“The conceptual design of the DTT superconducting magnet system”

Aldo Di Zenobio

on behalf of the DTT Magnet System design team:

L. Muzzi, S. Turtù, L. Affinito, A. Anemona, V. Corato, C. Fiamozzi Zignani, L. Giannini, G. Messina, L. Morici, R. Righetti, G. Romanelli, L. Zoboli and A. della Corte – ENEA

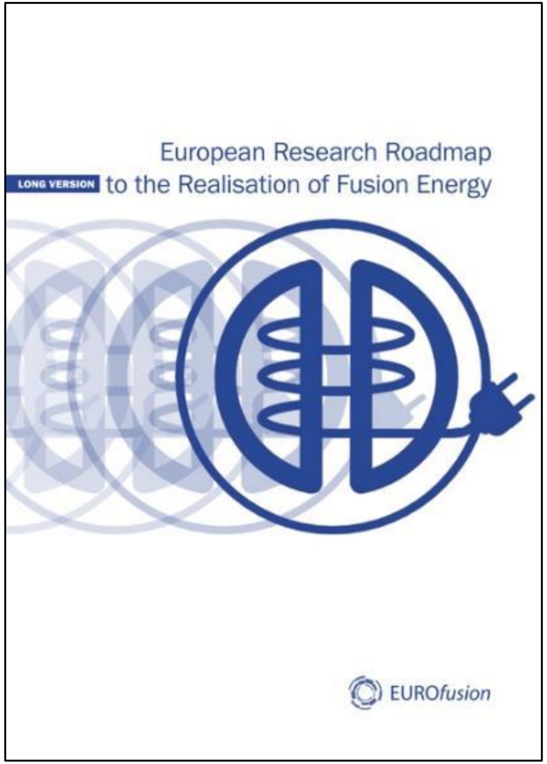
R. Bonifetto, L. Savoldi, A. Zappatore and R. Zanino – Politecnico di Torino (NEMO Group)

and DTT design contributors:

see Divertor Tokamak Test facility – Interim Design Report; ed. by R. Martone, R. Albanese, F. Crisanti, P. Martin and A. Pizzuto; *ISBN: 978-88-8286-378-4*

Background & Project Objectives

EU Research Roadmap to Fusion Energy



(1.2 - Sept. 2018)

4. How to face the challenges – the missions for the realisation of fusion

Mission 1 – Plasma regimes of operation

Mission 2 – Heat-exhaust systems

Mission 3 – Neutron tolerant materials

Mission 4 – Tritium self-sufficiency

Mission 5 – Implementation of the int… safety features of fusion

Mission 6 – Integrated DEMO design and system development

Mission 7 – Competitive cost of electricity

Mission 8 – Stellarator

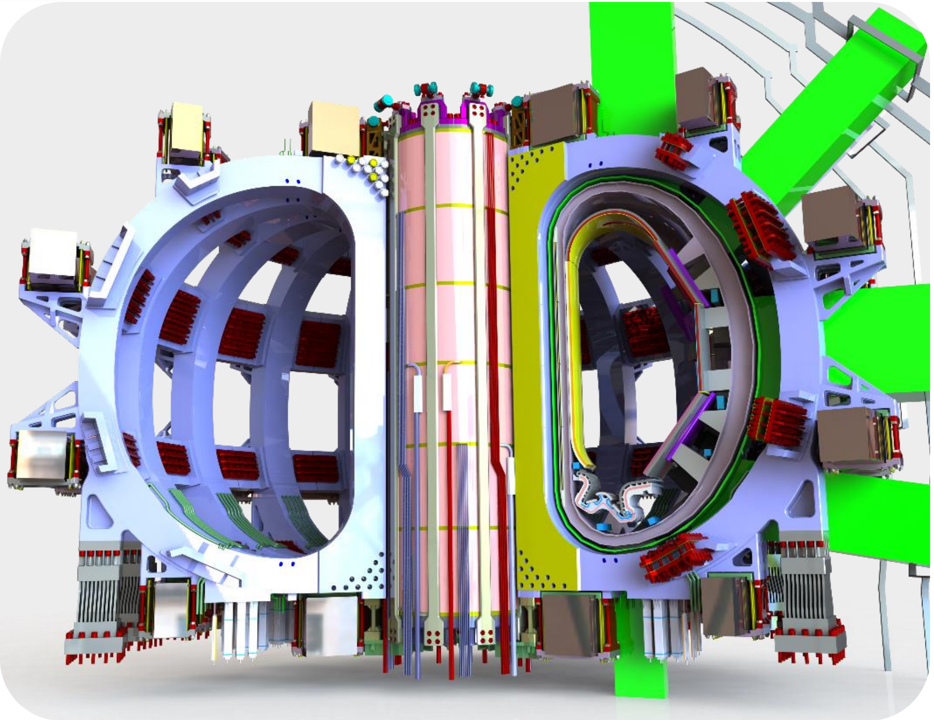
M2. Heat-exhaust systems:

Demonstrate an integrated approach that can handle the large power leaving ITER and DEMO plasmas.

DTT: Divertor Tokamak Test Facility project

General objective: create a research infrastructure addressed to the solution of the **power exhaust issues** in view of **DEMO.**

Test Divertor **alternative solutions & improve experimental knowledge in the PEX scientific area**



- **Replace Divertor by Remote Handling**
- **High Magnetic System flexibility to Implement Various Plasma configurations**

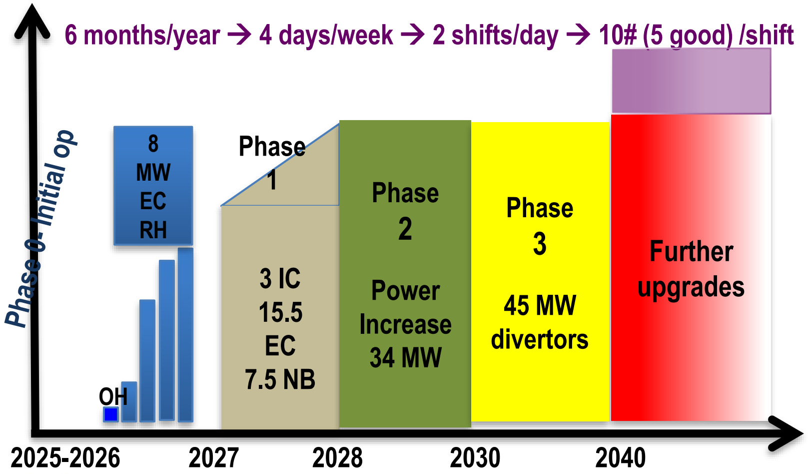
DTT: Divertor Tokamak Test Facility project

Max. plasma current: **5.5 MA**

Inductive operation with a max high β flat top up to **50 s**

Heating system providing **45 MW** (target)

(20-30 MW ECRH, 3-9 MW ICRH, 7-15 MW NNBI)



DTT main parameters

R(m)/a(m)	2.14/0.65 (SN/DN)
A	3.3 (SN/DN)
I_p (MA)	5.5
B_T (T)	6.0 @ R_0
Neutron production rate (n/s)	1.2-1.5 10^{17} DD + 1% DT
Maximum dwell time (s)	3’600
Nominal repetition time after disruption (s)	3’600
Number of shots per day	5-10
Days of operation per year	100
Years of operation	25
Number of max shots	25’000

see Divertor Tokamak Test facility – Interim Design Report; *ISBN: 978-88-8286-378-4*

DTT: Divertor Tokamak Test Facility project

The facility will offer **high flexibility** to test the candidate divertor concepts and to probe different magnetic (i.e. plasma) topologies

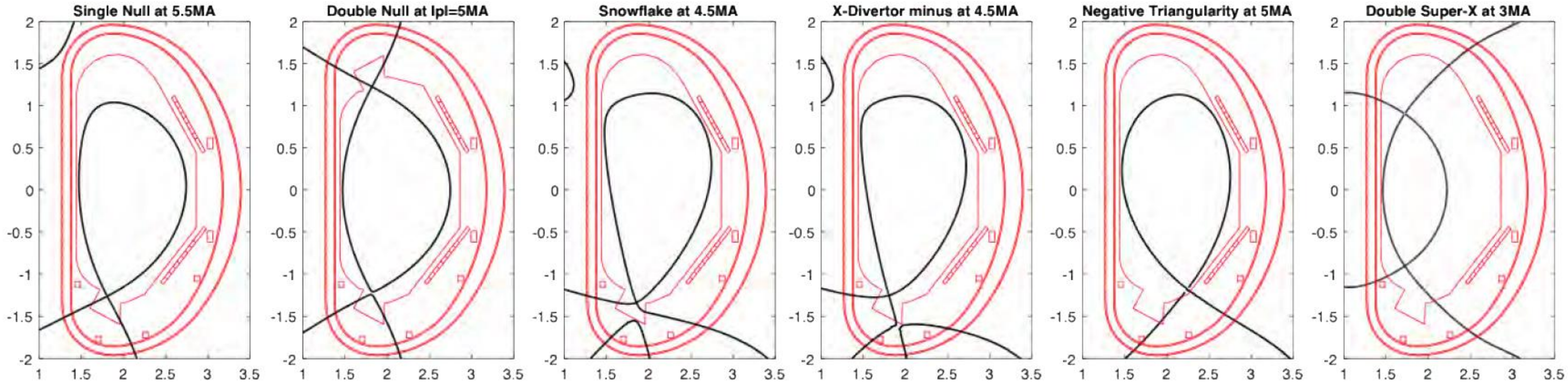


Figure I.4: Single Null (5.5 MA), Double Null (5 MA), Snow Flake (4.5 MA), X-Divertor (4.5 MA), Negative Triangularity (5 MA) and Double Super-X (3 MA) configurations at flat top. The DTT magnetic system is also compatible with a 5 MA long leg configuration. Negative Triangularity and Double Super-X require a dedicated divertor.

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see Divertor Tokamak Test facility – Interim Design Report; *ISBN: 978-88-8286-378-4*

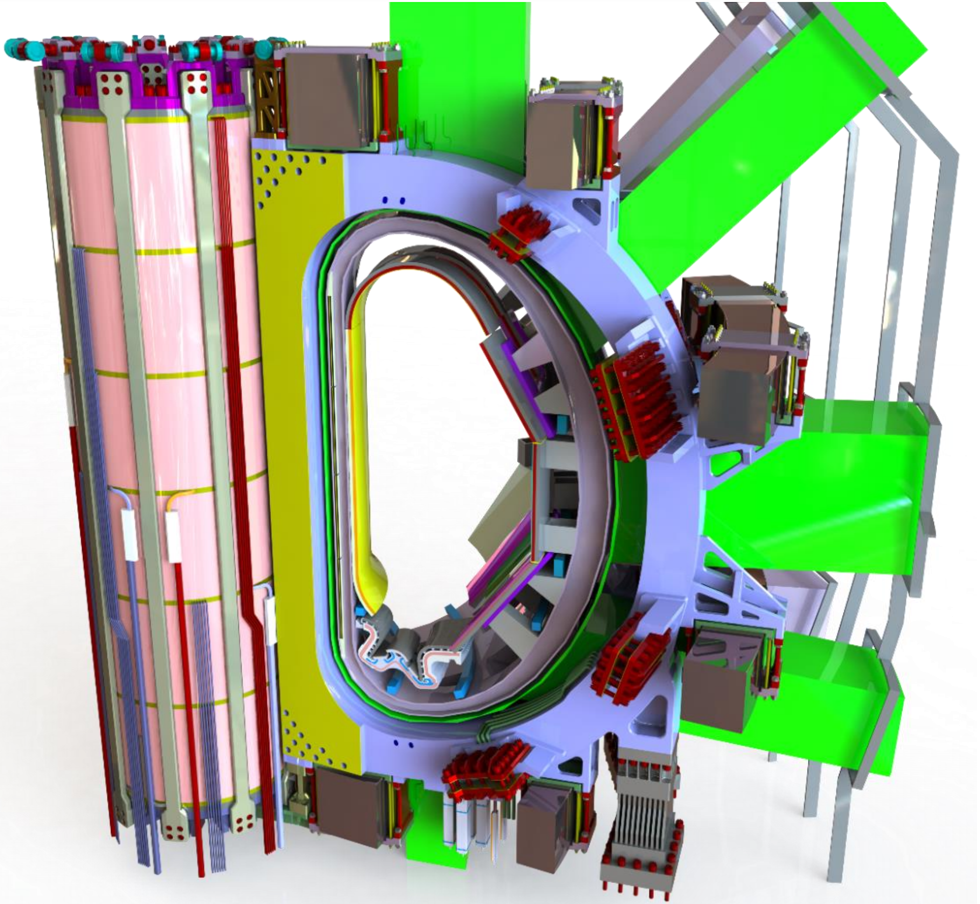
Overview of the Superconducting Magnet System

DTT Magnet System Overview

18 TF coils:
Nb_3Sn CICC: **44.8 kA – 11.9 T**
providing **6.0 T** over plasma major radius (**2.14 m**)

6 CS modules (indipendently fed)
Nb_3Sn CICC: **29 kA – 13.4 T**
providing **16.4 Weber** magnetic flux for plasma initiation at breakdown

6 PF coils
Nb_3Sn (PF1 & PF6) CICC: **28.3 kA – 9.1 T**
NbTi (PF2 to PF5) CICC: **28.6 kA – 5.4 T**
Identical in pairs to guarantee full top/down symmetry



DTT Magnet Syst

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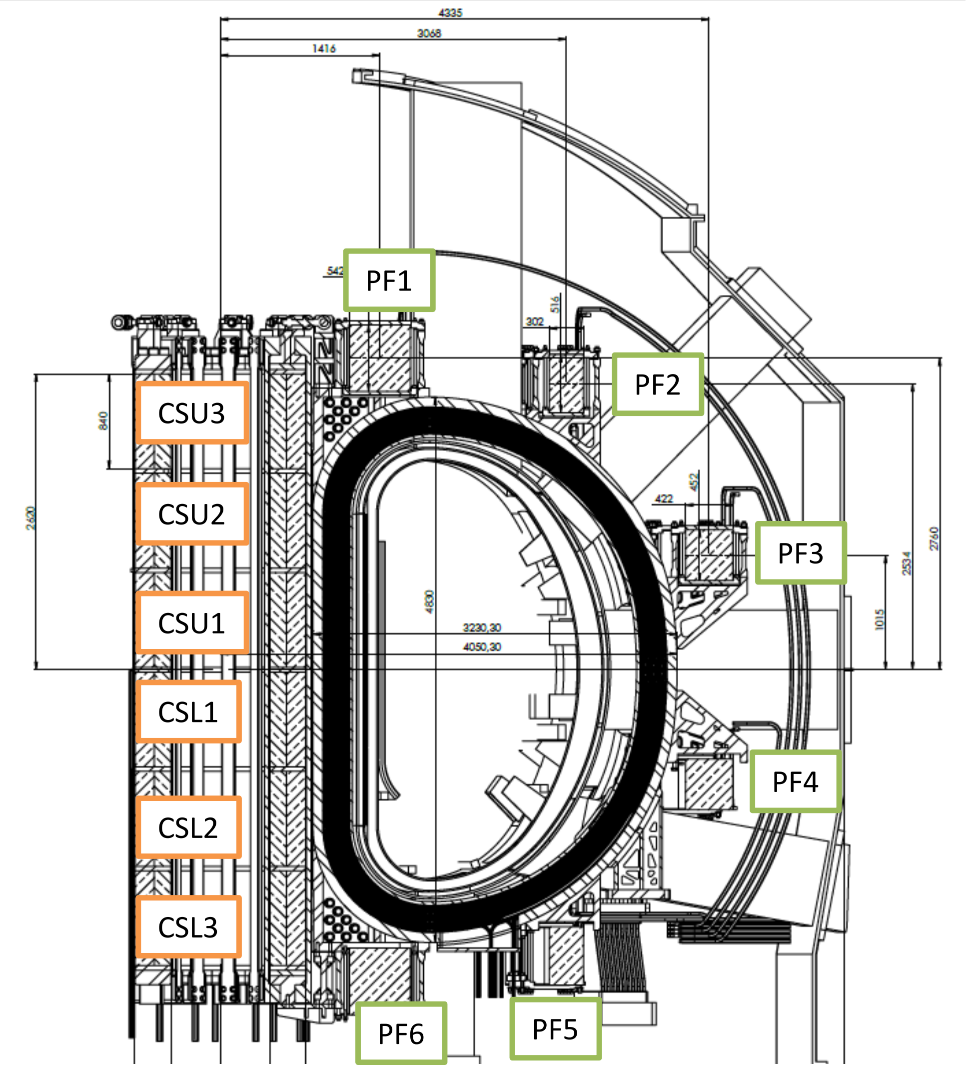

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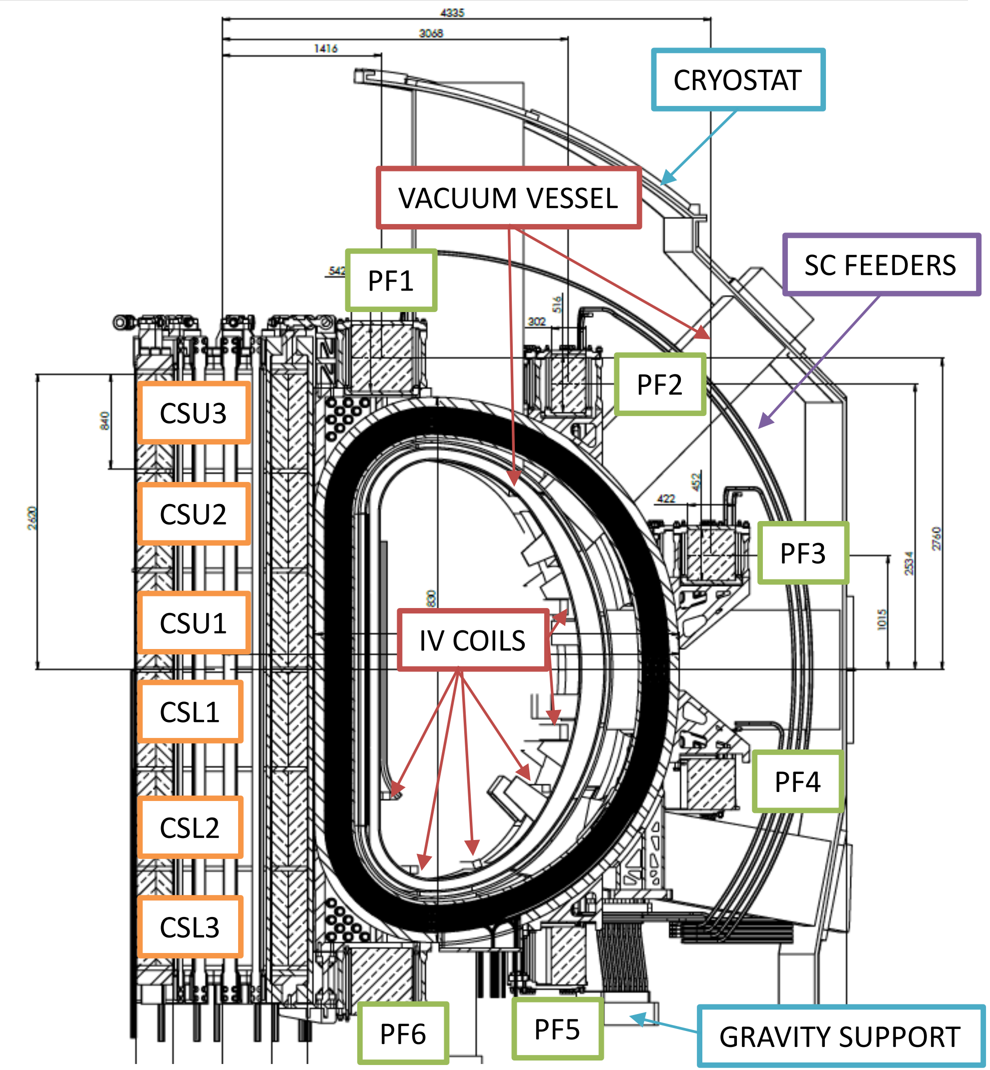

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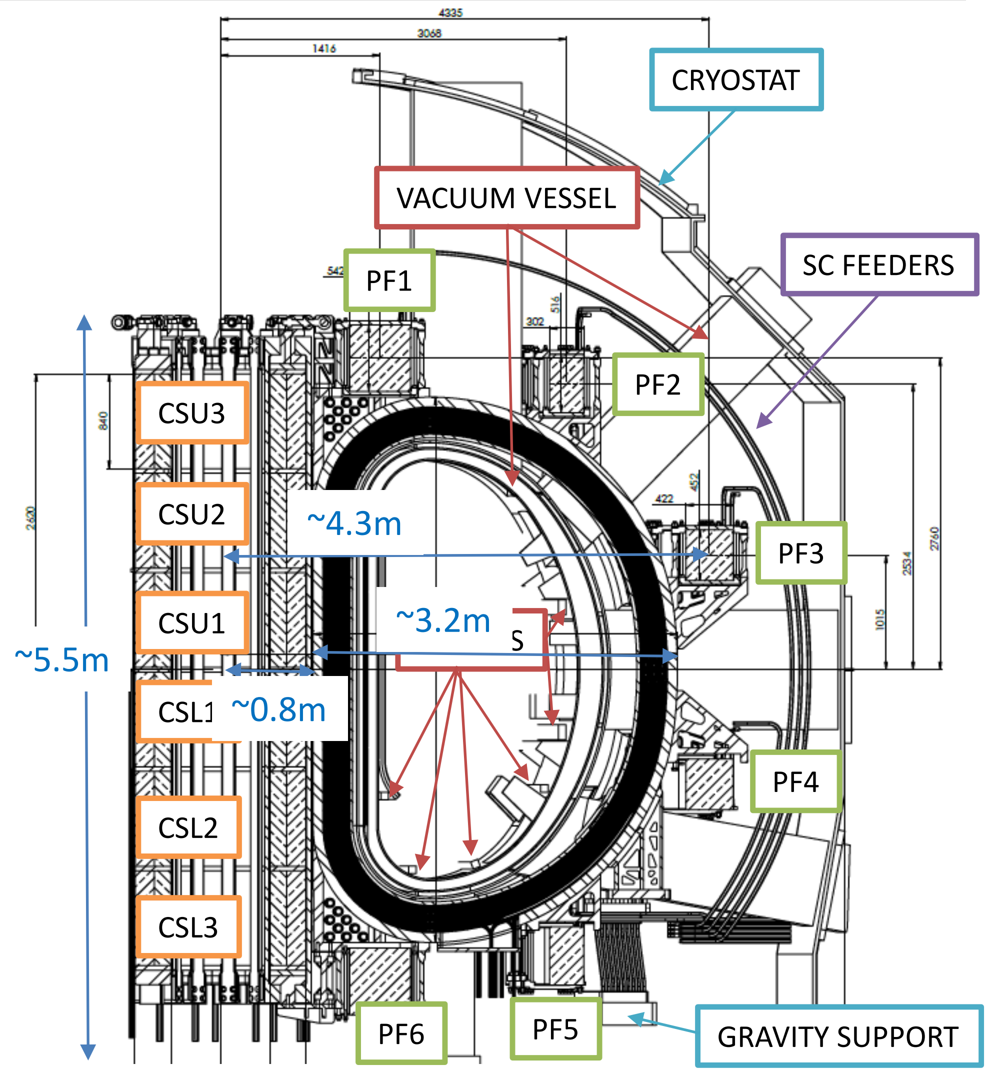


SC coils: rationale behind design choices

Superconducting coils design rationale

The design of the DTT superconducting coils in terms of:

- Performance of the superconducting wires (**strands**)
- Features of the Cable-in-Conduit Conductors (**CICC**)
- Coil (**winding) layout** and technologies

is based on

a large experience gained by the scientific fusion community and by industry mainly with the 3 large SC tokamaks

ITER, JT-60SA and K-STAR

and with the high field hybrid magnets of

NHFML, HFML & HZB

in order to **minimize R&D phase**, for time and cost constraints

Ic achieved: 190 A – 315 A
on 0.82 mm wire
(Vostner - SUST 2017)

...lucting coils design ...

Ic achieved: 325 A
on 0.73 mm wire @ 6.4 T
(Karasev – IEEE TAS 16)

0.82 mm wires	Min. Critical Current (requested by ENEA)	Min. Critical Current (guaranteed by the awarded supplier)
DTT TF specs (Nb_3Sn)	**285 A** (4.2 K; 12 T; 0% strain)	**300 A** (4.2 K; 12 T; 0% strain)
DTT CS & PF1/6 specs (Nb_3Sn)	**260 A** (4.2 K; 12 T; 0% strain)	**260 A** (4.2 K; 12 T; 0% strain)
DTT PF2-5 specs (NbTi)	**500 A** (4.2 K; 5 T)	*NA*

Tests (*performed by KAT*) on first samples, gave **> 330 A**

...ved > 260 A
...m wire
... SUST 2014)

Courtesy A. Devred

Br: Bronze
IT: Internal Tin

WST (CN)

Jastec (Br)
CS3&2L-CS3U

KAT (IT)
CS1L&CS2U

FUR (Br)
CS1U&Spare

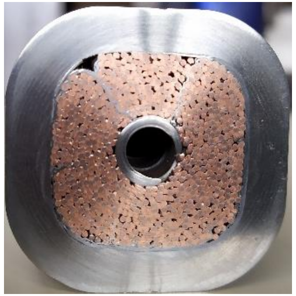
A.D. A lo...

Member ...

Superconducting coils design rationale

DTT CICC design is based on the results collected within a number of programs:

JT-60SA TF

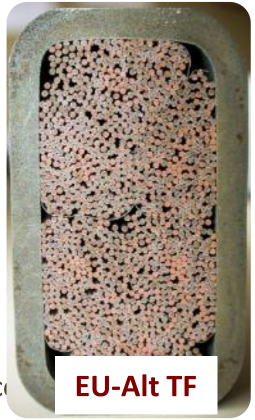


sample for K-DEMO

Present reference CICC solution based on:

1. rectangular (or square) geometry, with constant thickness steel jacket
2. very short twist pitch cable **OR** long twist pitch & low Void Fraction
3. Assumption: ε_{eff} **= - 0.65%**

Design verification with dedicated experimental tests *(DC properties with e.m. and thermal cycling + AC losses)* is foreseen in the next months, before giving green light to conductor production.

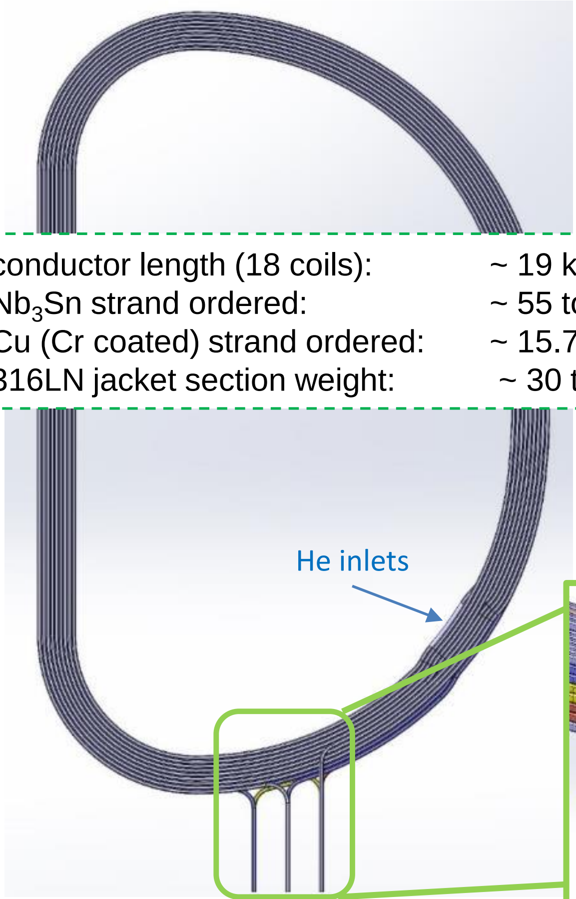


EU-Alt TF

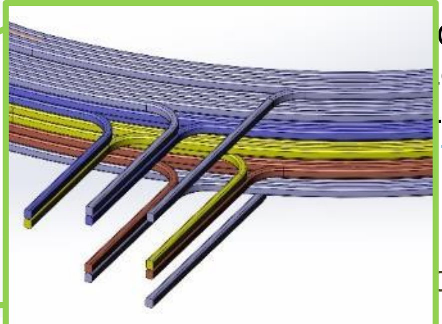
(N)HFML

Toroidal Field coils

Toroidal Field Coils – Winding Pack

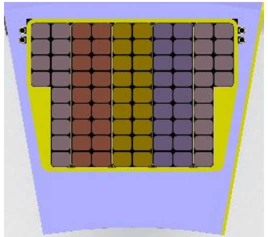


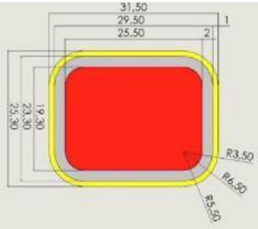
Total conductor length (18 coils):	~ 19 km
Total Nb_3Sn strand ordered:	~ 55 tons
Total Cu (Cr coated) strand ordered:	~ 15.7 tons
Total 316LN jacket section weight:	~ 30 tons



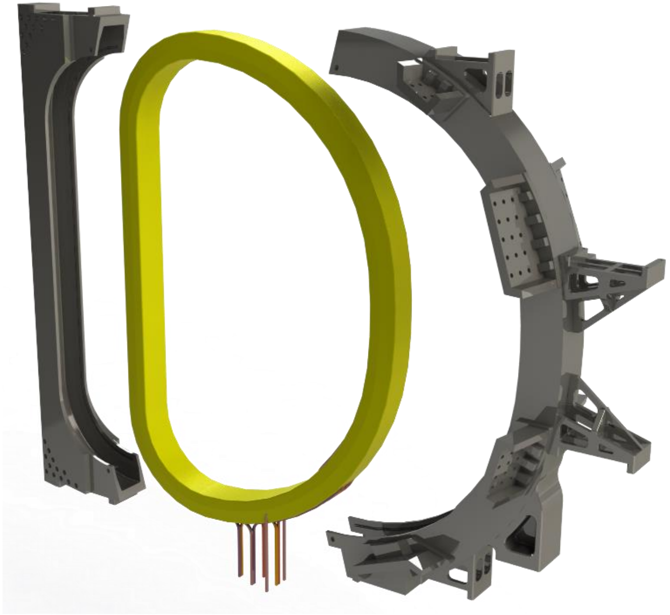
Operative current:44.8kA
B_{peak}: **11.9 T**
Double pancake-winding: **3 rDP**; **2 sDP**; 80 turns
Max. hydraulic length: **110 m**
ΔT_{margin} **> 1.4 K**
Turn insulation: **Fiber-glass + resin**
Wind → React → Insulation → Impregnation

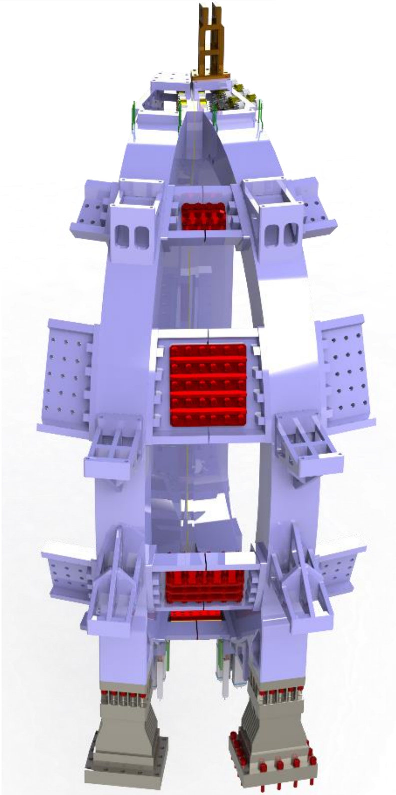
Jacket thickness: 2.0 mm
VF: 26.4%
Nb_3Sn strands: 504
Cu segregated strands: 144
Nb_3Sn strand: 0.82mm diam., Cu/nonCu: 1, RRR=100
Cu segregated strand: 0.82mm diam., RRR > 300
Cr coating: 2 μm
Cu+2Nb_3Sn)+(1Cu+2Nb_3Sn)+3Nb_3Sn]*3*4*6
ong Twist Pitch)
.05mm thick, overlap 30%





Toroidal Field Coils – case & supports



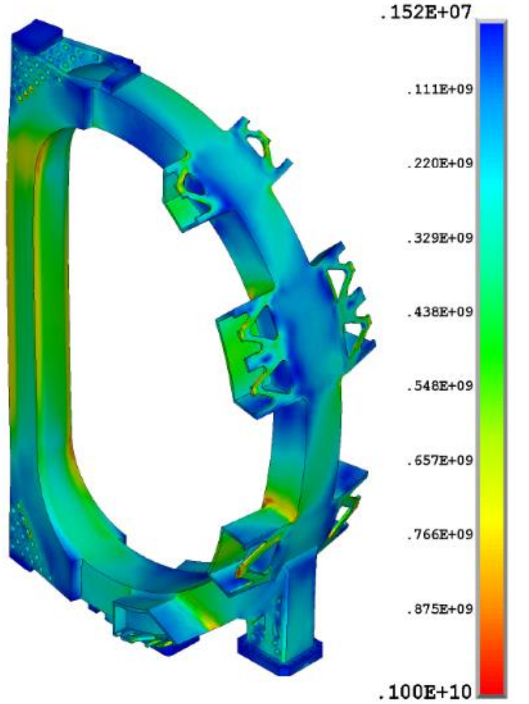


Simmetric shape of TF coils to allow DN and other possible simmetric scenarios (wrt equatorial plane).
All the magnet system weight loads the TF coils.
Structures are mainly based on machining of 316L(N) forged sectors.

For more details: **Alessandro Anemona (Mon-Mo-Or1-02)**, today at 11.45am

Toroidal Field Coils - analyses

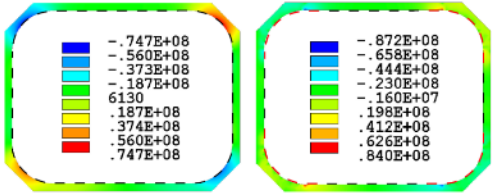
3D global



Stress intensity [Pa]

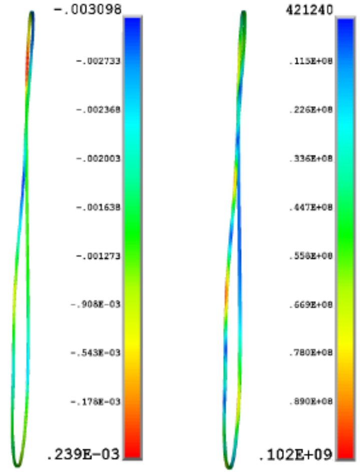
2D detailed

Turn Insulation shear stress [Pa]



- - - - = turn insulation glued to cable jacket.
- - - - = turn insulation can detach from the jacket.

3D submodeling

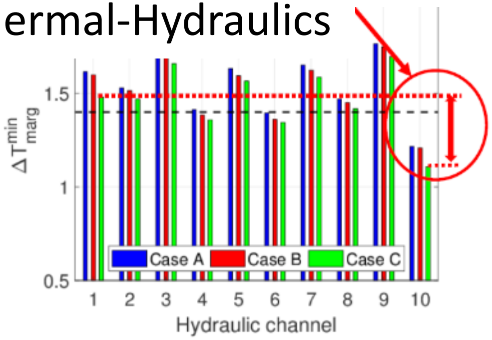


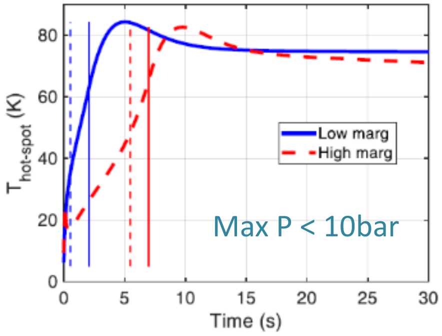
SC cable **longitudinal strain < 0.4%**

Cable jacket **Goodman stress [Pa] < 450MPa**

For more details: **G. Romanelli (Wed-Mo-Po3.01-02 [2]) & R. Zanino (Wed-Mo-Po3.01-03 [3])**, Wednesday poster session

Thermal-Hydraulics

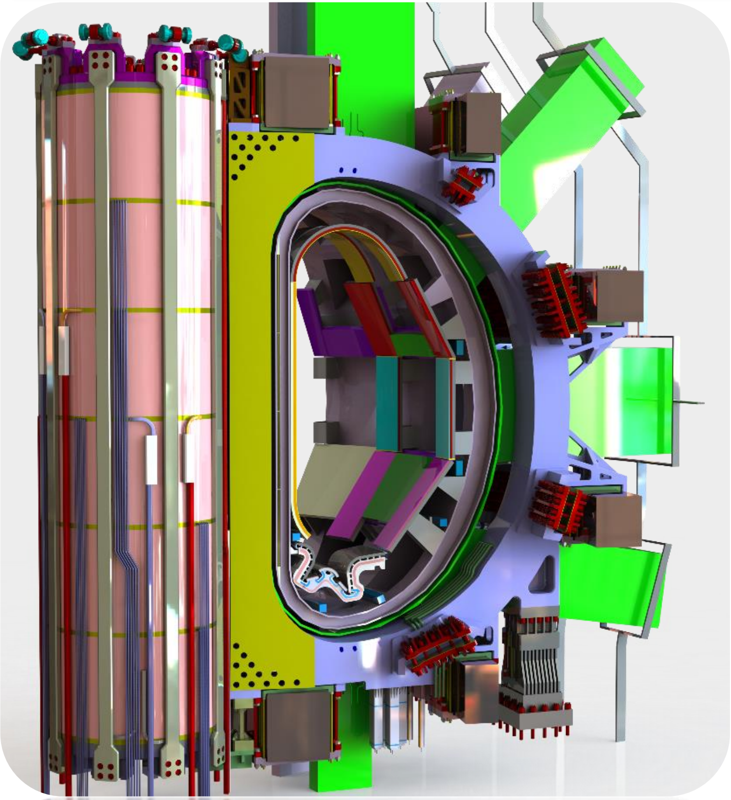




	$T_{max,cond}$ [K]	$T_{max,jk}$ [K]	p_{max} [bar]
ΔT_{marg}^{min}	85	75	10
ΔT_{marg}^{max}	83	73	9.2
ITER req.	<250 (dry)	<150	<250

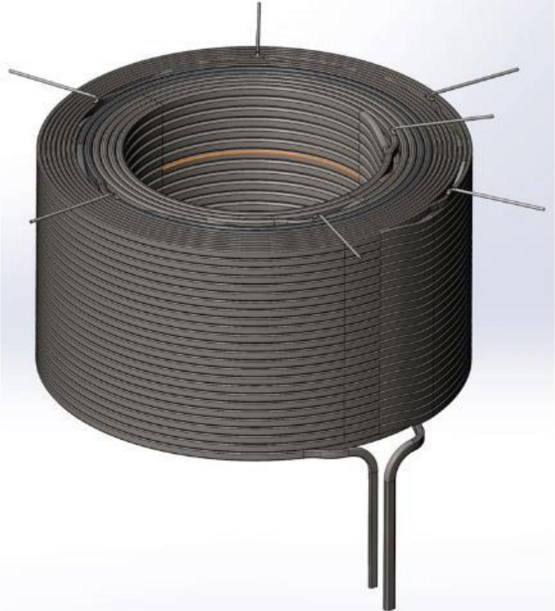
Central Solenoid

Central Solenoid modules



Requirements:

- 6 independently fed modules (flexibility)
- Magnetic flux **> 16.4 Weber**
- Limited room availability (high J_E values)
- Designed to foresee future installation of an insert coil (HTS)



Design choices:

- 6 identical modules
- Layer wound (2 conductor grades)
- Optimized concepts for inter-grade joints and terminations (small curvature radii, small gap between TF and CS,..)

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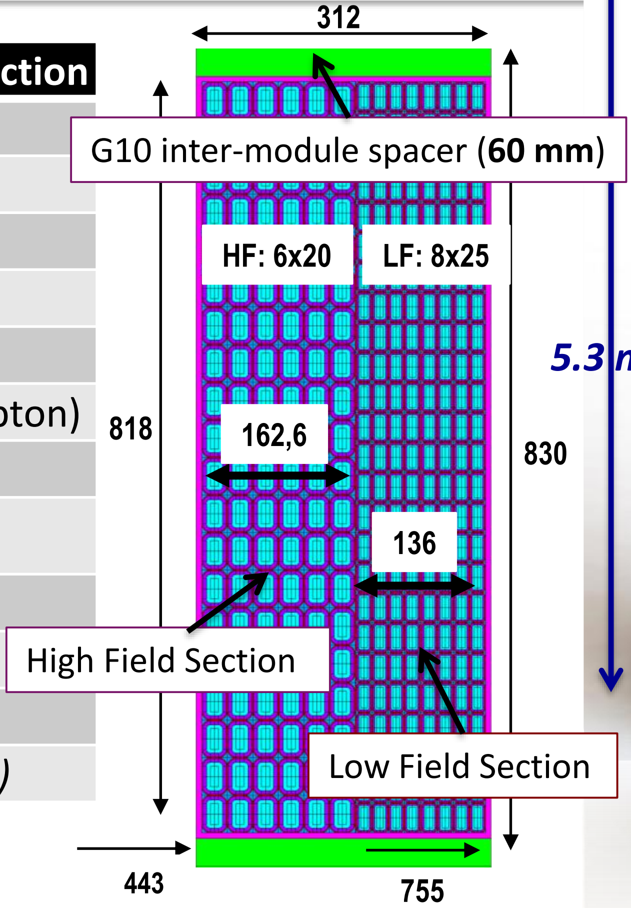
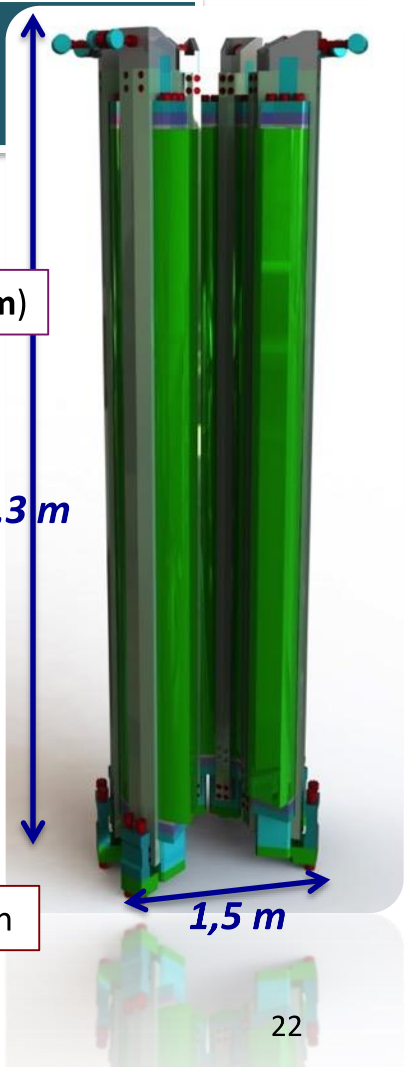
Central Solenoid modules

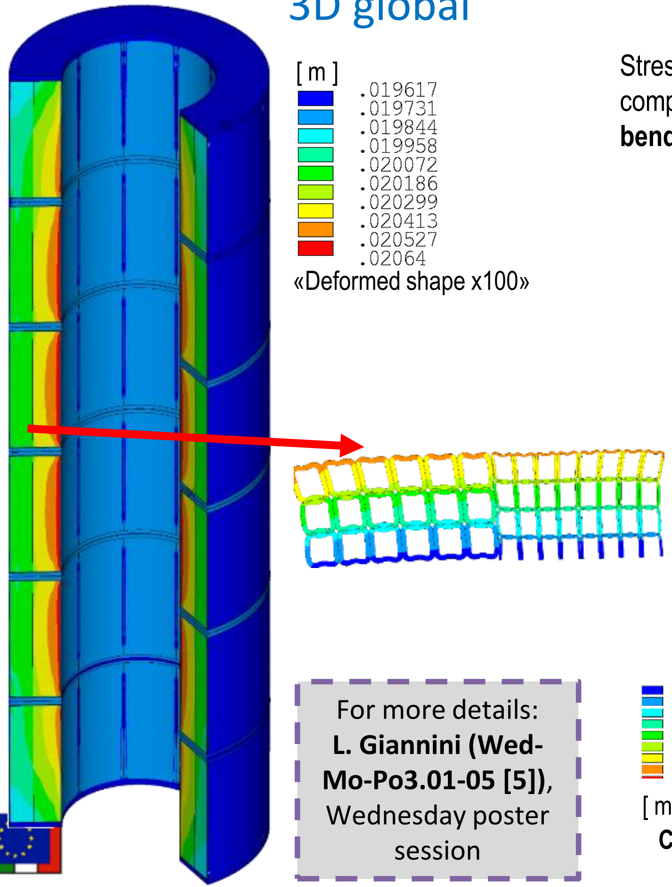
	HF (inner) section	LF (outer) section
Max operative I	29.04 kA	
Peak field	13.4 T	8.5 T
# s.c. wires	648	180
Jacket thickn.	4.1 mm	2.0 mm
Turn insulation	1.0 mm (glass-fiber + resin)	
Ground insulation	6.0 mm (glass-fiber + resin + Kapton)	
Wind & Insulate → React → Impregnate		
J_{ENG} (A/mm²)	26.2	52.2
# layers x turns	6 x 20	8 x 25
Magnetic Fux	16.4 Wb	
Target ΔT_{margin}	> 1.0 K	
Max. voltage	3.5 kV *(terminal to terminal)*	





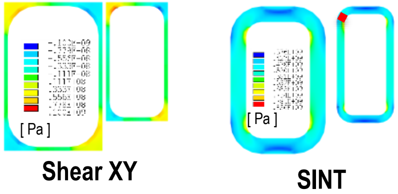
Central Solenoid - analyses

3D global

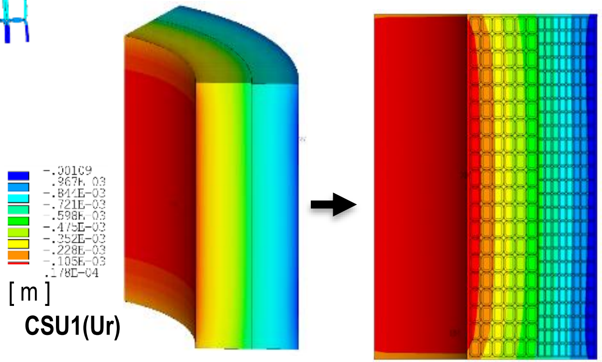


2D detailed

Stress level in SS is below the allowable limits for both components: **membrane (667 MPa)** and **membrane + bending (867 MPa)**

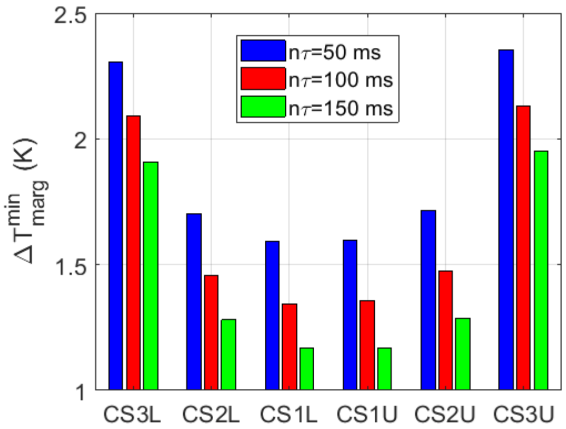


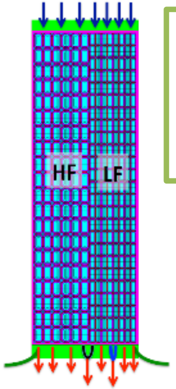
3D submodeling



For more details:
L. Giannini (Wed-Mo-Po3.01-05 [5]), Wednesday poster session

Thermal-Hydraulics



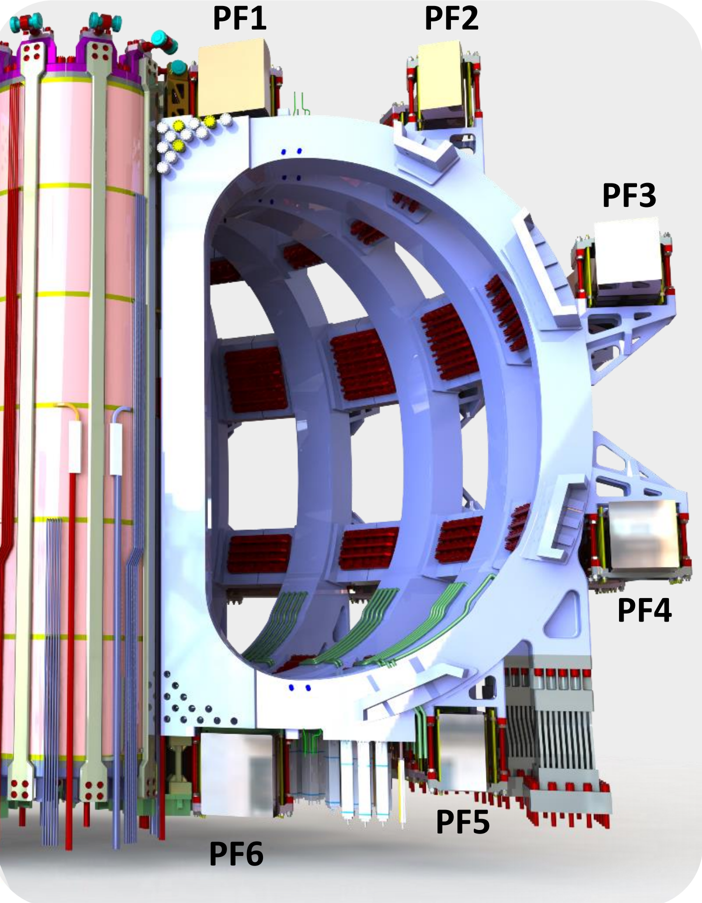


Target ΔT_{margin} > 1K (mainly affected by AC losses, nτ value to be measured experimentally)

7 He inlets & 8 He outlets per module

Poloidal Field coils

Poloidal Field Coils



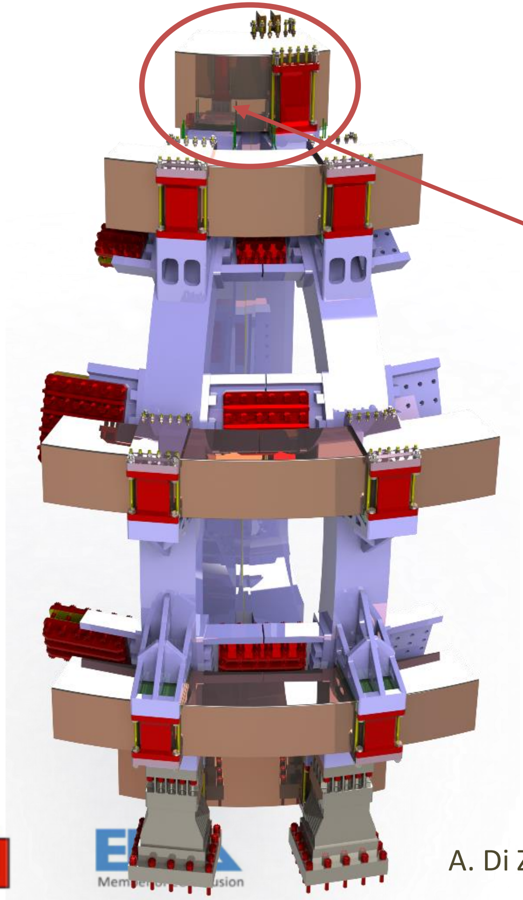
6 independent coils

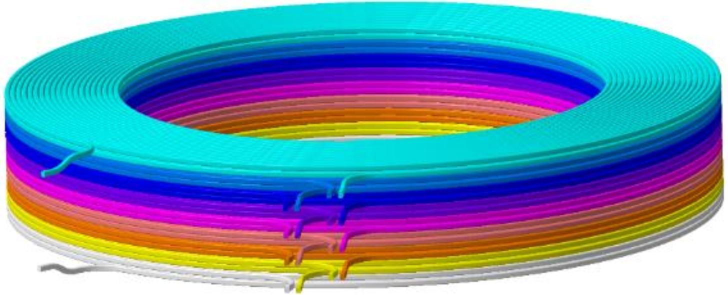
On PF1&6 max B around 9T → Nb_3Sn strands

Designed identical in pairs for symmetry

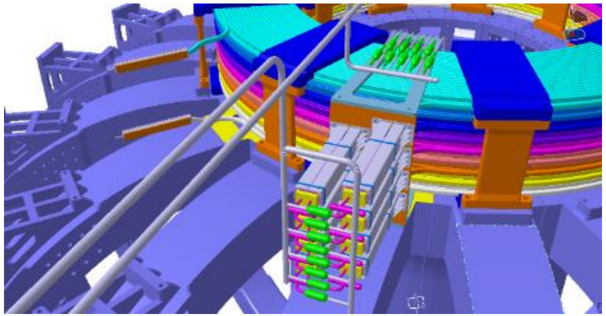
	PF1/6	PF2/5	PF3/4
Bmax (T) (input data)	9.1	4.2	5.3
R (mm)	1416	3068	4335
±ΔR (mm)	542	302	422
Z (mm)	±2760	±2534	±1015
±ΔZ (mm)	590.4	516.8	452.2
Ground Insulation	5mm		
# turns (radial)	20	10	14
# turns (vertical)	18	16	14
Total N turns	360	160	196
I_{op} max (kA)	28.3	27.1	28.6
ΔT_{margin} (T_{op}: 4.5K)	1.8	1.9	1.7
L (H)	0.454	0.298	0.690
V_{max} (V)	2150	1350	3290
Weight (tons)	15	16	28
delay / discharge constant	1.5 s / 6 s		

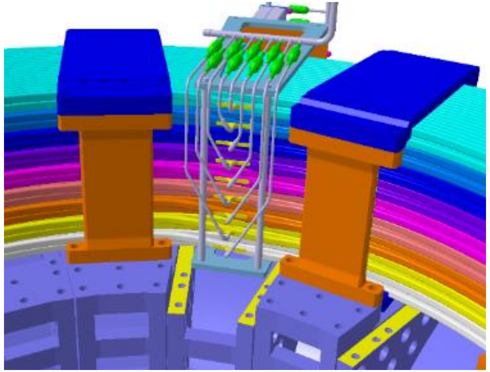
Poloidal Field Coils





Less room is available for joints & terminations of PF1/6
→ 1 support each 2 TF coils

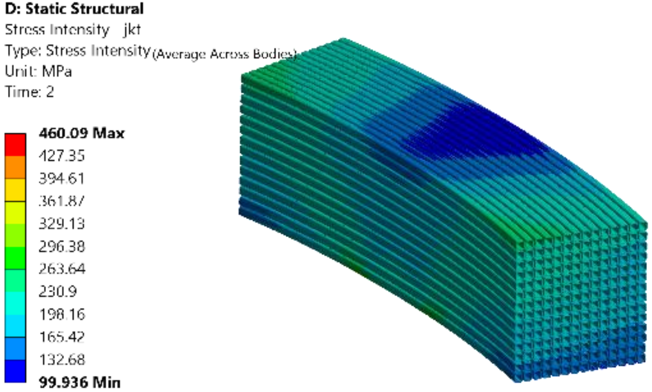


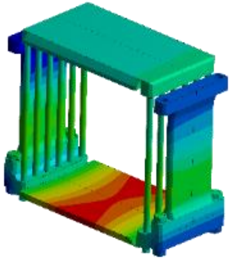


For more details: **S. Turtù (Wed-Mo-Po3.01-01 [1])**, Wednesday poster session

Poloidal Field Coils - analyses

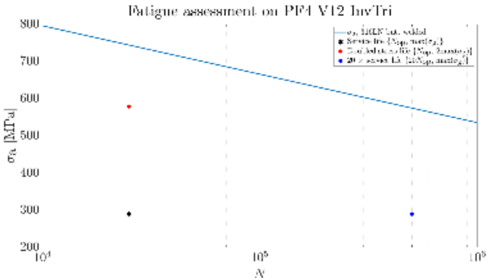
3D global

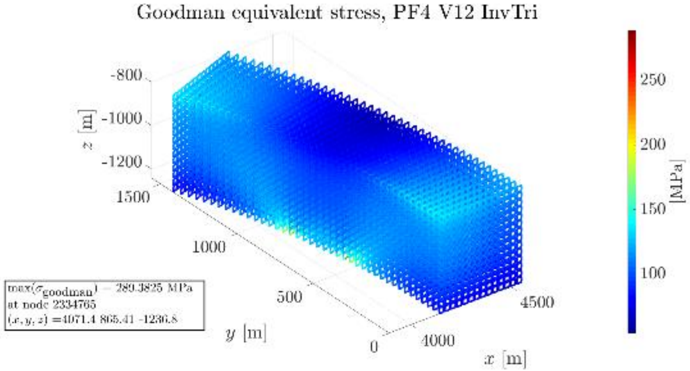




Cage total displacement

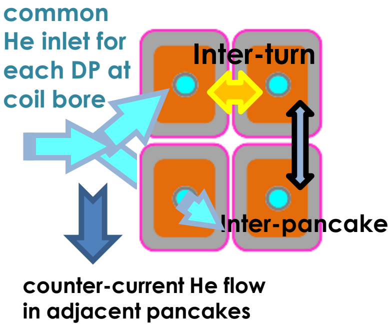
Fatigue assessment

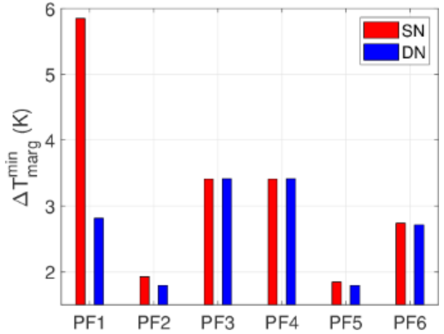




For more details:
L. Zoboli (Wed-Mo-Po3.01-04 [4]), Wednesday 1.45pm poster session

Thermal-Hydraulics





Target ΔT_{margin} > 1.7K is reached in each coil (AC losses values still to be experimentally verified)

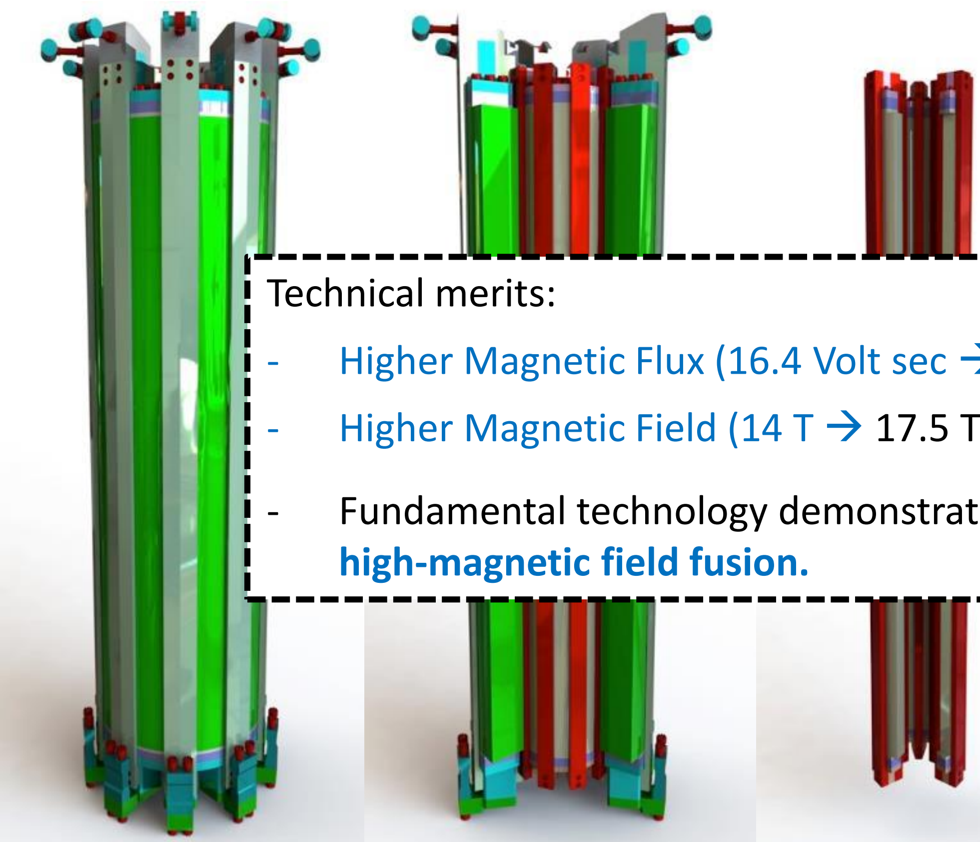
Member of EUROfusion

DTT Magnet System

Side projects/activities

CS HTS insert coil

DTT as a test-bed for **next generation fusion magnets**

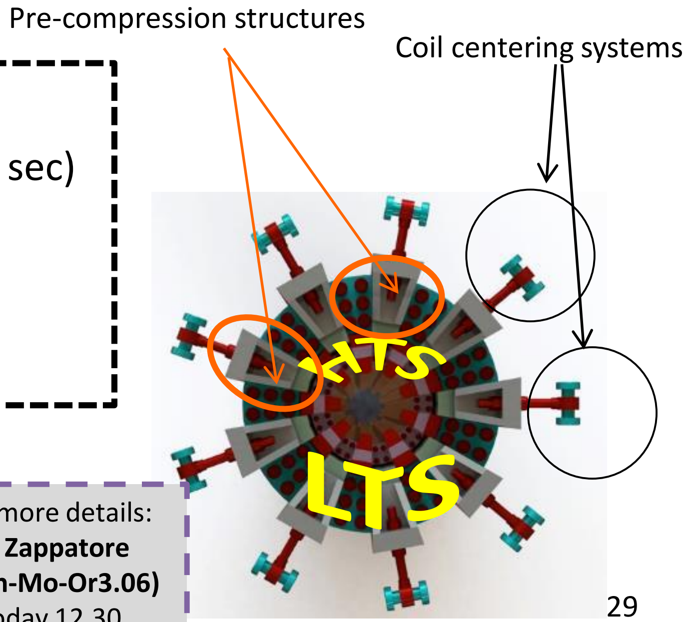


Technical merits:

- Higher Magnetic Flux (16.4 Volt sec → 17.3 Volt sec)
- Higher Magnetic Field (14 T → 17.5 T)
- Fundamental technology demonstration toward **high-magnetic field fusion.**

Design of a **HTS insert**

(presently outside of the DTT scope)



For more details:
A. Zappatore
(Mon-Mo-Or3.06)
today 12.30

Cold test facility

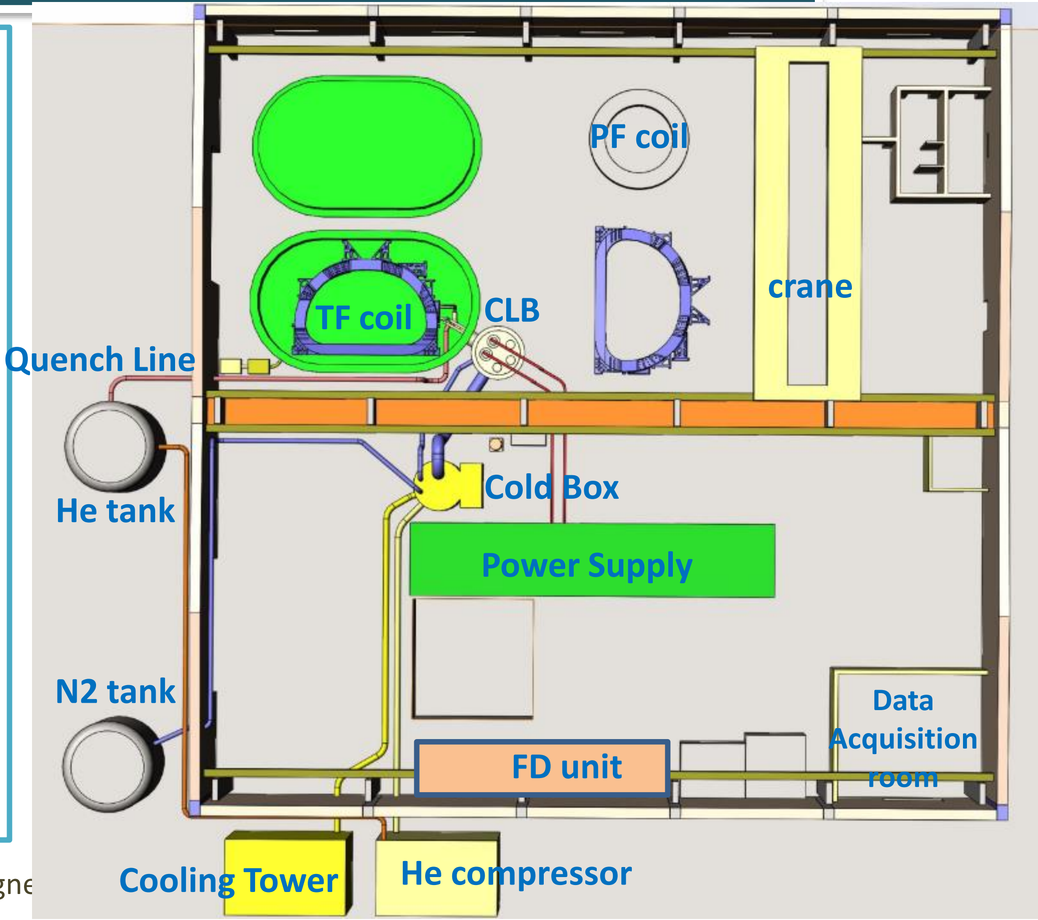
→ [ENEA decided to create a new infrastructure in Frascati]

18 TF coils + 7 CS modules + PF1 & 6
will be tested at 4.5K

Current leads, Power Supply & Quench protection prototypes will be used for cold tests and thus qualified against real conditions

This activity is in addition to the DTT budget (ENEA's investement only)

Adaptation of the Superconductivity lab to host the new facility is already started



DTT Magnet System

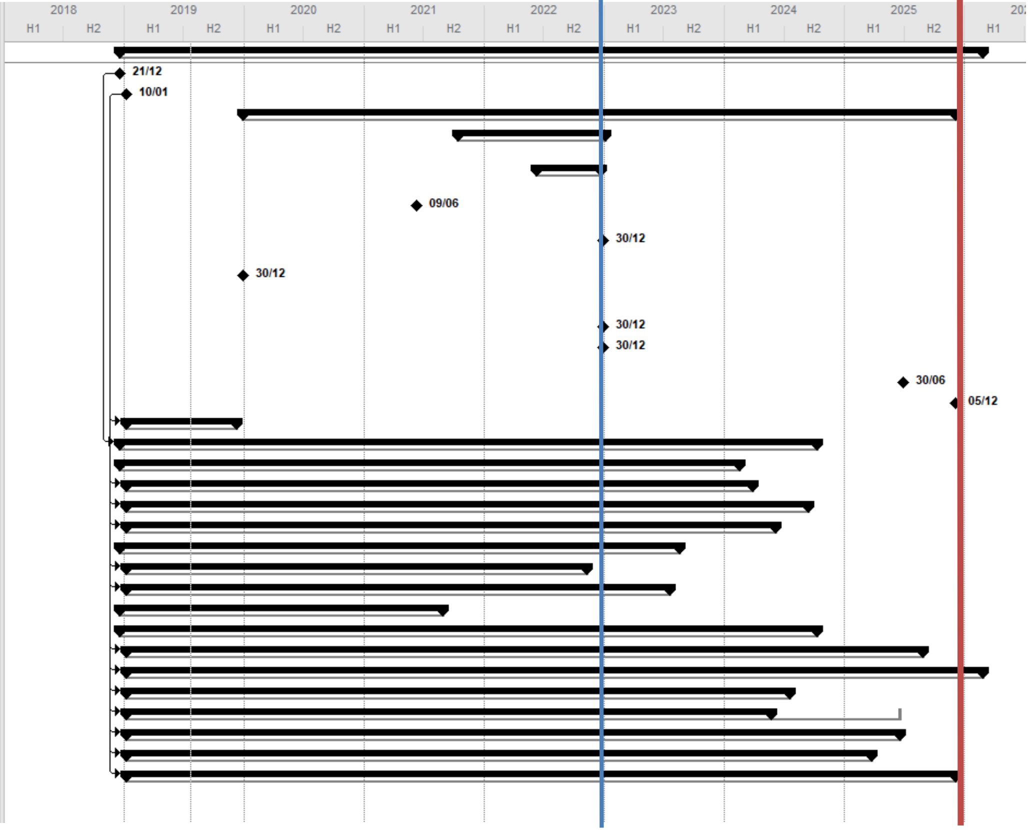
Planning & current status

DTT Project Planning

1/3 of the machine must be completed by 2022 (6 TFCs, 3 VV sectors, cryostat base, main hall, ...)

Commissioning of the machine shall be completed within 2025

Nome attività	Duration	Start	Finish	Predecessors
DTT-project	1874 d?	Fri 21/12/18	Wed 25/02/26	
Strands Market Survey launched	0 d	Fri 21/12/18	Fri 21/12/18	
DRM-01	0 d	Thu 10/01/19	Thu 10/01/19	
PROJECT MILESTONES	1550 d	Mon 30/12/19	Fri 05/12/25	
IDTT.M1 - DEMONSTRATION THAT REMAINING FABRICATION WILL BE COMPLETED AT LOW RISK	320 d	Wed 13/10/21	Wed 04/01/23	
IDTT.M2 - DEMONSTRATION THAT ASSEMBLY WILL BE COMPLETED AT LOW RISK	140 d	Thu 09/06/22	Wed 21/12/22	
IDTT.M3 - DEMONSTRATION THAT MACHINE CAN BE COMMISSIONED SUCCESSFULLY	0 d	Wed 09/06/21	Wed 09/06/21	
IDTT.M4 - DEMONSTRATION THAT THE FINANCIAL AND HUMAN RESOURCES ARE AVAILABLE FOR PROJECT COMPLETION	0 mo	Fri 30/12/22	Fri 30/12/22	
COM.M1 - IDTT FINAL DESIGN CONSISTEN WITH THE REQUIREMENTS FOR TESTING ALTERNATE EXHAUST COONCEPTS BASED ON THE KNOWLEDGE AT THE TIME	0 mo	Mon 30/12/19	Mon 30/12/19	
COM.M2 - DECISION ON THE FIRST IDTT DIVERTOR	0 mo	Fri 30/12/22	Fri 30/12/22	
COM.M3 - ASSESSMENT OF THE INTERFACES AND EXHAUST INFRASTRUCTURE AND DIAGNOSTIC OPPORTUNITIES IN IDTT	0 mo	Fri 30/12/22	Fri 30/12/22	
PRJ-MS-01 START OF INTEGRATED COMMISSIONING	0 d	Mon 30/06/25	Mon 30/06/25	949SS
PRJ-MS-02 FIRST PLASMA	0 mo	Fri 05/12/25	Fri 05/12/25	949FS+2 d
01 - PHY - PHYSICS	240 d	Thu 10/01/19	Wed 11/12/19	3SS
02 - MAG - MAGNETS	1514 d?	Fri 21/12/18	Wed 09/10/24	2SS
MAG-01 TFC	1345 d?	Fri 21/12/18	Thu 15/02/24	
MAG-02 CS COILS	1360 d	Thu 10/01/19	Wed 27/03/24	3SS
MAG-03 PF COILS	1480 d	Thu 10/01/19	Wed 11/09/24	3SS
MAG-04 CURRENT LEADS & CL BOXES	1410 d	Thu 10/01/19	Wed 05/06/24	3SS
MAG-05 STRANDS & CONDUCTORS	1214 d	Fri 21/12/18	Wed 16/08/23	
MAG-06 SC feeders	1000 d	Thu 10/01/19	Wed 09/11/22	3SS
MAG-07 In Vessel Coil CONDUCTORS	1180 d	Thu 10/01/19	Wed 19/07/23	3SS
MAG-08 QUENCH PRTECTION SYSTEM	700 d	Fri 21/12/18	Thu 26/08/21	
MAG-09 COLD TEST FACILITY	1514 d	Fri 21/12/18	Wed 09/10/24	
03 - MEC - MECHANICAL STRUCTURES	1730 d	Thu 10/01/19	Wed 27/08/25	3SS
04 - HCD - HEATING AND CURRENT DRIVE	1860 d	Thu 10/01/19	Wed 25/02/26	3SS
05 - AUXILIARY PLANT SYSTEMS	1440 d	Thu 10/01/19	Wed 17/07/24	3SS
06 - PSS - Power Supply Systems	1400 d	Thu 10/01/19	Wed 22/05/24	3SS
07 - BUI - Building Layout and Services	1680 d	Thu 10/01/19	Wed 18/06/25	3SS
08 - DCS DIAGNOSTICS AND CONTROL SYSTEMS	1619 d	Thu 10/01/19	Tue 25/03/25	3SS
09 - SLE SYSTEM LEVEL ENGINEERING	1800 d?	Thu 10/01/19	Wed 03/12/25	3SS



DTT Project Planning

- The project has been officially **financed and kicked-off.** The machine is being built at the **Frascati** Research Center of **ENEA** (Italy), where FTU is currently being de-commissioned and disassembled
- DTT Scrl legal entity (to manage DTT procurement and operation) has been settled

- To accomplish the **tight schedule the short term planning is**:
- **Strand supply partly assigned** (≈ **77 tons** of **Nb_3Sn**, ≈ **27 tons** of **NbTi**, ≈ **50 tons** of **Cu)**
- 10/2019: Conductor procurement tender
- Within the end of 2019: TF Winding Pack & Integration - TF case and structures (2 different tenders)
- Early 2020: PF coils / CS coils / SC current leads & Feeders Tenders

DTT Magnet System

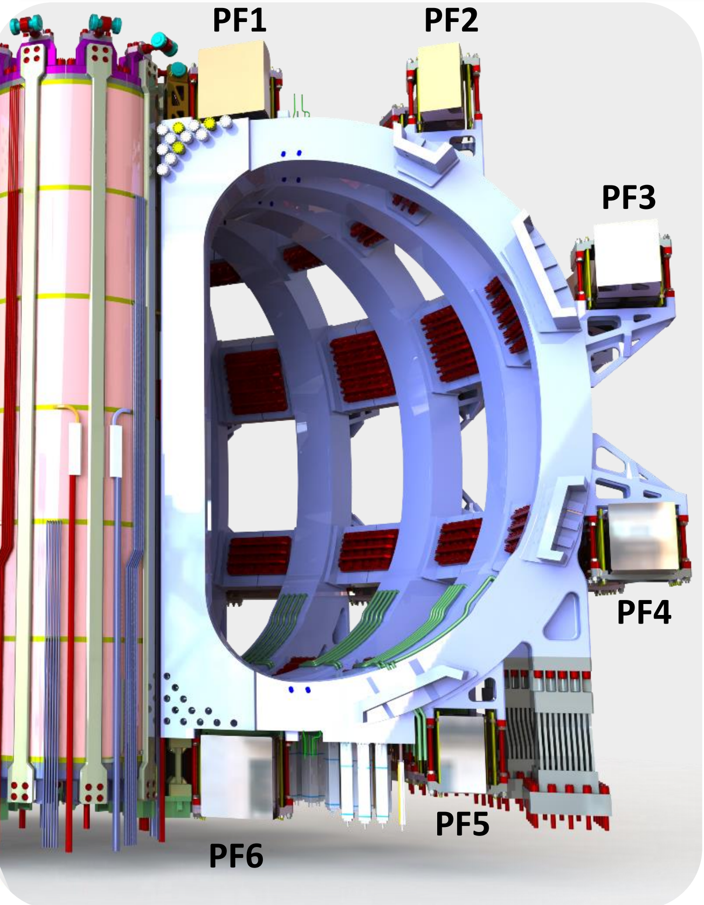
THANKS FOR YOUR ATTENTION!

Grazie!

https://agenda.enea.it/event/211/overview

Backup slides

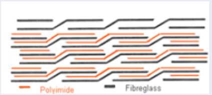
Poloidal Field Coils



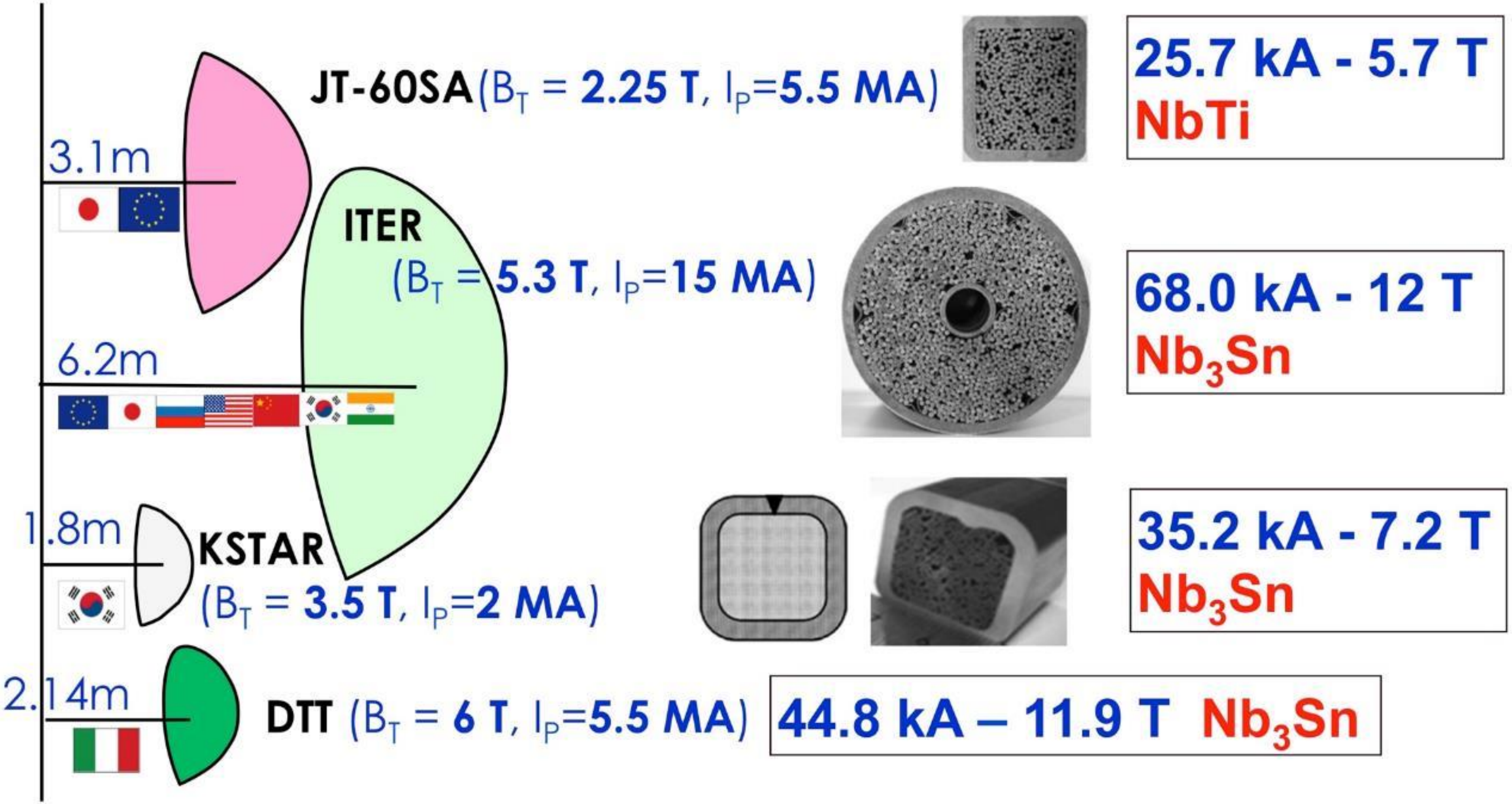
6 independent coils

On PF1&6 max B around 9T → Nb_3Sn strands

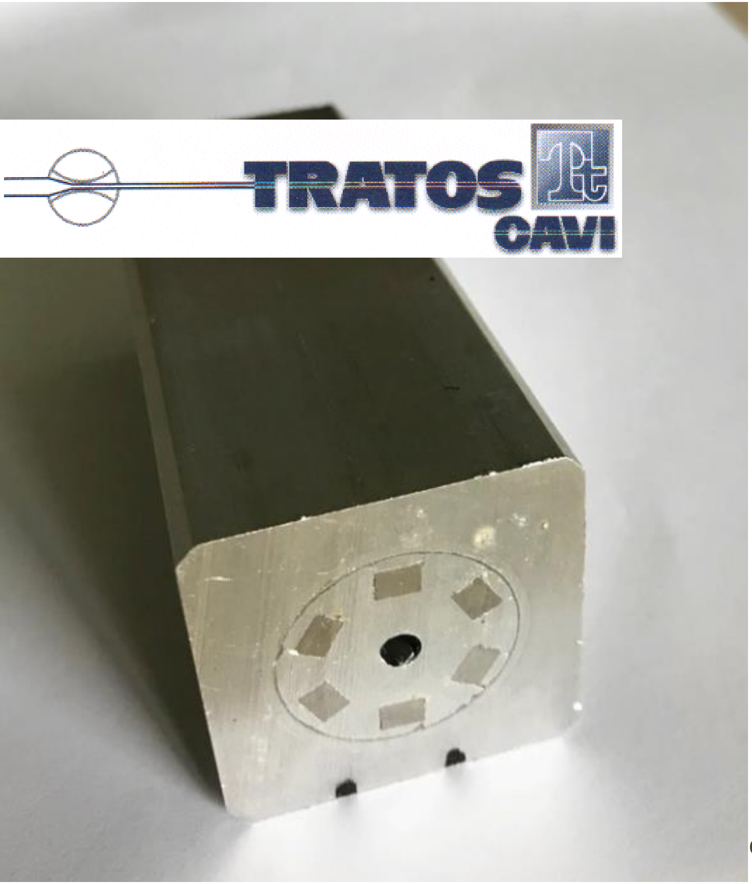
Designed identical in pairs for symmetry

Conductor	PF1/6	PF2/5	PF3/4
Radial Ext. Dim. (mm)	23.4	26.4	26.4
Vertical Ext. Dim. (mm)	28.2	27.7	27.7
Jacket thickness (mm)	3.0	3.0	3.0
Inner Corner Radius (mm)	3.5	3.5	3.5
Central Channel (OD/ID; mm)	7/5	7/5	7/5
Inter-turn insulation (mm)	• turn insulation should consist of layers of interleaved kapton and fiberglass. • 1.8mm turn insulation thickness is conservative, to have a big margin making a turn-to-turn and DP-to-DP insulation fault very unlikely • analyses to evaluate voltage values in normal and faulted conditions are on going  Polyimide Fibreglass *ITER PF like turn insulation layout*		
# SC strands (0.82mm)	180 (Nb_3Sn)	162 (NbTi)	324 (NbTi)
Strand Cu no-Cu ratio	1	1.9	1.9
# Cu strands (0.82mm)	216	324	162
Total strand number	396	486	486
Cabling sequence	[2x(2sc+Cu)+(sc+2Cu)]x(6+Cucore)x6 Cu core: 12 strand	(2Cu+1SC)x3x3x3x6	(1Cu+2SC)x3x3x3x6
Void fraction	29.9% (*)	30.2%	30.2%
LBO wrapping	(0.05 ± 0.01) mm x 12 mm, open area 50%, SS		
external wrapping	(0.05 ± 0.01) mm x 40mm, 50% overlapping, SS		
			

DTT wrt other superconducting Tokamaks



Central Solenoid modules



ENEA-TRATOS Aluminum slotted Core HTS CICC

Most recent concept

External high-strength Aluminum-alloy jacket.

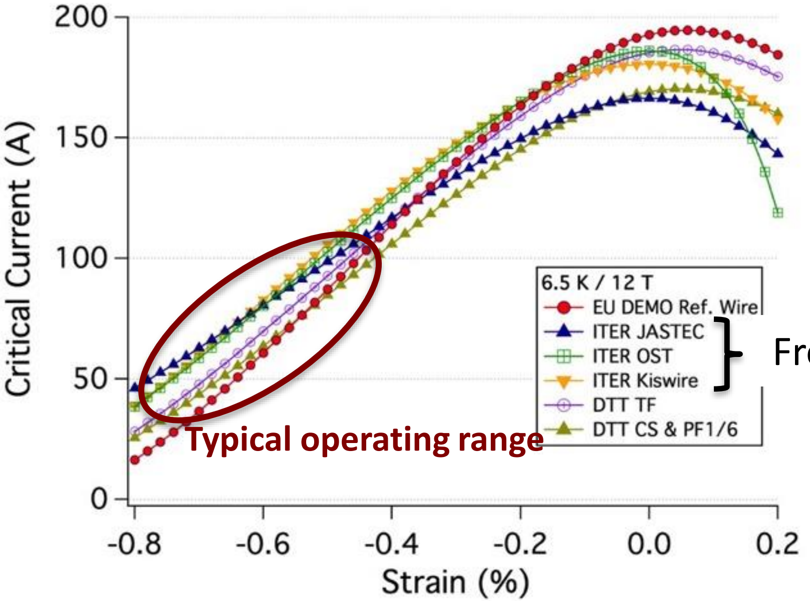
L = 36 mm

6 slots for twisted stack of s.c. tapes

30 – 35 kA current in 18 T – 20 T field
(to be tested)

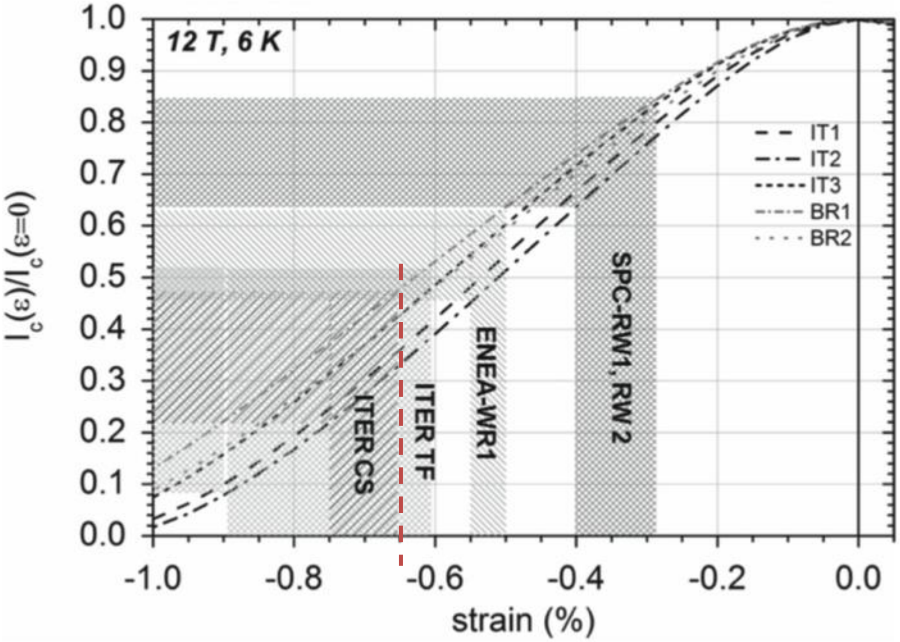
S.C. components design rationale: STRANDS

- **Nb_3Sn** performance depends (strongly) on strain state and sensitivity is hard to predict;
- **Nb_3Sn** wire inside Cable-in-Conduit conductors (CICC) is subject to **strain:**



From: Breschi_SUST 2017

S.C. components design rationale: CICC



Uglietti_SUST 2018