Trends and perspectives in radiation damage of HTS

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 61, Nov. 2025. Presentation given at EUCAS 2025, Porto, Portugal, Sept. 2025.

Acknowledgments

PoliTO group:

- Gianluca Ghigo
- Francesco Laviano
- Laura Gozzelino
- Roberto Gerbaldo
- Michela Fracasso
- Simone Sparacio
- Federico Ledda
- Niccolò Di Eugenio
- Martina Casciello
- Simone Severo
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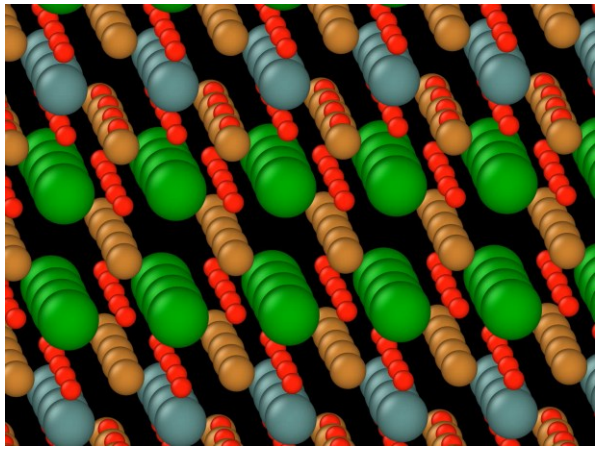
- Niccolò Gallino
- Simone Severo

External collaborators:

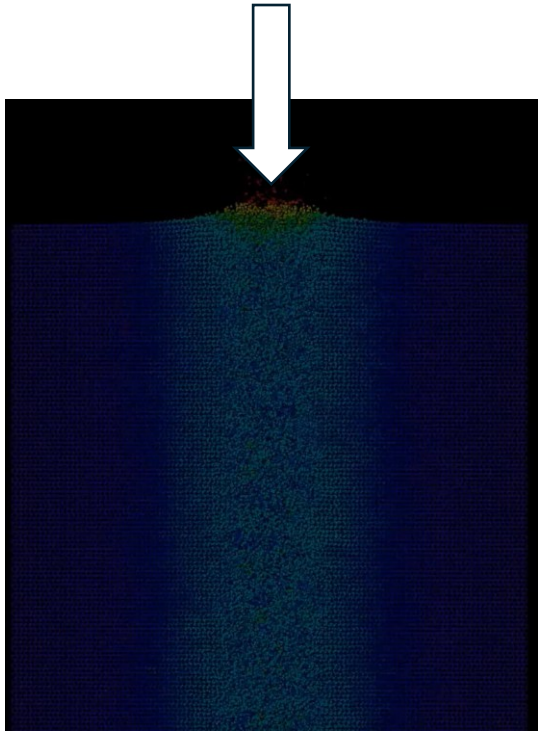
- Davide Gambino
- Michael Eisterer
- David Fischer
- Laura Savoldi
- Giuseppe Celentano
- Antonio Trotta

What is radiation damage?

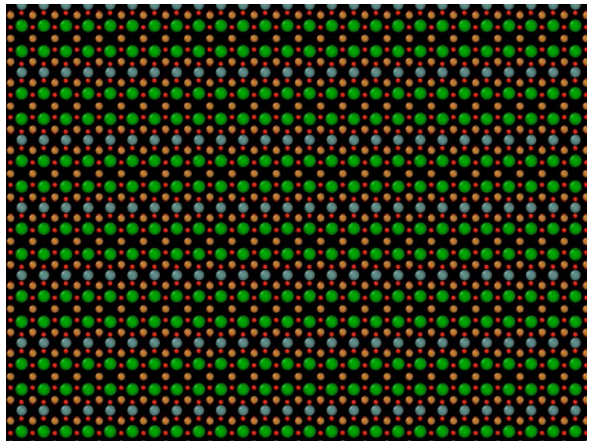
- **Radiation damage** is the consequence of **exposing a material to energetic particles**
- Can be an **issue for applications**
- And a **valuable tool for research**
- Irradiation facilities allow **introducing controlled disorder:**
  - Electron irradiation
  - Ion irradiation
  - Neutron irradiation
  - Gamma irradiation



Frenkel pairs



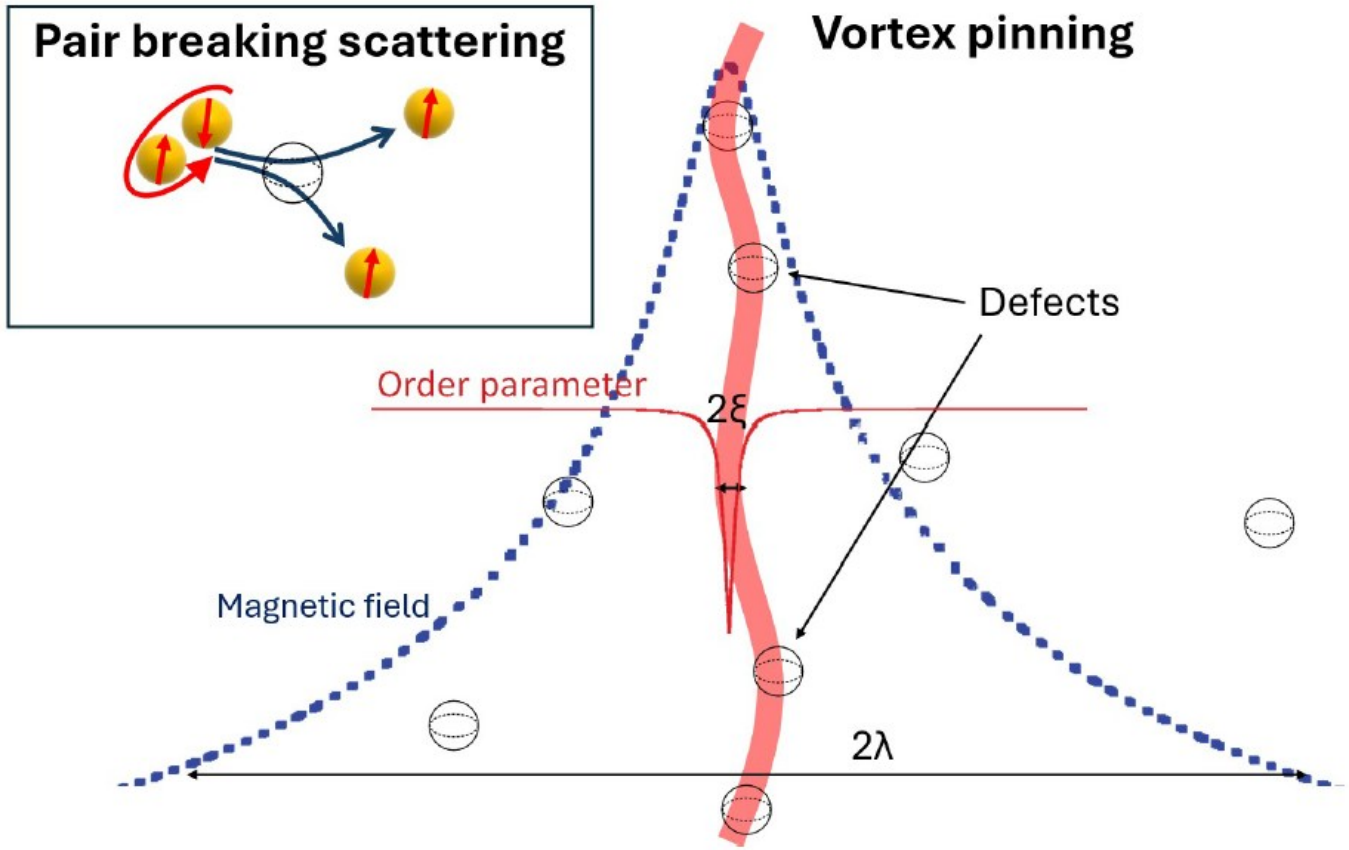
Columnar track



Cascade defect

Why does it matter for superconductors?

- Superconductivity is a fragile state, irradiation deposits a lot of energy
  - Irradiation heat load
  - Sensors
- Defects increase scattering
  - Superfluid density suppression
  - Decrease in T_c
  - Dirty superconductor
- Defects are pinning centers
  - J_c engineering
  - Field dependent



HTS radiation damage in the past

Pairing state studies:

Observation of the Crossover from Two-Gap to Single-Gap Superconductivity through Specific Heat Measurements in Neutron-Irradiated MgB_2

M. Putti[1], M. Affronte[2], C. Ferdeghini[1], P. Manfrinetti[1], C. Tarantini[1] and E. Lehmann[3]

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Phys. Rev. Lett. **96**, 077003 – **Published 23 February, 2006**

Disorder-Driven Transition from $s_{\pm}$ to s_{++} Superconducting Order Parameter in Proton Irradiated $Ba(Fe_{1-x}Rh_x)_2As_2$ Single Crystals

G. Ghigo[1,2,*], D. Torsello[1,2], G. A. Ummarino[1,3], L. Gozzelino[1,2], M. A. Tanatar[4,5], R. Prozorov[4,5], and P. C. Canfield[4,5]

Show more

Phys. Rev. Lett. **121**, 107001 – **Published 4 September, 2018**

Pinning optimization:

Defect independence of the irreversibility line in proton-irradiated Y-Ba-Cu-O crystals

L. Civale, A. D. Marwick, M. W. McElfresh, T. K. Worthington, A. P. Malozemoff, and F. H. Holtzberg

J. R. Thompson

M. A. Kirk

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Phys. Rev. Lett. **65**, 1164 – **Published 27 August, 1990**

Vortex confinement by columnar defects in $YBa_2Cu_3O_7$ crystals: Enhanced pinning at high fields and temperatures

L. Civale, A. D. Marwick, T. K. Worthington, M. A. Kirk, J. R. Thompson, L. Krusin-Elbaum, Y. Sun, J. R. Clem, and F. Holtzberg

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Phys. Rev. Lett. **67**, 648 – **Published 29 July, 1991**

LTS radiation hardness:

Journal of Nuclear Materials

Volumes 141–143, Part 1, November–December 1986, Pages 405-409

Simulation of fusion reactor conditions for superconducting magnet materials

P.A. Hahn [1 *], H. Hoch [1], H.W. Weber [1], R.C. Birtcher [2], B.S. Brown [2]

Neutron Irradiation of Superconductors and Damage Energy Scaling of Different Neutron Spectra

Chapter

pp 865–872 | Cite this chapter

Peter A. Hahn, Harald W. Weber, Michael W. Guinan, Robert C. Birtcher, Bruce S. Brown & Lawrence R. Greenwood

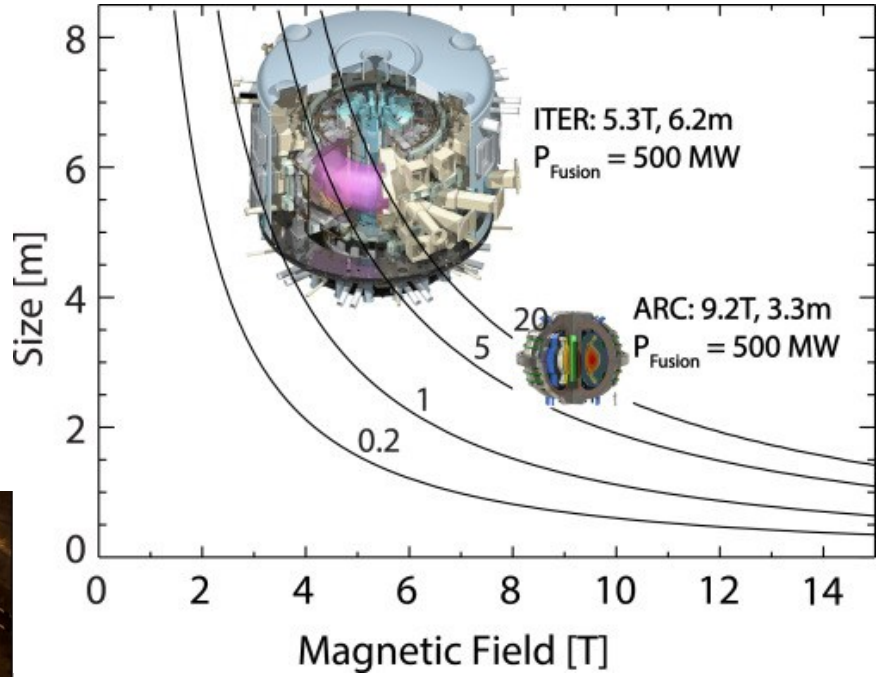
40 years of research

Why radiation damage in HTS in 2025?

Compact fusion reactors such as ARC, VNS and STX

Are enabled by HTS magnets

Due to the smaller size, the radiation environment of superconductors in compact fusion reactor will be much more challenging than in DEMO like systems



	ITER[1]	ARC[2] (unshielded)	ARC[2] (shielded)
Neutron flux on TFC	2×10^{10} n/cm^{2}s	1×10^{13} n/cm^{2}s	6×10^{10} n/cm^{2}s
dpa on TFC after 10 years	4×10^{-4}	1	3×10^{-3}

[1]L. El-Guebaly, FT 1991 (10.13182/FST91-A29549)
[2]F. Ledda et al., IEEE-TAS 2024 (10.1109/TASC.2024.3379114.)

Why radiation damage in HTS in 2025?

The magnet system in a compact fusion reactor might cost 10-30% of the total[1]
Therefore, a **quantitative understanding** of radiation damage in HTS is crucial, and the scientific community is taking on the challenge:

Journals & Magazines > IEEE Transactions on Applied ... > Volume: 34 Issue: 5

R&D Needs for a U.S. Fusion Magnet Base Program

Publisher: IEEE Cite This PDF

Yuhu Zhai ; David Larbalestier ; Robert Duckworth ; Zachary Hartwig ... **All Authors**

bilities of stakeholders is now being developed. The following list conveys the impression of emerging needs that were shared by multiple stakeholders.

- *Radiation effects in superconducting magnet materials:* Understanding the performance evolution of superconductors at fusion-relevant conditions is essential for fusion power plant design, operation, and costing.
- *Test facilities for fusion-relevant radiation damage:* New capabilities, providing cryogenic irradiation with neutrons, under magnet operating conditions. are required to irradiate magnet materials under relevant conditions.

Superconductor Science and Technology

ROADMAP • OPEN ACCESS

Roadmap for the investigation of irradiation effects in HTS for fusion

Daniele Torsello*, Giuseppe Celentano, Leonardo Civale, Valentina Corato, Michael Eisterer, Davide Gambino, Samuel Murphy, Susannah Speller and Francesco Laviano

Published 13 May 2025 • © 2025 The Author(s). Published by IOP Publishing Ltd

Superconductor Science and Technology, Volume 38, Number 5

Focus on Irradiation Effects on HTS for Fusion

Citation Daniele Torsello *et al* 2025 *Supercond. Sci. Technol.* **38** 053501

DOI 10.1088/1361-6668/adce40

Journals & Magazines > IEEE Transactions on Plasma S... > Early Access

STEP's Plan for Understanding REBCO Coated Conductors in the Fusion Environment

Publisher: IEEE Cite This PDF

William Iliffe ; Simon Chislett-McDonald ; Fiona Harden ; Kirk Adams ; ... **All Authors**

deuterium-tritium (DT) fusion. As STEP have selected REBCO coated conductor (CC) as the current carrier in most magnet systems, understanding how REBCO CC responds to the energetic particle environment of a compact tokamak is crucial, especially given reported changes to the properties of REBCO following neutron irradiation.

The STEP confinement system materials group has developed a plan to thoroughly test and validate the superconducting properties of REBCO under conditions as close as reasonably possible to those within STEP prior to its construction. Here our

The context and task

CONTEXT

- Fusion reactor designs are not fixed
  - Materials
  - Geometries
  - Size

Radiation environment keeps changing

- There is no *ideal* irradiation facility
  - Flux
  - Spectrum
  - Secondary particles

No direct experimental evaluation

- Results are urgent
  - Private companies have tight schedules
  - High dynamics in the research field

Thrilling!

TASK

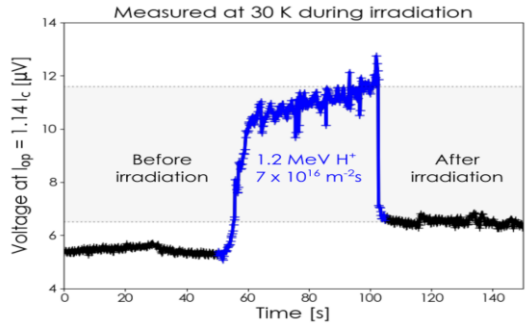
- Provide technological input for reactor development
- Define HTS damage threshold in a fusion environment
  - Understand what determines superconducting performance suppression
  - Experimental characterization in extreme conditions
- Quantify HTS performance during irradiation
  - Thermal aspects
  - Reliability (quench)

Physics, Materials science, Engineering

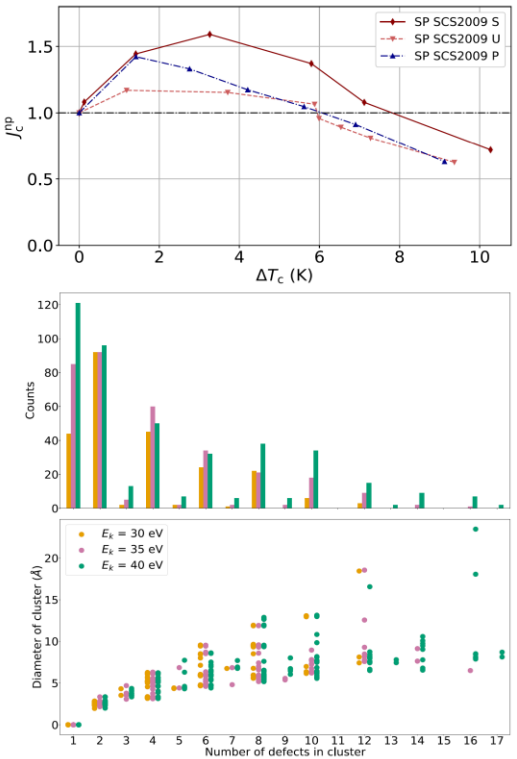
New perspectives!

BEFORE

- Experimental irradiation studies focused on before-after irradiation
- Pinning studies focused on clean systems: single crystals, films on insulating substrate
- Lack of combined experimental and simulation studies



Devitre, Rev. Sci. Instr. 2024



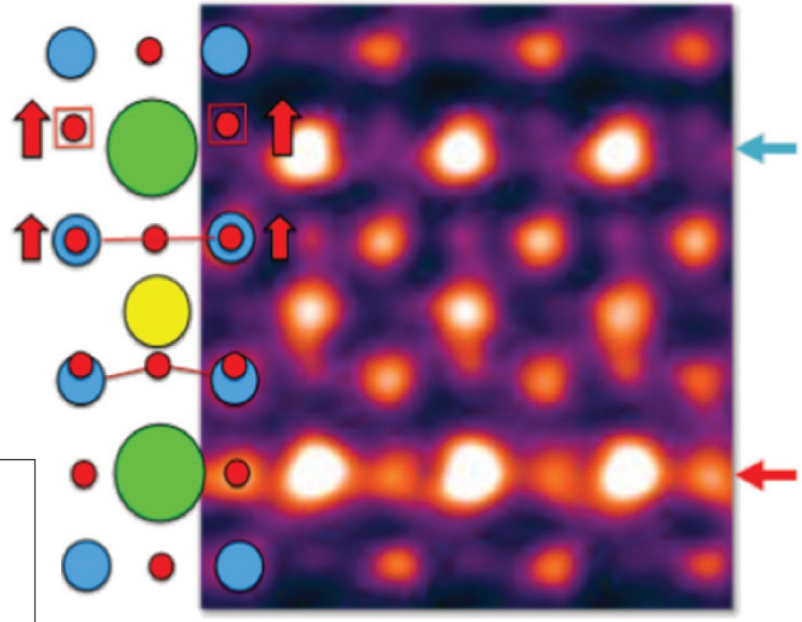
Unterrainer, SuST 2024

NOW

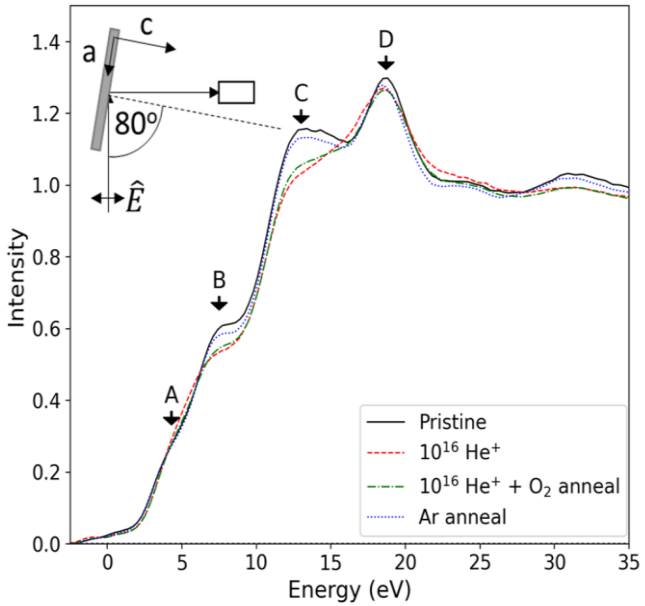
- Performance during irradiation is also critical:
  - thermal and stability aspects
- Clean systems useful for understanding
- Performance needs to be evaluated on REBCO tapes
- Simulations are mandatory to extrapolate to experimentally unachievable conditions

New measurements!

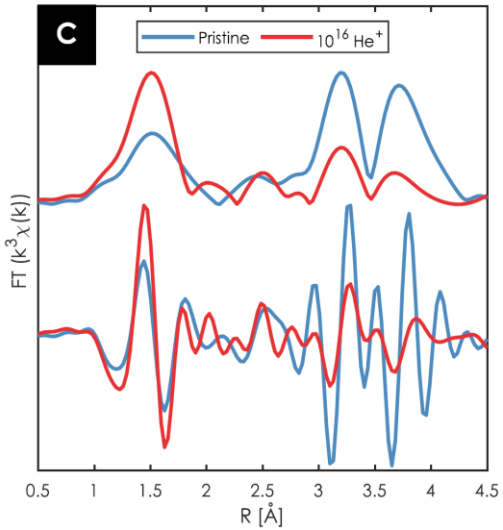
- Atomic resolution TEM
- Ptychography
- XAS:
  - XANES
  - EXAFS



Mundet, Nanoscale202

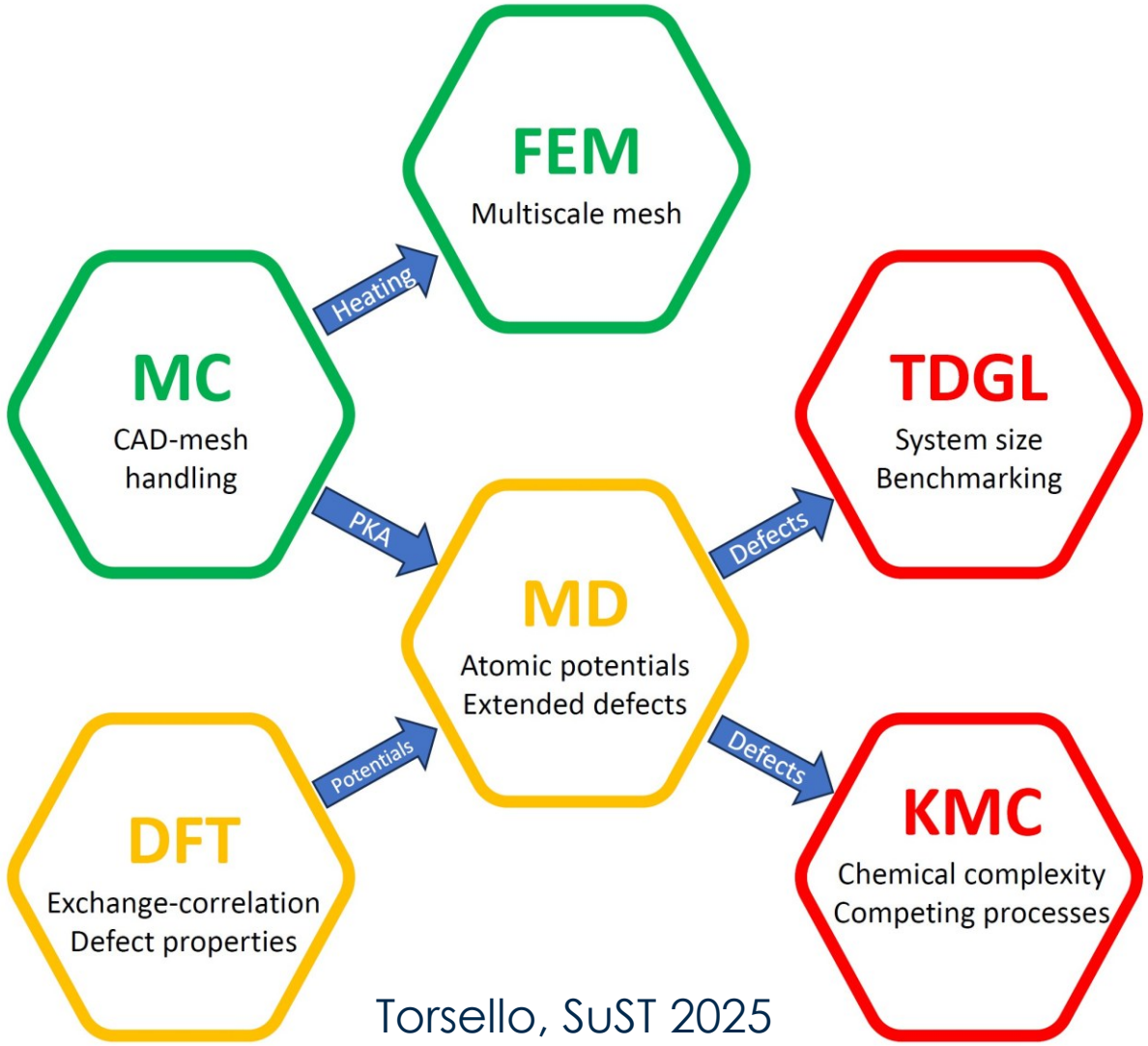


Nicholls, Comm. Mat. 2022



Lewis, SuST 2024

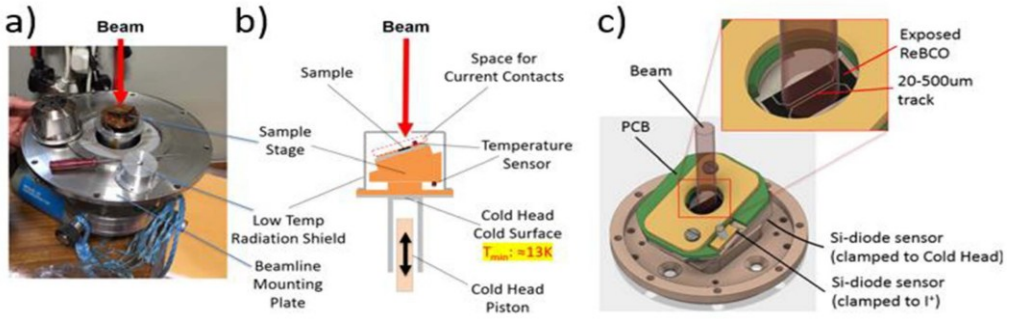
New simulations!



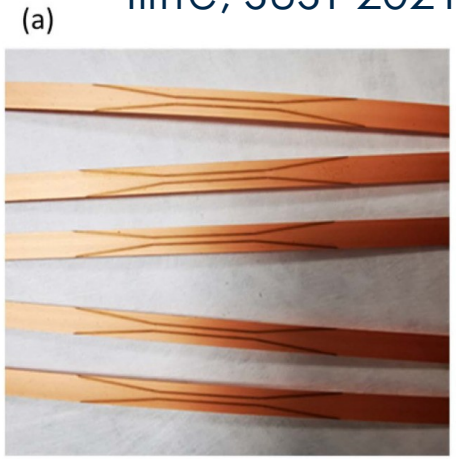
- **Monte Carlo** simulations and **Finite Element Models** are mature
- A comprehensive **atomistic description** of HTS material under irradiation is achievable soon
- The computational estimation of **long term behavior and superconducting properties** is challenging
- **Experimental validation** is a crucial and challenging task

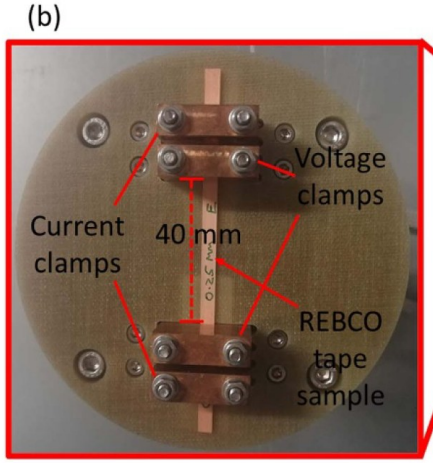
New facilities!

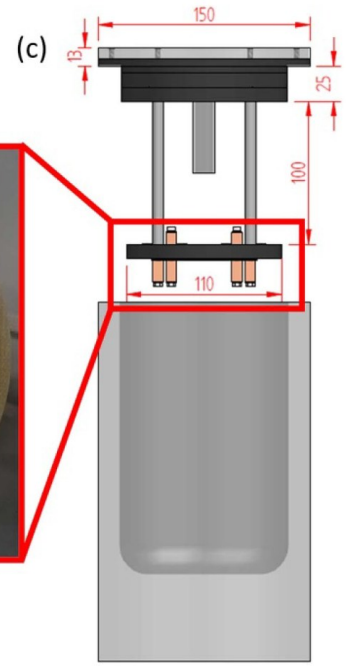
- Cryogenic gamma irradiation
- Cryogenic ion irradiation:
  - He
  - Protons
- Cryogenic neutron irradiation:
  - 14 MeV
  - Fast neutrons



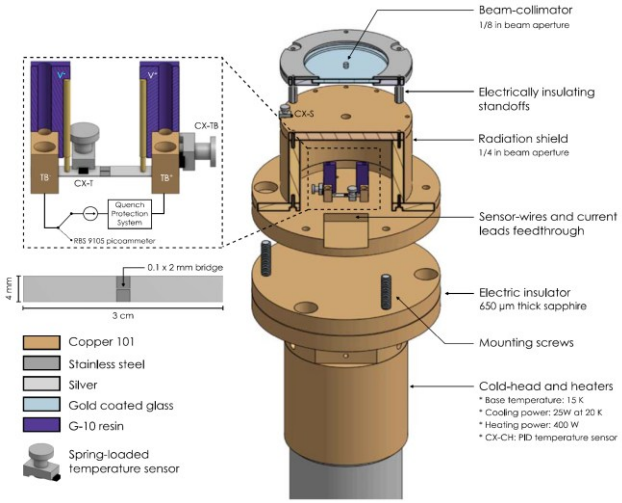
Iliffe, SuST 2021

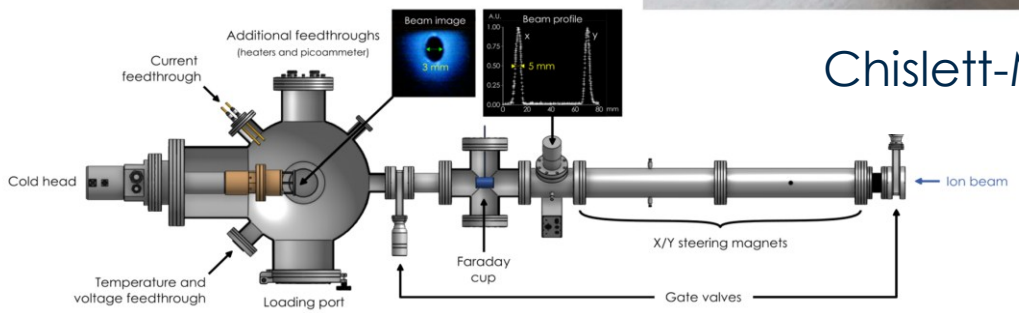






Chislett-McDonald, SuST 2023





Devitre, Rev. Sci. Instrum. 2024

New community!

Community created online by **Simon Chislett-McDonald** with the
Informal Workshop on the Irradiation of Superconductors

12-16 November 2023,
Arona (Italy)
www.superfusion.org/iref23

17-22 June 2025,
Gallipoli (Italy)
www.superfusion.org/iref25

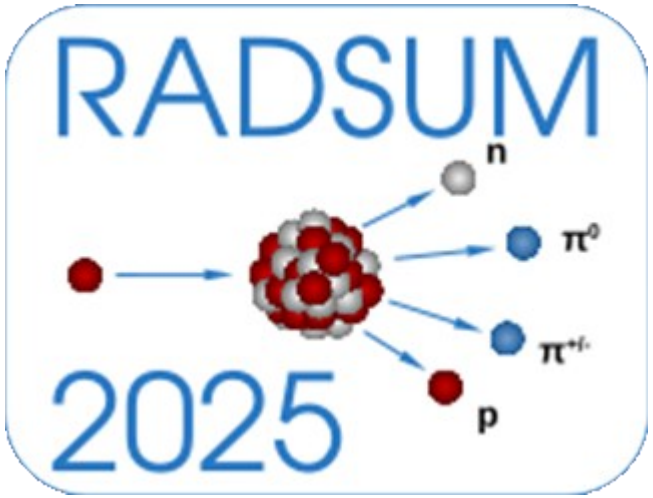
15-19 February 2027,
Torino (Italy)
www.superfusion.org/iref27

IRradiation Effects on HTS for Fusion

Contact: iref@polito.it

Applications with similar challenges

- **Radiation damage** is a challenge also for
  - **Accelerator magnets**
    - Neutrons, protons, electrons, gammas
    - Broad spectra up to GeV
    - High thermal loads
  - **Space applications**
    - Rare events
    - Extremely high energy particles



15-17 February 2025, CERN

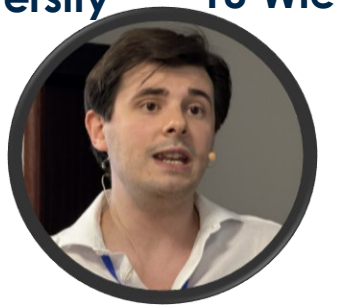
New challenges… new EC people!

Simon Chislett-McDonald
Tokamak Energy

Davide Gambino
Linkoping University

Raphael Unterrainer
TU Wien

Alexis Devitre
MIT-PSFC



Federico Ledda
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Ashley Dickson
Lancaster University

Jarrod Lewis
University of Oxford

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Supercond. Sci. Technol. **36** (2023) 095019 (8pp)

***In-situ* critical current measurements of REBCO coated conductors during gamma irradiation**

S B L Chislett-McDonald, L Bullock, A Turner, F Schoofs, Y Dieudonne and A Reilly

OPEN ACCESS
IOP Publishing
Supercond. Sci. Technol. **38** (2025) 053501 (18pp)

Roadmap

Roadmap for the investigation of irradiation effects in HTS for fusion

Daniele Torsello, Giuseppe Celentano, Leonardo Civale, Valentina Corato, Michael Eisterer, Davide Gambino, Samuel Murphy, Susannah Speller and Francesco Laviano

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Supercond. Sci. Technol. **37** (2024) 105008 (20pp)

Responsibility of small defects for the low radiation tolerance of coated conductors

Raphael Unterrainer, Davide Gambino, Florian Semper, Alexander Bodenseher, Daniele Torsello, Francesco Laviano, David X Fischer and Michael Eisterer

IOP Publishing
Supercond. Sci. Technol. **38** (2025) 015005 (14pp)

Beam heating explains critical current suppression measured during ion irradiation of REBCO tapes

A R Devitre, D X Fischer, N Riva, M Rae, L D Kortman, K B Woller, Z L Fisher, M P Short, D G Whyte and Z S Hartwig

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 3, MAY 2024 420610

3D Neutronic and Secondary Particles Analysis on $YBa_2Cu_3O_{7-\delta}$ Tapes for Compact Fusion Reactors

Federico Ledda, Daniele Torsello, *Member, IEEE*, Davide Pettinari, Simone Sparacio, Zachary Hartwig, Massimo Zucchetti, and Francesco Laviano

Cornell University
arXiv > cond-mat > arXiv:2506.17976
Condensed Matter > Superconductivity
[Submitted on 22 Jun 2025]

Threshold Displacement Energies of Oxygen in $YBa_2Cu_3O_7$: A Multi-Physics Analysis

Ashley Dickson, Mark R. Gilbert, Duc Nguyen-Manh, Samuel T. Murphy

OPEN ACCESS
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Supercond. Sci. Technol. **38** (2025) 015022 (14pp)

Local structure analysis of 300 keV He^+ irradiated REBCO coated conductor using polarisation dependent Cu K edge EXAFS

Jarrod C Lewis, Kirk Adams, William Iliffe, Matteo Aramini, Chris R M Grovenor, Rebecca J Nicholls, Sofia Diaz-Moreno and Susannah C Speller

Summary

- **Irradiation studies on superconductors have a long history:**
  - **Great papers to read!**
- **HTS radiation hardness in a fusion environment:**
  - **Complex, growing field**
  - **Need for material scientists, physicists, experimentalists, theoreticians, computationalists, engineers…**
  - **Highly dynamic, young community with great mentors**
- **For ECR:**
  - **Look for developing fields**
  - **Get involved!**
    - *https://www.esas.org/early-career-professionals*
    - *https://ieeecsc.org/ieee-csc-young-professionals*

Thanks for your attention!

February 2027,

Torino (Italy)

www.superfusion.org/iref27

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 61, Nov. 2025. Presentation given at EUCAS 2025, Porto, Portugal, Sept. 2025.