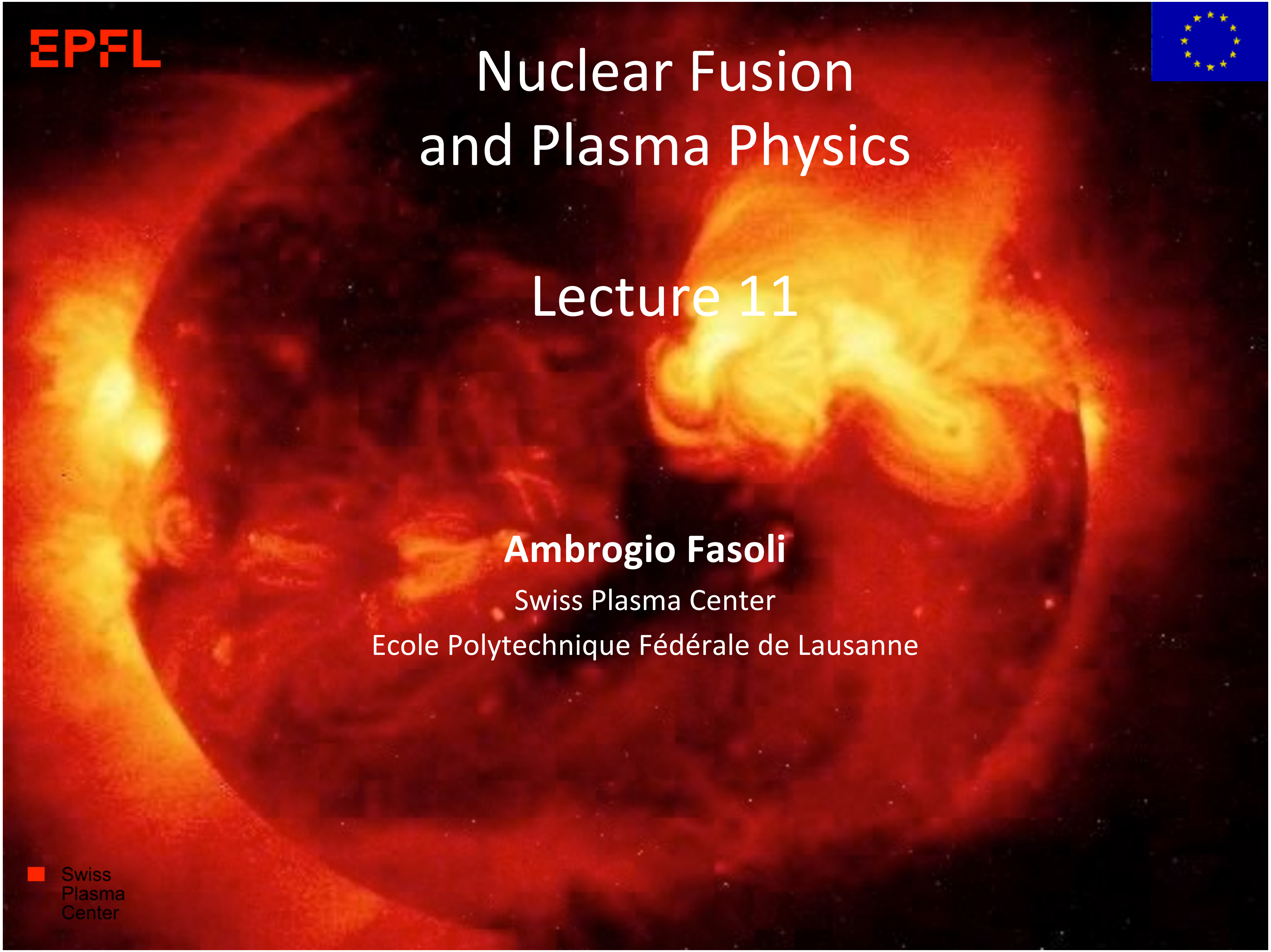


Nuclear Fusion and Plasma Physics

Lecture 11

Ambrogio Fasoli

Swiss Plasma Center

Ecole Polytechnique Fédérale de Lausanne

Swiss Plasma Center

Applied superconductivity for fusion
Layout of the lecture

The need for superconducting magnets

Superconductivity – generalities

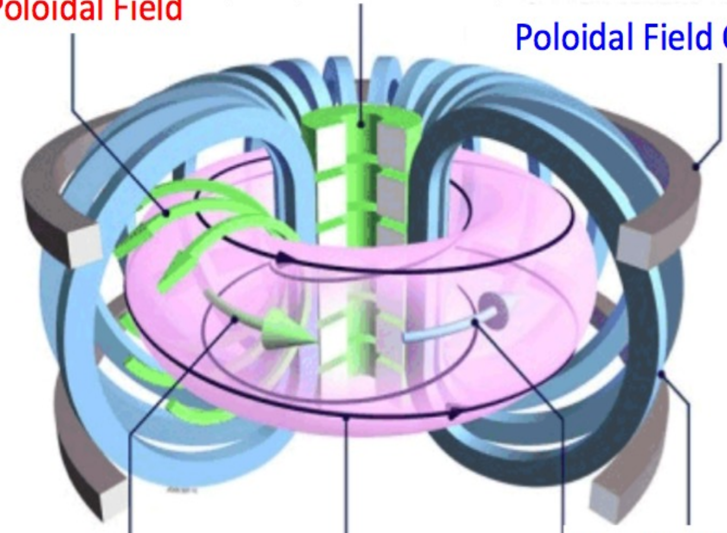
Requirements and challenges

Fusion devices with superconducting coils

ITER, DEMO and beyond

Presentation by Daniel Biek 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 $\alpha \geq 2$

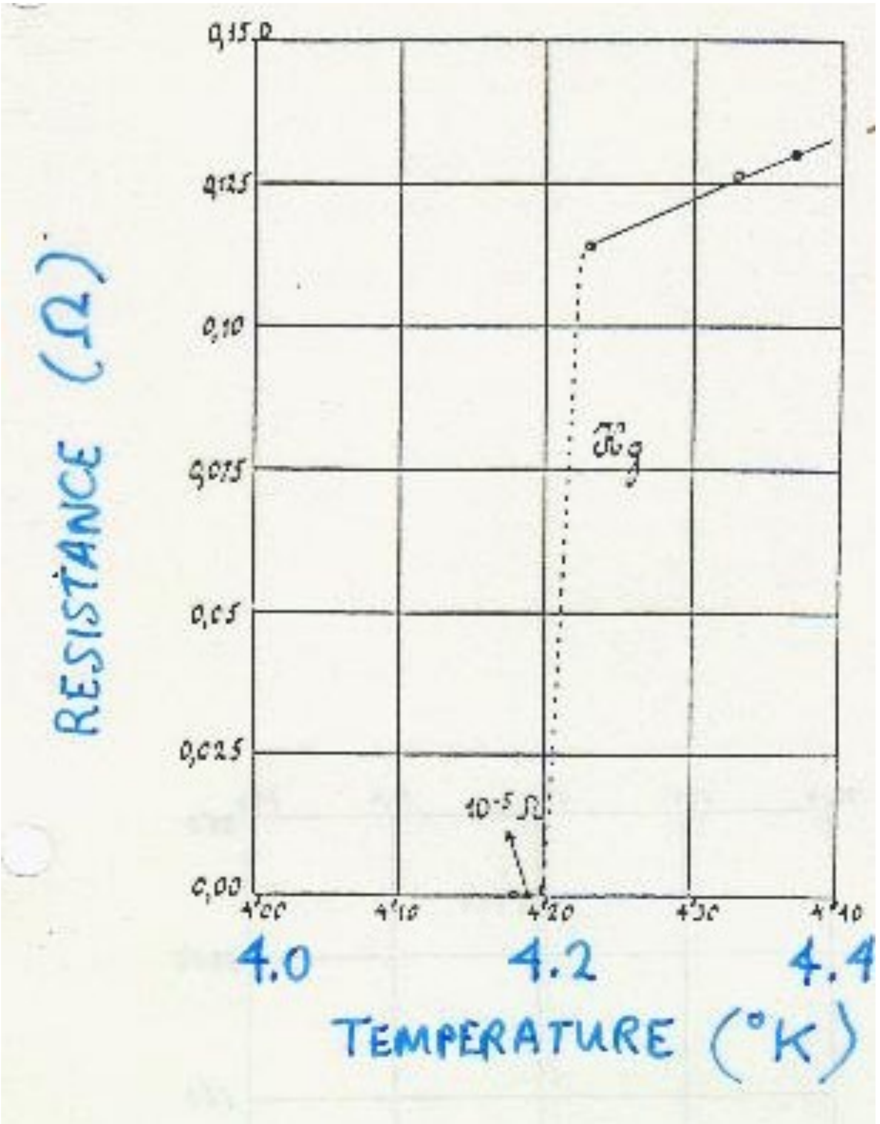
Copper coils can generate large fields, but not in steady-state

- 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

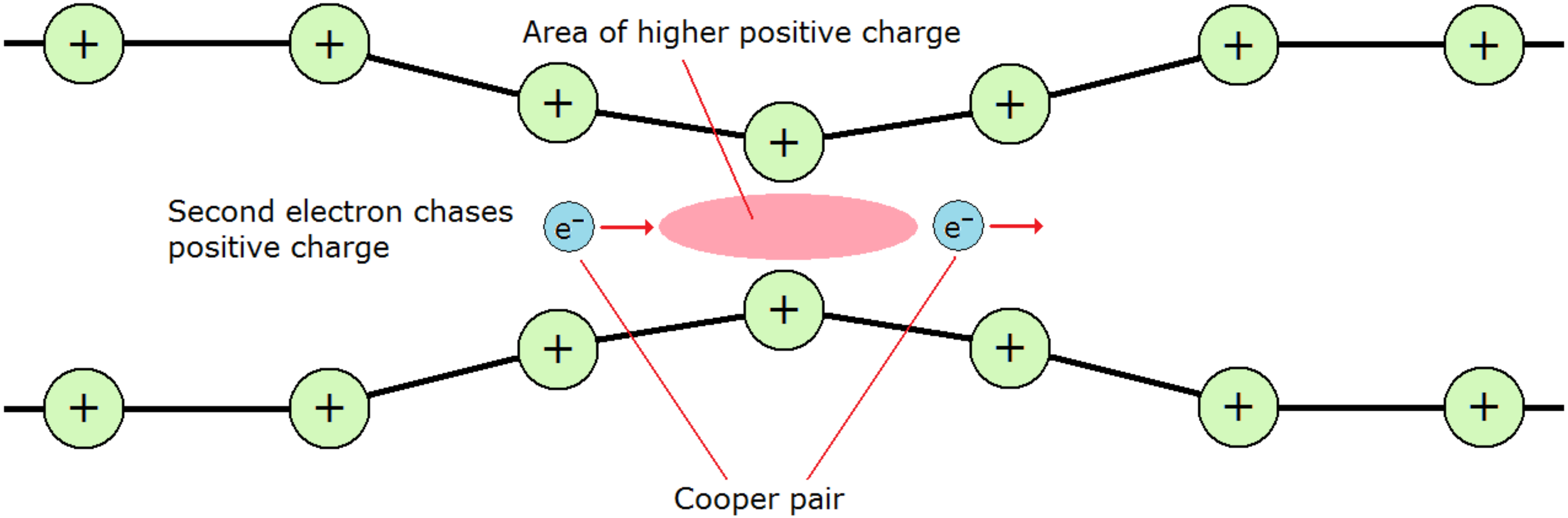
The discovery of superconductivity



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

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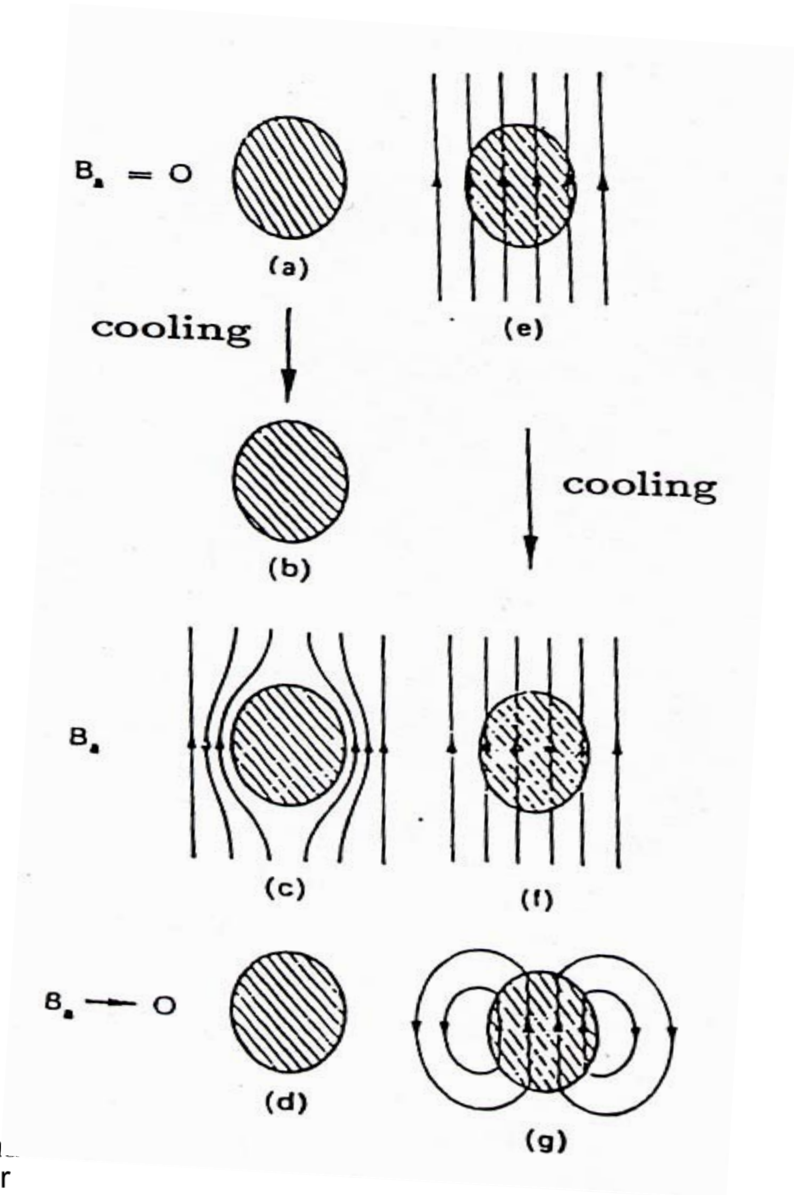
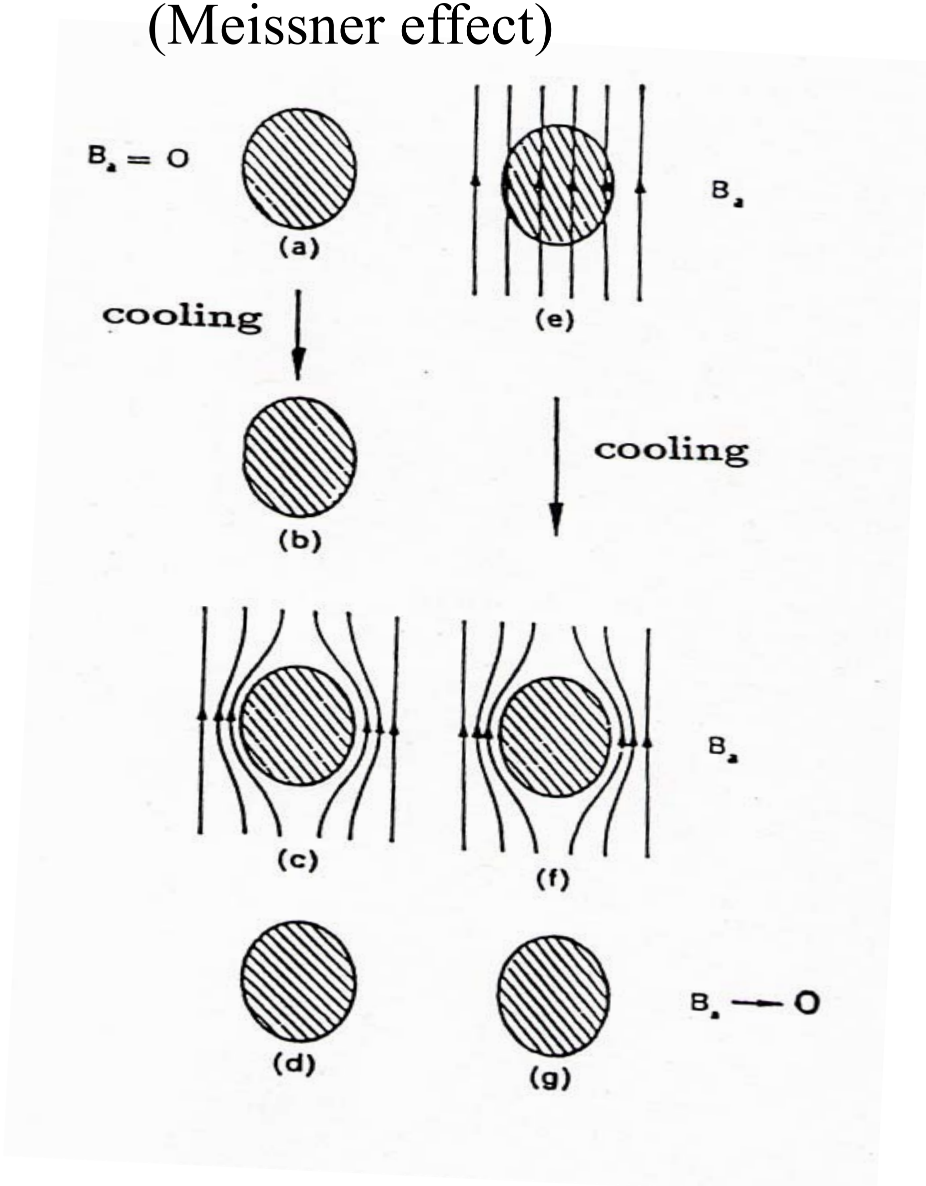
Superconductors vs. perfect conductors

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

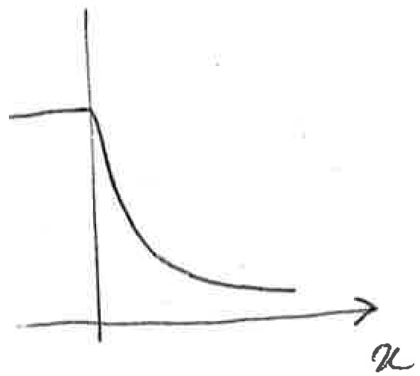
In the superconductor (London theory, 1935):

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

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

n_C = density of sc carriers

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



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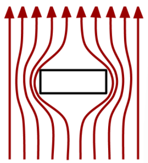
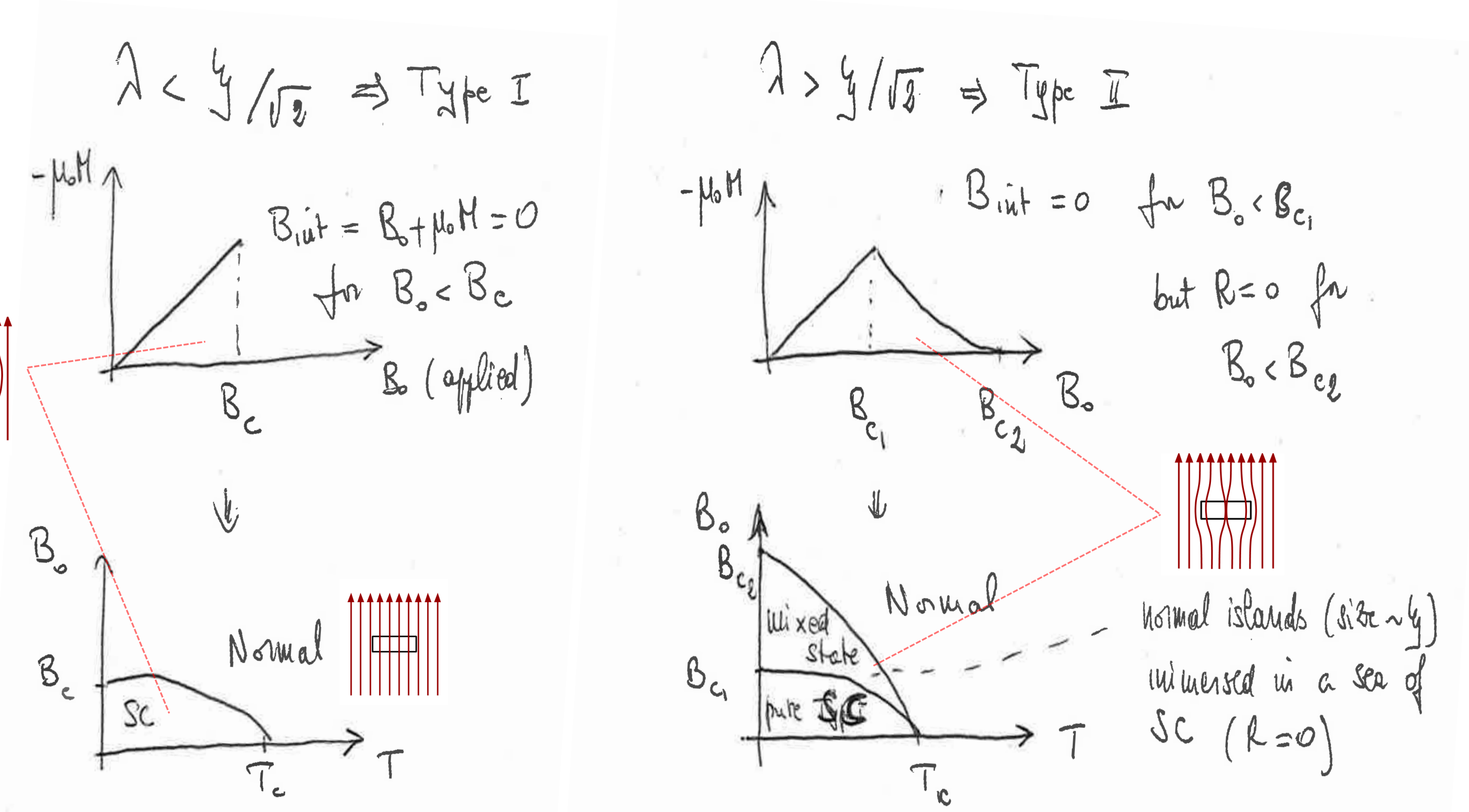
Magnetization and Type I vs. Type II SC's

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



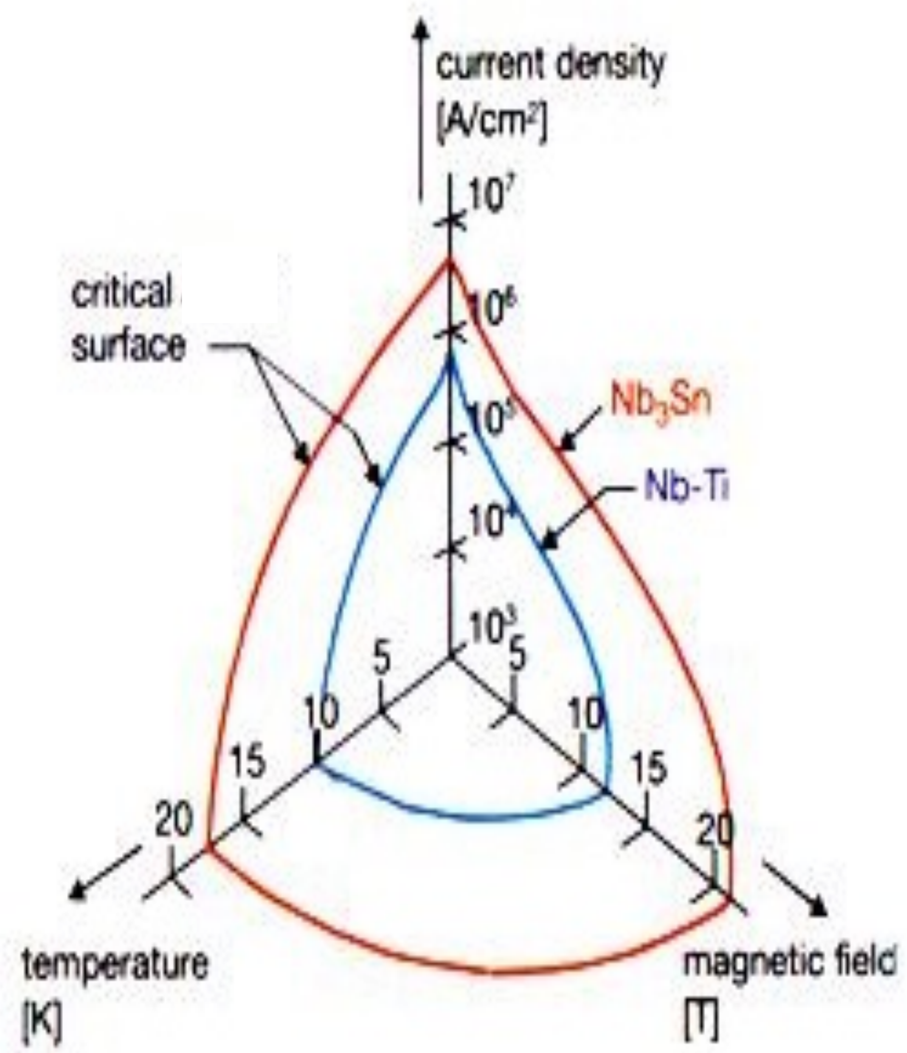


Superconductors for fusion magnets

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

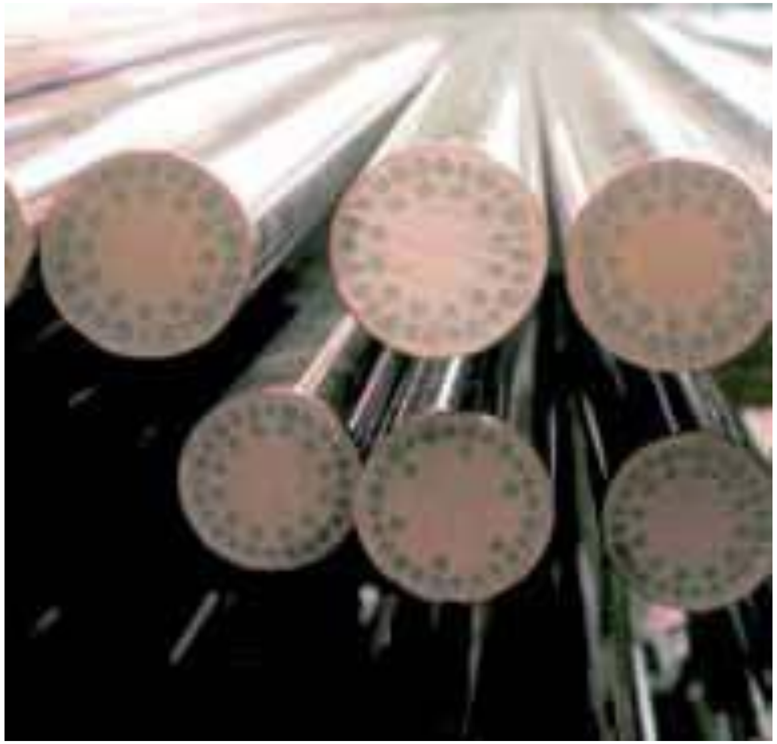


→ critical J, B and T surface

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

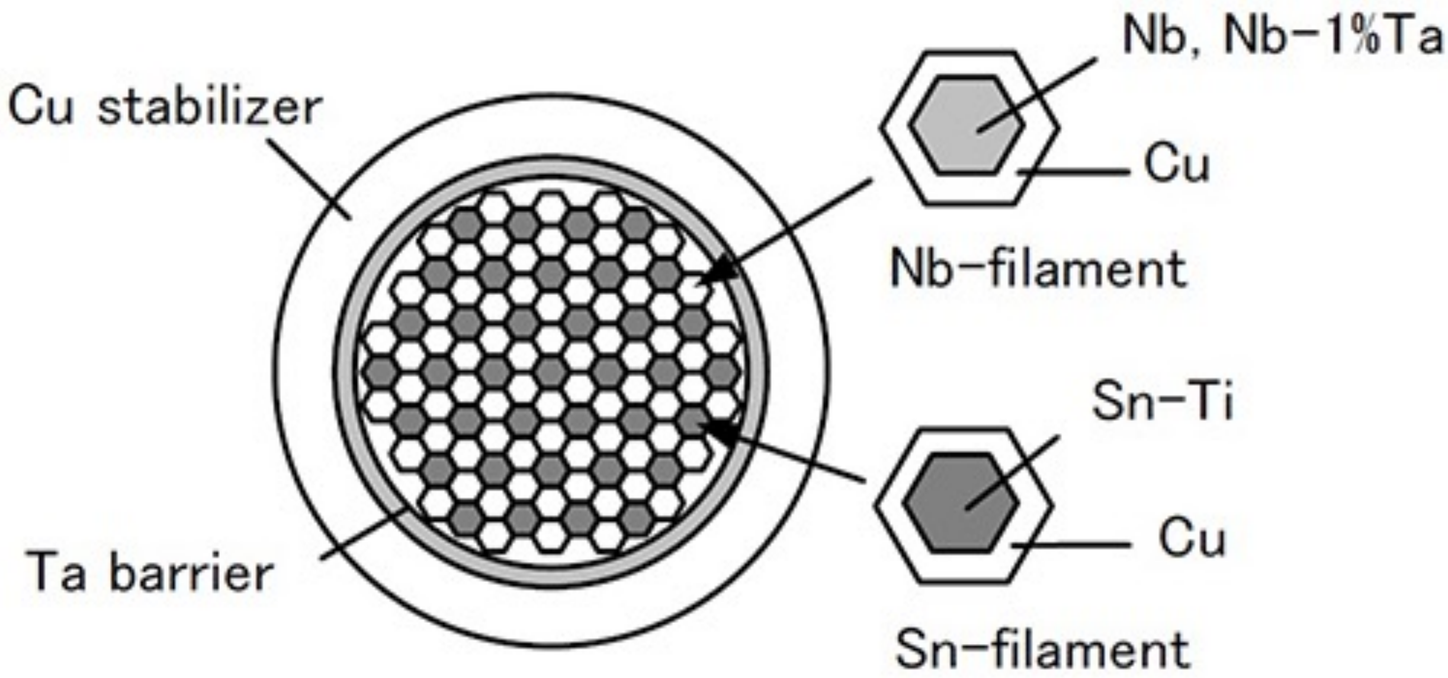
Superconducting materials for fusion

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



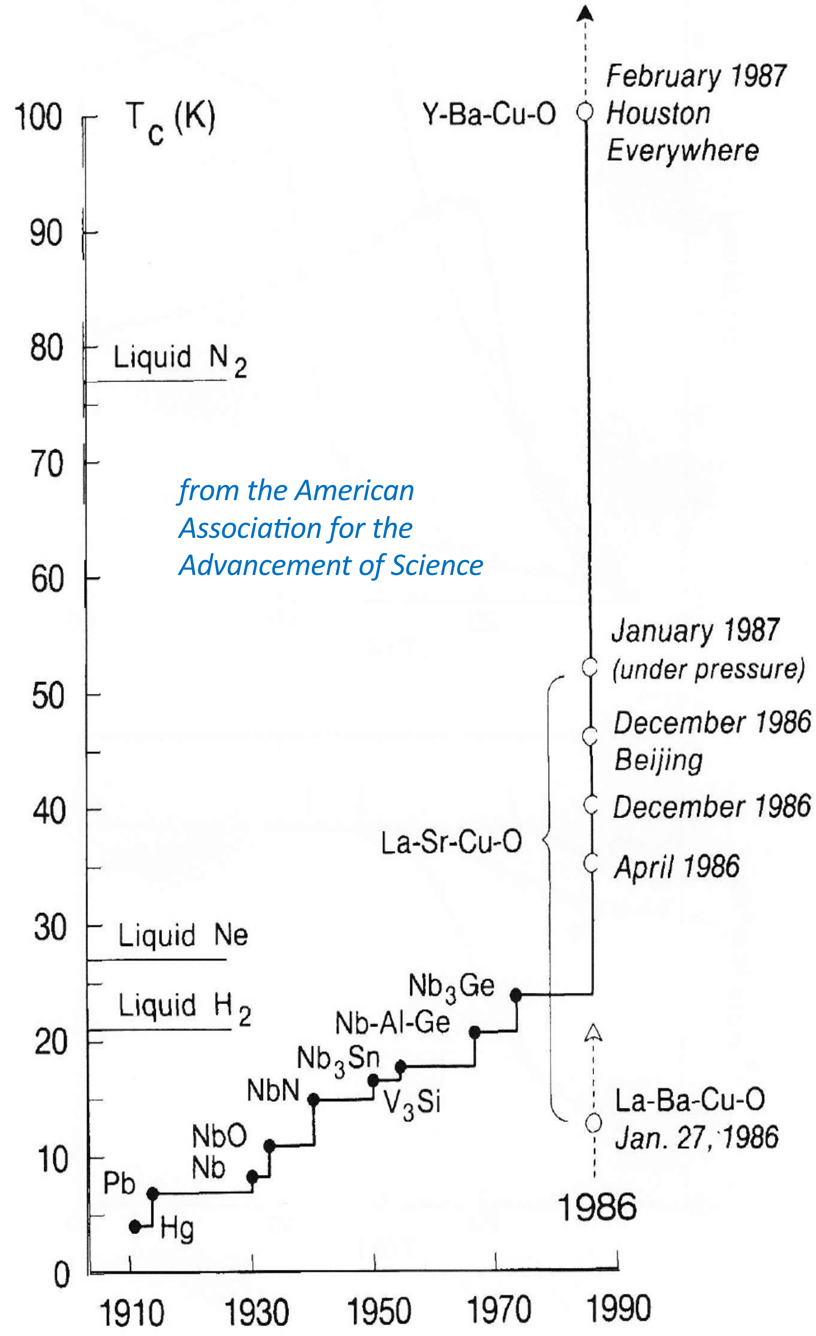
from Hitachi.cable.com

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

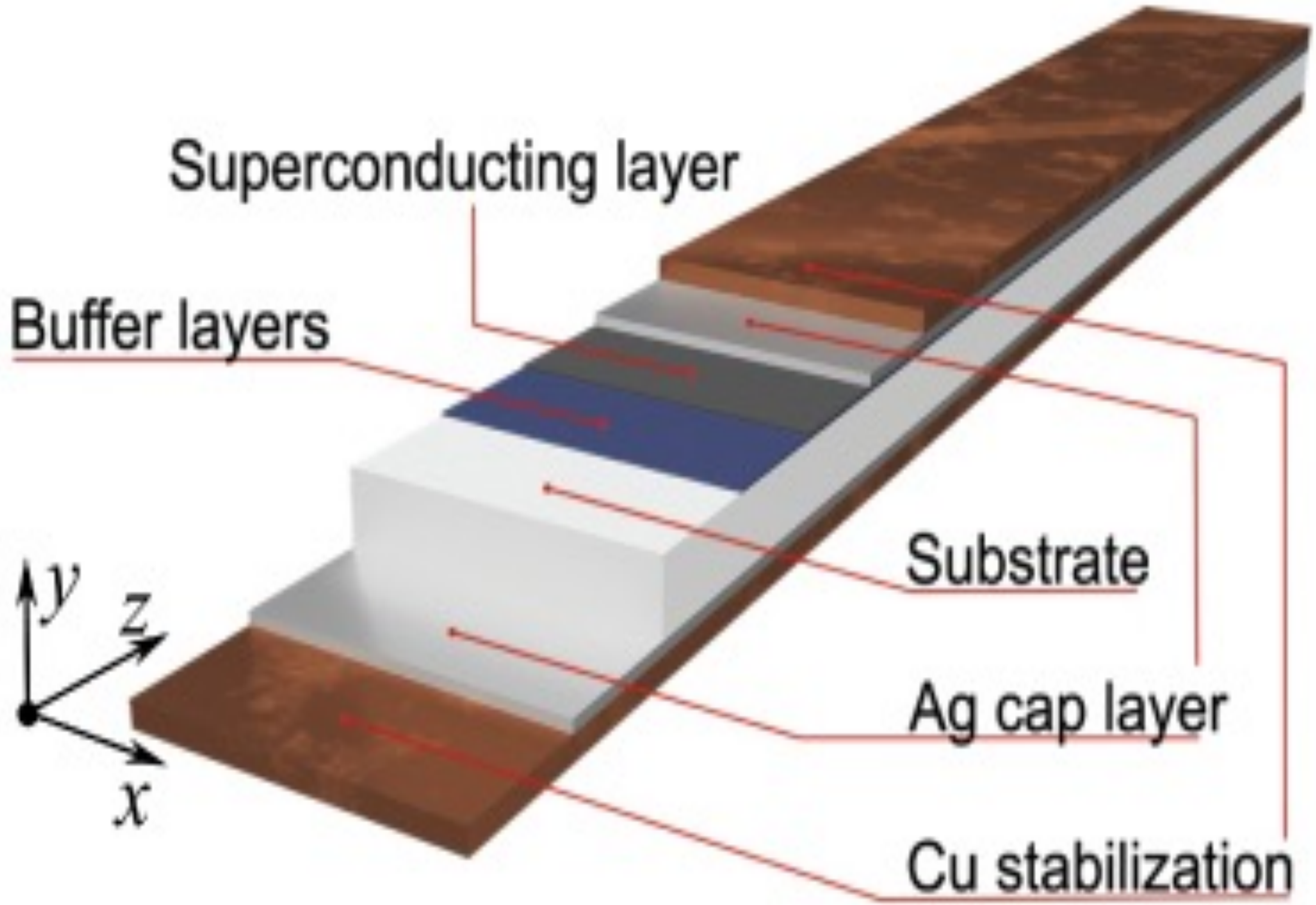
- Bismuth strontium calcium copper oxide compounds (Bi2212, Bi2223)
- Rare earth barium oxide oxide compounds (ReBCO)



from the American Association for the Advancement of Science

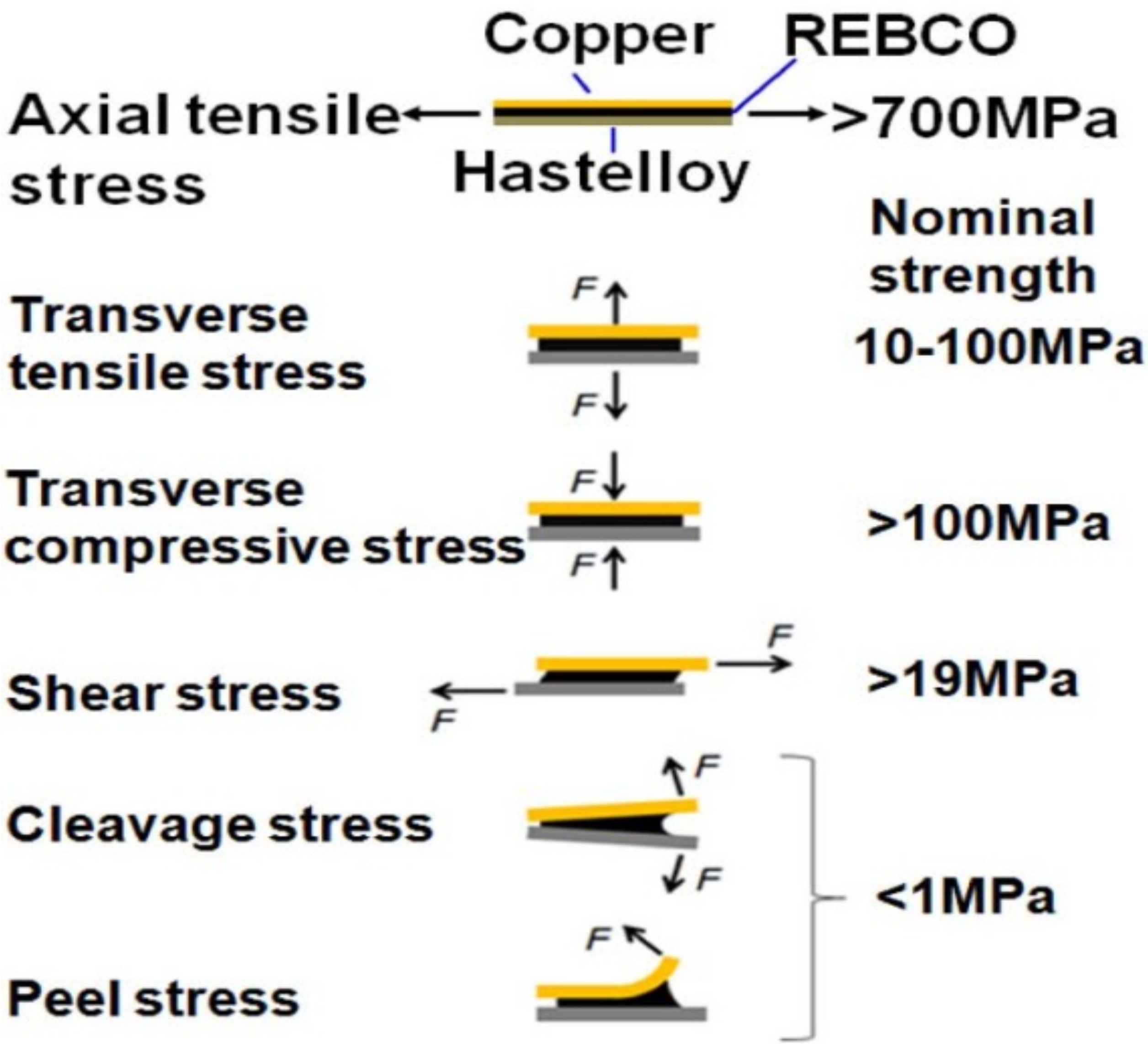
EPFL

HTS – REBCO tapes



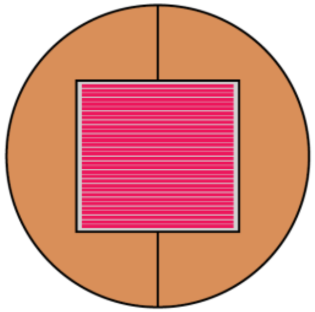
From Superpower.com

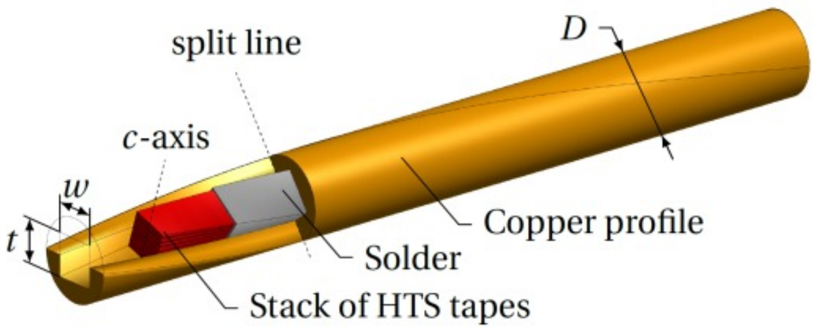
HTS – REBCO tape mechanical issues

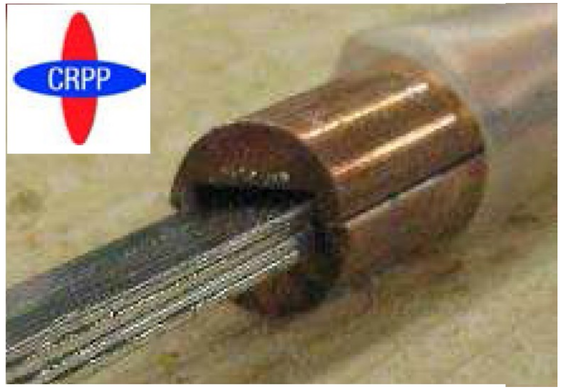


H. Maeda et al., TAS Critical current anisotropy ~ 5 **24** (2014) 4602412

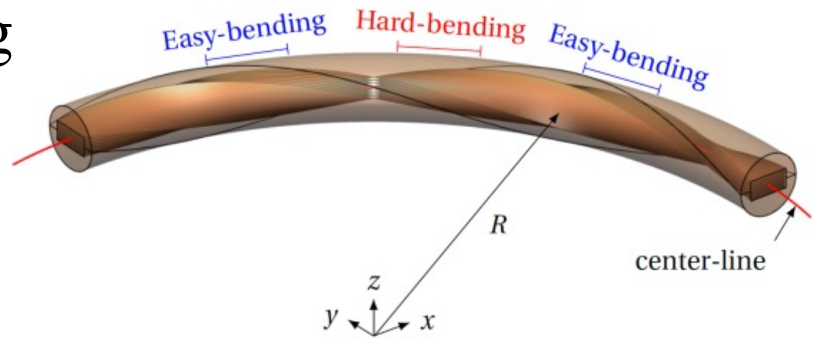
HTS – from tape to cable

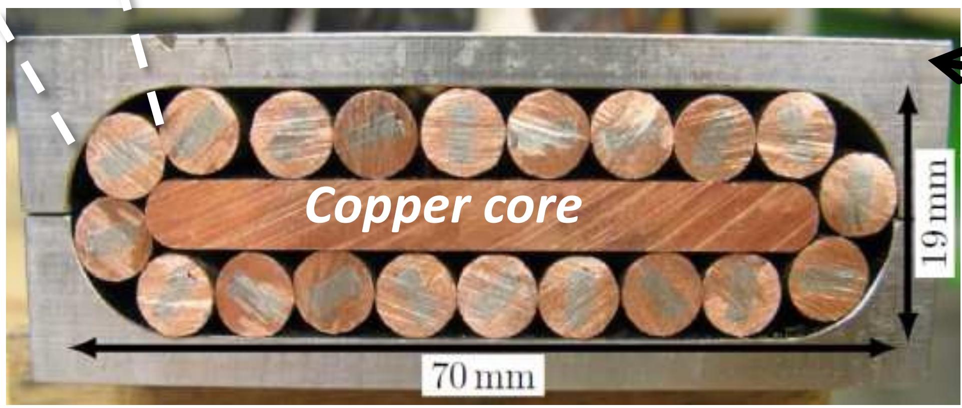






twisting and bending





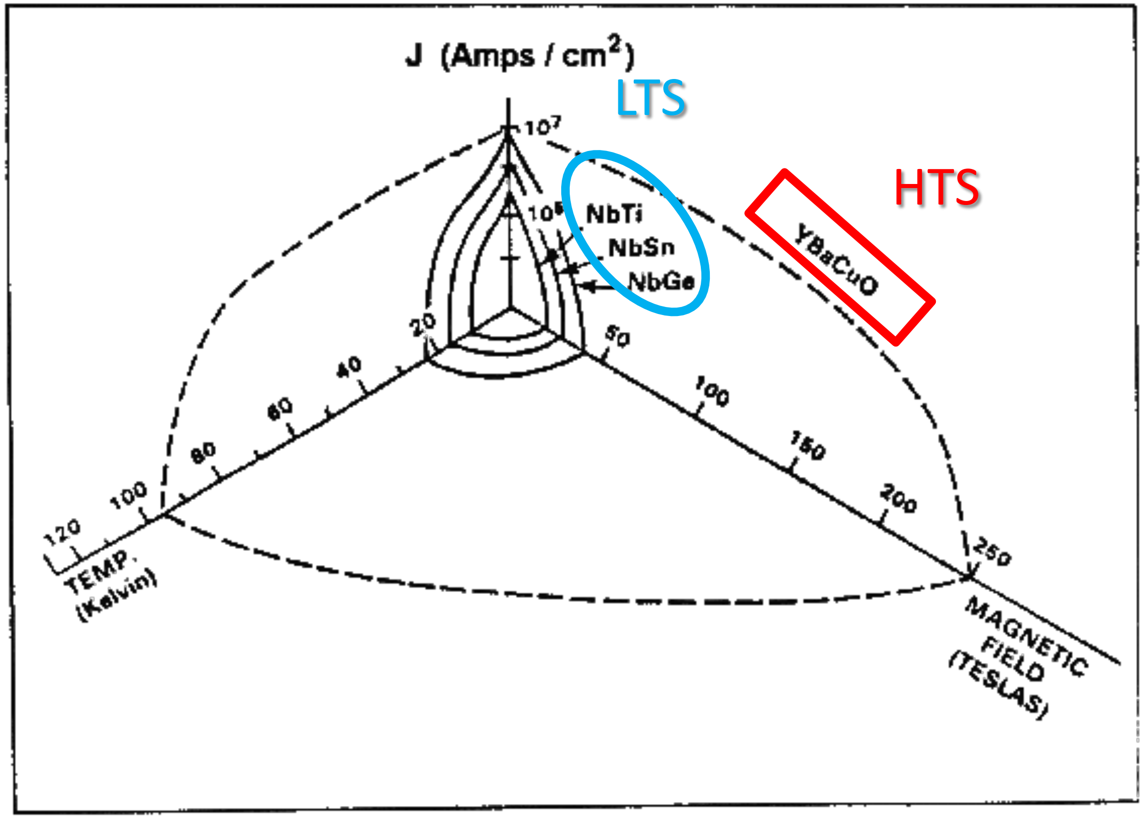
Jacket

Courtesy of O.Dicuonzo

Practical use of HTS

Low B → high temperature

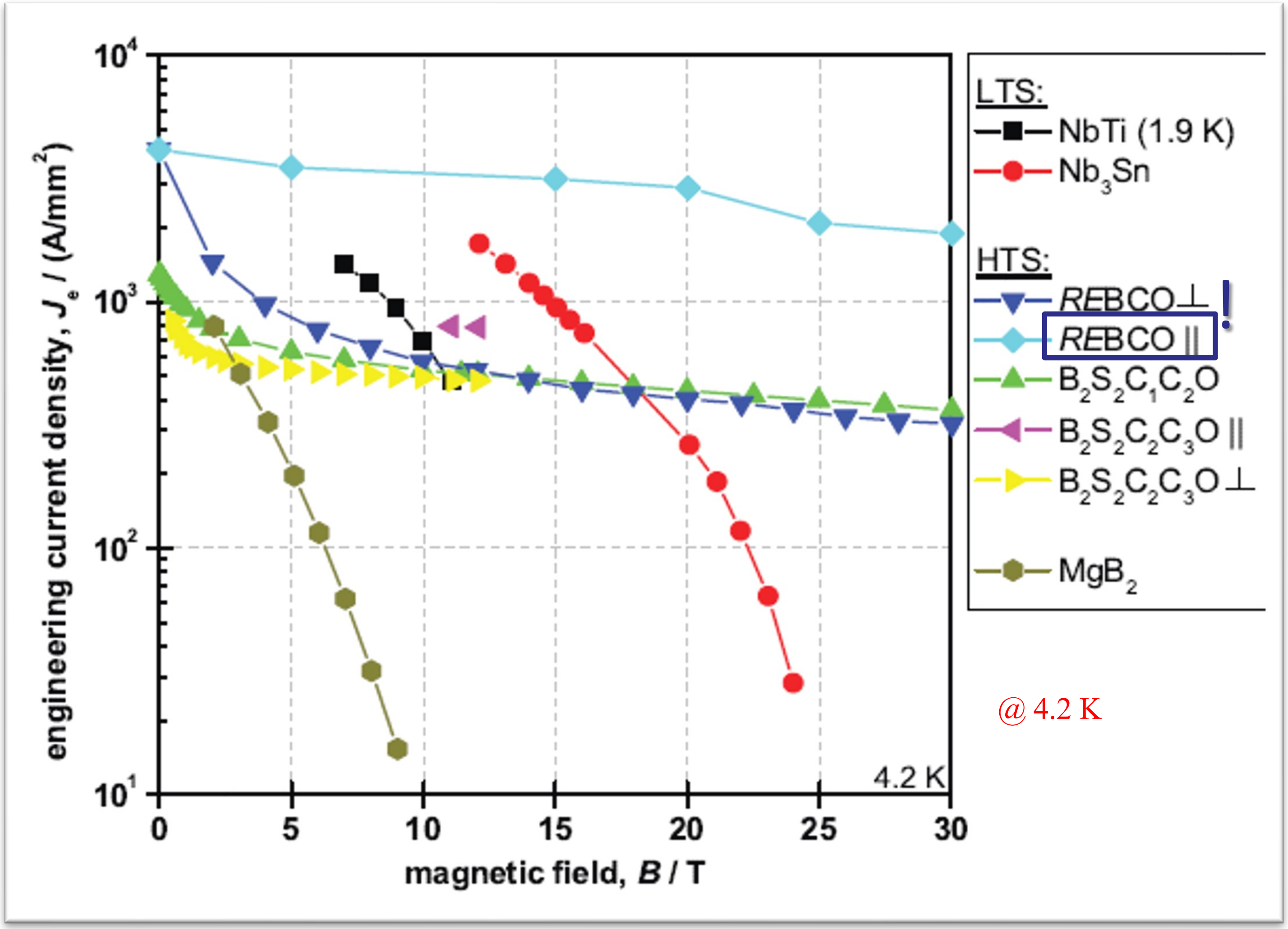
Simpler and cheaper cryogenic systems
OK for energy transportation



Phase Diagram

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

Which HTS for fusion?



Courtesy of O.Dicuonzo

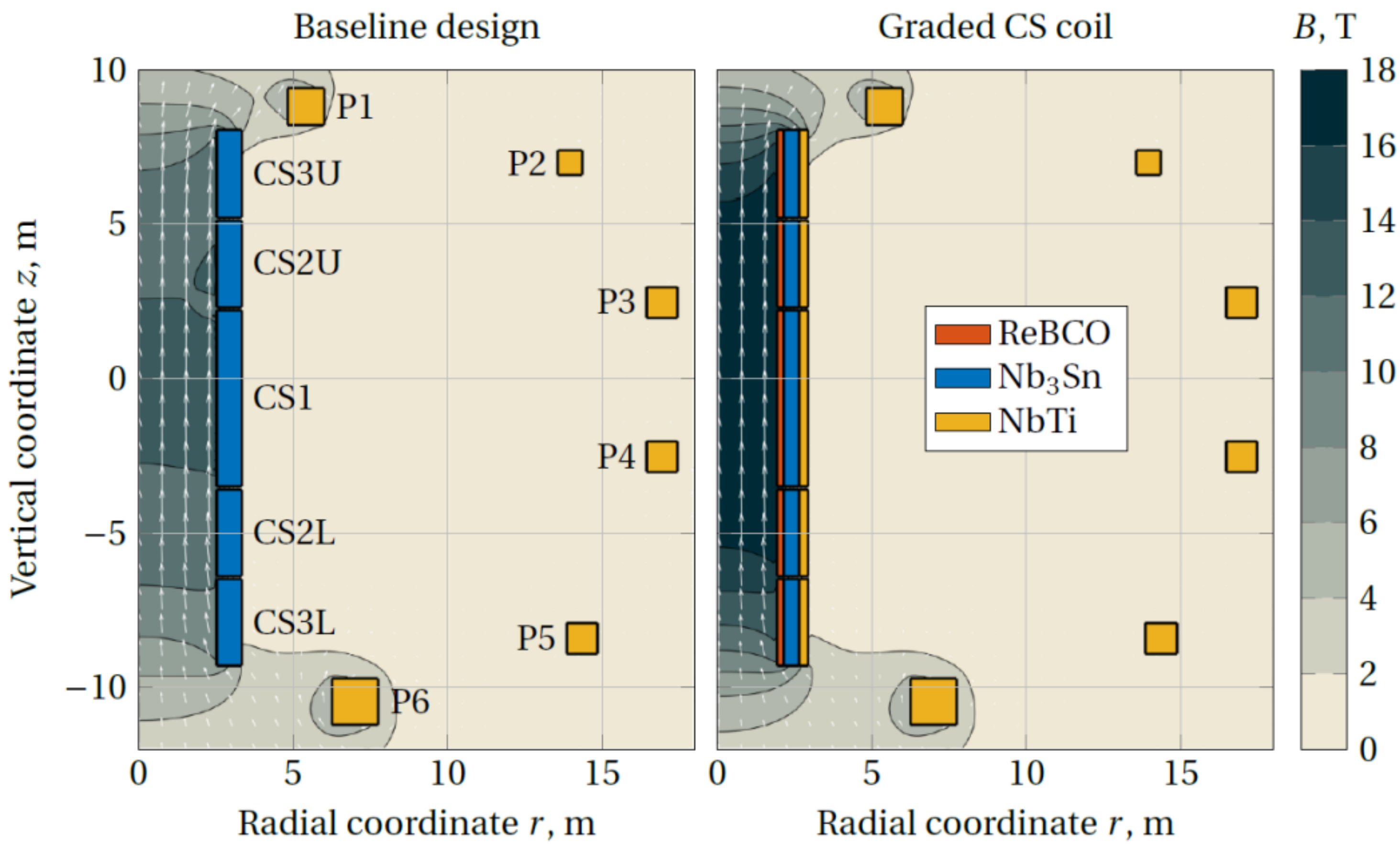
Need high current density at high B → REBCO

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

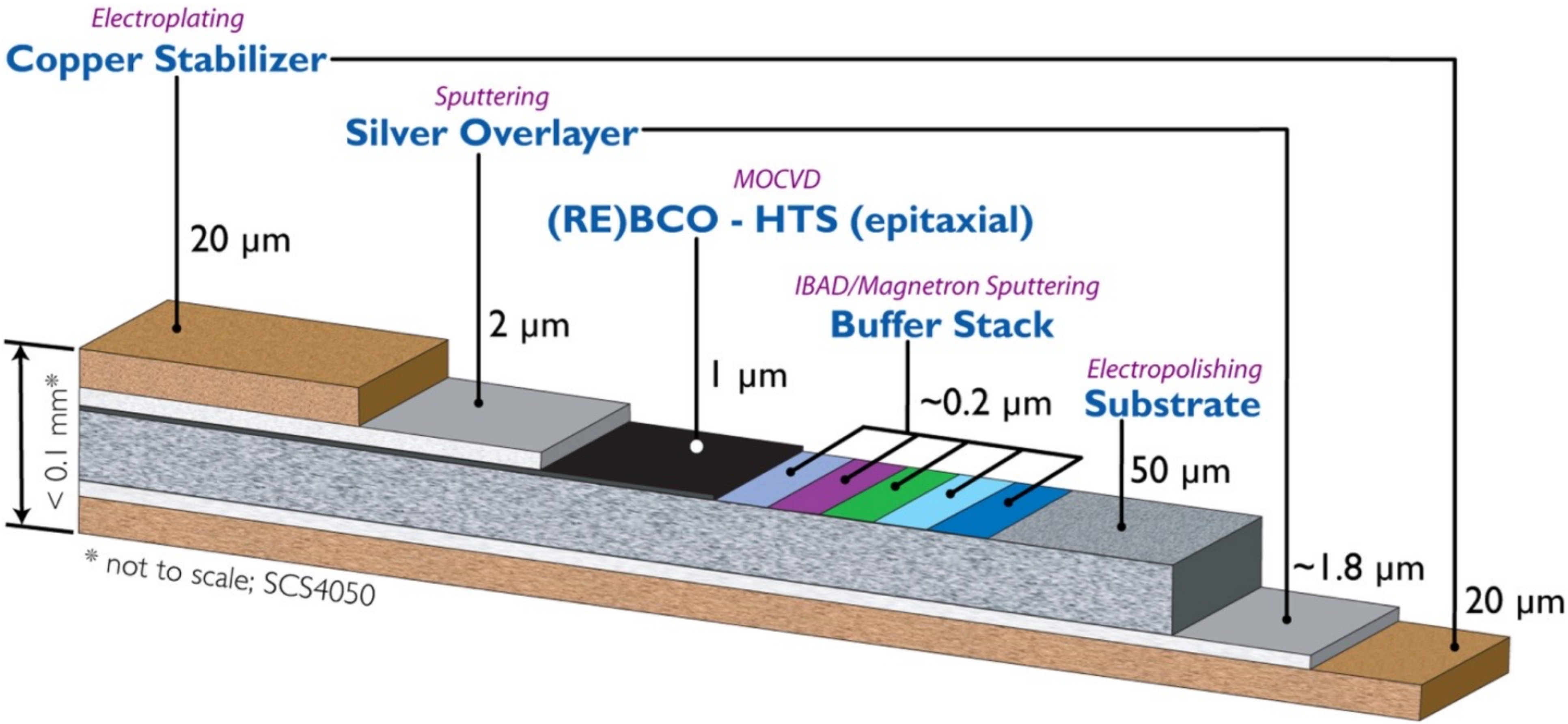
HTS materials for fusion

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

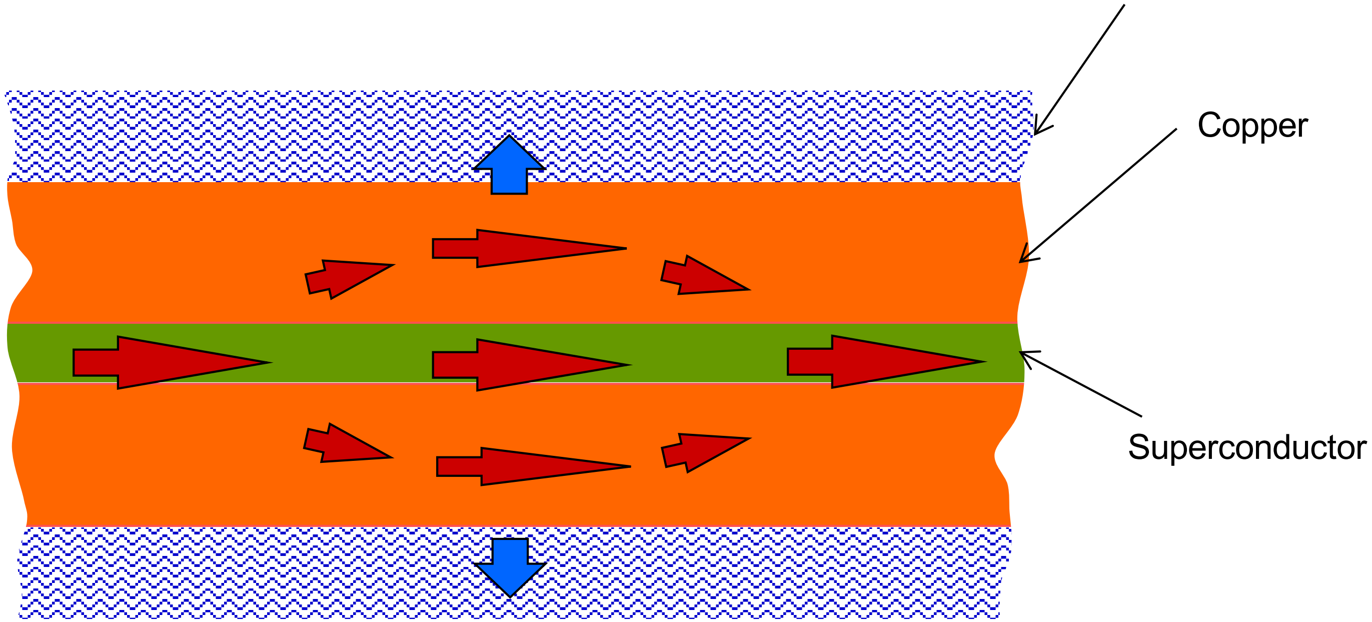
Why do we need copper ?

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.



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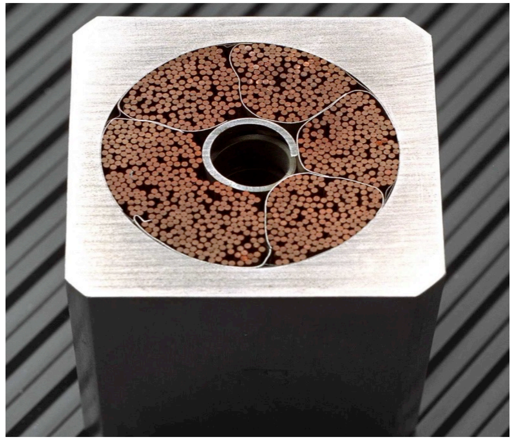
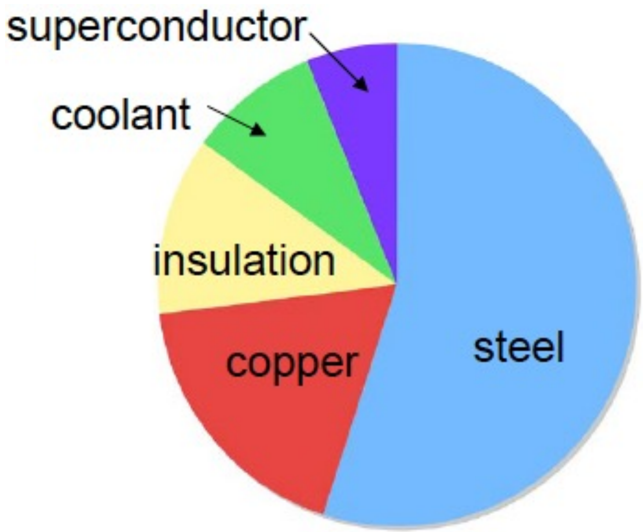
High current cables for fusion magnets

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



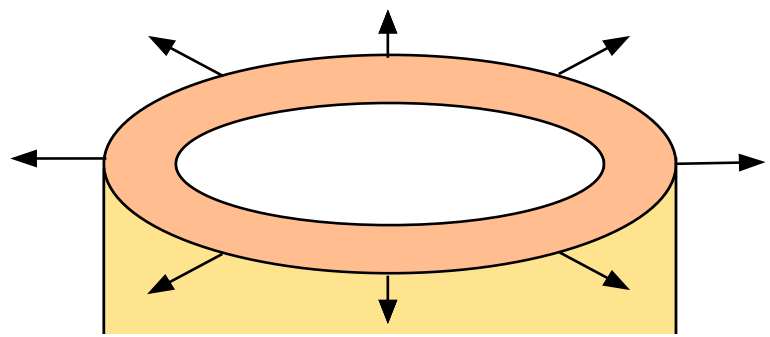


Requirements and challenges - Mechanical

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



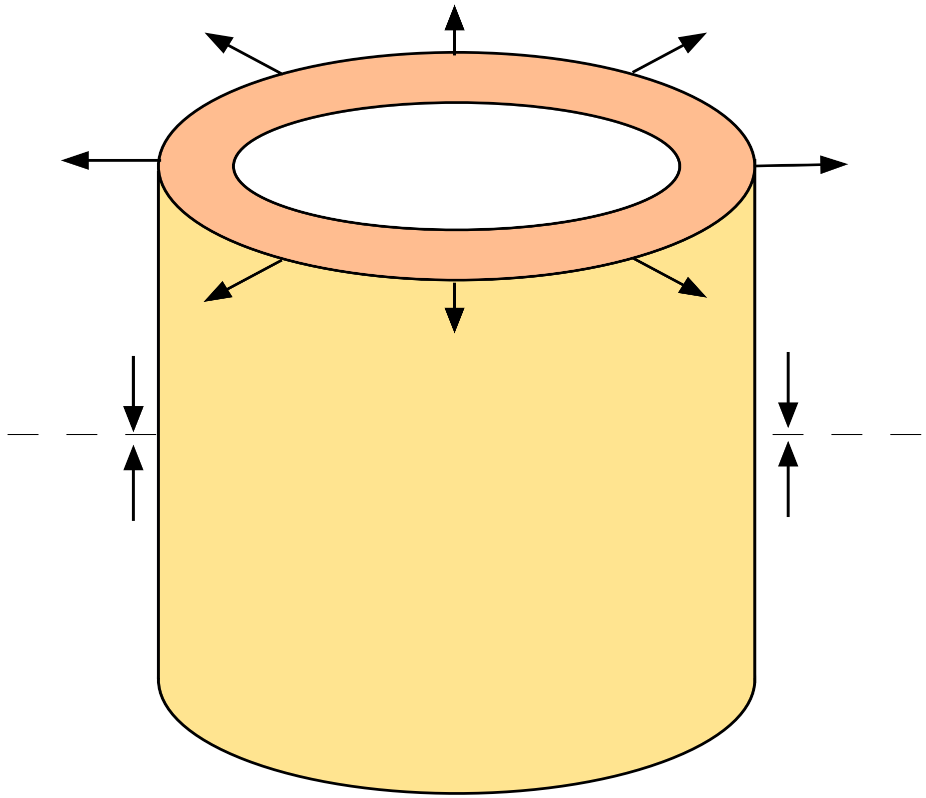
Solenoid

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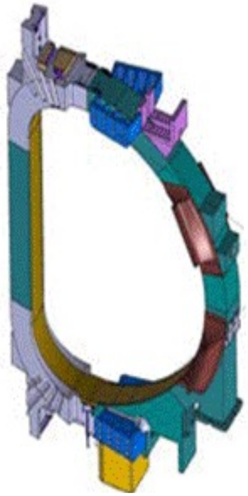
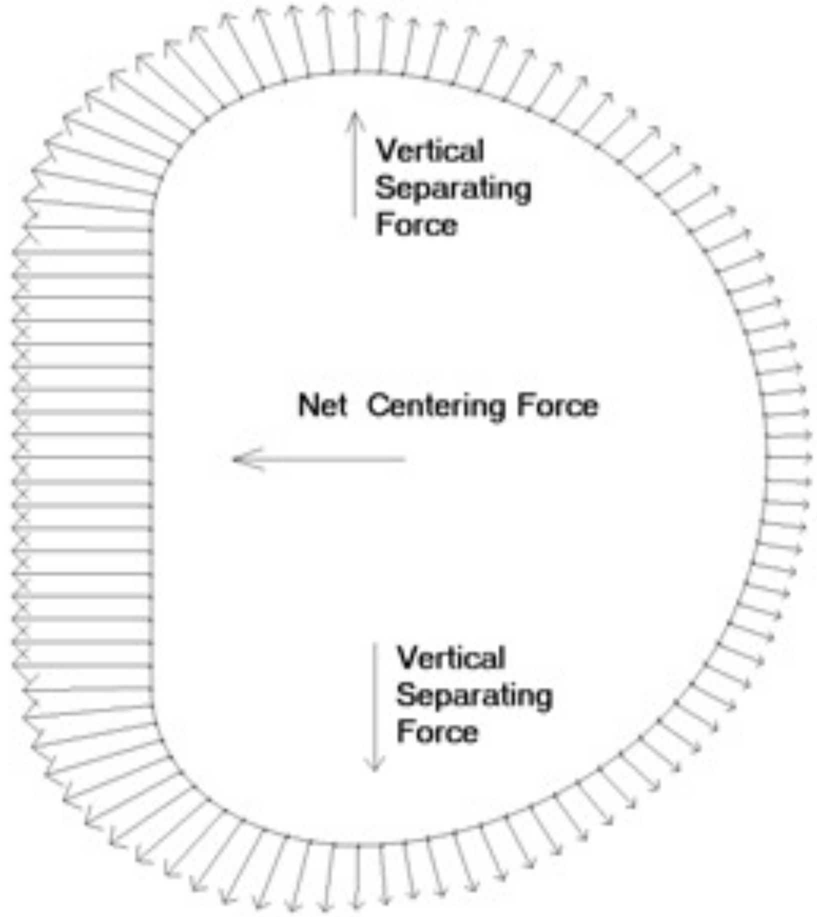
- Centering load on the in-board of non-circular toroidal field coils, ~BxI





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

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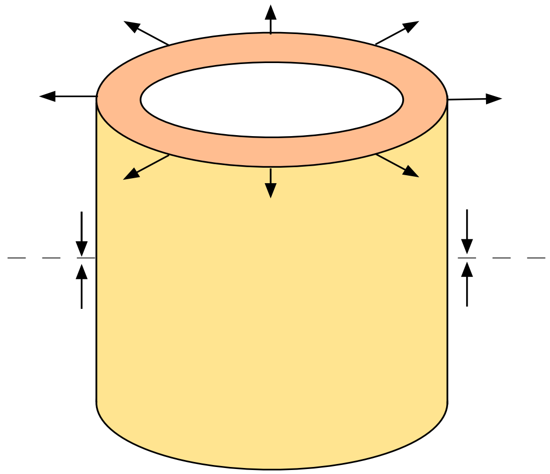
Requirements and challenges - Mechanical

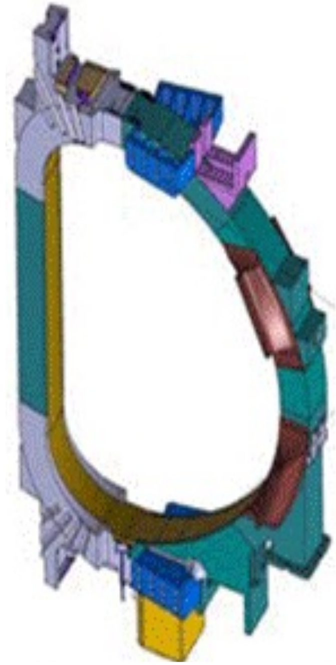
Large, high-B fusion magnets experience large electromagnetic loads, thus most of their volume consists of stainless steel

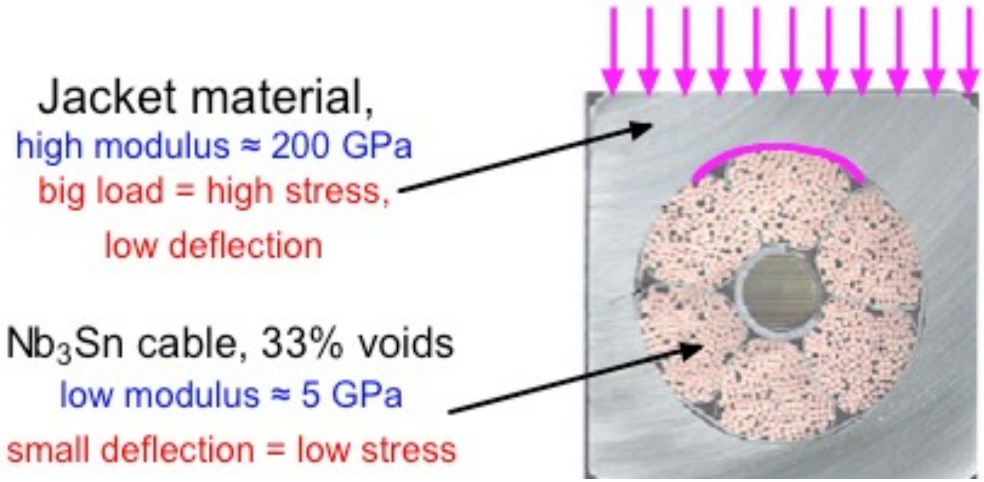
Main loads, all from JxB force

- 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







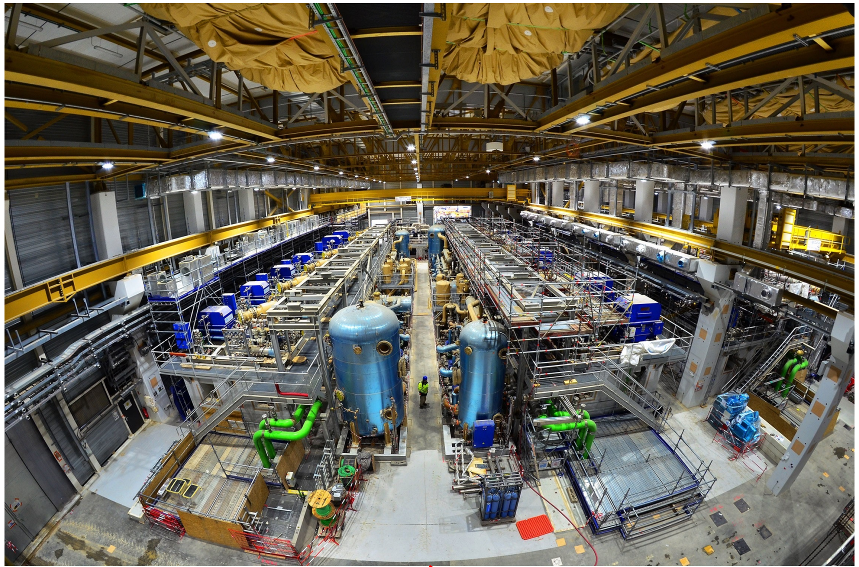
Requirement and challenges - Thermal

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

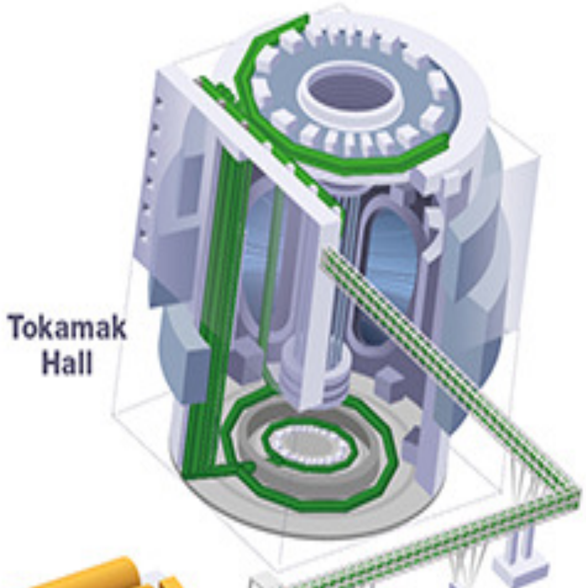
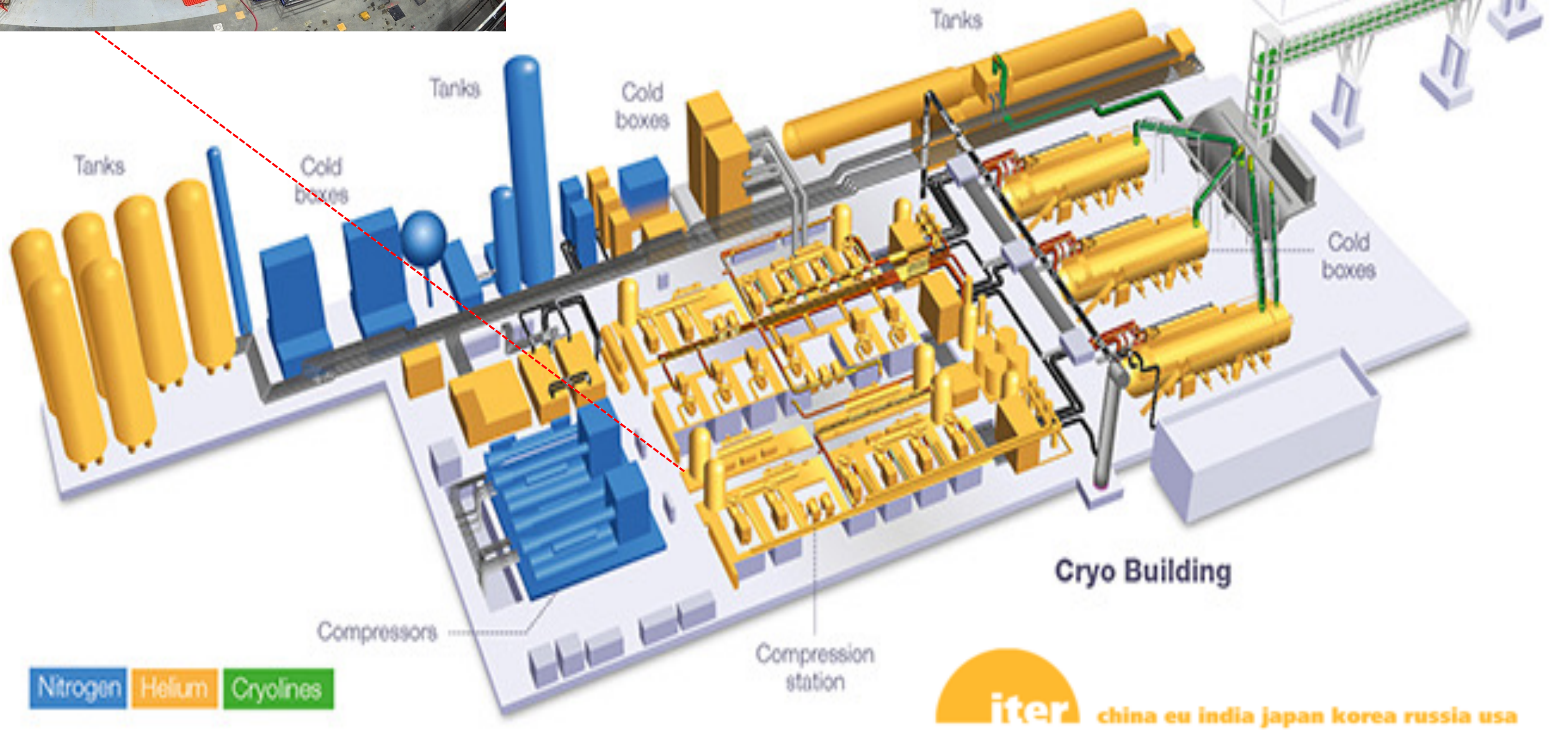
Requirement and challenges - Thermal



ITER

LHe: 75kW at 4.5K

LN_2: 1300kW at 80 K

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ITER
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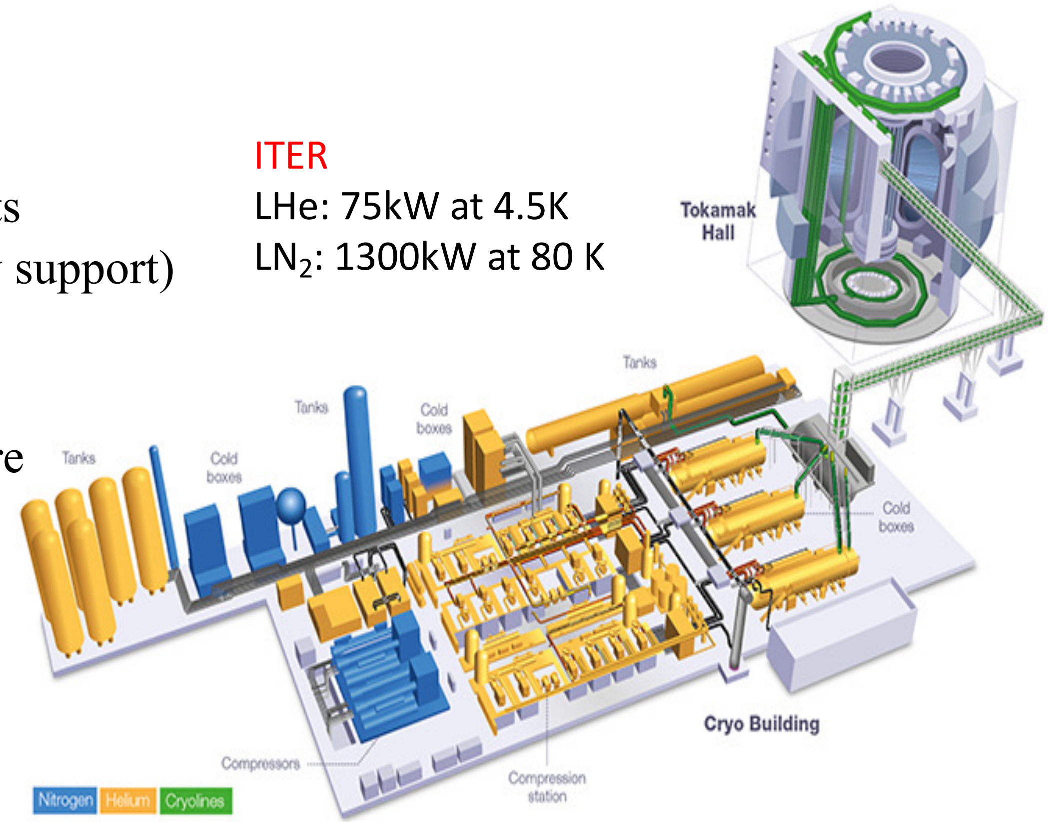
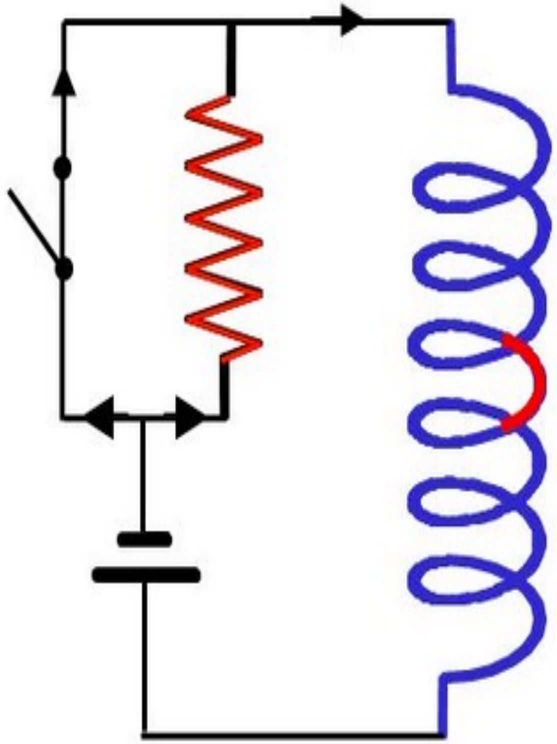


The variation of the operating temperature must be kept within a temperature margin of ~1-2 K

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

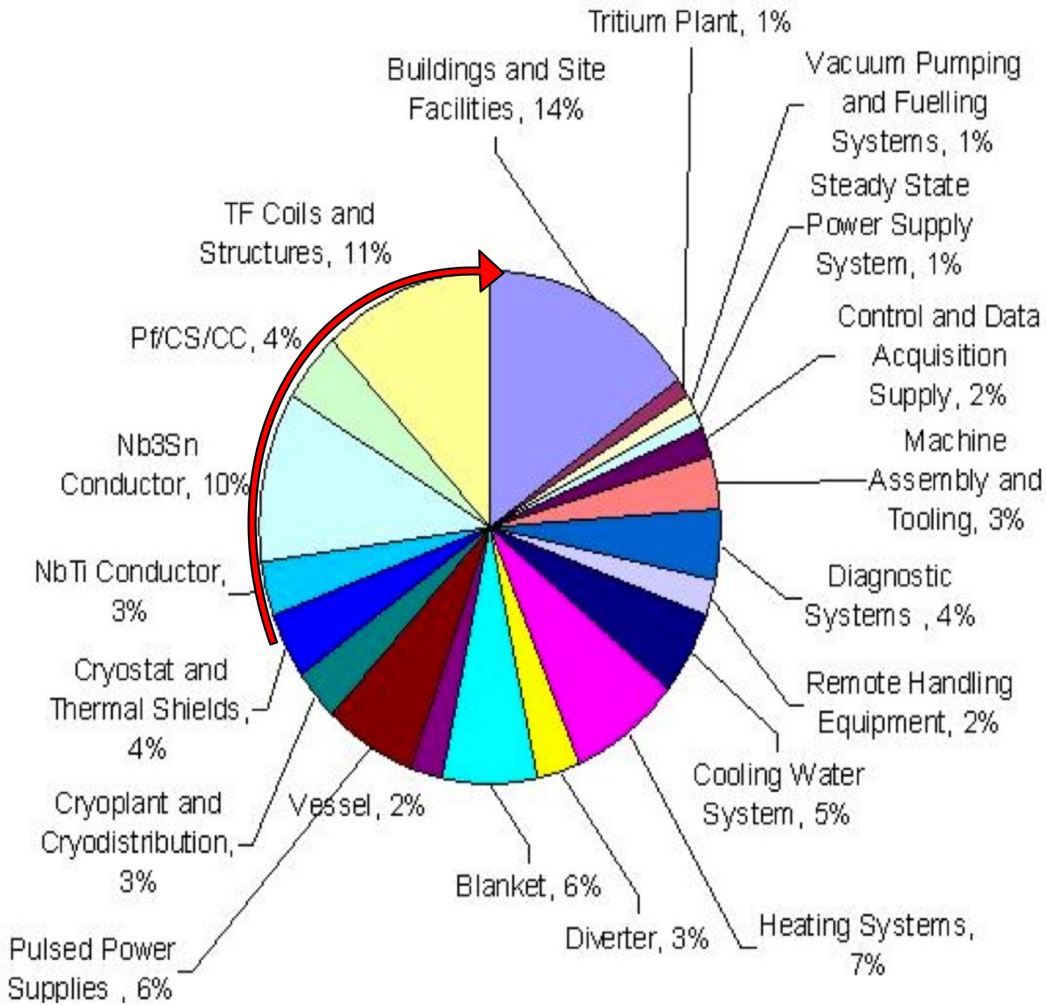
In fusion magnets, electrical insulation consists of Glass-Kapton wraps impregnated by epoxy. The quality of the impregnation is crucial for the coil mechanical integrity and to prevent flashovers to ground during the fast discharge

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

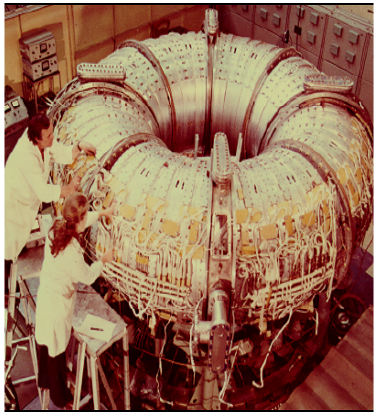
Cost effective design and manufacture of SC magnets are crucial issues on the way to commercially competitive fusion reactors



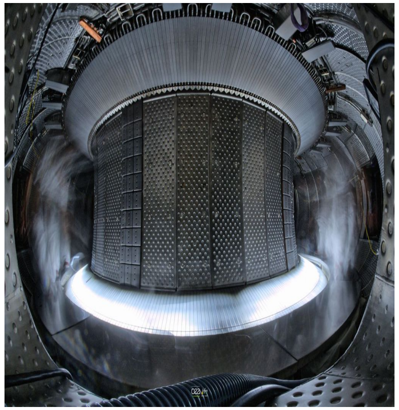
EPFL

Present fusion devices with sc coils

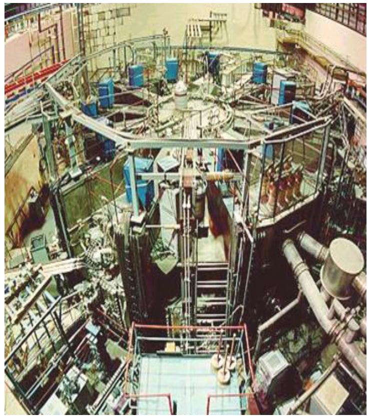
T 7 at Kurchatov -1977
NbTi, He forced flow, 5T



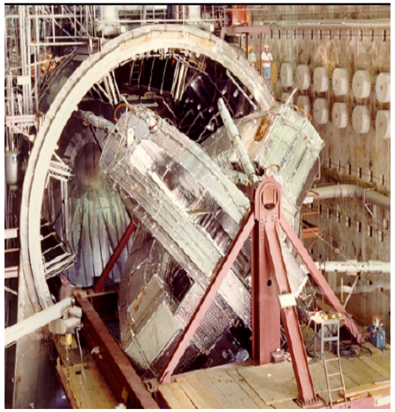
WEST at CEA -2017
NbTi, He bath, 9T



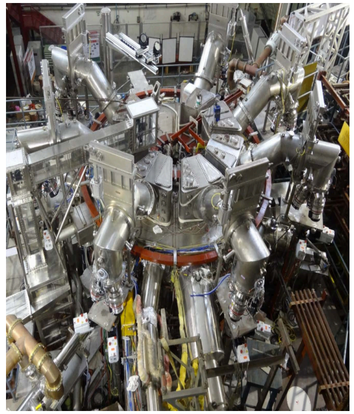
T 15 at Kurchatov -1983
Nb_3Sn, He forced flow, 9.3T



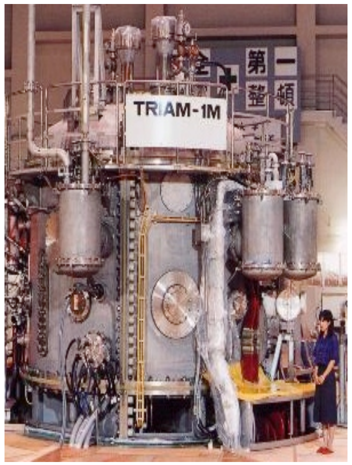
MFTF Livermore -1985
NbTi/Nb_3Sn, He bath 12.7T



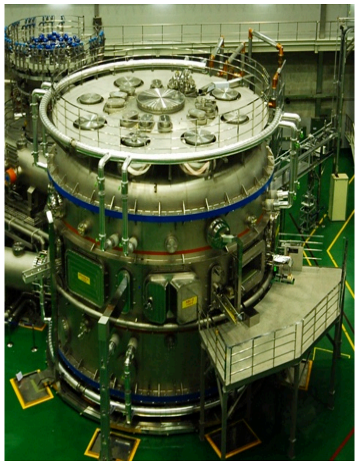
SST1 Bath - 2013
NbTi, He forced flow, 5T



TRIAM Fukuoka -1986
Nb_3Sn, He bath, 11T

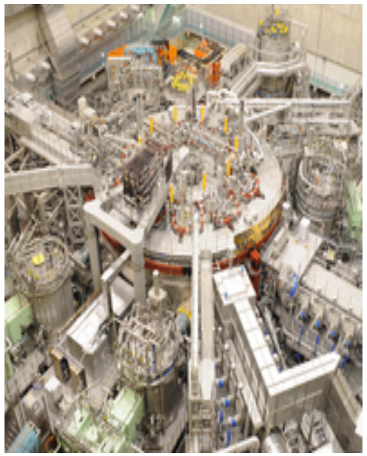


KSTAR- Daejeon 2007
Nb_3Sn, He forced flow, 8T

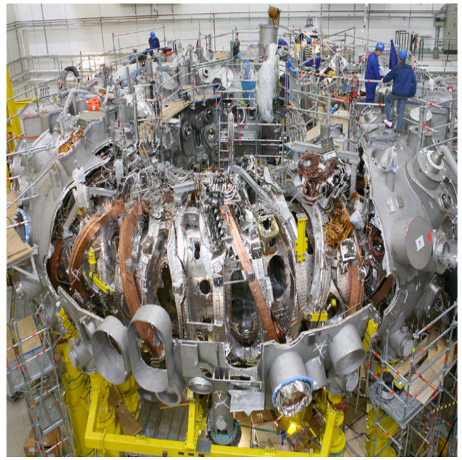


EAST Hefei - 2006
NbTi, He forced flow, 5.8T

LHD Toki - 1996
NbTi, He bath, 6.9T

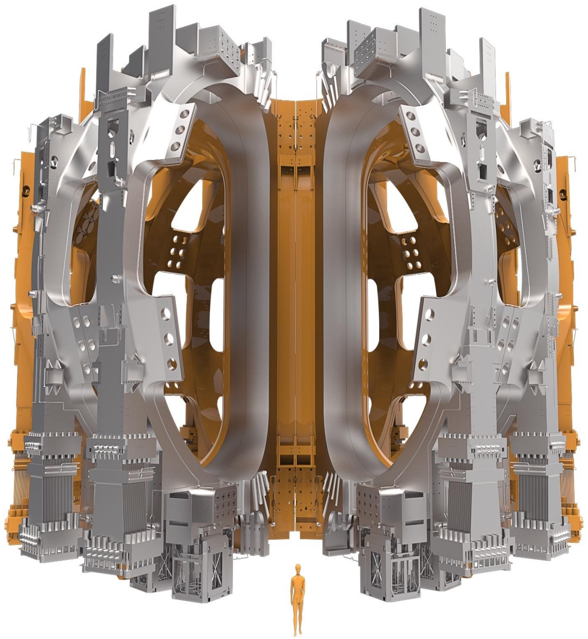


W7-X 7 Greifswald -2016
NbTi, He forced flow, 6T



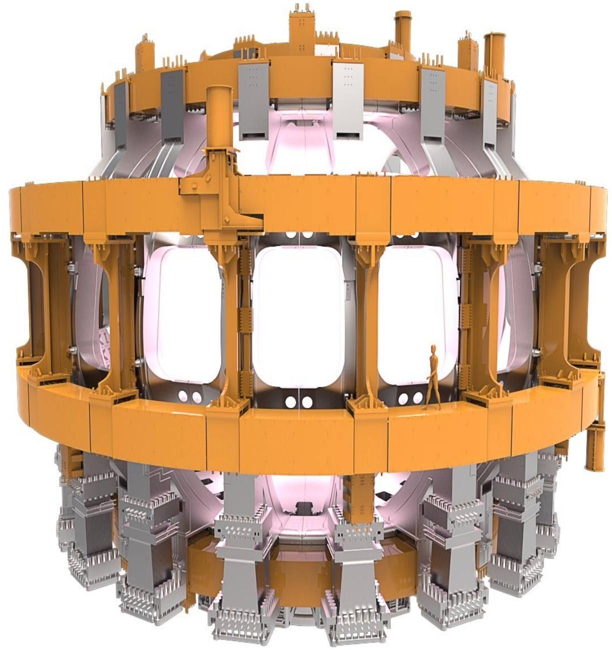
EPFL

ITER magnets system – the largest ever built

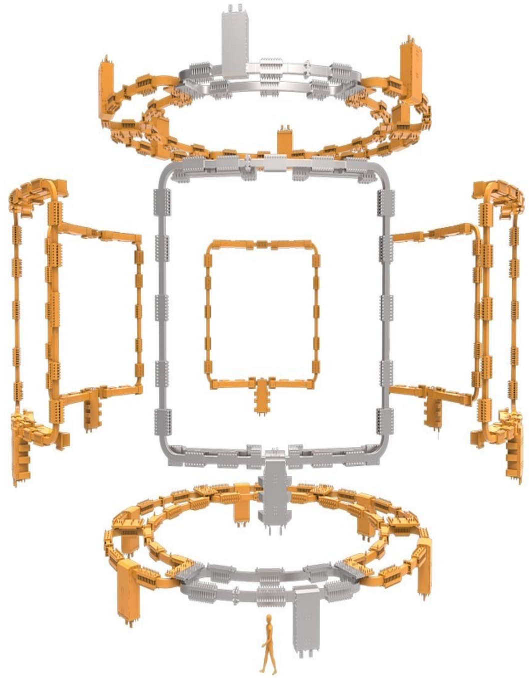


TF coils
Nb_3Sn, 11.8T

Central solenoid
Nb_3Sn, 13T



Poloidal coils
NbTi, 6T



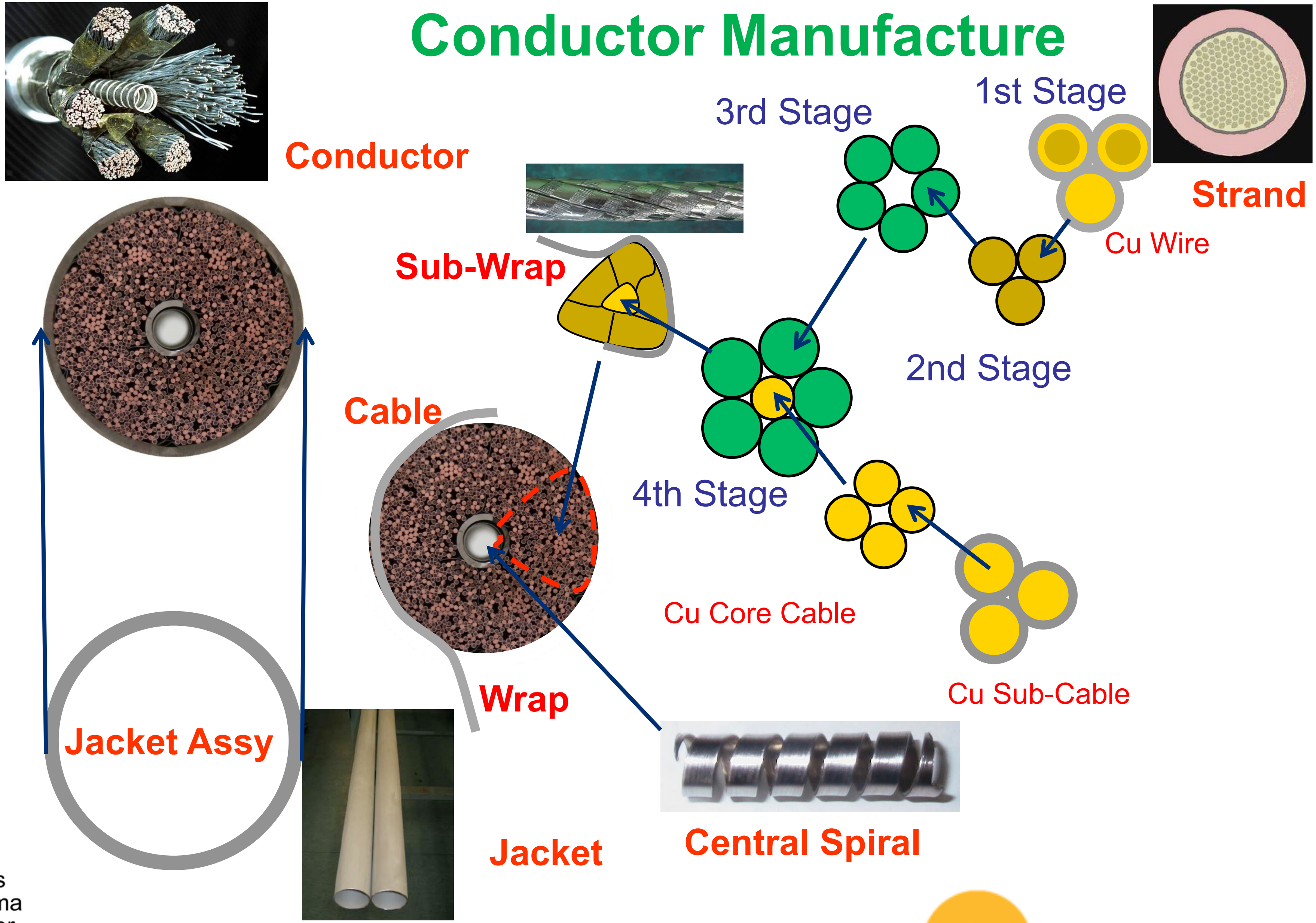
Correction coils
NbTi, 4.2T

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



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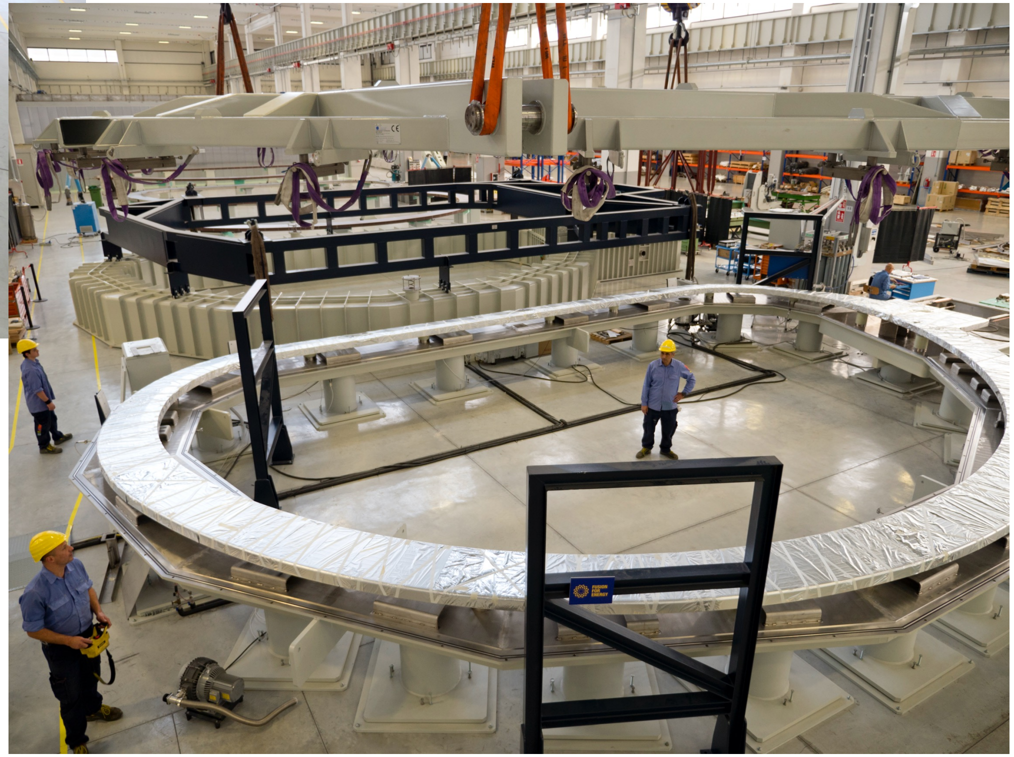
ITER magnets system – TF coils

Toroidal Field coils
winding pack in ASG – La Spezia



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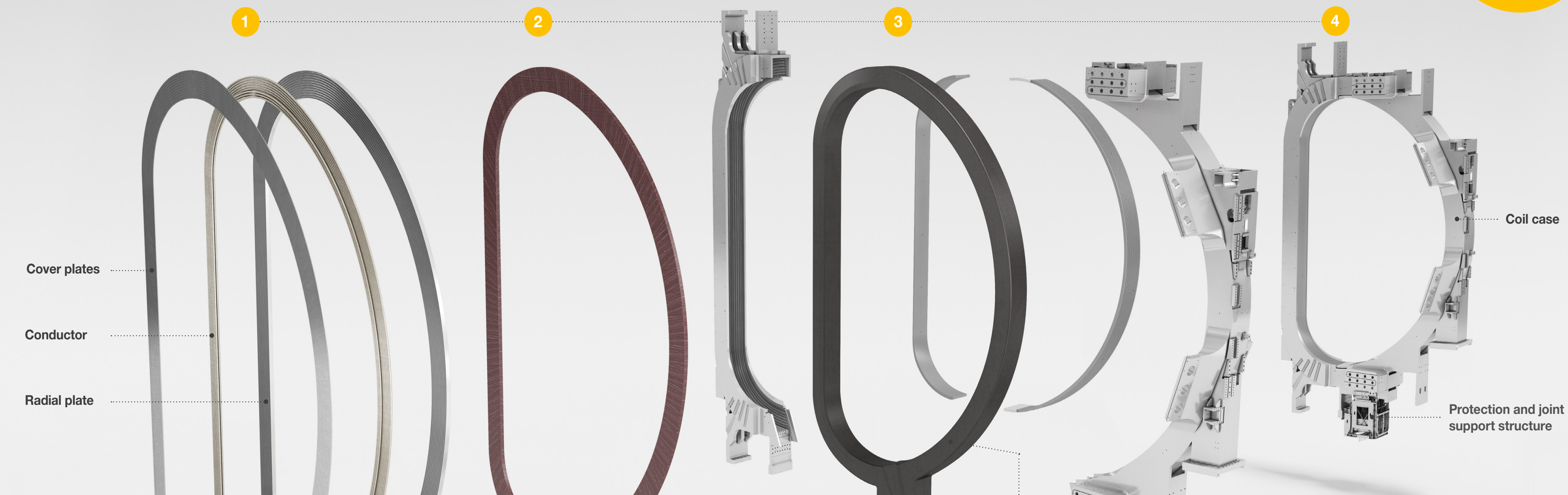
ITER magnets system – TF coils

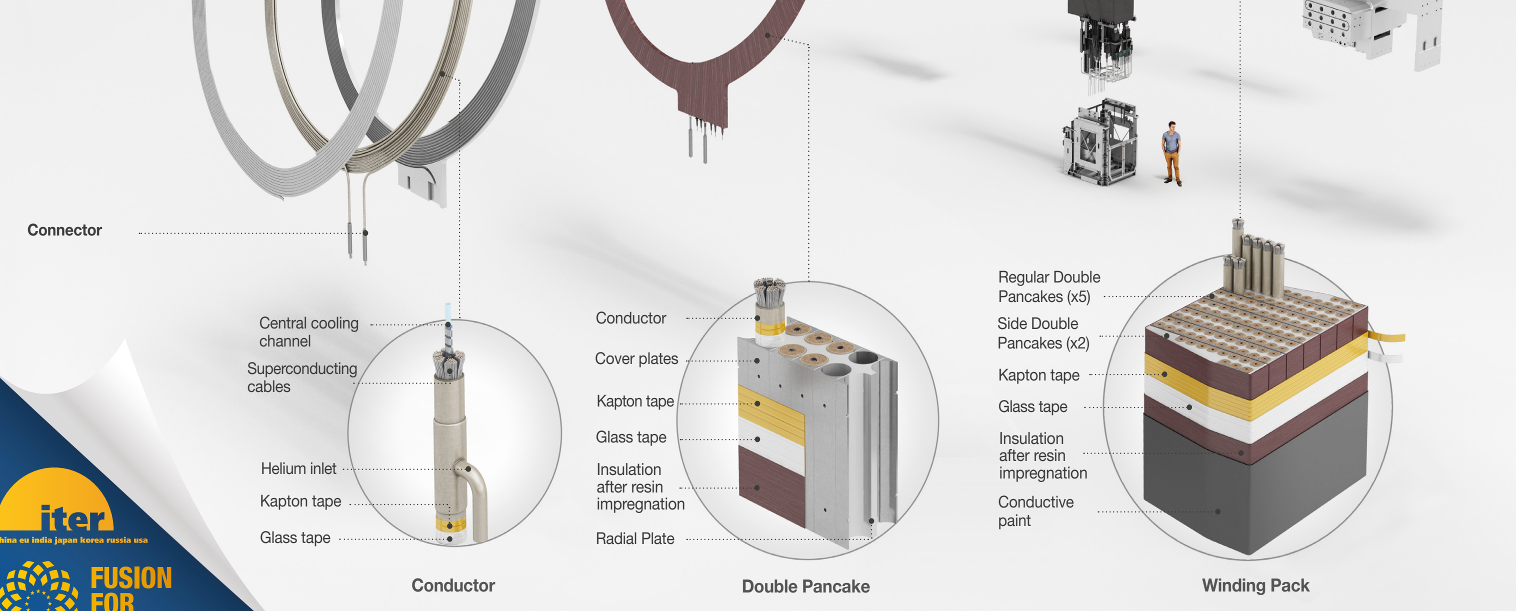
Transporting one Toroidal Field coil

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.

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ITER magnets system – PF coils

Poloidal Field coil winding facility on ITER site

ITER magnets – installation of 6th PF coil

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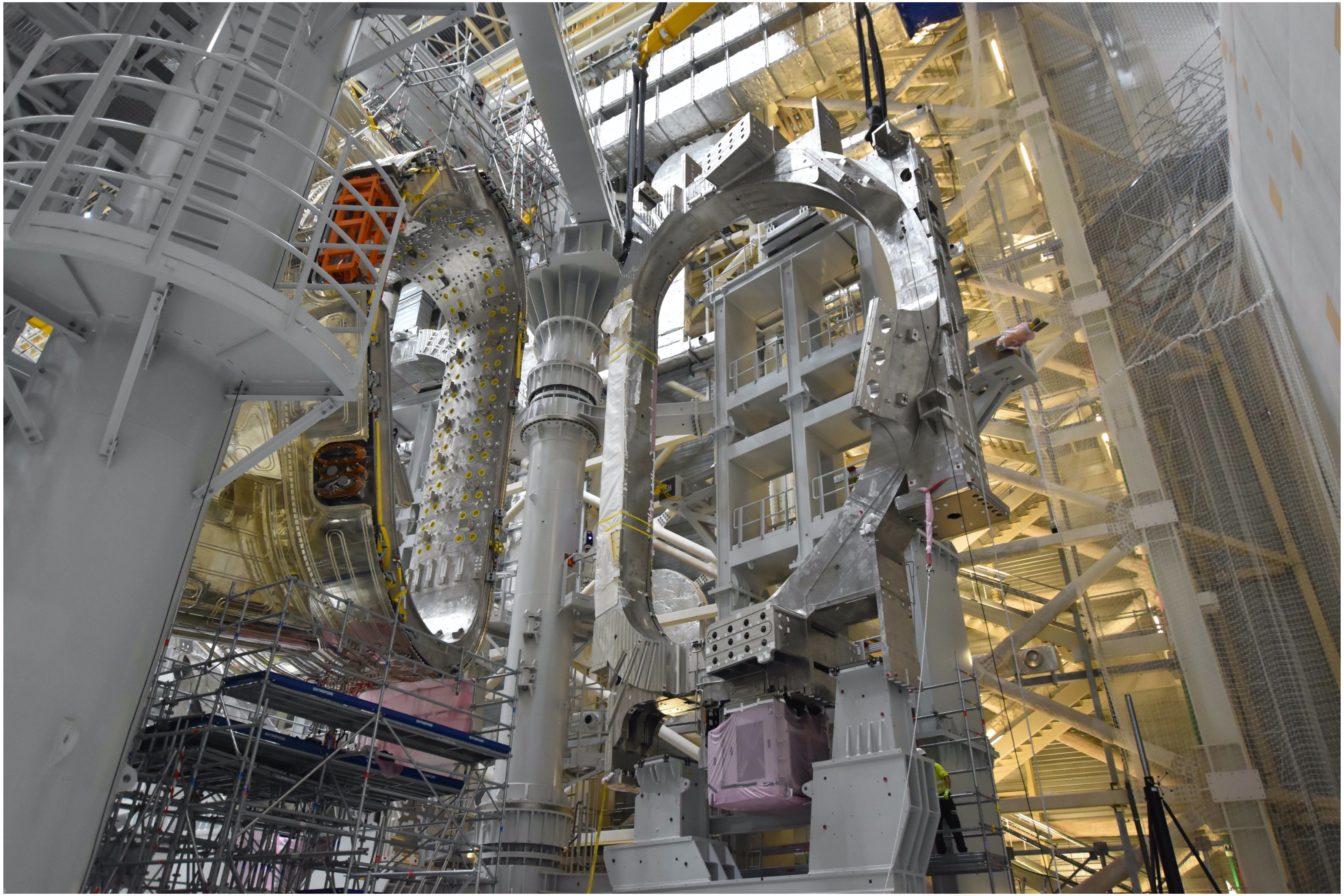
ITER magnets – installation of 1/18 TF coils with 1/9 of vacuum vessel



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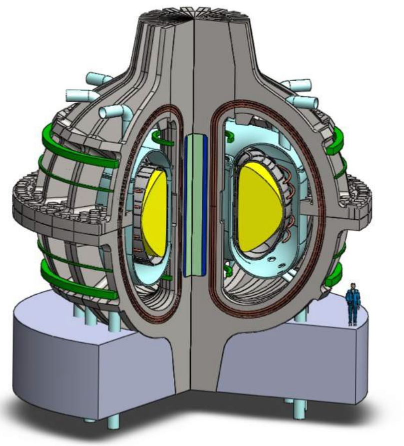
ITER magnets system – the cryostat

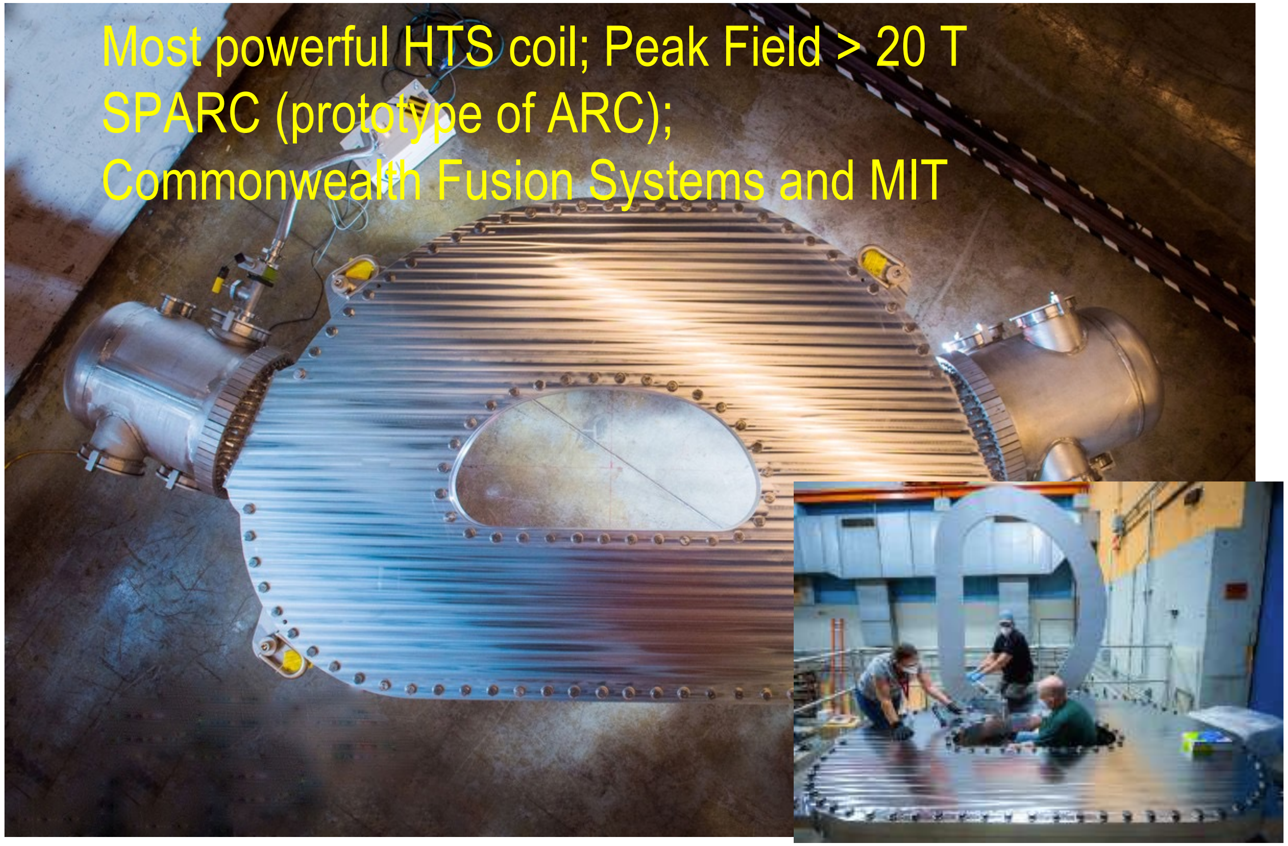
EPFL

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





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Superconducting magnets for DEMO

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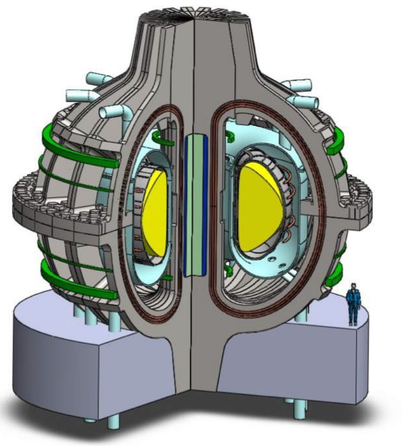
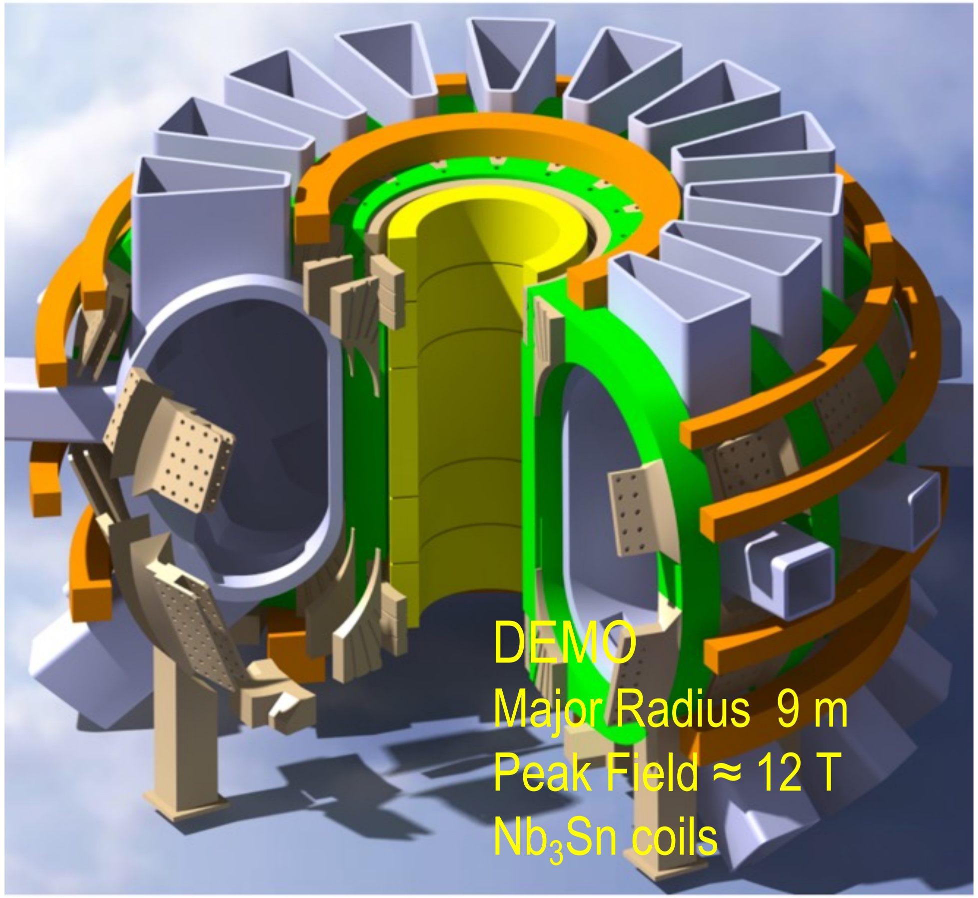


EUROfusion



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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

EPFL

Research activities at the SPC superconductivity group

Daniel Biek

28.11.2022

Swiss Plasma Center

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Content

- SPC at PSI
- Difference between Stellarators and Tokamaks
- Motivation
- My Research
- Challenges

EPFL

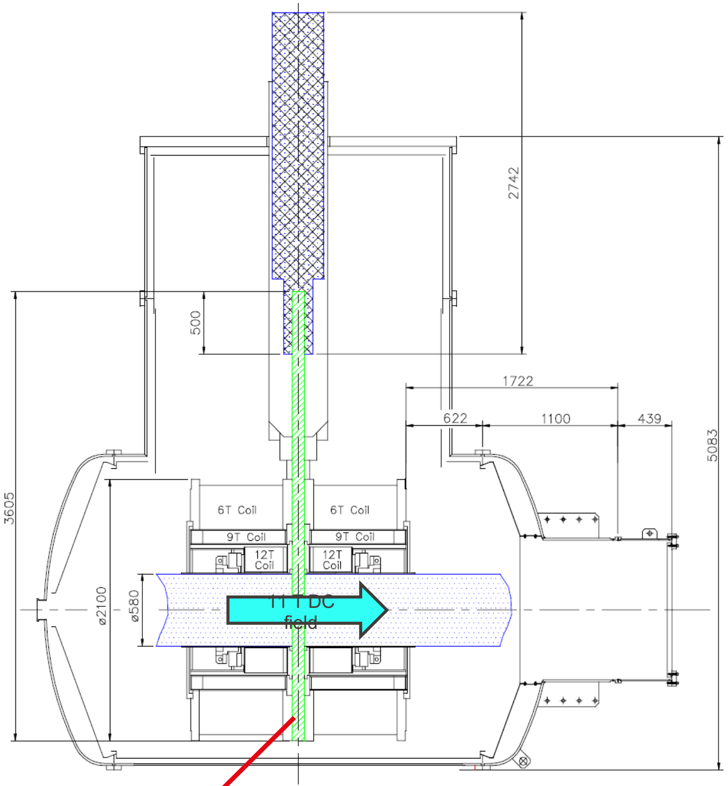
Who are we?

- Part of the Swiss Plasma Center
- Based at PSI, Villigen

Current activities:

- Development of conductors for Magnets of DEMO tokamak fusion power plants
  - For all parts of the tokamak (PF, TF and CS coils)
  - HTS- or LTS-based
- Stellarator magnets
- Testing of conductors for other fusion devices (CFS,DTT,CFETR,ITER)

SULTAN test facility at SPC-SG *



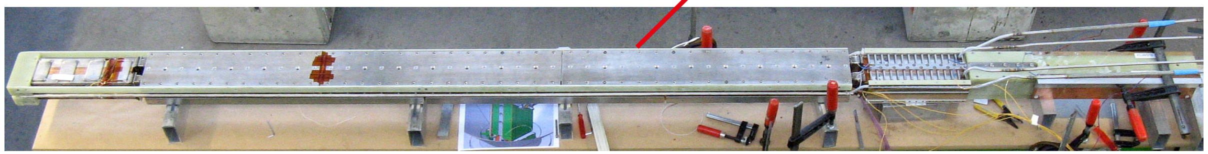
11 T DC magnetic field

~100 kA operating current in
4 – 50 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 tests:

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



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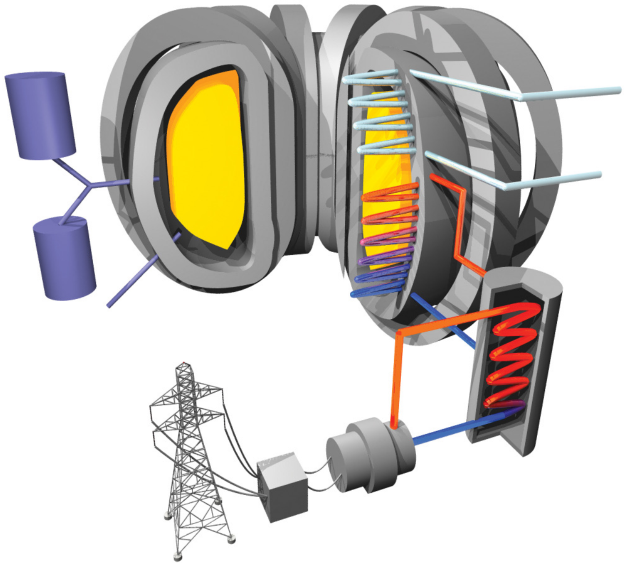
* other test capabilities: 15 T / 12 T magnets (80 mm bore); 1 kA; 4 K / 77 K / var T inserts

Magnetic Fusion Power Plants Types

Tokamaks:

- Pulsed operation
- Large currents in the plasma
- Coils easier to manufacture

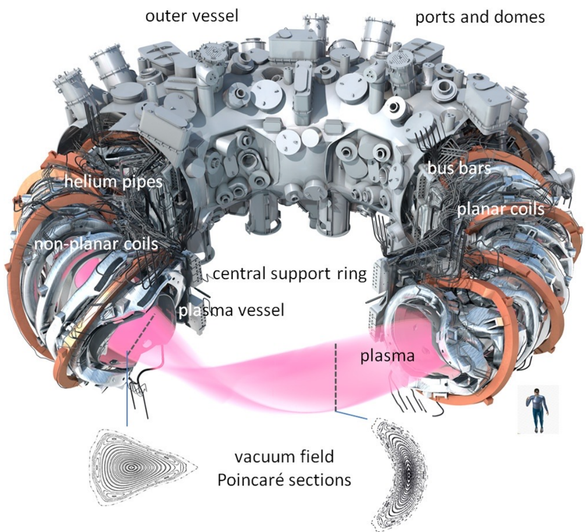
DEMO – Tokamak (only TF Coils)



Stellarators:

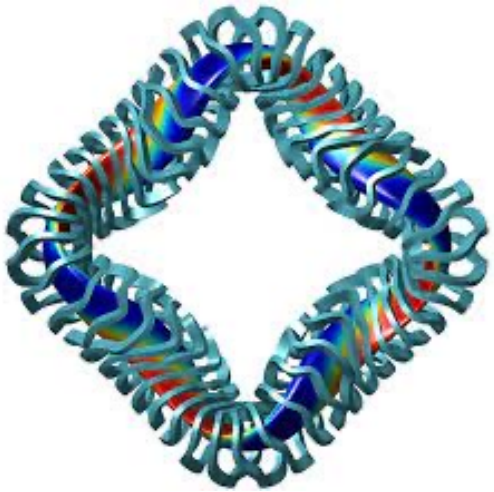
- Steady-state operation
- Different configurations
- Only self-created plasma current (bootstrap currents)
  - In some configurations there is no currents

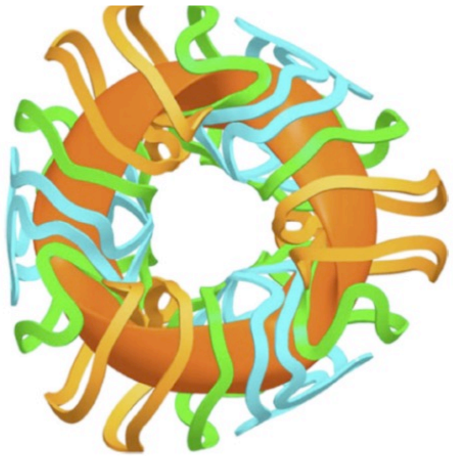
Wendelstein-7X



Motivation

- A new generation of magnetic fusion power devices as an alternative to tokamaks
- Steady-state operation one of the main motivator
- Results from experiments from W7-X motivates to further research
- Different configurations to explore
  1. Quasi-helical symmetry (QH) – HSX, Starblazer
  2. Quasi-axisymmetry (QA) – Compact Stelalrator
  3. Quasi-polodial (QP) – impossible from an engineering point of view
  4. Optimized configuration, also quasi-isodynamic (QI) – W7-X, HELIAS





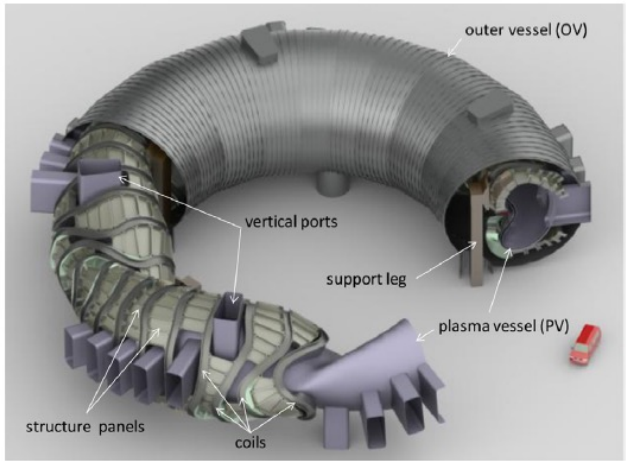
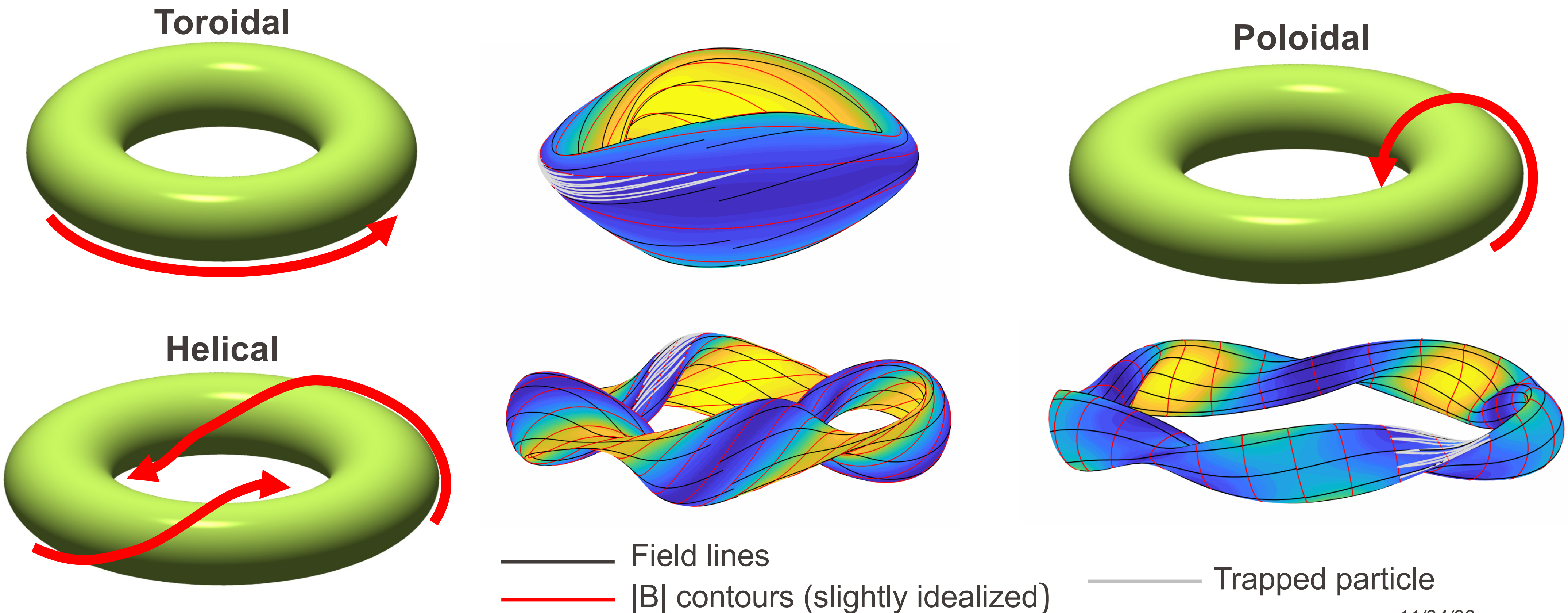


Fig. 1. HELIAS 5-B overview.

Stellarator configurations

Daniel Biek

- Trapped particles should drift toroidally, helically, or poloidally on a surface.
- B contours on a surface have the same topology as these drifts.



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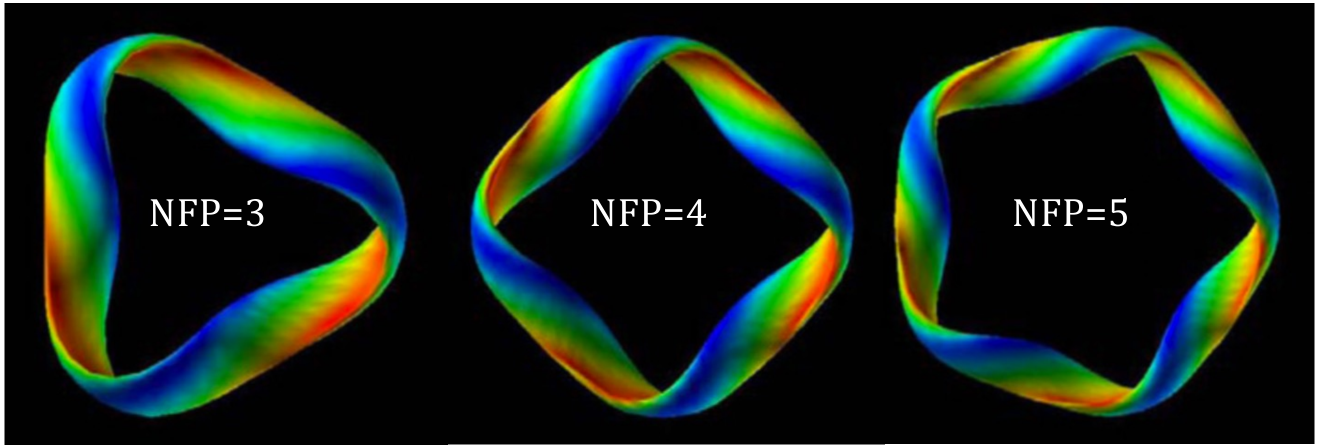
My research

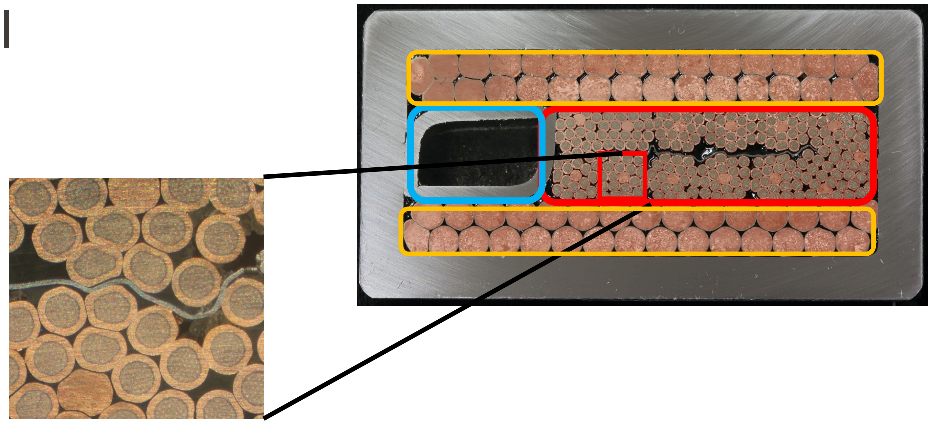
- Design of magnet coils for next generation of QI stellarators (HELIAS)
- Aim: to develop a reliable and cost-effective stellarator design for a demonstration power plant.
- HELIAS is an optimized stellarator
- Explore different design options
- The higher magnetic field is, the better is the confinement and the smaller the machine is



Design options – 1st approach: LTS

- LTS are the most used superconductors
  - A lot of experience from ITER and also DEMO
  - Manufacturing infrastructure is existing
- Only possible option: Nb_3Sn
- Coolant: liquid helium
- Magnetic field: up to 13T at the coil

Example of LTS conductor (TF coil)

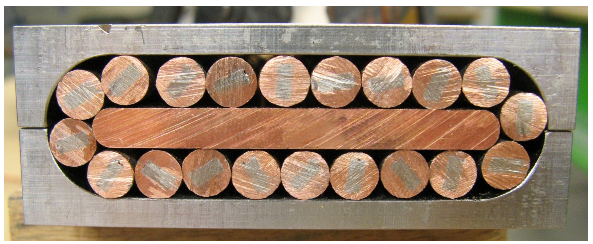


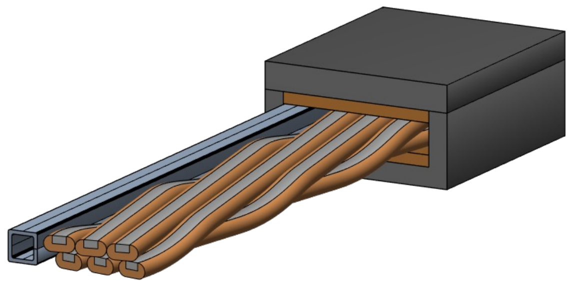
Design options – 2^{nd} approach: HTS

- Strong development in HTS technology and its research
  - Reduction of the price over the last years
- Main advantage: much higher critical field – up to twice the magnetic field in LTS conductors

➔ much more compact stellarator, i.e. lower manufacturing cost (despite presently higher price of HTS materials compared to LTS strands)

- Possibility to use higher operating temperature (20K)
  - Better thermal stability





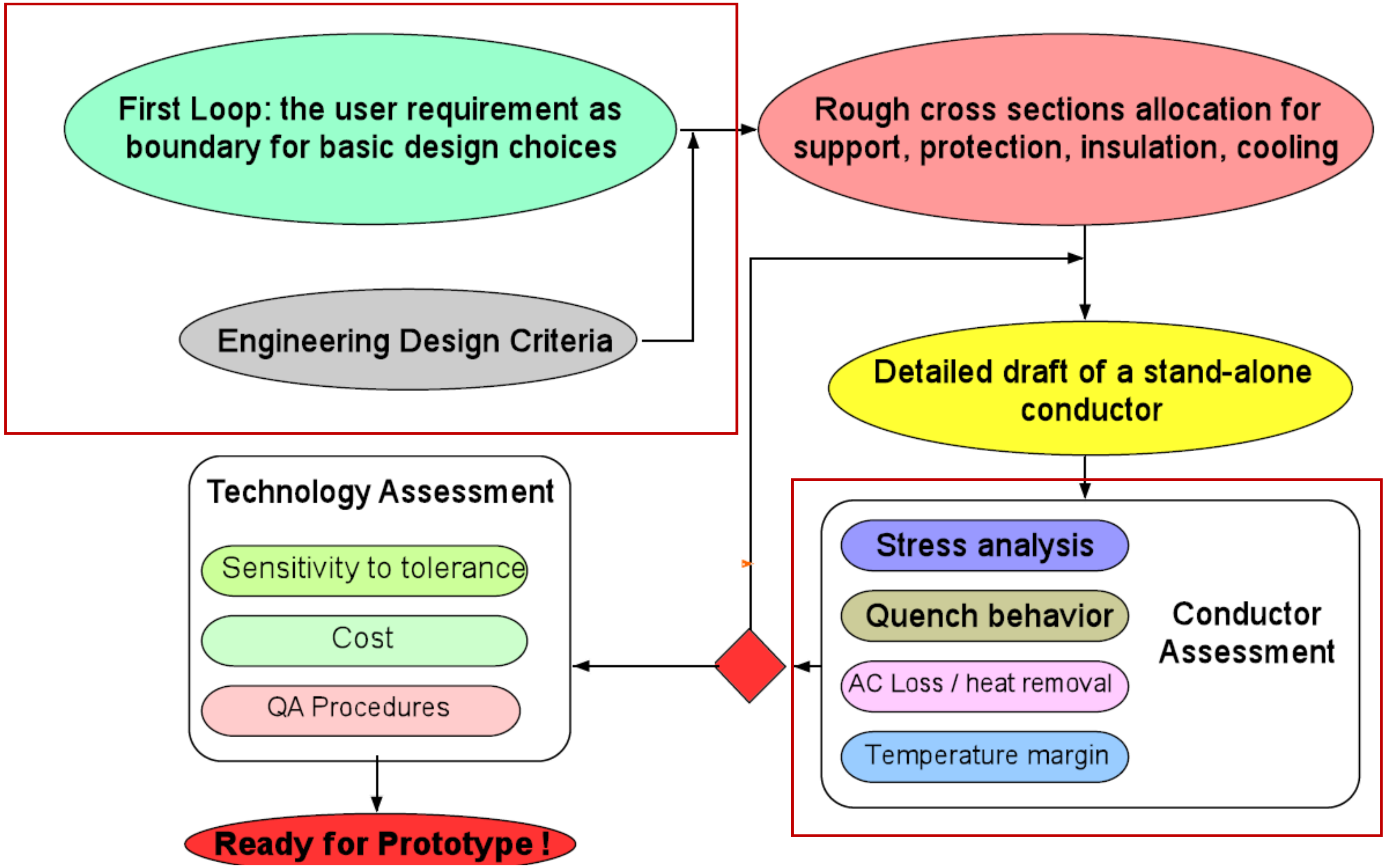
Design options – Non-insulated coils – Work principle

- Current can pass through both the superconducting windings and by the resistive short-cuts, i.e. transversely through the steel jackets of conductor turns/layers
  - Superconductive path dominates in DC mode (no resistance, except perhaps a small ($\leq 1n\Omega$) resistance in the joints)
  - Resistive path becomes active only during magnet charging (due to the inductive voltage) or during quench (resistive voltage in the superconductor)
- The non-insulated (or “partially insulated”) coil is applicable only to the DC coils

Design options – Non-insulated coils

- It relies on a passive quench protection (extremely valuable for the HTS coil).
- It also solves the issue of risks related to High-Voltage induced during safety current discharge (the major source of risk of coil damage during operation).
- Applicable to low temperature (LTS) and high temperature (HTS) superconductors.

Design parameters



Design procedure – Stellarator Magnets –First loop

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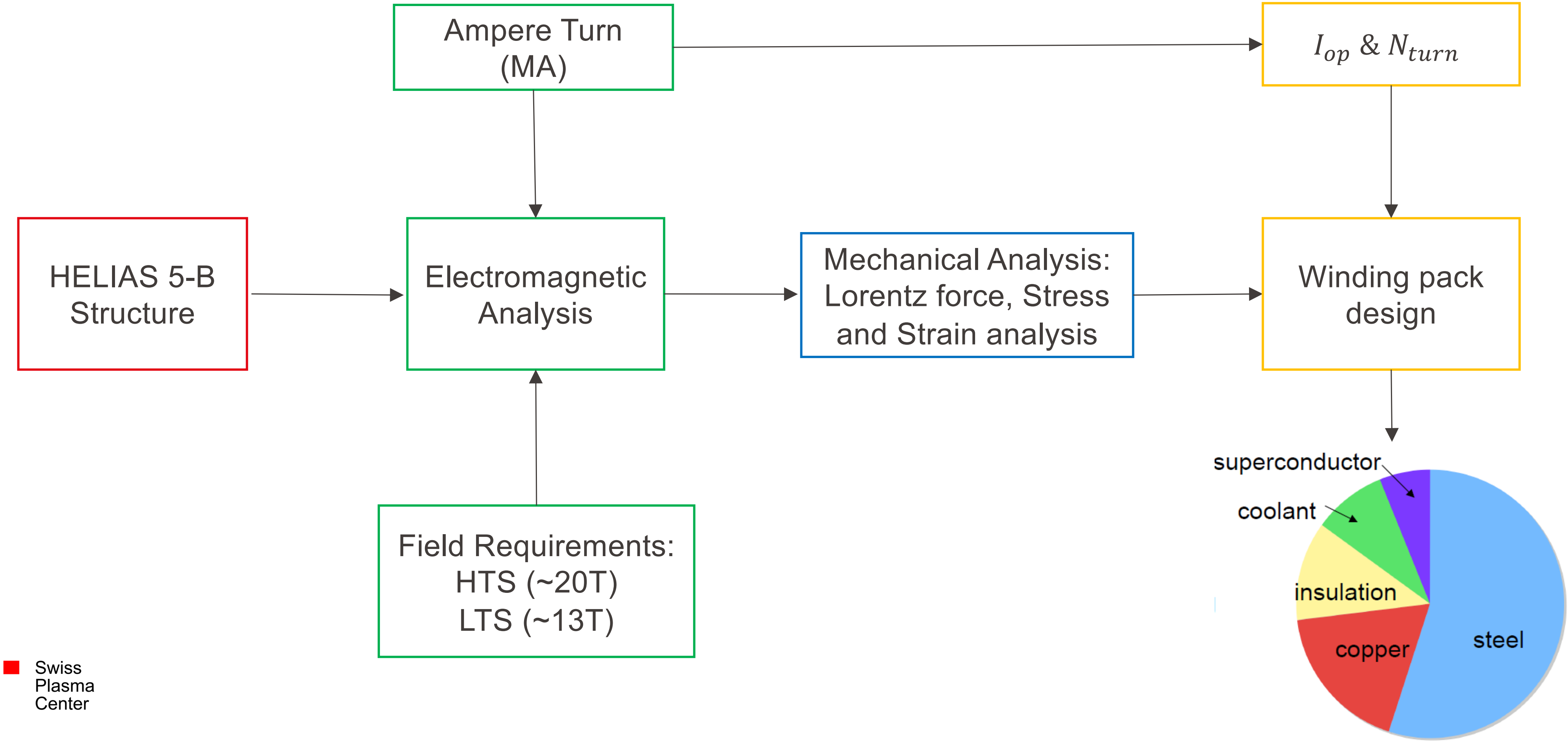
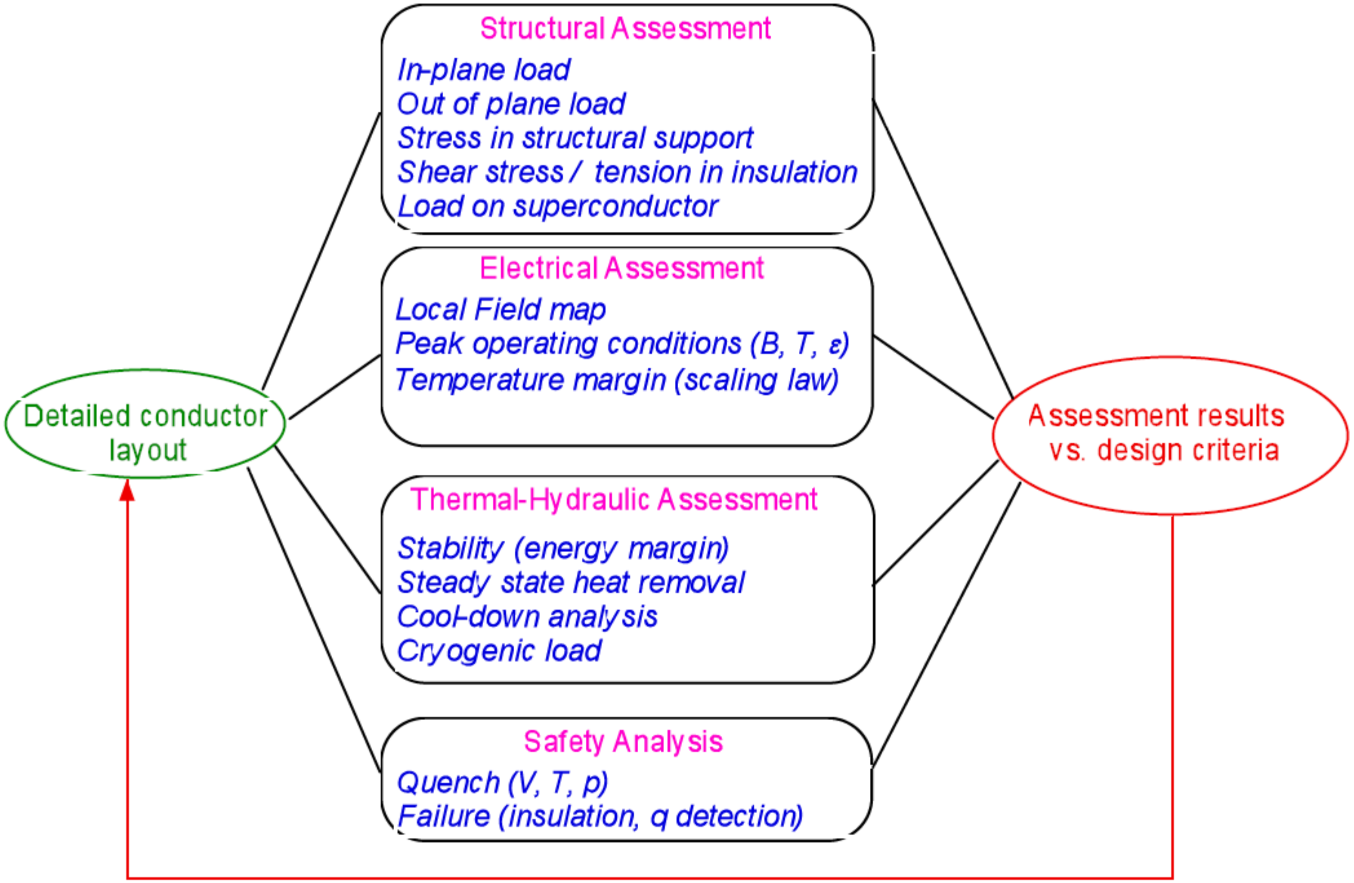


Conductor-Coil Performance Assessment



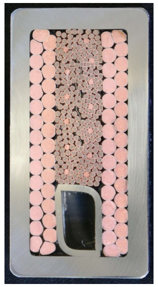
Challenges

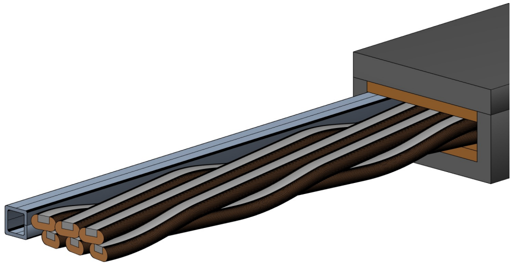
- Small bending radius and high mechanical stress
  - Superconductor could break
  - Design of a suitable conductor more difficult than in tokamak coils
- HTS: Quench protection, Degradation with EM-cycling
- Complex Geometry (manufacture, simulation, etc.)

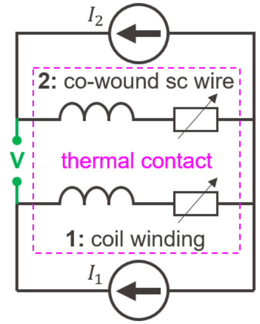
Non-insulated coils

- Technology still in the development phase
- Stored energy is deposited inside the coil → hot-spot temp. and thermal gradients.
- Force imbalance during quench; field quality depends on the manufacturing reproducibility of the joint and inter-turn resistances; field stability

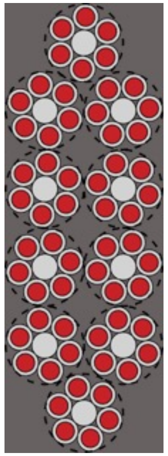
Conclusion

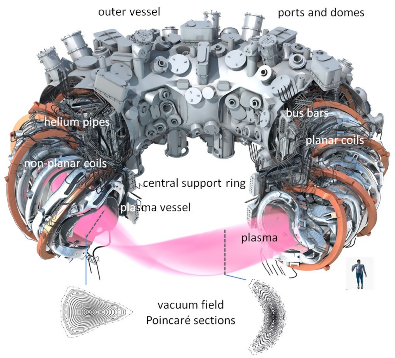






There are lots of challenging and interesting topics in applied superconductivity for fusion magnets!





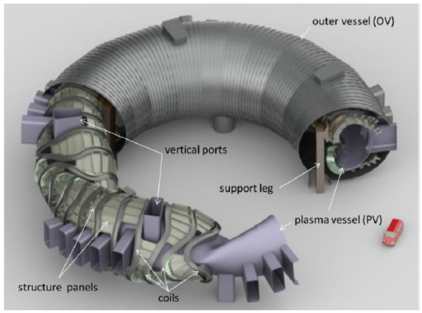
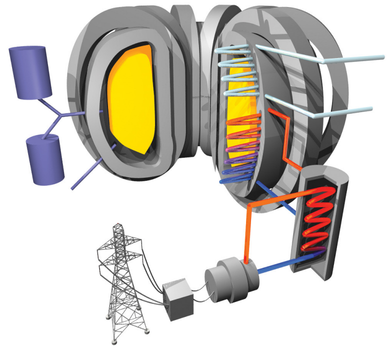


Fig. 1. HELIAS 5-B overview.



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THANK YOU FOR YOUR ATTENTION!