The evolution of design and manufacture of fusion conductors

Six milestones:

T-7 Tokamak	**1977**
T-15 Tokamak	**1987**
Tore Supra	**1987**
Large Helical Device	**1998**
Wendelstein 7-X	**2007**
ITER	**? ? ?**

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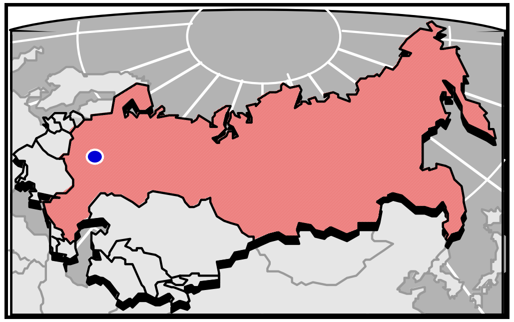
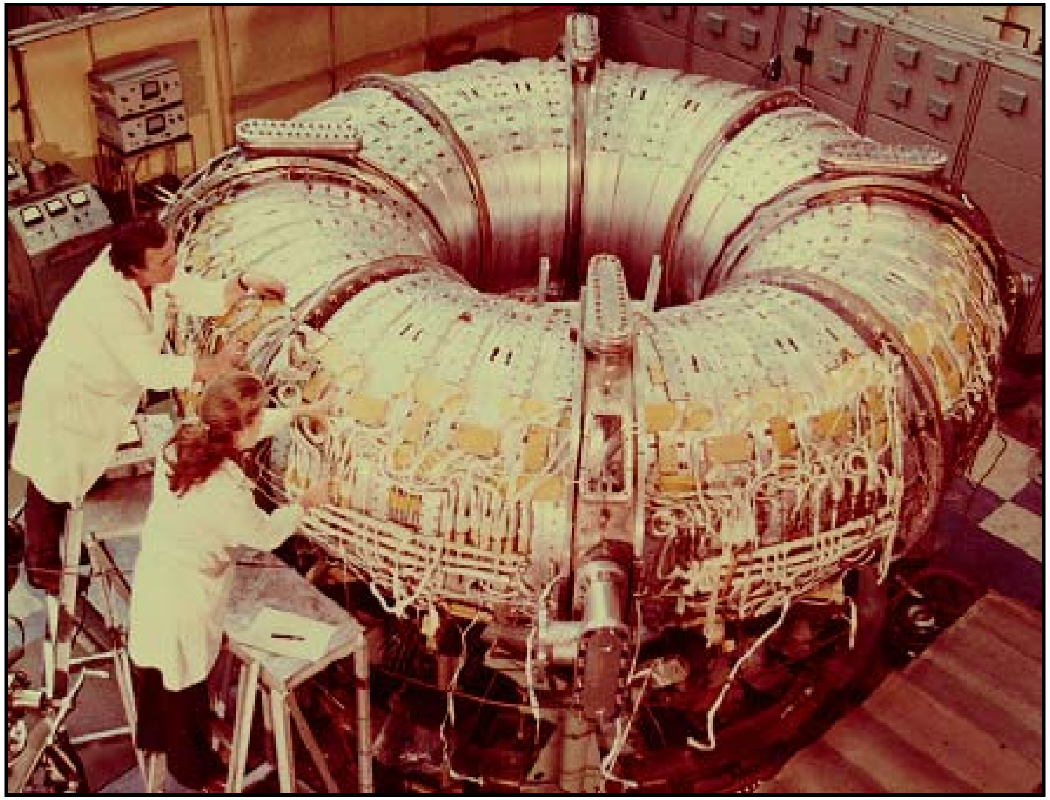
Tokamak T-7

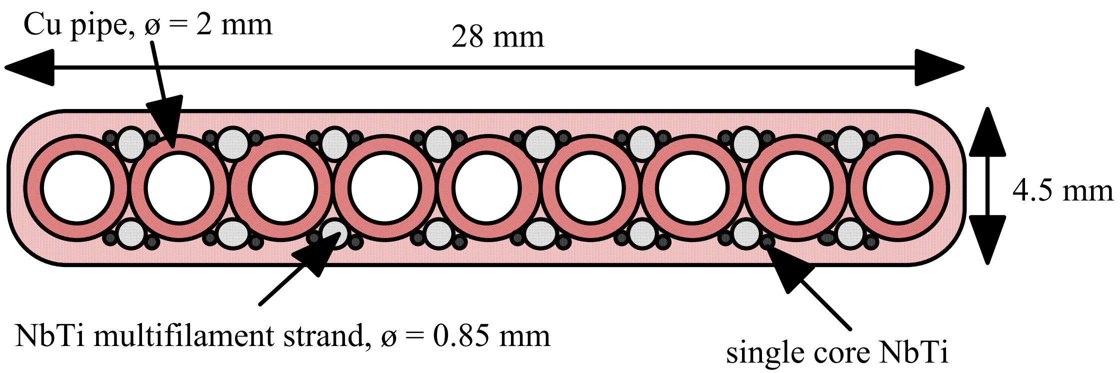
Kurchatov Institute, Moscow, Russian Federation

First ever superconducting Tokamak (operation in 1977)
cold mass 12 t, stored energy 20 MJ, peak field 5T





T-7 Conductor Layout
6kA, 5T



Cooling: forced flow, 2-phase He @ 4.5K in a linear array of nine copper pipes, 2 mm inner diameter, hydraulic length ≈ 200m

Supercondutor: 16 multifilamentary and 32 single core NbTi strands placed in the grooves between the pipes

Assembly: pipes and strands are bonded by continuous Cu plating in a $CuS0_4$ electrolyte, 0.6 mm thickness

Screen: A 15 mm thick copper shell surrounds each coil and acts as an eddy currents shield for the poloidal field variations

The design is dominated by the thermal stability issue:

-bring the coolant as close as possible to the superconductor (9 small cooling channels in parallel)

-provide very high heat conductivity between coolant and superconductor (avoid solder and use thick Cu plating)

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T-7 Conductor: Performance and Limits

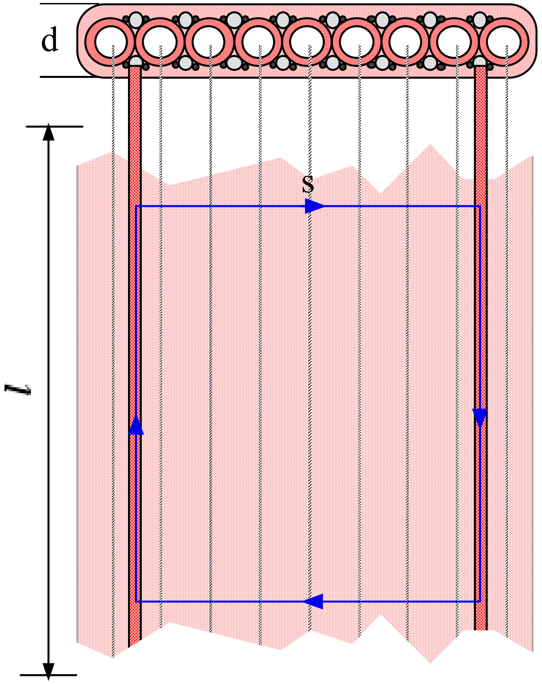
The major problems in operation were actually

-*the cooling* (bad flow partition, many channels were actually chocked)

-*the flux jumps* due to the non-transposed strands (huge coupling currents induced during charge)

$$I_{cc} = \frac{V}{R} = \frac{\dot{B}(l \cdot s)}{\rho_{Cu}(s/d \cdot l)} = \frac{\dot{B}\, l^2 \cdot d}{\rho_{Cu}}$$

With l ≈ 200m, even at dB/dt = 0.1G/s (one week charge time), the induced current are in MA range



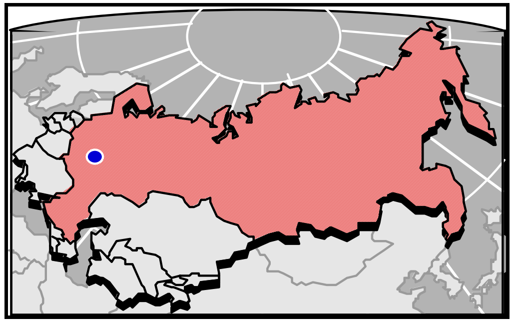
Despite the operation problems, T-7 achieved 80% of the nominal current and operated several years. In the nineties, T-7 was disassembled and transferred to the Chinese Institute of Plasma Physics, Hefei, where it operated again since 1996

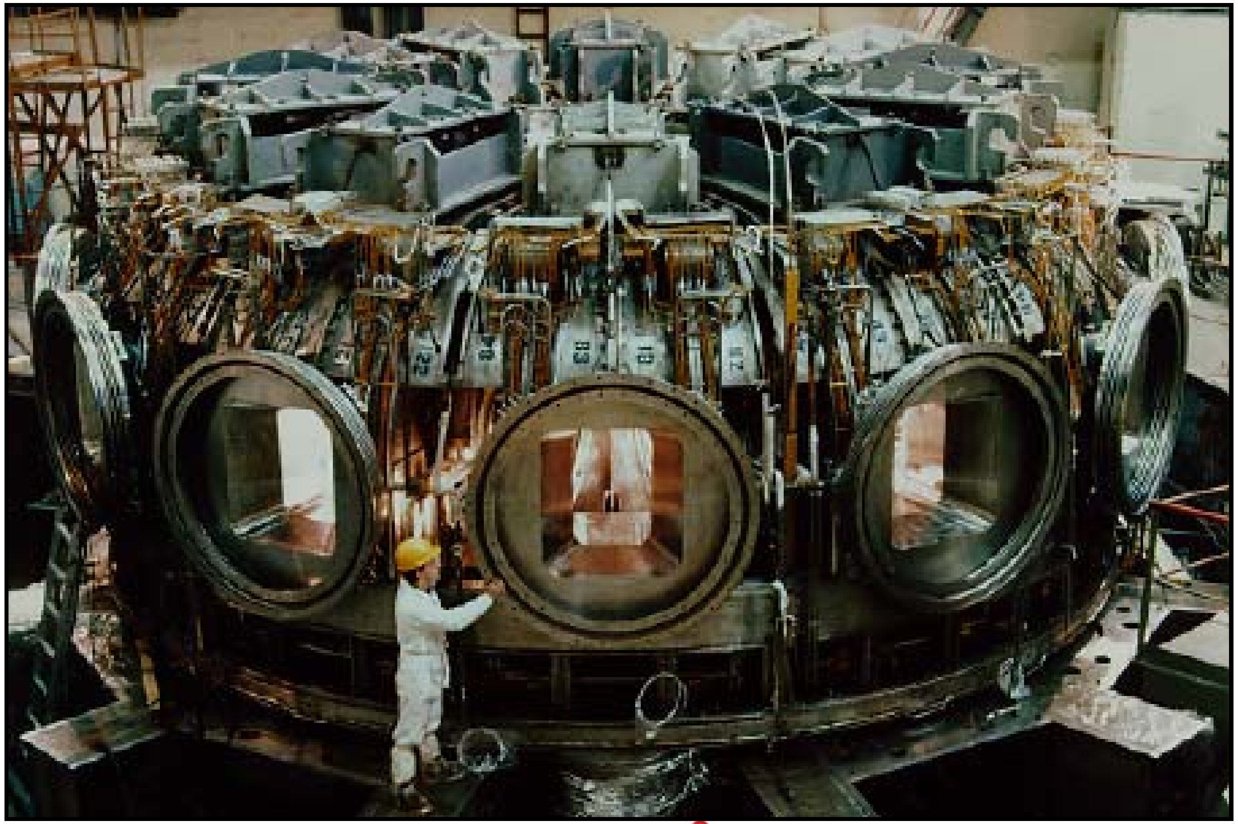
Tokamak T-15

Kurchatov Institute, Moscow, Russian Federation

Largest Nb_3Sn based device worldwide (operation in 1987)

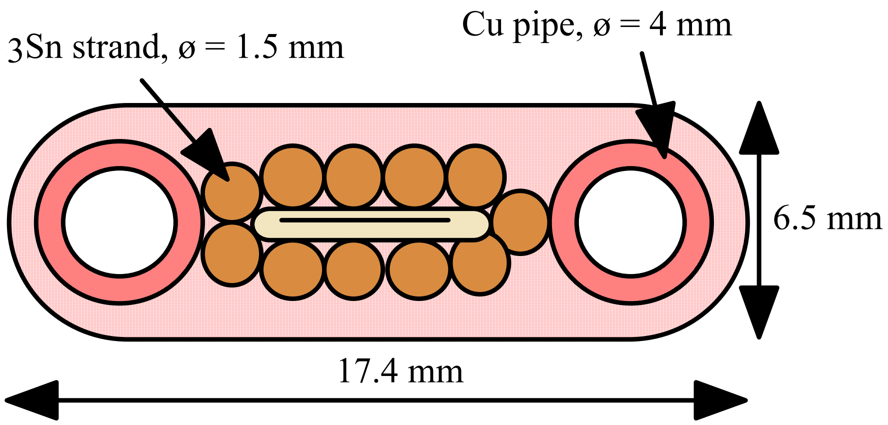
24 circular coils, average diameter 2.4 m, over 100 km conductor





T-15 Conductor Layout

5.6kA, 9.3T



Cooling: forced flow, on two copper pipes, 4 mm inner diameter, hydraulic length ≈ 200m

Supercondutor: 11 multifilamentary, non-stabilized Nb_3Sn strands cabled on a bronze strip

Assembly: pipes and strands are bonded *after heat treatment* by electroplated Cu, 1.2 mm thick

After the lesson of T-7, the cooling and the transposition are OK

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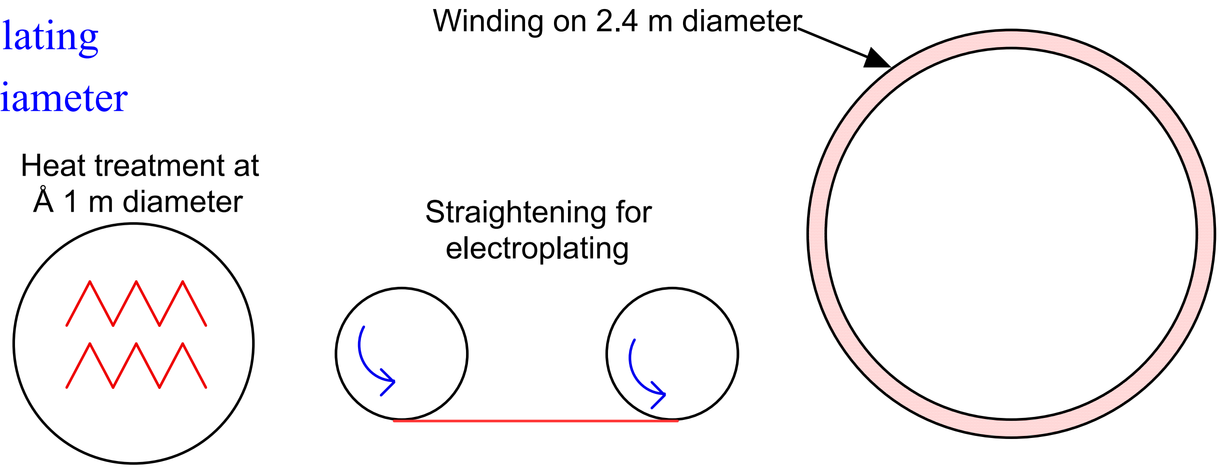
T-15 Conductor: Performance and Limits

The manufacturing method was React&Wind:

-Heat treat the cable of 11 strands

-Unwind for electroplating

-Wind on final coil diameter



Winding on 2.4 m diameter

Heat treatment at
Å 1 m diameter

Straightening for
electroplating

Each coil, tested before assembly, achieved the nominal operating point, and could withstand plasma disruptions. However, a voltage of 2.5 - 10 mV/coil was observed.

The operation of the assembled Tokamak was restricted by the temperature increase due to the large power (up to 700 W) and limited heat removal capability by the cryoplant.

T-15 Conductor: Strand bending in the R&W methos

The 4 mm thick cable of 11 strands, t=4mm, goes through bending radii of

$R_{ht} \approx 0.5$m at the heat treatment
$R_{straight} = \infty$ during straightening for electroplating
$R_{fin} \approx 1.2$ m in the final winding and operation

The bending strain through the manufacturing process is

$$\varepsilon_{bending} = \pm \frac{t}{2}\left(\frac{1}{R_{\min}} - \frac{1}{R_{\max}}\right) = \pm 0.8\%$$

The tensile strain of 0.8% exceeded the irreversibility limit of ≈0.5% and caused performance degradation in terms of early voltage (low n index due to micro-cracks)

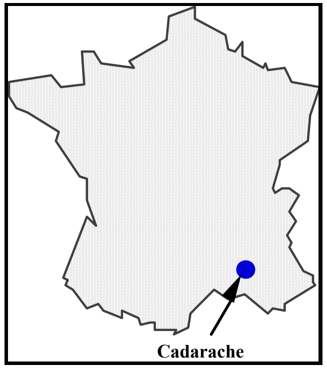
The unfortunate experience of T-15, due to a trivial reason (too small heat treatment furnace) caused a long term prejudice against the R&W method in fusion magnets.

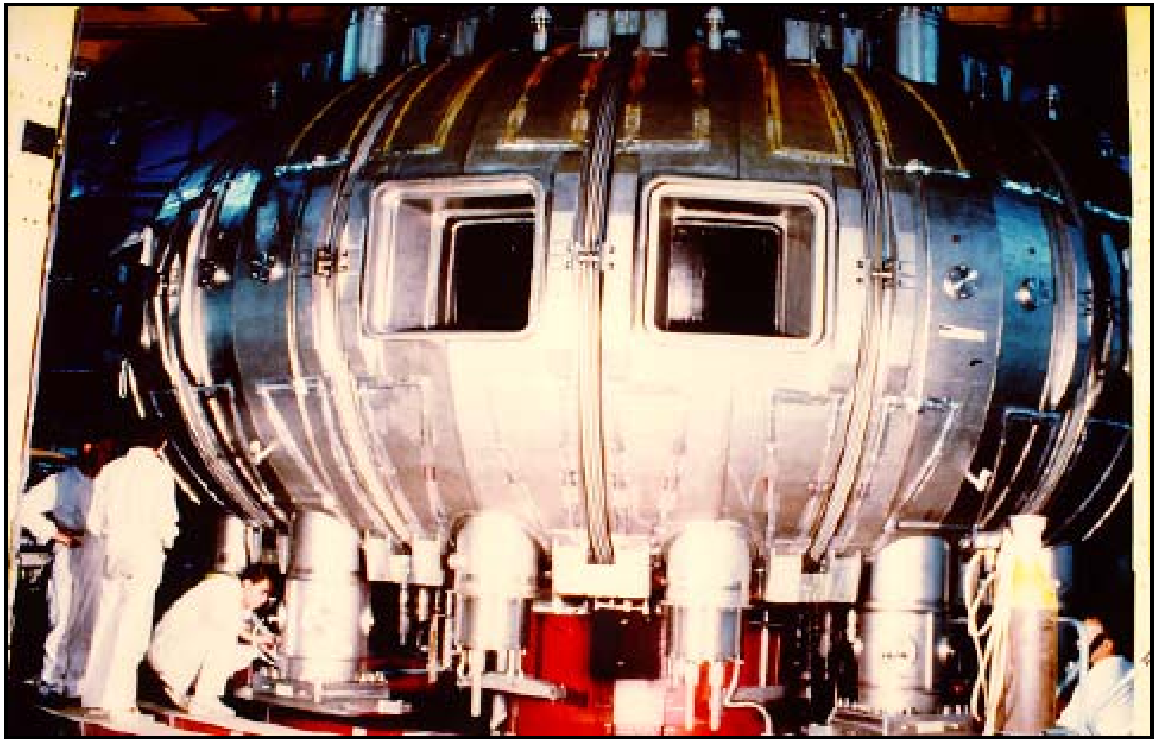
The conductor assembly by electroplating was not applied anymore: the slow process speed, the large electric power requirement and the poor dimensional tolerance overcame the advantage of a good, low resistance bonding of the components.

Tore Supra

***Centre d'Etude de Cadarache, France** 1987*

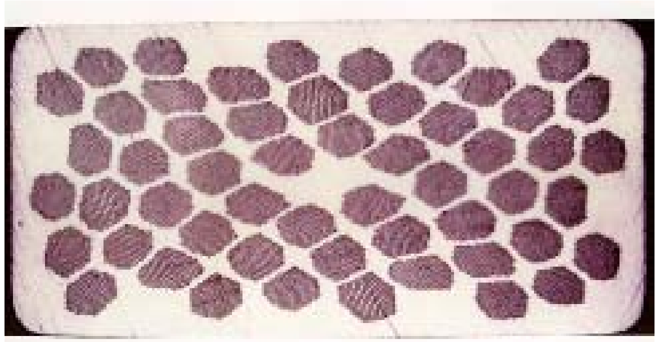
The largest device operating at 1.8 K





Tore Supra Conductor Layout

2.8 x 5.6 mm 1400A, 9T



Supercondutor: Large NbTi mixed matrix composite

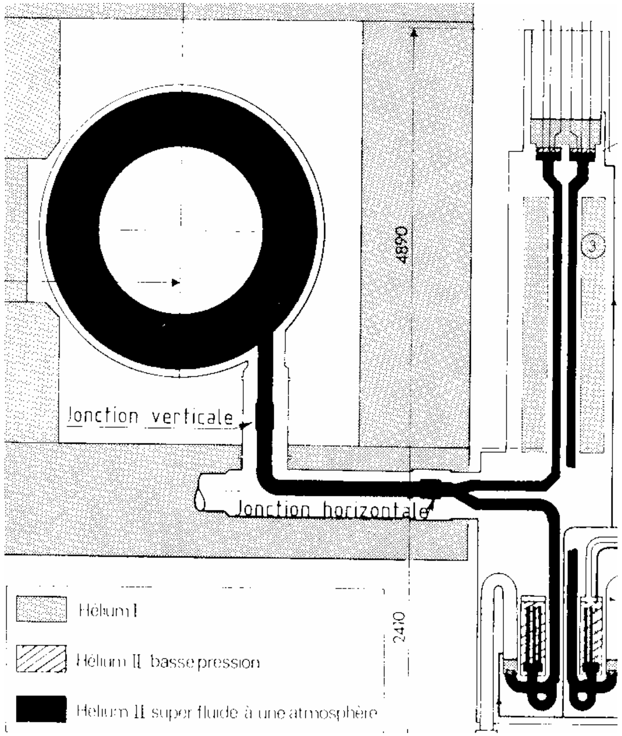
Cooling: atmospheric bath of super-fluid helium at 1.8 K(λ plate). Cryostat fed from the bottom.

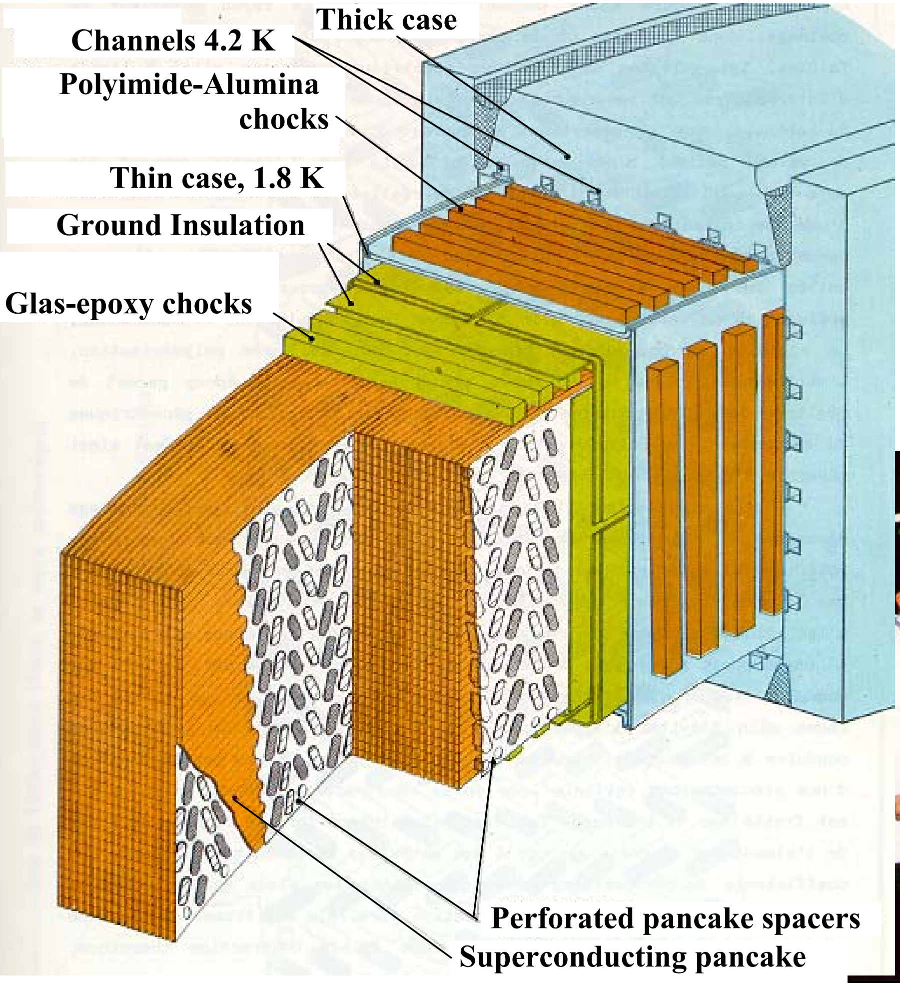
Quench Protection: Little Copper is used in the cross section. In case of quench, the He pressure building at the top of the coil case expels all the liquid He through the bottom port: within 3 s the winding is dry and all the conductor is normal

The design is a masterpiece of cryogenic, pushing the NbTi at its upper limit.

The disadvantages of a large monolith are overcome by the CuNi mixed matrix (coupling current time constant 20 ms).

The poor wet perimeter is balanced by the “infinite” heat conductivity of super-fluid helium





Tore Supra: bath cooling insulation issue

The 18 circular toroidal coils are wound as double pancake. The conductor is fully supported and insulated by prepreg tape in the radial direction. The coolant wets the conductor between pancakes, through a machined interpancake spacer.

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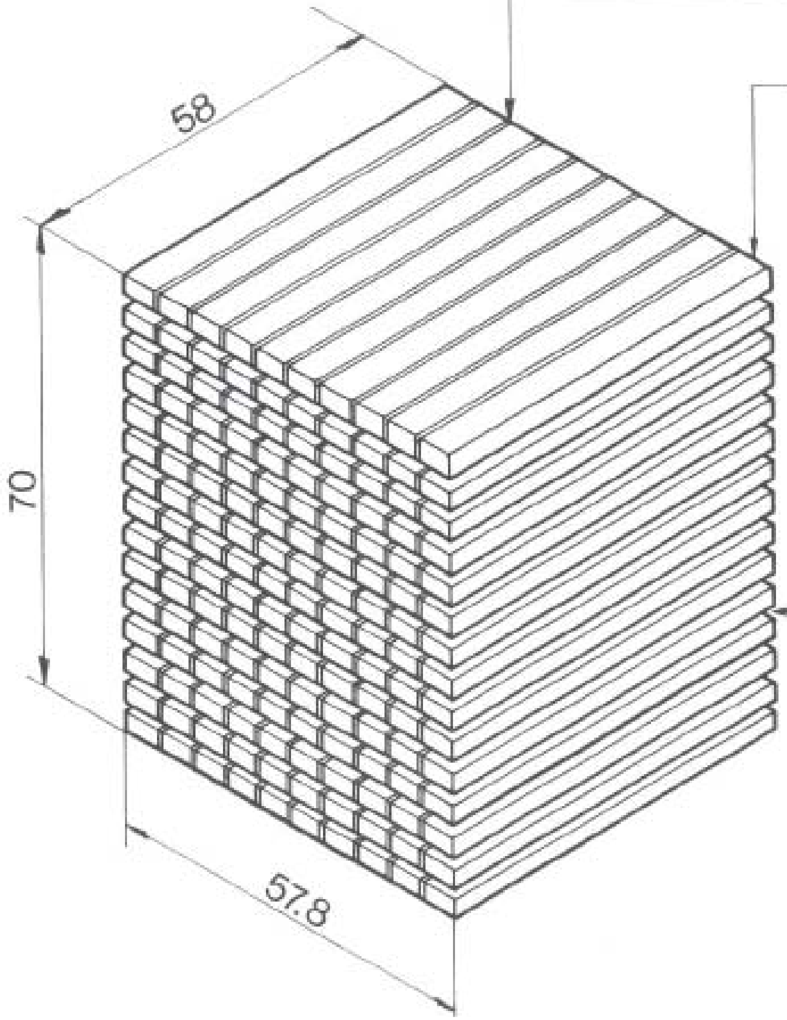
Tore Supra: bath cooling insulation issue



s used as a dielectricum
ıtion ≈ 2mm). The nominal
at a current dump was only
the Paschen minimum for
).

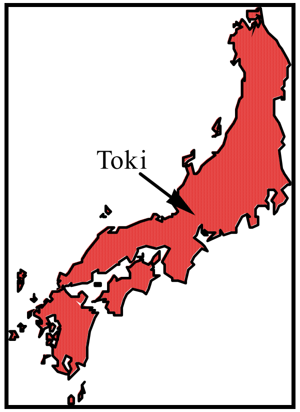
Nonetheless, a short occurred at a current dump and destroyed one coil, possibly due to some microscopic metallic chip, causing a high electric field peak

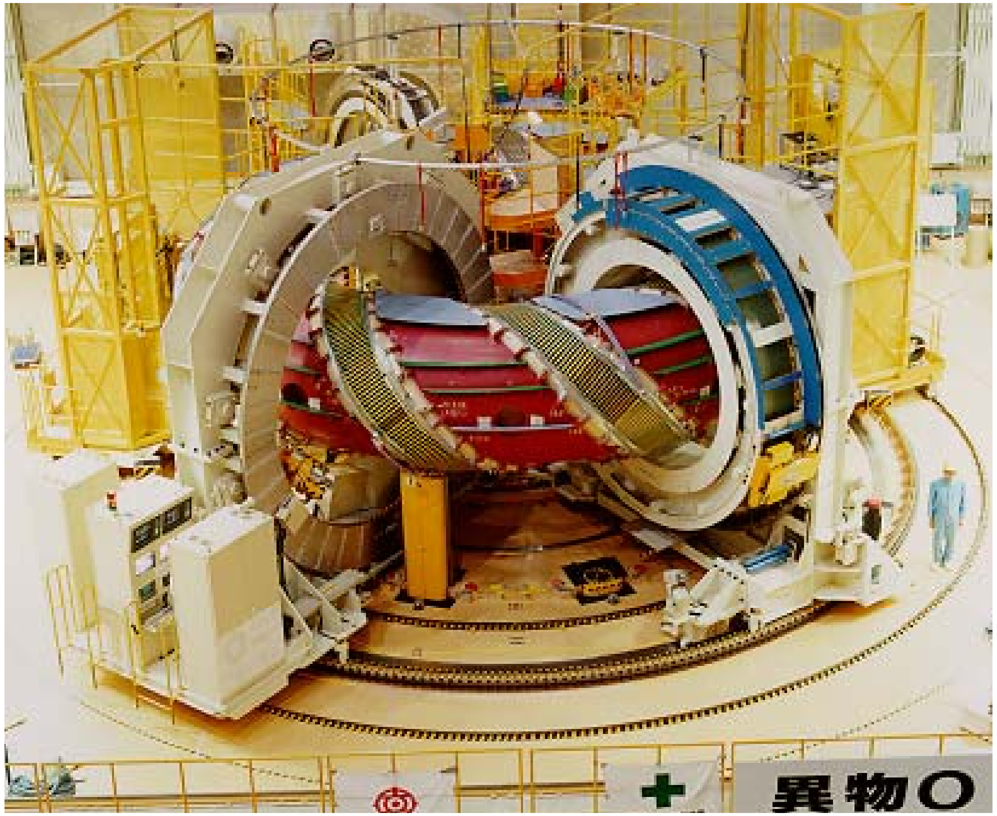
Large Helical Device

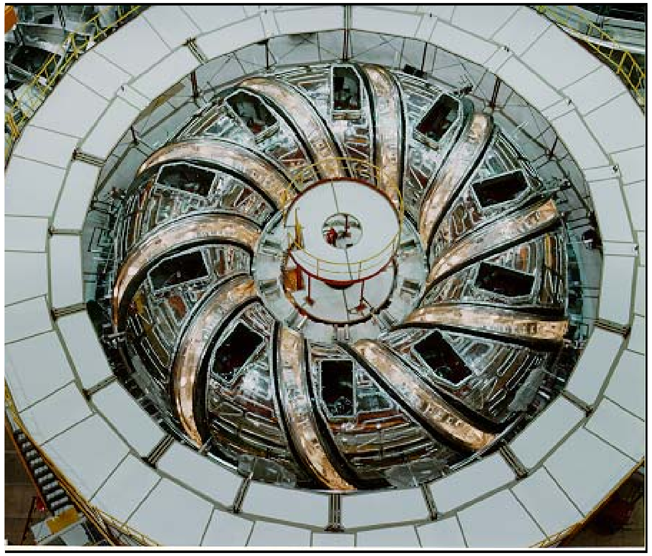
National Institute of Fusion Science, Toki, Japan

Largest stored energy for a single, bath cooled coil (operation in 1998)

2 Helical coils and 6 poloidal coils, all NbTi, over 400 t cold mass



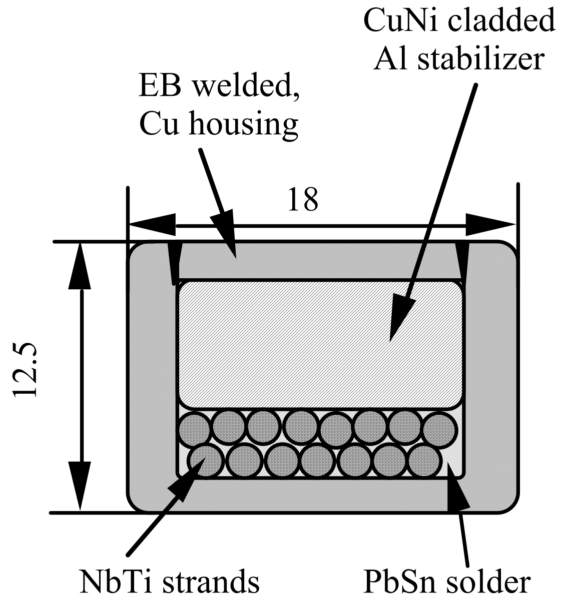




LHD Conductor Layout

World wide largest bath cooled monolith

13kA, 6.9T

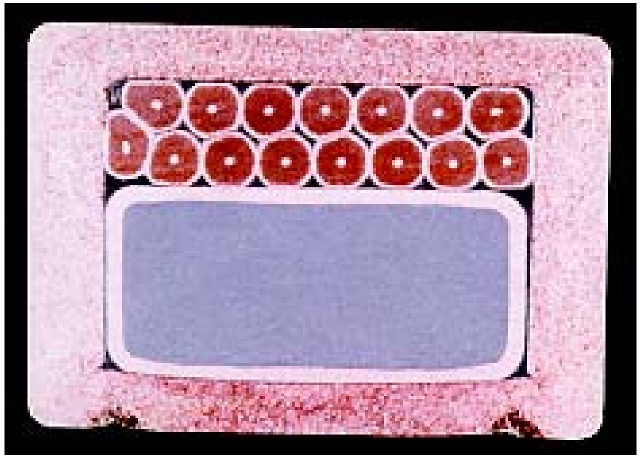


Cooling: helium bath @ 4.2K.

Supercondutor: flat cable of 15 NbTi strands, ø=1.74mm

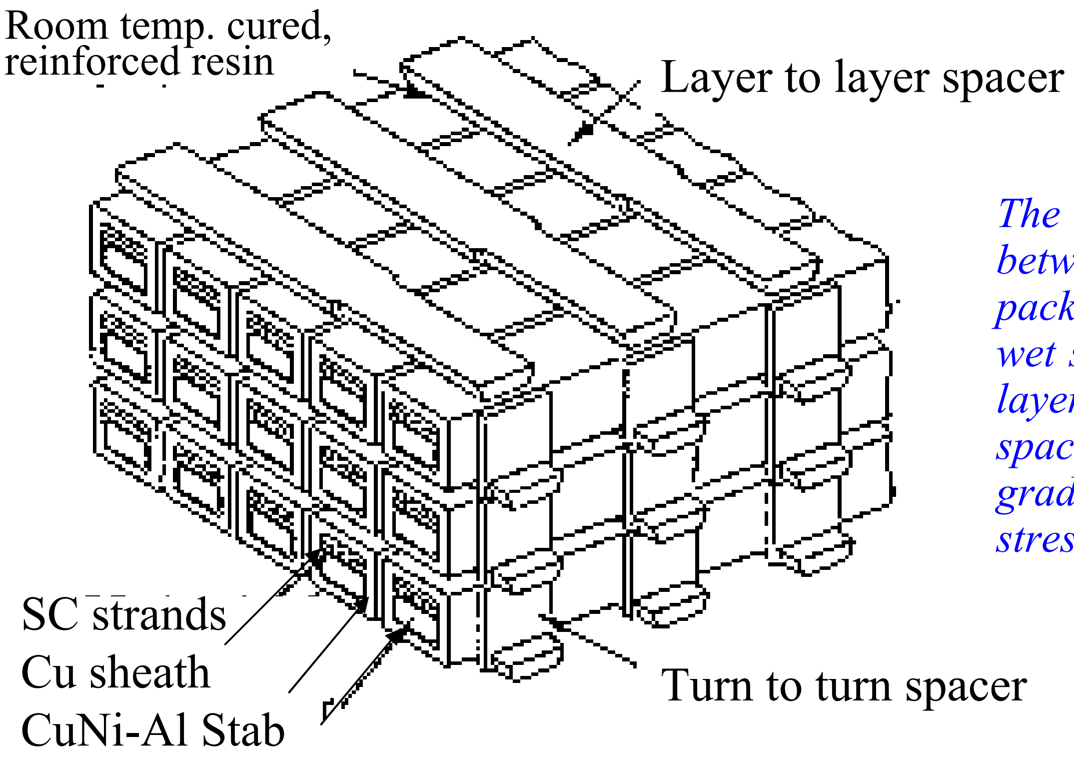
Stabilizer: high RRR Al, sheathed by CuNi

Assembly: cable and stabilizer are solder filled into a Cu housing, sealed by two longitudinal EB welds



The design is driven by cryo-stability. The copper surface is treated (CuO) to improve the heat exchange to helium.

LHD Conductor



The design is a critical compromise between a solid support of the winding pack against the loads and the large wet surface for stability. The turn and layer insulation are obtained by spacers (2 and 3.5 mm), with coverage graded from 69 % (low field, high stress) to 42% (peak field, low stress).

The expected cryo-stability, based on cold-end recovery, was actually not fully achieved. The operating current had to be limited to 11.3 kA due to observed propagating normal zone. Subcooled operation is planned at 3 K to improve stability

The raise of cable-in-conduit conductors for fusion

Forced Flow vs. He Bath

- **The bath cooled conductors offer**
  - superior stability (cryostability option)
  - well defined operating temperature
  - easy joining technique (conductor grading possible in pancake windings)
  - easier conductor manufacture (no need of vacuum tightness)

- **The forced flow conductors offer**
  - superior insulation, allowing high voltage operation for pulse and dump
  - potted, stiff, monolithic winding pack, to withstand high mechanical loads
  - structural reinforcement easily added to the conductor cross section

🖂 ***In the large magnets of the future fusion devices, the large stored energy requires fast dump for safety discharge, i.e. high voltage operation: the forced flow option prevail in the large fusion conductors***

The raise of cable-in-conduit conductors for fusion

Monolithic vs. Cable-in-conduit

- At very large current (> 30kA) the size of a soldered conductor was judged to be inadequate for heat removal and ac loss
- The pressure drop issue for the cable-in-conduit conductor becomes less severe at very large conductor size and can be overcome by a pressure release channel
- The low engineering current density, intrinsic for CICC design, is not a major problem for fusion conductor

Rather than experimental evidence, analytical demonstrations (based on assumptions no longer valid today) won the battle in favor of cable-in-conduit in the late '80, producing an avalanche effect and closing the design discussion

To some extent, the cable layout is dictated by the personal preference of the designer or by the manufacturing experience of the supplier

Prototypes, Model coils and fusion devices based on cable-in-conduit

Prototypes, Model Coils:

Westinghouse LCT 1984, Nb_3Sn, 17kA, 8T

US-DPC, 1898, Nb_3Sn, 26kA, 8T

DPC-EX, 1989, Nb_3Sn, 17kA, 6.7T

DPC-TJ, 1898, Nb_3Sn, 24kA, 7.6T

Polo, 1994, NbTi, 15kA, 3.6T

ITER CSMC, 2000, Nb_3Sn, 46kA, 13T

ITER TFMC, 2001, Nb_3Sn, 80kA, 9T

Fusion Devices:

LHD-OV, 1998, NbTi, 31kA, 5T

LHD-IV, 1998, NbTi, 21kA, 6.5T

SST-1, 2005, NbTi, 10kA, 5T

HT7-U TF, 2005, NbTi, 14.3kA, 5.8T

HT7-U PF, 2005, NbTi, 14.5kA, 4.3T

KSTAR TF, 2006, Nb_3Sn, 35kA, 7.2T

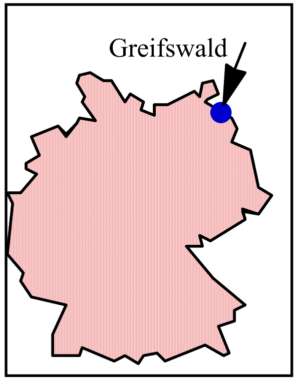
KSTAR PF, 2006, Nb_3Sn/NbTi

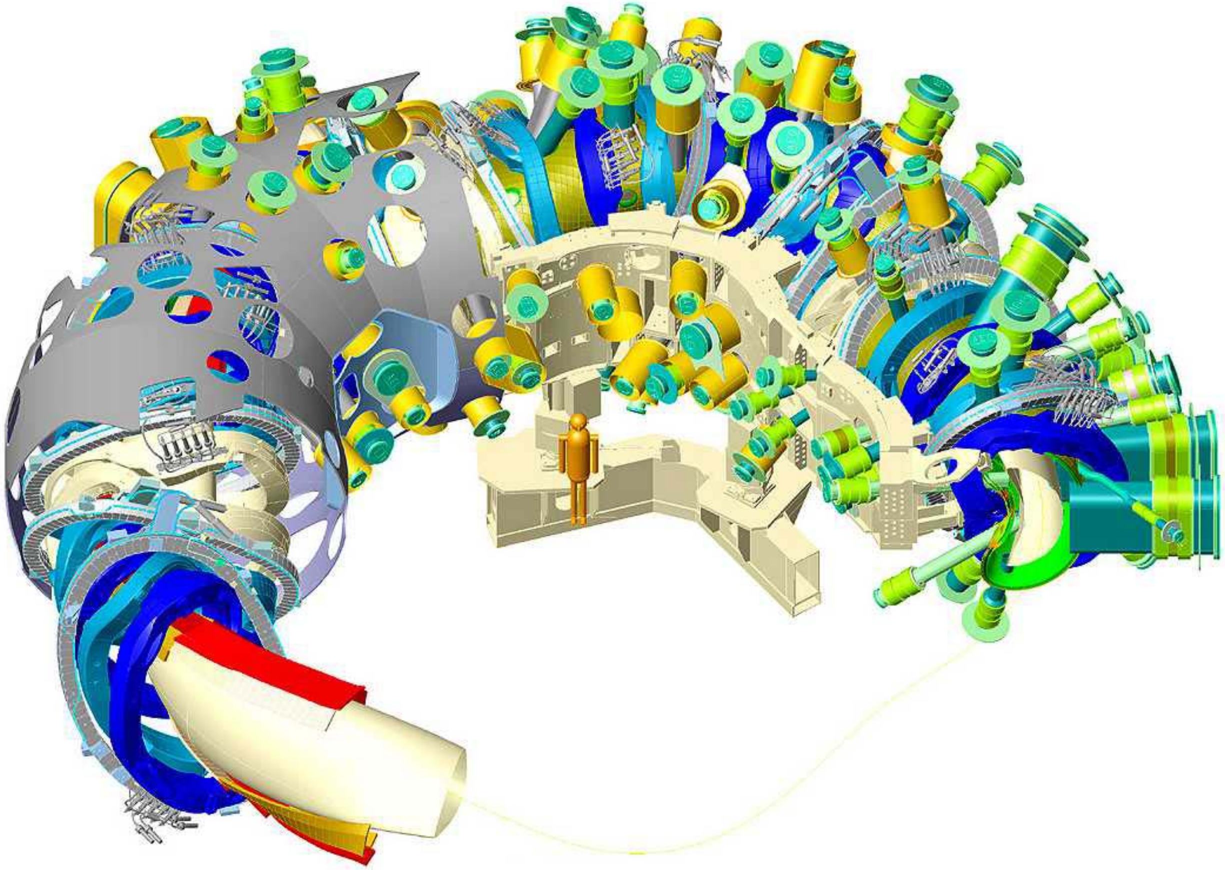
W7-X, 2007, NbTi, 17.6kA, 6T

Wendelstein 7-X

Max Planck Institute for Plasma Physics, Greifswald

Expected operation in 2007





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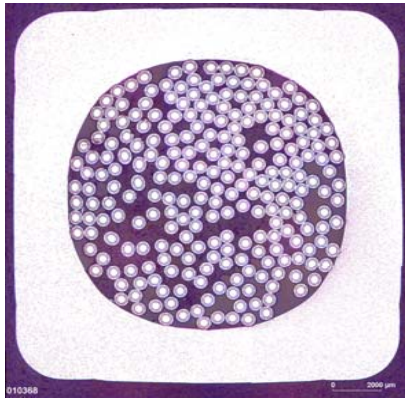
Wendelstein 7-X Conductor layout

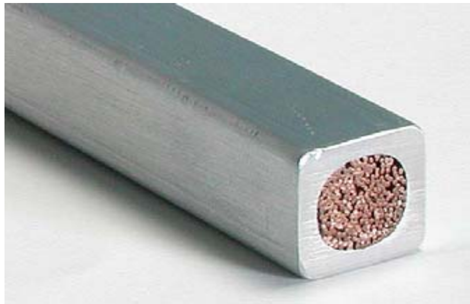
The only cable-in-conduit with Al jacket
16 x 16 mm 17kA, 6T



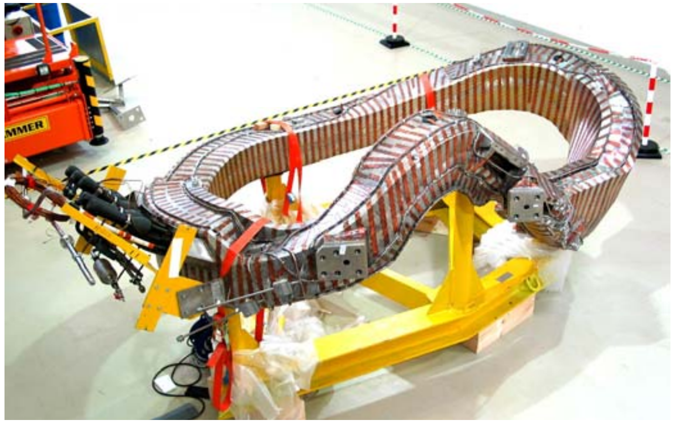
Cooling: supercritical helium flow at 4.5K.

Supercondutor: 243 NbTi strands, ø=0.57mm

Jacket: co-extruded AlMgSi alloy



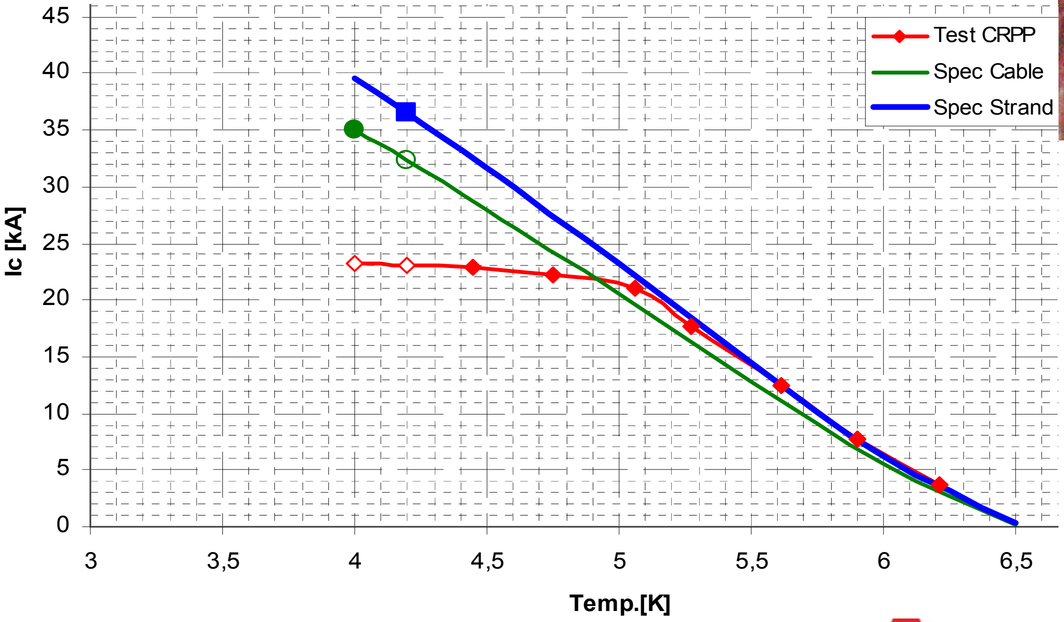
The design is driven by the very tight bending radii of the non-planar coils. The Al hardening alloy is soft “as extruded”, with $R_{p0.2}$ = 150 MPa, allowing easy winding into complex shape. After aging, $R_{p0.2}$ increases above 280 MPa and the winding pack achieves the stiffness necessary to withstand the operating loads



Wendelstein 7-X Conductor

The temperature/speed during the **co-extrusion** process must be controlled to avoid thermal degradation of the NbTi superconducting properties. Small variations of the extrusion parameters affect the void fraction and hence the flow distribution among the several parallel cooling channels.

The cable pattern, 3x3x3x3x3, leads to uneven cable surface and occasional strand breakage



As observed in other NbTi CICC, the critical current deviates from the expected behavior at large current (self field induced take-off)

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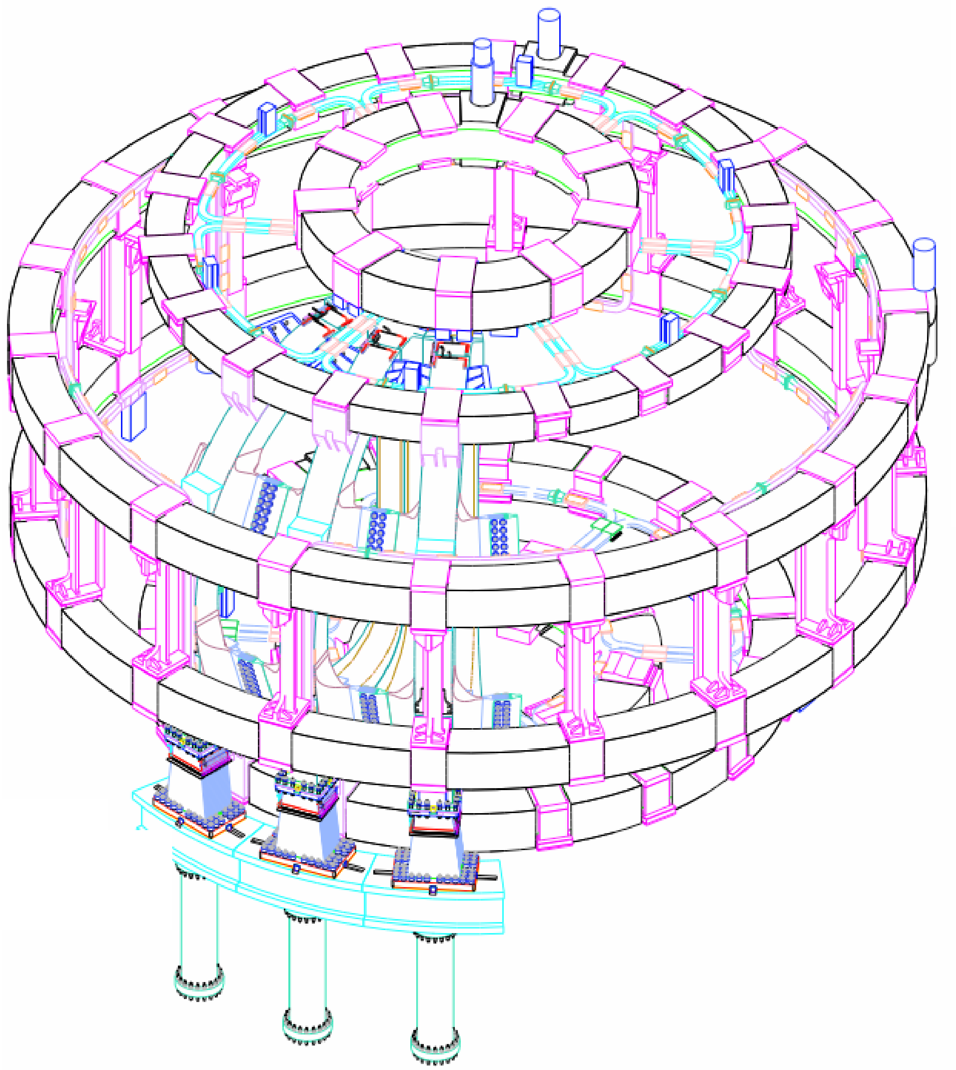
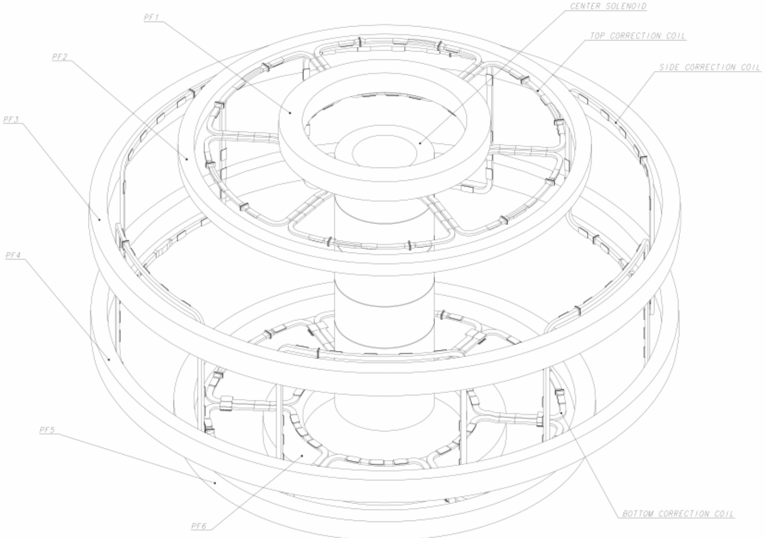
ITER - ……..

The largest stored energy compact system, >10GJ

Largest amount of Nb_3Sn

Largest cold mass in a single cryostat





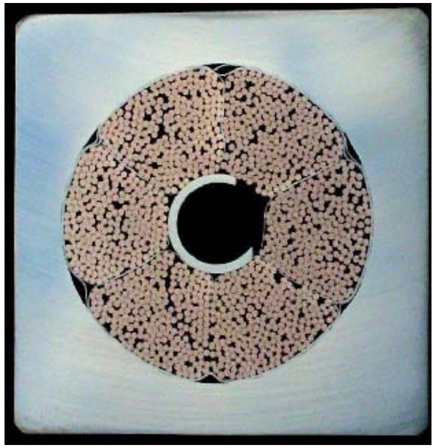
ITER - Conductor design

Two boundary conditions drive the design of the ITER conductors:

The size and the high field imply very *large electromagnetic loads*, i.e. rigid, monolithic, potted winding packs. Substantial amount of *heat from nuclear radiation and ac loss* must be effectively removed. The **forced flow** cooling option is compulsory

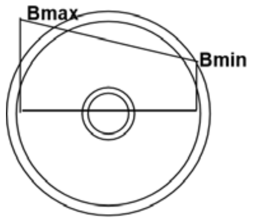
In case of quench, the *large stored energy* be effectively extracted to avoid damage/melting of the winding. To quickly dump the energy at reasonable voltage (≤ 14 kV), the number of turns must be small, i.e. the current must be large. All ITER conductors are at I_{op}> 45 kA

All the ITER superconducting coils use the same conductor design, disregarding the functional requirement of the specific coil (low and high field, dc-slow sweep-fast sweep).



ITER - Operating Conditions

	Iop (kA)	Bmin – Bmax (T)
TF	68	10.5 – 11.8
CS $_{IM}$	40	12.4 – 13.0
CS $_{EOB}$	45	12.0 – 12.6



Nb_3Sn

NbTi

	PF2/3/4	PF5	PF1/6
Iop (kA)	45	45	45
Bpeak (T)	4	5	6

All conductors are cooled by supercritical helium with inlet temperature ≈ ***4.5 K*** and inlet pressure ***6 bar***. The helium flows mostly in the central channel at high speed, ≈1m/s. The central channel, at large hydraulic diameter, acts as a ***pressure release channel*** to limit the pressure drop (pumping power) and increase the heat removal rate in normal operation. In case of quench, the central channel prevents high pressure raise (bursting) of the conductor

ITER Conductors - open issues

The test of prototype conductor samples and Model Coils brought good and less good news:

- The stability (as in most fusion conductors) is not an issue
- The coupling current time constant is not "constant", with very low loss at medium/high frequency and higher loss at very low frequency
- In NbTi conductors, the dc performance at high current is limited by the self field gradient across the cable
- In Nb_3Sn conductor, the transverse load on the strand bundle from the electromagnetic forces causes an additional performance degradation
- The coolant flow in parallel channels at different speed leads in vertical orientation to unpredicted "thermo-siphon" loops which affect the heat removal capability