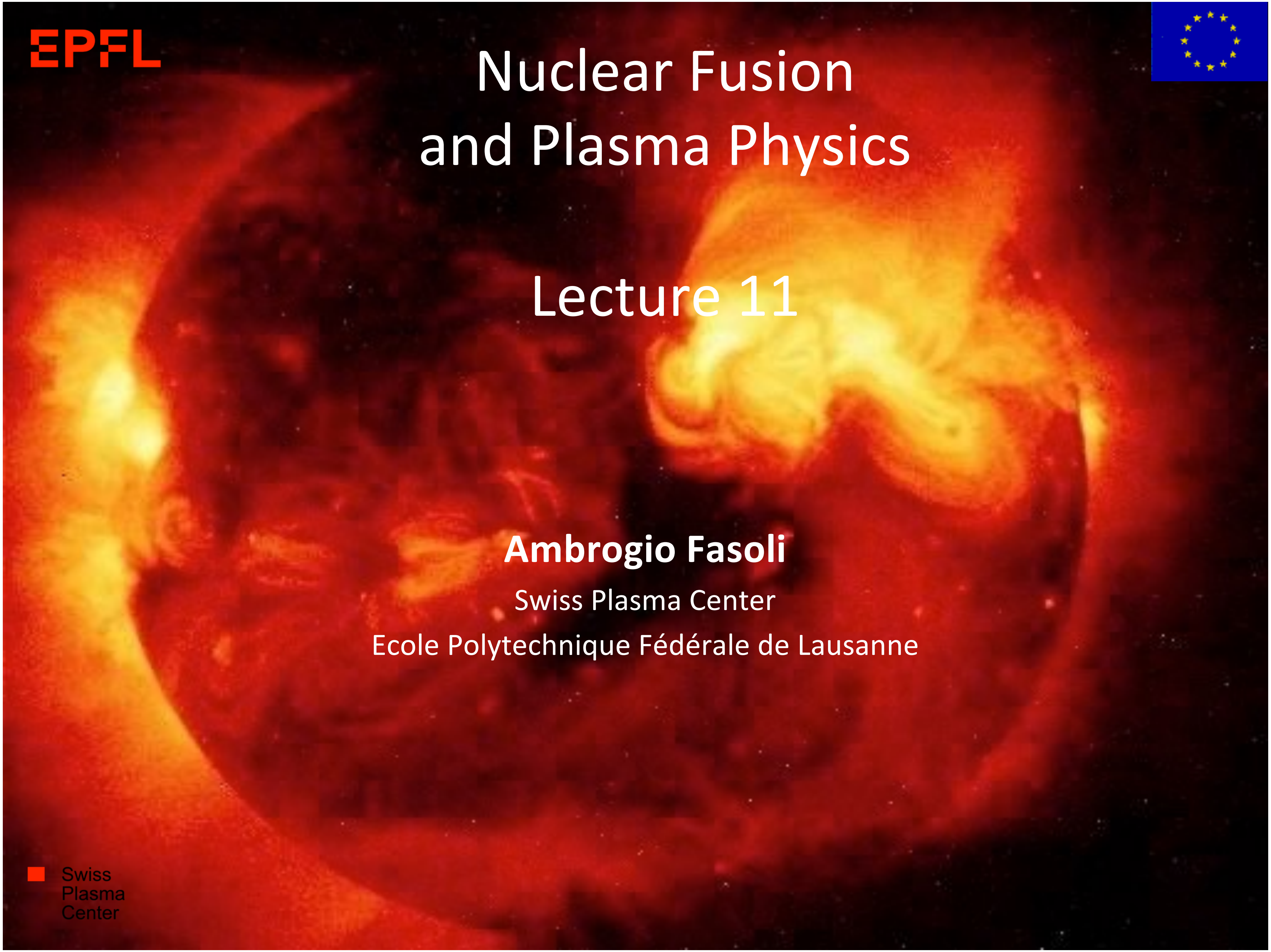


Nuclear Fusion and Plasma Physics

Lecture 11

Ambrogio Fasoli

Swiss Plasma Center

Ecole Polytechnique Fédérale de Lausanne

Applied superconductivity for fusion
Layout of the lecture

The need for superconducting magnets

Superconductivity – generalities

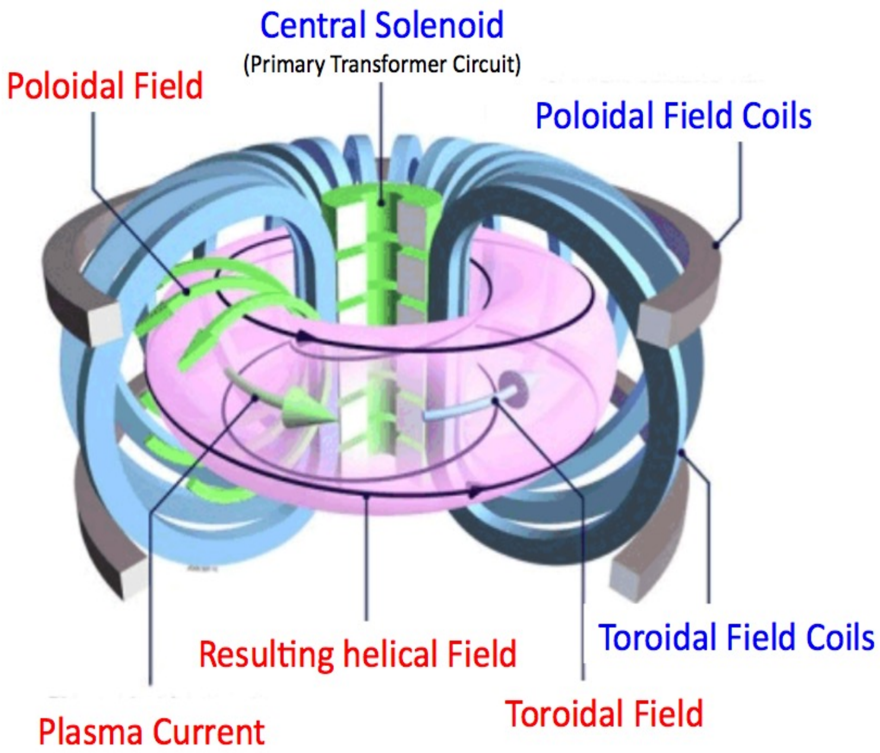
Requirements and challenges

Fusion devices with superconducting coils

ITER, DEMO and beyond

Presentation by Nikolay Bykovskiy on his project in Applied Superconductivity for fusion

The need for superconducting magnets



Plasma confinement needs high magnetic fields over large volumes

- Increasing B is key for performance of magnetic fusion reactors
- $n\tau_E T$ scales with B^α, where $\alpha \geq 2$

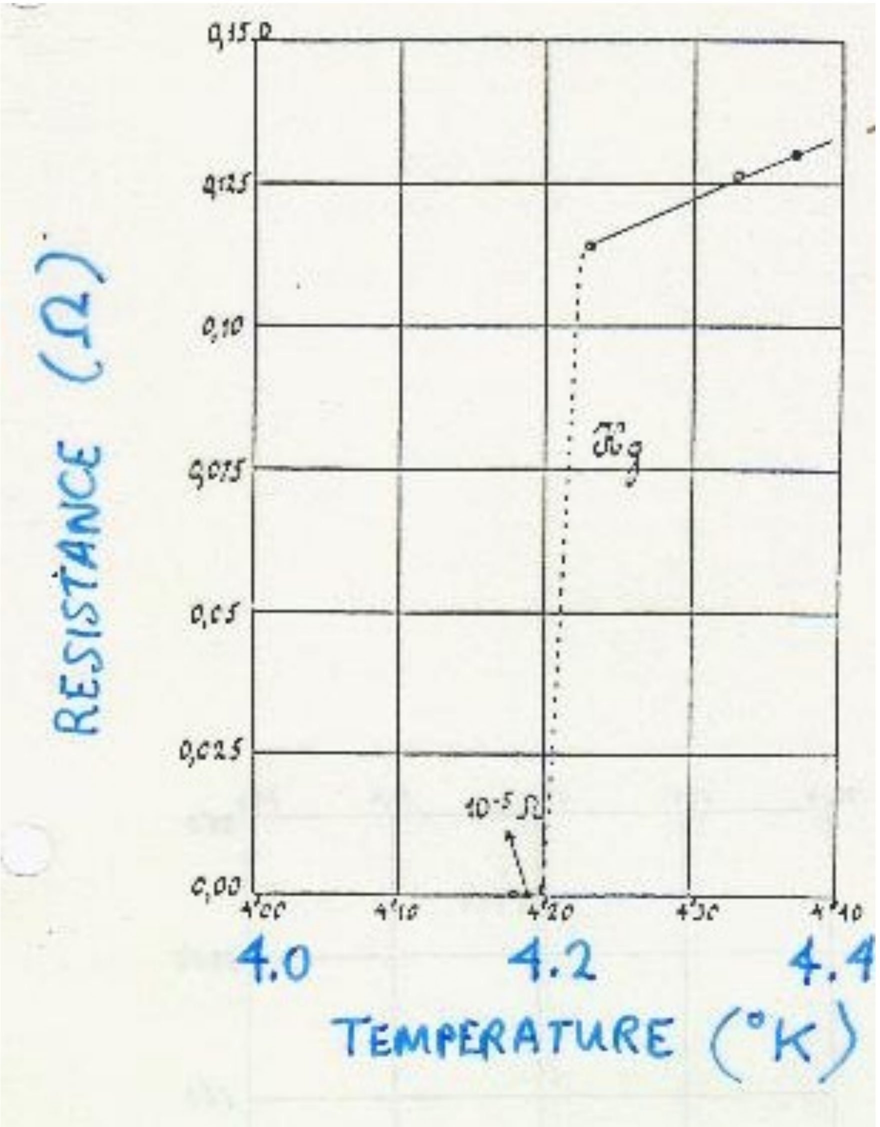
Copper coils can generate large fields, but not in steady-state

- Current density in steady-state ≤10 A/mm^2

For steady-state, superconductors are necessary

- Current density in steady-state ≤1000 A/mm^2
- Low dissipation in coils, low recirculating power

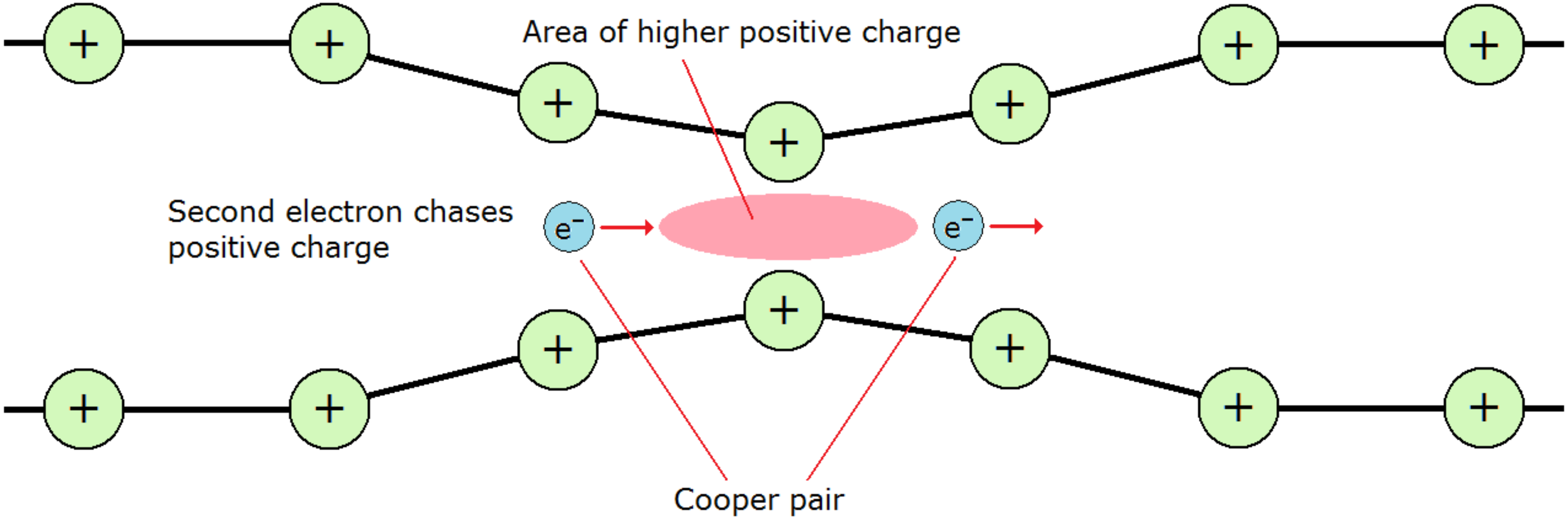
The discovery of superconductivity



In 1911 Kamerlingh Onnes observed that the electrical resistance of a sample of mercury becomes exactly 0 when the sample is brought at the temperature of liquid Helium

Superconductivity – simple interpretation

BCS theory (1972): below a critical temperature T_c, an effective attraction between pairs of electrons (Cooper pairs) via the lattice promotes a condensed state in which the phases of all the individual wave functions are locked together



https://dc.edu.au/wp-content/uploads/cooper-pair-phonon.png

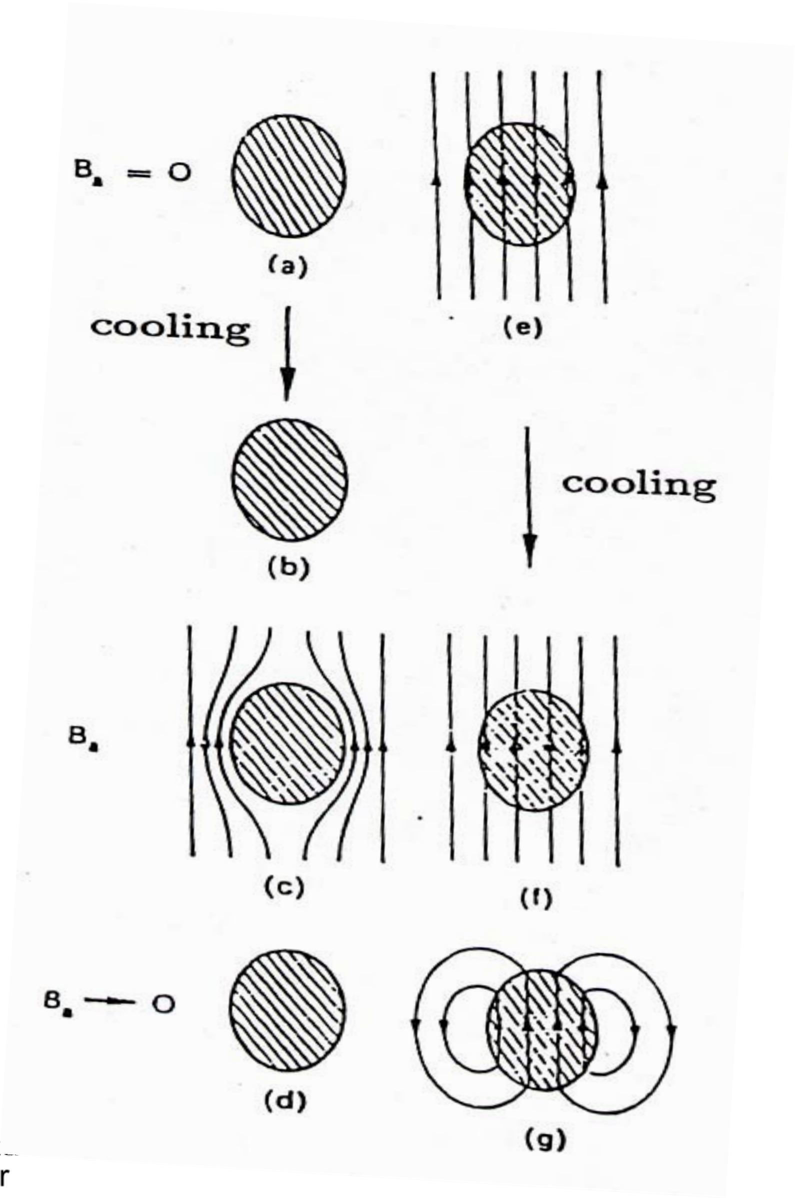
Contrary to the unpaired electrons with spin ½ (fermions), the Cooper pairs have integer spin, i.e. are bosons and can be in the same quantum state, moving resistance-less through lattice

Superconductivity – simple interpretation

https://www.youtube.com/watch?v=O6sukIs0ozk

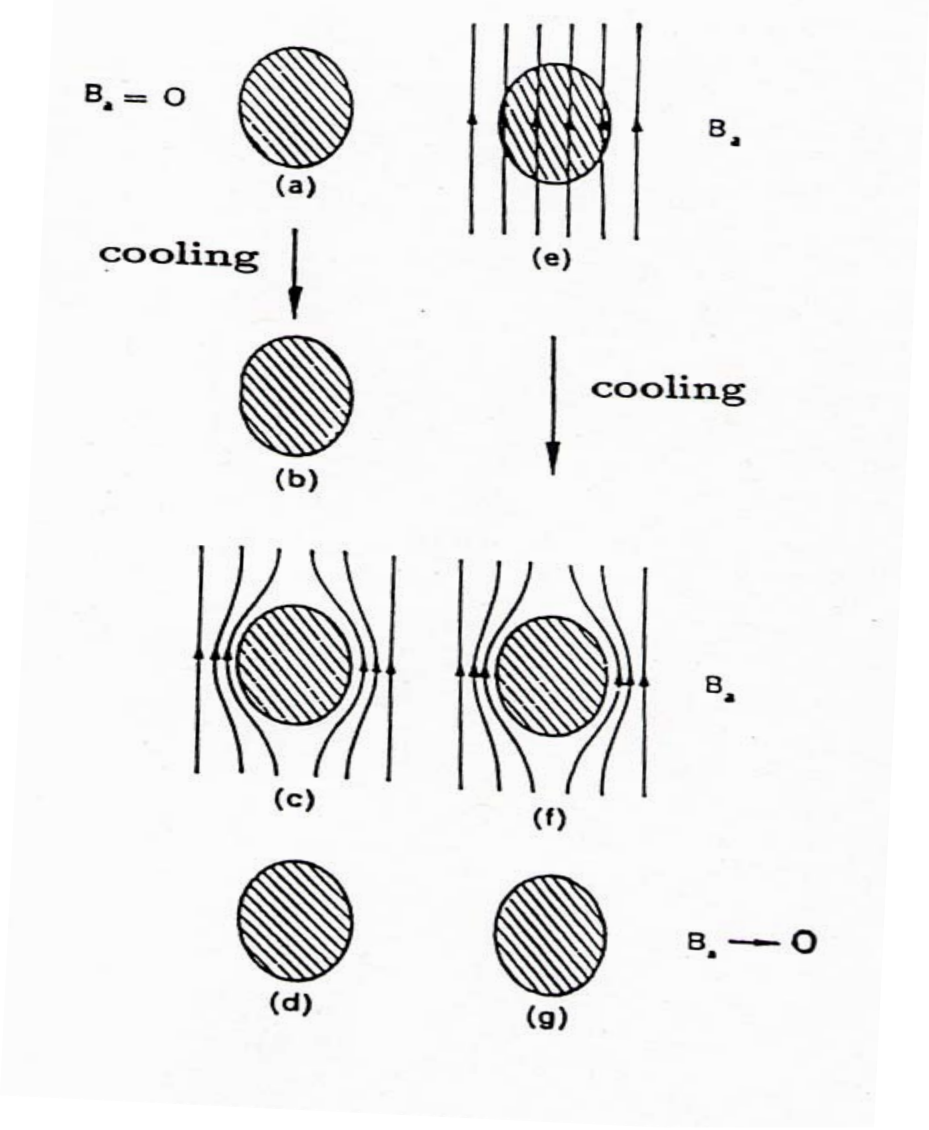
Superconductors vs. perfect conductors

Perfect conductors R=0, dB/dt=0



Superconductors R=0, B=0

(Meissner effect)



Magnetization and Type I vs. Type II SC's

Magnetic flux is excluded from the bulk of superconductors by screening currents flowing at the surface, within the London penetration depth, λ

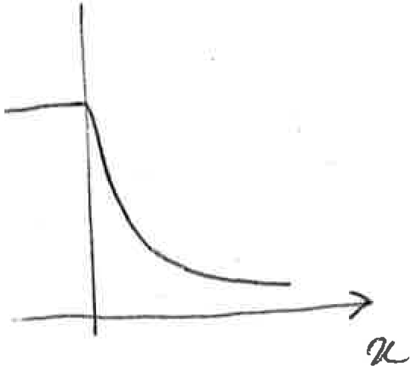
In the superconductor (London theory, 1935):

$$\nabla^2 B = \frac{B}{\lambda^2}$$

$$\lambda^2 = \frac{m_e}{2e^2 \mu_0 n_C}$$

n_C = density of sc carriers

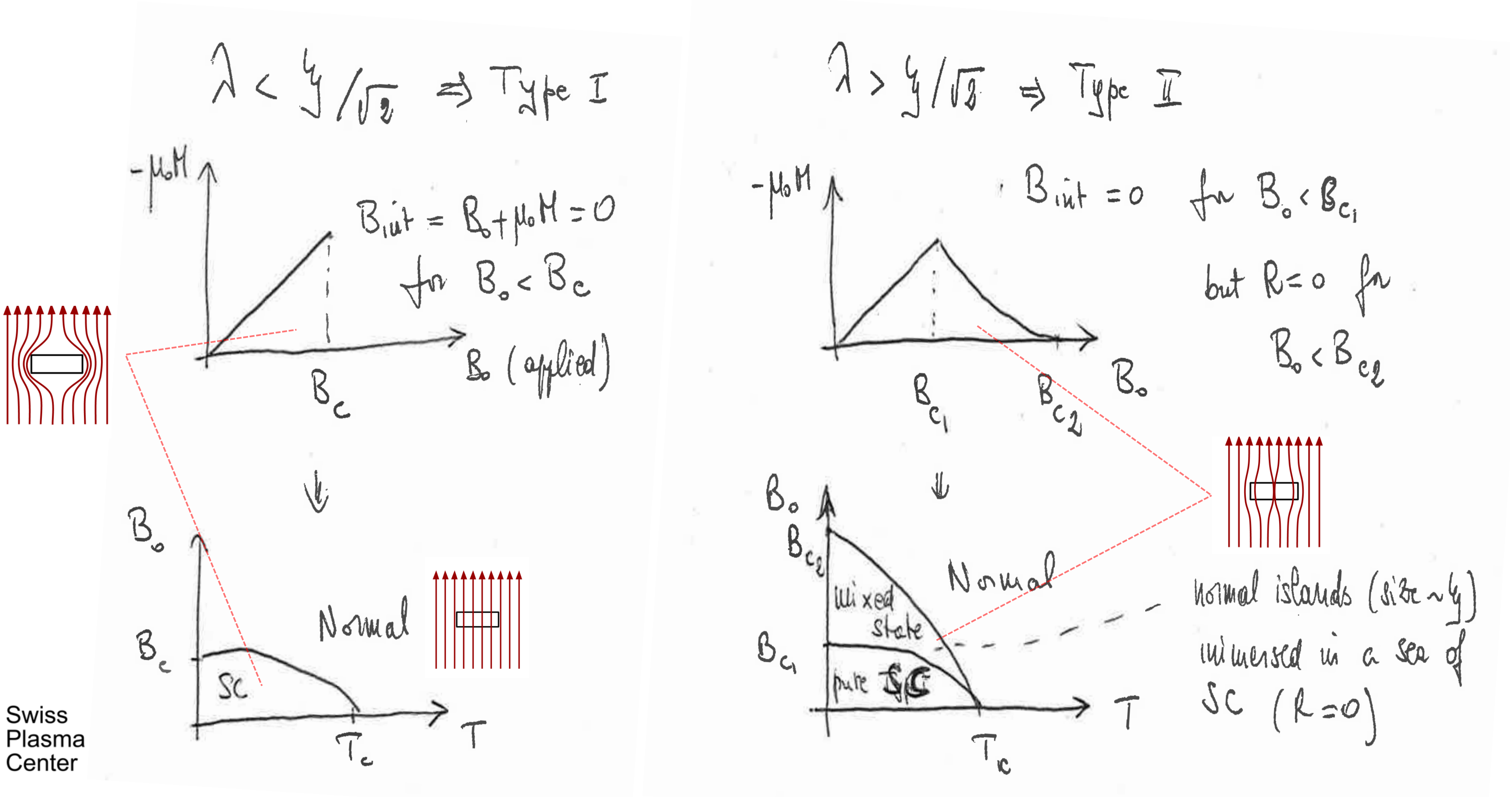
At the boundary $B = B_0 e^{-\frac{x}{\lambda}}$



Magnetization and Type I vs. Type II SC's

Magnetic flux is excluded from the bulk of superconductors by screening currents flowing at the surface, within the London penetration depth, λ

The behavior of superconductors is determined by the ratio between λ and the coherence length ξ, the distance over which superconducting state can change

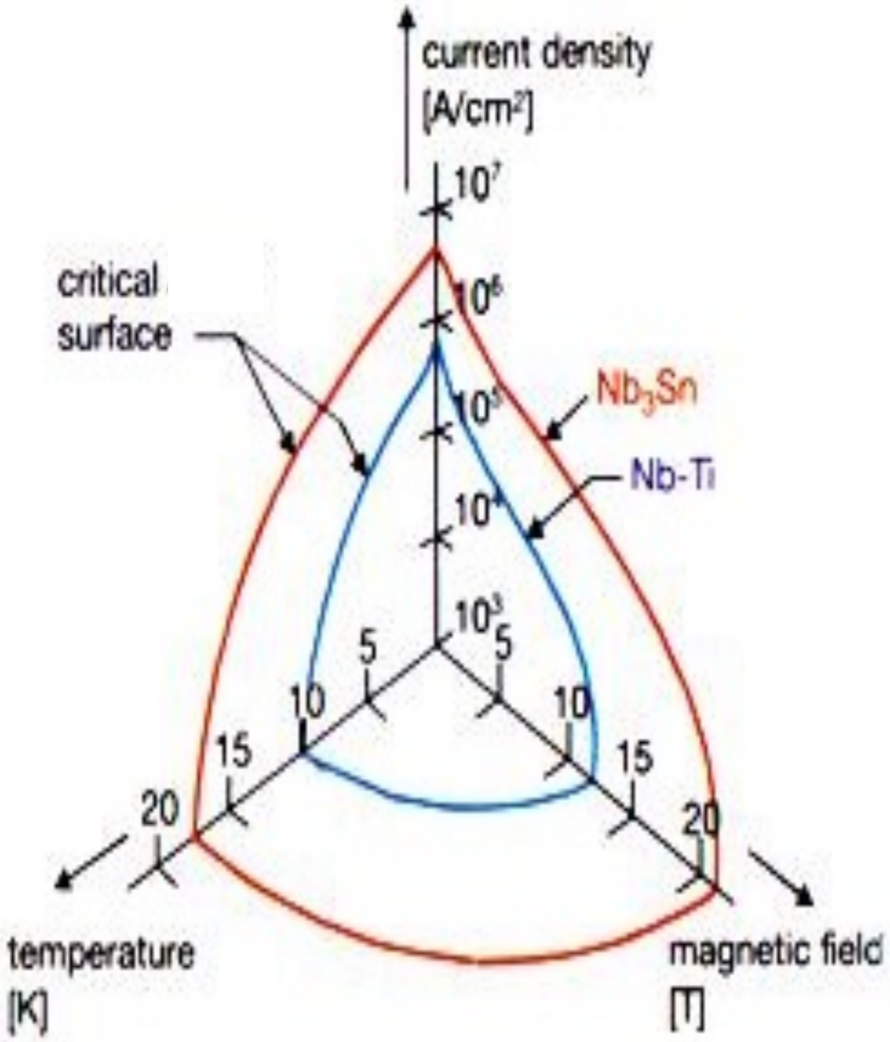


Superconductors for fusion magnets

Low B_c values for Type I SCs prevent their utilisation for fusion magnets

Fusion magnets are based only on Type II SCs and are in mixed magnetic state

For R to drop to zero for temperatures below T_c and magnetic fields below B_{c2}, the current density must also be below a critical value, J_c

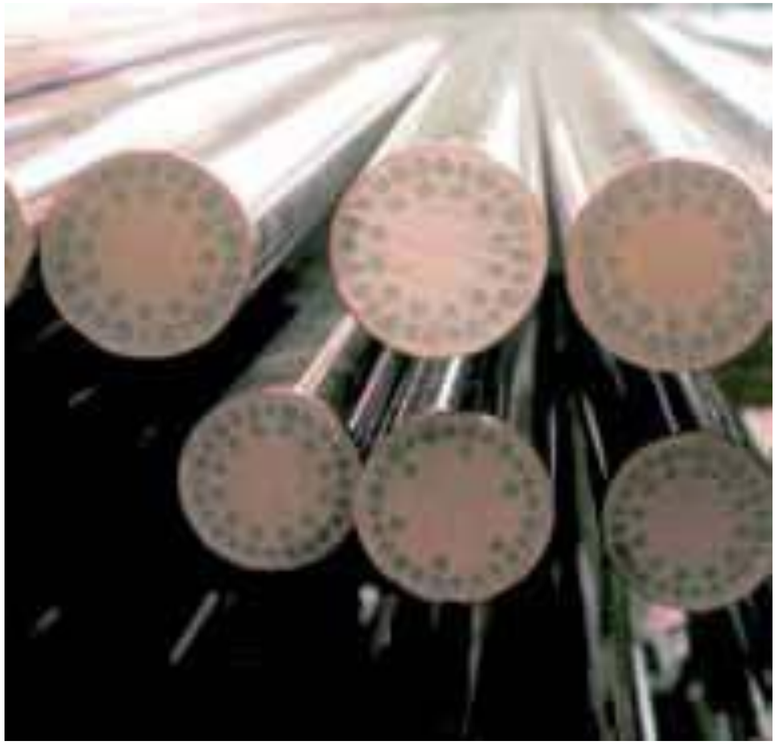


→ **critical J, B and T surface**

Superconducting materials for fusion

NbTi

Typically, the alloy is based on 44% Ti to maximize B_{c2}
T_c = 9.2K; magnets up to 8T
Very ductile, co-drawn with copper, produced in thousands of tons mostly for MRI, ~150-200 €/kg



from Bruker.com

Superconducting materials for fusion

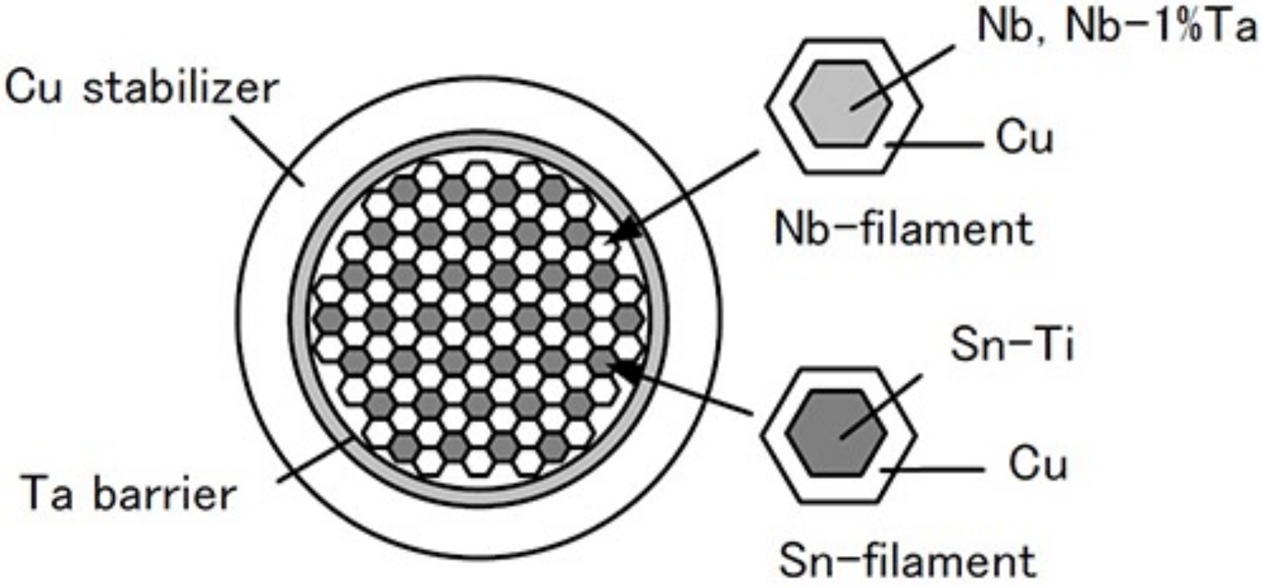
Nb_3Sn

Intermetallic compound created by solid state diffusion of Sn into Nb; T_c = 18K; magnets up to 18T

Issues:

J_c strongly decreases under strain (by 30% for 0.5% strain)

Brittle (difficult to wind); limited production, ~600-1000 €/kg



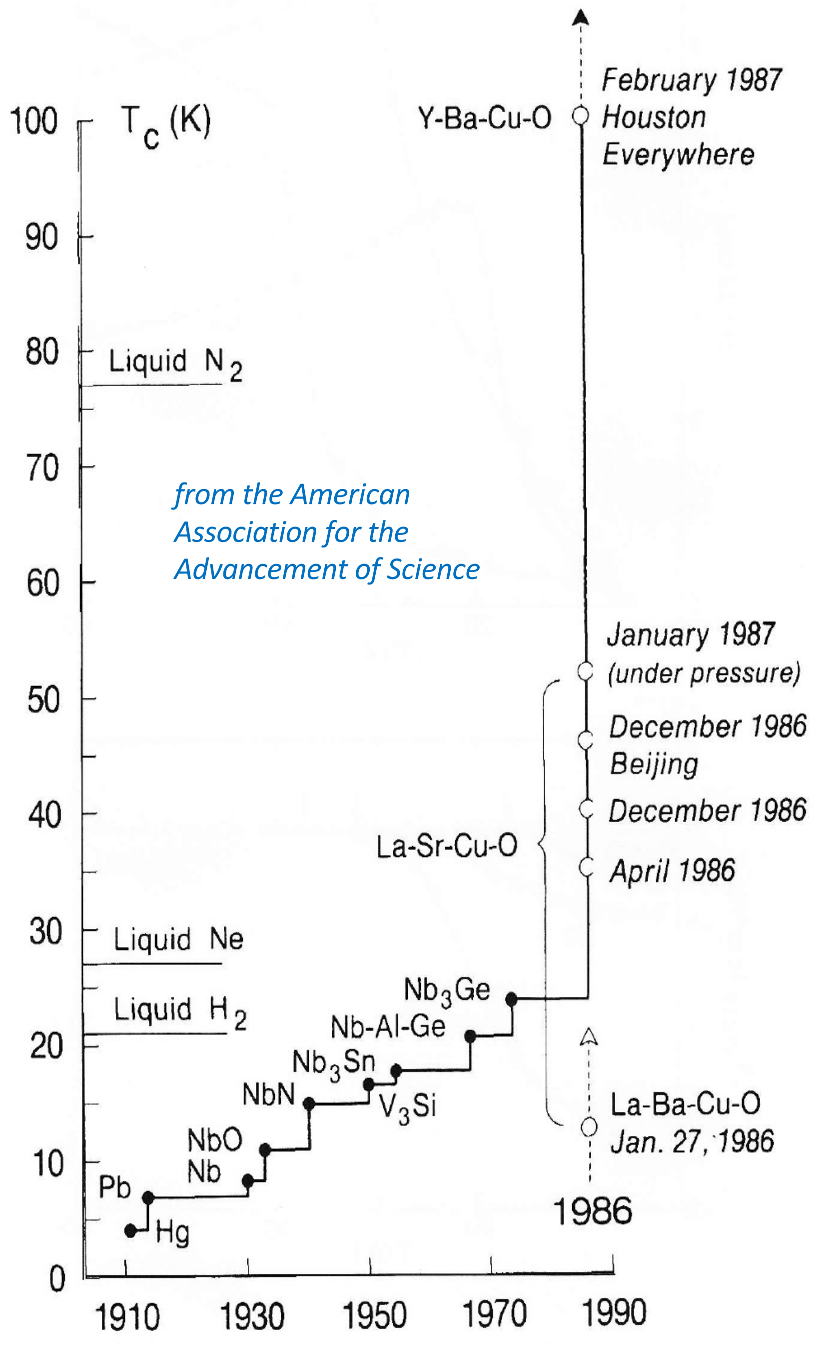
from Hitachi.cable.com

High temperature superconductivity

In 1986 Bednorz and Müller discovered superconductivity at 30K in $(LaBa)^2CuO^4$

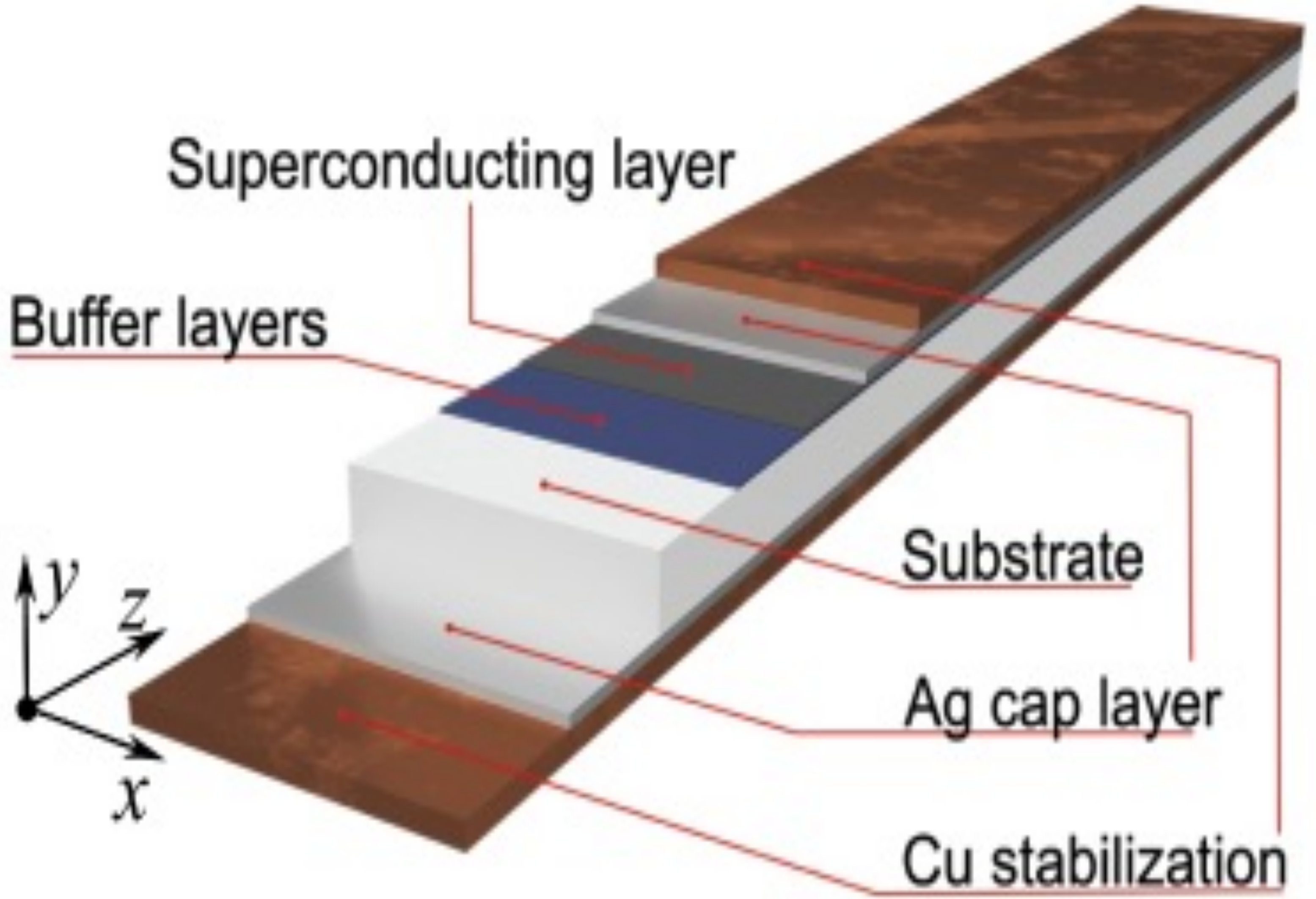
Two classes of HTS materials are potentially suitable for fusion magnets

- Bismuth strontium calcium copper oxide compounds (Bi2212, Bi2223)
- Rare earth barium oxide oxide compounds (ReBCO)



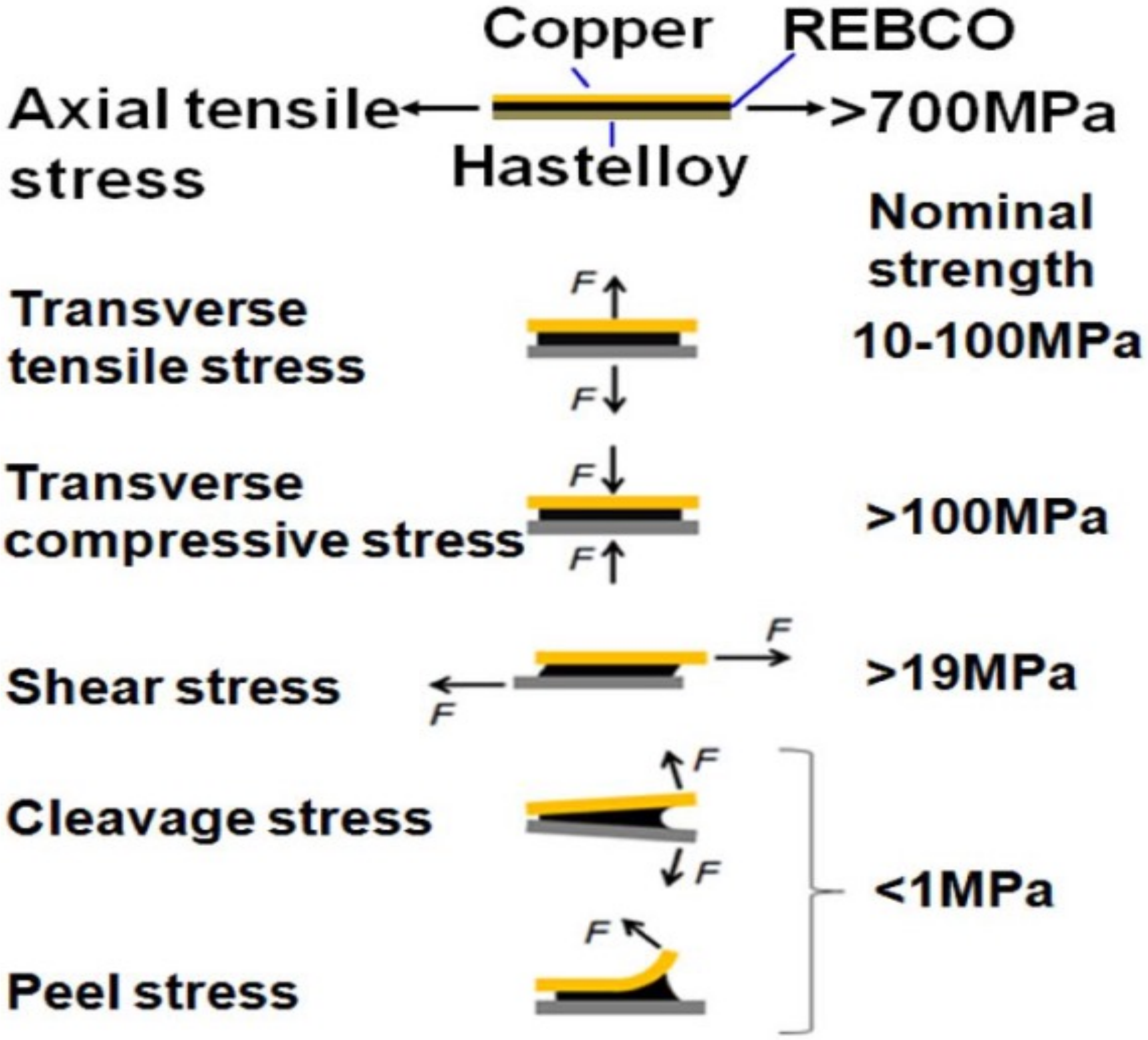
from the American Association for the Advancement of Science

HTS – REBCO tapes



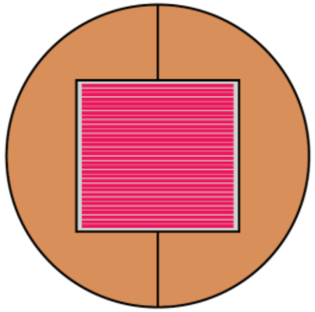
From Superpower.com

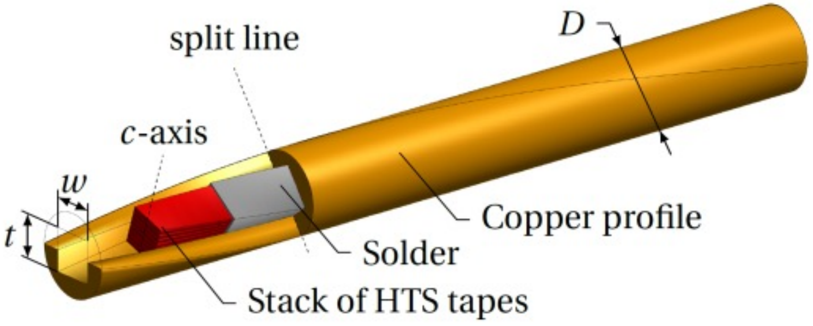
HTS – REBCO tape mechanical issues

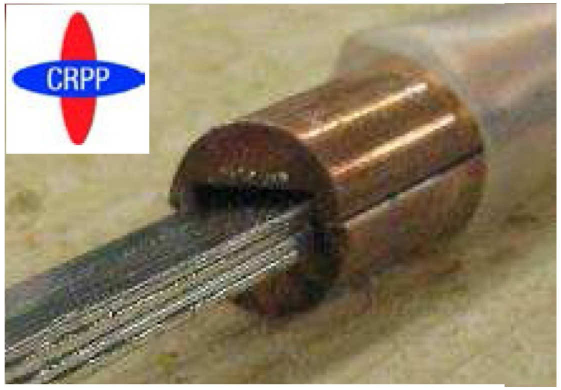


H. Maeda et al., TAS Critical current anisotropy ~ 5 **24** (2014) 4602412

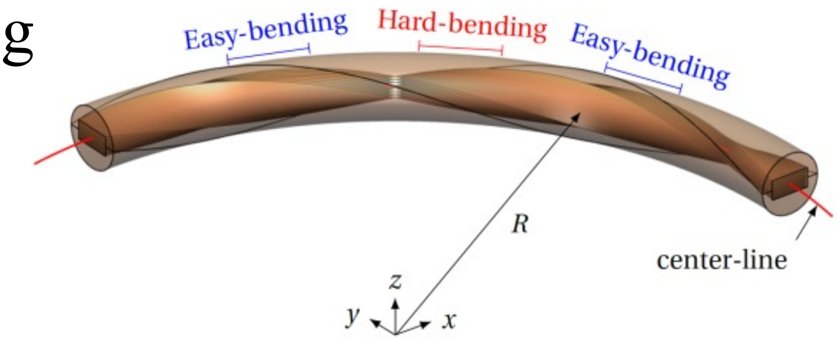
HTS – from tape to cable

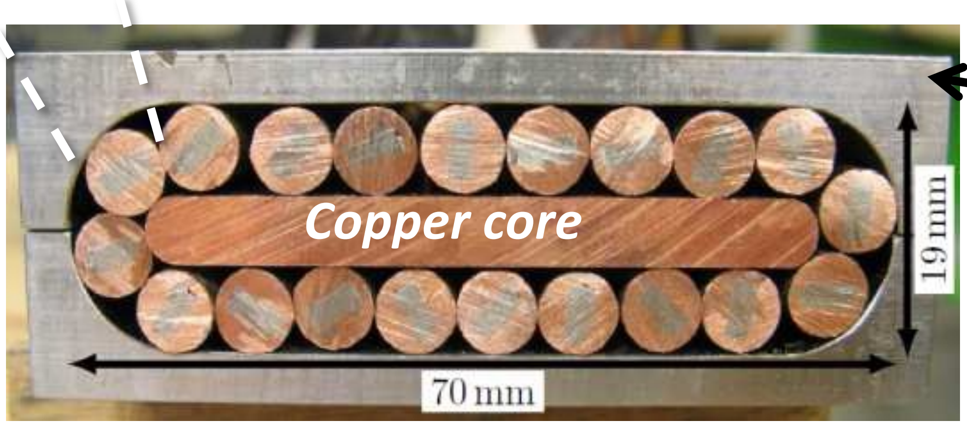






twisting and bending





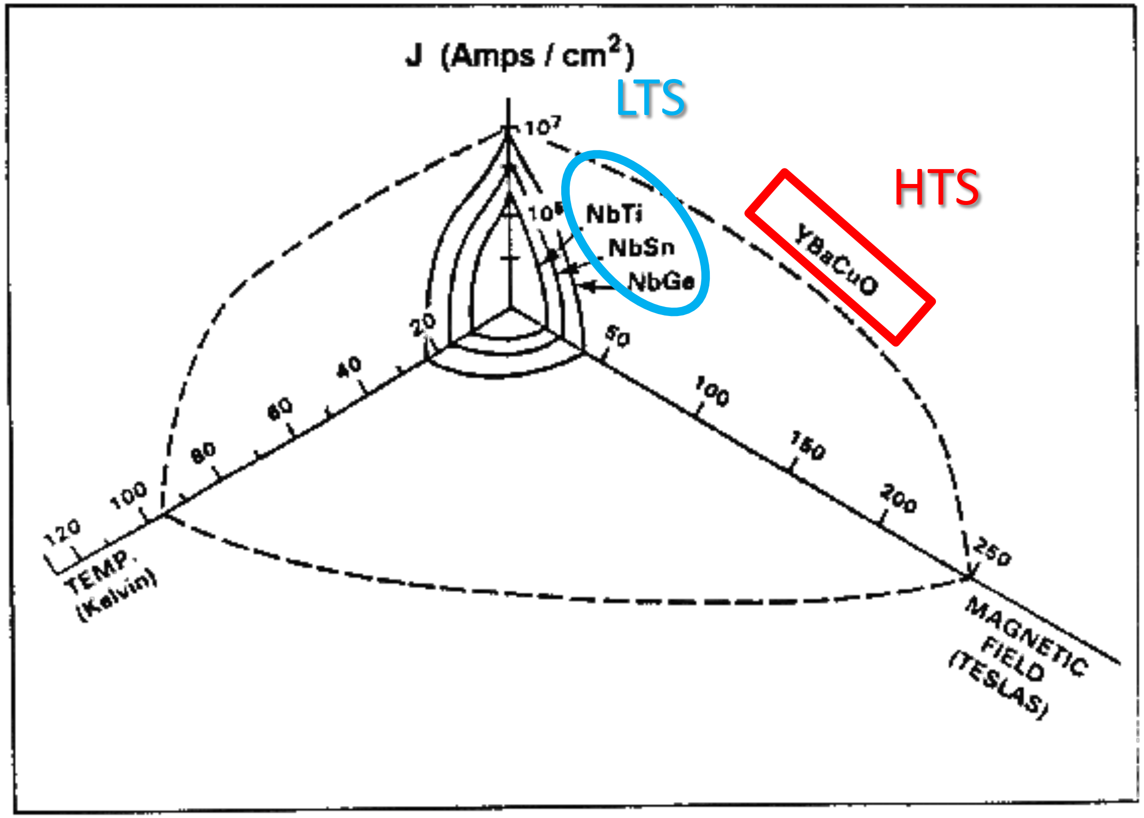
Jacket

Courtesy of O.Dicuonzo

Practical use of HTS

Low B → high temperature

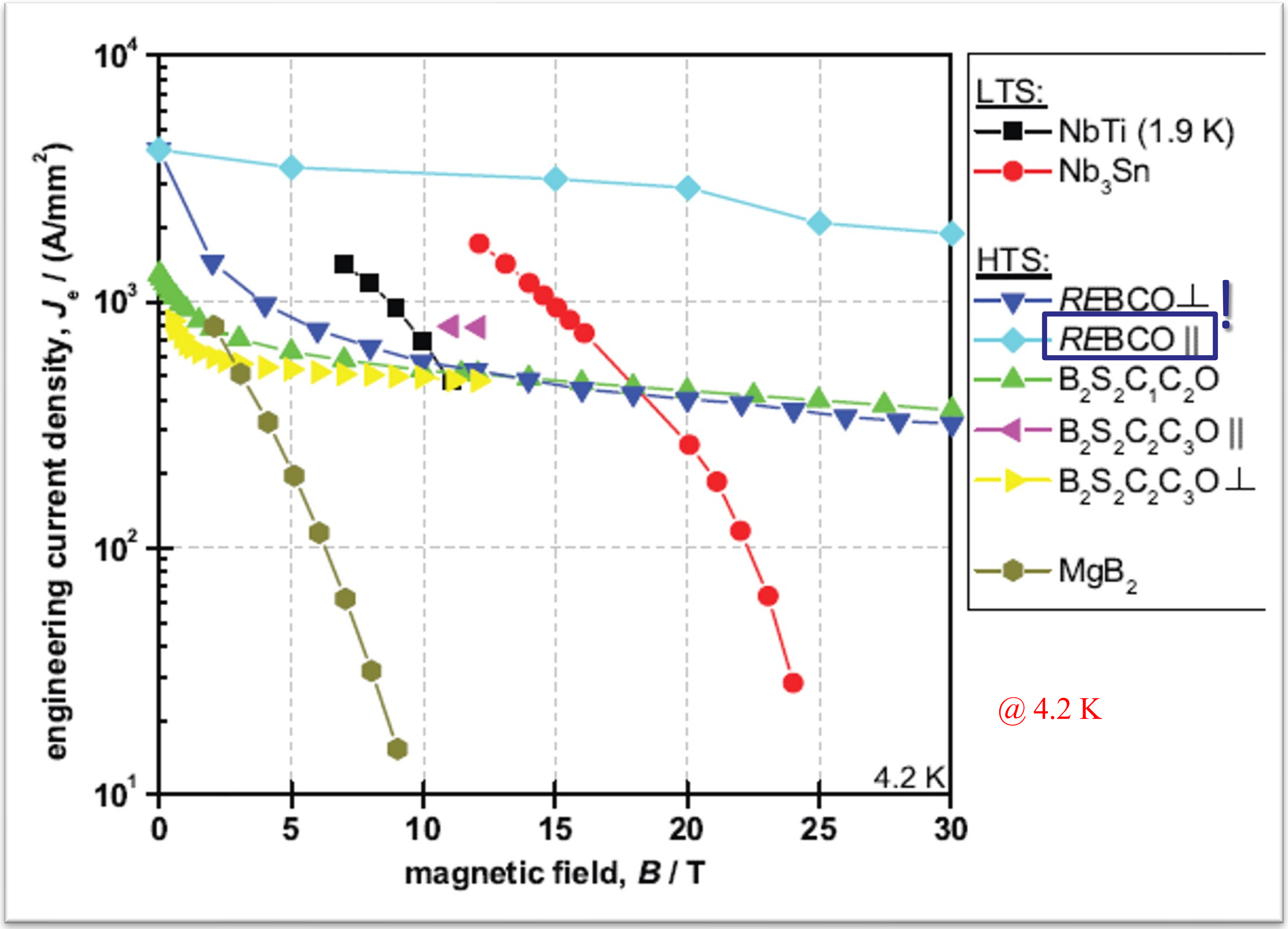
Simpler and cheaper cryogenic systems
OK for energy transportation



Phase Diagram

But for fusion we need high B → low temperature (4.2 K ?)

Which HTS for fusion?



@ 4.2 K

Courtesy of O.Dicuonzo

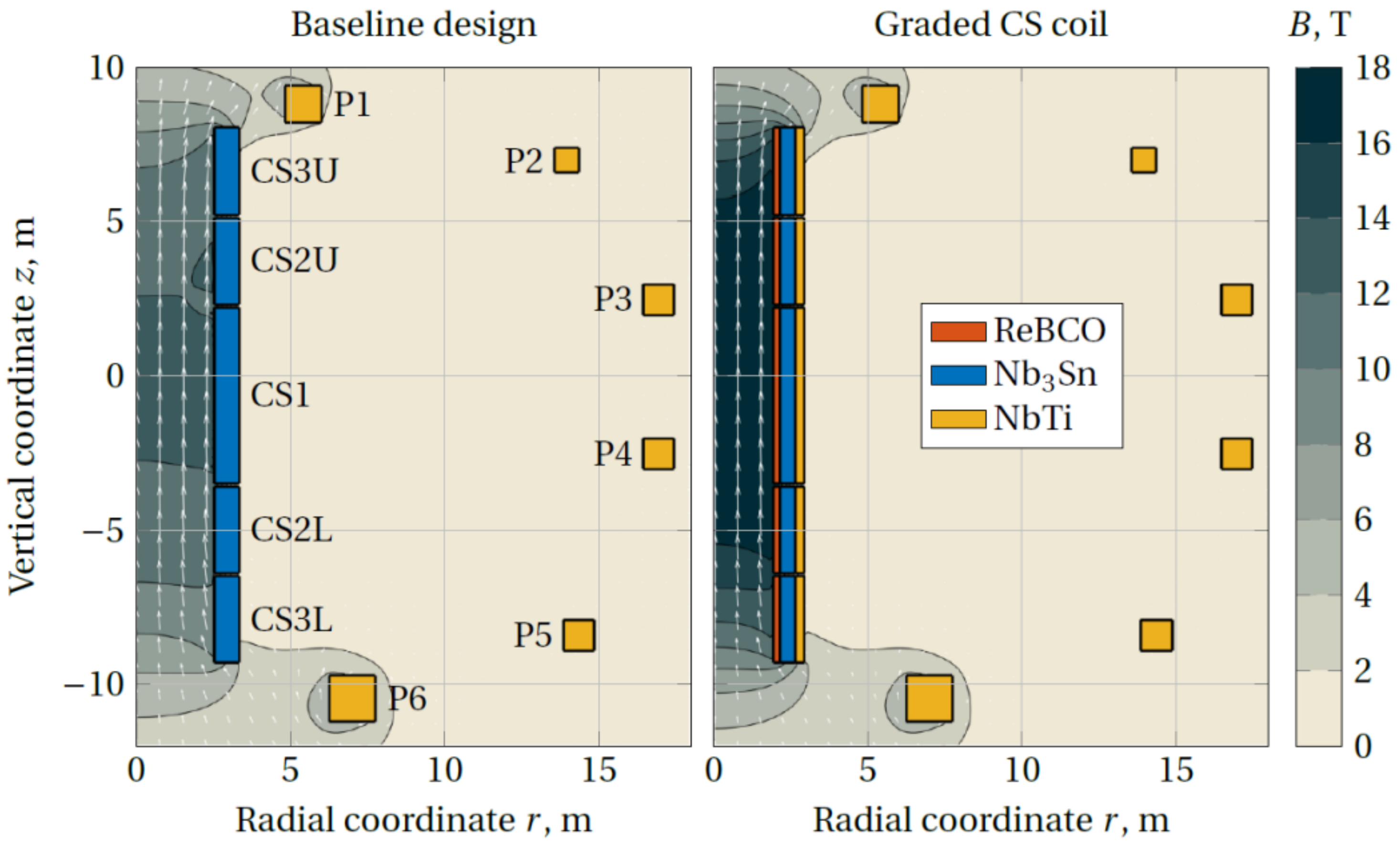
Need high current density at high B → REBCO

Practical use of HTS - grading

Idea: combine LTS and HTS to take advantage of HTS only where it is needed, i.e. in the higher field part of the magnet

Ex. for DEMO central solenoid

- For the same volume, the flux can be increased, or for the same flux the volume (i.e. the cost) can be decreased



N. Bykovsky, “HTS high current cable for fusion application”, PhD thesis

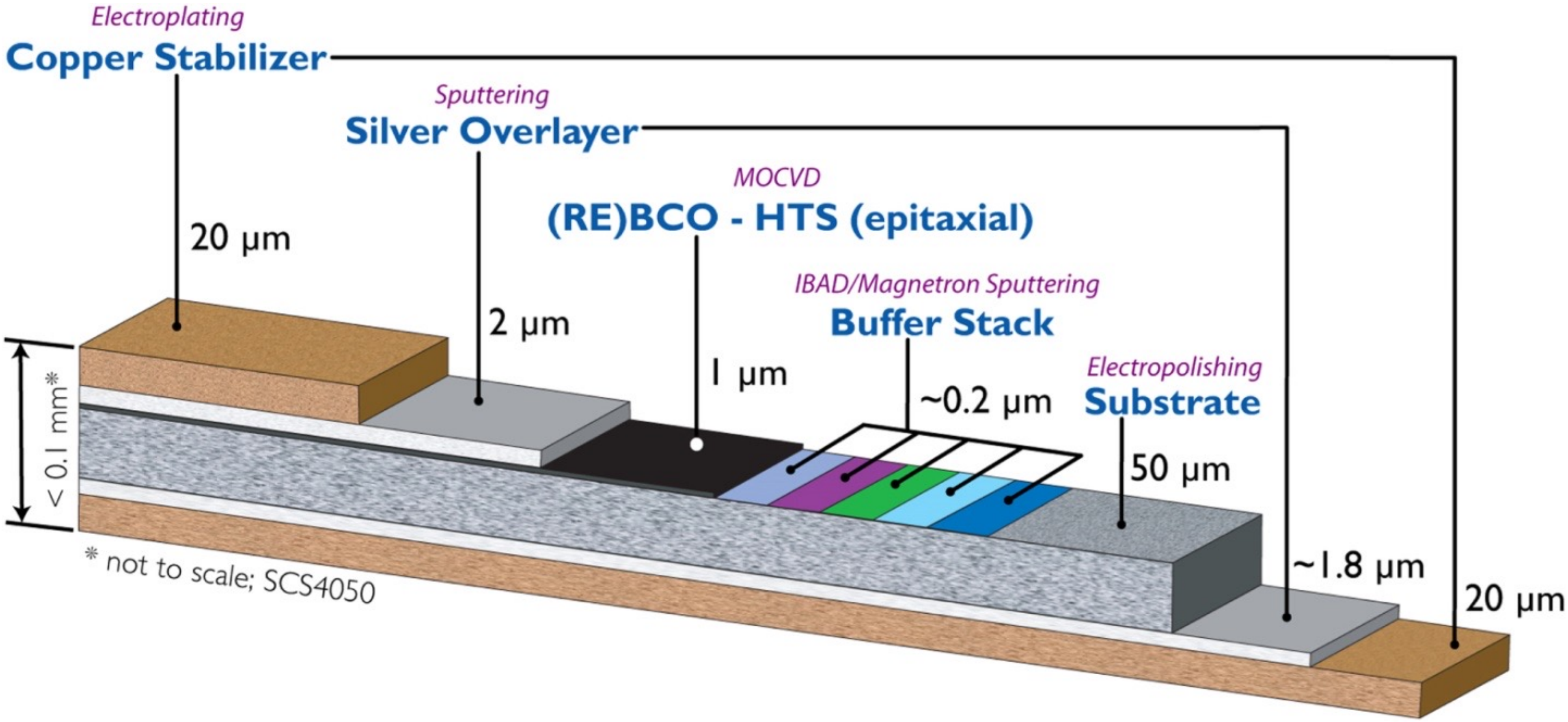
HTS materials for fusion

HTS (YBCO)

Ceramic thin film on tape

T_c~100K; at low temperature withstands fields up to 50T

Limited industrial production, ~12-17 k€/kg



Schematic of SuperPower's 2G HTS wire with 50 μm substrate [Sundaram, A., et al.: Supercond. Sci. Technol. **29**, 104007 (2016).]

High current cables for fusion magnets

Cables based on NbTi or Nb_3Sn consist of small strands formed by thin SC filaments (ø~50µm) inside a Cu matrix

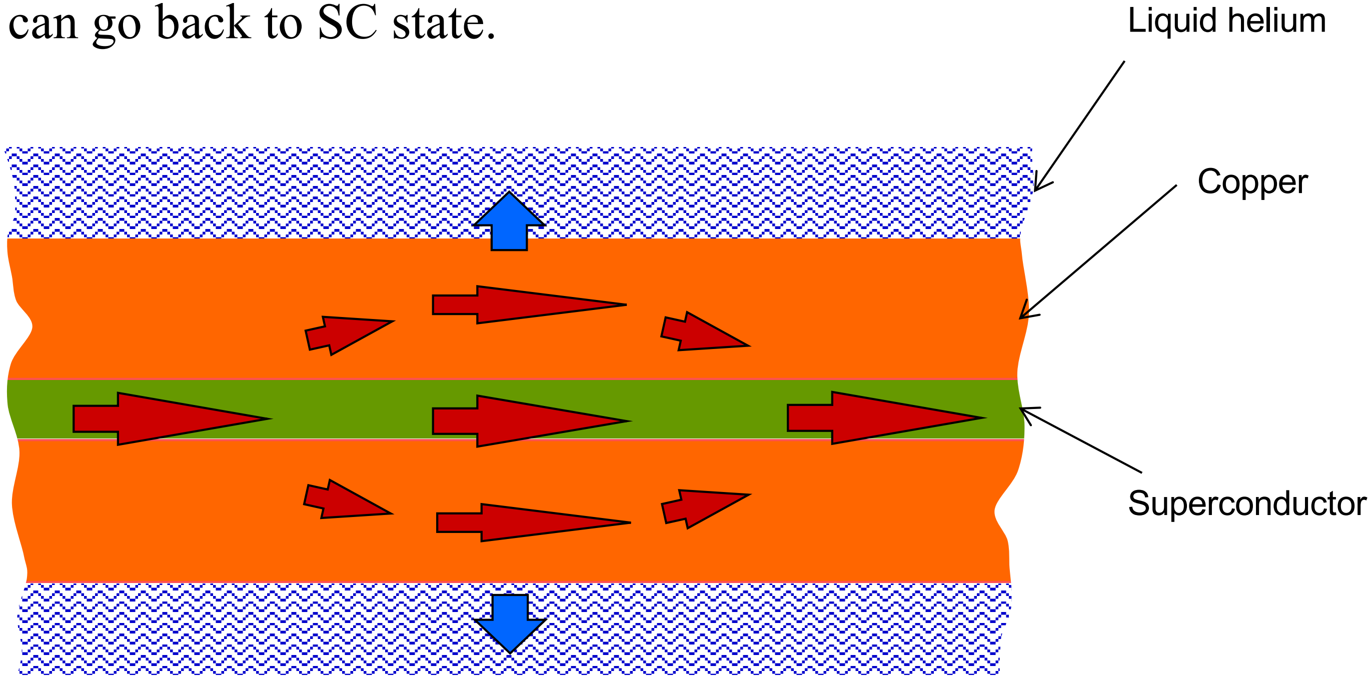
Why do we need copper ?

High current cables for fusion magnets

Cables based on NbTi or Nb_3Sn consist of small strands formed by thin SC filaments (ø~50µm) inside a Cu matrix

Why do we need copper ?

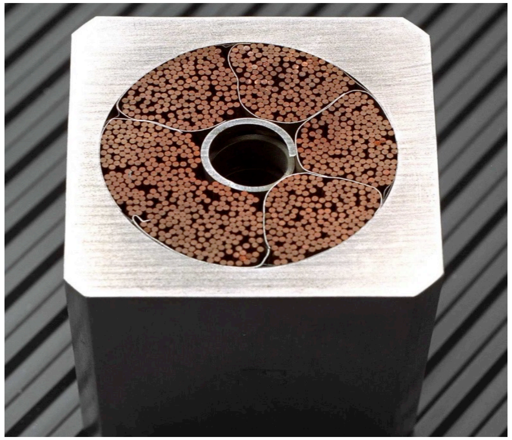
Cu is needed as disturbances may cause a short portion of the SC to become normal. The current then flows in the Cu section, as Cu has lower resistance than non-SC NbTi or Nb_3Sn. If the heat generated is evacuated efficiently, the conductor can go back to SC state.



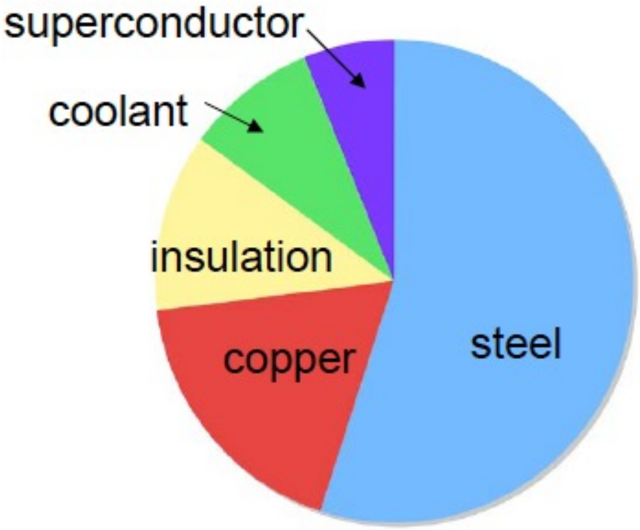
High current cables for fusion magnets

Cables based on NbTi or Nb_3Sn consist of small strands formed by thin SC filaments (ø~50µm) inside a Cu matrix

Fusion magnets use large cables with high current because they allow reducing the number of turns, hence the magnet inductance



ITER uses *Cable in Conduit Conductors*. Helium flows between the strands and in the central hole. The steel jacket is needed to cope with the JxB force

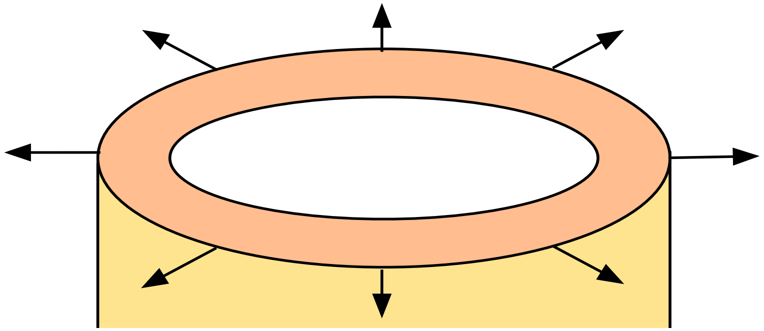


Requirements and challenges - Mechanical

Large, high-B fusion magnets experience large electromagnetic loads, thus most of their volume consists of stainless steel

Main loads, all from JxB force

- Hoop load along the conductor axis, ~BxIxR



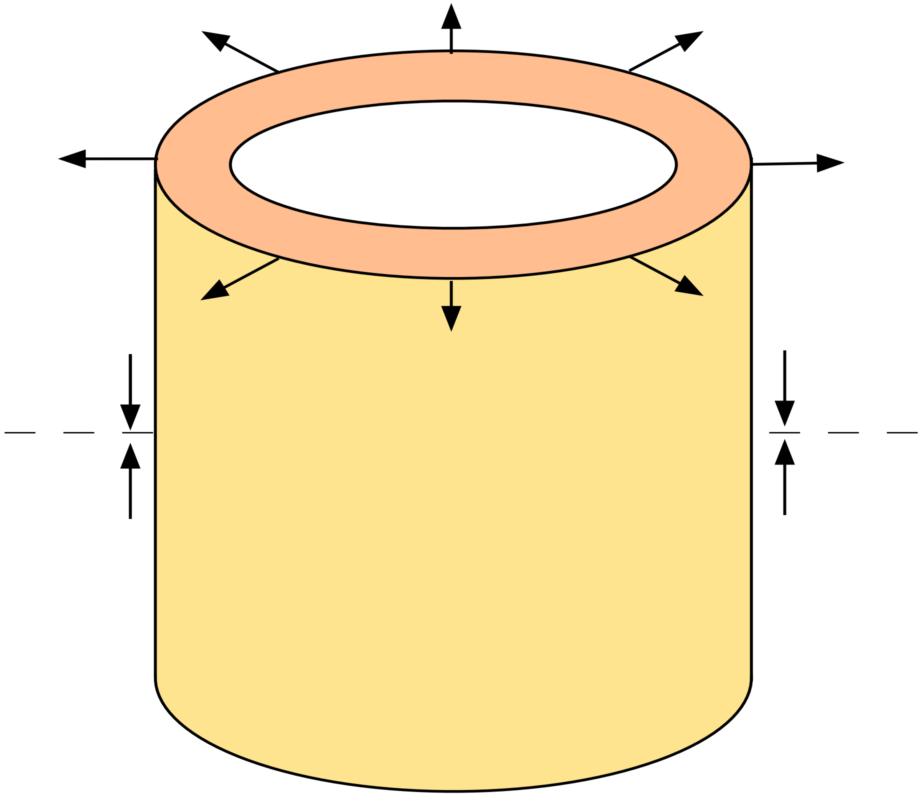
Solenoid

Requirements and challenges - Mechanical

Large, high-B fusion magnets experience large electromagnetic loads, thus most of their volume consists of stainless steel

Main loads, all from JxB force

- Hoop load along the conductor axis, ~BxIxR
- Vertical load on the coil mid-plane (axial compression of solenoid as B_r is high at the coil ends)



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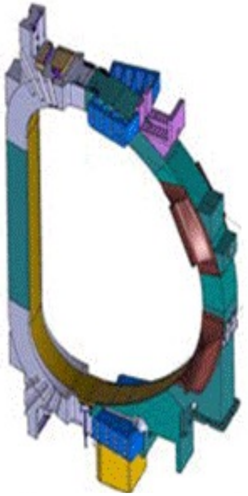
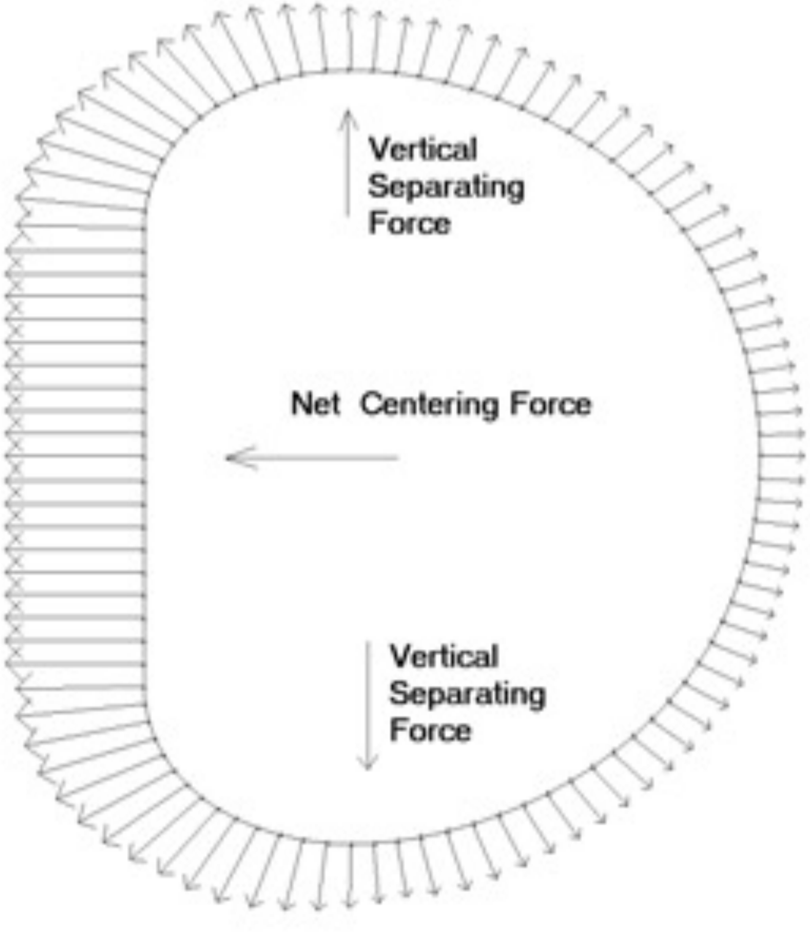
- Centering load on the in-board of non-circular toroidal field coils, ~BxI





Non-circular TF coil (e.g. ITER)

Requirements and challenges - Mechanical

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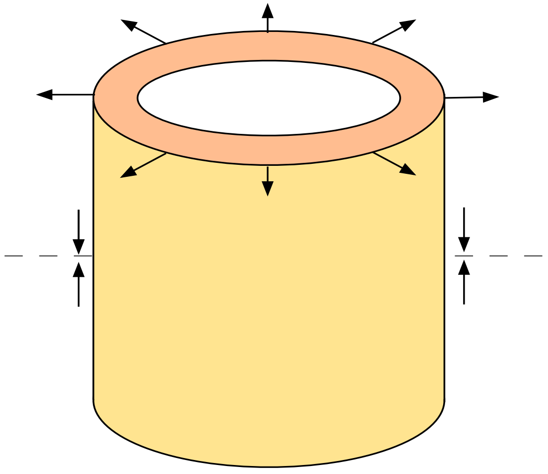
- Centering load on the in-board of non-circular toroidal field coils, ~BxI

Transverse load accumulation from turn to turn must be avoided for brittle SC (Nb_3Sn and HTS); for this, a high elastic modulus conduit surrounds the cable



Solenoid

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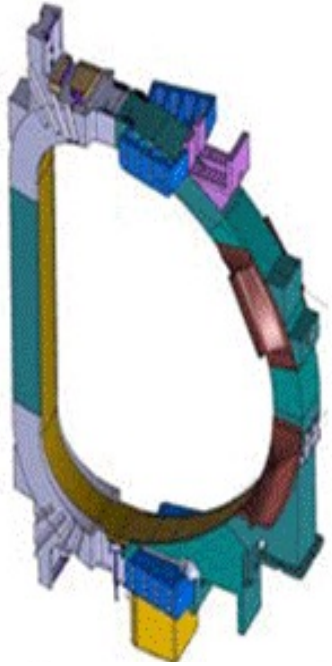
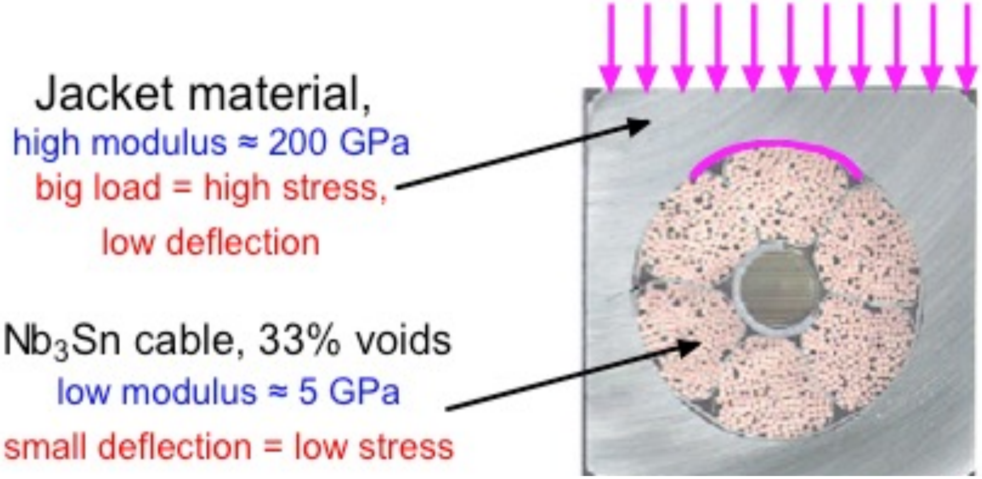




Jacket material,
high modulus ≈ 200 GPa
big load = high stress,
low deflection

Nb_3Sn cable, 33% voids
low modulus ≈ 5 GPa
small deflection = low stress

Requirement and challenges - Thermal

The large mass of the SC magnets is kept cold in a cryostat by large He refrigerators, which use a few tens MW electric power to remove heat load of several tens kW at low temperature

Main heat loads

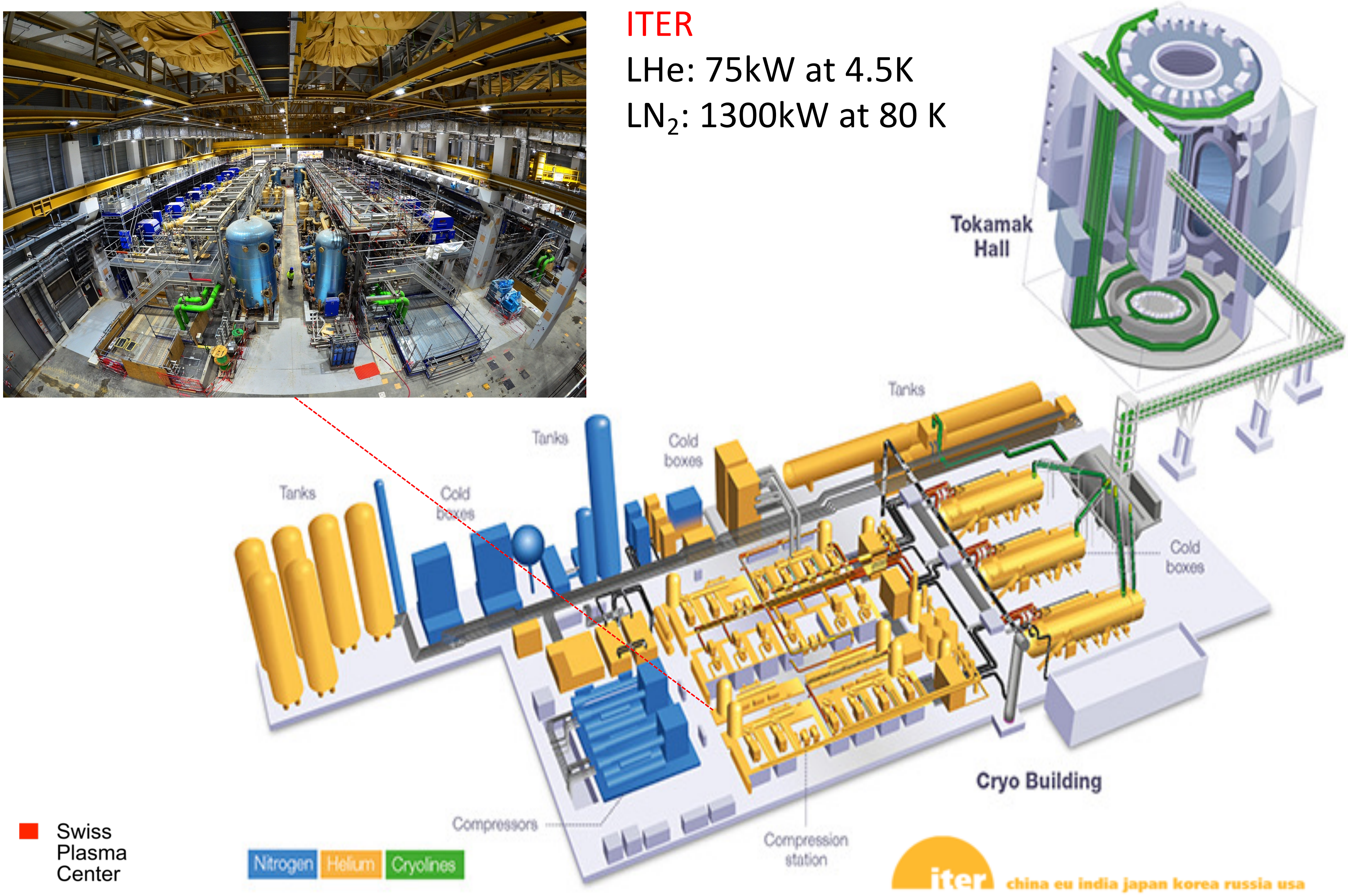
- Nuclear radiation on the TF coils
- Ohmic heating of the conductor joints
- Heat conduction (feeders and gravity support)
- AC losses in the coils
- Pumping losses for He circulation
- Heat radiation from room temperature

Requirement and challenges - Thermal

ITER

LHe: 75kW at 4.5K

LN_2: 1300kW at 80 K



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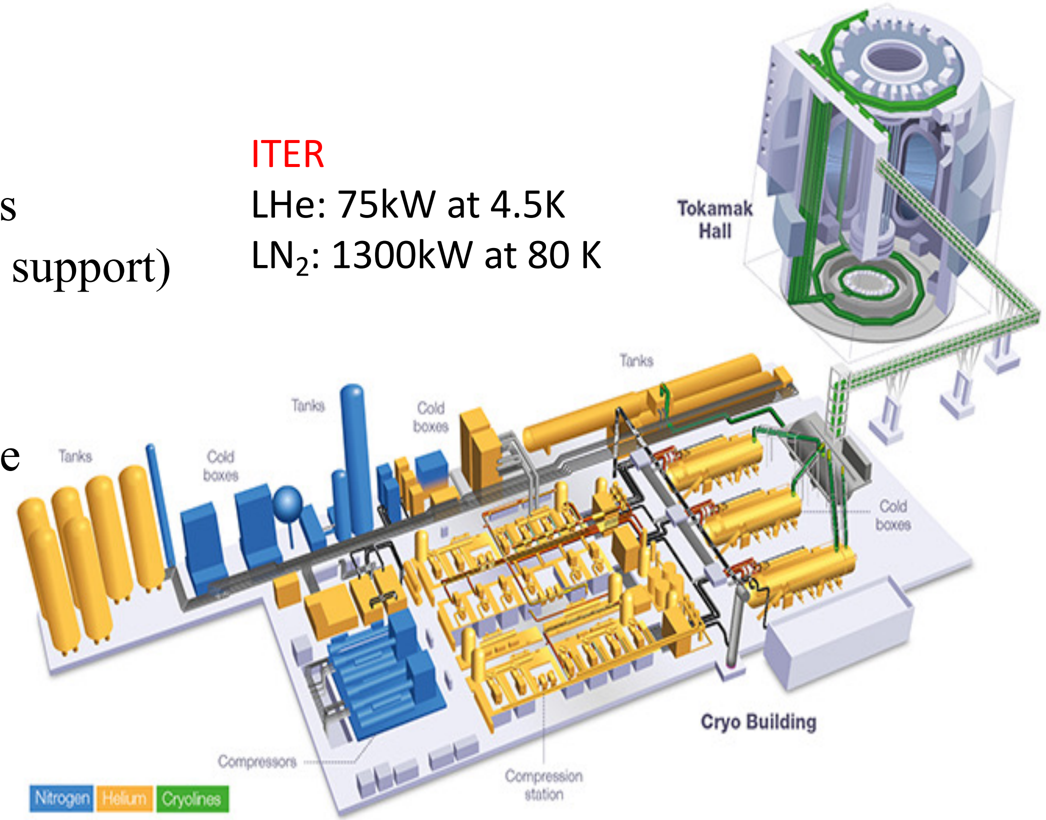
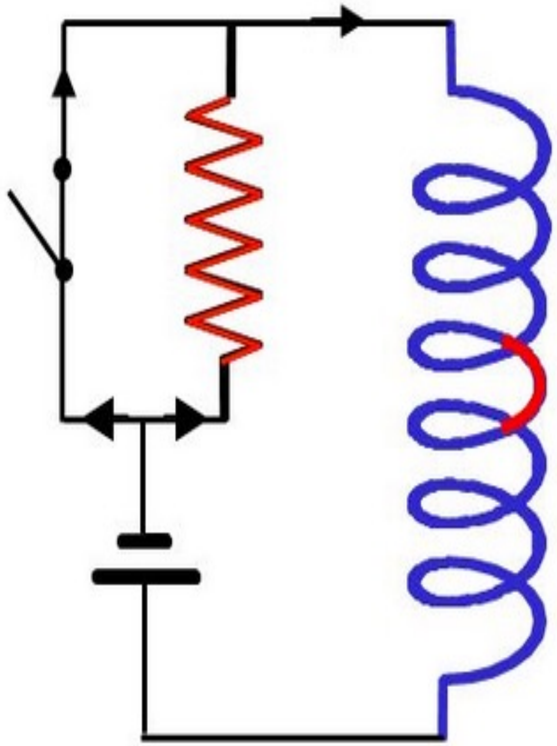


The variation of the operating temperature must be kept within a temperature margin of ~1-2 K

Also HTS also must be cooled below ~10-20 K to withstand high fields

Requirement and challenges - Electrical

In case of *quench* (local, irreversible loss of superconductivity), the SC magnets must be quickly discharged, dumping the large stored energy in external resistors and preventing damage by high temperature spots in the winding



Main challenges

- 100% reliable, fast quench detection system
- High voltage, high current, fast current breakers
- High voltage insulation for feeders and winding

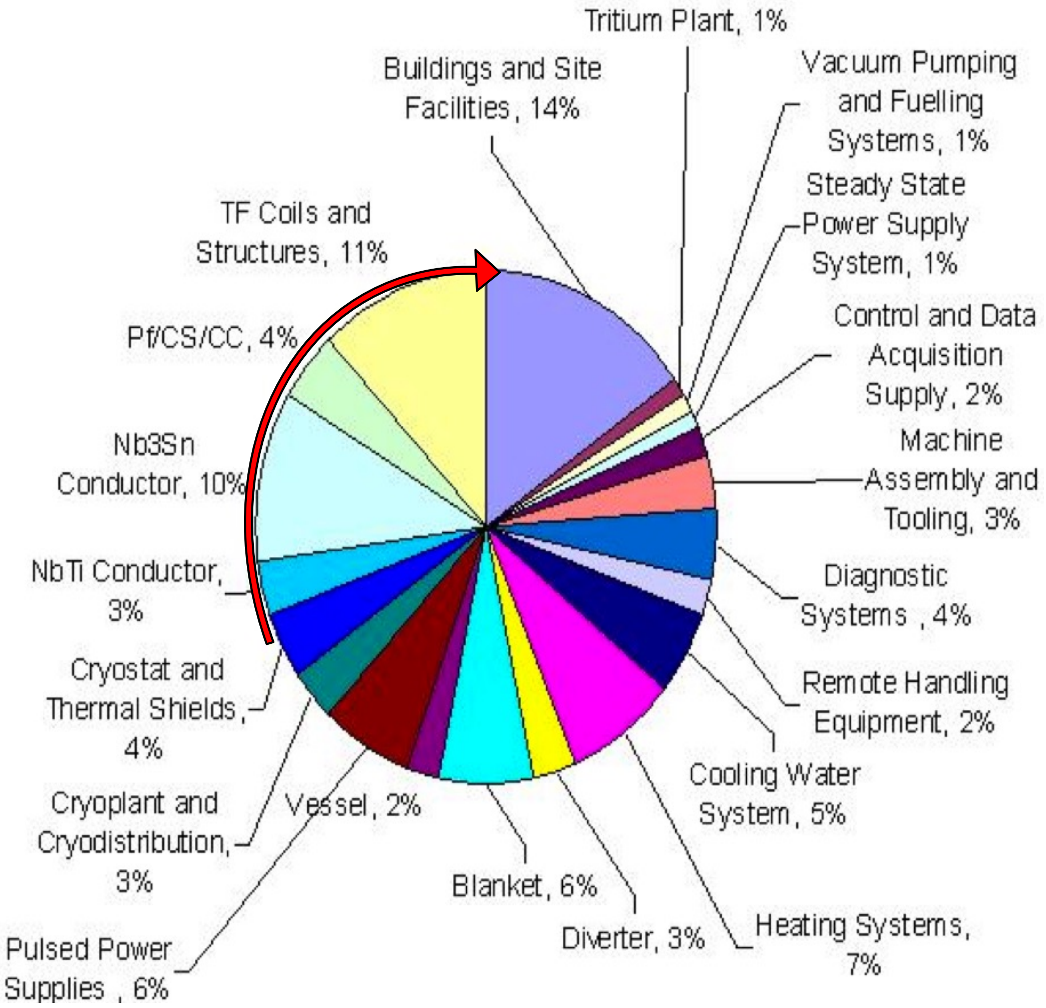
In fusion magnets, electrical insulation consists of Glass-Kapton wraps impregnated by epoxy. The quality of the impregnation is crucial for the coil mechanical integrity and to prevent flashovers to ground during the fast discharge

Requirement and challenges - Economical

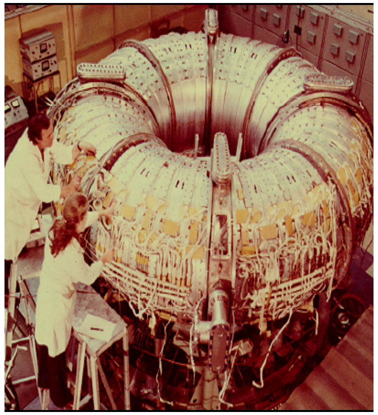
Cost of SC material is ~100-1000 times that of Cu

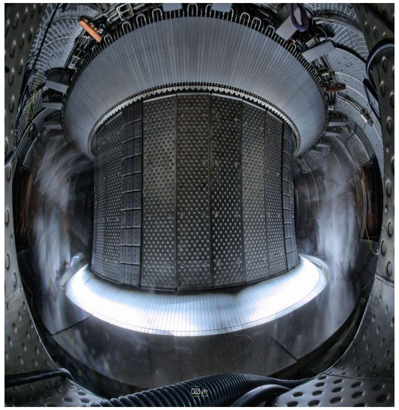
SC magnets make up a substantial fraction of the capital cost for a large fusion device, 30% for ITER

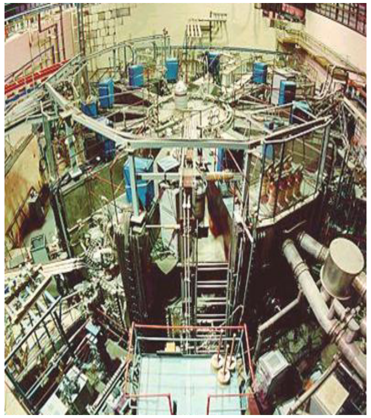
Cost effective design and manufacture of SC magnets are crucial issues on the way to commercially competitive fusion reactors

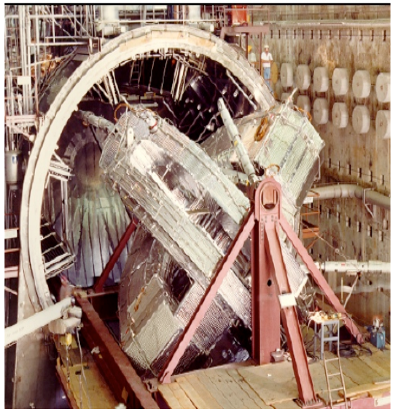


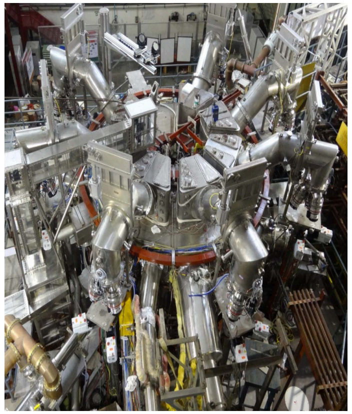
Present fusion devices with sc coils

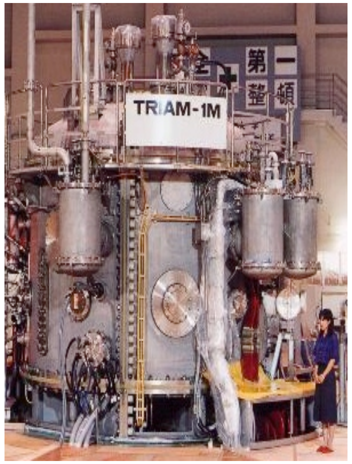

T 7 at Kurchatov -1977
NbTi, He forced flow, 5T


WEST at CEA -2017
NbTi, He bath, 9T

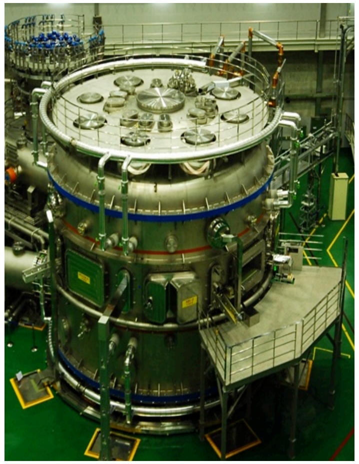

T 15 at Kurchatov -1983
Nb_3Sn, He forced flow, 9.3T


MFTF Livermore -1985
NbTi/Nb_3Sn, He bath 12.7T

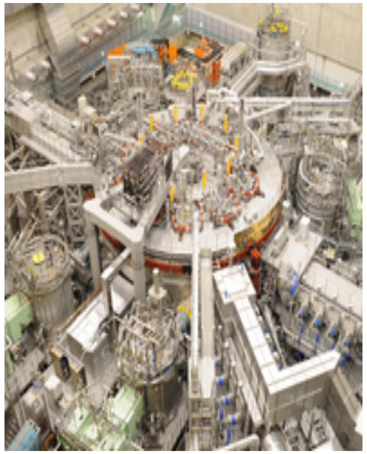

SST1 Bath - 2013
NbTi, He forced flow, 5T

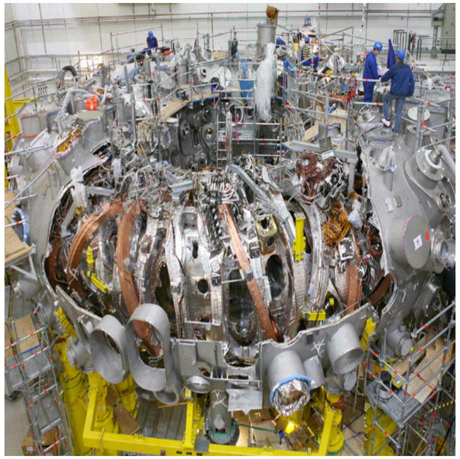


TRIAM Fukuoka -1986
Nb_3Sn, He bath, 11T

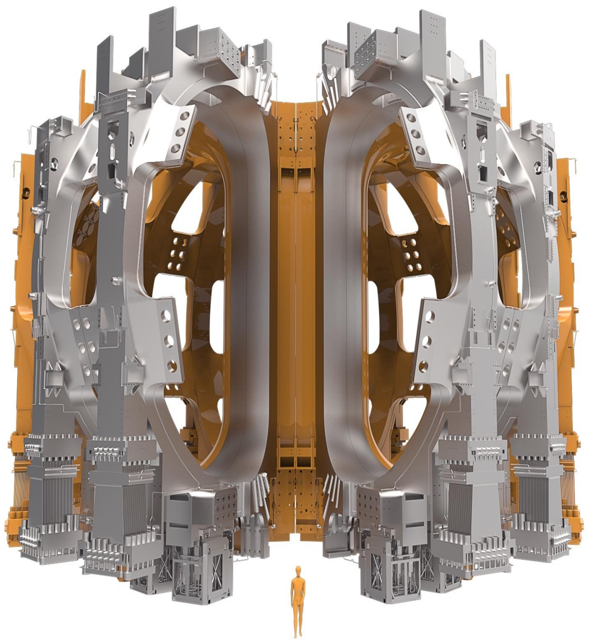

KSTAR- Daejeon 2007
Nb_3Sn, He forced flow, 8T


EAST Hefei - 2006
NbTi, He forced flow, 5.8T

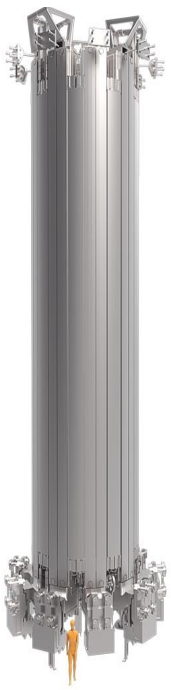

LHD Toki - 1996
NbTi, He bath, 6.9T


W7-X 7 Greifswald -2016
NbTi, He forced flow, 6T

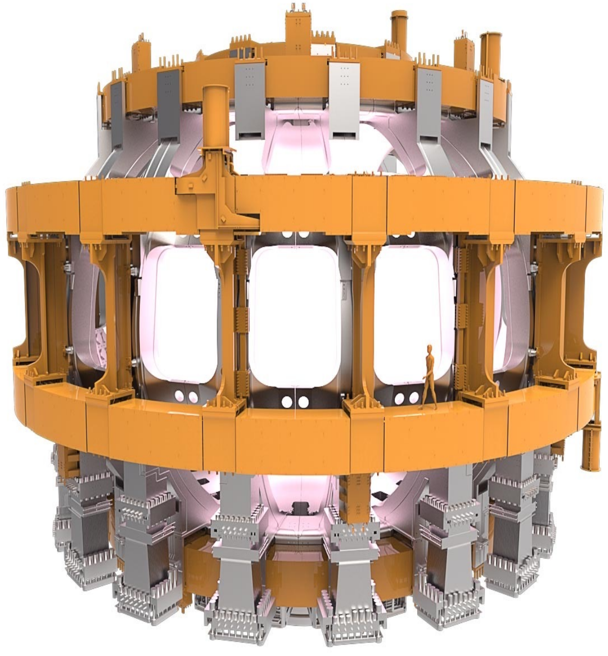
ITER magnets system – the largest ever built



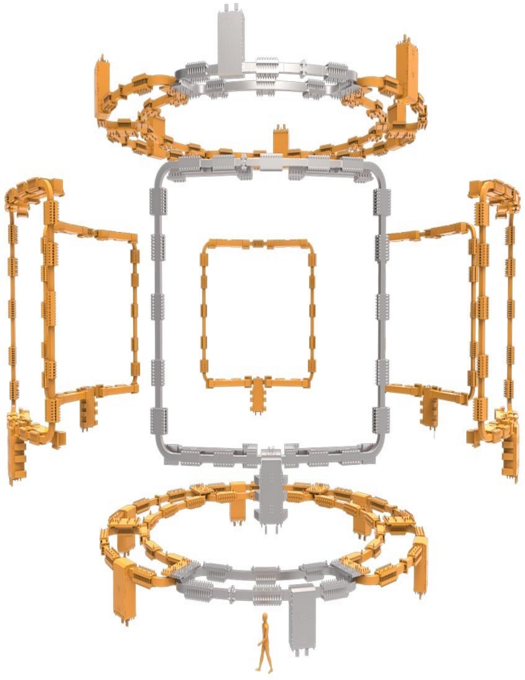
TF coils
Nb_3Sn, 11.8T



Central solenoid
Nb_3Sn, 13T



Poloidal coils
NbTi, 6T



Correction coils
NbTi, 4.2T

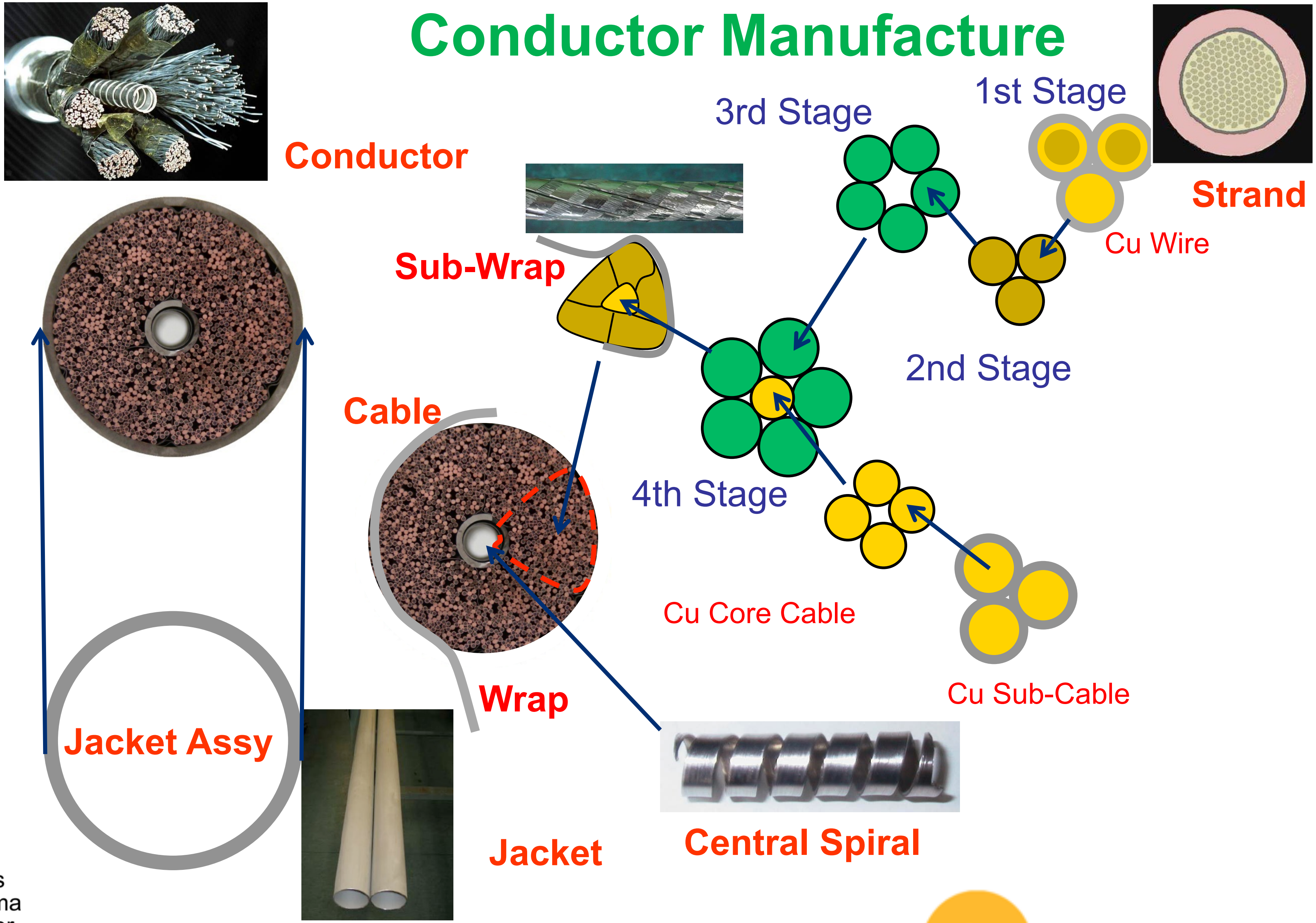
48 SC coils, total stored energy = 51GJ

Cooled with supercritical He at 4K

Nb_3Sn strand for TF coils and central solenoid: 500 tons, 100’000km

ITER magnets system – construction

Conductor Manufacture



Conductor

Strand

1st Stage

3rd Stage

Cu Wire

Sub-Wrap

2nd Stage

Cable

4th Stage

Cu Core Cable

Cu Sub-Cable

Wrap

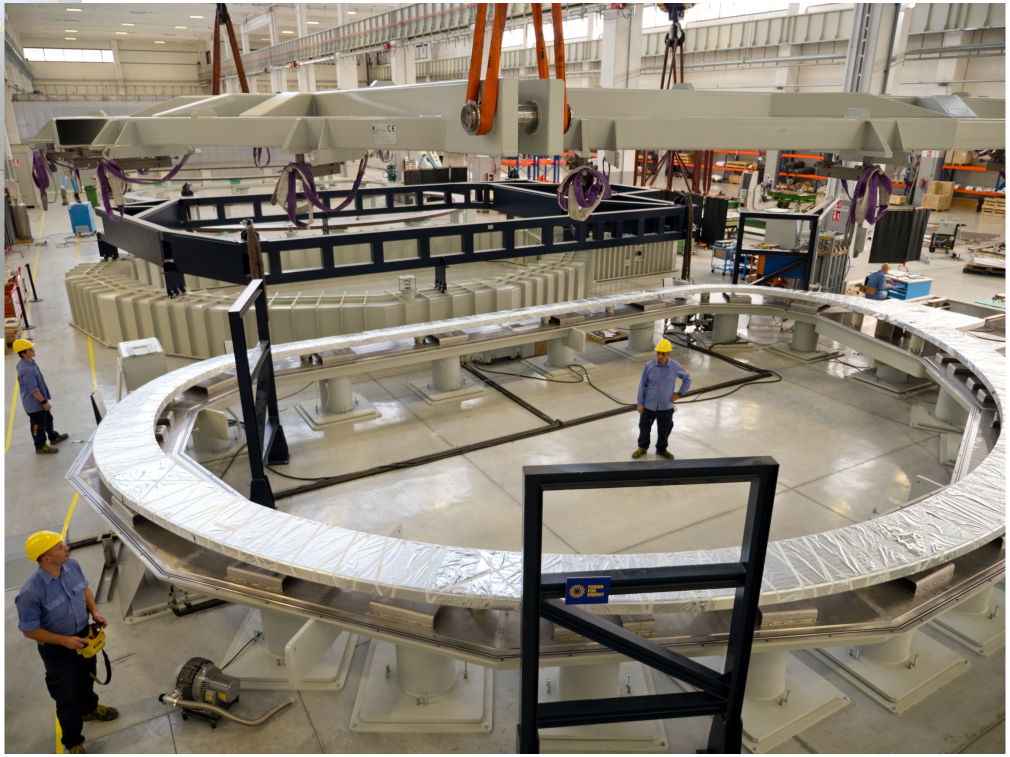
Jacket Assy

Jacket

Central Spiral

ITER magnets system – TF coils

Toroidal Field coils
winding pack in ASG – La Spezia



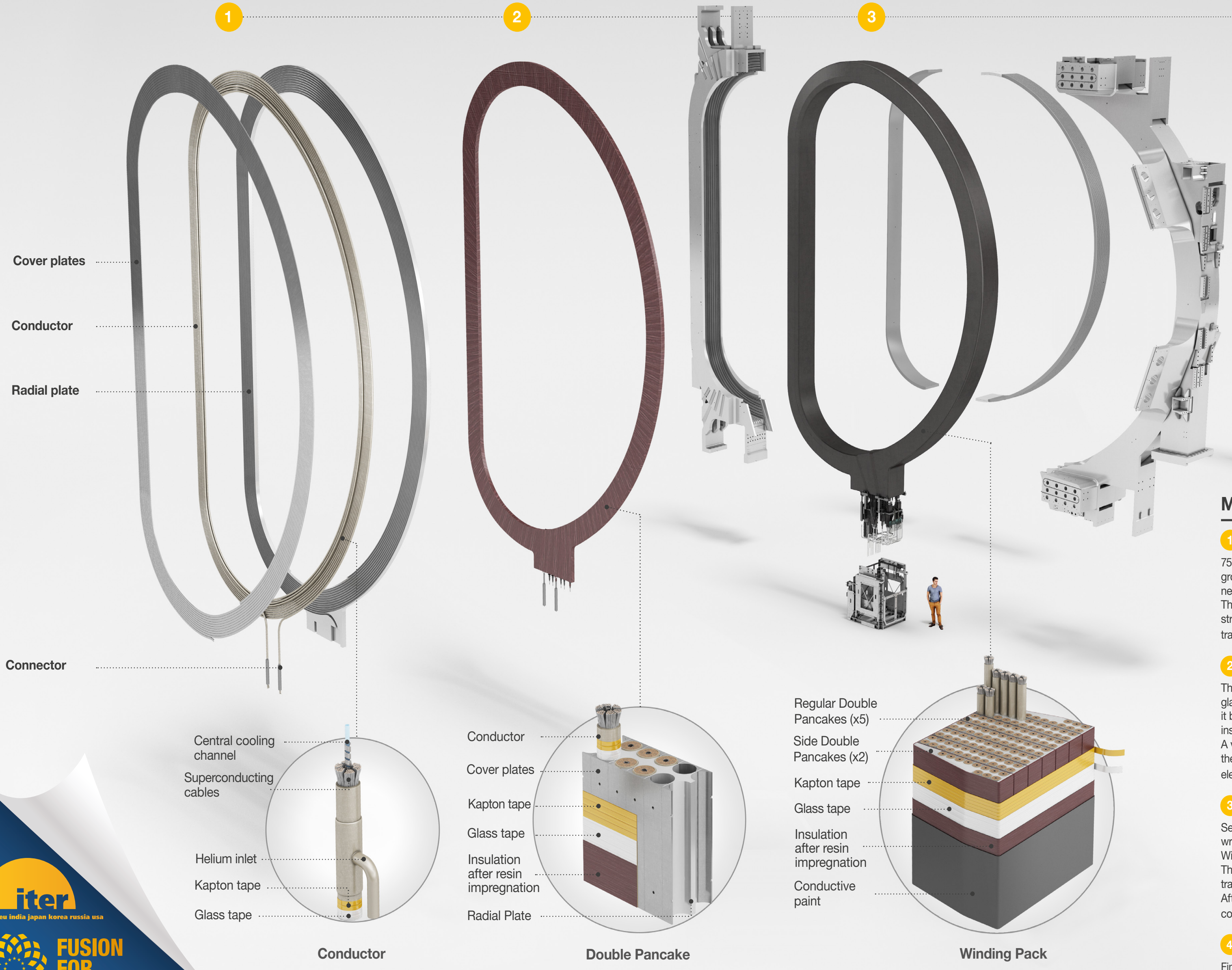
ITER magnets system – TF coils

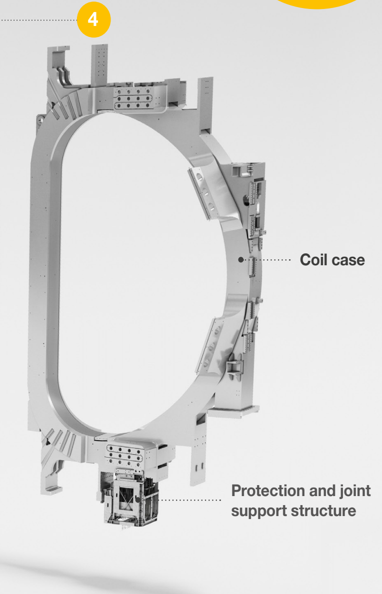
Transporting one
Toroidal Field coil

ITER Toroidal Field Coils

18 powerful superconducting magnets will confine the ITER plasma reaching 150 million °C.
Powered with 68 000 A they will generate a strong magnetic field of 11.8 Tesla (approximately 1 million times stronger the magnetic fields of the Earth).
Europe will manufacture 10 of the TF coils and Japan 8 plus one spare. They will be the biggest Niobium-tin (Nb_3Sn) magnets ever produced.
More than **600 people from 26 companies** have collaborated to produce the European TF coils.

Each coil is approximately:
14 m high
9 m wide
300 t with its case - the weight of a Boeing 747





Manufacturing steps

1 Preparing a "Double Pancake"

750 m of conductor are bent into a double-spiral trajectory to fit into the grooves of a radial plate. To make the conductor superconductive it first needs to be heat treated at 650 °C in inert atmosphere.
The conductor is then inserted into the radial plate, a stainless steel structure with grooves on both sides in which the conductor nestles. Its trajectory must match exactly that of the radial plate.

2 Double Pancake

The conductor is wrapped and electrically insulated using several layers of glass & Kapton tape. Cover plates are fitted and laser welded. At this stage it becomes a Double Pancake (DP). The DP is wrapped and electrically insulated with glass & Kapton tape before impregnation with epoxy resin.
A vacuum-pressure process is used to eliminate gaps or voids. Once cured the resin gives mechanical strength to the insulation and consolidates its electrical properties.

3 Winding Pack

Seven Double Pancakes are stacked and electrically jointed. They are wrapped, and electrically insulated with glass & Kapton tape to form a Winding Pack (WP) - the core of the magnet!
Then, the WP is heat-dried in vacuum at 110 °C to eliminate any humidity trapped and finally, resin is injected to fill in any gap in the electrical insulation. After that, tests are done to reassure engineers that the component is in compliance.

4 Final Toroidal Filed coil

Finally, the WP is inserted into a massive stainless steel case, weighing almost 200 tonnes, strong enough to resist the huge forces generated during operation.

iter
china eu india japan korea russia usa

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FOR
ENERGY
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ITER magnets system – PF coils

Poloidal Field coils after successful cold test on ITER site (5 of 6 completed)

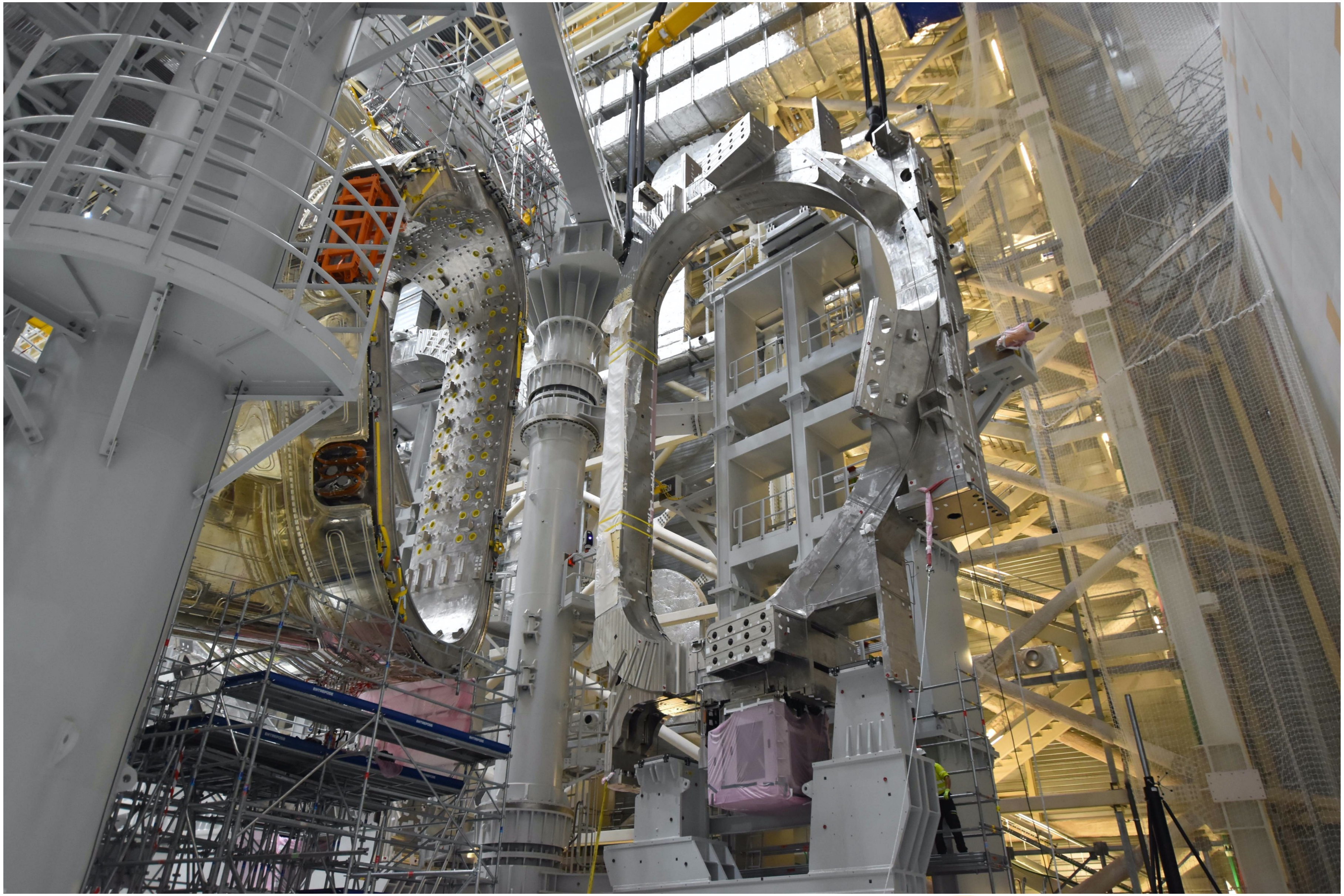
EPFL

ITER magnets – installation of 6th PF coil

Swiss
Plasma
Center

iter china eu india japan korea russia usa

ITER magnets – installation of 1/18 TF coils with 1/9 of vacuum vessel



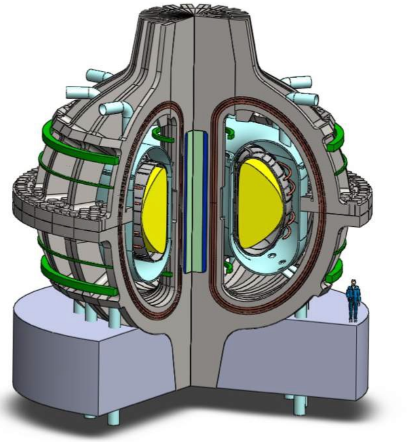
ITER magnets system – the cryostat

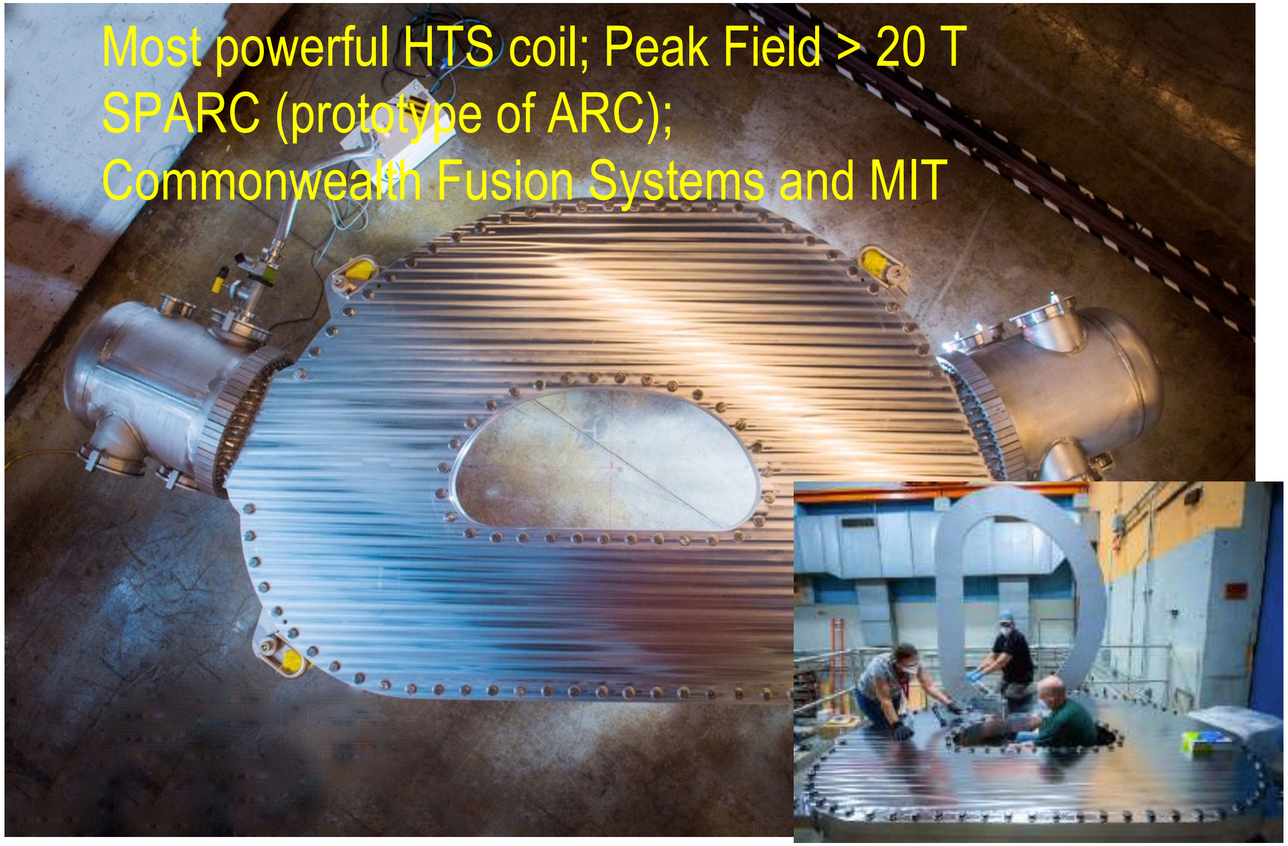
EPFL

Superconducting magnets for next steps

While ITER is being built, several DEMO devices are proposed worldwide, with a broad range of design approaches, from high field tokamak, more compact than ITER, to very large tokamaks with field similar to ITER – all with superconducting magnets

ARC
Major Radius 3.2 m
Peak Field ≈ 23 T
HTS coils





Most powerful HTS coil; Peak Field > 20 T
SPARC (prototype of ARC);
Commonwealth Fusion Systems and MIT

Swiss Plasma Center

PSFC

MIT

Superconducting magnets for DEMO

While ITER is being built, several DEMO devices are proposed worldwide, with a broad range of design approaches, from high field tokamak, more compact than ITER, to very large tokamaks with field similar to ITER – all with superconducting magnets

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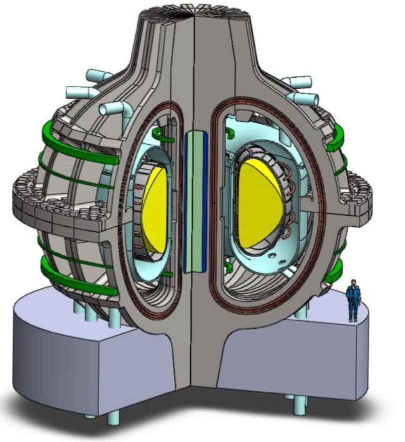
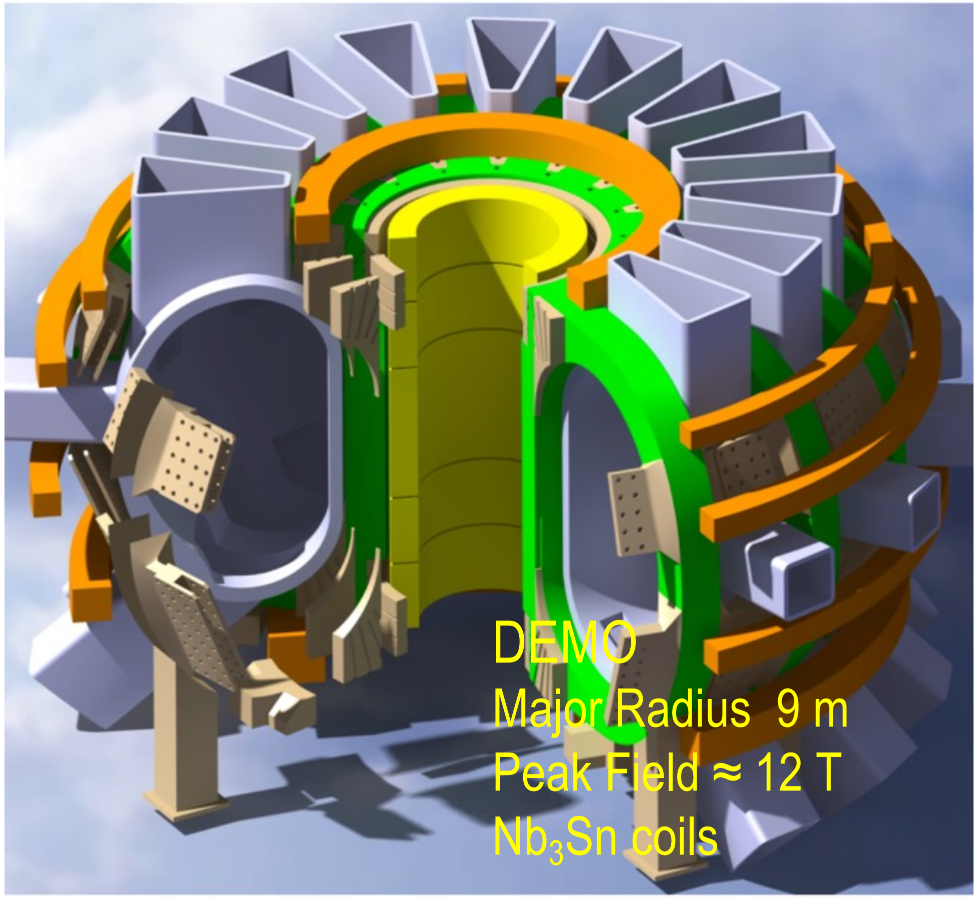




DEMO
Major Radius 9 m
Peak Field ≈ 12 T
Nb_3Sn coils

Summary

SC magnets are the enabling technology for steady state fusion reactors

ITER and future fusion devices set new technical challenges for SCs

Cost requirements for power plants constrain design and manufacture

New avenues for compact magnetic fusion reactors can be opened by application of HTS technology

Selected activities at the SPC superconductivity group

Nikolay Bykovskiy

December 11

SWISS
PLASMA
CENTER

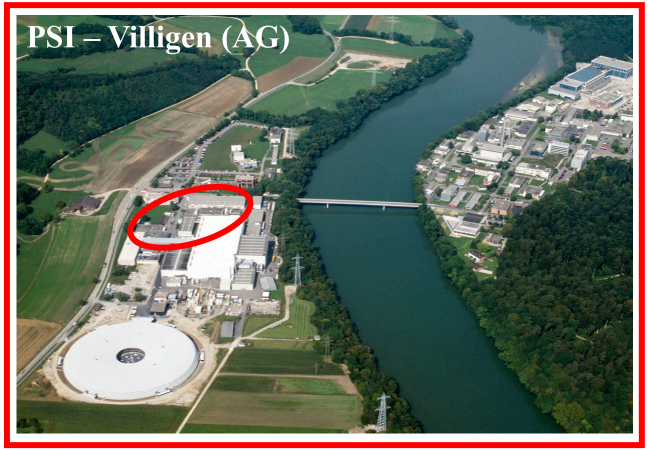
Swiss Plasma Center

Goals of research

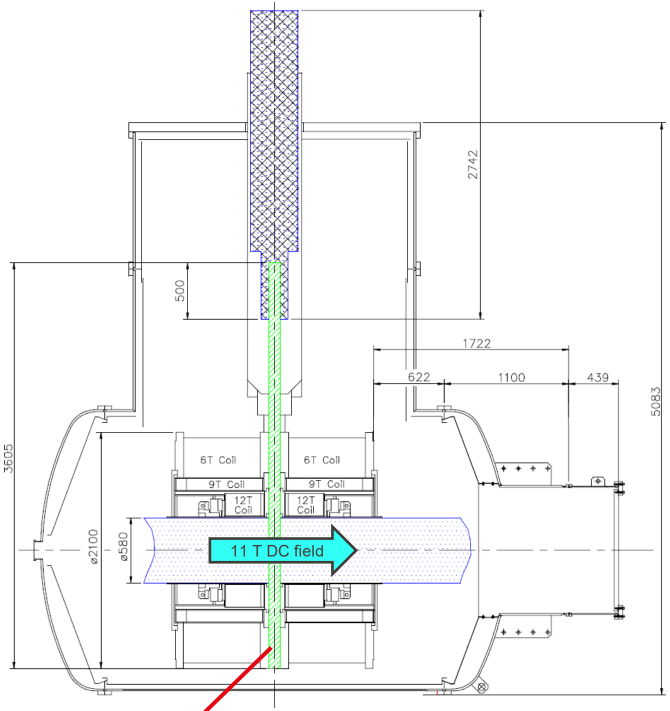
- Contribution to the success of ITER (construction, planning of experiments, ...)
- Improvement of the tokamak concept, understanding of fusion plasmas, and technology for DEMO
- Industrial and societal applications of plasmas

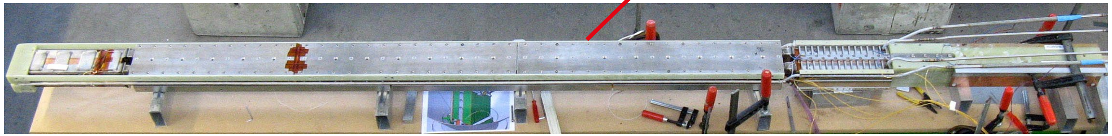
SPC: 9 groups, ~200 people

SPC-SG group, ~20 people



SULTAN test facility at SPC-SG *





11 T DC magnetic field

~100 kA operating current in
4 – 20 K temperature range *or*
15 kA current in **4 – 300 K** range

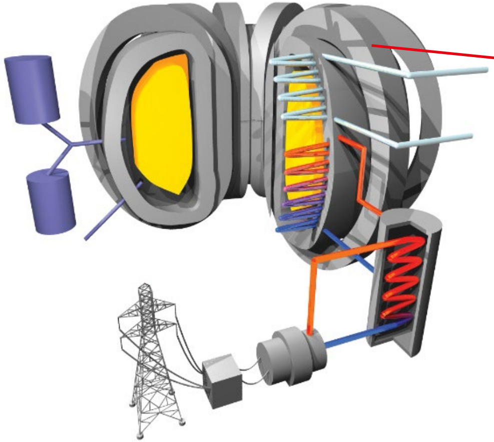
SULTAN sample = pair of ~3.6 m long conductors with joints at the top and the bottom

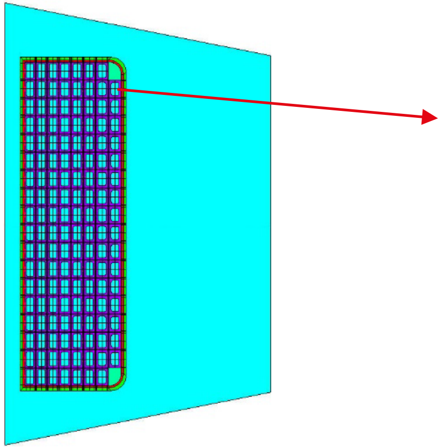
Typical measurements:

- V-T curves at fixed B and I
- V-I curves at fixed B and T
- 0 → I_max → 0 →… cycling of transport current at fixed B (i.e. EM load cycling)
- AC losses in alternating magnetic field
- Warm-up-cool-down

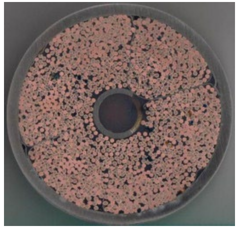
* other test capabilities: 15 T / 12 T magnets (80 mm bore); 2 kA / 10 kA PS; 4 K / 77 K / var T inserts

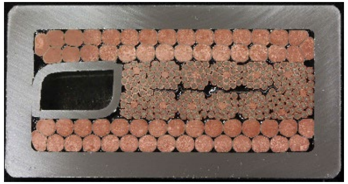
Superconducting magnets



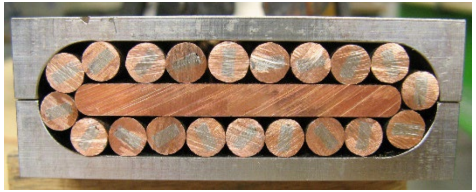


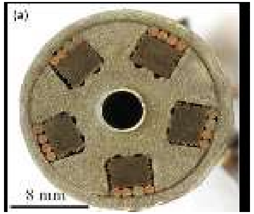
LTS wire-based cables





HTS tape-based cables

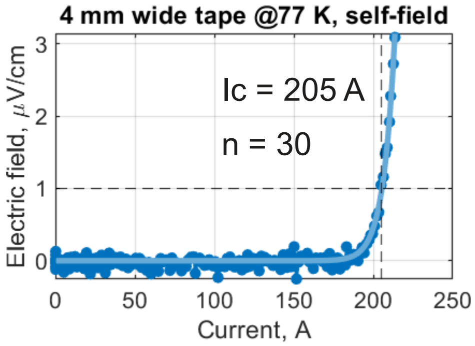




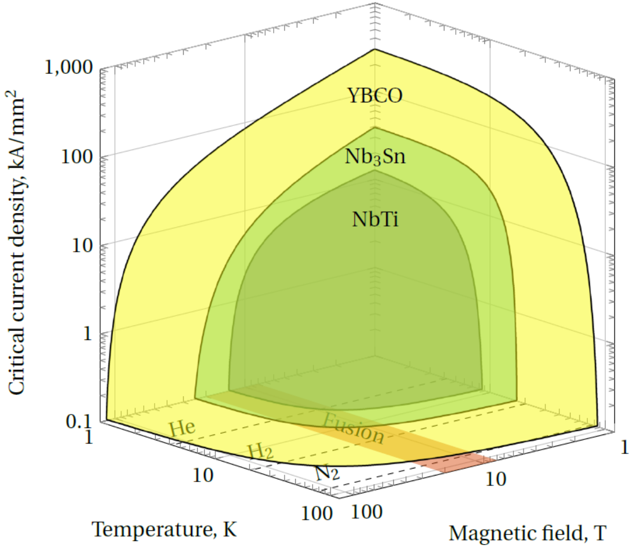
HTS materials: ReBCO coated conductors

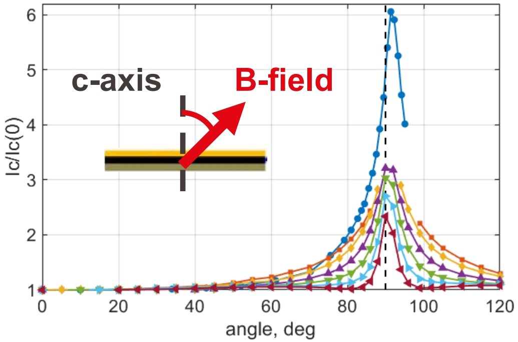
Typical width: 3 mm – 12 mm

Thickness: ~1 µm (sc), ~100 µm (tape)



$$E = E_0\left(\frac{j}{j_c(B,T,\theta,\varepsilon)}\right)^{n(j_c)}$$

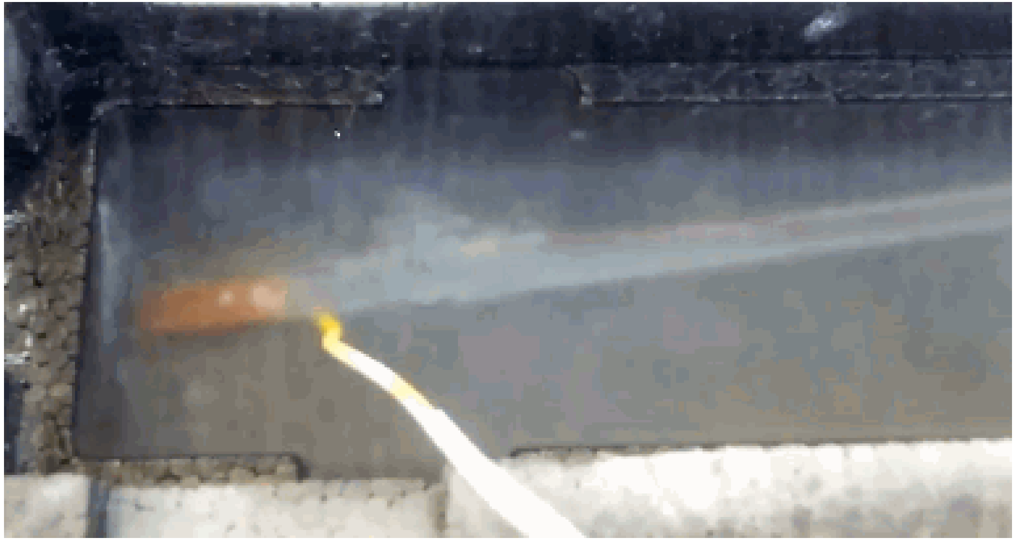




Thermal runaway (‘**quench**’) propagates very slow, thus difficult detection and protection…

- ➢ High **Tc**, ~100 K
- ➢ High **Bc**, ~100 T
- ➢ High **jc**, ~10^{10} A/m^2
- ➢ **Strong anisotropy** of electrical and mechanical properties

Quench detection



Quench propagation velocity (QPV):

~ m/s for LTS

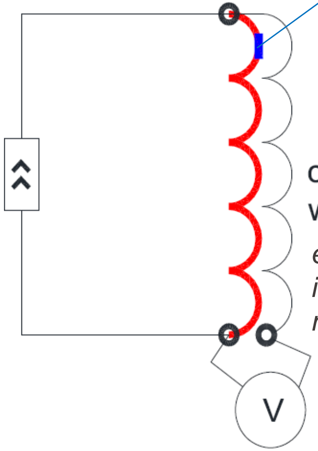
~ cm/s for HTS

$$V_R \sim I_{op} R_1(T_{max}) \cdot QPV \cdot t$$

- T_{max} rises fast, V responces slow
- Pulsed operation in Tokamaks (inductive voltage ~10 kV!)

Quench detection by measuring coil voltage is problematic for HTS in fusion magnets…

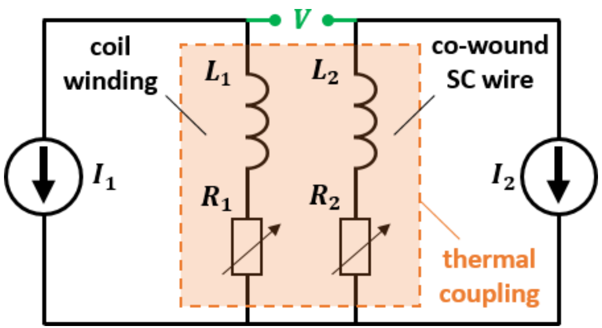
Quench detection: co-wound wires



R (quench precursor)

cowound wire

electrically insulated from the main conductor



aka SQD wires

in good thermal contact with the main conductor: $T_1(x) \approx T_2(x)$

$$V = V_{R_2} - V_{R_1} + V_{L_2} - V_{L_1} \approx \boldsymbol{V_{R_2} \gg V_{R_1}},$$

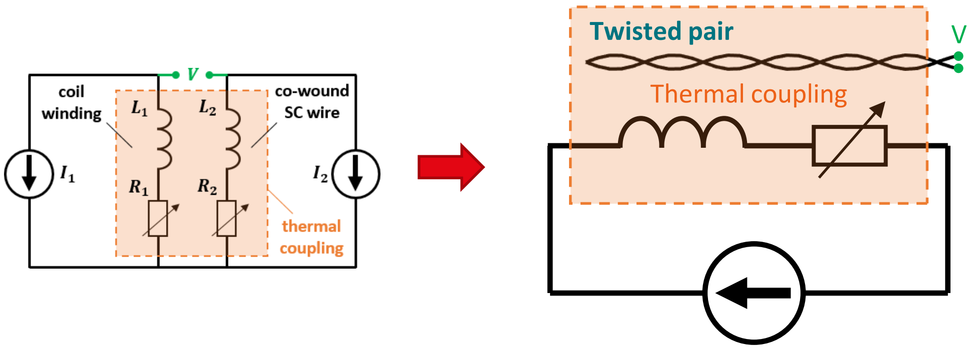
assuming that:

- $T_c(B_{max})$ of detection wire > T quench,
- High voltage along SQD in normal state due to:
  - Material composition (exclude Cu or Ag!)
  - Operating current I_2

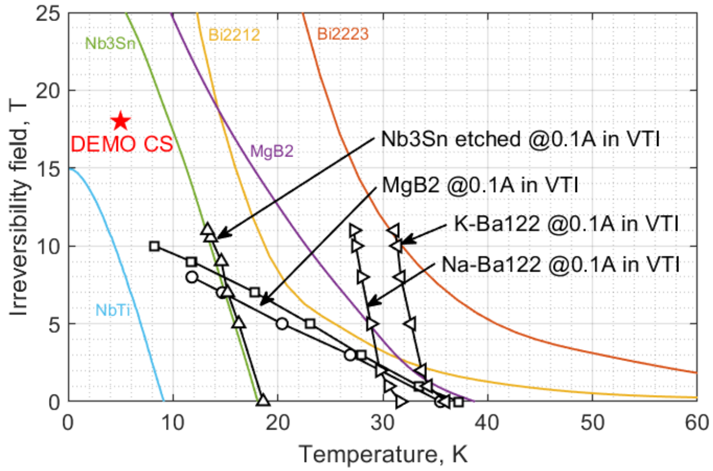
$$V = V_R + V_{L_2} - V_{L_1} \approx V_R$$

How to increase detection sensitivity?

Quench detection: non-invasive integration



Twisted-pair SQD wires to enhance cancellation of inductive signal + **complete electrical insulation**



Material selection for SQD wires is broad but limited, i.e. not suitable for certain applications?

→ alternative methods being also developed at SPC, including thermocouple chain and optical fibers…

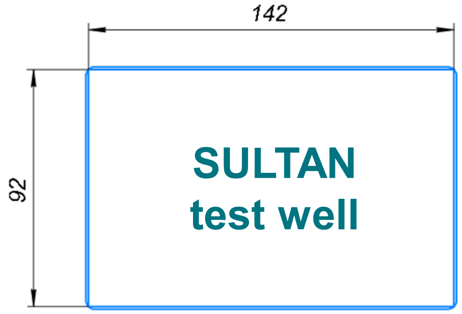
Quench experiment in SULTAN* on long lengths

Task objective – development of temperature-based quench detection immune to EM noise and mechanical strain

Pursued options:

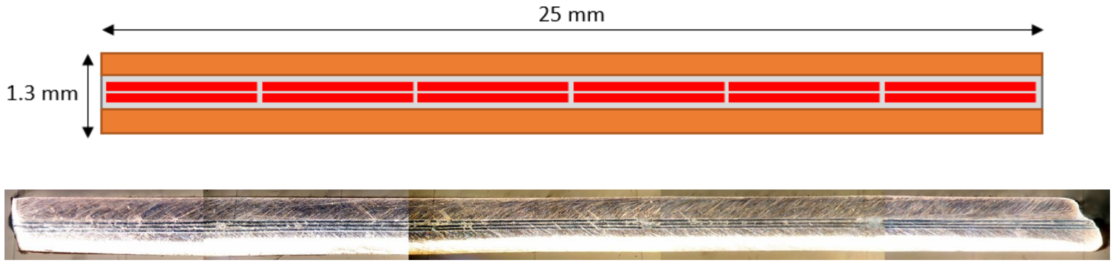
- Superconducting twisted-pair wires (electrical method)
- Shielded thermocouple chain (electrical)
- Mechanically decoupled optical fiber (optical)

→ But first, need for high-current ReBCO insert coil…

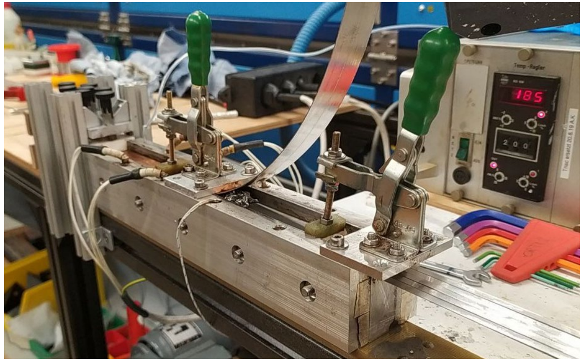


* direct current drive up to 15 kA / 10 V, thus T range from ~5 K to ~300 K

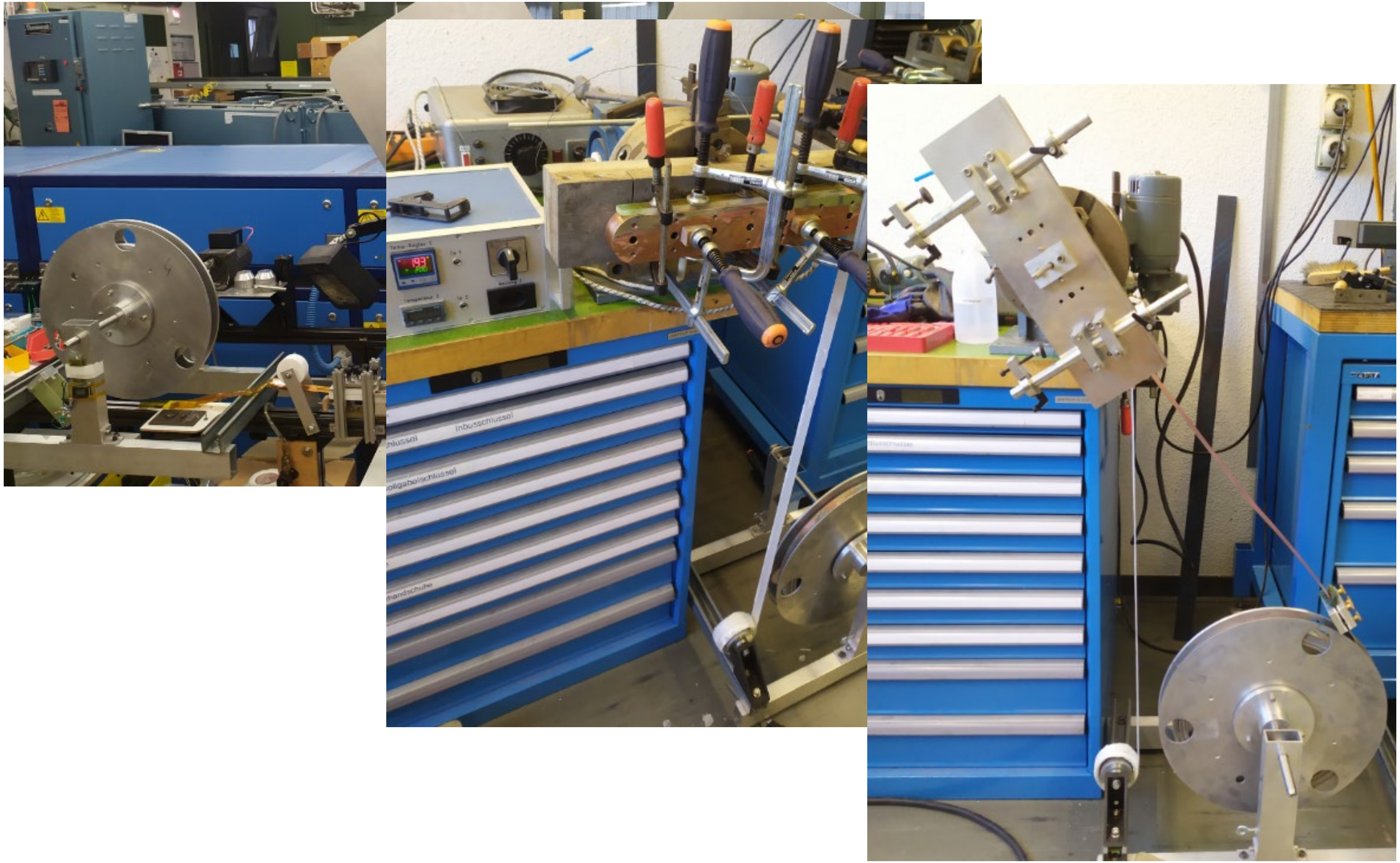
Laminated stacked-tape soldered conductor (LASSO)



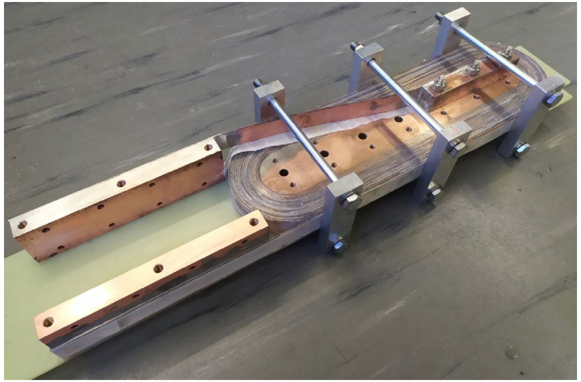
Copper pre-tinning & Cable soldering



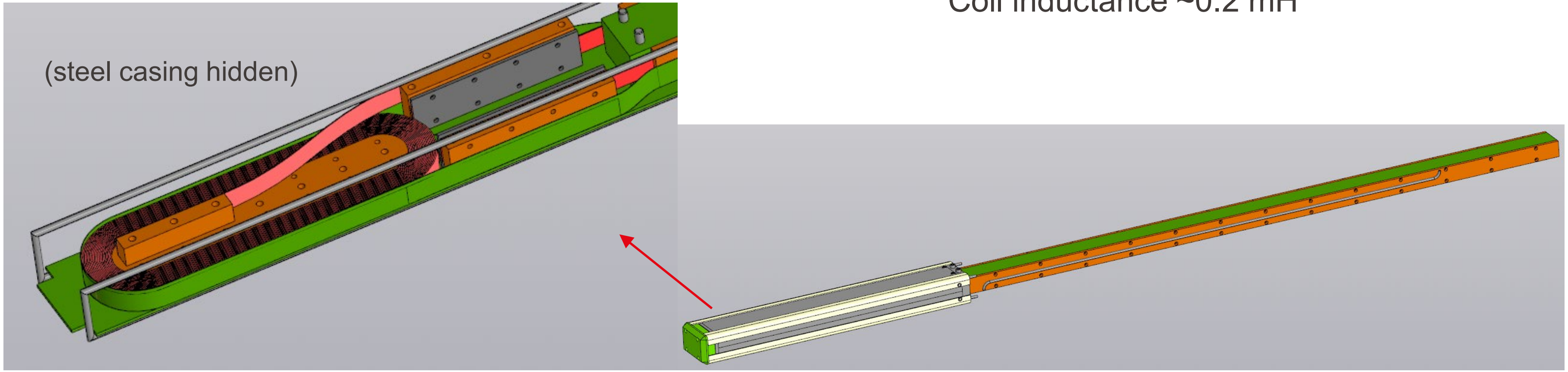
Cable soldering & coil winding



SULTAN sample



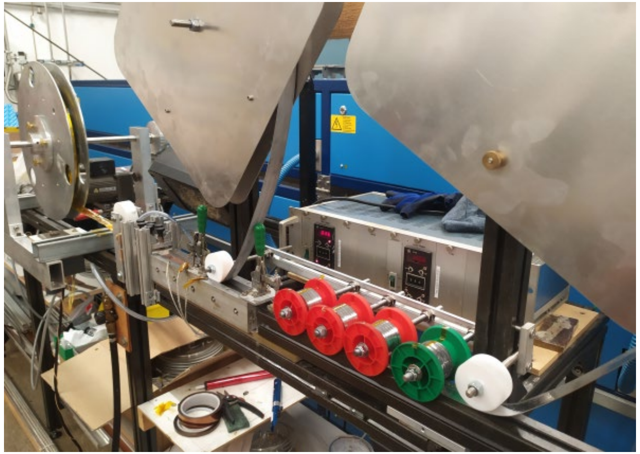
- 20-turn winding, Rmin 30 mm, no hard bending, fiberglass turn insulation
- Impregnation and indirect cooling by aqueous DMSO solution
- Ic ~12 kA at 5 K, 11 T (predicted) and ~1 kA at 77 K, self-field (predicted & measured)
- Field constant ~0.2 T/kA (coil center), Coil inductance ~0.2 mH

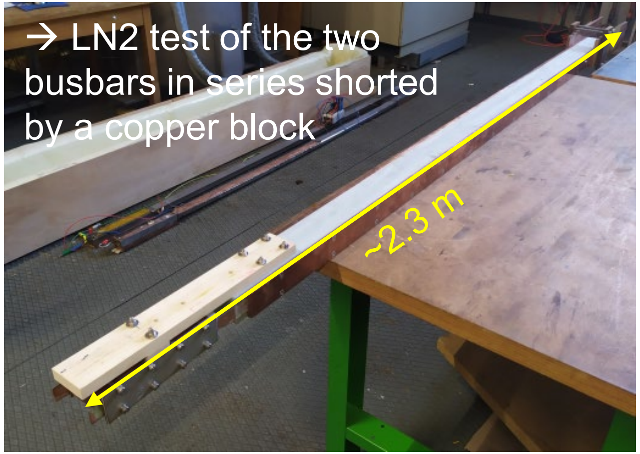


(steel casing hidden)

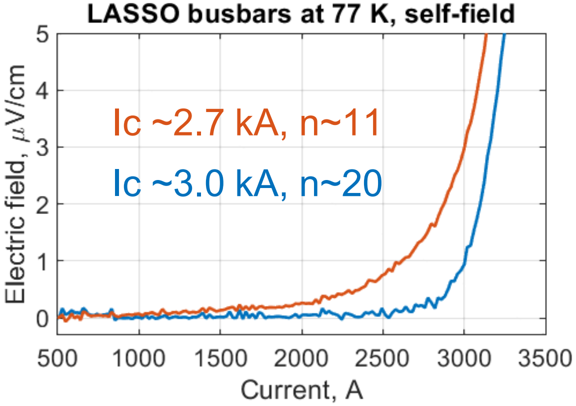
SULTAN sample: ReBCO busbars

→ Soldering 5-m long LASSO cable made of 25 ReBCO tapes in 4 layers

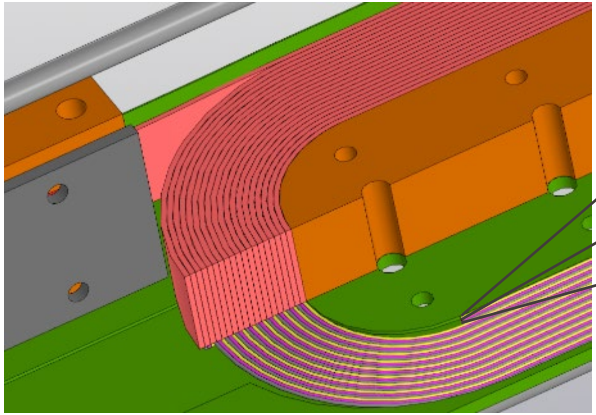




→ LN2 test of the two busbars in series shorted by a copper block



Quench detection: instrumentation

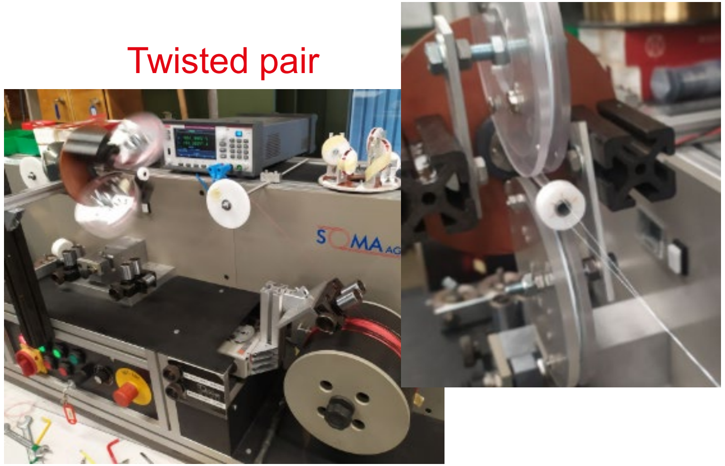


Quench detection embedded in G10 support plate:

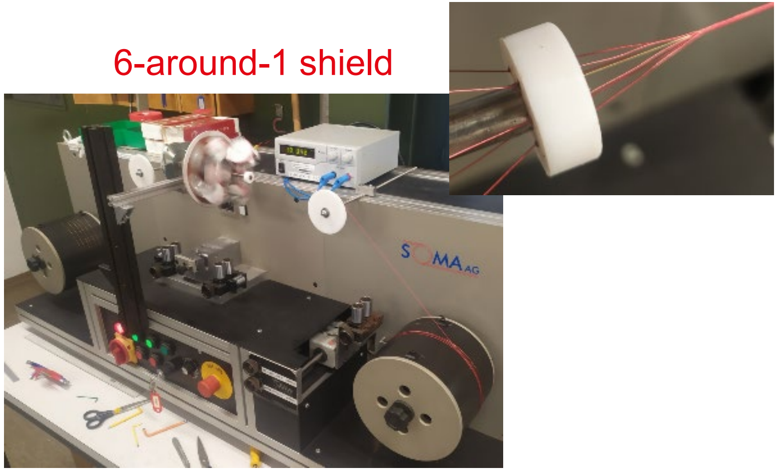
- SQD twisted-pair (bronze-route Nb3Sn, OD 0.2 mm)
- Shielded thermocouple chain (type K, OD 0.2 mm)
- FBG optical fiber in Teflon capillary tube (ID 0.6 mm)…

→ All three as non-invasive instruments, each ~10 m long

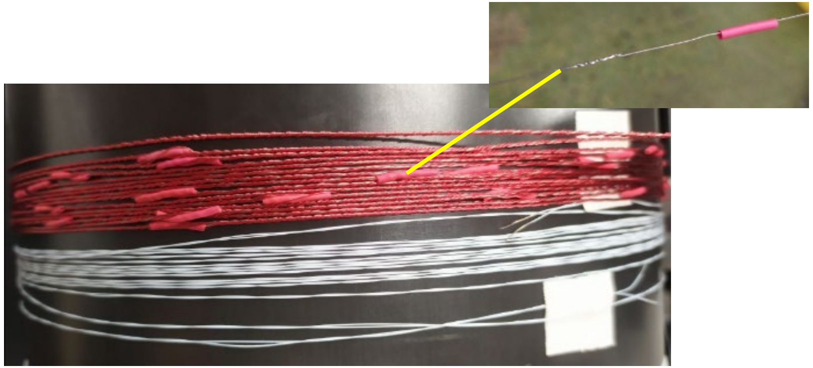
Twisted pair

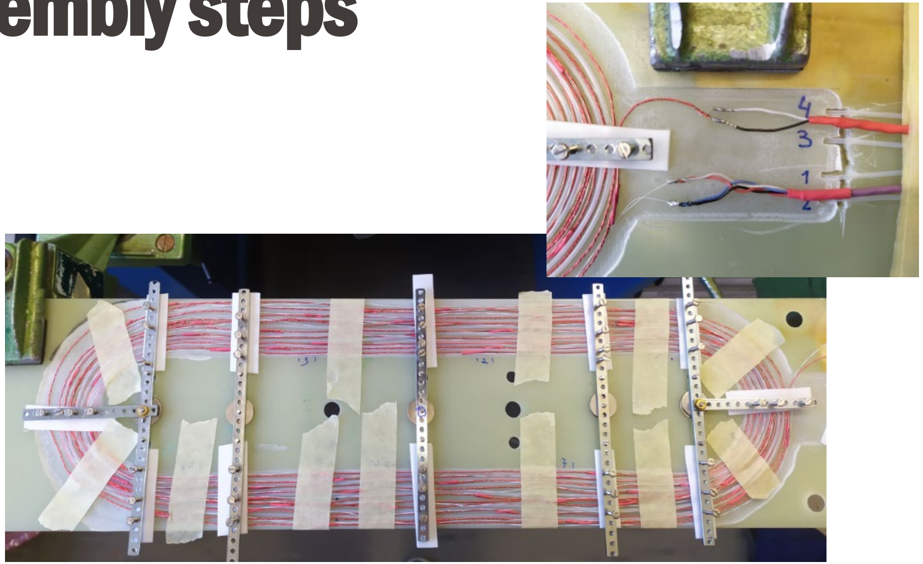


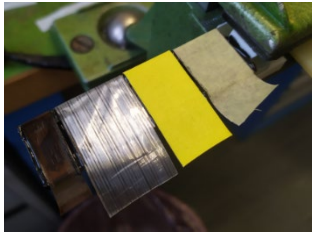
6-around-1 shield

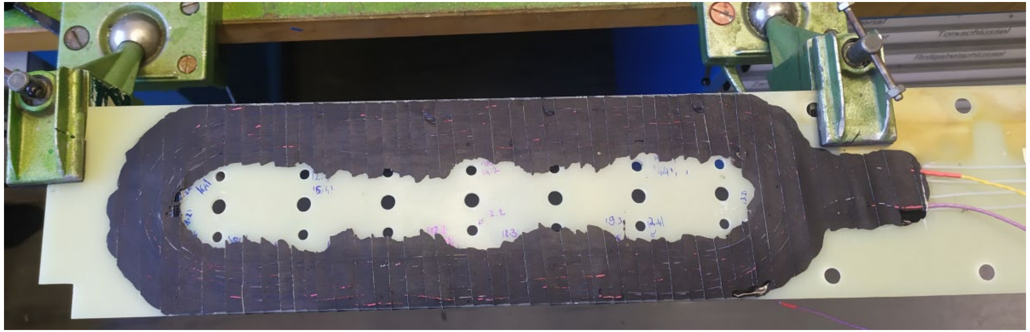


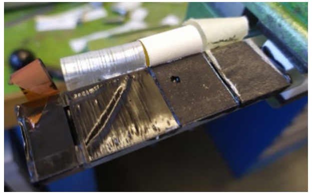
Quench detection: assembly steps



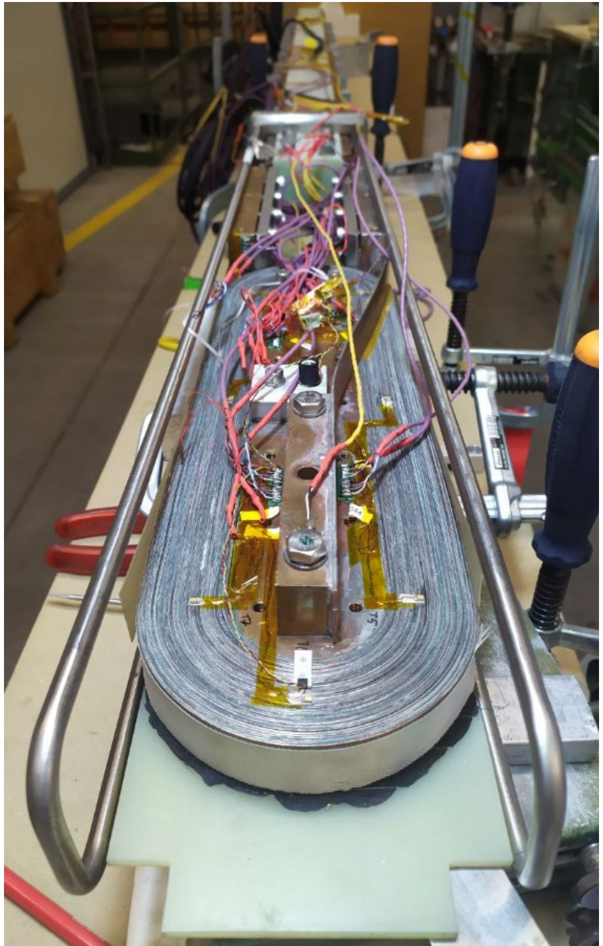


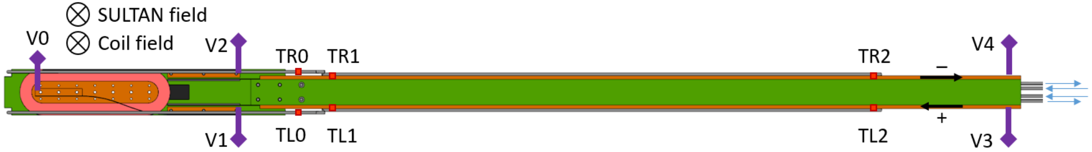


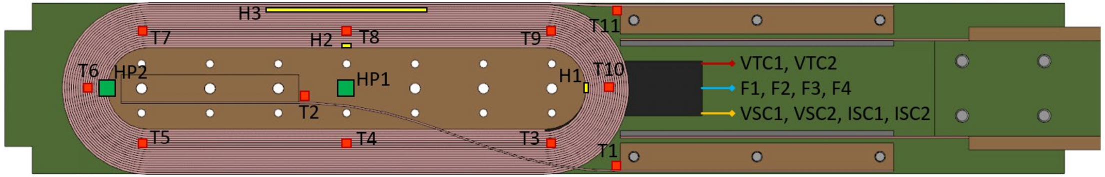


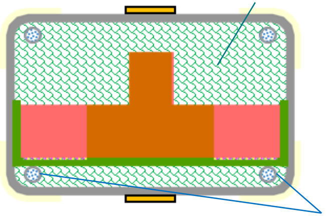


Current status







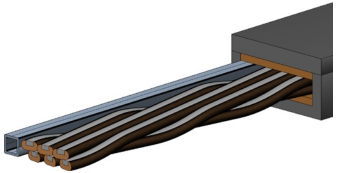


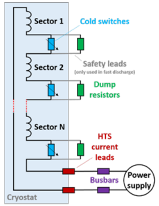
~10% DMSO (common cryoprotective agent)

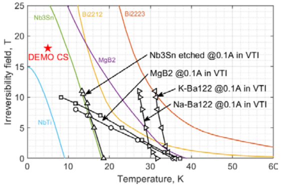
Inlet cooling
(supercritical helium)

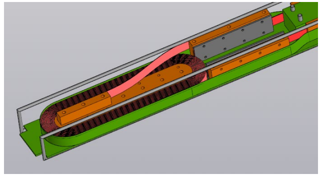
→ Test in SULTAN
in the coming weeks…

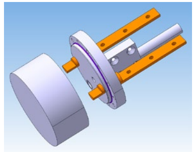
THANK YOU FOR YOUR ATTENTION!

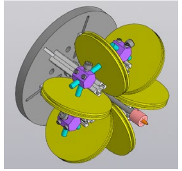


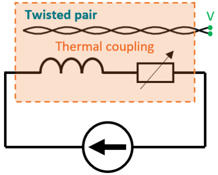


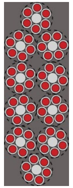












Former internship students at SPC-SG:
Max Bernheim, Alessio Rossi, Giuseppe Drago, Eduardo Baldo, Julia Haack

There are lots of multi-disciplinary topics in applied superconductivity for fusion magnets, join the effort!

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