EPFL

Nuclear Fusion and Plasma Physics

Lecture 11

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Swiss Plasma Center

Applied superconductivity for fusion
Layout of the lecture

The need for superconducting magnets

Superconductivity – generalities

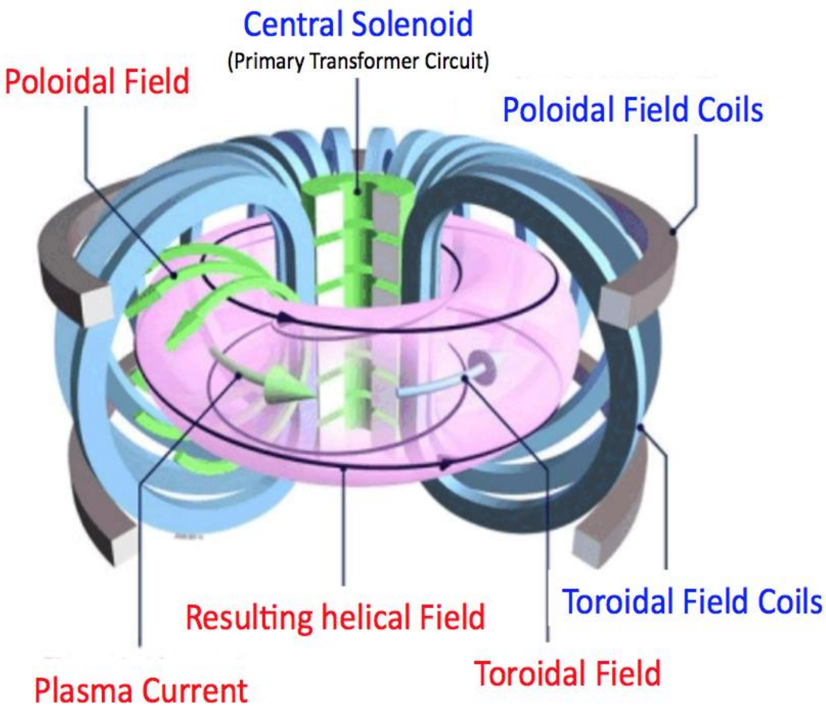
Requirements and challenges

Fusion devices with superconducting coils

ITER, DEMO and beyond

Presentation by 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 $\alpha \geq 2$

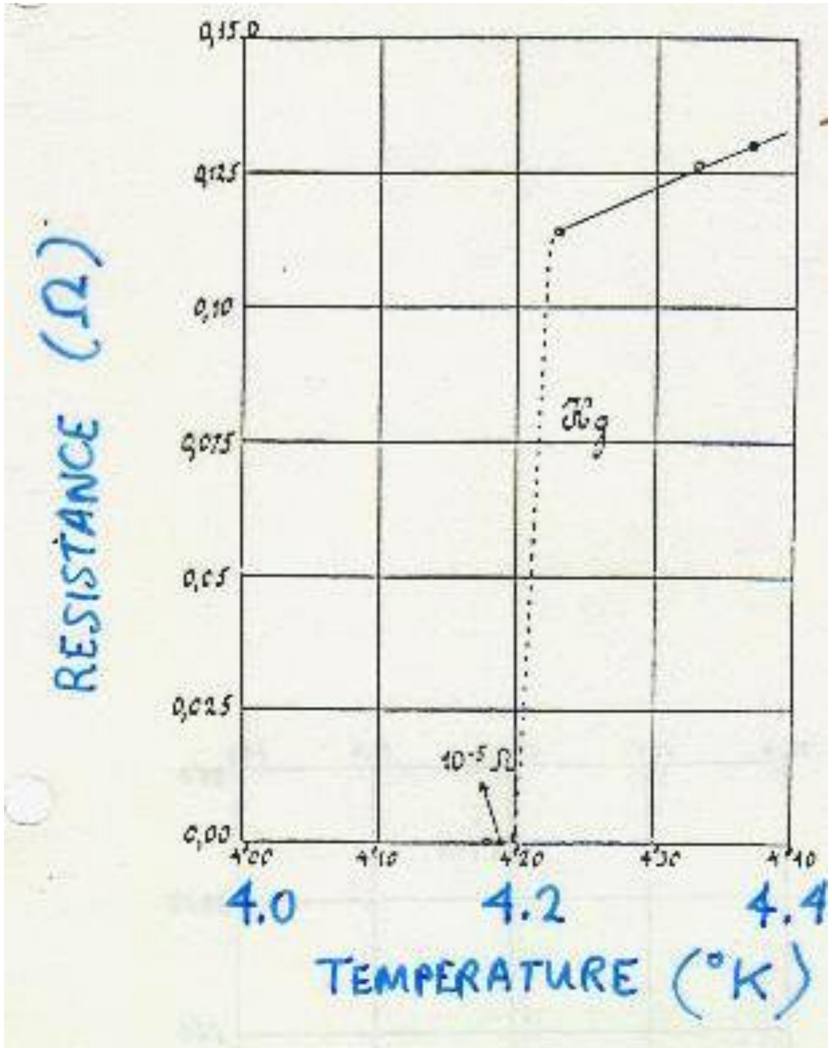
Copper coils can generate large fields, but not in steady-state

- Current density in steady-state $\leq$10 A/mm^2

For steady-state, superconductors are necessary

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

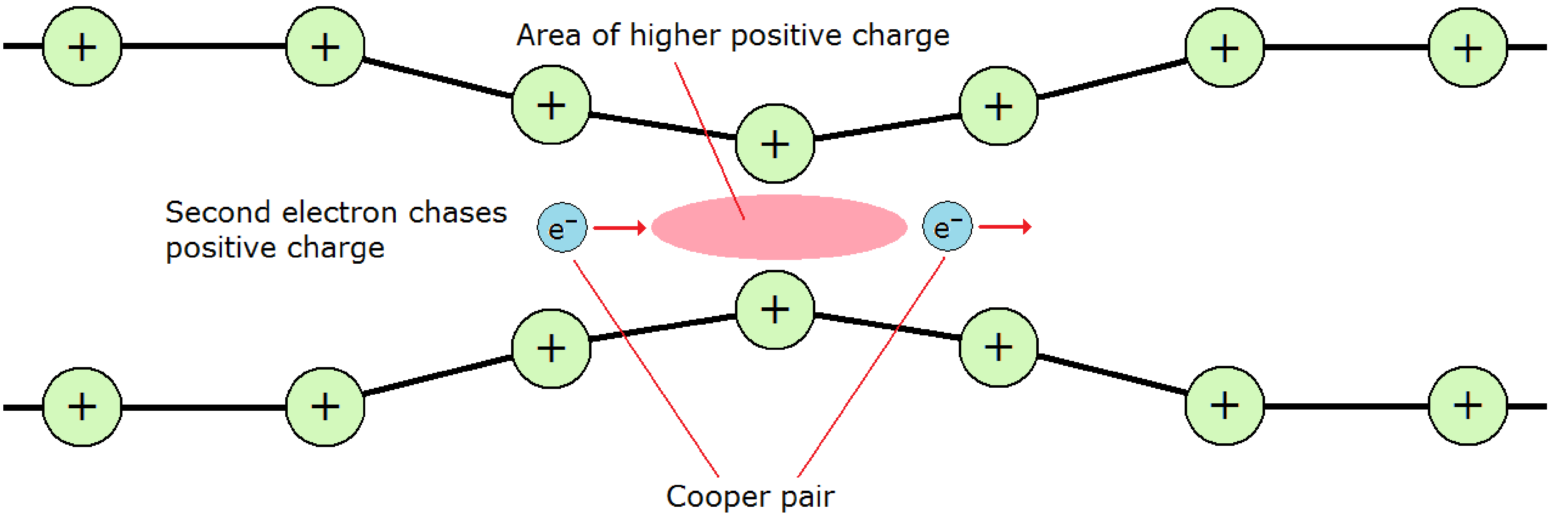
The discovery of superconductivity



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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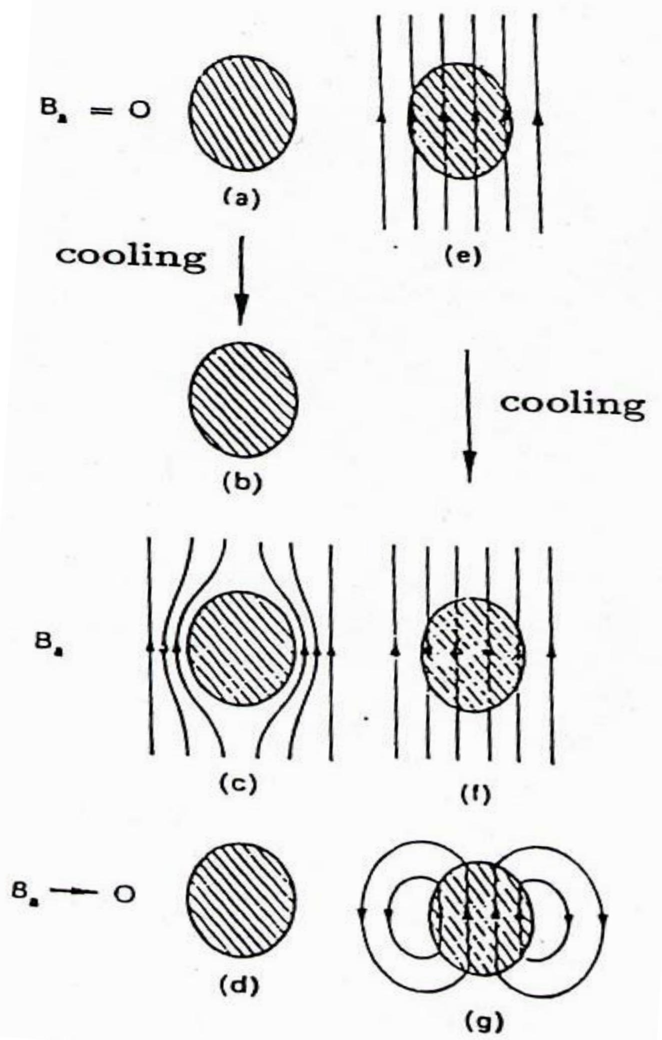
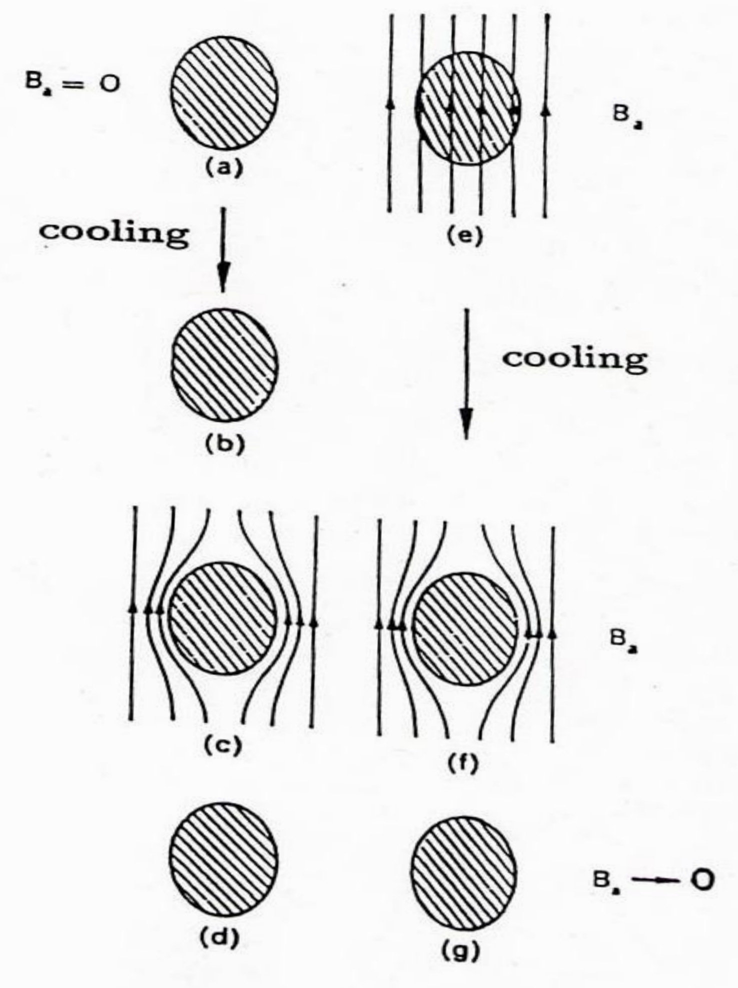
Superconductors vs. perfect conductors

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

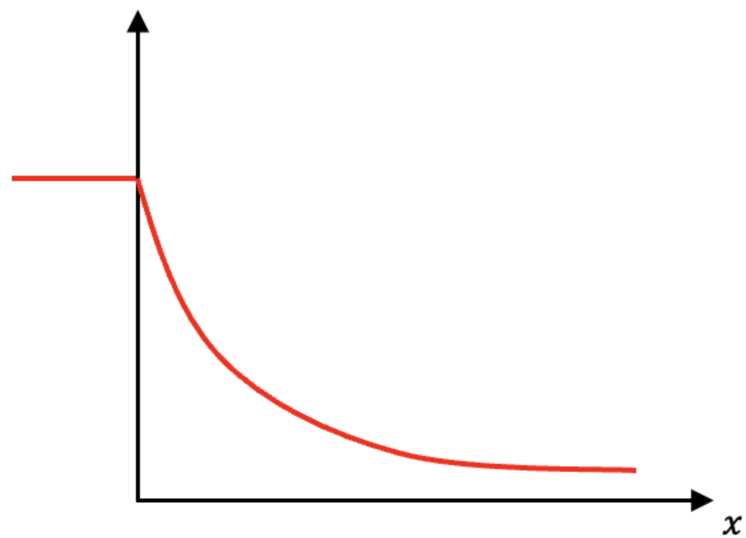
In the superconductor (London theory, 1935):

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

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

n_C = density of sc carriers

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



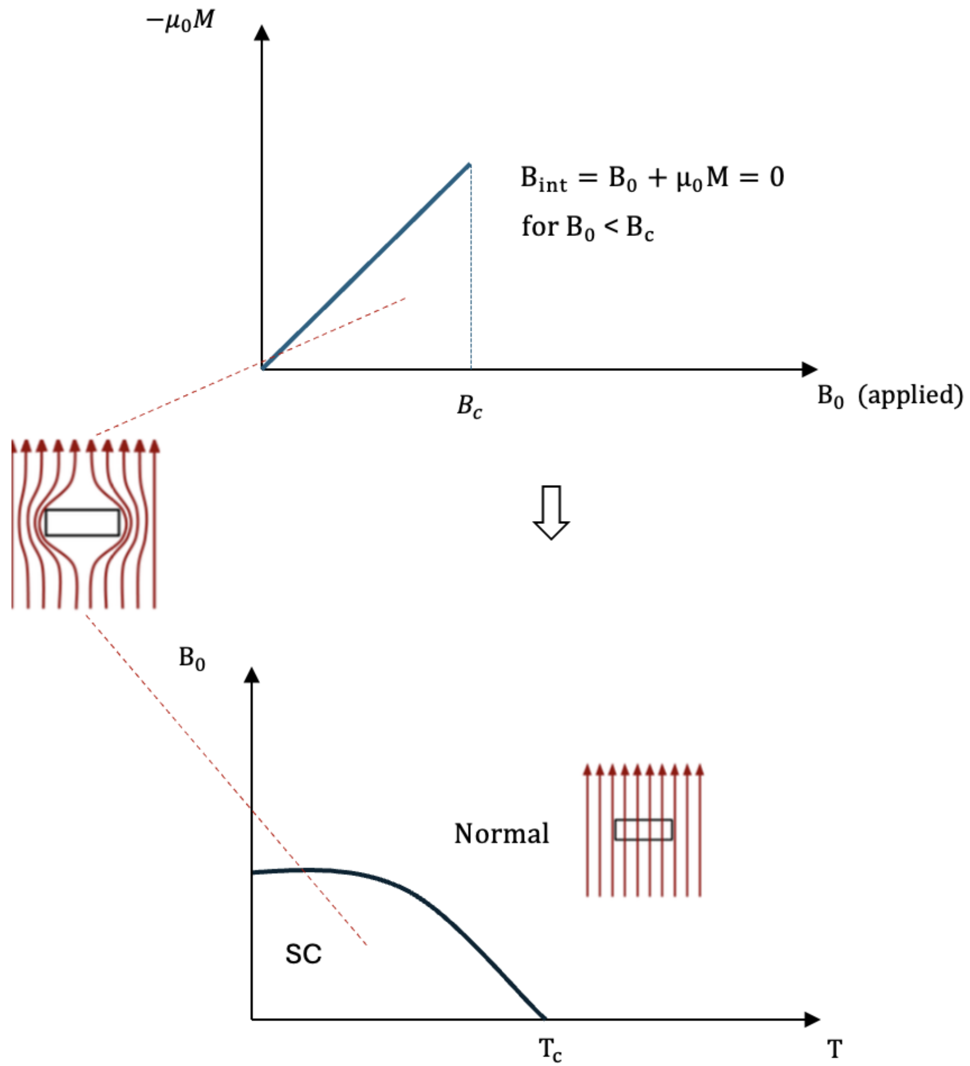
Magnetization and Type I vs. Type II SC's

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

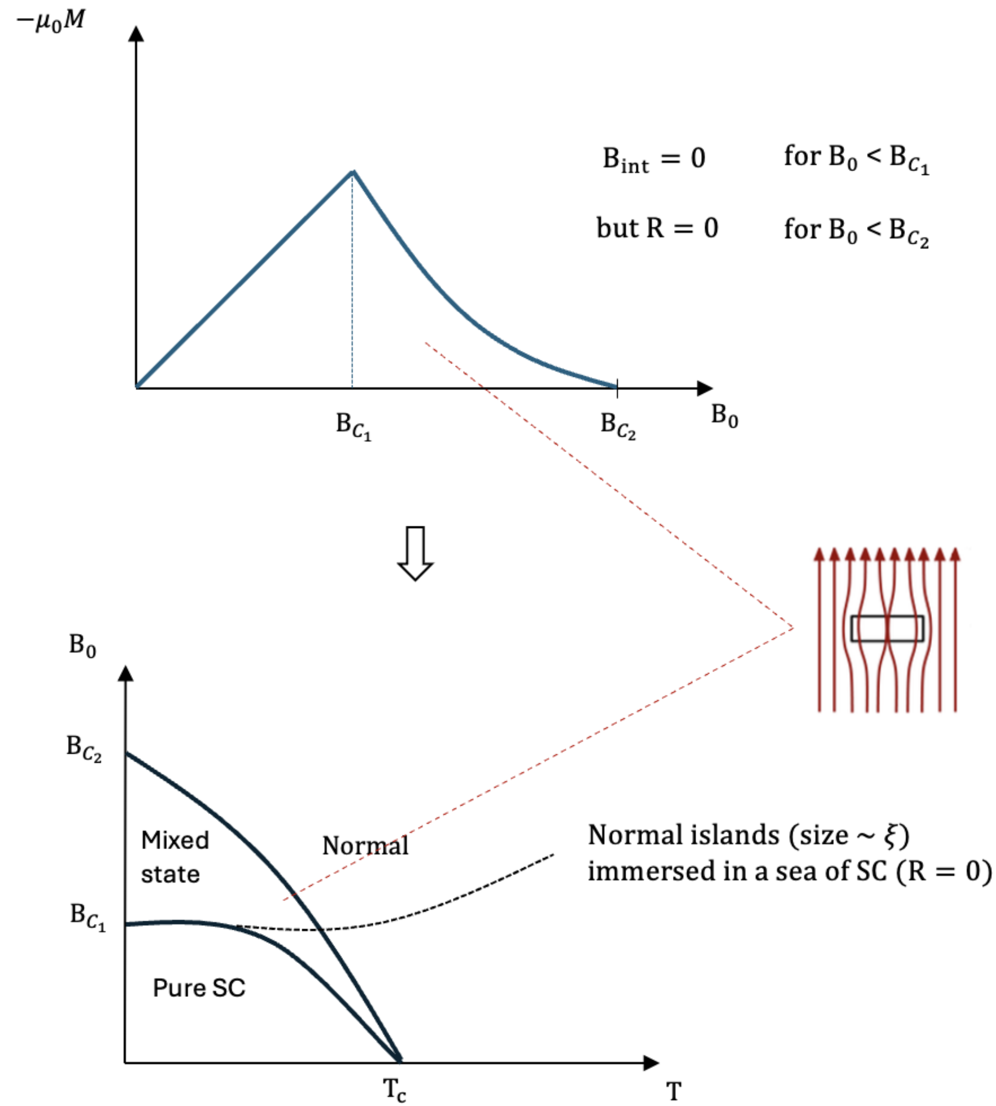
Type I SC's

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



Type II SC's

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

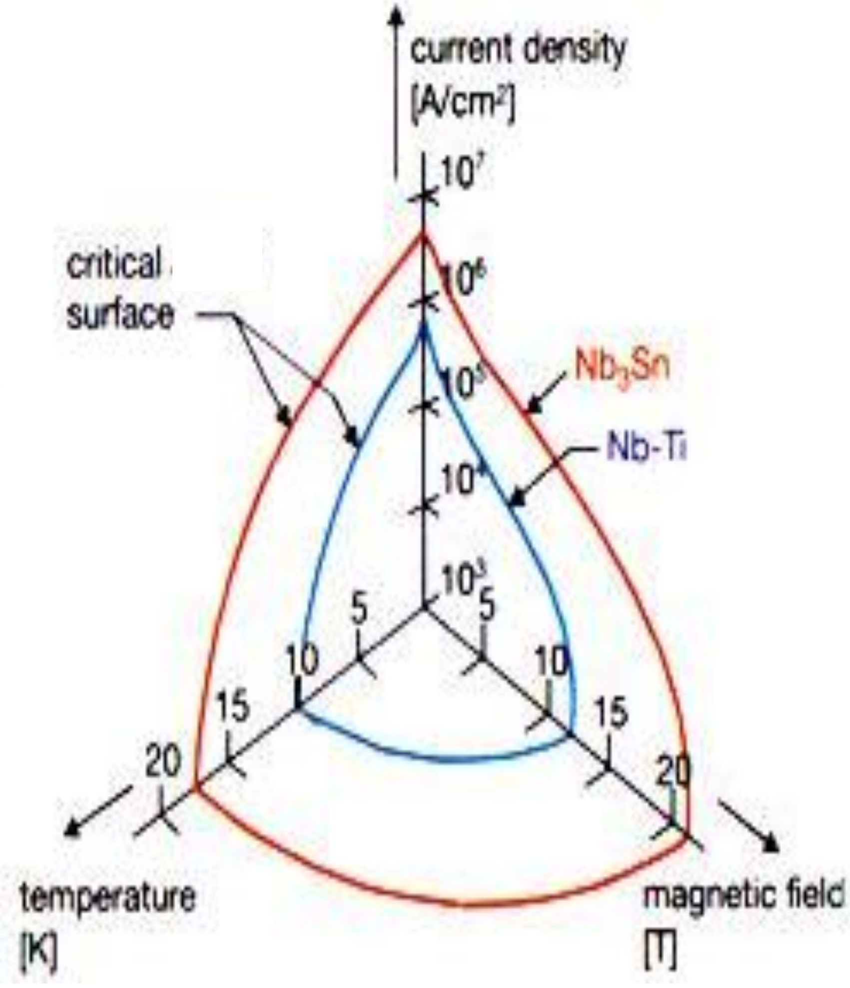


Superconductors for fusion magnets

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

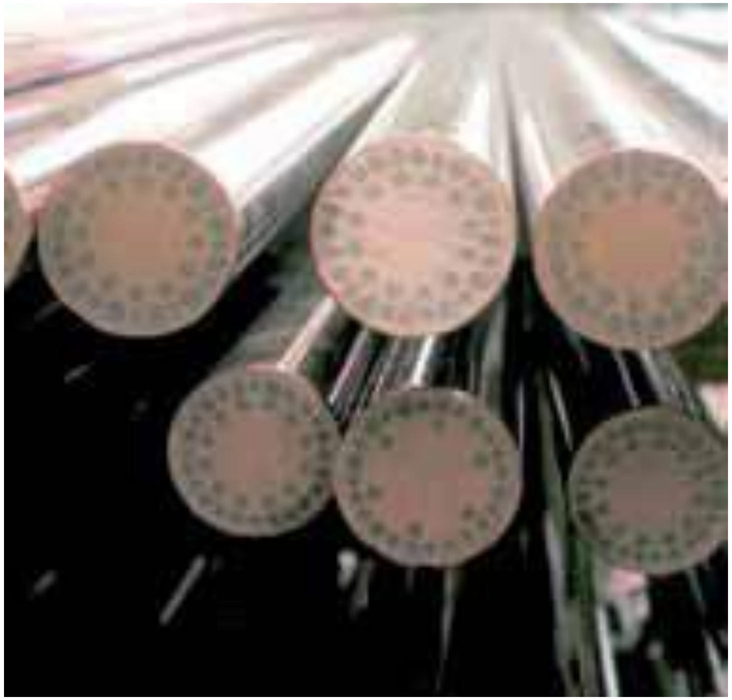


→ **critical J, B and T surface**

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

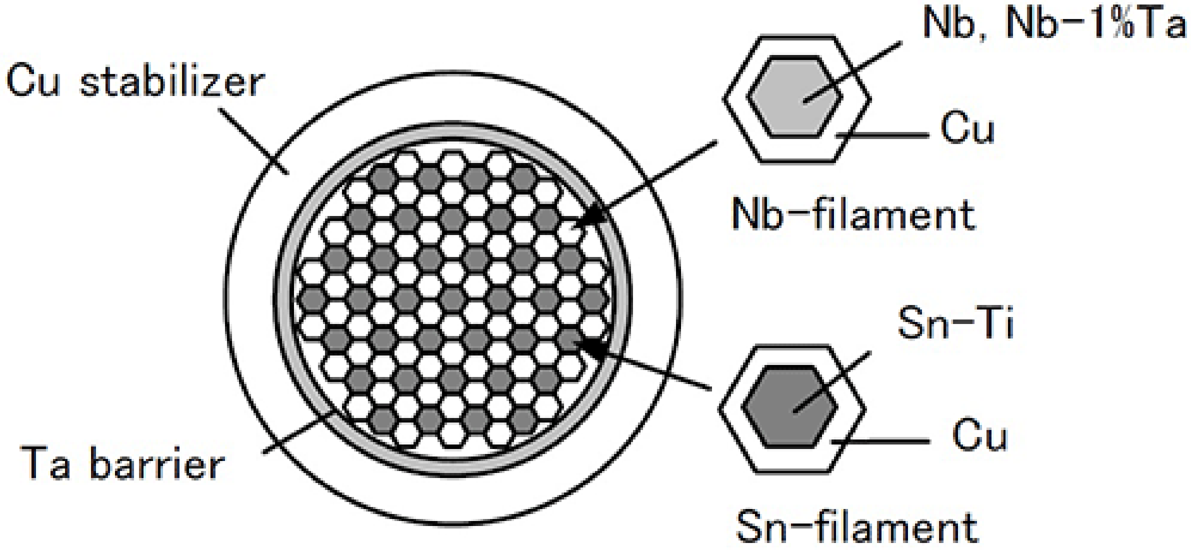
Superconducting materials for fusion

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

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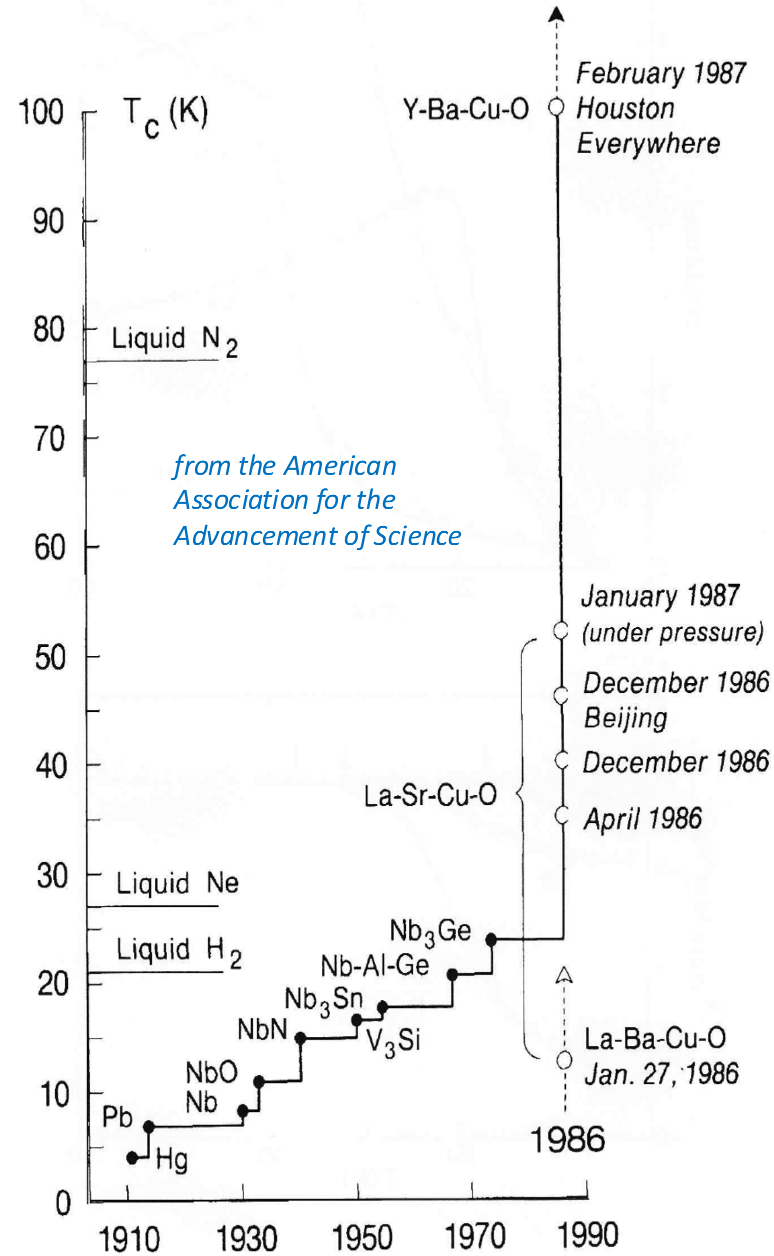
High temperature superconductivity

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

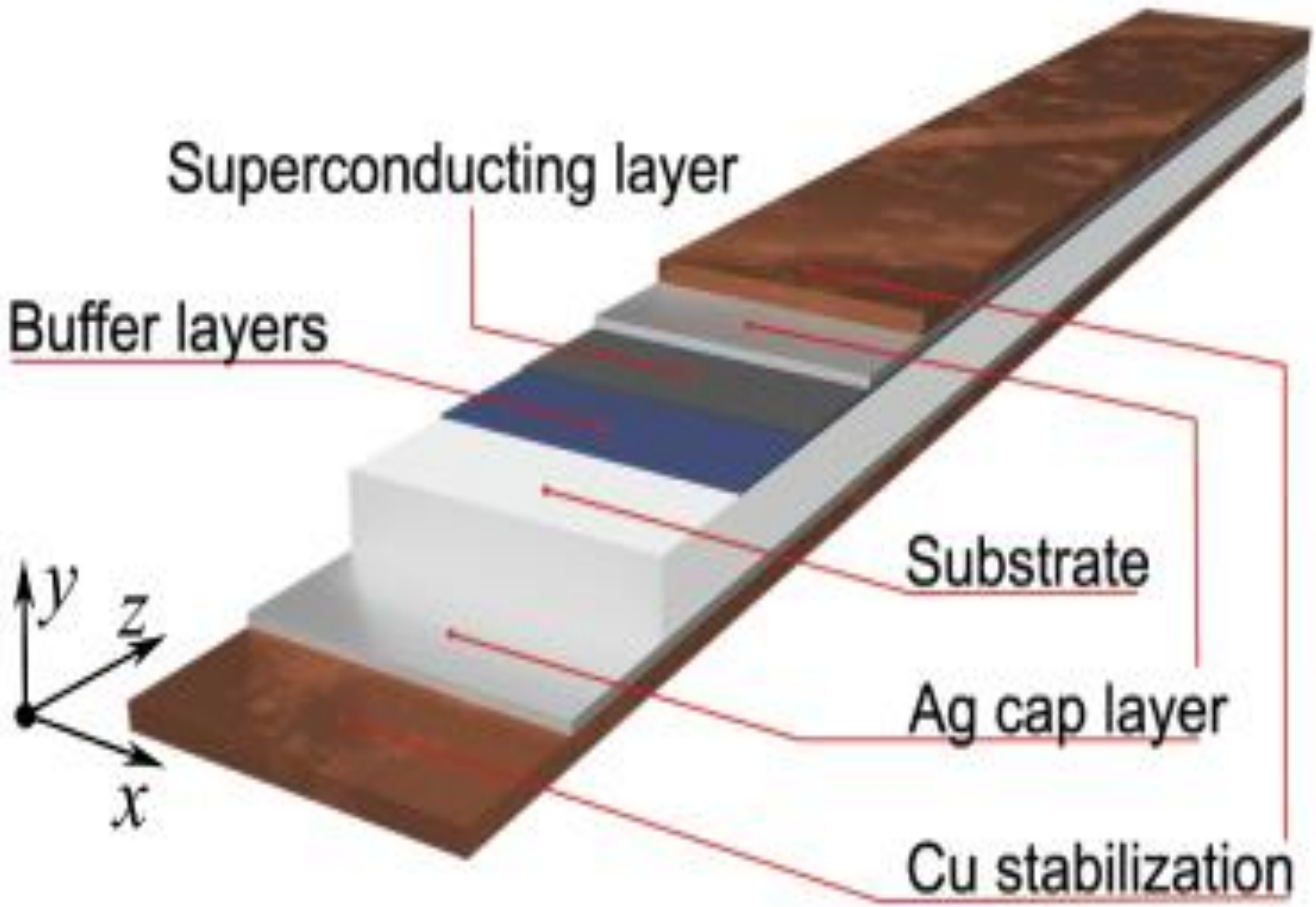
Two classes of HTS materials are potentially suitable for fusion magnets

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



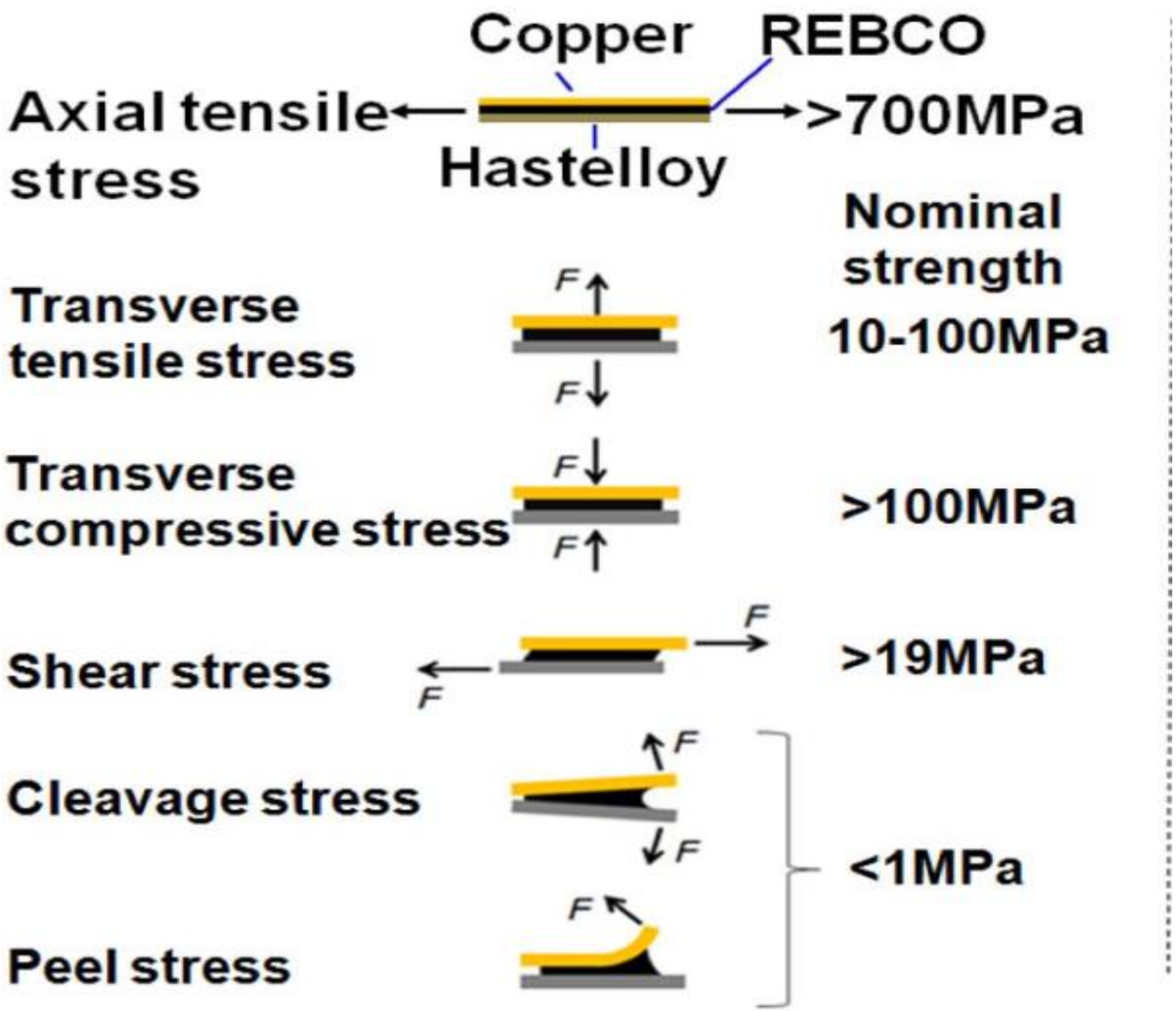
from the American Association for the Advancement of Science

HTS – REBCO tapes



From Superpower.com

HTS – REBCO tape mechanical issues



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

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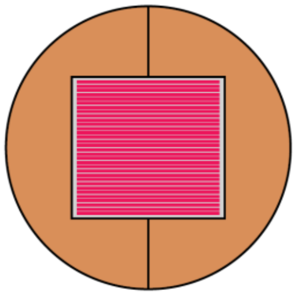
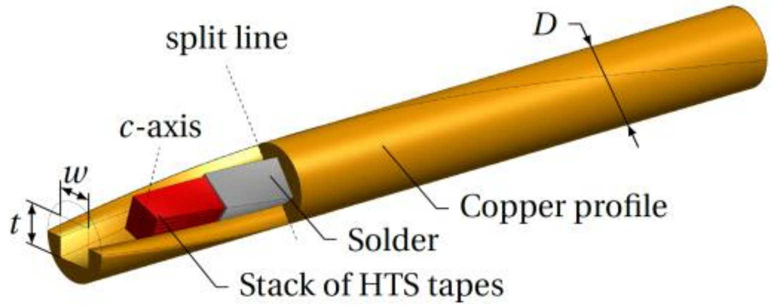
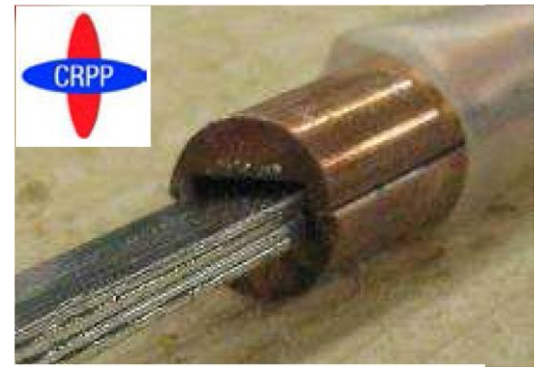
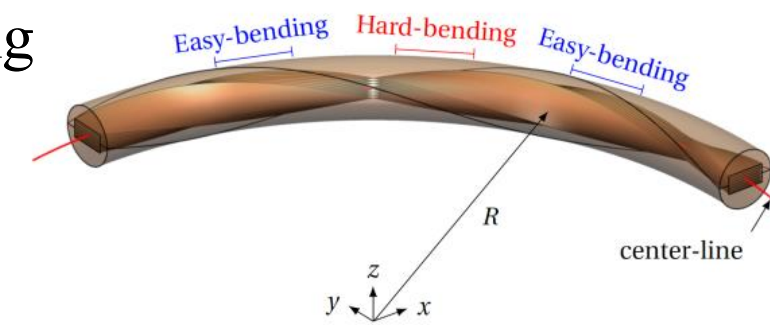
HTS – from tape to cable

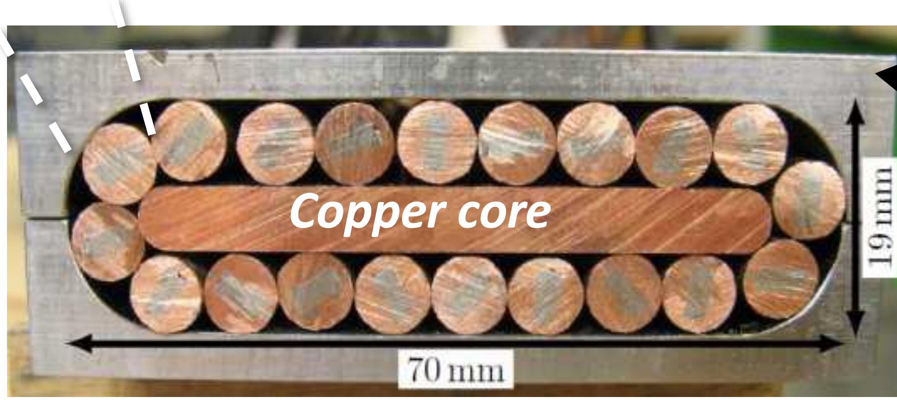






twisting and bending





Jacket

Courtesy of O.Dicuonzo

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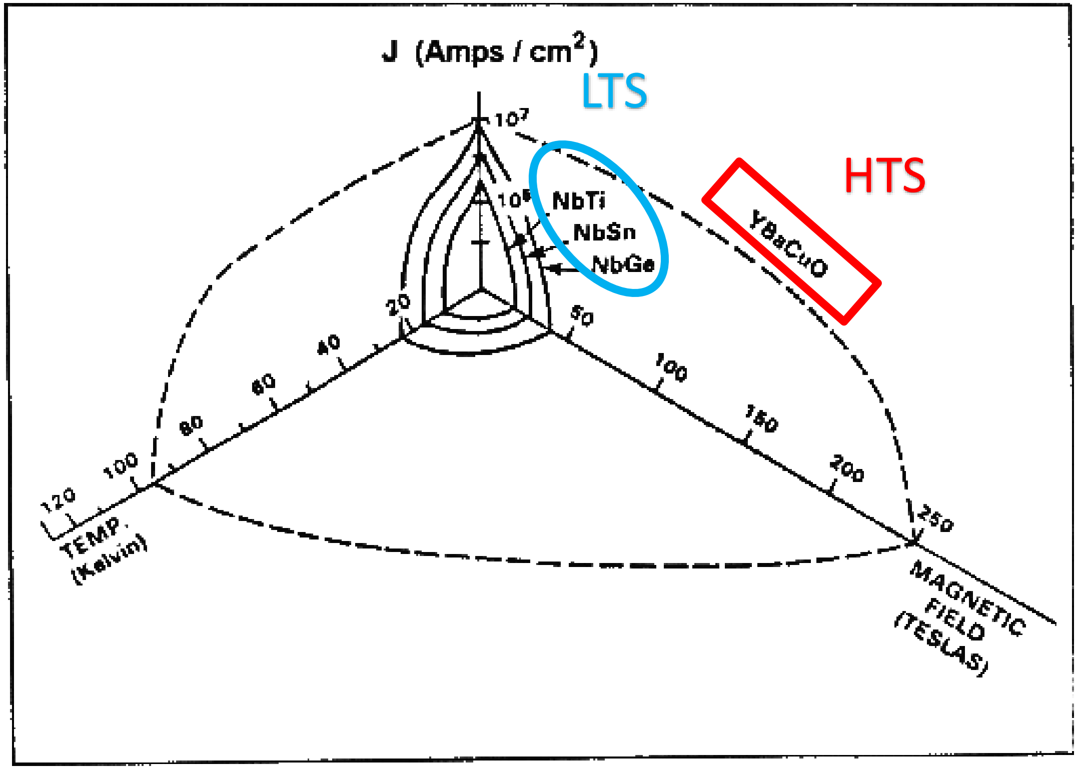
Practical use of HTS

Low B → high temperature

Simpler and cheaper cryogenic systems

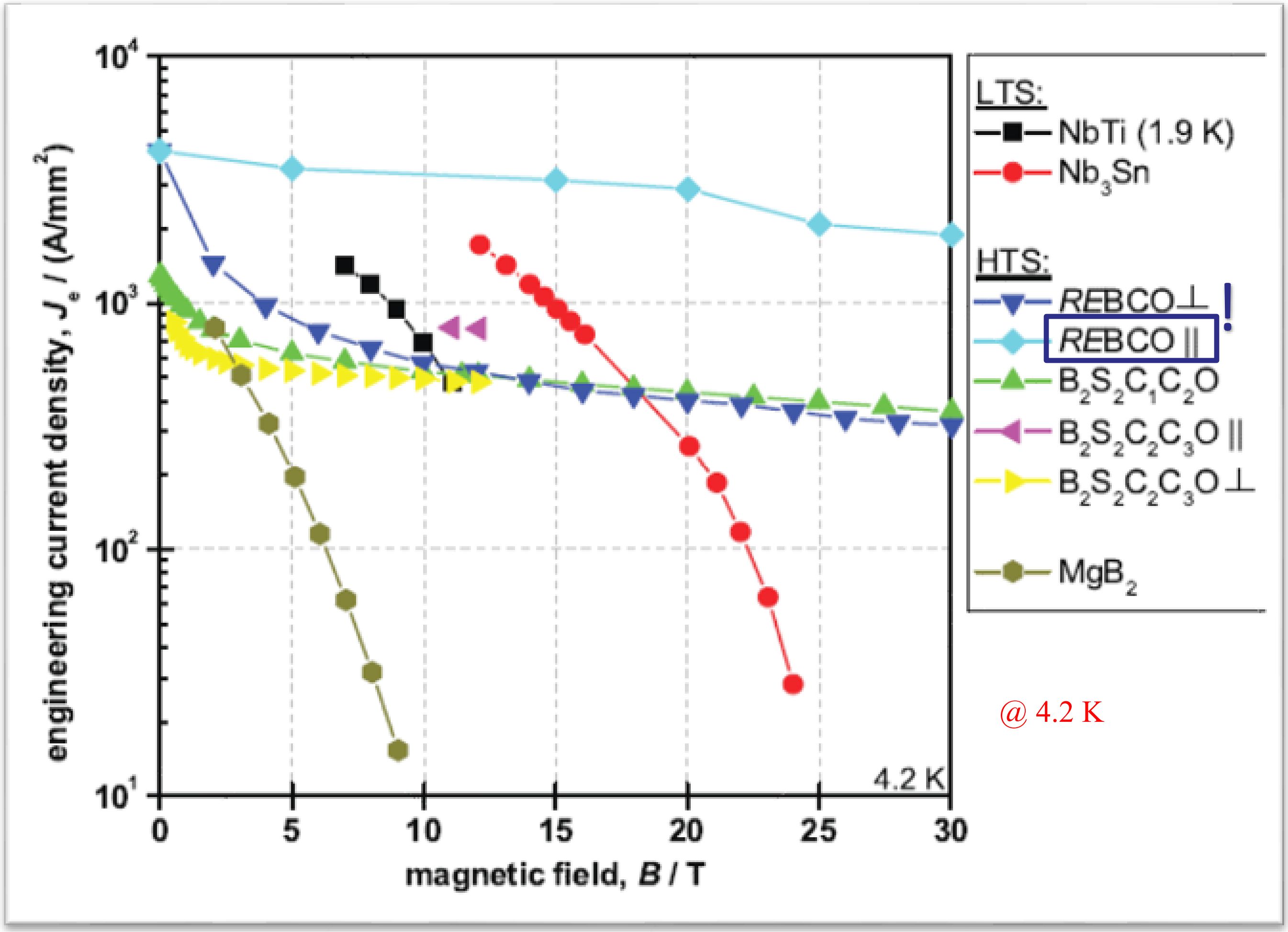
OK for energy transportation



Phase Diagram

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

Which HTS for fusion?



Courtesy of O.Dicuonzo

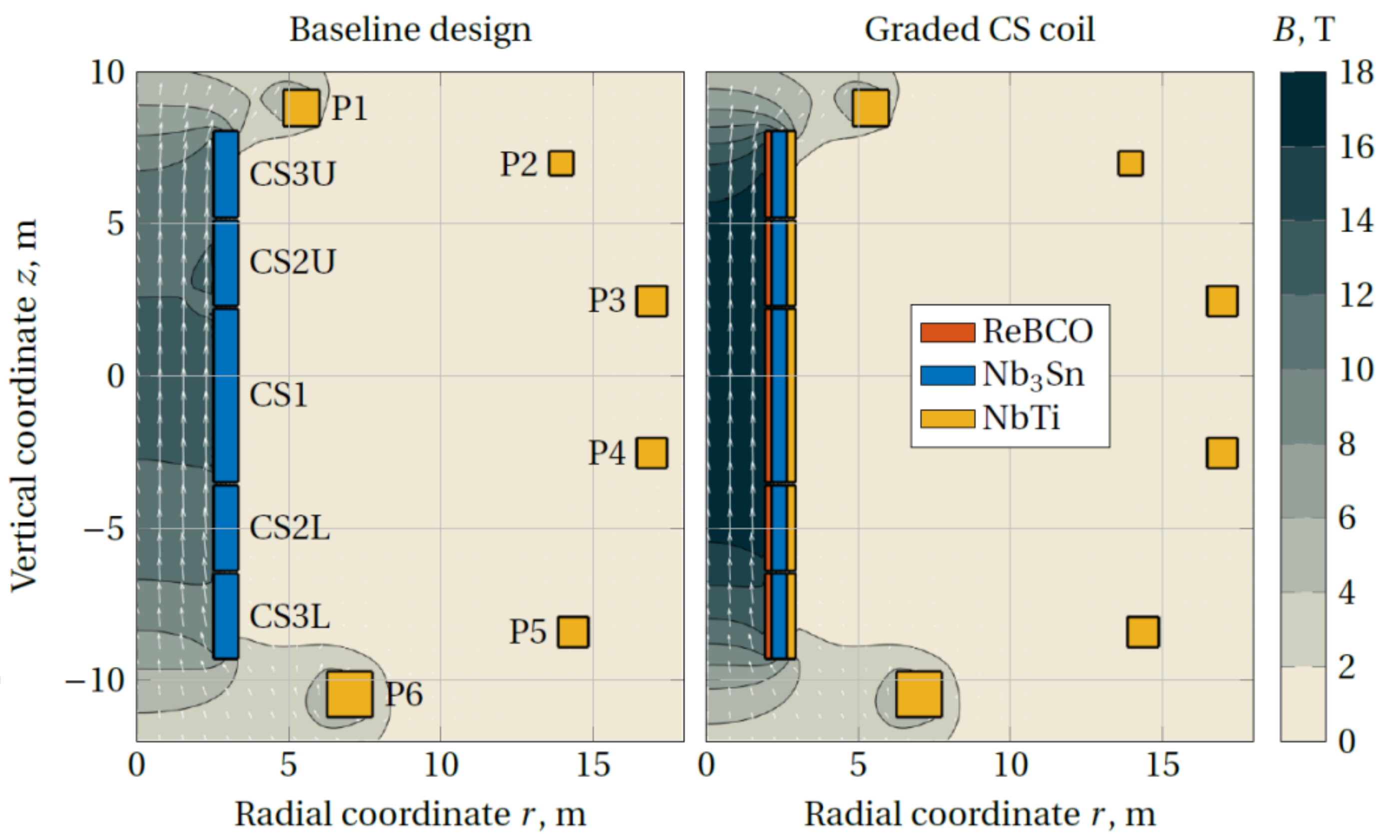
Need high current density at high B → REBCO

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

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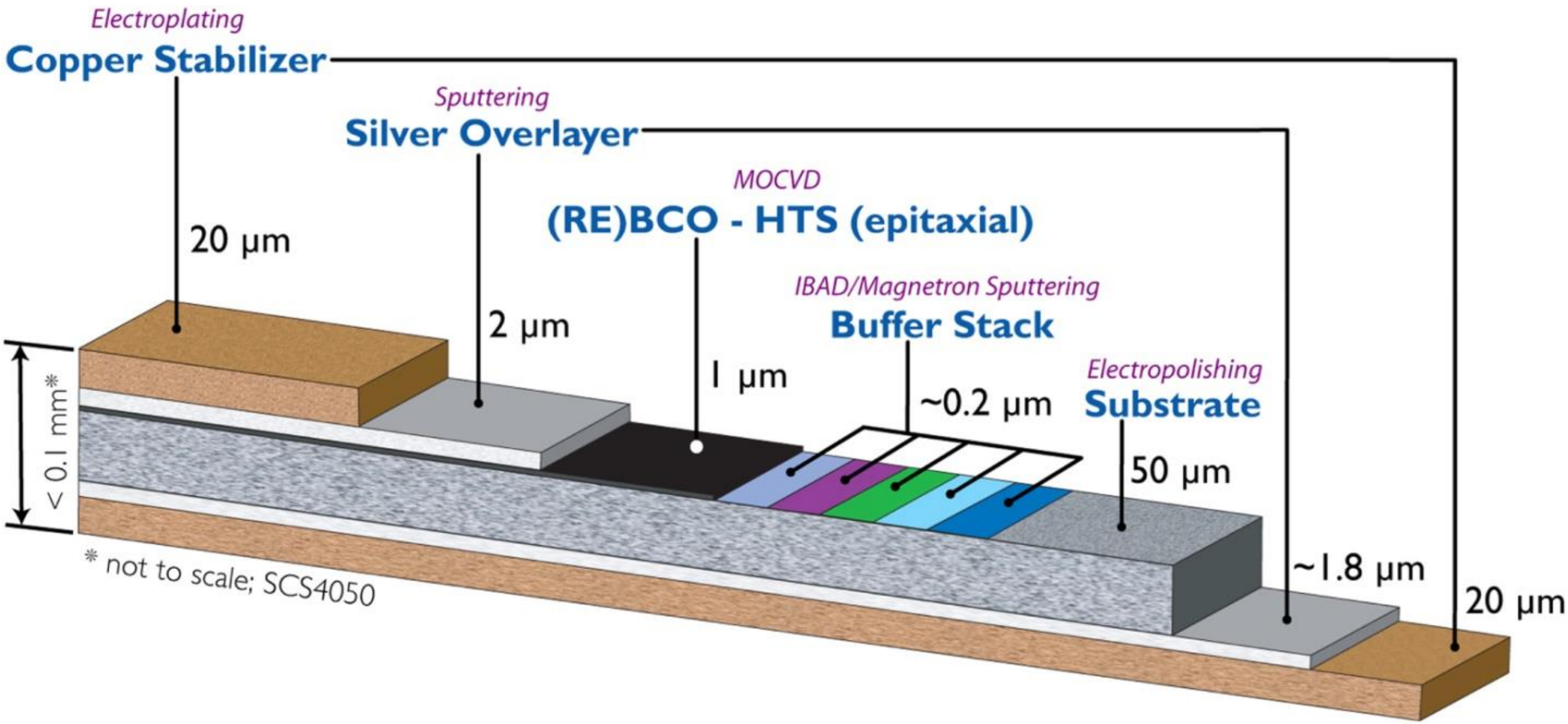
HTS materials for fusion

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



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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

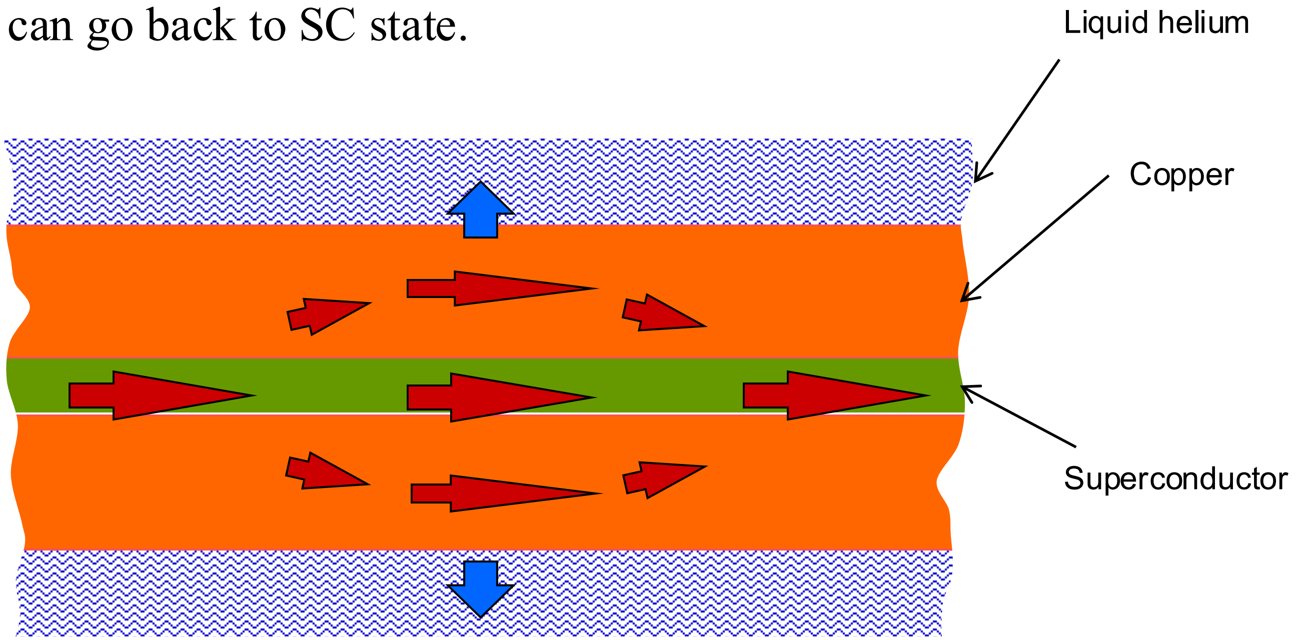
Why do we need copper ?

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 ?

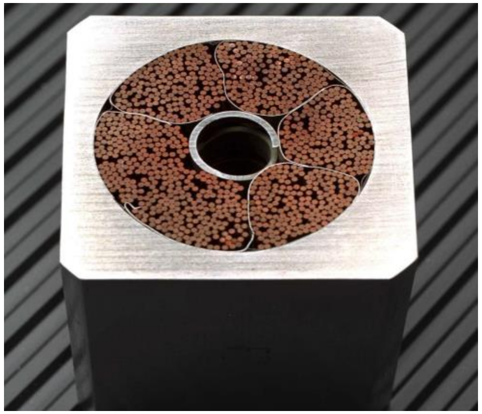
Cu is needed as disturbances may cause a short portion of the SC to become normal. The current then flows in the Cu section, as Cu has lower resistance than non-SC NbTi or Nb_3Sn. If the heat generated is evacuated efficiently, the conductor can go back to SC state.



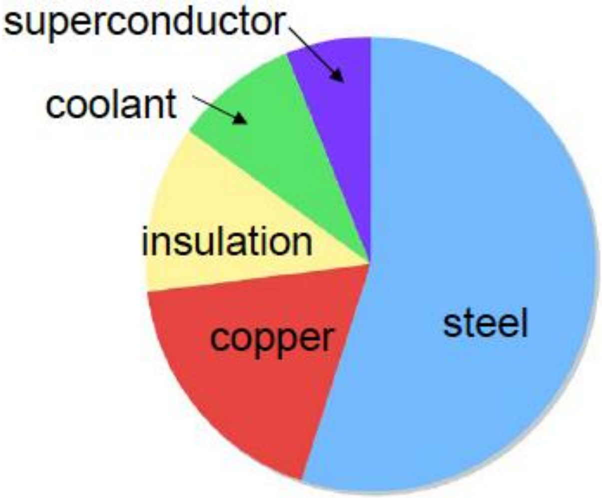
High current cables for fusion magnets

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

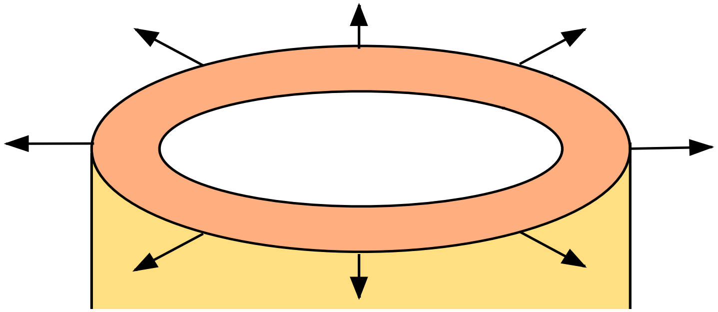


Requirements and challenges - Mechanical

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



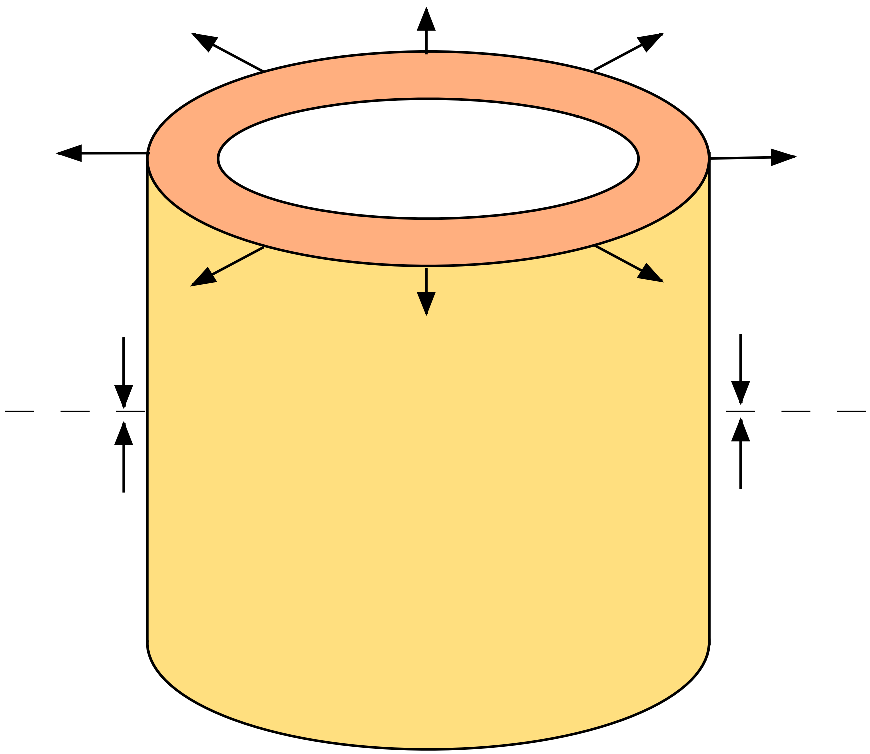
Solenoid

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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- Hoop load along the conductor axis, ~BxIxR
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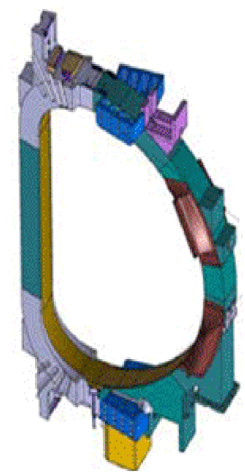
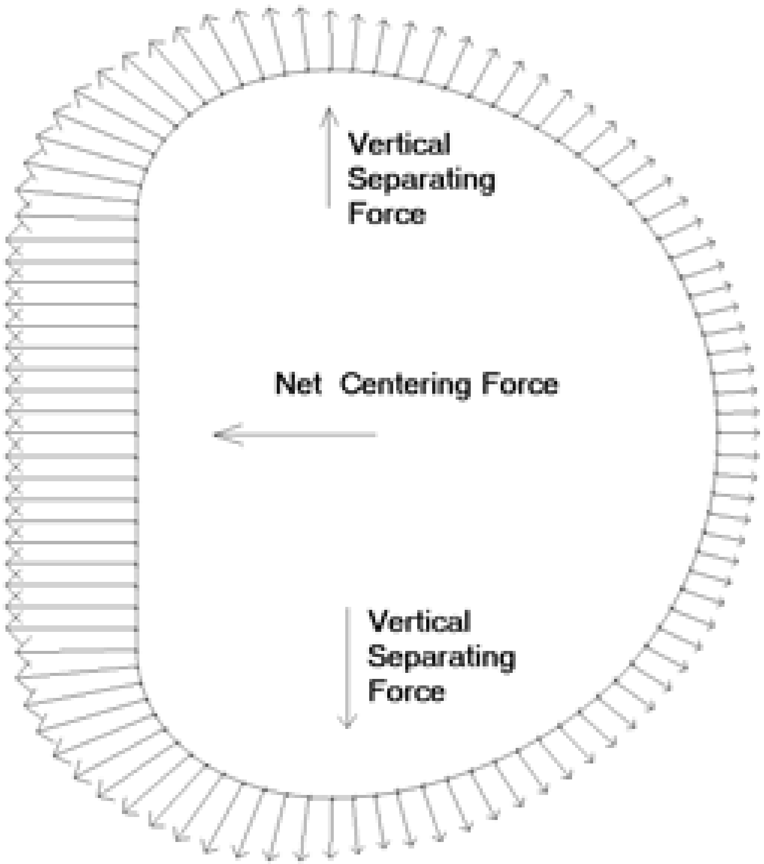
- Centering load on the in-board of non-circular toroidal field coils, ~BxI





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

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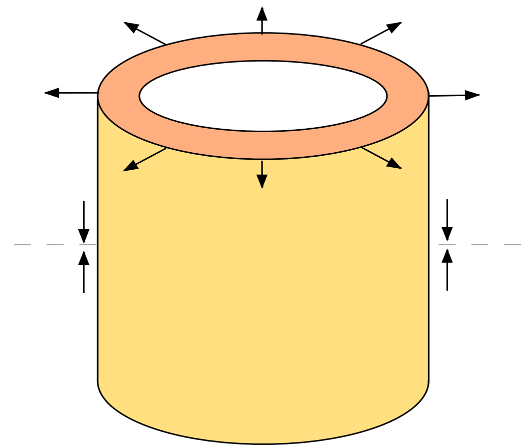
- Centering load on the in-board of non-circular toroidal field coils, ~BxI

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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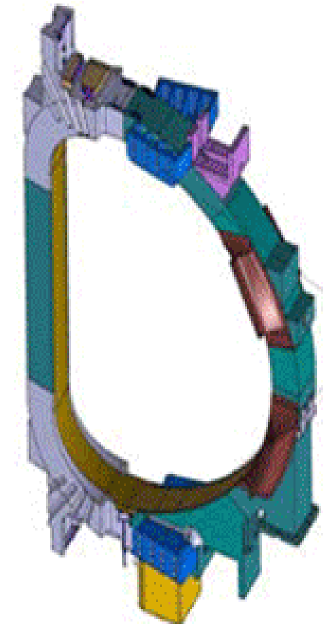

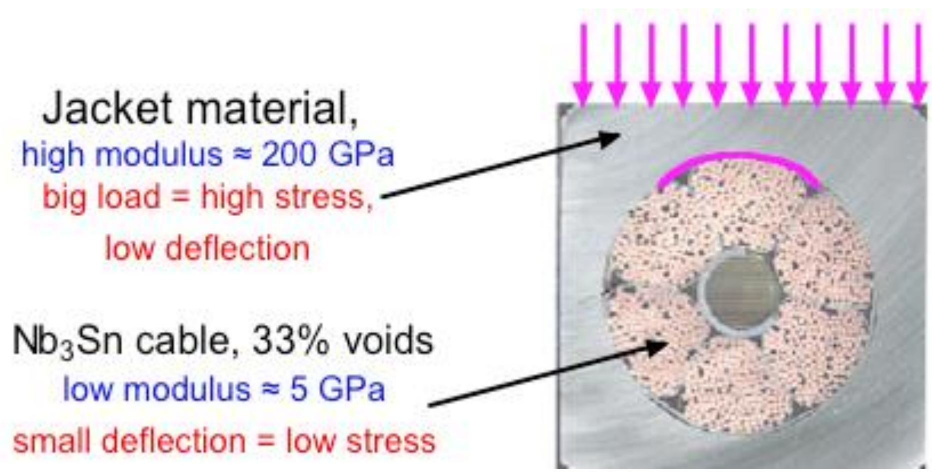

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Requirement and challenges - Thermal

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

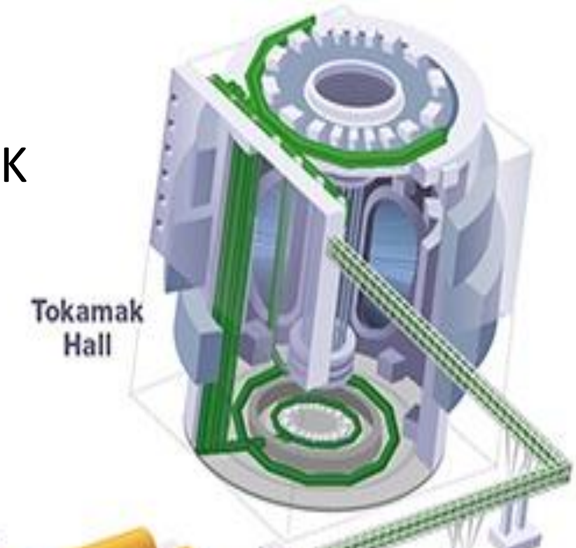
- Nuclear radiation on the TF coils
- Ohmic heating of the conductor joints
- Heat conduction (feeders and gravity support)
- AC losses in the coils
- Pumping losses for He circulation
- Heat radiation from room temperature

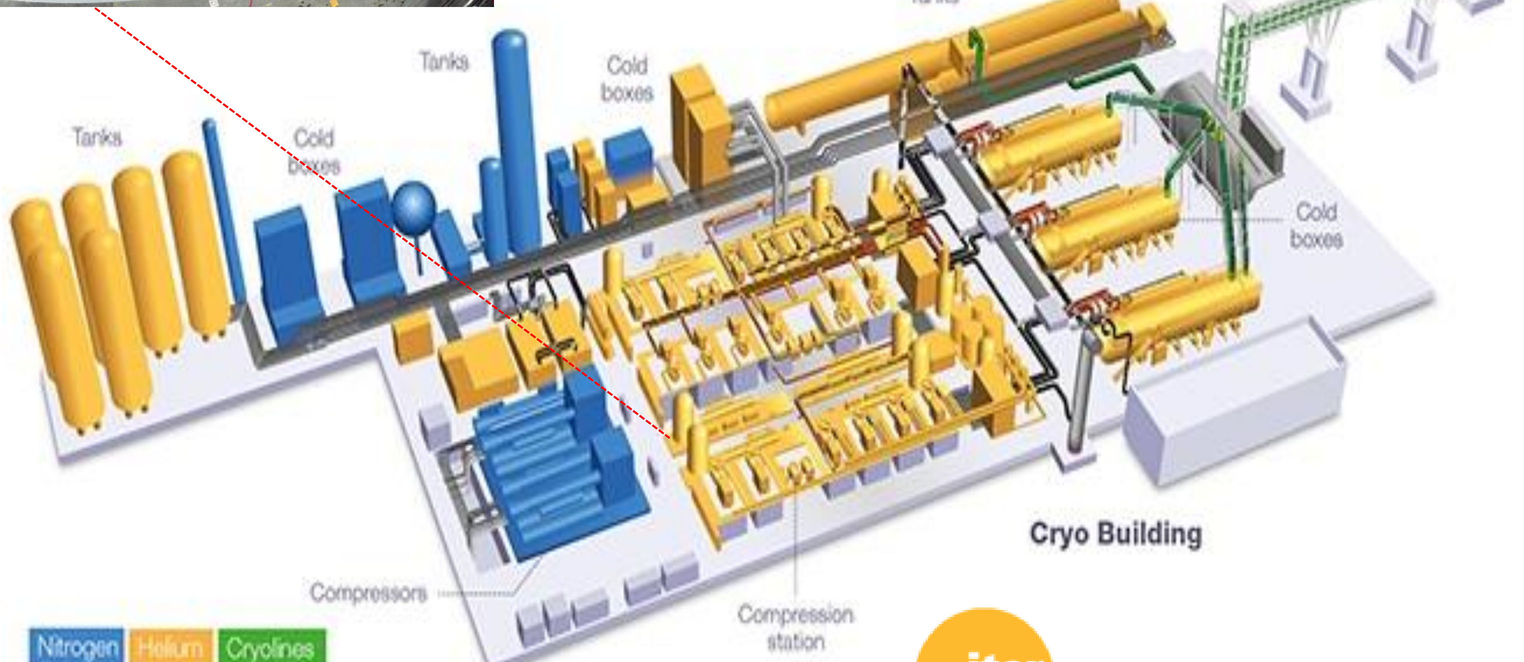
Requirement and challenges - Thermal

ITER

LHe: 75kW at 4.5K

LN_2: 1300kW at 80 K





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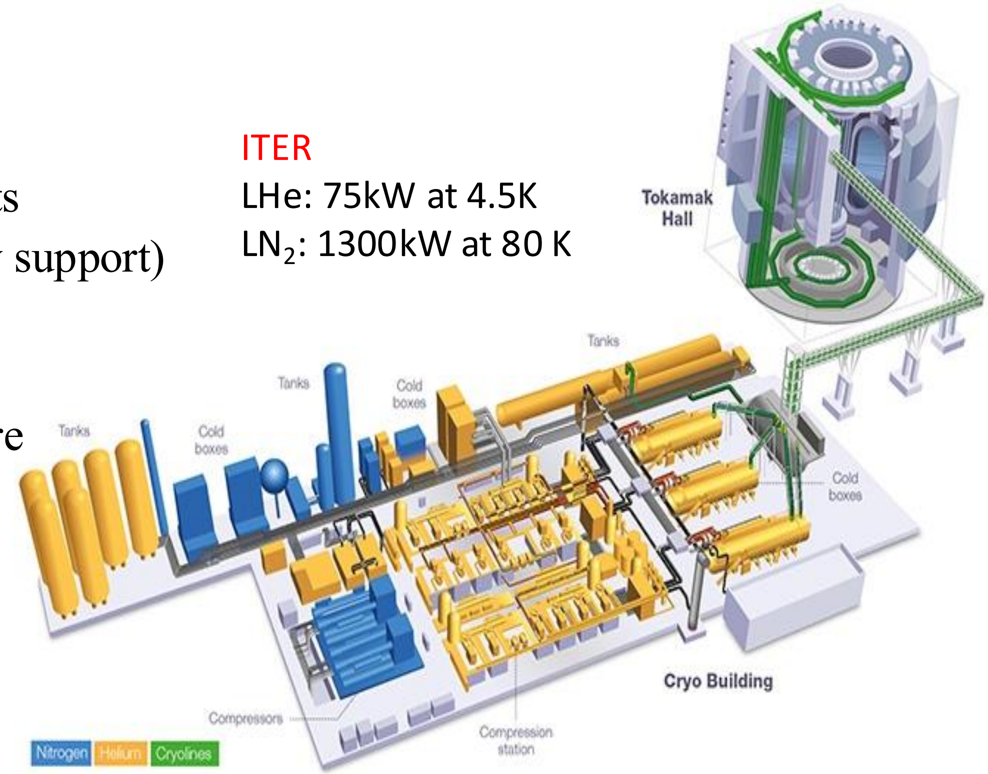
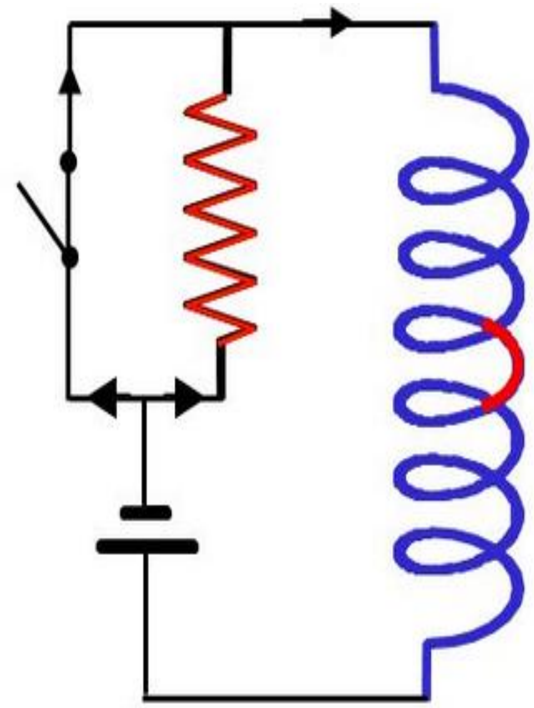


The variation of the operating temperature must be kept within a temperature margin of ~1-2 K

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

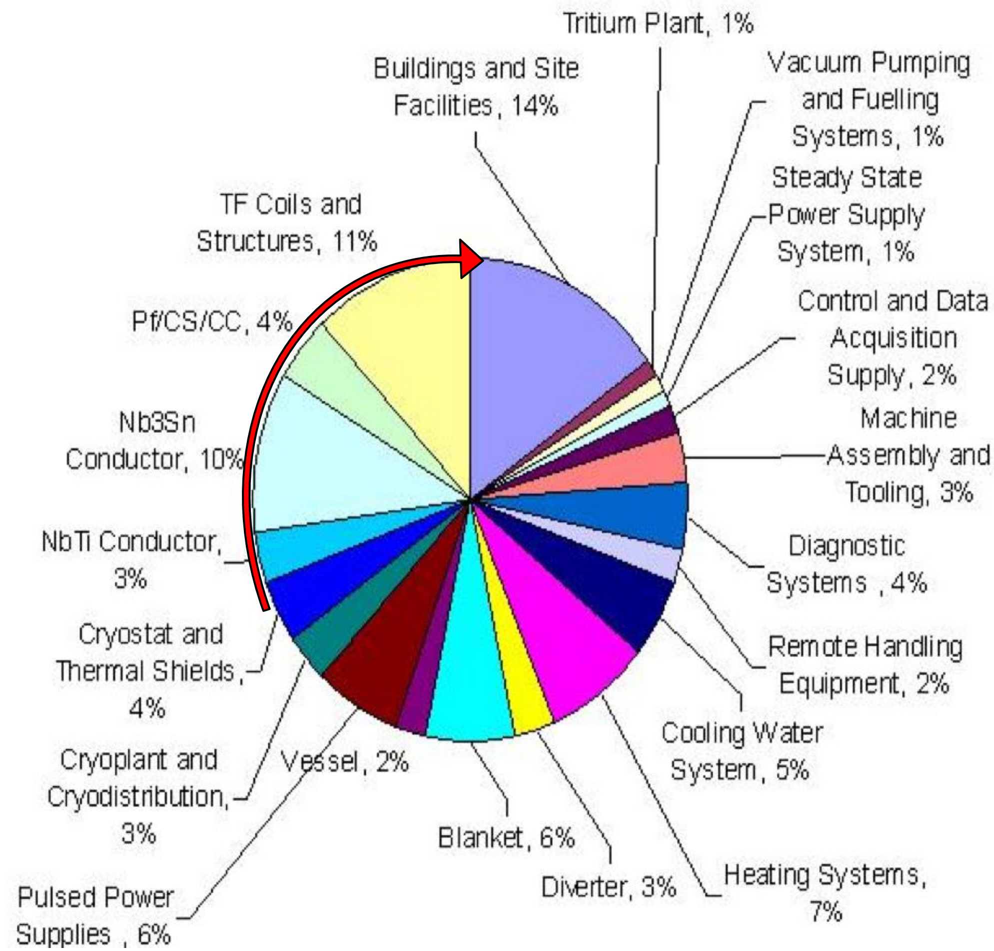
In fusion magnets, electrical insulation consists of Glass-Kapton wraps impregnated by epoxy. The quality of the impregnation is crucial for the coil mechanical integrity and to prevent flashovers to ground during the fast discharge

Requirement and challenges - Economical

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

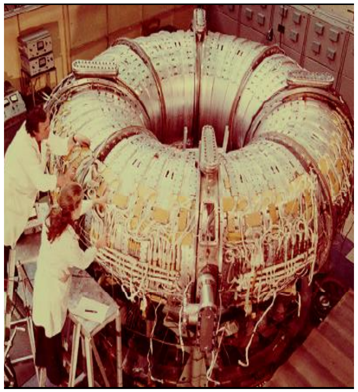
SC magnets make up a substantial fraction of the capital cost for a large fusion device, 30% for ITER

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



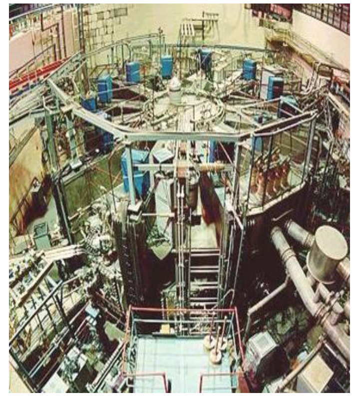
Present fusion devices with sc coils

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

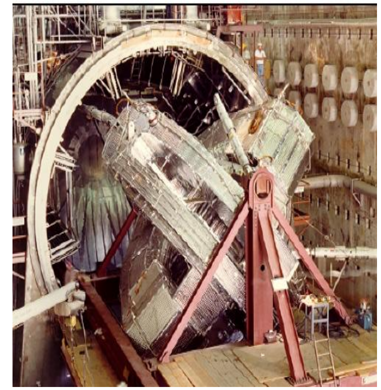


WEST at CEA -2017
NbTi, He bath, 9T

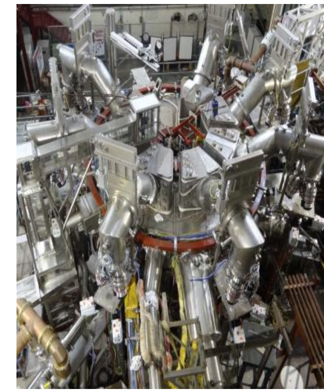
T 15 at Kurchatov -1983
Nb_3Sn, He forced flow, 9.3T



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

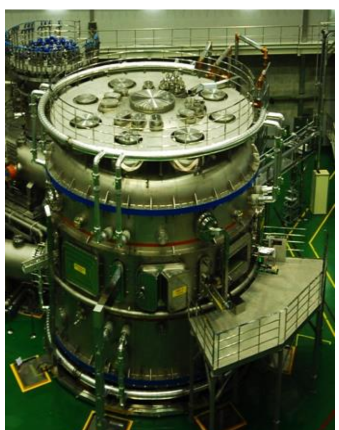


SST1 Bath - 2013
NbTi, He forced flow, 5T



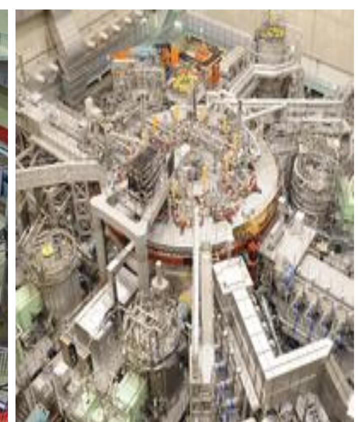
TRIAM Fukuoka -1986
Nb_3Sn, He bath, 11T

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

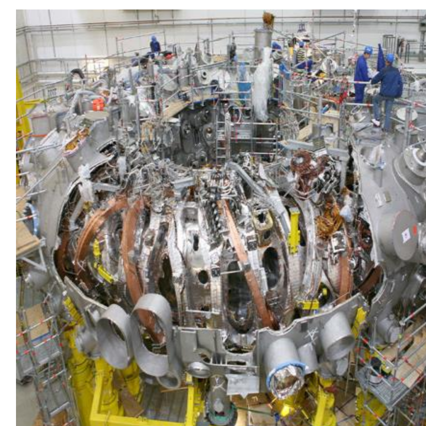


EAST Hefei - 2006
NbTi, He forced flow, 5.8T

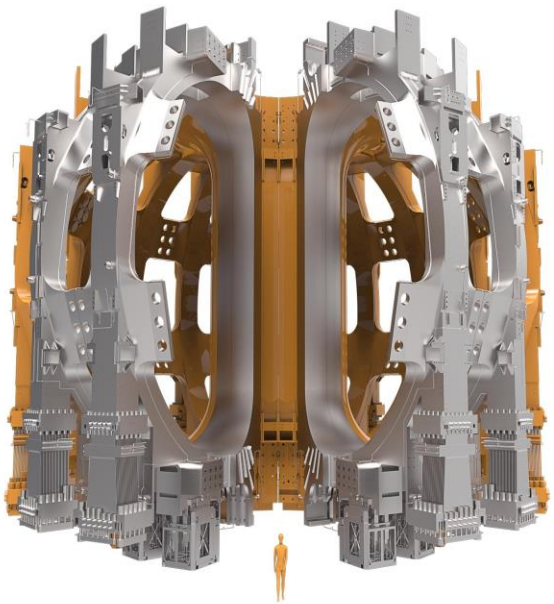
LHD Toki - 1996
NbTi, He bath, 6.9T



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

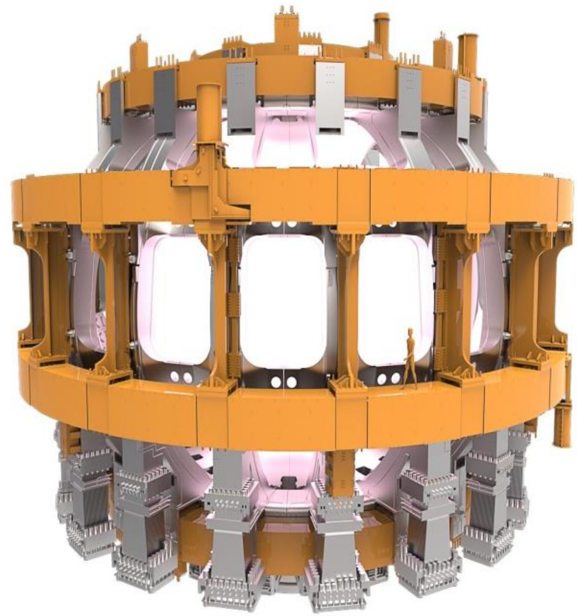


ITER magnets system – the largest ever built

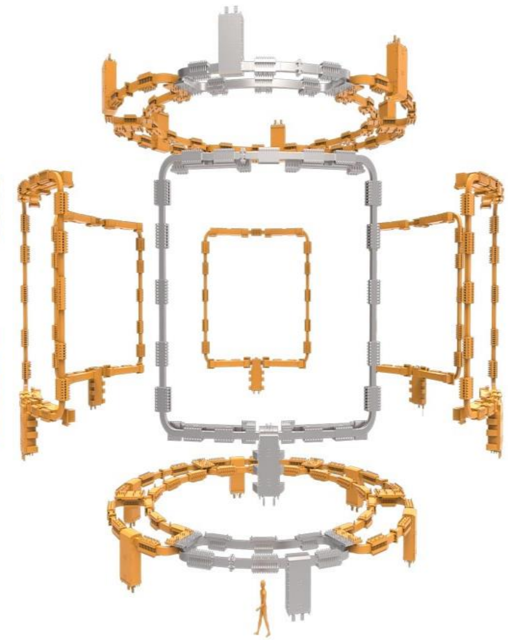


TF coils
Nb_3Sn, 11.8T

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

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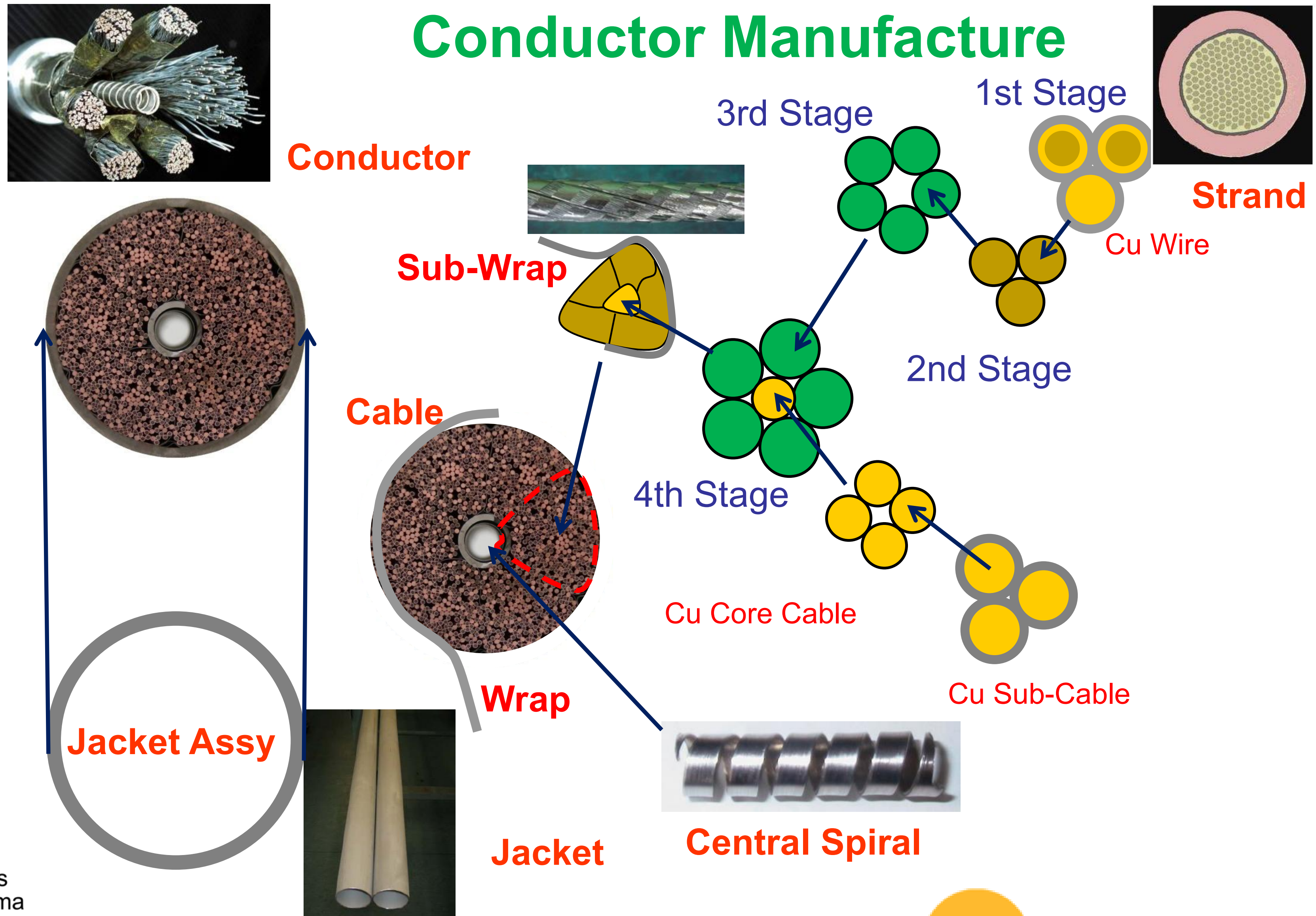
iter china eu india japan korea russia usa

ITER magnets system – construction



ITER magnets system – TF coils

Toroidal Field coils
winding pack in ASG – La Spezia

EPFL

ITER magnets system – TF coils

Transporting one Toroidal Field coil

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

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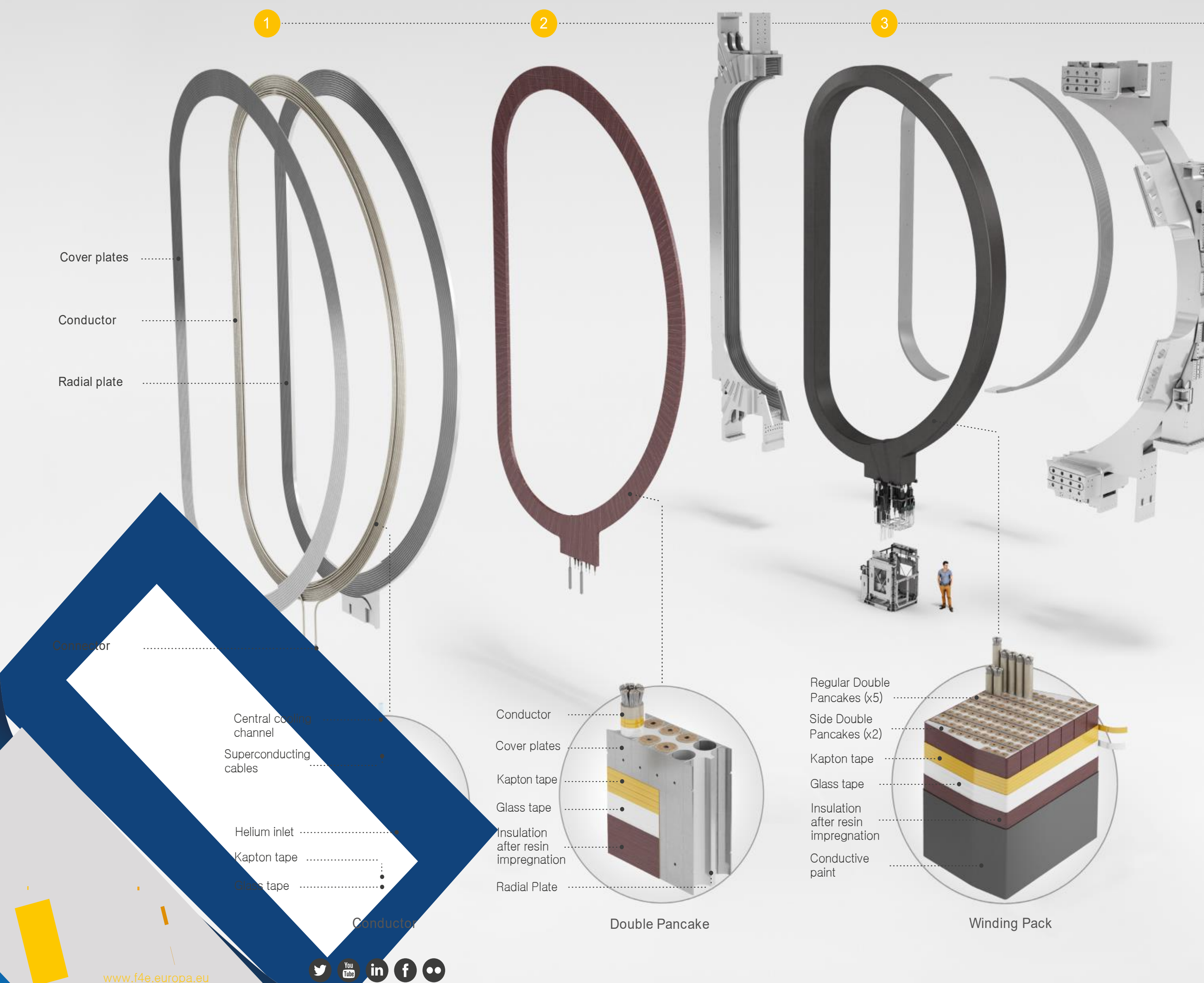
ITER Toroidal Field Coils

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

ITER magnets – installation of 6th PF coil

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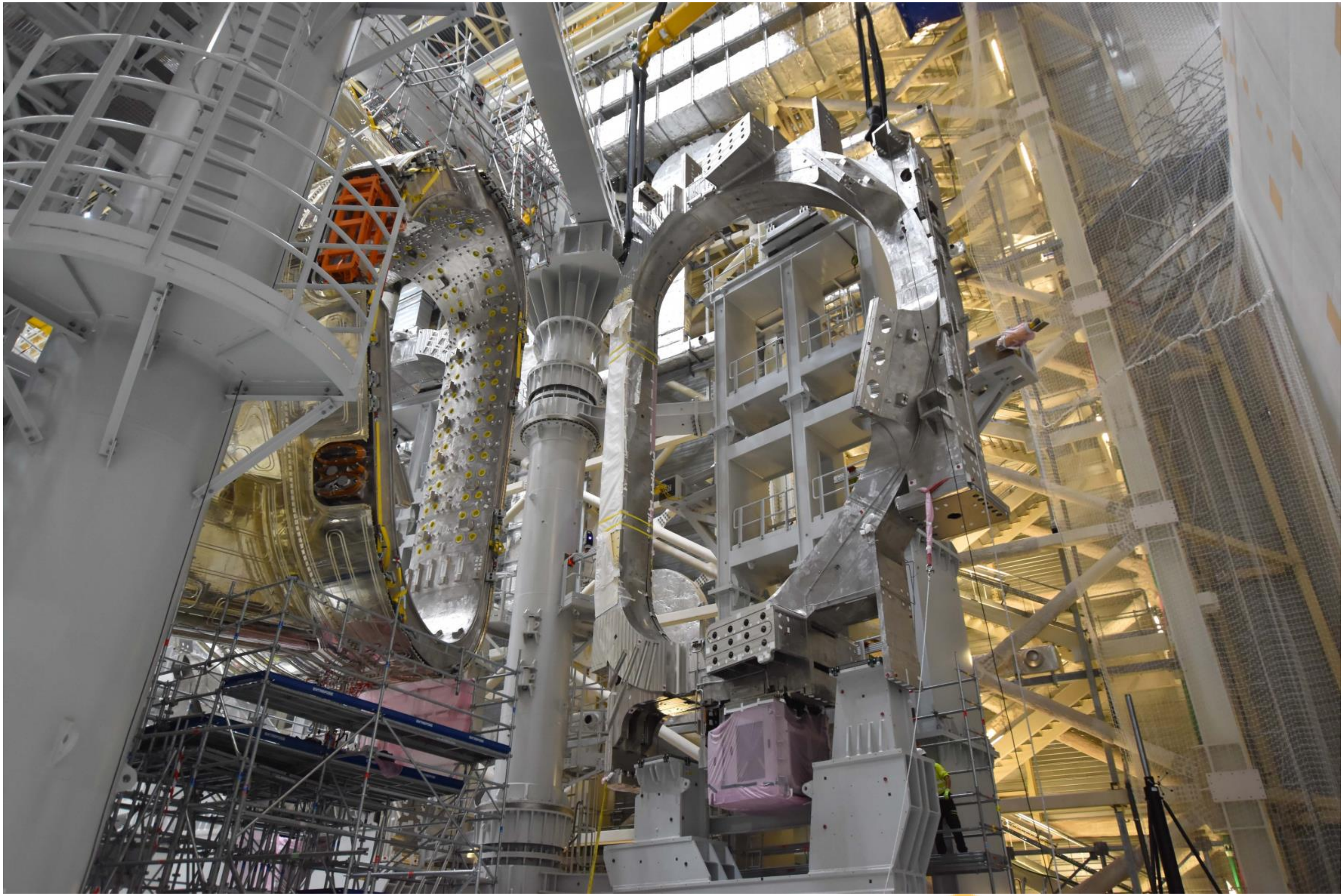
ITER magnets – installation of 1/18 TF coils with 1/9 of vacuum vessel



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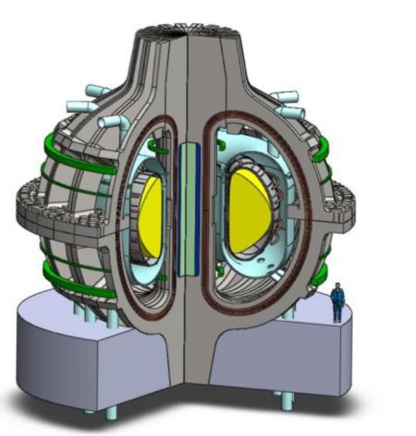
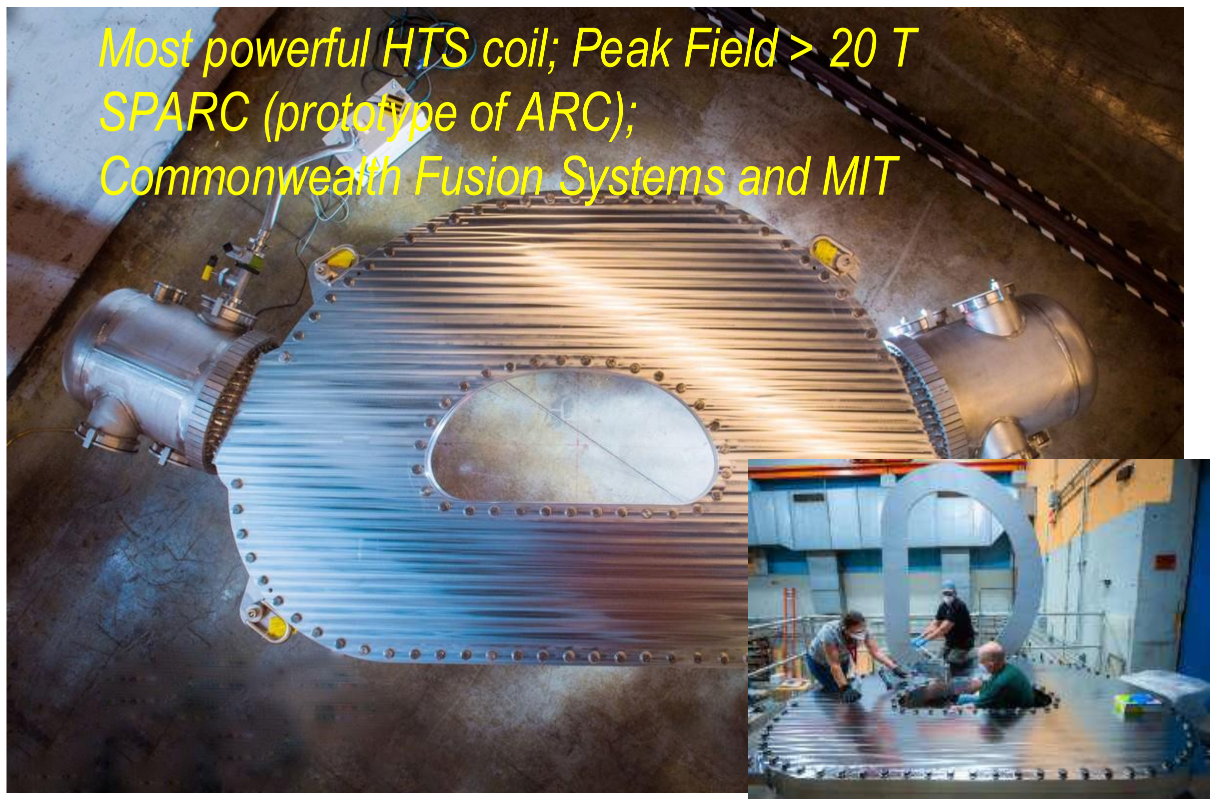
ITER magnets system – the cryostat

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

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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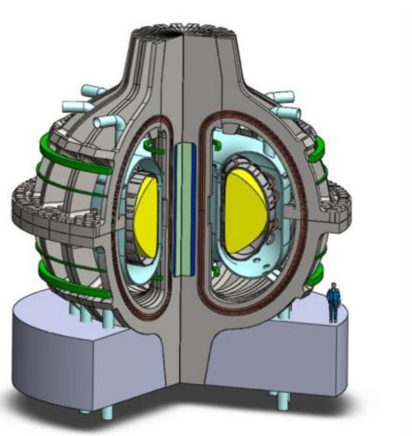

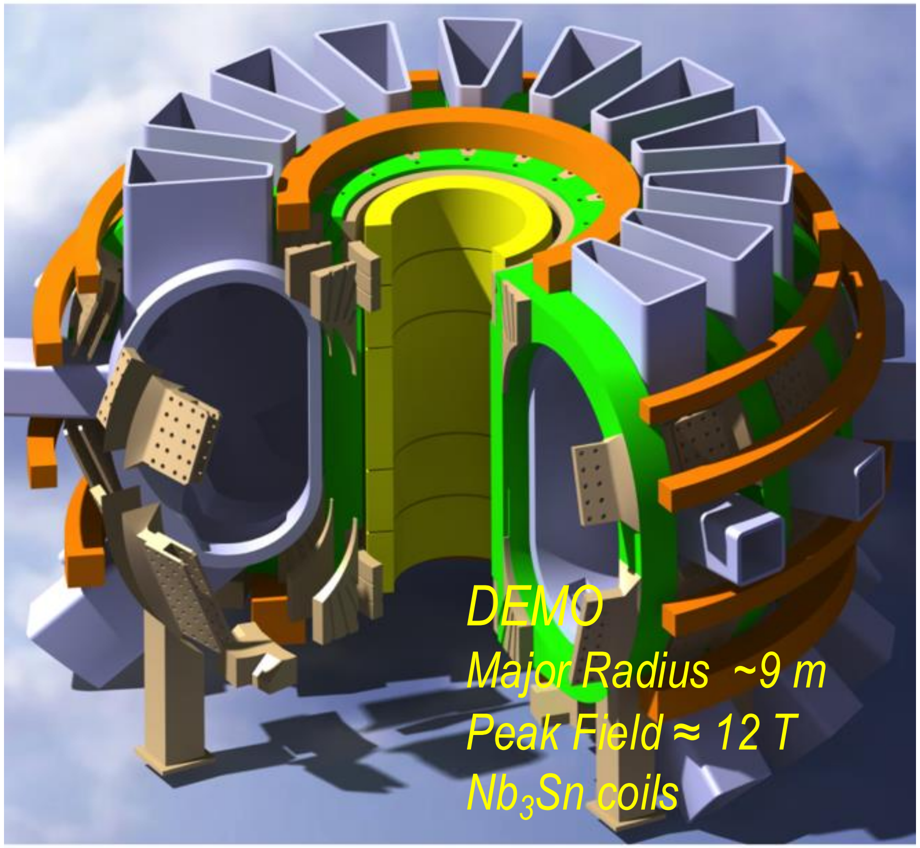

Summary

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

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Testing of Superconductors for Fusion

Kamil Sedlak

Dec 1, 2025

SWISS PLASMA CENTER

Our Test Facilities

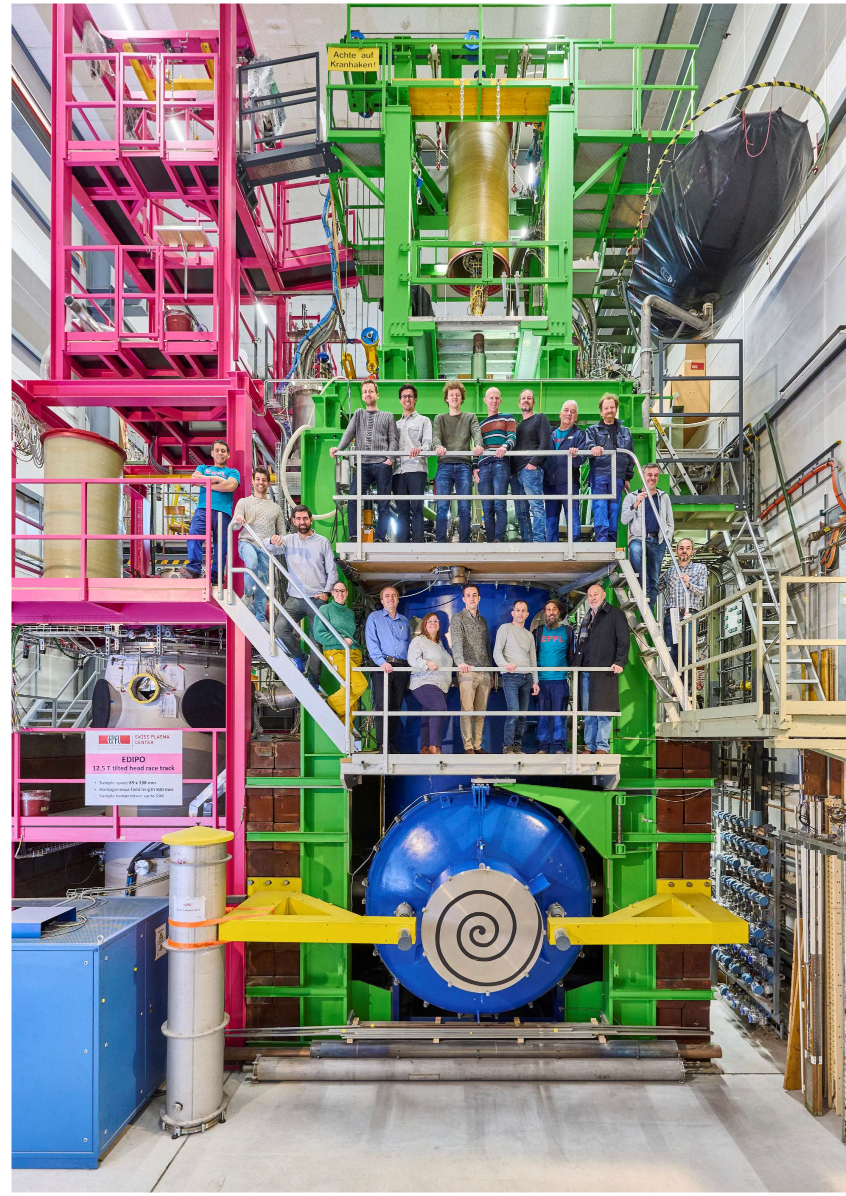
- Testing of superconductors for fusion magnets, i.e. tokamaks and stellarators:
  - Sample assembly
  - Sample testing

SULTAN (“**SU**pra**L**eitende **T**est **ANL**age”) (11T)

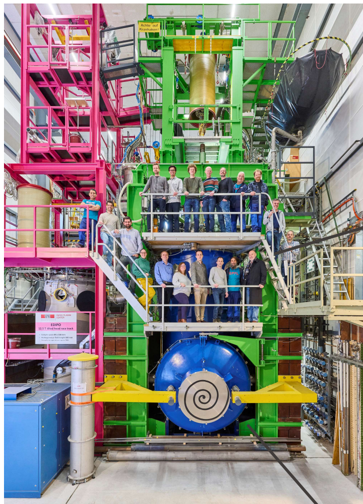
- our work-horse, build in 80s, and still the only facility worldwide, where ITER-like conductors can be tested in real operating conditions.

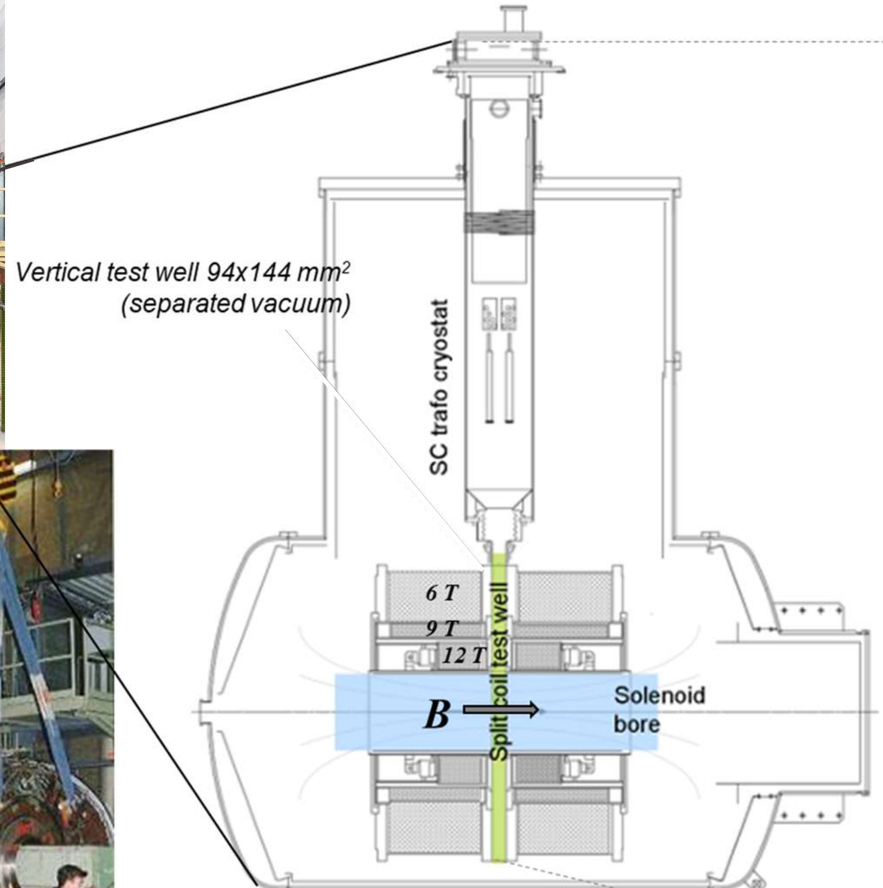
EDIPO (“**E**uropean **DIPO**le”) (15T)

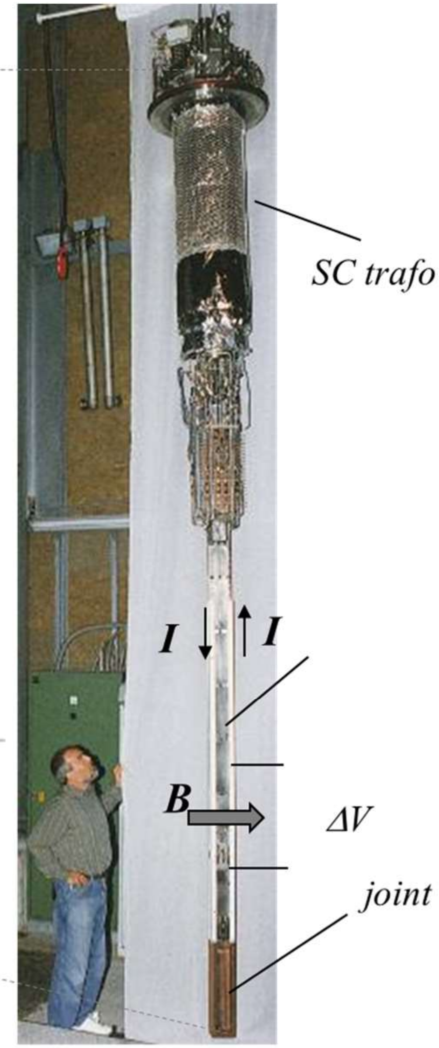
- a facility that shall become even more powerful than SULTAN. (Under construction.)



SULTAN Test Facility – DC Field up to 10.9 T







Magnet and sample cooled by forced flow of supercritical He (4.5 K- 20 K)

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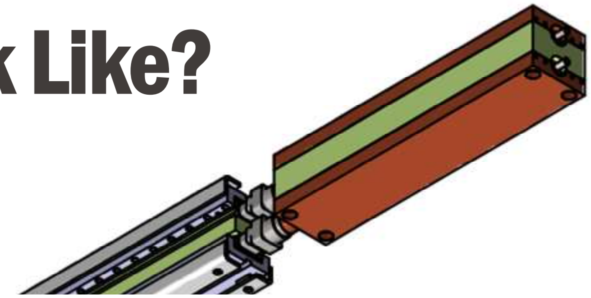
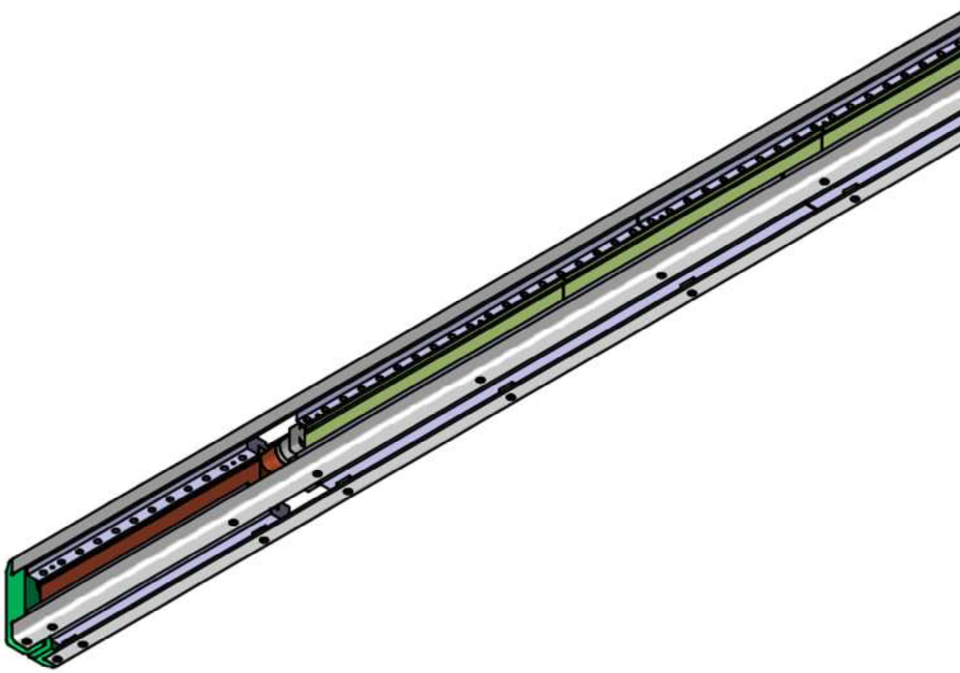
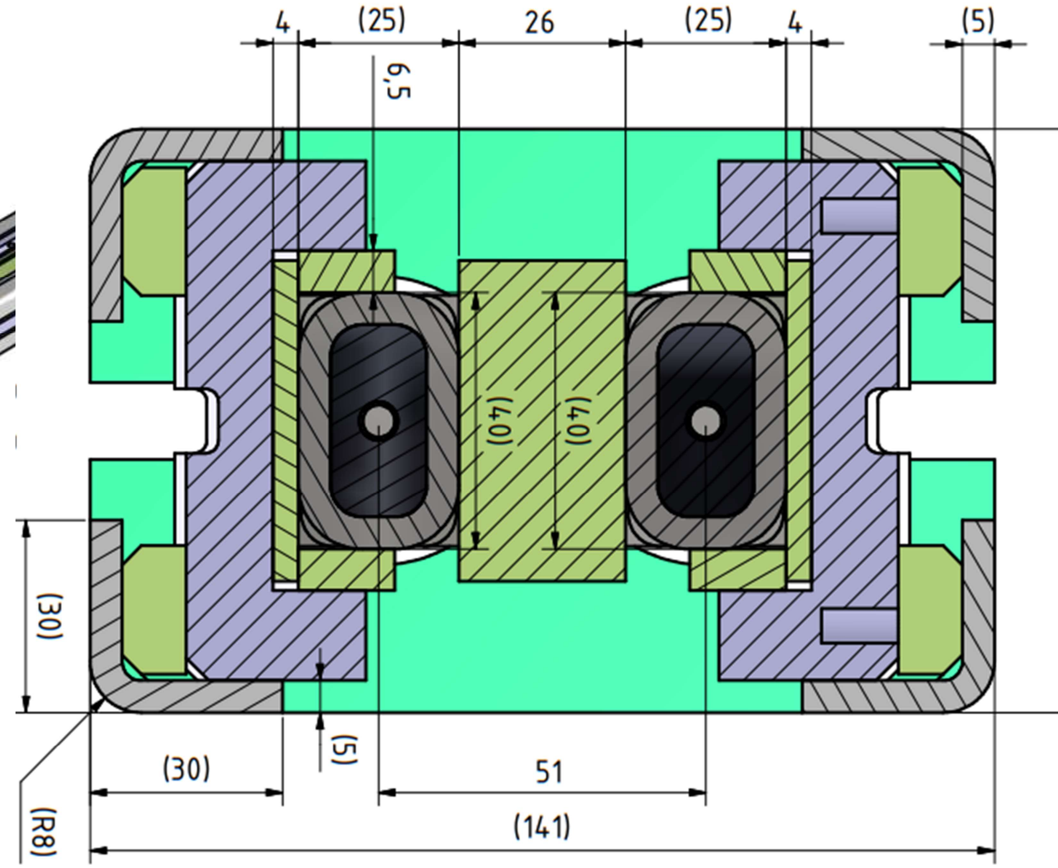
Preparation of a SULTAN Sample

How Does the SULTAN Sample Look Like?







Conductor Lengths delivery at SPC Villigen

- A box with a superconductor shiped to Villigen from China, Korea, Japan, USA, Europe, ...

- Example conductors – ITER Central Solenoid

Removal of the Steel Jacket at the Terminations

Kamil Sedlak

- Milling of the steel jacket in the termination region.

- Removal of the steel jacket (ITER Toroidal Field conductor)

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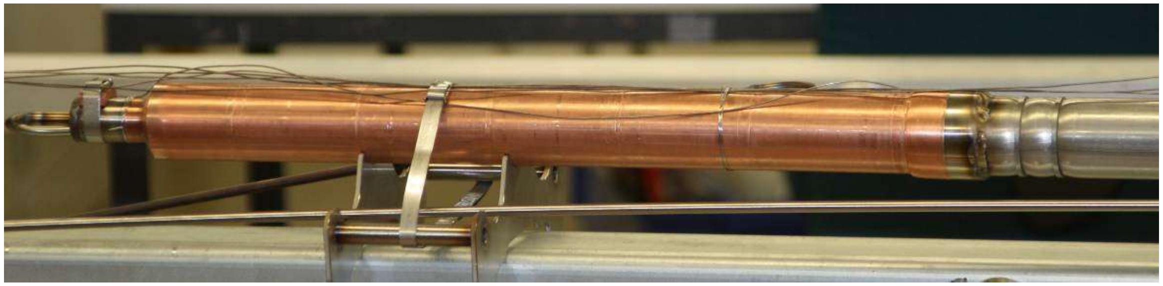
Chemical Removal of Cr Plating

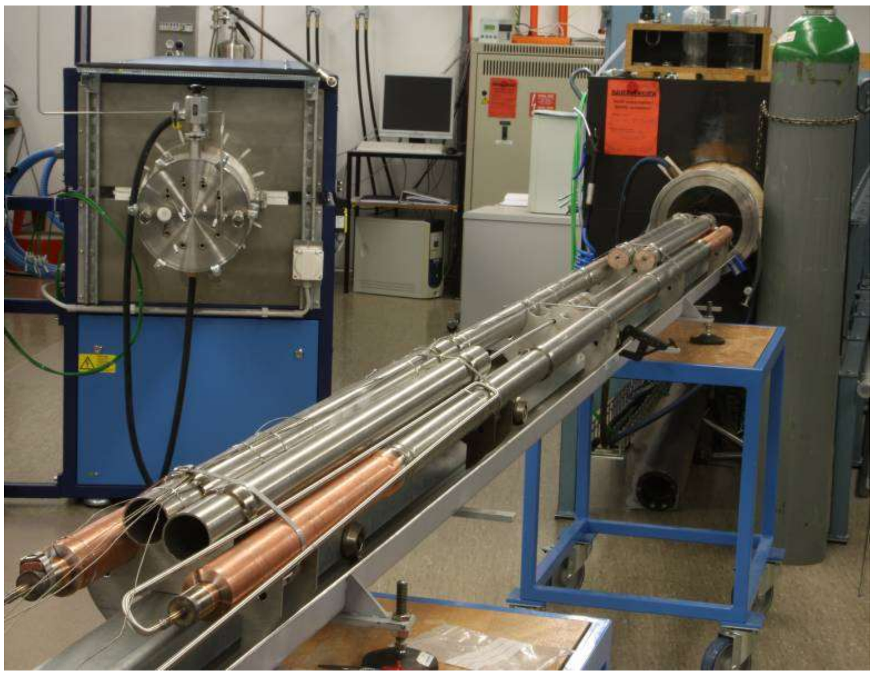
- Chemical removal of Cr plating from the surface of superconducting (Nb_3Sn) strands.

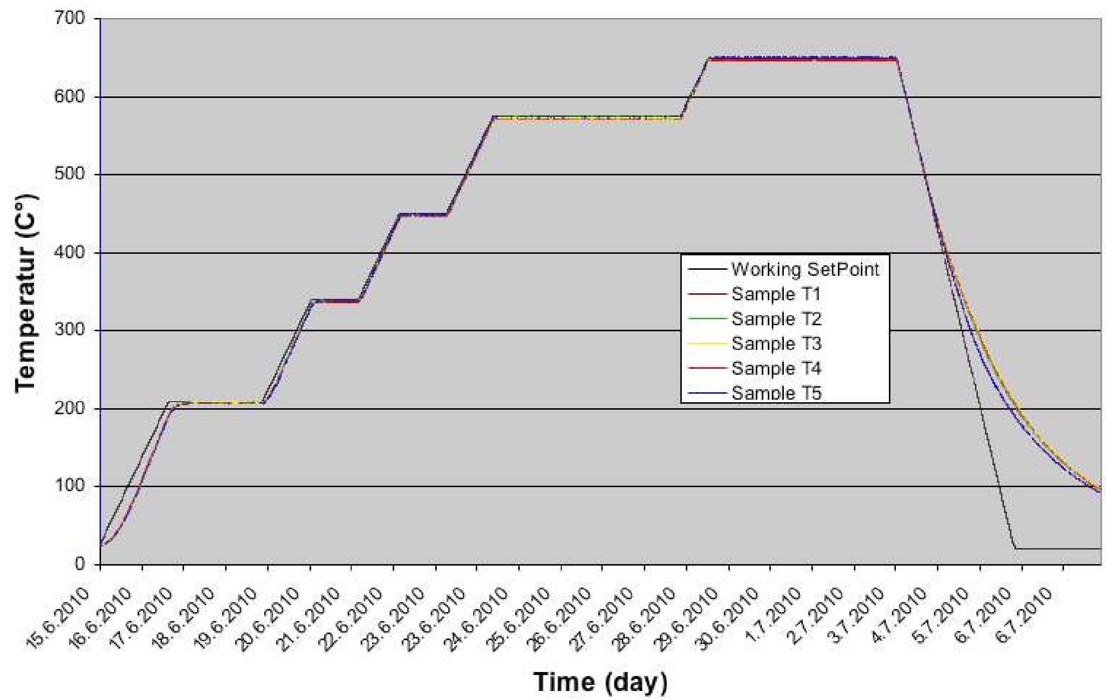
Insertion of the Cable Terminations into Copper Sleeves



- Installation of Copper sleeve at the conductor terminal

Heat Treatment (only for Nb_3Sn)



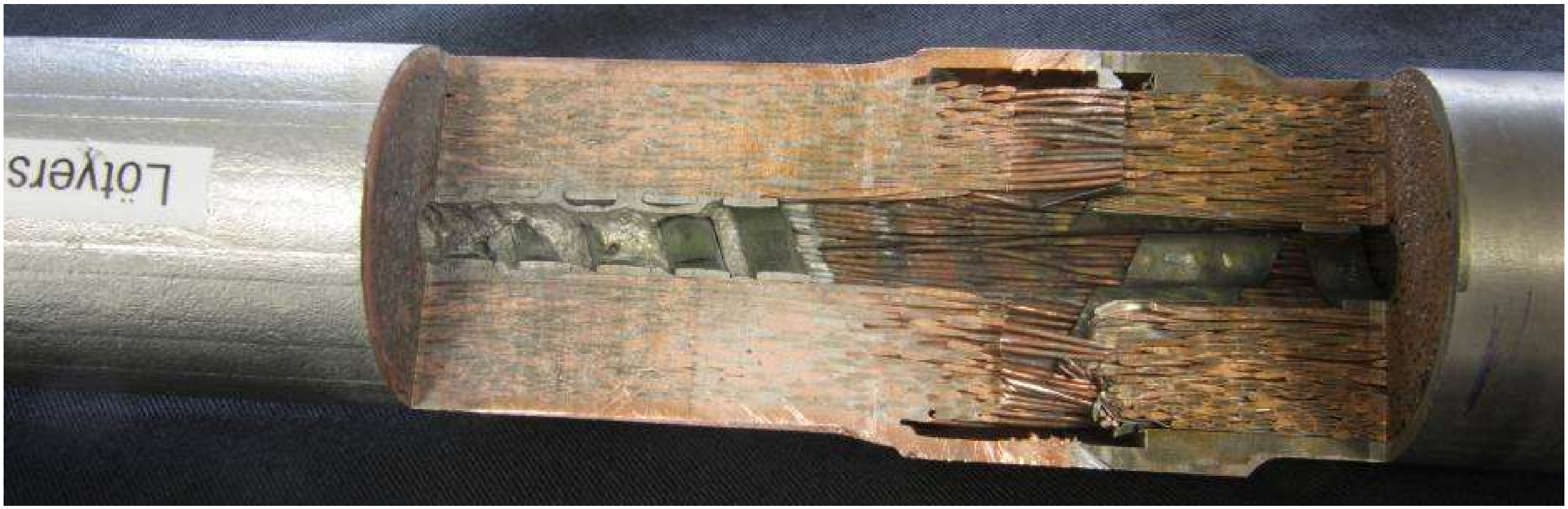


- Heat treatment in steps up to 650°C
- Total duration 3-4 weeks

Solder Filling of the Terminations

- Filling the termination region by a solder for as low as possible electrical resistance of the sample termination.

Solder-Filled Termination

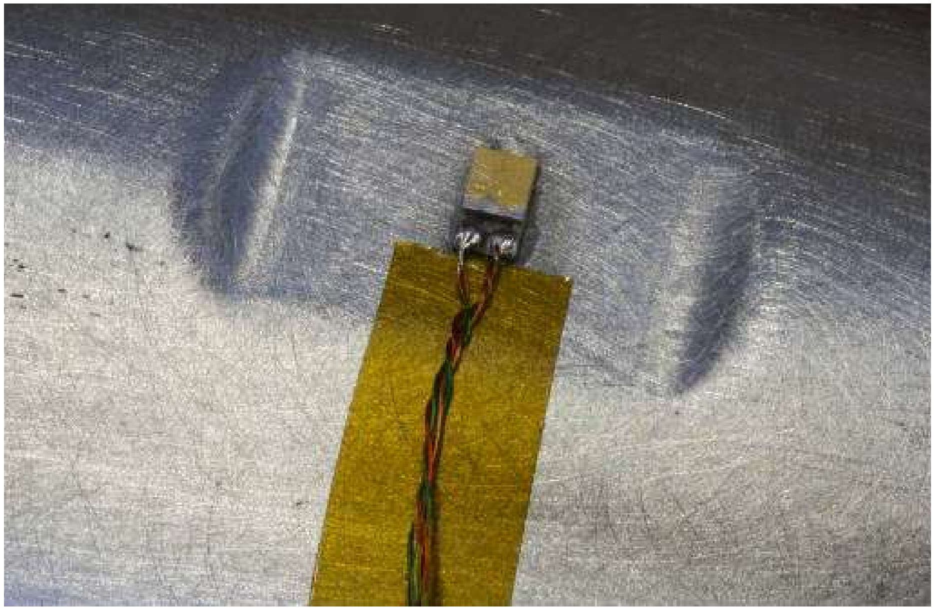


- Section of a solder filled termination

Attaching Copper Blocks to the Terminations

- Upper termination soldered into a copper block. Upper termination will be later connected to current source (superconducting transformer)
- Bottom joint, where current must pass from one conductor to the neighboring one

Instrumentations – Voltage Taps and Temp. Sensors



- Spot-welded **voltage taps**. By measuring the voltage over the 50 cm of the conductor (over the high-magnetic field region of SULTAN) we can determine when the superconductor switches to normal state.

- Temperature Sensor CERNOX ($3x3mm^2$) measures precisely the temperature.

Is it OK to measure the voltage and temp. on the surface of the steel jacket?

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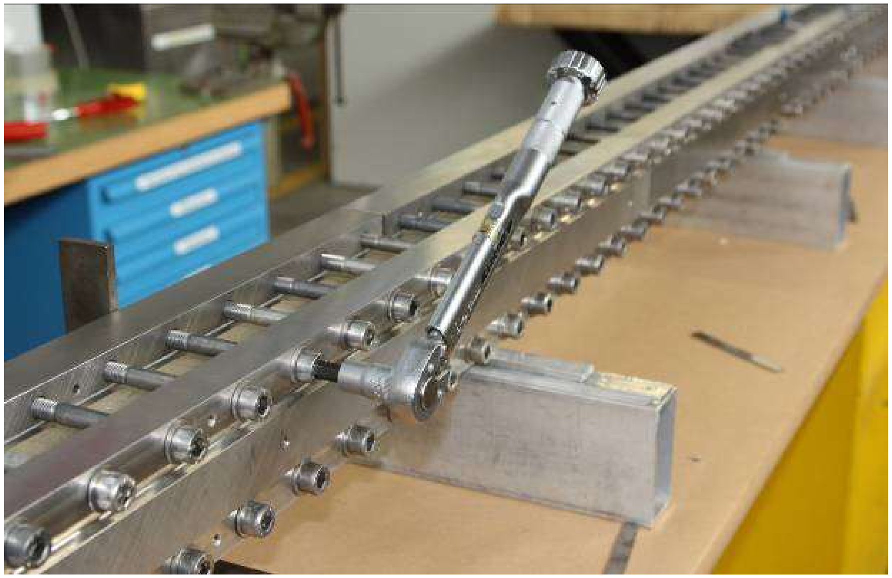
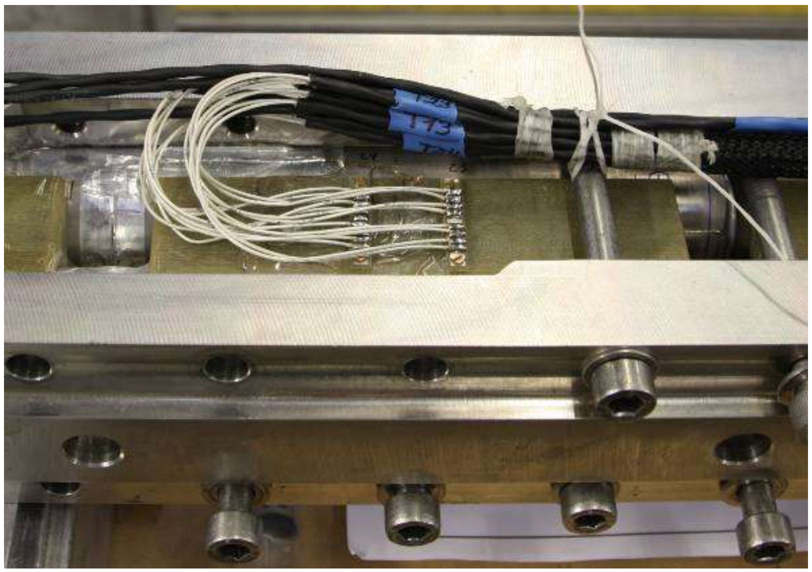
Lorentz Force between the Two Legs

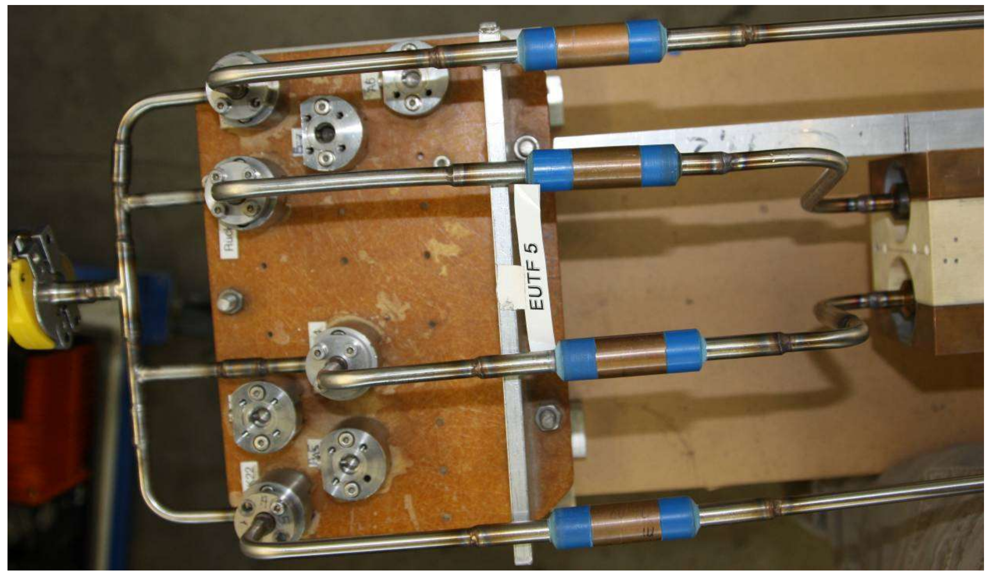


- The two sample legs must be hold together by clamps to withstand the Lorentz force between the conductors:
- F = 11T * 68kA * 0.5m = 374 kN

… an equivalent of a fully loaded (37.4 ton) semi-truck

Attaching Readout Wires and He Cooling Pipes





- Instrumentation wires

- Cooling pipes for supercritical Helium

Sample Ready for the Test in SULTAN

It takes 2-3 months to manufacture a SULTAN sample.

Testing in SULTAN

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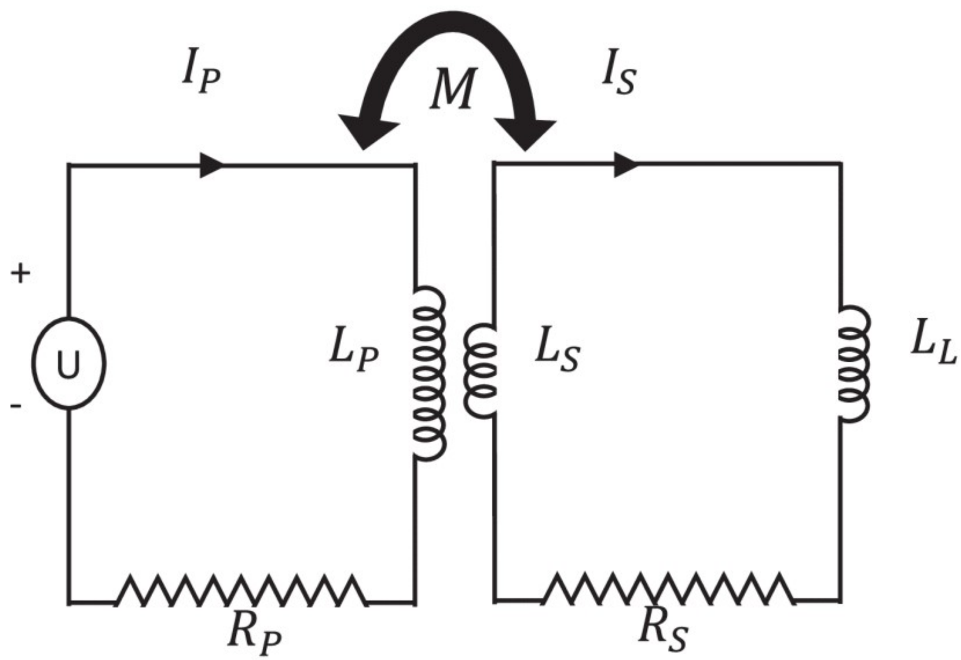
A Typical Test Week

- Sample is attached to the superconducting transformer (photo) on Friday noon, and afterwards it is lowered into the SULTAN test well.
- Cool down of the sample is started on Friday afternoon, and proceeds over the weekend (48 hours are needed).
- Monday morning – Wednesday afternoon: testing
- Wednesday evening – start of sample warm up.
- Thursday – removal of the sample (0°C) out of the test well into Nitrogen protective gas to avoid moisture condensation on the sample.
- Friday morning – sample is uninstalled such that the next one can be mounted.

Superconducting Transformer



- Provides sample current I_S up to 100 kA.
- Primary coil: 3700 turns of NbTi wire with current up to 200 A.
- Secondary coil: 8 turns of a NbTi cable with current up to 100 kA.
- Rising current in primary coil induces current in the secondary coil. **Amplification factor α= 290**.
- Coupling coef.: k = 0.63

$$\frac{I_S}{I_p} = \frac{V_p}{V_S} = k\sqrt{\frac{L_P}{(L_S+L_L)}} = \alpha$$

(assuming R_P and R_S = 0Ω)

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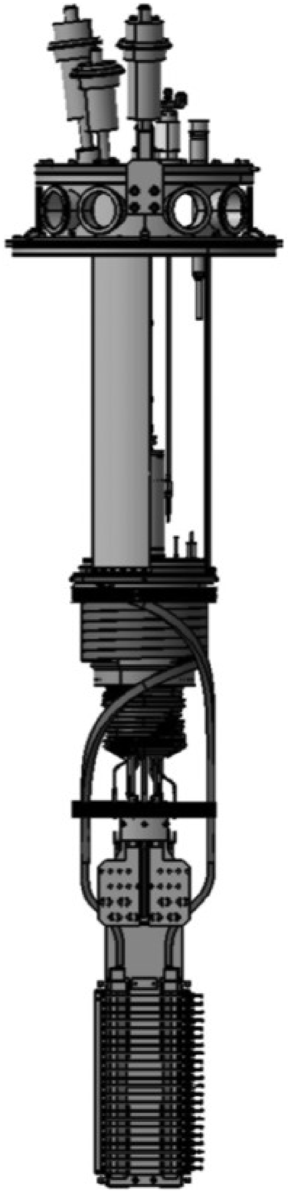
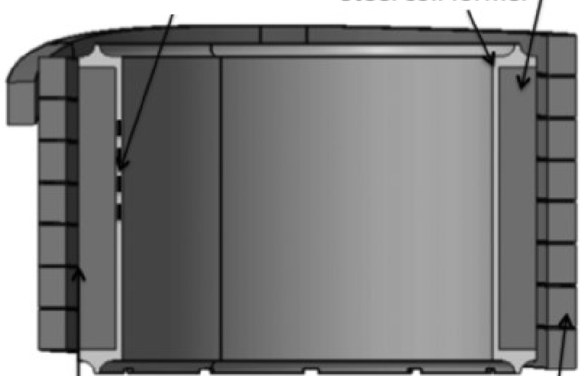
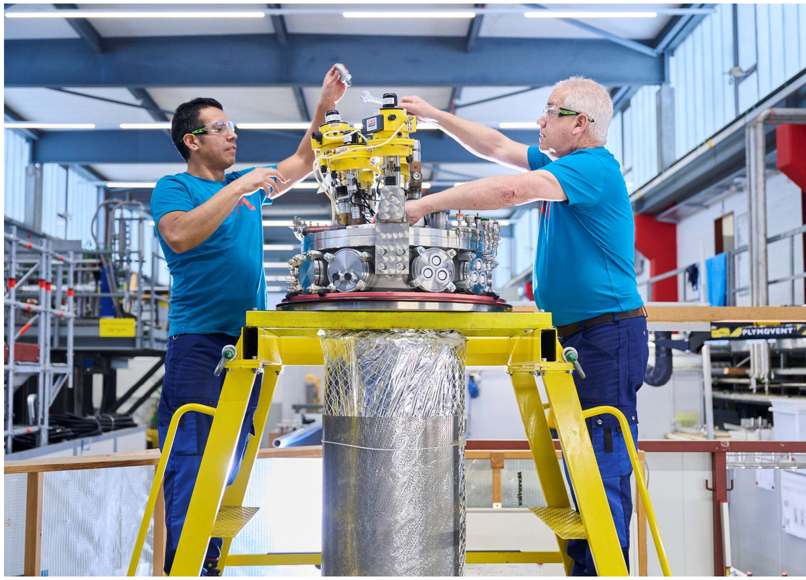
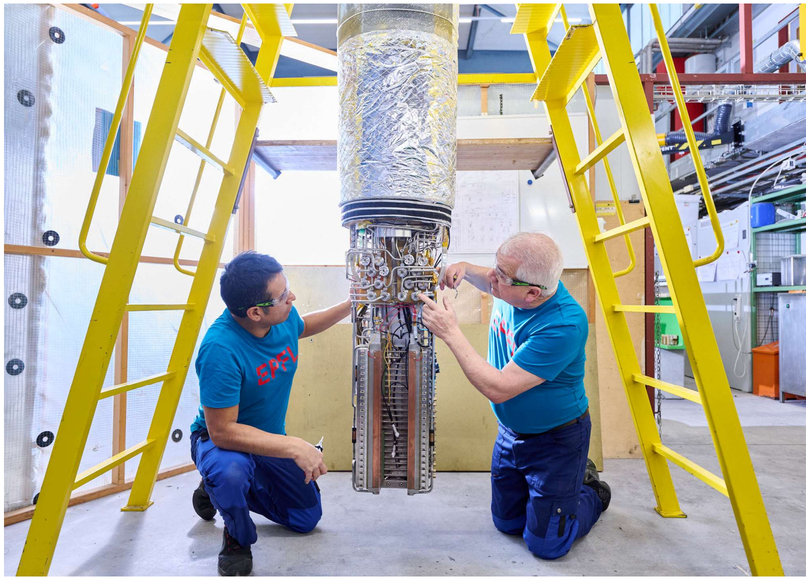


Superconducting Transformer

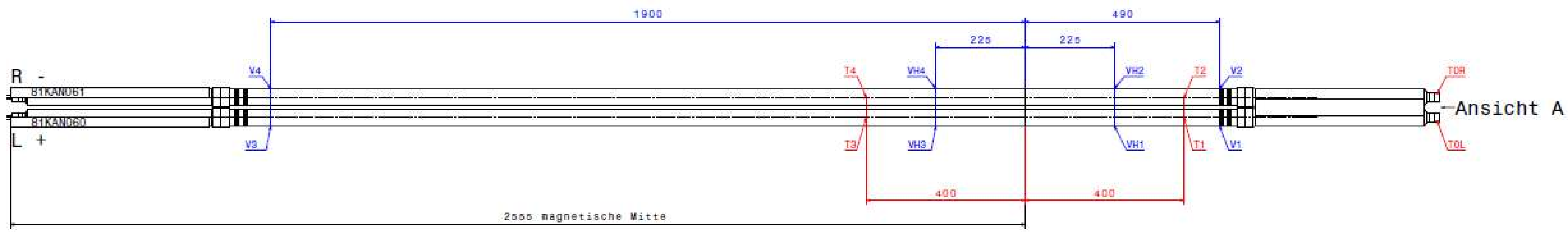


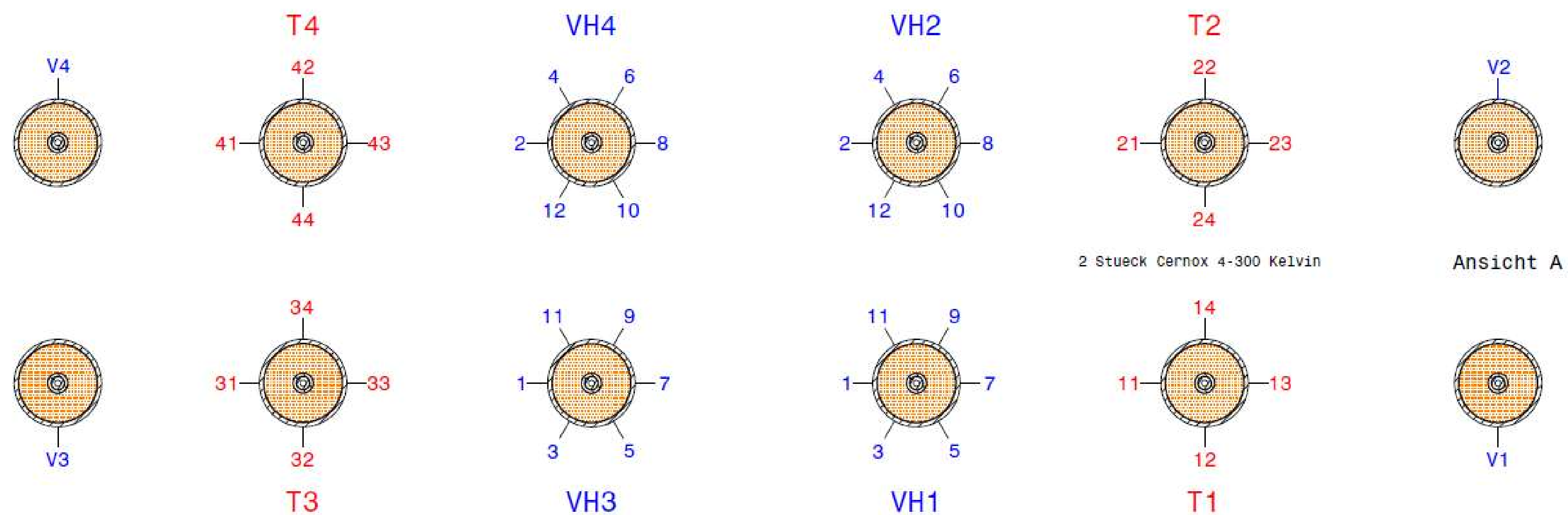




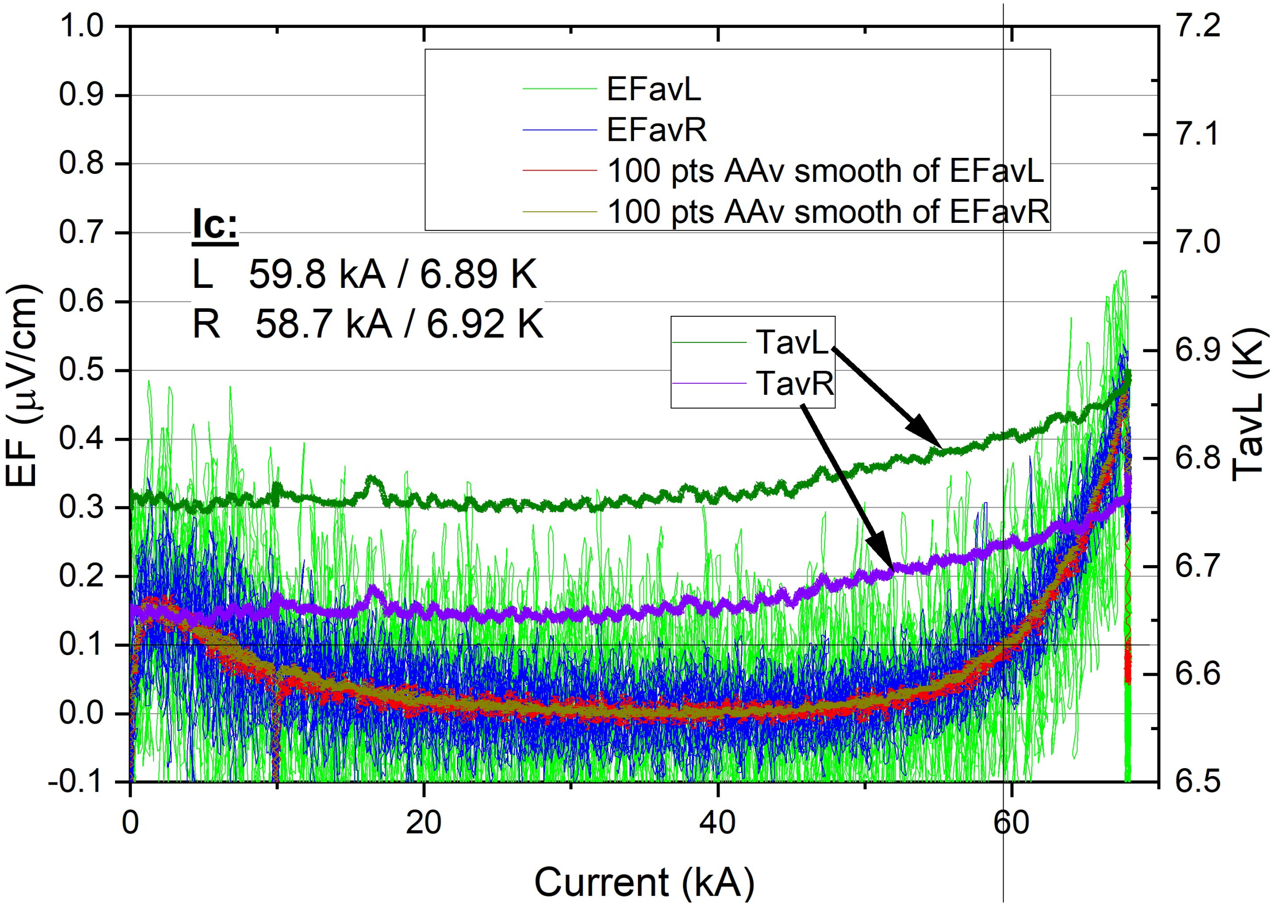
Sample Instrumentation

Kamil Sedlak



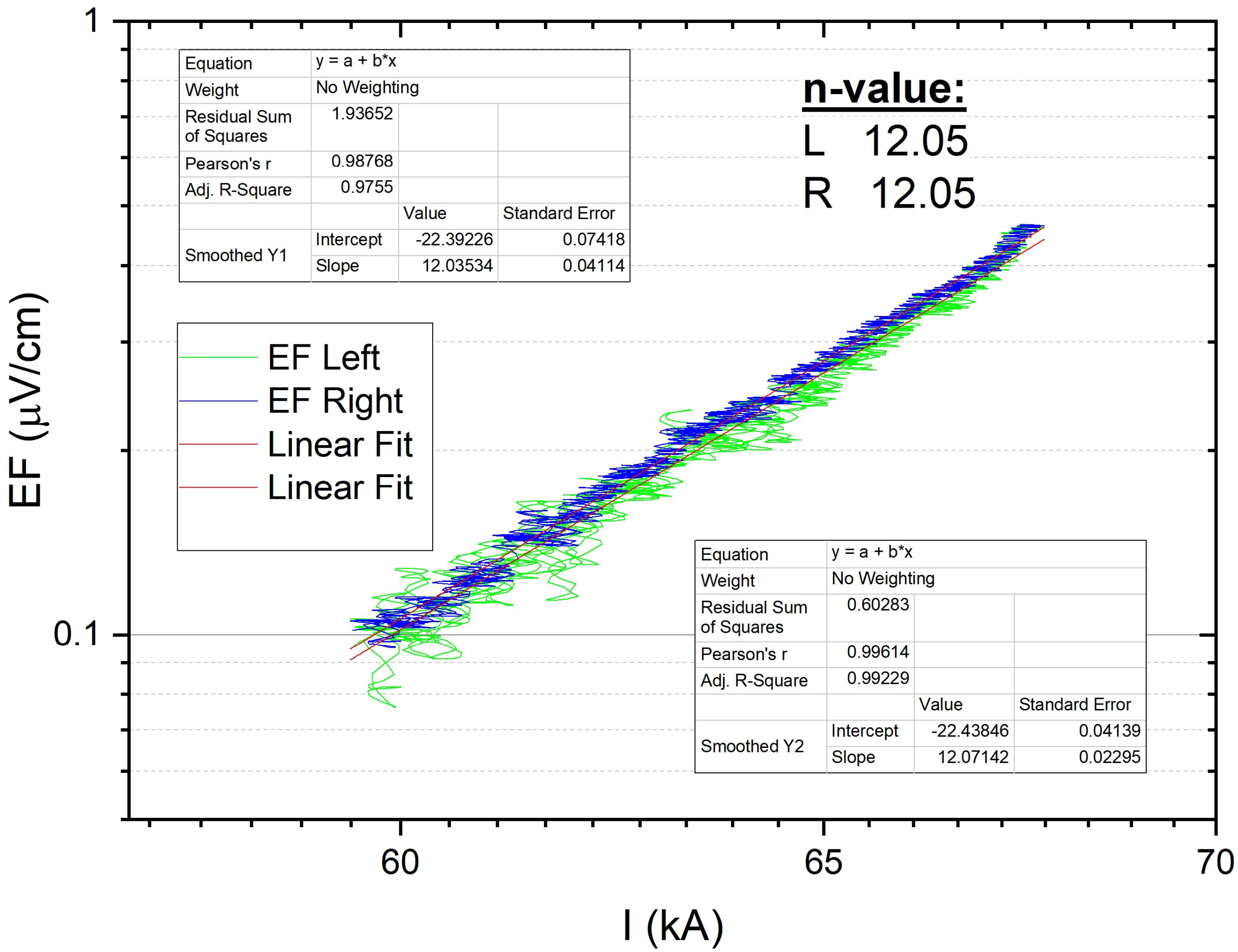


Ic (Critical Current) Run



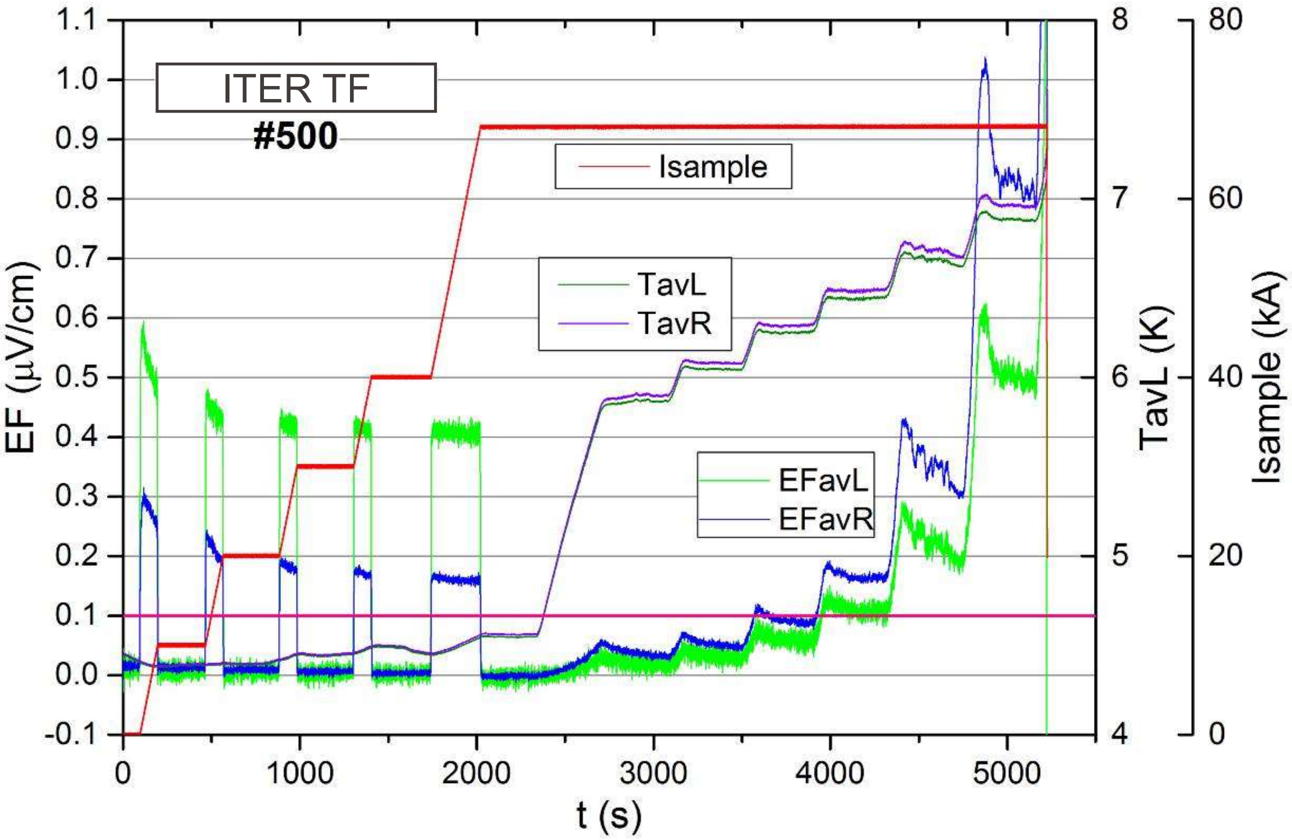
- Magnetic field is set to required value, i.e. 11 T.
- Initial temperature is set to required value.
- Current is increased continuously.
- Inductive voltage is subtracted in the plot.
- Ic is defined as the current, at which the lines cross critical EF = 0.1 μV/cm.
- Note that the temperate increases during run (ohmic heating in the bottom joint).

n-Value Determination from the Ic Run



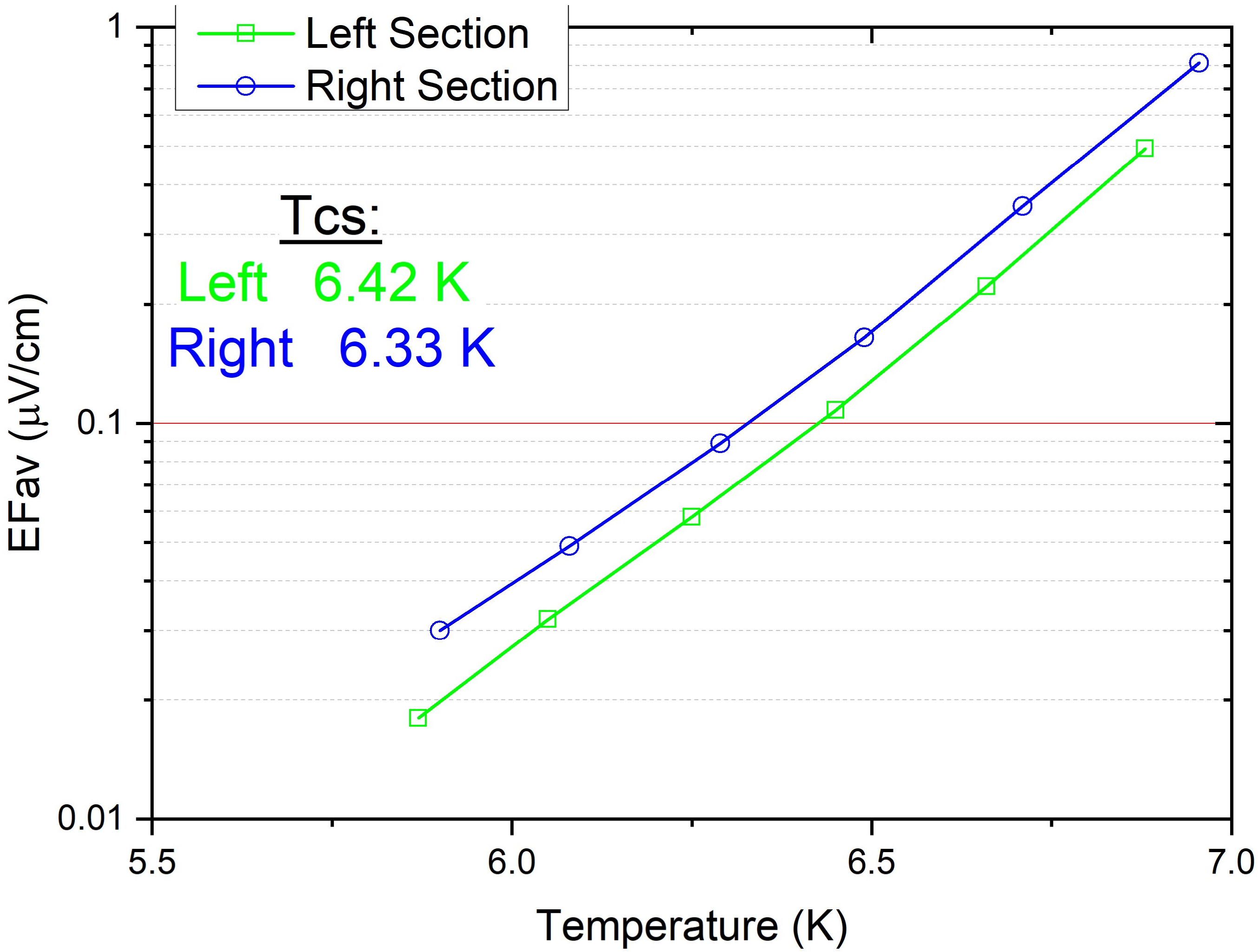
- EF(I) is plotted in log-log plot.
- n-Value is fitted, ideally in the EF range of 0.1 – 1.0 µV/cm.

Tcs (Current Sharing Temperature) Run



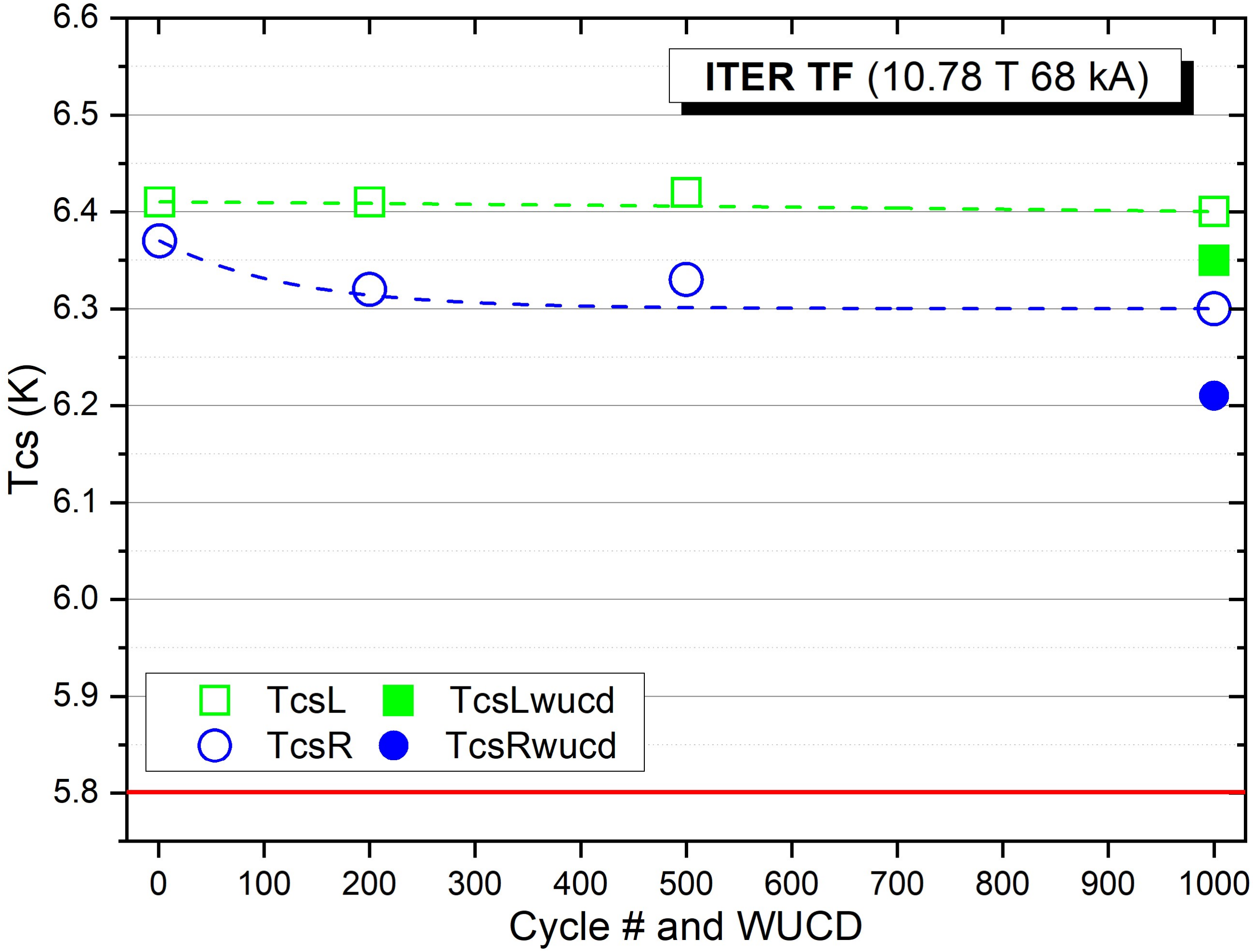
- Magnetic field is set to required value, i.e. 11 T
- Current is increased in steps to required I_{OP} .
- Temperature is increased in steps with waiting time of 5min.
- Notice the relaxation of the electric field (EF) during the temperature plateau.
- For the Tcs assessment, EF vs. temperature graph is constructed – see next slide.

Tcs (Current Sharing Temperature) Run



- EF vs. Temperature is plotted as log-log graph.
- Tcs is defined as the temperature, at which the lines cross critical EF = 0.1 μV/cm.
- In SULTAN, usually there are two independent cooling circuits for the left leg and right leg. This allows us to adjust the temperature in each leg independently.

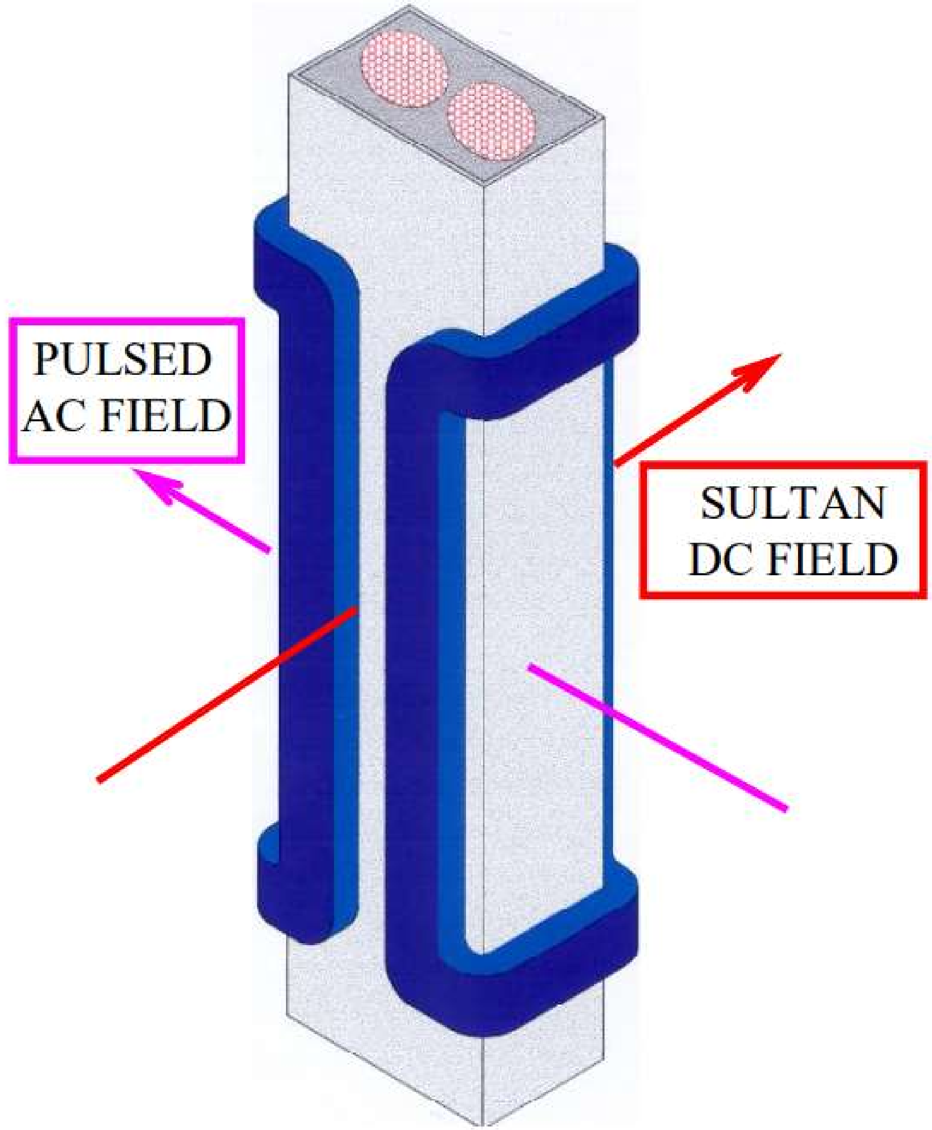
Evolution of Tcs along Cyclic Loading



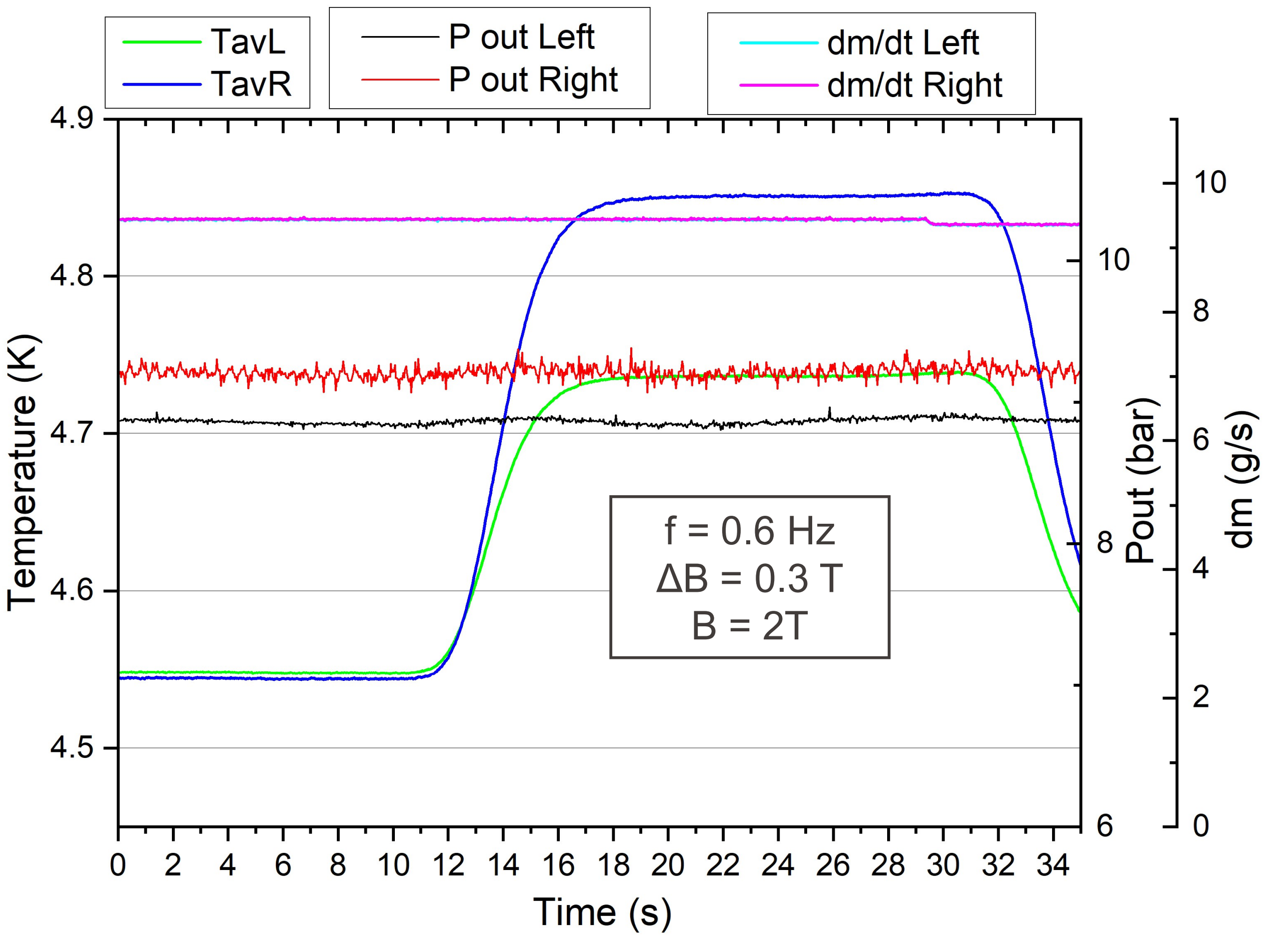
- Conductor performance may change (degrade or improve) along cyclic electromagnetic loading or due to a thermal cycle.
- Usually, the biggest degradation is seen at the beginning of the test campaign, and when electromagnetic and thermal cycles are combined.

AC Coil in SULTAN

- AC magnetic field perpendicular to the DC magnetic field can be generated.
- AC field up to 0.4 T in repetitive sinusoidal pulses, (0.02 Hz – 10 Hz).
- AC field up to 4 T in a single pulse mode (capacitor bank used instead of power supply).

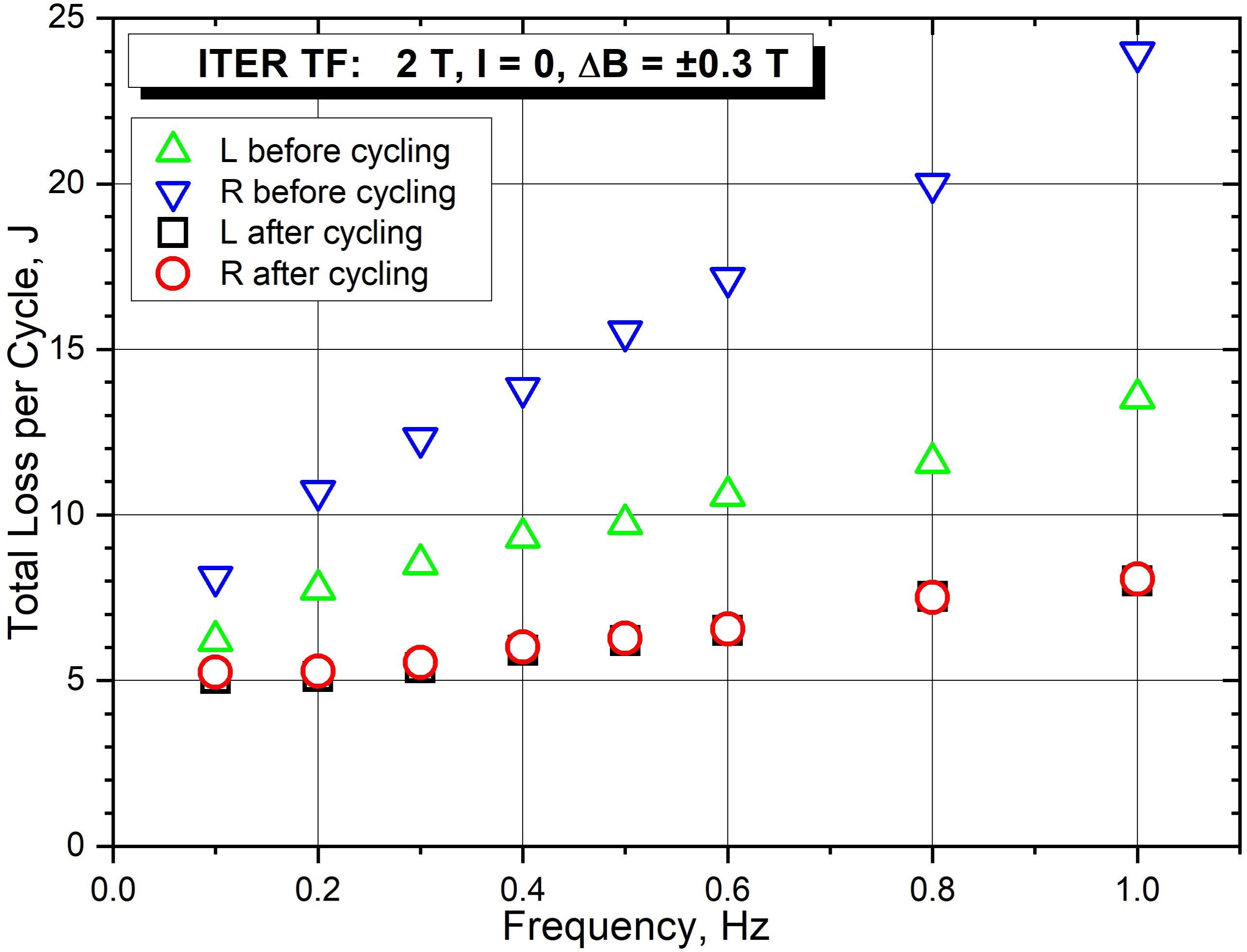


AC Loss



- AC loss is measured when AC magnetic field is generated by a dedicated AC coil.
- Function of AC field amplitude (typically 0.4T) and frequency (0.1 Hz – 10 Hz).
- Usually at 2 T SULTAN background field.
- AC loss can be determined from the temperature increase due to AC field, mass flow rate and pressure using enthalpy calculation.

AC Loss



- Assessment of the previous graph will add one point to the overall AC loss graph, here shown as AC = AC(f).
- For Nb3Sn, the losses in pristine conductor are usually higher than losses in the conductor after cyclic loading.

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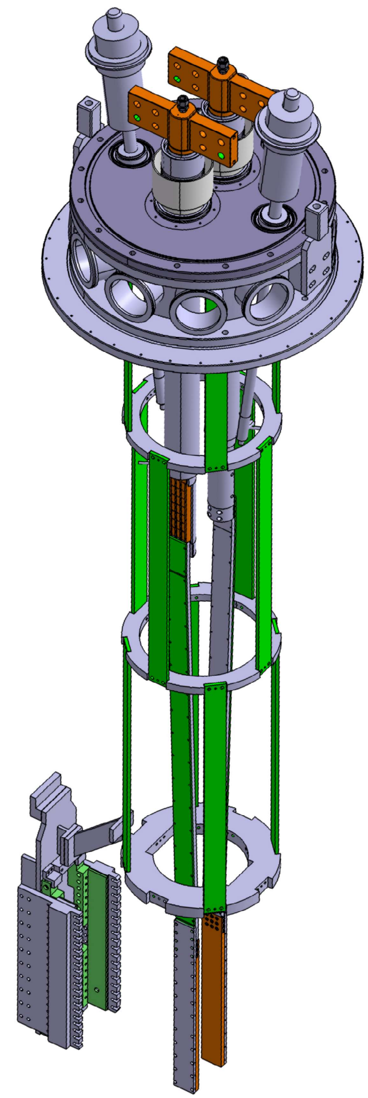
Additional SULTAN Capabilities

- Quench Propagation Studies:
  - Power supply is used instead of superconducting transformer, but with a limited current (max. 15 kA).

- HTS samples: An HTS Adaptor needs to be inserted between the superconducting transformer and the sample, to allow temperature gradient between the transformer (cold end, up to ~8K) and HTS sample (up to ~50K).



Conductor Design

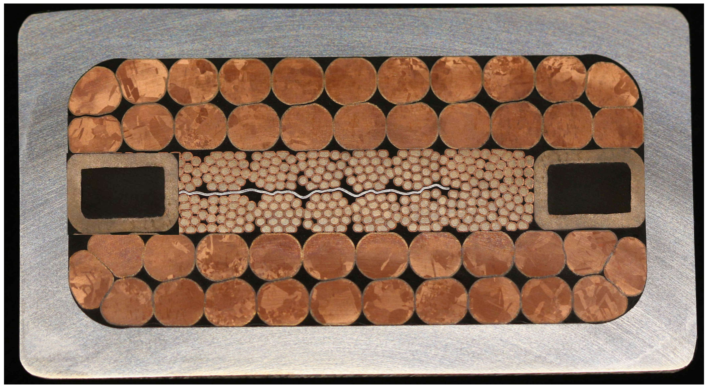
React & Wind Nb_3Sn Conductor for DEMO

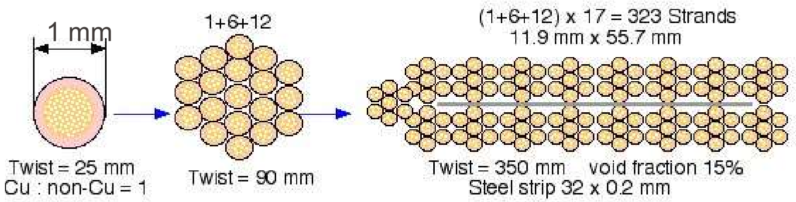
Post-ITER LTS conductor development

- Cable assembled at room temperature from heat-treated Nb_3Sn cable. Steel jacket laser welded from two symmetric half-profiles.
- Measured effective strain:
  - ε_{eff} = -0.28%
  - (ITER TF: $\varepsilon_{eff} \approx$ -0.7%)

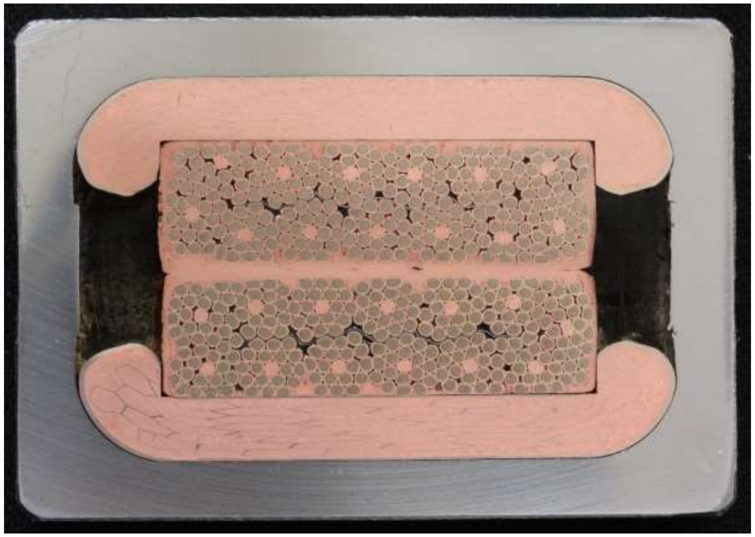
➔ DEMO RW conductor reaches ITER TF cable performance with only 50% of Nb_3Sn.

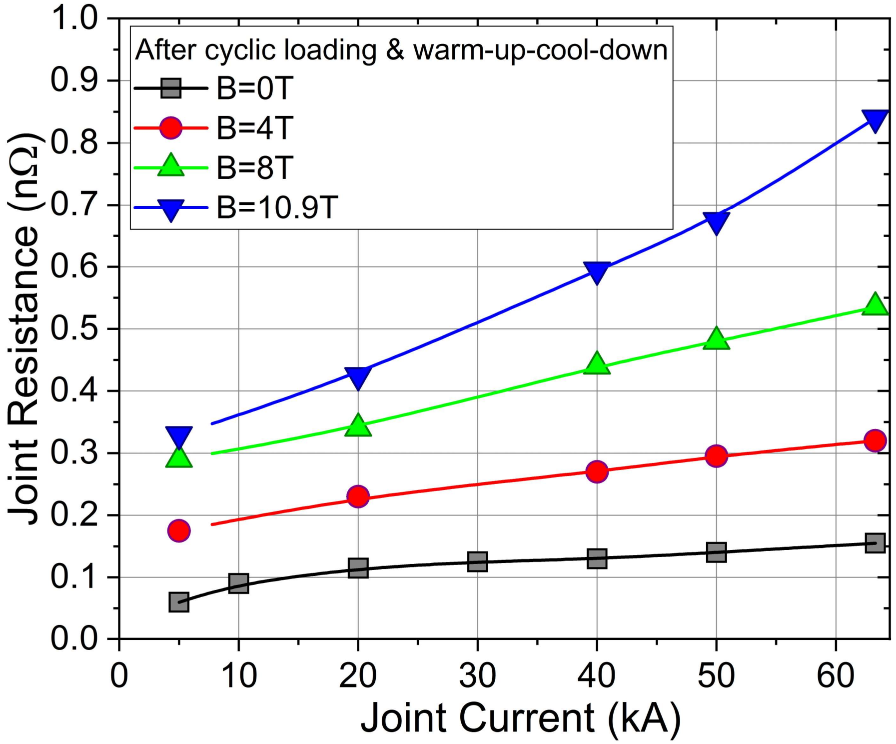
- Additional saving due to grading of Nb_3Sn and steel in the layer-wound winding pack.
- Very small AC loss (cable might be used also in the CS coil).
- In 2025-2026: We work on an industrial demonstration of 100m long conductor manufacture.





RW Diffusion-Bonded Joint



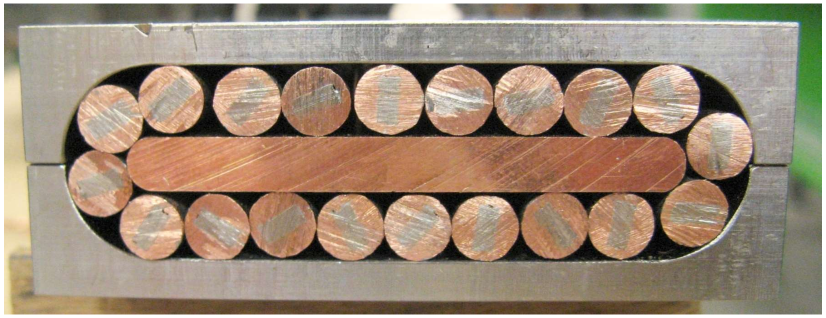


In operating conditions :
R at 8 T, 63.3 kA = 0.54 nΩ
(Target: 1.0 nΩ)

Diffusion-bonding (DB) of two overlapping RW conductors. The bonding is done after the Nb_3Sn heat treatment.

R&D on HTS Conductors

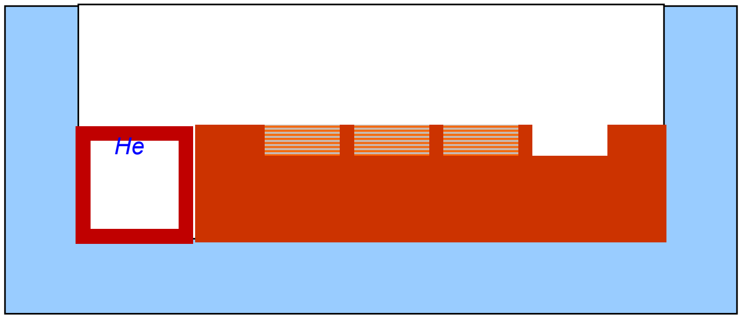
SPC: 60 kA, $B_\perp$ 12.5 T, 7.8 K, **2016**



The SPC conductor is transposed, scalable to 50-100 kA, designed for $B_\perp > 12$ T, AC tolerant, force flow.

(Nikolay Bykovskiy)

NTNT – Non-Twisted
Non-Transposed conductor, **2024**



(Davide Uglietti)

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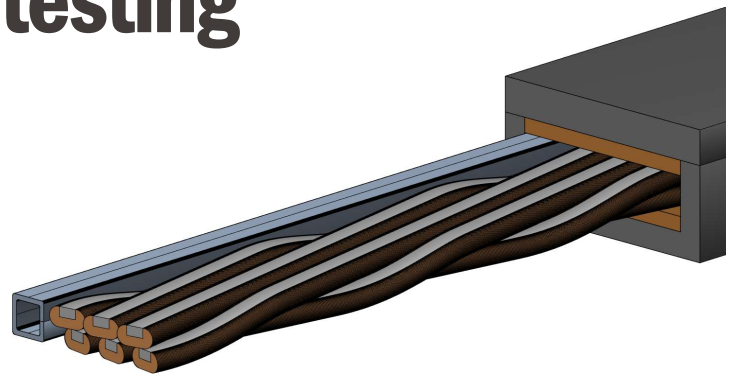
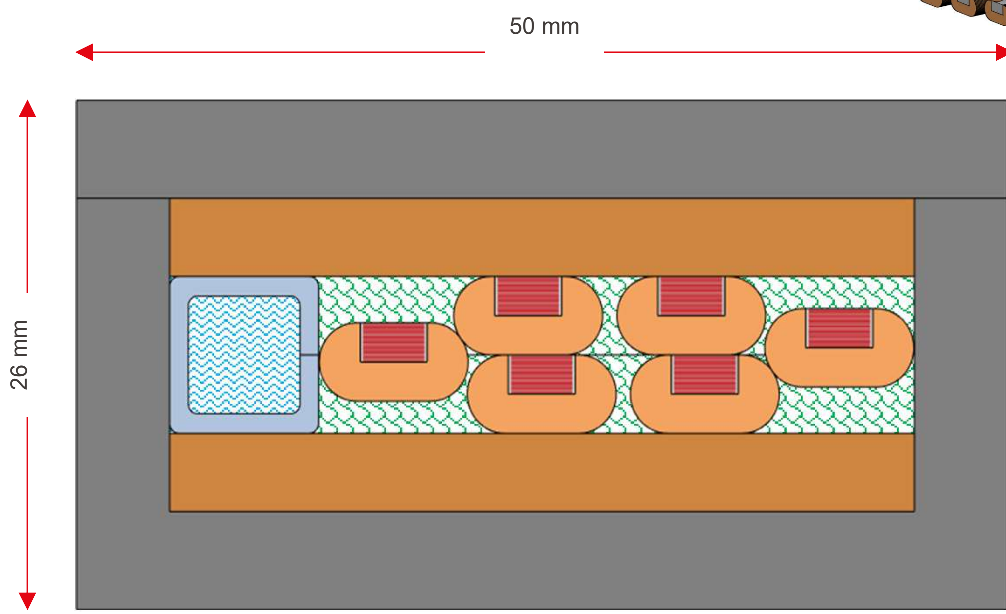
ASTRA prototype construction & testing

3.3 mm tapes
21 tapes in a stack
8 x 4 mm copper profile



Kamil Sedlak

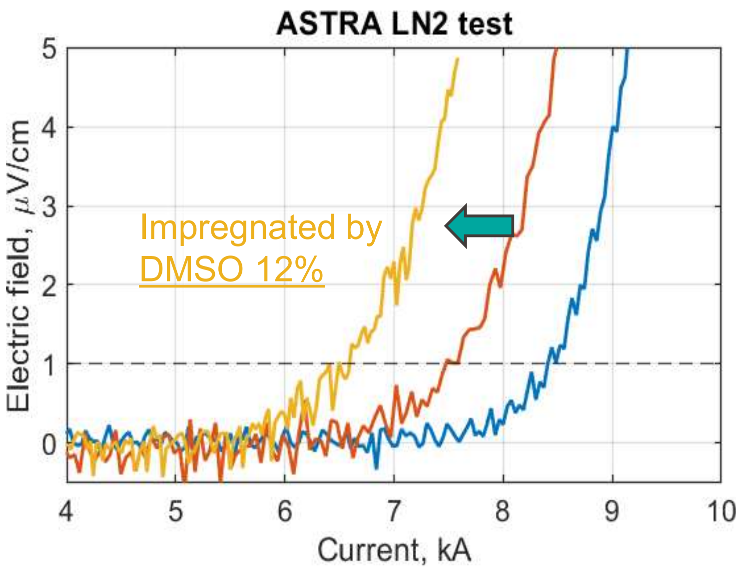


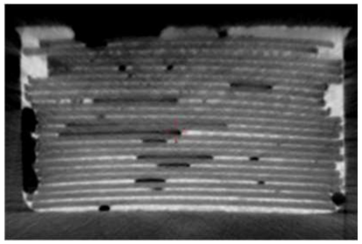
Designed for 60 kA at 18 T

Impregnation with dimethyl sulfoxide (DMSO) – water solution

Nikolay Bykovskiy, SPC, 2023

ASTRA full-size conductor 2023





- Performance degradation of the ASTRA conductor, likely due to voids in the solder in between the tapes.

Overall observation for HTS samples tested in SULTAN from all the world:

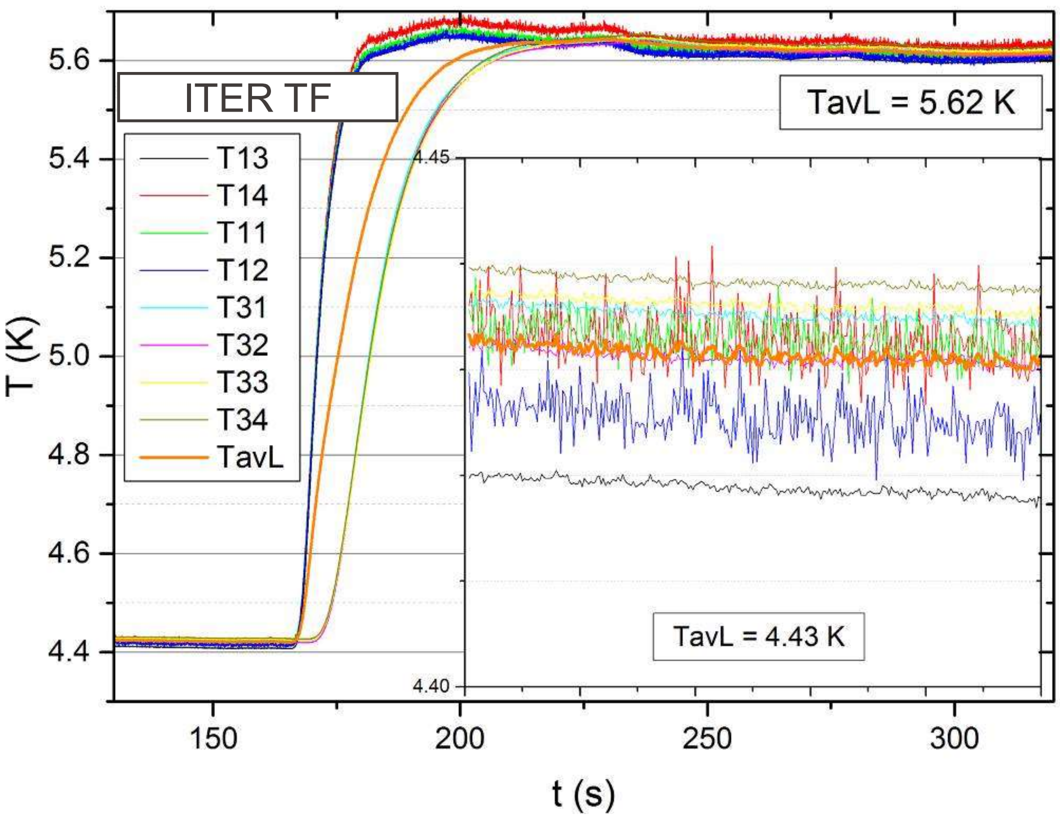
- Conductors are usually very stable against quench (as expected).
- Making the terminations (joints) with low resistance is challenging.
- Very often there is a performance degradation with electromagnetic cycling.

Take-Away Message

- It may take 2-3 months to prepare a SULTAN sample, and 1-2 weeks to test it.
- The usual aims of a superconductor tests are:
  - DC performance (I_C, T_{CS})
  - AC performance = AC losses as function frequency
  - Stability of the performance with respect to the cyclic loading and thermal cycle (warm-up and cool-down).
- Goals in the present development of superconducting magnets for fusion devices:
  - Increase of magnetic field (reducing the machine size), which means moving from LTS to HTS. (HTS is in fact "High Field Superconductor")
  - Make HTS design more reliable (non-degrading, quench-protected)
  - Reducing the overall cost by more efficient use of superconducting material and by simplifying the manufacturing of the conductor and coil.

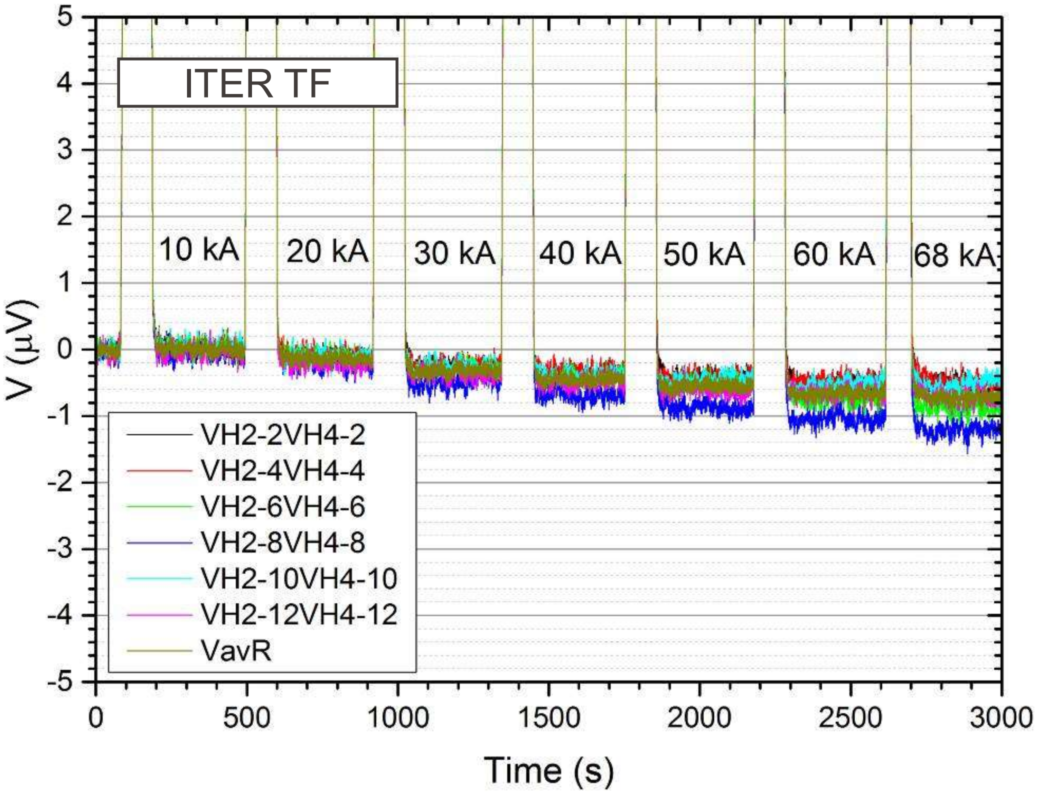
Additional Info

Check of Temperature Sensors – Heat Slug



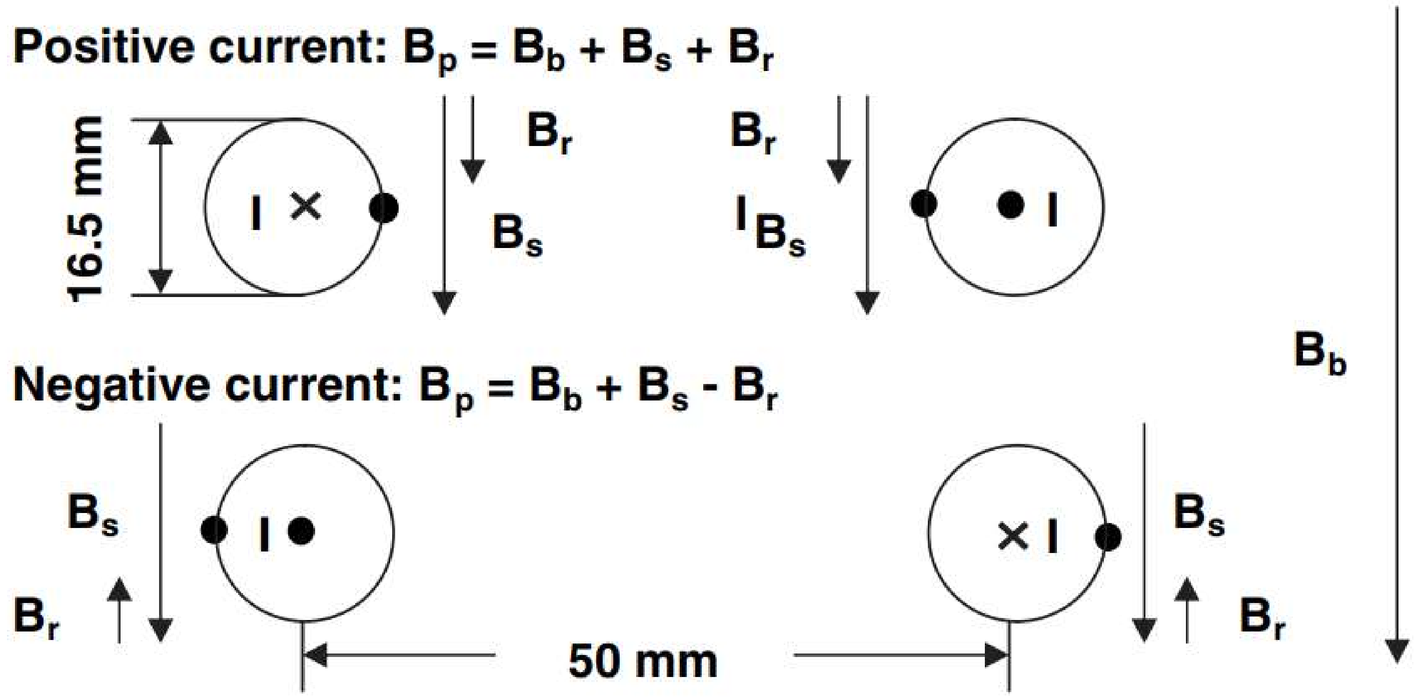
- Step-like increase of He inlet temperature. We check that:
- Temperature sensors show the “same” temperature (both before and after the heat slug).
- That upstream sensors react before the downstream sensors.
- The temperature increase corresponds to the heater power and He mass flow.

Voltage Response to Increasing Current



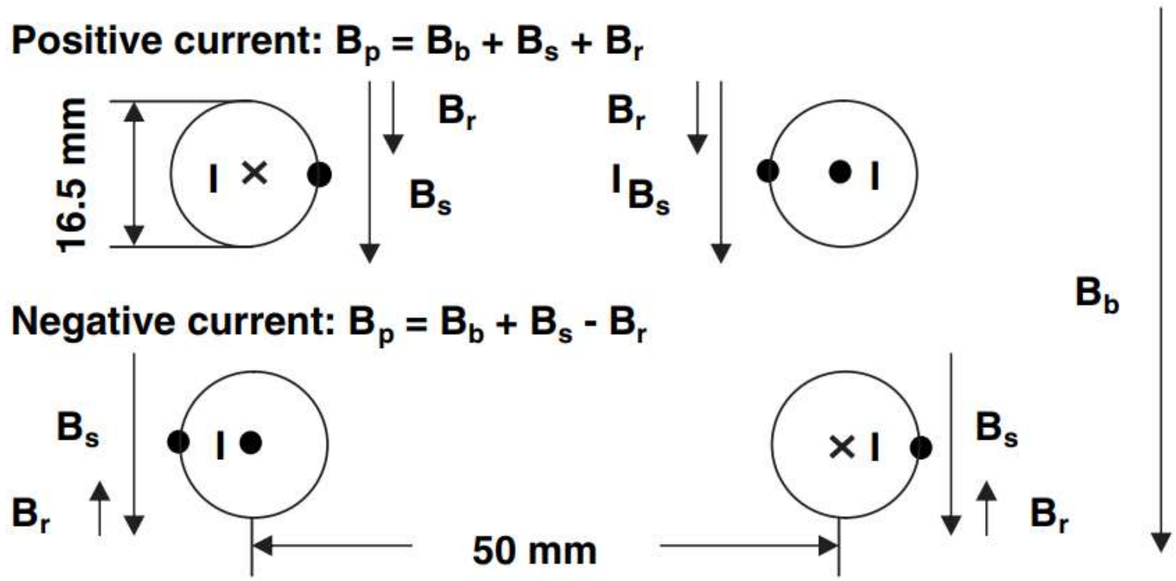
- Step-like increase of current up to 68 kA.
- Inductive voltage during ramping.
- Voltage should ideally be zero at current plateaus.
- In reality:
- Spread between the 6 voltage tap pairs positioned over the same high-field region, but at different angular positions → Averaging usually helps to get closer to 0 µV.
- If it does not work → ITER introduced a procedure to correct for V(I) slope, which is not due to resistive behavior.

Self-Field Effect



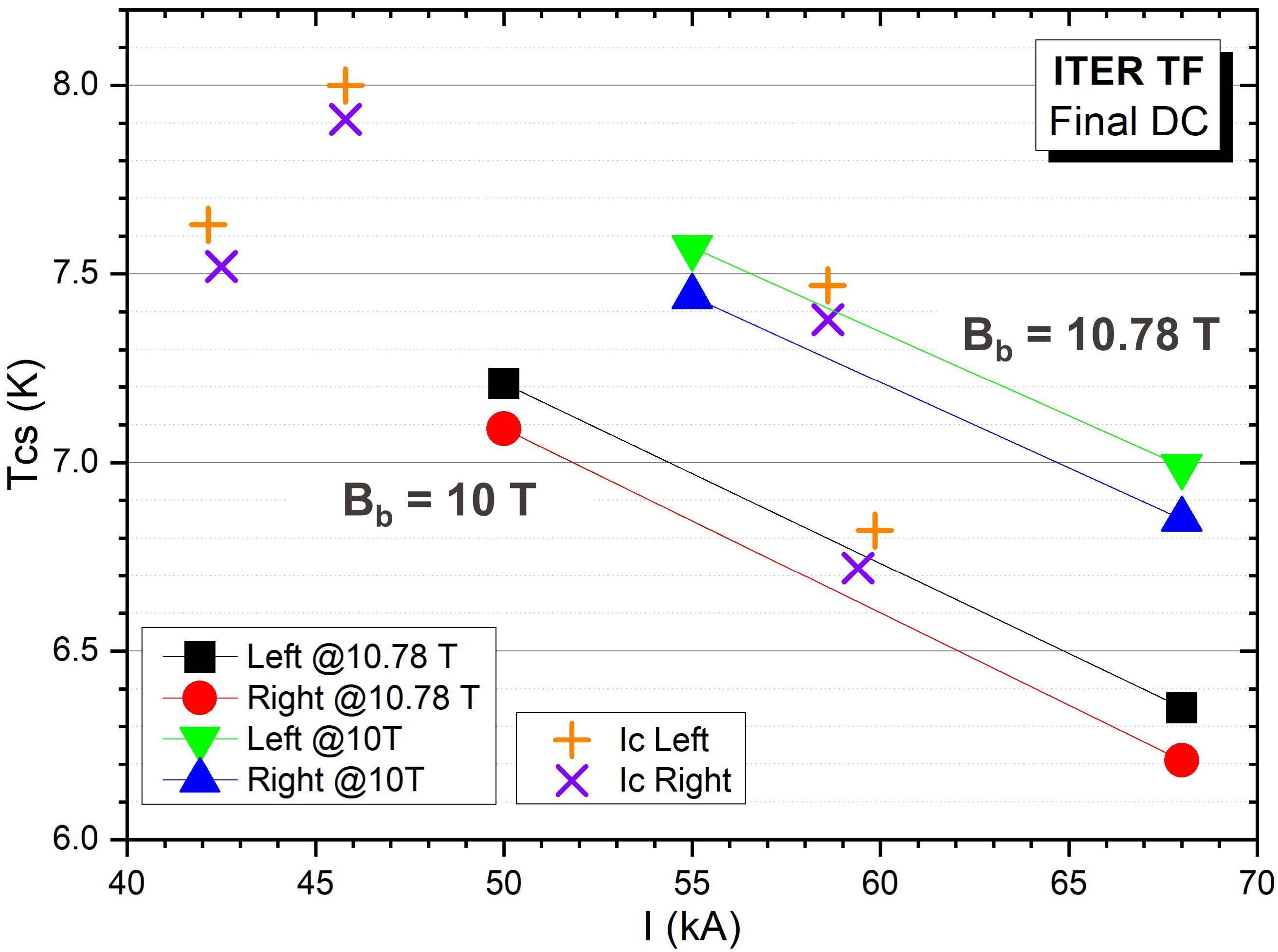
- The magnetic field in the sample is a superposition of three fields:
- B_b = SULTAN background field; B_s = self field of the conductor itself; B_r field generated by the other conductor leg

Self-Field Effect



- “Positive current configuration”: Bs, Bb and Br are aligned – highest effective field (higher than just the SULTAN background field). Conductors in the sample are repelled.
- “Negative current configuration”: when Bs is aligned with Bb than Br is pointing in the opposite direction → Beff is smaller compared to the “positive current”. Conductors in the sample are attracted.

Final DC Results



- Conductor performance may change (degrade or improve) along cyclic electromagnetic loading or due to a thermal cycle.
- Usually, the biggest degradation is seen at the beginning of the test campaign, and when electromagnetic and thermal cycles are combined.