
- as nm-powder filler in resins for impregnation.

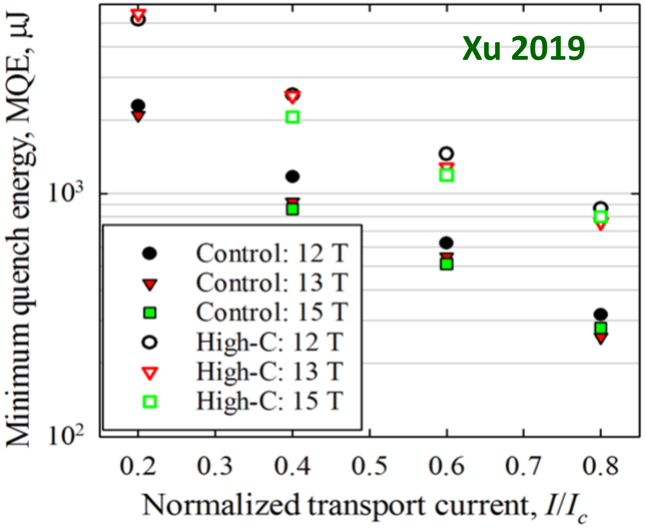




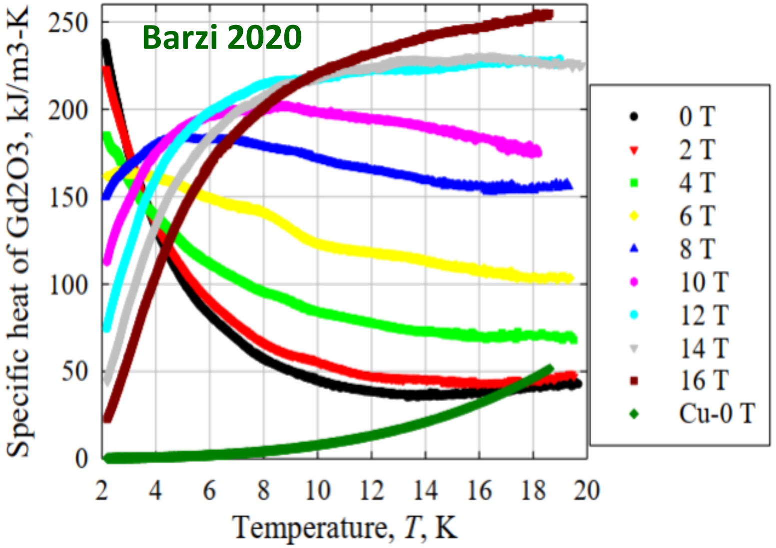
Wire with GdO filaments, cable with wrap, GdO tape



Barzi 2021



MQE gain with loaded wire, FNAL.



Gd_2O_3 C_p(4.2K, 12T) = 160 kJ/(m³K)

Cu C_p = 1 kJ/(m³K)

Nb_3Sn C_p ~ 2 kJ/(m³K)

Bare Cable C_p ~ 1.5 kJ/(m³K)

✓ **Proof of principle delivered, worth to develop and do extensive MQE stability tests on range of cables.**

4.3 Reducing training – BOX, a new benchmark

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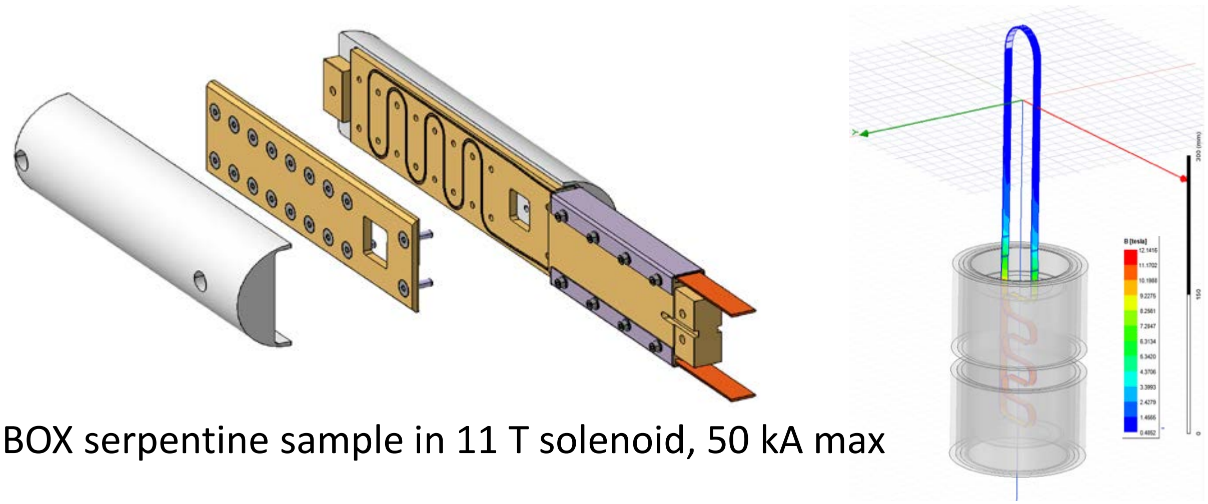
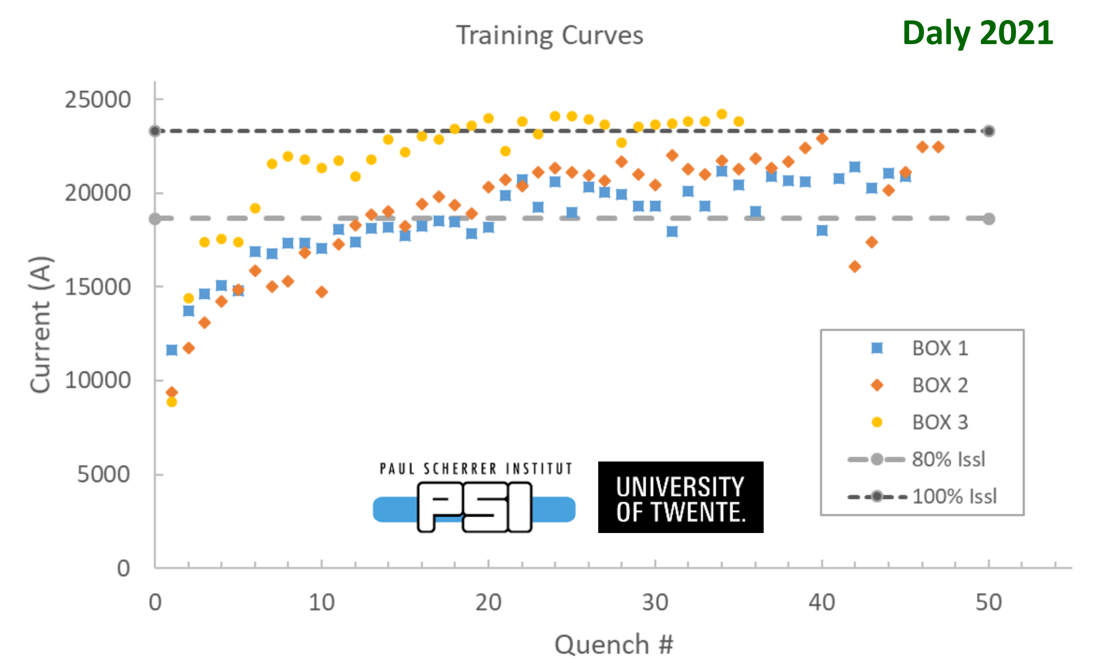
- Extensive studies required to understand training vs bonding (surfaces - resin - insulation - cable)
- Building small R&D magnets too expensive and time consuming, looking for a smarter way
- PSI developed with UTwente a facility called BOX for fast turn-around testing of samples at representative stress and strain conditions
- Serpentine with 7 straight section in high field $(B \times Ic)_{max}$, pulling/pushing on cable, VI taps, acoustic sensors
- First 3 Boxes recently done, “magnet-like” training curves seen, improvements visible, promising technique!



BOX serpentine sample in 11 T solenoid, 50 kA max



- Seems to work very nicely
- Some 20 BOX samples with variations waiting……

5. Conclusion

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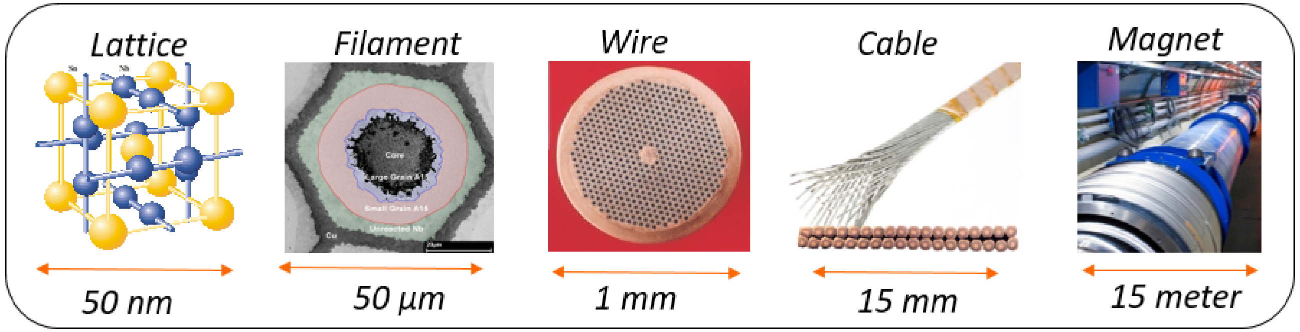
- Key issues for Nb_3Sn in high-field accelerator magnets are **proper J_c, robust stability** and **no/little training**.
- Critical current reduction by **transverse stress** is understood in terms of lattice deformation (reversible), changing pre-strain state (not reversible), and filament cracking (degradation), determined by wire layout and composition.
- When assessing magnet performance, the **I_c of the mechanically loaded strands** must be taken into account (some 70-85% of virgin wire I_c at 150-200 MPa).
- For allowing series of full-size magnets, the **stability & training issue must be solved** to get robustness, allowing practical production tolerances and sufficient yield.

  Accepting comfortable margin seems hard, but is an investment.



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