New facilities to advance understanding of radiation damage in REBCO superconductor

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MIT Plasma Science and Fusion Center (PSFC)

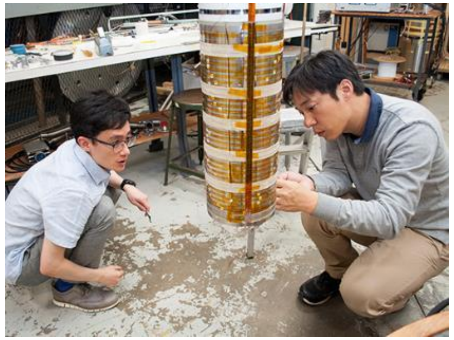
Presentation to the First Muon Collider Collaboration @ CERN

*Eni S.p.A has generously supported all work
in REBCO irradiation shown in this presentation*

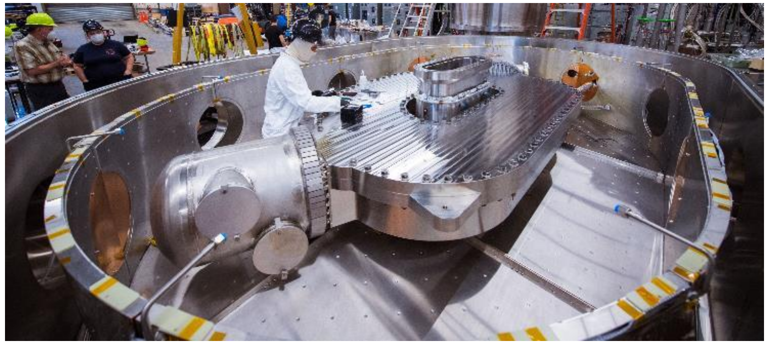
MIT PSFC is pursuing broad R&D in high-field REBCO magnets

Insulated cables (>50 kA)

No insulation coils (>30 T)

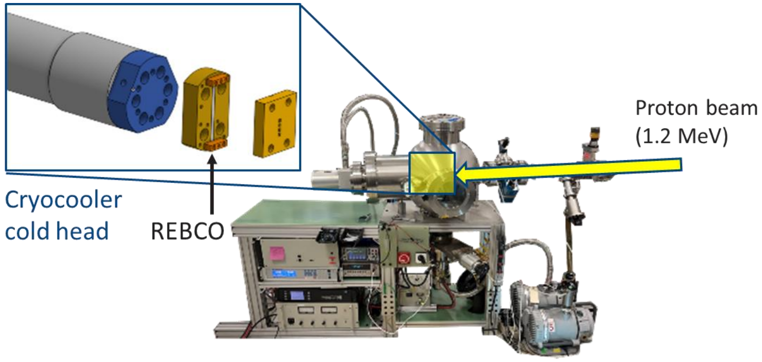


The SPARC Toroidal Field Model Coil (large-scale 20 T 110 MJ coil)

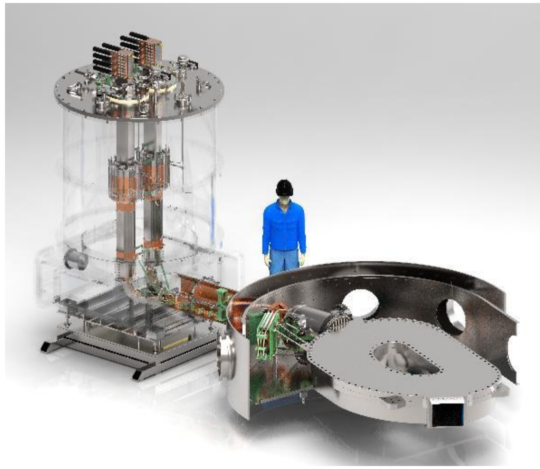


Non-planar 3D cables and coils

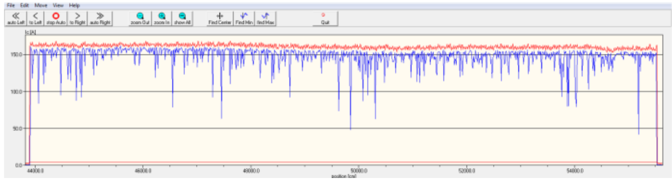
High-fidelity radiation damage in REBCO

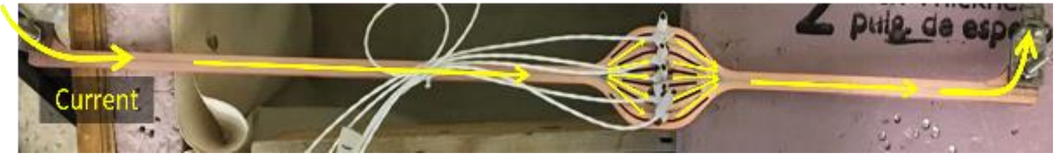


50 kA LN2-cooled binary current leads



Defect tolerant cables and magnets

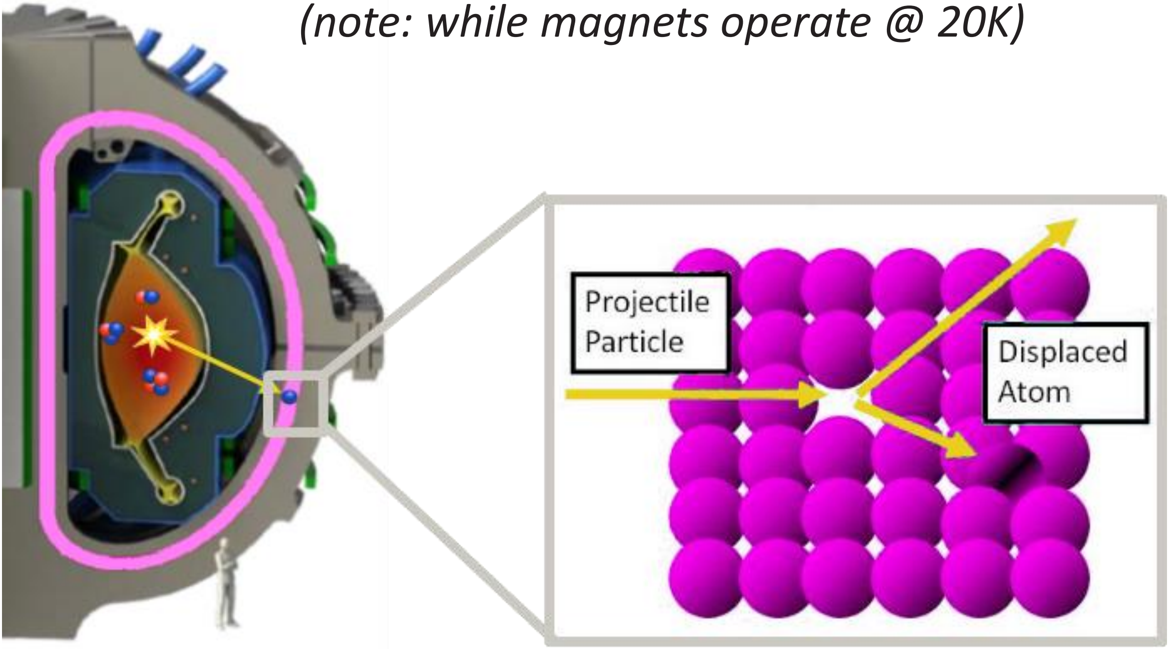




MIT PSFC is interested in collaborating on high-field REBCO technologies

Radiation damage in REBCO magnets is a key technical, operational, and economic challenge for fusion devices

Despite shielding, fast neutrons reach
REBCO in the toroidal field coils
of a tokamak fusion power plant
(note: while magnets operate @ 20K)



Displacements in the REBCO
crystal change pinning structures
ultimately degrading superconducting
performance of the material

Toroidal Field (TF) magnets in a fusion tokamak power plant are a significant fraction of capital cost and are expected to be lifetime components.

Quantifying limits due to radiation damage in high-field REBCO magnets will be necessary to:

- Optimize complex system design of tokamak core
- Anticipate operational concerns (e.g. thermal annealing, magnet stability changes, etc.) and understanding plant availability (key cost driver)
- Forecast capital cost of fusion power plants and ultimately economic viability as an energy tech.

What have we done in this area and, more importantly, what new capabilities based on what we've learned so far can we deploy to advance our knowledge?

The TFMC was built on no-insulation REBCO magnet technology; Perhaps removing insulation is a first-step in radiation tolerance?

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The TFMC winding pack, with no turn-to-turn insulation nor high-voltage to drive breakdown should pancake-to-pancake insulation degradation occur…

Aside: ~20 K operation with single pass helium cooling via pressure vessel provides very high heat removal capabilities with intrinsic cryostability

Propose Design Features	Advantage(s) to be proven in the TFMC Project
Intrinsically low voltage (<1 V)	Minimal insulation; simple fabrication, low voltage leads and feeds, safety
Maximized radiation tolerance	Eliminate organic insulation, irreducible is radiation hardness of REBCO
Modular, simple construction	Rapid assembly; Maintenance options; scalable for commercial production
High winding pack current density	Compact magnet; expanded design space
High thermal stability	Robust to damage, defects, and off-normal events
Resiliency to quench	No quench detection systems, no active mitigation systems
Maximized cooling for heat removal	20 K (high heat capacity, thermal conduction), high cooling via single pass cooling

Radiation damage in REBCO has been advanced through reactor neutron irradiations and, more recently, proton irradiation

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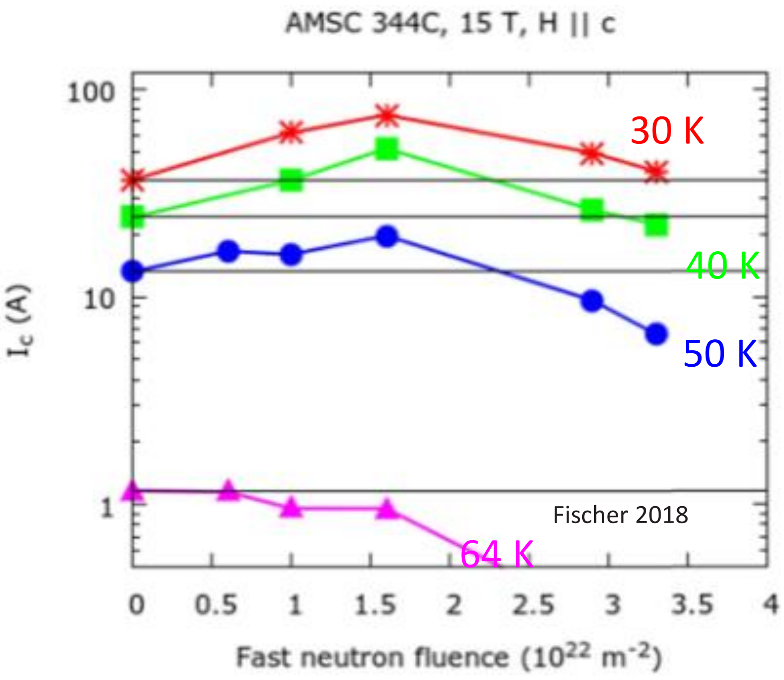
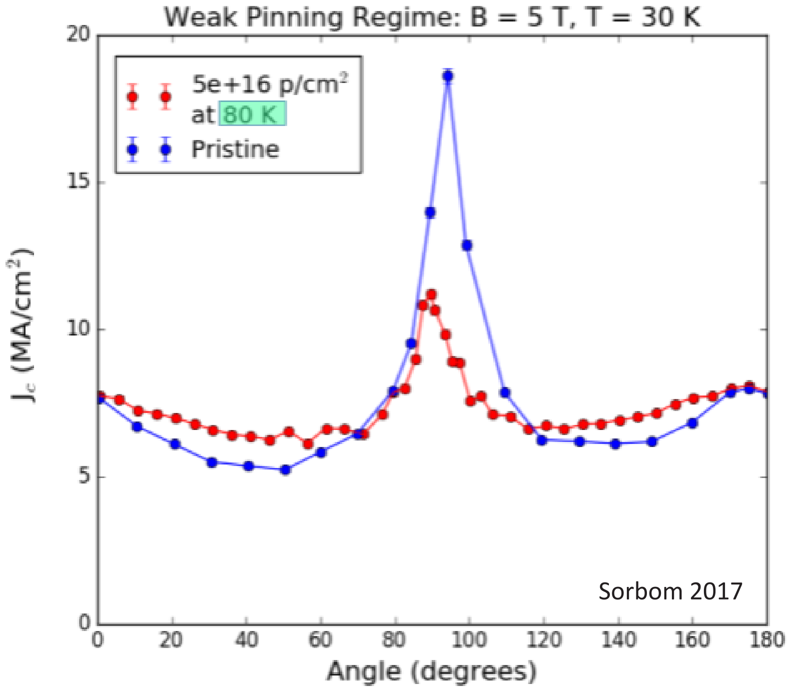


Fischer 2018



Sorbom 2017

- Neutron irradiations @ 330 K followed by cryogenic, high-field Ic(B,T) characterization
- Clear temperature dependence indicates pinning force changes via defect size vs. vortex scale length
- Degradation limits determined to be ~5x10^{22} n/m^2

- Proton irradiations @ 80 K followed by cryogenic, mid-field Ic(B,T,θ) characterization
- Radiation damage destroys "advanced pinning" advantage for B||ab but enhances off-axis Ic
- Irradiation temperatures make a critical difference

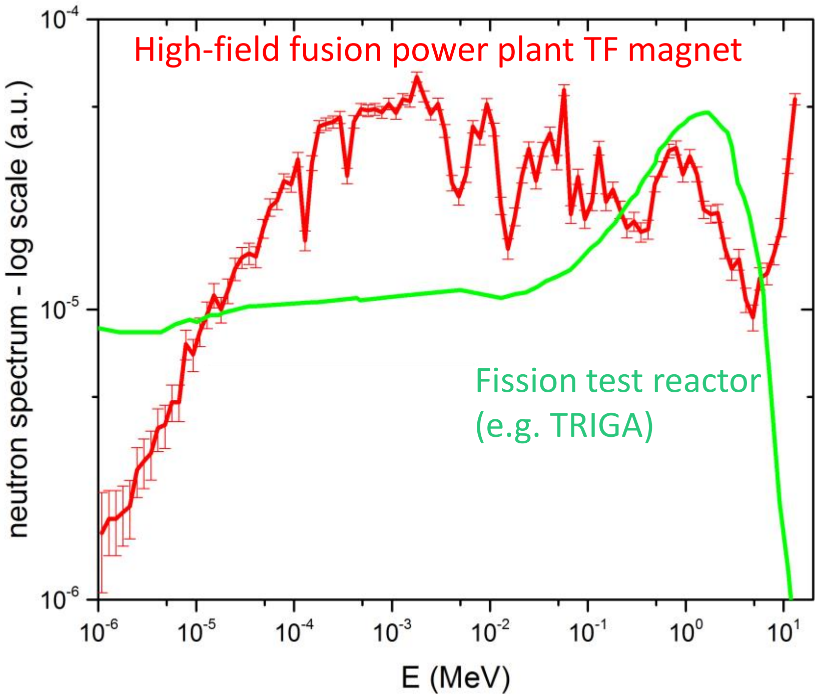
[1] D X Fischer, Sup. Sci. and Techn. **31** (2018) 044006.

[2] B. N. Sorbom, MIT Ph.D. Thesis, 2017.

MIT has been pursuing increasingly high-fidelity capabilities to properly understand radiation damage in REBCO tapes

- The vast majority of radiation damage in REBCO has been studied in conditions that are not representative of an operating SC magnet. Examples:
  - Elevated irradiation temperature (>330 K vs ~20K)
  - Poorly matched neutron energy spectra
  - Thermal annealing between damage and Ic(B,T,A)

- Why?
  - Lack of cryogenic neutron irradiation capability worldwide (Russian, German, Japanese, US reactors shuttered)
  - Difficult to match D-T 14.1 MeV fusion neutron spectra (especially at relevant ~3x10^{22} n/cm^2 fluences)
  - Challenging to perform in-situ irradiation and Ic(B,T,A) measurements (particularly in test reactors)



Parameter	Compact fusion power plant	Nuclear test reactor
Fast neutron fluence (n/cm^2)	1.6×10^{19}	4.0×10^{18}
dpa	0.52	0.02
H yield (appm/dpa)	0.5	0
He yield (appm/dpa)	10.6	0

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One method of attack is through materials simulation to interpret experimental Ic degradation from microstructural evolution

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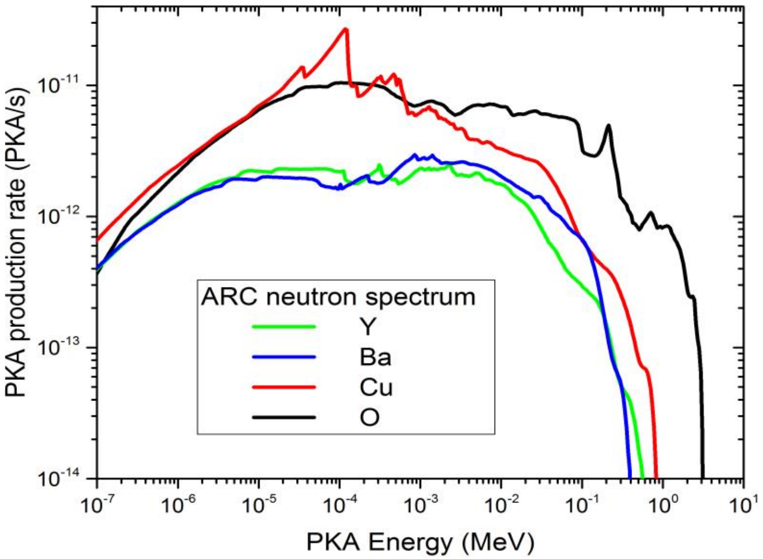
Monte Carlo transport on tokamak geometry generate neutron spectra, DPA, H/He generation in REBCO

PHITS
Particle and Heavy Ion Transport code System

Computational framework to investigate irradiation variables (particle, spectra, temperature, magnetic field, etc) on REBCO microstructural evolution.

Can SEM/TEM imaging of defect morphology combined with modeling enable prediction of Ic degradation from primary irradiation conditions?

Neutron spectra used to generate recoil spectra of damaged materials



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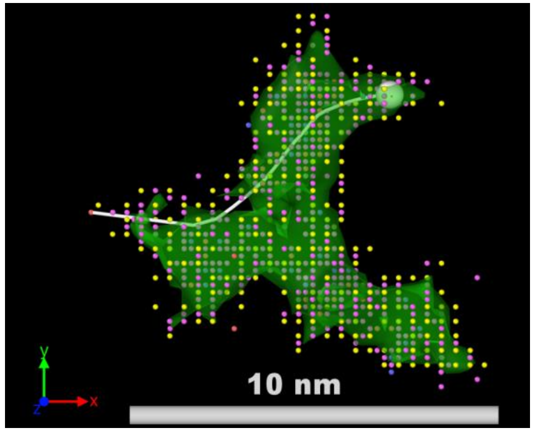
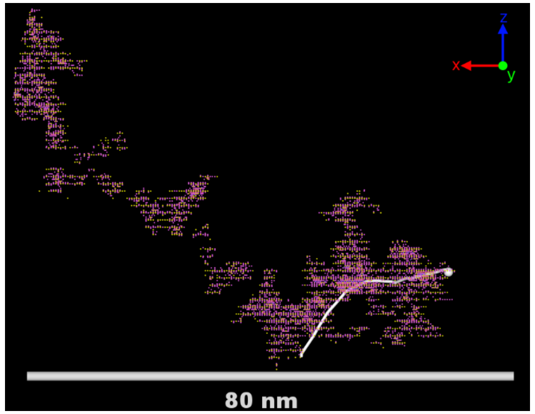
Politecnico di Torino
1859

Molecular Dynamics provides insight into material morphology, time and temperature dynamics, spectra and proton/neutron differences

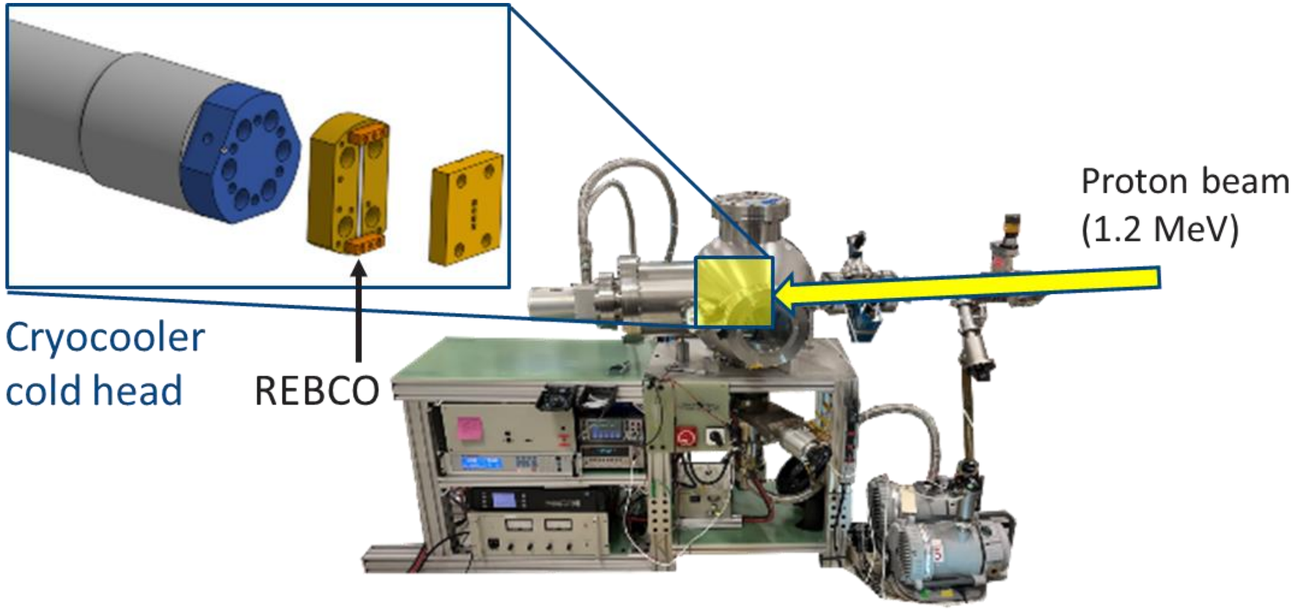
7 keV Ba recoil @ 20 K



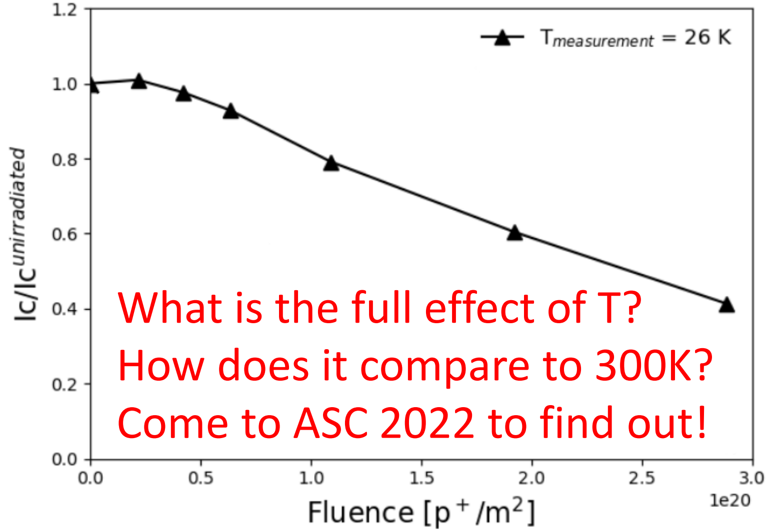
110 keV Ba recoil @ 300 K



Primary experimental approach has been cryogenic 1.2 MeV proton irradiation with in-situ Ic(T) characterization of REBCO tapes



First cryogenic irradiation with no annealing before Ic characterization

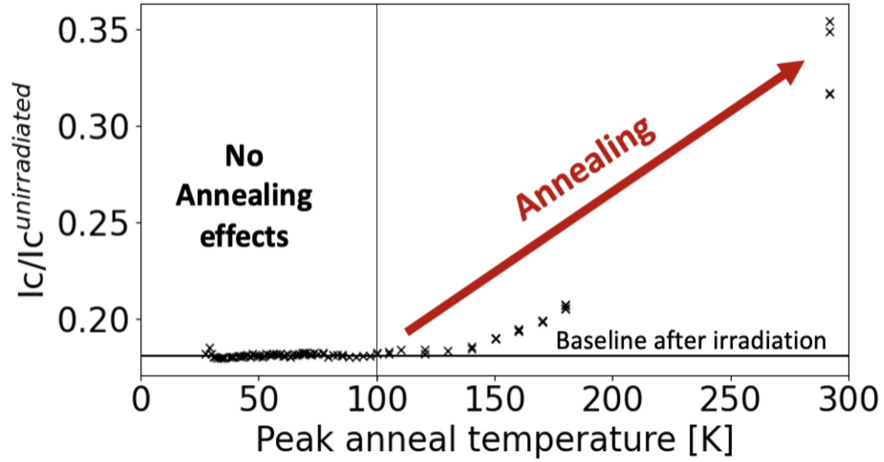


What is the full effect of T?
How does it compare to 300K?
Come to ASC 2022 to find out!

Cryogenic proton irradiation (down to 20 K) with in-situ critical current testing and thermal annealing capability emulates irradiation of operating REBCO magnets at 20 K

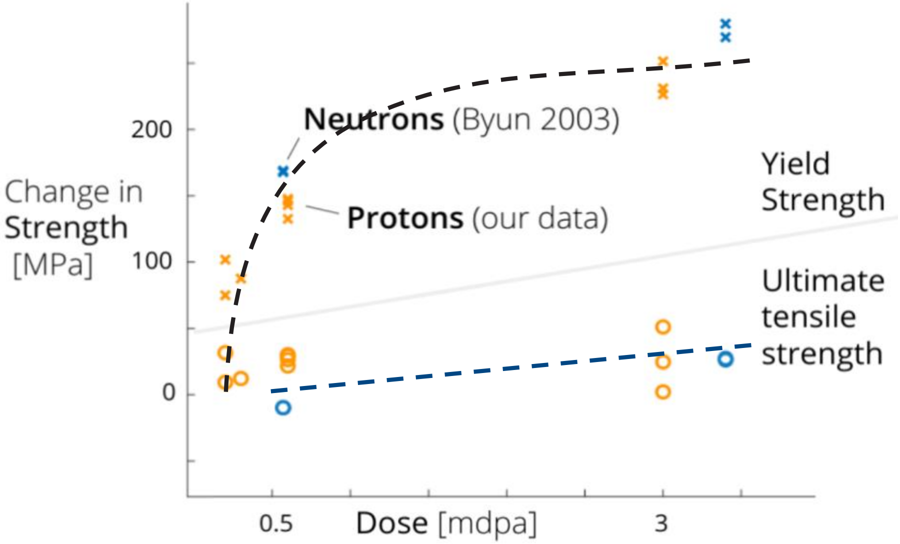
- Captures radiation damage dynamics at magnet op. temperature
- Provides Ic degradation without effects of room temp. annealing
- Provides data on post-cryogenic irradiation annealing recovery of Ic
- Upgrade underway to provide 5T magnet for Ic(B,T,θ) characterization to capture angle-dependent effects in advanced pinning REBCO

Measured at 26 K in self-field



Developing higher energy (12 MeV) cryogenic proton irradiation of bulk material specimens and commercial REBCO tapes (2023)

12 MeV proton irradiation of Inconel 718 compared to neutrons

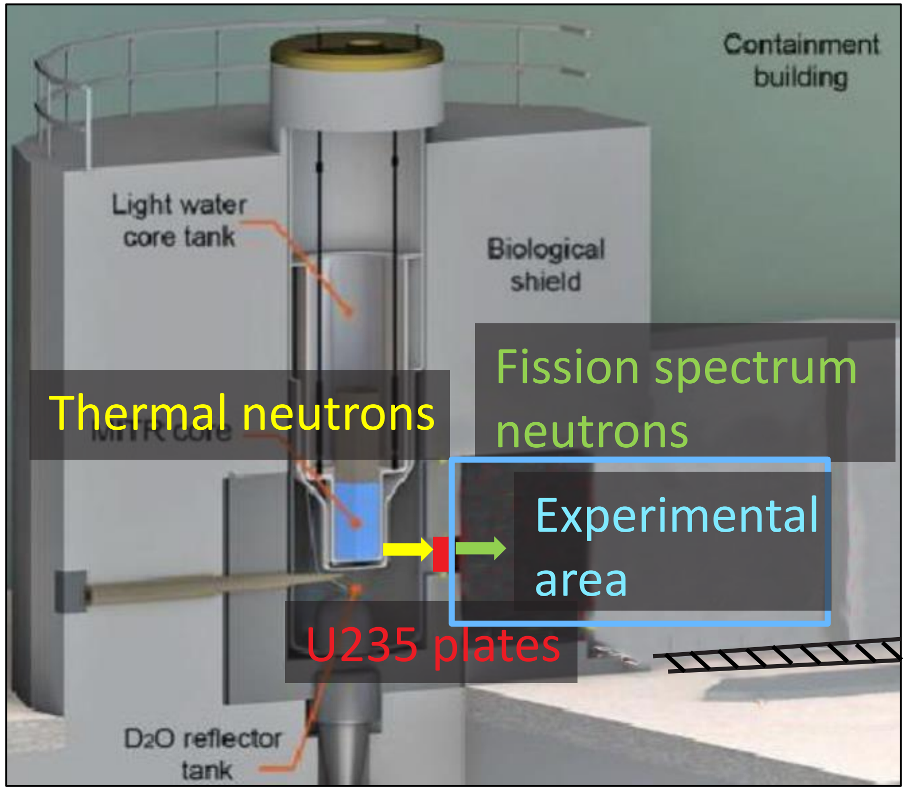


- Ionetix 12 MeV superconducting proton cyclotron provides irradiation of bulk materials [1,2]
  - Presently utilize 300K -> 800K irradiation targets
  - Proposing to upgrade to 20K -> 300 K target useful for REBCO and other cryogenic magnet materials

- 12 MeV protons provide O(100s) um of uniform radiation damage in bulk specimens such that macroscopic material properties can be obtained as function of radiation dose
  - Structural materials (steels, OHFC copper, etc.)
  - Epoxies, resins, insulation (20K -> 300K)
  - Commercial REBCO tapes w/ in-situ Ic(B,T) testing

[1] S. J. Jepeal *et al.* Materials & Design, 200 (2021) 109445.
[2] S. J. Jepeal *et al.* NIM B, 489 (2021) 41-49.

New experiment will enable flexible cryogenic neutron irradiation with matched energy spectra at MIT Reactor (2023/2024)



- MIT Reactor is a 6 MW HEU-fueled research reactor located adjacent to the PSFC laboratories on main campus
- Historically, the problem of cryogenic irradiation is dealing with the high thermal loads placed on in-core samples
- We are working with MITR to recommission their “fast fission convertor” capability and to use for cryogenic irradiation at 20 K and with fluxes of ~10^{23} n/m^2/yr
    - Utilize U235 plates external to the core to generate high fluence of fast neutrons in space adjacent to the power core
    - Eliminates high thermal load from reactor core
    - Provides significant space for irradiation but also Ic(B,T,A) characterization with a high-field external research magnet
- Opportunities for REBCO but other magnet materials experiencing similar lifetime fluences of ~5×10^{22} n/m^2
    - OHFC copper, epoxies/insulation, instrumentation, etc.

Accelerating understanding of radiation damage in REBCO

While substantial progress has been made, understanding performance of REBCO under irradiation requires new facilities and experimental capabilities that emulate superconducting magnet operating conditions under irradiation.

New facilities at MIT are enabling cryogenic proton and neutron irradiation and testing of REBCO and magnet materials under higher fidelity conditions

High level summary of some things we have learned to date:

- Irradiation particle type(s), energy spectra, and temperature matter
- Post-irradiation Ic(B,T,A) characterization must be done in relevant regimes to capture substantial changes from field, temperature, and angle
- The sample's thermal history is critical to understanding damage evolution as well as potential to recover with annealing