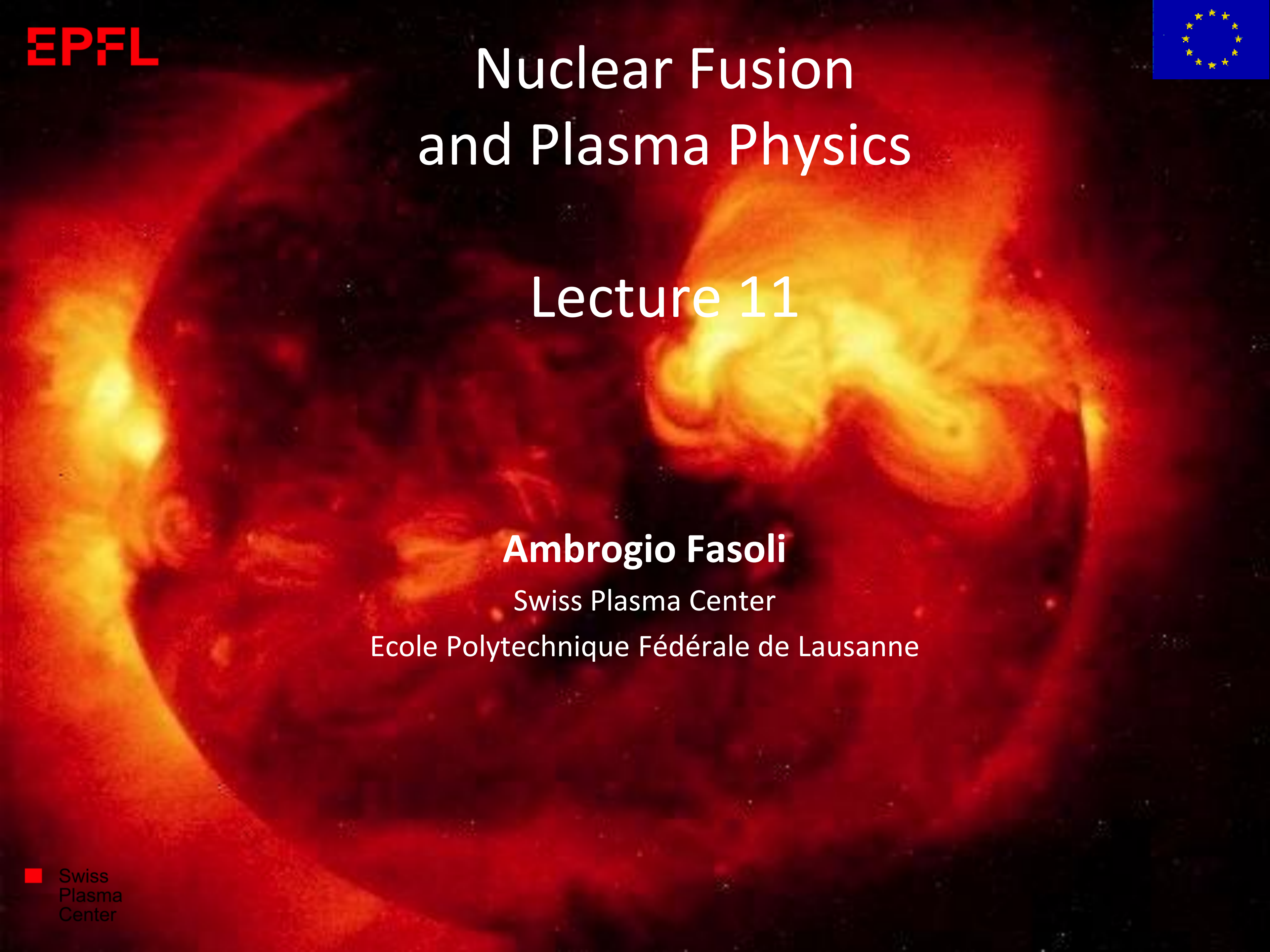


Nuclear Fusion and Plasma Physics

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

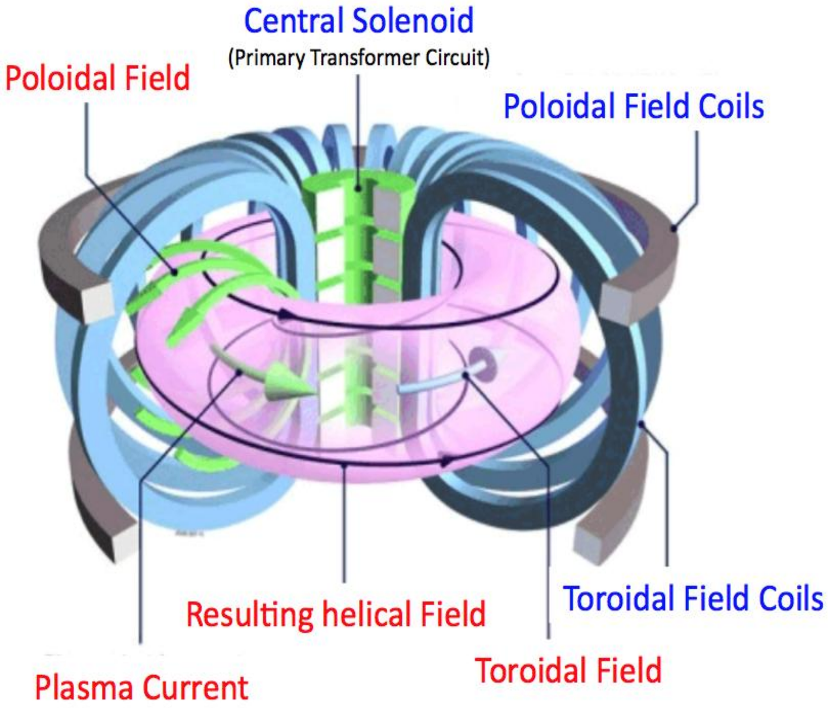
Requirements and challenges

Fusion devices with superconducting coils

ITER, DEMO and beyond

Presentation by Jack Greenwood on R&D projects in the SPC Applied Superconductivity group

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 $\alpha \geq 2$

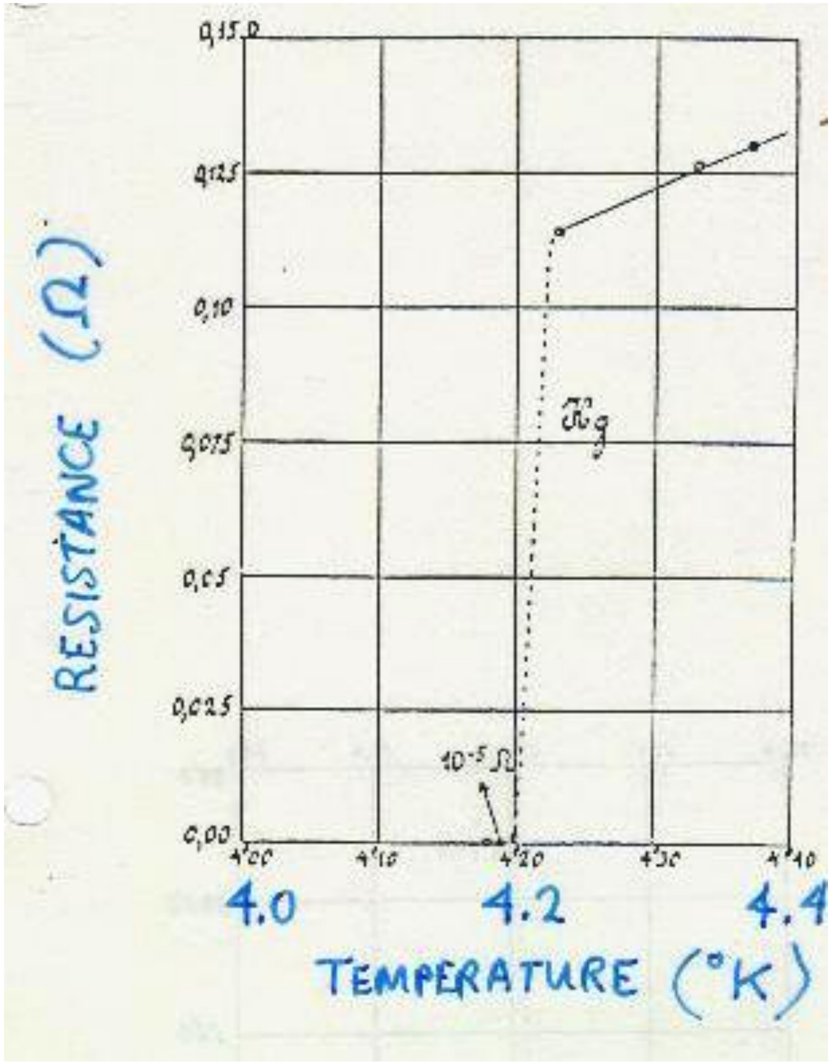
Copper coils can generate large fields, but not in steady-state

- 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

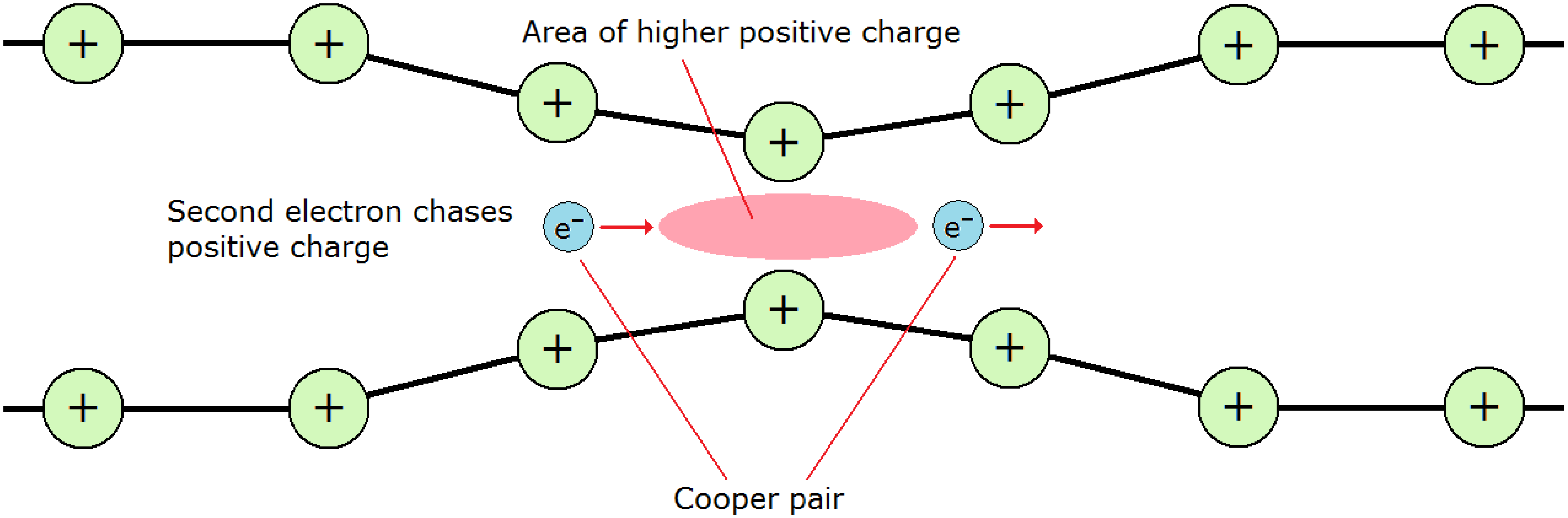
The discovery of superconductivity



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

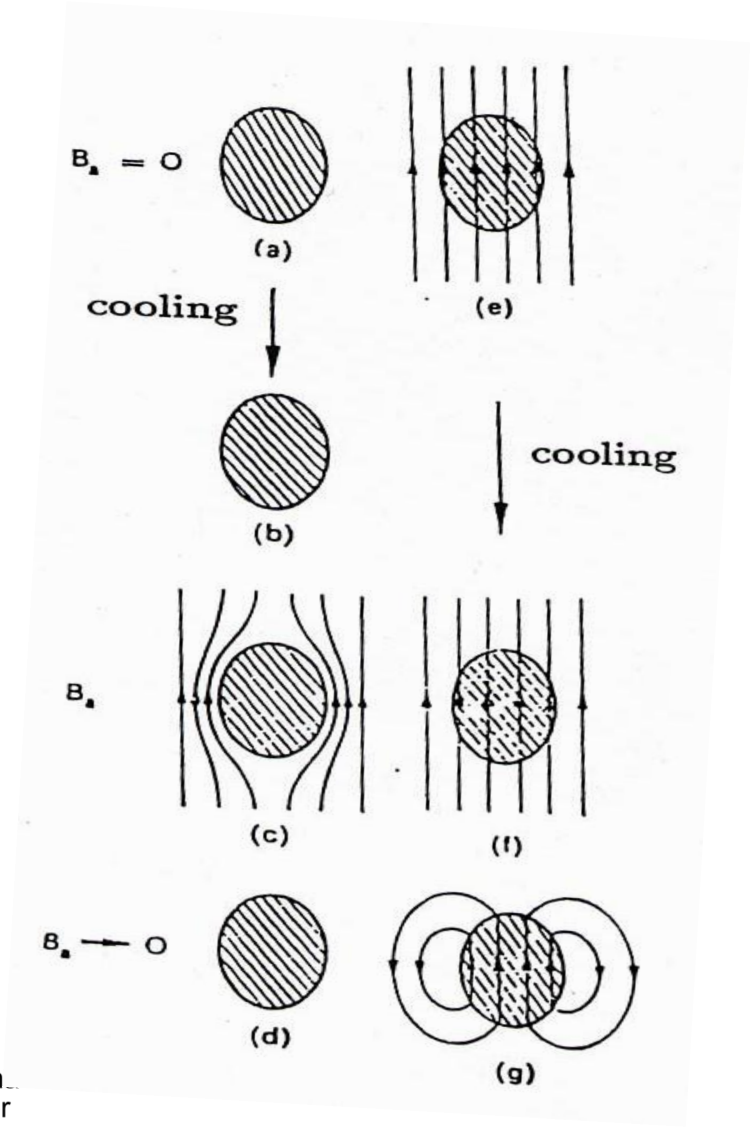
Contrary to the unpaired electrons with spin ½ (fermions), the Cooper pairs have integer spin, i.e. are bosons and can be in the same quantum state, moving resistance-less through lattice

Superconductivity – simple interpretation

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

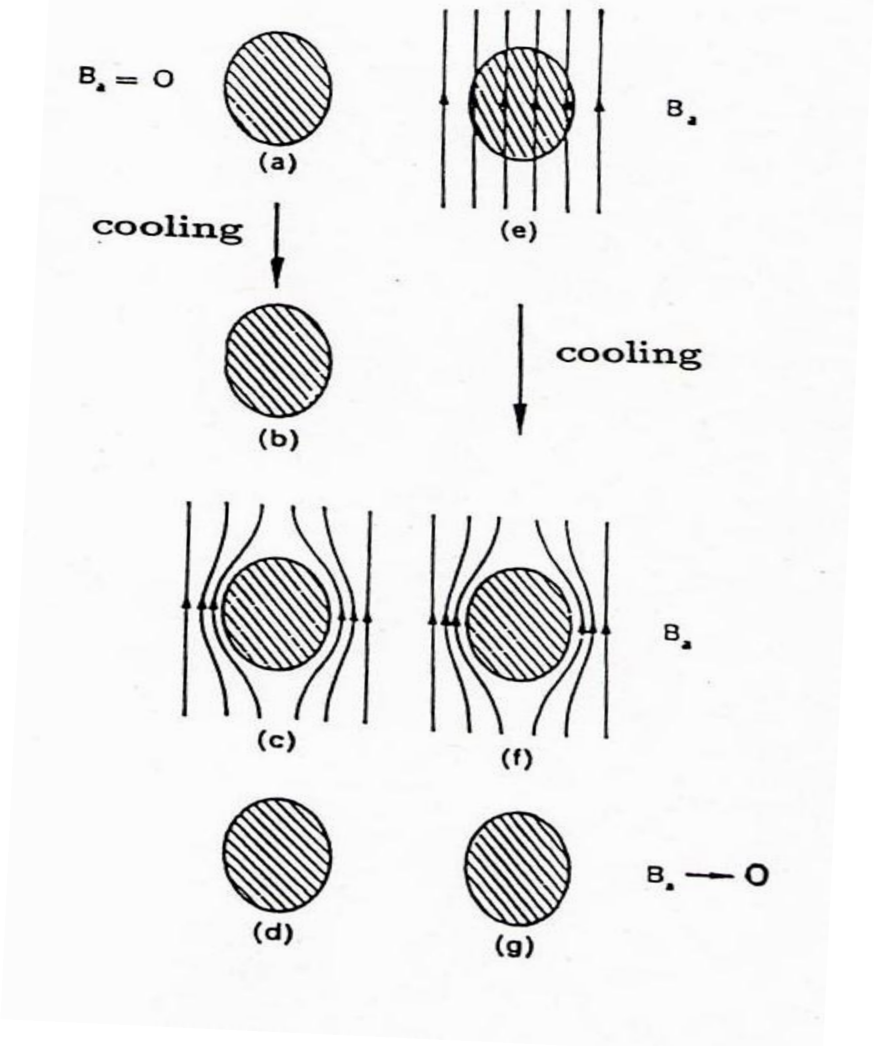
Superconductors vs. perfect conductors

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

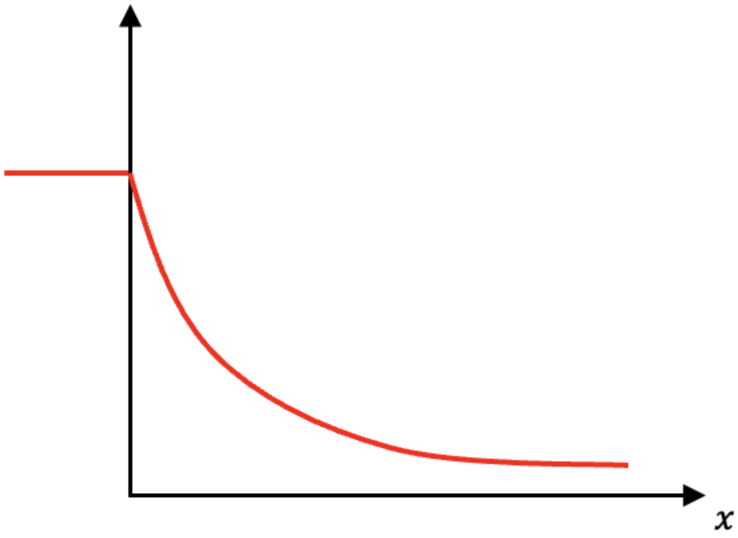
In the superconductor (London theory, 1935):

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

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

n_C = density of sc carriers

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



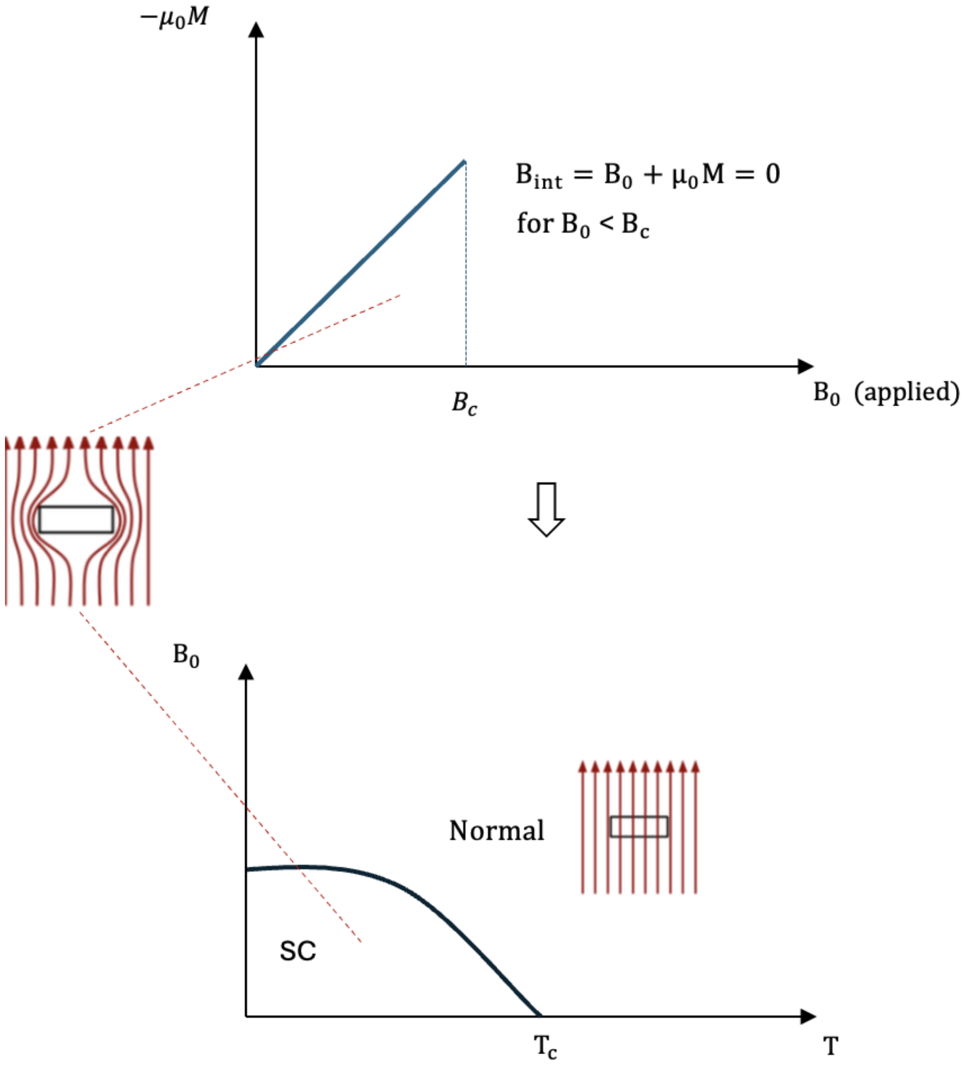
Magnetization and Type I vs. Type II SC's

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

Type I SC's

$$\lambda < \frac{\xi}{\sqrt{2}} \Rightarrow \text{Type I}$$



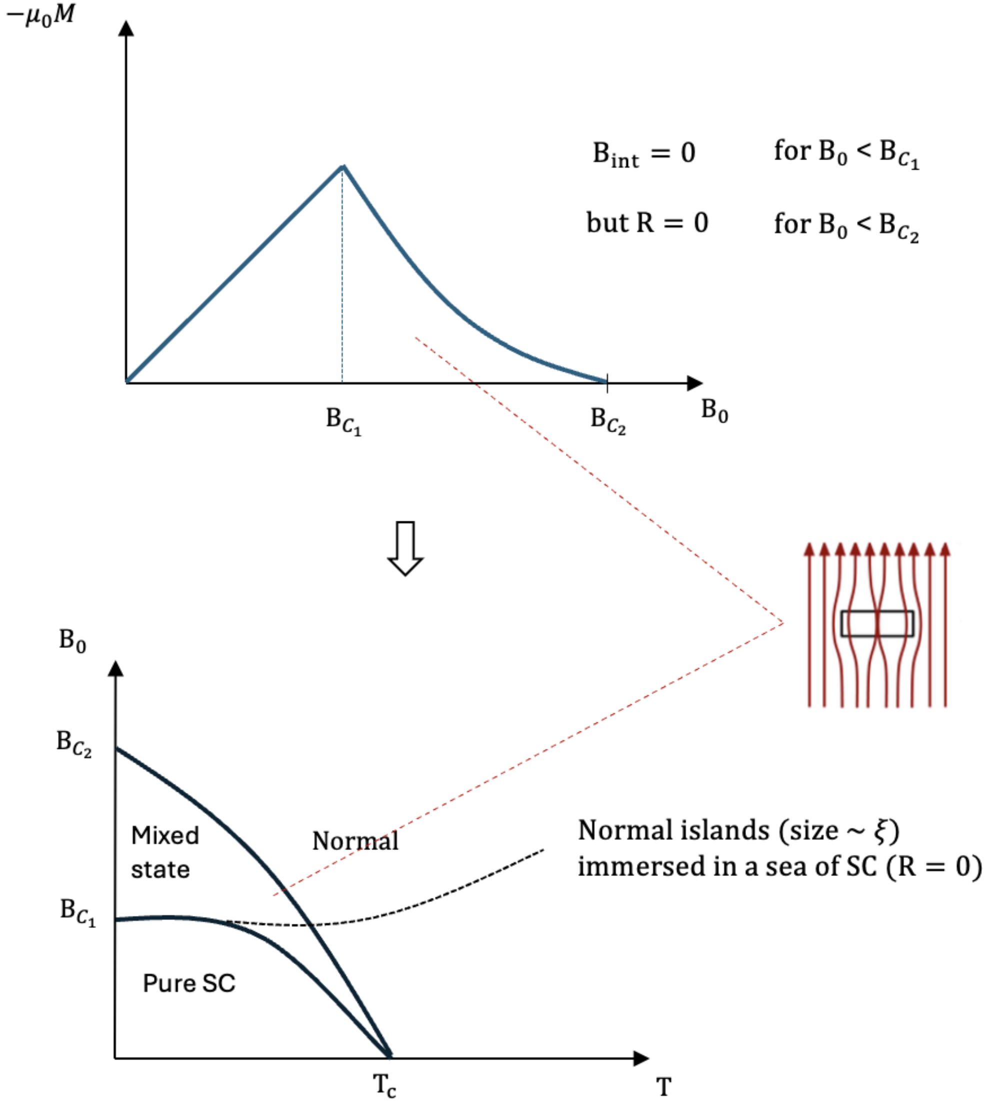
$B_{int} = B_0 + \mu_0 M = 0$

for $B_0 < B_c$

⇩

Type II SC's

$$\lambda > \frac{\xi}{\sqrt{2}} \Rightarrow \text{Type II}$$



$B_{int} = 0$ for $B_0 < B_{C_1}$

but $R = 0$ for $B_0 < B_{C_2}$

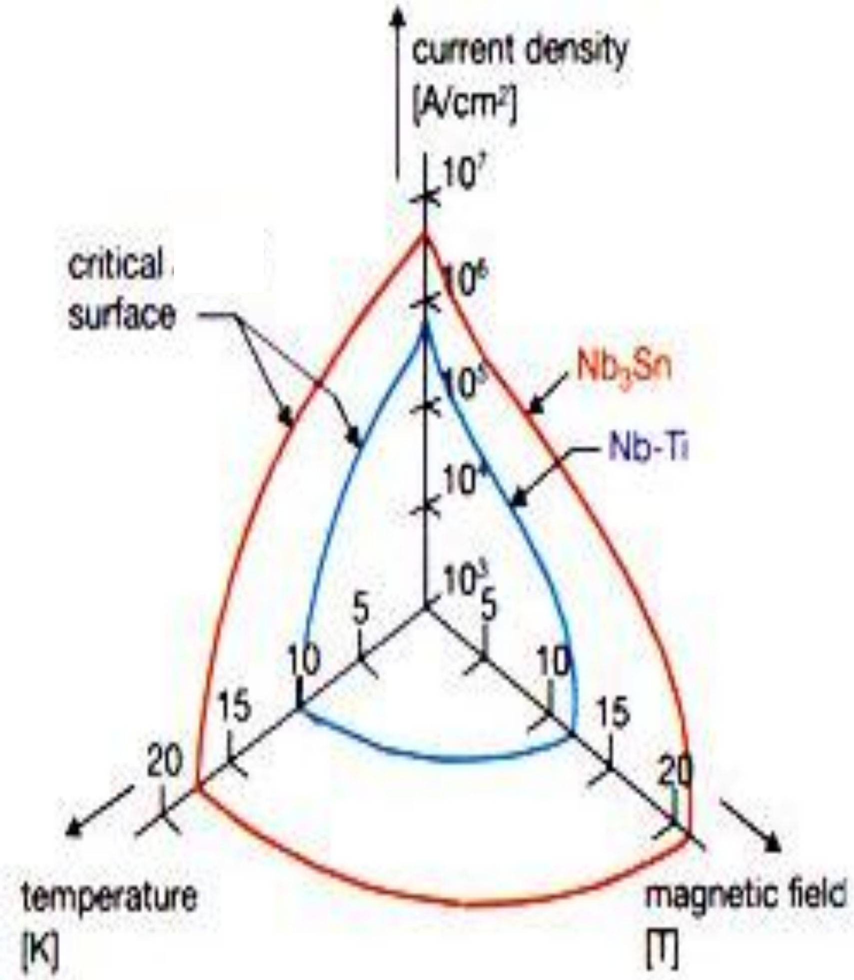
Normal islands (size ~ ξ) immersed in a sea of SC ($R = 0$)

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

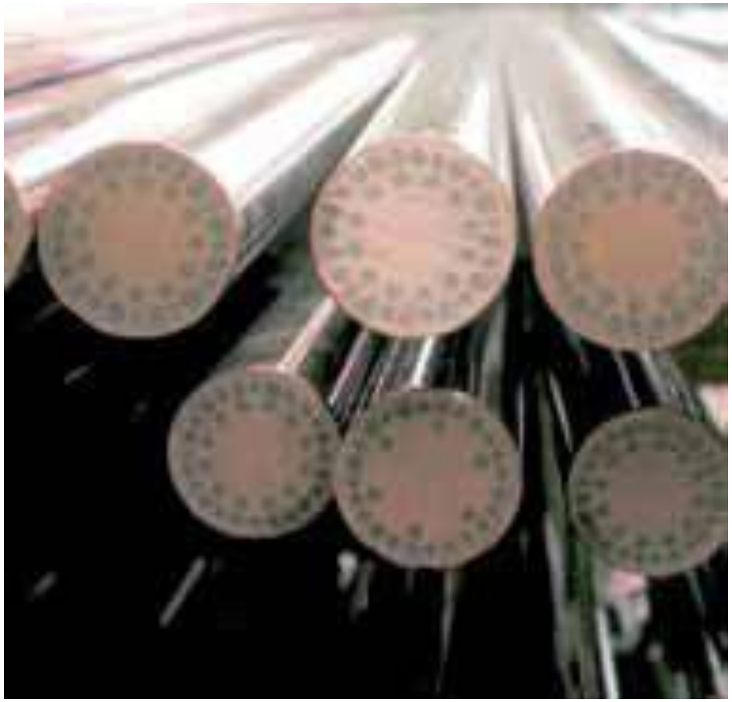
Superconducting materials for fusion

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

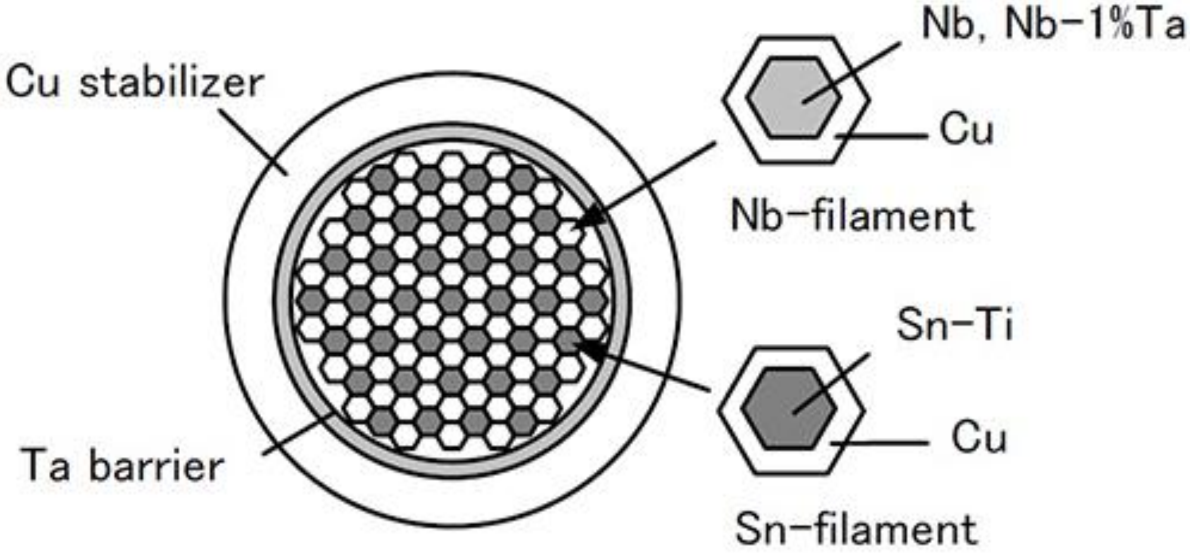
Superconducting materials for fusion

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



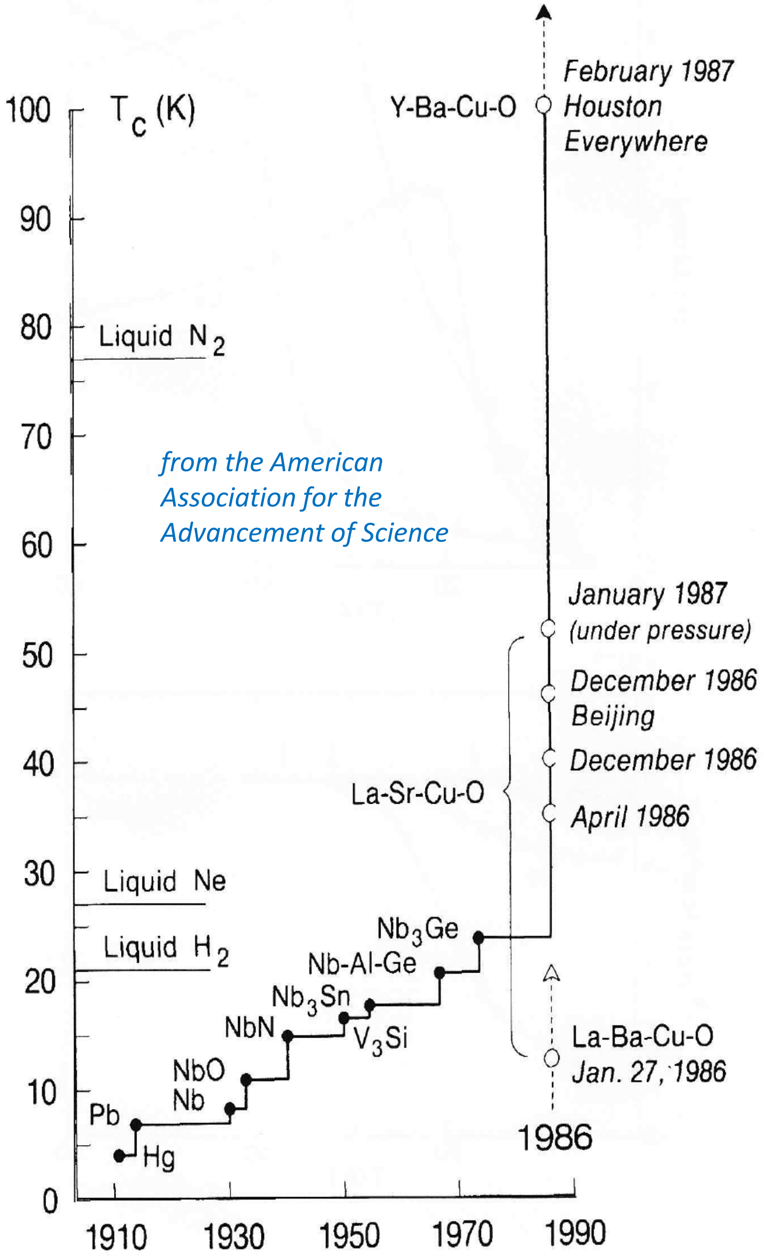
from Hitachi.cable.com

High temperature superconductivity

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

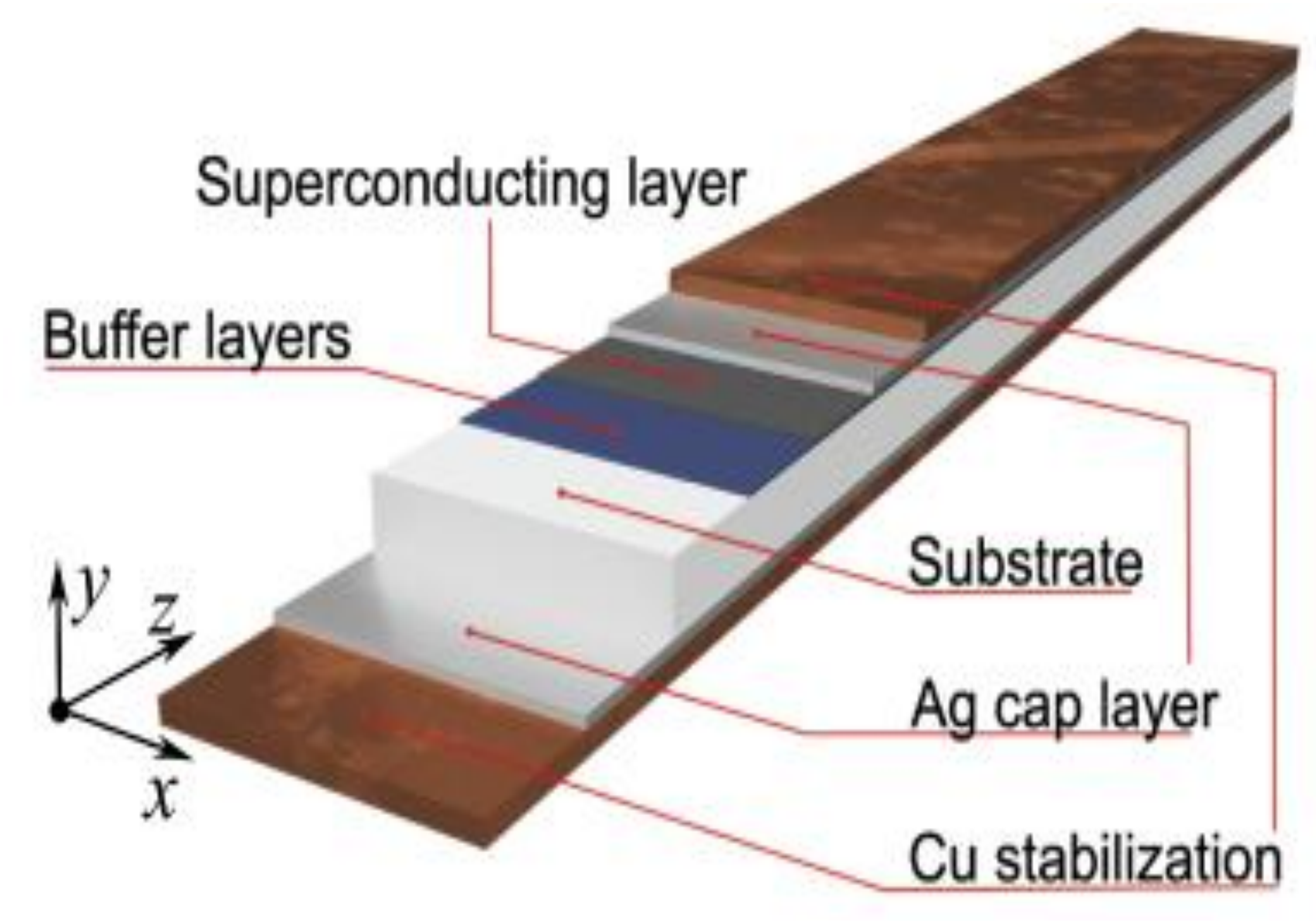
Two classes of HTS materials are potentially suitable for fusion magnets

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



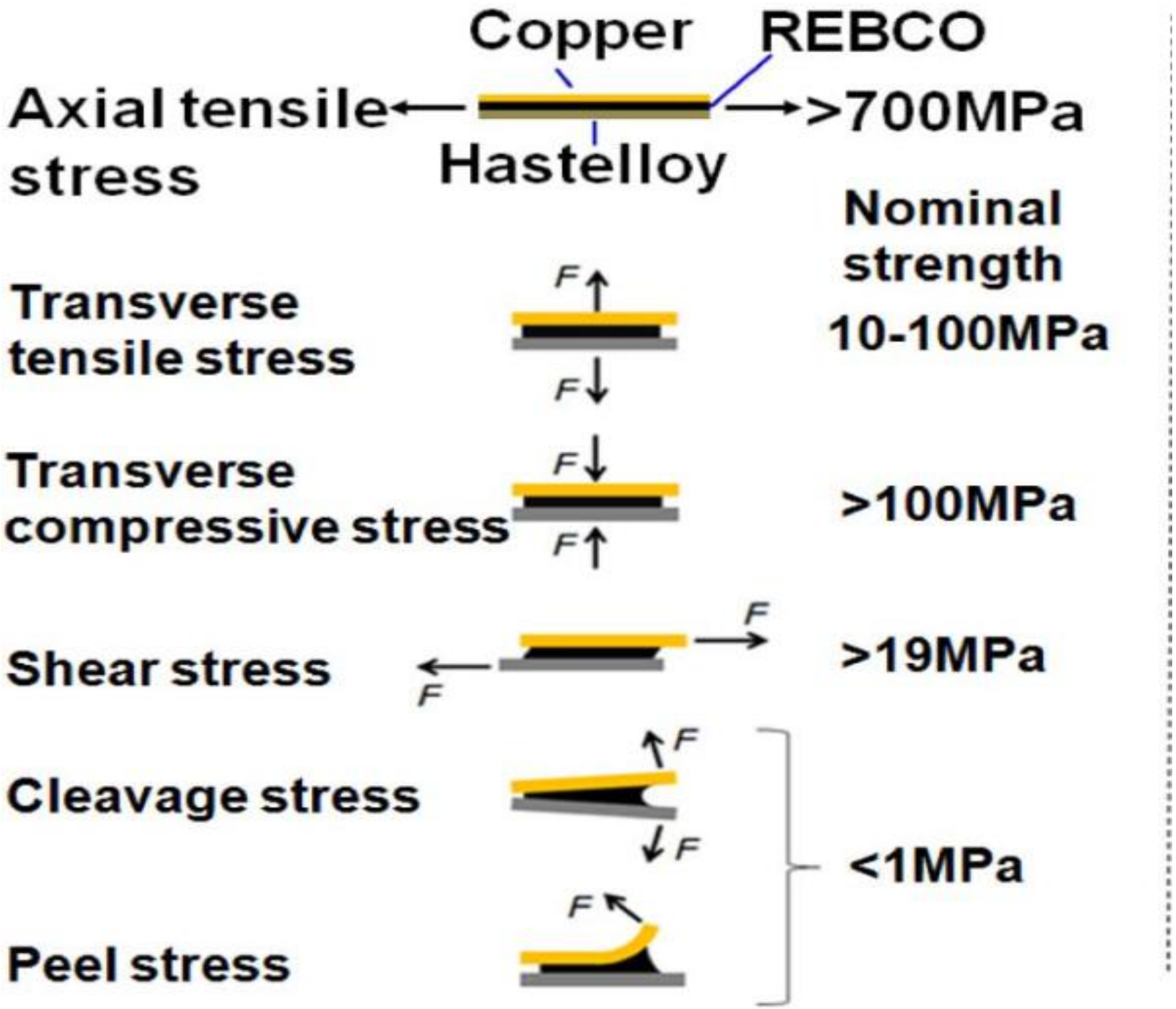
from the American Association for the Advancement of Science

HTS – REBCO tapes



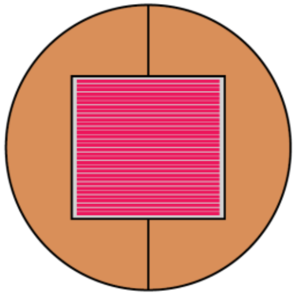
From Superpower.com

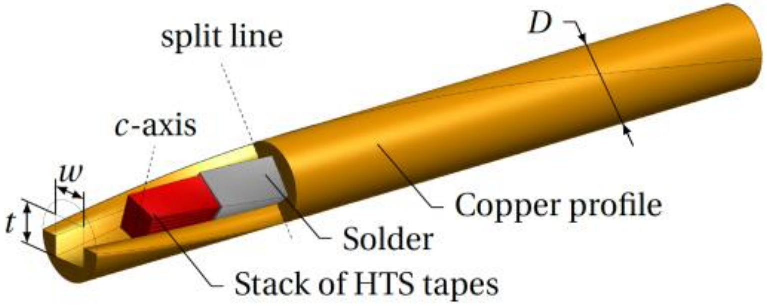
HTS – REBCO tape mechanical issues

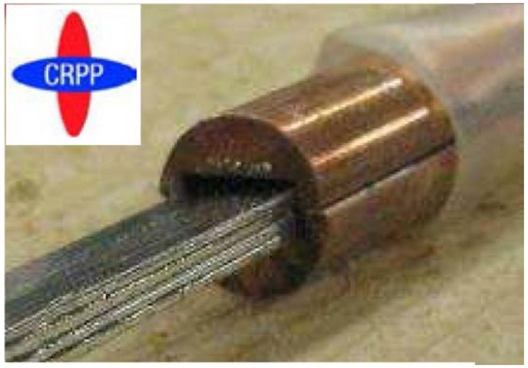


H. Maeda et al., TAS Critical current anisotropy ~ 5 **24** (2014) 4602412

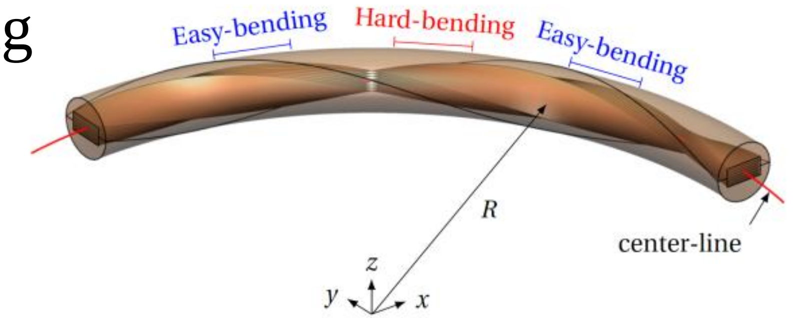
HTS – from tape to cable

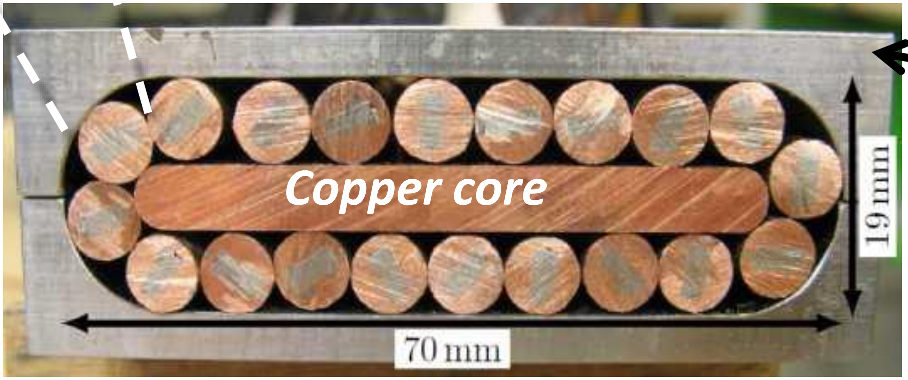






twisting and bending





Jacket

Courtesy of O.Dicuonzo

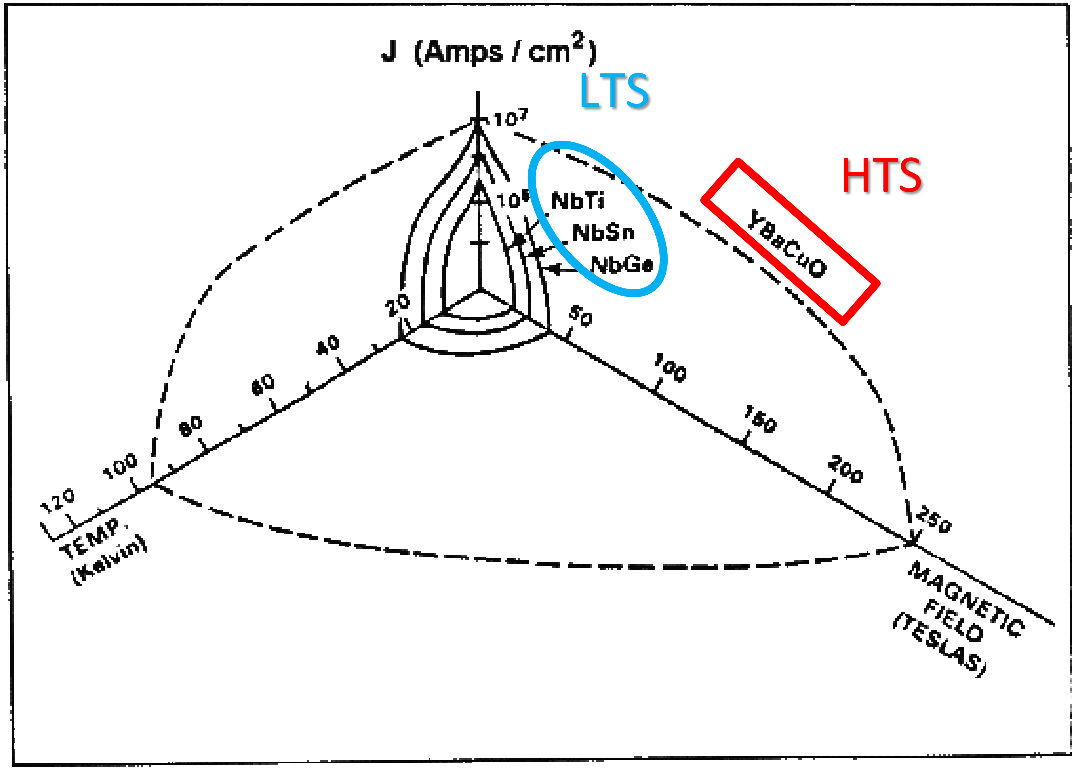
EPFL

Practical use of HTS

Low B → high temperature

Simpler and cheaper cryogenic systems

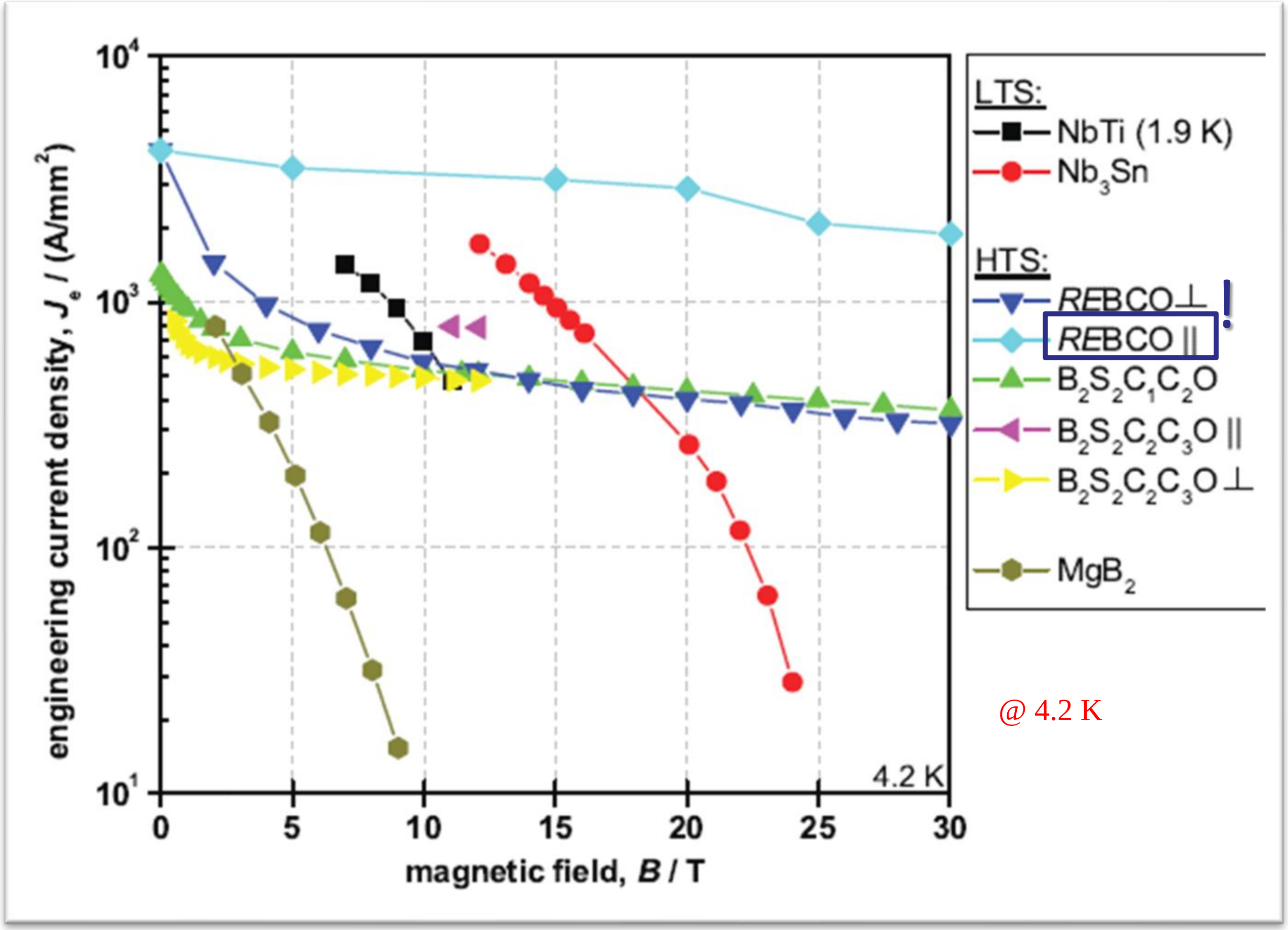
OK for energy transportation



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

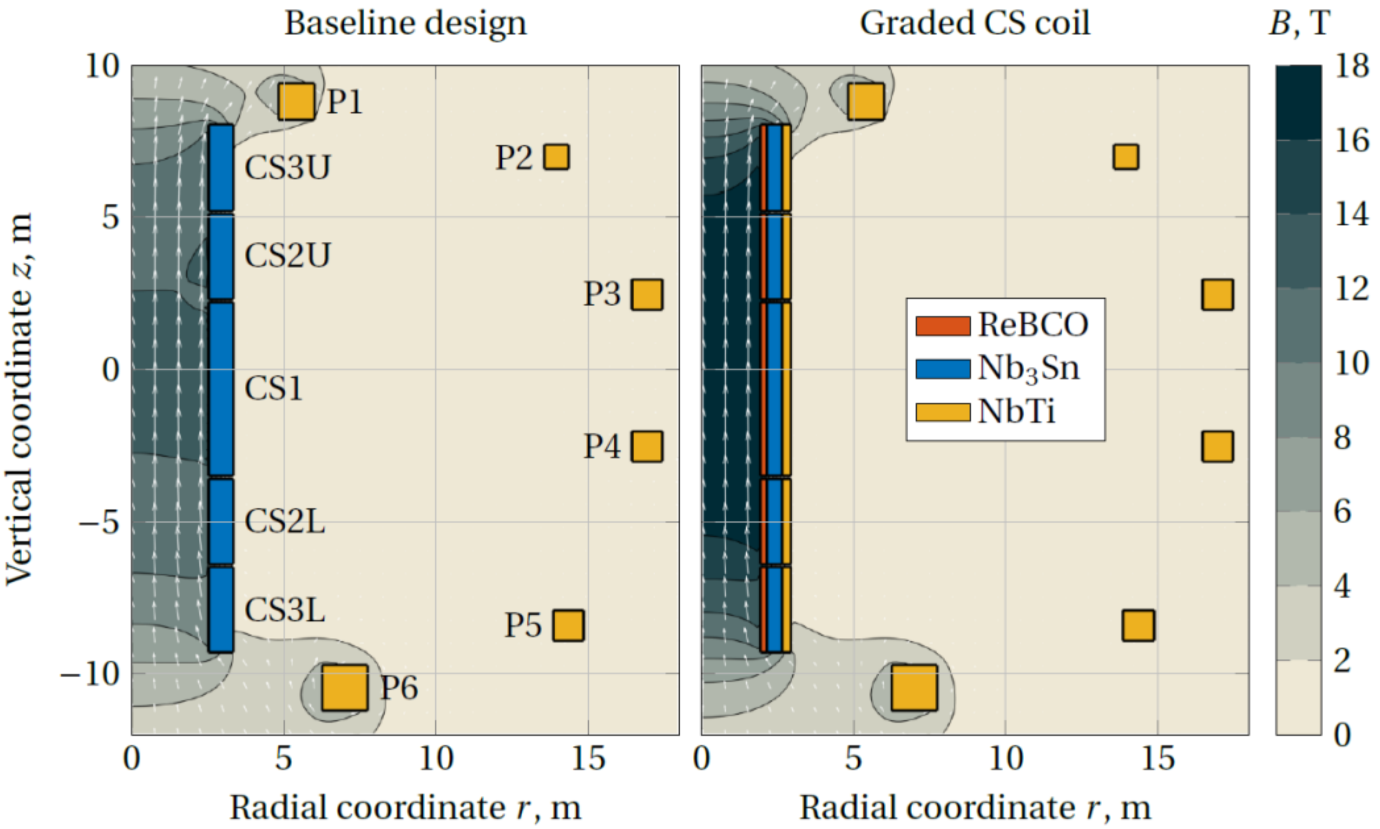
Need high current density at high B → REBCO

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

Swiss Plasma Center

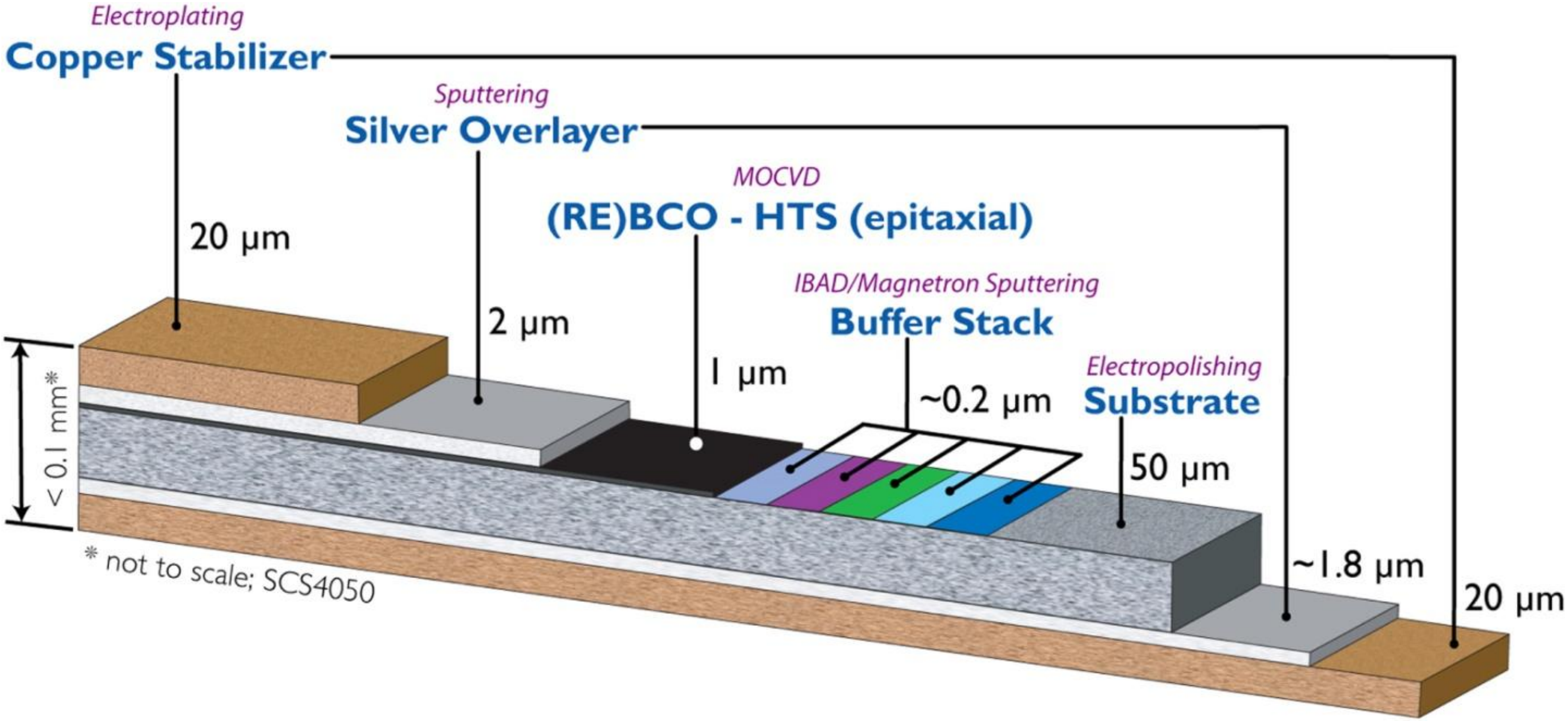
HTS materials for fusion

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

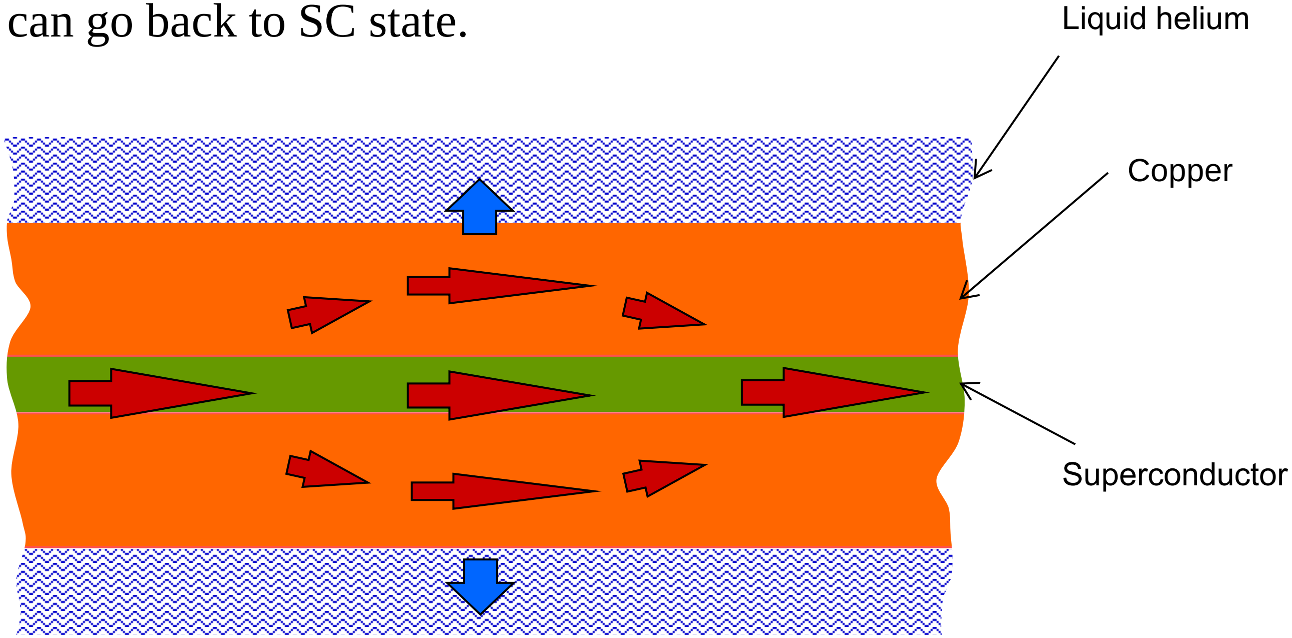
Why do we need copper ?

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.

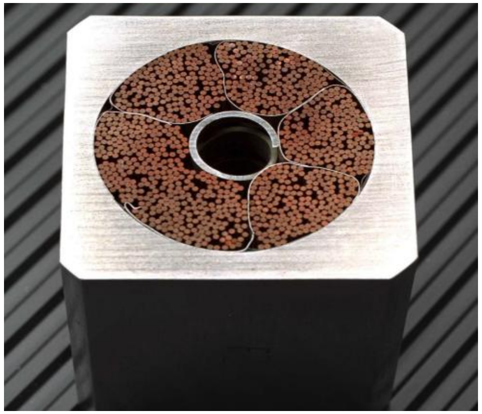


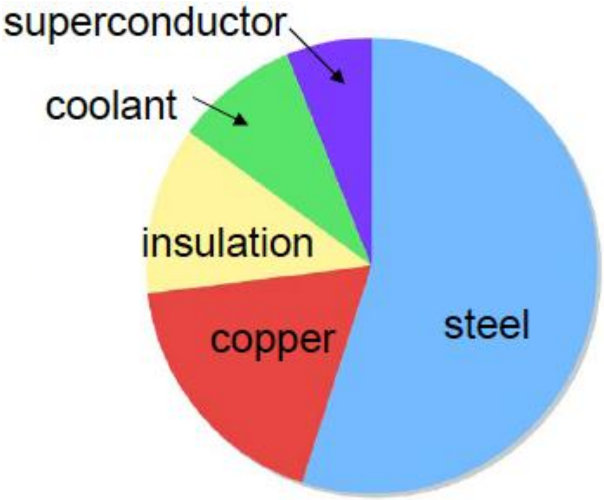
High current cables for fusion magnets

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



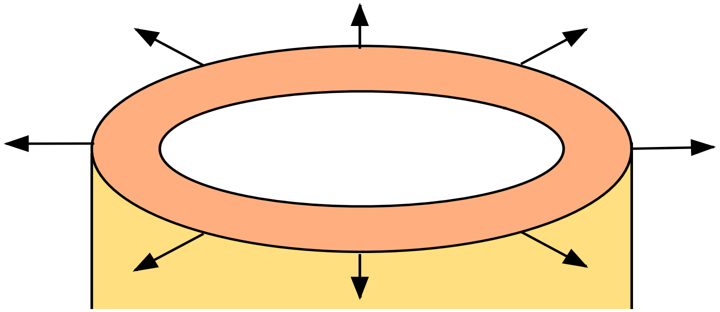


Requirements and challenges - Mechanical

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



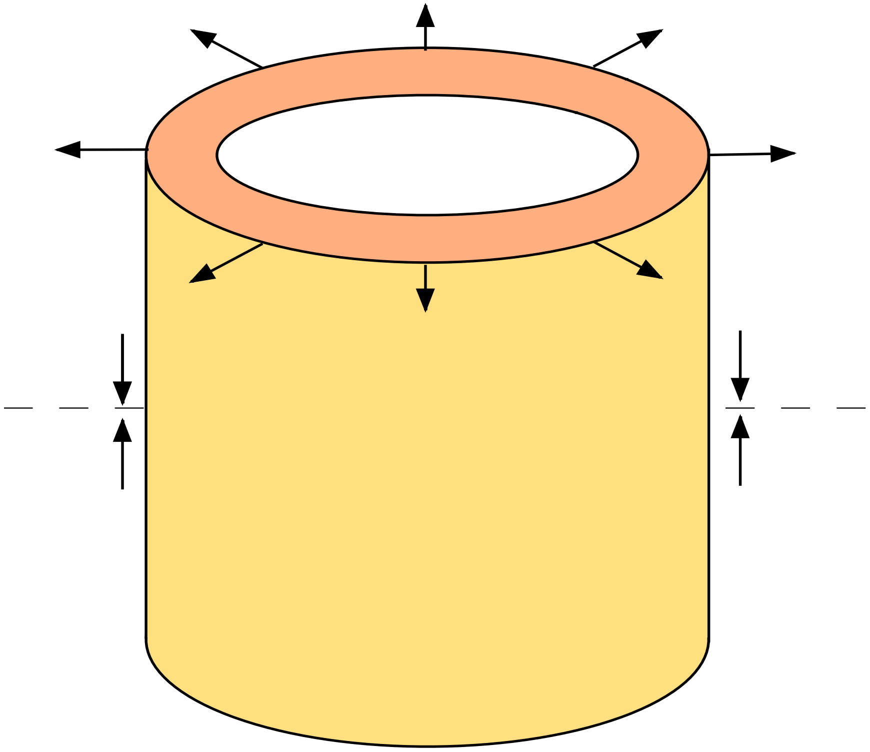
Solenoid

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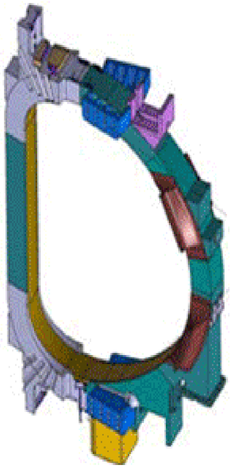
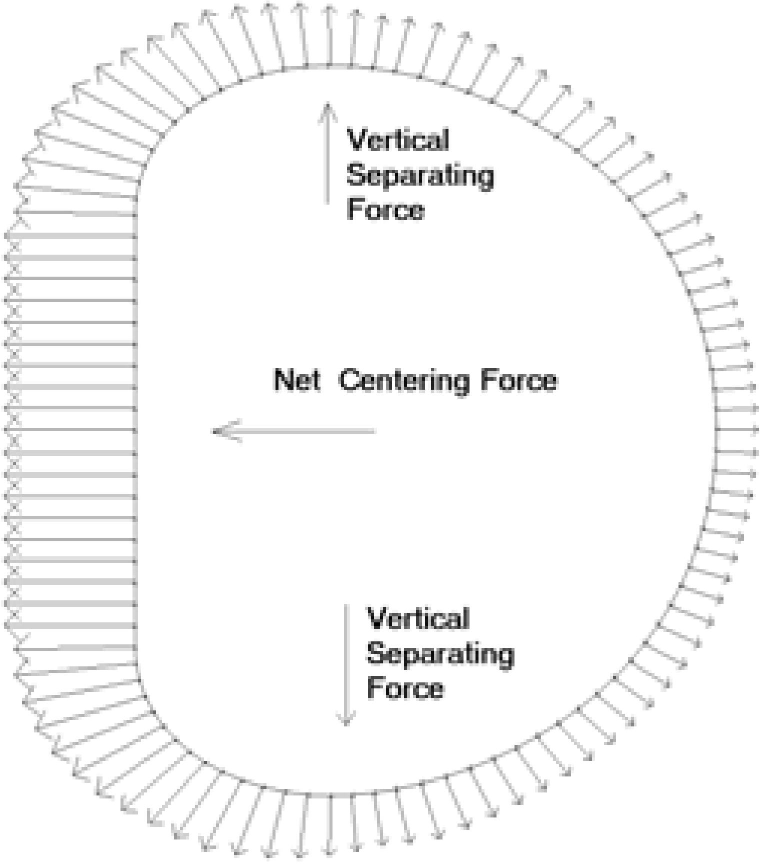
- Centering load on the in-board of non-circular toroidal field coils, ~BxI





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

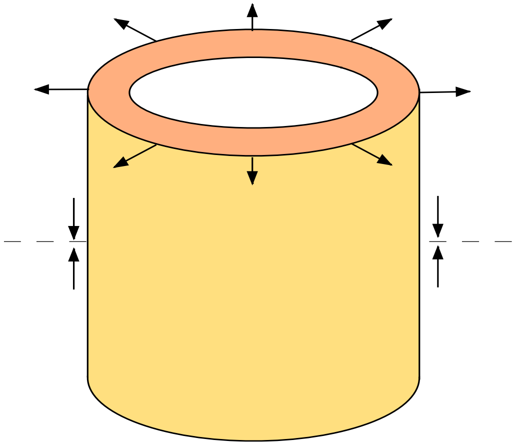
Requirements and challenges - Mechanical

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

Main loads, all from JxB force

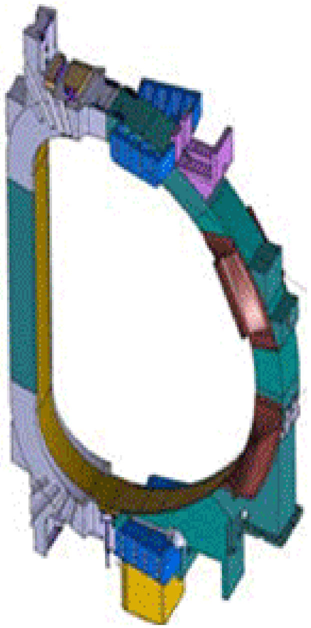
- Hoop load along the conductor axis, ~BxIxR
- Vertical load on the coil mid-plane (axial compression of solenoid as B_r is high at the coil ends)
- Centering load on the in-board of non-circular toroidal field coils, ~BxI

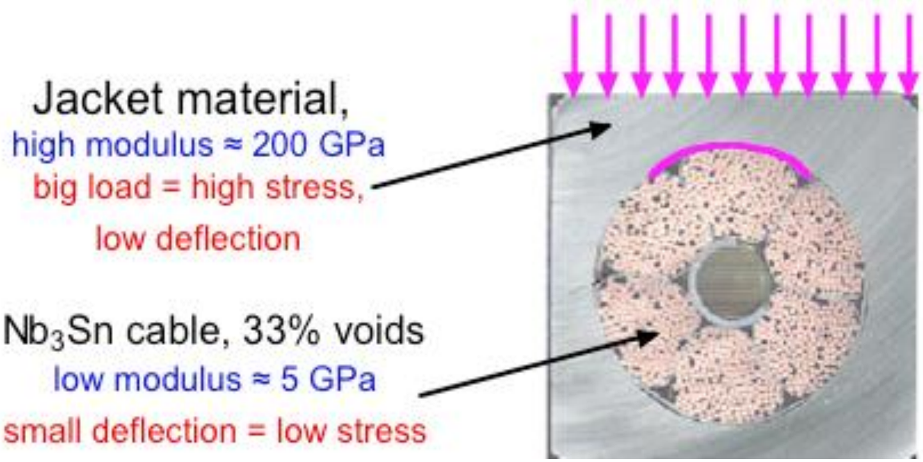
Transverse load accumulation from turn to turn must be avoided for brittle SC (Nb_3Sn and HTS); for this, a high elastic modulus conduit surrounds the cable



Solenoid

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





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

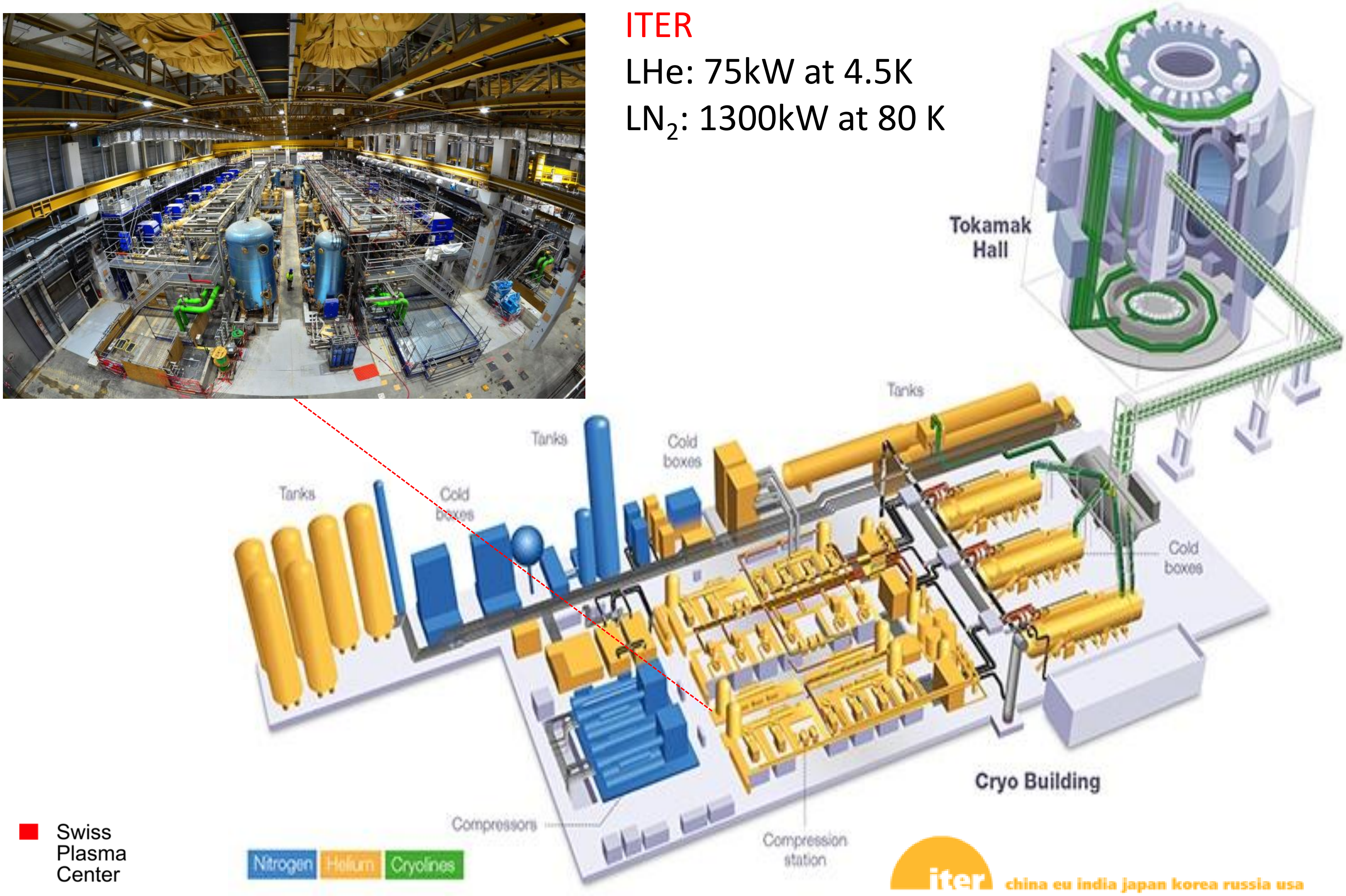
- Nuclear radiation on the TF coils
- Ohmic heating of the conductor joints
- Heat conduction (feeders and gravity support)
- AC losses in the coils
- Pumping losses for He circulation
- Heat radiation from room temperature

Requirement and challenges - Thermal

ITER

LHe: 75kW at 4.5K

LN_2: 1300kW at 80 K



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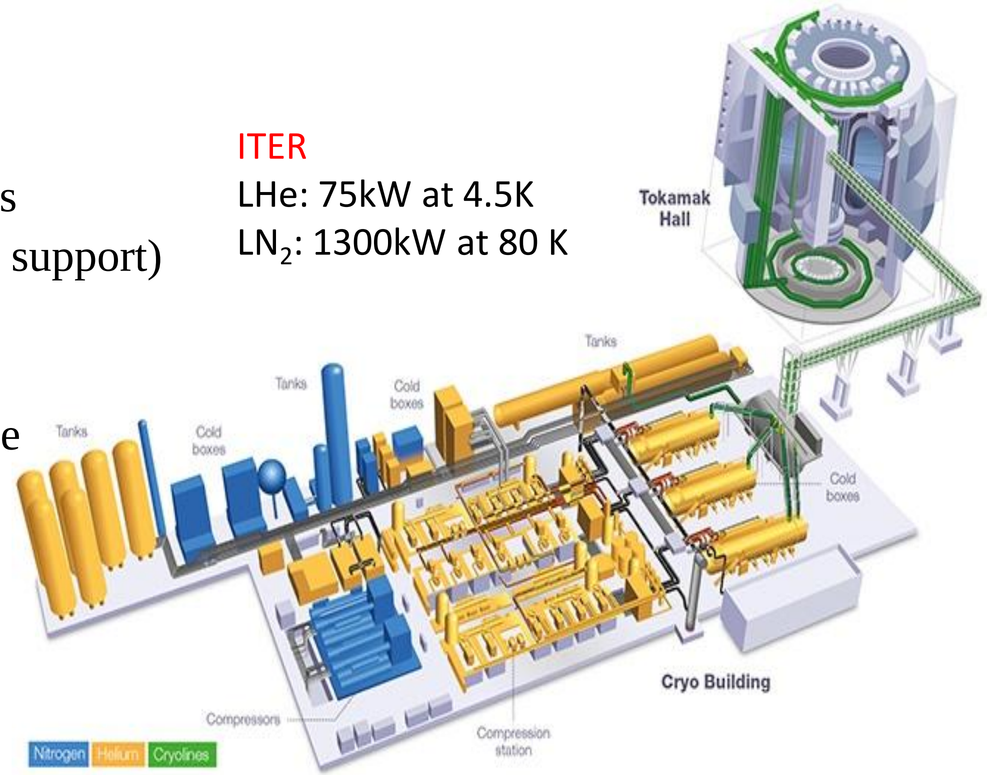


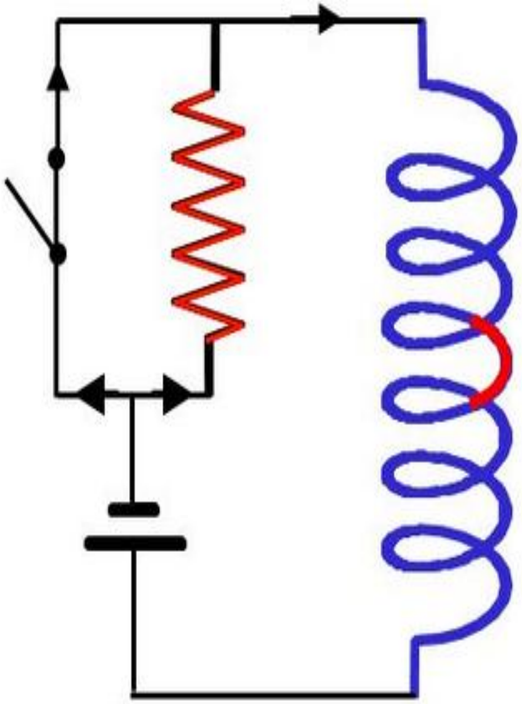
ITER
LHe: 75kW at 4.5K
LN$_2$: 1300kW at 80 K

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

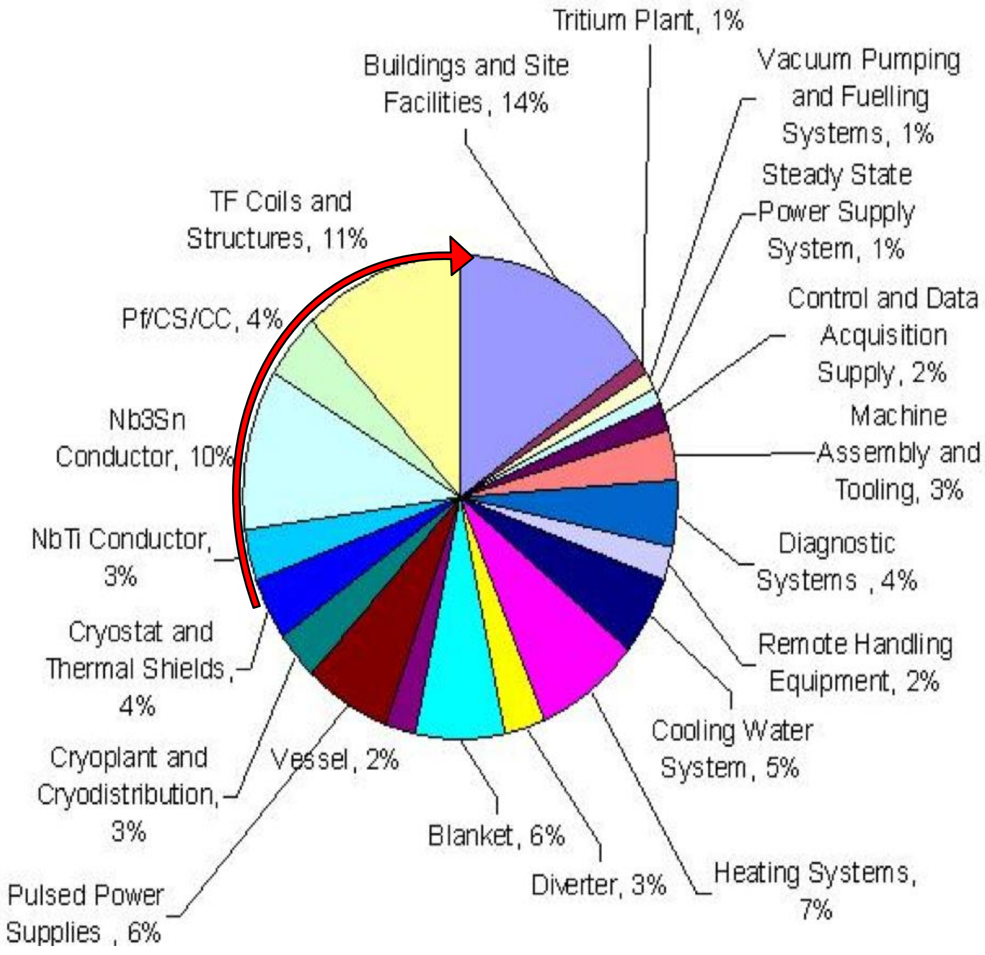
In fusion magnets, electrical insulation consists of Glass-Kapton wraps impregnated by epoxy. The quality of the impregnation is crucial for the coil mechanical integrity and to prevent flashovers to ground during the fast discharge

Requirement and challenges - Economical

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

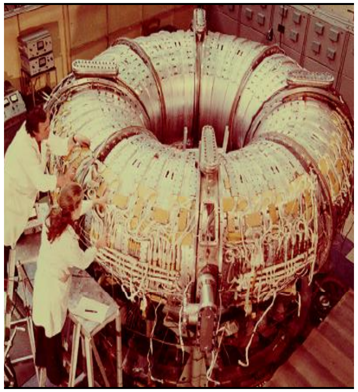
SC magnets make up a substantial fraction of the capital cost for a large fusion device, 30% for ITER

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



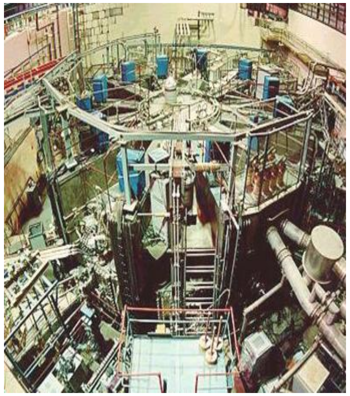
Present fusion devices with sc coils

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

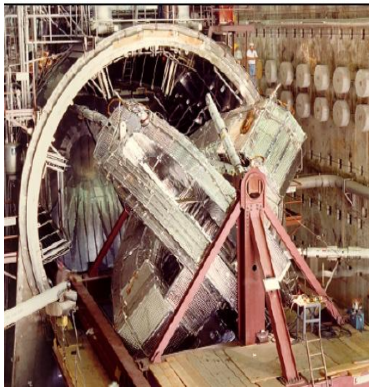


WEST at CEA -2017
NbTi, He bath, 9T

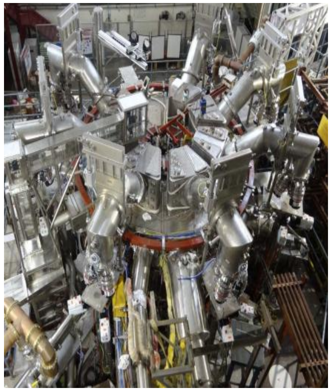
T 15 at Kurchatov -1983
Nb$_3$Sn, He forced flow, 9.3T



MFTF Livermore -1985
NbTi/Nb$_3$Sn, He bath 12.7T

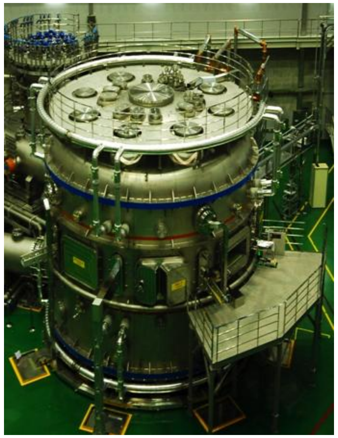


SST1 Bath - 2013
NbTi, He forced flow, 5T



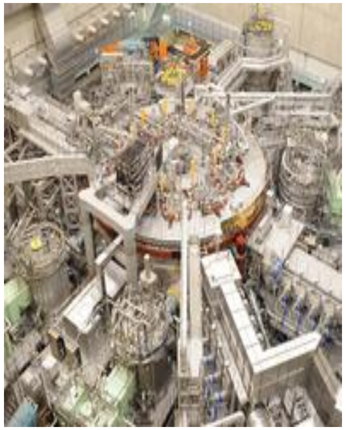
TRIAM Fukuoka -1986
Nb$_3$Sn, He bath, 11T

KSTAR- Daejeon 2007
Nb$_3$Sn, He forced flow, 8T

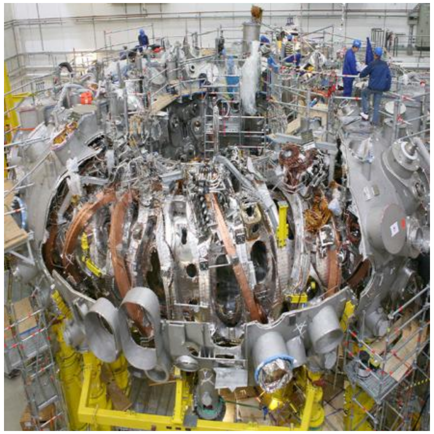


EAST Hefei - 2006
NbTi, He forced flow, 5.8T

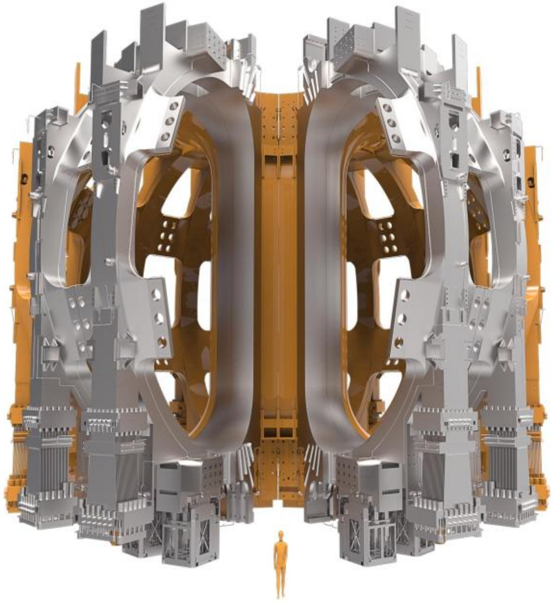
LHD Toki - 1996
NbTi, He bath, 6.9T



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

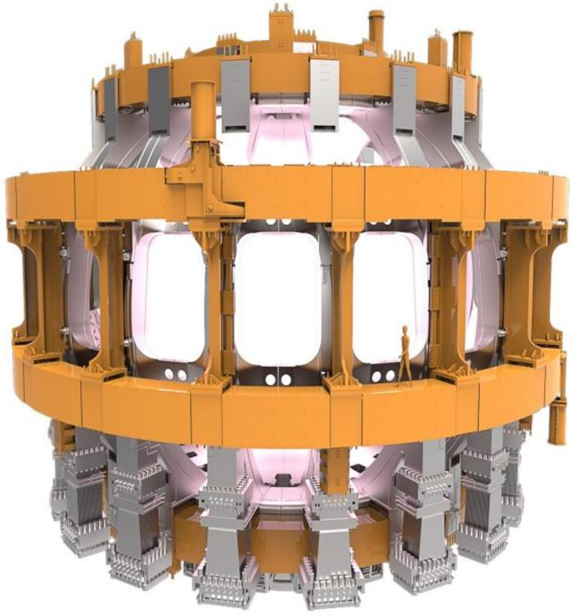


ITER magnets system – the largest ever built

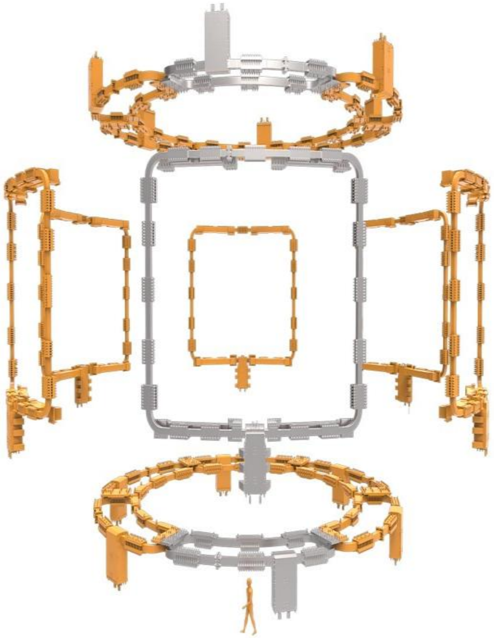


TF coils
Nb_3Sn, 11.8T

Central solenoid
Nb_3Sn, 13T



Poloidal coils
NbTi, 6T



Correction coils
NbTi, 4.2T

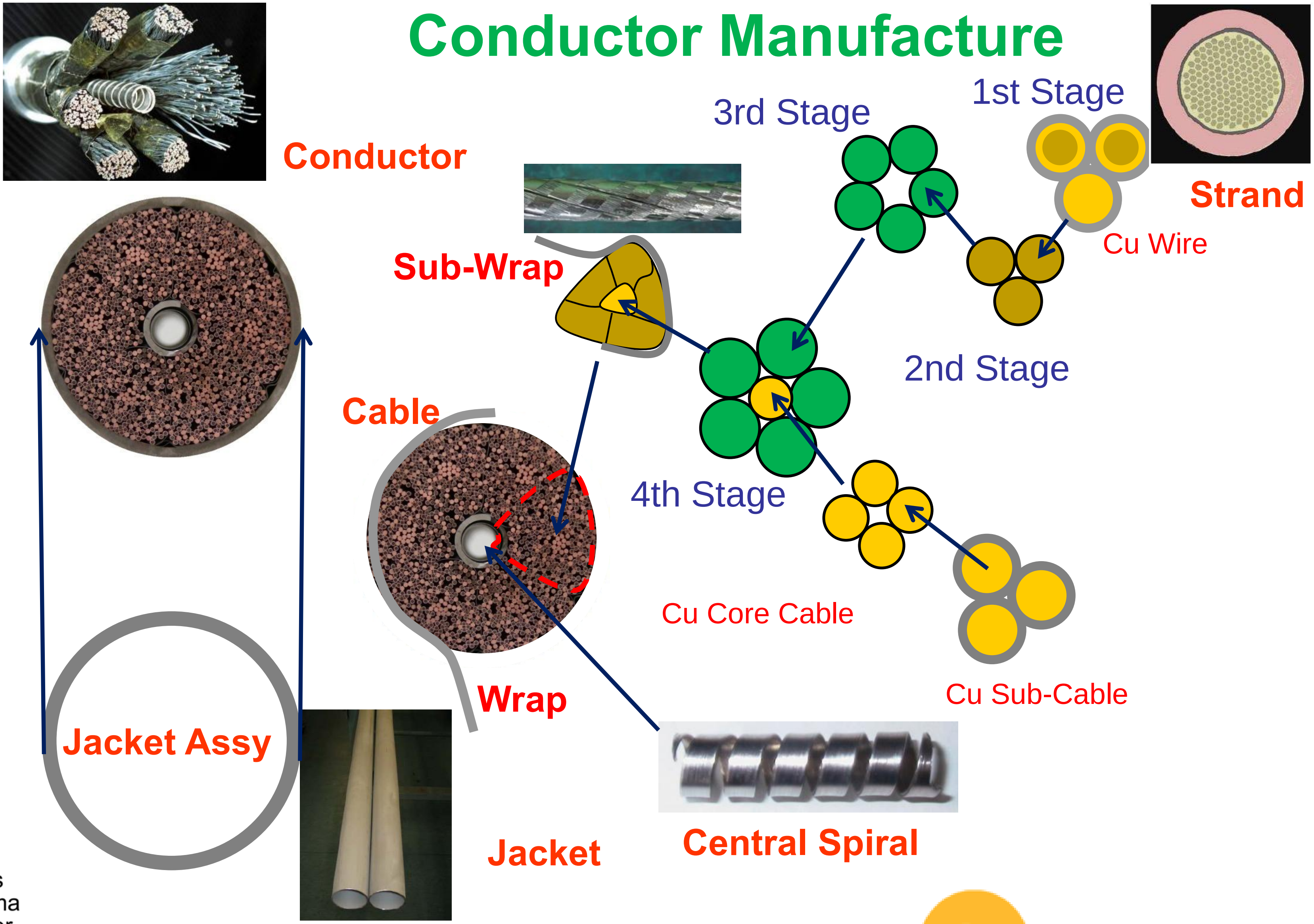
48 SC coils, total stored energy = 51GJ

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

Cu Wire

3rd Stage

2nd Stage

Sub-Wrap

Cable

4th Stage

Cu Core Cable

Cu Sub-Cable

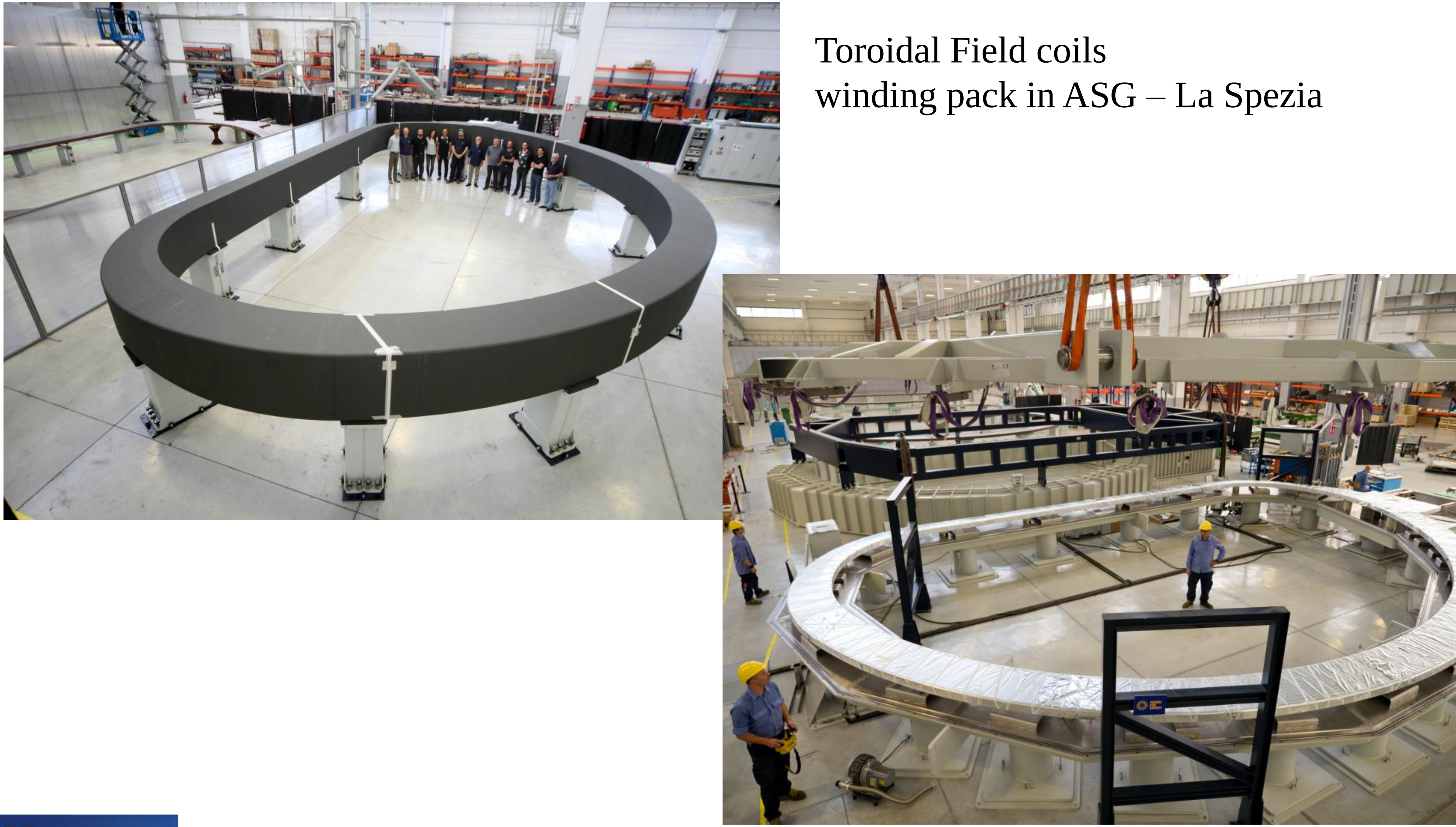
Wrap

Jacket Assy

Jacket

Central Spiral

ITER magnets system – TF coils



Toroidal Field coils
winding pack in ASG – La Spezia

ITER magnets system – TF coils

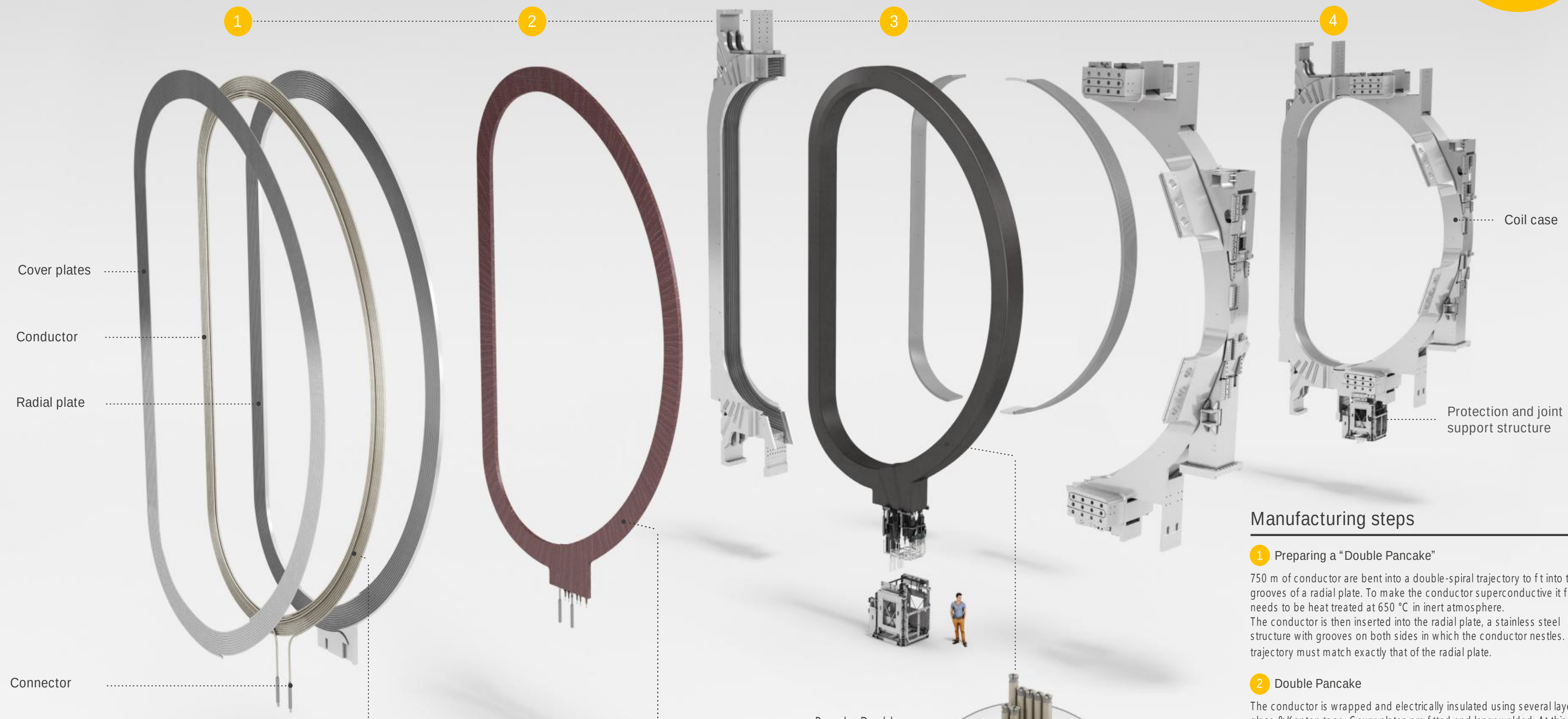
Transporting one
Toroidal Field coil

All 18 (+1 spare) TF coils are manufactured (9 in Japan, 10 in Europe)

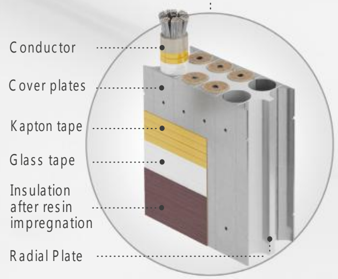
ITER Toroidal Field Coils

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.

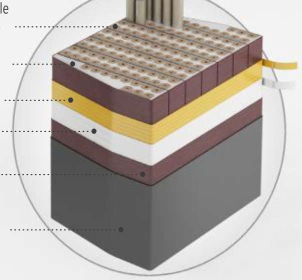
Each coil is approximately:
14 m high
9 m wide
300 t with its case - the weight of a Boeing 747



Conductor



Double Pancake



Winding Pack

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 ℃ 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.

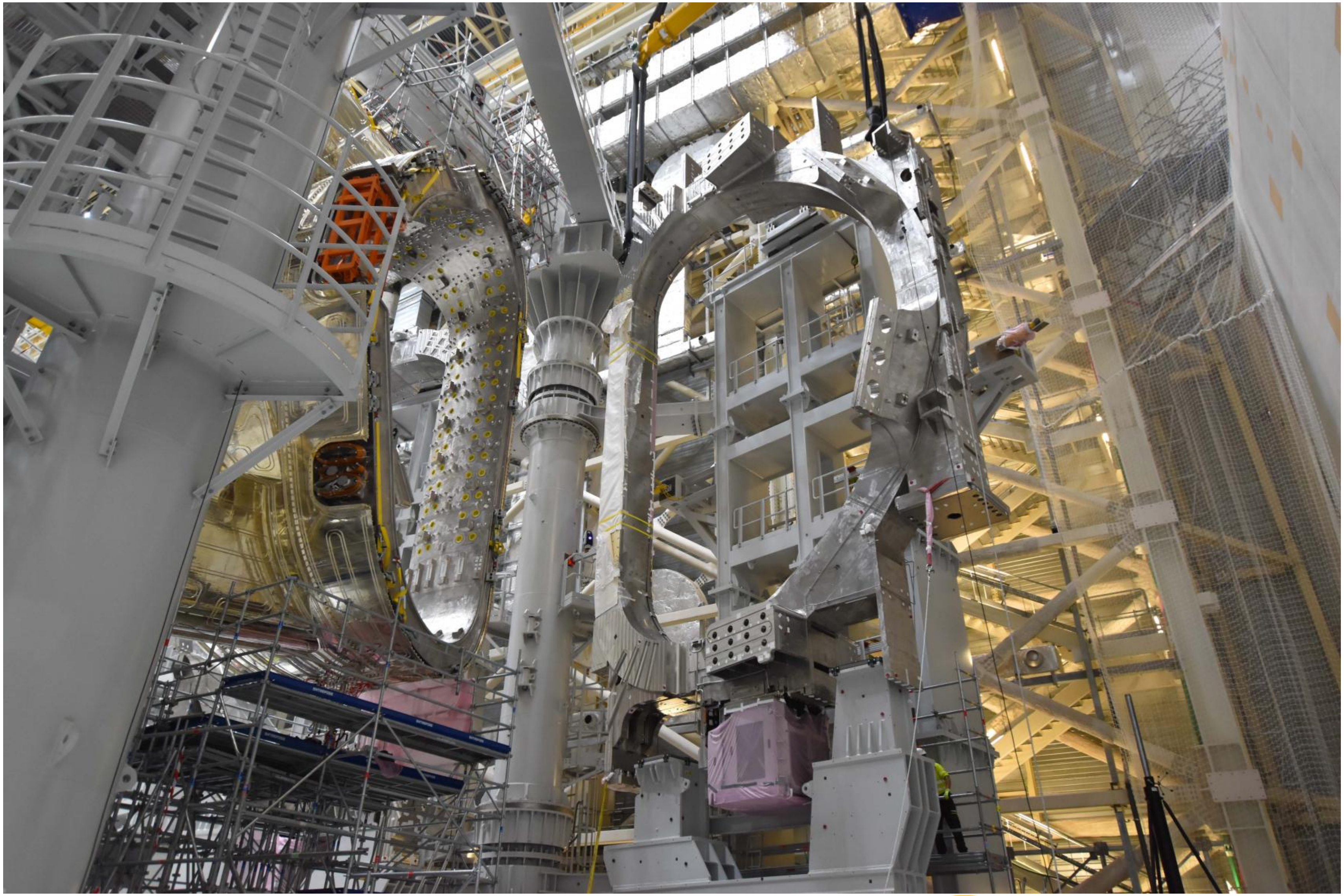
www.f4e.europa.eu

ITER magnets system – PF coils

Poloidal Field coils after successful cold test on ITER site (all coils completed)

ITER magnets – installation of 6th PF coil

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



Swiss
Plasma
Center

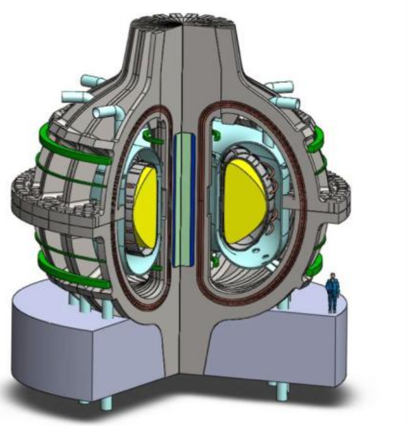
china eu india japan korea russia usa

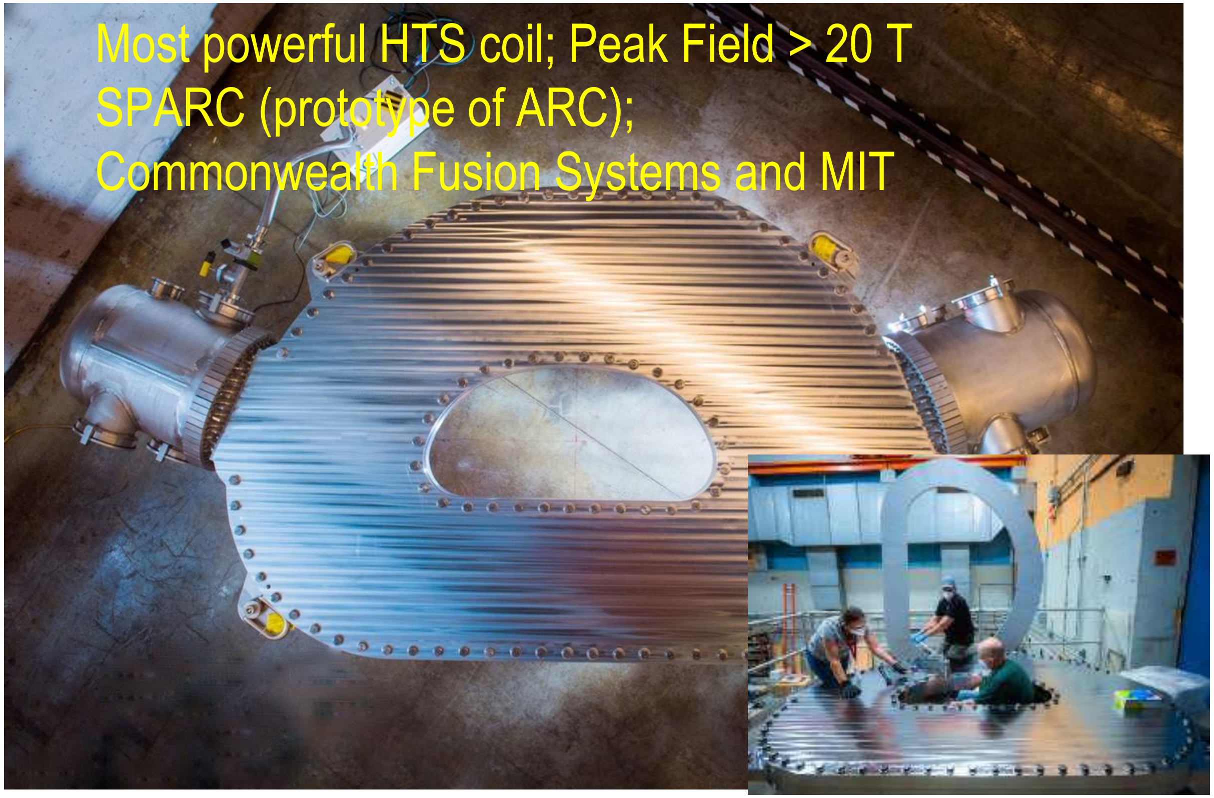
ITER magnets system – the cryostat

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

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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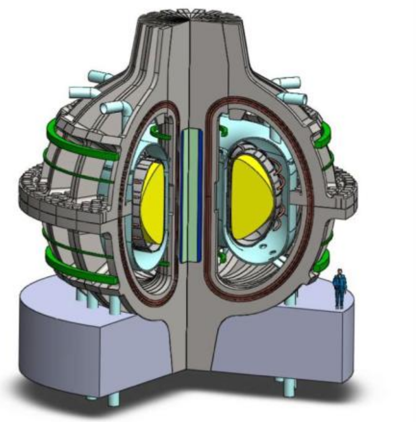
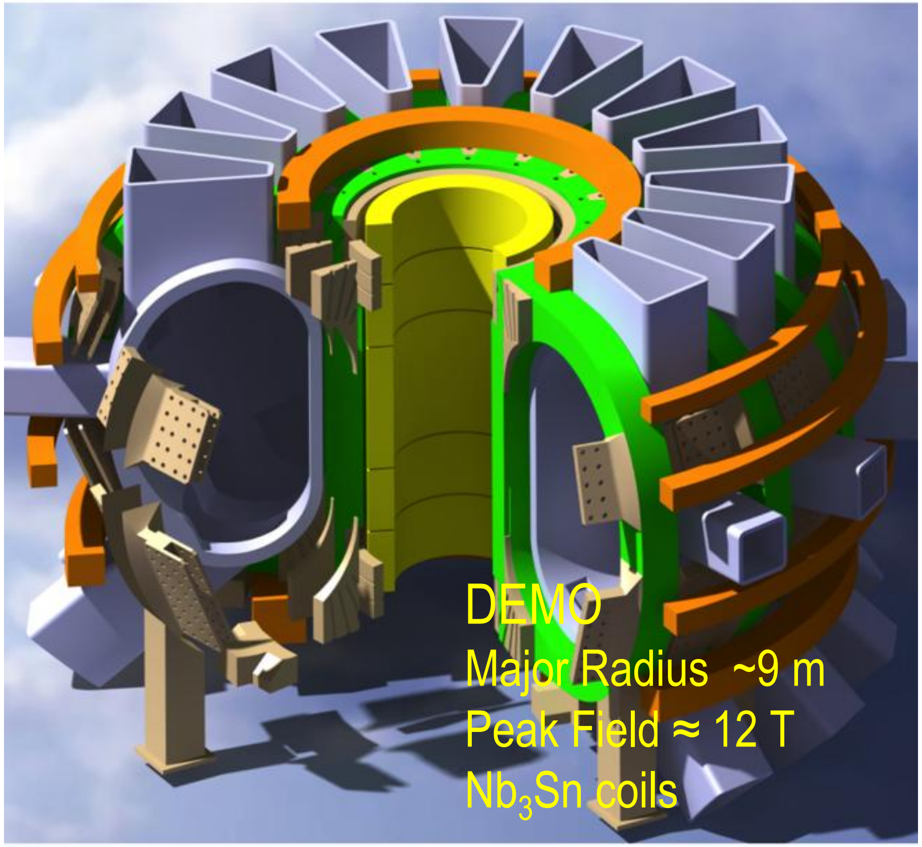




DEMO
Major Radius ~9 m
Peak Field ≈ 12 T
Nb_3Sn coils

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

Nb_3Sn Superconductors for Fusion and their Behaviour under Strain

J. Greenwood

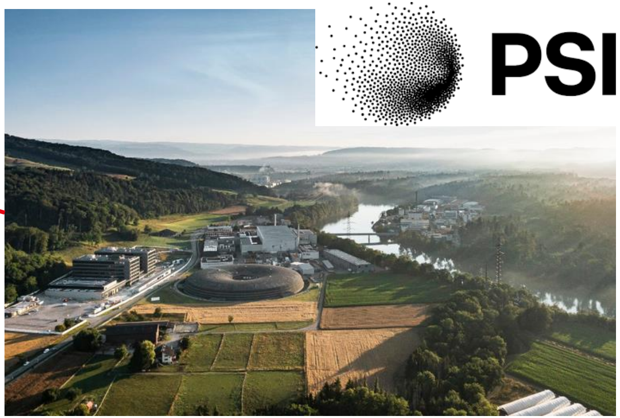
02.12.2024

SWISS
PLASMA
CENTER

Outline

- Overview of Swiss Plasma Center – Superconductivity Group
- The critical current as a key fusion conductor performance parameter
- Nb_3Sn fusion magnet conductors: react and wind, or wind and react?
- The effect of bending strain on the critical currents of RRP® Nb_3Sn strands

Swiss Plasma Center – Superconductivity Group



SULTAN Test Facility

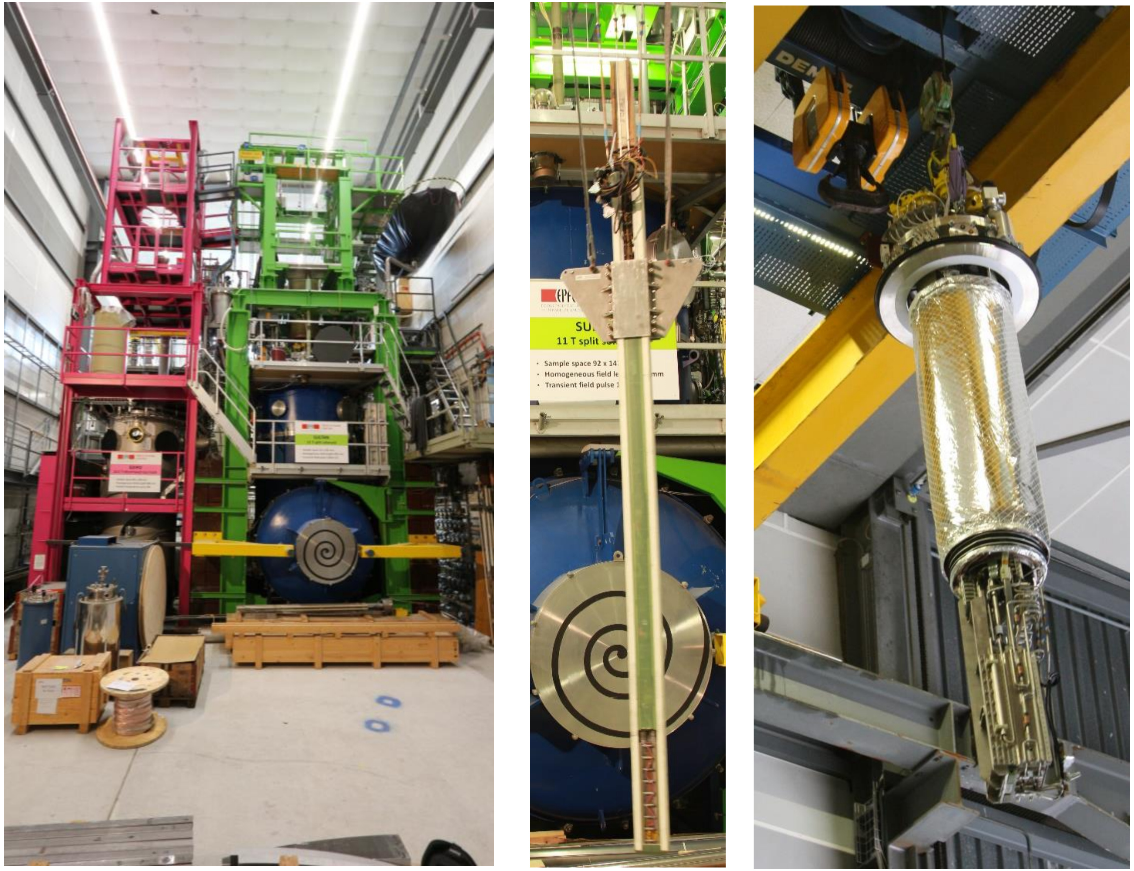
A world-unique facility for testing superconductors in the fusion environment

$$B \leq 10.9\ \mathrm{T}$$

$$4.5\ \mathrm{K} \leq T \leq 300\ \mathrm{K}$$

$$I \leq 100\ \mathrm{kA}$$

Customers include ITER, EU-DEMO, W7-X, SPARC, BEST, CFETR, JT60-SA



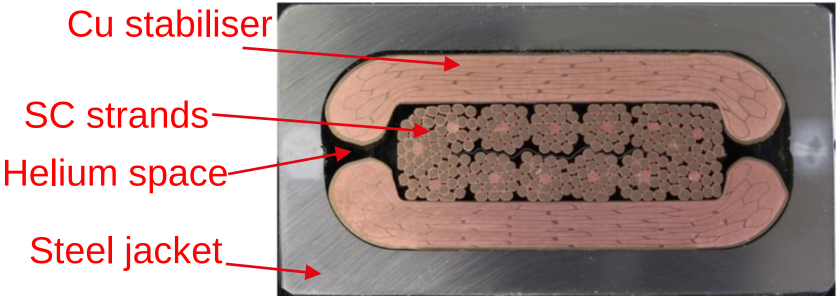
Swiss Plasma Center – Superconductivity Group

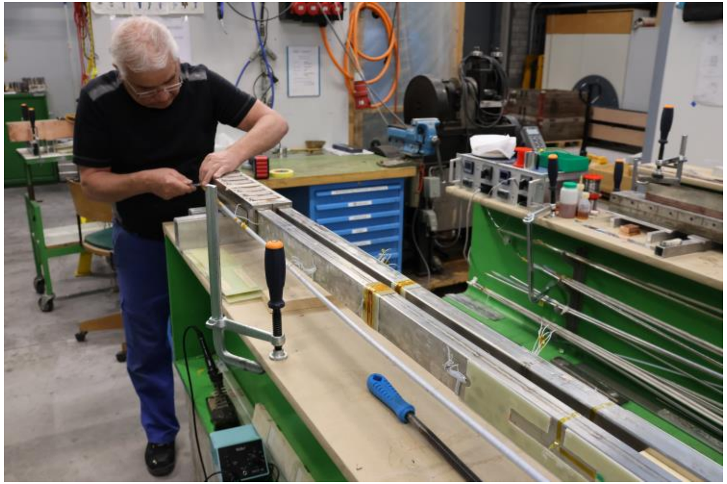
The group also specialises in the development of prototye LTS and HTS fusion magnet conductors, mainly for EU-DEMO.

The conductors must:

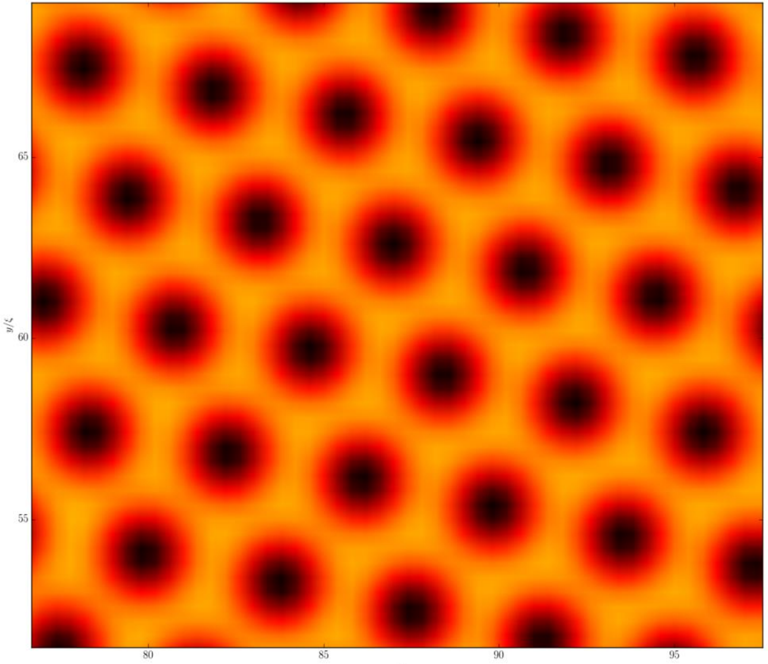
- Be mechanically robust, cooled efficiently, and cost effective.
- Have critical currents in the 10^4-10^5 A range in high fields.

EU-DEMO: RW2 Conductor





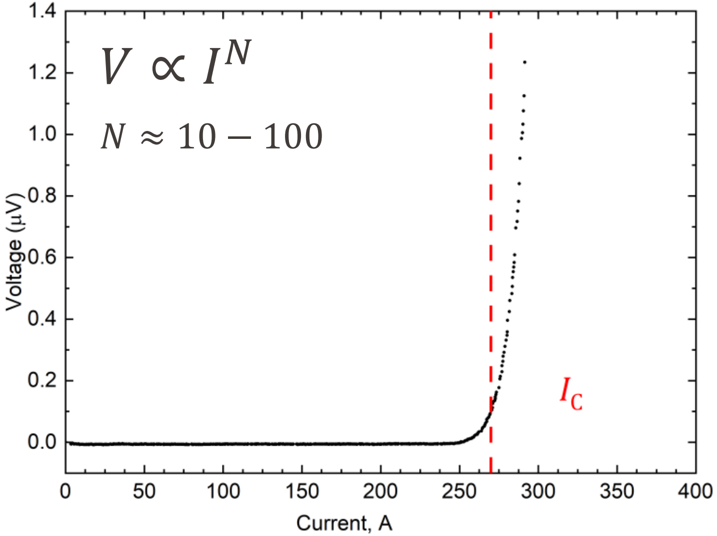
The Vortex Lattice

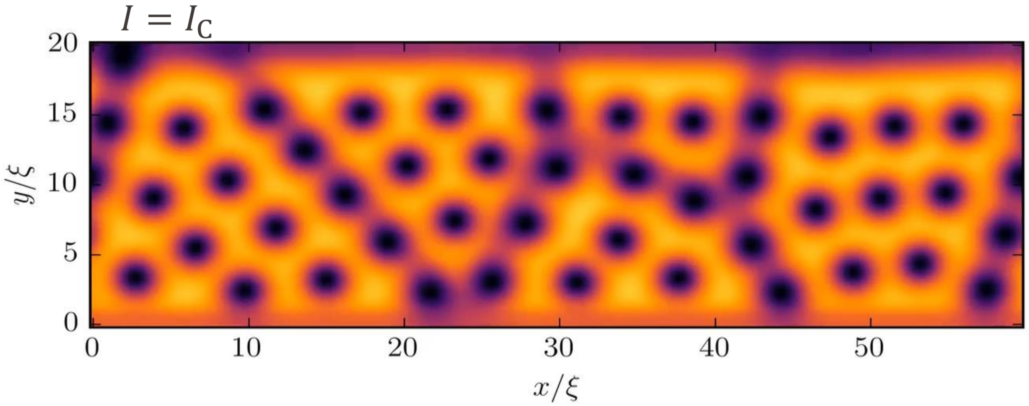


The Critical Current I_C

At $I = I_C$, the vortices in the material begin to move.

I_C is far lower than the current at which the Cooper pairs are destroyed (<1%).



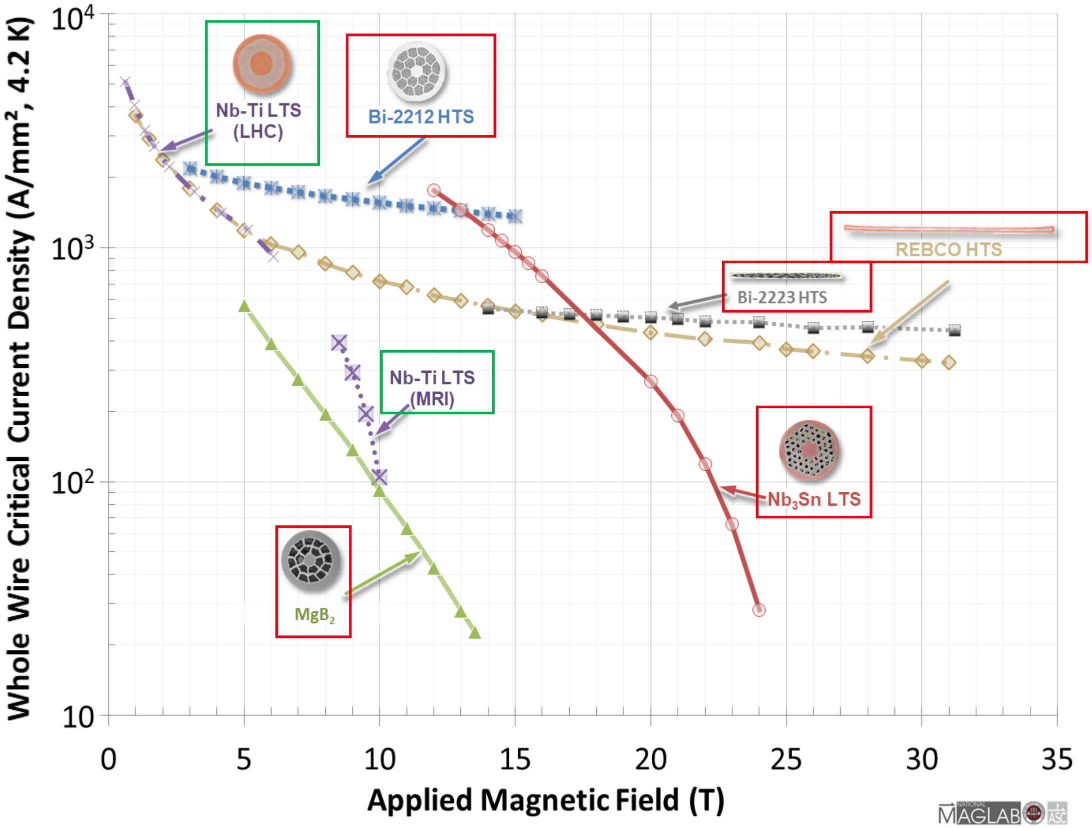


Simulation: Alex Blair, Durham University / CCFE, UK

Superconductors under Strain

The forces on fusion magnets during manufacturing and operation are large.

Most superconductors are **brittle** and their I_C's are **strain sensitive**.

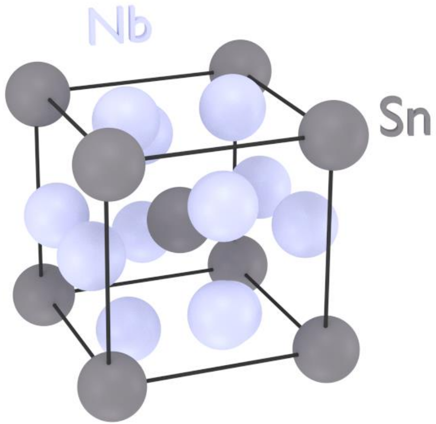


Nb_3Sn

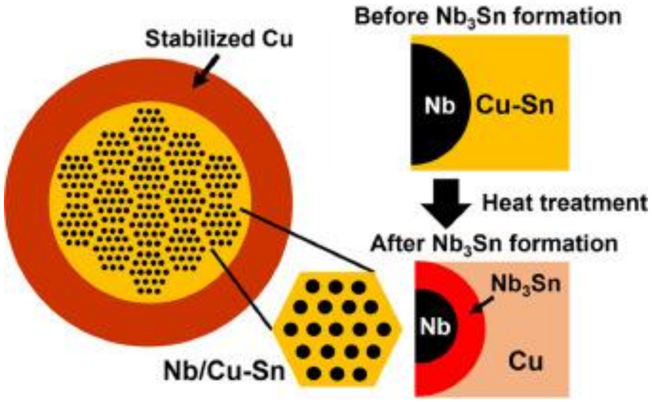
$$T_\mathrm{C} \approx 18\ \mathrm{K}$$

$$B_{\mathrm{c2}}(4\ \mathrm{K}) \approx 25\ \mathrm{T}$$

A15



Conventional bronze processed Nb_3Sn wire



Used in ITER’s TF and CS coils and under consideration for EU-DEMO.

The wires must be reacted at 650 °C to form the Nb_3Sn compound.

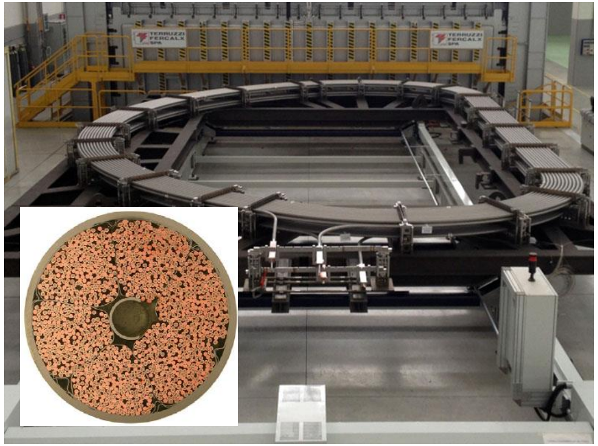
Nb_3Sn: Wind and React, or React and Wind ?

Wind and react

Used in ITER, KSTAR, JT60-SA.

Nb_3Sn assembled with steel jacket + Cu before heat treatment.

Differential thermal contraction reduces strand I_C by **~1/3** from zero strain value.



Nb$_3$Sn: Wind and React, or React and Wind ?

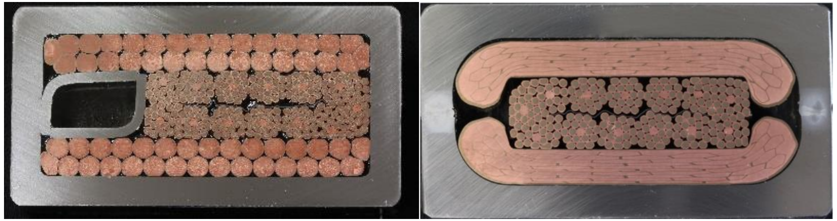
React and wind

The Nb$_3$Sn cable is heat treated on a spool without the steel and Cu components.

It is then straightened so that it can be jacketed, and then it is bent to its final shape.

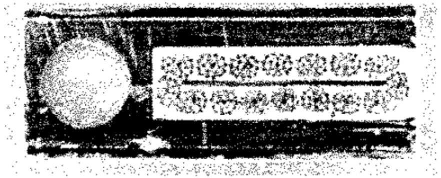
Lower strain from differential thermal contraction, so higher I_C. However, bending strains are introduced.

EU-DEMO RW2



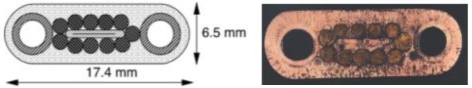
SULTAN

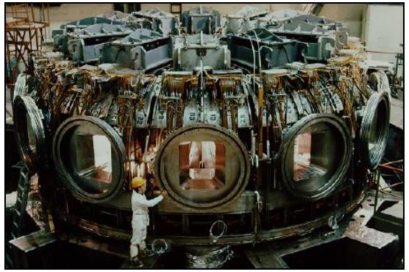
Innermost, Nb$_3$Sn coil



Intermediate, Nb$_3$Sn coil

T-15, Russia

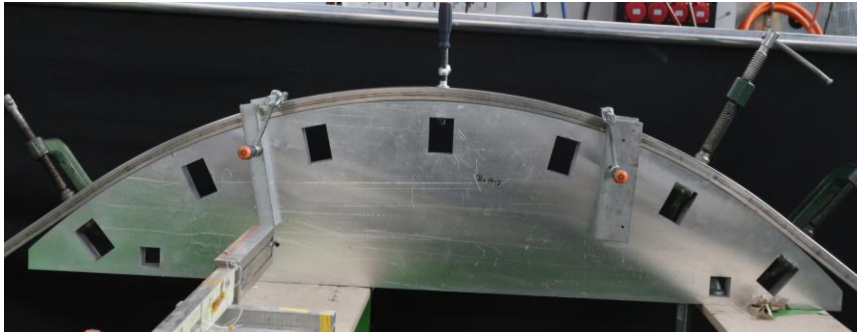




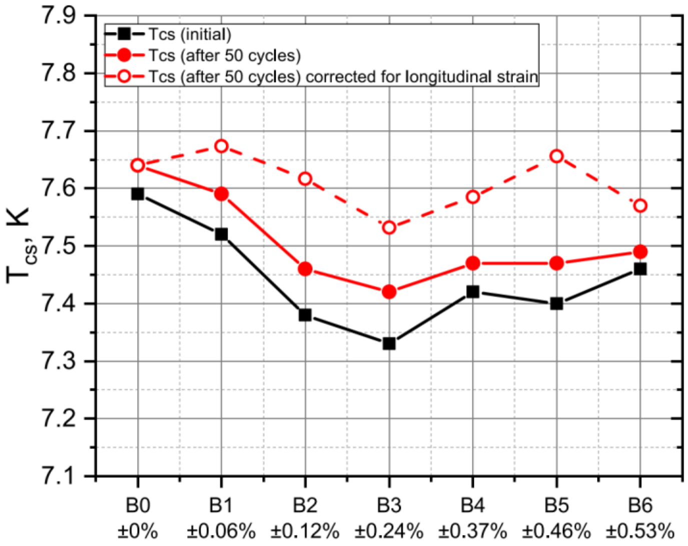
Nb_3Sn: Wind and React, or React and Wind ?

Bending tests on RW2: 2023

The EU-DEMO RW2 conductor has been subjected to different ε_B's and then re-straightened and tested in SULTAN.



No significant performance degradation was observed for $|\varepsilon_B| \leq 0.5\%$.

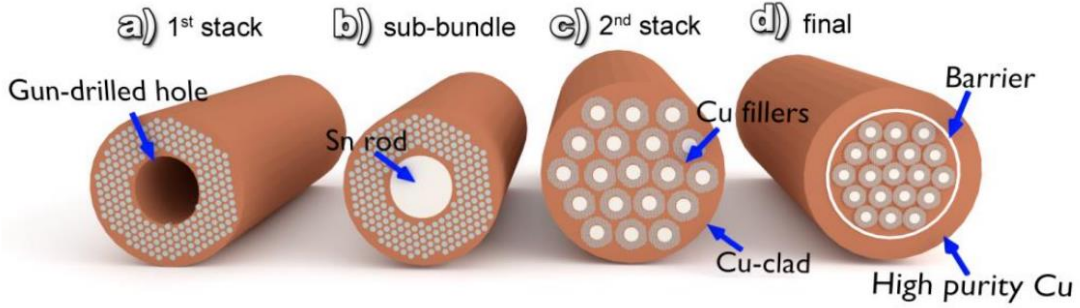


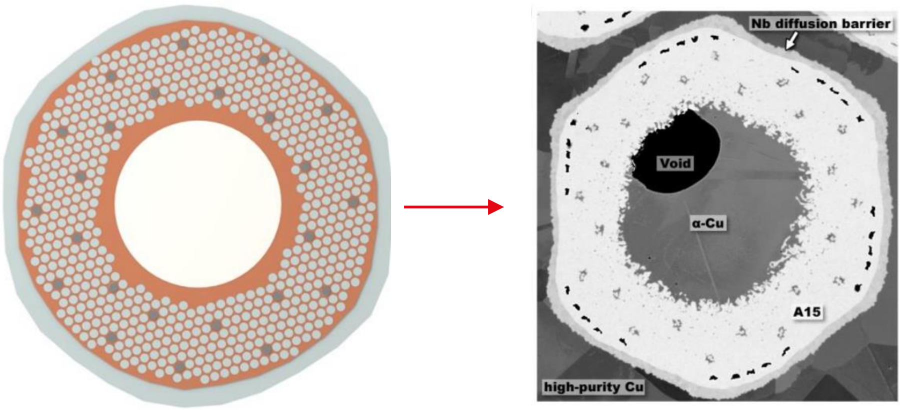
- RW2 used Internal Tin Nb_3Sn strands

Rod Restack Process (RRP®) Nb_3Sn

RRP® strands have much higher J_C's than conventional (e.g., ITER bronze route) Nb_3Sn strands.

This is achieved through an increase of the cross-section of Nb_3Sn compared to the Cu stabiliser.





Method

1. Wind and then react RRP® strands on cylinders with different diameters.

2. Transfer the strands to I_C measurement barrels with a diameter of 30 mm.

$$\varepsilon_B = \pm\frac{D}{2}\left(\frac{1}{R_m} - \frac{1}{R_{HT}}\right)$$

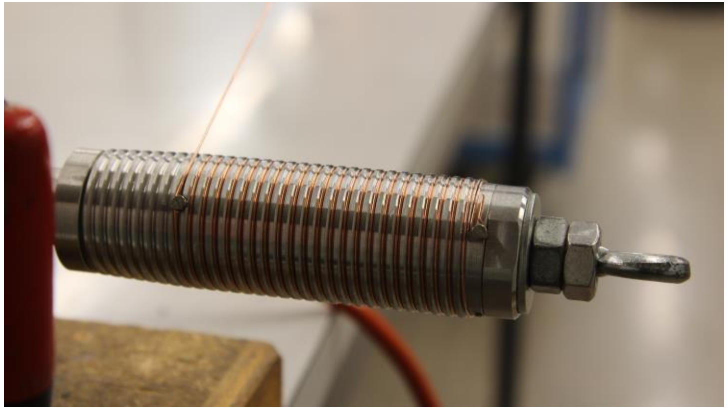
D: strand diameter (0.697 mm)

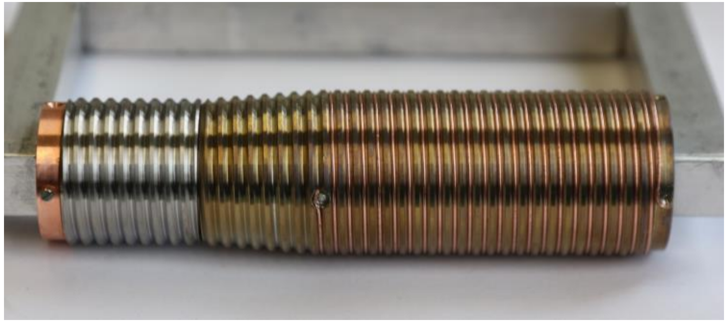
R_m: I_C measurement neutral axis radius (15.45 mm)

R_{HT}: heat treatment neutral axis radius (15.45 mm – 18.85 mm)

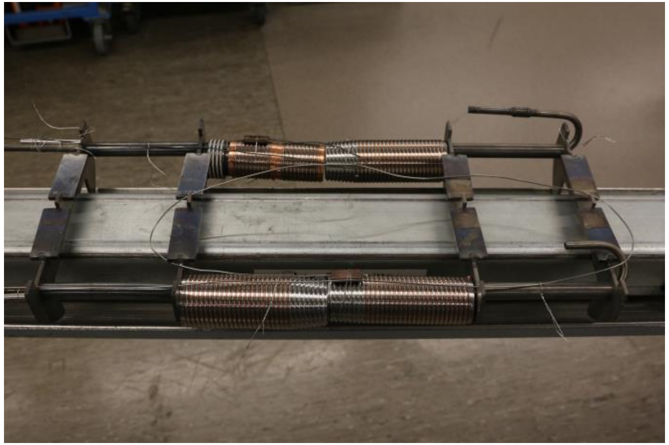
$$0\% \leq |\varepsilon_B| \leq 0.41\%$$

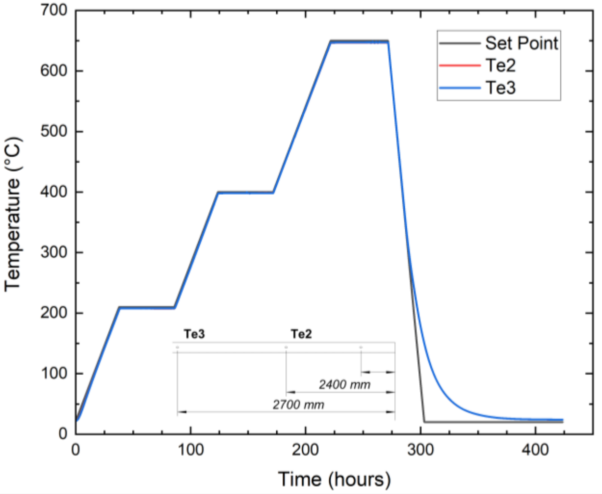
3. Measure the critical current at 4 K.



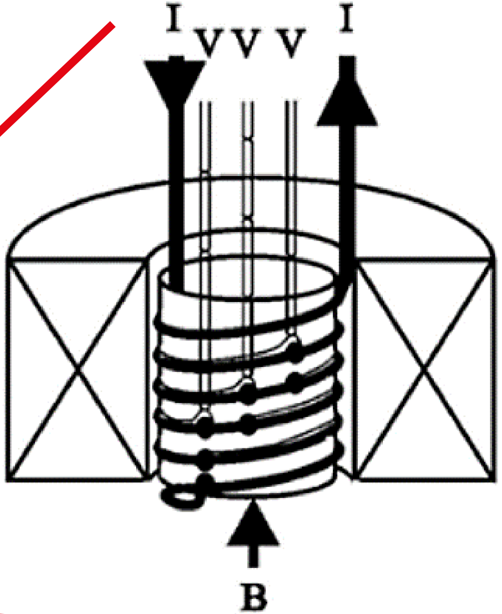


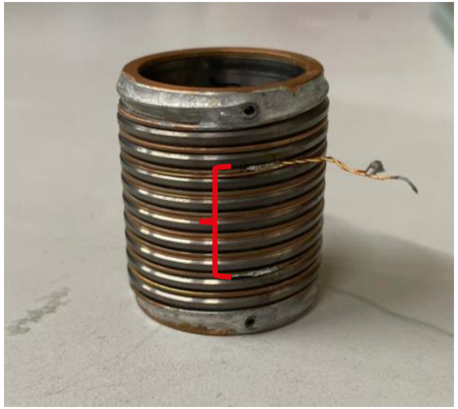
Method – Heat Treatment





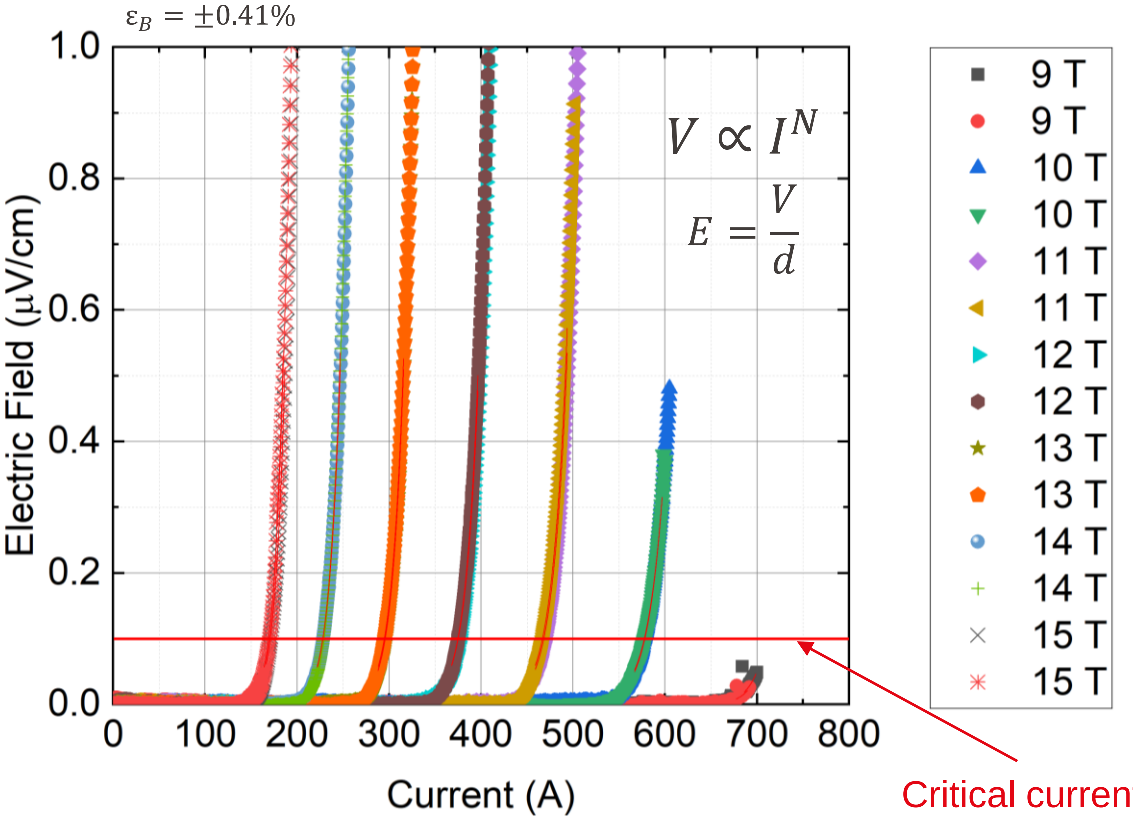
I_C Measurement Setup





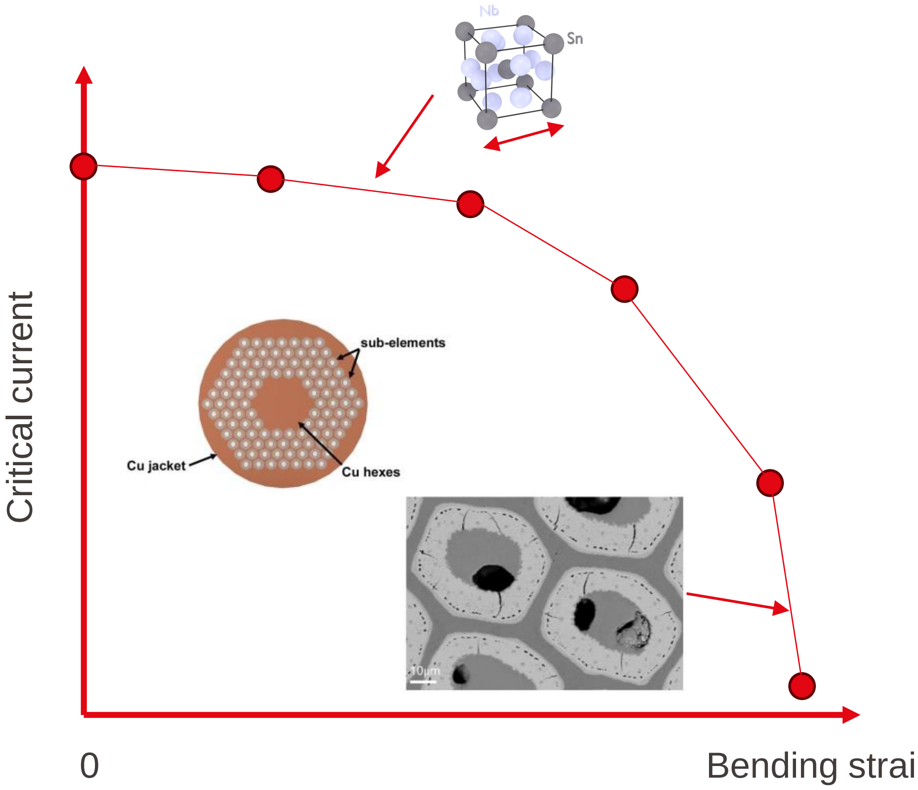
Voltage tap separation of 45 cm for a good SNR

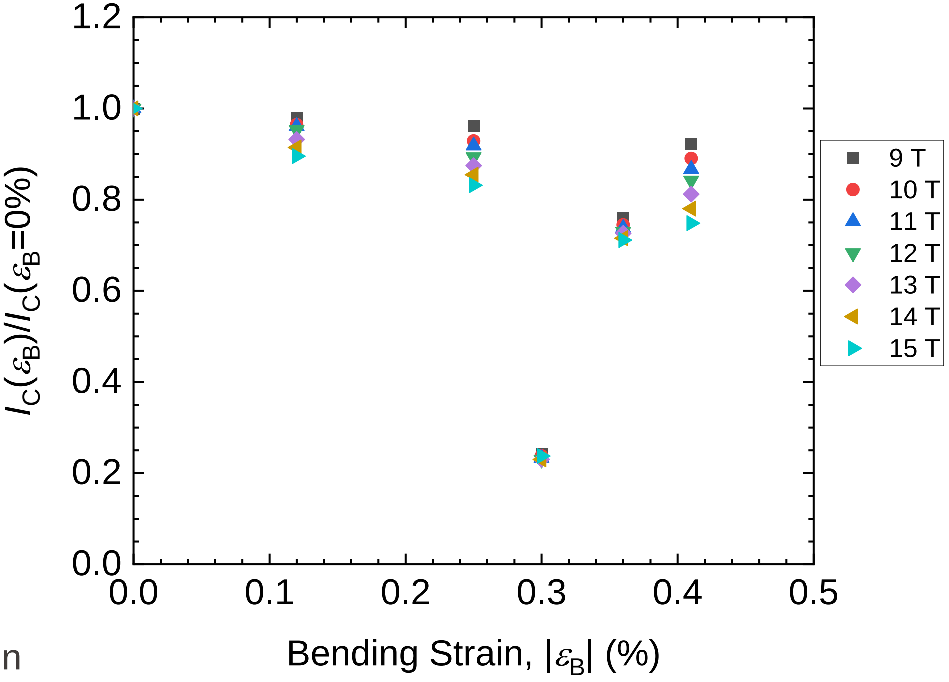
Critical Current Results



Critical current (I_C) is extracted at 0.1 μV/cm for Nb_3Sn

Ic vs Bending Strain – Expectation and Reality





Next Steps

1. Use $I_C(\varepsilon_B)$ data to design new react and wind Nb_3Sn conductors.

2. Manufacture prototype magnet conductors and test them in SULTAN.

3. Use new conductor designs in EU-DEMO.

Summary

SPC-SG specialises in the development and testing of LTS and HTS fusion conductors. The conductors must carry $\leq 10^5$ A in high fields and be mechanically robust.

The critical current I_C is the practical current limit for fusion conductors. It is determined by the motion of flux vortices on the microscopic scale.

I_C is sensitive to strain, which has motivated the development of react and wind Nb_3Sn conductors.

Experiments for $I_C\,(\varepsilon_B)$ on high performance RRP Nb_3Sn strands suggest that they are tolerant to $|\varepsilon_B| \leq 0.41\%$, making them suitable for use in future R&W conductors.

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