Superconducting Magnets - 4

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Outline

1. Stepped Approach for the Design of large Conductors and Magnets
2. Examples of Superconducting Fusion Magnets from last Century
3. The ITER Conductors and Coils
4. Toward DEMO - HTS

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Fusion today in Europe and beyond

- According to the roadmap 2014, *“DEMO” is the step between ITER and the commercial power plant*. The design of DEMO is finalized after crucial knowledge is gained from early operation of ITER.
- The *sliding delay of ITER* plasma forces the EUROfusion DEMO in a never ending phase of Pre-Conceptual Studies and technology R&D.
- In China, two large Tokamaks, *CFETR and BEST* are in advanced manufacturing. Korea is also willing to launch a DEMO Tokamak, without waiting for ITER results.
- In US, the Commonwealth Fusion Science (CFS, a spin-off of MIT) launched 10 years ago the *SPARC – a smaller size, very high field Tokamak* to demonstrate the HTS technology for Fusion.
- The European roadmap to Fusion needs an update…

Trends for Fusion Magnets

Despite the variety of design, materials, shape and performance, some clear trends can be identified in the fusion magnets:

- Forced flow cooling – Bonded (potted) coils
- Large stored energy, e.g. 10GJ in one DEMO TF 2018 $E = L\frac{I_{op}^2}{2}$
- For TF magnets, long dump time constant, τ = 35 s in TF DEMO 2018, must be used to limit the electromagnetic loads on the vacuum vessel

$$V_d = L\frac{I_{op}}{\tau}$$

- The dump voltage and operating current are linked by the stored energy and dump time constant

$$V_d \cdot I_{op} = \frac{2E}{\tau} \approx 570\,kW$$

-> e.g. for V_d= 10 kV, I_{op}= 57 kA

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High Voltage Operation

In W7-X, JT60 and ITER failures are detected for the ground insulation during the acceptance test. In 2021, two major accidents occurred in JT60 PF coil and ITER CS#3.

The pressure on the designers increases for magnets operating at low voltage, <5 kV maximum terminal voltage.

For the steady state TF coils, the highest voltage occurs at the safety discharge. For CS and PF, the highest voltage is at plasma breakdown and plasma control actions.

Low Voltage DEMO Coils

The key parameter to reduce the operating voltage is the self-inductance, ***L***, which is proportional to the square of the number of turns, N_t^2. For a magnet with a given Ampère Turns ($N_t \cdot I_{op}$), the number of turns can be reduced by increasing the operating current.

In EUROfusion DEMO, in TF, CS and PF coils, the terminal voltage can be reduced well below 5kV increasing the operating current to the range of 100-105 kA.

A R&D is started to develop superconducting cables with high operating current. China also goes for 100 kA conductors for BEST. The major challenges are self-field instability (NbTi), internal electro-magnetic loads (Nb_3Sn and HTS), current distribution, AC loss…

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Tokamaks: pulsed or steady state?

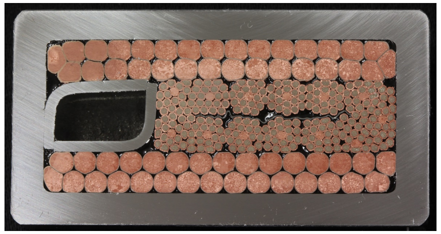
With the exception of the spherical DEMO Tokamak (US Princeton), all other Tokamaks are pulsed, with burn time of the range of few hours. A critical parameter for the design of a pulsed tokamak power plant is the number of operating plasma burn cycles. For a lifetime of 40 years the **number of cycles** is in the range of 1-2 10^5. Is it a problem?

YES, a big one.

- Applying fatigue-crack growth criteria to *the conduit of the CS* (hoop load), the allowable stress drastically decreases. The steel cross section increases by a factor of 2-3 and the available flux decreases…
- The *vacuum vessel and in-vessel components* are exposed to a prohibitive number of thermal cycles.

In the long term, the tokamaks must become quasi steady state devices. However, the DEMO of next generation are still pulsed tokamaks, with an intrinsic conflict of requirement between DEMO and Power Plant.

Alternative conductor designs



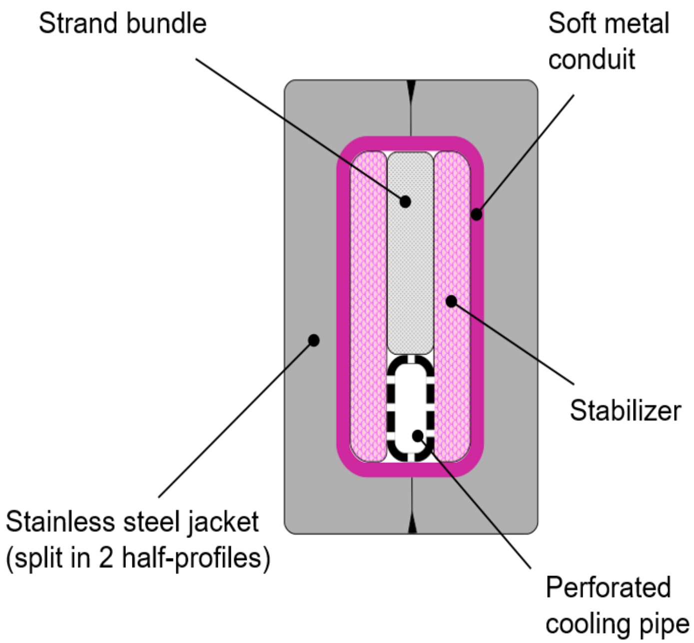
In standard CICCs, the jacket provides:

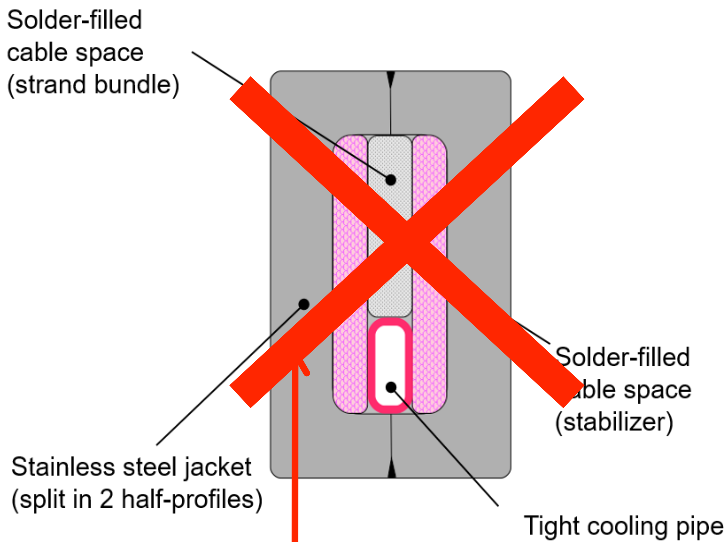
- ***Structural support*** *for the operating loads*
- ***Helium containment*** *function (which imposes stringent constraints in the mechanical design, since no local crack can be tolerated through the jacket wall thickness).*

Decoupling the two main functions of a CICC jacket can be very attractive.

If the presence of a local crack is acceptable from the structural point of view, the **required** jacket **cross section** might be **closer to** the **static** load case.

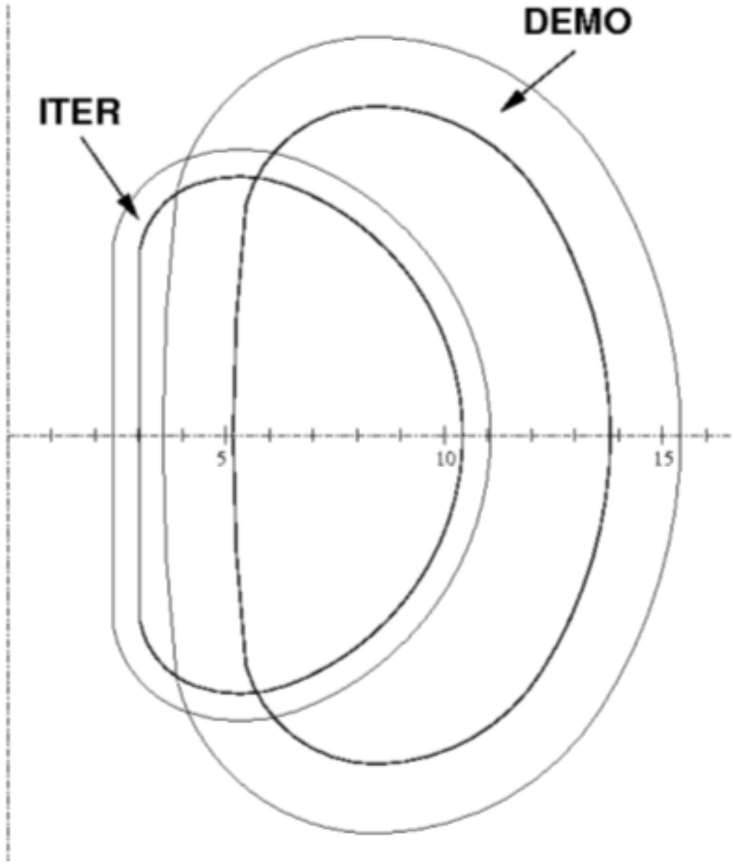
Two alternatives are considered:





Prohibitive AC loss
Poor transient stability

DEMO vs. ITER: the giant and the ant



	ITER	DEMO 2018
Number of TF coils	18	16
Peak Field on TF coils	11.8 T	12 T
Current in one TF coil	9.1MA	14.9 MA
Stored Energy/TF coil	2.28 GJ	10.0 GJ
Dump time constant	11 s	35 s
TF case thickness	286 mm	520 mm
One TF coil assembly	340 t	>1000 t

The increase of the major radius from **6m to 9m** is a challenge in terms of engineering, logistics and price. The ITER technology experience will be of little help for DEMO.

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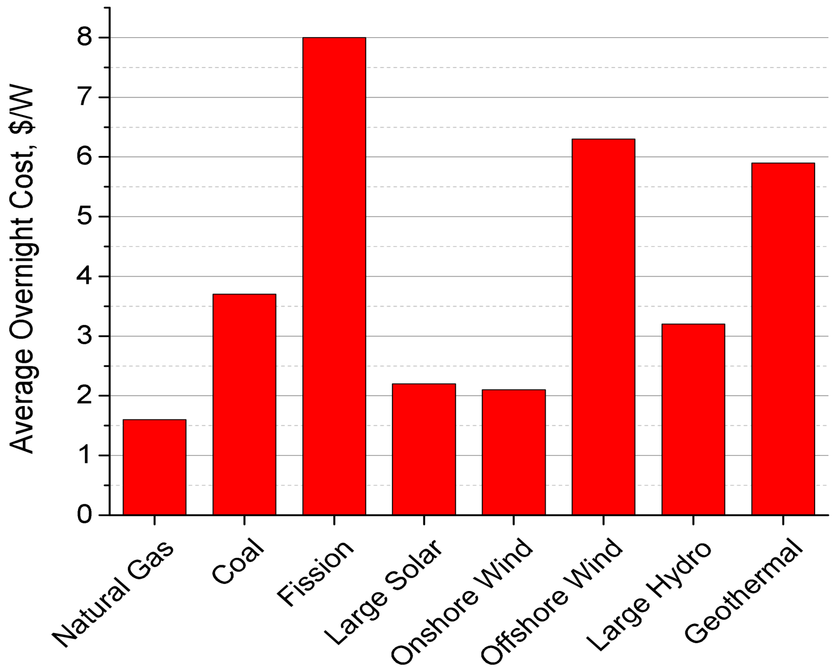
A crude Estimate

- Take a 1.2 GW fusion power plant with Q = 20 and burn/dwell time = 2
- The averaged electric power is, say, (1200•0.4)·2/3 = 320 MW.
- For heating, the power recirculation is 110 MW and for cryogenics 30 MW
- Disregarding shut down for maintenance, we sell 320 – 110 – 30 = 180 MW.
- At an energy price of 6-8 ¢/kWh, we earn 110 M/year before taxes.
- The operation cost (maintenance, consumable, salaries) makes > 30 M/year.
- In a very optimistic view, ***80 M/year*** are left to mortgage the investment.
- To keep the mortgaging period within 30 years, the construction cost must be 2.4 B

A capital investment of 2.4 B for 180 MW gives an **overnight cost** of 13.3, even higher than a nuclear power plant.



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Pro and Cons for HTS in Fusion

A new technology/material can successful establish if:

- The newcomer is cheaper than the old one for the same performance
- The new technology enables a new/broader range of applications

E.g.	**NbTi**	replaces	Copper	($B > 1$ T, $J_{op} > 20$ A/mm^2)
	Nb_3Sn	replaces	NbTi	(magnets with $B > 9$ T)
	HTS	replaces	Nb_3Sn	(either $T > 20$ K or $B > 18$ T)

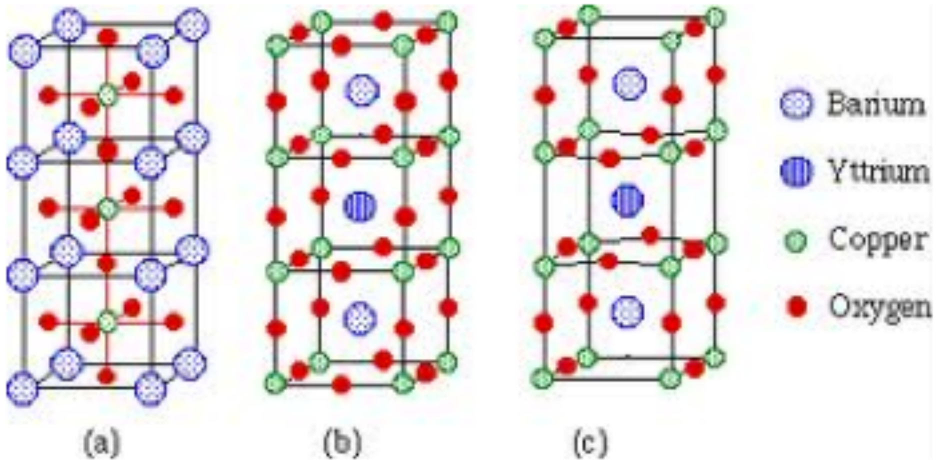
A successful example of use of HTS in Fusion are the Current Leads (only self field, T up to 70K), where the advantage in terms of cryogenic power saving overcomes the material cost.

For the large DEMO Tokamaks (EUROfusion, China and Korea), the peak field in TF is < 16T, no HTS is required in TF, but the use of HTS is considered in CS to enhance the flux generation.

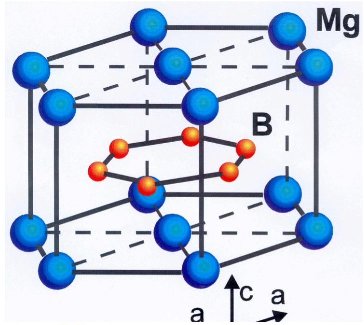
The use of HTS in TF coils would allow drastically increasing the field on Torus and the power ($P \alpha B^4$), hence reducing the major radius. Besides the feasibility of large HTS coils (SPARC), a broad criticism is raised about the exhaust of very large power density and the high radiation load.

HTS – Materials

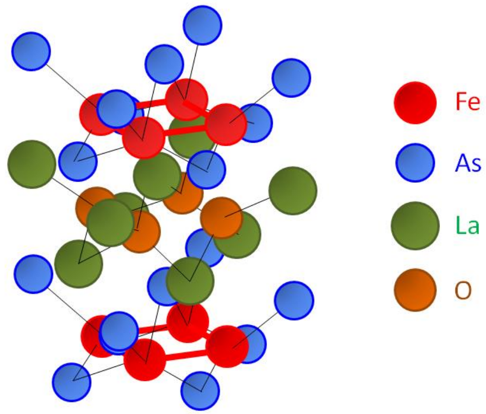
1986. The main family of HTS superconductors belongs to the perovskite, a kind of cuprates, with T_c up 120 K and B_{c0} up 50 T.



2001. Another popular new material is MgB_2 a binary compound with T_c 39 K and B_{c0} < 10 T.



2008. The youngest family of HTS materials is iron based pnictides, with T_c in the range of 50 K.



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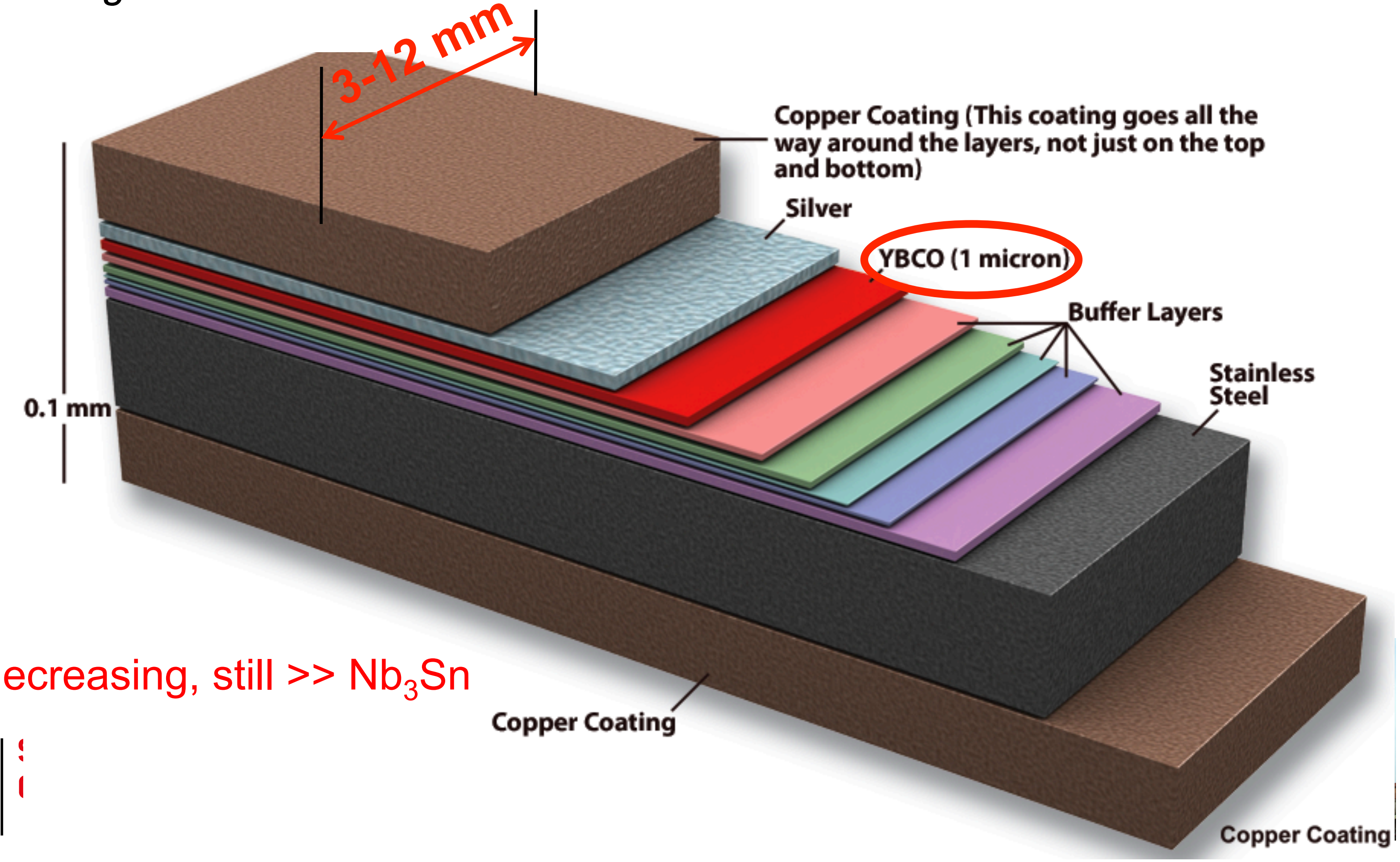
HTS superconductors today – Rare Earth perovskite

Two perovskite superconductors are produced commercially on small scale:

REBCO *based cuprates ("coated conductors"), Y(or Ga)$Ba_2Cu_3O_{7-x}$ are available as thin tapes prepared by CVD or laser assisted PVD. Best candidate for high field coils.*



Price/kg decreasing, still >> Nb_3Sn

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HTS superconductors today – Bi perovskite (highest T_c)

Two perovskite superconductors are produced commercially on small scale:

Bi - Sr *based cuprates,* $Bi_2Sr_2Ca_{n-1}CuO_{2n+4+x}$*, available as*

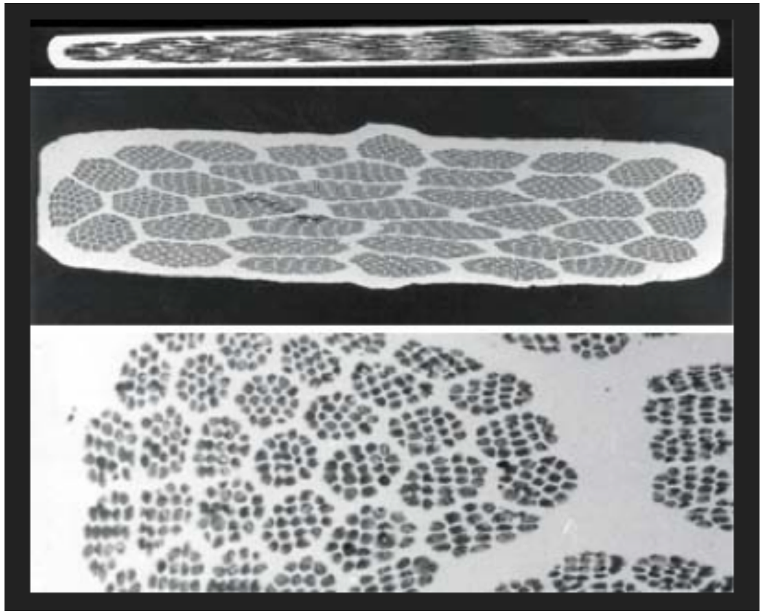
wire Bi2212 (precursor)

tape Bi2223 (heat treated)

The matrix of both multifilament composites is Ag (transparent to Oxygen) The Bi2223 tape, with high anisotropy, is in use mostly for HTS hybrid current leads. The Bi2212 wire is a candidate for high field winding, but with serious problems at the heat treatment.

Price/kg stationary >> Nb_3Sn

For Bi2223 tape, no commercial production after 2024, For Bi2212, very limited production by only one supplier



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IF the price would not be an issue….

Which technical advantages would HTS bring in a fusion magnet?

Operating temperature

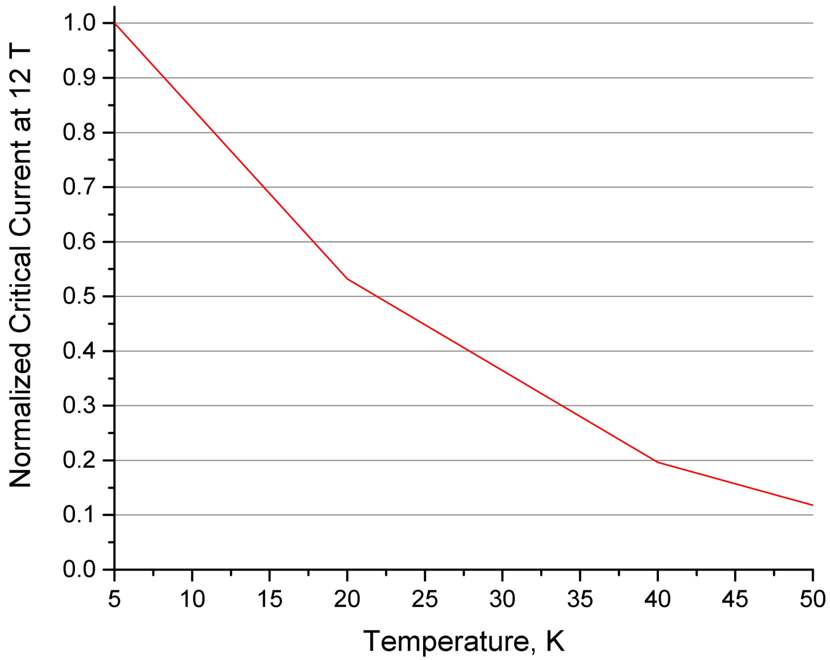
At B > 12 T, HTS require low operating temperature, say T < 25 K.

The available cryogenic fluids are He, H and Ne:

He density is very low at 25K

Ne is a poor dielectricum

Liquid H could be ok (if accepted)



The low dJ_c/dT compared to NbTi and Nb3Sn allows operating close to I_c with large T margin

Operating Field

Field > 20 T would be accessible, but large magnets > 20 T are mechanically challenging

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IF the price would not be an issue….

Which technical drawbacks would HTS bring in a fusion magnet?

Protection

When operating with large temperature margin and at higher temperature, the quench propagation is very slow, making the quench detection challenging -> NI magnets?

AC Loss

Hysteresis loss is large for REBCO tapes (tape width). It matters for CS and PF coils.

Anisotropy

The performance sensitivity to field orientation limits the exploitation of the high J_c.

Technology

HTS are made of ceramic.

As a Wind&React (Bi2212) HTS has similar issues as Nb_3Sn

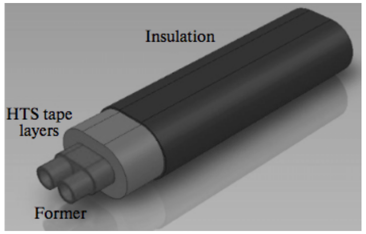
As React&Wind tape (ReBCO) HTS has limited bending and poor shear strength

IF the price would not be an issue….

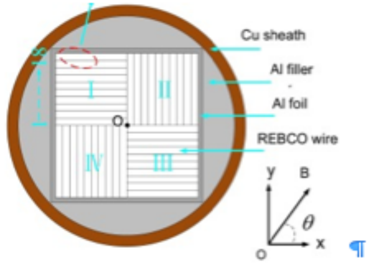
HTS Conductor could compete with Nb_3Sn for high field fusion magnets

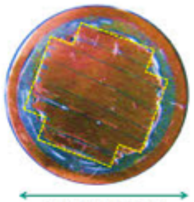
For REBCO tapes, three cable architectures

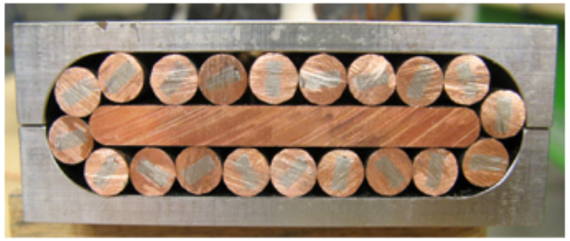
- *“Wrapped” tapes (CORC)*

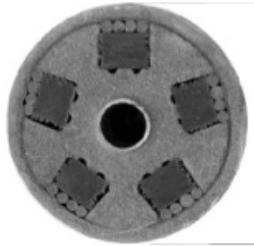


- *Stacks of tapes*

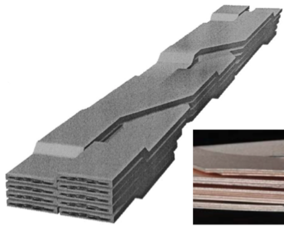


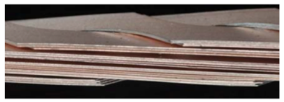






- *Transposed tapes (Röbel)*





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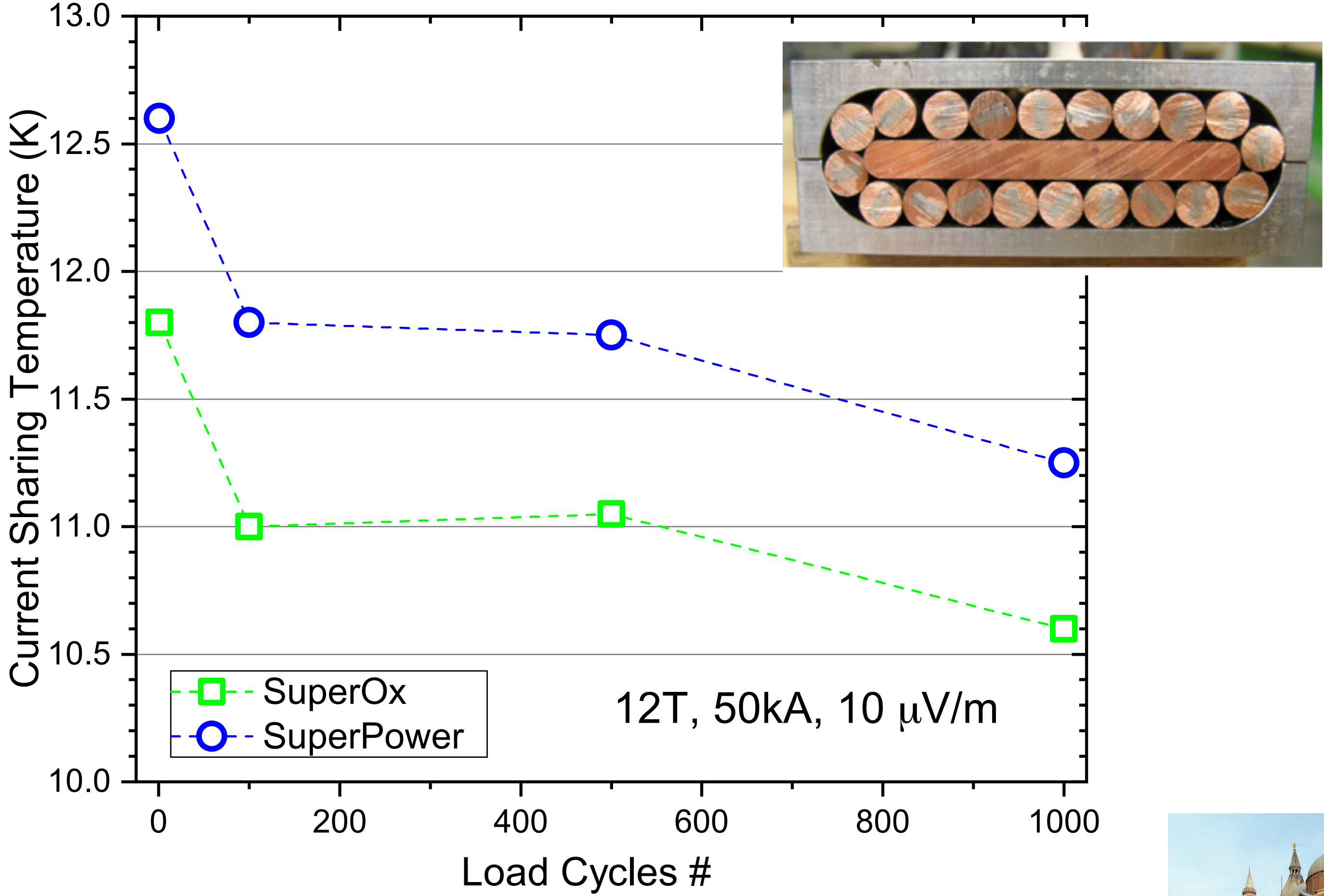
2015
Good initial results (zero resistance).
Substantial performance loss upon cyclic loading.



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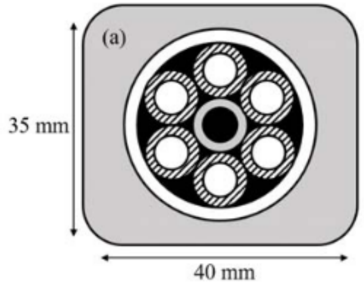
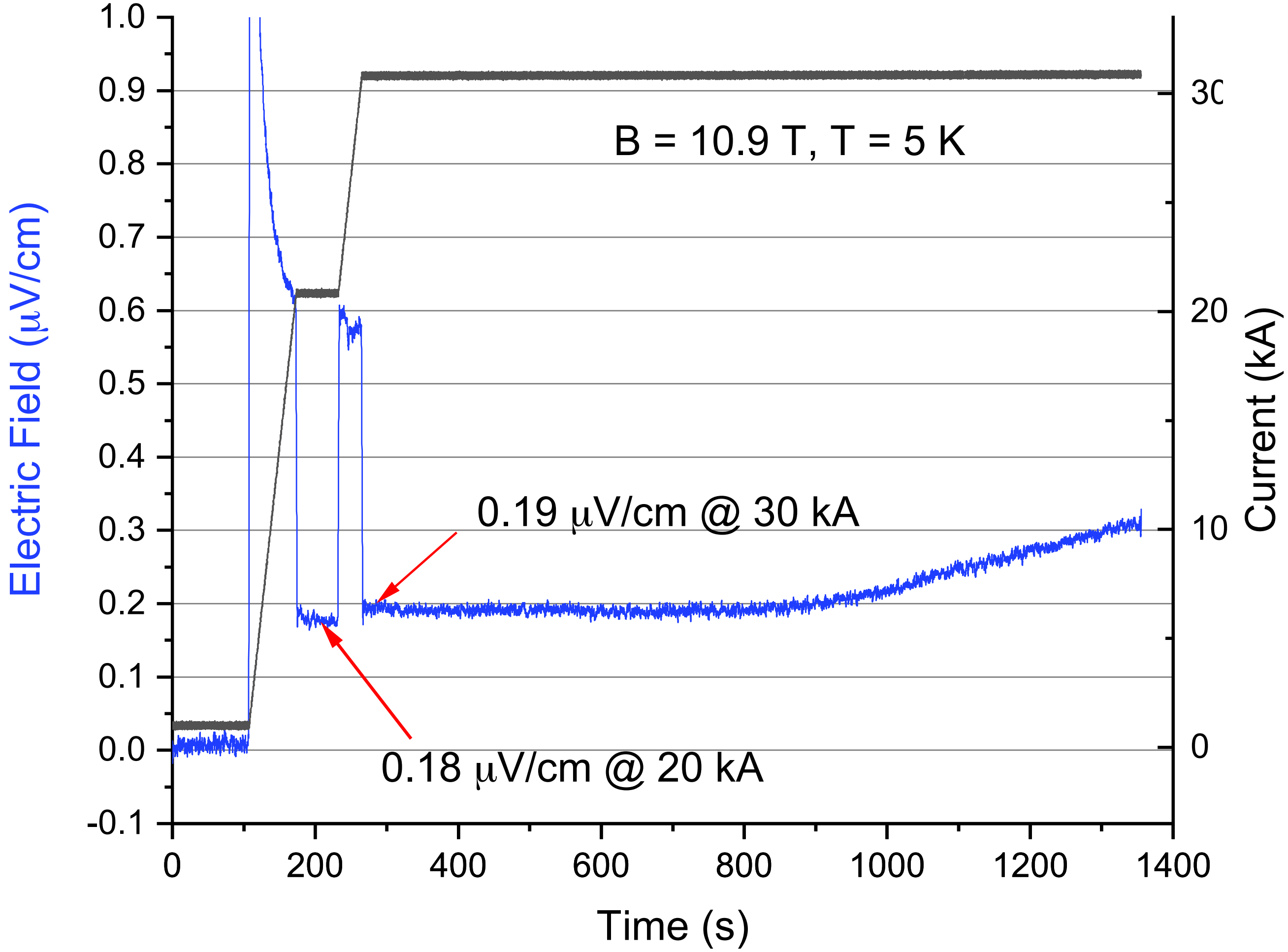
2017 - 2024
Voltage (resistance) > criterion even at low current.





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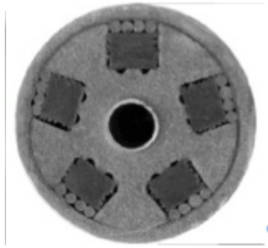
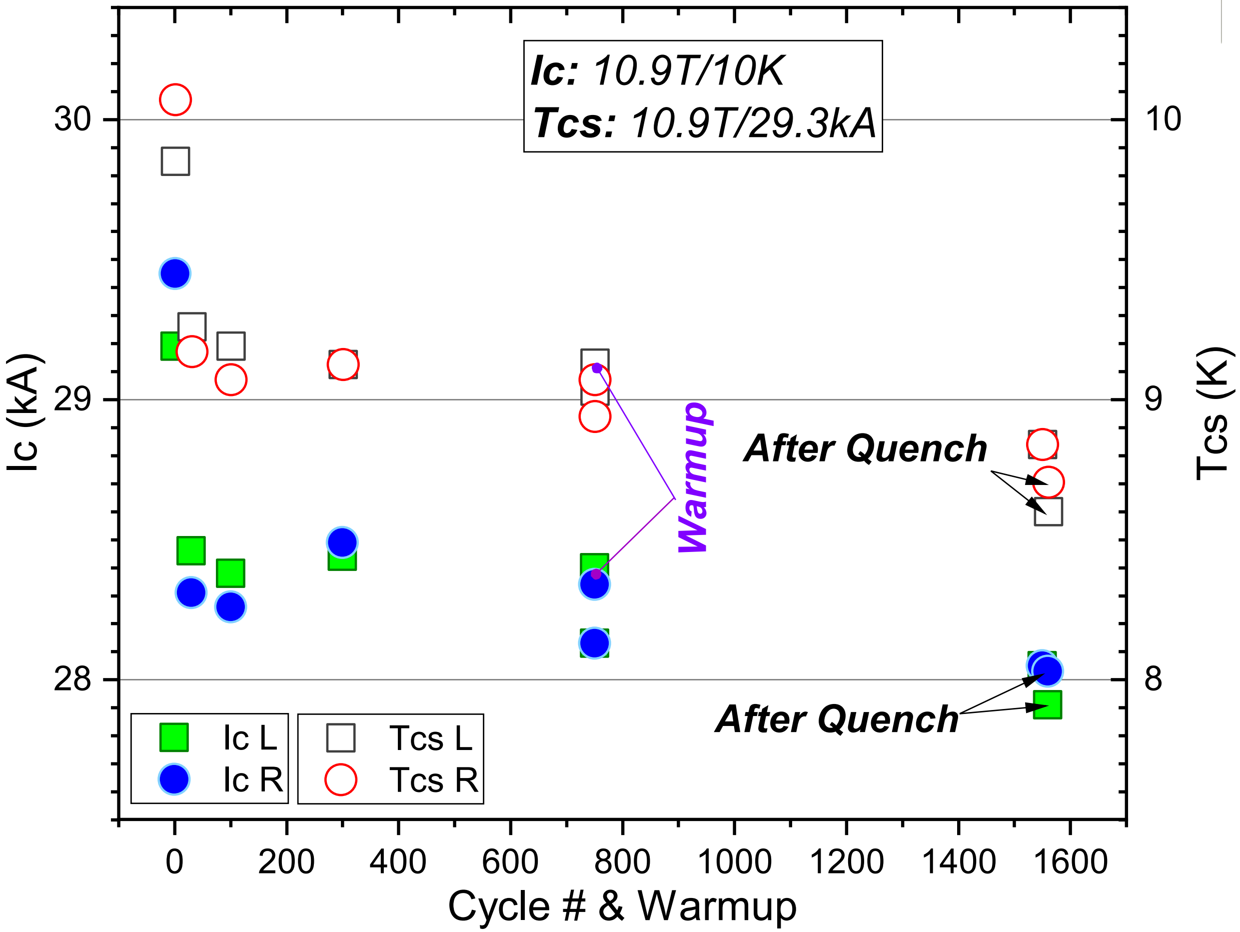
2019 (later improved)
Good initial results (zero resistance).
Performance loss upon cyclic loading.





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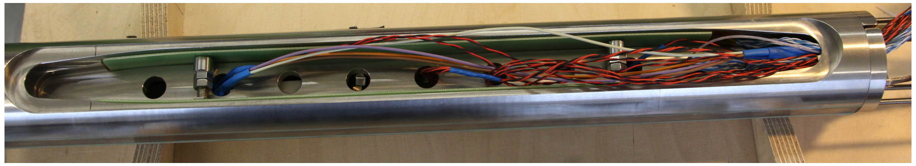
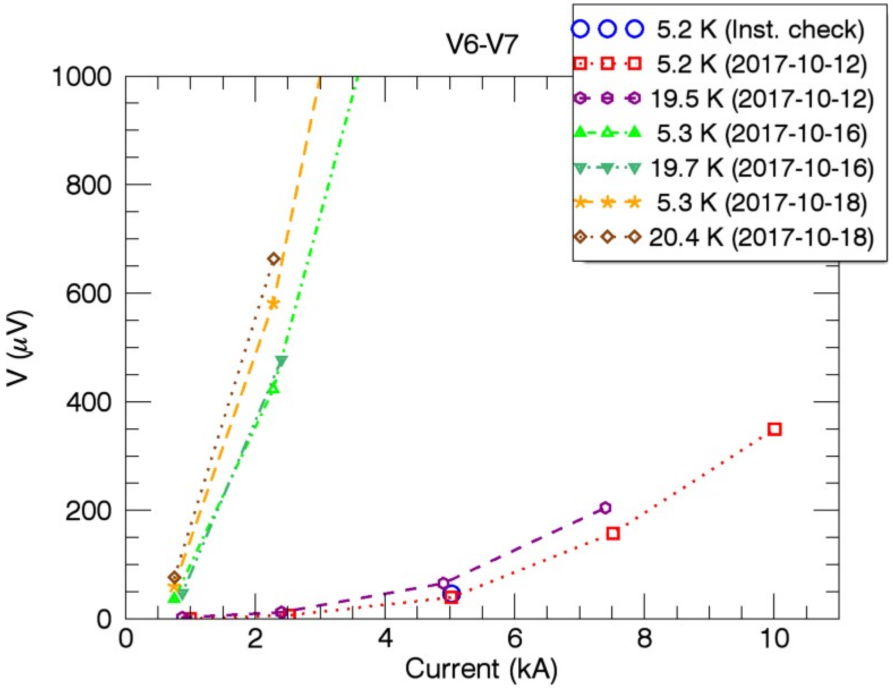
2017 (FM04) – 2019 (FM05)

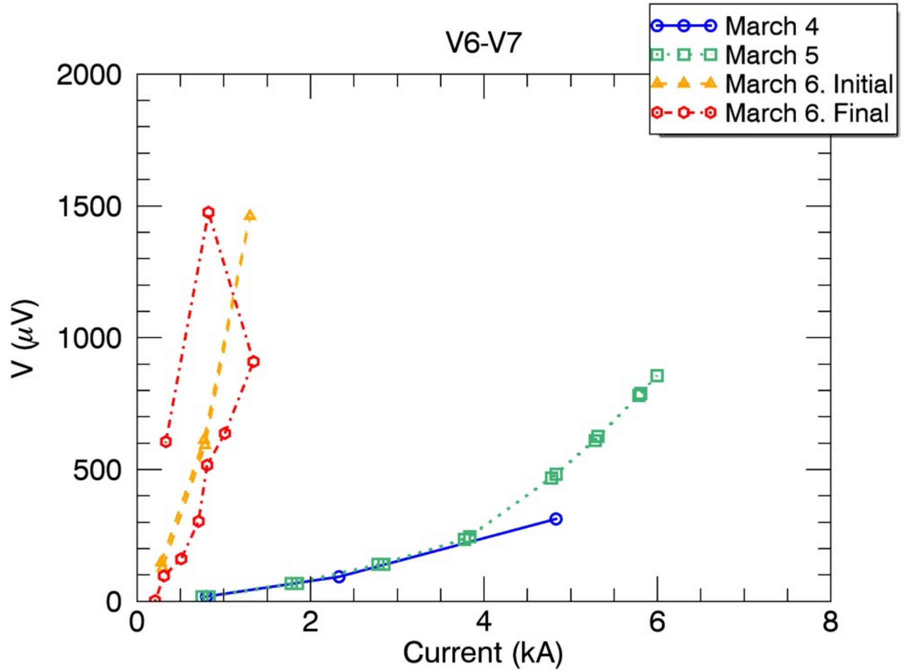


Two race-track insert coils made by Röbel cables show large voltage since the first run. The resistance increases by over one order of magnitude after test in field.

FM04 (2017)



FM05 (2019)



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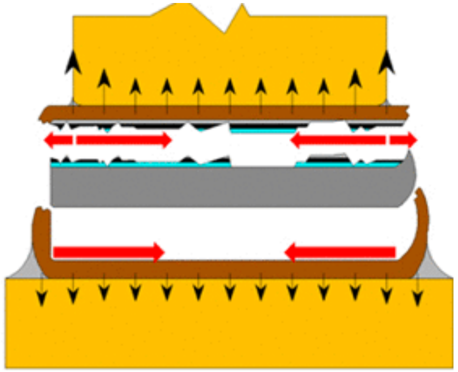
Summary on HTS cables (today)

- So far, the best (not perfect) performance is obtained by the VIPER cable of SPARC (CS coil), possibly due to the solder impregnation *under vacuum*, which suppress micro-bubbles.

- The typical failure mechanism for 2G tapes is the delamination of the REBCO film under shear load. Preventing "tape displacement" is not sufficient to avoid shear load.

- In CORC cables, the main issue is current injection / current sharing (apparent resistive behavior) together with sensitivity to transverse load.



As 2024, the only two examples of HTS coils made by sizeable cables (I_{op} > 30 kA) are the Model Coils of SPARC, TF (2019) and CS (2024)

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(Conceptual) Designs of HTS Fusion Magnets

- EUROfusion. Use HTS REBCO in the high grade of CS. Allow a peak field up to 18T to increase the flux (burn time) for the same coil size.

- CFETR (China). Multi-CORC cable planned in CS high grade.

- **SPARC (CFS).** Up to 23 T, compact tokamak for technology demonstration, NI TF coils. (ARC, larger tokamak with demountable coils).

- FFHR (NIFS). Helical coils assembled by hundreds of segments (several thousands of joints). HTS is chosen for cryogenic economy.

- FNSF (PPPL). Spherical tokamak, field up to 16 T, HTS is proposed for the high current density.

- STEP (UKAEA). Compact spherical tokamak, with demountable HTS TF coils.

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