Superconducting materials for the magnetic confinement coils

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EASISchool3 Summer School

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"The views and opinions expressed herein do not necessarily reflect those of the ITER Organization"

content

Magnetic confinement

ITER magnet system

ITER superconductors

Manufacturing status

Magnetic confinement

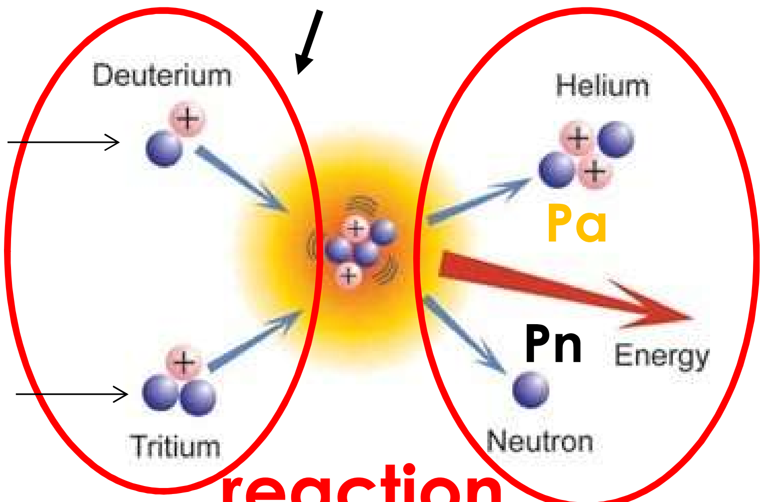
Fusion reaction

Available on earth

fuels

To be produced

P_{in} P_{loss}



reaction

Independant travel of charged particles:

→ **plasma required**

Issues: **- electrostatic repulsion**

- energy losses P_{loss}

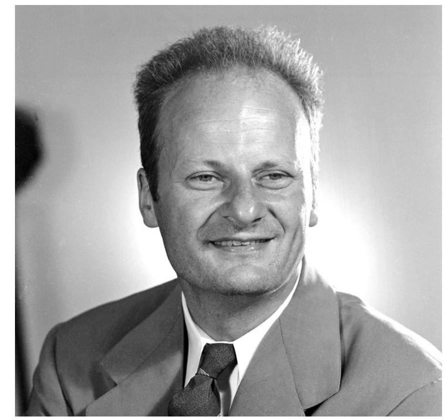
$P_{fus} = P_{\alpha} + P_n$

distribution:

$P_{\alpha} \sim 20\%$

$P_n \sim 80\%$

fusion products



Hans Bethe (1906 - 2005)

Nobel Prize of Physics 1967

Q energy gain

$Q = P_{fus}/P_{in}$

Q = 1 breakeven

$Q = \infty$ Ignition $\tau_E = W/P_{loss}$

τ_E energy confinement time

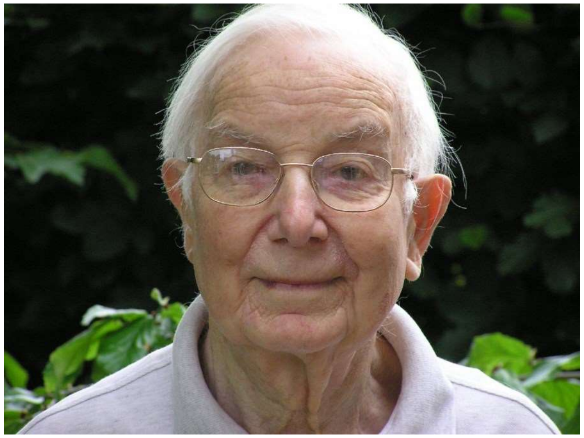
Magnetic confinement

Lawson criterion (1955)

Plasma energy balance: dW/dt = 0

Density (n) x confinement time (τ_E) x temperature (T)

$$n.\tau_E.T > 10^{21} (keV.s.m^{-3})$$



John D. Lawson
(1923-2008)

Fusion routes

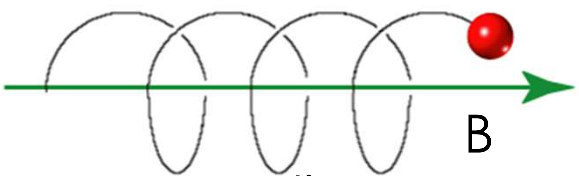
Inertial fusion (sun)
High density
(10^{27} . m^{-3})
Low temperature (1.5 keV)

Magnetic fusion (ITER)
Low density (10^{20}. m^{-3})
High temperature (10 keV)
Energy confinement time 3 s
$n.\tau_E.T = 3.10^{21}$

Magnetic confinement

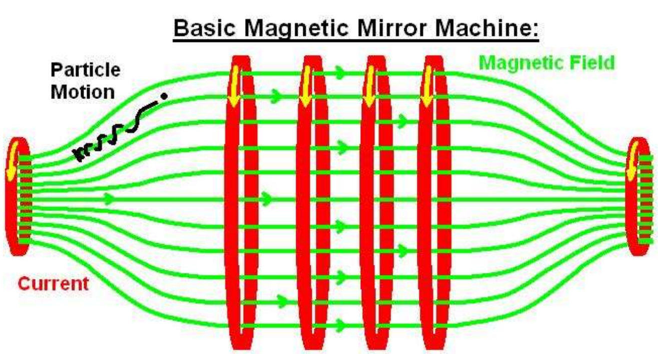
Magnetic configurations

linear configuration



Larmor radius:

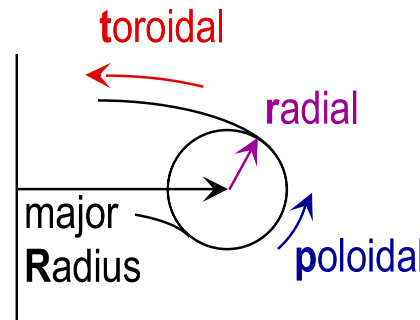
$r_L = m.v_{\perp}/q.B$

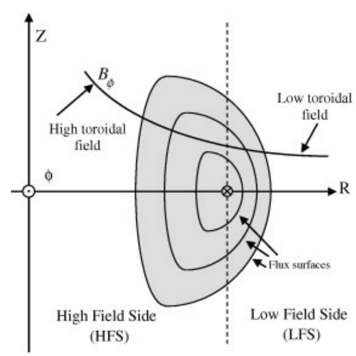


Issue: losses at the ends

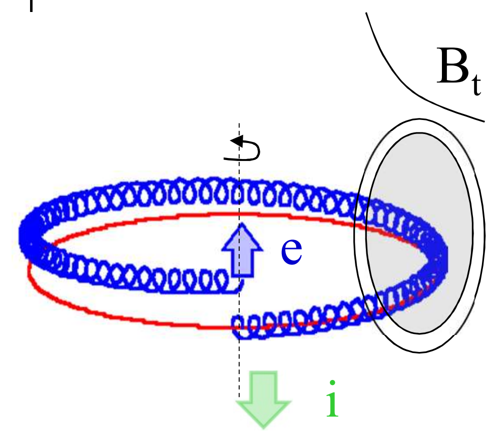
toroidal configuration

Magnetic torus





Toroidal Field varies in 1/r

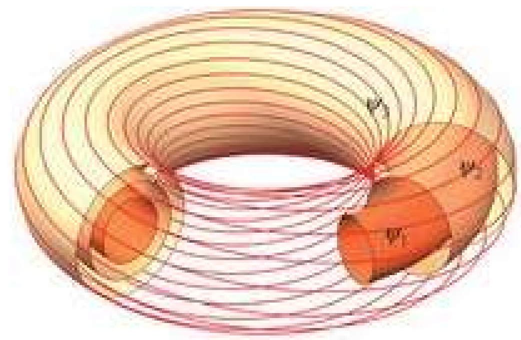


Issue: vertical drift of particles

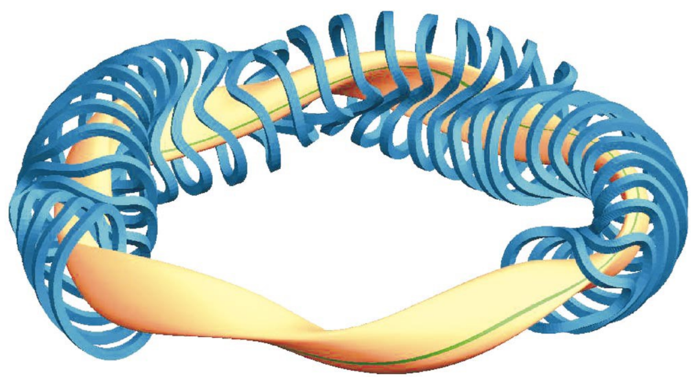
Magnetic confinement

Helical magnetic configurations

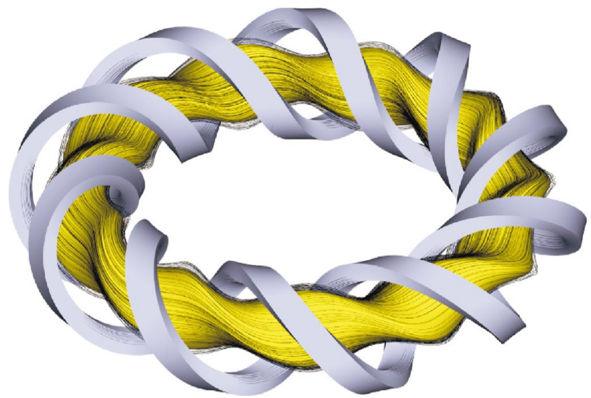
The magnetic field lines form a series of nested magnetic surfaces.
Charged particles remain trapped within magnetic surfaces



How to achieve it?



stellarator

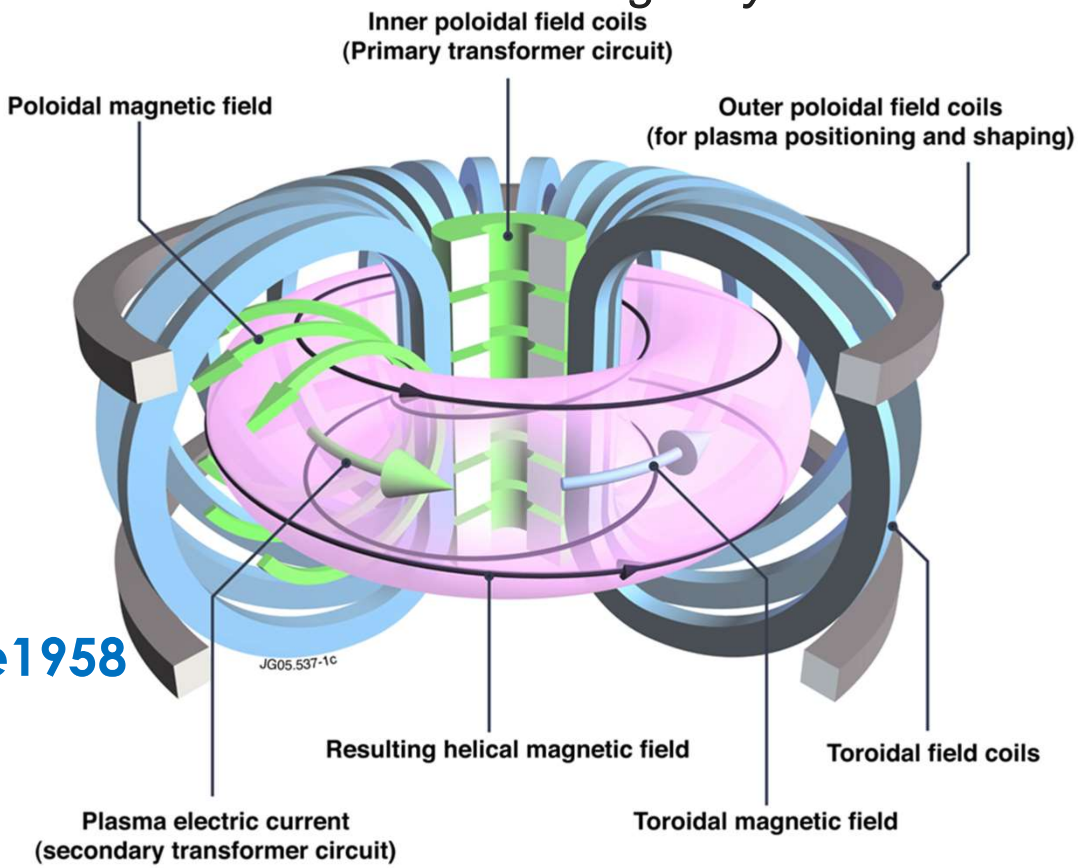


heliotron

Magnetic confinement

Tokamak design (1958)

***to**roidalnaïa **ka**mera s **ma**gnitnymi **k**atushkami*



Igor Kurtchatov (1903-1960)

Geneva Conference1958

Researches opening

Lev A. Artsimovitch (1909-1973)

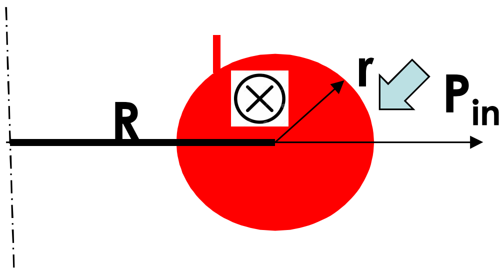
Novosibirsk Conference 1968

T_e > 1 keV

τ_E > 10 ms

Magnetic confinement

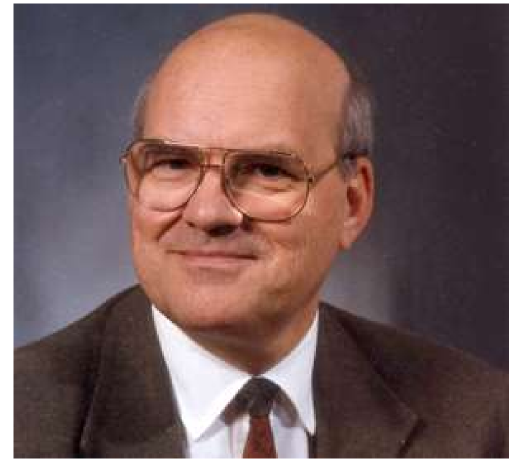
The tokamak route



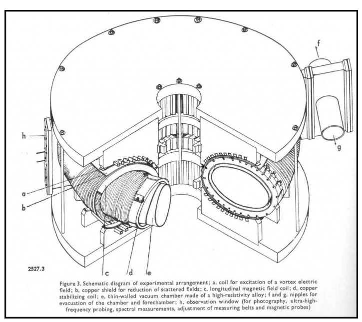
$\tau_E \propto I_p R^2 P_{in}^{-2/3}$

T1 (Moscow): 1958
T3 (Moscow): 1968
TFR (Fontenay-aux-Roses): 1973
JET (Culham):

- commissioning: 1983
- 1st DT exp. 1991
- 2nd DT exp. 1997
- ***3rd DT exp. 2020 ?***



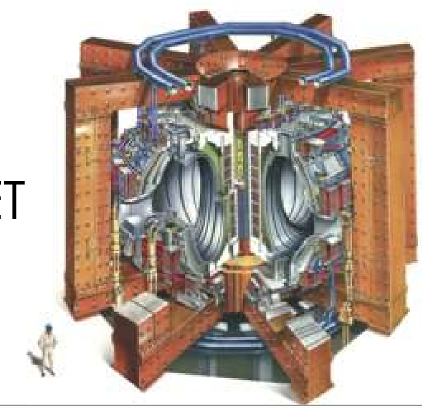
Paul-Henri Rebut (1935-)



T1

TFR

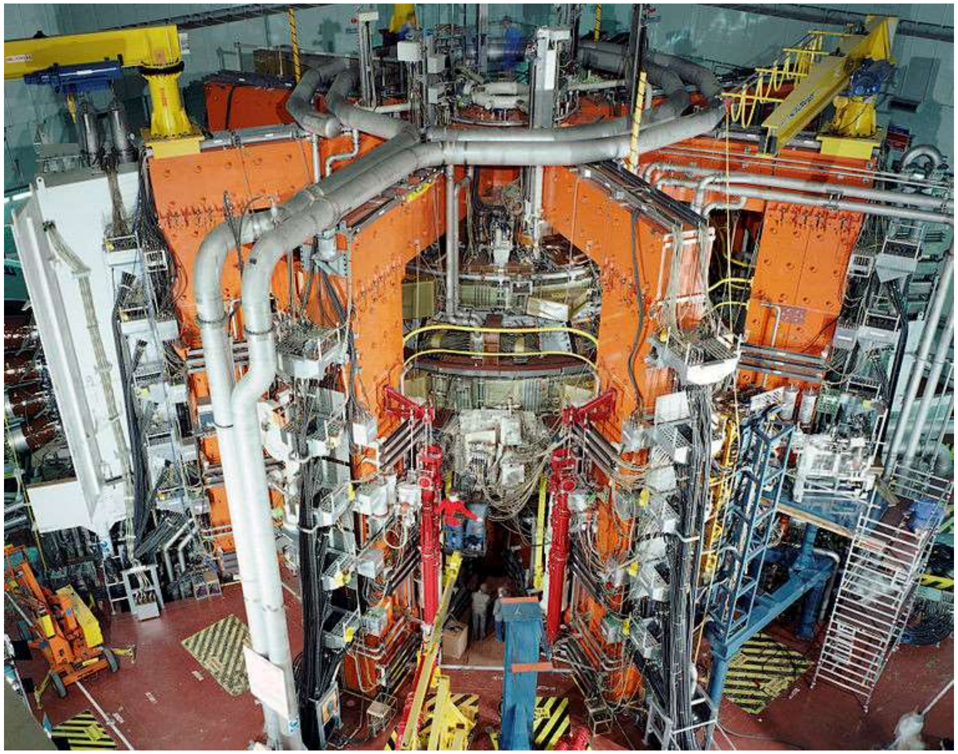
JET



Magnetic confinement

Copper magnets

Production of magnetic fields in tokamaks was first achieved using copper magnets.
JET electric power supply: **400 MW**
→ motor generator **flywheels** required



JET European tokamak(Culham)

→ **issue: electrical energy consumption**

Magnetic confinement

Superconducting magnets

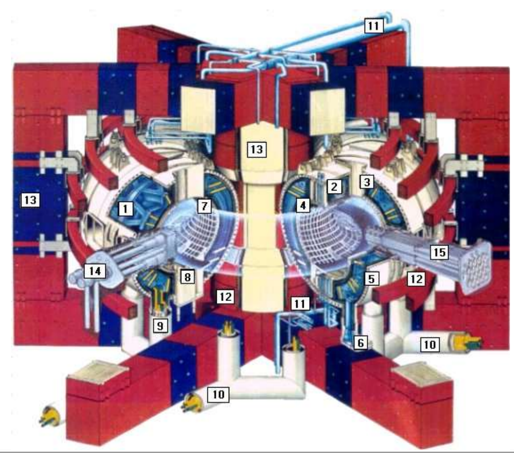
The construction of magnets using superconducting materials allowed a considerable reduction of the needed electrical power for production of magnetic fields and long pulses.

Robert Aymar (1936 -)

T7 (NbTi, Moscow): 1979
Tore Supra (NbTi, Cadarache): 1988
T15 (Nb_3Sn, Moscow): 1988

Tore Supra TF electrical power: **1 MW**

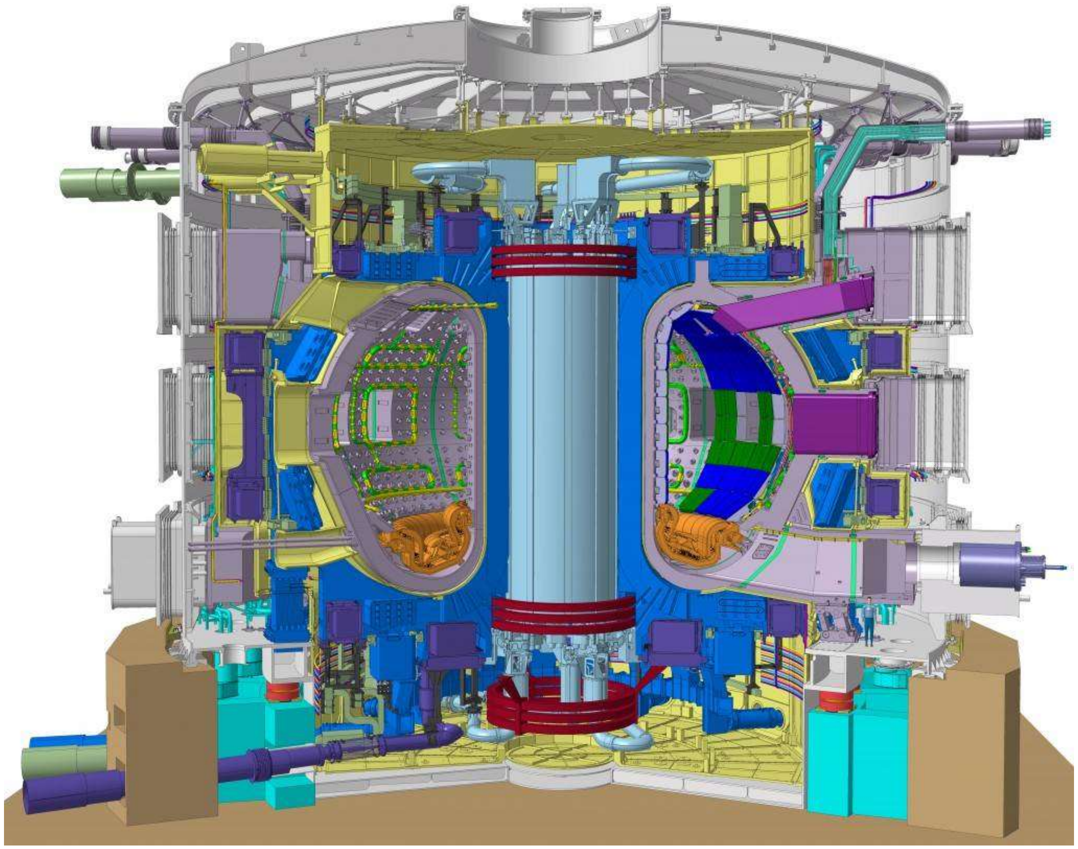
Tore Supra



Magnetic confinement

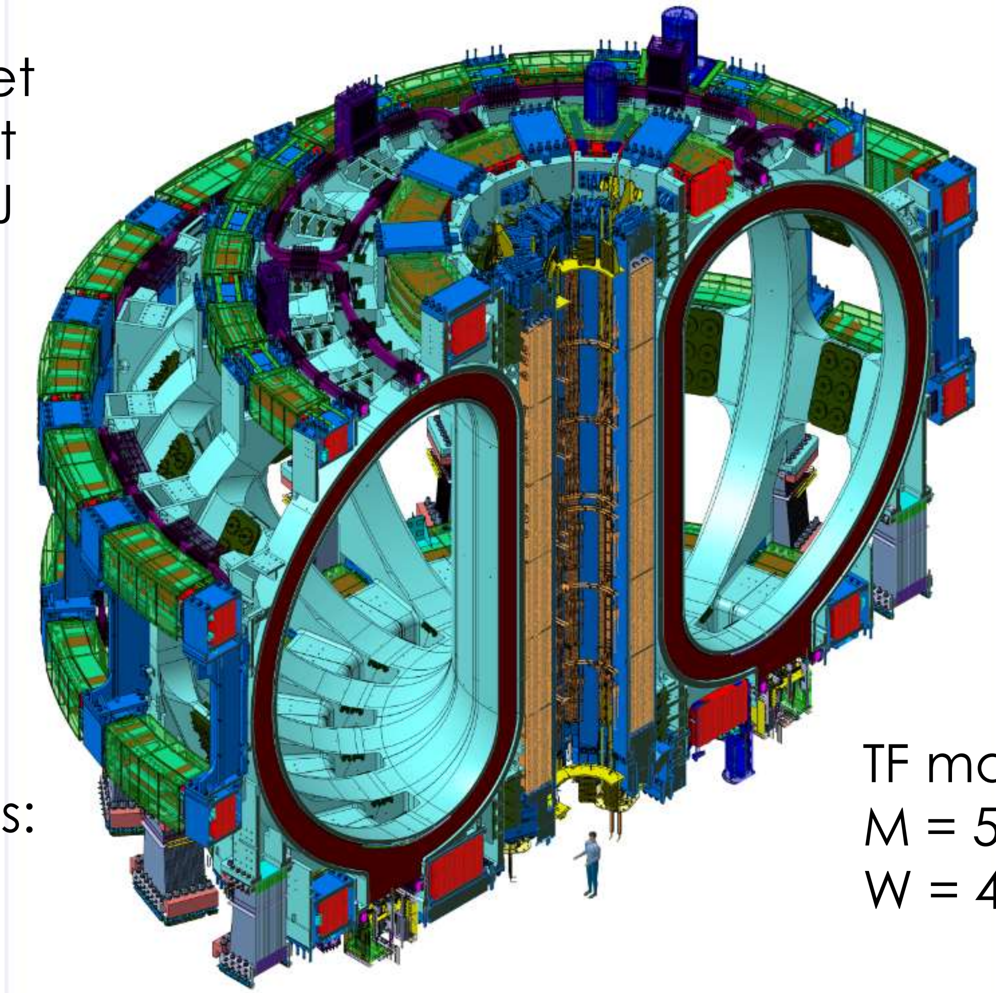
ITER design

Fusion power	500 MW
Energy gain	Q ≥ 10
Inductive discharge	≥ 400 s
Large plasma radius	6.2 m
Small plasma radius	2.0 m
Plasma current	15 MA
Toroidal field	5.3 T



ITER Magnet System

PF magnet
M = 2746 t
W = 10 GJ
(17 MA)

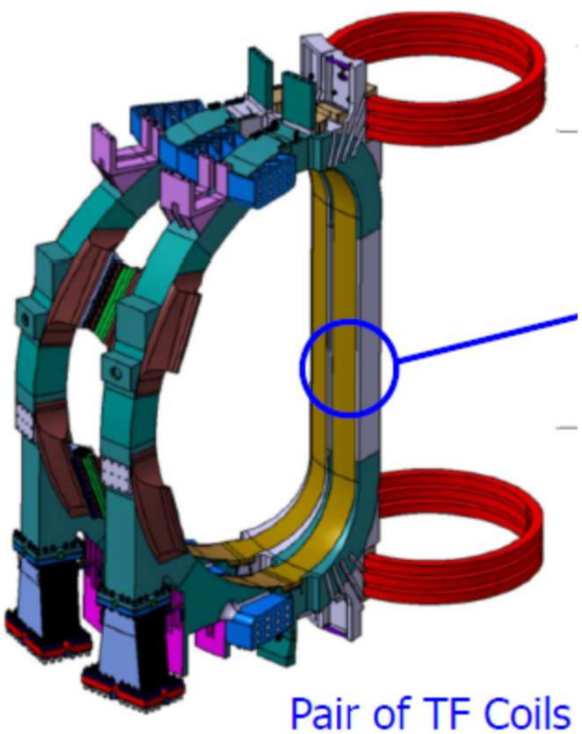


Total mass:
10 360 t

TF magnet
M = 5373 t
W = 41 GJ

ITER Magnet System

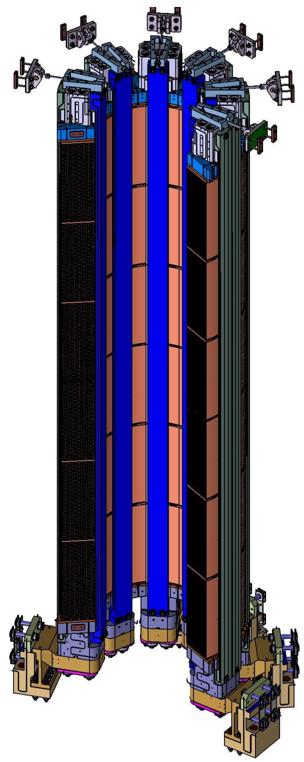
18 TF coils



current capacity

I = 9.1 MA/coil

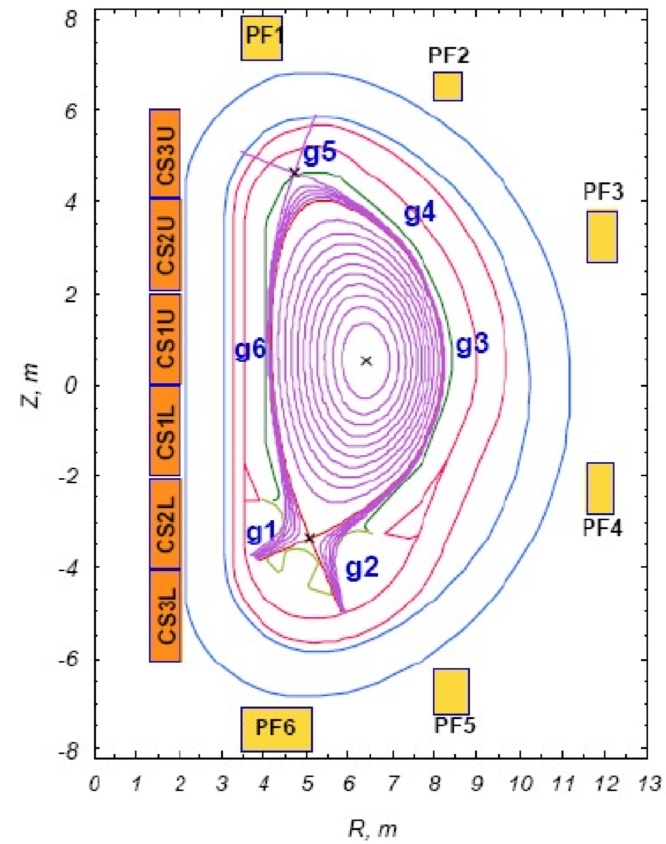
6 CS coils



current capacity

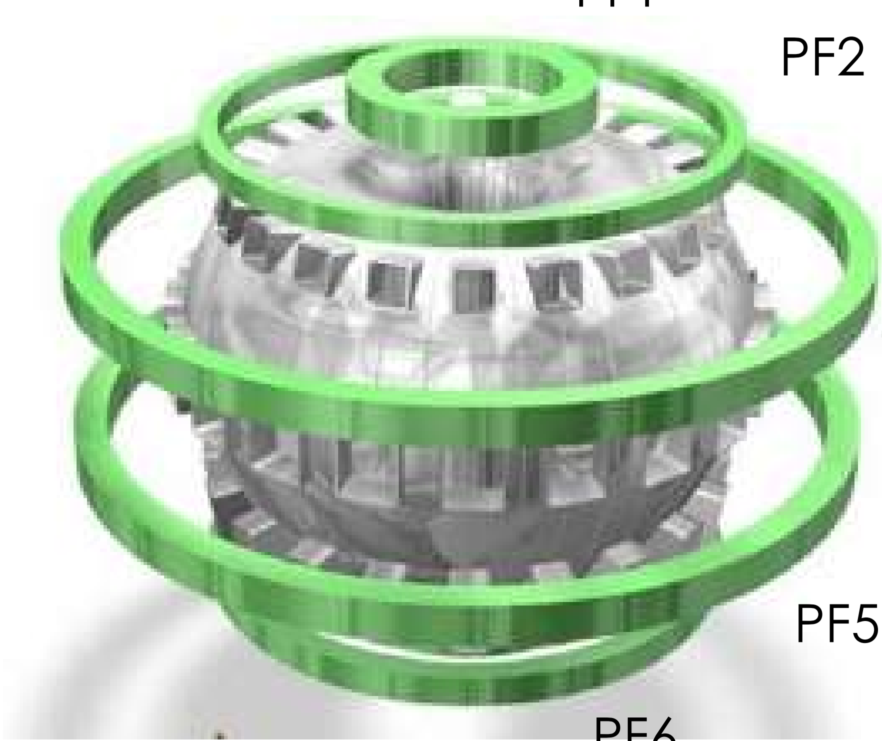
I = 22.2 MA/coil

Poloidal cross-section



ITER Magnet System

6 PF coils

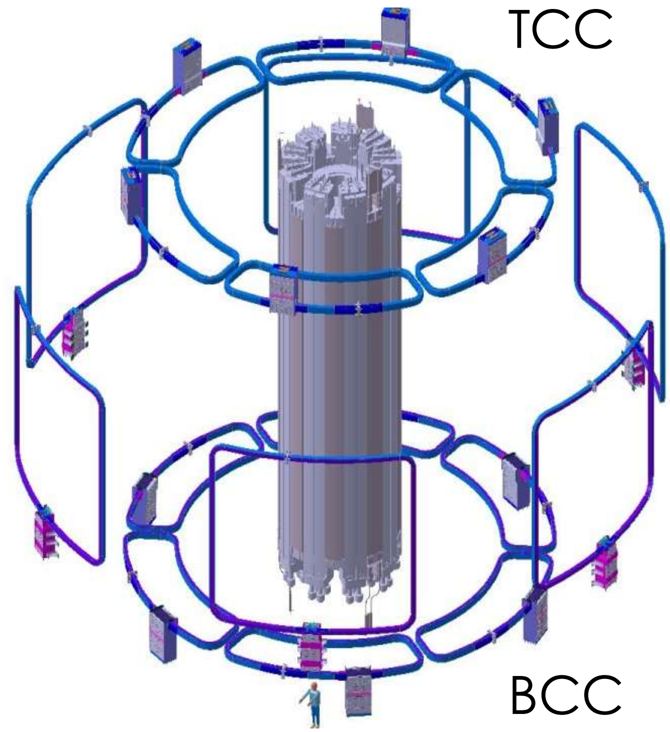


current capacity

I = 55.8 MA

(PF1+PF2+PF3+PF4+PF5+PF6)

18 Correction coils



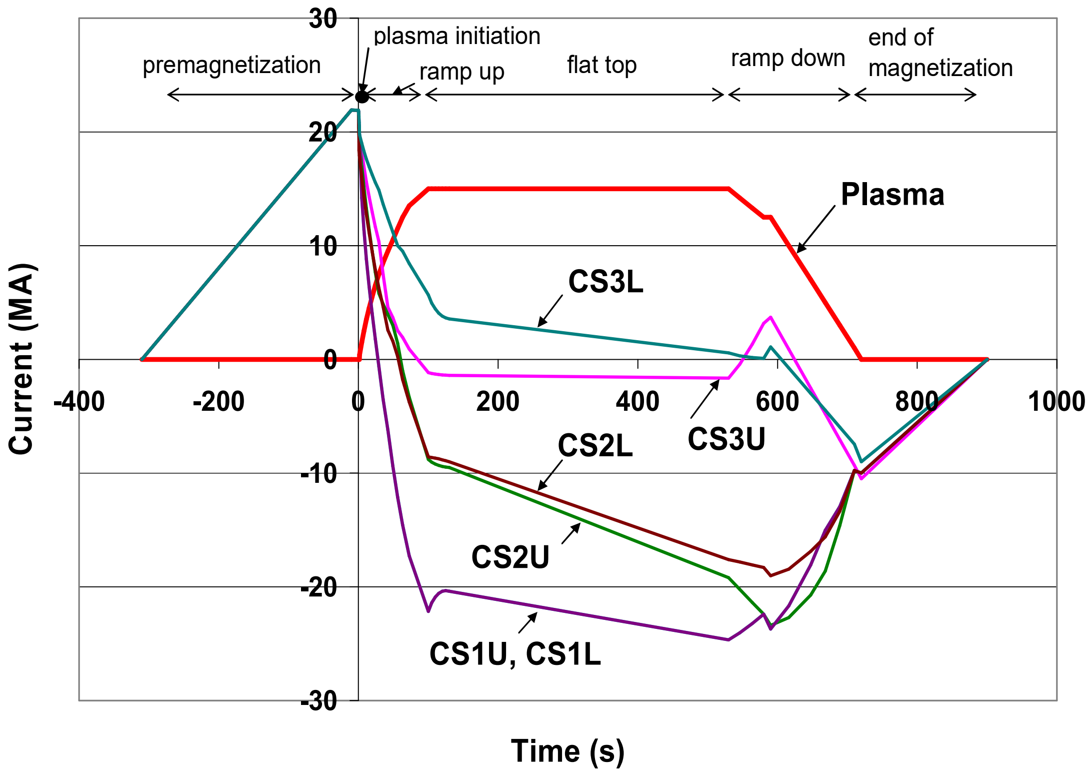
current capacity

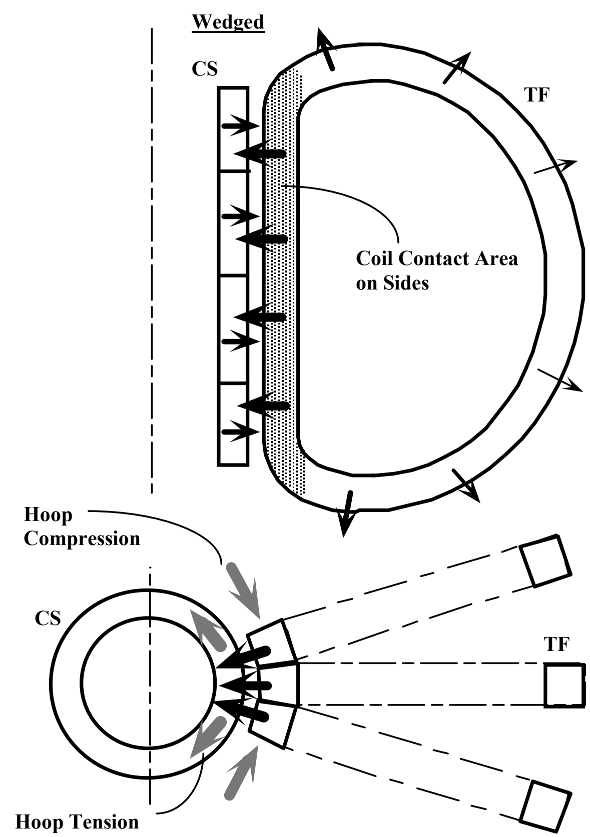
I = 0.32 MA/BCC TCC coil

I = 0.20 MA/SCC coil

ITER Magnet System

Plasma operation





ITER Superconductors

Conductor design

Conductor current is determined by the maximum allowable voltage to discharge the coils

U = L dI/dt

Discharge time constant: 11 s

→ **high current conductor required**

TF coil: 134 turns x **68 kA** = 9.1 MA/coil

CS coil: 556 turns x **40 kA** = 22.2 MA/coil

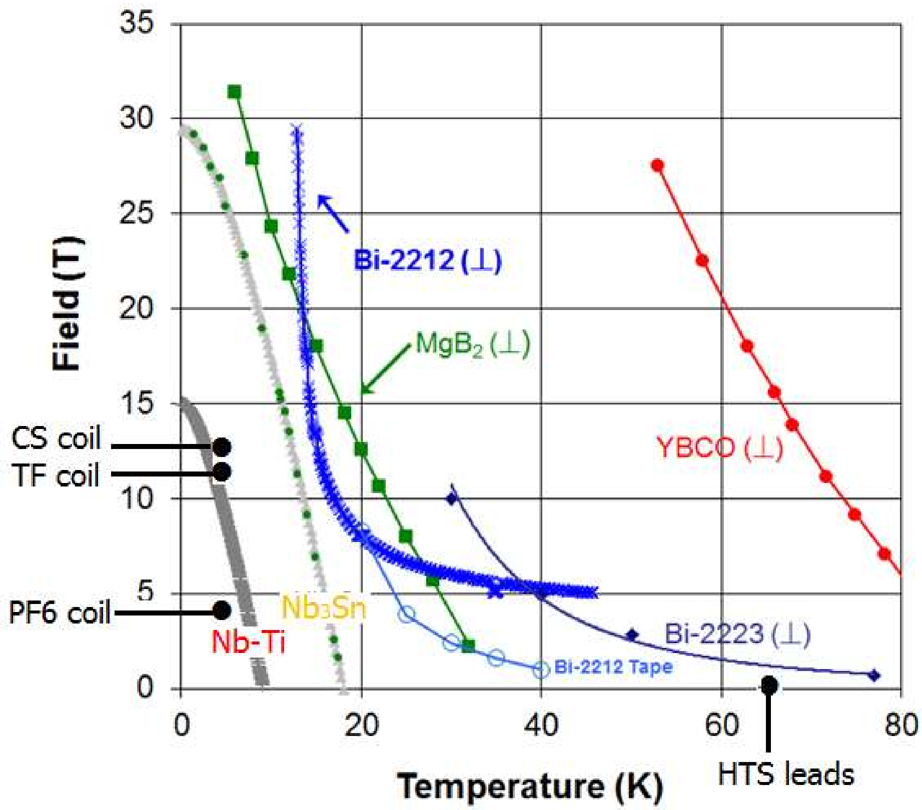
Maximum voltage

30 kV test voltage for CS coils

→ **high voltage insulation materials required**

ITER Superconductors

Superconducting materials



CS coils

Bmax = 13 T

→ **Nb_3Sn**

TF coils

Bmax = 11.8 T

→ **Nb_3Sn**

PF coils

Bmax = 6.4 T

→ **NbTi**

Correction Coils

Bmax = 6 T

→ **NbTi**

Feeders

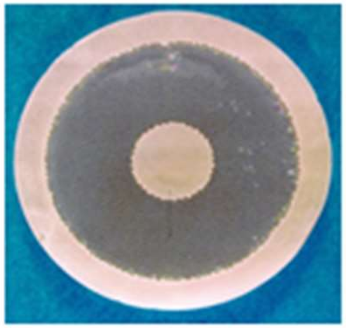
Bmax = 3.5 T → **NbTi**

Current leads B max = 0.065 T → **Bi2223**

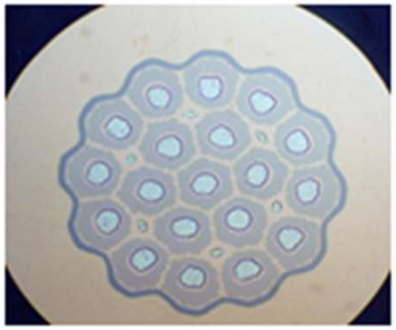
ITER Superconductors

Superconducting wires

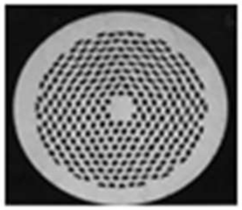
- For practical applications, the superconductor is subdivided into **fine filaments,** which are **twisted together** and **embedded in a low-resistivity matrix** of normal metal (e.g., pure OFHC Cu for Nb-Ti and Nb_3Sn, Ag or Ag–Au for HTS).
- The superconducting multifilament composites are manufactured under the form of **wires** (with an outer diameter of ~1 mm) or **tapes.**



Nb–Ti Wire for ITER



Nb_3Sn Wire for ITER



BSCCO 2212 Wire

BSCCO 2223 Tape

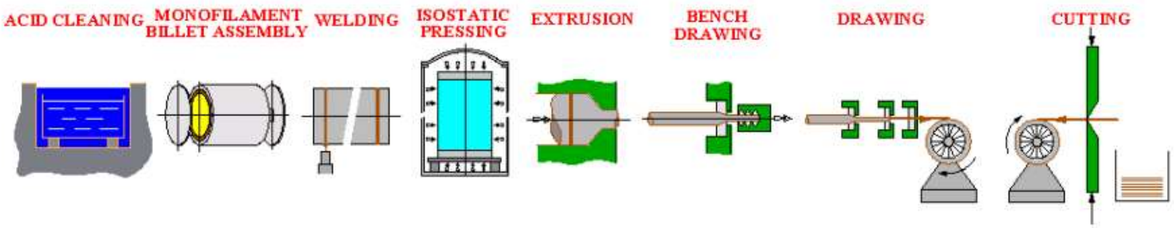
ITER Superconductors

Industrial manufacture of supraconducting wires

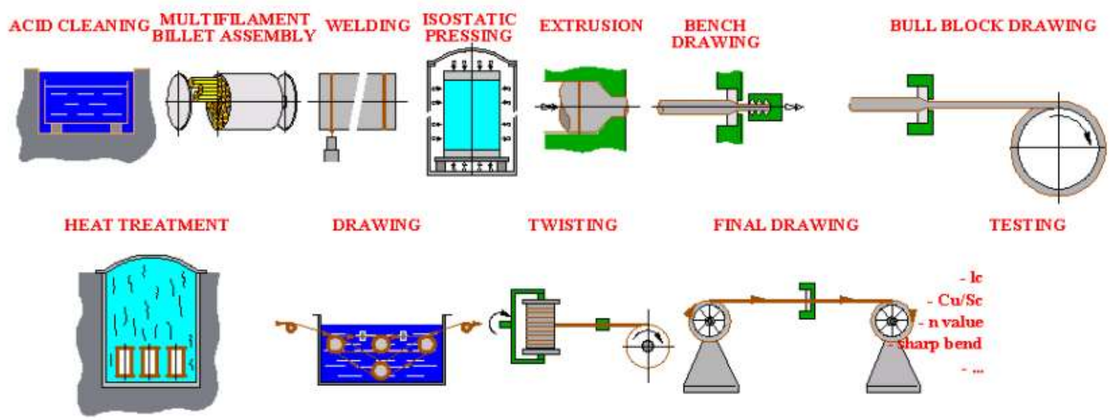
A superconducting wire is made of superconducting **filaments** embedded into a copper matrix.

The manufacture is performed in two steps:
- a **monofilamentary step**
- a **multifilamentary step**

→ **multifilamentary twisted composite wire**
(l ~ km, Ø ~mm)



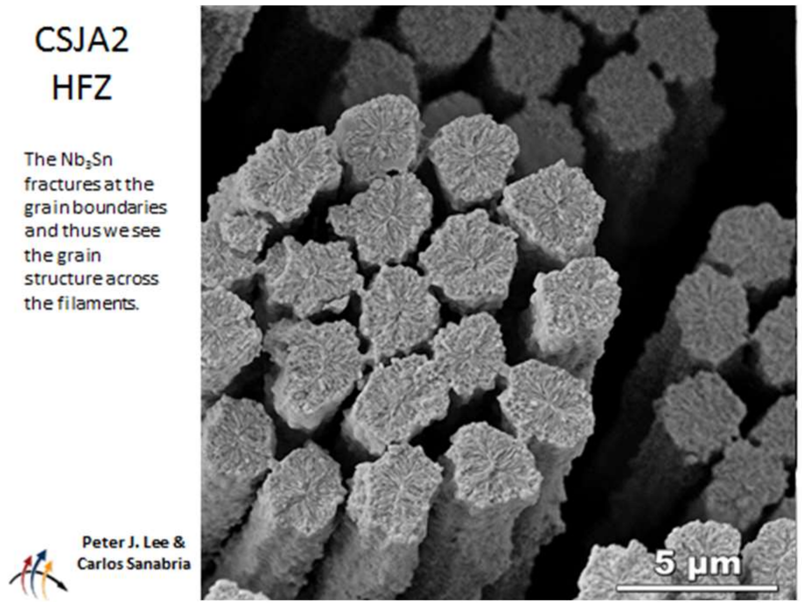
Monofilamentary step



Multifilamentary step

ITER Superconductors

Multifilamentary twisted composite wire

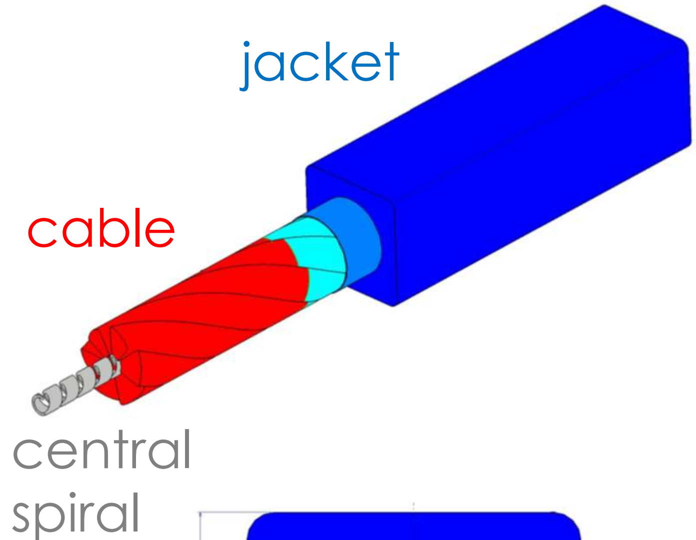


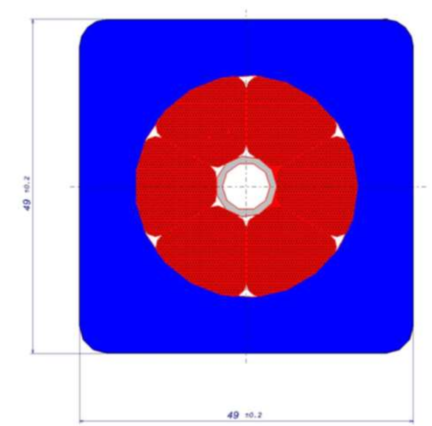
Deep Zoom into ITER CS conductor put together by Carlos Sanabria and Peter Lee, FSU

ITER Superconductors

Cable-in-conduit conductors

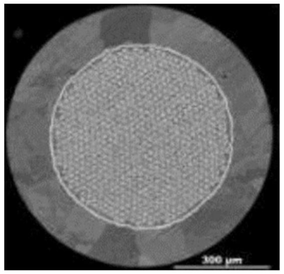
- a cable-in-conduit conductor allows achieving **high transport current,** by twisting together into a cable **several hundreds** of strands contained in a steel pipe internally cooled by a flow of supercritical helium
- in a **dual channel** cable-in-conduit conductor, a central channel is managed along the conductor axis



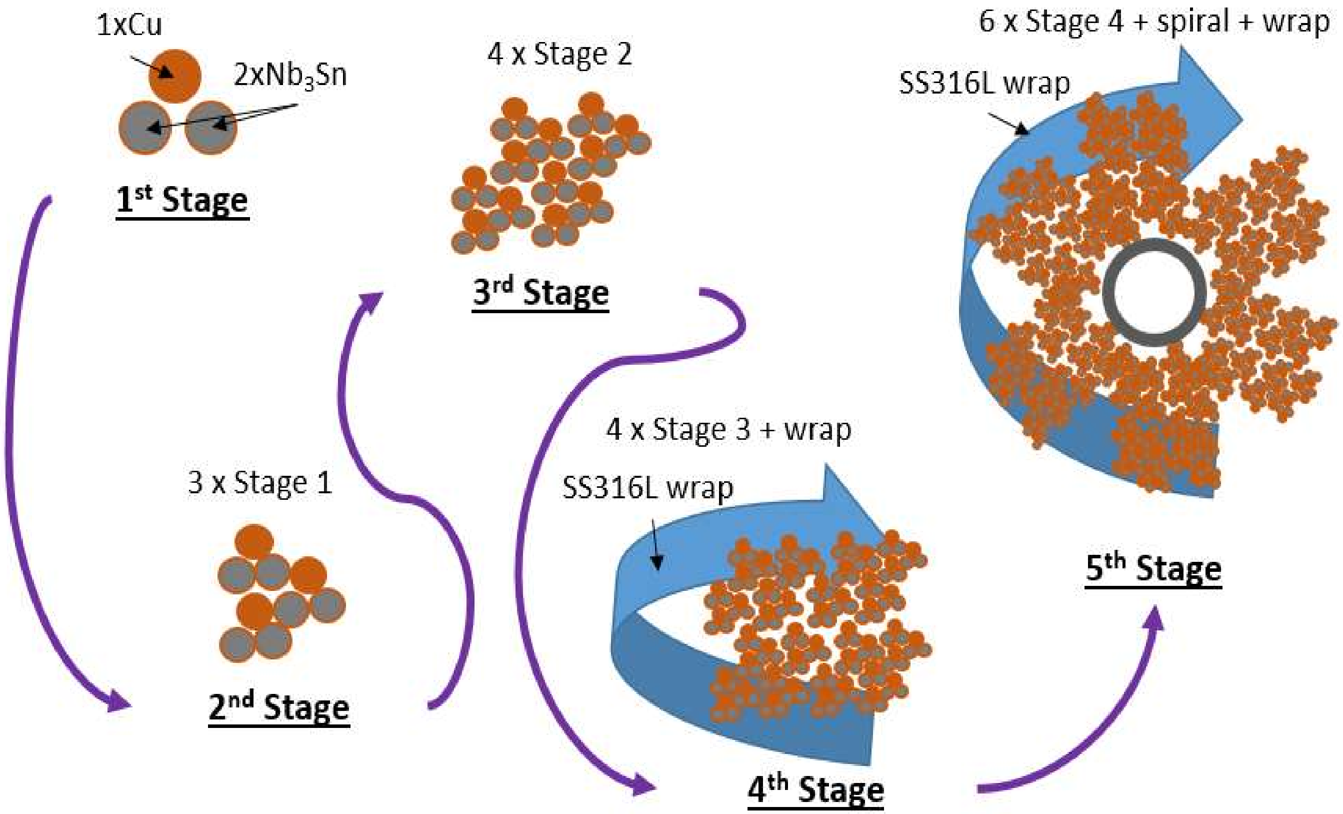


ITER Superconductors

Multistage twisted cables



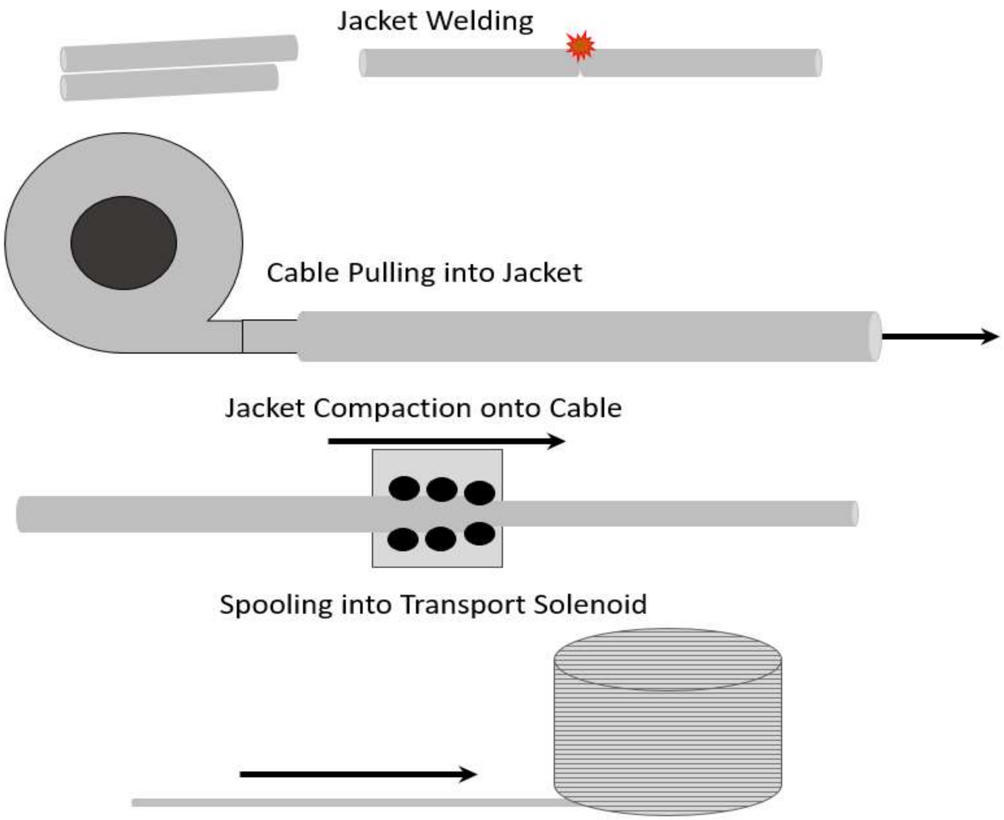
Strand cabling is performed in a multistage process



ITER Superconductors

Cable jacketing

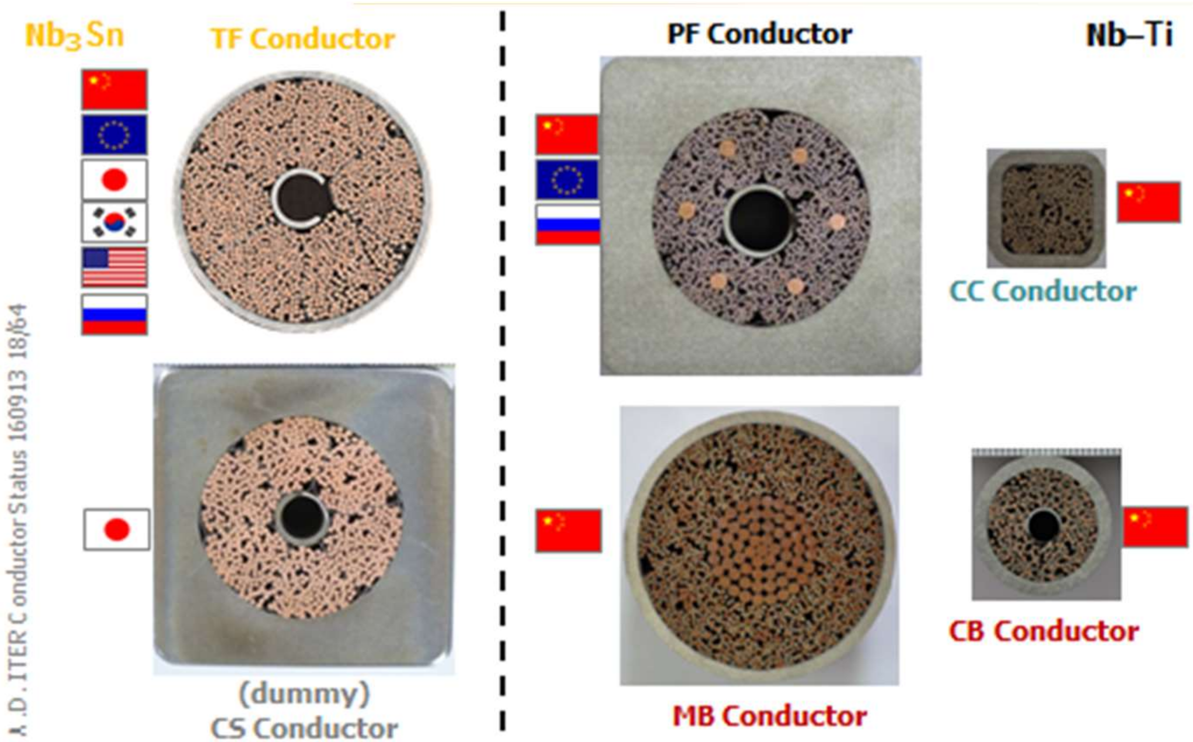
Cable jacketing is performed in 3 steps:
- Jacket manufacture
- Cable pulling through
- Jacket compaction



ITER Superconductors

ITER Conductors

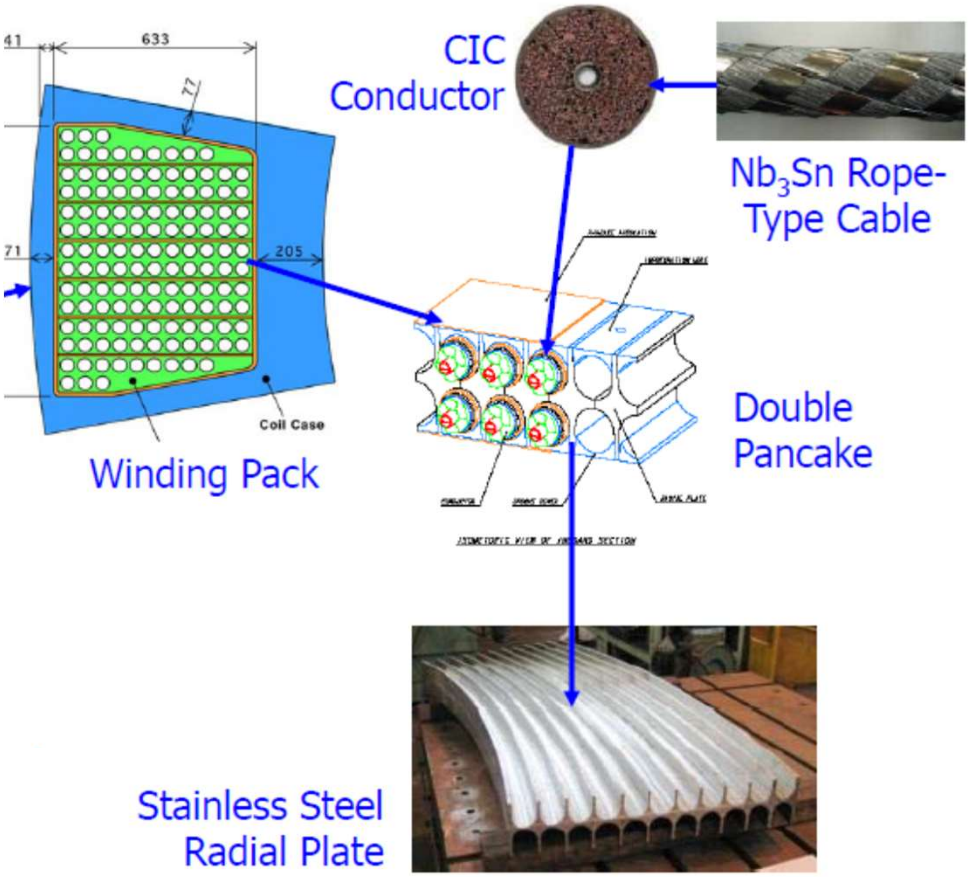
Cable-in-conduit ITER conductors cooled by supercritical He flow at 4.5 K



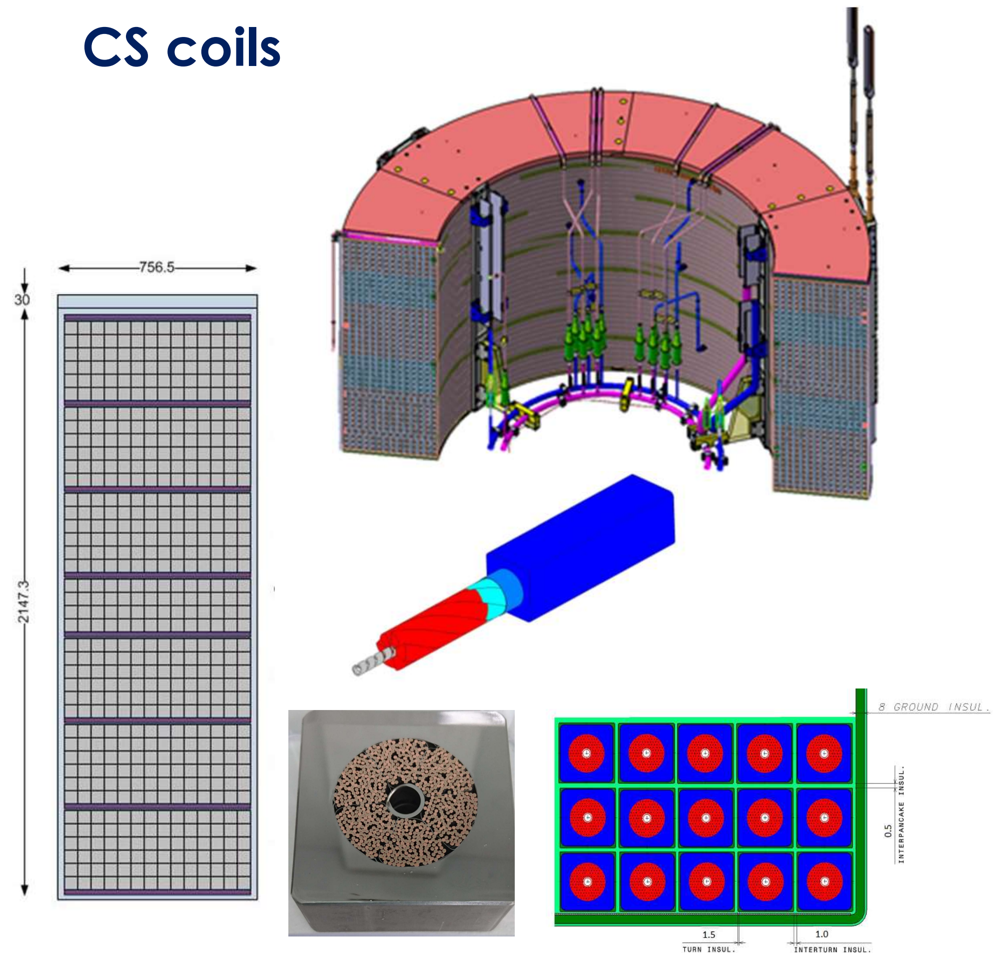
ITER Superconductors

Nb_3Sn coils

TF coils



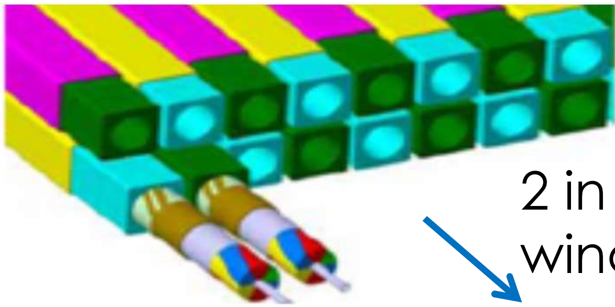
CS coils



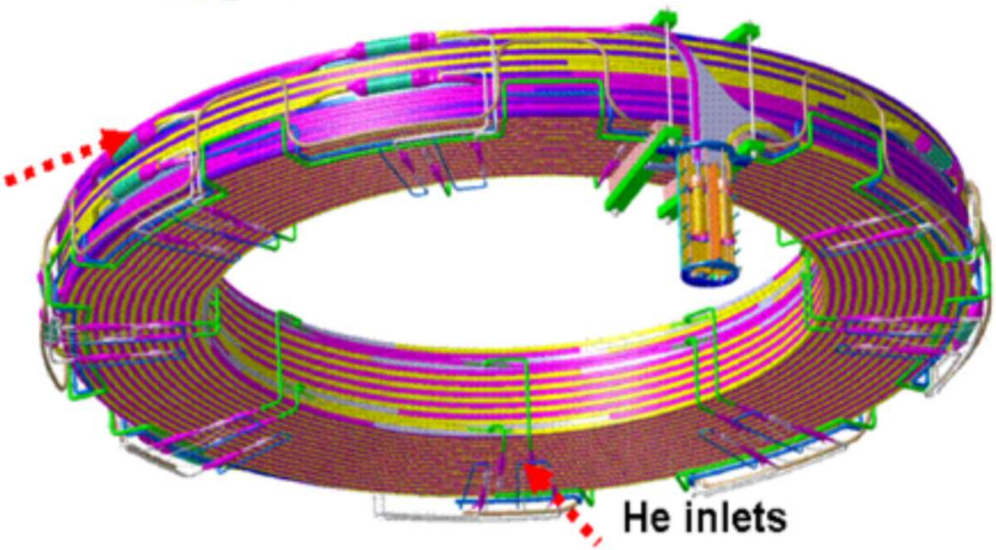
ITER Superconductors

NbTi coils

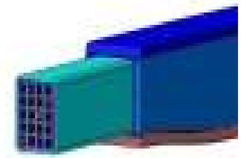
PF coils

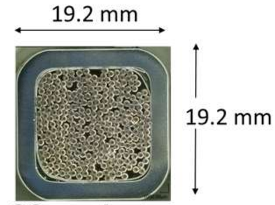


2 in hand winding

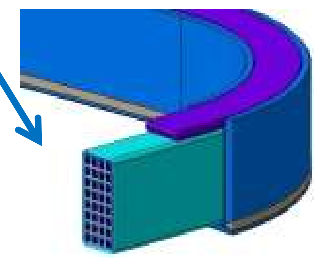


Correction Coils





CC conductor cross-section



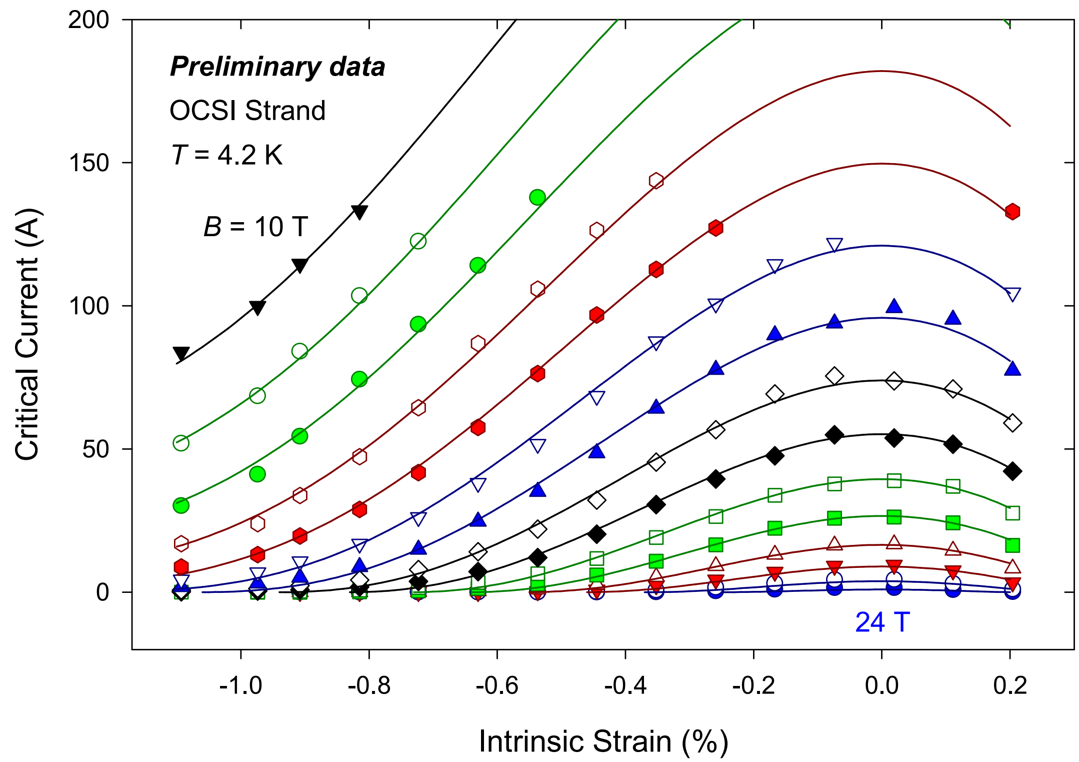
ITER Superconductors

Nb_3Sn critical current strain dependence

Nb_3Sn critical current is highly sensitive to applied **strain**

→ **selection of wind and react process to minimize applied strain**

- Winding
- Reaction heat treatment (650C, 200 h)
- Turn insulation



Manufacturing status

Nb_3Sn industrial production

- TF and CS strand productions are completed with **over 500 tons (~7800 billets and 100,000 km) for TF** and ~170 tons for CS.

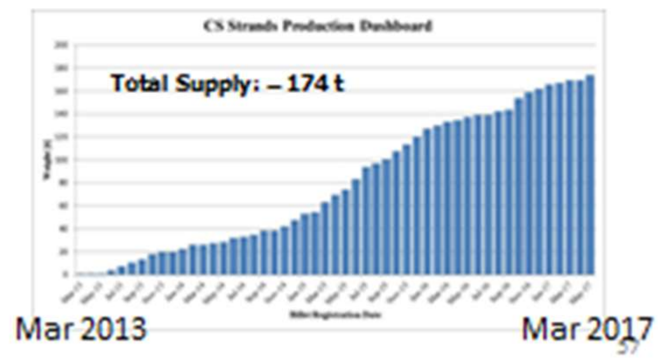
- It is the **largest Nb_3Sn strand production** ever and has called for a significant worldwide production **ramp up.**

- Pre-ITER world production was estimated at ~15 t/year; it has been steady for the last five years at ~100 t/year.

Data Compiled by D. Karerin as of 31 May 2017 (ITER-CT)

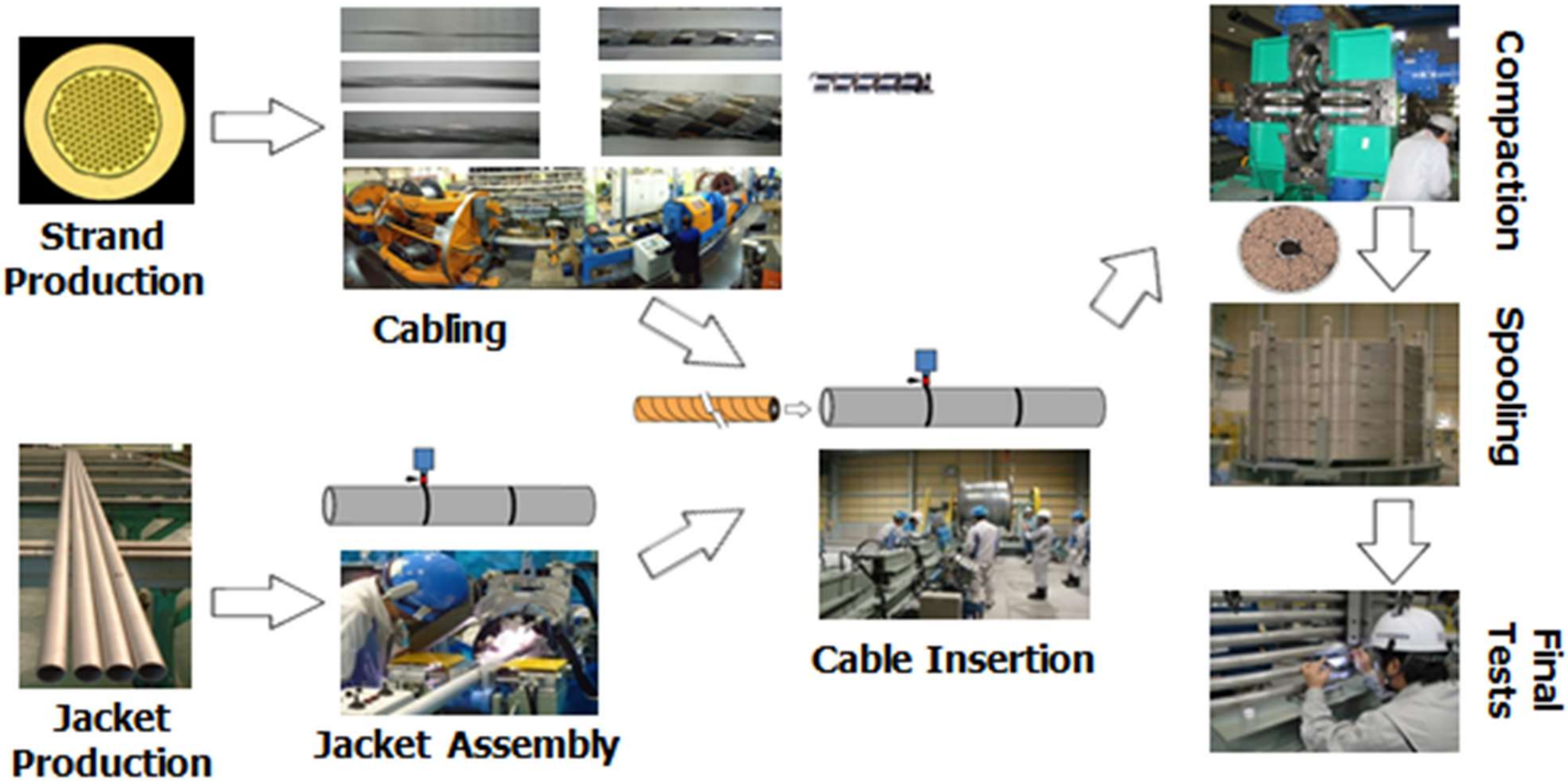
- Nb_3Sn for TF: ~100% complete.

- Nb_3Sn for CS: ~100% complete.



Manufacturing status

Conductor manufacture is complete



Manufacturing status

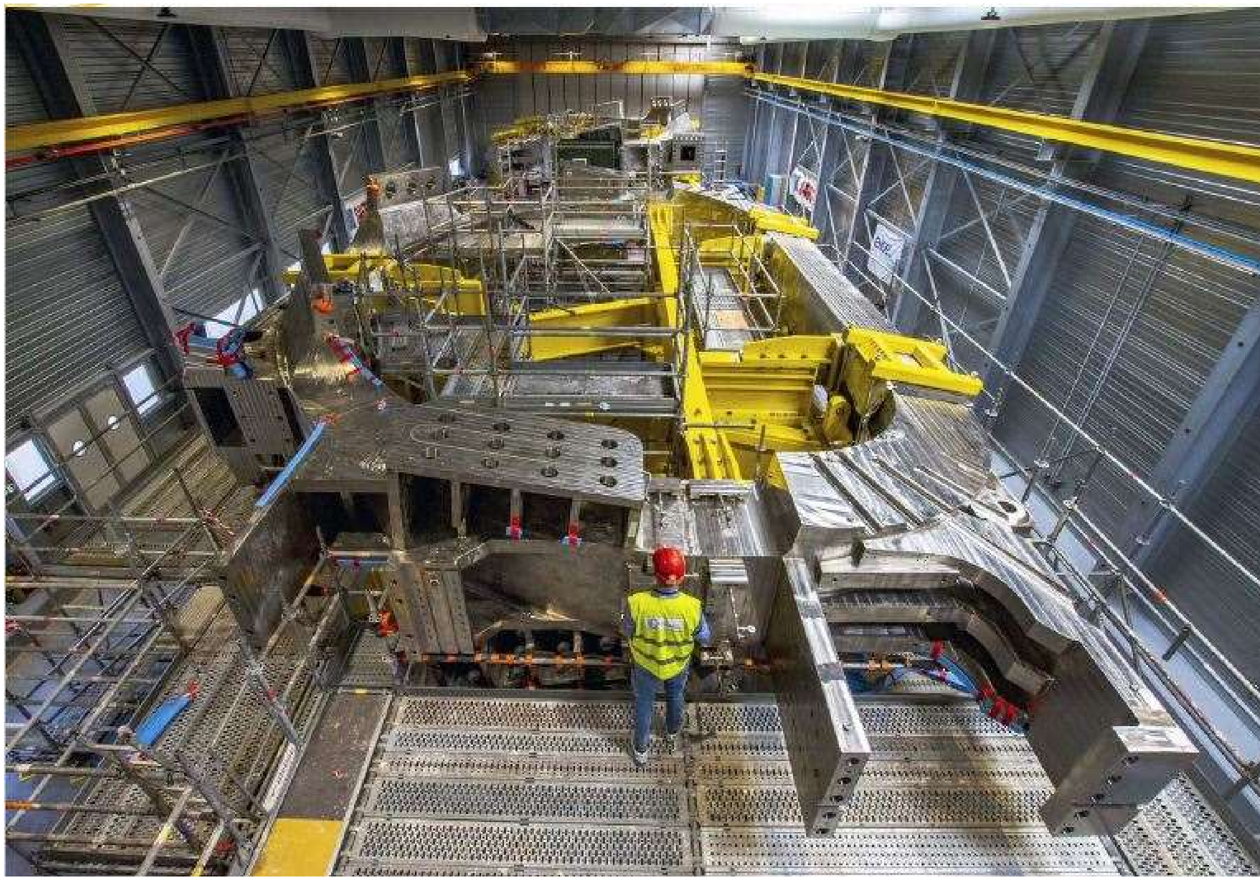
TF coils

First TF winding-pack before resin impregnation

First TF case before assembly with winding-pack

Manufacturing status

TF coils



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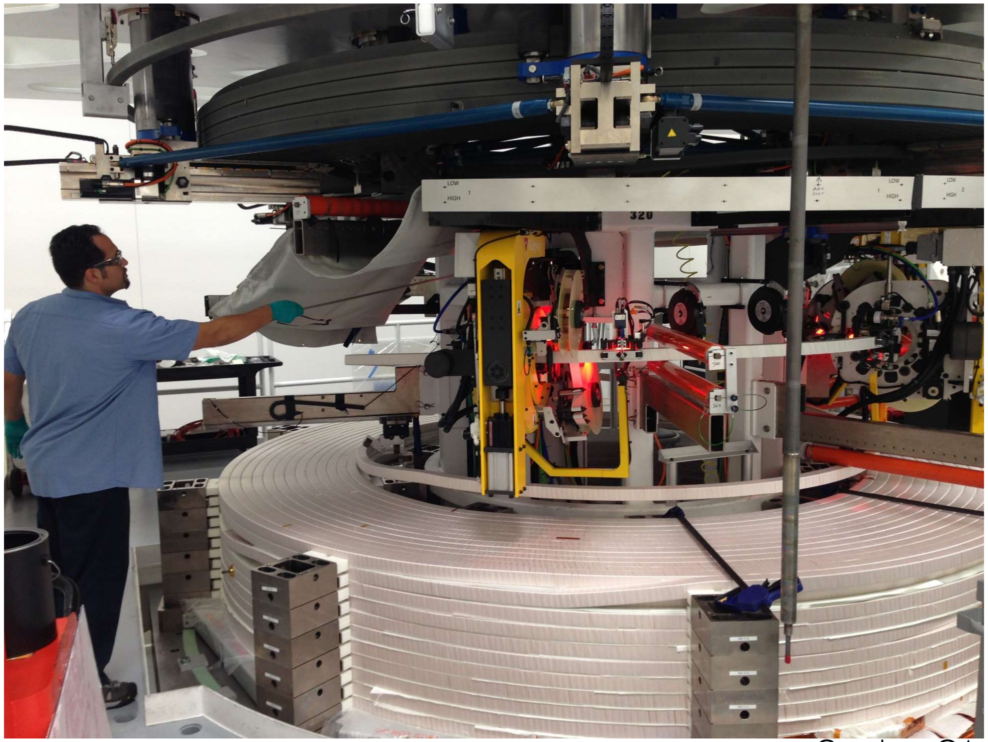
First TF coil delivered to ITER

Manufacturing status

CS coils

Courtesy GA

CS Module heat treated



Courtesy GA

CS Module mock-up turn insulation application

Manufacturing status

CS coils

Courtesy GA

CS Module 1 ground insulated

Courtesy GA

CS Module 1 cold testing

Manufacturing status

PF coils

Courtesy F4E

PF4 2nd double pancake winding

Courtesy F4E

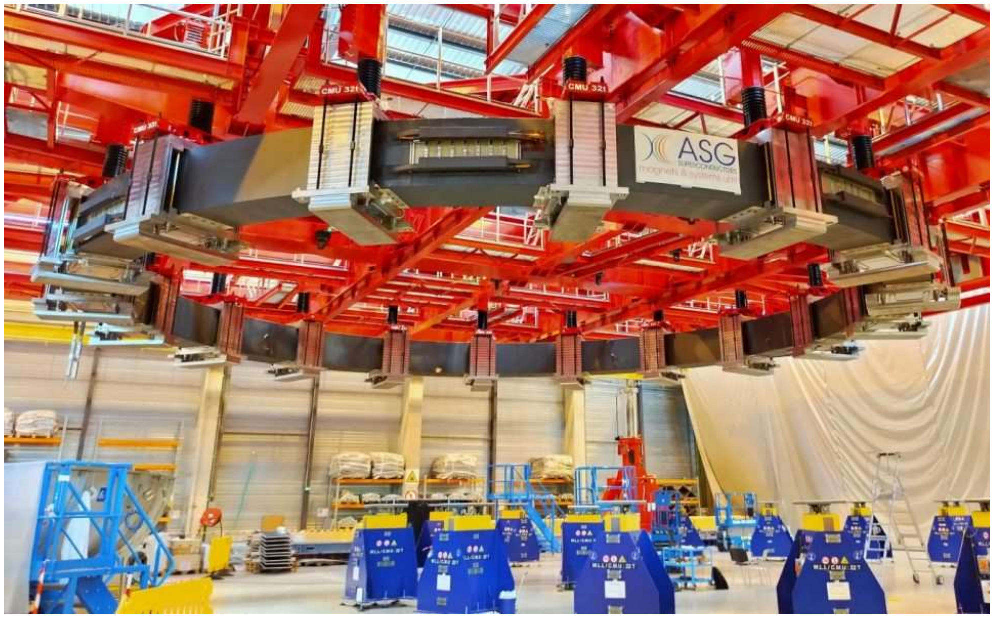
PF coils manufacturing hall

Manufacturing status

PF coils

Courtesy F4E

PF2 resin impregnation preparation



Courtesy F4E

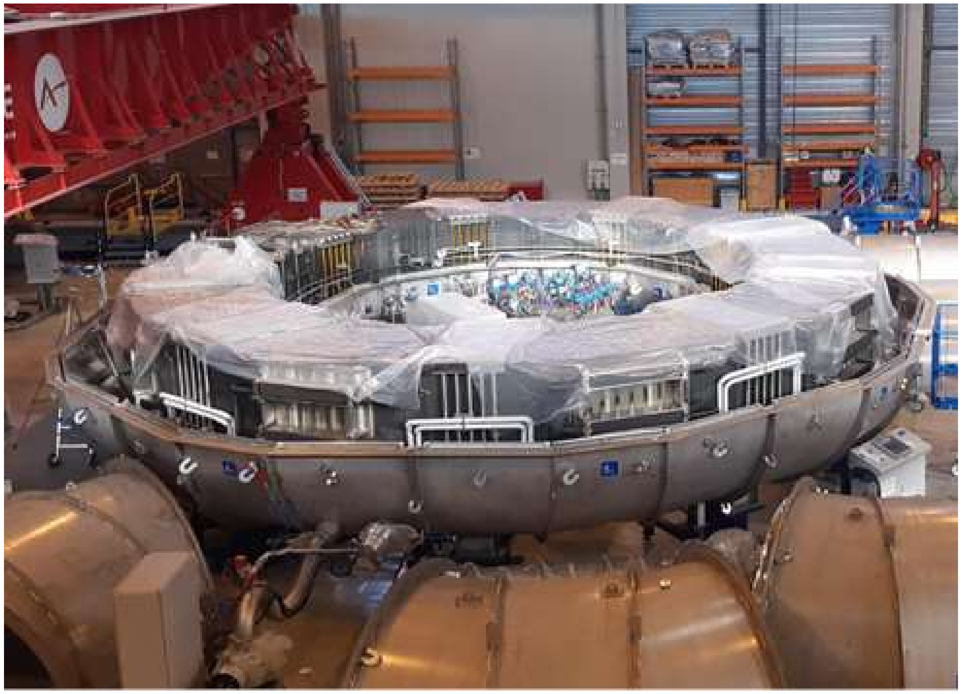
PF5 resin impregnated

Manufacturing status

PF coils

Courtesy Efremov

PF1 ground insulated



Courtesy F4E

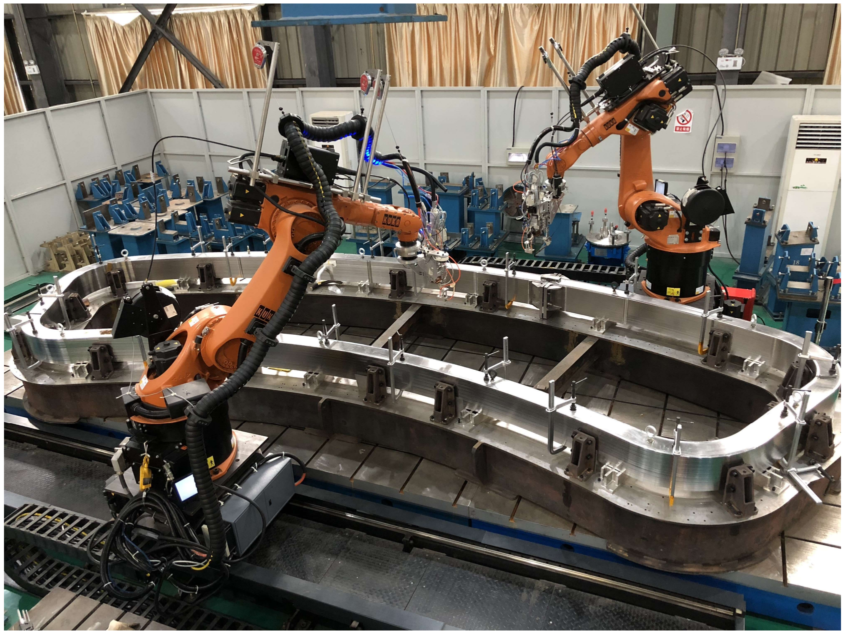
PF6 cold testing preparation

Manufacturing status

Correction coils

Courtesy ASIPP

BCC1 winding-pack



Courtesy ASIPP

Prototype BCC case closure welding

Manufacturing status

Summary

ITER Magnet System component	Status
Nb_3Sn conductor lengths	Delivered to coil manufacturers
NbTi conductor lengths	Delivered to coil manufacturers
TF coils	3 TF coils delivered to IO
PF coils	PF6 prepared for cold testing PF5 resin impregnated PF4 under winding PF1 ground insulated
CS coils	Module 1 cold tested Module 2 prepared for cold testing Module 3 resin impregnated Module 4 ground insulated Module 5 under turn insulation application Module 6 stacked, preparing for heat treatment
Correction Coils	6 BCC coils manufactured, ready for delivery to IO