Thermonuclear Fusion

Presented by

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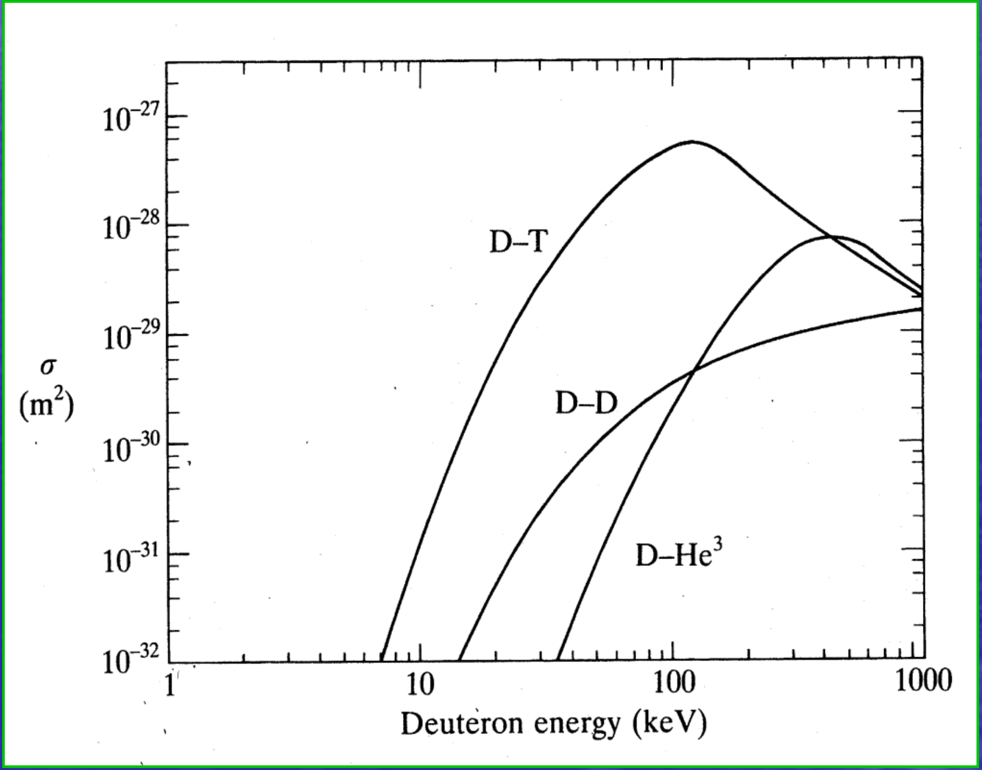
Outline

- Fusion General Aspects
- Power Plant Concept, Safety and Environmental Aspects
- Experimental Devices and Results
- ITER Design and R&D
- ITER Magnets
- Conclusions

Fusion Reaction: D + T

$${}_{1}D^{2} + {}_{1}T^{3} \rightarrow {}_{2}He^{4} + {}_{0}n^{1} + 17.6\ \text{MeV}$$

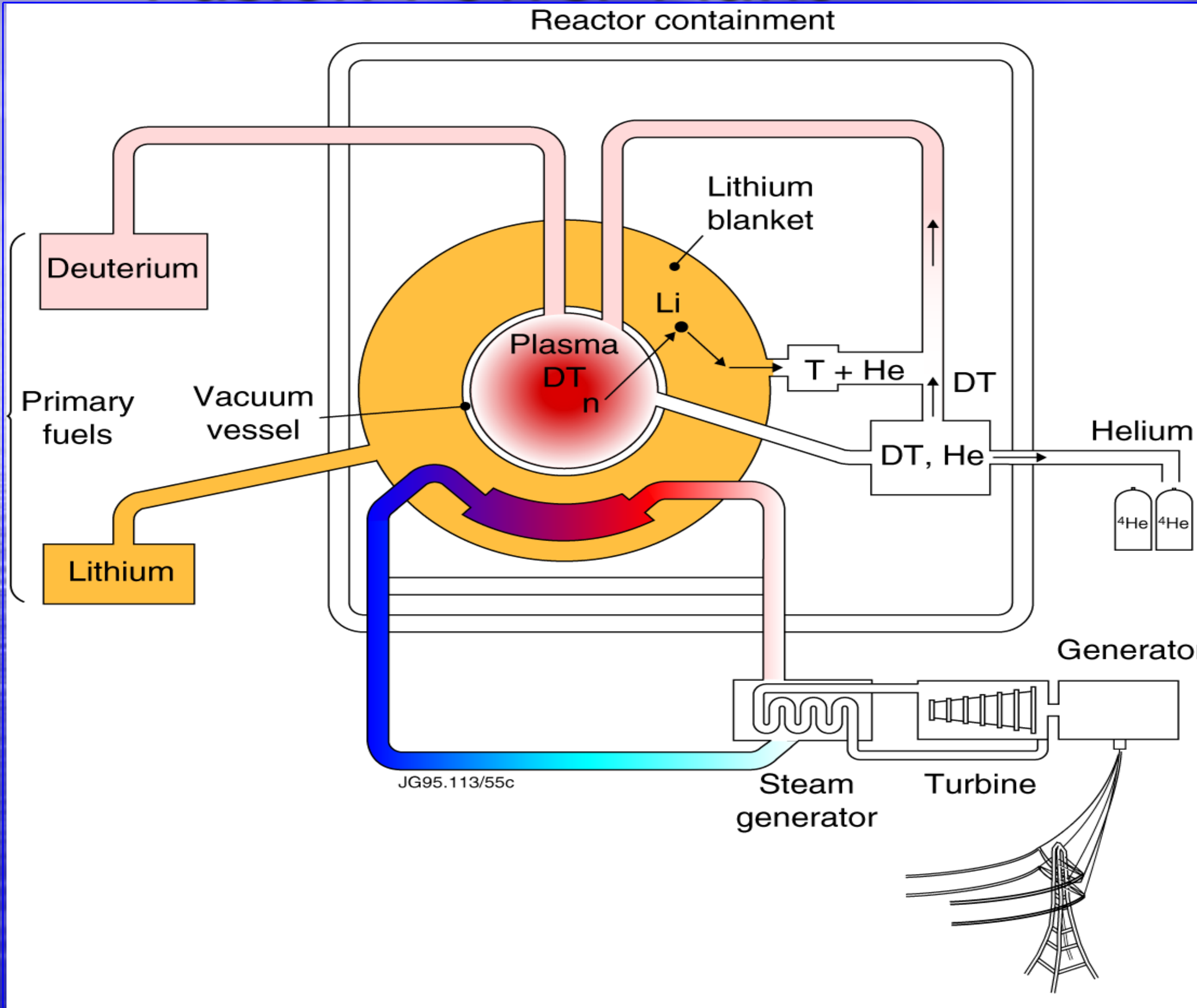
Cross-section of fusion reactions



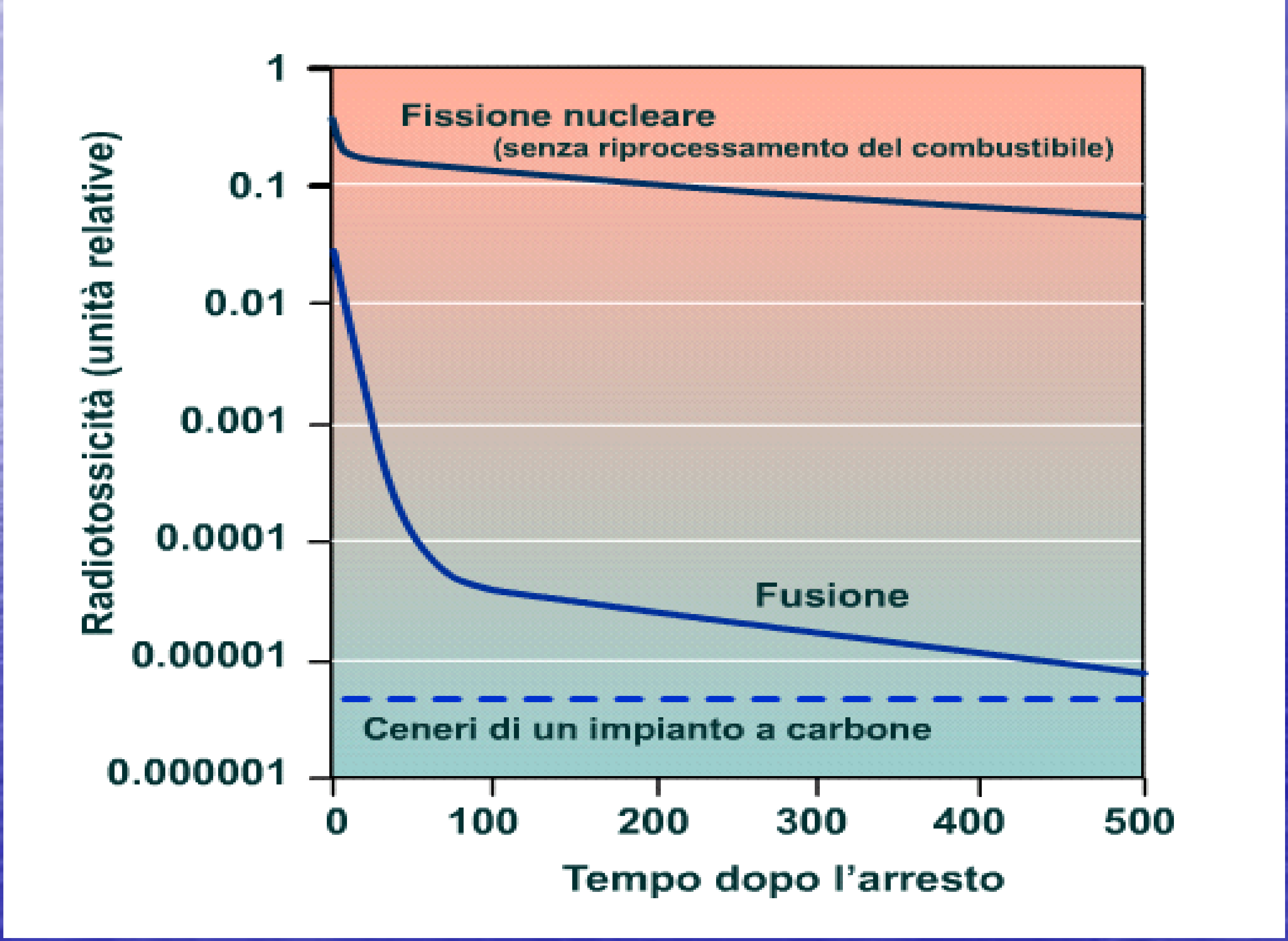
$$D^{2} + D^{2} \rightarrow \begin{cases} He^{3} + n^{1} + 3.27\ \text{MeV} \\ T^{3} + H^{1} + 4.03\ \text{MeV} \end{cases}$$

$$D^{2} + He^{3} \rightarrow He^{4} + H^{1} + 18.3\ \text{MeV}$$

Fusion Power Plant



Waste Radio Toxicity



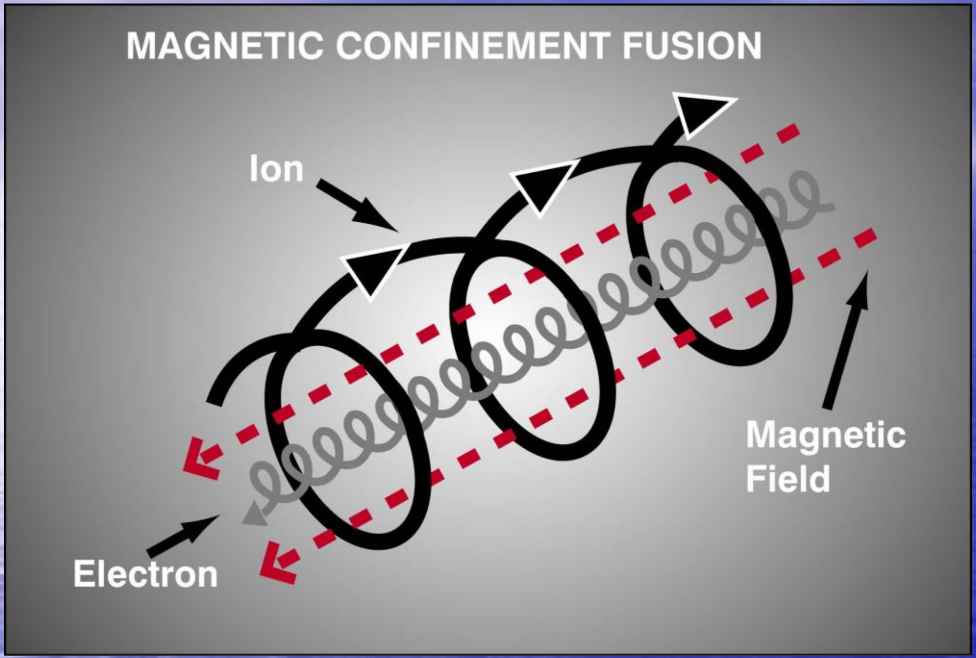
Fusion is an Attractive Energy Source

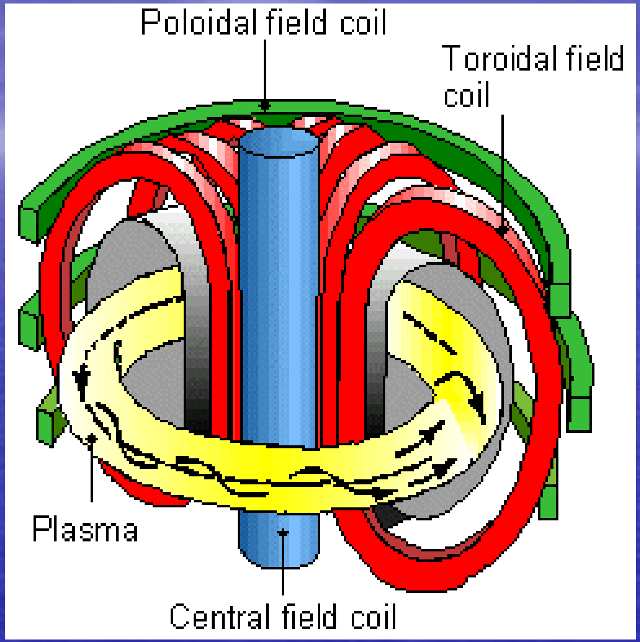
- Abundant fuel, available to all nations
- Environmentally benign
  - No carbon dioxide emissions, short-lived radioactivity
- Can't explode, resistant to terrorist attack
- Low risk of nuclear materials proliferation
  - No fissile or fertile nuclear materials required
- Not subject to daily, seasonal or regional weather variation (e.g. solar, wind)

What Must Be Achieved to Produce Fusion Power

- high temperature: T
  high Ion density: n
  high confinement time: τ
- A measure of performance is thus given by $n\ T\ \tau$: Density * Temperature* Confinement Time

MAGNETIC CONFINEMENT





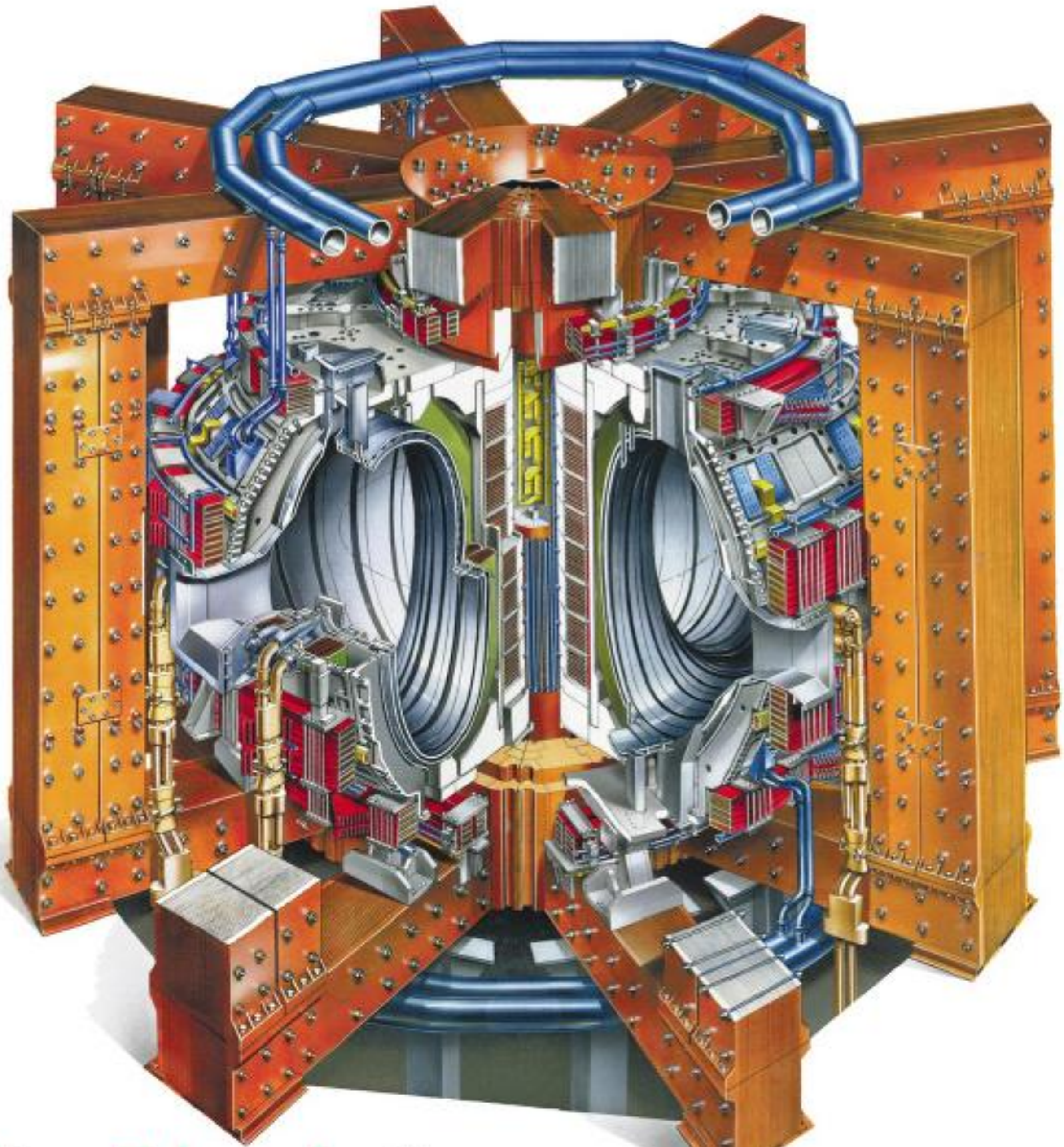
Charged particles have helical orbits in a magnetic field; they describe circular orbits perpendicular to the field with gyro-radius $r_l = v_\perp/\Omega$, where $\Omega = qB/mc$

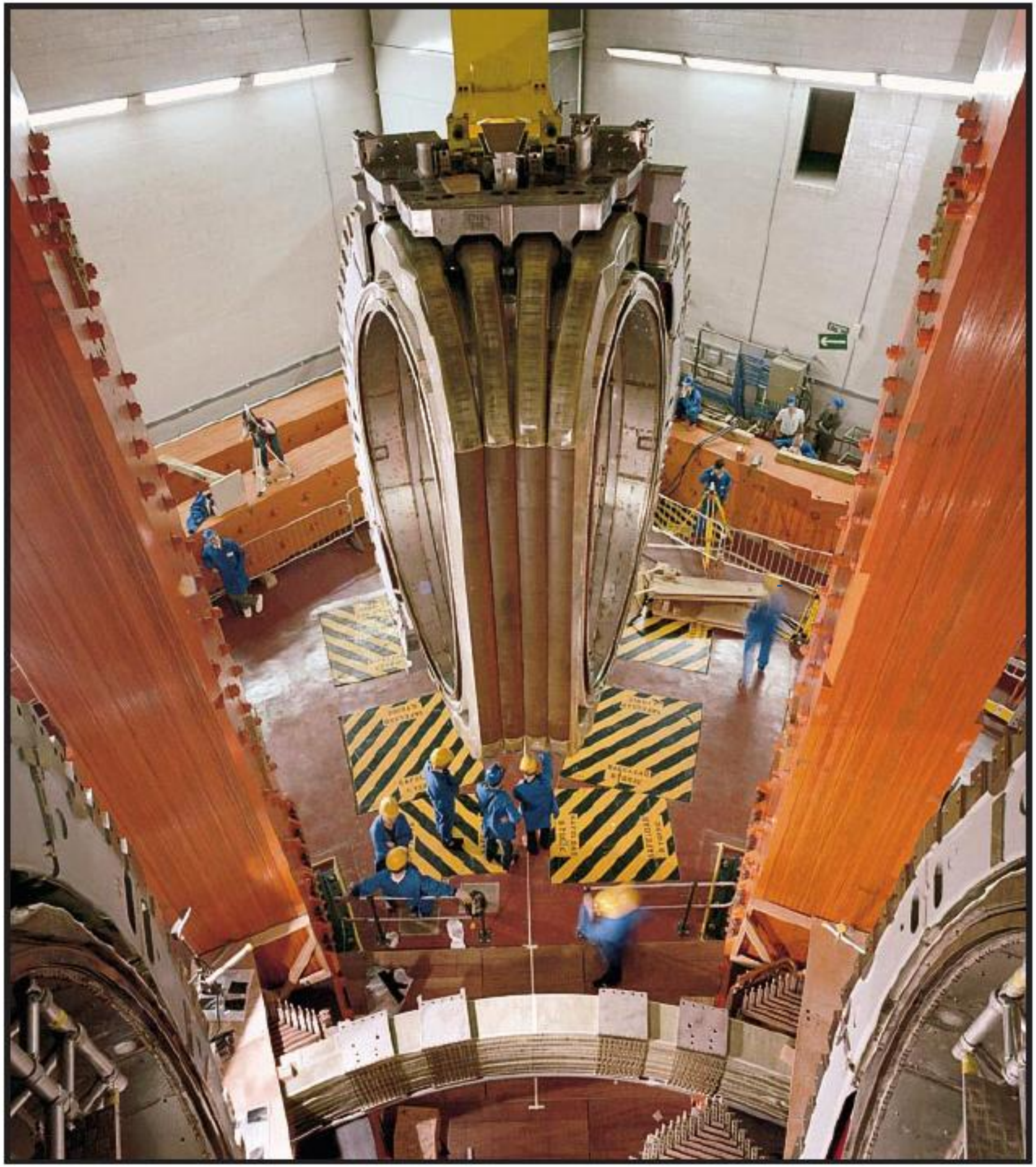
"TOKAMAK"

(Russian abbreviation for "toroidal chamber" with magnetic fields); includes an induced toroidal plasma current to form, heat and confine the plasma

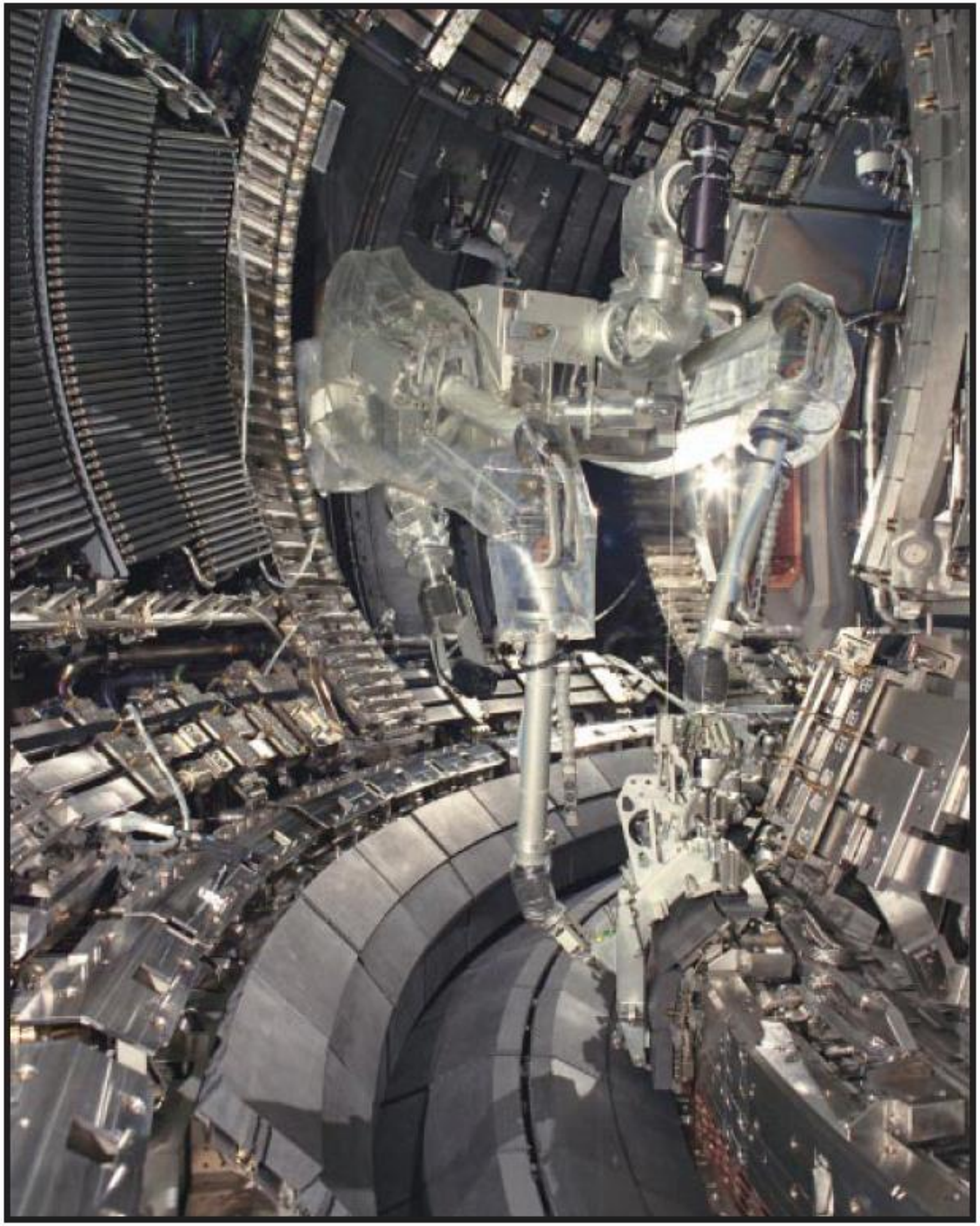
European Fusion Devices

JET



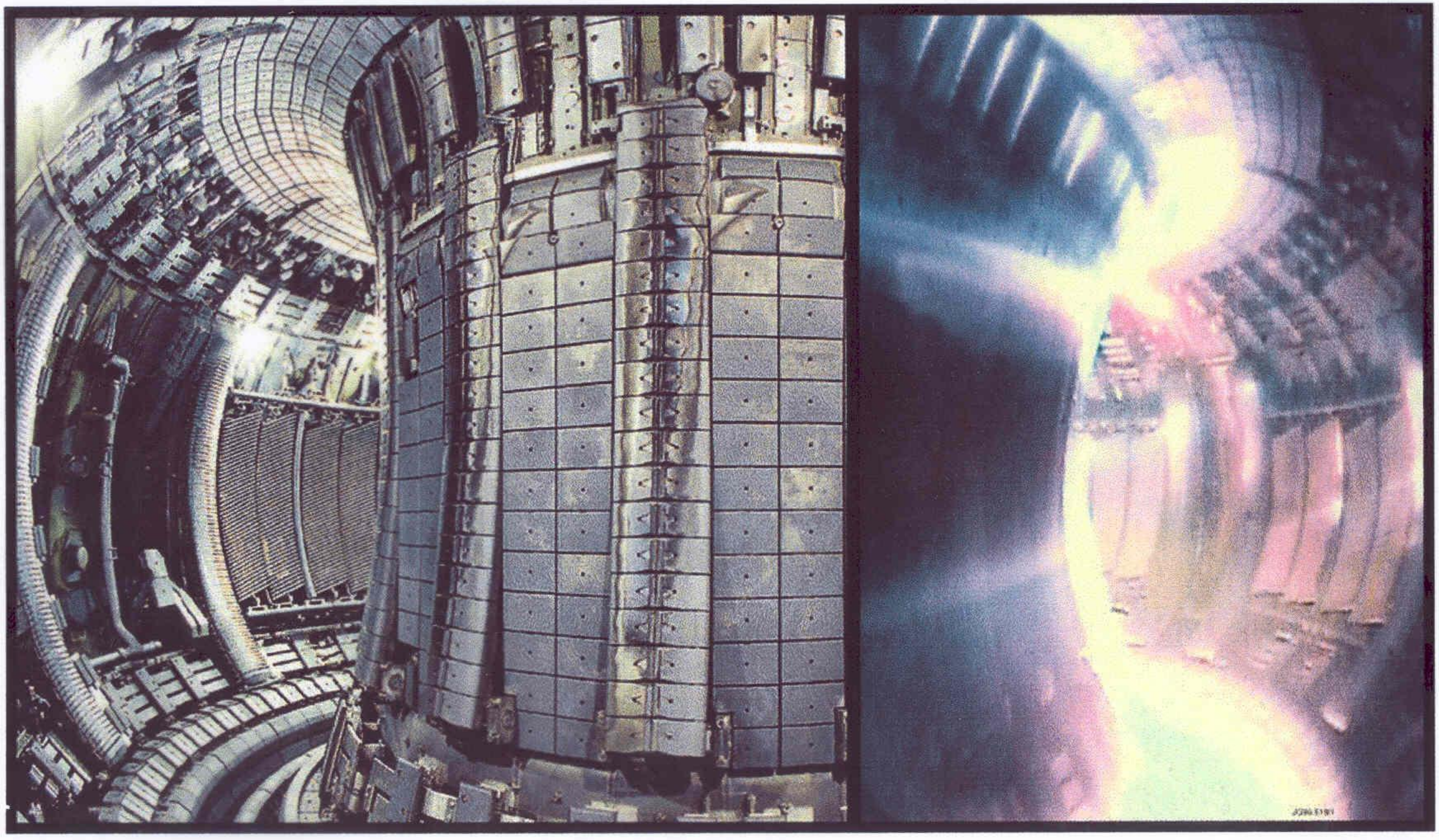


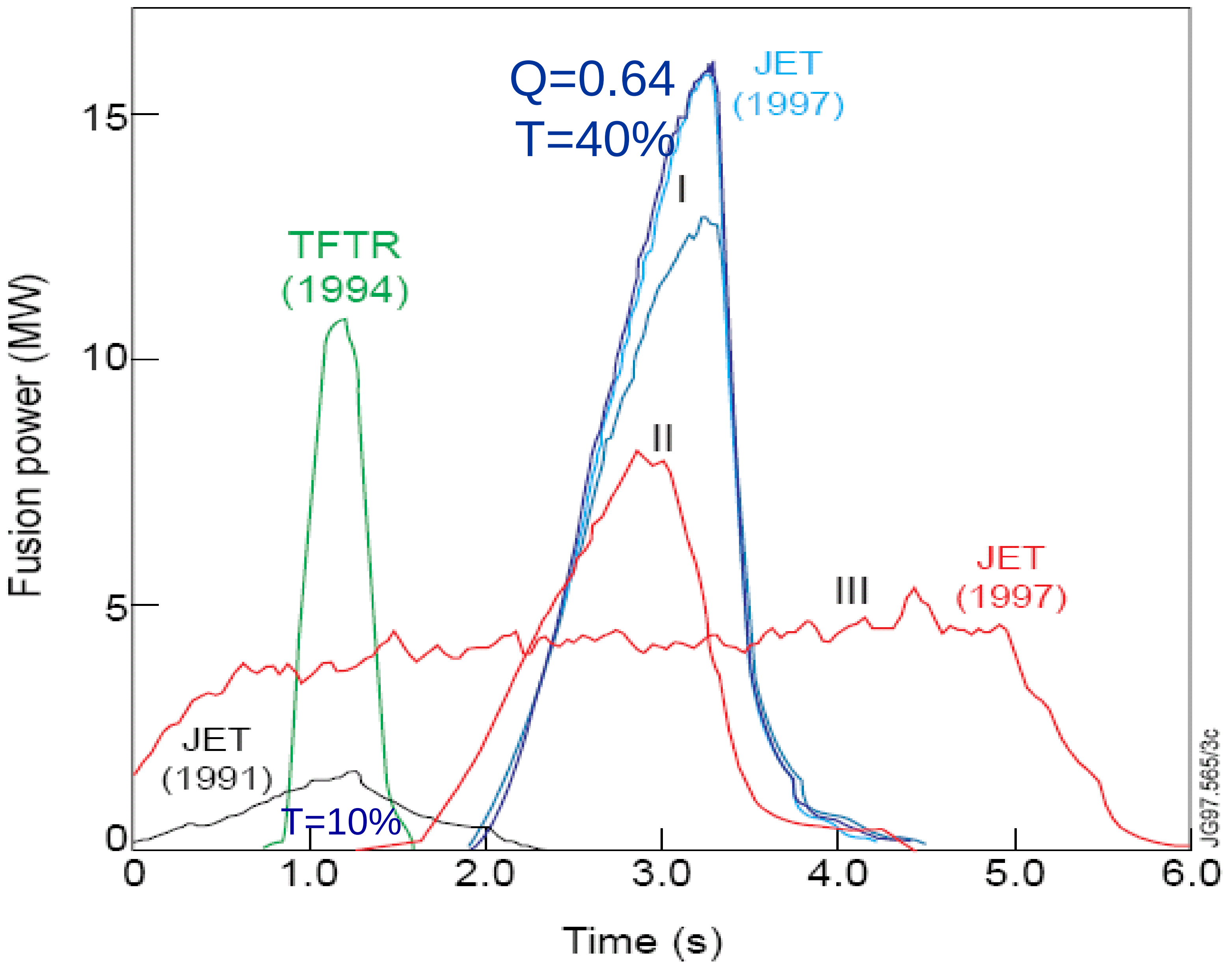
Jet last octant



JET remote maintenance

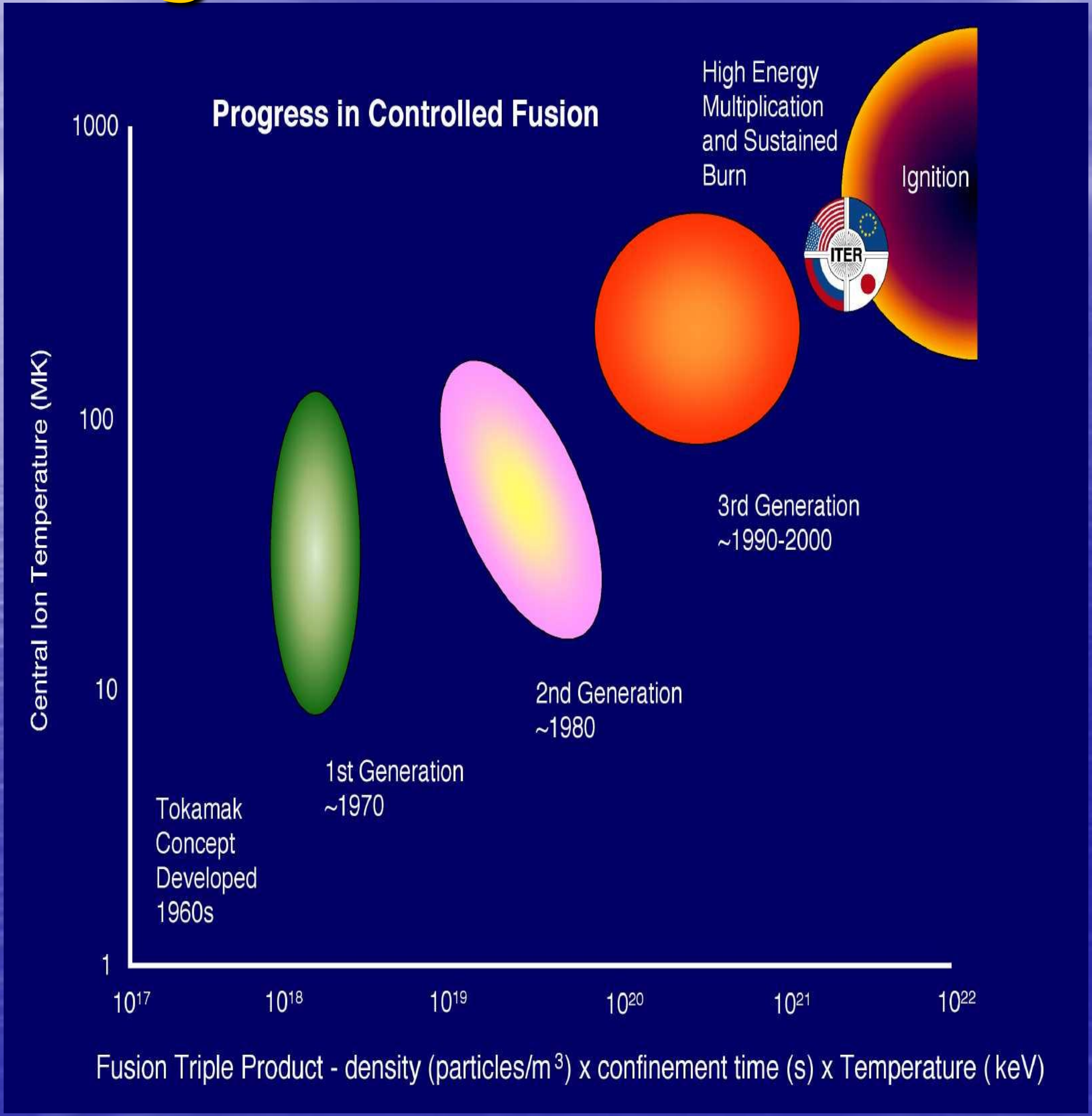
JET-JOINT EUROPEAN TORUS -CULHAM





Q=0.64
T=40%
JET
(1997)
I
TFTR
(1994)
II
III
JET
(1997)
JET
(1991)
T=10%
Fusion power (MW)
15
10
5
0
0
1.0
2.0
3.0
4.0
5.0
6.0
Time (s)
JG97.565/3c

Progress in Fusion

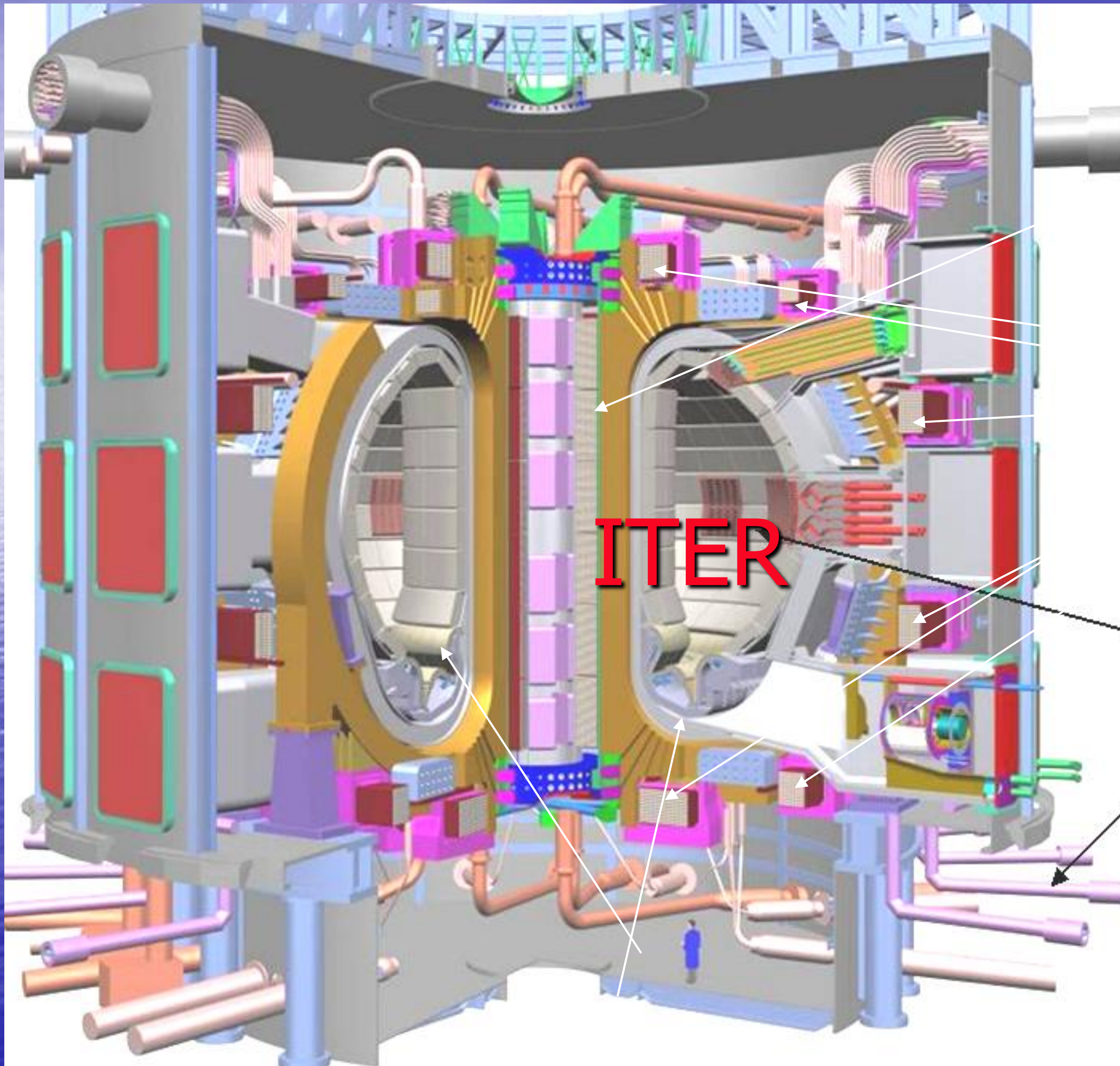


Plasma Heating and Current Drive

- Ion Cyclotron (IC)
- Electron Cyclotron (EC)
- Neutral Beam Injection (NBI)
- Lower Hybrid (LH)

Hystory towards ITER

- INTOR 1978-1985
- NET 1983-1988 (similar to ITER CDA)
- ITER CDA 1988-1990
  - Plasma Major Radius 6.0 m
  - D.N. Vertical Elongation 95% 2
  - Plasma Current 22 MA
  - Magnetic Filed at 5.8m / max. 4.9T/10.4T
- ITER EDA 1992-1998
  - Plasma Major Radius 8.1m
  - S.N. Vertical Elongation 95% 1.6
  - Plasma Current 21 MA
  - Magnetic Field at 8.1m/max 5.7T/12.5T
- ITER FEAT 1999-today
  - Plasma Major Radius 6.2m
  - S.N. Vertical Elongation 95 % 1.7
  - Plasma Current 15/17 MA
  - Toroidal Field at 6.2m/max 5.3T/11.8T



Central Solenoid

Outer PF Coils

In vessel components

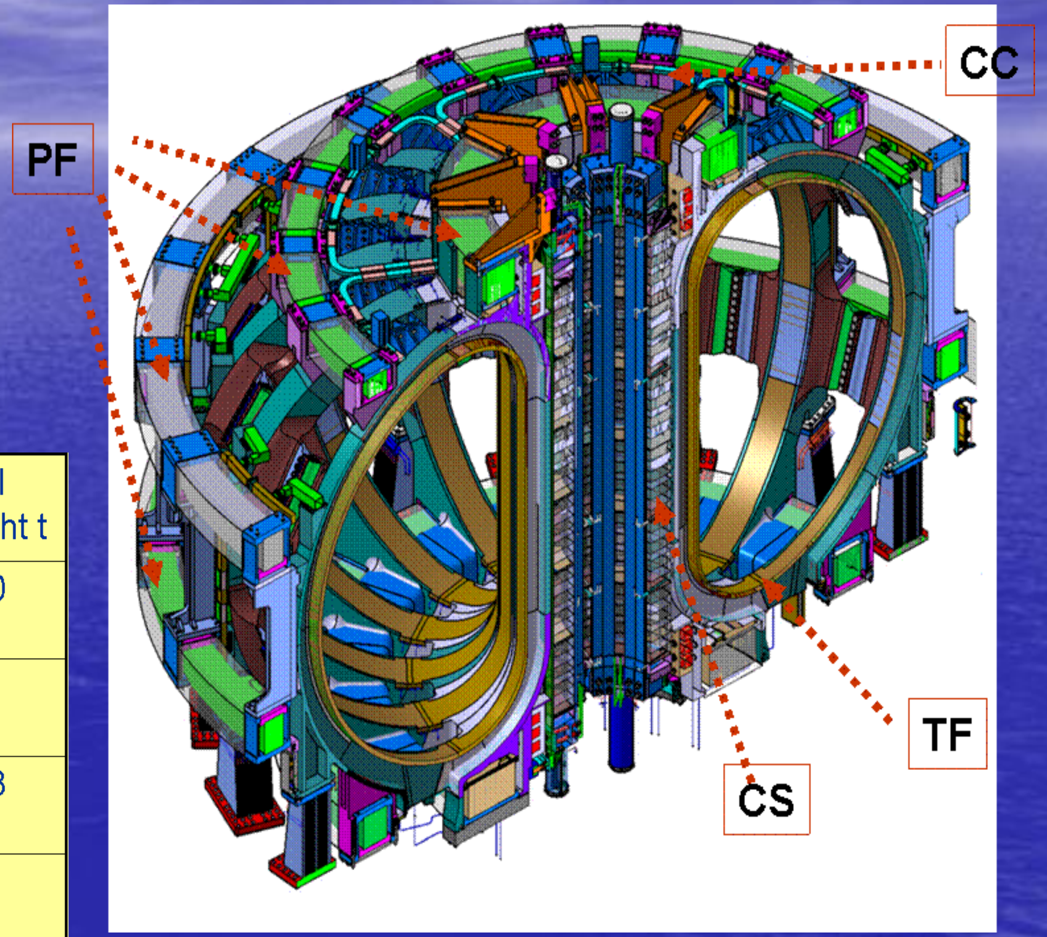
Current feedthr
horizontal posi

ITER Magnet System

48 Superconducting Coils:

- 18 TF coils
- 6 CS modules
- 6 PF coils
- 9 pairs of CC
- Feeders

System	Energy GJ	Peak Field T	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85



(i.e. 41 GJ vs. 10.5 GJ magnetic energy in the 27 km tunnel of the Large Hadron Collider at CERN)

Why Superconducting?

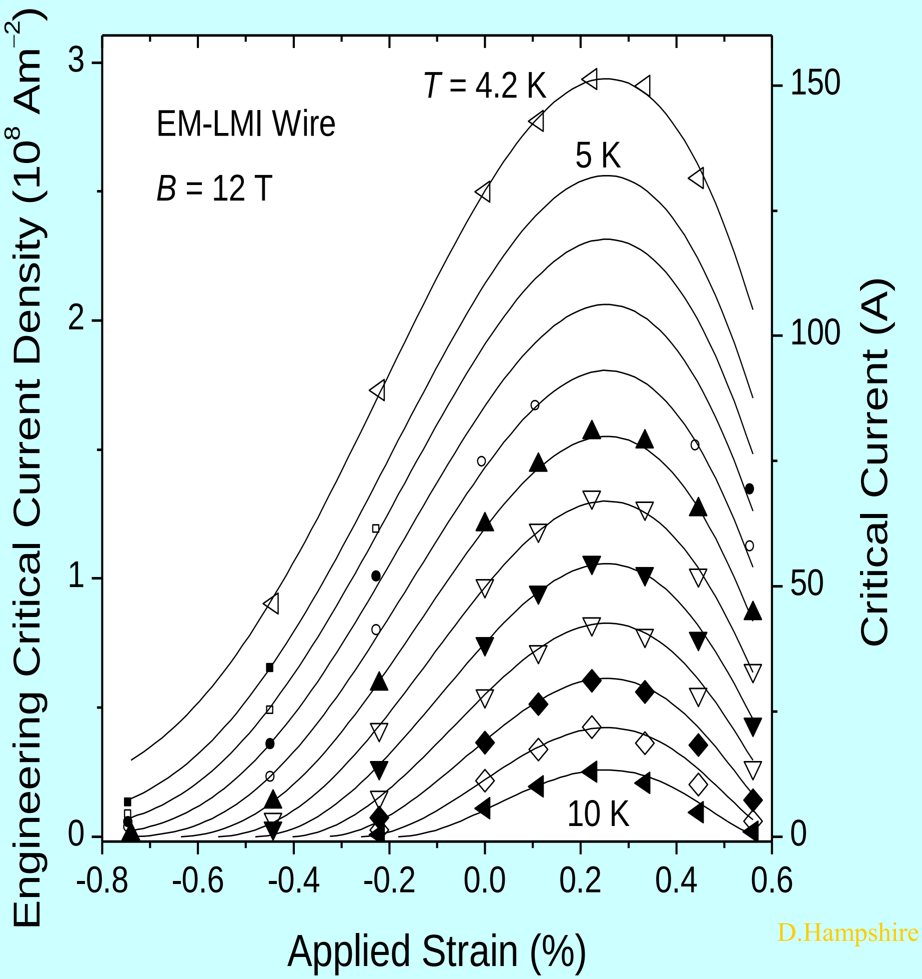
- No resistive losses (GW)
- Refrigeration power required much lower (tens MW)
- More compact reactor: Cable current density much higher(~10times) and Structural material strength higher (4 times)
- Disadvantages: operation at 4 K (Vacuum) and new technology

Superconducting Strands

- **High field > 5 T**
  - Nb_3Sn
  - $E = Ec(J/Jc\{B,T,E\})^{n\ \{B,T\}}$
  - Heat treatment (650 °C, ~ 200 h)
  - Cromium coating (~ 2µm)
- **Low Field < 5 T**
  - NbTi
  - $E = Ec(J/Jc\ \{B,T\})^{n}$
  - No strain senstivity
  - Coating Ni (~ 2 µm)

$J_C(B,T,\varepsilon)$ data

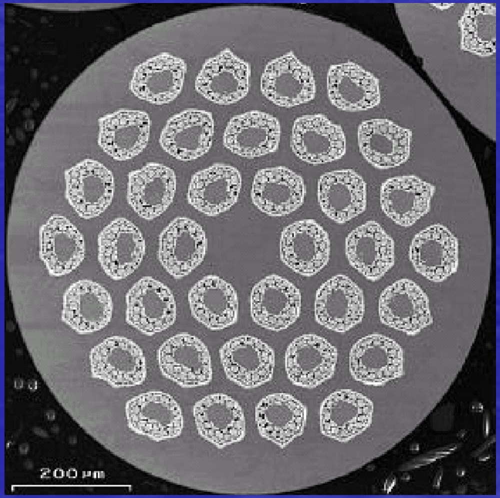
- Engineering critical current density (and critical current) of the EM-LMI wire as a function of applied strain at a magnetic field of 12 T and at temperatures of 4.2 K and 0.5 K increments between 5 K and 10 K.
- The symbols show the measured data, and the lines show the parameterization using the Interpolative Scaling Law.



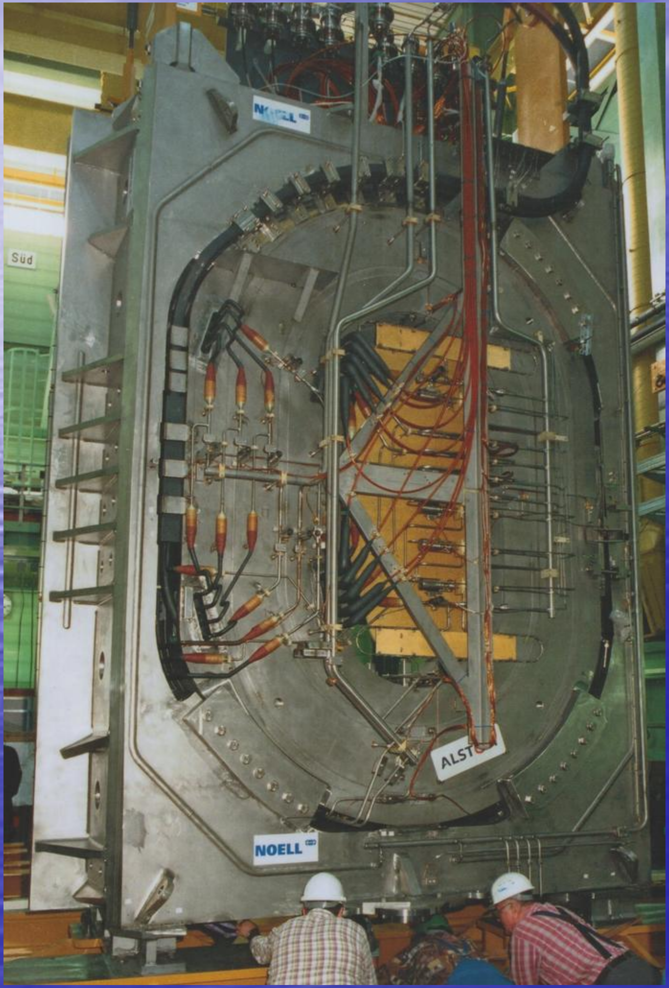
Developed ITER Conductors - TF Model Coil

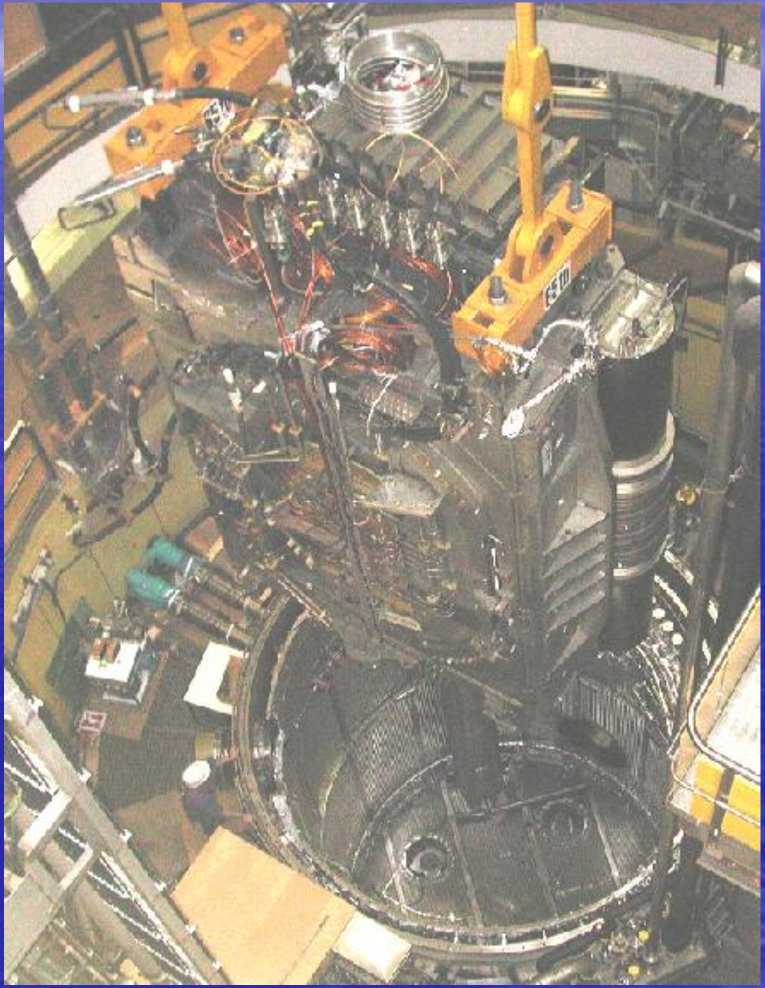
- Current: **80 kA** (4.5 K, 9.7 T)
- 316LN stainless steel jacket (Ø 40.7 mm) wound in radial plates
- Cable diameter: 37.5 mm
- 720 **Nb_3Sn** strands (1080 strands total)

Strand Layout



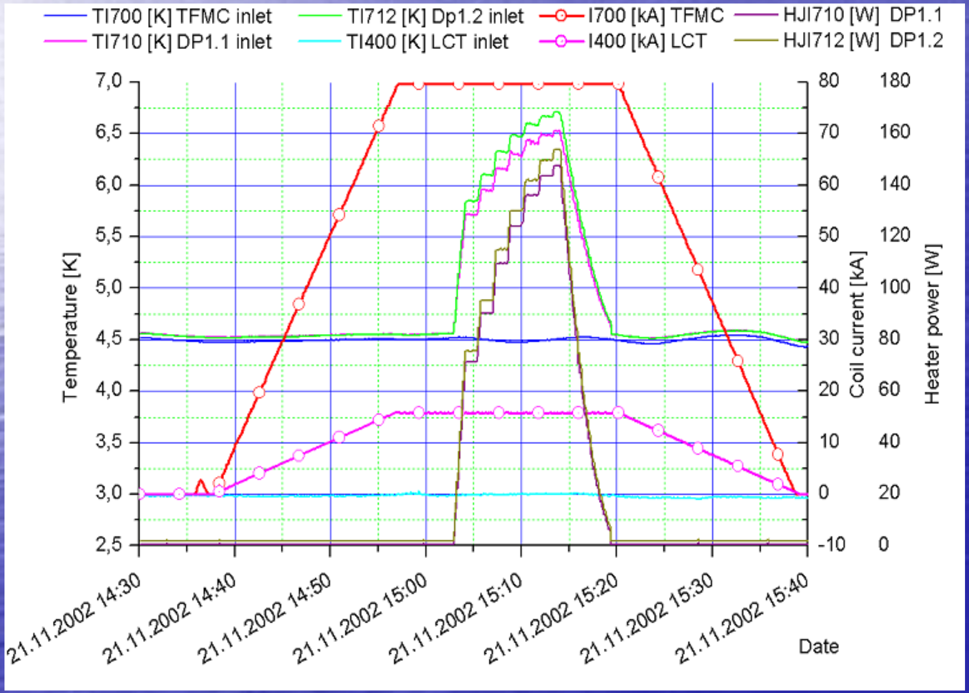
TFMC Assembly





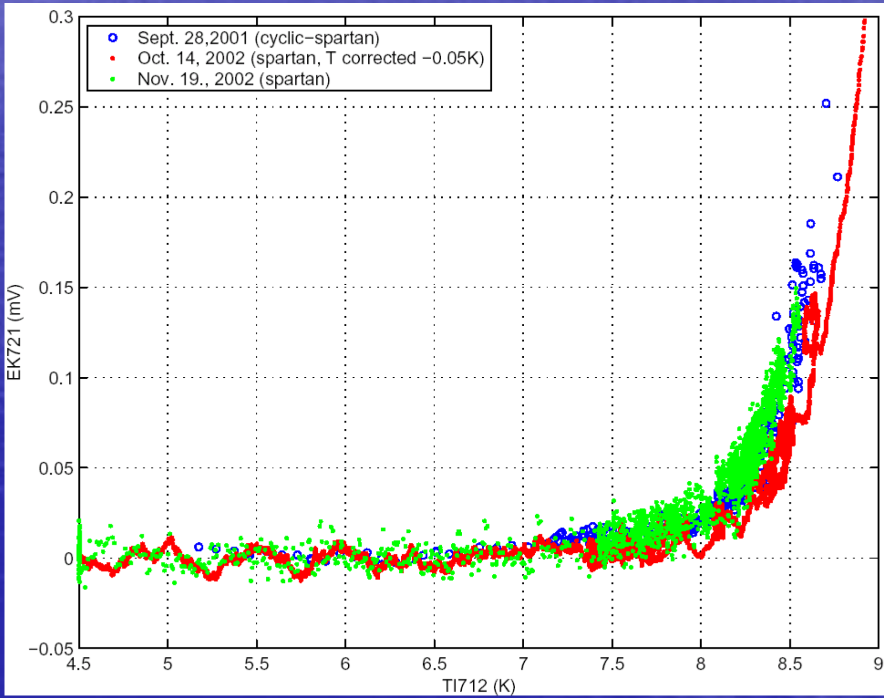
ITER - EFDA Magnets R&D Programme - TF Model Coil

TFMC (80 kA) + LCT (16 kA)

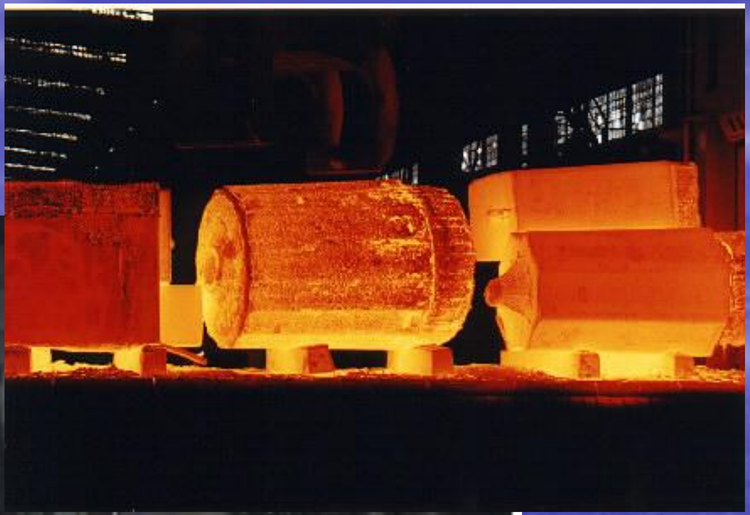


TFMC exceeded design values

TFMC (80 kA)



No performance degradation

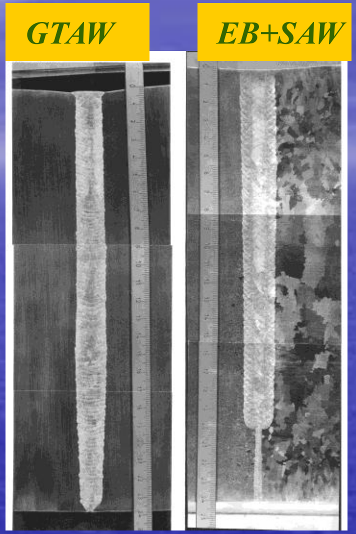


Free hand forging

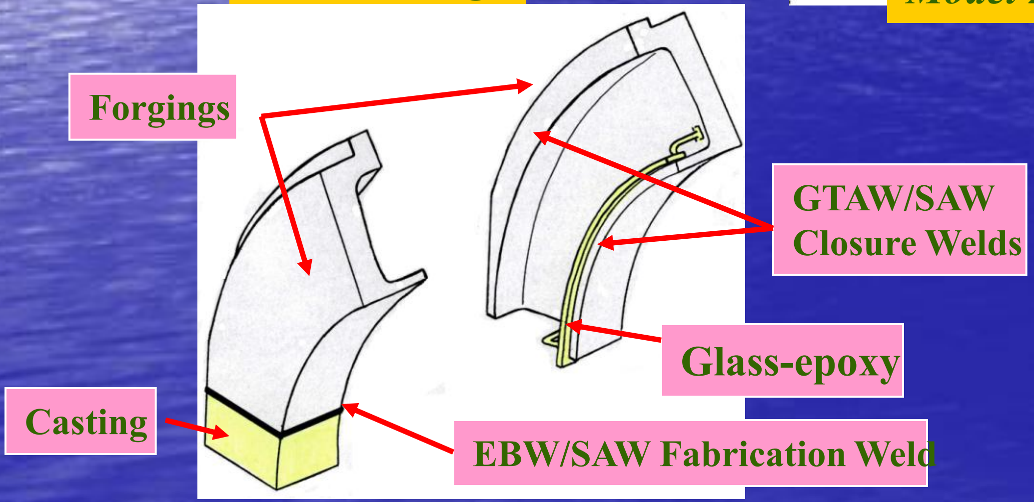
TF Coil Case R&D

Model 1 Forged

Model 2 Cast



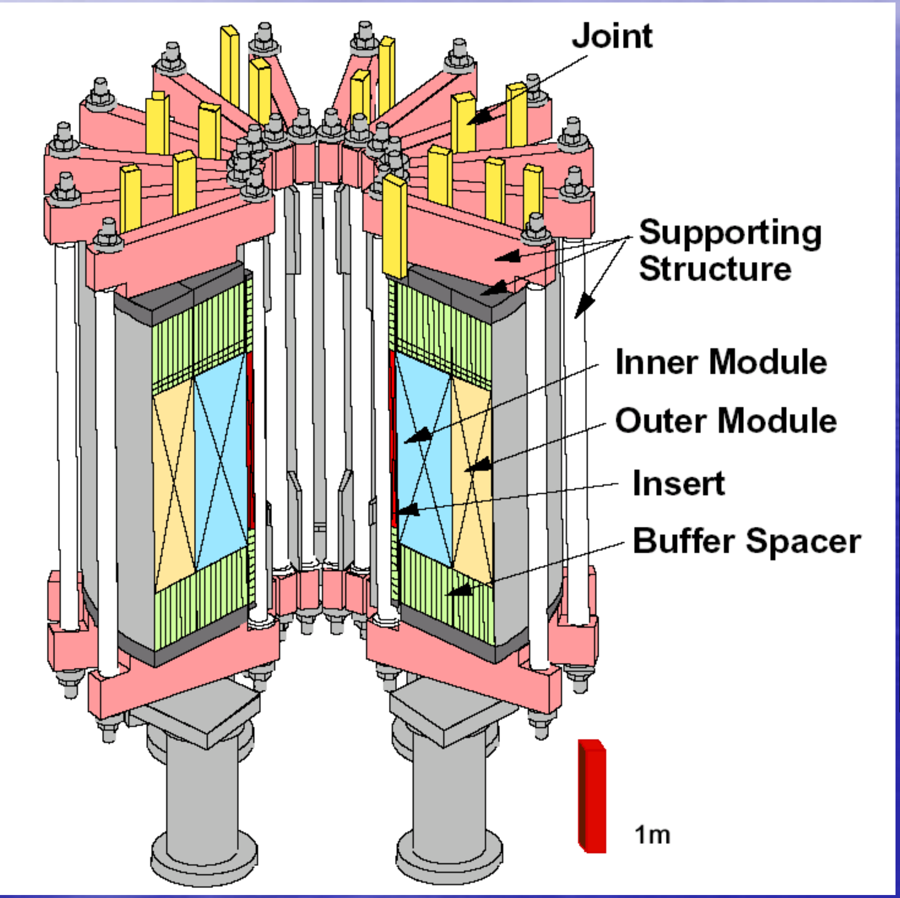
Weld Qualification



Main Goals

- Qualify manufacturing techniques for production of base elements
- Qualify welding processes and NDT methods
- Provide input to the detailed design

ITER - EFDA Magnets R&D Programme - CS Model Coil



Coil Design Parameters

	CSI	CSMC IM	CSMC OM
Maximum Field	13 T	13 T	7.3 T
Operating Current	40 kA	46 kA	46 kA
Outer Diameter	1.57 m	2.71 m	3.62 m
Height	2.80 m	2.80 m	2.80 m
Weight	7.7 t	49.3 t	52 t
Stored Energy	11 MJ	640 MJ	

ITER - EFDA Magnets R&D Programme - CS Model Coil

CSMC: Inner module

CSMC: Outer module

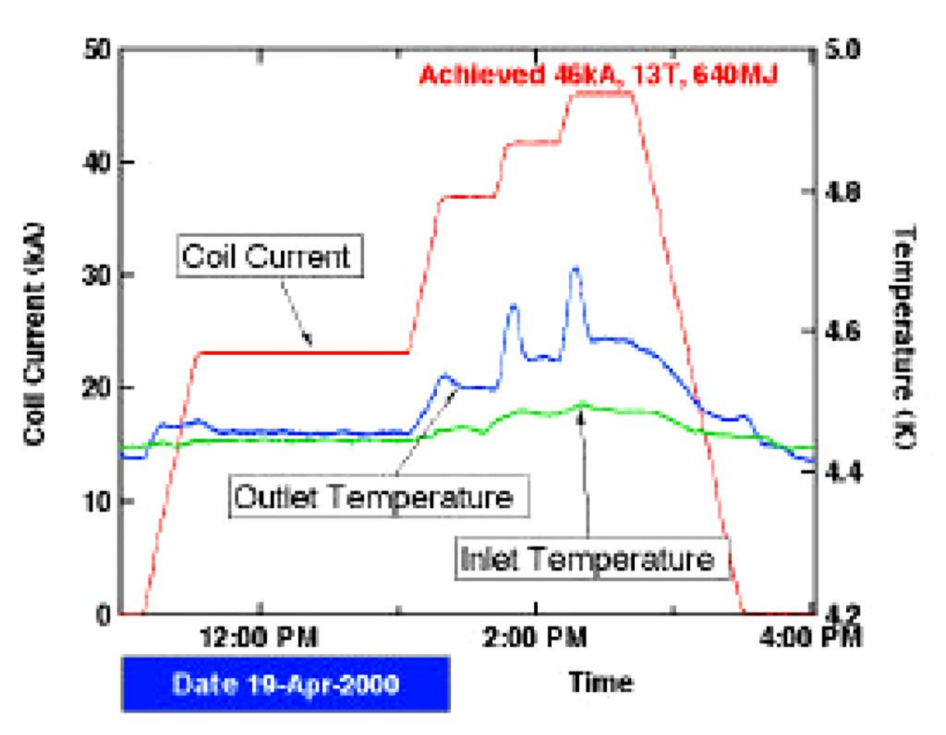
CSMC Insert Coils

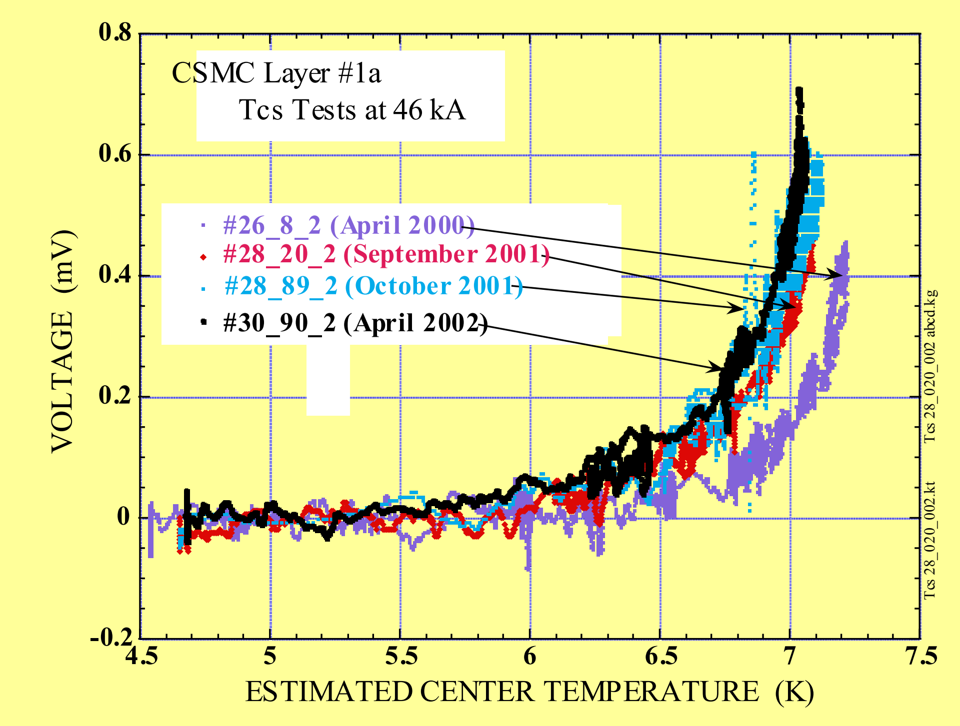
CS Insert
(JA)

TF Insert
(RF)

Nb_3Al Insert
(JA)

ITER - EFDA Magnets R&D Programme - CS Model Coil

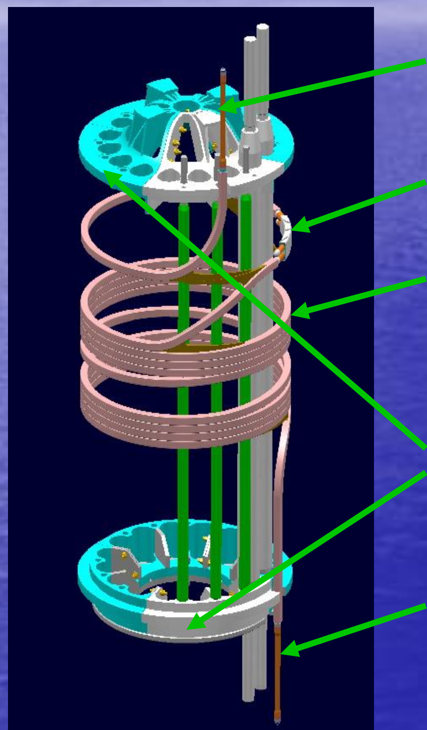




CSMC successfully achieved design values

Small degradation (0.1 to 0.2 K)

PF Insert Coil

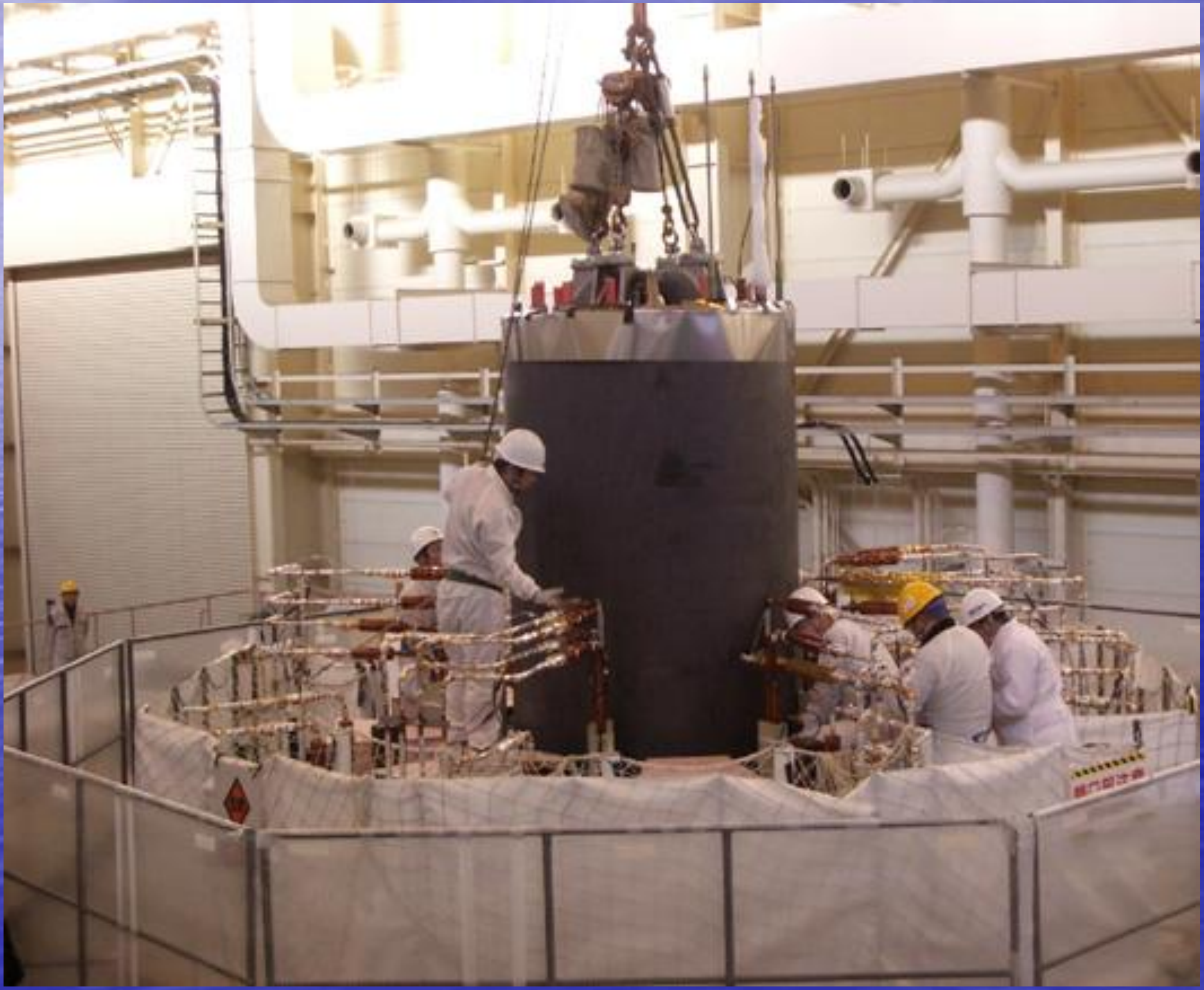


Coil Design Parameters

		PFI
Maximum Field		6.3 T
Maximum Operating Current		50 kA
Maximum Field Change		2 T/s
Conductor length		49.50 m
Main Winding Envelope	Outer Diameter	1.57 m
	Inner Diameter	1.39 m
	Height	1.40 m
Height		1.40 m
Weight		6 t

Test carried out in June-Aug. 2008

PFCI Assembly in CSMC facility

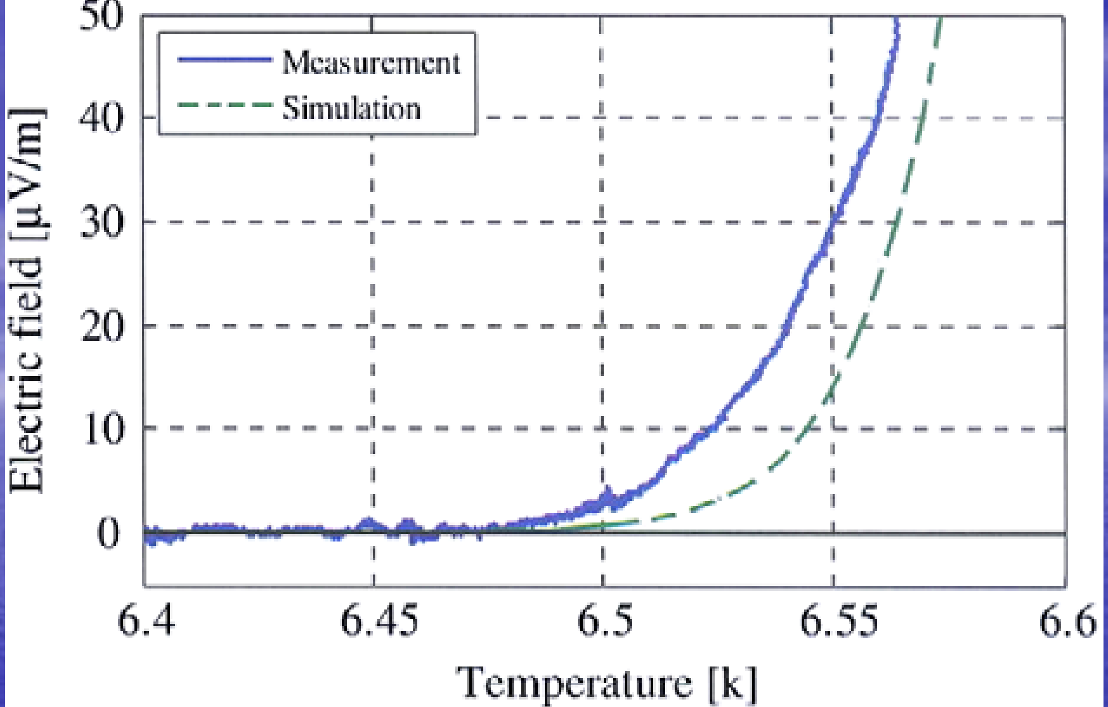


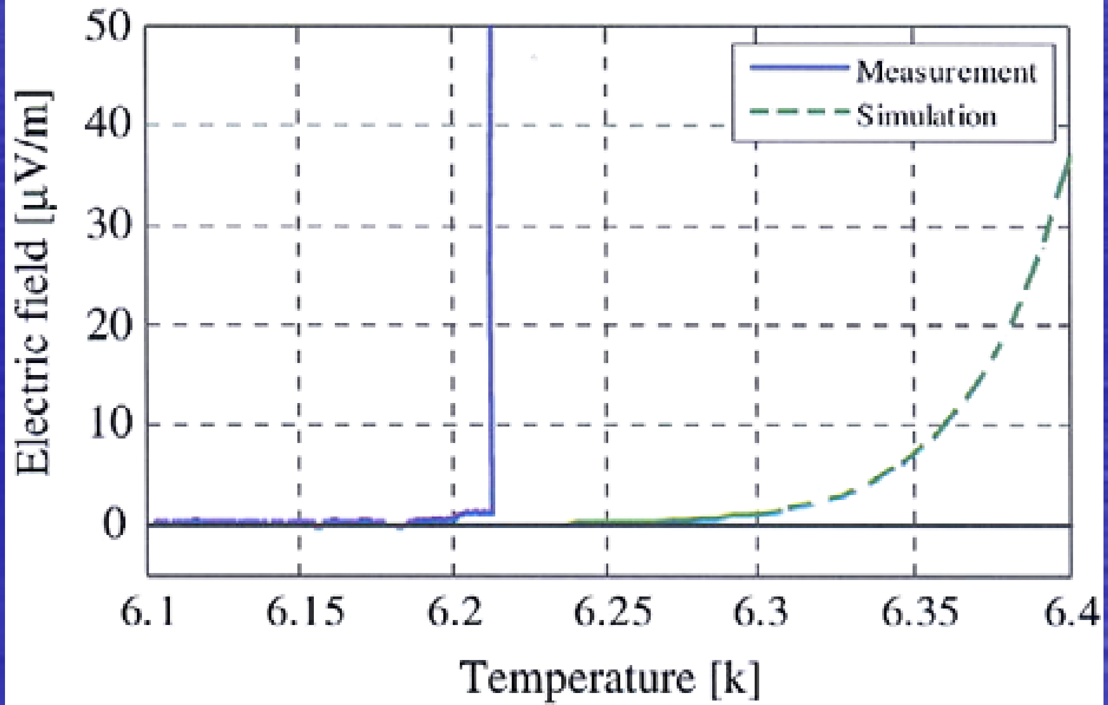
PFCI results

Evolution of measured and computed voltage in the case of two tests:

(top) I-PFCI = 6 kA and *B*-CSMC = 5.9 T

(bottom) I-PFCI = 55 kA and *B*-CSMC = 5.15 T





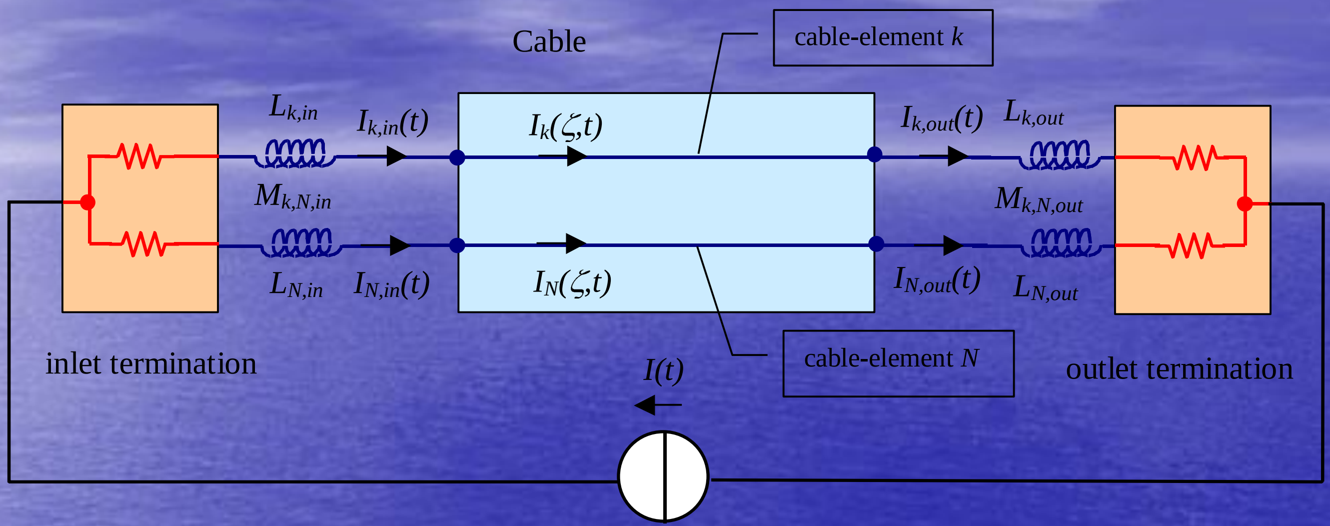
Superconducting Conductor Analysis

- Coupled Fields Problem:
  - Temperature
  - Hydraulic
  - Mechanical strain
  - Electric Field
  - Magnetic Field

Conductor Analysis: The Thelma code

- Compute the coupled electromagnetic and thermohydraulic fields
- Strain field external input

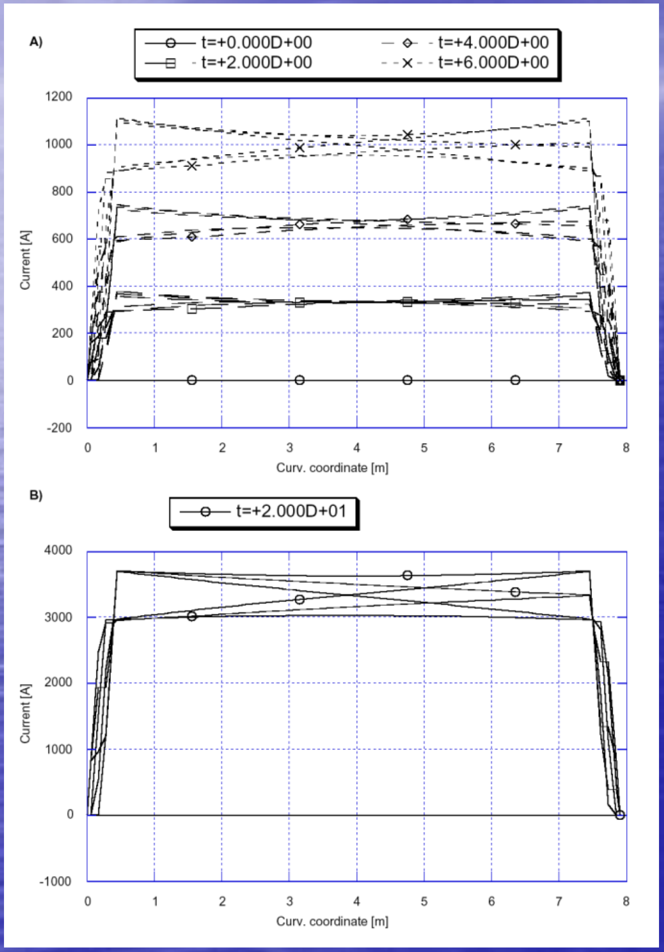
THELMA CABLE MODEL



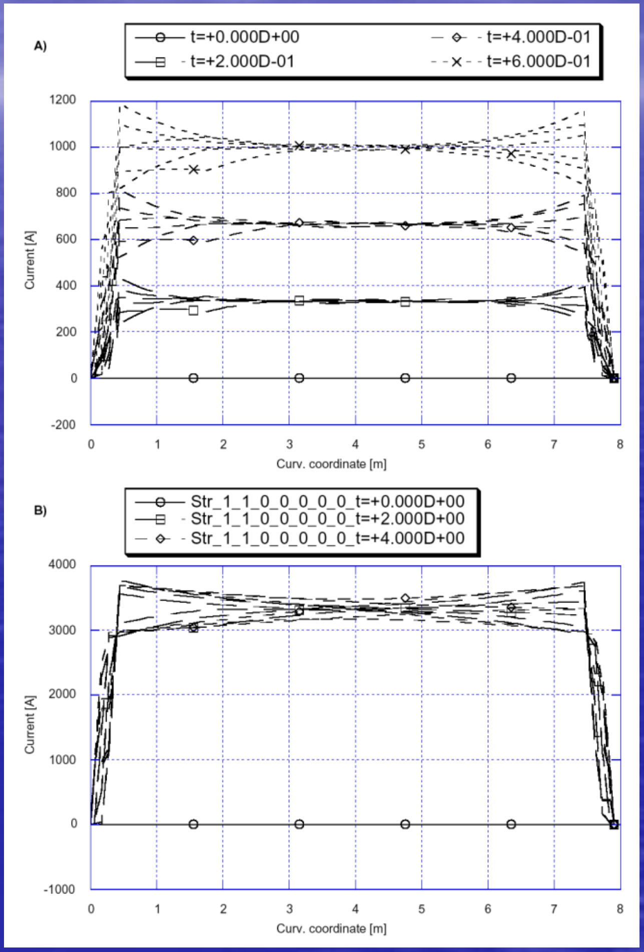
- ♦ A current driven system is considered.
- ♦ A cable-element can be either a single strand or a strand bundle.
- ♦ The model is self consistent with given inlet and outlet currents or can be coupled with a termination/joint model.
- ♦ **The model is aimed to simulate real size coils**

BB3

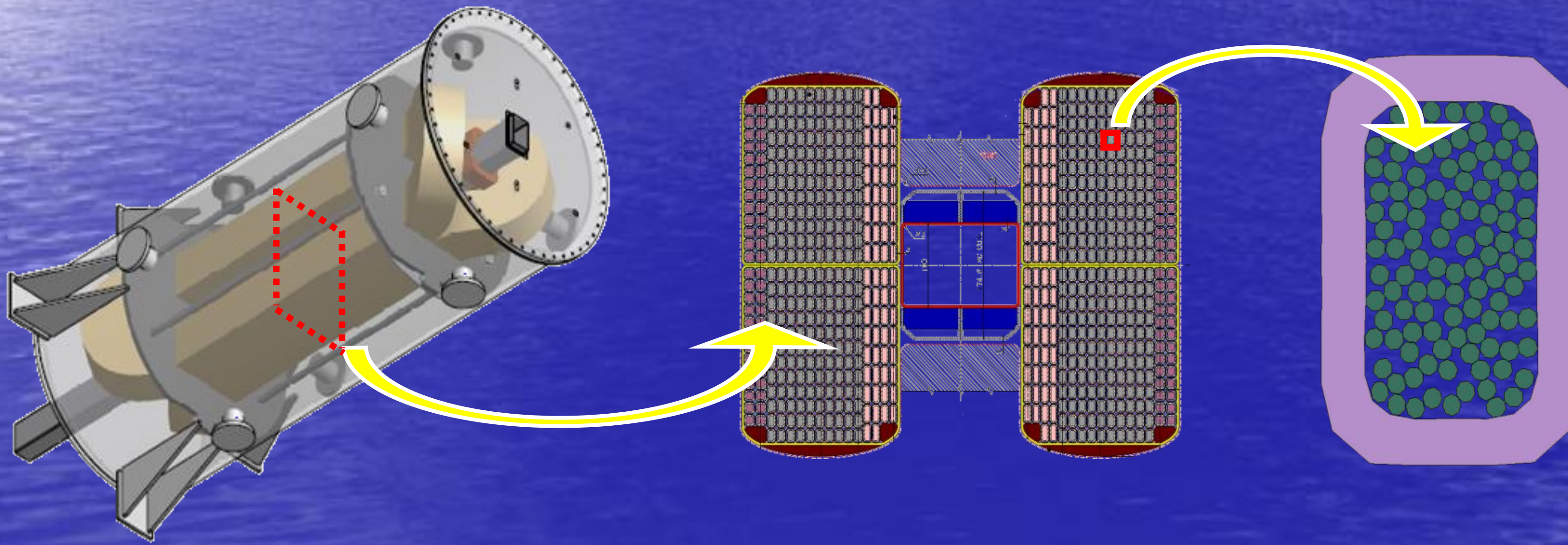
Current in the macrostrands in the case of dI/dt=1 kA/s



Current in the macrostrands in the case of dI/dt=10 kA/s

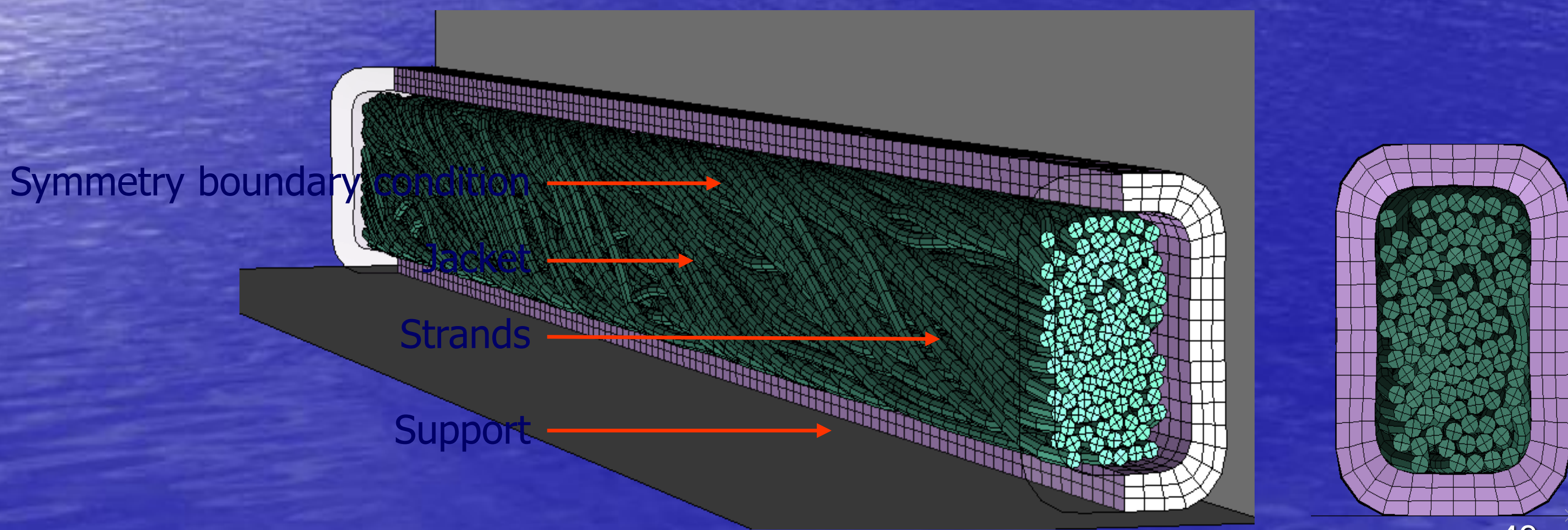


Computational mechanical models of the EDIPO Conductor



Analysis of the EDIPO Conductor

- The 3D solid model includes:
  - 108 strands, 0.81 mm in diameter, with pitches as 58/95/139/213 mm;
  - each strand is modeled with **solid elements**, in contact with the others and with the inner surface of the jacket;
  - a total length of 2 pitches (426 mm) are modeled (actually, half of it with symmetry boundary conditions applied at the middle-plane);
  - Jacket, Supporting plane.

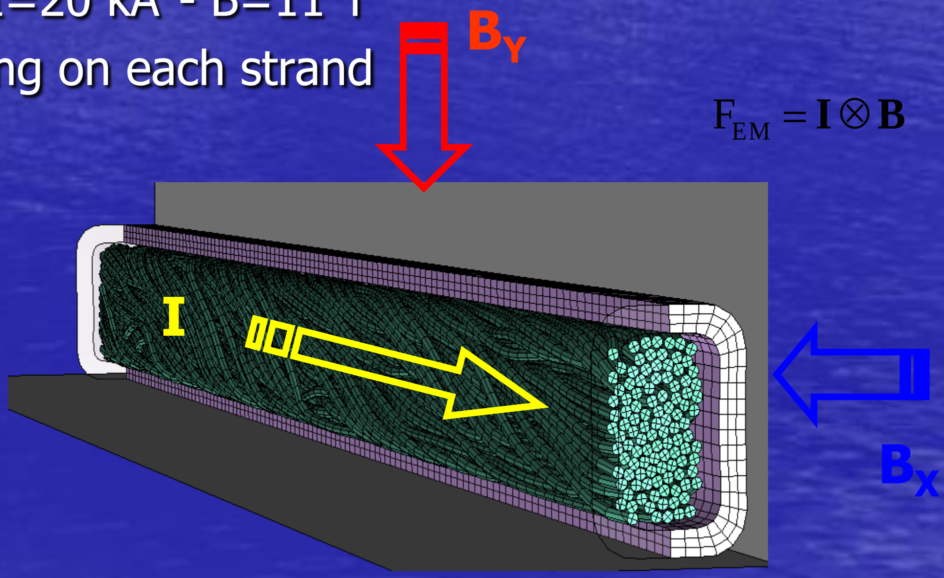


Analysis of the EDIPO Conductor

- Simulation of the Conductor in operation
  - At the end of the "forming" process (jacketing +rolling), the following loads were applied to the conductor.
    - Thermal charge and discharge (923 →4.2 K)
    - Test condition: two load cases
      - Nominal test I=17 kA - B=9 T
      - Peak test I=20 kA - B=11 T
    - Force per unit length acting on each strand

$$F_{EM} = \mathbf{I} \otimes \mathbf{B}$$

EM LOADS	Nominal	Peak test
Magnetic field [T]	9	11
Total current [KA]	17	20
Current per strand [A]	354.2	416.7
EM force [N/mm]	3.2	4.6
EM force [N/mm³]	6.19	8.89
Total force [KN]	32.6	46.9

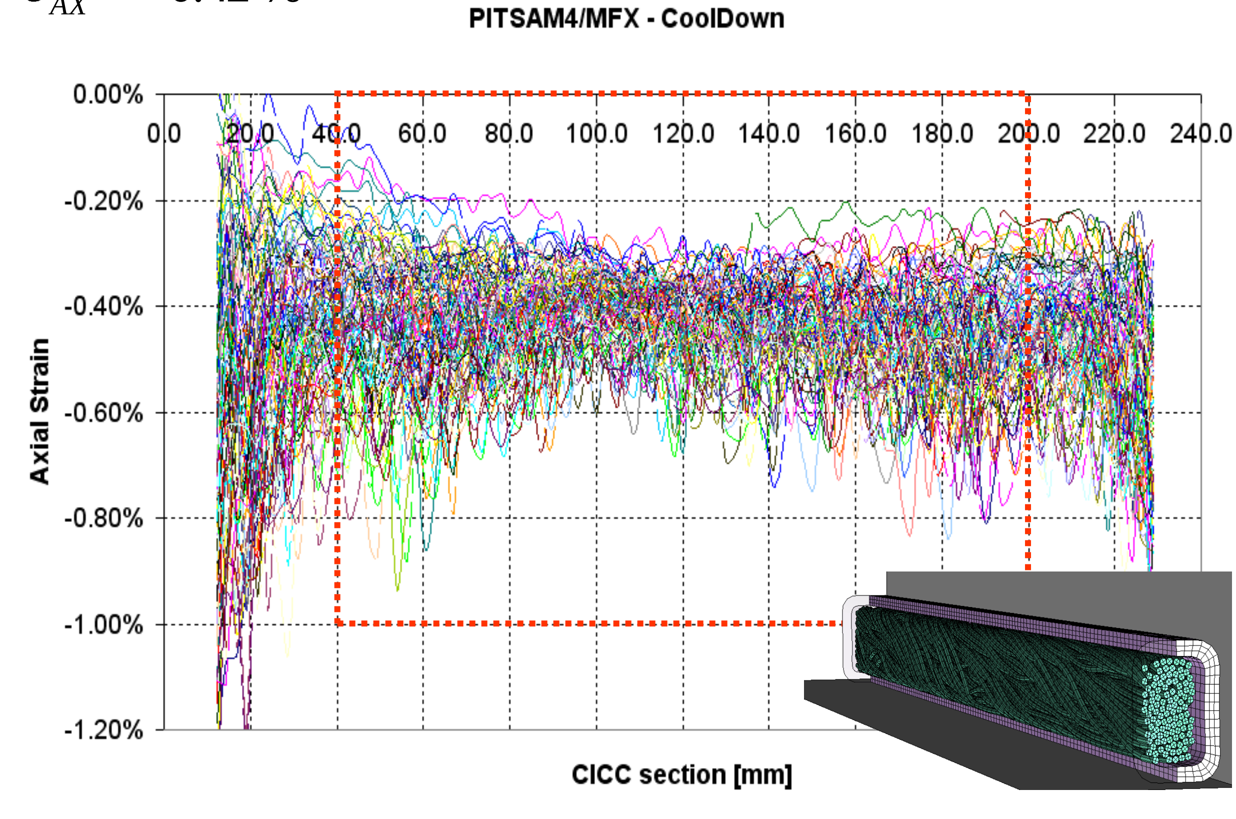


Analysis of the EDIPO Conductor 5/6

- simulation of the Conductor in operation
  - Axial strain in Strands after Cool-down

Average compressive strain after cool-down in the center of the conductor

$$\varepsilon_{AX}^{CD} = -0.42\ \%$$



High axial strain is observed at the conductor ends, because the steel jacket contraction causes local buckling of the strands during cool-down.

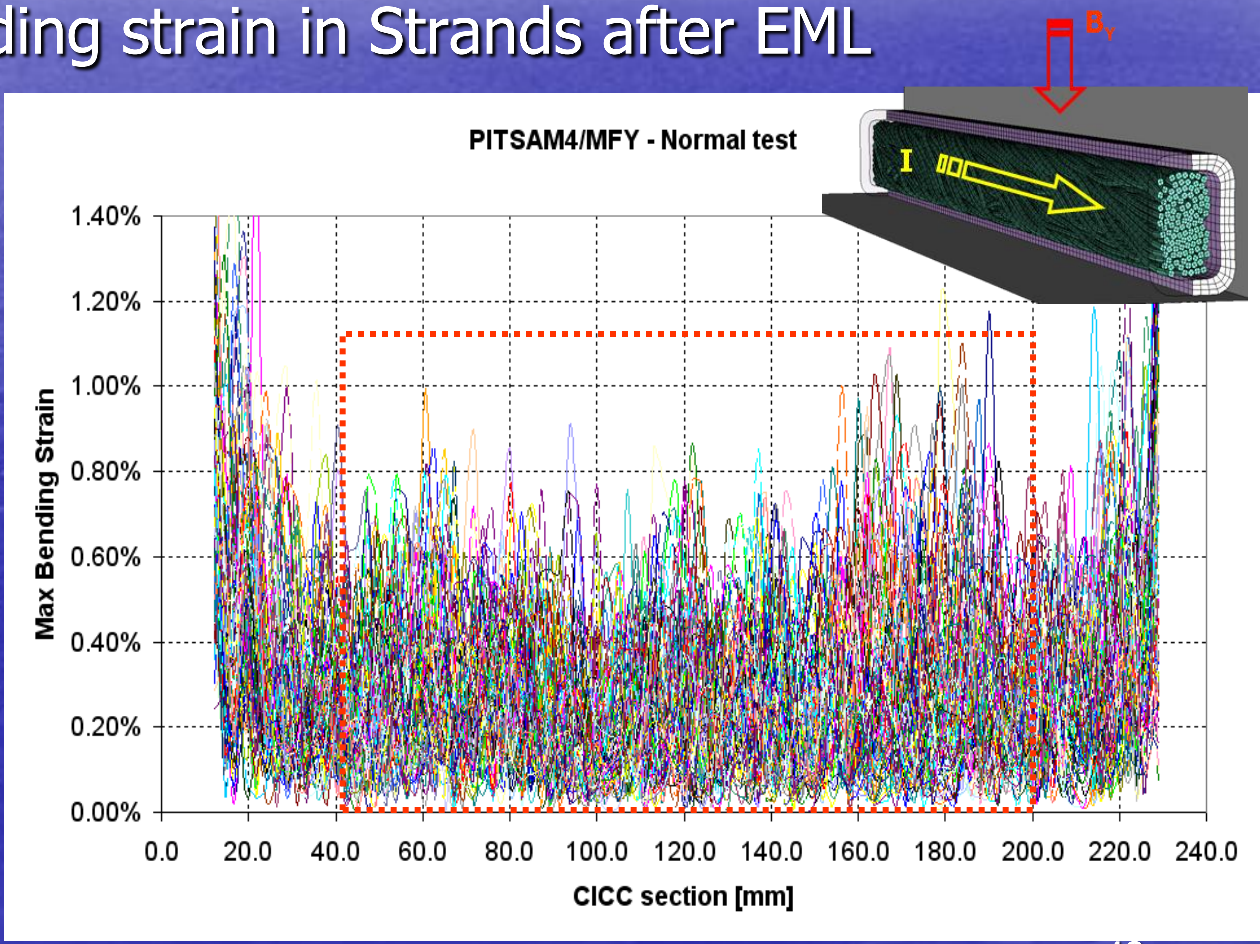
Such “boundary effects” are consequence of the finite length of the conductor model. This means that the results at a certain distance from the border (say equal to the conductor cross-section) should be considered.

Analysis of the EDIPO Conductor

- Simulation of the Conductor in operation
  - Test conditions: Nominal test + B_Y + **Void Fraction 31%**
  - Maximum bending strain in Strands after EML application

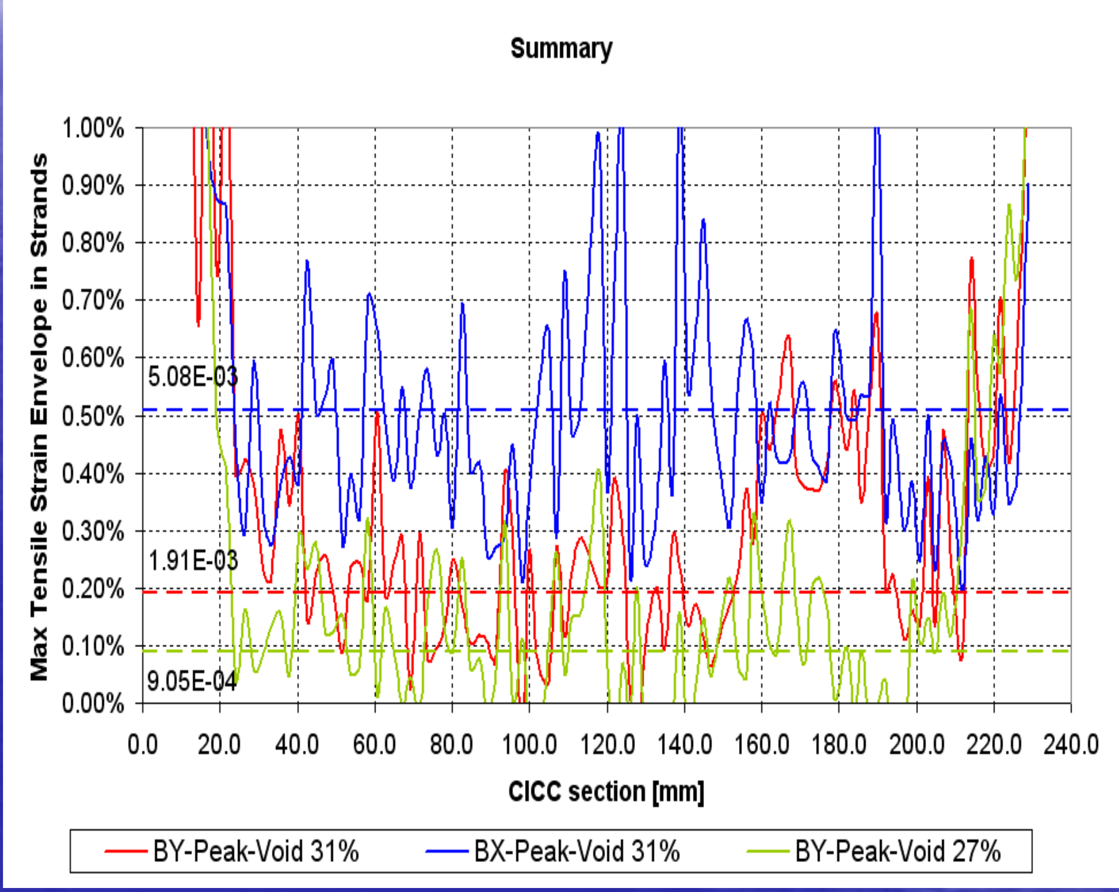
Again high bending strain is observed at the conductor ends due to local bucking of the strands.

Some peak in bending occur in the inner part of the conductor due to strands cross-over



EDIPO Conductor Strain

	Test conditions		
	BY-Peak-Void 31%	BX-Peak-Void 31%	BY-Peak-Void 27%
Intrinsic compressive strain in Nb_3Sn fil.	-0.150 %	-0.150 %	-0.150 %
Axial compressive strain due to steel jacket contraction	-0.420 %	-0.420 %	-0.420 %
Maximum tensile strain due to local bending	0.791 %	1.108 %	0.691 %
Total strain in most critical Nb_3Sn fil.	0.221 %	0.538 %	0.121 %

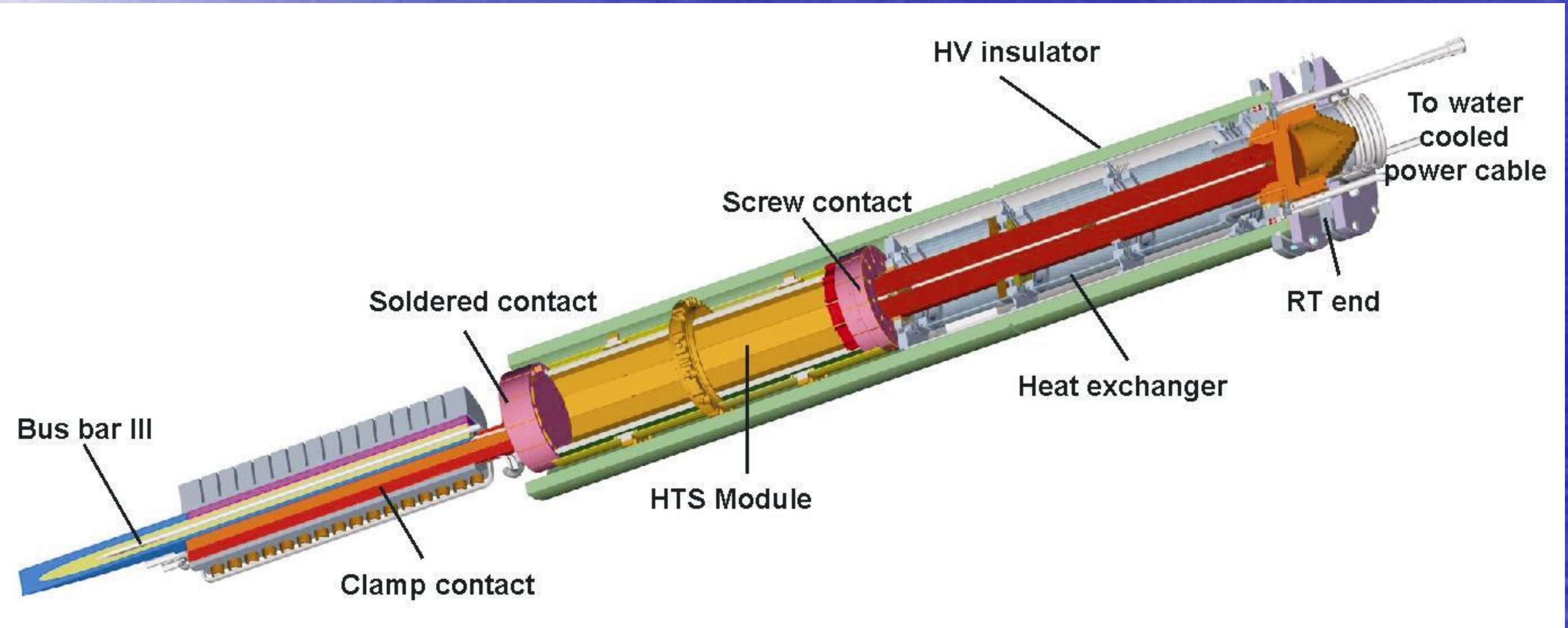


ITER - EFDA Current Lead R&D Programme - Design of the 70 kA HTS CL

PART 1: Clamp contact with three Nb_3Sn inserts

PART 2: HTS module with Ag/Au sheated Bi-2223 tapes

PART 3: Conventional heat exchanger with Cu - discs



70 KA HTSC Current Lead

- The current lead is designed with respect to the requirements given in the ITER-magnet design document
  - Location: The current lead needs to be installed horizontally in coil-terminal-boxes CTB.
  - Safety requirement: The current lead has to withstand a loss of helium mass flow for 3 minutes at nominal current. To reach this goal the heat capacity of the HTS part has to be large.
- Current leads needed for ITER (total current of 2.5 MA)

Coils	No. of pairs	I_{max}	Type	V_{max}
TF Coil	9	68 kA	F	10 kV
PF Coil	6	45 kA	V	14 kV
Correction Coil	9	8 kA	V	3 kV
CS Coil	6	45 kA	V	10 kV

ITER - EFDA 70 kA HTS Current Lead

- 68 kA steady state up to a warm end temperature of 80 K (T_{HTS} = 80 K)
- Quench temperature at 68 kA: 92 K
- 80 kA steady state (T_{HTS} = 55 K)
- Heat load into 4.5 K : 13.5 W
- Cold end contact: 1.9 nΩ
- LOFA (68 kA, T_{HTS} = 65 K): > 6 min before quench (ITER requirement: > 3 min)
- Poor screw contact between HTS module and heat exchanger at warm end ($\approx$ 100 nΩ)

Conclusions

- A Fusion Power Plant can be safe and acceptable for the environment
- ITER feasibility demonstration is well advanced
- ITER should demonstrate the feasibility of a Fusion Power Plant