

Is transposition necessary in superconducting cables?

Consequences of lack of transposition on stability, field quality and AC losses in coated conductor cables

D. Uglietti

Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC),
CH-5232 Villigen PSI, Switzerland

Summary

- Definitions
- Stability
- Field Quality
- AC losses

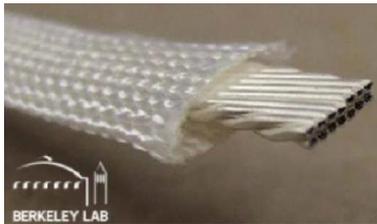
Definitions

“Transposition” means:

- Identical strands trajectories (upon axial translation along the cable).
- Transposition equalizes the impedance in strands.

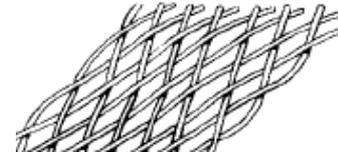
Transposed cables:

Rutherford cables, Roebel cables, braided and multistage cables



Punched tapes

In-plane bending



All other REBCO cable concepts are non-transposed.

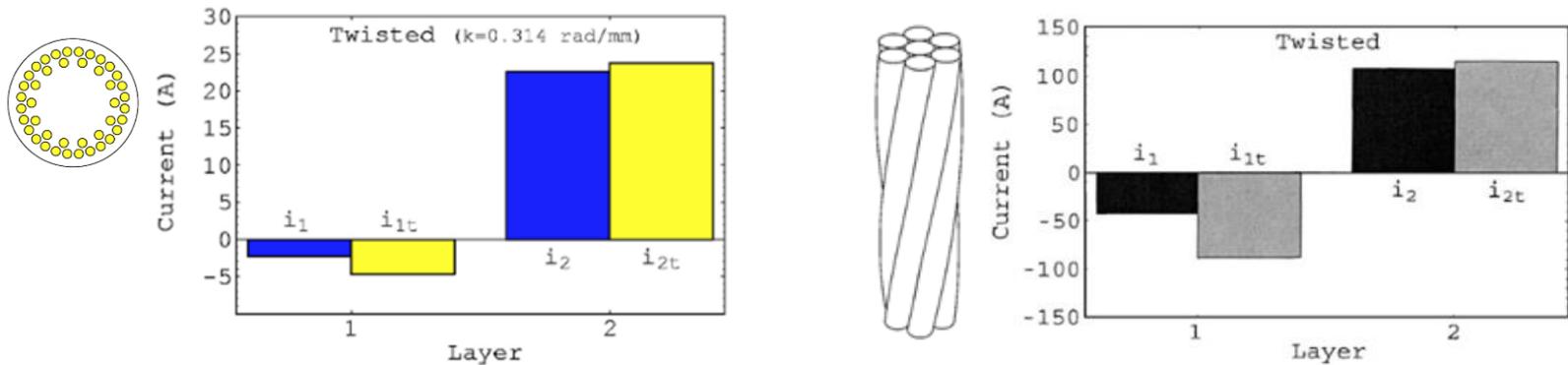
Definitions

Transposition is not an obligation even for NbTi and Nb₃Sn.

In fact:

- filaments in NbTi, Nb₃Sn are not transposed
- 6-around-1 strands are not transposed
- 12-around-6 strands are not transposed

2004 *The negative current in the inner layer is a universal feature of the current distributions during the current sweep* <https://doi.org/10.1063/1.1782964>



Also in 1980-81 Turck, <https://doi.org/10.1109/TMAG.1981.1061087> https://doi.org/10.1007/978-1-4613-9859-2_71

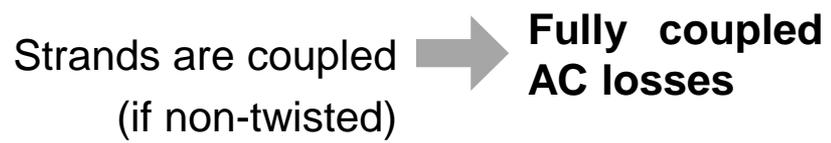
Is a Rutherford cable with twisted multilamentary strands still transposed?
Perhaps, only at the strand (wire) level?

Definitions

Transposition (or the lack of transposition) has effects on: AC losses, stability and field quality.

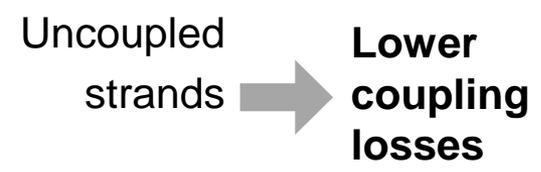
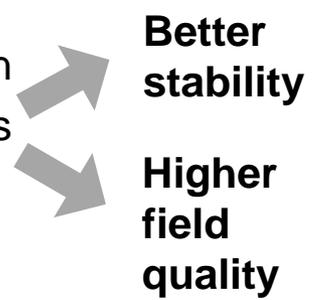
NON-TRANSDPOSED

Non-uniform impedance,
leading to non-uniform
current distribution



TRANSDPOSED

Uniform current in
the strands



Let's look at each one separately, with LTS and REBCO examples...

Stability — LTS fast ramped magnets

Non-uniform current → overloading some strands → premature quenches.

Examples of fast ramped magnets with transposed cables:

DPC-U, 1994-98

30 kA, 5-stages, NbTi, insulated strands

Quench current is only 10% of the design value. Impedance imbalance is only 0.1%

US-DPC, 1991-97

8 MJ coil, 1.8 m diameter, 30 kA Nb3Sn CICC

Achieved 70% of its ambitious goal of 10 T/s from 0 to 10 T *Adv. in Cryogenic Engineering Vol 37, IssueA, Pages 345 – 354*

Joule heating accumulation (periodic disturbances, for ex. flux jumps) rises the temperature above T_{cs} , the conductor quenches. The model predicts the US-DPC and the small scale tests. <https://doi.org/10.1109/77.233742>

About 0.1% deviation in self-inductances led to a significant current imbalance and premature quenches [https://doi.org/10.1016/S0011-2275\(98\)00007-1](https://doi.org/10.1016/S0011-2275(98)00007-1)

Polo, worked fine. *Polo team ascribes this result to the very precise cable construction, plus a lot of attention to maintaining symmetry in the joints and current feeds.*

Nuclotron, 1993

2 Tcoil, 6 kA NbTi CICC, 4 T/s

<https://doi.org/10.1109/77.402687>

SIS300 Synchrotron, 2014

4.5 T coil, 8.9 kA NbTi, 1 T/s

<https://doi.org/10.1109/TASC.2013.2287635>

Conclusion in 2008 Wilson <https://doi.org/10.1016/j.cryogenics.2008.04.008>

Ideally, inter-strand resistance should be high or even infinite to minimize coupling losses, but this would lead to instability if the impedance is not exactly the same for all strands. We need “*some transverse resistive contact between the wires; the difficult task is deciding how much*”.

Stability — fast ramped REBCO magnets

HTS110, NZ <https://doi.org/10.1088/1742-6596/1054/1/012066>

7-8XU03 Single tape or cable?

7 T, 4-quadrants in 60 s, corresponding to 0.5 T/s.

Stable despite the modest heat removal (cryocooler).



Examples with non-transposed cables:

CORC, 2016 <https://doi.org/10.1088/0953-2048/29/4/045003>

Repeated current pulses in a background field of 19 T

Current ramp rates of up to 67.8 kA/s to approximately 90% of the cable's quench current at that field.

Stable despite lack of transposition and huge inter-tape resistance.

SPARC Central Solenoid, 2024 <https://doi.org/10.1088/1361-6668/ad7efc>

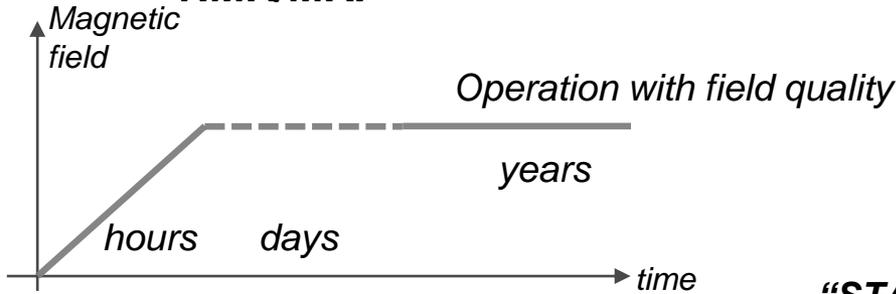
25 T, will be ramped at about 4.6 T/s

Model coil was tested up to 0.9 T/s

No premature quench in
fast-ramped REBCO
magnets so far...

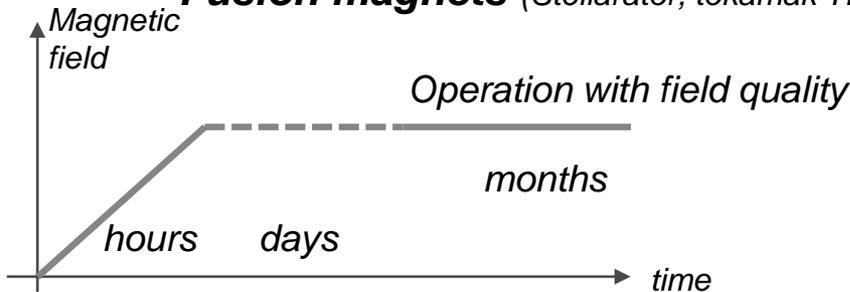
Field Quality — magnet operation

NMR/MRI

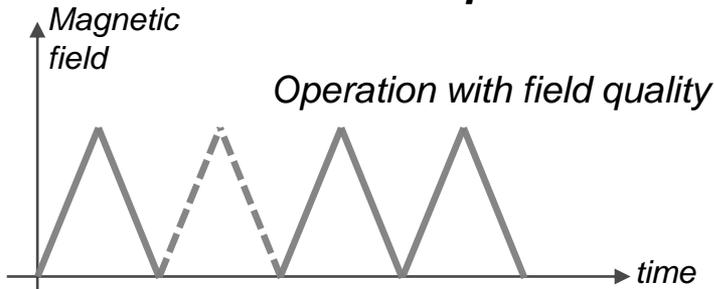


“STATIC” FIELD QUALITY

Fusion magnets (Stellarator, tokamak TF)



Accelerator dipoles



“DYNAMIC” FIELD QUALITY

What works for NMR/MRI/fusion, may not work for accelerators...

Field Quality — dipoles

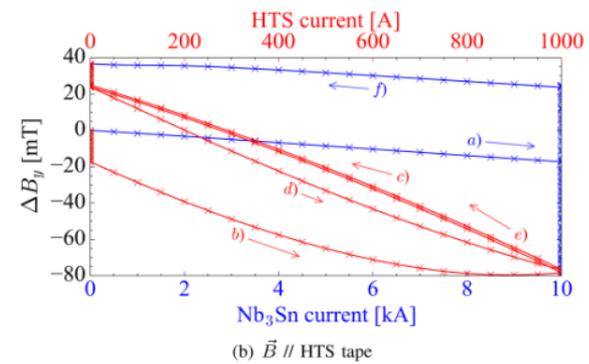
2017 **Robinson Research Institute** 3 T MRI
Single tape <https://doi.org/10.1088/1361-6668/aa90b2>
...changes in field consistent with the presence of screening currents; however ... they have not practical effects on the MRI images ... providing adequate settling time is allowed.

2023 **Neoscan Solutions** is building a 14 T, cryogen-free MRI for a consortium led by Radboud University of Nijmegen.
 HTS, but which one? REBCO? Bi2212?.

HTS110 <https://doi.org/10.1088/1742-6596/1054/1/012066>
 7-8XU03 7 T, 4-quadrants in 60 s, corresponding to 0.5 T/s.
 ...a sufficient control strategy has been to employ multi-stage ramp cycles which depress the effect of screening currents.

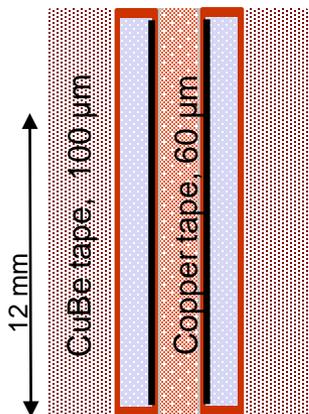


KEK, 2025 <https://doi.org/10.1109/TASC.2025.3528378>
 Racetrack coil with single EuBCO tape, ceramic insulation (radiation resistant).
 A large field error is induced with the background field applied perpendicular to the tape.



Field Quality — dipoles

CEA dipole, 2016



2 tapes per stack



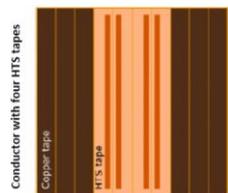
<https://doi.org/10.1109/TASC.2018.2796063>
<https://doi.org/10.1109/TASC.2018.2809780>

Screening currents, rather than coupling currents, deteriorate field quality

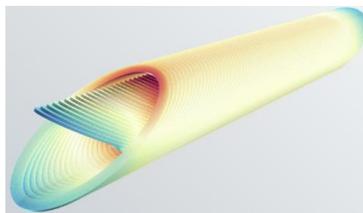
REBCO Canted Cosine Theta for gantry 2025

IFAST's WP8 Innovative Superconducting Magnets

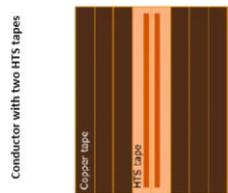
<https://doi.org/10.1109/TA-SC.2024.3360210>



4 tapes per stack



“Precise field quality is achieved by controlling Fourier series coefficients describing the coil's radius.”



2 tapes per stack

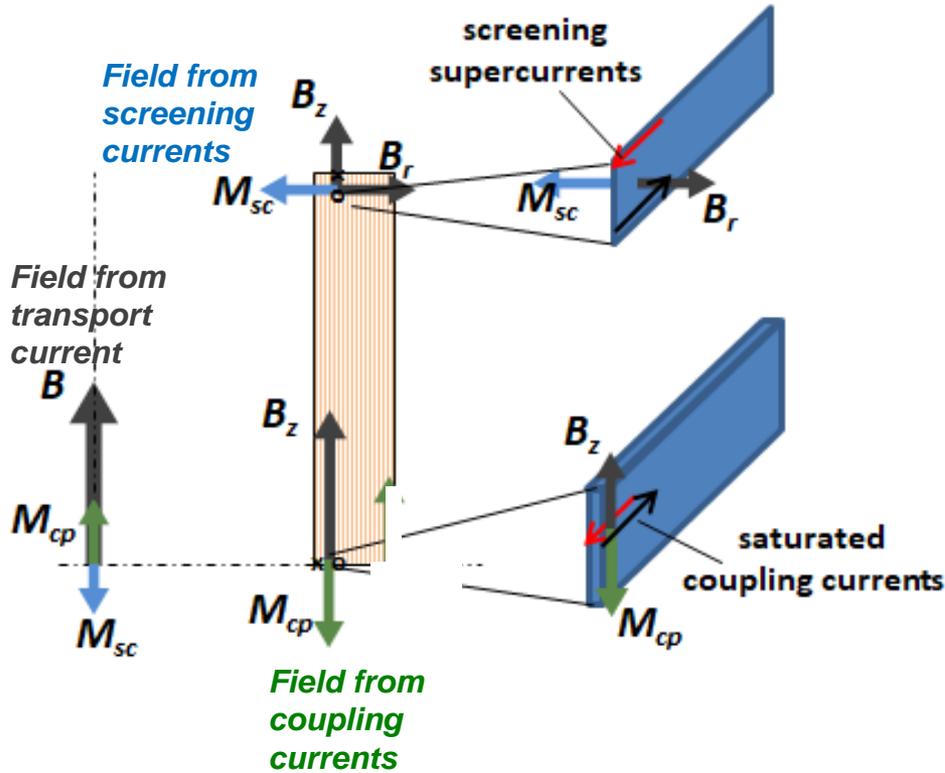
Lower critical bending radius than a single tape

What about coupling currents and magnetization currents...?

Field Quality — non-transposed stack in solenoids

What happen in solenoids? Qualitative description, valid also for dipoles.

Quarter cross-section, stack of non-twisted tapes:



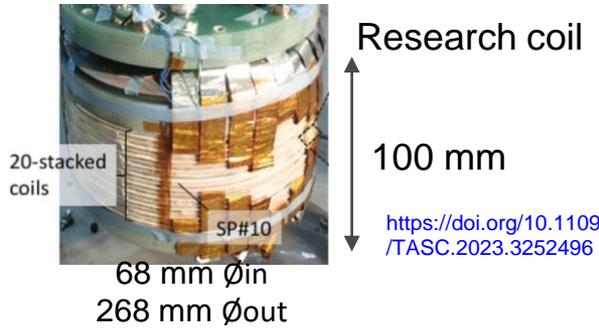
How to distinguish the two contributions?

- Magnetisation (versus time) is linear in demi-log scale.
- Coupling current field is (versus time) is linear in log-log scale.

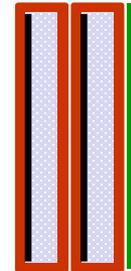
Coupling field sum up to the main field, while the screening field is in opposite direction. Let's look at experiments...

Field Quality — Tohoku

Tohoku University is developing a 16 T insert for a 33 T solenoid.



<https://doi.org/10.1109/TASC.2023.3252496>

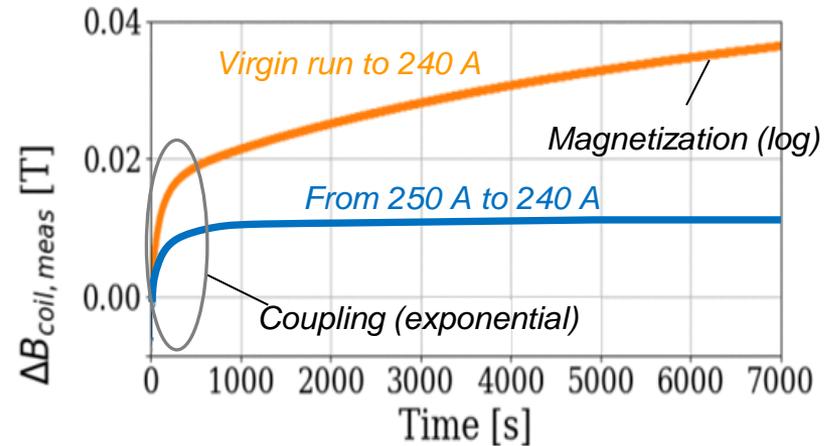
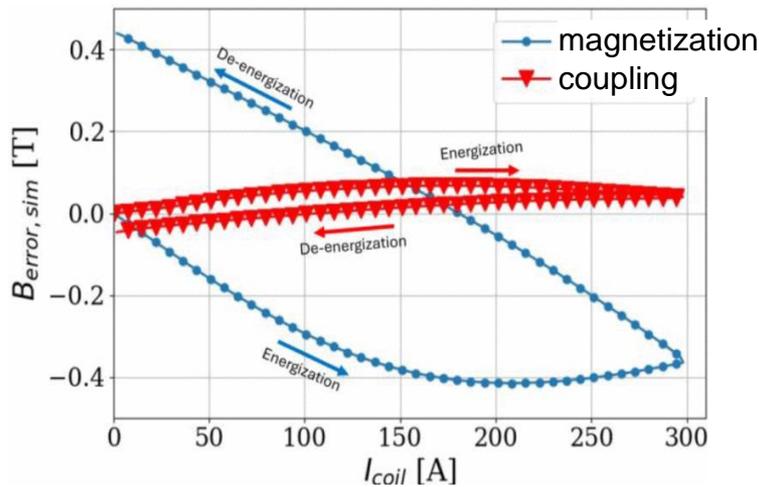


Two tapes (4 mm wide) face to back and one insulating tape.

All three tapes are co-wound.

<https://doi.org/10.1109/TASC.2022.3163690>

<https://doi.org/10.1109/TASC.2024.3514994>



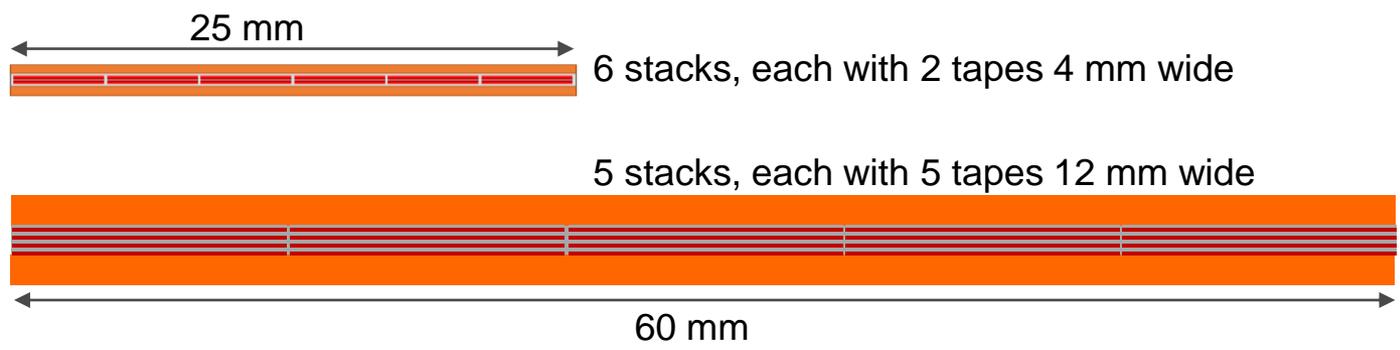
- Coupling and magnetization errors partially cancel each other.
- Magnetization is larger than coupling

- Drift from coupling current dies out fast.
- Overshooting reduces magnetization drift

Field Quality — LASSO

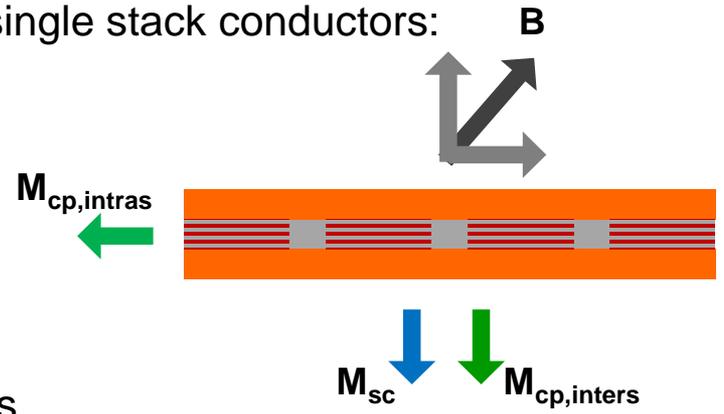
We saw examples with 2 to 4 tapes in parallel, but there is no limitation on the number of tapes (any aspect ratio is possible):

Laminated stacked-tape soldered (LASSO) conductor, cross sections:



More complex magnetic behavior than in the single stack conductors:

- 1) magnetization
- 2) coupling currents in the stack
- 3) coupling currents among stacks



We do not plan any field quality measurements.

AC loss

Upper limit for AC losses?

- Electric power to remove losses should be the lower than powering a copper magnet...
- Transient temperature increment should be lower than T_{CS} , otherwise the magnet quenches.

LTS and REBCO have usually much lower losses than this.

LTS have lower margin than REBCO, losses must be lower...

PIT VIPER, SPARC Central Solenoid

<https://doi.org/10.1088/1361-6668/ad7efc>

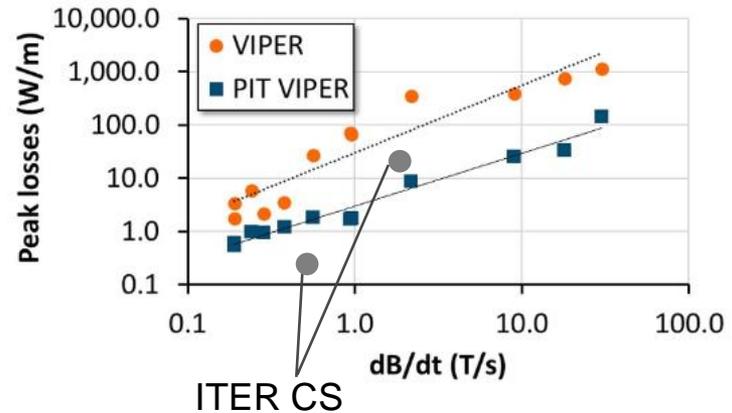
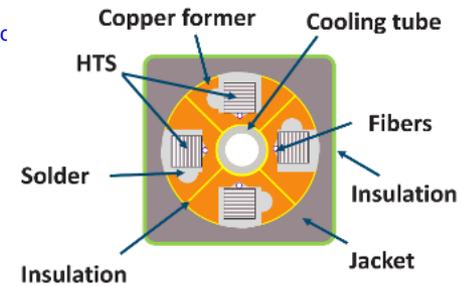
At fast ramp rates, eddy losses in large copper former are the main contribution.

“Main lever to reduce AC losses: partitioning the copper.

Segmented copper petals in PIT-VIPER.

AC losses reduction up to 15 times.

Below 0.5 T/s: losses in PIT VIPER are largely hysteretic.



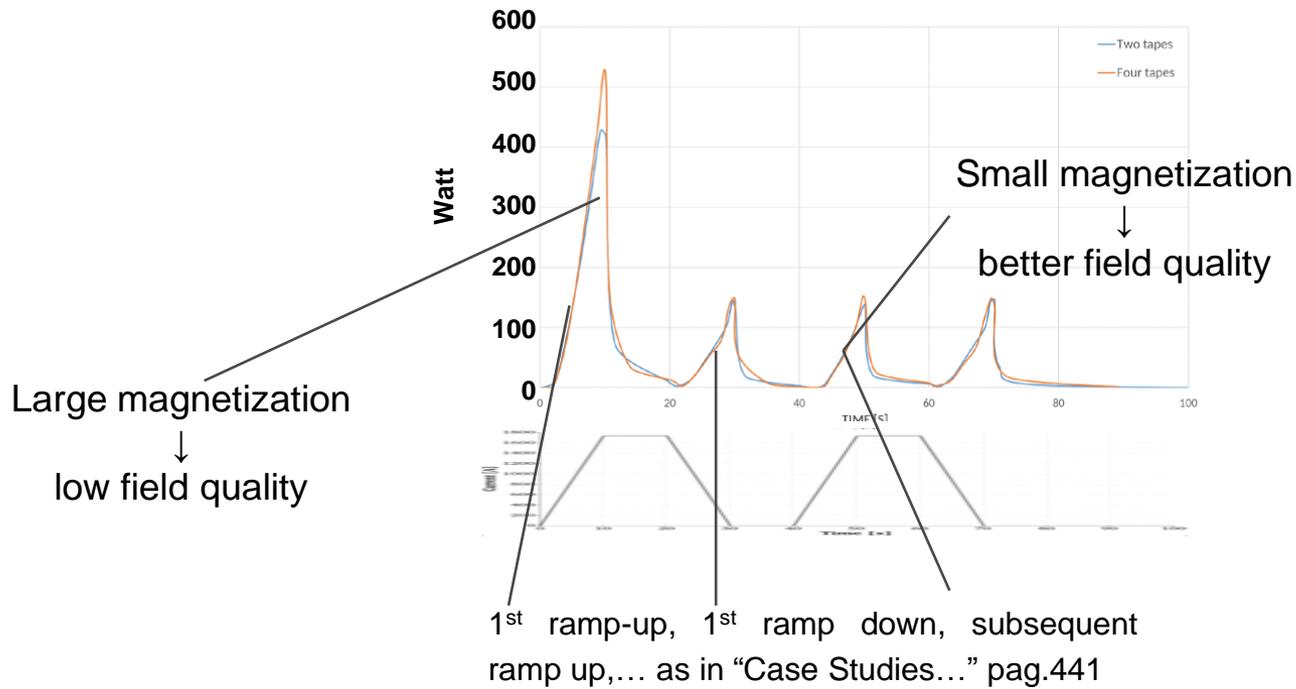
AC loss

IFAST's WP8 Innovative Superconducting Magnets
REBCO Canted Cosine Theta for gantry 2025

<https://doi.org/10.1109/TASC.2024.3360210>

0 T to 4 T in under 10 seconds.

Hysteresis losses are the predominant contribution.



Summary

Stability

- REBCO cables can be ramped up at very large rate even if not transposed.

Field quality

- REBCO magnets have intrinsically large magnetization (superconducting layer is 100 times larger than LTS filaments).
- Magnetisation can be reduced, for example with “overshooting”.
- Transposition or twisting comes usually in second place as source of error.

AC losses

- Any REBCO cable has intrinsically large losses (hysteretic contribution).
- Transposition does not matter much (Roebel cables have still large losses).
- Large temperature margin means high tolerance to large transient losses.

In REBCO, large temperature margin and thus high stability protects from the consequences of lack of transposition.