Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Cable-in-Conduit Conductors and Coils for nuclear fusion magnets

Seminario per Studenti Univ. Roma TRE

ENEA Frascati, 7 Dicembre 2018

L. Muzzi / FSN – Superconductivity Laboratory

Outline

- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ ENEA activities beyond ITER

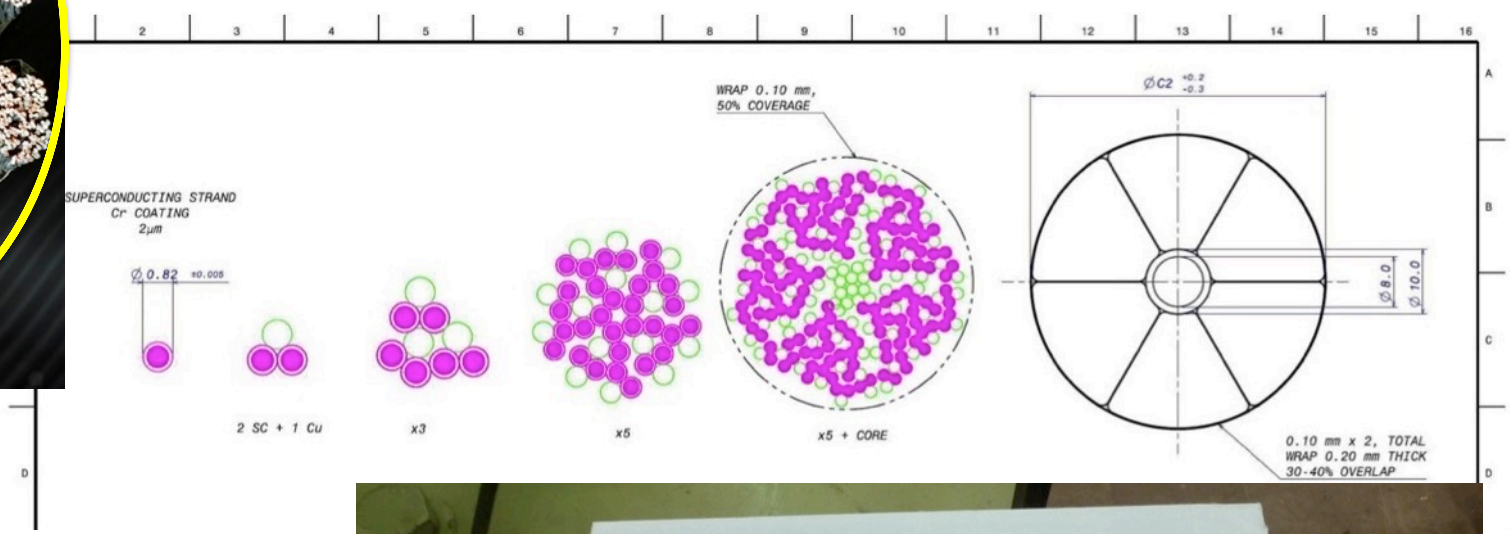
Some nomenclature

Some nomenclature

- **Wire (or strand)**
  - Cable
    - Conductor
      - Coil

Some nomenclature

- Wire (or strand)
    - **Cable**



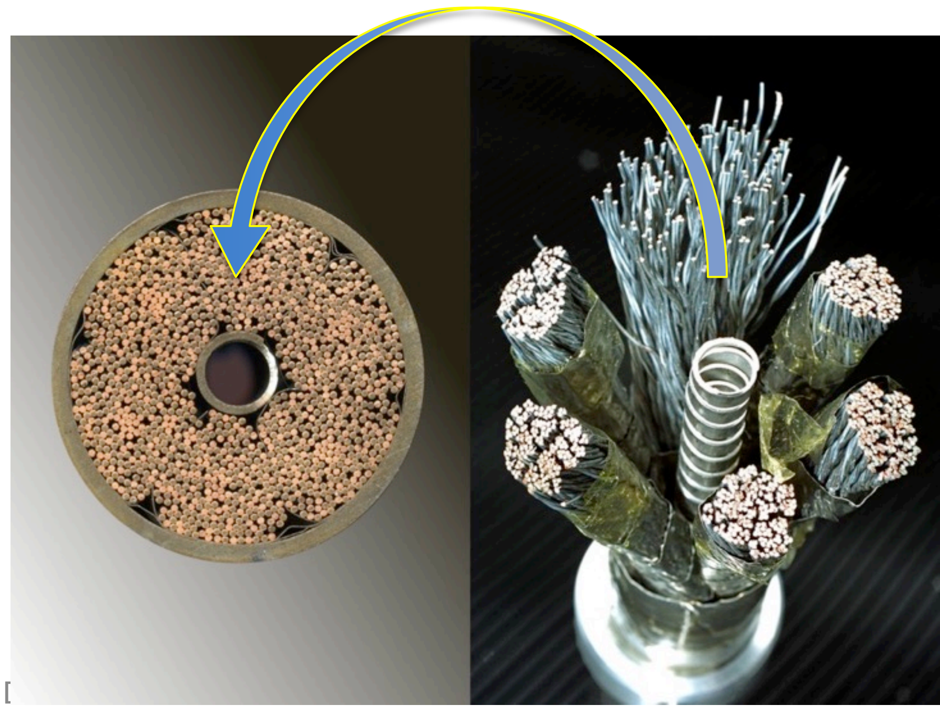
Some nomenclature

- Wire (or strand)

Cable

- **Conductor**

-



Some nomenclature

- Wire (or strand)
- Cable
- Conductor
- **Coil**

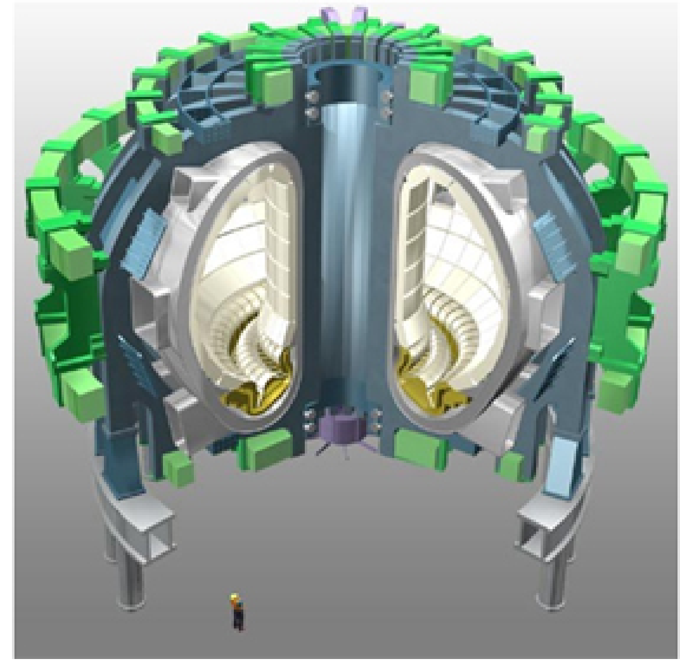
Some nomenclature: ITER

INTERNATIONAL

THERMONUCLEAR

EXPERIMENTAL

REACTOR



SITO:

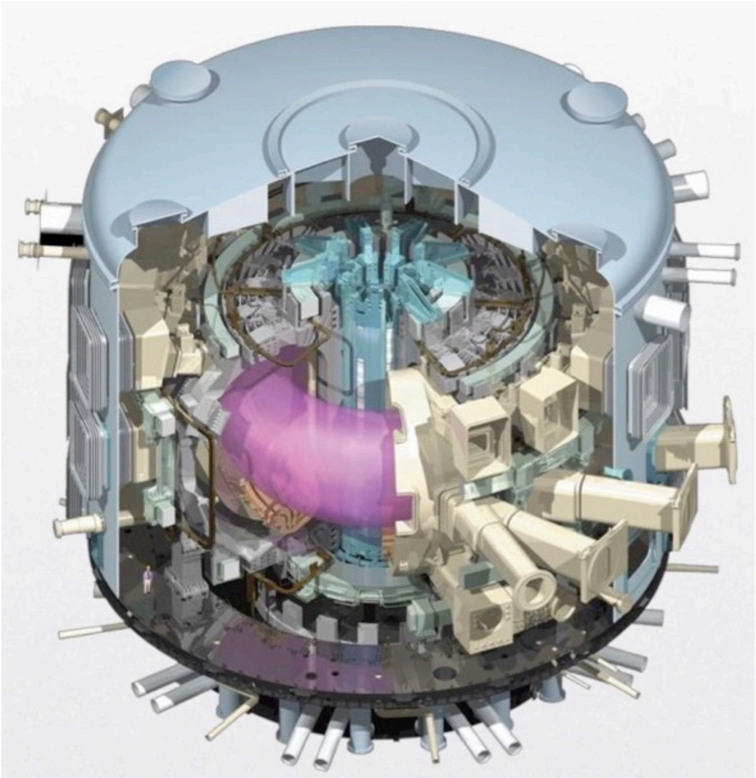
Cadarache (Francia)

Some nomenclature: ITER

china eu india japan korea russia usa

Demonstrate fusion as practicable energy source

- Fusion energy generation on large scale
- 10 times more energy generated than consumed (500 MW)
- Study of "burning plasma" and its long operation
- Testing key technologies for future fusion reactors

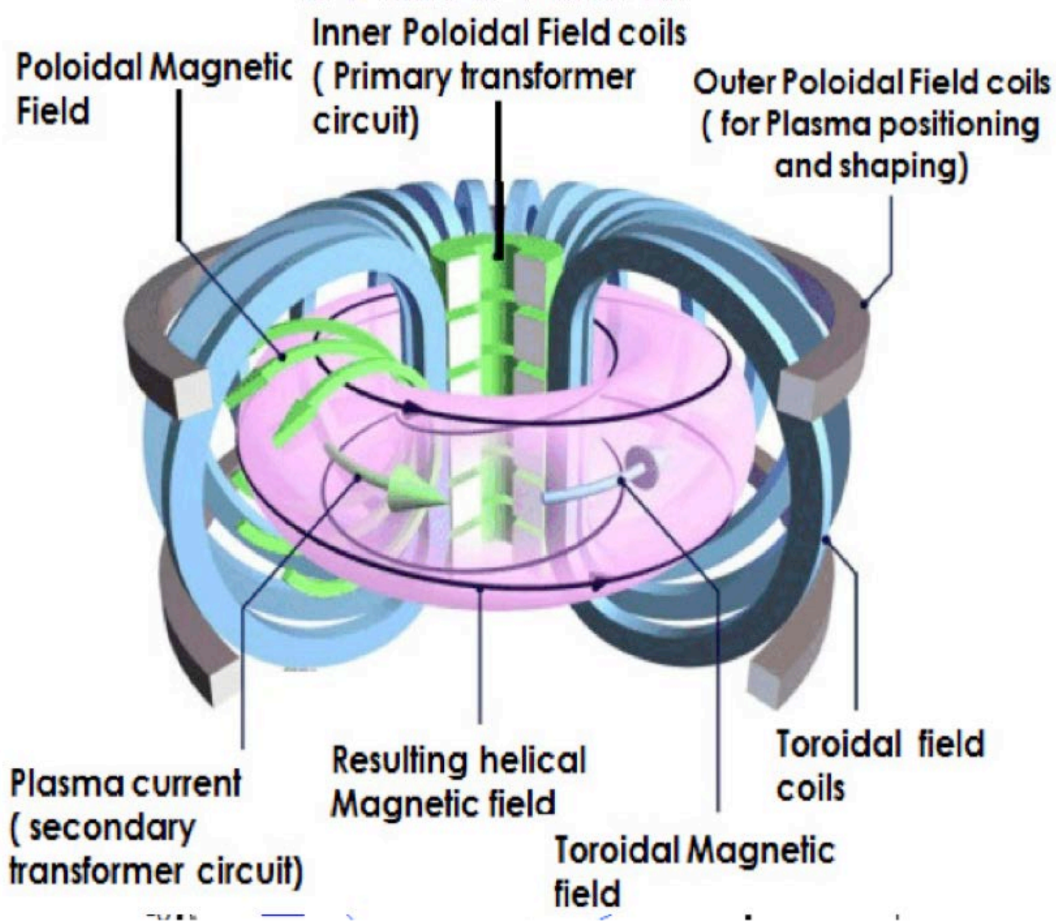


WATCH THIS VIDEO!

www.youtube.com/watch?v=kdfQUftpv1Q

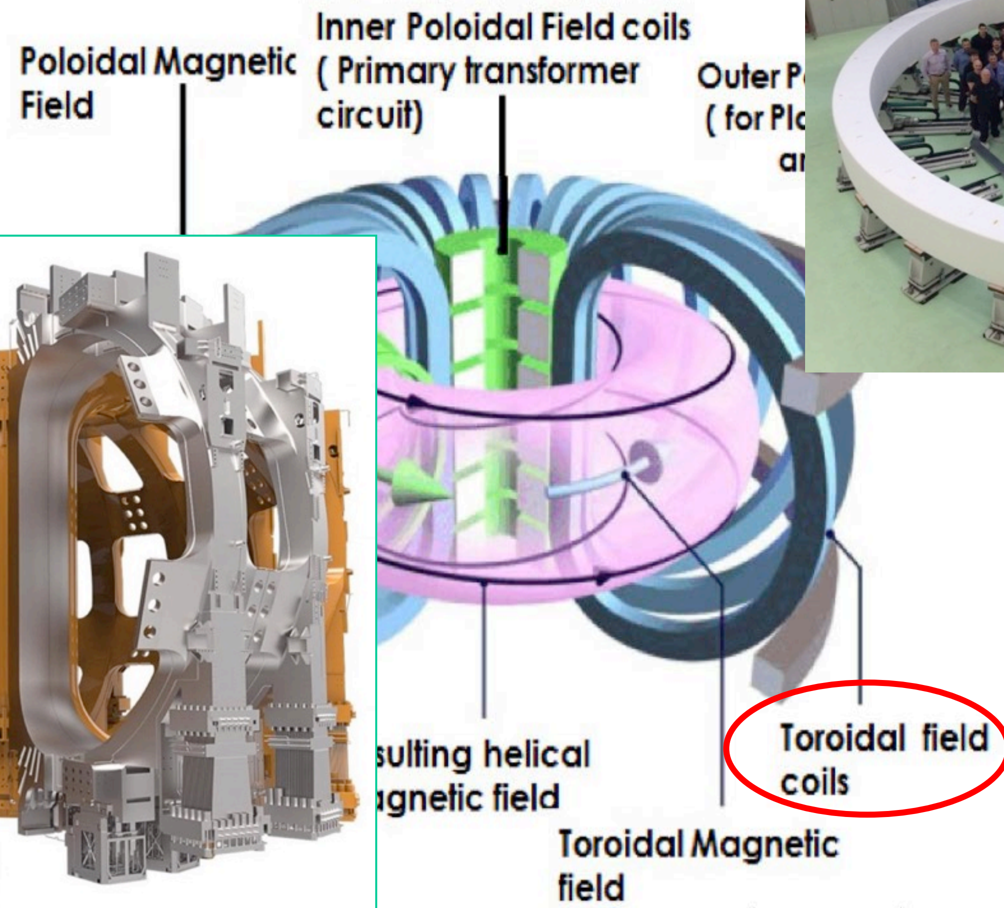
Fusion magnets: the ITER coils

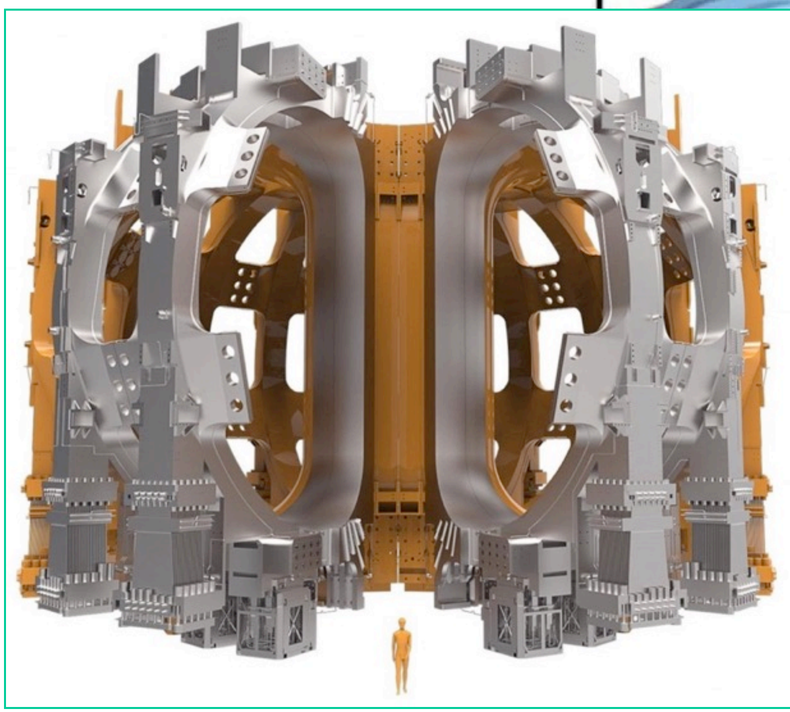
Magnetic confinement fusion: the **tokamak** concept



Fusion magnets: the ITER coils

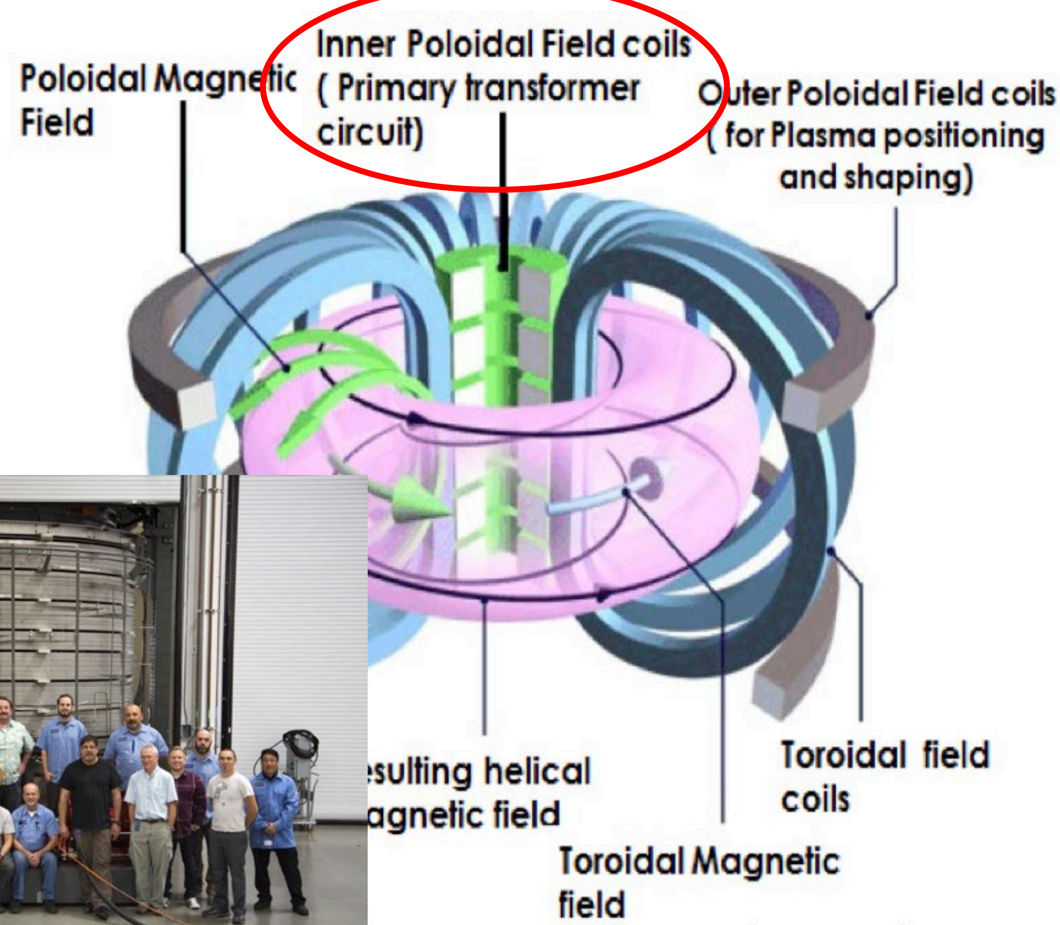
Magnetic confinement fusion: the





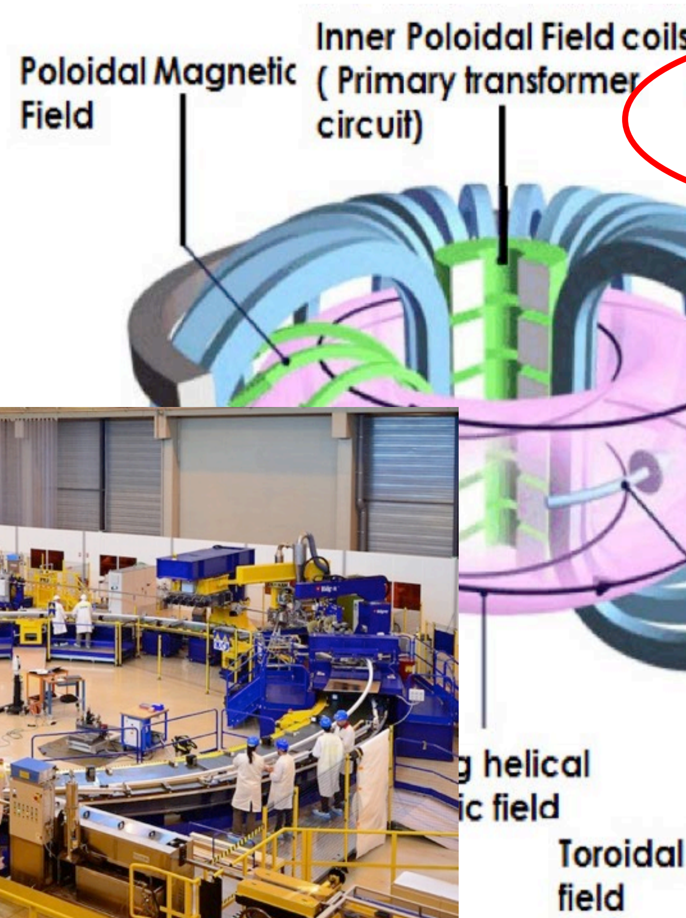
Fusion magnets: the ITER coils

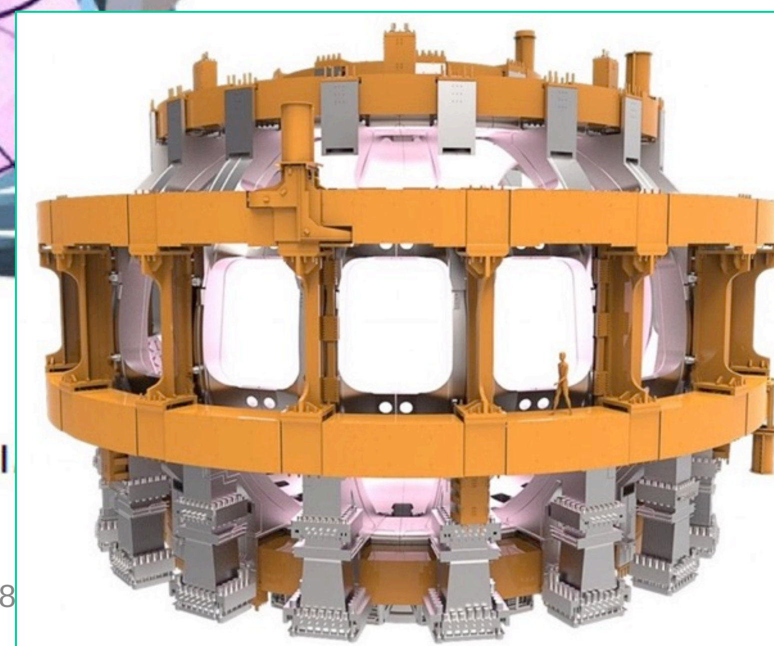
Magnetic confinement fusion: the **tokamak** concept



Fusion magnets: the ITER coils

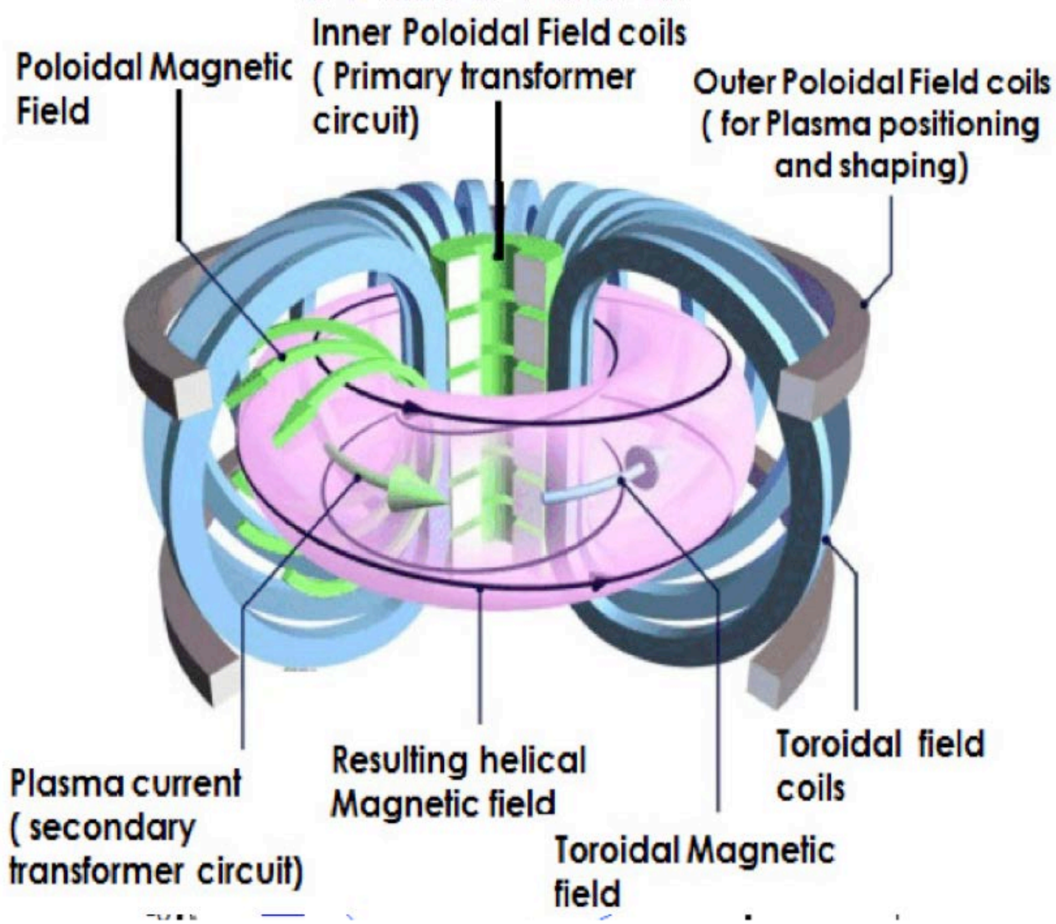
Magnetic confinement fusion: the **tokamak** concept





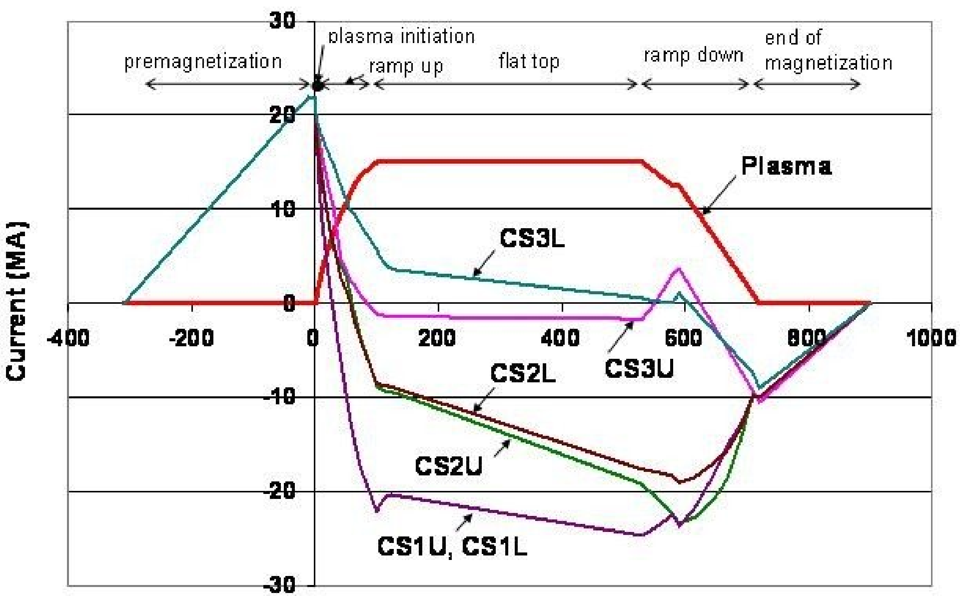
Fusion magnets: the ITER coils

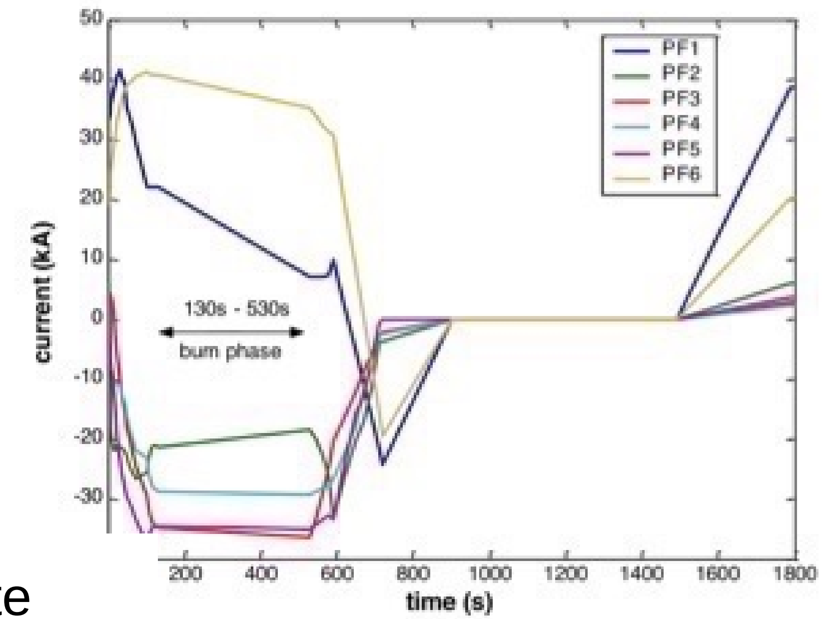
Magnetic confinement fusion: the **tokamak** concept



Fusion magnets: the ITER coils

Magnetic confinement fusion: the **tokamak** concept





TF (Torodial Field): 12T-68kA – steady state

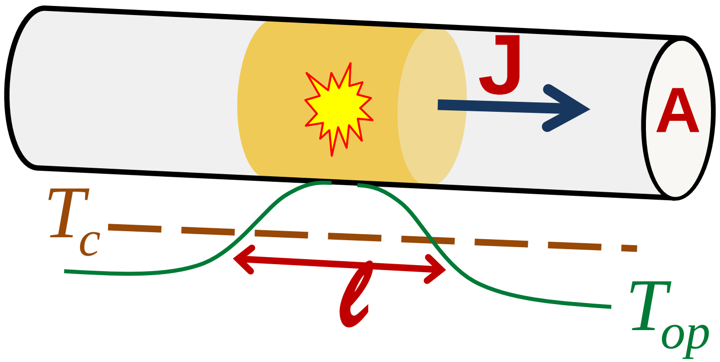
CS (Central Solenoid): 13T-46kA – transient

PF (Poloidal Field): 6.4T-52kA – transient

Outline

- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ ENEA activities beyond ITER

Superconducting wires (strands): layout



- if a zone of length l is heated up until transition, it dissipates (Joule effect)
- if the heat is removed more rapidly than its generation, the zone will reduce – *otherwise*, will increase
- The transition between the two cases defines the *Minimum Propagation Zone* (MPZ)

In adiabatic conditions (*approximation*), the generated heat is equal to that removed:

$$2kA(T_c-T_{op})/l = J_c^2 \rho A l$$

Superconducting wires (strands): layout

To *stabilize* the conductor, we need to increase the MPZ, thus ℓ.

$$2kA(T_c - T_{op})/l = J_c^2 \rho A l$$

- increase thermal conductivity, κ
- decrease the electrical resistivity, ρ

Superconducting wires (strands): layout

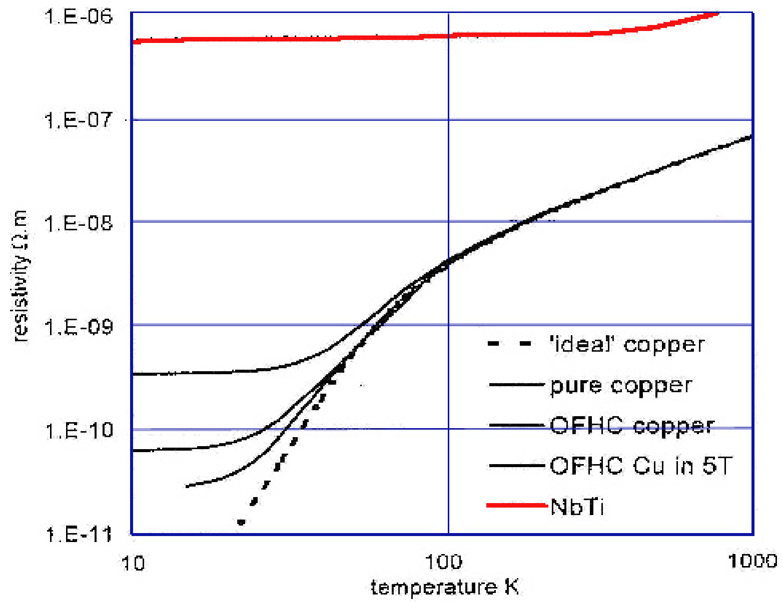
To *stabilize* the conductor, we need to increase the MPZ, thus ℓ

$$2kA(T_c - T_{op})/l = J_c^2 \rho A l$$

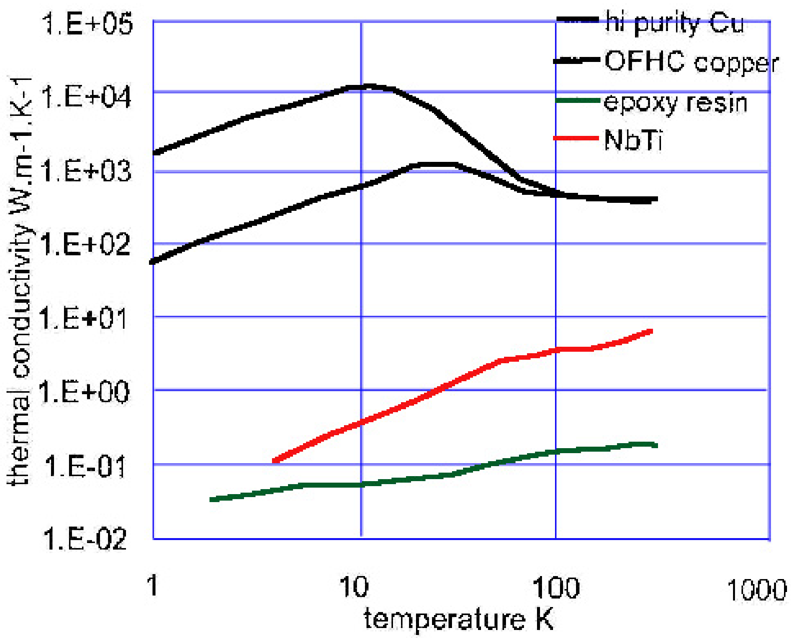
- increase thermal conductivity, κ
- decrease the electrical resistivity, ρ

BUT the superconductor is not *ideal*

Resistivity



Thermal conductivity



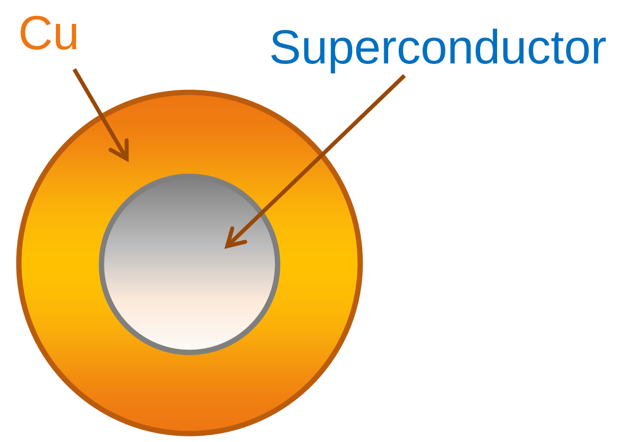
Superconducting wires (strands): layout

To *stabilize* the conductor, we need to increase the MPZ, thus ℓ

$$2kA(T_c-T_{op})/l = J_c^2\rho Al$$

- increase thermal conductivity, κ
- decrease the electrical resistivity, ρ

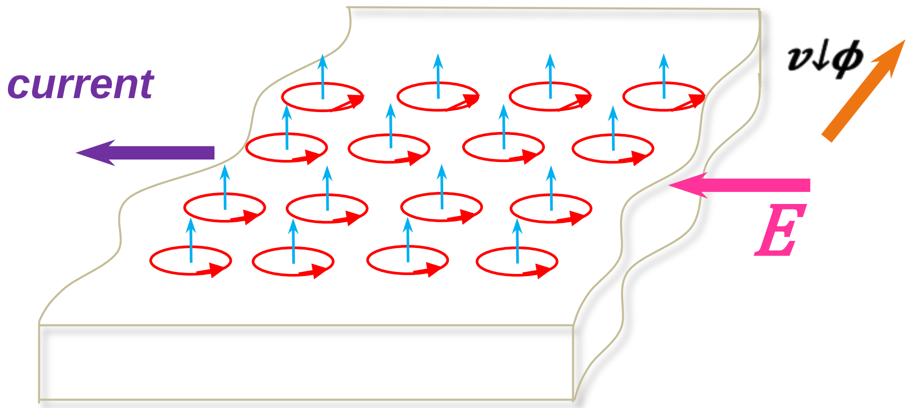
It's thus necessary to couple (*stabilize*) the material for example with *Copper* or *Aluminum*



α = Cu/nonCu ratio

Superconducting wires (strands): stability

Practical SC are all **type-II** materials. If ***I > I*** $_c$ the fluxons move under the effect of the Lorentz force, and generate dissipation.



Superconducting wires (strands): stability

Practical SC are all **type-II** materials. If ***I > I_c*** the fluxons move under the effect of the Lorentz force, and generate dissipation.

Below ***Ic:*** **pinning** of fluxons → hysteretic behavior under varying magnetic field.

Currents and field profiles inside a s.c. slab described by **BEAN (Critical State)** model.

Bean model

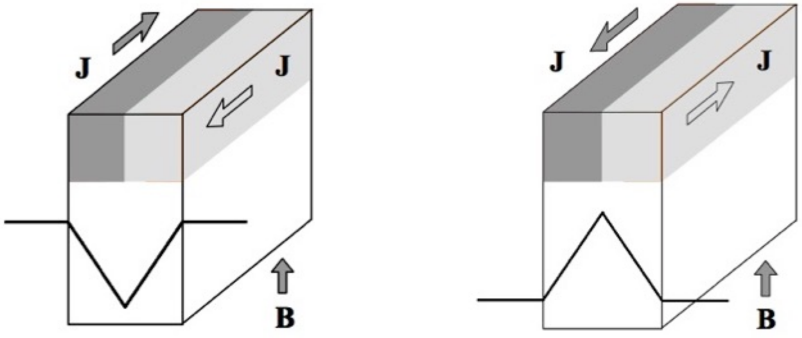


FIGURE 9. Screening currents induced by (a) rising and (b) falling field.

Superconducting wires (strands): stability

Practical SC are all **type-II** materials. If ***I > I_c*** the fluxons move under the effect of the Lorentz force, and generate dissipation.

Below ***Ic:*** **pinning** of fluxons → hysteretic behavior under varying magnetic field.

Currents and field profiles inside a s.c. slab described by **BEAN (Critical State)** model.

Any instability, of both electrical and thermal nature, might drive a "depinning" of a flux quantum (flux jumping). The phenomenon might even induce a *quench* of the magnet.

Bean model

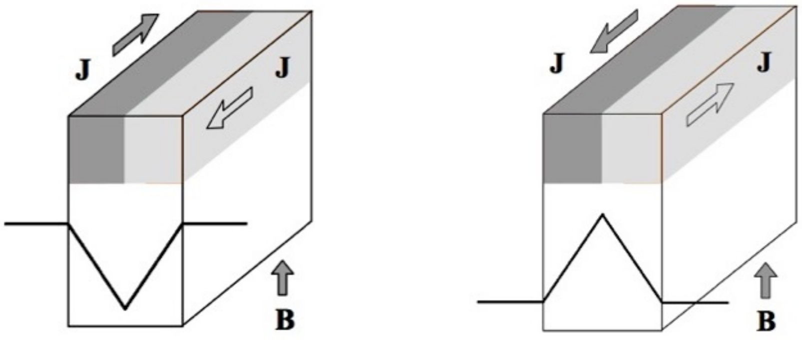


FIGURE 9. Screening currents induced by (a) rising and (b) falling field.

Flux Jumping

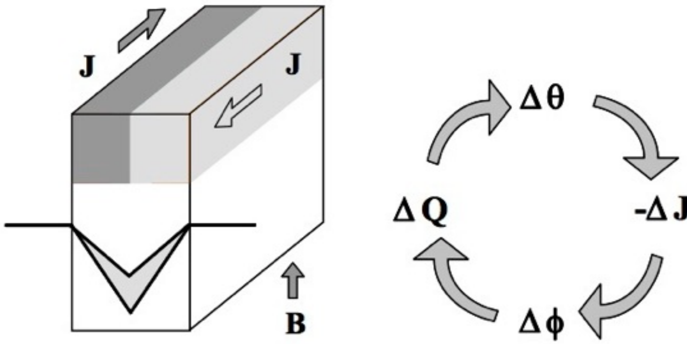
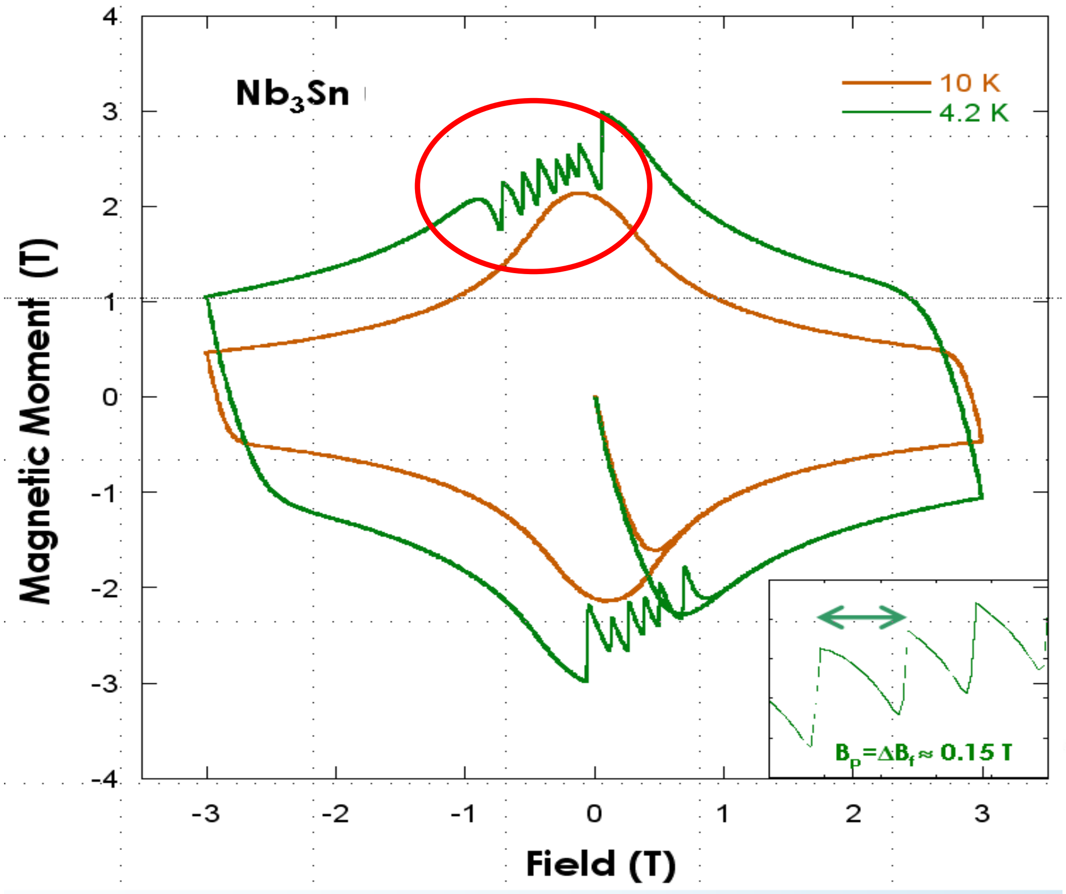


FIGURE 10(a). Flux motion caused by change in current density **(b)** feedb

Superconducting wires (strands): stability

Flux Jumping as observed



- Less stable at low fields, where J_c is higher
- The instability is worse at lower T because J_c increases and C decreases

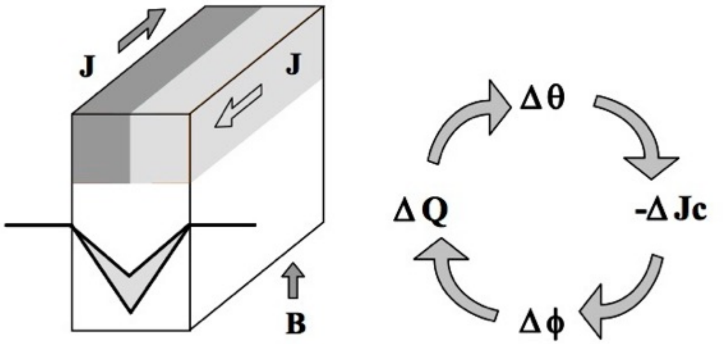
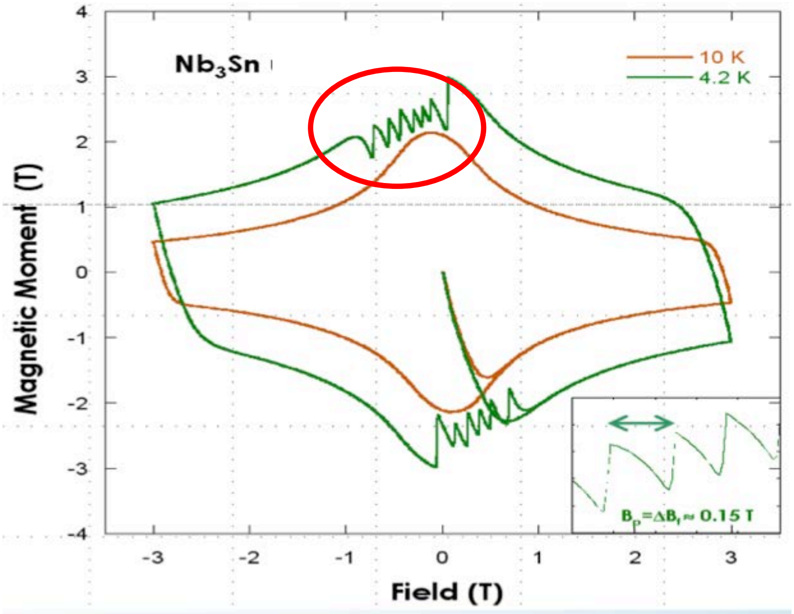


FIGURE 10(a). Flux motion caused by change in current density (b) feedb

Superconducting wires (strands): stability

The adiabatic stability condition to prevent flux jumping:

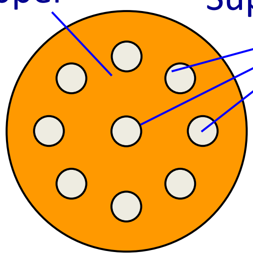
$$\beta_s \approx \frac{\mu_0 J_c^2 a^2}{\gamma C_s \left(T_c - T_{op}\right)} < 3$$



Where γ e C_s are the density and the specific heat of the material; T_c e J_c its critical temperature and current; a the diameter of the conducting element

A reduction of the diameter of the s.c. filaments is necessary

Multi-filamentary superconducting wires

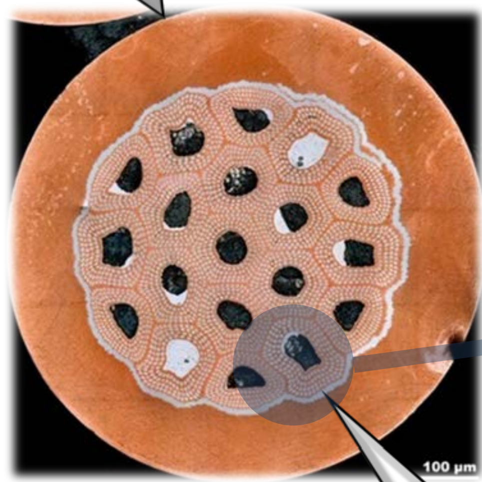


The superconduct. wire is formed of many **thin filaments** of s.c. materials, within a **Cu** stabilizing **matrix**

Wire diameter	0.5÷1 mm
# supecond. filaments	1000÷10000
Filament diameter	5÷50 μm
Cu/non Cu	4/1 ÷ 1/1

Wire

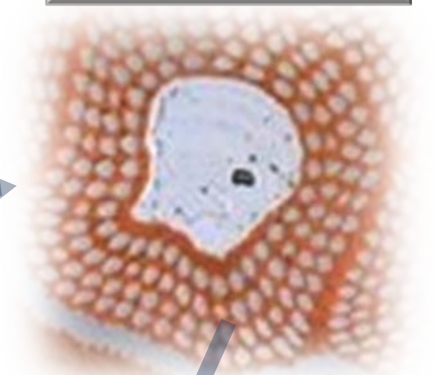
Photo courtesy of Peter Lee, FSU

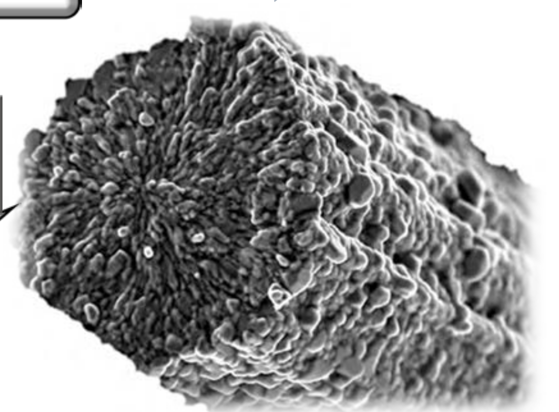


Φ = 0.81 mm

Bundle

Φ ~ 50-100 μm





Φ ~ few μm

Filament

Photo courtesy of J. Minervini MIT

AC losses in the superconductor

In the presence of **varying field:**

Type-II superconductors present a magnetic hysteresis due to the pinning of fluxons.

Hysteresis losses:

$$Q = \int \mu_0 M \, dH \longrightarrow Q_H = \frac{B_m^2}{2\mu_0}\Gamma(\beta)$$

$$\beta = \frac{B_m}{B_p} = \begin{cases} \dfrac{B_m}{\mu_0 J_C a} & (slab) \\ \dfrac{\pi B_m}{2\mu_0 J_C a} & (cylinder) \end{cases}$$

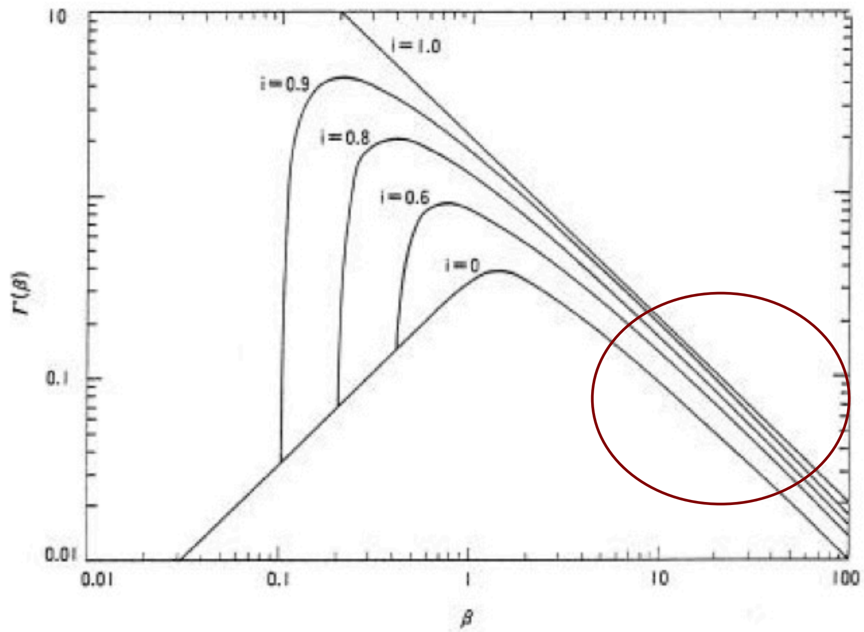


Figure 2.5: loss factor determining hysteresis losses for a slab carrying a transport current and subject to an external varying field.

AC losses in the superconductor

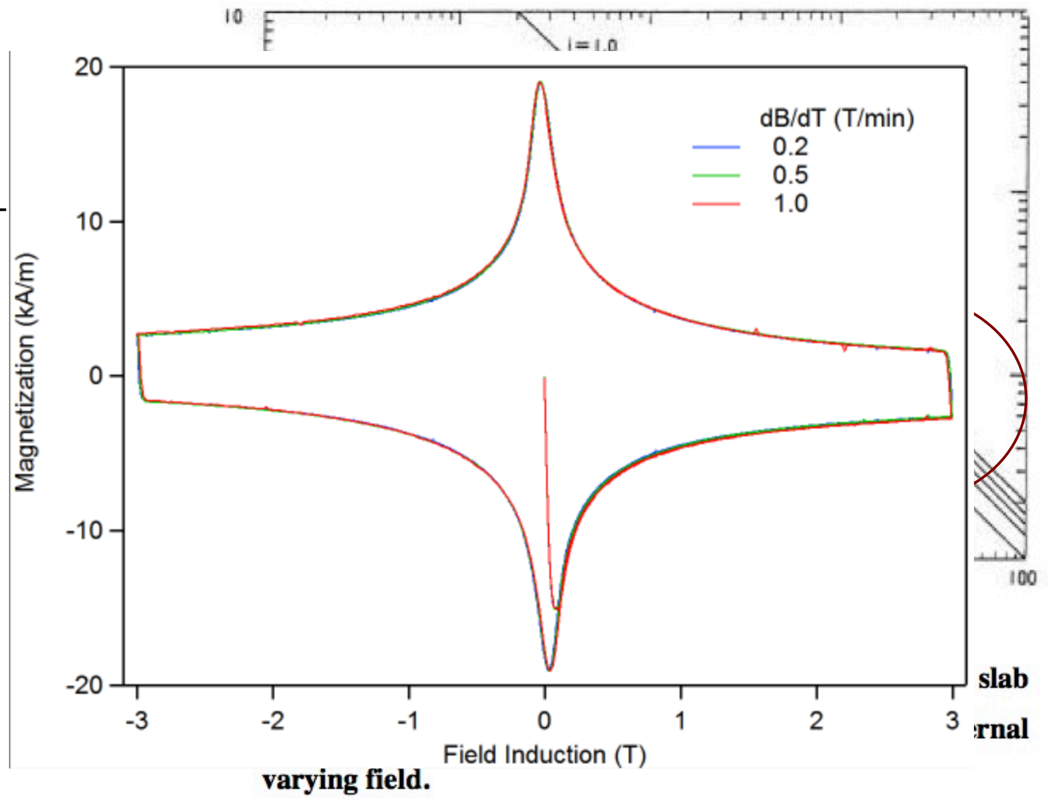
In the presence of **varying field:**

Type-II superconductors present a magnetic hysteresis due to the pinning of fluxons.

Hysteresis losses:

$$Q = \int \mu_0 M \, dH \longrightarrow Q_H = \frac{B_m^2}{2\mu_0}$$

$$\beta = \frac{B_m}{B_p} = \begin{cases} \dfrac{B_m}{\mu_0 J_C a} & (slab) \\[2ex] \dfrac{\pi B_m}{2\mu_0 J_C a} & (cylinder) \end{cases}$$



AC losses in the superconductor

In the presence of **varying field:**

time variation of the magnetic flux generates screening currents in the wire, which tend to oppose to the field variations.

Coupling losses:

$$P = \frac{n\tau}{\mu_0}\left(\frac{dB}{dt}\right)^2 \qquad \tau = \frac{\mu_0}{2\rho_{et}}\left(\frac{p}{2\pi}\right)^2$$

"Twisting" of superconducting filaments is necessary

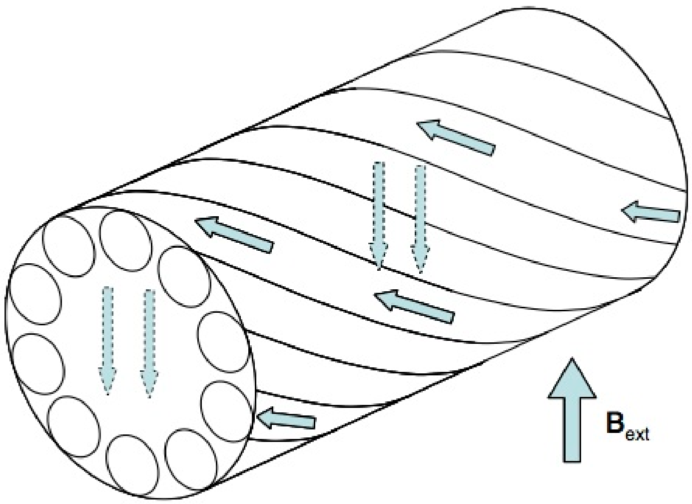
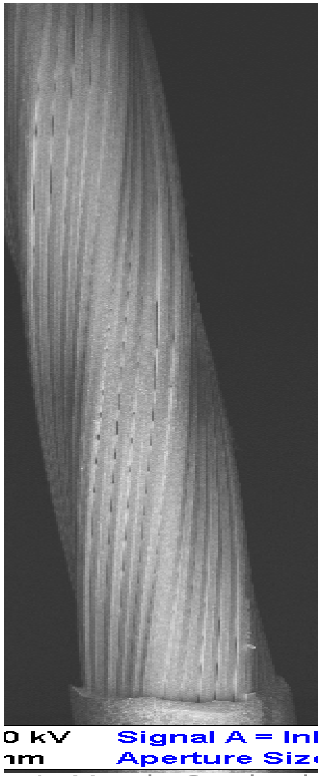


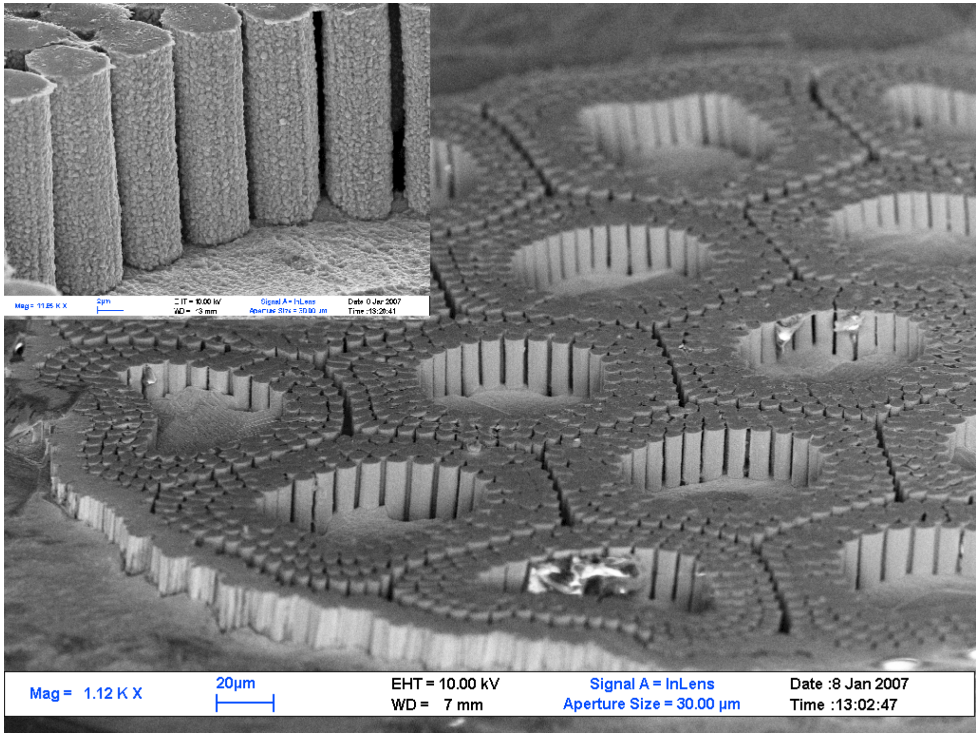
Fig. 2. The flow of coupling currents in a twisted composite wire.

Multi-filamentary superconducting wires

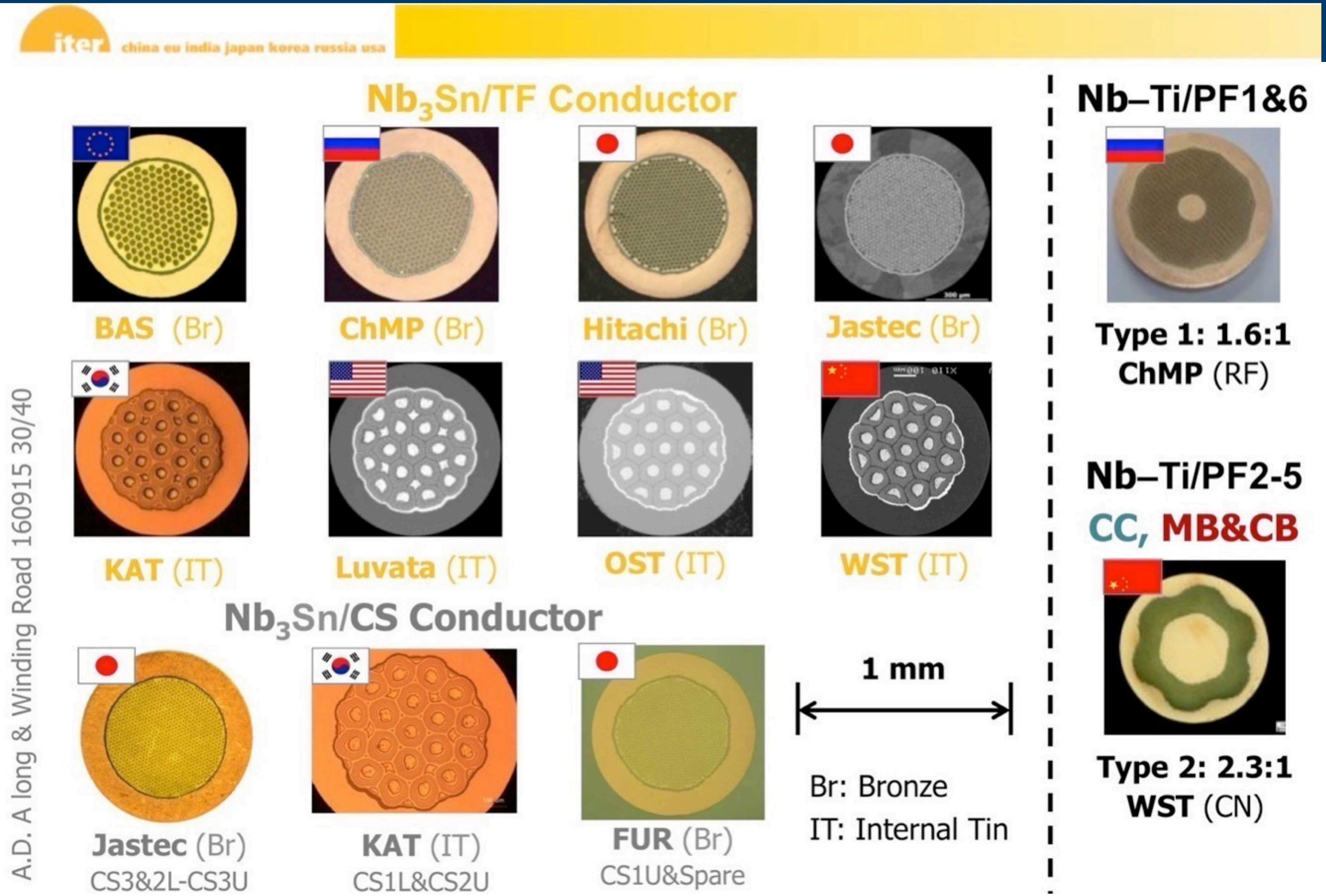
Superconducting wires (strands):

- **thin s.c. filaments (multi-filamentary);**
- **s.c. filaments within a Cu matrix;**
- **twisted filament structure.**



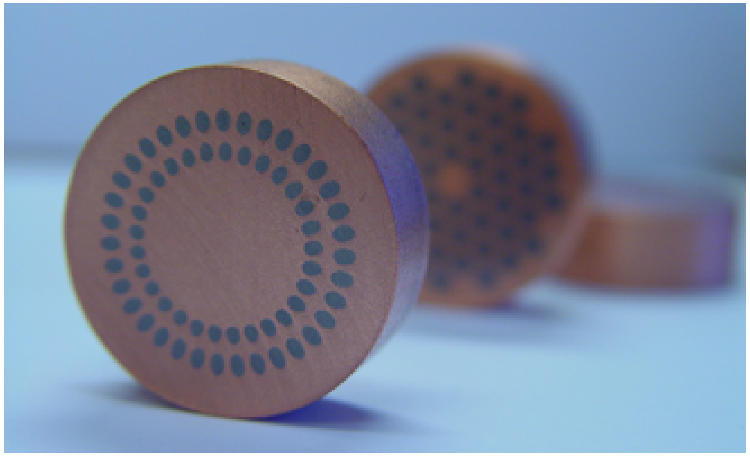


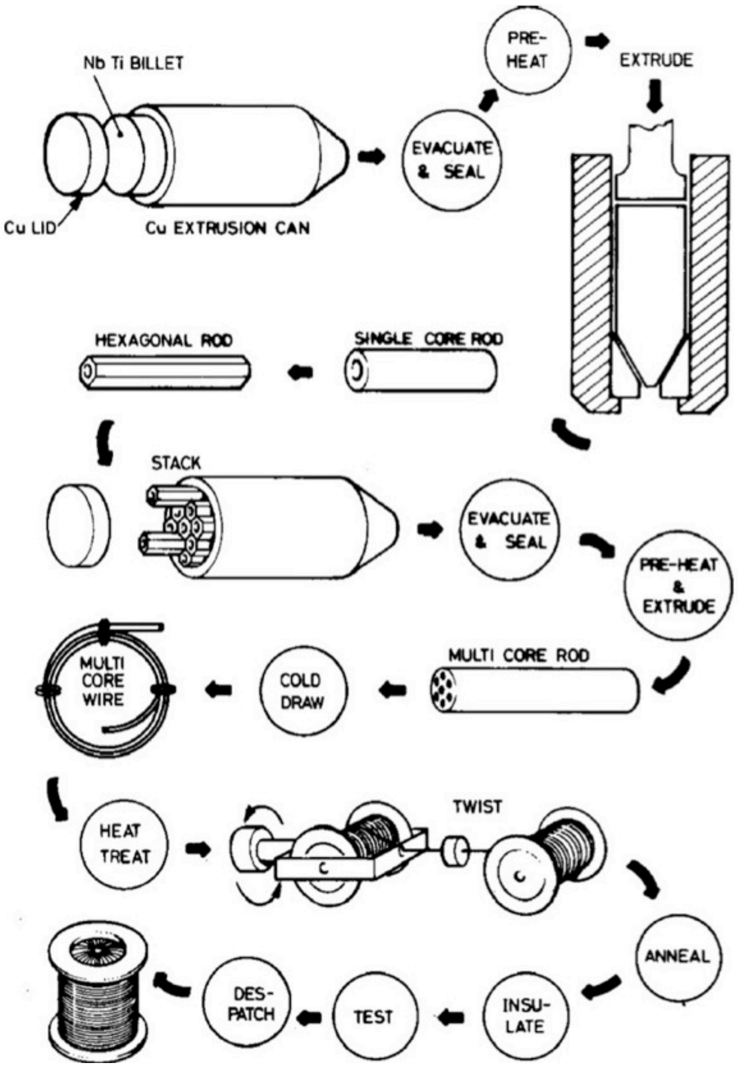
The ITER strands



Fabrication of s.c. wires

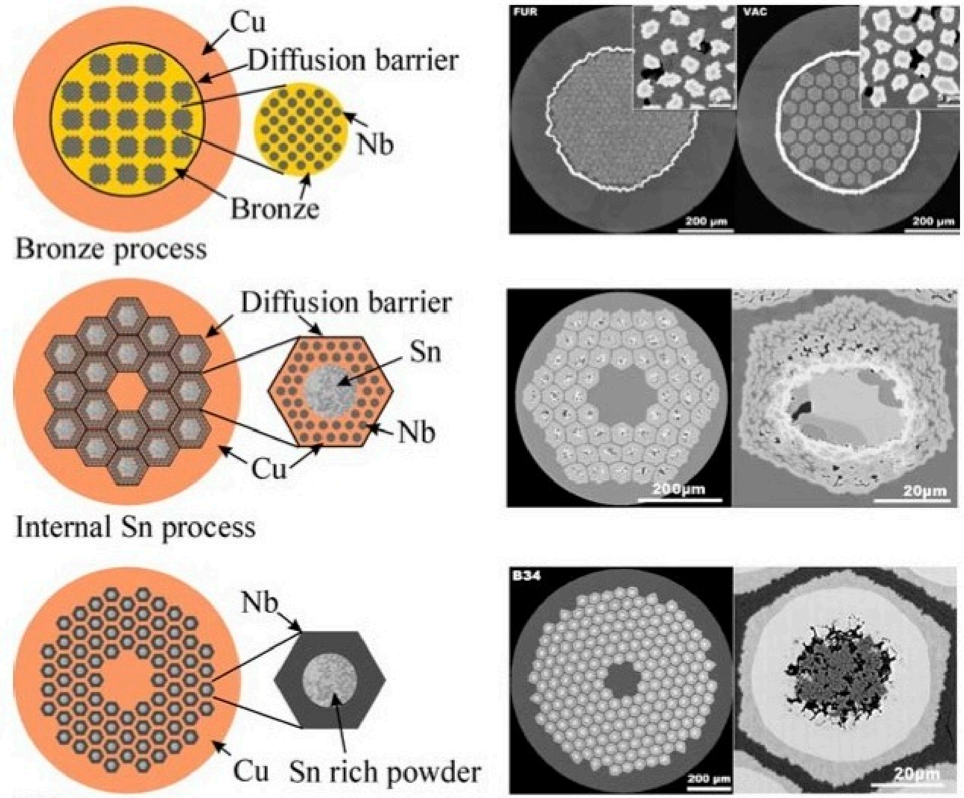
NbTi





Fabrication of s.c. wires

Nb_3Sn

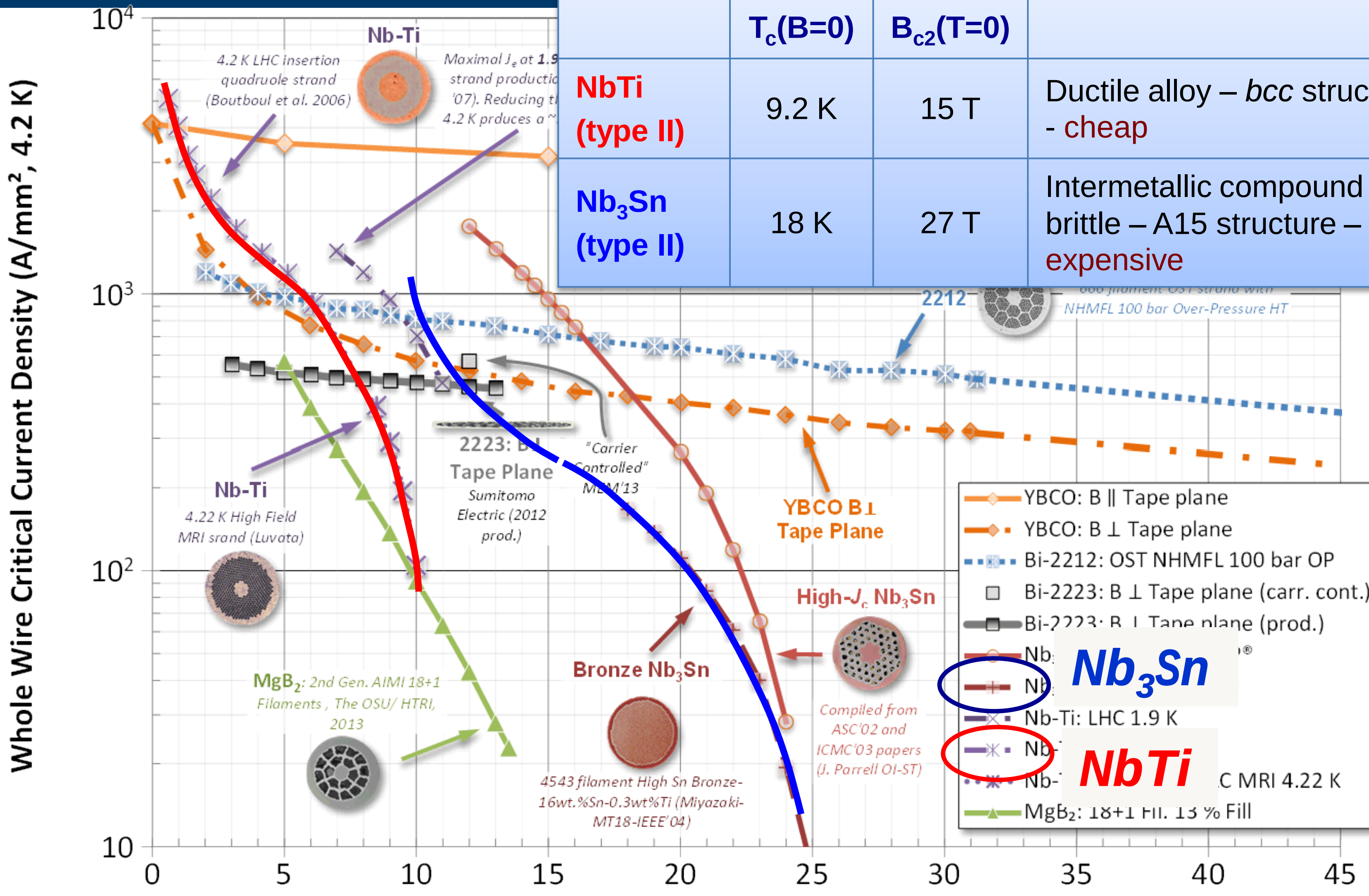


From
(PIT)
ding to

It requires a heat treament at 650 ° C to form the s.c. phase.

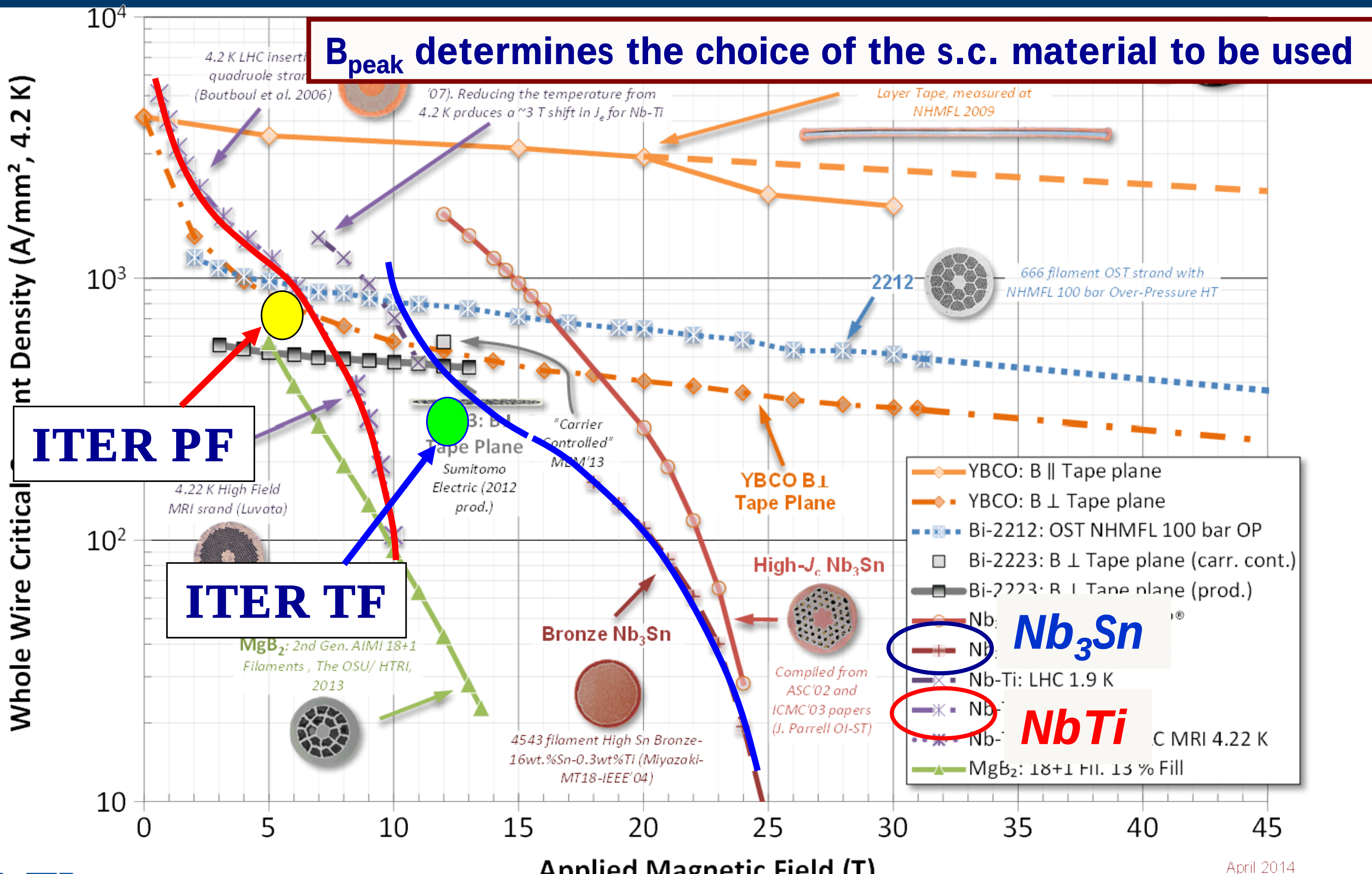
Once formed, it is a brittle material!

Practical Materials



	$T_c(B=0)$	$B_{c2}(T=0)$	
NbTi (type II)	9.2 K	15 T	Ductile alloy – *bcc* structure - cheap
Nb_3Sn (type II)	18 K	27 T	Intermetallic compound – brittle – A15 structure – expensive

Practical Materials



Outline

- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ ENEA activities beyond ITER

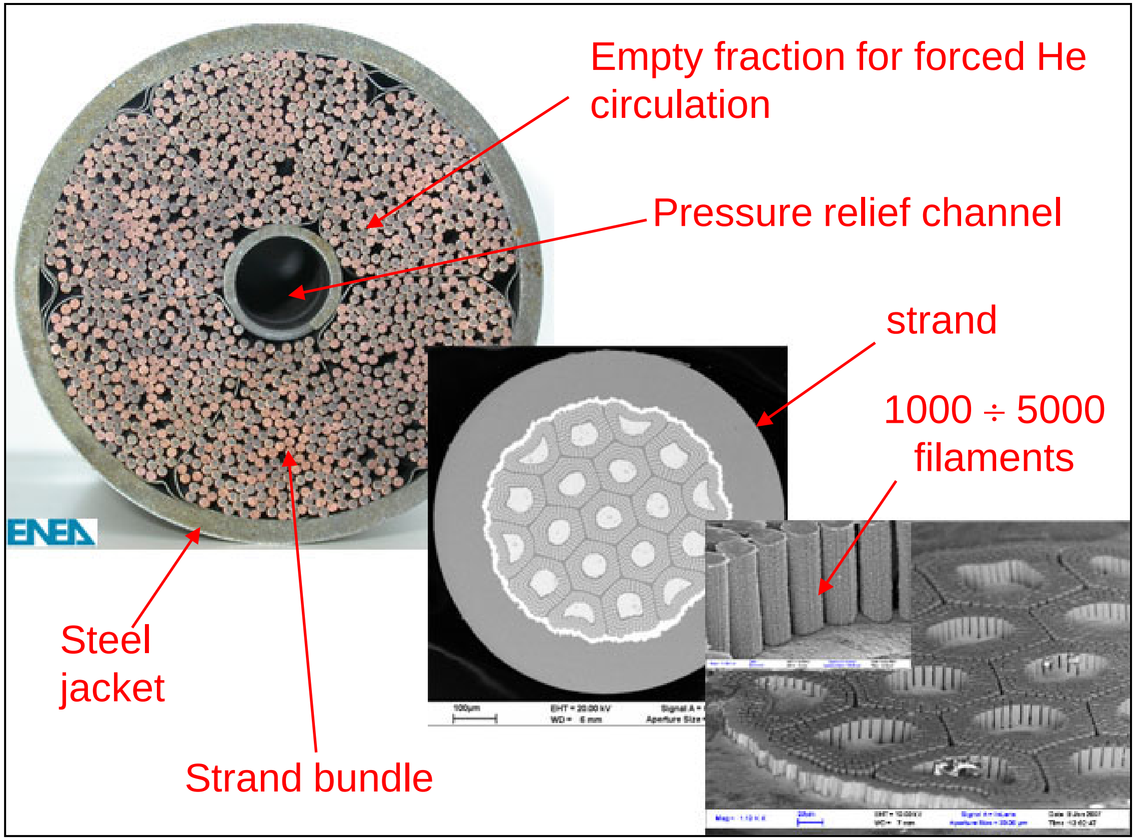
Superconducting cables

How should a certain number of s.c. wires be assembled into a cabled structure, that constitutes the conductor, by which fusion coils are wound?

Cryogenics of superconducting magnets

Hoenig; Montgomery; Iwasa (1975):

high cooling efficiency of single phase *(supercritical)* He in turbulent flow and in direct contact with a large wetted surface



Typically: *T ~ 4.5K, P ~ 6 ÷10 bar*

Convective heat transfer:

$$q_{S-He} = S \cdot h_{He-S}(T_S - T_{He})$$

- Effective cooling
- Mechanically strong
- Flexible layout
- Effective electrical insulation

BUT: Low J_{ENG}

Cryogenics of superconducting magnets

In Fusion magnets:

Cooling by *forced circulation of supercritical* helium ($P > P_{cr} = 2.26$ bar):

A high pressure He flow is used, which guarantees a better heat exchange and a rapid heat diffusion.

Above 2.26 bar, Helium is ***supercritical***, *i.e.* it exists in the form of a single-phase fluid, with high density. This prevents local evaporation and the formation of the vapour film that limits heat exchange.

It is the solution adopted in most of the superconducting tokamaks, as well as in ITER.

Typically: *T ~ 4.5K, P ~ 6 ÷10 bar*

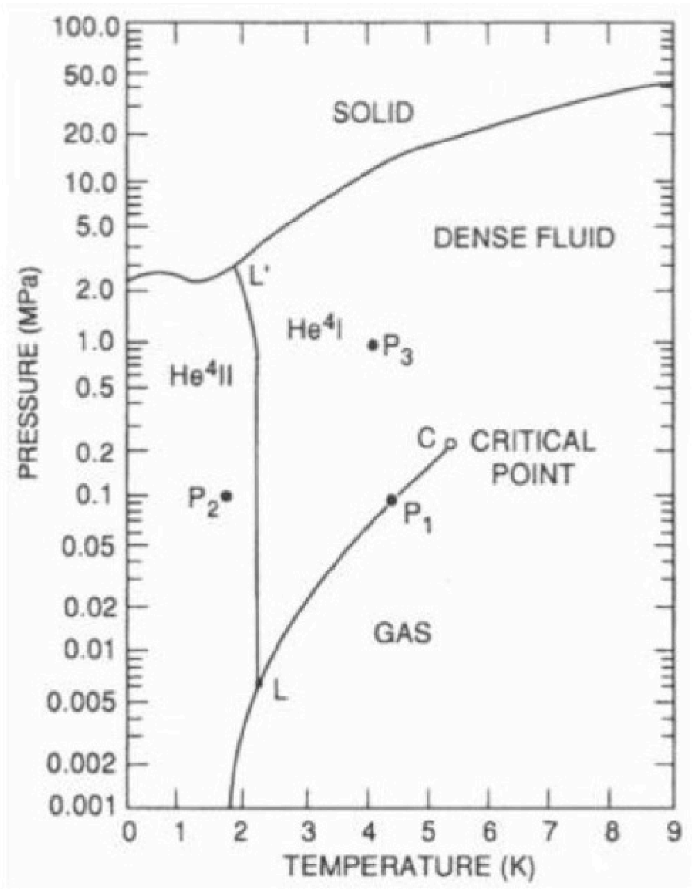


Figure 2.16: helium phase diagram.

Heat Loads in fusion coils

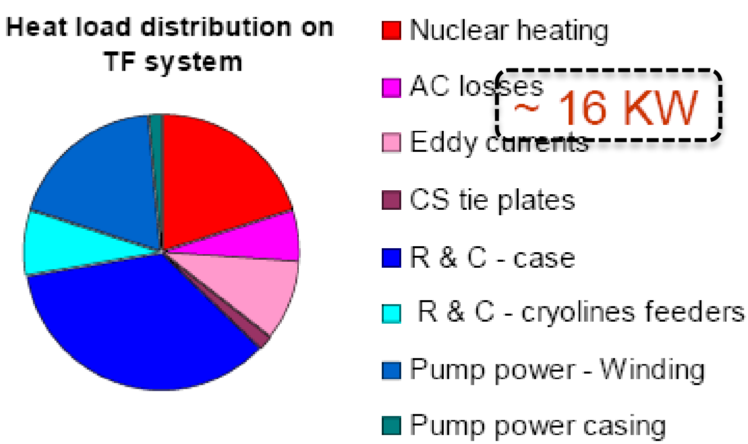
Source of losses:

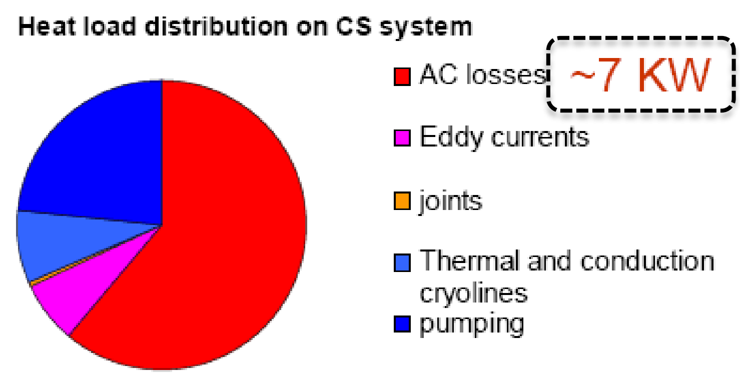
- *Hysteresis*
- *AC*
- *Coupling*
- *Eddy-*
- *Neutrons*
- *Thermal radiation & Conduction*

Due to varying field and currents → ***Specific of CS conductors***

Neutrons → ***Specific of TF conductors***

ITER design experience:

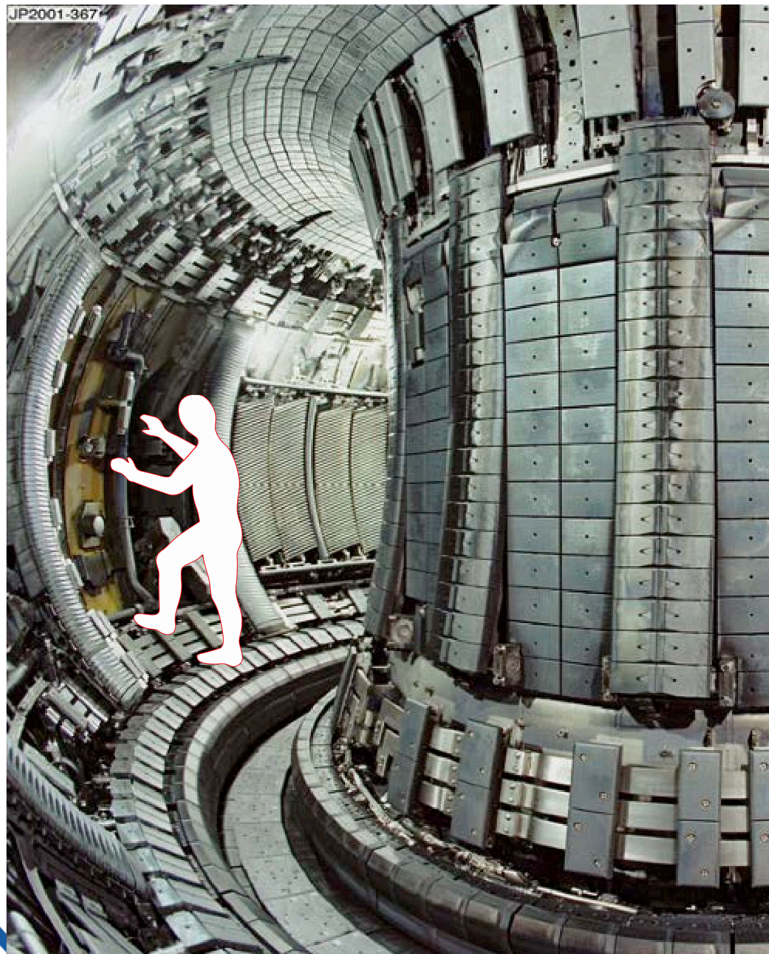




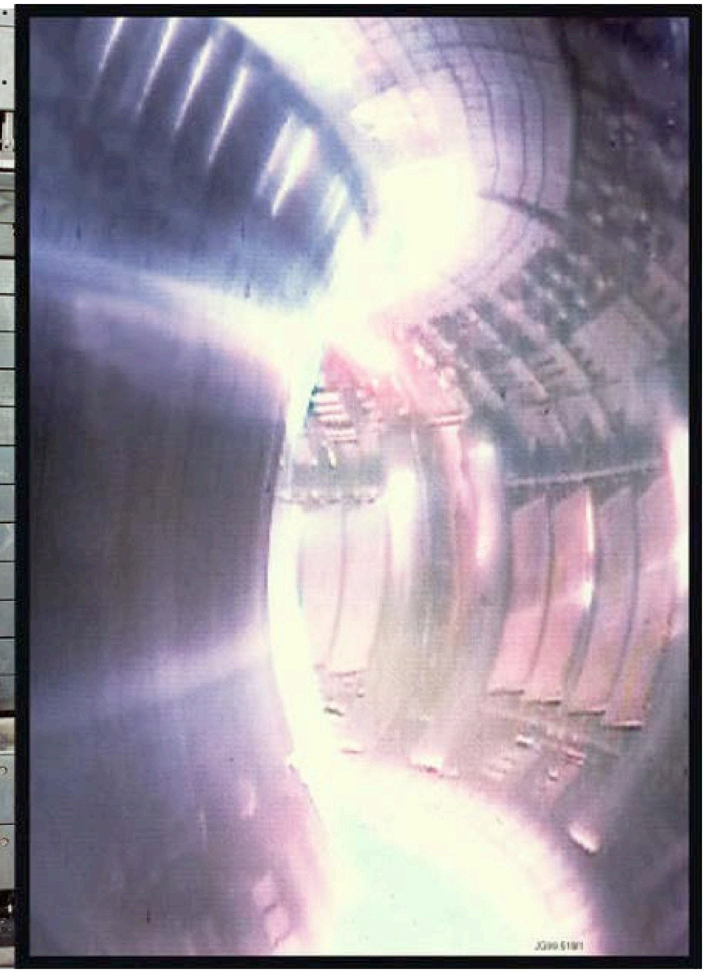
Heat Loads in fusion coils: nuclear heating

JET interior of vacuum vessel

no plasma

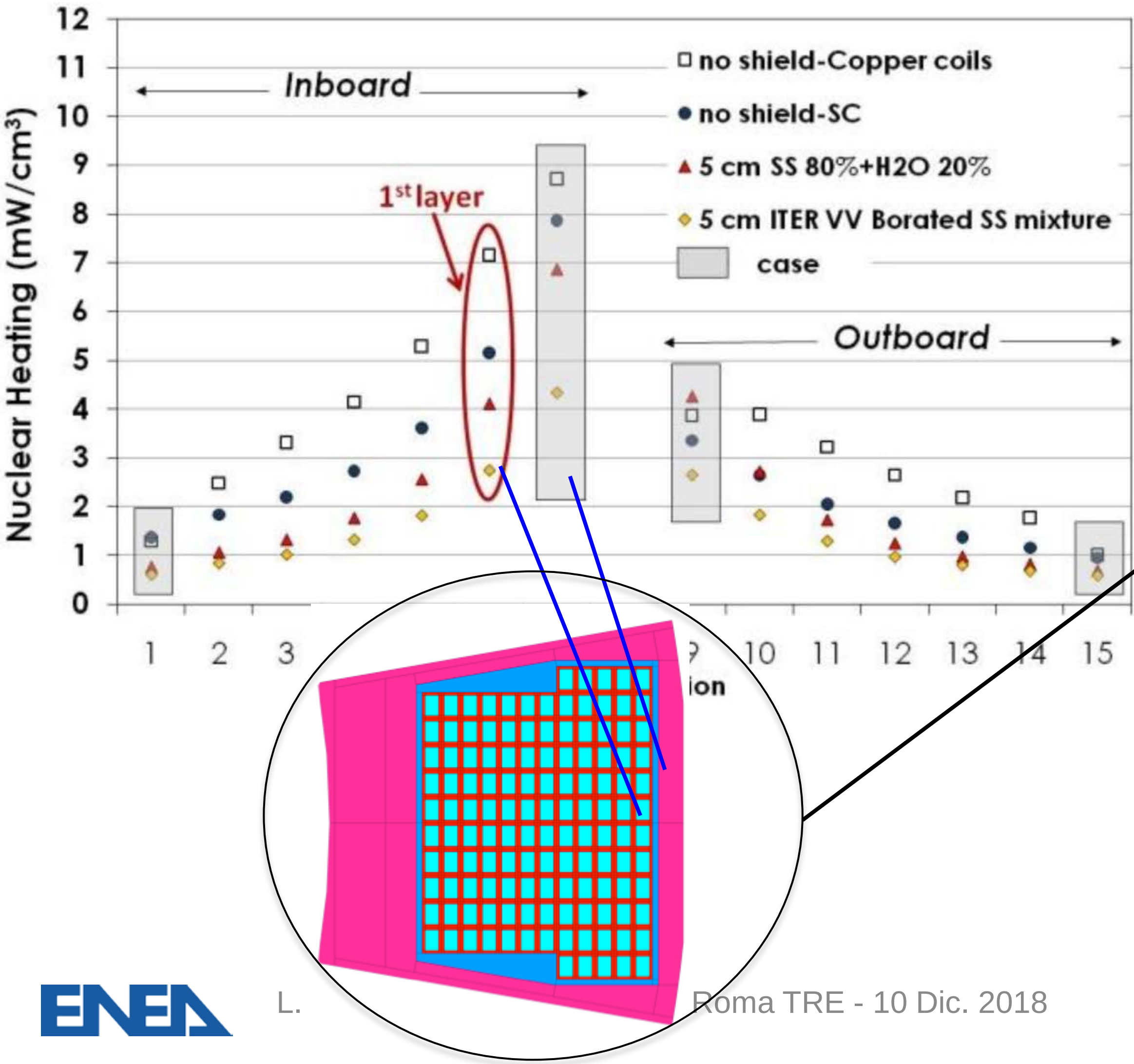


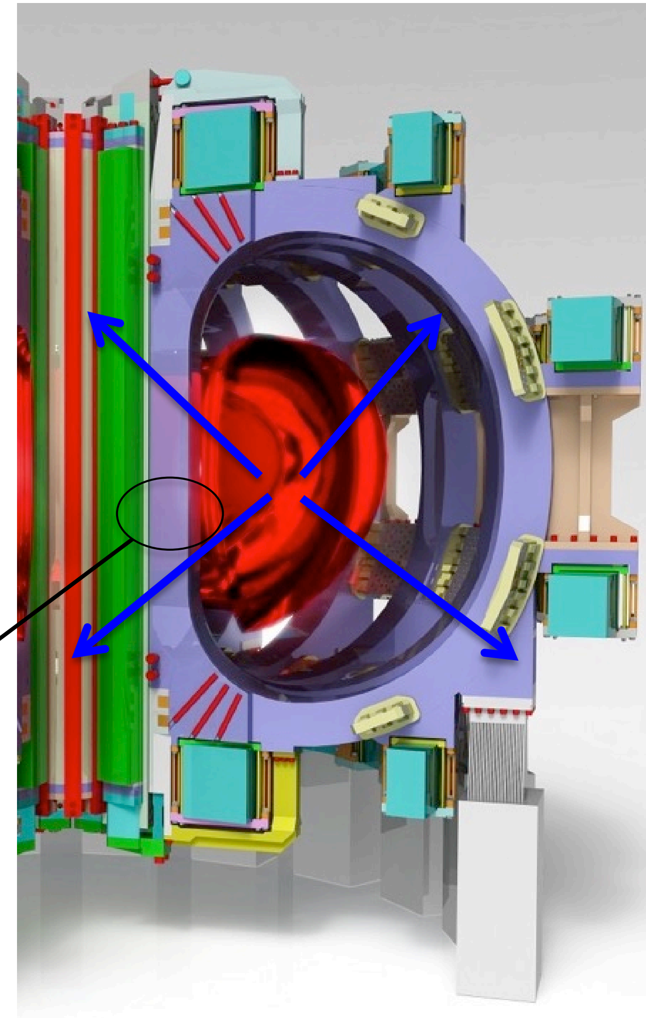
with plasma



Heat Loads in fusion coils: nuclear heating

Nuclear Heat load FAST TF (2011)





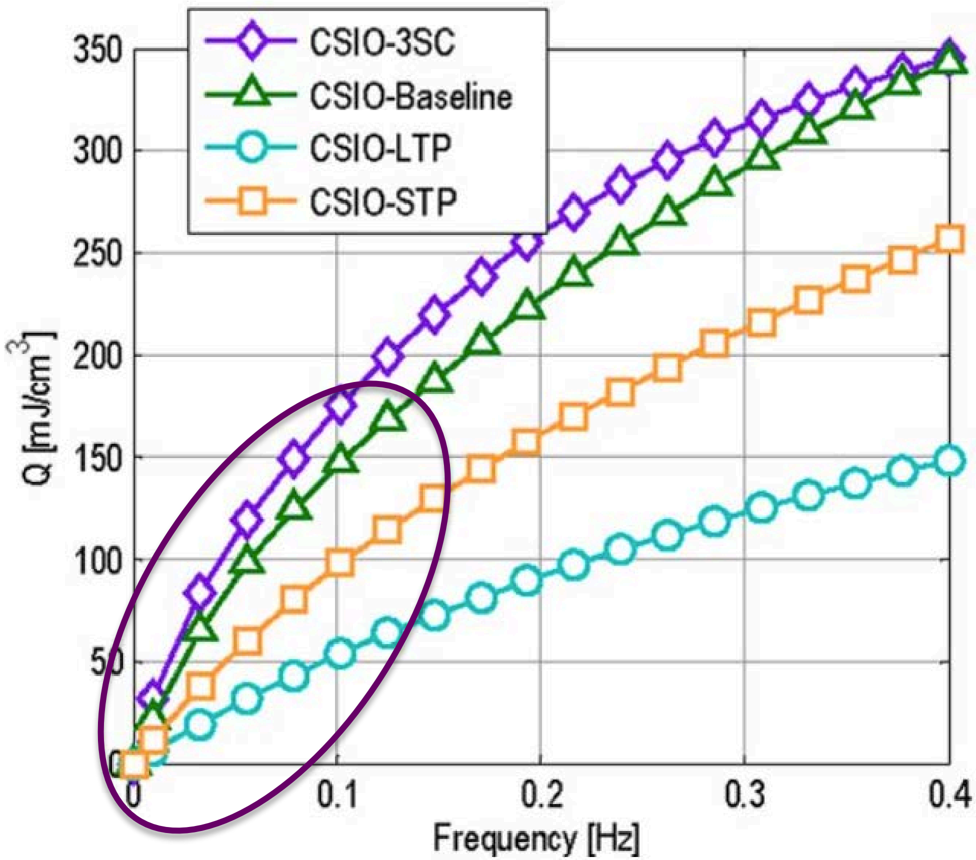
Heat Loads in fusion coils: AC losses

Example of measured losses in the ITER CS CICCs

Hysteresis are the extrapolated value to zero frequency (present plot is normalized!)

Coupling time constant ***(nτ)*** is obtained form the linear fit of the low-frequency range.

Nijhuis_IEEE TAS 13



Multiple time constants ***($n\tau_1$, $n\tau_2$, $n\tau_3$, …)*** would be more appropriate for CICCs.

$$Q_{hyst} = \frac{2}{3\pi}(1+i^2)d_{eff}J_c(B,T)\left|\frac{dB_e}{dt}\right|$$

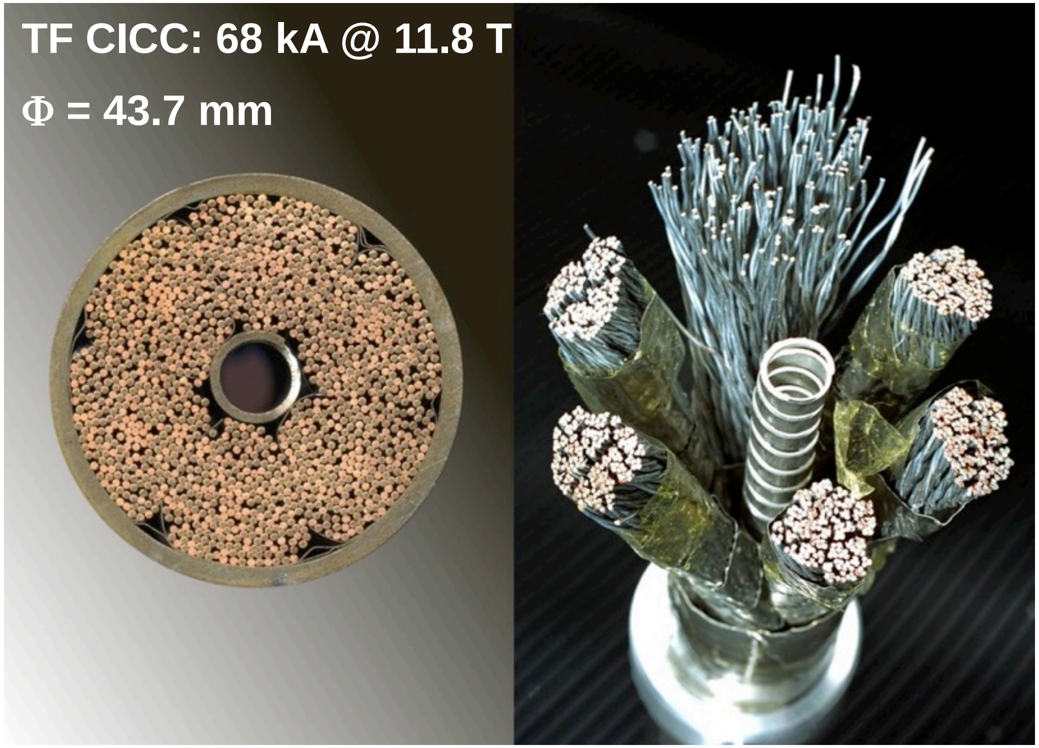
$$Q_{coup} = \frac{n\tau}{\mu_0}\left|\left(\frac{dB_e}{dt}\right)\left(\frac{dB_i}{dt}\right)\right|$$

$$Q_{eddy} = \frac{l_{out}^2}{12\,\rho_{jacket}}\left(\frac{dB_i}{dt}\right)^2$$

The ITER CICCs

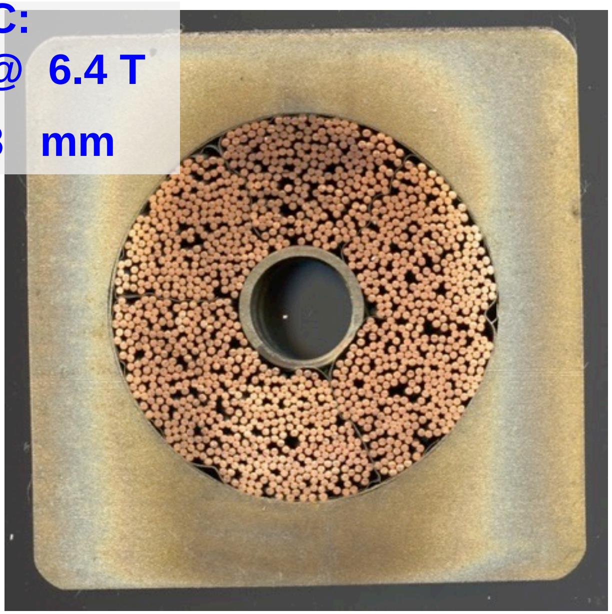
TF CICC: 68 kA @ 11.8 T

Φ = 43.7 mm



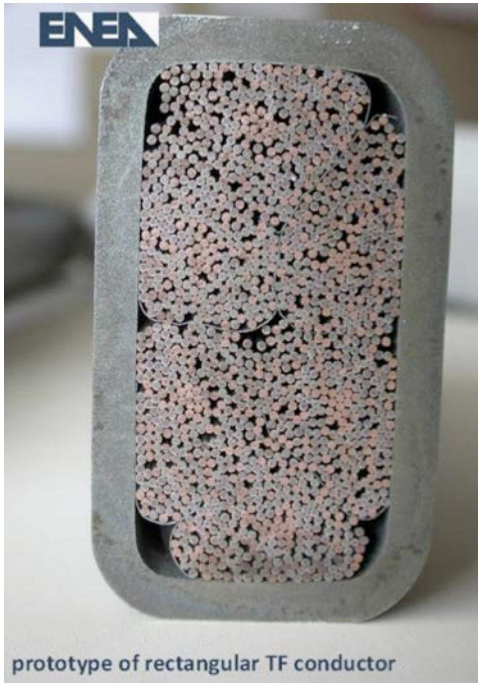
PF CICC:
52 kA @ 6.4 T

L = 53.8 mm



CS CICC: 46 kA @ 13 T; L = 49

… or other prototypes



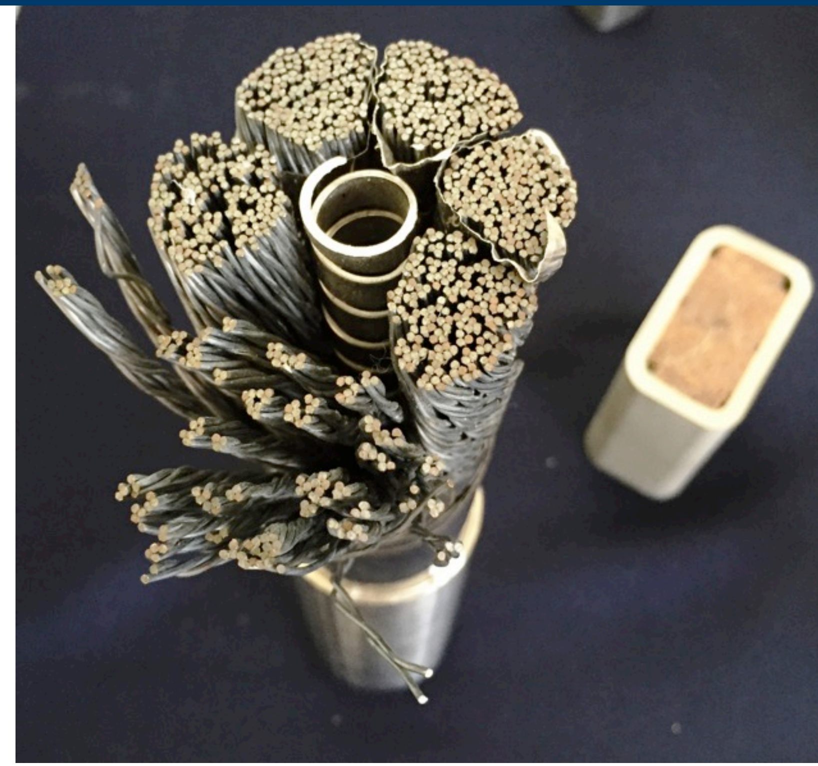
56 mm

32 mm

22 mm

26 mm

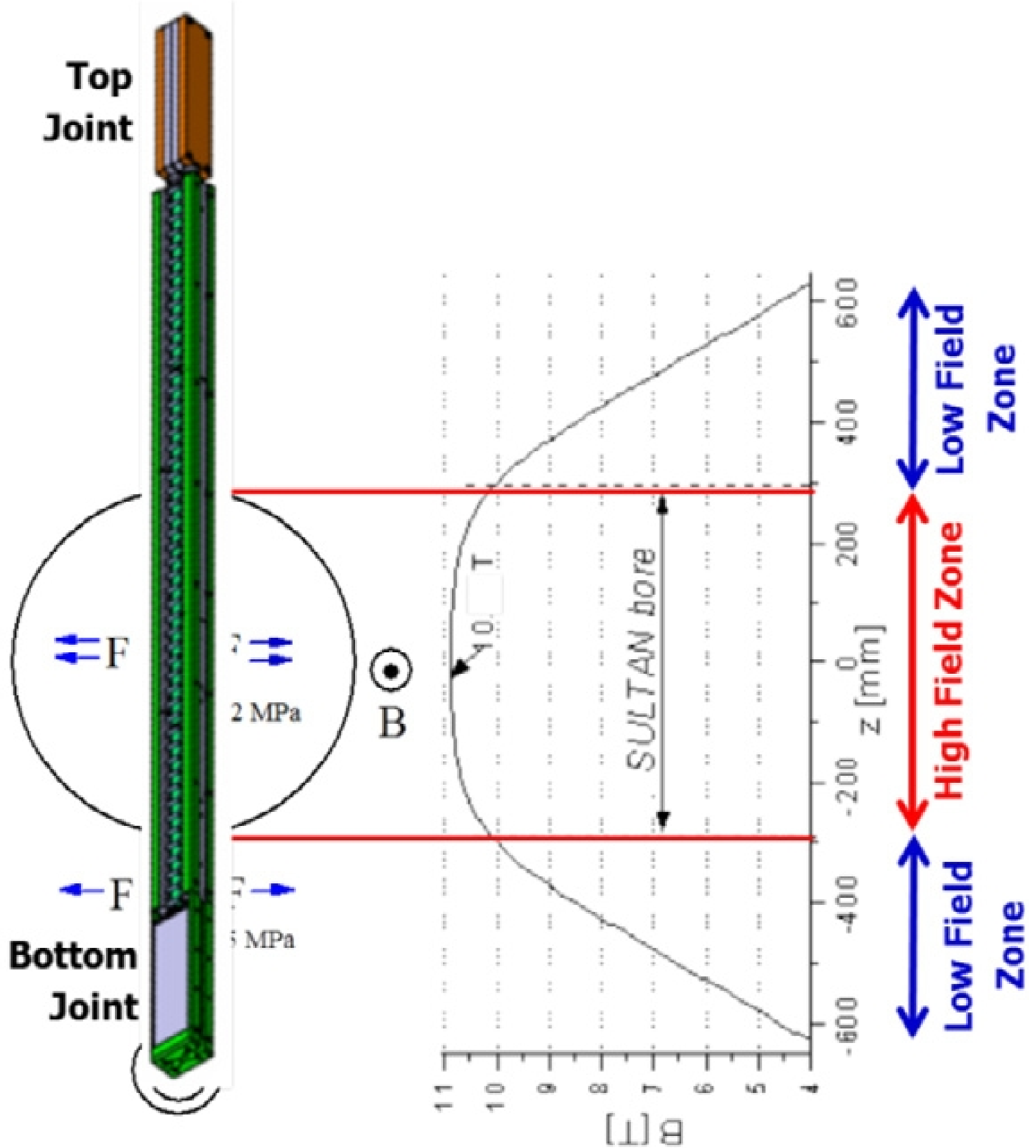
JT-60SA TF →



TF CICC: 68 kA @ 11.8 T

… or other prototypes

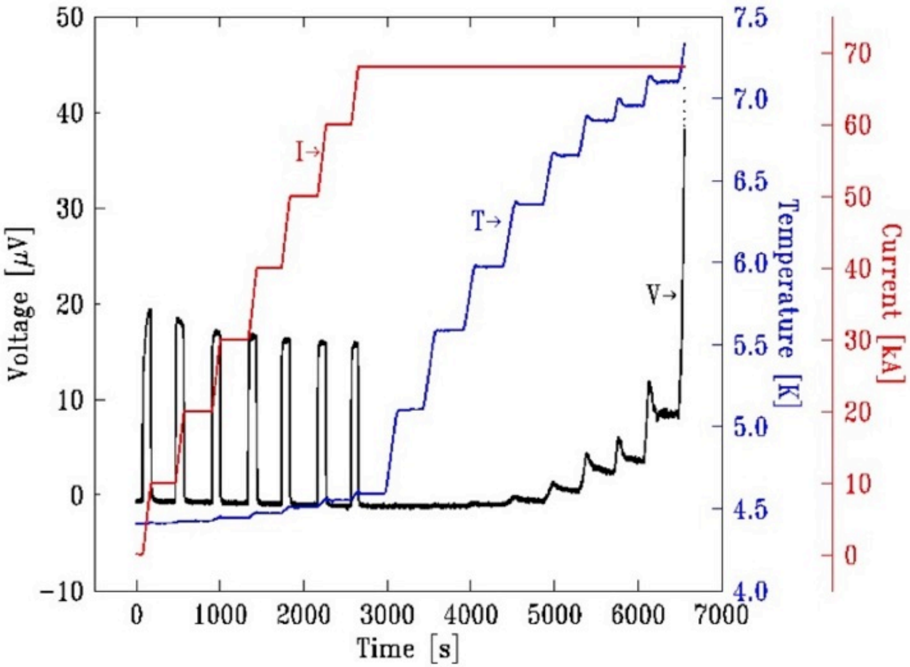
CICC qualification tests: the SULTAN facility

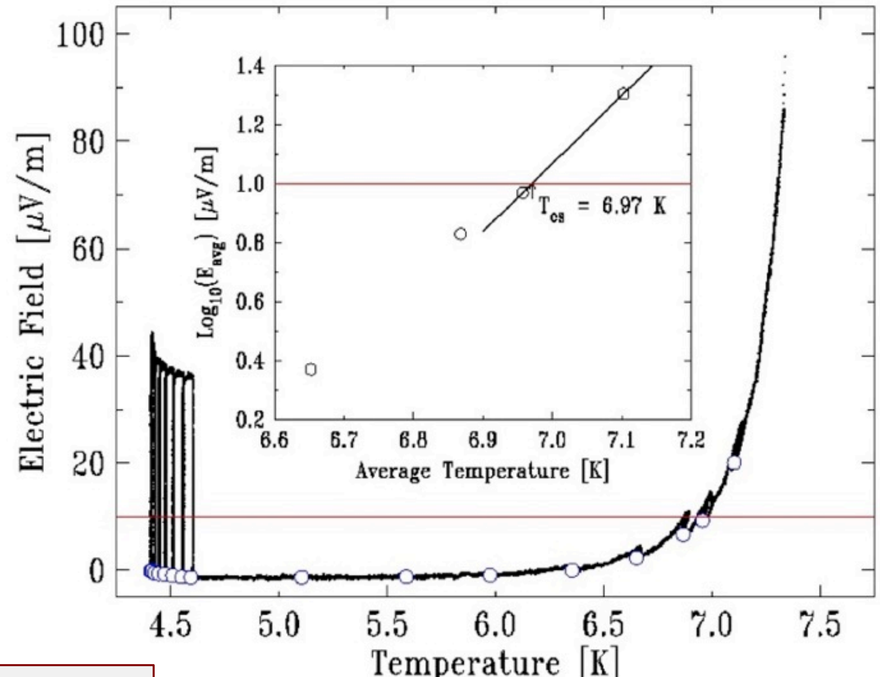


CICC qualification tests: T_{cs}

SULTAN facility at the:

Typical Current Sharing Temperature (T_{cs}) test





Breschi_SUST 2012

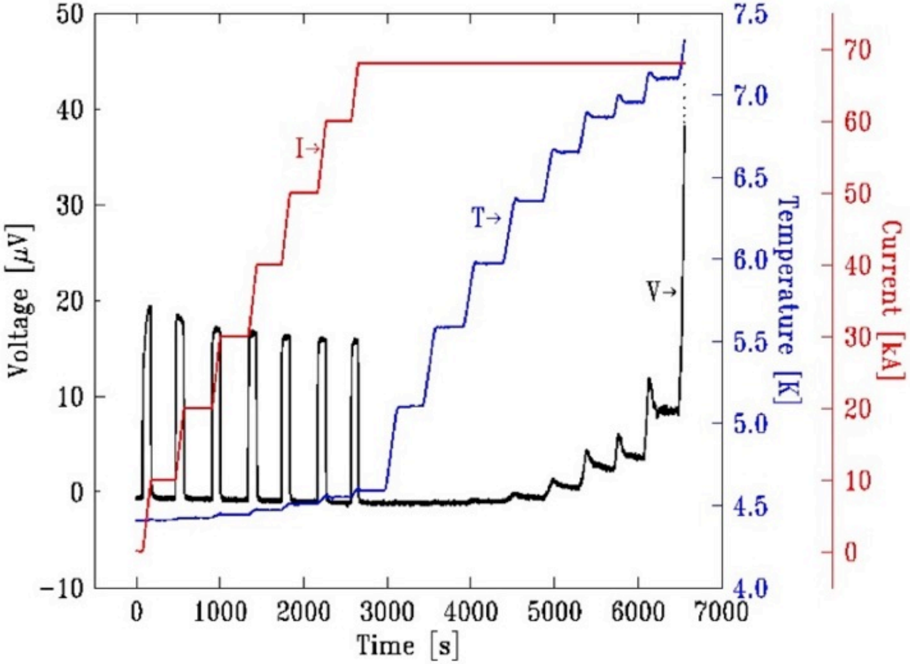
CICC qualification tests: T_{cs}

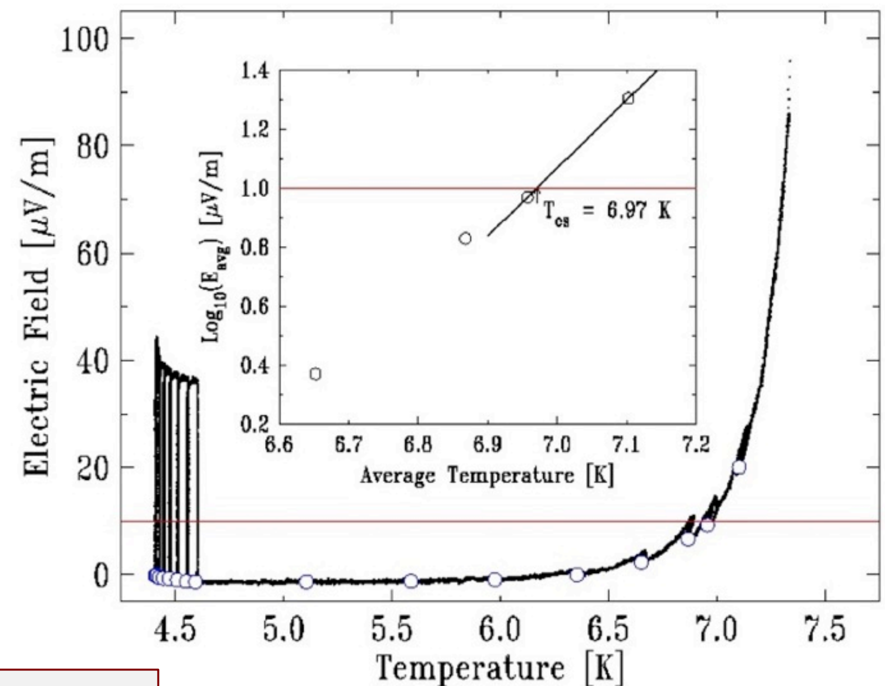
SULTAN facility at the:

SWISS PLASMA CENTER

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Typical Current Sharing Temperature (T_{cs}) test





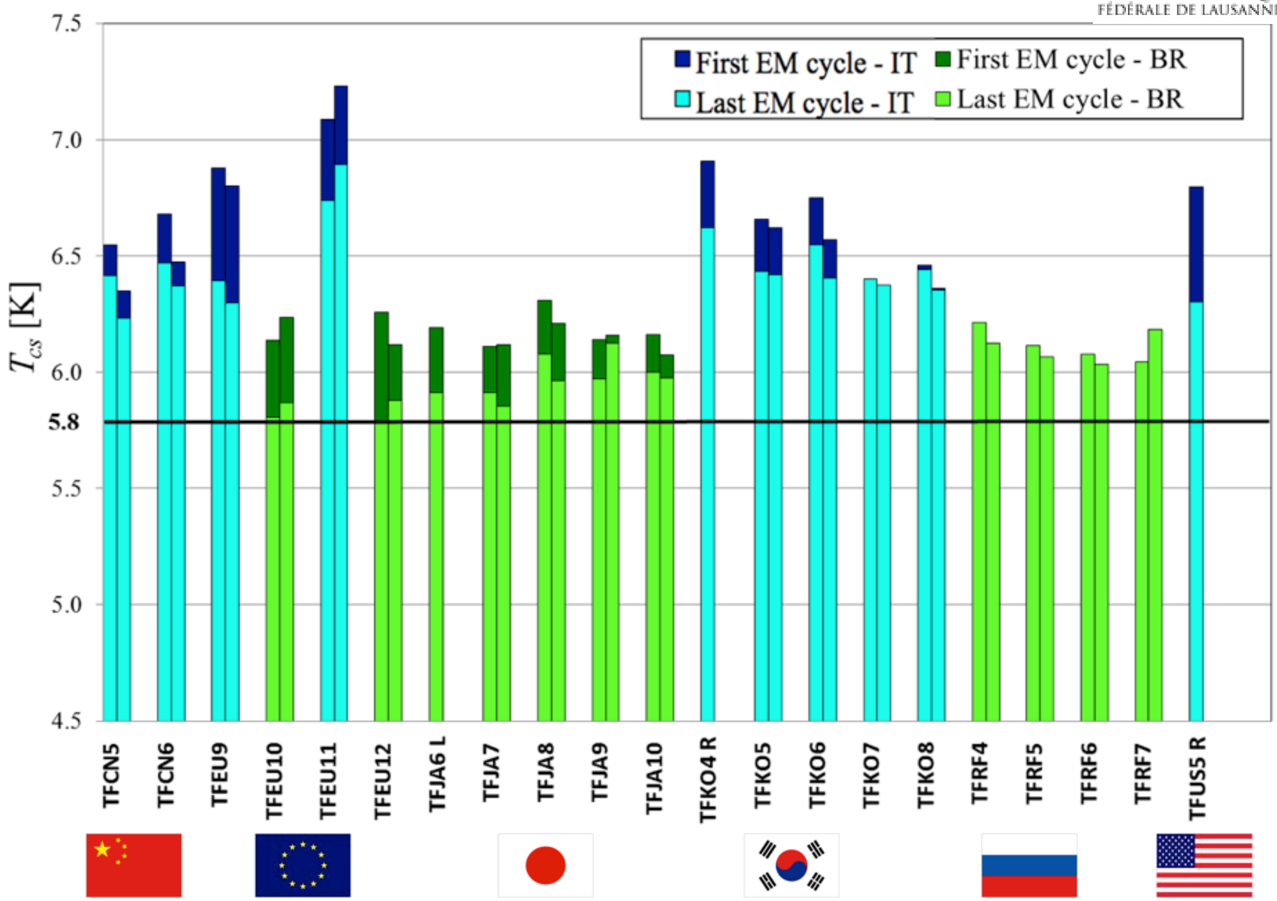
Breschi_SUST 2012

Repeated after e.m. loading cycles + Warm-up-Cooldown (WUCD) cycles

CICC qualification tests: T_{cs}

SULTAN facility at the:

ITER TF: T_{cs} measurements with cycles



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

M. Breschi – A. Devred

Outline

- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ The ENEA activities beyond ITER

Manufacturing of ITER Conductors

1. cabling (strands; spiral; steel wrapping)
2. jacket assembly
3. Cable insertion (by pull-through)
4. Conductor compaction
5. Conductor spooling
6. Final acceptance tests
7. Shipment to magnet

supplier

Manufacturing of ITER Conductors

1. **cabling (strands; spiral; steel wrapping)**
2. jacket assembly
3. Cable insertion (by pull-through)
4. Conductor compaction
5. Conductor spooling
6. Final acceptance tests
7. Shipment to magnet

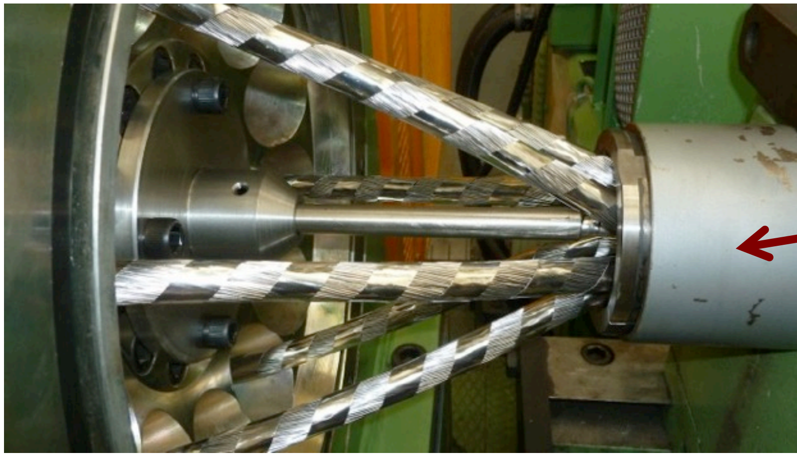
supplier

Manufacturing of ITER Conductors

TRATOS Production line for ITER cables

Manufacturing of ITER Conductors

Final Cable compaction system



Manufacturing of ITER Conductors

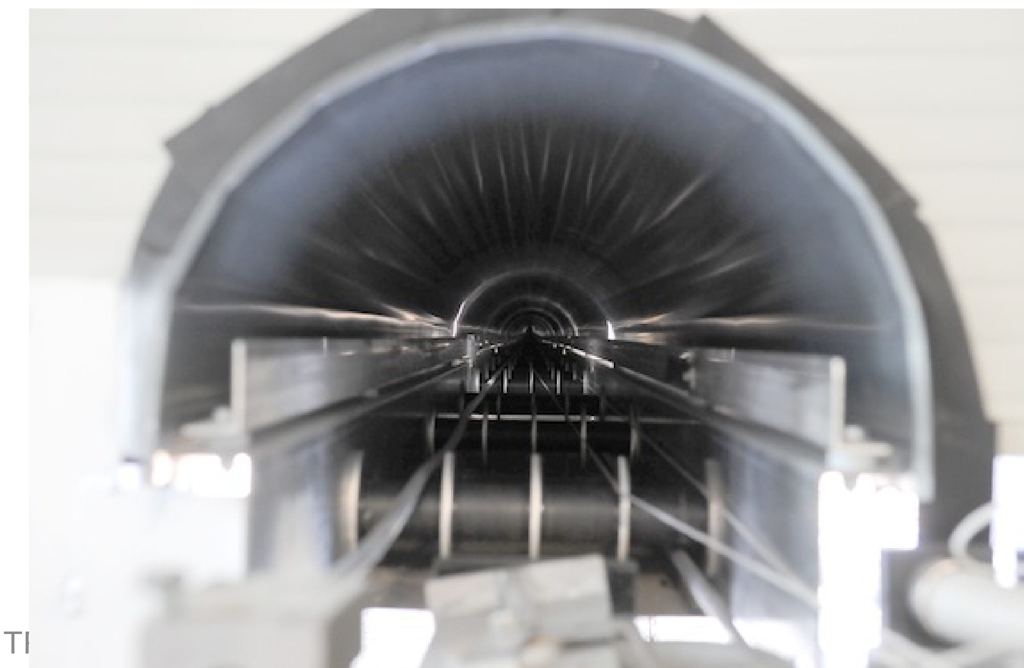
1. cabling (strands; spiral; steel wrapping)
2. **jacket assembly**
3. Cable insertion (by pull-through)
4. Conductor compaction
5. Conductor spooling
6. Final acceptance tests
7. Shipment to magnet

supplier

Manufacturing of ITER Conductors

A straight tube length of **760 m** has to be obtained by butt-welding (**Jacket Assembly**):

CRIOTEC Jacketing Line

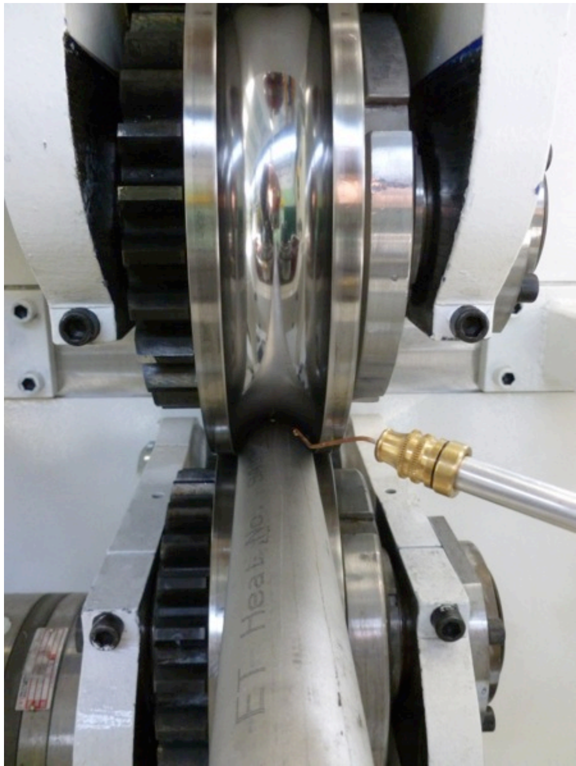


Manufacturing of ITER Conductors

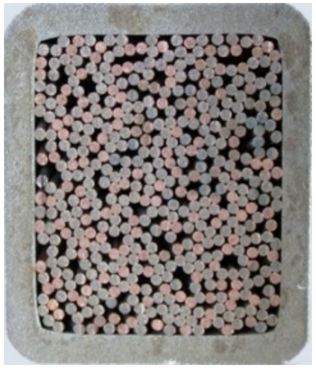
1. cabling (strands; spiral; steel wrapping)
2. jacket assembly
3. Cable insertion (by pull-through)
4. **Conductor compaction**
5. Conductor spooling
6. Final acceptance tests
7. Shipment to magnet

supplier

Manufacturing of ITER Conductors

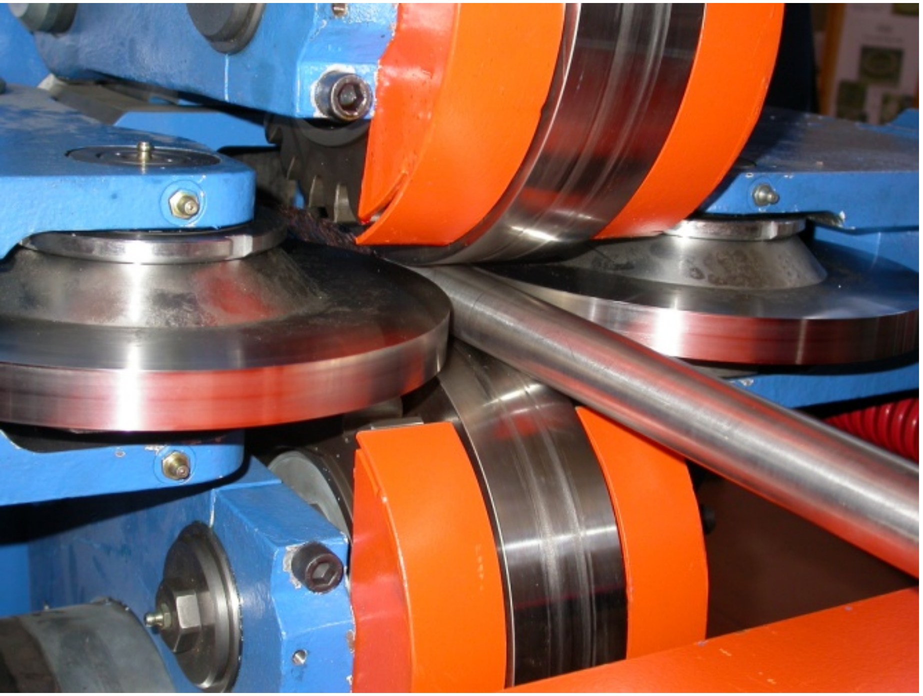


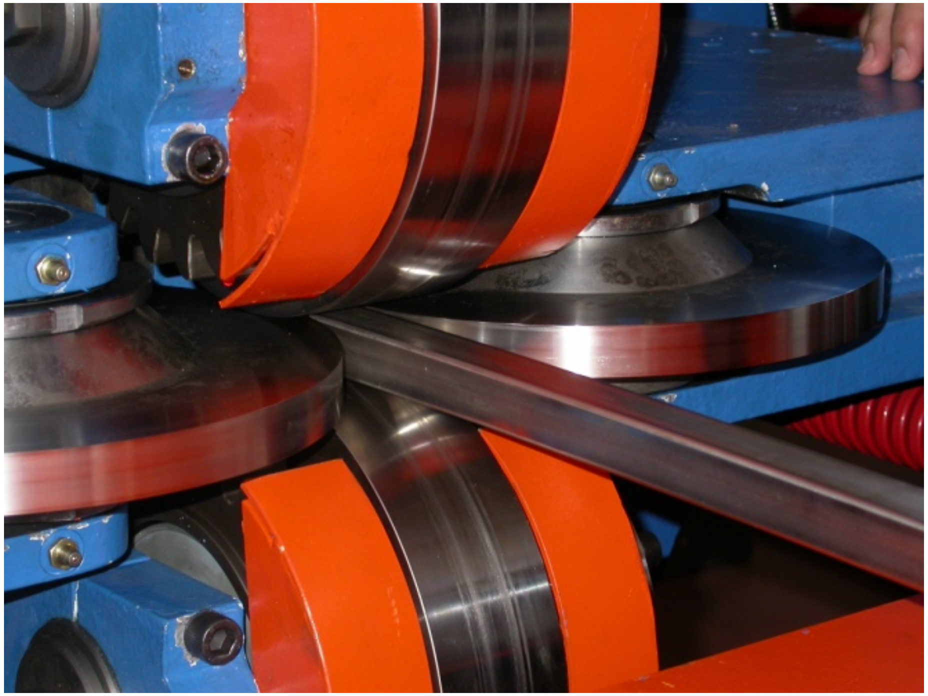
Manufacturing of ITER Conductors



Before compaction

After compaction

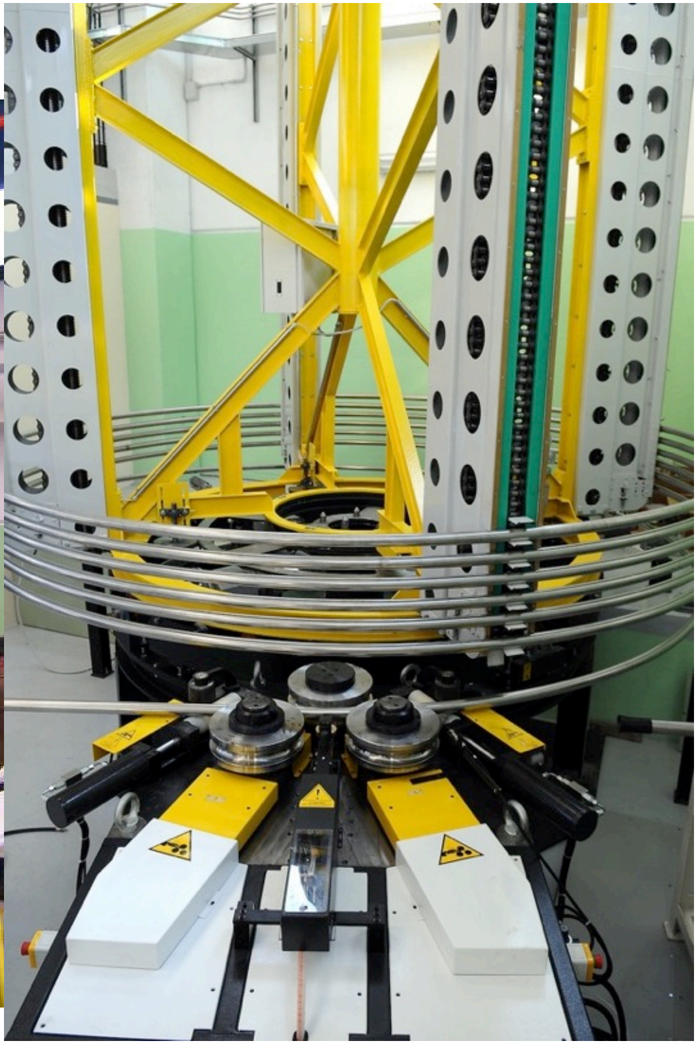




Manufacturing of ITER Conductors

1. cabling (strands; spiral; steel wrapping)
2. jacket assembly
3. Cable insertion (by pull-through)
4. Conductor compaction
5. **Conductor spooling**
6. Final acceptance tests
7. Shipment to magnet

Manufacturing of ITER Conductors



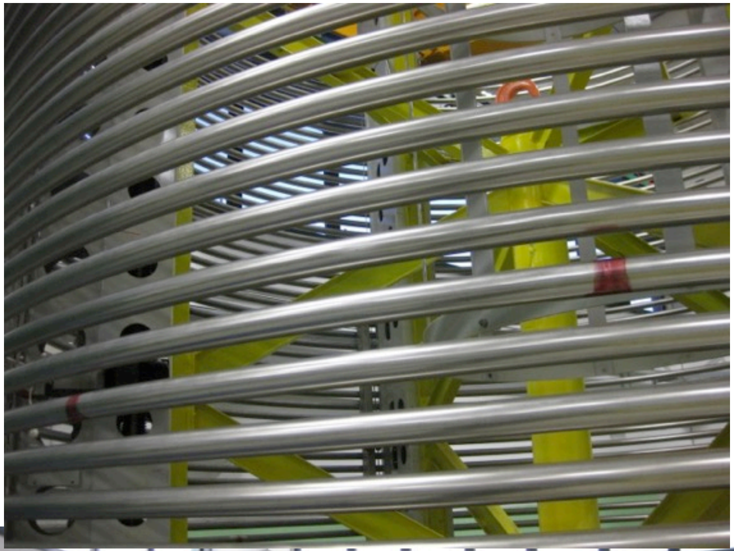
Manufacturing of ITER Conductors

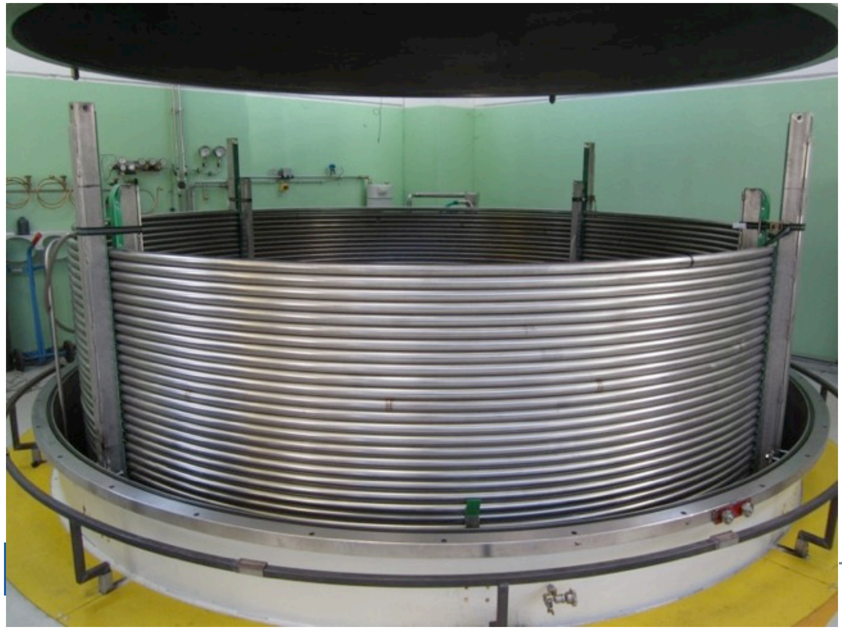
1. cabling (strands; spiral; steel wrapping)
2. jacket assembly
3. Cable insertion (by pull-through)
4. Conductor compaction
5. Conductor spooling
6. **Final acceptance tests**
7. Shipment to magnet

supplier

Manufacturing of ITER Conductors

1. Dye penetrant test of each weld on spooled conductor;
2. Mass flow test of conductor unit length with gas N_2;
3. He leak test in vacuum chamber.



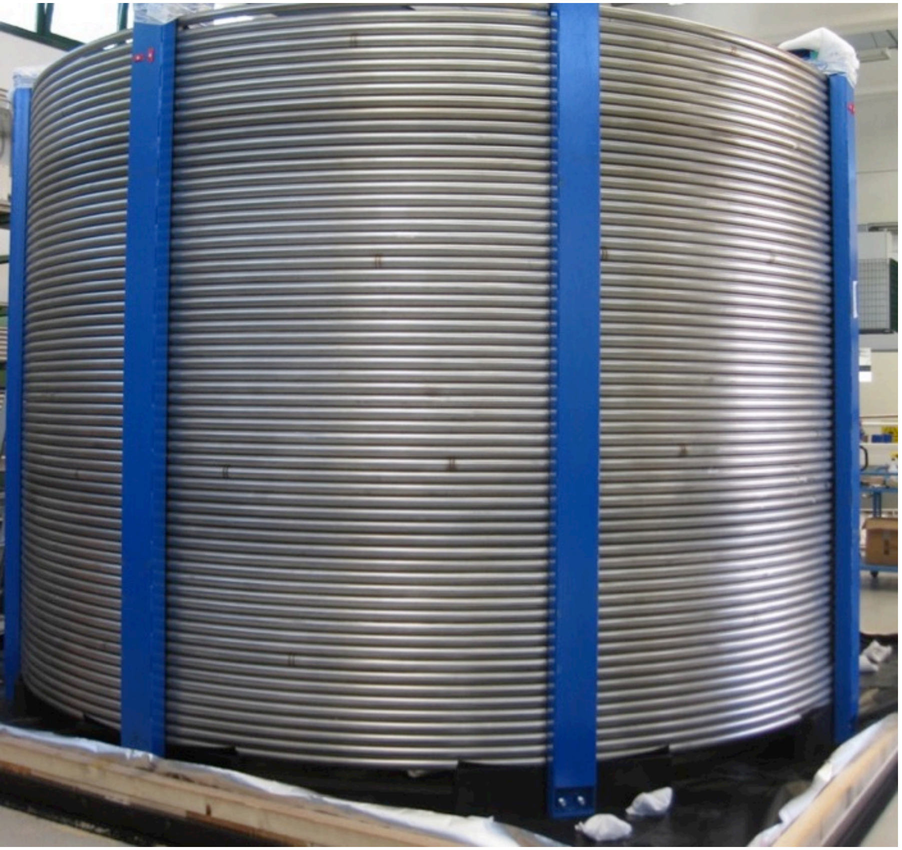


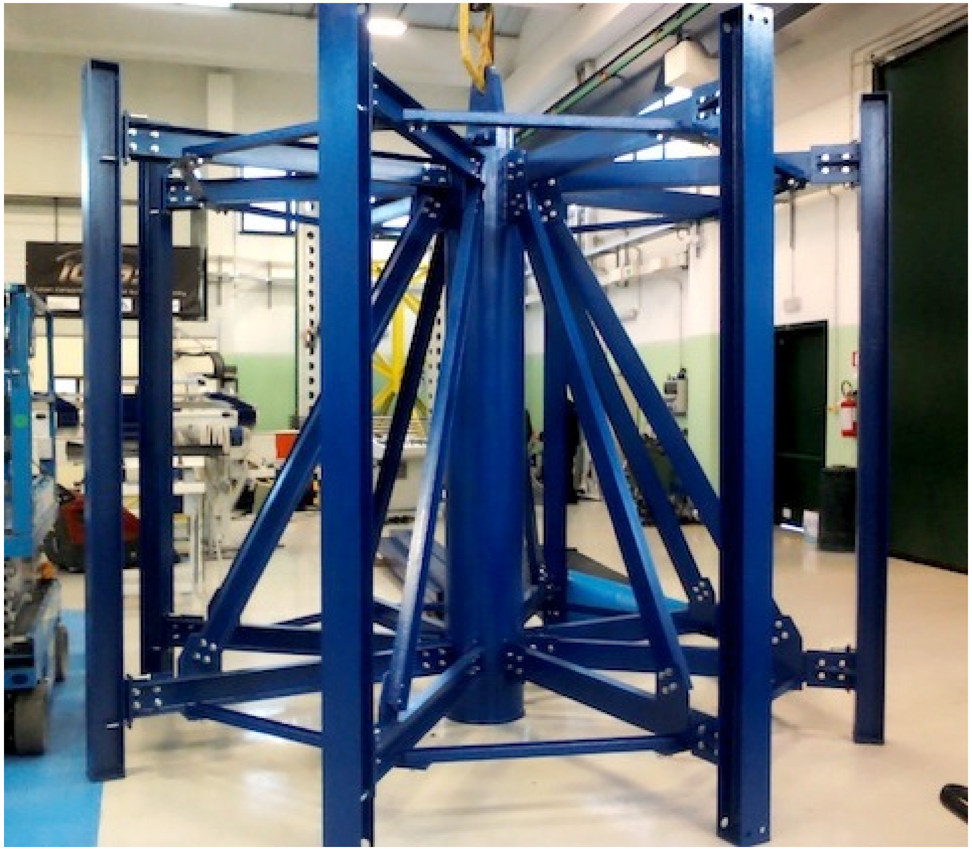
Manufacturing of ITER Conductors

1. cabling (strands; spiral; steel wrapping)
2. jacket assembly
3. Cable insertion (by pull-through)
4. Conductor compaction
5. Conductor spooling
6. Final acceptance tests
7. **Shipment to magnet**

supplier

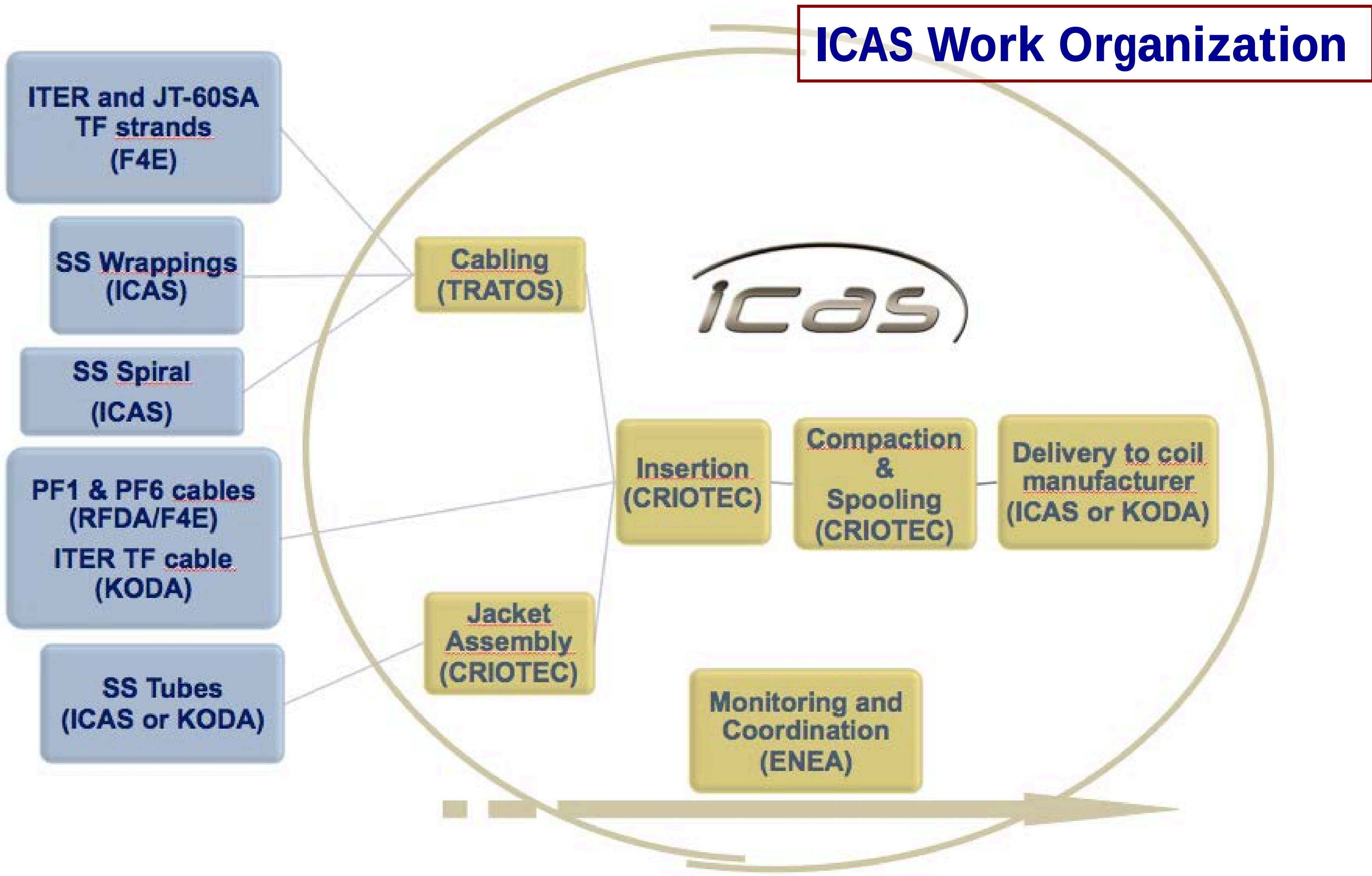
Manufacturing of ITER Conductors





Manufacturing of ITER Conductors

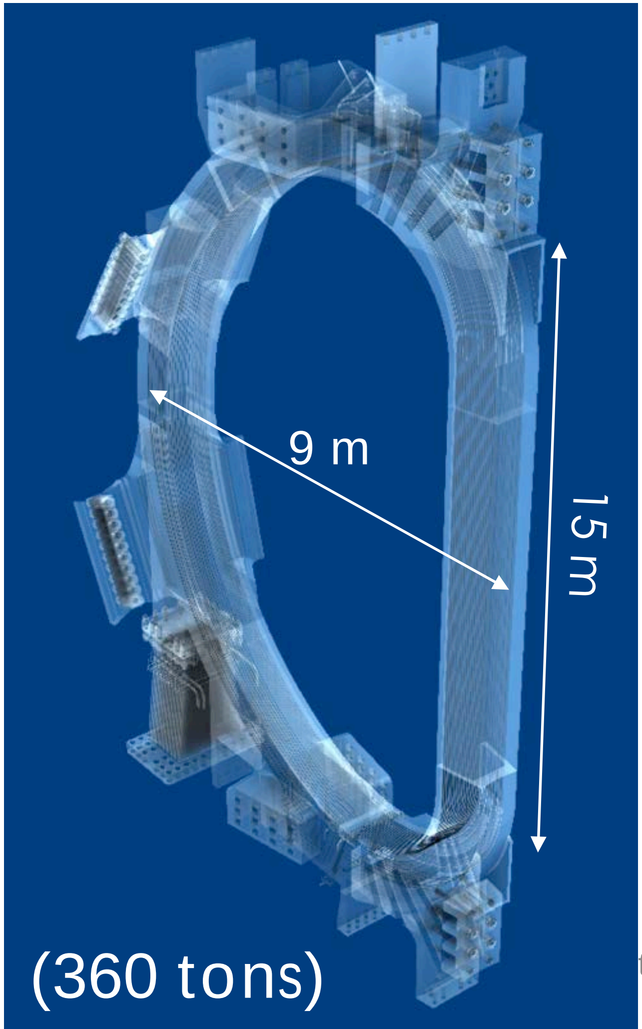
Summary on the fabrication of CICCs



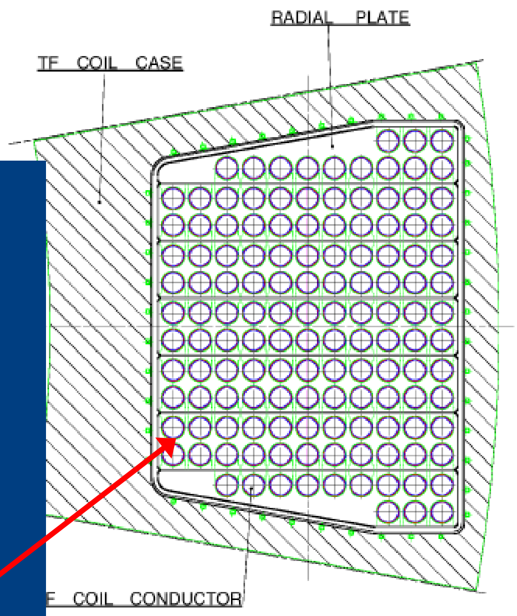
Outline

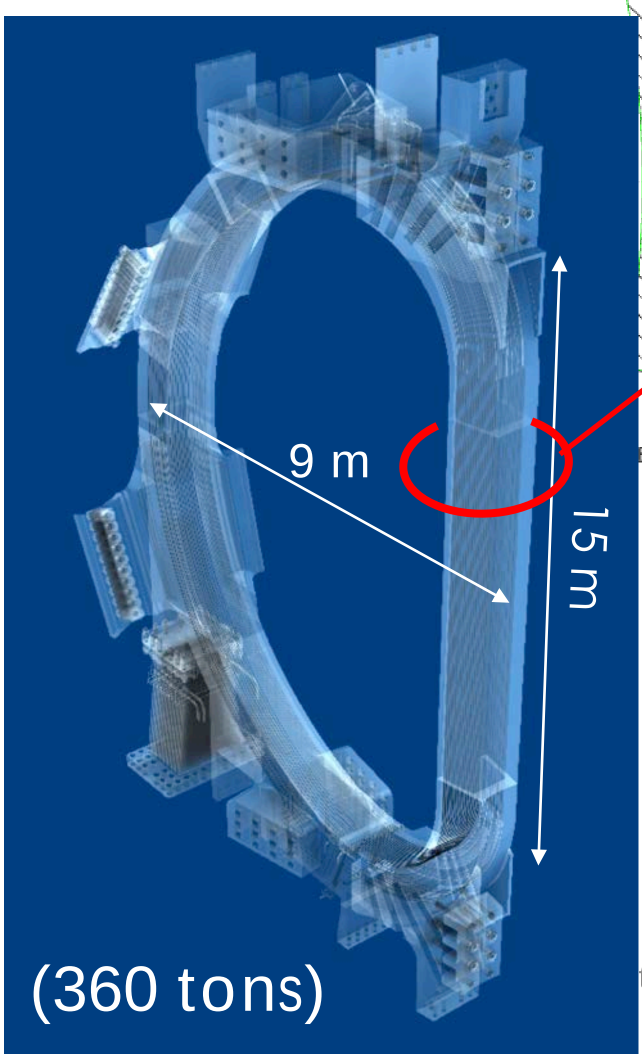
- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ ENEA activities beyond ITER

Manufacturing steps of ITER coils

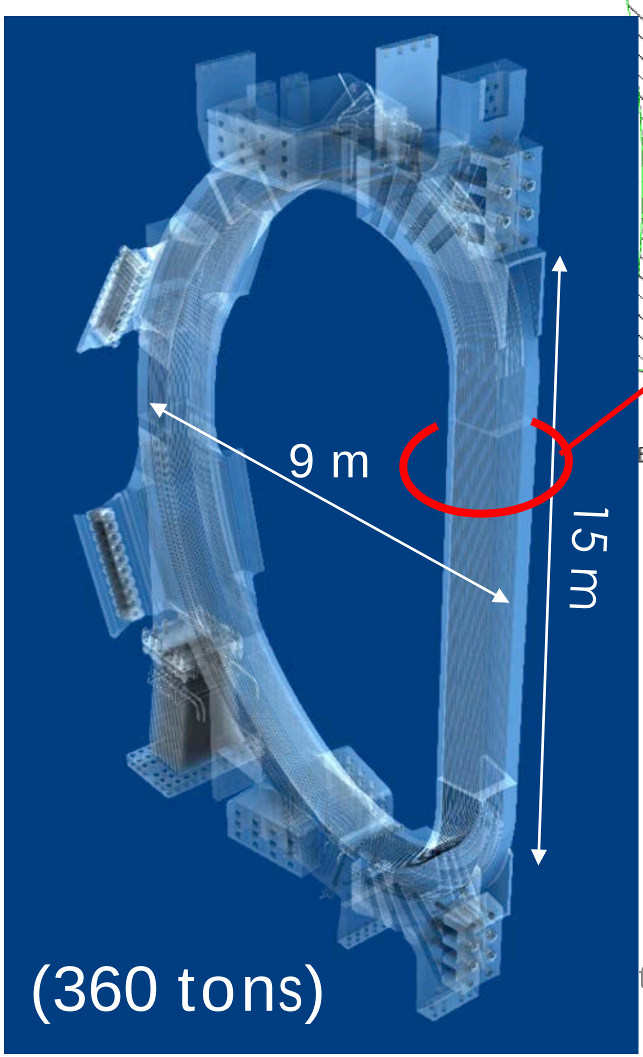


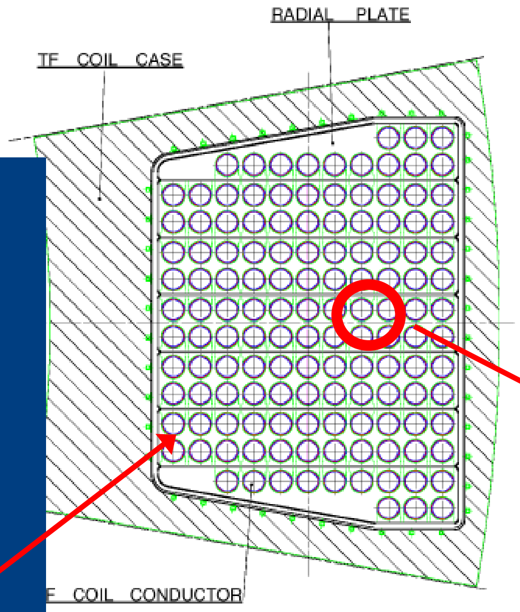
Manufacturing steps of ITER coils



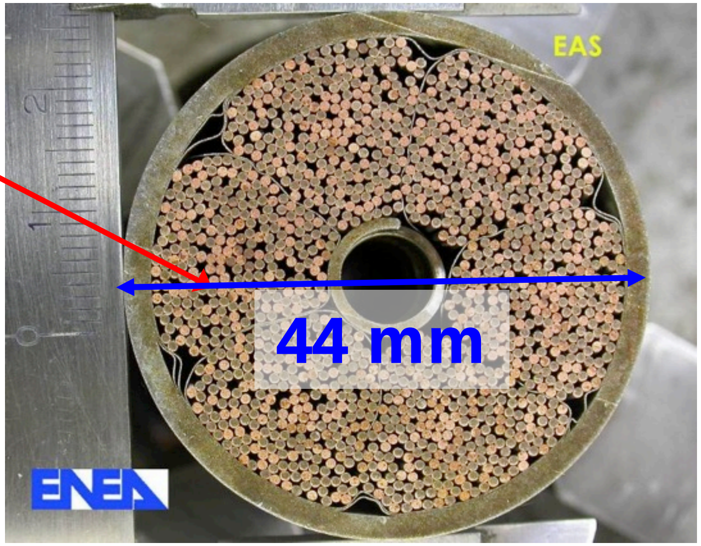


Manufacturing steps of ITER coils

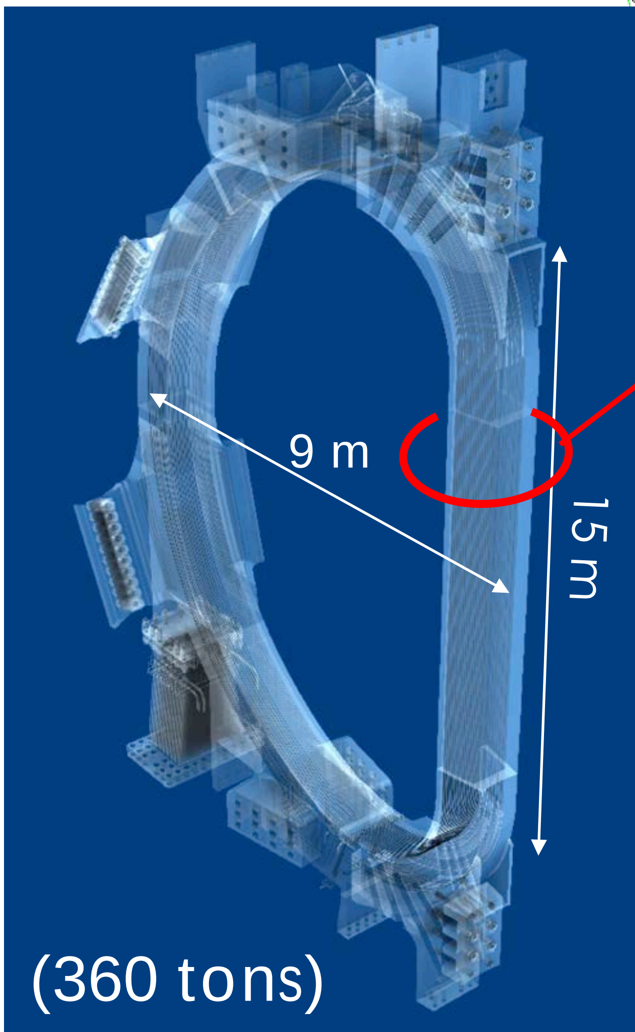


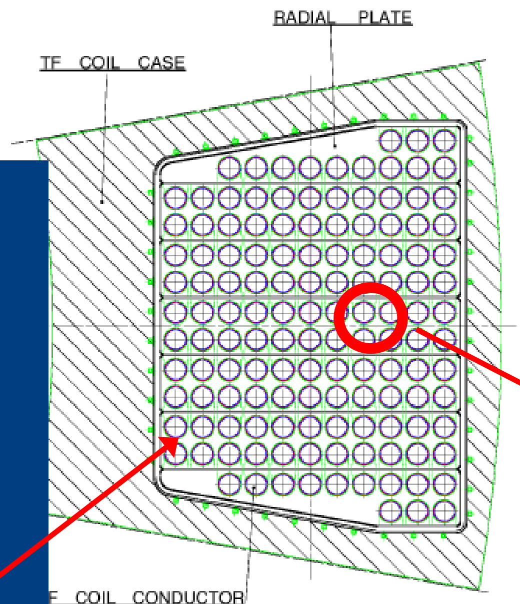


Cable in Conduit Conductor: 1422 fili (900 sup. + 522 Cu)

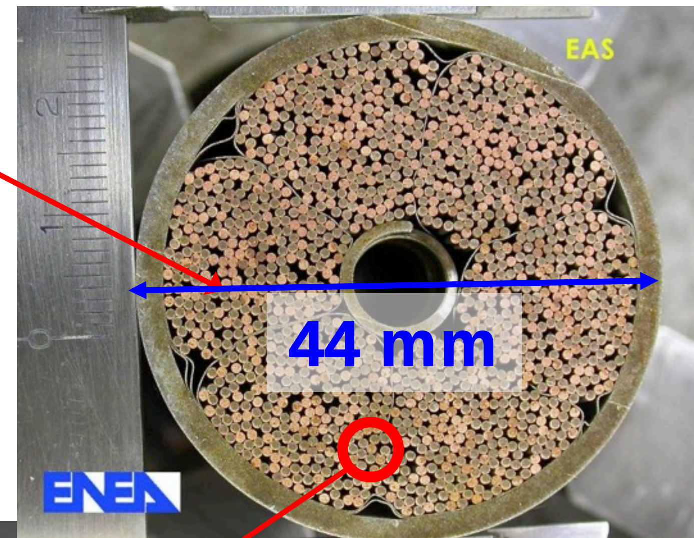


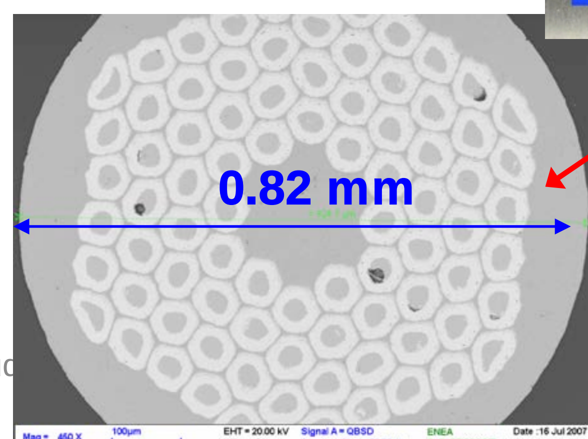
Manufacturing steps of ITER coils





Cable in Conduit Conductor: 1422 fili (900 sup. + 522 Cu)

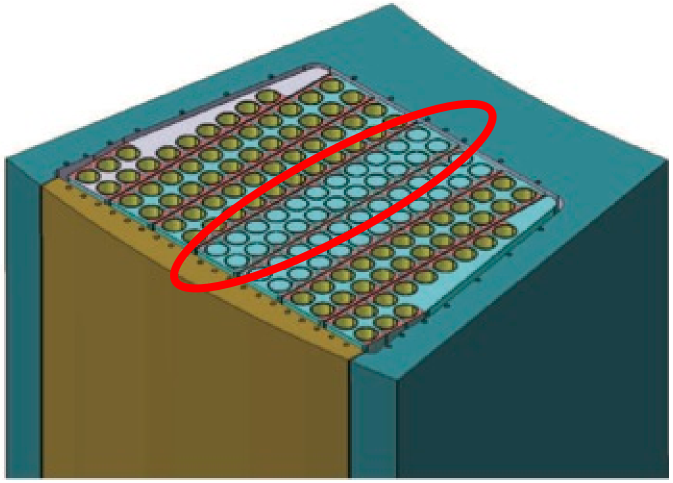




un filo è costituito da ~3000 filamenti

Step 1: winding

Conductor is wound in *Double-Pancakes*

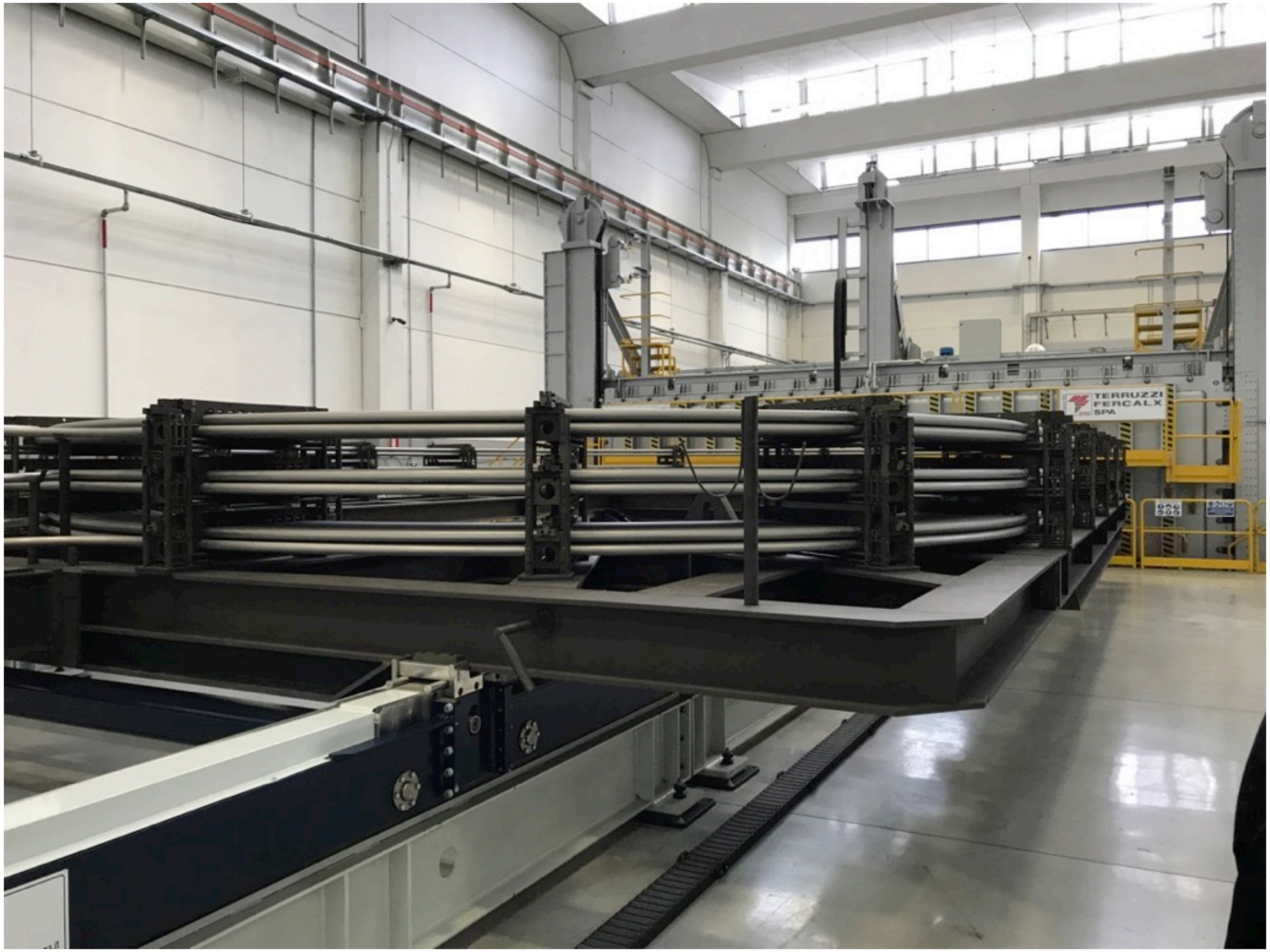


Step 1: winding

Conductor is wound in *Double-Pancakes*

Step 2: heat treatment

Large furnaces required for curing Nb_3Sn for about 3 weeks, in temperature steps up to 650 °C +/- 5 °C



Step 3: CICC insertion in radial plates

Manufacturing steps of ITER coils

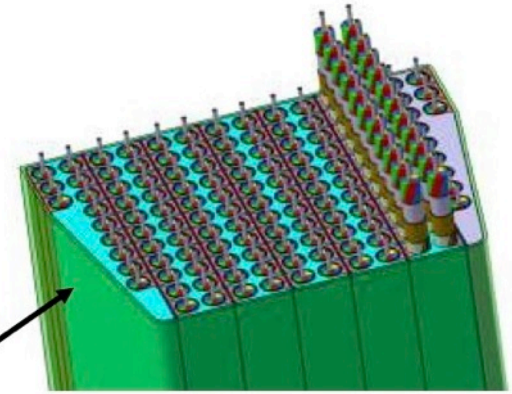
ITER TF Radial Plate

Step 4: conductor insulation

Voltage during TF coil operation

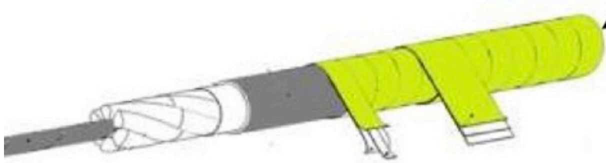
	Normal Operation (fast discharge) V_n (kV)	Fault scenario V_f (kV)
Turn to RP	0.6 (1.2 for a few ms)	1.2
DP to DP	1.2 (2.4 for a few ms)	2.4
WP to ground	3.5 (7 for a few ms)	18
Co-wound QD tape to conductor	0.01	0.1

17 layers of Glass/Polyimide



…has driven decision to use polyimide barrier ….

TF Coil Conductor



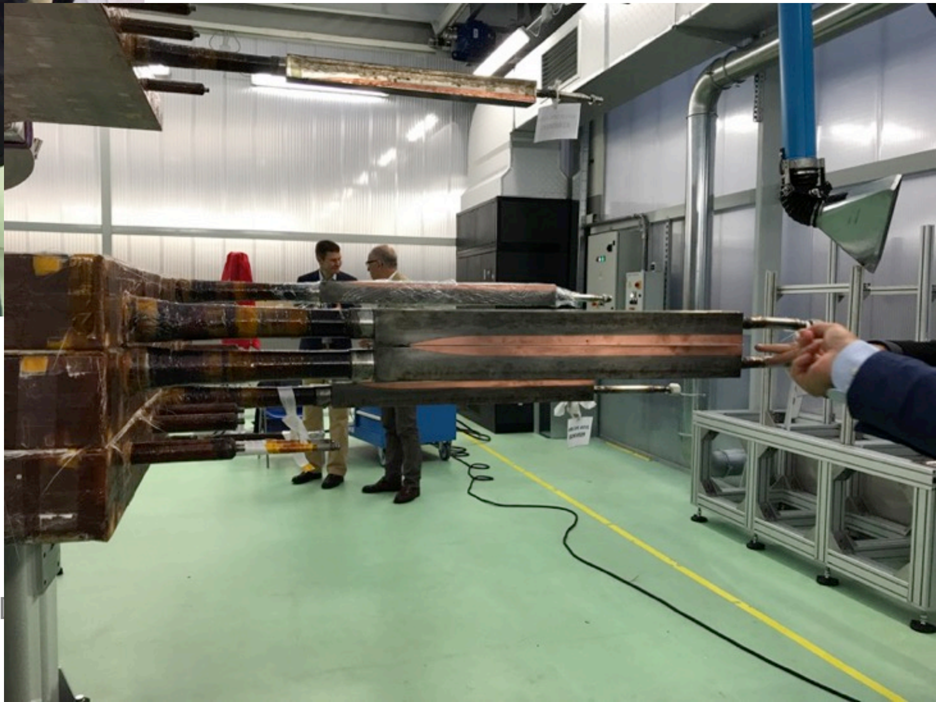
>3 layers of Glass/Polyimide half lapped

For Nb_3Sn coils (TF and CS) the insulation must be applied after the heat treatment

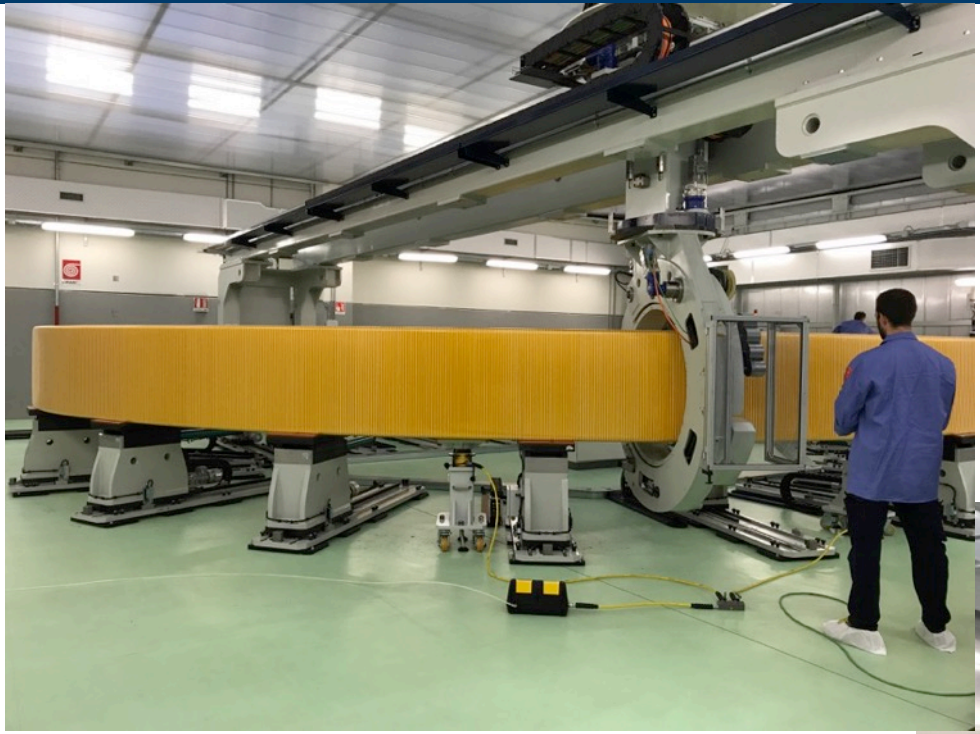
Step 4: conductor insulation

Step 5: Double Pancake impregnation

Step 6: stacking of DPs



Step 7: insulation of coil pack



Some Video(s)

ASG, on TF coil manufacture (*4.19 min*):
https://www.youtube.com/watch?v=4xTedApXHNA

CNIM, on radial plates manufacture (*7.23 min*):
https://www.youtube.com/watch?v=w_b53lhHJ54

SIMIC, on radial plates manufacture (*5.13 min*):
https://www.youtube.com/watch?v=5OmkaaVazJ4

Outline

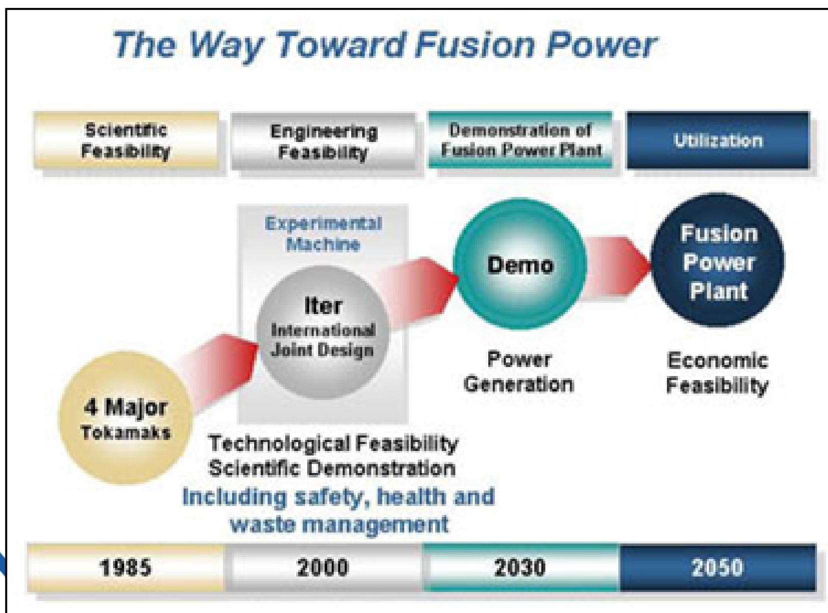
- ✓ Introduction on the Magnet system of a tokamak reactor
- ✓ Multi-filamentary superconducting strands
- ✓ Cable-in-Conduit conductors (CICCs)
- ✓ Manufacturing aspects of CICCs
- ✓ Manufacturing aspects of ITER coils
- ✓ ENEA activities beyond ITER

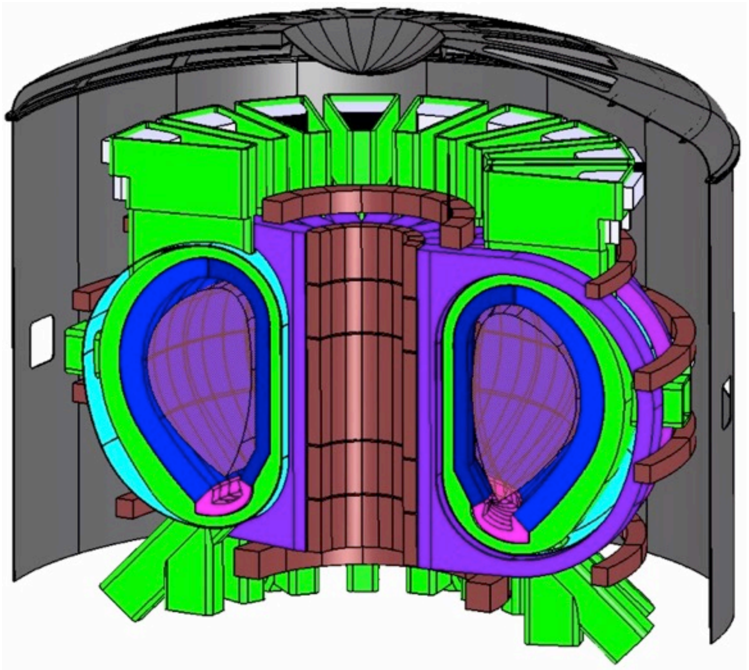
From ITER to (EU)-DEMO

- European Roadmap: demonstrate fusion electricity by 2050

- DEMO: 500 MW electric power, and supply to the grid;

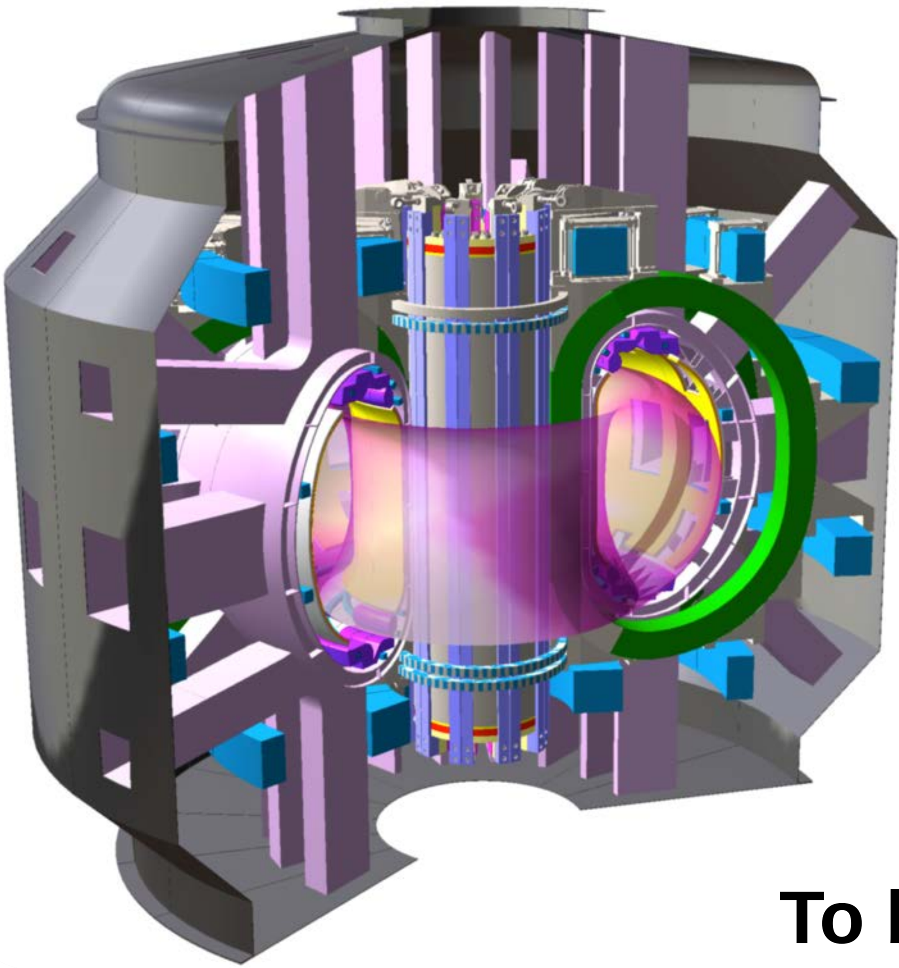
- since 2011 R&D activities in EU on the superconducting magnet system of DEMO. Coordinated by EUROfusion.





DEMO CAD model (30 April 2014)

The Italian DTT project

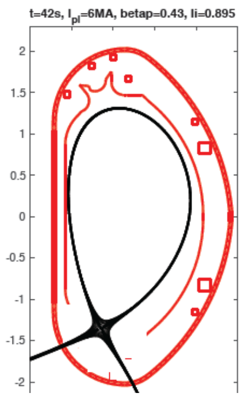


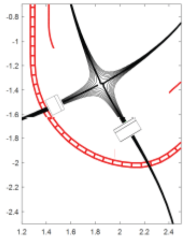
Divertor Tokamak Test facility:
the general objective of the DTT project is to design an experiment addressed to the **solution of the power exhaust issues in view of DEMO**

it must provide enough positive evidence that the alternative solutions could be integrated in a DEMO device in case the conventional divertor solution does not yield the necessary capabilities for power exhaust

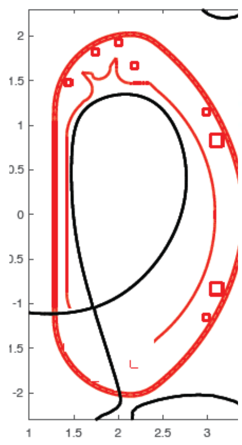
To be built here in Frascati!

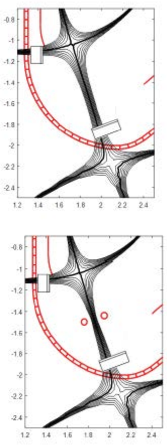
Magnet system flexibility for plasma shaping



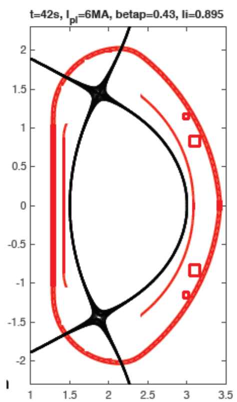


Single Null
5.5MA

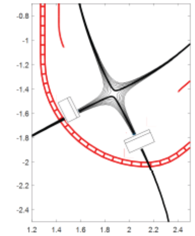


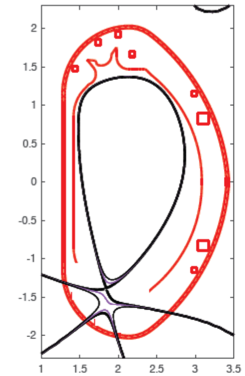


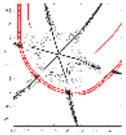
X-Divertor
4.5MA



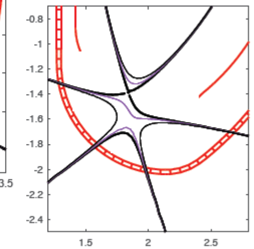
Double Null
5.5MA



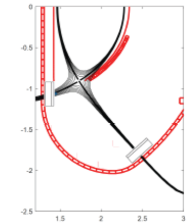


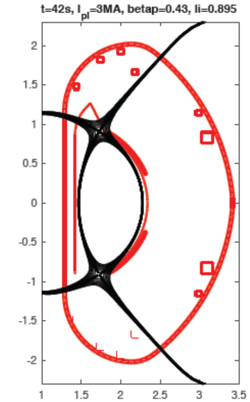


Snowflake
4.5MA



Super-X
3MA



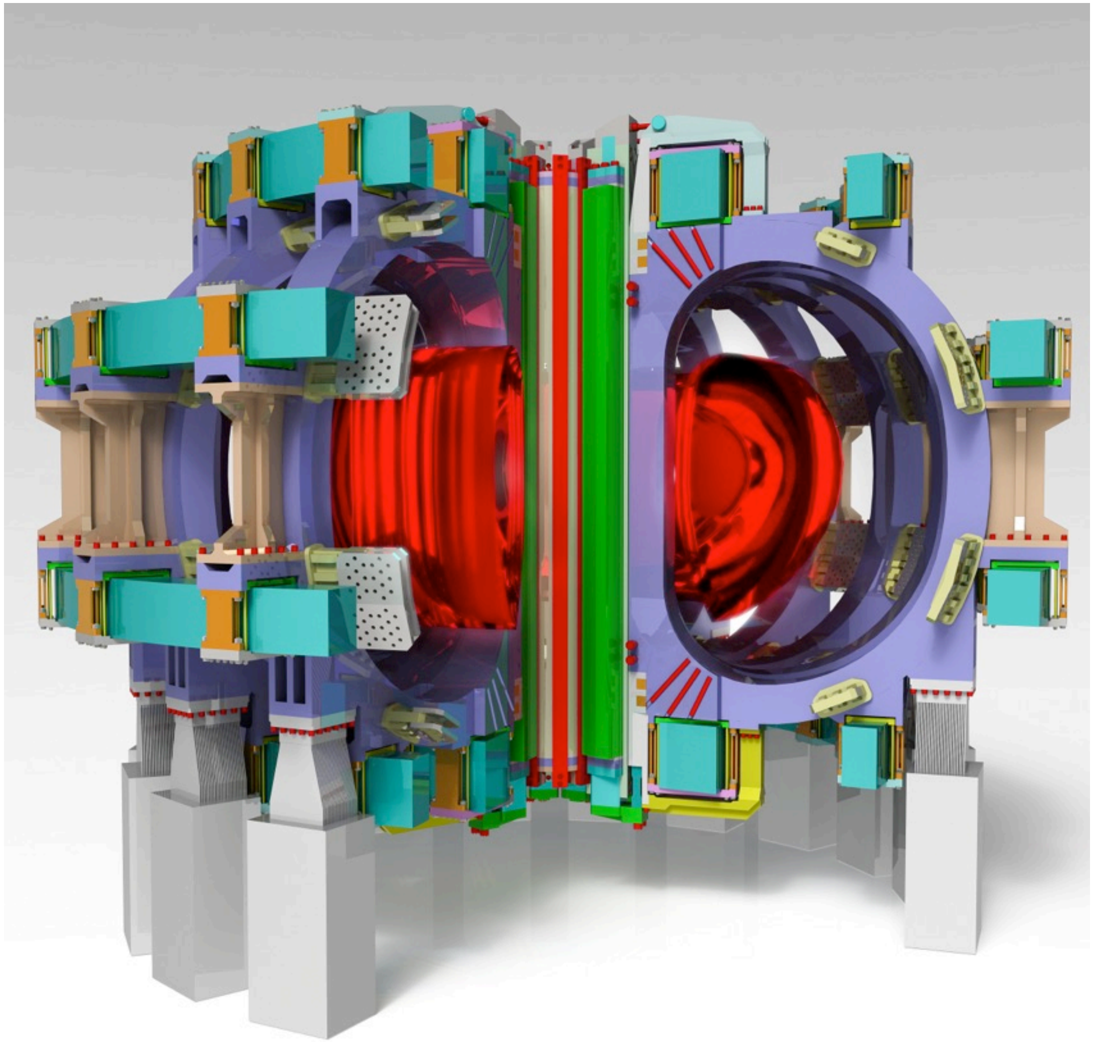


The Italian DTT project

Magnet Design is:

- performed in order to have a flexible and fully symmetric tokamak
- committed to a tight, but realistic, time schedule and cost containment
- based to the state-of-art magnet technology choices (or close to), in order to reduce at minimum the R&D phase

The Italian DTT project



18 TF coils:
Nb_3Sn Cable-In-Conduit Conductors
6 *Double-Pancakes* (4 regular + 2 side)
B_{max} = 11.7 T; I_{op} = 26.9 kA
ΔT_{margin} > 1.6 K

6 CS module coils
Nb_3Sn Cable-In-Conduit Conductors
graded (3 sections) *Layer Wound*
B_{max} = 14 T, 12 T, 8.2 T; I_{op} = 28 kA
ΔT_{margin} > 1 K

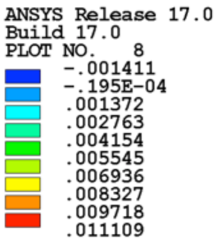
6 PF coils
NbTi Cable-In-Conduit Conductors
Double-Pancakes winding
B_{max} = 2.5 – 6.0 T; $I_{op\text{-}max}$ = 11 - 29 kA
ΔT_{margin} > 1.7 K in all coils

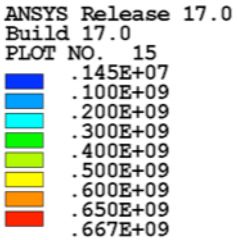
The Italian DTT project

3D FEM

ANSYS, cooldown + energization (Out of Plane forces included)

Detailed models for IIS, OIS and gravity supports analyses are being developed





The Italian DTT project

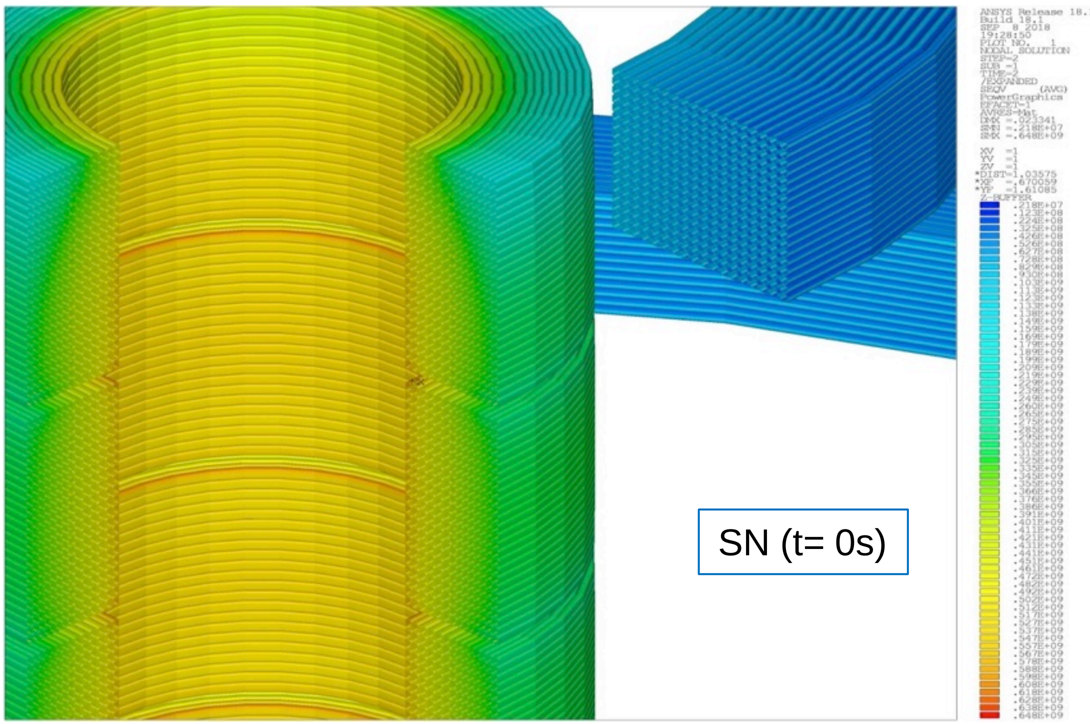
3D FEM (ANSYS, cooldown + energization)

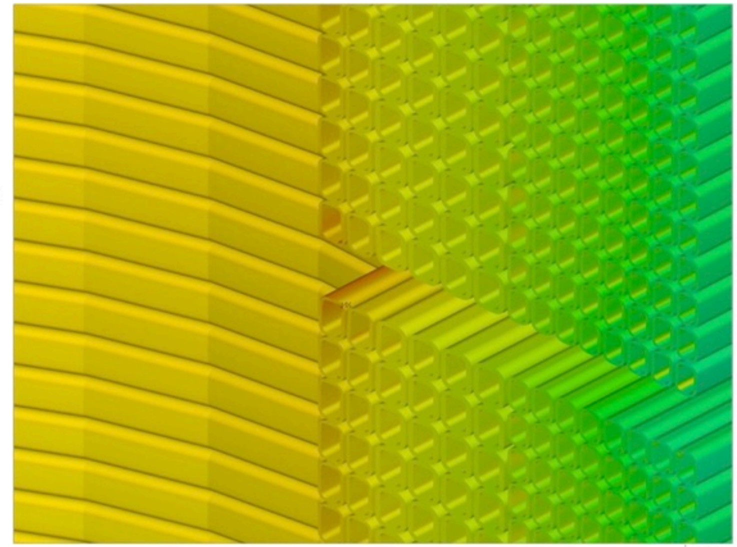
→ **Von Mises** stress in Steel and **Insulation Shear** within acceptance criteria

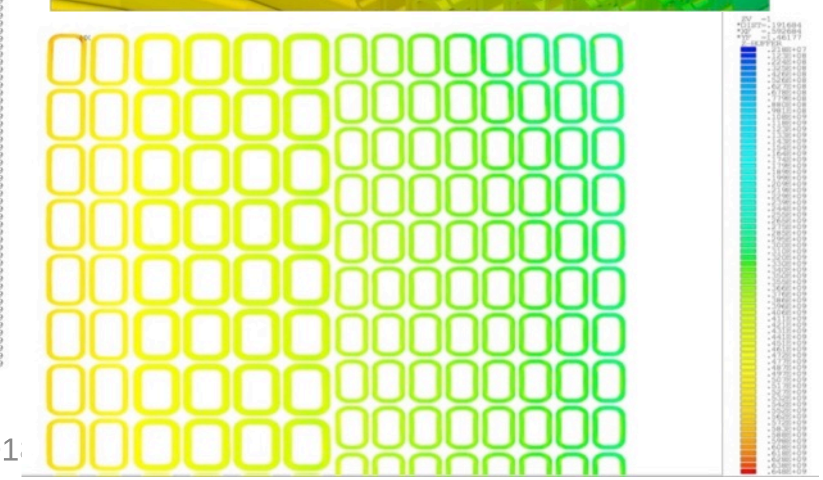
Complete system of 6 modules modelled with ANSYS

Self-field and SN scenario: max VonMises stress < 667MPa

Fatigue analysis and structures analysis are ongoing



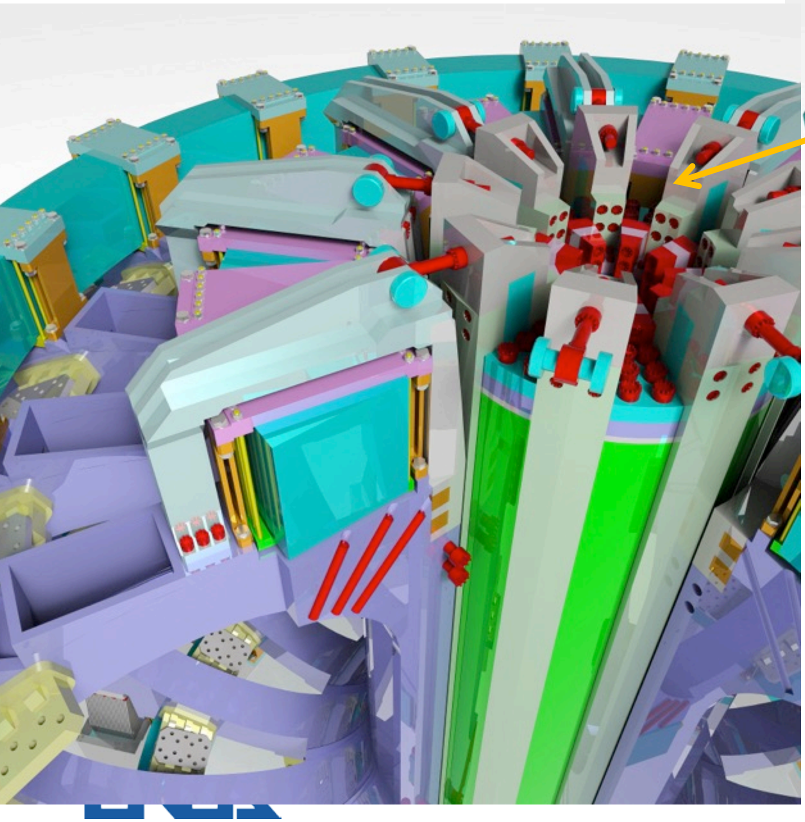


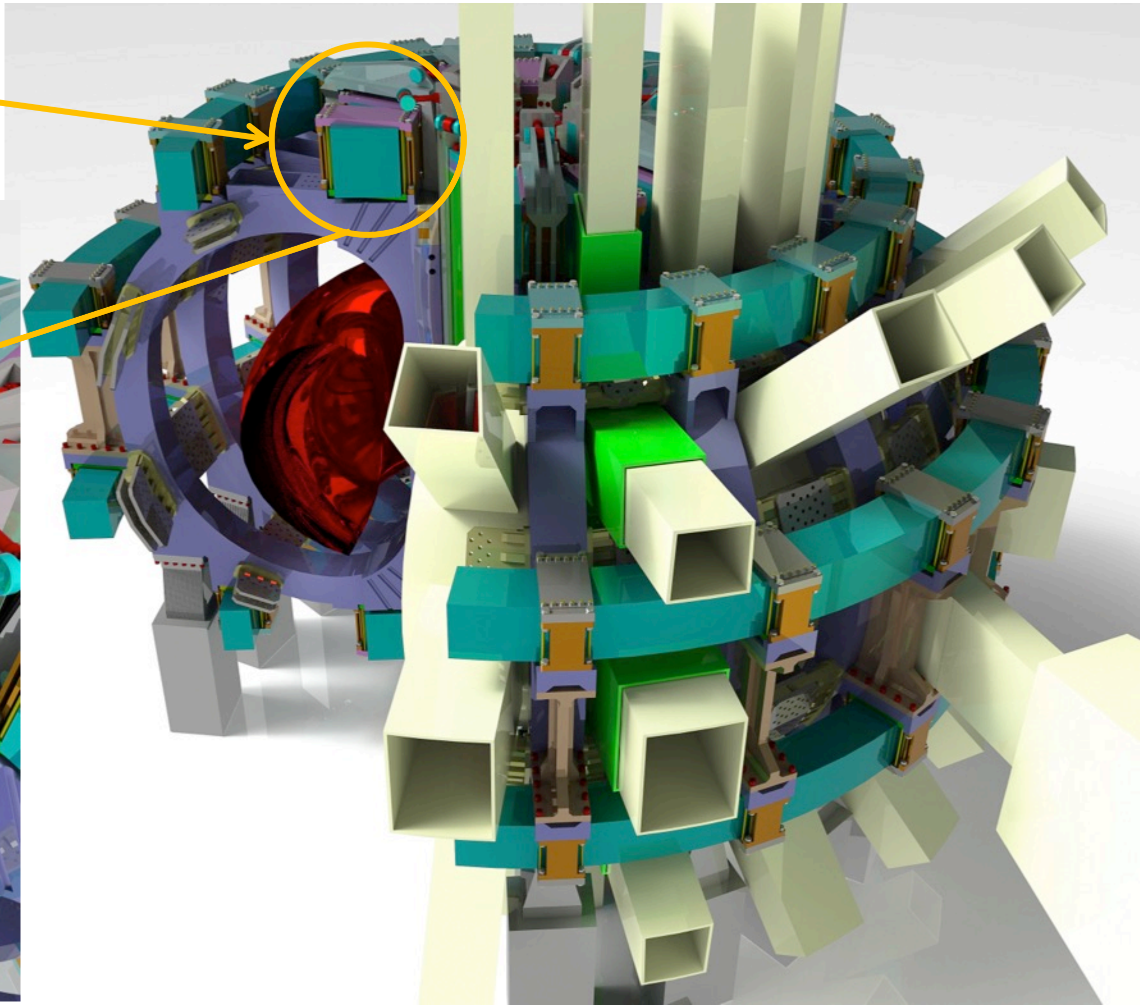


The Italian DTT project

The full set of Inner-Intercoil Structures (pre-compression rings, shear keys, Outer-Intercoil Structures and gravity supports) is under detailed study

Around PF1/6 the area is quite "crowded"





Luigi Muzzi
luigi.muzzi@enea.it