IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 63, Mar. 2026. Presentation given at ISS 2025, Nagasaki, Japan, Dec. 2025.

ENEA | ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

High-current HTS cables for fusion: development status and prospects

38th International Symposium on Superconductivity (ISS2025)
Nagasaki (Japan)

Luigi Muzzi
Superconductivity Laboratory / Fusion Energy Development Division

Acknowledgements

- Gabriele Colombo – Andrea Masi – Gianluca De Marzi – Achille Angrisani Armenio – Giuseppe Celentano – Valentina Corato – Antonio della Corte – Aldo Di Zenobio – Simonetta Turtù: ENEA Superconductivity Lab. & ICAS
- Marco Breschi: University of Bologna
- Chao Zhou – Jinxing Zheng: Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP)
- Nagato Yanagi: National Institute for Fusion Science (NIFS)
- Nikolay Bykovskiy: Swiss Plasma Center - EPFL
- Arend Nijhuis: University of Twente
- The many here unlisted colleagues and friends around the world, with whom I had the opportunity to share experience, ideas, challenges, disappointment and enthusiasm!

Content of the talk

- **Fusion:** «pulling» application for superconducting technologies
- **HTS** for fusion: opportunities and possible approaches
- From high-current / high-field **LTS** Cable-in-Conduit Conductors

  … to the HTS cable technologies for Fusion
- Prototype development: some selected examples
- Quench behaviour of HTS cables
- Industrial maturity
- Concluding remarks

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2. Introduction to REBCO high-current / high field cables

3. Development status, open issues, industrial maturity

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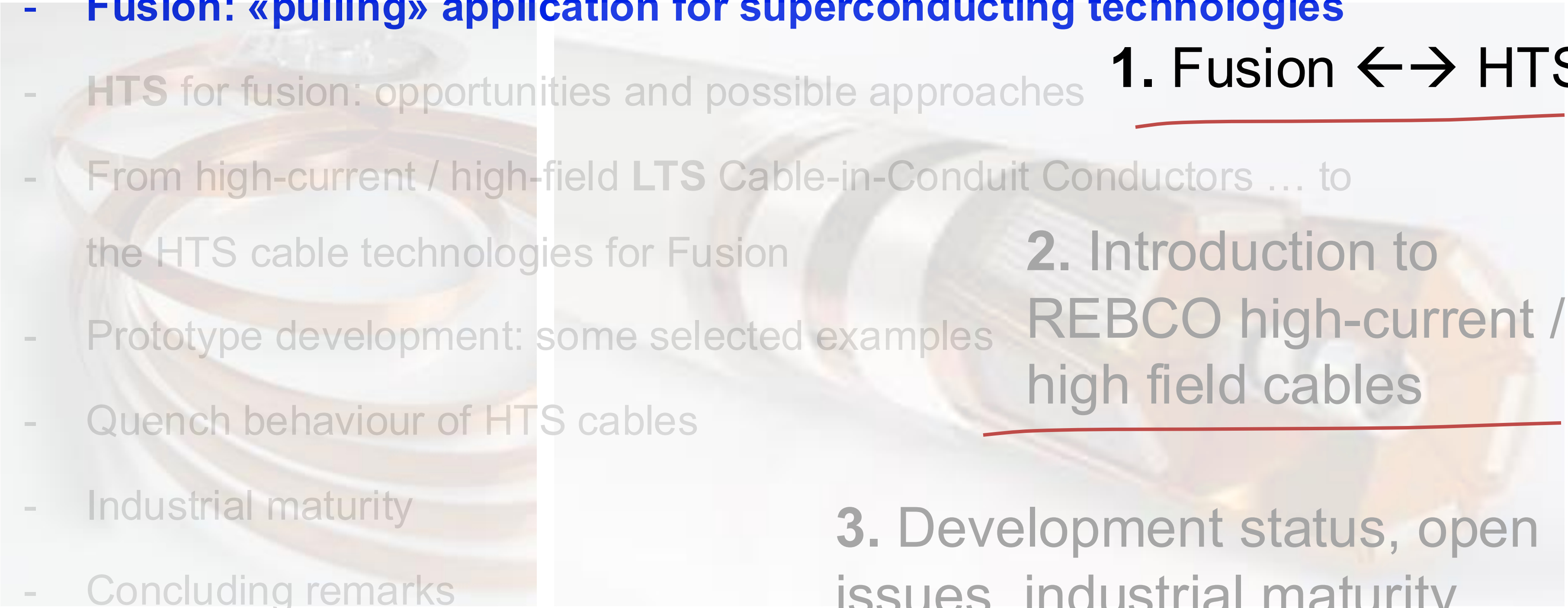

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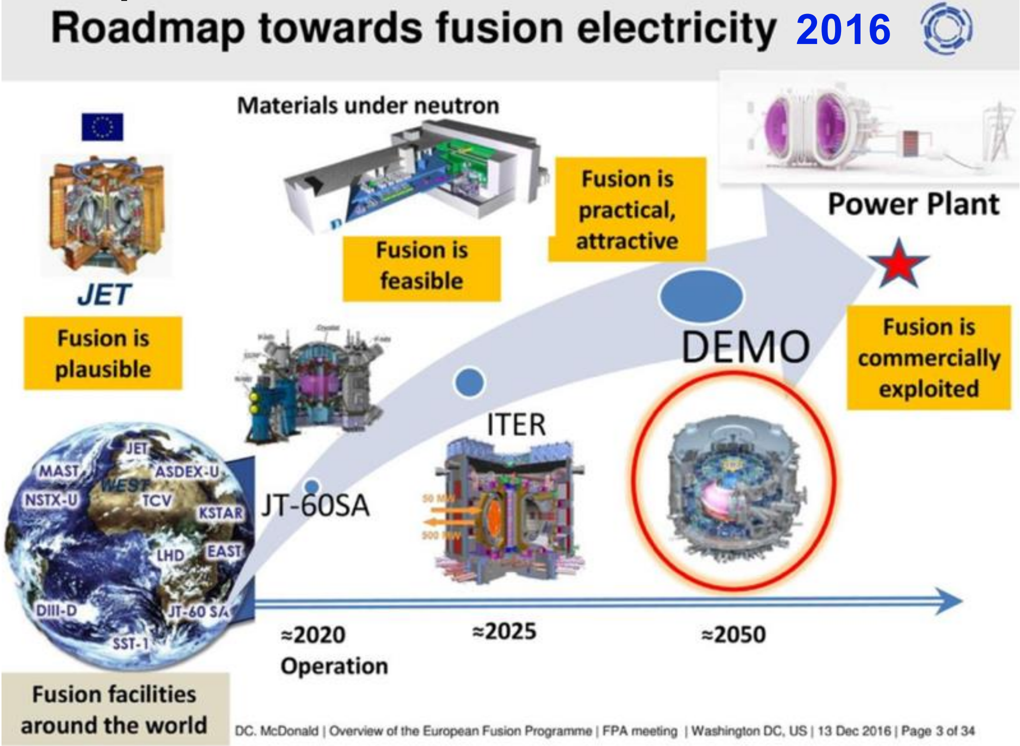
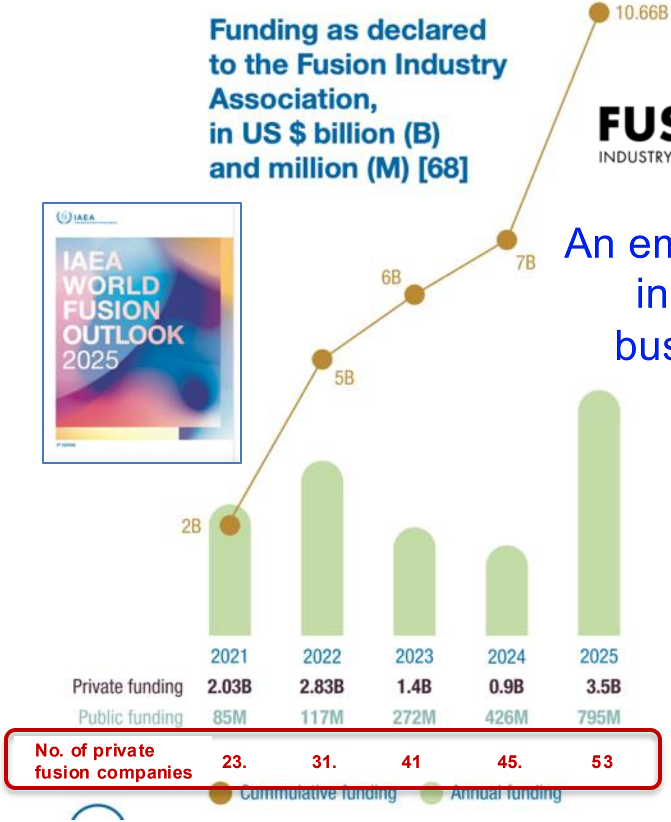
The Fusion «momentum». Evolution of the landscape

from a few, publicly run projects …

European



…. to private actors entering the stage



An emerging industrial business?

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The Fusion «momentum». Evolution of the landscape: public-private partnerships

INFUSE

Energy Department Announces $134 Million to Advance U.S. Fusion Leadership Through Targeted Research

Public-private partnership

UK Atomic Energy Authority

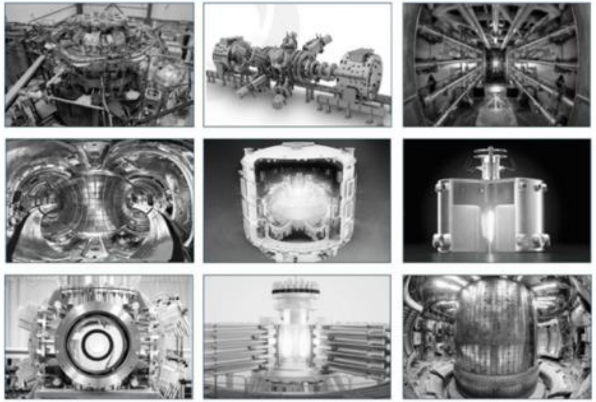
STEP's goal is a pathway to commercial viability of fusion. We need commercial partners to succeed.

THE CHANGING FUSION LANDSCAPE

ITER hosting private sector workshop

21 MAY 2024 - LABAN COBLENTZ, HEAD OF COMMUNICATION   Print   Read the latest published articles

Take out your smart phone and search your favourite news site for "nuclear fusion" or "fusion energy." On any given day, you will find articles discussing breakthroughs or innovative approaches to fusion. Dig deeper: you will find that the fusion projects under discussion are a mix of public and private initiatives—unique, because both sectors are still in the R&D phase. Not infrequently, you will find the current state of fusion characterized as a "competition" between public enterprises such as ITER and emerging private sector initiatives.



iter
china eu india japan korea russia usa

The ITER Organization is hosting an inaugural Private Sector Fusion Workshop from 27 to 29 May. The outcomes from the workshop will help to establish priorities and formulate plans for how ITER will engage with private sector fusion companies going forward.

NEWS ANNOUNCEMENT | 7 March 2024 | Directorate-General for Energy | 1 min read

New Commission study on potential public-private partnership approach to foster innovation in fusion energy

European Commission

GO4FUSION | BUILDING A EUROPEAN FUSION ENERGY PARTNERSHIP

EnF EnableFusion Inc. (주)인애이블퓨전

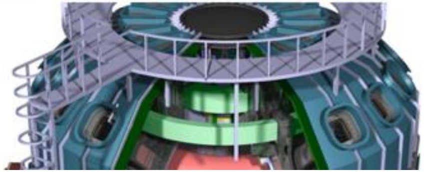
Korean Public-Private Partnership (K-PPP) for Fusion Development

FUSION WORLD

Public/private consortium is building the DTT tokamak

18 MAR 2024 - JACK MOORE   Print   Read the latest published articles

The Divertor Test Tokamak in Italy is creating a new model for engagement with industry in fusion research. ITER helped to pave the way.



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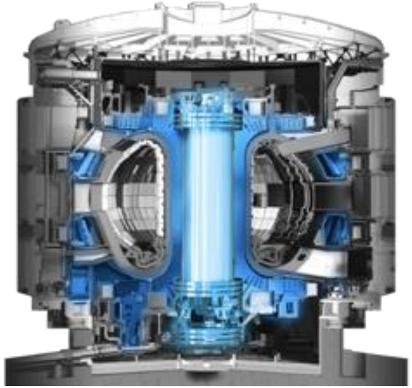
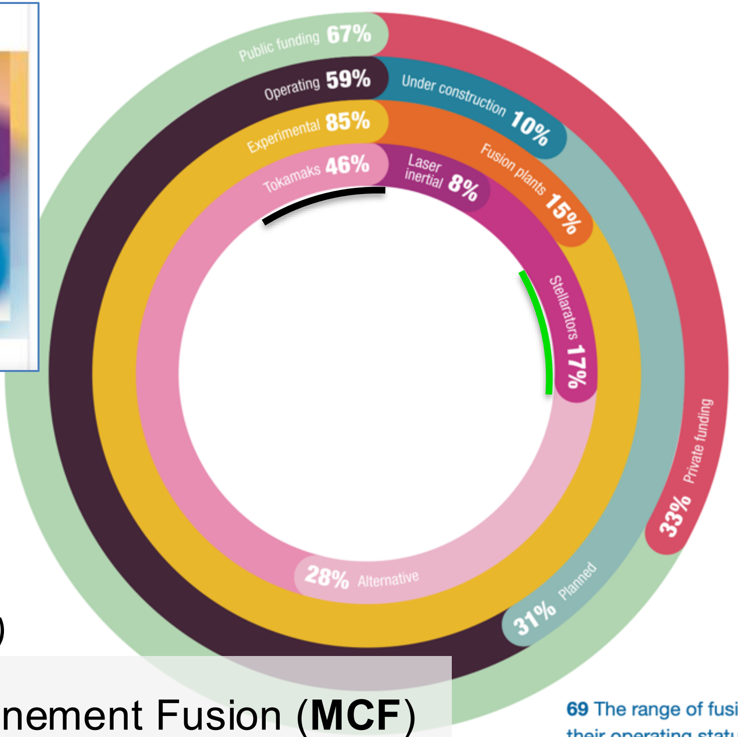
Fusion and superconducting technologies



e.g. ITER



69 The range of fusion devices, their operating status and ownership (public vs private funding) in 2025 [67].

46%: Tokamaks
(MCF pulsed machines)

17%: Stellarators
(MCF steady-state machines)

e.g. W7-X

Magnetic Confinement Fusion (**MCF**) relies on **superconducting** magnets

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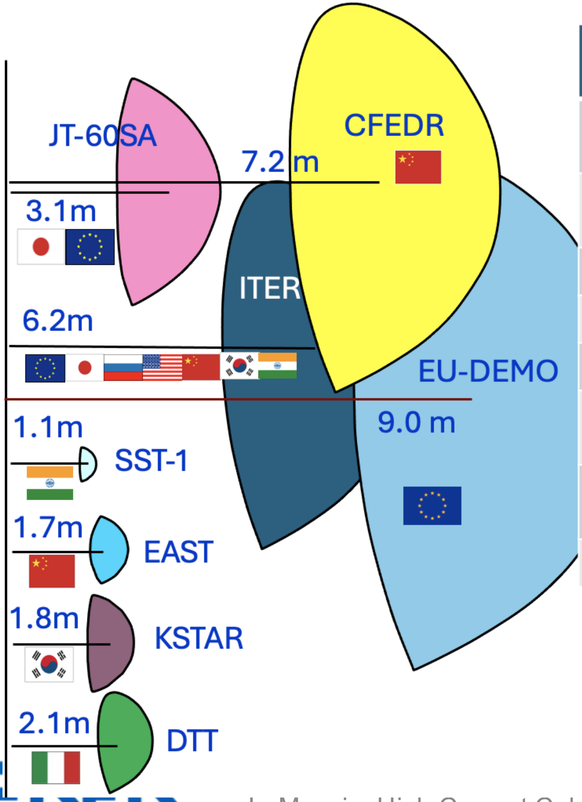
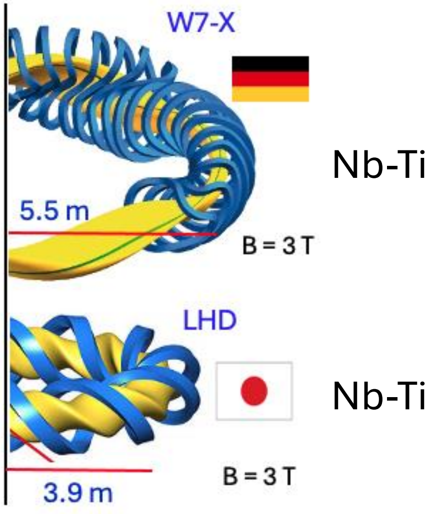
What Superconductor type in fusion (*so far*)?

Recent generation of superconducting tokamaks / stellarators use Nb-based materials:



	$B_{toroidal}$ (T)	I_{plasma} (MA)	Superconductor
JT-60SA	2.25	5.5	TF – PF: Nb-Ti CS: Nb_3Sn
ITER	5.3	15.0	PF: Nb-Ti TF – CS: Nb_3Sn
DEMO	5.2	17.9	Hybrid Nb-Ti / Nb_3Sn
SST-1	5.5	0.22	Nb-Ti
EAST	3.5	1.0	Nb-Ti
KSTAR	3.5	2.0	PF: Nb-Ti TF – CS: Nb_3Sn
DTT	6.0	5.5	PF: Nb-Ti & Nb_3Sn TF – CS: Nb_3Sn
CFETR	7.4	15	Hybrid Nb-Ti / Nb_3Sn



But with **LTS** the achievable magnetic field is limited at about **6 ÷ 7 T** and operational temperature at **4.5 K**.

Content of the talk

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Opportunities offered by the use of HTS in Fusion (wrt LTS-based approaches)

1. Possibility to work at higher temperature (10 ÷ 20 K, instead of 4.5 K)

- Evident decrease of operating costs
- Remarkable improvement in heat **absorption** capability
- Possibility to abandon Helium as a coolant?

Heat capacity

Superconductor Operating Temperature Range	⟸ NbTi(T_c=9.8 K) ⟹				
	⟸ MgB$_2$ (T_c=39 K) ⟹				
	⟸ YBCO (T_c=93 K)				
	$C_p(T)$ [J/cm^3 K]				
Material	2 K	4 K	10 K	20 K	30 K
Copper	0.00025	0.00089	0.0076	0.067	0.236
NbTi	0.00018	0.0014	0.022	—	—
MgB$_2$	0.000040	0.00032	0.00181	0.0081	0.0242
YBCO	0.000086	0.0007			0.120
Stainless steel	0.0014	0.003	0.01	0.04	0.1
Epoxy	0.00008	0.00066	0.014	0.080	
Helium @3 atm	—	0.47*	0.095*	—	—
Solid Neon	0.003	0.027	0.42	1.39	—
Solid Nitrogen	0.007	0.031	0.17	0.71	1.21

* Liquid (4 K) & vapor (10 K).

Iwasa, "Case studies in superconducting magnets"

BUT less effective Helium heat **removal** capability

At 6 bar	Density x Cp (kJ/K m^3)
4.5 K	**512.4**
10 K	**238.4**
20 K	**80.4**

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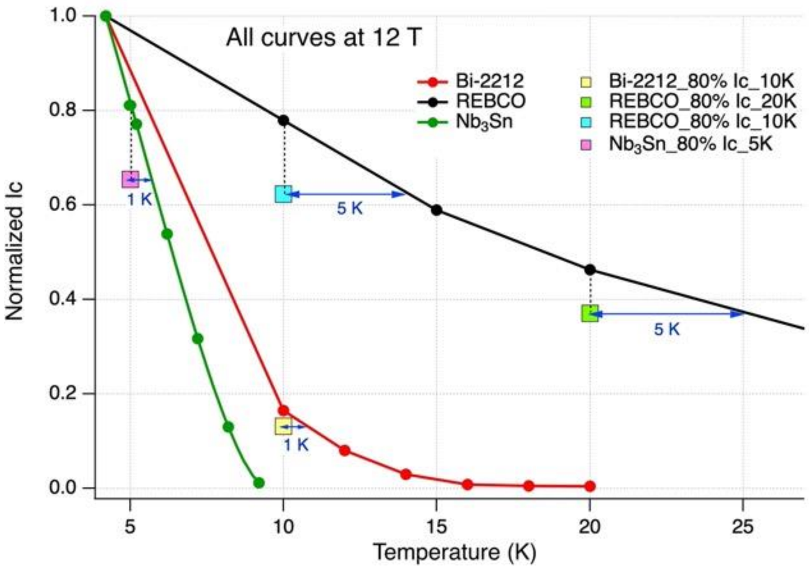

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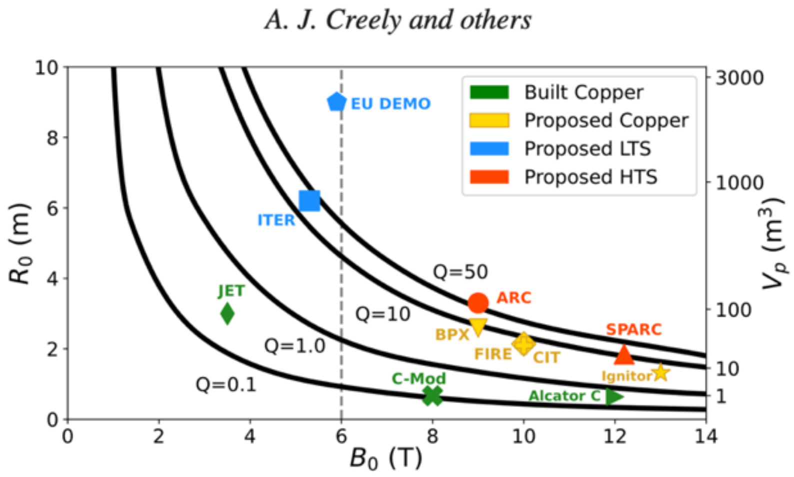
3. **Possibility to access higher magnetic fields** (> 15 ÷ 16 T)



Creely_J. Plasma Phys. 2020

ENERGY GAIN: (science feasibility) $$nT\tau_E \sim \frac{\beta_N H}{q^2} R^{1.3} B^3$$

POWER DENSITY: $$\frac{P_{fusion}}{S_{wall}} \sim \frac{{\beta_N}^2 \varepsilon^2}{q^2} R B^4$$

E. Salazar_2021

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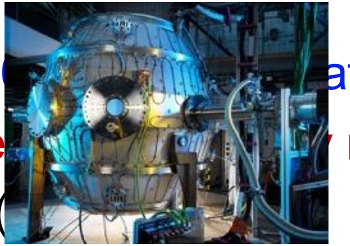
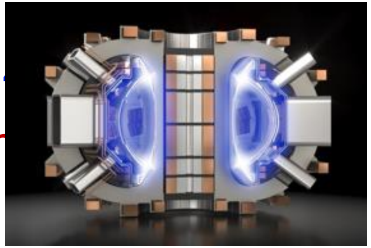
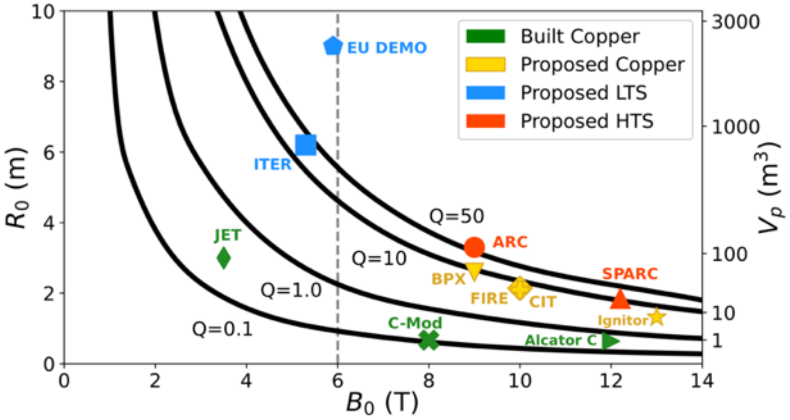


HTS Spherical Tokamak
https://tokamakenergy.com/



SPARC – Commonwealth Fusion Systems. https://cfs.energy/

A. J. Creely and others



Creely_J. Plasma Phys. 2020

HTS considered as a **Key Enabling Technology**

D. Whyte; J Fus Energy 2016

Affordable, **R**eliable, **C**ompact

"the possibility to access B > 20 T would be a "*game changer*" for fusion development"

→ More compact designs!

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BUT in large magnets with fields > 15 T mechanical **structures** are **demanding**.

Federici_Nucl. Fus. 2024

… as neutron fluence is, in compact reactors!

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Opportunities offered by the use of HTS in Fusion (wrt LTS-based approaches)

In Summary: HTS-based fusion coils. Might allow operation:

a) at higher temperature; b) with larger margin; c) at higher field

ENABLING or EXTENDING technology?

Substitute or Integrate **LTS**?

What most **start-ups** are aiming at, with aggressive roadmaps

THEA ENERGY · Commonwealth Fusion Systems · Helical Fusion · 能量奇点 ENERGY SINGULARITY · Tokamak Energy · TYPE ONE ENERGY · Proxima Fusion · GAUSS FUSION · RENAISSANCE FUSION

HH70: successfully achieved **first plasma** in **June 2024**

Approach mostly adopted in **projects driven by public fundings on larger-size reactors**

Hybrid LTS+HTS Central Solenoid systems adopted for BEST ; DTT ; EU-DEMO…

Burning plasma Experimental Superconducting Tokamak · EUROfusion

Which HTS Material? *(today!)*

MAIN requirements:

- J_{ENG}(T, B) in the requested range
- Mechanically robust material (*processing* + *operation stress*)
- large industrial production volumes
- ....

REBCO C.C.

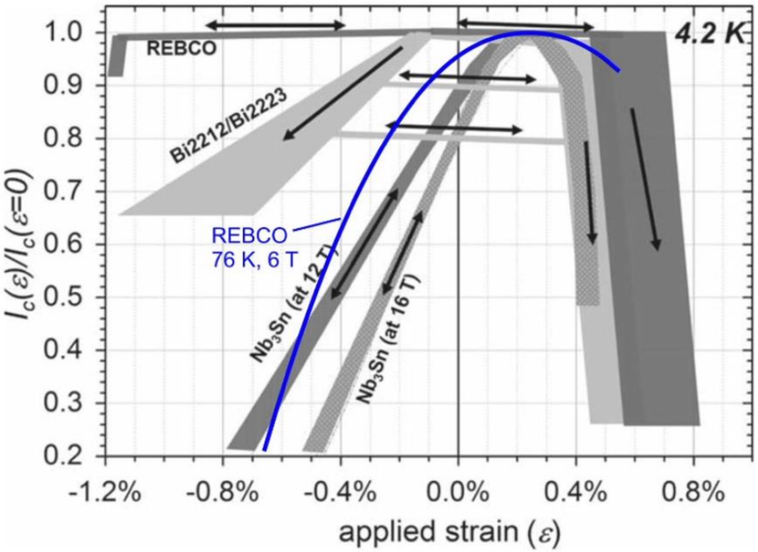
Bi-2212 **Wires**

Bi-2223 Tapes

Fe-based

REBCO has «good-enough» J_C performance (even at **20 K**)

Godeke_SUST 2023



REBCO:
$E_{TAPE} \sim 130 \div 150\ GPa$

Nb_3Sn:
$E_{WIRE} \sim 30 \div 40\ GPa$;

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Which HTS Material? → REBCO C.C. (tapes)

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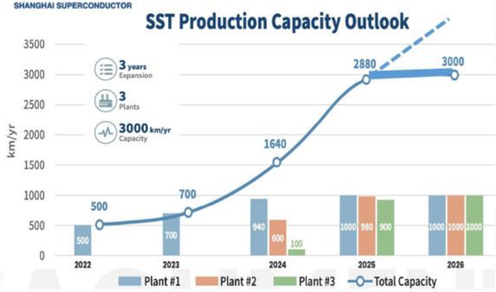
Fusion-driven expansion of REBCO production capacity

上海超导 SHANGHAI SUPERCONDUCTOR



1600 km_{12}/yr (2024) → 3000 km_{12}/yr (2026)

FARADAY FACTORY JAPAN

1300 km_{12}/yr (2024) → 25000 km_{12}/yr (2028)

SuperPower Inc. A Furukawa Company

200 km_{12}/yr (2024) → 1200 km_{12}/yr (2026)

THEVA

100 km_{12}/yr (2023) → 2500 km_{12}/yr (after 2025)

Senatore_Plenary at ICEC-ICMC 2024
(available at: https://snf.ieeecsc.org/)

high-field, compact fusion enabled by developments in HTS tape technology

industrial scale-up / price decrease / performance optimization of REBCO tapes stimulated by fusion requirements

Several Companies producing Coated-Conductors

FARADAY FACTORY JAPAN · 上海超导 SHANGHAI SUPERCONDUCTOR · SuperPower Inc. FURUKAWA ELECTRIC GROUP · SuNAM · THEVA · Fujikura

And many others coming... METOX · HTS · SUPREMA TAPE

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On the definition of high-current cables for fusion

I_{OP} = 30 kA ÷ 100 kA

ITER TF CICC @ TRATOS CAVI, ICAS, Criotec IMPIANTI S.r.l.





ITER TF Unit Length (**780 m)**






CABLING

JACKETING

iter china eu india japan korea russia usa

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CABLING

ITER CS

ITER TF

CICC: Cable-in-Conduit Conductor

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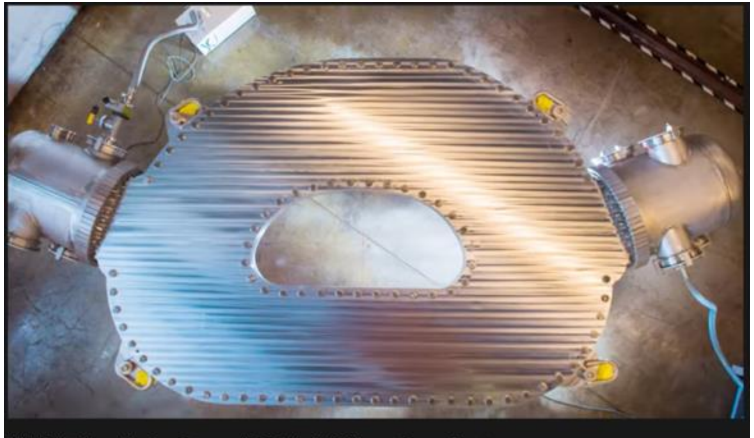
On the definition of high-current cables: DTW

Do all fusion coils use «cables»? → Not necessarily:

a new paradigm has emerged, with the introduction of HTS in fusion …

I call it: **No-insulation, Direct Tape Winding (DTW)** approach.

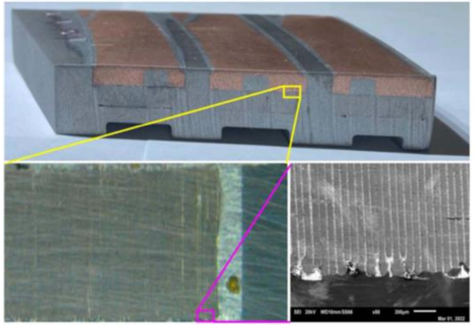
Non-twisted Stacks of tapes directly wound into magnet structure



Highlights from the Live-Streamed 20 Tesla HTS Magnet Demo Event

Commonwealth Fusion Systems

Vieira_IEEE TAS 24



From TE website

Tokamak Energy

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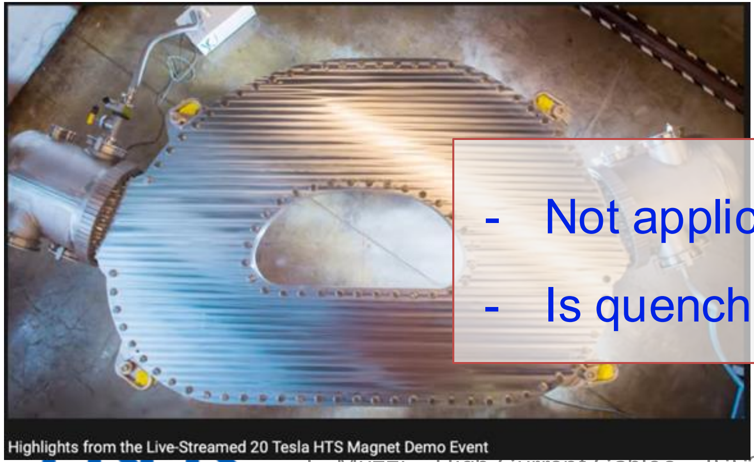


Vieira_IEEE TAS 24

From TE website

Tokamak Energy

- Not applicable to pulsed magnets
- Is quench management fully qualified?

Milestones on the path to the current development of LTS Cable-in-Conduit Conductors

The experience of ITER Nb_3Sn Cable-in-Conduit Conductors.

Development **strategy**:

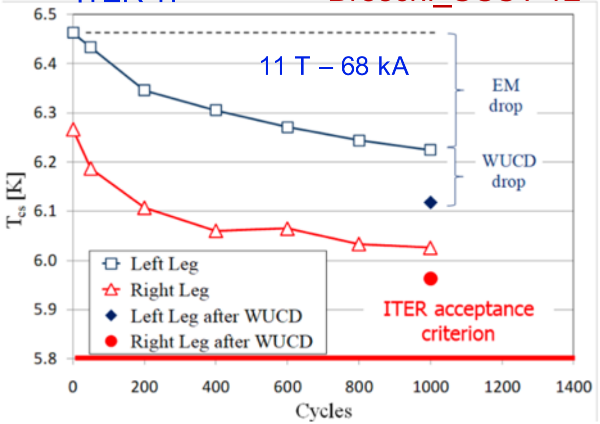
1. improve wire performance; stimulate scale-up of industrial production.

    BUT: neglecting or deferring parallel cable/conductor development led to performance issues.

    → **degradation** with e.m. and thermal loading cycles

ITER TF

Breschi_SUST 12



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Root cause: filament fracture

Post-mortem metallographic studies of tested CICCs

C. Sanabria - NHMFL

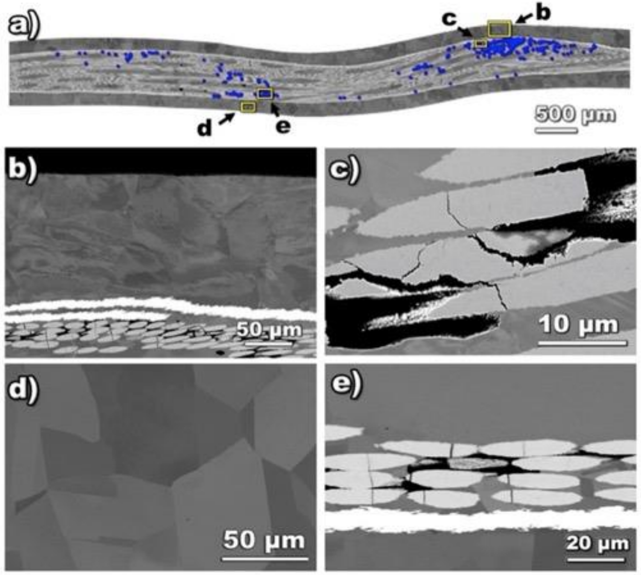

Figure 8. (a) This FESEM–BSE image of a longitudinal cross-section of an extracted strand (CSIO1-1, 'HP' side) shows two heavily damaged regions with different filament fracture morphologies (the locations of cracks are shown with digitally applied blue marks). Details in this image show (b) cold worked copper at a contact point with a neighboring strand or jacket, (c) cracks induced by contact stresses, (d) strain free copper grains, and (e) cracks induced by tensile stresses.

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Cured by: strategies to **reduce** strand **displacement:**

- optimizing cable twist pitches;
- limiting the void fraction in cable bundle.

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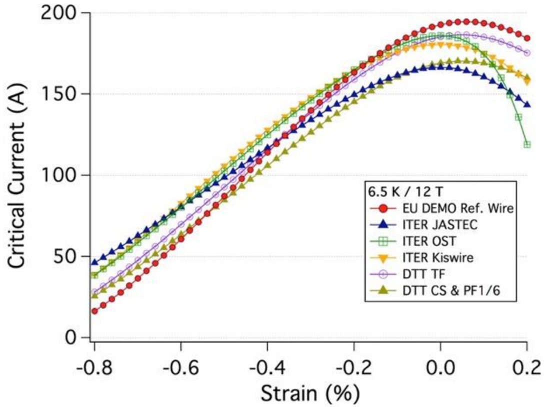
Root cause: filament fracture

Cured by: strategies to **reduce** strand **displacement**.

2. Different wires may behave differently,

   → a wire is **fully qualified** only after a CICC is demonstrated to satisfy requirements.

Strain sensitivity in different wires



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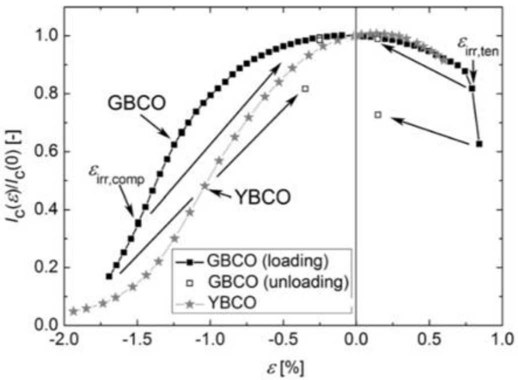
HTS Cables Design Principles

How to assemble flat tapes (rather than round wires)?

…. to guarantee:

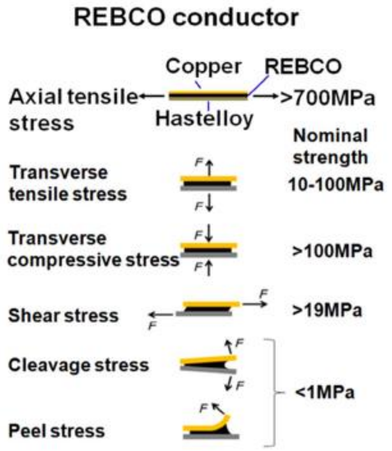
- Tens of kA current carrying capacity
- Effective cooling;
- Electrical and thermal stability;
- Some transposition between wires;
- Local current re-distribution;
- ……….



Van der Laan_SUST 2011

Considering that:

REBCO is also **brittle**, and **strain-sensitive,** it is a **R&W** material, and subject to mechanical **failure mechanisms**.



Maeda_IEEE TAS 2014

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HTS Cables Design Principles

How to assemble flat tapes (rather than round wires)?

…. **to guarantee:**

- Tens of kA current carrying capacity
- ~~Effective cooling;~~ → Indirect cooling possible
- Electrical and thermal stability;
- ~~Some transposition between wires;~~ → Twisting might be avoided …. Uglietti_Cryogenics 20
  … and anisotropy exploited in some coil geometries
- Local current re-distribution;
- ……….

Considering that:

REBCO is also **brittle**, and **strain-sensitive,** it is a **R&W** material, and subject to mechanical **failure mechanisms**.

consider the «lessons learned», **but** at the same time avoid being constrained by *design principles* of LTS cables, and be open to exploit the peculiarities of HTS

HTS Cables Design Principles

How to assemble flat tapes (rather than round wires)?

…. to guarantee:

- Tens of kA current carrying capacity
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- Electrical and thermal stability;
- ~~Some transposition between wires;~~ → Twisting might be avoided …. Uglietti_Cryogenics 20 … and anisotropy exploited in some coil geometries
- Local current re-distribution;
- …………

In addition

- **Bending** to "reasonable" diameters
- **Joints** / terminations feasibility
- **AC losses** management (in pulsed machines)

consider the «lessons learned», **but** at the same time avoid being constrained by *design principles* of LTS cables, and be open to exploit the peculiarities of HTS

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REBCO Cable Technologies for Fusion

(not exhausitve, and intentionally over-crowded)

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HTS Cable Technologies for Fusion

Investigated solutions can be categorized in:

Twisted stacked-tape — **MIT**, M. Takayasu

Takayasu_SUST 2012

Roebel-assembled — **KIT**, W. Goldacker

Goldacker_SUST 2014

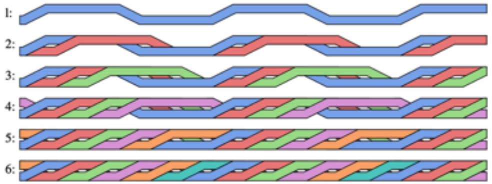


Figure 1.6: Assembly of a Roebel cable with six strands.

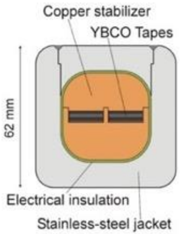
Conductor on Round Core (CORC®)

Van der Laan_SUST 2011

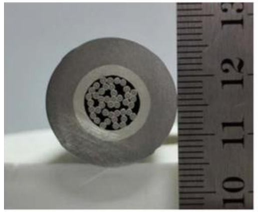
Advanced Conductor Technologies LLC
www.advancedconductor.com

Simple Stacking — **NIFS**, N. Yanagi

Yanagi_Cryogenics 2016



The **ASIPP** Bi-2212 CICC option



Qin_SUST 2017

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Content of the talk

- Fusion: «pulling» application for superconducting technologies
- **HTS** for fusion: opportunities and possible approaches
- From high-current / high-field **LTS** Cable-in-Conduit Conductors … to the HTS cable technologies for Fusion
- **Prototype development: some selected examples**
- Quench behaviour of HTS cables
- Industrial maturity
- Concluding remarks

1. Fusion ←→ HTS

2. Introduction to REBCO high-current / high field cables

3. Development status, open issues, industrial maturity

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Non-Twisted stacked cables: the STARS Conductor

2015 – 530 kN/m

Stacked Tapes Assembled in Rigid Structure (STARS): NIFS (Japan)
First proposal back in 2005 (initially with Bi-2223)

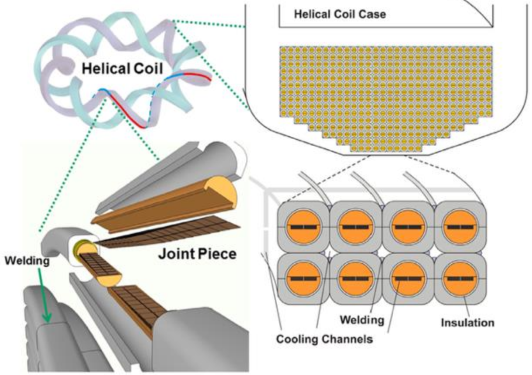
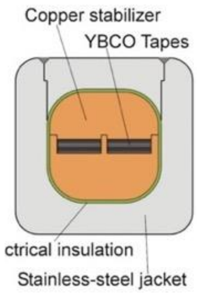
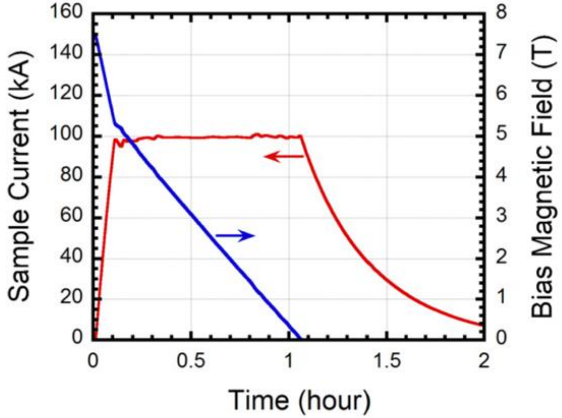


Figure 2. Schematic illustration of the FFHR-d1 helical coils with joint-winding of the segmented HTS conductors. The jointing work should be performed by slight lifting of the conductors.



Yanagi_Nucl Fus 2015

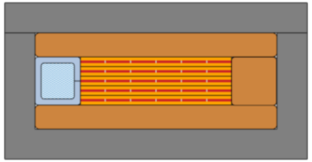
First experimental demonstration of a **100 kA HTS Cable** (@ 5.3 T / 20 K)



Recent similar solution:

LASSO

(Laminated stacked-tape soldered conductor)



EPFL SWISS PLASMA CENTER

Under consideration for the European **VNS** Tokamak

ENEA

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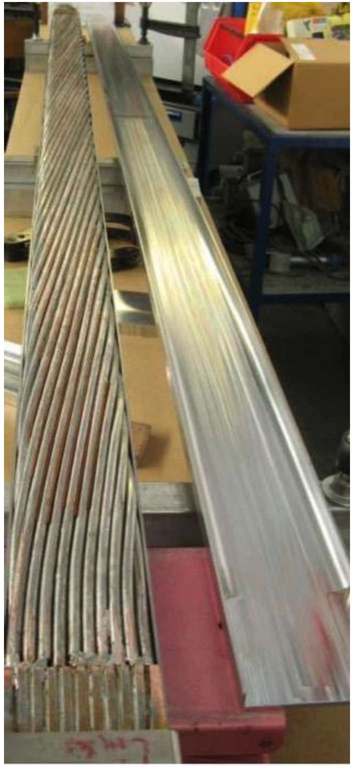
Cables based on stacked-tape «*macro-strands*»: the SPC flat conductor

2015 – 720 kN/m

Round Strand – «Rutherford-like» assembled

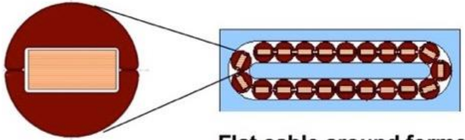
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER

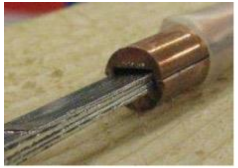


D. Uglietti_SUST 2015

Solder filled stack.
No-solder filling in conductor

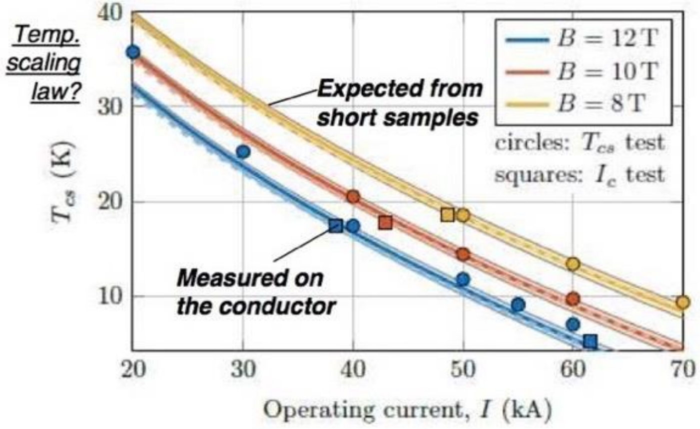


Flat cable around former

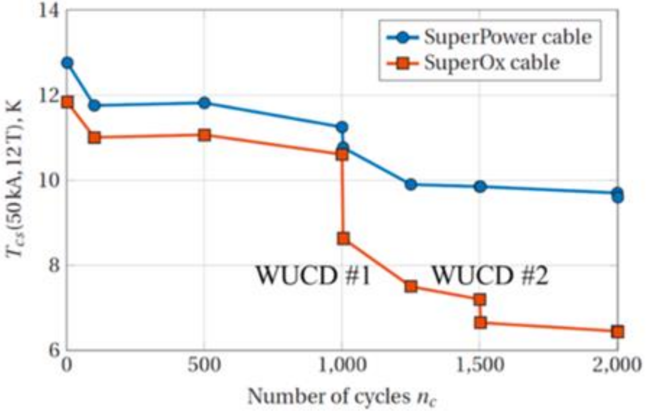


First exp. demonstration of a **60 kA Tw.** Stacked Tapes **CICC** @ 5K, 12T

Remarkable performance prediction capability



BUT: degradation with loading cycles



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Other cables with stacked-tape «*macro-strands*»

ASTRA: 2025 – 660 kN/m

Aligned Stacks Transposed in Roebel Arrangement (ASTRA) CICC – «Roebel-like» assembled

SWISS PLASMA CENTER

EPFL

N. Bykovskiy_SUST 2023

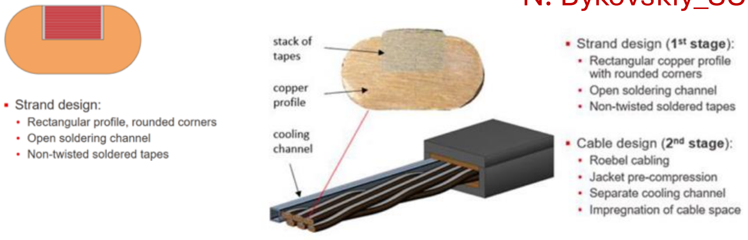
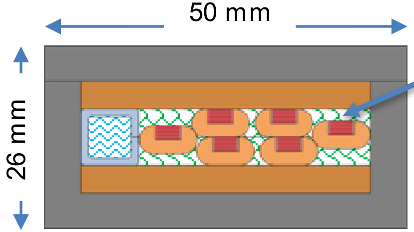


Fig. 4. ASTRA conductor layout for DEMO CS.

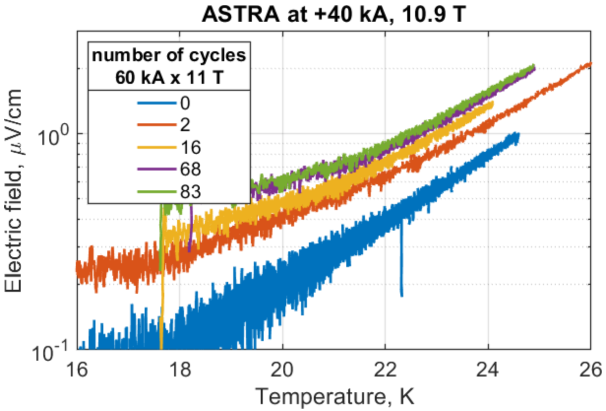
Solder filled stack.
DMSO impregnation in conductor



Cable space filled with aqueous DMSO impregnation

First tests showed degradation by e.m. loads up to 660 kN/m.

Likely due to voids in the soldered stack. Soldering method being improved.



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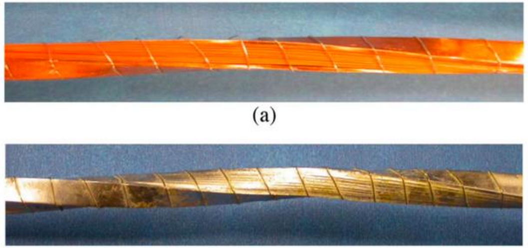
Twisted stacked tape conductor (TSTC)

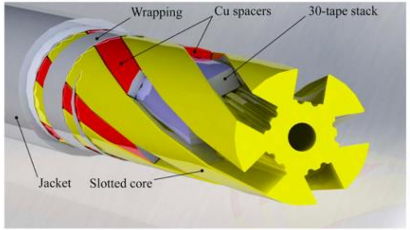
MIT – 2011
ENEA – 2014

Original proposal by MIT
Takayasu_IEEE TAS 2011


(a)
(b)

Then taken over by many. For example at ENEA:

Al-slotted core – TST conductor
Celentano_IEEE TAS 2014

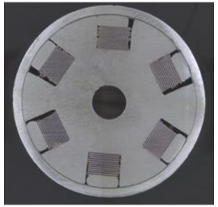


Industrial feasibility constantly kept as a design driver

Mostly developed in two versions:

5 HTS stacks

Target: 20 kA
@ 4.2 K - 12 T

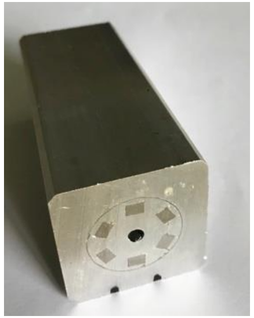


6 HTS stacks

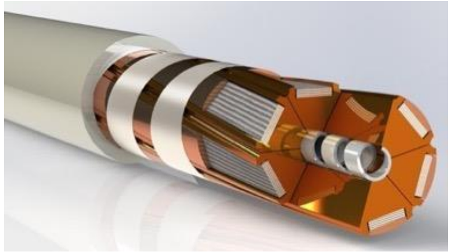
Target: 35 kA
@ 4.2 K - 18 T

No filling of tape slot

High-strength Al-alloy (*or steel*) jacket.
L = 36 mm
(target: 30kA - 18T)



BRAST-SECAS
Muzzi_IEEE TAS 23



Some performance degradation with thermal cycles

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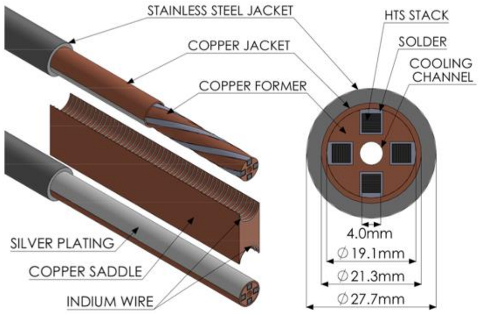
Twisted stacked cables: the VIPER Conductor

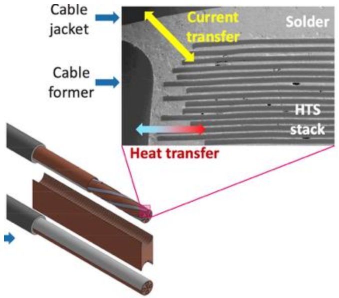
2020 – 382 kN/m

Vacuum pressure Impregnated, insulated, Partially transposed, Extruded, and Roll-formed (**VIPER**)

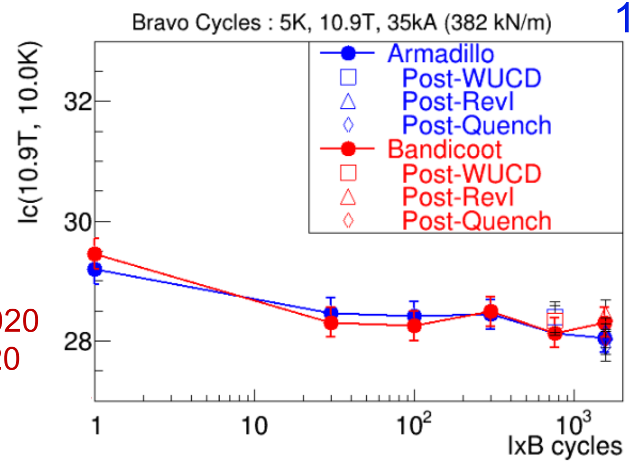
TSTC – type cable



First experimental demonstration of solder filling technique as an effective way to immobilize the tapes.



Hartwig_SUST 2020
Hartwig_ASC 2020



1 stack only

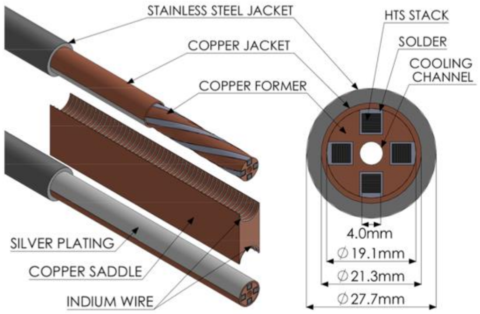
Fully relevant:
with solid, monolithic core, no load accumulation effect

< 4% degradation

Twisted stacked cables: the VIPER Conductor

2020 – 382 kN/m

Vacuum pressure Impregnated, insulated, Partially transposed, Extruded, and Roll-formed (**VIPER**)
TSTC – type cable



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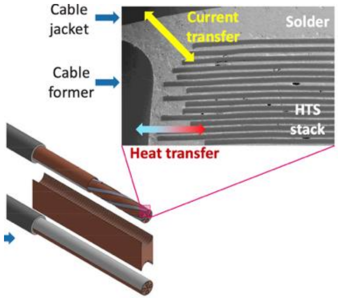
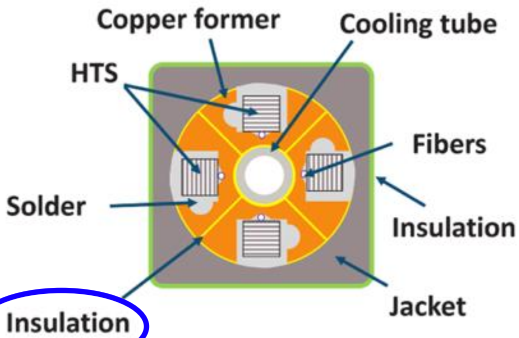
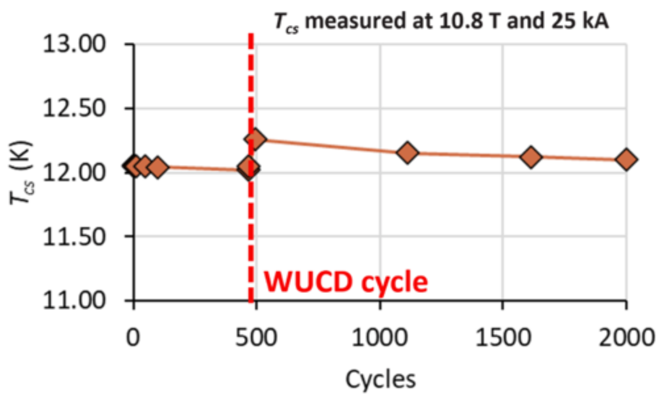




Partitionally Insulated and Transposed – VIPER

PIT-VIPER

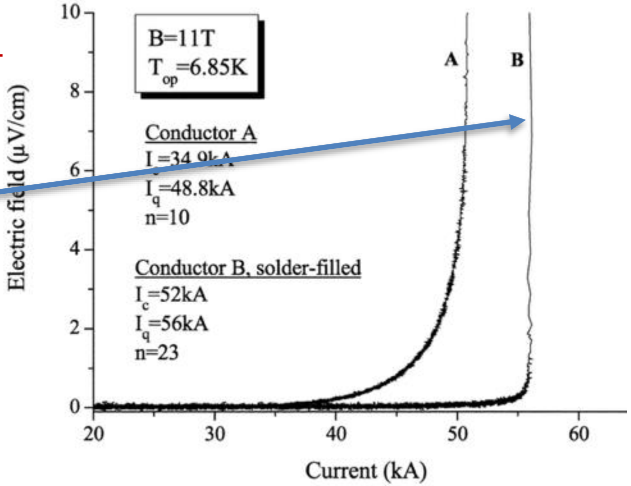
Sanabria_SUST 2024



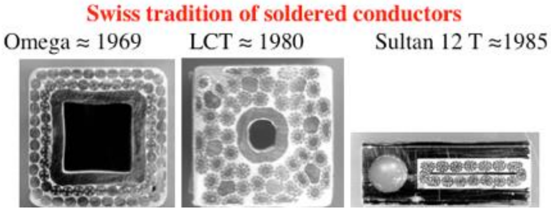
The approach based on solder-filling

To solder or not to solder?

Pasztor_IEEE TAS 04

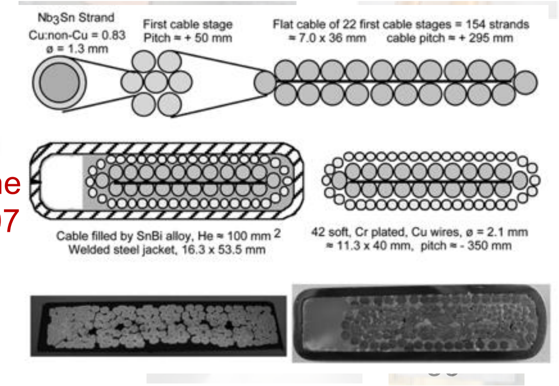


Solder-filling: effective to prevent Nb_3Sn strand movement in highly-loaded CICC → preventing performance degradation.



Bruzzone_IEEE TAS 06

Nicely applicable in HTS Conductors thanks to their high stability margin → «indirect» cooling.



Bruzzone
IEEE TAS 07

To be considered:

- Trade-off with **AC losses** requirements
- Possible **stress concentration** with a localized quench

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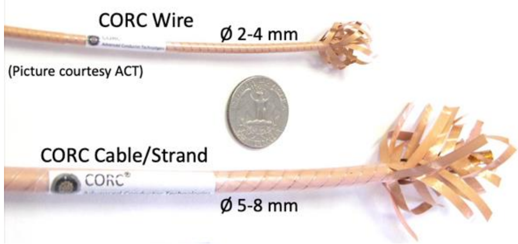
Wound tape cable concepts: CORC® - based

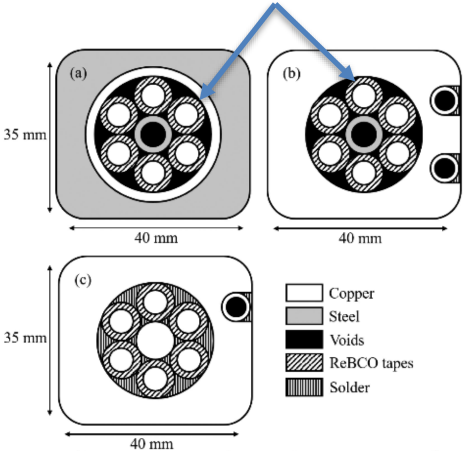
2016

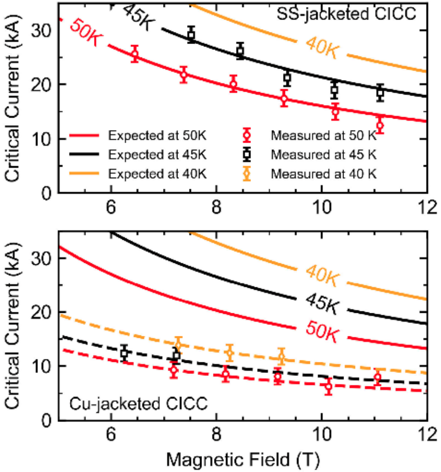
Conductor on Round Core (CORC®), a flexible HTS tape assembly constituting the base element of cabled Conductors.



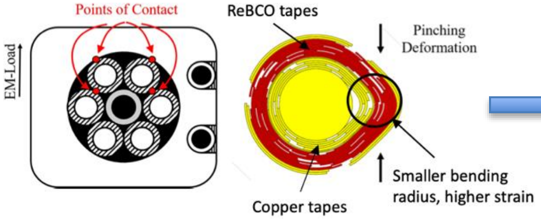
Mulder_IEEE TAS 20

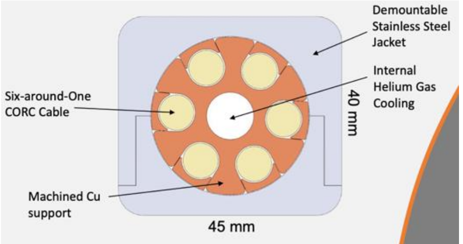
Different CORC core





Large transverse load deforms tape (thus REBCO layer).
When Strain > irreversibility limit:
→ I_C degradation





- **Next sample in preparation right now, mainly designed and prepared at ACT, instrumented and integrated at CERN and tested in Sultan early 2020.**

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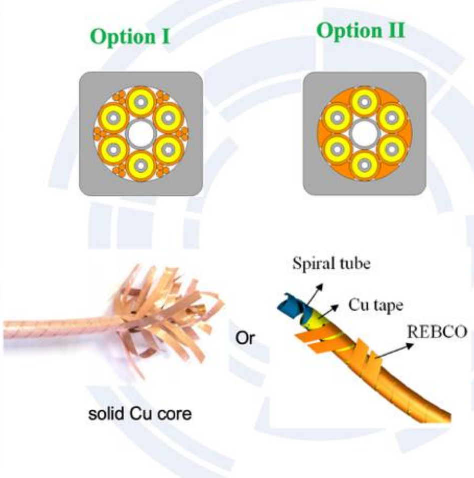
Wound tape cable concepts: HFRC

2023 → 2025 – **900** kN/m

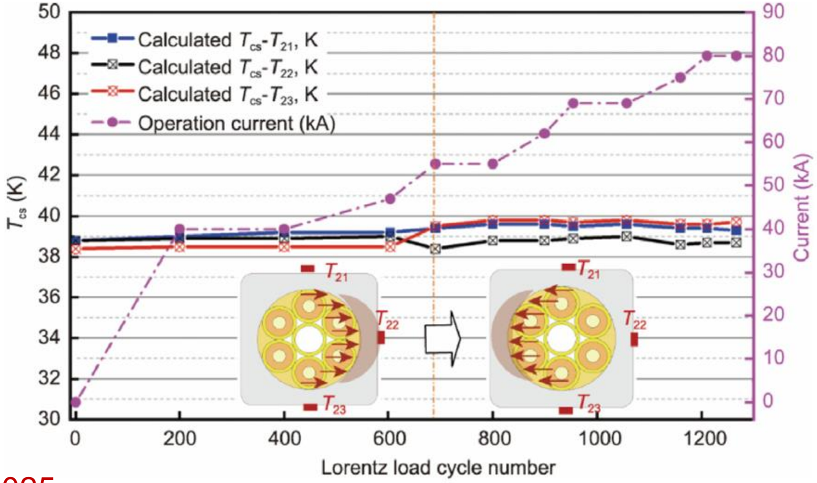
ASIPP

Highly Flexible REBCO Cable (HFRC), with a "CORC-like" base element

Item	Parameter
Maximum field	~ 18.8 T
Iop of conductor	46.5 kA
No. of sub-cable	6
Jacket material	Modified N50 (N50H)
Jacket thickness	4.3 mm
Outer dimension of jacket	42.5 x 42.5 mm
OD of CICC cable	~33.8 mm
Cooling method	Cable void & hollow pipe of sub-size cable



The first to achieve 900 kN/m and demonstrate stable performance with loading cycles.



- Performance checked with Tcs @ 40 kA, 10.85T
  - Loading cycles at increasing current levels
  - Projected performance: 80 kA / 11 T / 20 K

Jin_Engineering 2025

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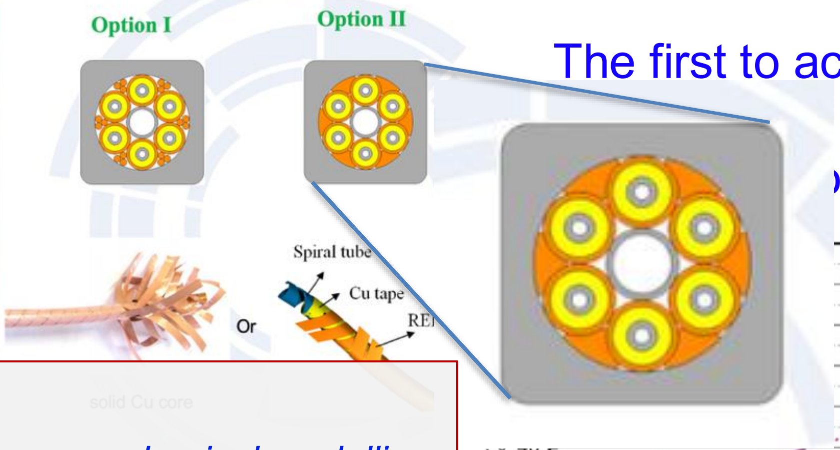
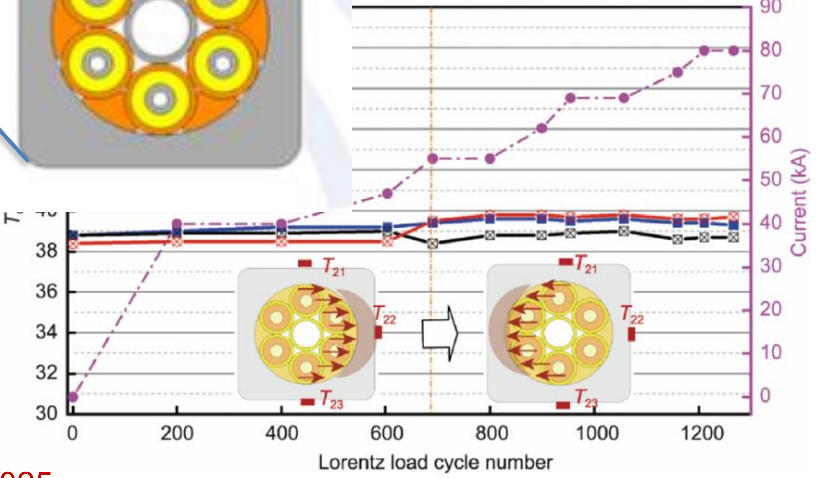
Co[illegible]	[illegible]



The first to achieve 900 kN/m and stable performance ...ading cycles.



Key to the success:

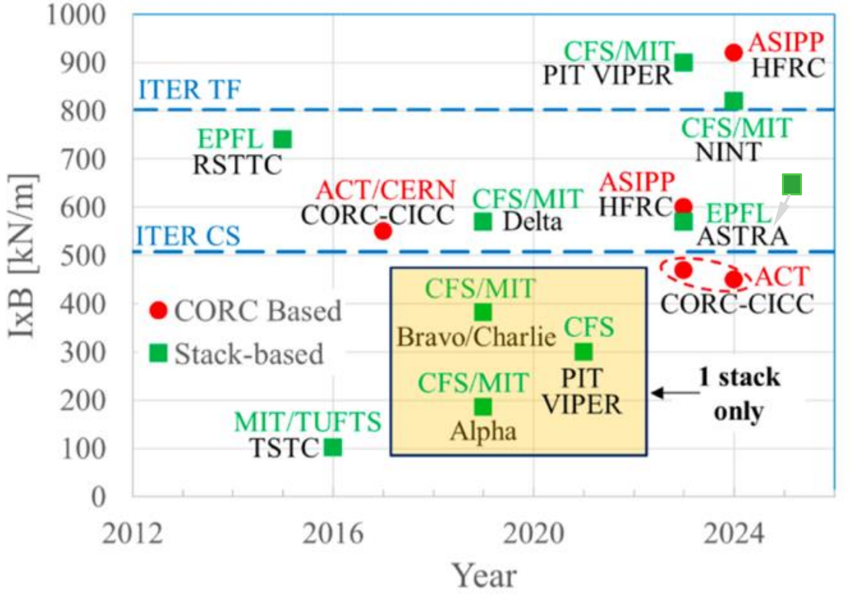
(as evidenced through an intense mechanical modelling and testing activity at the UNIVERSITY OF TWENTE. *)*

- Cu tube around wound-tape sub-cable
- Corner filler with appropriate geometry

Jin_Engineering 2025

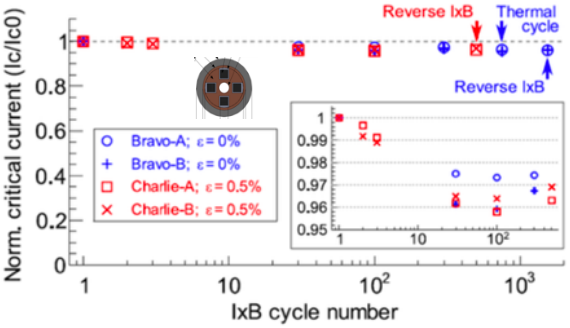
Development of HTS Fusion Conductors: probed range of electro-magnetic load (SULTAN tests)

Breschi_IEEE TAS 25_accepted



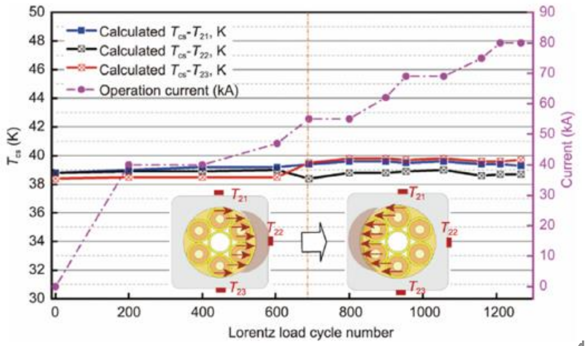
Stacked tape - Solder Filled Conductor (& Stack)

372 kN/m (1 stack only) /



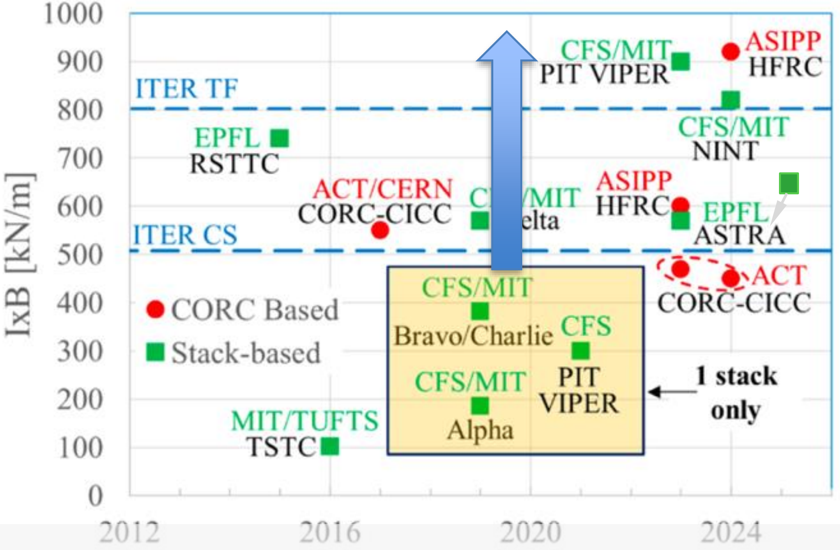
«CORC-like» – NO SolderFill.

900 KN/m

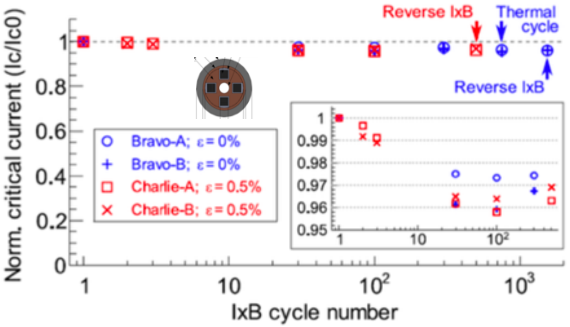


Development of HTS Fusion Conductors: probed range of electro-magnetic load (SULTAN tests)

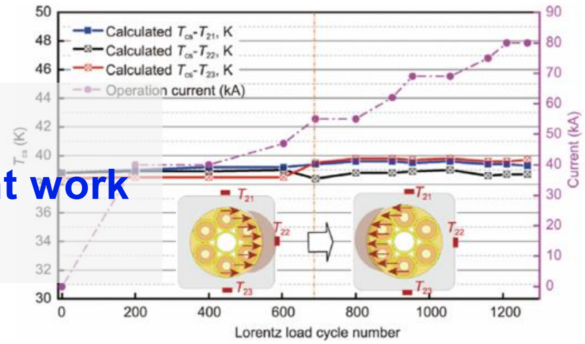
Breschi_IEEE TAS 25_accepted



Stacked tape - Solder Filled Conductor (& Stack)
372 kN/m (1 stack only) /



«CORC-like» – NO SolderFill.
900 KN/m



From the fairly limited database available:

- **Both Stacked tape and «CORC-like» concepts might work**
- **Both Solder-filled or Non-solder-Filled might work**

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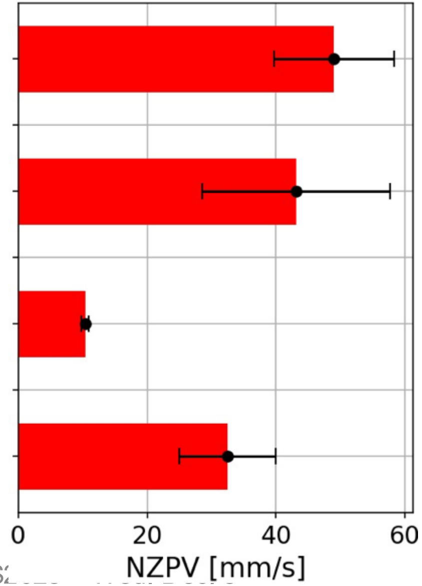
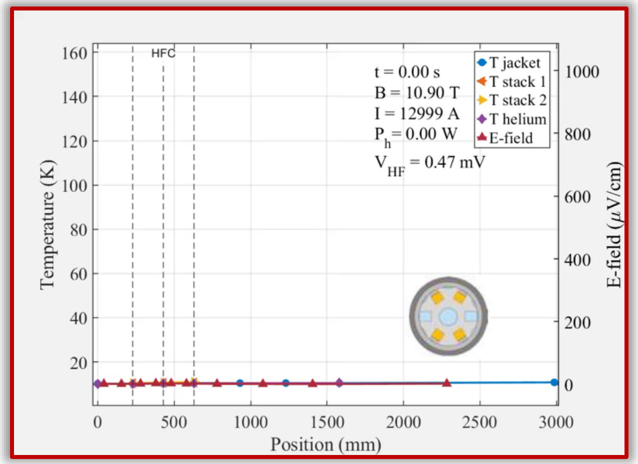
Quench studies in SULTAN (I_{op} = 15 kA)

In HTS: $\frac{T_{op}}{T_C(B_{op})} \sim 0.1 \div 0.2$ ⟹ high cryogenic stability $NZPV \sim few \frac{cm}{sec}$

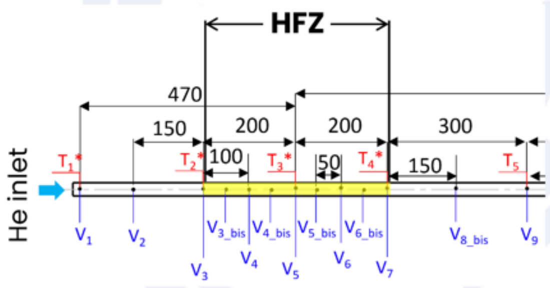
the local $T_{HOTSPOT}$ increases sharply before the threshold for voltage detection is reached

	Conductor	Design and manufacture
	Reference (twisted)	SPC
	Non-twisted	SPC
	Solder-filled ($Bi_{57}Sn_{42}Ag_1$ solder)	SPC
	Aluminum Slotted Core	ENEA





Courtesy G. Colombo



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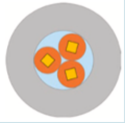	Reference (twisted)	SPC
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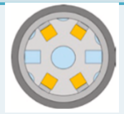
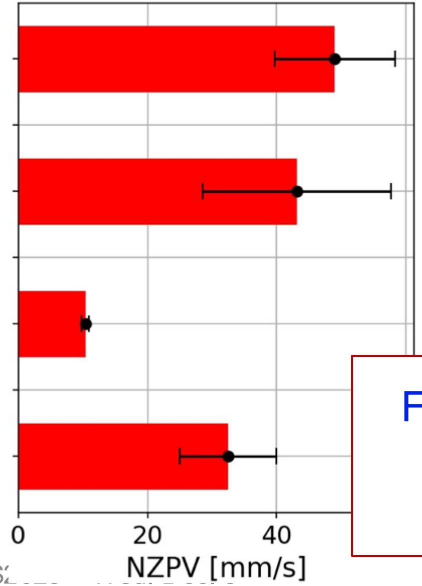
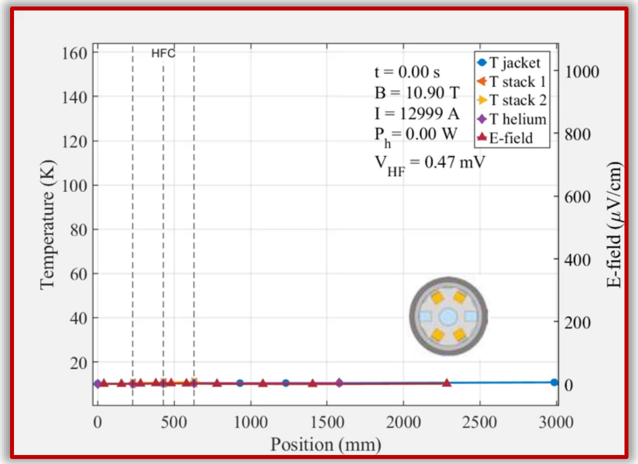
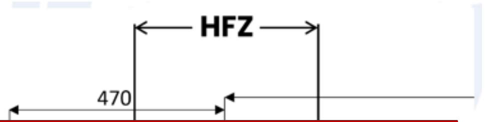
	Aluminum Slotted Core	ENEA





Courtesy G. Colombo



For all, a Temp. peak above **150 K** has been observed to cause DC **performance degradation.**

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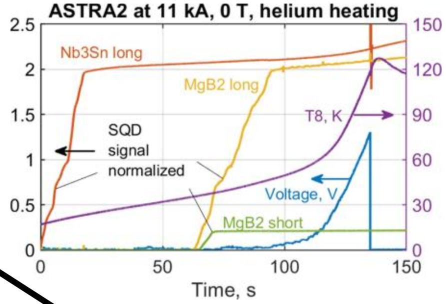
(Non-Voltage based) Quench detection techniques

Many alternative quench detection schemes currently being considered

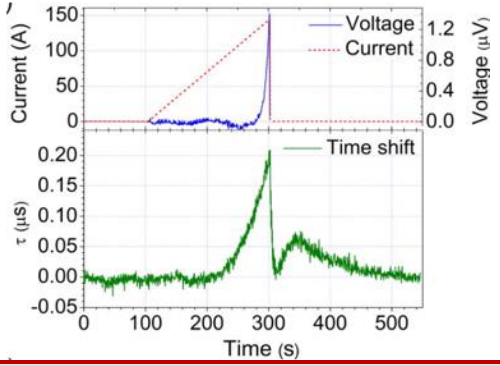


N. Bykovskiy_SUST_**2023**

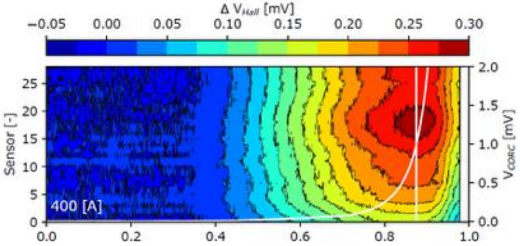
SQD (Superconducting Q. D.)

Active Acoustic Detection

M. Marchevsky_Instruments_**2021**



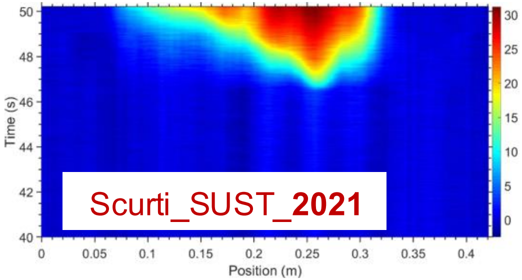
Teyber_SUST_**2020**



Magnetic (Hall Sensors)

FOS (Fiber Optic Sensors)

Monitor changes in the optical path travelled by light in an optical fiber co-wound with the conductor. Both discrete (FBG) and distributed (OFRD/OTDR) techniques are possible.



Scurti_SUST_**2021**

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(Non-Voltage based) Quench detection techniques

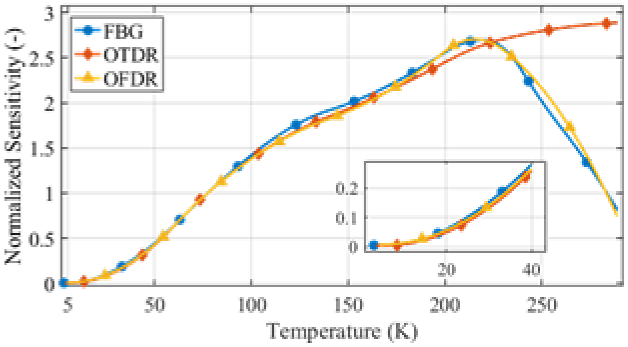
Demonstrated to be effective

Challenges:

- Decouple strain and temp. effects
- Mitigate Irradiation effects on fibers
- **Improve sensitivity** at low. Temp.

e.g. working on fiber coatings

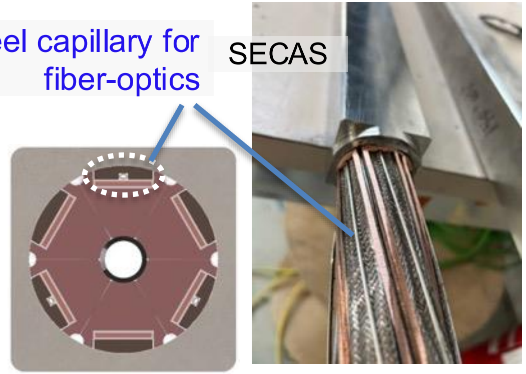
- **Integration in cables**



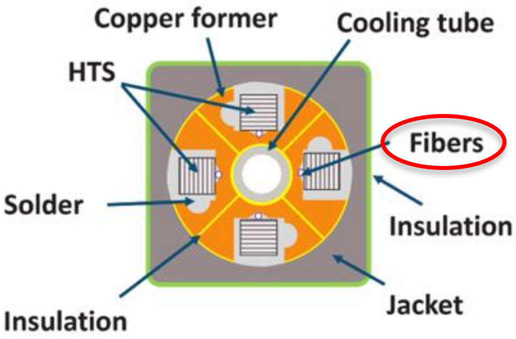
Colombo_IEEE TAS 2025

Steel capillary for fiber-optics

SECAS



Fibers integration in PIT-VIPER



Sanabria_SUST 2024

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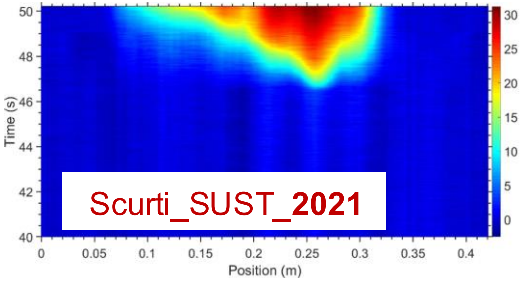

Scurti_SUST_**2021**

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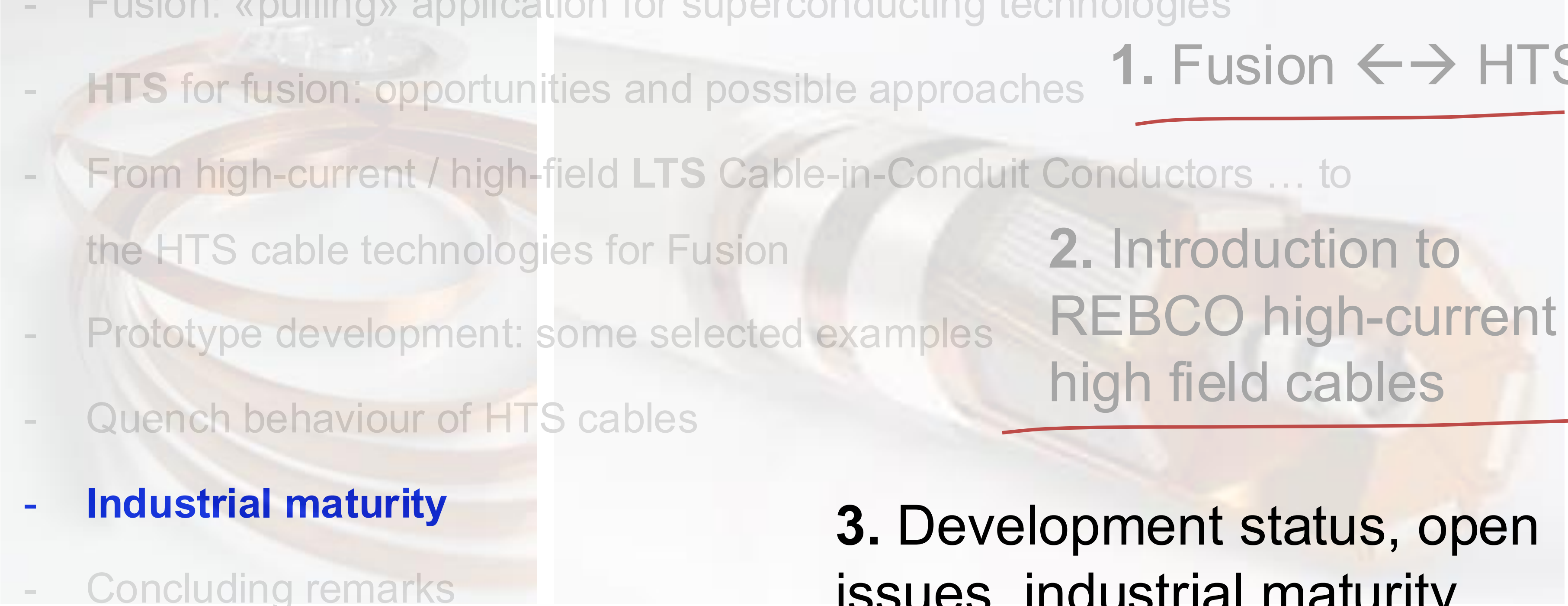

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Development status: industrial readiness level

Assuming technological issues are mostly solved, and cable designs qualified: are we ready to scale-up from prototype *«hand-made»* HTS conductors to their large-volume industrial manufacture? Are there production lines available?

Just an example:

2011/12

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 22, NO. 3, JUNE 2012 4804504

A New European Production Line for CIC Conductors

Antonio della Corte, *Senior Member, IEEE*, L. Affinito, U. Besi Vetrella, S. Chiarelli, A. Di Zenobio, L. Morici, L. Muzzi, G. M. Polli, L. Reccia, S. Turtù, *Senior Member, IEEE*, A. Bragagni, G. Scoccini, M. Seri, D. Valori, *Member, IEEE*, F. Quagliata, G. Roveta, and M. Roveta

2017

BUT the new fusion paradigm (**going private!**) requires aggressive timelines …

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Assuming technological issues are mostly solved, and cable designs qualified:
are we ready to scale-up from prototype *«hand-made»* HTS conductors to their large-volume industrial manufacture? Are there production lines available?

«*Project pull*» effect has proven successful
(in some cases)**:**

ASIPP HFRC for **BEST** manufactured in-house

VIPER / PIT-VIPER for **SPARC** manufactured in-house

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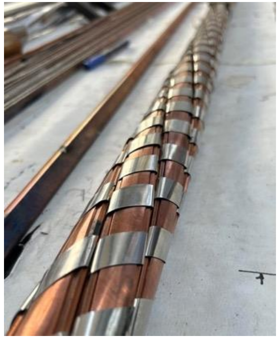
ASIPP HFRC for **BEST** manufactured in-house

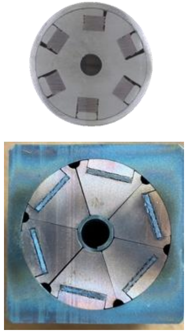
TRATOS CAVI, ICAS, Ciotec IMPIANTI S.r.l. → Al-slotted core TSTC and BRAST-SECAS prototypes manufactured partly using available industrial production lines … but a real «project pull» effect and the setup of dedicated lines has not taken place yet.

Advanced Conductor Technologies LLC www.advancedconductor.com — An important available supplier for CORC®: production capacity?


Tape Stacks Assembly and Braiding line


Cabling machines






Jacketing line

Development status: industrial readiness level

Assuming technological issues are mostly solved, and cable designs qualified: are we ready to scale-up from prototype *«hand-made»* HTS conductors to their large-volume industrial manufacture? Are there production lines available?

«*Project pull*» effect has proven successful (in some cases)**:**

But it looks like there are **many more projects than available** production **capacity**.

Does it make sense that **each** fusion start-up sets up **its own** cable production line?

→ Risk?
- of setback;
- of limitation in further developments, and in the sharing of information and experience

Looking at cable technology readiness level: some steps still to be taken. Experts in cable technologies should be stimulated to participate.

unless strictly necessary for project scope, I would refrain from completely abandoning today **LTS-based** coil technologies for fusion.

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Concluding remarks

- ✓ **HTS** have opened new perspectives in the design space of magnetic confinement fusion. Still in the R&D phase, fusion is now a ***pulling application for HTS***, with many privately-funded projects relying entirely on HTS as **enabling technology**. In parallel, publicly funded projects have been stimulated to integrate HTS for the improvement of coil performance.

- ✓ Development activities on **HTS high current / high field cables** for fusion based on **REBCO tapes** have been carried out for about two decades, with a wide spectrum of options proposed. Lessons can be learned from the history of Nb_3Sn CICC development.

- ✓ Beside some technological open issues, **some steps still** need **to be taken before** HTS REBCO cables can be considered a **fully mature industrial technology**.

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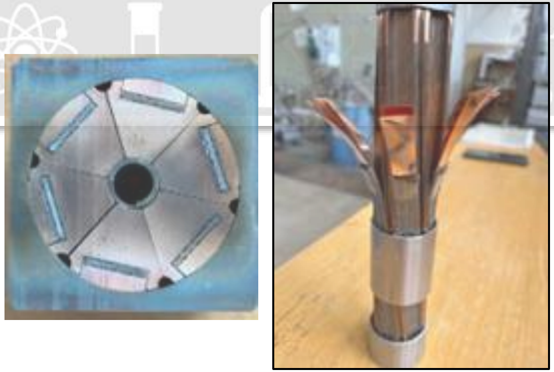
ITER Nb_3Sn TF CICC

Luigi Muzzi
luigi.muzzi@enea.it



REBCO BRAST-SECAS CICC

and wish you a wonderful banquet !