Nb$_3$Sn conductors with artificial pinning centers and high specific heat
- $J_c$ of present best Nb$_3$Sn 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$_3$Sn since the 1980s: only became possible recently.
  - 2014: realized internal oxidation in Nb$_3$Sn 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.
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$_3$Sn fraction. Layer $J_c$ is 3x.
- Next, improve recipe $\rightarrow$ increase Nb$_3$Sn %.
Further significant progress in optimizing wire recipe.

This leads to large increase in Nb$_3$Sn 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.
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 $D_s < 50 \mu m$.
  - 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)
Two types of instability for Nb$_3$Sn 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 = $\int_{T_b}^{T_{cs}} CdT$

For intrinsic instability:

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

History for high-$C$ technique

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

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

- We developed a design to make practical Nb$_3$Sn conductors.
Hyper Tech fabricated the first prototype high-C wire for us.

All technical parameters: tentatively selected, w/o optimization.

The control wire:

The high-C wire (Cu/Gd₂O₃ = 0.5):

Improper Cu/Gd₂O₃ ratio:
Cu cannot conduct heat.

Gd₂O₃ heat diffusivity low: time constant big.

Hyper Tech fabricated the first prototype high-C wire for us.

All technical parameters: tentatively selected, w/o optimization.

How much can high MQE help to reduce training?
Plan:

- First, optimize of high-C rods, including:
  - Ratio of Cu/Gd$_2$O$_3$ 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$_2$O$_3$ 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.
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, HoCu₅, GdCu₅, etc. – but, not commercially available.
   - Our scheme: use Ho and Cu powder mixture. During Nb₃Sn heat treatment, Ho + Cu → HoCu₅.
   - 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?

Possible physical mechanism:

Cracking regime

=> slip-stick regime (?)

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


Need to understand training more.

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

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

U_r.m.s. (V)

Magnet current (A)
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Thank you for your attention