Cable Behavior

and specific Issues for HTS tapes

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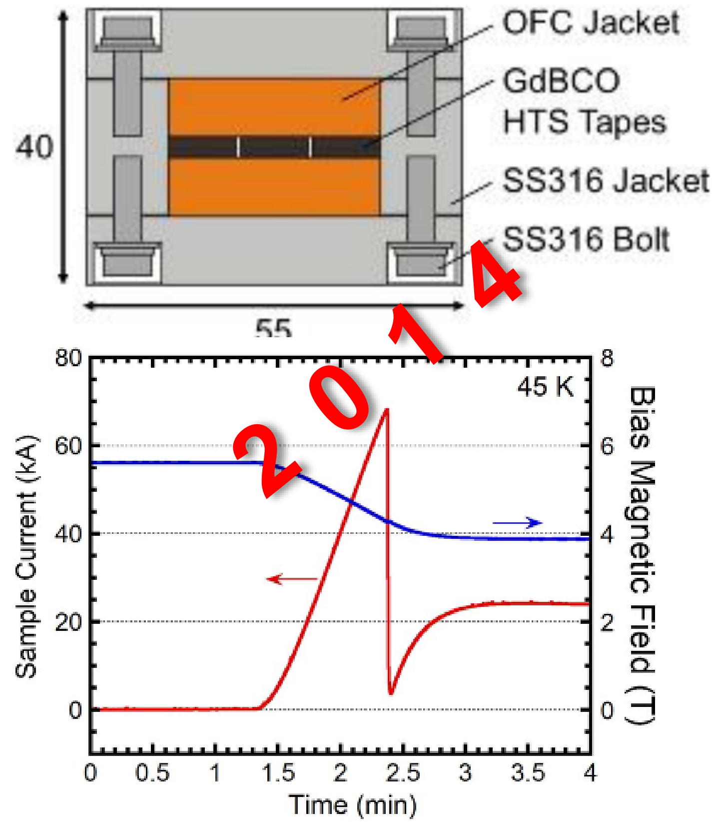
- HTS high current / high field cables – a green field
- Three architectures and common behavior issues
- The path forward – address or avoid the issues
- Any useful lesson from Nb_3Sn cables?

A green field

Cables made by REBCO tapes are young, < 10 years old, but attract now more attention than the older 1G based cables.

The testing of *high current / high field* short length cables by REBCO is even younger, likely 5 years since the milestone of the “plain stack” assembled conductor in Japan (67 kA @ 45 K, 4.3 T).

So far we are collecting results of short prototypes or “few turns” inserts. A full high field magnet wound by a high current (>20 kA) HTS cable is not yet in the pipeline, both in accelerator and fusion.



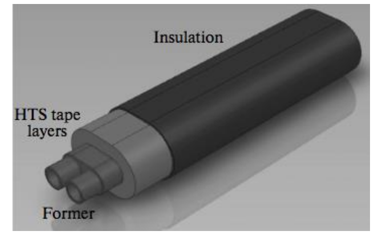
A privileged observatory

Prototype high current HTS cables and inserts have been tested in SULTAN in the last 5 years.

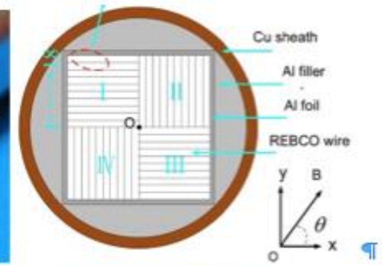
The experience with the SULTAN tests is the basis for today considerations.

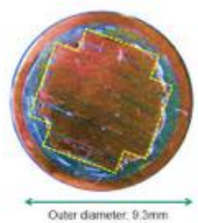
(Only?) Three cable architectures – all tested in SULTAN

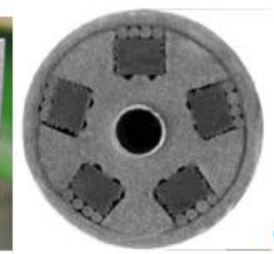
- *“Wrapped” tapes*



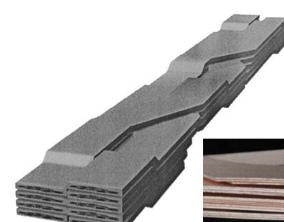
- *Stacks of tapes*





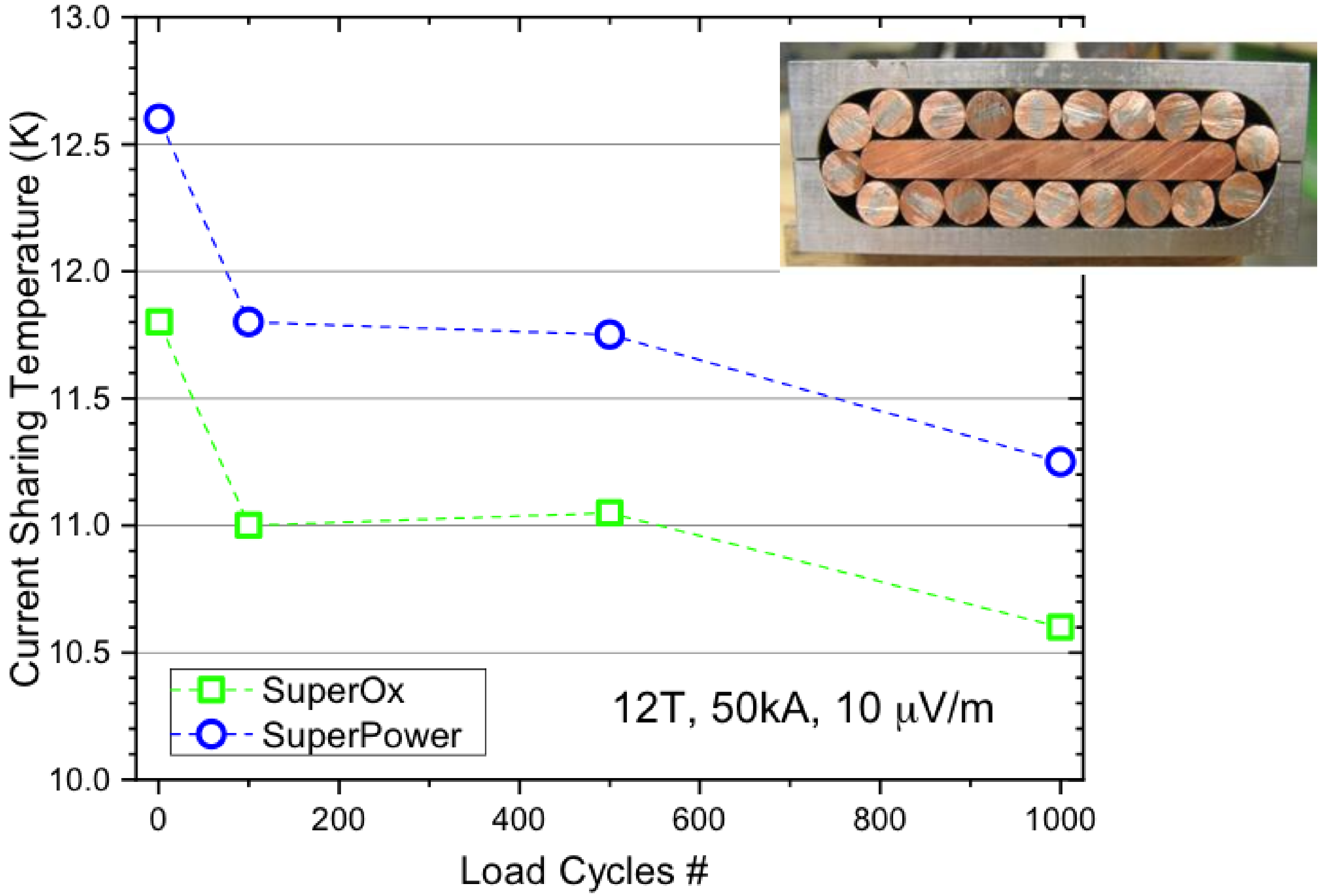


- *“Braided” tapes (Röbel)*



2015

Good initial results (zero resistance). Substantial performance loss upon cyclic loading.



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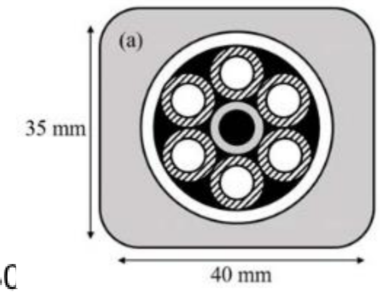
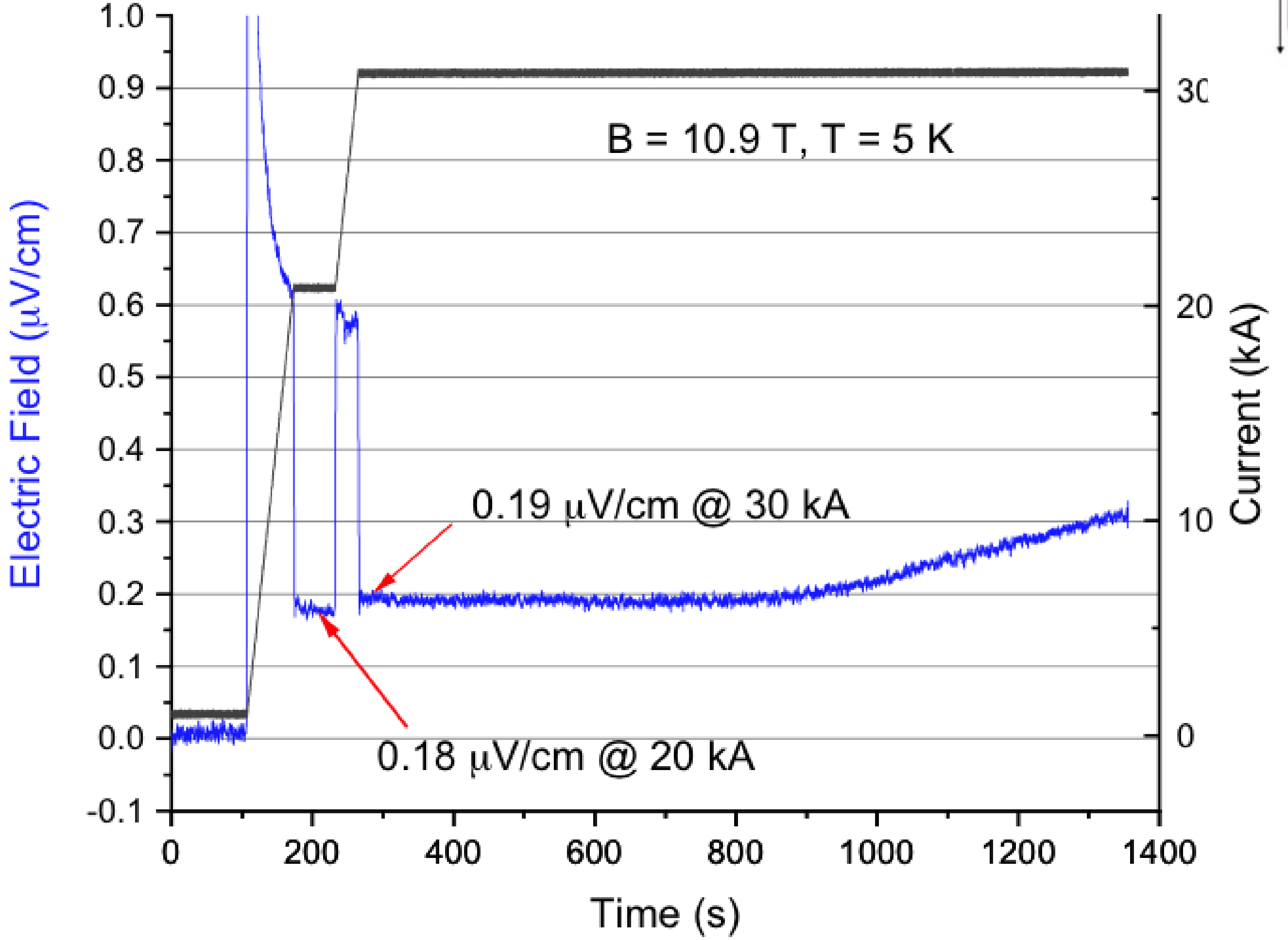
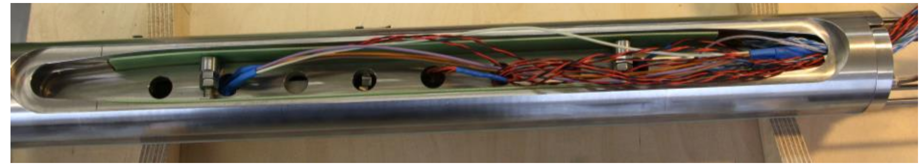
2017
Voltage (resistance) > criterion since low current.





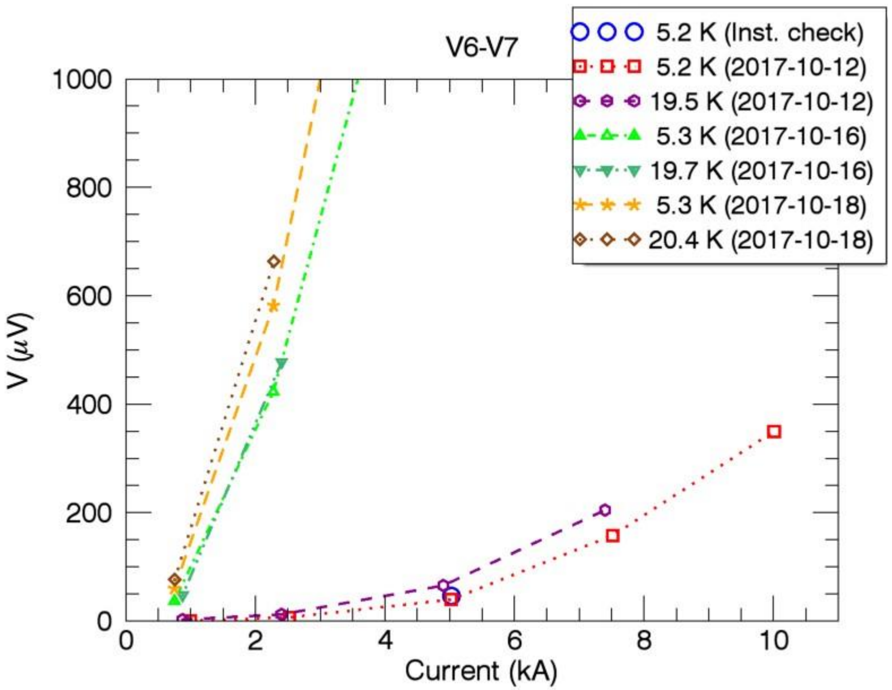
2017 (FM04)

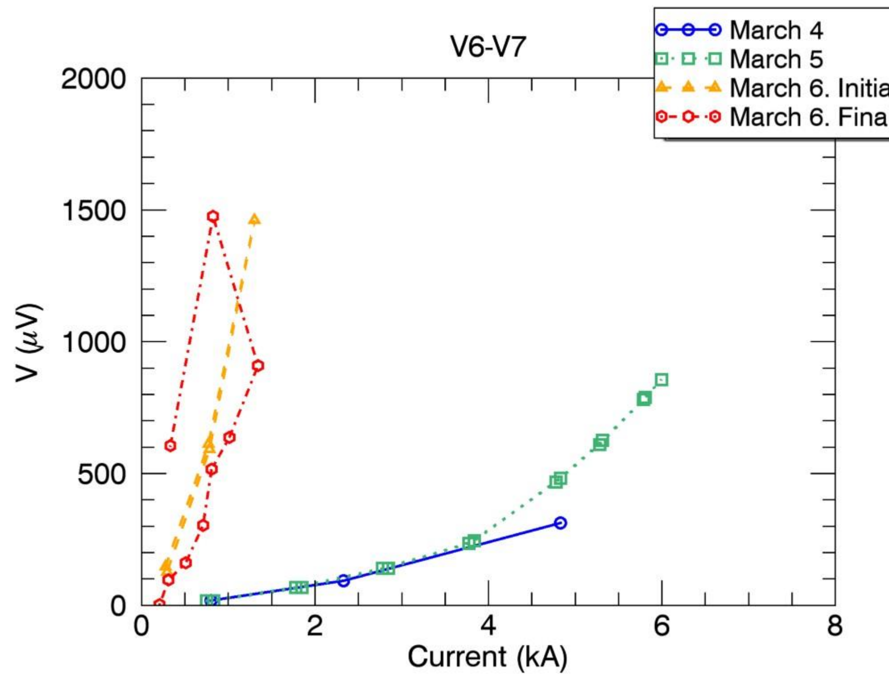


Two race-track insert coils made by Röbel cables show large voltage since the first run. The resistance increases by over one order of magnitude after test in field.

FM04 (2017)

05 (2019)





Where we are and where we want to be

- So far we have not reproduced in cables made by 2G tapes the performance of the free standing tape, disregarding the cable architecture.
    - *For twisted stacks we have observed a performance degradation upon em loading without clear landing.*
    - *For the other options we have unacceptable large resistance since the beginning*

- The test in self-field went much better than in field. A relevant em load is mandatory to assess the cable performance.

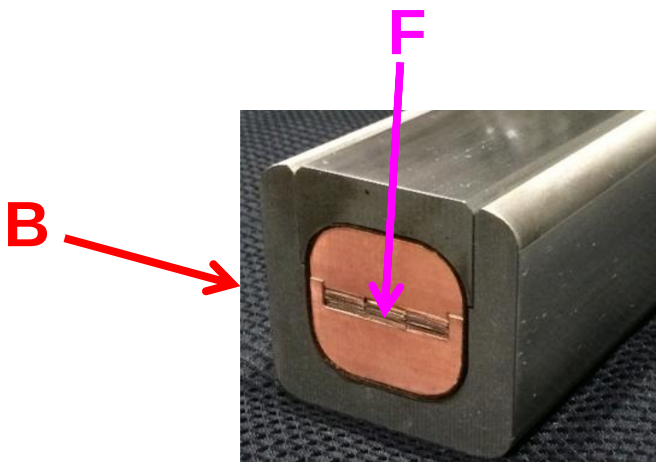
- For design purposes, it is essential to obtain in cables a predictable and stable performance.

Tape or cable issue?

- Although the statistic is limited so far, the suspicion arises that the tape mechanical properties are at the root of the problem.
- The mechanical characterization of the tapes frequently focuses on tensile, bending, twist tests to assess the deformation limits at the cable assembly.
  - *The evidence that at self field test the tape performance is retained in the twisted stacks suggests that the cable assembly is not at the root of the problem.*
  - *For cables made of twisted stacks, the performance loss is very similar for four different tape suppliers. So far we do not have a clear "better tape vendor".*
  - *Whenever resistance is observed since the first, zero field run, the attention should focus on the cable-sample preparation.*

Today, is any cable made of 2G tapes full performing?

- Probably, the cable by plain (non-twisted) stacks is ok. However:
  - *No cyclic load was applied so far...*
  - *The external field orientation (over a short length) was perfectly parallel (compression load on the “good” direction). This ideal configuration cannot be fully granted in a coil.*



The path forward

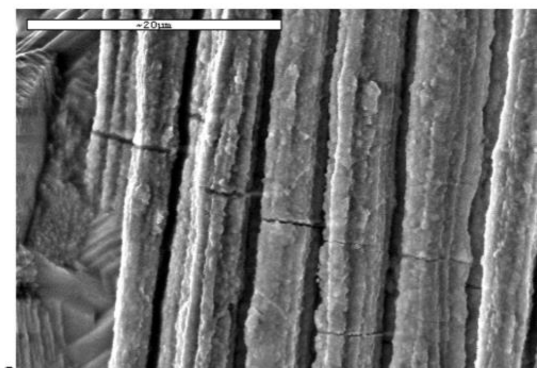
- Definitely, we need to collect more data, i.e. more cable samples with creative design variations.
- A critical assessment of the shortcomings is essential to make progress. Claiming success for “strategic reasons” is discrediting the whole community in the medium term.
- The tolerance to shear load must be assessed for each target cable geometry starting from dedicated, small size electro-mechanical experiments.
- A dialog with the tape vendors may be useful, but the market of 2G based cables is too small to drive substantial changes.

Can we learn anything from the Nb_3Sn cables?

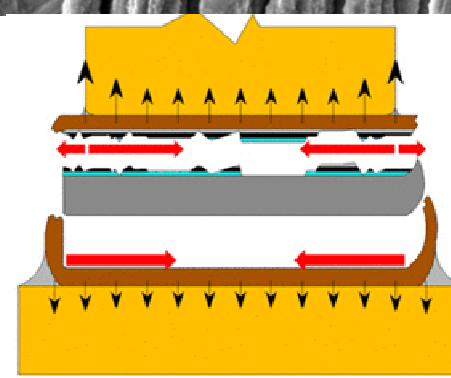
- The 2G tapes (all the HTS) share with Nb_3Sn the issue of brittleness, but Nb_3Sn strands have a much broader elastic (reversible) range.

- From the point of view of magnet technology, the 2G cables compare with the react&wind Nb_3Sn cable. However the 2G tapes are cabled “as reacted”, opposite to the Nb_3Sn strands.

- The typical degradation mechanism for Nb_3Sn is the filament breakages (irreversible) and/or a broad strain distribution.

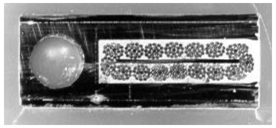


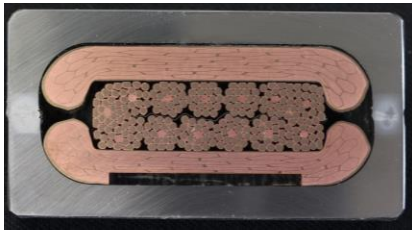
- The typical failure mechanism for 2G tapes is the delamination of the REBCO film under shear load.

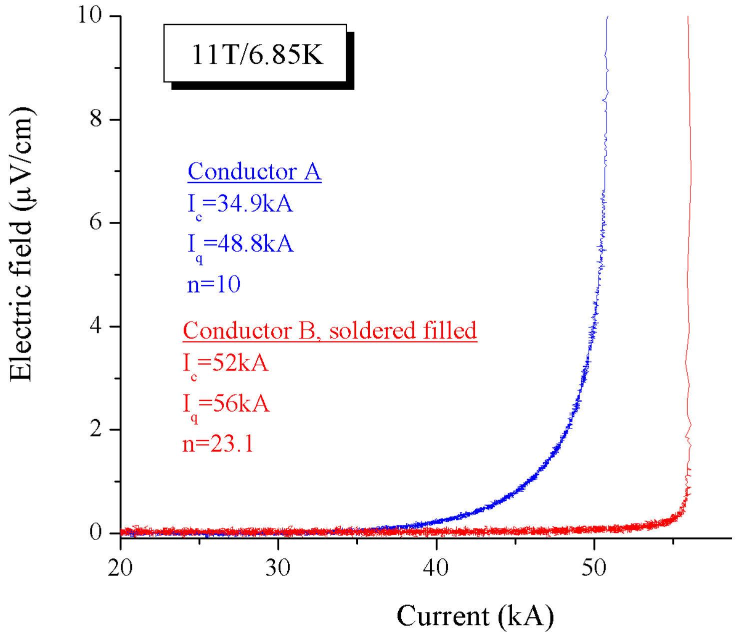


Nb_3Sn strands – 2G Tapes
Different failure – Different cure

Nb_3Sn. Preventing load accumulation and strand movement in operation is the key to avoid micro-bending with filament breakage and stress concentration.







For 2G cables micro-bending is not an issue. Preventing tape movement, e.g. by solder filling, is not effective to avoid shear load at the REBCO film.

ITER accepts degradation and limited lifetime for Nb_3Sn TF CICC. Should we go the same way for 2G cables?

Conclusion

- We learned to wind magnets with single 2G tape, including NI pancakes and wax impregnation. For high current / high field cables by 2G tapes we have not-yet stable superconducting performance.
- A critical, professional scrutiny of the test results is mandatory for progress – tests should be considered only at relevant loads, the electric field criterion cannot be larger than 10µV/m, **no discounts** on voltage offset and straightened baseline.
- Creative cable layouts are required to match the tape properties and the application requirements. No single solution.

Hopefully there are solutions…