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Nb_3Sn conductors with artificial pinning centers and high specific heat

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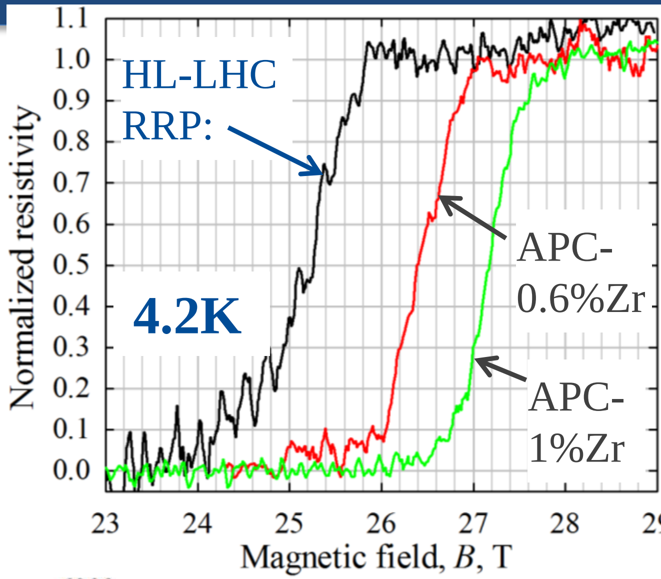
APC work – introduction

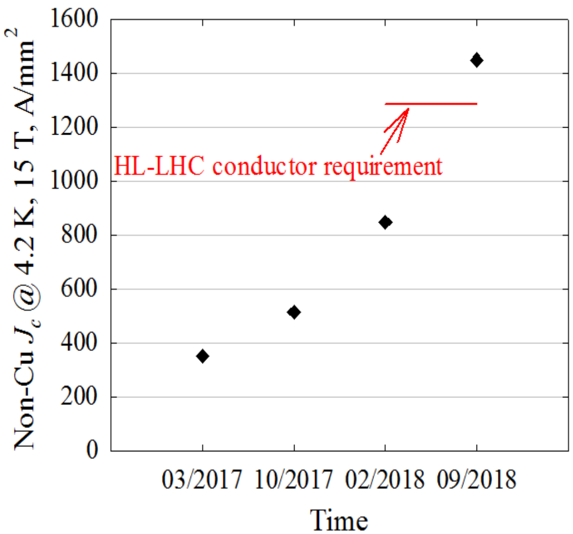
- **J_c of present best Nb_3Sn is insufficient for 16 T dipoles for FCC or HE-LHC.**
- **State-of-the-art J_c has plateaued for nearly 2 decades.**
- **Further large J_c improvement calls for engineering fluxon pinning.**
- **A lot of efforts on APC Nb_3Sn since the 1980s: only became possible recently.**
  - 2014: realized internal oxidation in Nb_3Sn wires, showed great layer J_c.
  - 2015 and 2016: learning curves towards PIT wires.
  - Starting from 2017: develop "real" ternary APC wires, an FNAL-HTR-OSU collaboration, supported by HTR SBIR from US DOE and FNAL LDRD.
  - Also inspired other groups to pursue APC approach:
    - ASC: explore interesting new alloys.
    - U. Geneva & CERN: monofilaments.

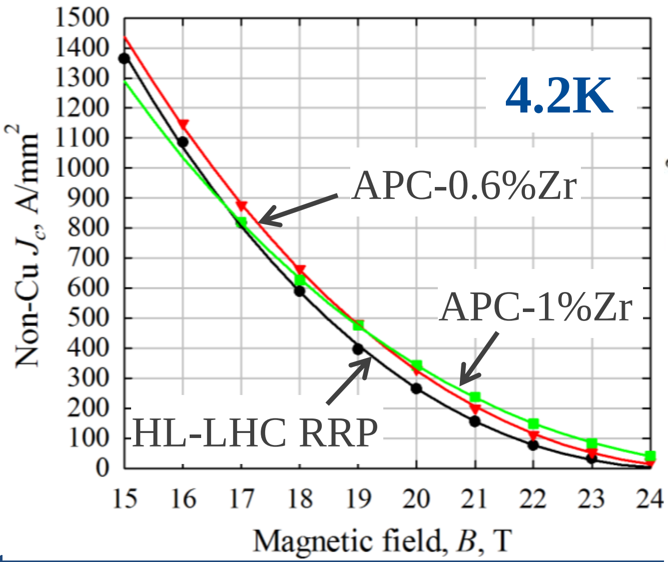
Progress from MDP-2018 to Sept 2018

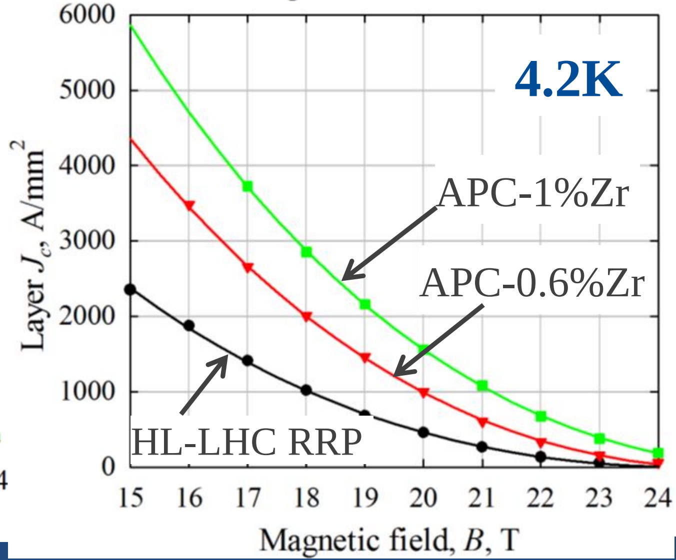


A few highlights in this period:

- Solved B_{irr} (B_{c2}) issue by developing Ta doped wires.
- Improved wire recipe and quality significantly.
- Improved non-Cu J_c quickly.
- As of Sept 2018, non-Cu J_c caught up with RRP, using only 1/3 of Nb_3Sn fraction. Layer J_c is 3x.
- Next, improve recipe ➔ increase Nb_3Sn %.

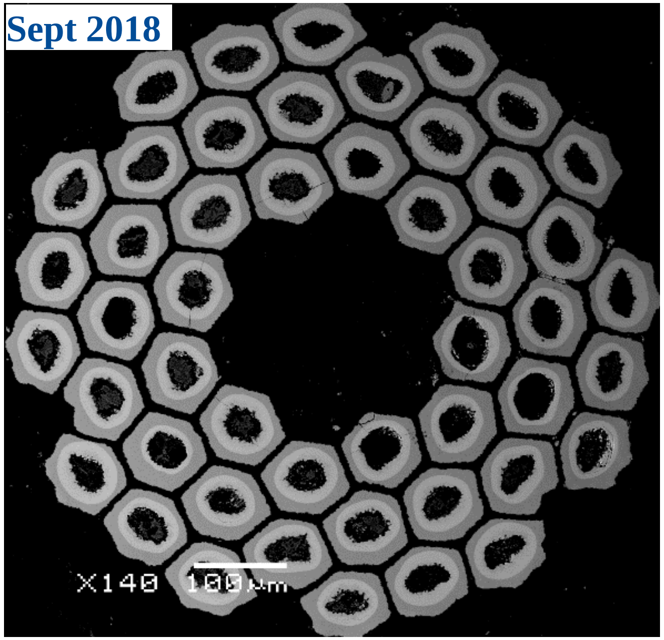


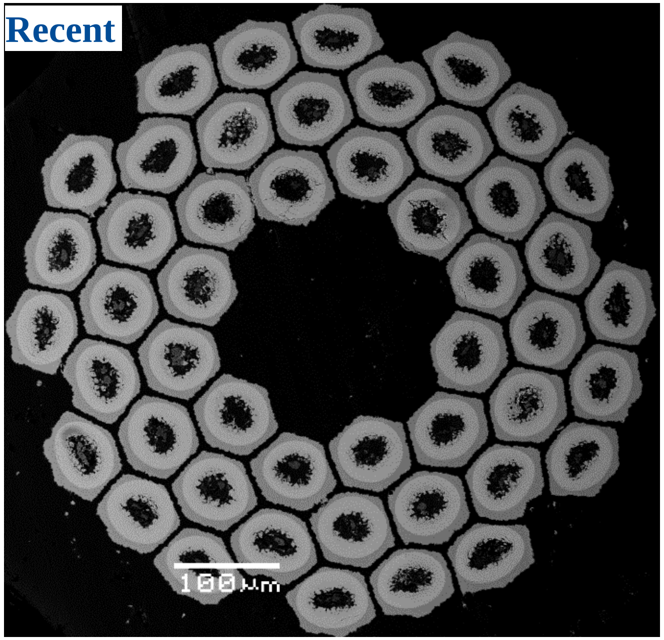


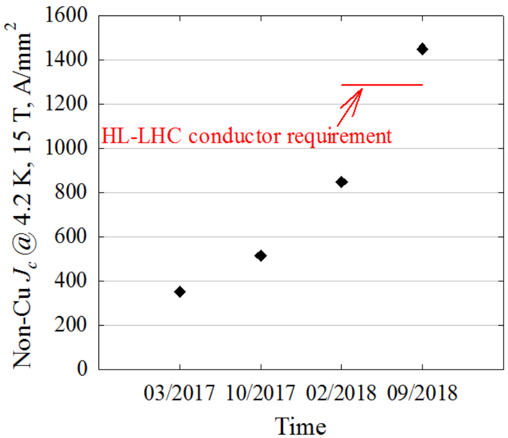


Progress since Sept. 2018

- Further significant progress in optimizing wire recipe.
- This leads to large increase in Nb_3Sn fraction.
- Tests at 4.2 K, 15 T quenched: due to moderate RRR, D_s=70 μm, and higher J_c.
- Non-Cu J_c at 8 K, 15 T surpassed the FCC spec.
- Tests at higher fields at NHMFL soon.







On the other hand, increased J_c ➔ attention to instability.

Next work with APC conductors

The goal is to make such conductors ready for application in magnets ASAP.

Still a lot of work to do:

Step 1: first demonstrate non-Cu J_c above FCC spec, better with margin.

- **Further optimization of recipe**

Step 2: fabricate 217-restack wires, with D_s < 50 µm.

- **In preparation, will make a 217-Re wire in the next few weeks**

Step 3: make wires good for cabling

- **Better subelement surface cleaning for bonding.**
- **Increase billet size from 0.75” to 2”.**
- **Change subelement shape from hex to round.**

Step 4: Necessary tests

- **Uni-axial tensile test (with ASC)**
- **Transverse pressure test (with CERN)**

Increase specific heat of Nb_3Sn conductors

Two types of instability for Nb_3Sn conductors:

(1) "External": with external perturbations, if Q>MQE, conductors quench. ➔ training

(2) "Intrinsic": w/o external perturbations, conductors still quench in *V-I*, *V-H*; flux jump.

Increasing specific heat is promising to suppress both types of instability:

For external perturbations: energy margin = $\int_{T_b}^{T_{cs}} \boldsymbol{C} dT$

For intrinsic instability: $\frac{\mu_0 J_c^2 d_{eff}^2}{4\gamma \boldsymbol{C}(T_c - T_b)} < 3$

History for high-*C* technique

- **The idea of increasing specific heat by adding high-*C* materials dates back to 1960s.**

  R. Hancox, *IEEE Trans. Magn.*, vol. 4, Pages 486-8, 1968.

- **First experiments: proof-of-principle work in Russia, showed remarkable effect, not feasible for practical application.**

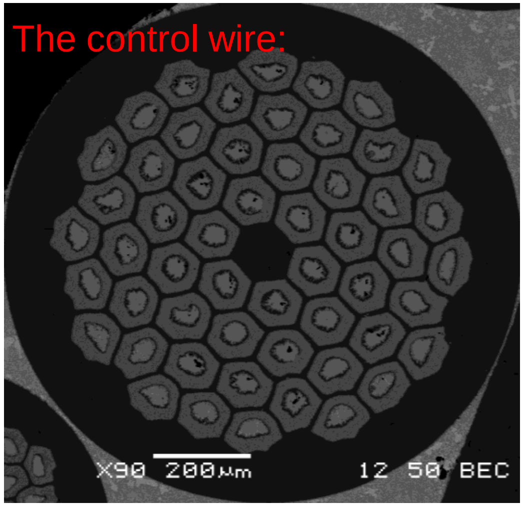
  V. E. Keilin *et al.*, *Supercond. Sci. Technol.*, vol. 22, Art. no. 085007, 2009.

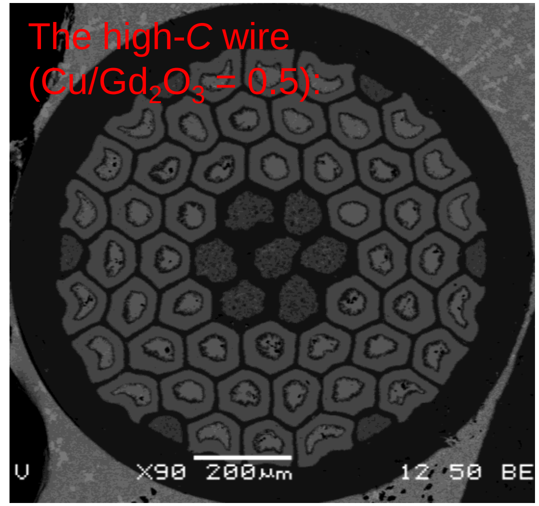
- **We developed a design to make practical Nb_3Sn conductors.**

  X. Xu, P. Li, A. Zlobin and X. Peng, *IEEE Trans. Appl. Supercond.*, vol. 23, Art. no. 4001605, 2018.

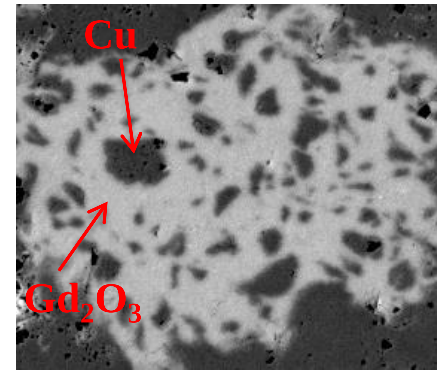
Results since MDP-2018

- Hyper Tech fabricated the first prototype high-*C* wire for us.
- All technical parameters: tentatively selected, w/o optimization.

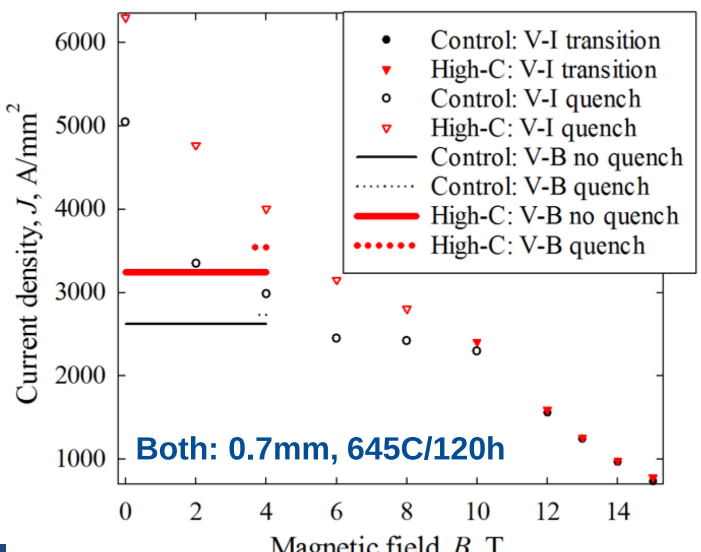




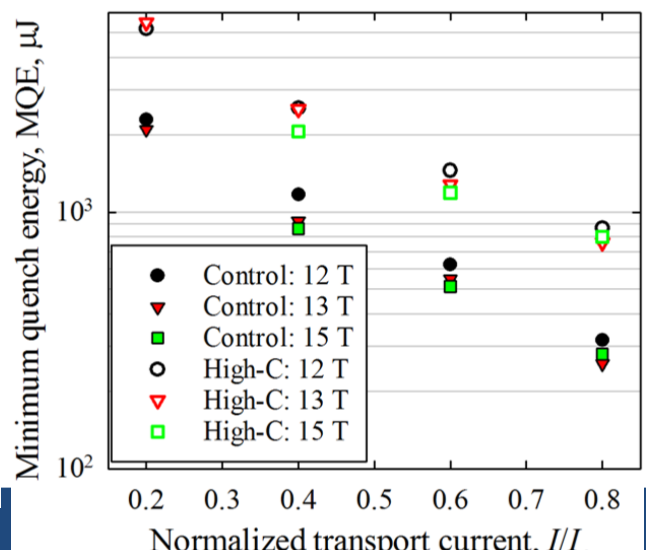
Improper Cu/Gd_2O_3 ratio: Cu cannot conduct heat.

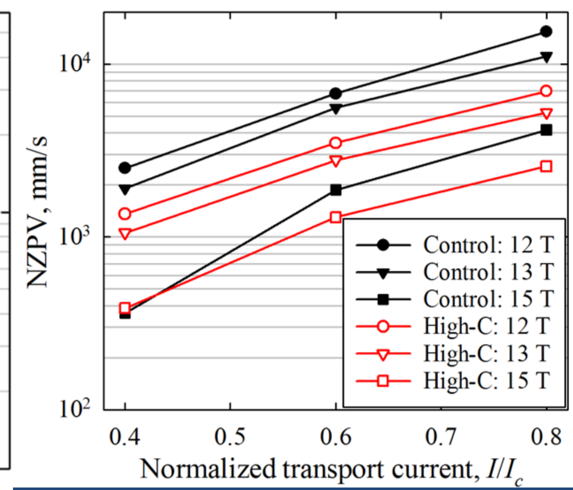


Gd_2O_3 heat diffusivity low: time constant big.



How much can high MQE help to reduce training?





Optimization and industrialization with Bruker-EAS and Bruker-OST

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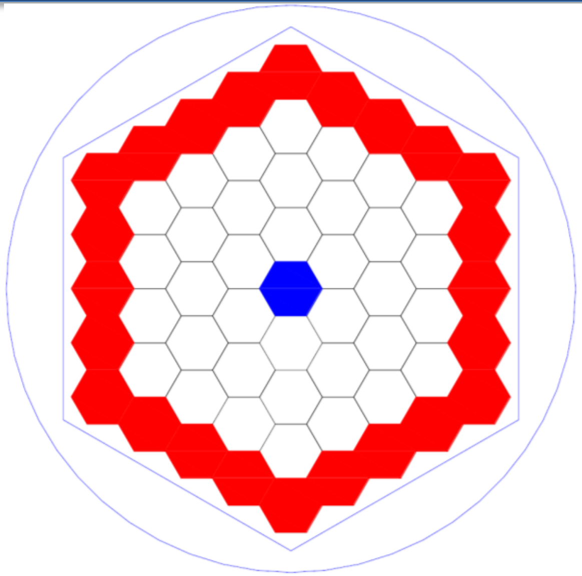
Plan:

- First, optimize of high-*C* rods, including:
  - Ratio of Cu/Gd_2O_3 powders
  - Powder packing density
  - Cu tube I.D./O.D.
- Second, make RRP wires with the high-*C* rods.



- In the past year, a lot of work in optimizing high-*C* rod recipe.
- Four rods with various Cu/Gd_2O_3 ratios and Cu tube I.D./O.D. fabricated.
- B-EAS is fabricating the last two rods, close to finalizing it.

Expected timeline:

- **Finalize high-*C* rod recipe in Feb, send rods to B-OST in Apr, make wire before July.**
- **Then test wires in FNAL. Could give wires to other institutes who are interested.**

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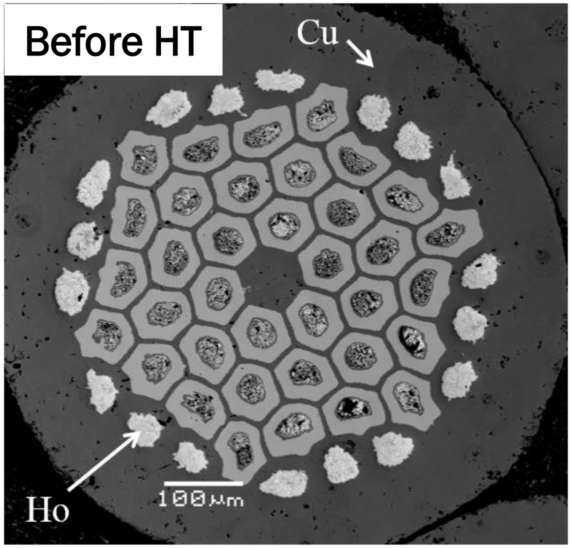
Other emerging ideas

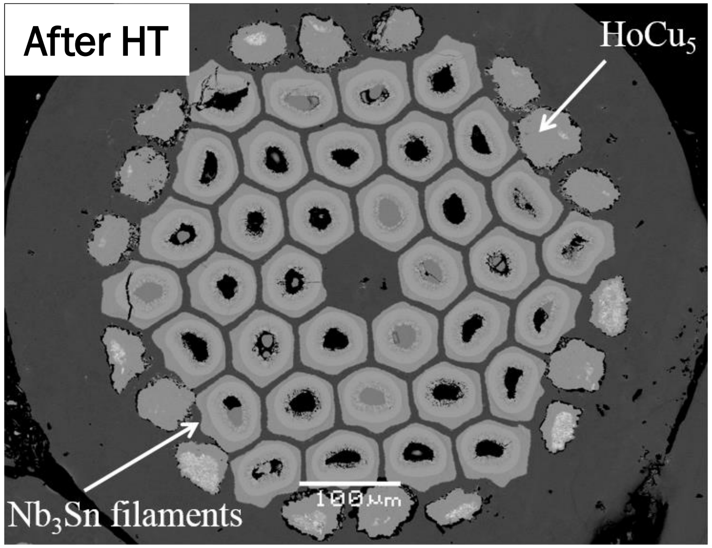
1: Add high-*C* substance into each subelement core to improve intrinsic stability.

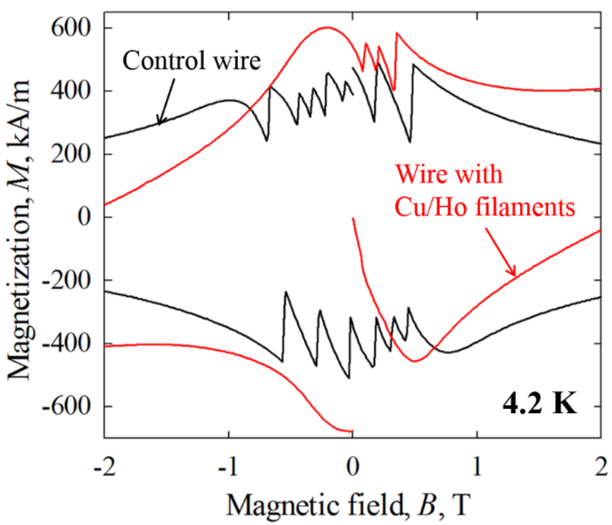
2: Use high-*C* substance with much higher thermal diffusivity.

- Some intermetallics, $HoCu_5$, $GdCu_5$, etc. – but, not commercially available.
- Our scheme: use Ho and Cu powder mixture. During Nb_3Sn heat treatment, Ho + Cu ➔ $HoCu_5$.
- Advantages over the previous scheme:
  1) Absorbing heat faster ➔ better intrinsic stabilization
  2) Use only metal powders ➔ wires may draw better

A little proof-of-principle work already done: great promise.



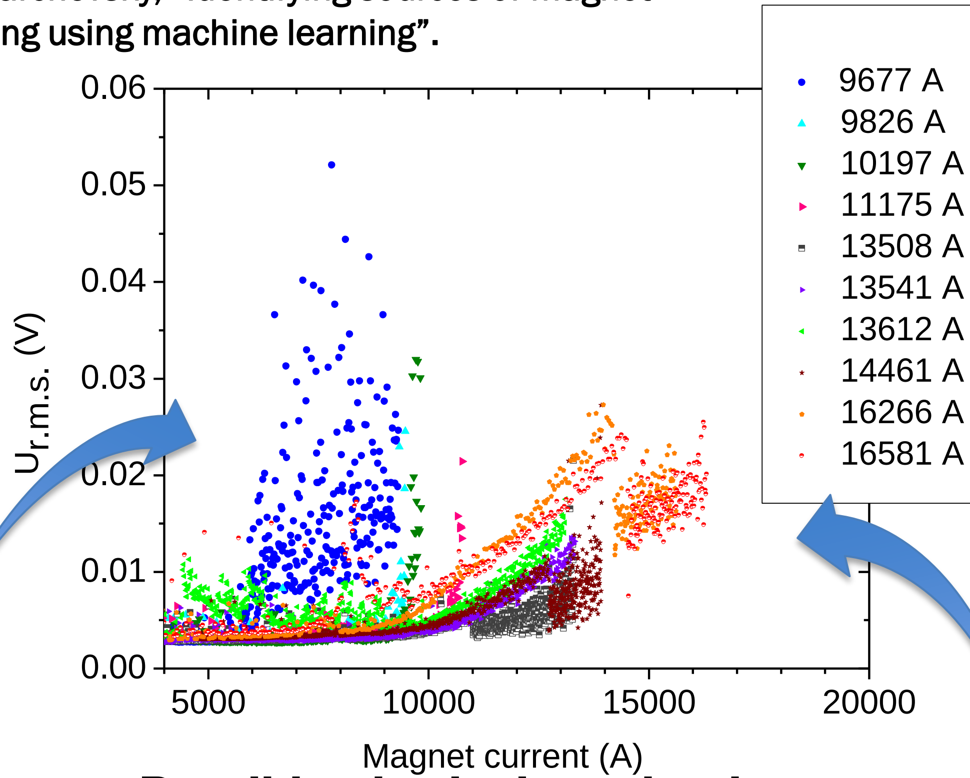




Still looking for resources to pursue these new ideas.

A question for discussion: how much can increased MQE help to reduce training?

M. Marchevsky, "Identifying sources of magnet training using machine learning".



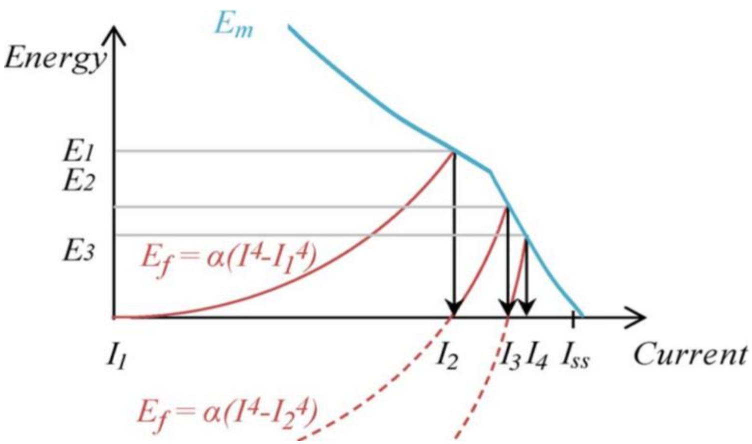
Possible physical mechanism:

Cracking regime

=> slip-stick regime (?)

Slip–Stick Mechanism in Training the Superconducting Magnets in the Large Hadron Collider

-- Pier P. Granieri, Clément Lorin, and Ezio Todesco, IEEE Trans. Appl. Supercon., 21, P. 3555, 2001.



Need to understand training more.

Need tests to find out if increased energy margin can help to make the slow training faster.

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Acknowledgement

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Thank you for your attention