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COLLEGE OF ENGINEERING

Flux Jumping in High Magnetic Fields for Stack Tape Cables and its Mitigation

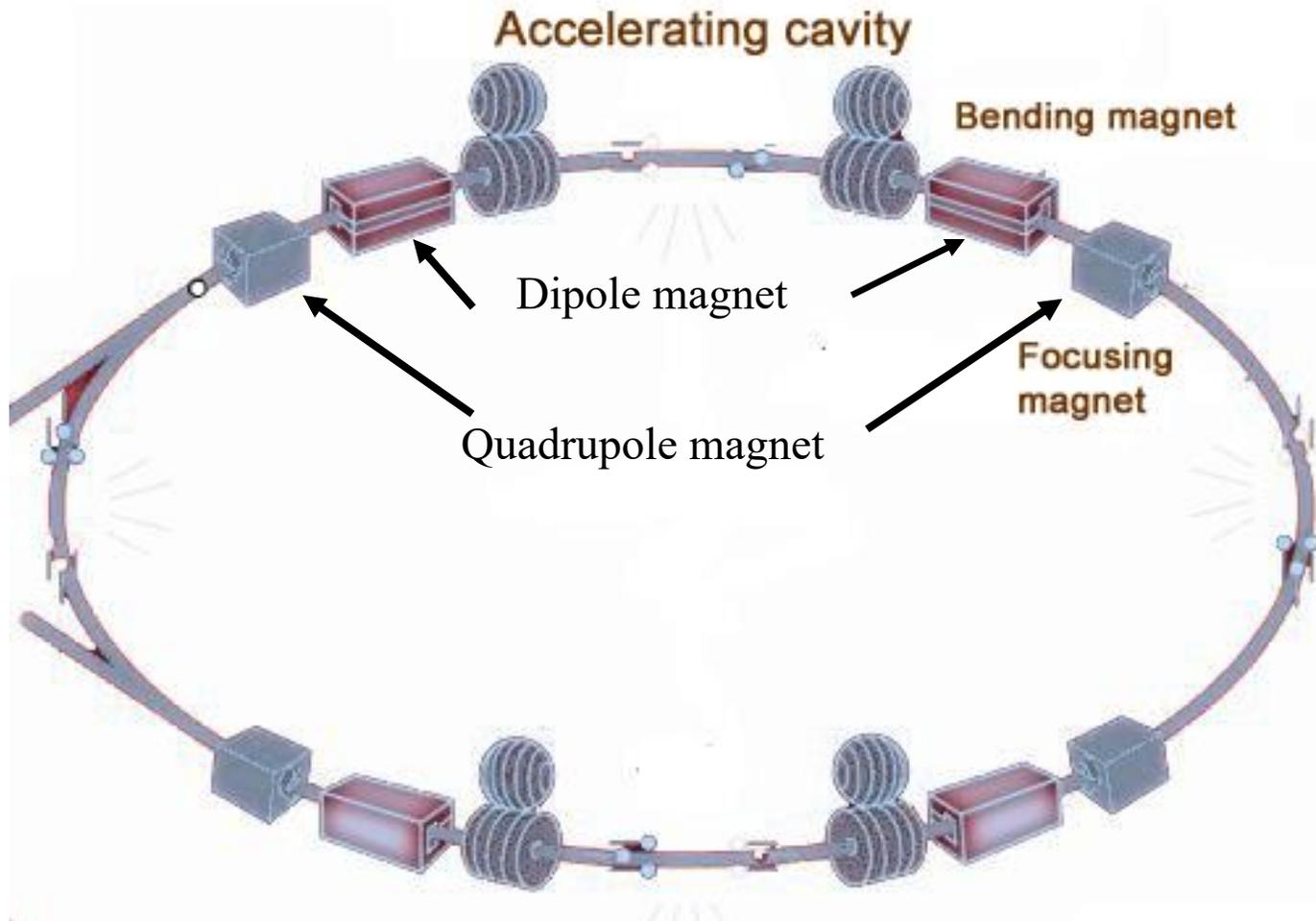
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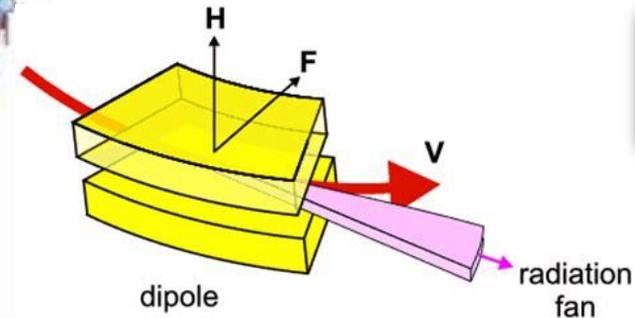
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Motivation – Accelerator Magnets: We want to use ReBCO cables for Accelerators



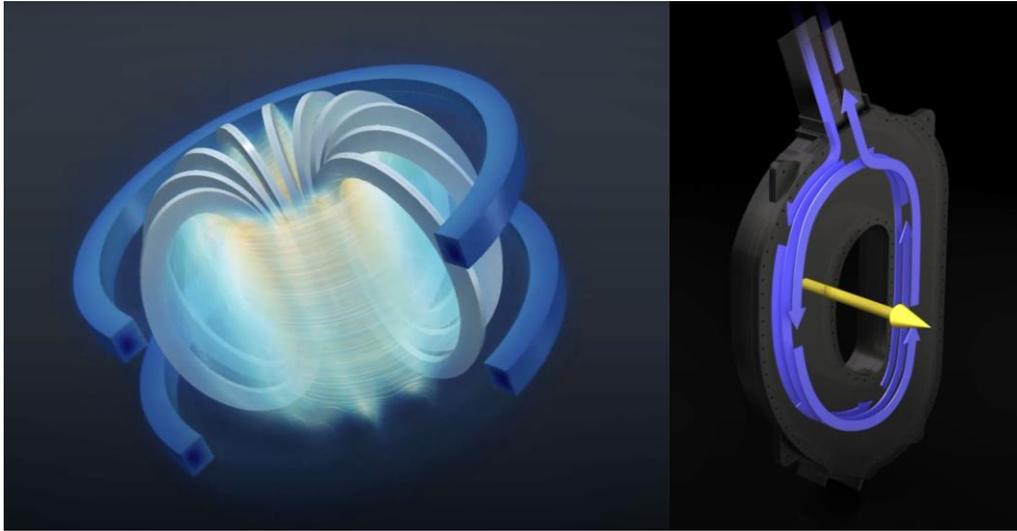
- Dipoles keep the beam trajectory (Bend the beam)
- Quadrupoles keep the beam compact (Focus the beam)

Required to steer the particle beam: A pure, uniform dipole field



Uniform in Space & Time

Motivation – Fusion Magnets: We want to use ReBCO cables for Fusion Systems



Current Fusion Magnet Technology

- Use large **toroidal and poloidal superconducting coils** at cryogenic temperatures.
- **NbTi** (W7-X, EAST): ~5–6 T, ductile, easy to handle.
- **Nb₃Sn** (ITER): ~12 T, higher field but brittle and complex to manufacture.

Examples:

- **ITER**: Nb₃Sn CICC TF coils (France)
- **W7-X**: NbTi modular coils (Germany)
- **JT-60SA**: NbTi PF/TF coils (Japan)

Why ReBCO?

- **Higher field and current density** than NbTi/Nb₃Sn
- Operates at **20–30 K** → easier cooling
- Key to **compact fusion designs** (SPARC, ARC)

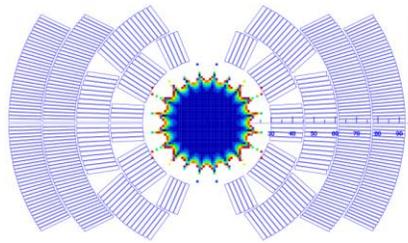
Research Examples:

- **SPARC (MIT/CFS)**: 20 T REBCO TF coils
- **Tokamak Energy (UK)**: Demo4 coil set
- **HH70 (China)**: REBCO-based compact tokamak

Key Challenges:

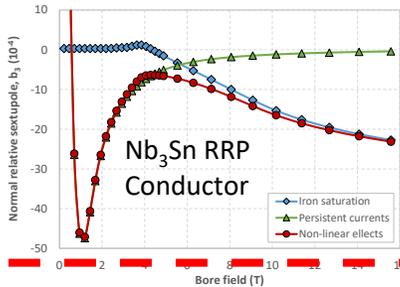
- Mechanical & thermal stress under high fields
- Quench detection in HTS
- **Instabilities** in stacked configurations
- Cable choice: Roebel, CORC, or tape stacks

Motivation – Why we need to know the magnetization of ReBCO?

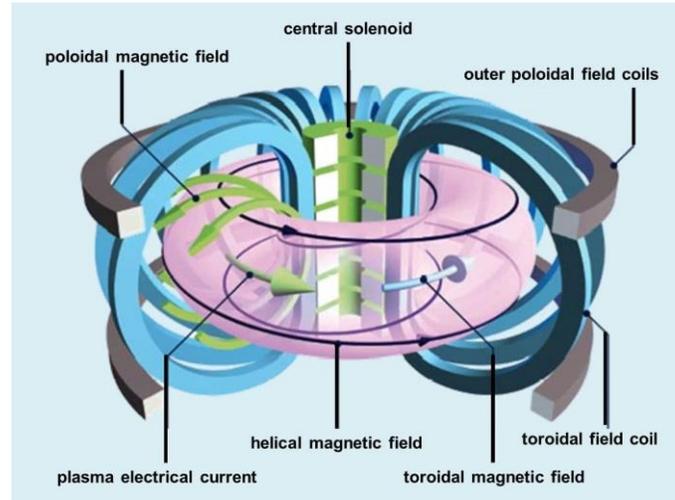


Cos Theta Magnets

Required to steer the particle beam: A pure, uniform dipole field



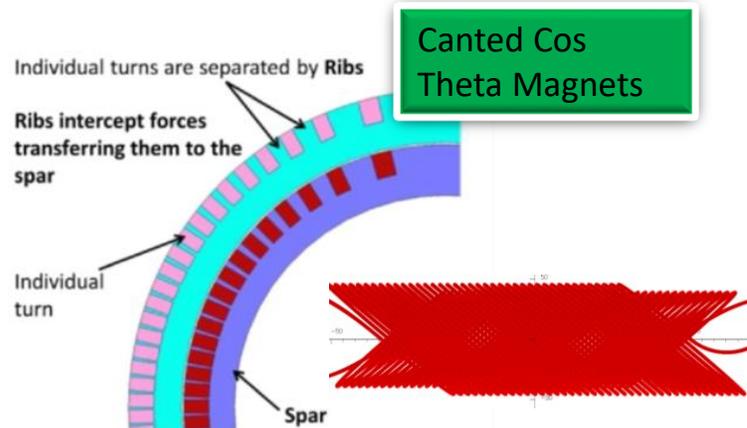
A Zlobin, "15 T dipole design concept, magnetic design and quench protection", Presentation at the US MDP workshop Jan 2017



Tokamak-type Fusion Reactor Magnet

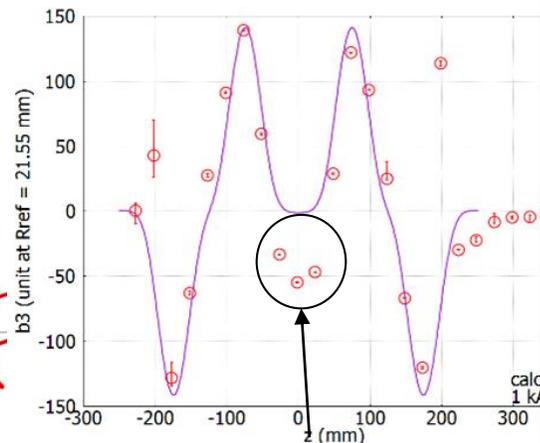
Toroidal Field Needs to be spatially uniform around the torus

Schematic of the Tokamak Image credits: EFDA-JET
<https://www.sciencecue.it/2021/01/02/tokamak-fusione-magnetica-fonte-energia-alternativa/>



Canted Cos Theta Magnets

YBCO CORC Canted cos coil (Wang, LBNL 2018 MDP)



Magnetization related b3

Bottom Line: Pure uniform field required, BUT ..

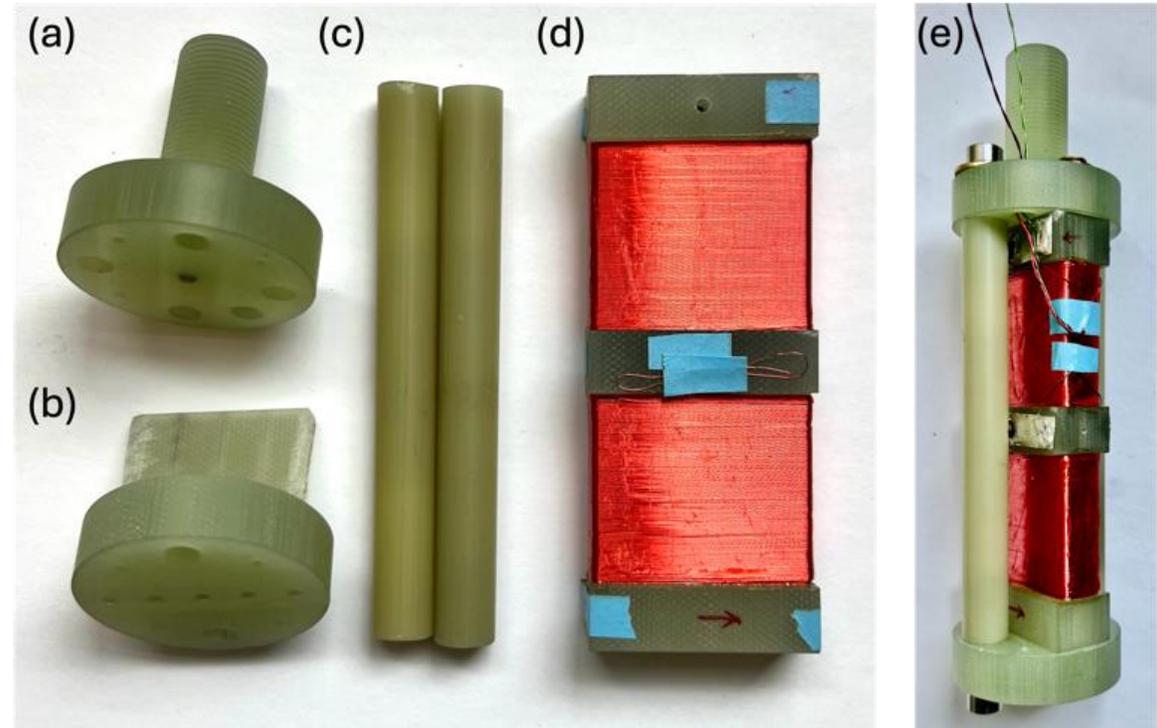
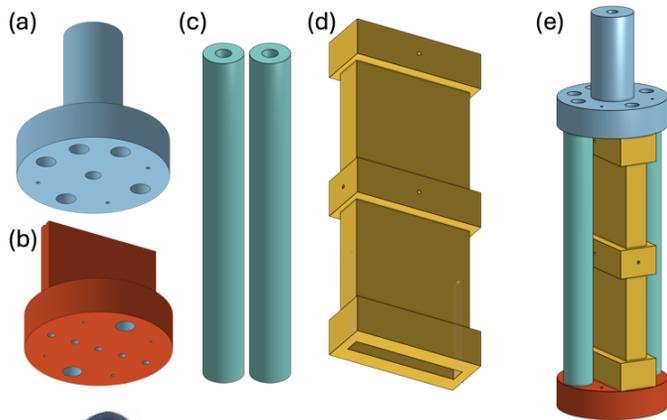
- Magnetization in superconductors creates field distortions.
- In accelerators: causes multipole errors (like b_3), defocusing the beam.
- In fusion: leads to ripple, destabilizing plasma boundary.
- ReBCO's magnetization must be measured and understood for real cable stacks.

How to Measure M-H for ReBCO cables, and how to measure at relevant fields and cycles

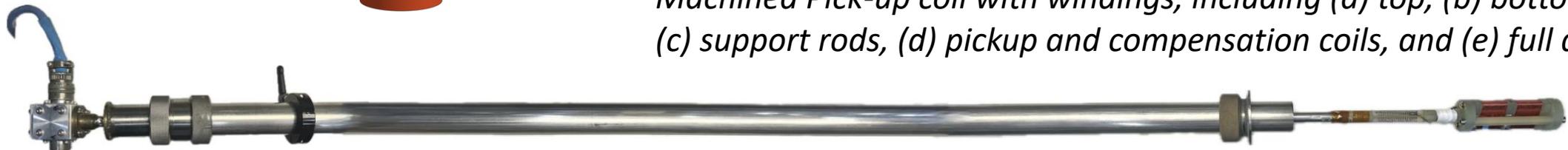
- Problem 1: Most devices that measure magnetization do small samples (PPMS) – can't get a useful measurement of cable – Our Answer – SUSCEPTIBILITY MEASUREMENT of segment of cable
- Problem 2: Most Susceptibility rigs (even those that can measure cable) have low fields and fast AC ramping (e.g., 150 mT at 50-200 Hz, or 1 T at mHz)
- But large fields are needed to set up proper state and to mimic accelerator cycle. To get to large fields, (above 2 T) superconducting magnets are usually used, but these are very slow ramping
- Our Proposed Solution:
 - Use a Bitter Magnet to act as the primary of the susceptibility system – ramps moderately fast, high field (30 T, 10 T/min)
 - Make a special secondary which holds the sample and obtains the voltage proportional to the time changing flux

Our Pick-up Coil for insertion in Bitter Magnet: Design and fabrication

Shape	Square cylinder type
Dimensions	32.5 × 30 × 8 mm
Number of turns per layer	~165
Number of layers	7
Wire material	Cu with PUR/Nylon insulation
Wire diameter	0.18 mm (AWG-34)



Machined Pick-up coil with windings, including (a) top, (b) bottom, (c) support rods, (d) pickup and compensation coils, and (e) full assembly.



Full sample rod with sample holder

Basic Measurement Procedure: M-H Susceptibility in a Bitter magnet

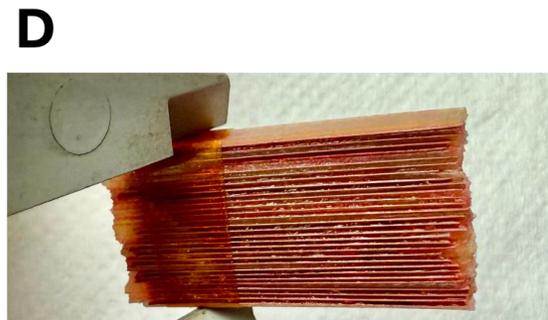
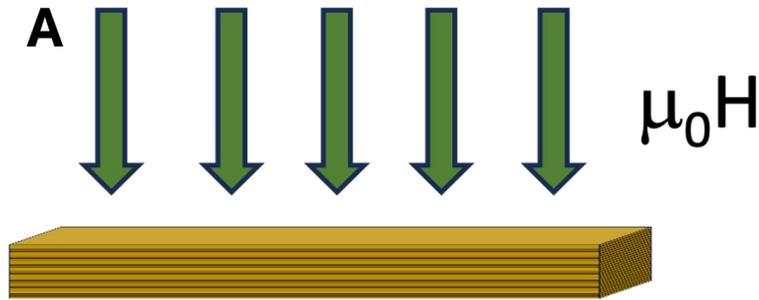
Bitter Magnet



- We use here a Bitter Magnet for the primary and a coil set made at OSU for primary and secondary
- Fields are induced in secondary by ramping field provided by primary (Bitter Magnet).
 - $V = -d\phi/dt$
- Bucking coil measured in anti-parallel takes voltage signal induced to zero
- Sample placed in secondary unbalances coils, and resultant voltage can be integrated with time to get flux
- Flux can be calibrated to get M
- Calibration performed by flux exclusion on Meissner slope of initial branch of sample (cylinder with demag = $\frac{1}{2}$)

Cables we measured: Stack tape Cable

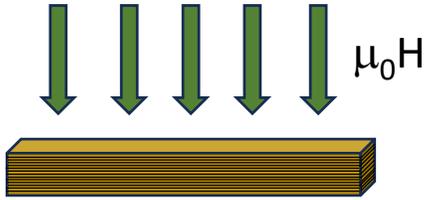
Stack Tape Sample Details



Tape thickness	~ 0.06 mm
Cu stabilizer thickness	10 μm
ReBCO thickness	1 μm
Tape width	4 mm
Substrate thickness	30 μm
Sample length	27 mm
Critical Current @77K and self-Field, I_c	100 A
60 tape stack (cable) sample thickness	3.90 mm
60 tape stack (cable) with Cu-spacers tape sample thickness	13.80 mm
30 tape stack (cable) with G10-spacers tape sample thickness	14.00 mm

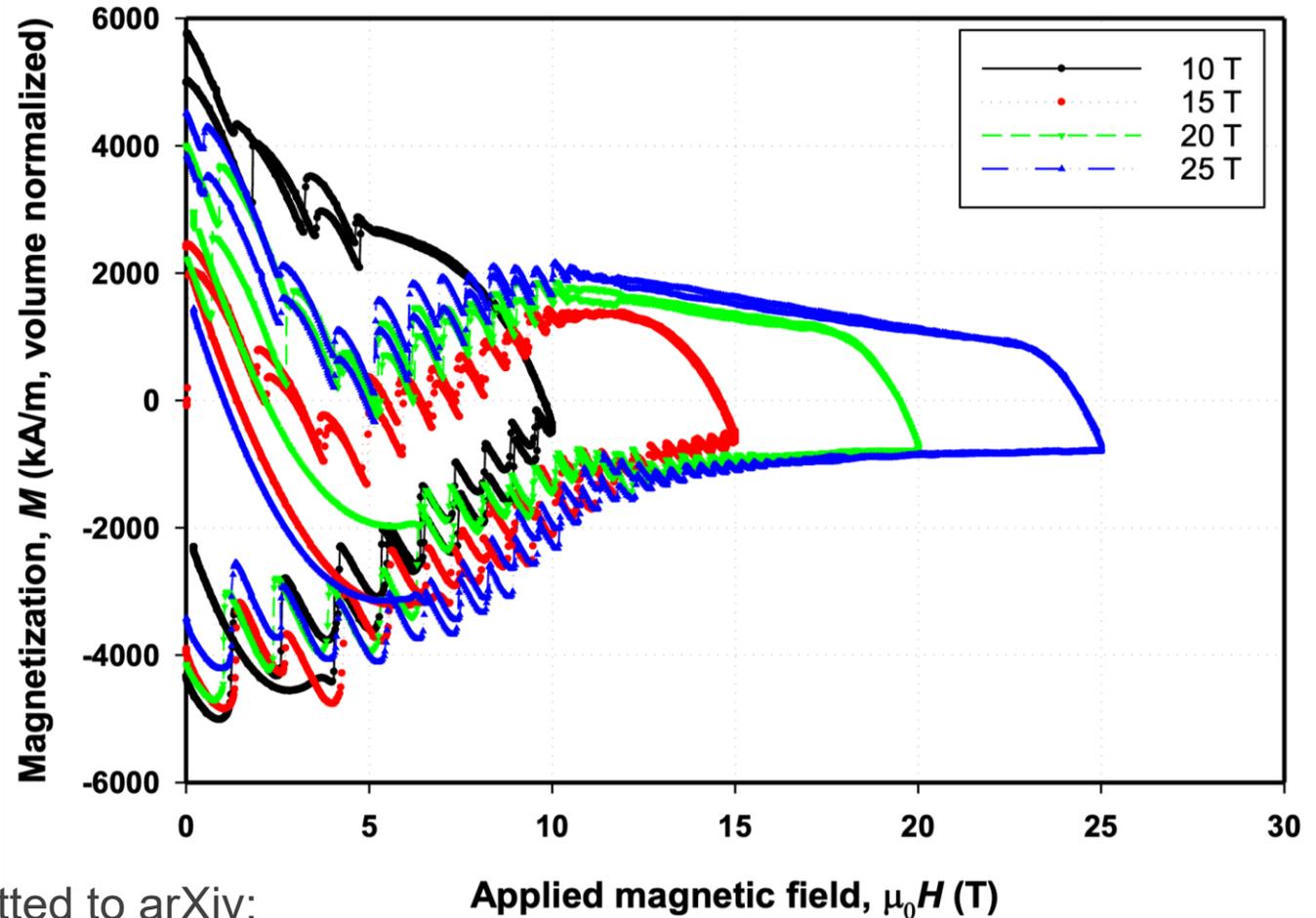
(A) Schematics of the applied field perpendicular to the tape stack cables, (B) 60-tape stack cable, (C) 60-tape stack cable with Cu spacers, (D) 30-tape stack cable with G10 spacers.

ReBCO 60 Tape Stack (cable)



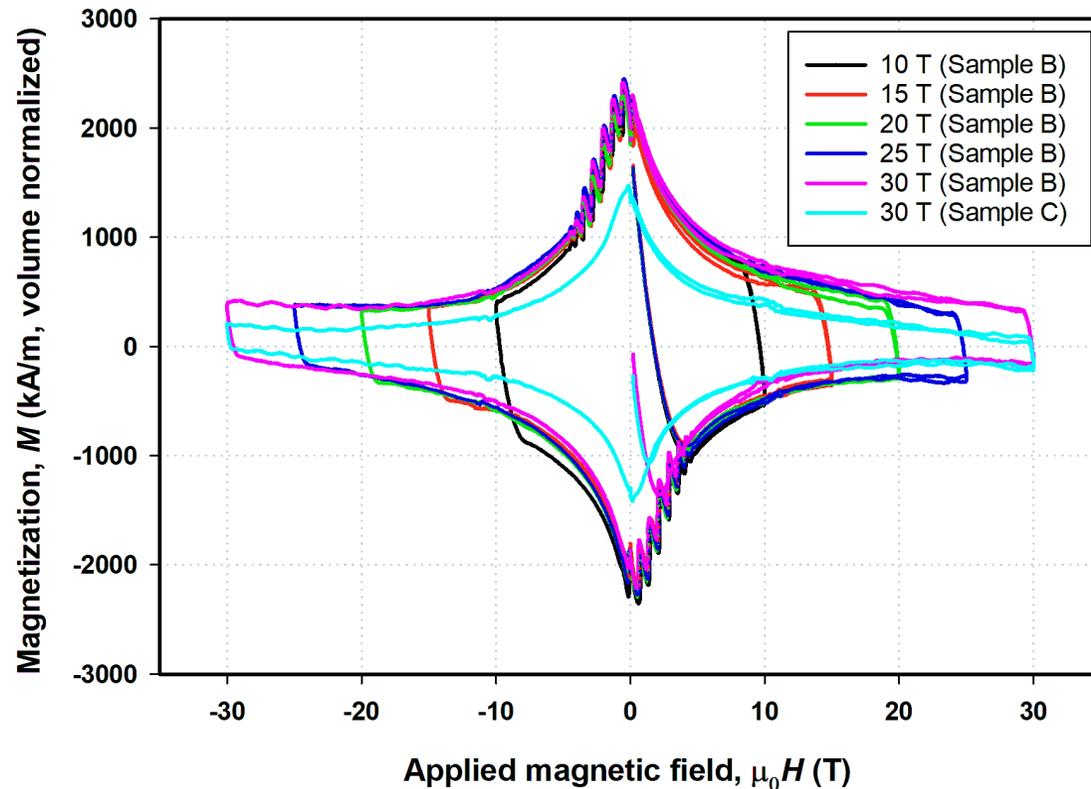
Note: Tape Stack “Cable” Flux jumping up to 17-18 T
Take note dipole magnet winders and fusion aficionados

Strong flux jumping is observed up to 17 T in the M - H of a 60-tape stack cable measured at 4.2 K, with a maximum applied magnetic field of 25 T perpendicular to the cable width and its longitudinal axis (sample A). Magnetization is normalized to the total volume of the cable.



Submitted to Science Advances, and preprint submitted to arXiv:
Flux Jumps up to 17 T in ReBCO Tape Stack Cables and their
Suppression with Increased Intertape Spacing

ReBCO Tape Stack (cable) with Cu and G10 Spacers



Sample B

60-Tape Stack (Cu Spacers) — 0.16 mm spacing

Sample C

30-Tape Stack (G10 Spacers) — 0.38 mm spacing

Why Spacing Helps:

- Increases thermal stability → absorbs local heating
- Lowers effective magnetization volume (ΔM)
- Reduces inductive coupling between layers
- Prevents conditions that trigger thermomagnetic avalanches

The M - H of sample B, a 60-tape stack cable with Cu, and Sample C, a 30-tape stack cable with G10 spacers, each measured at 4.2 K, with a maximum applied magnetic field of 30 T perpendicular to the longitudinal axis of the cable and to its width. Notice the large suppression of flux jump events. Magnetization is normalized to the total volume of the cable.

Why G10-Spaced Stacks Are More Stable

Factor	Effect
Increased inter-tape spacing	Reduces total magnetization (ΔM), which lowers thermal energy released during flux entry.
Lower packing density	Lowers inductive coupling between layers — reduces thermomagnetic feedback.
G10 (fiberglass epoxy)	Thermally insulating and structurally stiff — limits rapid heat transfer and vibration.

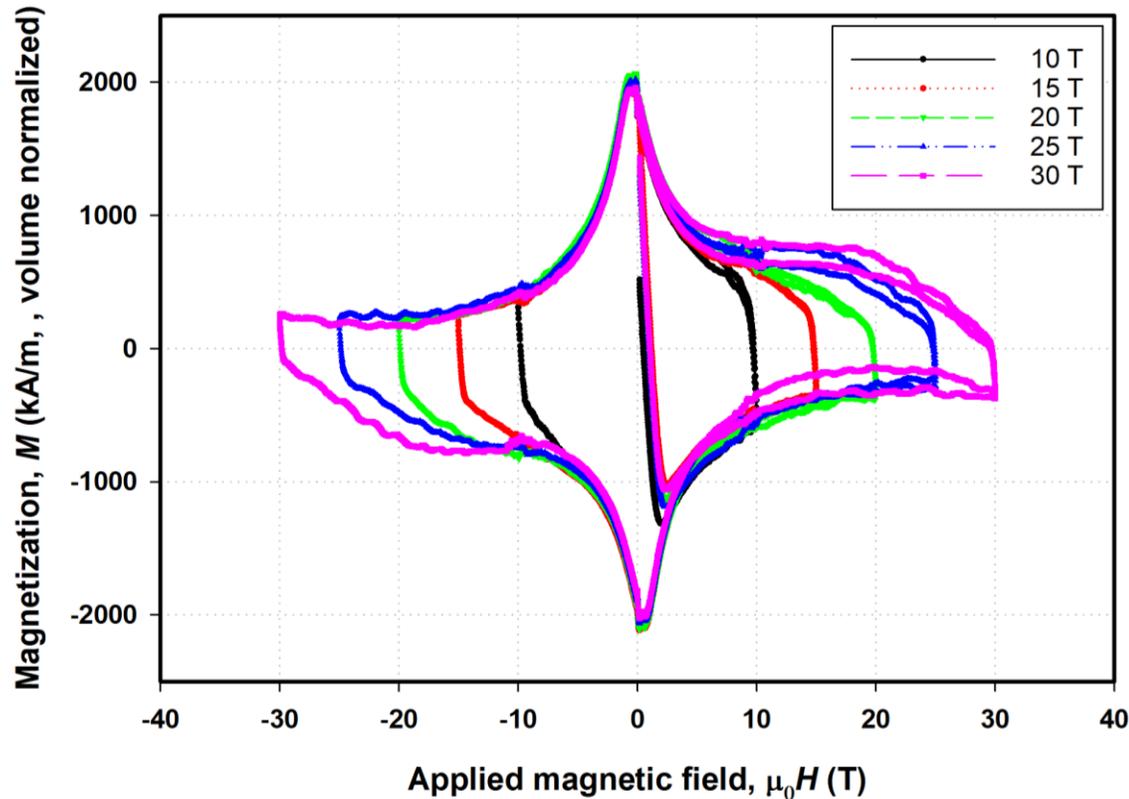
Together, these factors prevent the conditions that trigger thermomagnetic flux jumps.

Why This Matters for Fusion & Accelerator Magnets

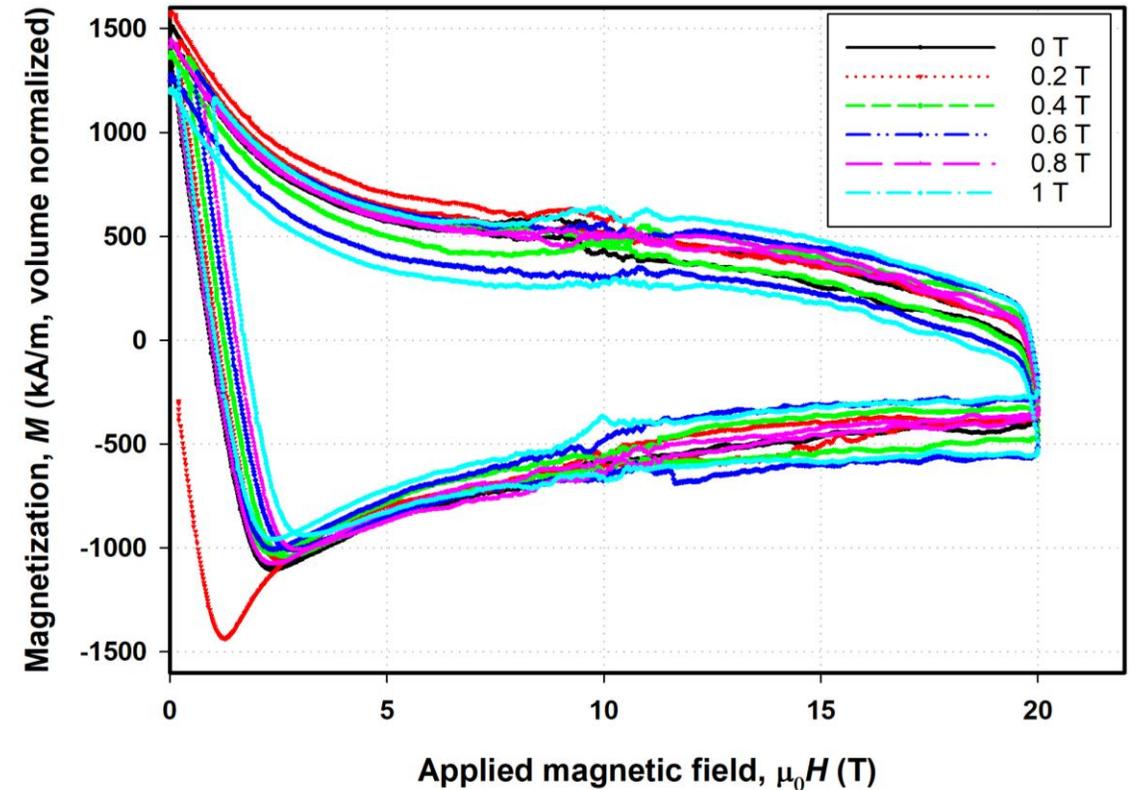
Sample Type	Onset Field (T)
60-Tape Stack (No Spacer)	~17
60-Tape Stack with Cu Spacers	~5
30-Tape Stack with G10 Spacers	~0

- Flux jumps persisted up to **17 T**.
- The **stacked geometry** behaves like a thick slab → high stored energy → high flux jump tendency.
- Introducing **Cu or G10 spacers**:
 - **Reduced volume magnetization,**
 - Improved **thermal isolation,**
 - Resulted in **suppressed or eliminated** flux jumps.

CORC – Three Layers (like a magnet winding)



The measured M-H hysteresis loop at 4.2 K of a three-stack CORC stack sample, subjected to a maximum field of 30 T, applied orthogonal to the cable's longitudinal axis.



Accelerator like M-H cycle measured at different hold fields of 0, 0.2, 0.4, 0.6, 0.8, 1 T for three-stack CORC sample, replicating the field cycling sequence of acceleration, collision, beam dump, and reinjection.

T. Garg, J. Jaroszynski, E. S. Choi, M. D. Sumption, M. Majoros and E. W. Collings, "Magnetization in ReBCO-Based CORC Cables in Magnetic Fields up to 30 T for Accelerator Applications," in *IEEE Transactions on Applied Superconductivity*, vol. 35, no. 5, pp. 1-5, Aug. 2025, Art no. 6603605, doi: 10.1109/TASC.2025.3540991

Conclusions

- We measured magnetization (M-H) in **stacked ReBCO tape cables** up to **30 T** using a **Bitter magnet-based susceptibility rig**.
- **Severe flux jumps** were observed up to **17 T** in densely packed 60-tape stacks — a field range **much higher** than typically expected for such instabilities.
- Introducing **inter-tape spacing** with **Cu (0.16 mm)** or **G10 (0.38 mm)** spacers led to **dramatic suppression or elimination** of flux jumps.
- These results suggest a **critical magnetization threshold** (~ 1000 kA/m) governs jump onset, providing a potential **design criterion** for future HTS magnet systems.
- Present data should prove useful for HEP dipole magnet designers and be of interest for Fusion magnets as well



Questions?

