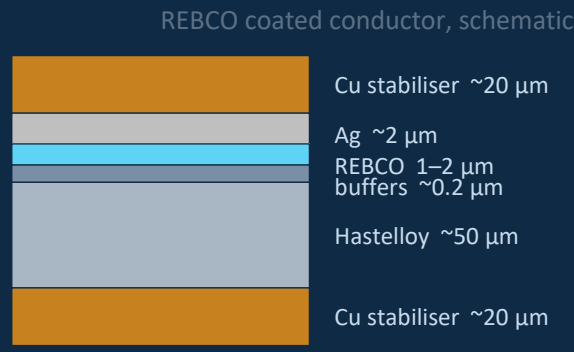
SPAS 2026 · SUPERCONDUCTIVITY IN FUSION TECHNOLOGY

Superconductors for fusion: the problems we have not solved

NbTi, Nb_3Sn and HTS conductors - delamination, joints, impregnation, stabilisation, and what happens when the neutrons stop



The superconductor is ~2 % of the tape.

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IFJ PAN, Kraków · 20-22 October 2026

WHERE WE ARE

Fusion became a magnet problem

ITER - the large, low-field route

- New 2024 baseline: start of research operations 2034, D-T deferred to 2039
- Nb_3Sn in TF and central solenoid, NbTi in the poloidal field coils
- ~5.3 T on axis, 51 GJ stored in the TF system

SPARC - the compact, high-field route

- ~80 % assembled as of July 2026; all 18 TF magnets due in place by end of summer 2026
- REBCO, 12.2 T on axis, 1.85 m major radius
- ~1/40 of the ITER plasma volume, designed for net energy

$$P \propto \beta^2 B^4$$

Fusion power density scales as the fourth power of the field. Doubling B buys a factor of sixteen - or lets the same physics fit in a machine a fraction of the volume.

That is why the machine got smaller: not a plasma result, a conductor decision.

The consequence for this room: fusion has just made itself dependent on REBCO, at scale, in a radiation field - and inherited every problem you already know from accelerator magnets.

LTS

The low-temperature conductors, and where they stop

	NbTi	Nb_3Sn
Practical field, 4.2 K	~8-10 T	~15-20 T
Mechanical character	ductile, forgiving	brittle A15, wind-and-react
Strain sensitivity	weak	severe - Ic falls sharply beyond ~0.3 %
Joints	superconducting, routine	resistive in practice
In ITER	poloidal field coils	TF and central solenoid
In accelerators	LHC main ring	HL-LHC MQXF, FCC 16 T programme

The activation problem

$^{93}Nb\ (n,\gamma)\ ^{94}Nb$

$T½ \approx 2 \times 10^4$ years, strong gamma emitter. Both niobium conductors carry it, and Nb_3Sn carries more Nb.

And the design fluence

The ITER design limit for Nb_3Sn is 10^{22} n/m² at E > 0.1 MeV. That number sets shield thickness - and therefore machine radius and cost. It is an extrapolation from fission-spectrum data.

HTS

Two ways to go above 20 T

REBCO - coated conductor tape

- Highest Jc in high field of any practical conductor; the enabling material for compact fusion
- But it is a laminate, not a wire: Hastelloy substrate, oxide buffers, 1-2 µm of REBCO, silver, copper
- Strongly anisotropic mechanically and electromagnetically
- Cabling is hard; joints are harder; screening currents distort field and add stress

Bi-2212 - round wire

- The only HTS available as an isotropic round wire - it can be made into Rutherford cable
- Melt-processed joints are feasible, which REBCO cannot yet match
- Pushed largely by the accelerator magnet community rather than by fusion
- Cost: overpressure heat treatment near 890 °C in oxygen, after winding

The choice is not "which has the higher Jc". It is which set of engineering problems you prefer to own.

LOW ACTIVATION

$Mg^{11}B_2$: chosen for what it does not become

Why it is attractive at all

- Tc ≈ 39 K, practical operation at 15-25 K - cryogenics without liquid helium
- Cheap, light, mechanically far more forgiving than a coated conductor
- Activation-wise the most attractive superconductor available - provided the boron is right

Where it actually belongs

- Not in a toroidal field coil: Jc collapses above roughly 5 T at 20 K (~10 T at 4.2 K)
- Current leads, feeders, cold-powering links, low-field auxiliary and correction coils
- The niche is real, and in a fusion plant it is not a small one

The isotope is not a detail

Natural boron is 19.9 % ^{10}B, and **$^{10}B(n,\alpha)^{7}Li$ has σ ≈ 3840 barn** at thermal energies. Inside a magnet that means helium generated within the conductor, local nuclear heating in the cold mass, lattice damage and loss of grain connectivity.

Enrichment in ^{11}B is therefore not an optimisation. It is a precondition - and isotope separation is what makes the conductor expensive.

And this room already runs it. The HL-LHC cold-powering links are MgB_2 - around 20 K, currents up to ~120 kA, over roughly 100 m. The technology is not speculative; the isotope specification is what fusion would add.

Caveat worth stating: magnesium is not inert either - $^{24}Mg(n,p)^{24}Na$ gives a 15 h emitter with 1.37 and 2.75 MeV gammas. The low-activation claim needs qualifying, not abandoning.

MECHANICS

Delamination: the number that governs REBCO windings

> 700 MPa

Longitudinal tensile strength of the tape - excellent, and the number usually quoted

10-50 MPa

Transverse (peel) strength perpendicular to the tape face, depending on architecture

~100 ×

The anisotropy between the strong and the weak direction of the same conductor

Where the transverse stress comes from

- Differential thermal contraction against a rigid impregnant on cooldown
- Hoop stress and radial Lorentz loading in pancake windings
- Screening currents in the tape - a field-quality problem in accelerators, a stress problem here
- Steep thermal gradients during a quench

And it couples to irradiation

Emhofer and Eisterer at the Atominstitut measured the stress dependence of Ic in coated conductors after irradiation to the ITER design fluence of 10^{22} m^{-2}. The mechanical limit and the radiation limit are not independent problems.

In a REBCO fusion coil the binding constraint is usually mechanical, not electromagnetic. Jc is not what limits the design.

MATERIALS

Impregnation: the resin is often the lifetime limit

System	Dose to failure	Character
Epoxy (e.g. CTD-101K)	~10 MGy	Standard for Nb_3Sn: ITER, HL-LHC MQXF. Rigid, strong, and a delamination hazard for HTS
Cyanate ester blends	~50-100 MGy	The usual answer when dose is the constraint; more expensive, harder processing
Polyimide, inorganic	higher	Best radiation tolerance, weakest mechanical integration

How the resin fails

- Chain scission and cross-link breakdown; gas evolution inside a sealed winding
- Loss of interlaminar shear strength - the winding stops behaving as one body
- Embrittlement, then cracking on the next thermal cycle

The escape routes

If rigid impregnation is what tears REBCO apart, remove it - but each route costs something:

- No-insulation winding (Hahn, Iwasa): self-protecting, but slow charging and hard quench detection
- Paraffin wax: low stress transfer, little mechanical support
- Co-wound Kapton, deliberate release layers: controlled debonding by design

For HL-LHC and for a fusion TF coil the failure mode is the same: the organic material dies before the superconductor does.

JOINTS

Joints: solved, tolerated, and unsolved

NbTi

SOLVED

Genuinely superconducting joints are routine. Persistent-mode operation is standard practice.

Nb_3Sn

TOLERATED

Brittle, so joints are resistive lap joints in practice. ITER CICC joints target ~1-2 nΩ each - a heat load accepted, not eliminated.

REBCO

UNSOLVED

A ceramic requiring biaxial texture across the interface. Persistent-mode joints remain a research topic, not a fusion-ready technology.

Bi-2212

PROMISING

Melt processing allows genuine superconducting joints - the strongest single argument for keeping round wire in the picture.

And joints degrade under irradiation. Solder resistivity rises through transmutation, and that component does not anneal out on warm-up. A joint specified at 1 nΩ does not stay a 1 nΩ joint. This room needs no reminder of what one bad interconnect can do to a machine.

STABILISATION

Copper: two damage mechanisms, one of them permanent

1 Displacement damage

Frenkel pairs collapse RRR immediately - but recover on warm-up to room temperature (recovery stages I-III). This is why periodic warm-up cycles are part of the ITER magnet plan.

2 Transmutation

Cu → Zn, Ni, Co accumulates monotonically and never anneals. This is the component that actually sets magnet lifetime - and the one a post-irradiation measurement on a warmed-up sample cannot separate from the first.

A caveat worth stating

In a 12–20 T magnet, magnetoresistance has already degraded copper's effective conductivity through Kohler's rule. The marginal value of high RRR is partly masked in exactly the high-field magnets we care most about - so the bare RRR degradation numbers overstate the operational penalty.

Activation, for completeness

$^{63}Cu(n,\gamma)^{64}Cu$ (12.7 h) · $^{63}Cu(n,2n)^{62}Cu$ (9.7 min) · trace $^{59}Co(n,\gamma)^{60}Co$ (5.27 y)

Aluminium is the low-activation alternative, at the cost of mechanical strength.

IRRADIATION

What we thought we knew about REBCO under neutrons

The established, ex-situ picture

- At low fluence, fast neutrons improve Jc: nanoscale collision cascades act as pinning centres
- The enhancement persists to roughly 1-2 × 10^{22} n/m^2 above 10 T before degradation sets in
- Tc falls at roughly 0.024 per mdpa
- Tapes with artificial pinning centres begin degrading earlier - the tape optimised for today's Jc is the fragile one
- Almost all of it measured in a fission spectrum, without field, without stress, and after warming the sample to room temperature

Every one of those measurements has a step in common.

The sample was warmed up before it was measured.

If part of the damage anneals below room temperature - as we know it does in copper - then the measurement has already destroyed what it was meant to record.

IRRADIATION

The first in-beam measurement, 2026

Oxford, published February 2026: the first in-situ measurement of a REBCO coated conductor during neutron irradiation. 14 MeV neutrons, fluxes to 7.3×10^{7} n cm^{-2} s^{-1}, tape carrying current at 40 K, voltage recorded while the beam was on.

1. **No sudden loss of superconductivity** but Ic fell linearly with fluence, at 0.03 A per 10^{12} n cm^{-2}, with thermal explanations excluded

2. **Degradation began orders of magnitude earlier** than the critical fluences the ex-situ literature had led everyone to expect

3. **And it recovered completely on warming to room temperature** which is precisely why forty years of post-irradiation measurement never saw it

The conclusion drawn by the authors:

REBCO magnet service lifetimes may be substantially shorter than current projections.

Every compact high-field fusion design now under construction rests on the older number.

This is not a small correction to a materials database. It is a lifetime assumption for machines already being built.

Supercond.Sci.Technol. **39** (2026) 02LT01

BEYOND D–T

And if we stop making neutrons?

What the candidates actually offer

- D-^{3}He: only partly aneutronic, and ^{3}He is essentially absent on Earth (~35 kg planetary inventory)
- p-^{11}B: genuinely aneutronic, three alphas, 8.68 MeV - about 10 MeV less than D-T, with abundant fuel

Where it stands

- TAE: ~75 million K for ~30 ms, still well short of p-^{11}B requirements
- Helion: Polaris running D-T as of February 2026, to validate scaling toward a D-^{3}He cycle
- The Coulomb barrier and bremsstrahlung losses remain the central obstacles

What it changes for the magnet designer

Gained: no activation, no ^{94}Nb waste problem, no thick neutron shield, no irradiation-driven lifetime limit. Niobium conductors become acceptable again on waste grounds.

Lost: a far harder triple product, so the field requirement rises rather than falls. You become ***more*** dependent on REBCO, not less. Bremsstrahlung X-rays still attack the insulation. And delamination becomes the single binding constraint, with nothing else to blame.

A small irony: p-^{11}B needs enriched ^{11}B as fuel, and $Mg^{11}B_2$ needs the same enrichment as a conductor - for opposite reasons.

CONCLUSION

The conductor is not the limit

1	**Delamination**	A hundredfold anisotropy between the strong and weak directions of the tape
2	**Impregnation**	Organic material that fails at 10-100 MGy, long before the superconductor does
3	**Joints**	Unsolved for REBCO, and degrading under irradiation in a way that does not anneal
4	**Stabiliser**	Copper whose transmutation component accumulates permanently

And every one of these is measured today on samples that were warmed to room temperature first.

In a fusion magnet the superconductor is about two per cent of the conductor.

Almost every lifetime-limiting mechanism lives in the other ninety-eight per cent - and in the interfaces between them.

That is also true of your accelerator magnets. Fusion is simply meeting it first, at higher dose.

KRAKÓW → MADRID

What follows from this

The measurement that is missing

Nobody can currently irradiate a superconducting component in a fusion spectrum, at 4 K, and measure it without warming it up. The in-situ result shows that this is not a refinement - it is the difference between two answers that differ by orders of magnitude.

The proposal

An Advanced Superconducting Components and Materials Laboratory at IFMIF-DONES: conductors, joints, impregnation and sub-scale coils irradiated and measured at 4.2 K, in beam, under remote control - with IFJ PAN among the partners.

[VARIANT A]

Presented in Madrid last week

The proposal was put to the DONES workshop and received a positive response. A conceptual design study is now being prepared jointly with the DONES Test Systems team.

What we need next is exactly what is in this room: conductor specialists, cryogenic engineers and irradiation expertise.

Andrzej Zaleski · ILT&SR PAS Wrocław · a.zaleski@intibs.pl — *Thank you.*

BACKUP

Backup: activation of magnet materials

Element / material	Key product	Half-life	Comment
Nb (NbTi, Nb_3Sn)	^{94}Nb via (n,γ)	~2×10^4 y	Strong gamma; the dominant long-term problem for both LTS conductors
Nb	^{92}Nb ground state	3.5×10^7 y	Very long-lived; ^{92m}Nb (10.15 d) decays by EC to ^{92}Zr
Cu	^{64}Cu, ^{62}Cu	12.7 h, 9.7 min	Short-lived; the engineering issue is transmutation to Zn/Ni, not activity
Co (trace impurity)	^{60}Co via (n,γ)	5.27 y	Catastrophic for maintenance; drives low-Co specification of Hastelloy
Fe	^{56}Mn (n,p), ^{59}Fe	2.58 h, 44.5 d	Acceptable long-term - the basis of RAFM steels such as EUROFER
Al	^{24}Na (n,α), ^{27}Mg (n,p)	15 h, 9.5 min	Low-activation stabiliser alternative to copper
Mg (in MgB_2)	^{24}Na via (n,p)	15 h	Hard gammas at 1.37 and 2.75 MeV - less benign than often stated
^{10}B (natural boron)	(n,α) to ^{7}Li	—	σ ≈ 3840 barn thermal: He production and local heating; hence ^{11}B enrichment
Gd, Sm, Dy (in REBCO)	various	—	σ up to ~10^5 barn for ^{155}Gd, ^{157}Gd - Y is the benign rare earth

Cross-sections quoted at thermal energies where relevant. At a magnet position the spectrum is degraded but not thermalised, so the effective penalty depends on shield design.

BACKUP

Backup: sources

- K. Adams, J. R. Winger, J. C. Lewis, C. Cazzaniga, C. Frost, M. Kastriotou, W. Iliffe, C. R. M. Grovenor, S. C. Speller, "The performance of REBCO coated conductor during in situ cryogenic irradiation with fusion-spectrum neutrons", Supercond. Sci. Technol. **29** (2026) 021T01, doi:10.1088/1361-6668/ae4548.
- J. Emhofer, M. Eisterer, H. W. Weber, "Stress dependence of the critical currents in neutron irradiated (RE)BCO coated conductors", Atominstitut, TU Wien; Supercond. Sci. Technol. **26** (2013) 035009, doi:10.1088/0953-2048/26/3/035009.
- Yuxiang Li, Ningning Liu, Ziheng Guo, Liangkang Chen, Dongliang Gong, Dongliang Wang, Yanwei Ma, "Irradiation-induced defect engineering in REBCO coated conductors: mechanisms, effects and perspectives", Materials **19**(2) (2026) 300, doi:10.3390/ma19020300.
- Holly Jane Campbell, Yifei Zhang, Toru Fukushima, "Probing evolution of the flux-pinning landscape in REBCO coated conductors caused by gamma irradiation", J. Supercond. Nov. Magn. **37** (2024) 41-55, doi:10.1007/s10948-023-06663-9
- A.Loarte et al., ITER Organization, 2024 project baseline: start of research operation 2034, D–T operation 2039. Plasma Physics and Controlled Fusion, **67** (2025) 065023, doi: 10.1088/1361-6587/add9c9.
- Rui F, Vieira et al., IEEE Trans. On Appl. Supercod. **34** (2024) 0600615, doi:10.1109/TASC.2024.3356571 (Commonwealth Fusion Systems, SPARC assembly status and 20 T TF model coil (2021, 2026)).
- Irfan Maulana Ahmad, Abd. Djamil Husin, Duong Thanh Tai, Nissren Tamam, Abdelmoneim Sulieman, Sitt Yani, “Evaluation of the Lawson criterion for aneutronic proton-boron 11 fusion: effects of ion temperature and bremsstrahlung losses”, Frontiers in Nuclear Engineering (2026), doi:10.3389/fnuen.2026.1714531.
- IFMIF-DONES Test Systems and Complementary Experiments design papers, Nucl. Fusion / Fusion Eng. Des. (2022–2026). (Raquel Roman, David Jimenez, Maria Luque, Beatriz Branas, Moises Weber, the Eurofusion WPENS Team, Fusion Energy and Design **230** (2026) 115828, doi:10.1016/j.fusengdes.2026.115828).