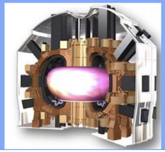
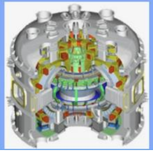
1st ENEA-KFE Remote Meeting on bilateral collaboration activities

Thursday, November 28
Teams videoconference





DTT superconducting magnet system: design challenges, fabrication route and testing

GIAN MARIO POLLI

DTT S.c.a r.l., ENEA NUC, C.R.Frascati

On behalf of DTT team

1° ENEA-KFE remote meeting on bilateral collaboration acitvities

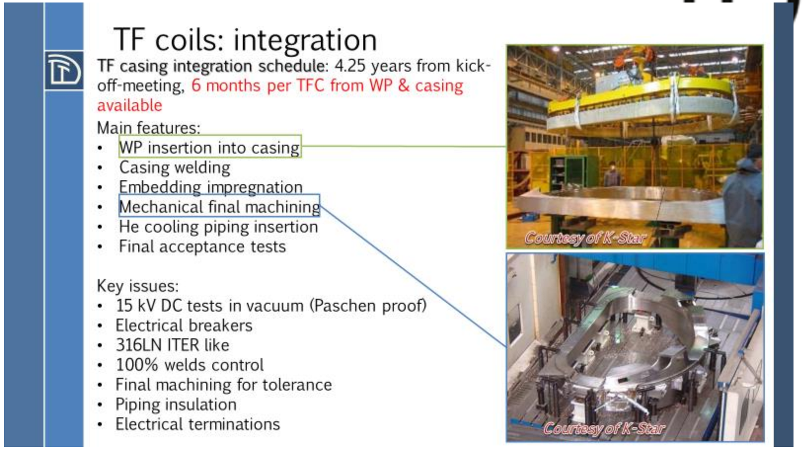
28/11/2024

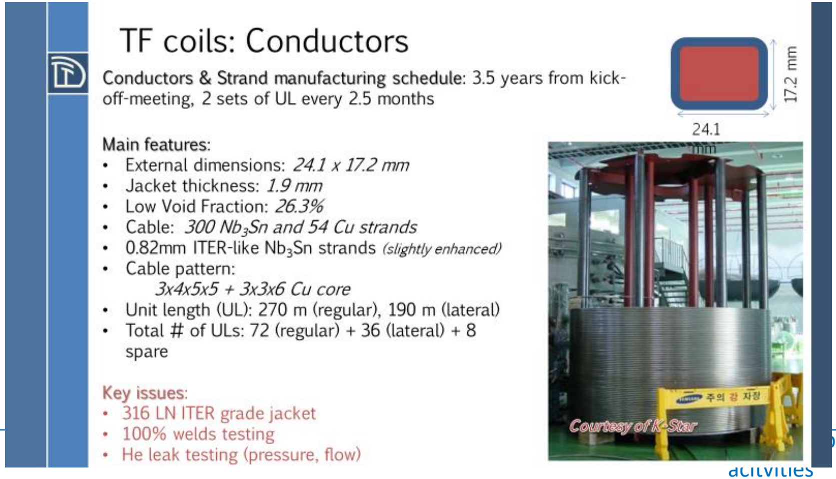
Teams videoconference

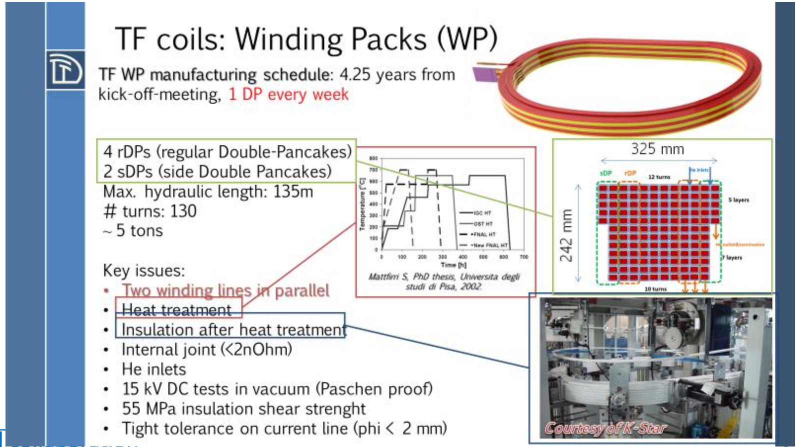
Outline

- Introduction: KSTAR a source of inspiration
- DTT magnet design challenges
- Fabrication route and prototyping
- Testing and assembly
- Concluding remarks

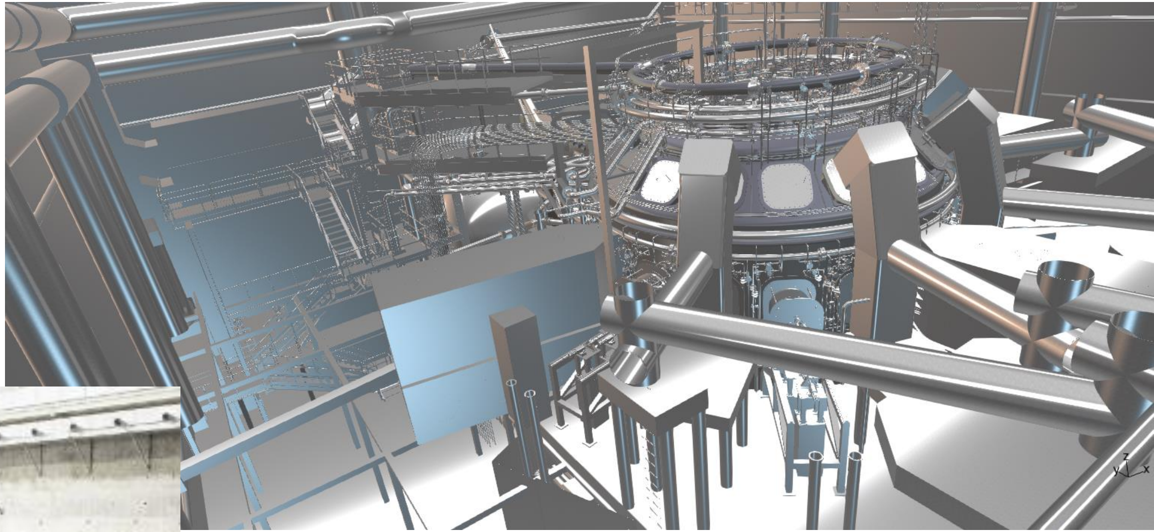
A source of inspiration

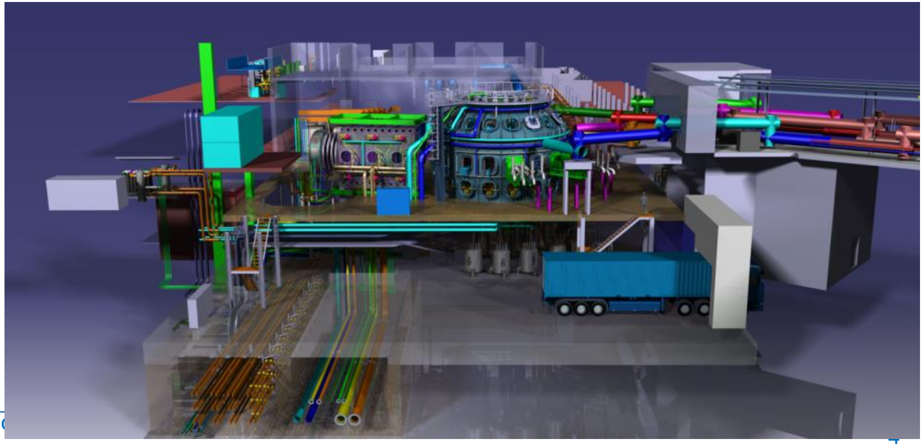






A source of inspiration



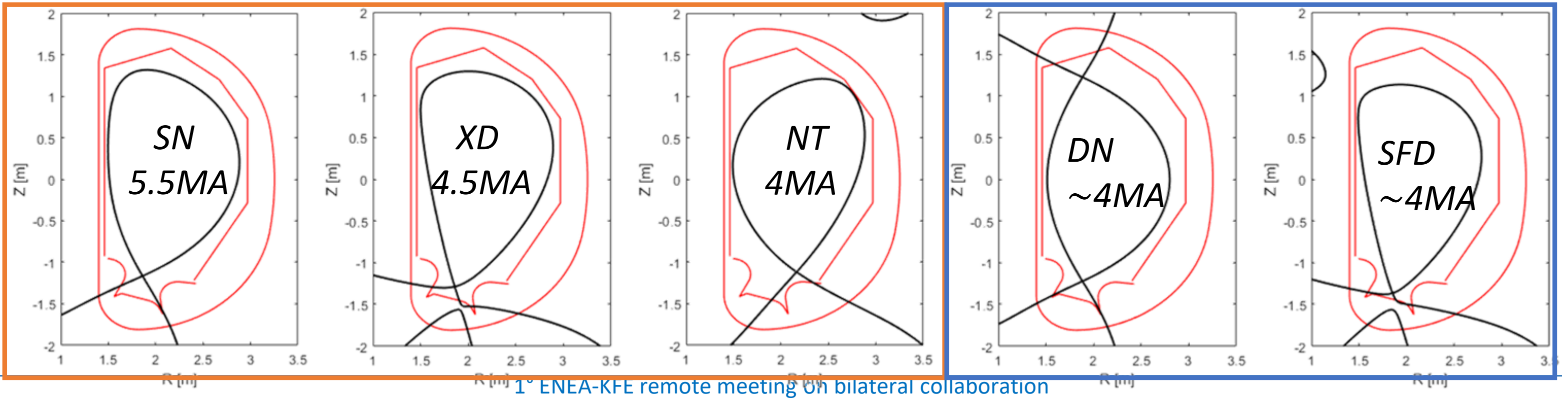


Primary design requirements

The design of DTT magnet system was carried out under many demanding requirements:

- High plasma current (up to 5.5 MA)
- High toroidal field (6 T)
- Long plasma pulse duration (up to 100 s)
- Relatively high neutron heating on superconductors
- Compact medium-size machine
- Wide and still evolving research program
- **Largest possible flexibility in terms of achievable plasma configurations**

DTT reference scenarios



DTT future scenarios not optimized

SC Magnet System Design

It has been performed basing on the state-of-the-art of SC magnets available.

Due to tokamak size and requirements, challenges have been faced to increase performances, in particular for CS.

The design of the magnet system was assessed in the following conservative conditions:

- **No plasma** (i.e. after a plasma disruption event)
- **& PF coils increased** according to the current induced by plasma quenching and possible position & shape control request, in any instant of the reference scenarios

Most demanding conditions have been found in DN and XD configurations

High engineering current densities; high range of SC operation; high stress in some areas of SS and insulation; flexibility in operations resulting in contrasting requirements depending on plasma configurations.

Parameter for TF coils	DTT	ITER	JT-60SA	K-STAR
SC material adopted	Nb_3Sn	Nb_3Sn	NbTi	Nb_3Sn
I_{op} (kA)	42.5	68.0	25.7	35.2
B_{peak} (T)	**11.9**	11.8	5.7	7.2
Min T_{margin} (K)	>1.2	0.7	1.2	1.1
J_E on conductor (A/mm^2)	**67**	45	58	54
J_E on WP (A/mm^2)	**56**	18	36	?

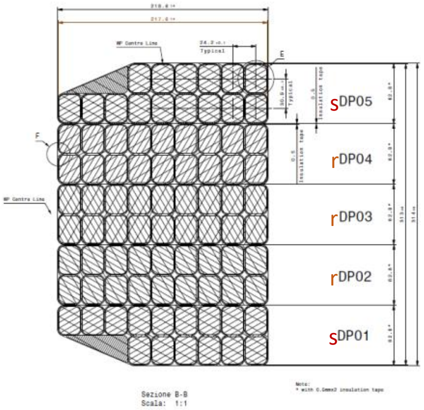
Toroidal Field coils

(Project Leader: A. Di Zenobio, ENEA)

TF coils confine plasma inside the chamber
6 T are also a requirement from ECR heating

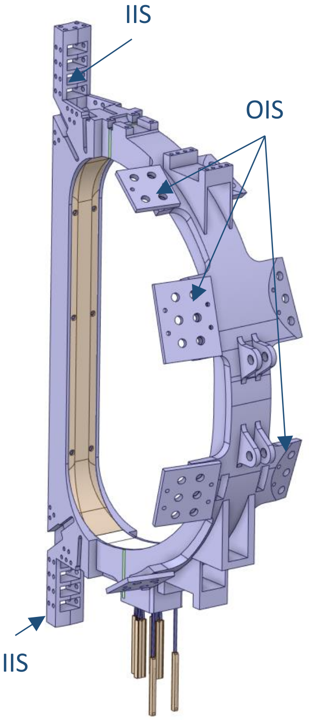
18 Toroidal Field coils
- **Nb_3Sn** CICCs
- B_{peak} = 11.9 T; I_{op} = 42.5 kA
- ΔT_{margin} > 1.4 K
- to provide 6.0 T @2.19m

Winding Pack

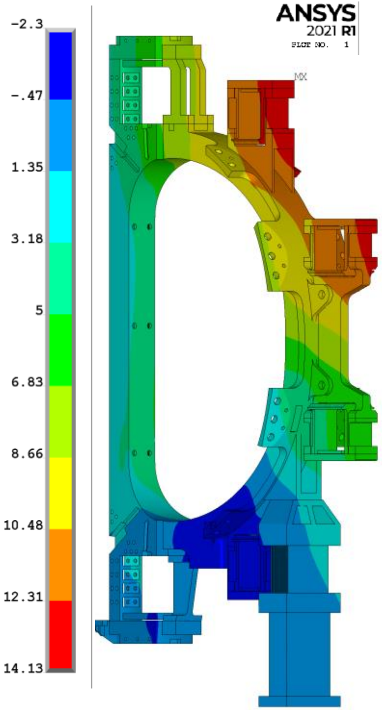


2 side DPs + 3 central DPs
(190m and 220m ULs)

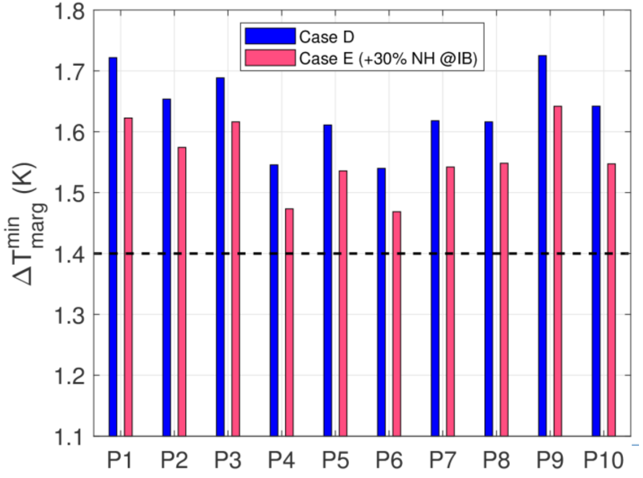
Casing



Structural Analyses



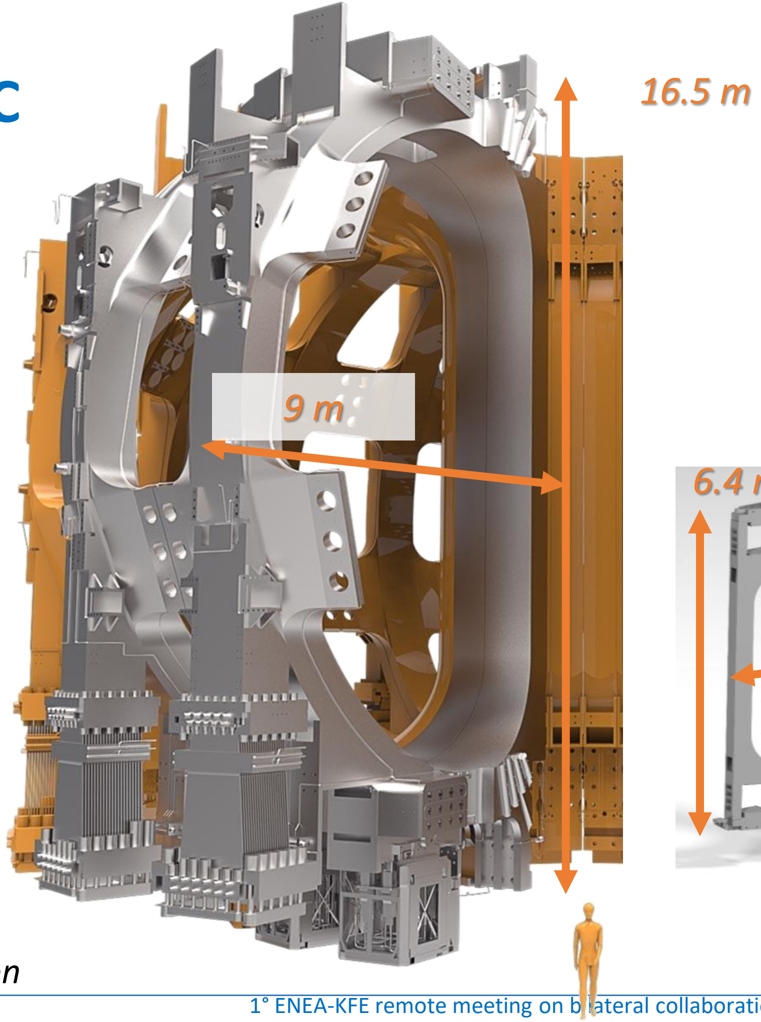
Thermal-Hydraulic Analyses

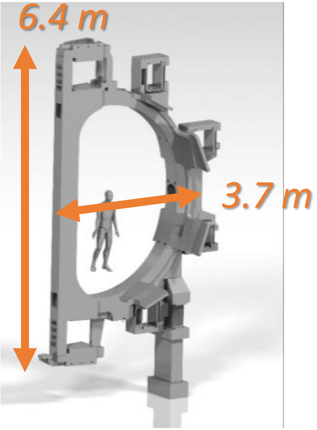


Analyses are following updates of plasma scenarios and optimization of procurement (R. Bonifetto, POLITO)

DTT vs ITER TFC

ITER TFC:
Nb3Sn coils
Bmax = 11.8T
I_turn=68 kA
Turns=134
R=6.2 m
B_plasma=5.3 T





DTT TFC:
Nb3Sn coils
Bmax = 11.9T
I_turn=42.5 kA
Turns=84
R=2.19 m
B_plasma=5.85 T

Courtesy of ITER Organization

SC Magnet System Design

Current status

TF coils: completed	Procurements are on-going. Further analyses were performed to optimize and/or verify the production choices and the compliance with new plasma scenarios.
PF coils: completed	Engineering design is completed. Tender is on-going.
CS: under review	Reference conceptual design is completed. Alternative designs are being investigated for operation risk minimization and plasma scenarios optimization. Tender to be launched in 2025.
SC Feeders: on-going	Conceptual design is completed. Further thermal-hydraulic and FEM analyses are on-going. Tender to be launched in 2025.
Cryoplant: on-going	Conceptual design is completed. Collaboration with CEA to complete design, integration, technical specification. Tender to be launched in 2025.

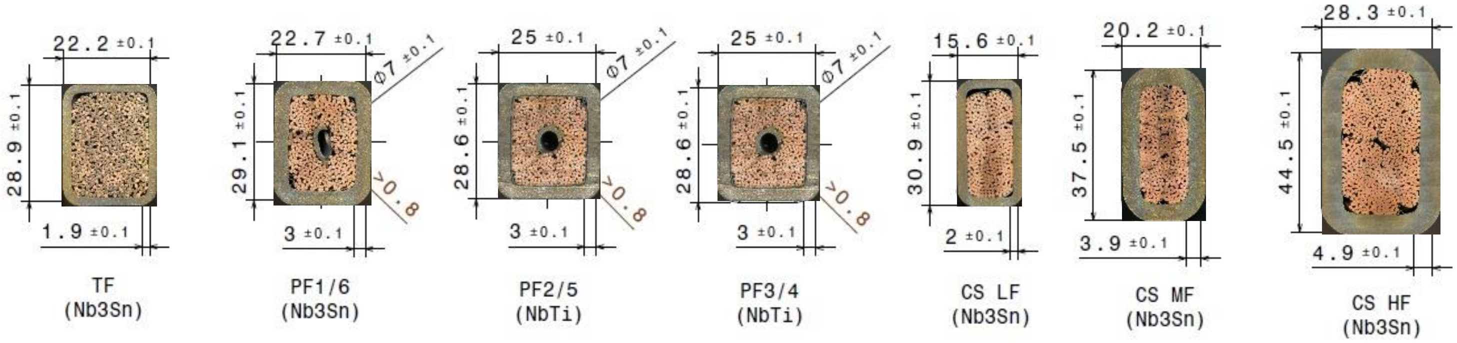
Superconducting Strands

0.82 mm wires	Min. Critical Current (requested by DTT)	Min. Critical Current (guaranteed by the awarded supplier)	Awarded Supplier	Delivered amount (tons)
DTT TF (Nb_3Sn)	**285 A** (4.2 K; 12 T; 0% strain)	**320 A** (4.2 K; 12 T; 0% strain)	KISWIRE KAT	*55 completed*
DTT CS & PF1/6 (Nb_3Sn)	**270 A** (4.2 K; 12 T; 0% strain)	**--**		*0/18,6 (contract withdrawn)**
DTT PF2-5 (NbTi)	**500 A** (4.2 K; 5 T)	*confirmed*	FURUKAWA ELECTRIC GROUP	*27.5 completed*

** = new tender on-going*

Conductors

7 different CICC layouts are foreseen for the 3 sets of magnets with Unit Lengths going from 195m up to 780m



Copper dummies have been manufactured for all the 7 conductors
Super-dummies and SULTAN samples have been prepared for the TF, PF2 to PF5 ones

Conductors

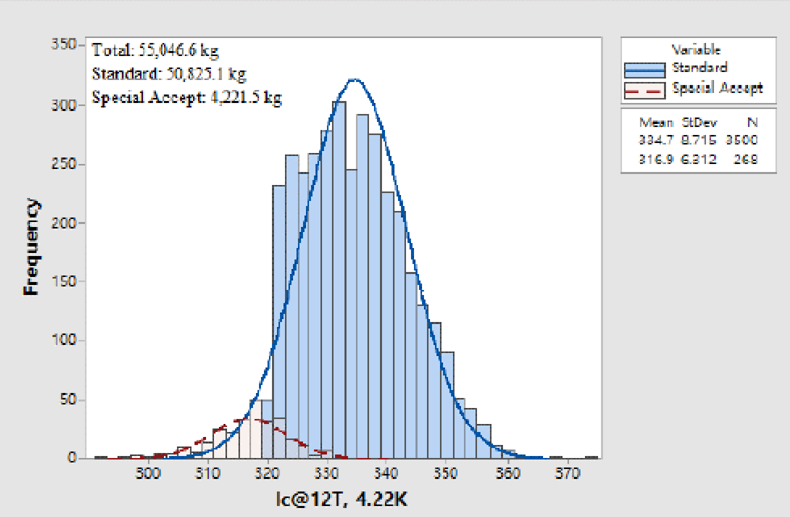
The first **50 conductor Unit Lengths for TF** have been delivered to coil manufacturer ASG

Strands - TF

Strand measurements were repeated in ENEA SC labs for verification, over a randomly selected samples population.
Inspectors have been also sent to suppliers for QA verifications.

0.82 mm wires	Min. Critical Current (requested by ENEA)	Min. Critical Current (guaranteed by the awarded supplier)
DTT TF (Nb_3Sn)	**285 A** (4.2 K; 12 T; 0% strain)	**320 A** (4.2 K; 12 T; 0% strain)

Wire design: 19 Sub-elements of 180 Nb filaments, each with a Sn-Ti core, 18 Sn-Ti spacers between the sub-elements surrounded by a pure Ta diffusion barrier.
Cu:nonCu = 1
Wire diameter = 0.82mm
Wire coating: Cr



Total quantity of Nb_3Sn strand (55 tons) has been delivered to ENEA.

It is currently being cabled by conductor manufacturer.

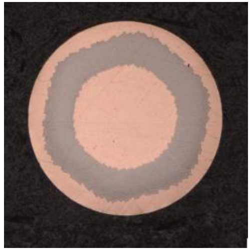
<10% of non-conform strands have been accepted, as they are above the original Ic minimum requirement (used mainly for super-dummies).

Strands - PF

	Min. Critical Current (requested by DTT)
DTT PF2-5 (NbTi)	**500 A** (4.2 K; 5 T)

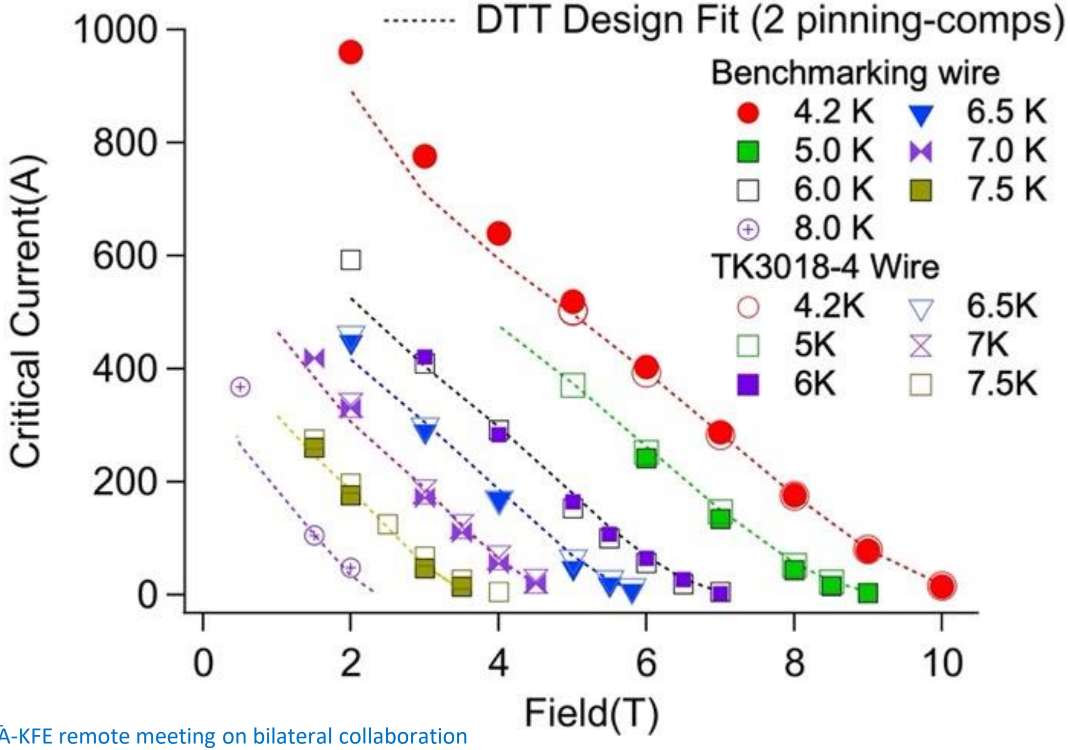
«Standard» requirements for Nb-Ti wires

Wire design: Nb-Ti filament bundles.
Cu:nonCu = 1.9
Wire diameter = 0.82 mm
Wire coating: Ni



ENEA **VTI** measurements

performed for a **reliable scaling law** for analysis of coil in operation



TF SULTAN qualification tests at Swiss Plasma Center

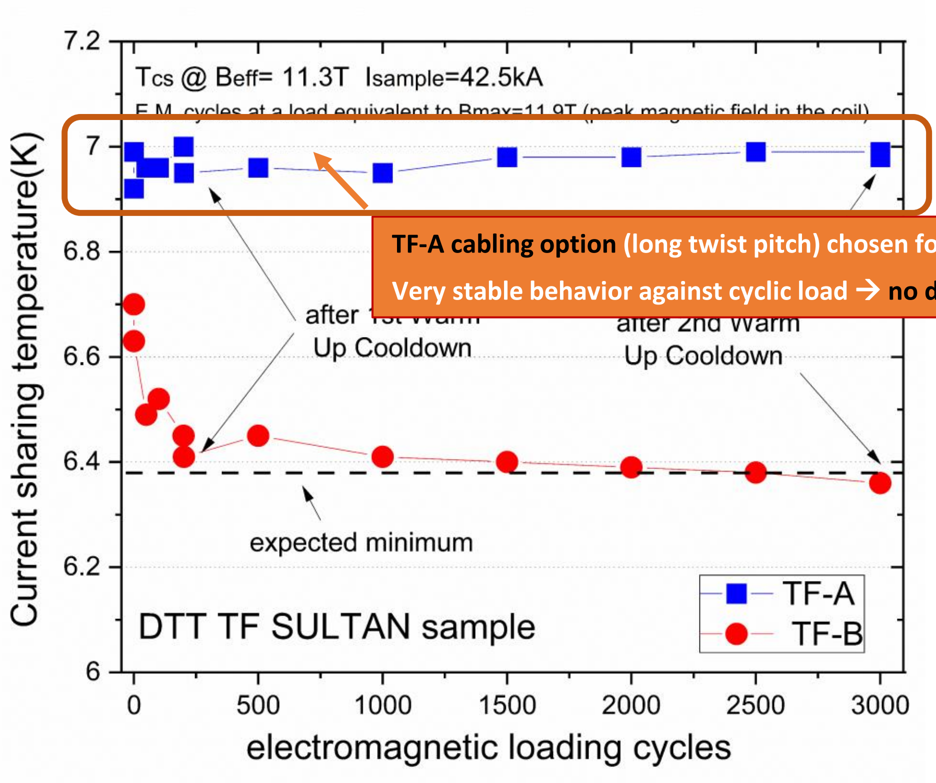
Parameter	DTT TF Q1 (Nb_3Sn)
I_{op} / B_{max}	**42.5 kA / 11.9 T**
# Sc strands/diameter	420/0.82 mm
# Cu strands/diameter	180/0.82 mm
Cable twist pitches (mm)	**TFA: 100/110/125/140/300** TFB: 82/135/180/220/290
CICC ext. dimensions	28.8x22.1 mm
Jacket thickness	1.9 mm
VF in bundle	26.7%

ε_{eff} from tests (TF-A): -0.56%

ε_{eff} adopted in design: -0.65%

TF-A sample is well above the black dashed lines which represents the DTT coils design acceptance line.

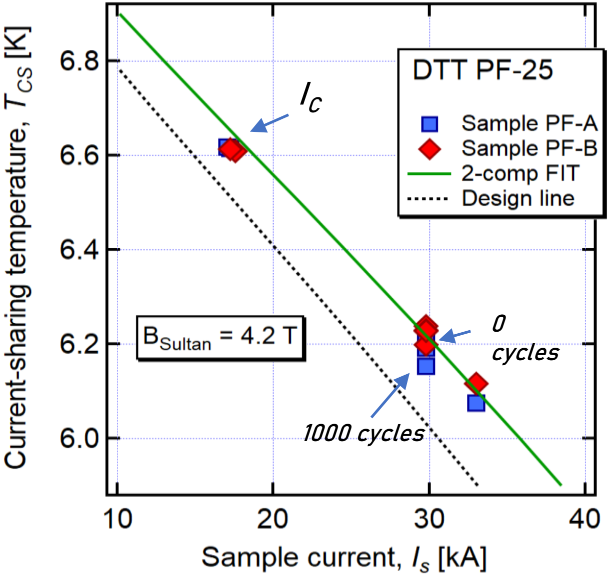
TF-B shows an initial degradation that brings the performance to minimum, but then is stable.

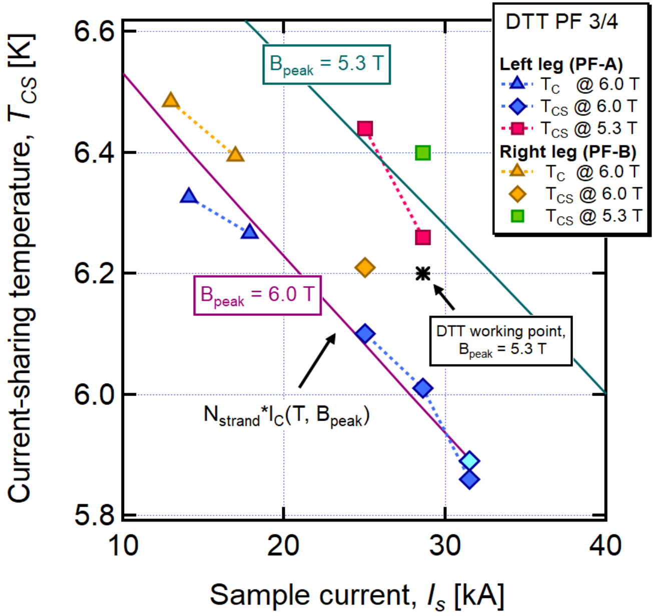


TF-A cabling option (long twist pitch) chosen for production

Very stable behavior against cyclic load → no degradation

PF SULTAN qualification tests at Swiss Plasma Center





Parameter	DTT PF2/5 (NbTi)	DTT PF3/4 (NbTi)
I_{op} / B_{max}	**29.8 kA / 4.2 T**	**24.9 kA / 5.3 T**
# Sc strands/diameter	162/0.82 mm	324/0.82 mm
# Cu strands/diameter	324/0.82 mm	162/0.82 mm
CICC external dimensions	25.1x28.6 mm	24.9x28.5 mm
Jacket thickness	3.0 mm	3.0 mm

Both PF2/5 and PF3/4 samples are well above the expected values at the Sultan test conditions.

TF coil magnet system: supply chain

completed

Kiswire + LUVATA

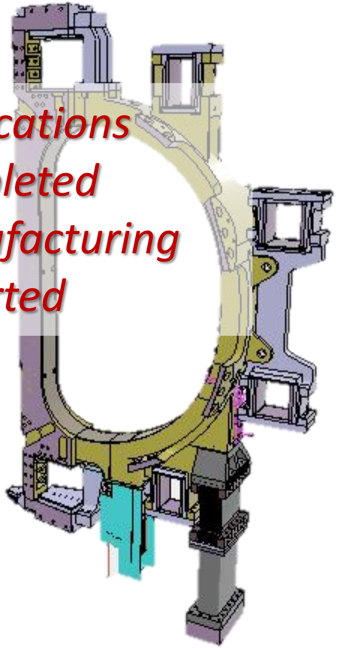
55 tons Nb_3Sn strands

31 tons Cr coated Cu strands

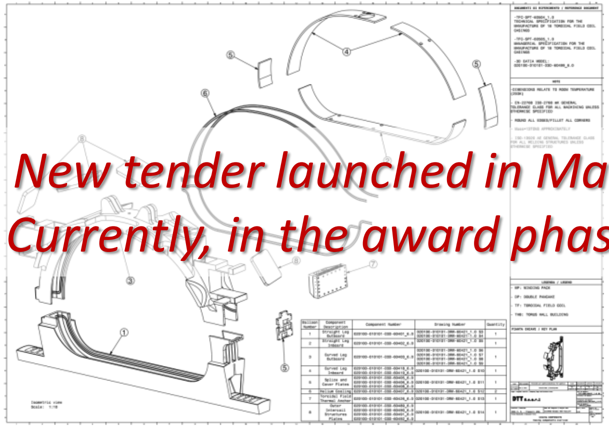
In production
(9 sets delivered)

ICAS

20,4 km of conductors (95 unit lengths)

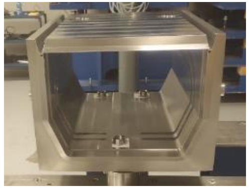


Qualifications completed
WP manufacturing started



New tender launched in May
Currently, in the award phase

18 Casing components (~360 tons of 316LN material delivered)



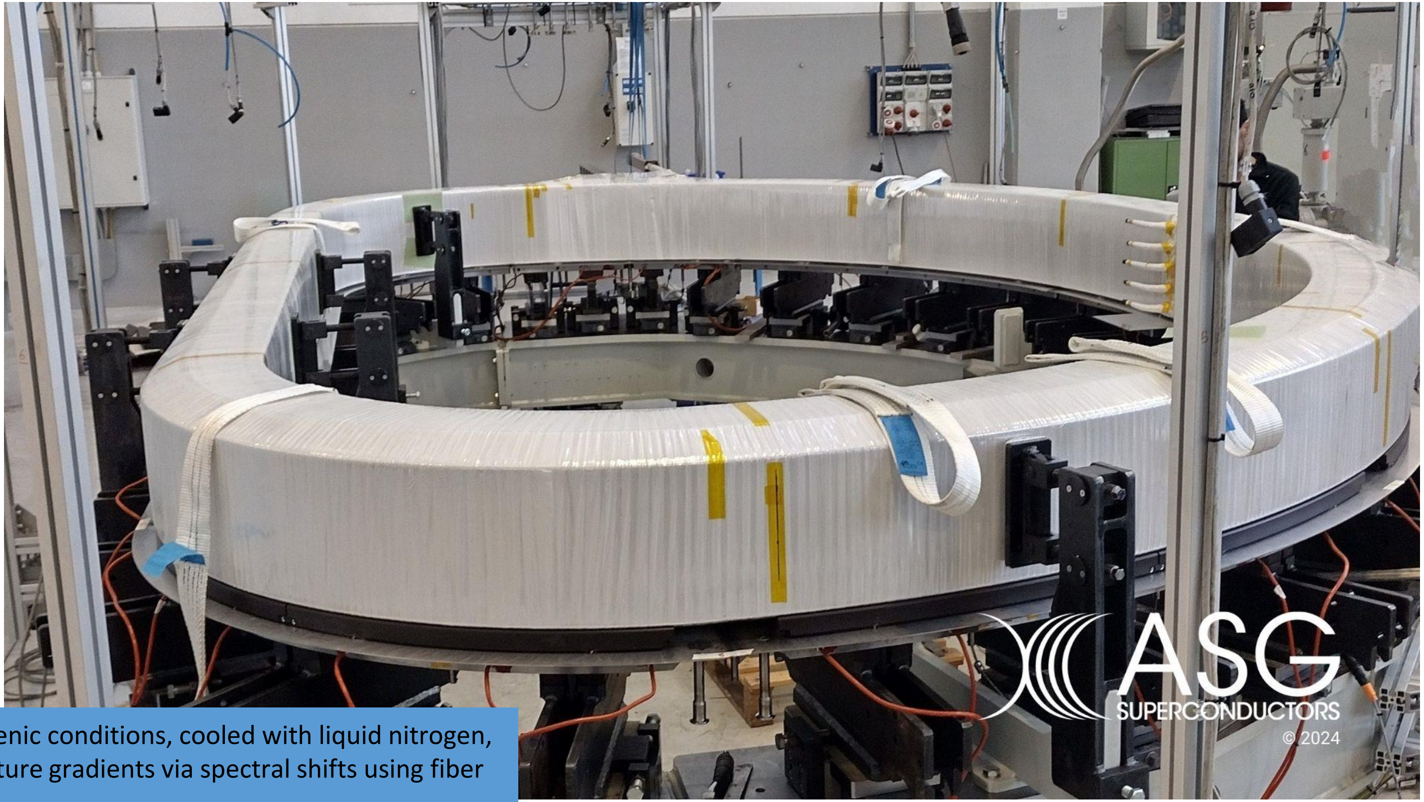
18 TF modules

ASG SUPERCONDUCTORS

Courtesy of G. Ramogida & MAG team

TF coil winding

- WP1: mounted on the impregnation frame on 15/11/24
- WP1: ready before the end of 2024
- WP2: all DP wound; joint between DP on-going
- WP3: DP1 in winding



The mock-up was subjected to cryogenic conditions, cooled with liquid nitrogen, while monitoring strain and temperature gradients via spectral shifts using fiber optic technologies.

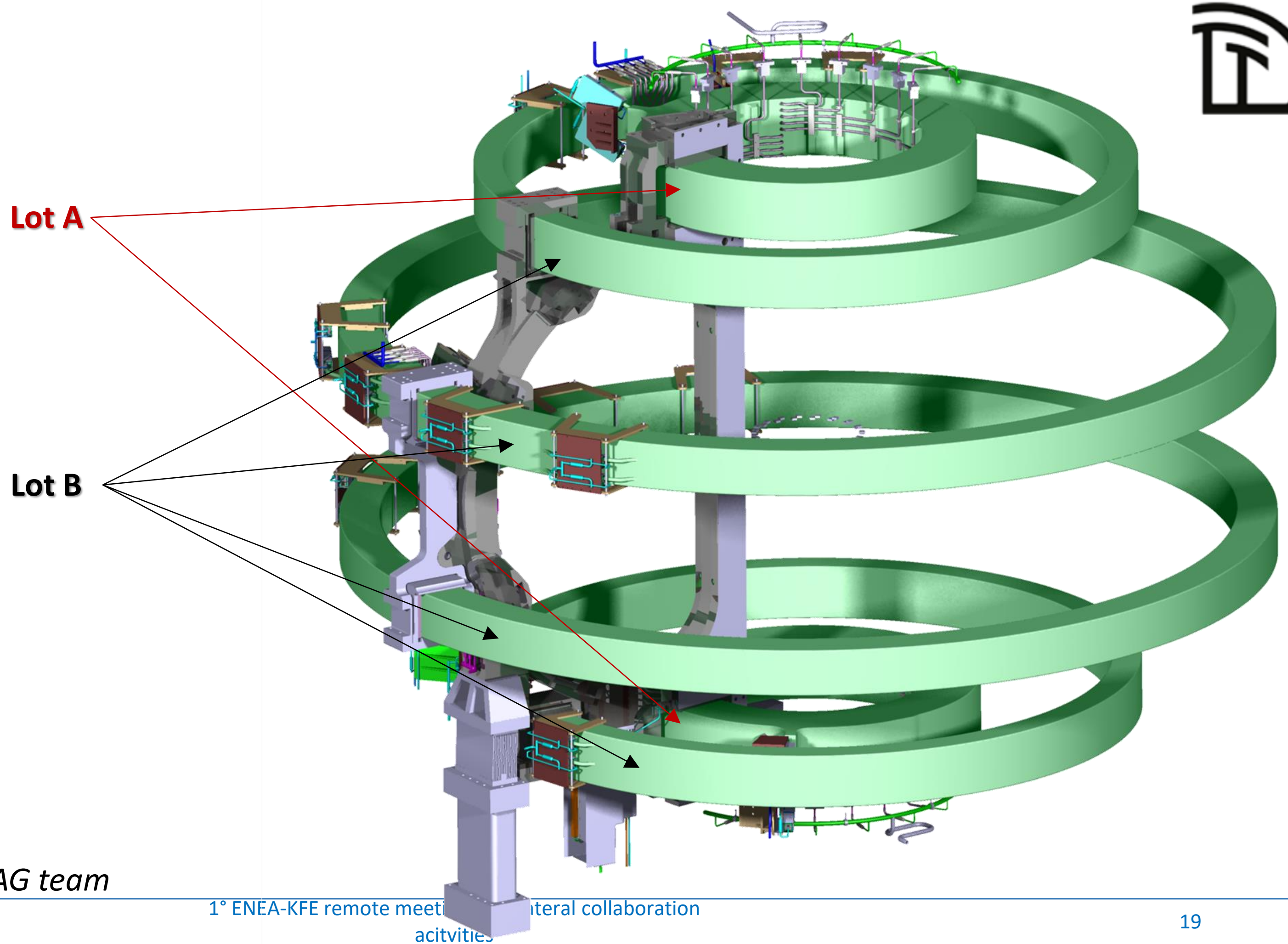
PF system

PF1/6 – Nb_3Sn:
- Bmax = 9,1 T
- I=10,2 MAt (Nt=360)
- M=15 ton
- D = 3,3 m

PF2/5 – NbTi:
- Bmax = 4,2 T
- I=4,3 MAt (Nt=160)
- M=16 ton

PF3/4 – NbTi:
- Bmax = 5,3 T
- I=5,6 MAt (Nt=196)
- M=28 ton

Call for tender on-going
Deliveries from 2026



Courtesy of G.Ramogida & MAG team

CS status

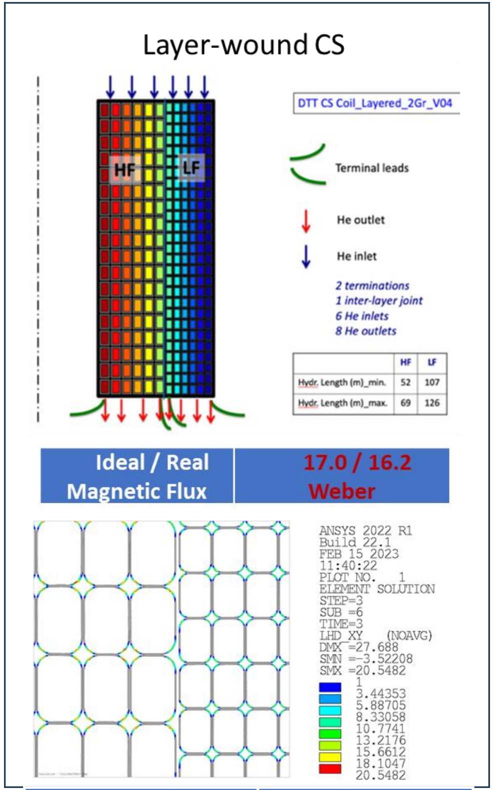
Two reference solutions have been developed and brought to an equivalent conceptual design level:

- Layer-wound
- Pancake-wound

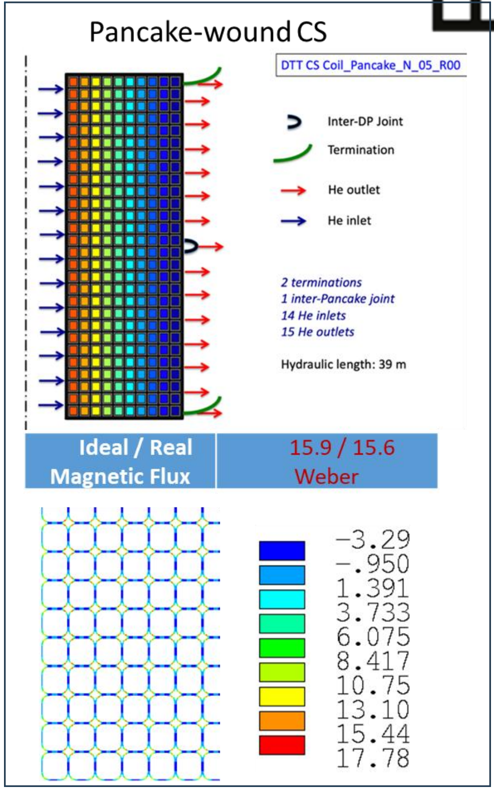
Both solutions present the same criticality wrt the insulation at the corners of the CICC (and similar to the other past projects).
According to the standard design criteria the insulation should fail due to the excessive load.

The strategy implemented by DTT, following past projcets, consists in:

- Producing two mock-ups
- Testing the mockups in:
    - cryogenic conditions
    - Under cyclic loading
- Scope: assess the electrical insulation during and at the end of the tests



Max. inter-turn volt. @ breakdown(***)	640 V (between layers 11 and 12)



Max. inter-turn volt. @ breakdown(***)	195 V (between pancakes 14 and 15)

CS issues

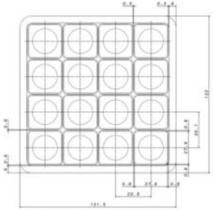
JT-60SA

JT-60SA | Euratom | 6

Turn Insulation

- Share stress in CS turn insulation is beyond LHD criteria.
- Mechanical test is required as demonstrated by US

ITER CS Test sample by US
N. Martovetskey (US IPO)



JT60SA CS test sample

K. Yoshida, et al. Third JT-60SA Technical Coordination Meeting at Naka Japan, 9-12 September 2008

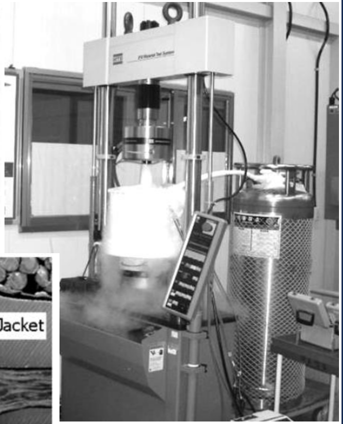
KSTAR

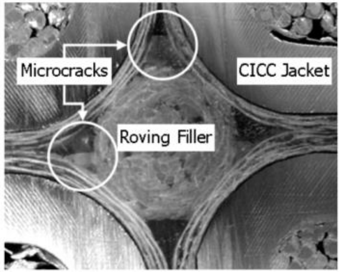
Mechanical Test of Stacked 4 × 4 CICC for the KSTAR Central Solenoid

H. K. Kim,* J. W. Sa, H. T. Kim, C. H. Choi, H. L. Yang, K. R. Park, K. S. Lee and J. S. Bak
National Fusion Research Center, Daejeon 305-333

Y. D. Kim
Doosan Heavy Industries Co., Ltd., Changwon 641-892

(Received 29 August 2005)





TPX

UCRL-CR-121739-U01.5

TPX Insulation & Impregnation R&D - 3x3 Test Report Electrical Insulation

J. F. Roach and W. M. Urban
Advanced Electromechanical Systems Department

D. Hartman
Everson Electric Company

August 4, 1995

TPX 14-950630-WEC-FRoach-02

Figure 7-3 Sample A1 - Section 2 - After 19 Thermal Cycles.

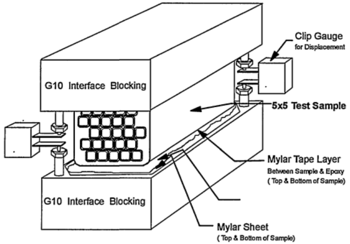


Figure 7-4 CS 5x5 Sample Prepared for Testing

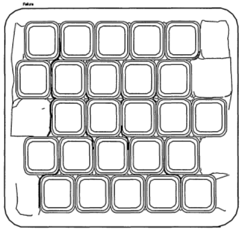


Figure 7-14 Characterization of cracking in - sample A1 - section 5

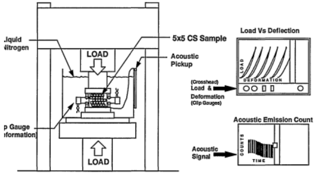
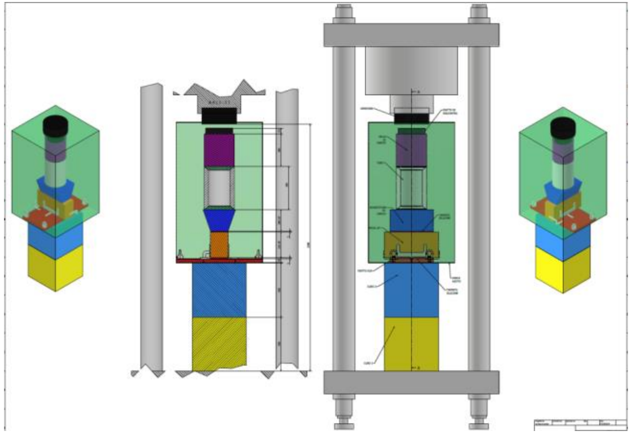


Figure 7-5 Test Setup Schematic

CS system

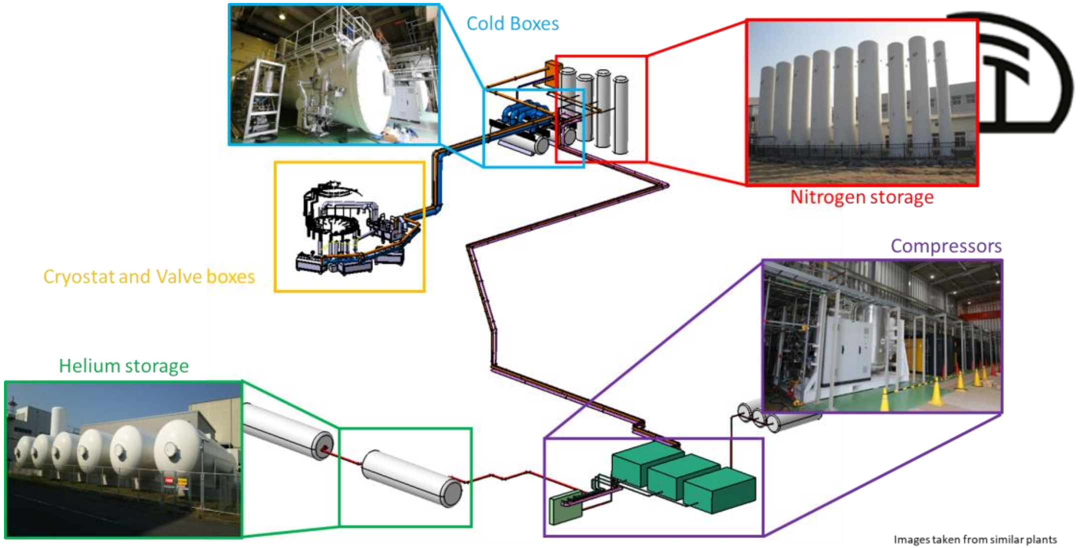
- Mock-ups for testing insulation strength under relevant cyclic loading at 77K are under fabrication
- Heat treatment done including de-sizing in O2 atmosphere @ 450°C
- Impregnation will be before the end of the year

- Procurement procedure for hydraulic and control system for Giunone Facility in CR ENEA @ Brasimone on-going -> testing Q1-2025



Cryogenic system:

- S-DRM under preparation;
- Tender to be published in early 2025



Heat loads during POS

LOOP	Utilities	DP (bar)	$\dot{m}$ (g/s)	T_{in}/T_{out} avg (K)	Eq. Heat load @4.5K (W)	Eq. pressure drop load @4.5K (W)	Circulator dissipation load @4.5K (W)	Total equivalent load @4.5K
1	- TF WP - TF case + thermal anchor - TF feeders	1.2 (5.4-4.2)	825	4.3/4.98	2170	513	1088	**3771**
2	- PF coils - CS coils - PF feeders - CS feeders	1 (5-4)	788	4.3/[illegible]	1277	348	866	**2491**
3	- Cryopanels	0.5 (5-4.5)	180	4.5/4.8	214	40	-	**254**
4	- Thermal shield - Cryop. chevron baffle - Th. Anchor GS TF + VB/CTB thermal shield	2 (15-13)	443	80/100	1655	606	-	**2261**
5	- CL TF - CL PF - CL CS	3 (4-1)	71.87	50/300	1638	947	-	**2585**
			48	50/300	1094	632	-	**1726**
					TOTAL	**11362 W 10503 W (lower $\dot{m}$ on CL)**		

Heat loads during BAK

LOOP	Utilities	Average heat load during POS (W)	Average heat load during LBAK (W)	Average heat load during SBAK (W)	DP (bar)	$\dot{m}$ (g/s)	T_{in}/T_{out} avg (K)	Total equivalent load @4.5K
1	- TF WP - TF case + thermal anchor - TF feeders	1952		**1350**	0.3 (5.4-4.2)	50	5/8	**1065**
2	- PF coils/feeders - CS coils/feeders	1055		**1160**	0.3 (5-4.5)	40	5/8	**856**
3	- Cryopanels	185	**0**	**0**	-	0	-	**-**
4	- Thermal shield	41420	**50000(1)**	**100000(2)**	2 (15-13) (2)	330(2)	80/140(2)	**3280(2)**
	- Cryop. chevron baffle - Th. Anchor GS TF + VB/CTB thermal shield		**6750**	**6750**	1 (15-14)	101	80/100	**444**
5	- CL TF - CL PF - CL CS	93318	**51935**	**51935 (0)**	3 (4-1)	40	50/300	**1438**
					TOTAL	**7083 W**		

(1) Port and Vacuum Vessel temperature 110°C
(2) Port and Vacuum Vessel temperature 200°C

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Frascati Coil Cold Test Facility

ENEA, in parallel to DTT, is also preparing a dedicated cryogenic test facility in CR Frascati (Rome), where all the Nb_3Sn coils of DTT will be tested in cryogenic conditions and full current. The first contract for the procurement of the cryostat and the current leads has been awarded in June 2023. The facility will be ready for testing at the end of 2025/start of 2026 in time for the first TF coil.

Courtesy of ENEA & MAG team

Courtesy of G. Ramogida & MAG team

Frascati Coil Cold Test Facility

In the facility all the Nb3Sn coils will be tested as a QA measure in order to assess:

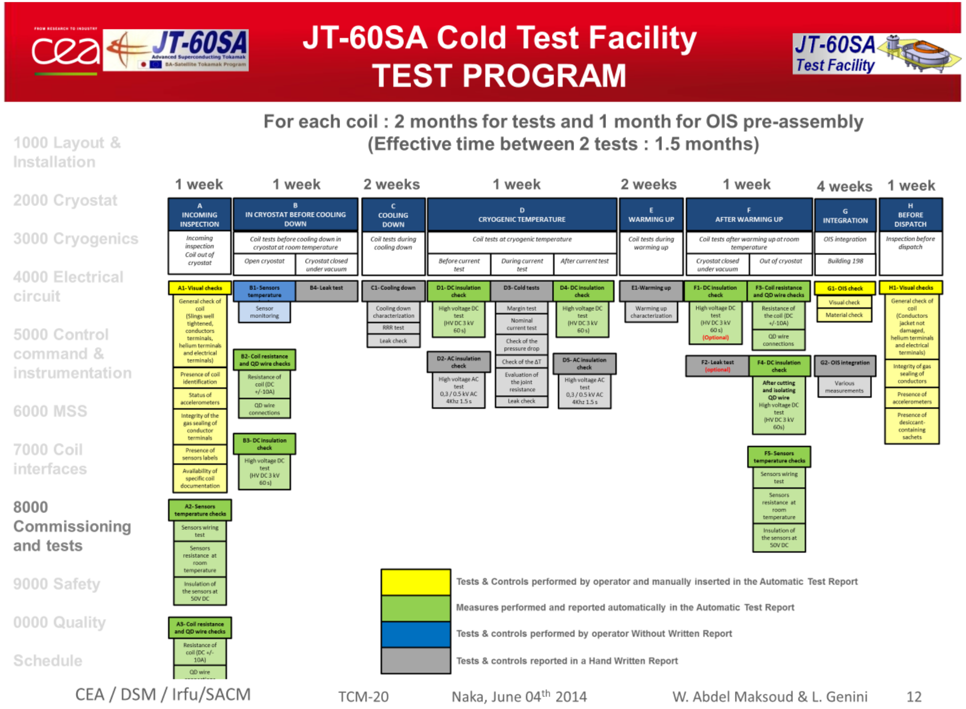
- Magnets performance characterization
- Superconducting performance homogeneity through the manufacture
- Testing of insulation in cryogenics

Tests of:

- 18 TF coils
- 7 CS coils
- PF6 and PF1 (plus a dummy coil)

All the tests shall be performed using the TF power supply, so only fast discharges will be possible during the test of the PF and CS coils

Test program inspired by JT-60SA TF facility

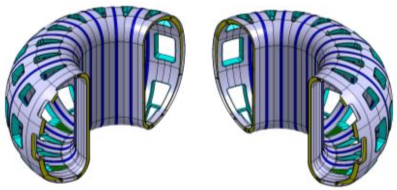


Courtesy of ENEA & MAG team

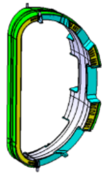
Courtesy of G. Ramogida & MAG team

Assembly procedure

TF coils and Vacuum Vessel

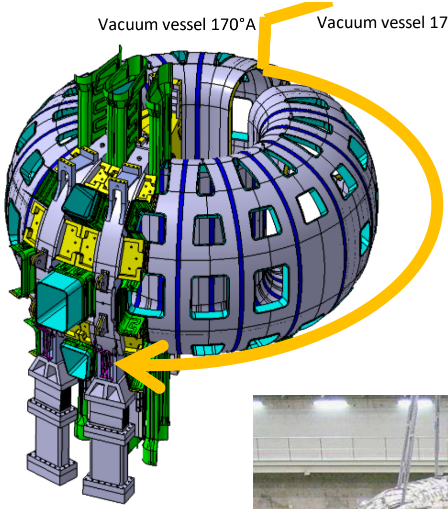


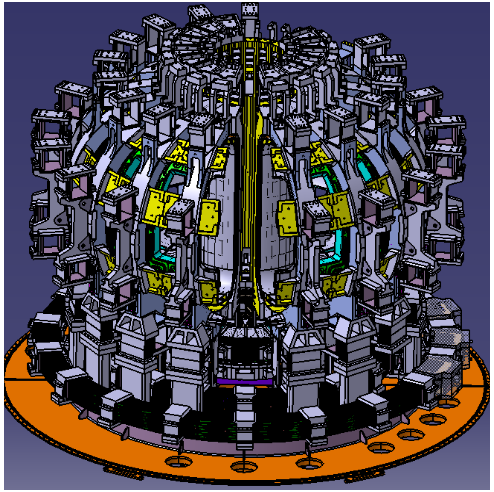
Vacuum vessel 170°A Vacuum vessel 170°B

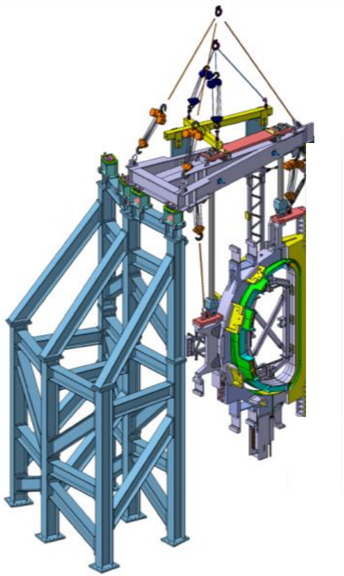


Last Sector 20°

JT-60SA/KSTAR-like assembly

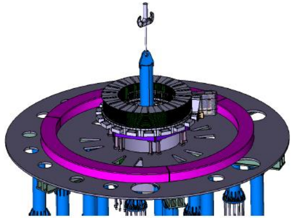




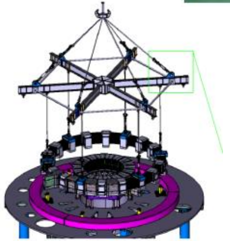


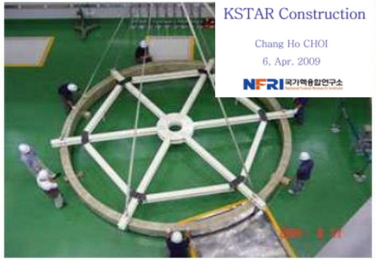
Assembly procedure

PF6



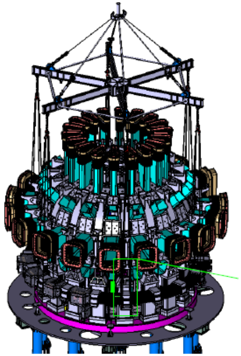
PF5



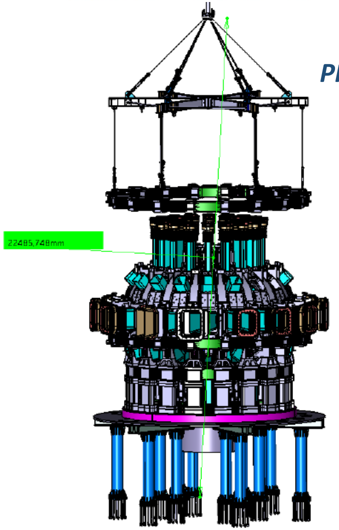


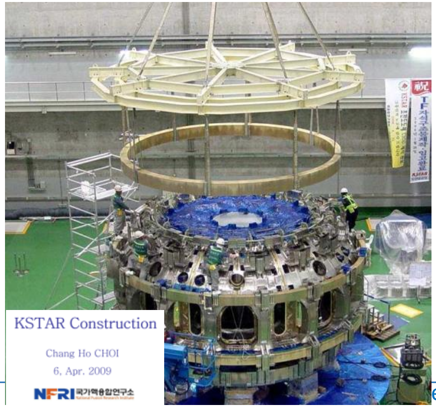
PF4

TF & VV

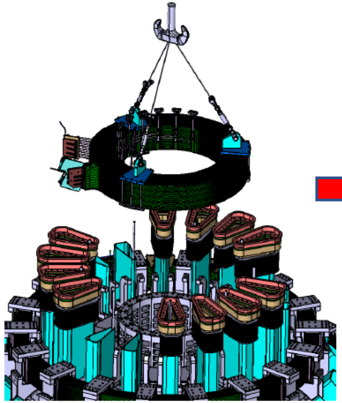


PF3/2

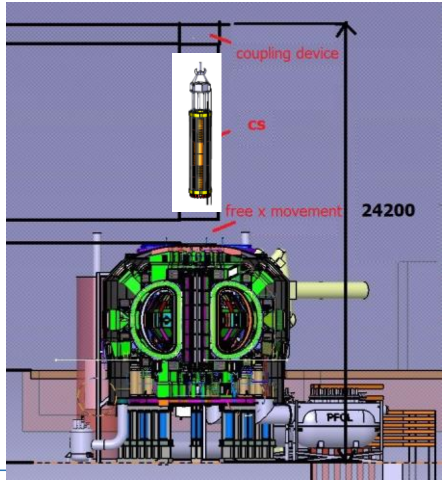




PF1

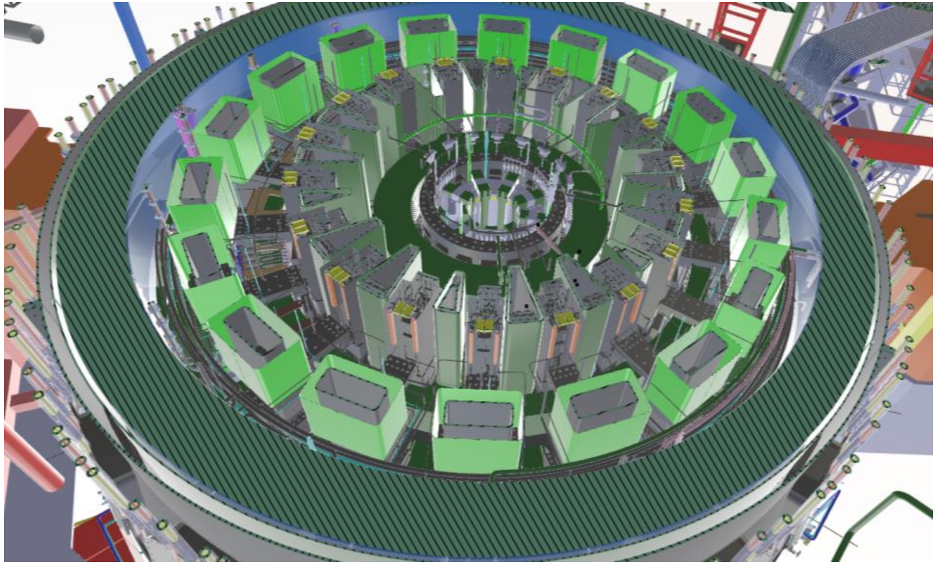


CS

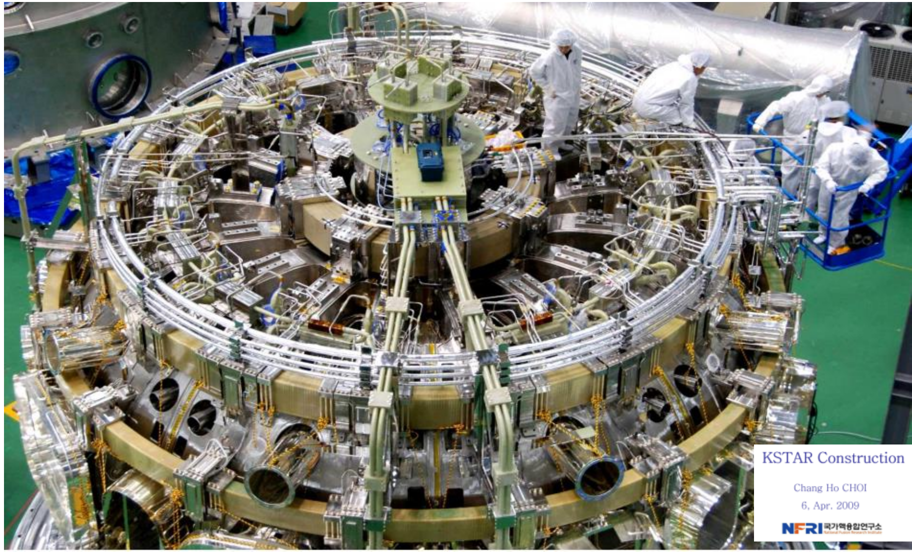


Assembly procedure: cryodistribution

One of the main challenges included in the assembly contract to be placed next year is the definition, procurement, assembly and testing of the cryodistribution inside the cryostat.



DTT model: Bottom view

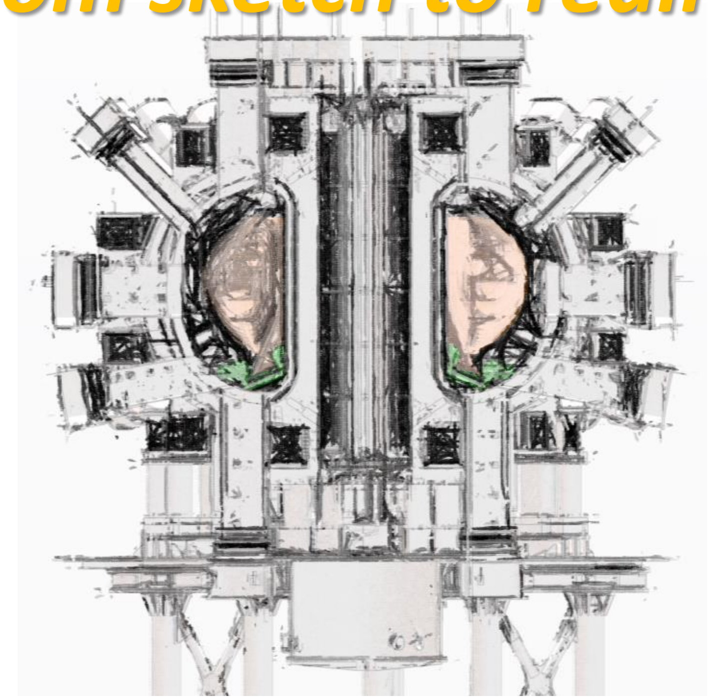


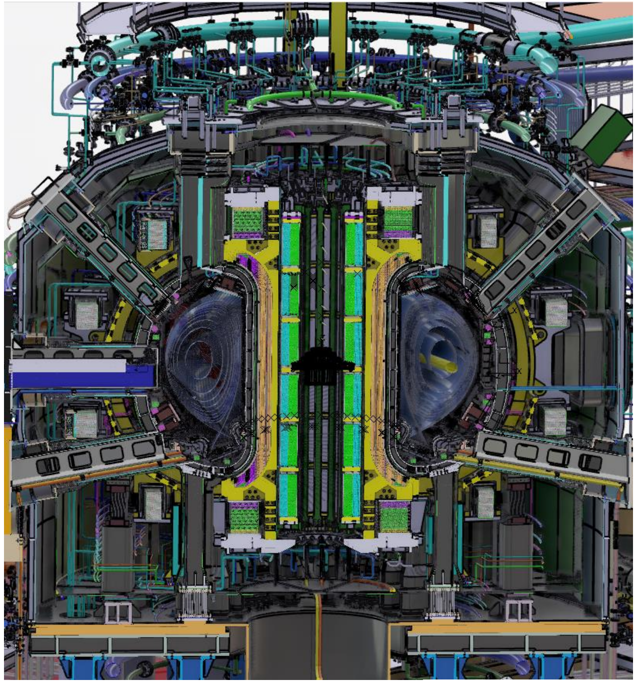
KSTAR: top view

Concluding remarks

- ✓ DTT magnet design based on state-of-the-art of SC magnets available
- ✓ Prototypes before tender and qualification during tender are anyhow foreseen
- ✓ KSTAR experience would be highly valuable for:
  - ✓ Manufacturing issues (NC, CR, etc)
  - ✓ Magnet testing procedures
  - ✓ Assembly procedures and assembly tools
  - ✓ Cryogenic/feeders distribution
  - ✓ Integrated commissioning program

From sketch to reality





Thank you for your attention

www.dtt-project.it

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EF consortium

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