Overcoming the Challenges of the ITER Magnets

china eu india japan korea russia usa

Neil Mitchell

ITER Organization, on behalf of the ITER, Domestic Agency and Supplier Magnet Teams

with particular thanks to Arnaud Devred, Sandro Bonito-Oliva, Nori Koizumi, Nick Clayton

EUCAS

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

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Progress on the Site Construction

ITER Site Construction – 1 (June 2013)

PF Coil Winding Building
(17 m high; 252 x 45 m)

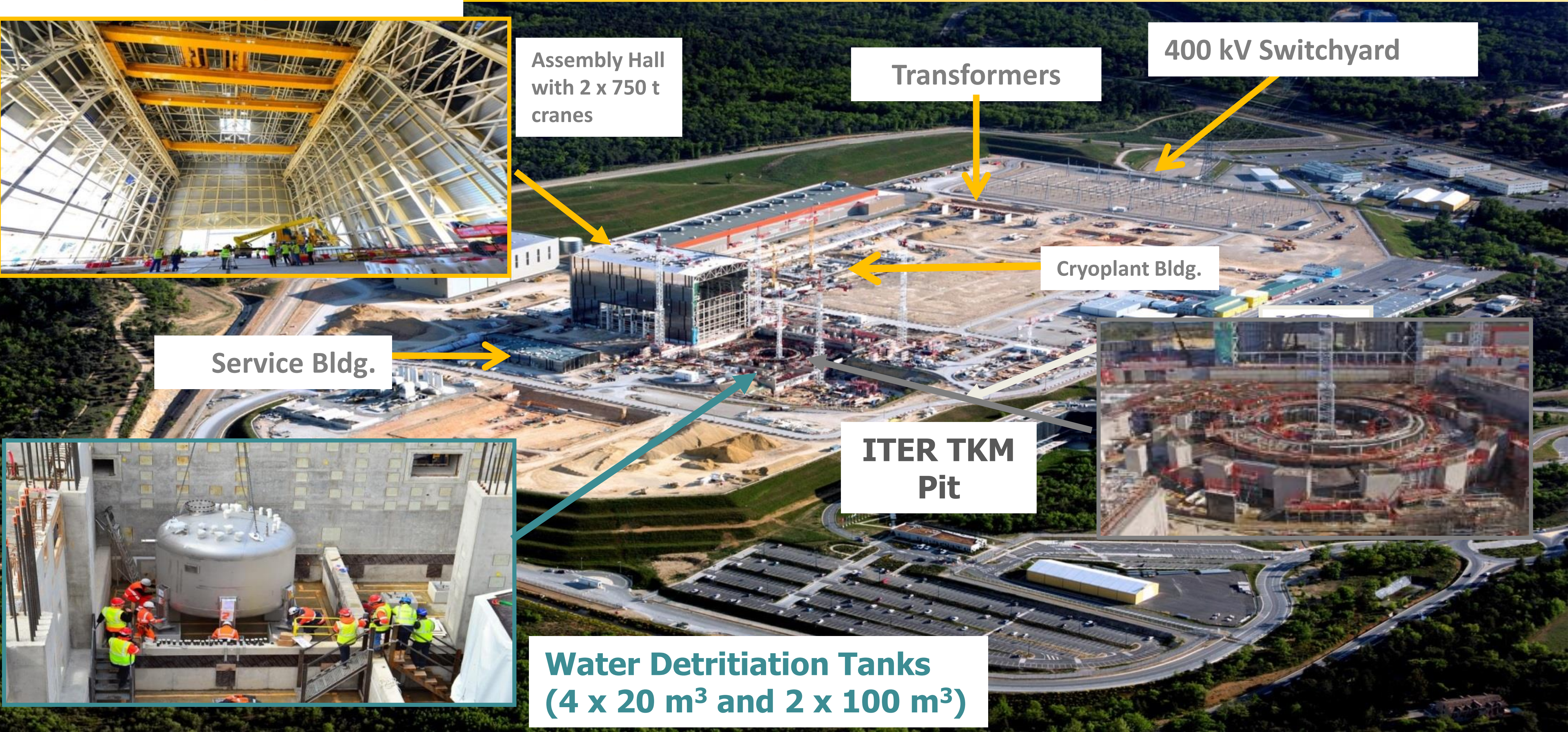
Tokamak Building Pit and Foundation
(17 m deep; 120 x 90 m)

ITER TKM Pit

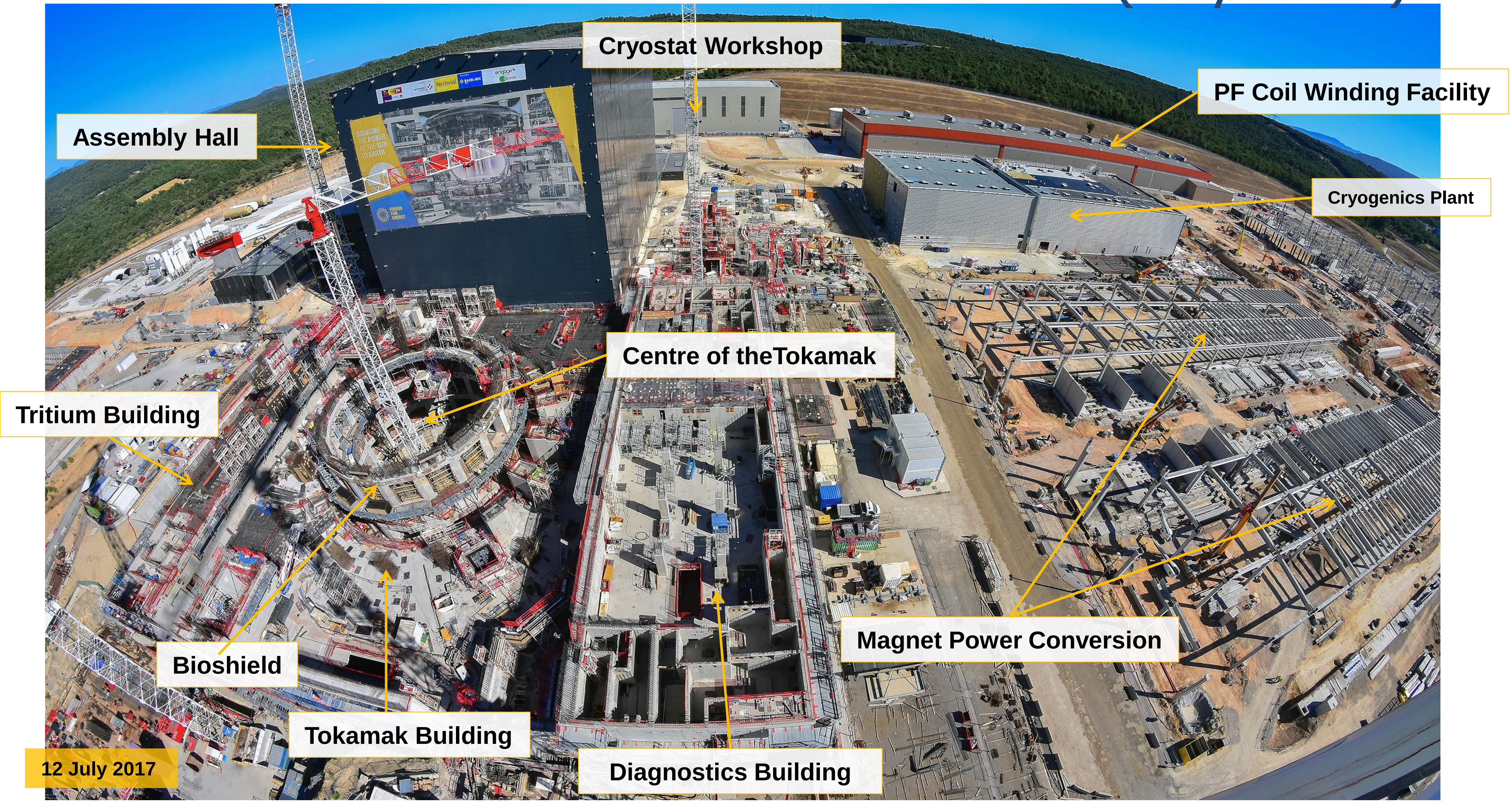
ITER Headquarter Building
(4 story; 16,000 m²)

ITER Site Construction – 2 (April 2015)

ITER Site Construction – 3 (April 2016)

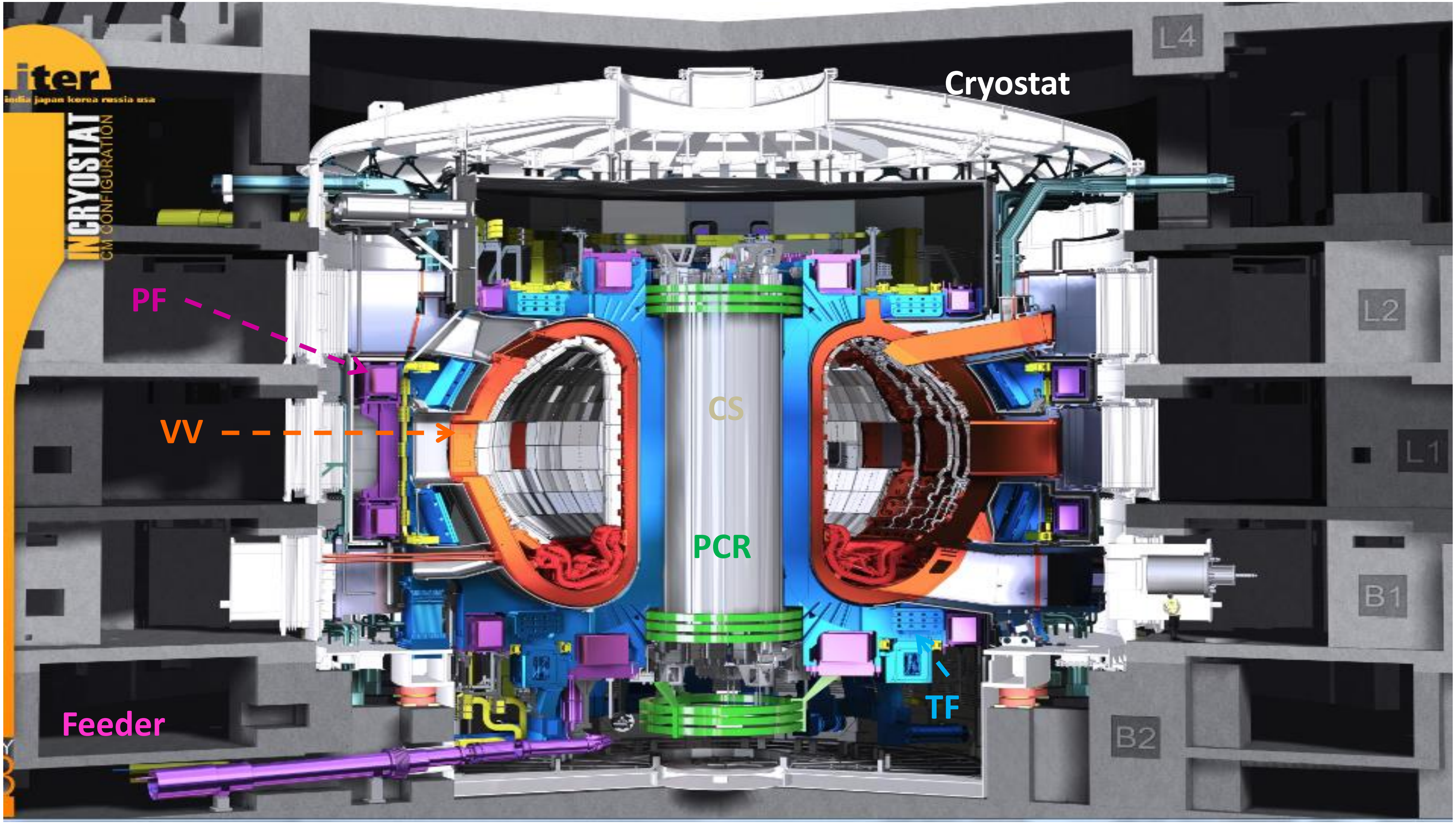


ITER Site Construction – 4 (July 2017)



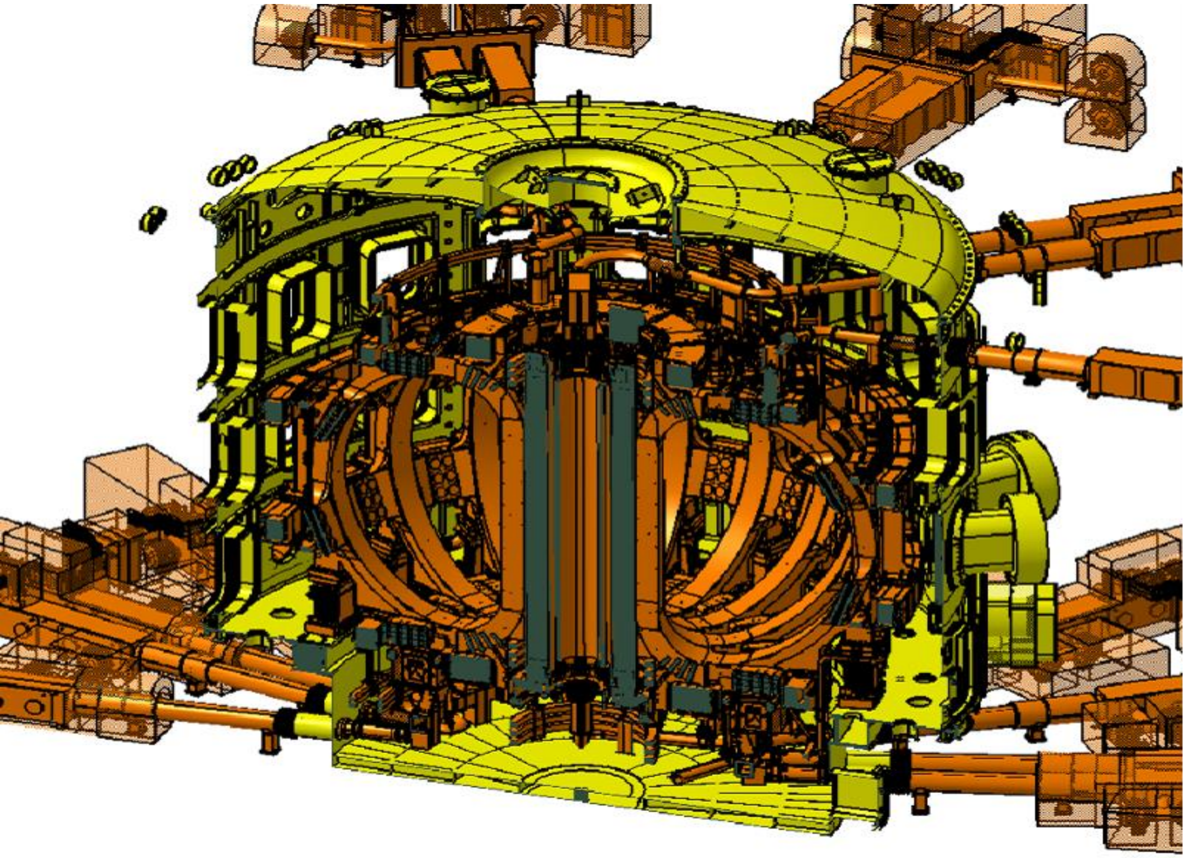
Status of Magnets

Overall Magnet System

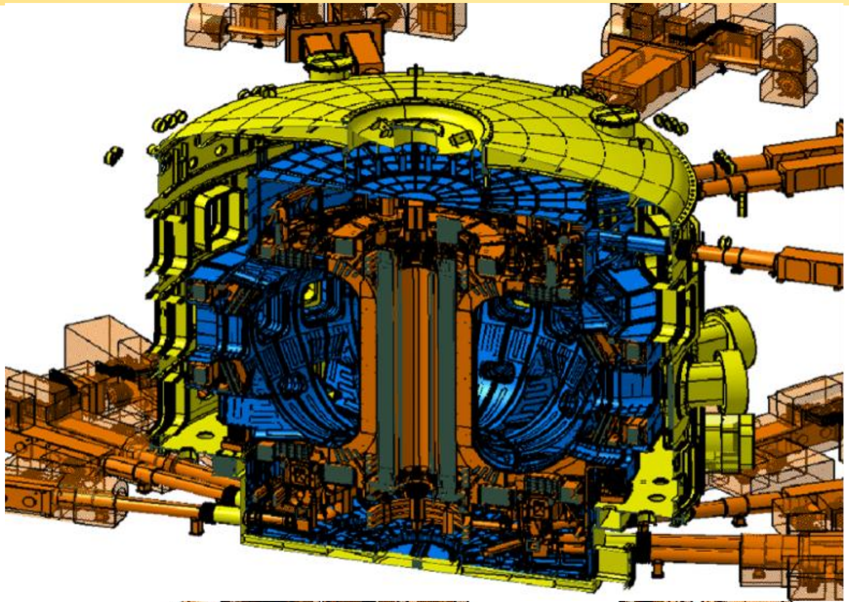


Superconducting Magnet In-Cryostat Environment

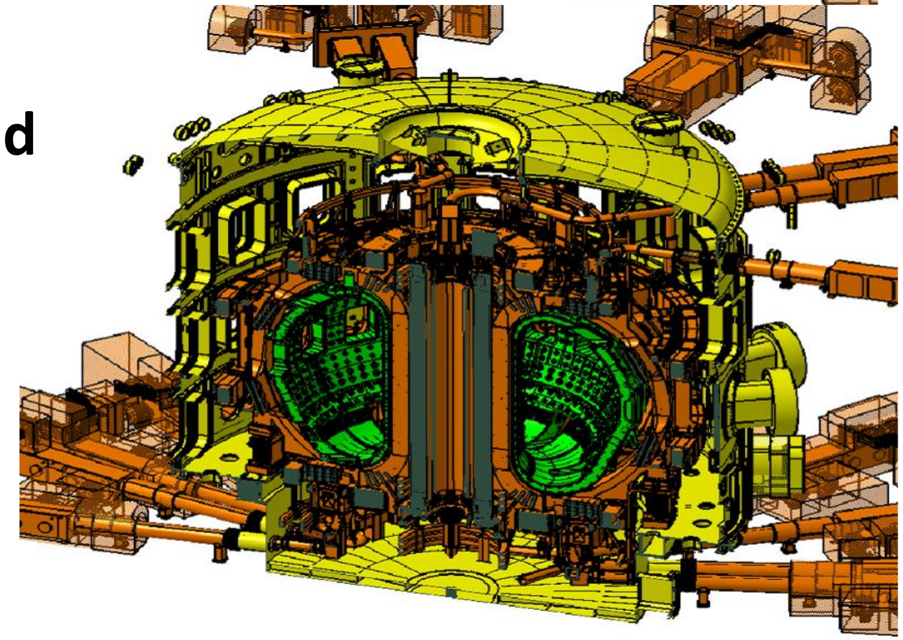
Magnets and Cryostat



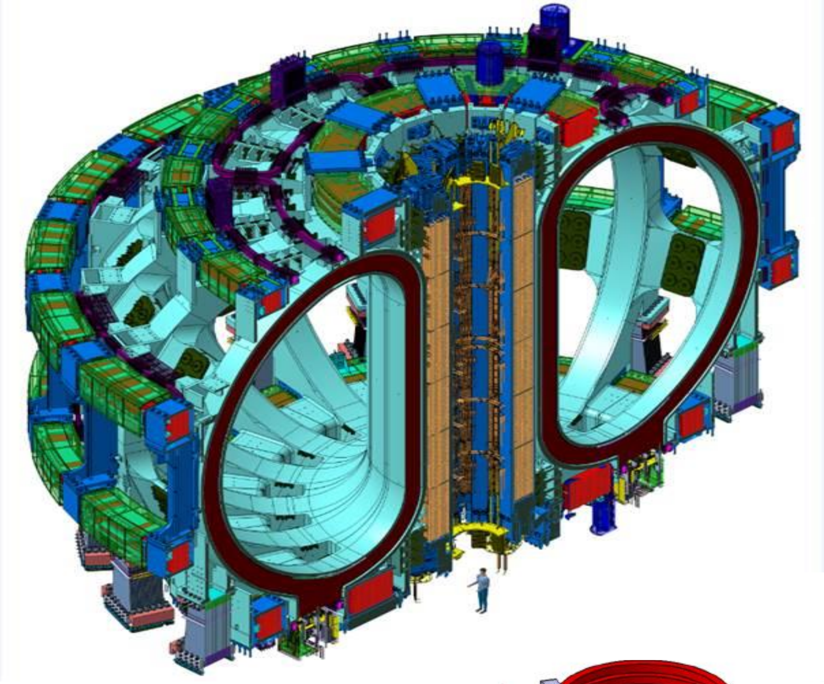
Magnets, Cryostat and Thermal Shield



Magnets, Cryostat and VV



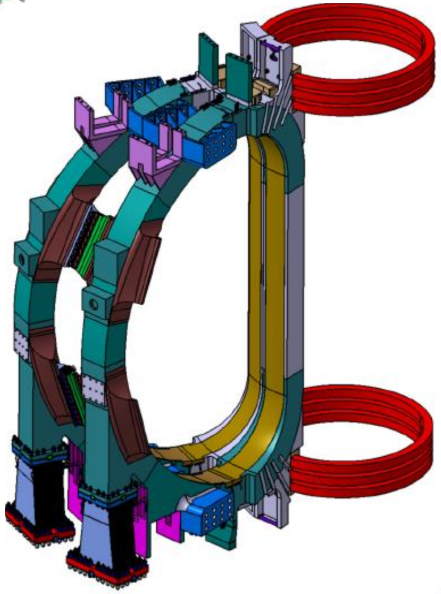
ITER Magnet System – 1



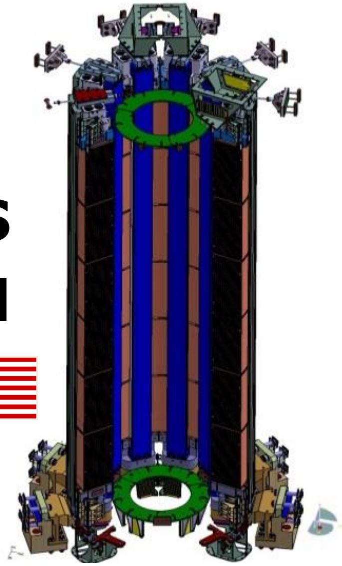
- The ITER magnet system is made up of
  - **18 Nb_3Sn Toroidal Field (TF) Coils,**
  - **a 6-module Nb_3Sn Central Solenoid (CS),**
  - **6 Nb–Ti Poloidal Field (PF) Coils,**
  - **9 Nb–Ti pairs of Correction Coils (CCs).**

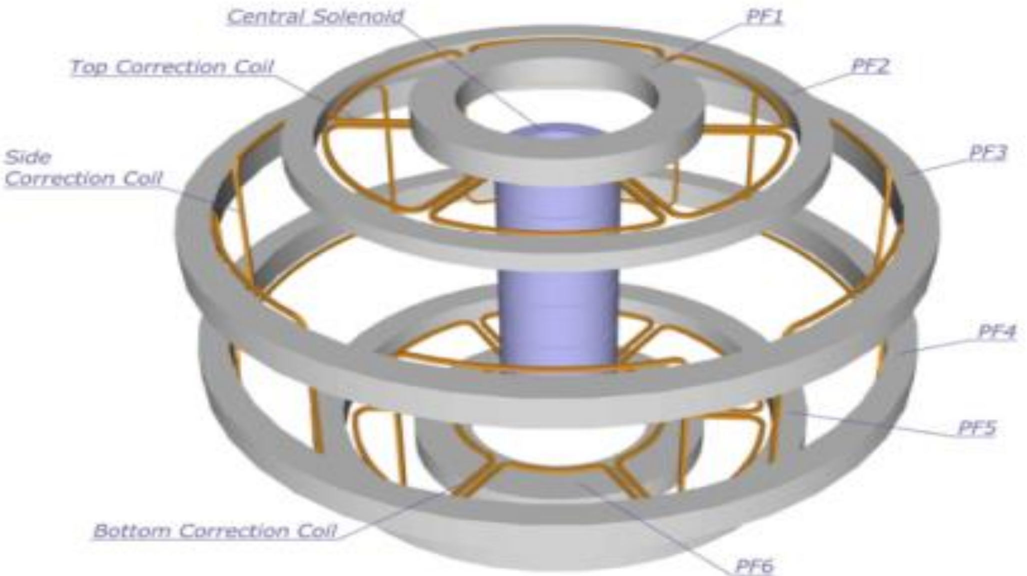
ITER Magnet System

Pair of TF Coils



CS Coil





(PF1)

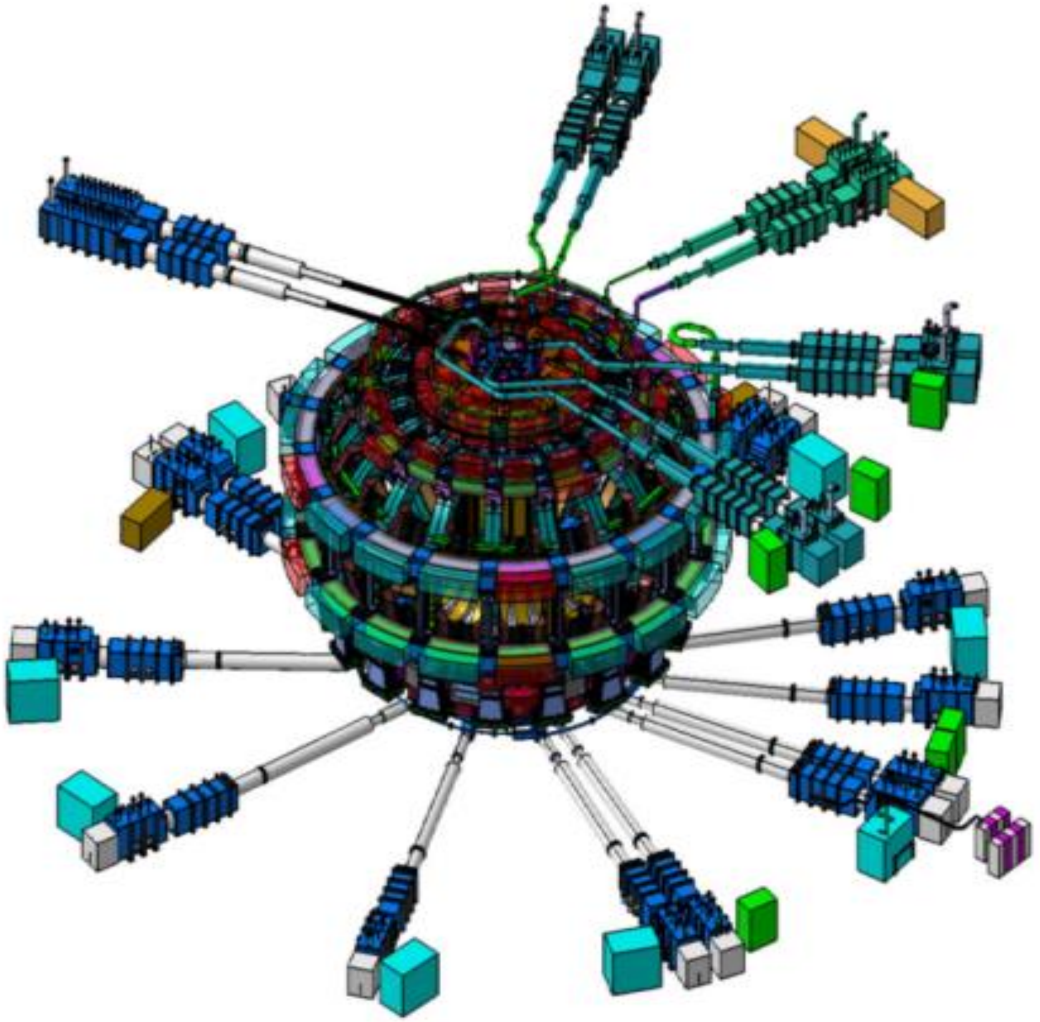
PF Coils

(PF2-6)

CCs

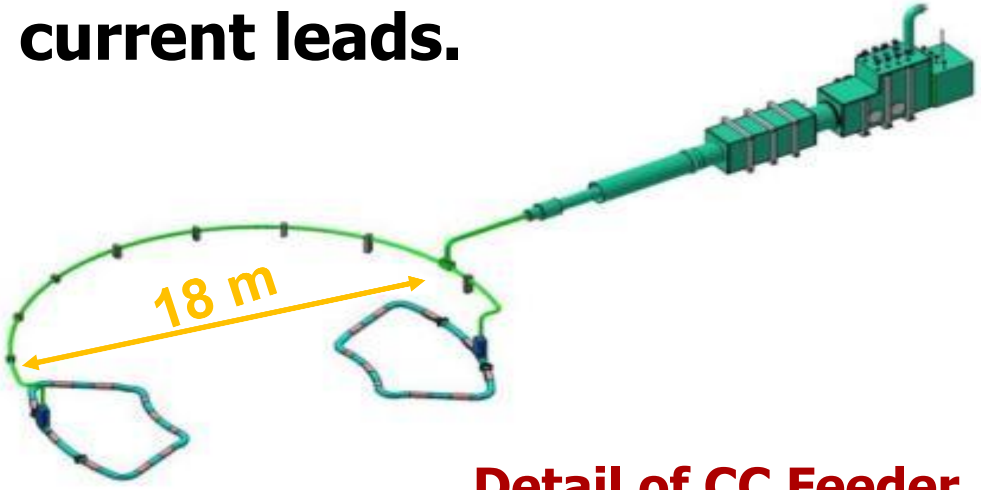
ITER Magnet System – 2

- ITER magnets are supplied with current/cryogenic fluids by **31 Feeders.**



ITER Feeder System

- The magnet Feeders include
  - **Nb–Ti CICC busbars (MB & CB),**
  - **Ag-Au(5.4%) BiSCCO 2223 HTS current leads.**



Detail of CC Feeder

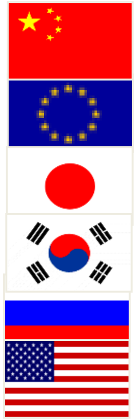
68 kA Trial Lead Developed by ASIPP

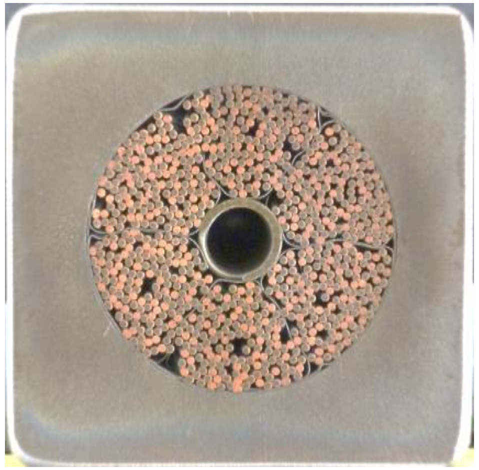
ITER Conductor Supply

Nb_3Sn

88 km, 825 t
215 kIUA
(334 M€)

TF Conductors



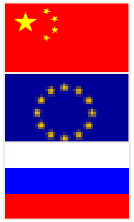


CS Conductor

43 km, 745 t
90 kIUA
(140 M€)

Nb–Ti

PF Conductors

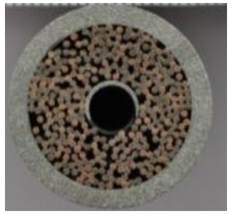


65 km, 1224 t
81 kIUA
(126 M€)

10.7 km (CC)
3.7 km (MB+CB)
2.13 kIUA (3.3 M€)

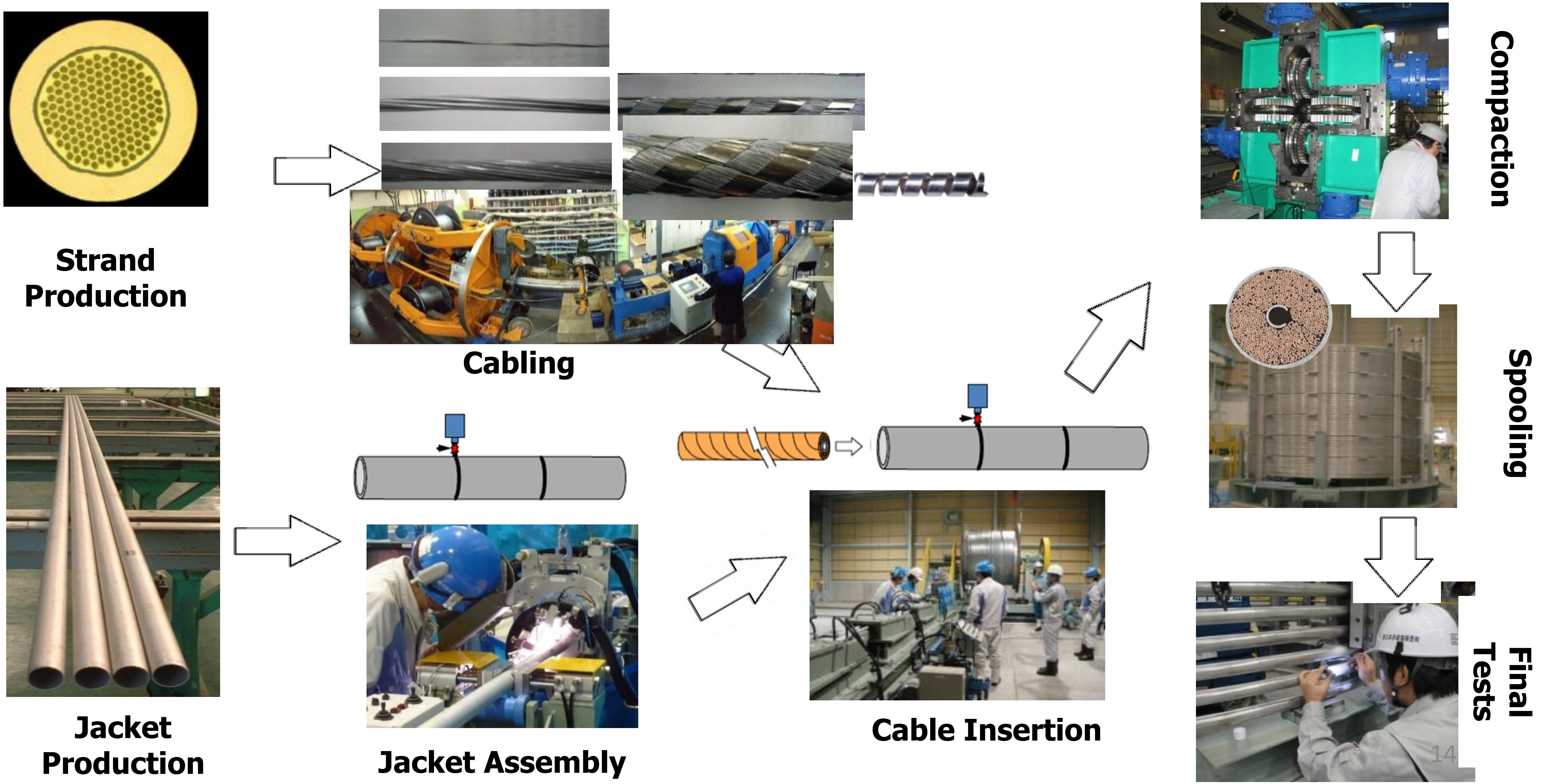
MB Conductor

CC Conductor



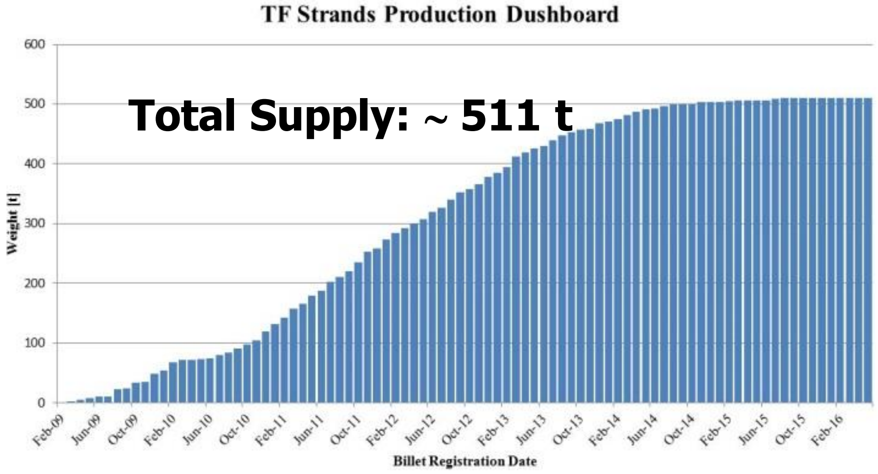
CB Conductor

ITER Conductor Manufacture

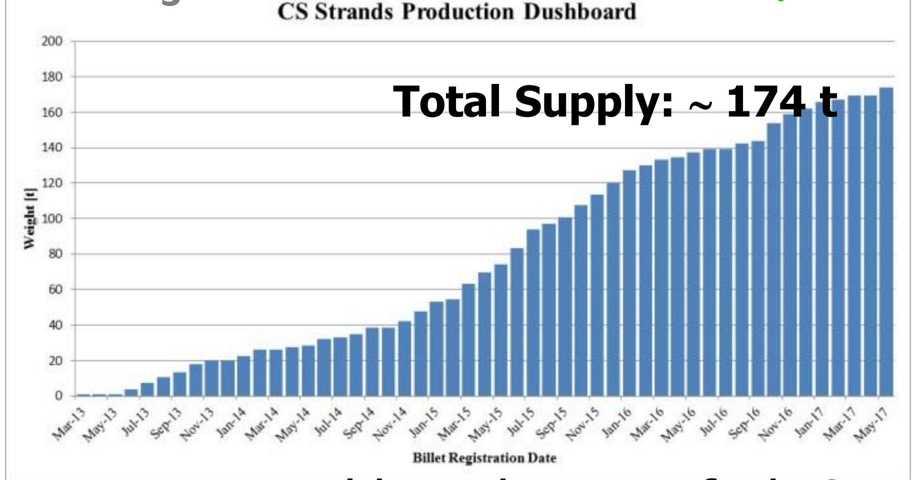


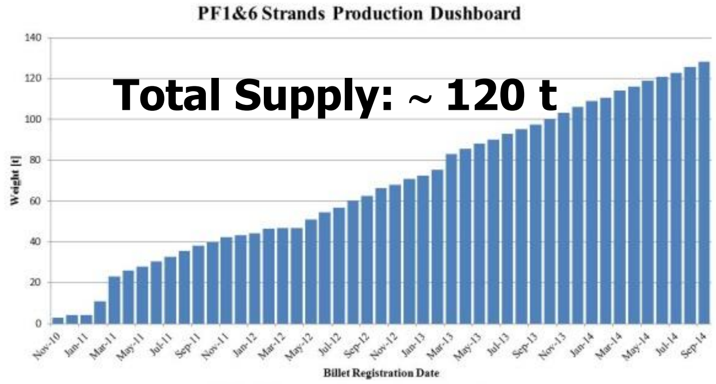
ITER Strand Status (31 May 2017)

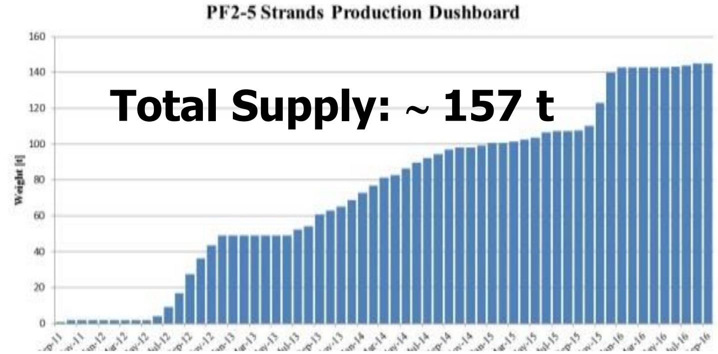
- **Nb_3Sn** for **TF:** ~100% complete.

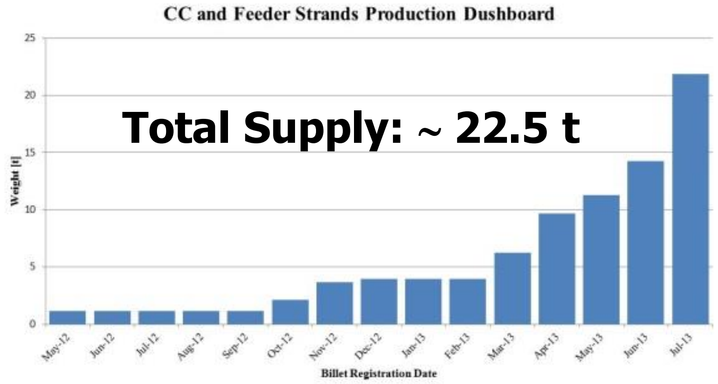


- **Nb_3Sn** for **CS:** ~100% complete.









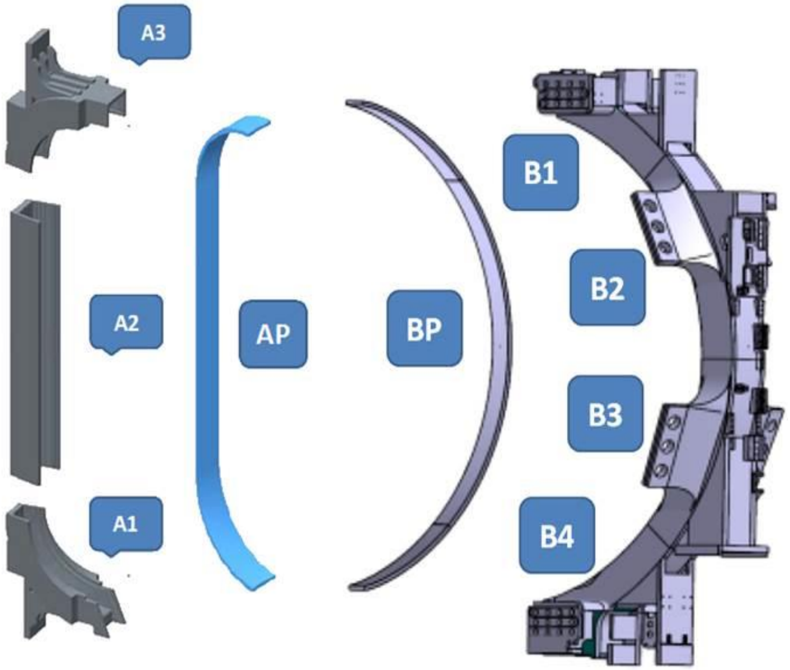
- **Nb–Ti Type 1** for **PF1&6:** 100% complete since Aug. 2014.
- **Nb–Ti Type 2** for **PF2-5:** ~92% complete.
- **Nb–Ti Type 2** for **CC** & **Feed.:** 100% complete since Jul. 2013.

- Pre-ITER world production of Nb_3Sn was **~15 t/year;** it has been scaled up to **~100 t/year** for the last 4 years.

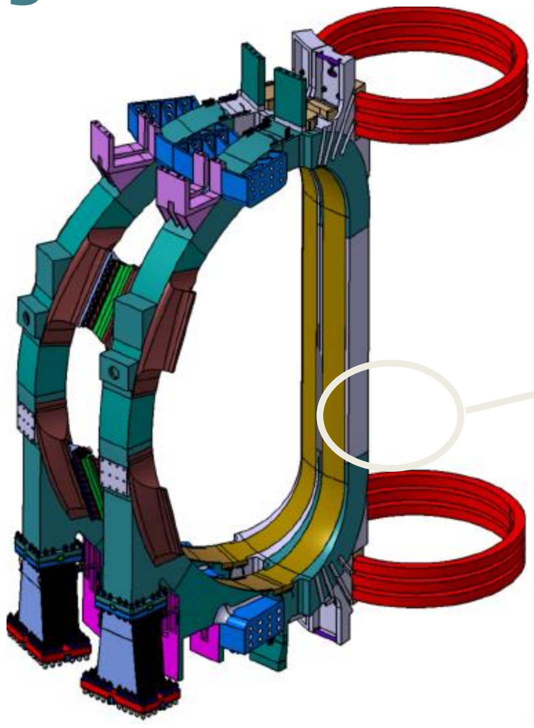
Data compiled by D. Kaverin (ITER-CT)

Main Features of ITER TF Coils

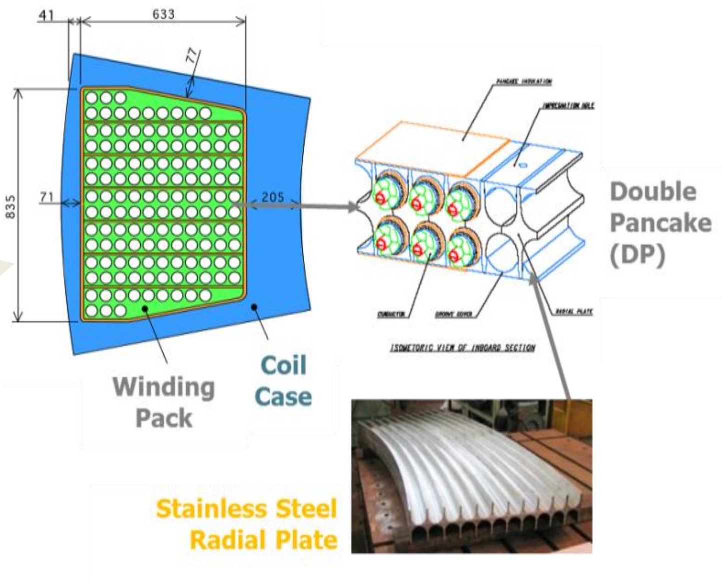
- The TF coil is made up of a winding pack **(WP)** inserted inside a thick **coil case** made of welded, stainless steel **segments.**



TF Coil Structure



Pair of TF Coils

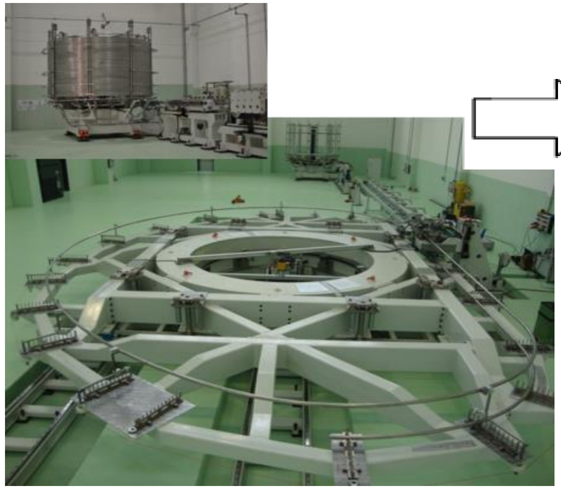


TF Coil Winding Pack

- Each **winding pack (WP)** comprises **7 double pancakes (DPs)**, made up of a **radial plate** with precisely machined grooves into which the **CICC** is transferred upon heat treatment completion.

ITER TF DP Manufacture – 1

Conductor Spool



DP Winding (12 m x 9 m)

Elec. Terminal

He Inlet

DP Heat Treatment

Radial Plate Section Welding

Courtesy of A. Bonito-Oliva (F4E)

Radial Plate Assembly

Transfer of HTd DP into Radial Plate

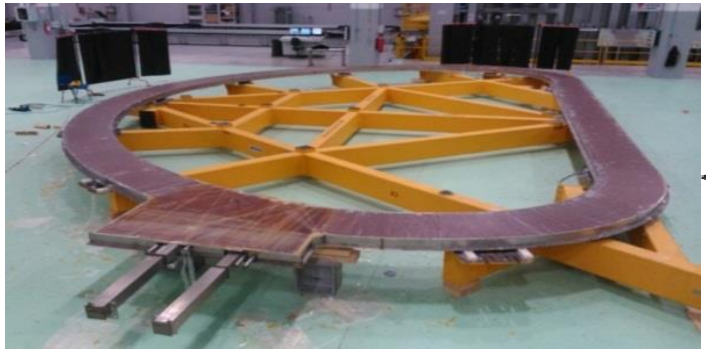
ITER TF DP Manufacture – 2

DP Turn Insulation inside Radial Plate

Cover Plate Welding

DP Ground Insulation

DP Loading into Vacuum Impregnation Mold (radiation-hard cyanate esther resin)



Impregnated DP

Hi-Post Test on Impregnated DP

Courtesy of A. Bonito-Oliva (F4E) **and N. Koizumi** (QST)

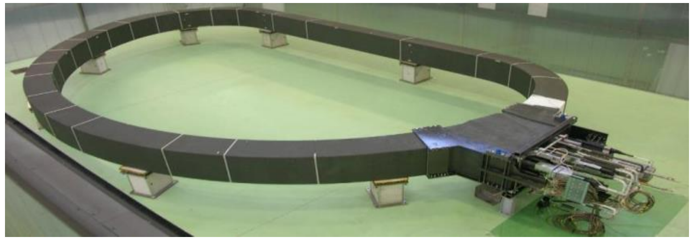
TF Coil Production Status (August 2017)

	EU	JA
DP Winding	70	31
DP Heat Treatment	67	29
DP Transfer, Turn Insulation, Welded	49	17
DP Completed	44	14
WP Insulation	4	1
WP Impregnated	2	0
WP Terminal Region Assembled	1	0

18 +1 WPs
1 WP = 7 DPs
133 DPs
(70 EU, 63 JA)

Assembly Line at ASG

1st and 2nd complete WPs



Magnet Supports

1st TF
Gravity
Support

PF3, 4, 5
U shaped
clamps

(below) thermal cycle and pressure test

PF 3- PF 4
strut under
welding

courtesy Zhang Bo and HTXL

PF1 Coil Status (April 2017)

- **RFDA** has completed winding of **two** (out of 8) **PF1 Double Pancake.**

1st PF1 DP Winding (September 2016)

1st PF1 DP VPI (April 2017)

2nd PF1 DP Winding (April 2017)

Courtesy RFDA & Efremov Institute

PF2-6 Coil Status

- **EU** suppliers have completed winding of dummy double pancakes for PF5 & PF6 and have started winding of first production Double Pancakes.

PF5 Dummy DP Winding (February 2017)

Courtesy F4E & B.-S. Lim (ITER-CT)

1st PF6 DP Winding (Apr 2017)

2nd PF6 DP Winding(underway)

8th DP now complete

CS Coil Status

2.1 m

1st CS Module

Assembly platform during final inspection at Robatel Technologies

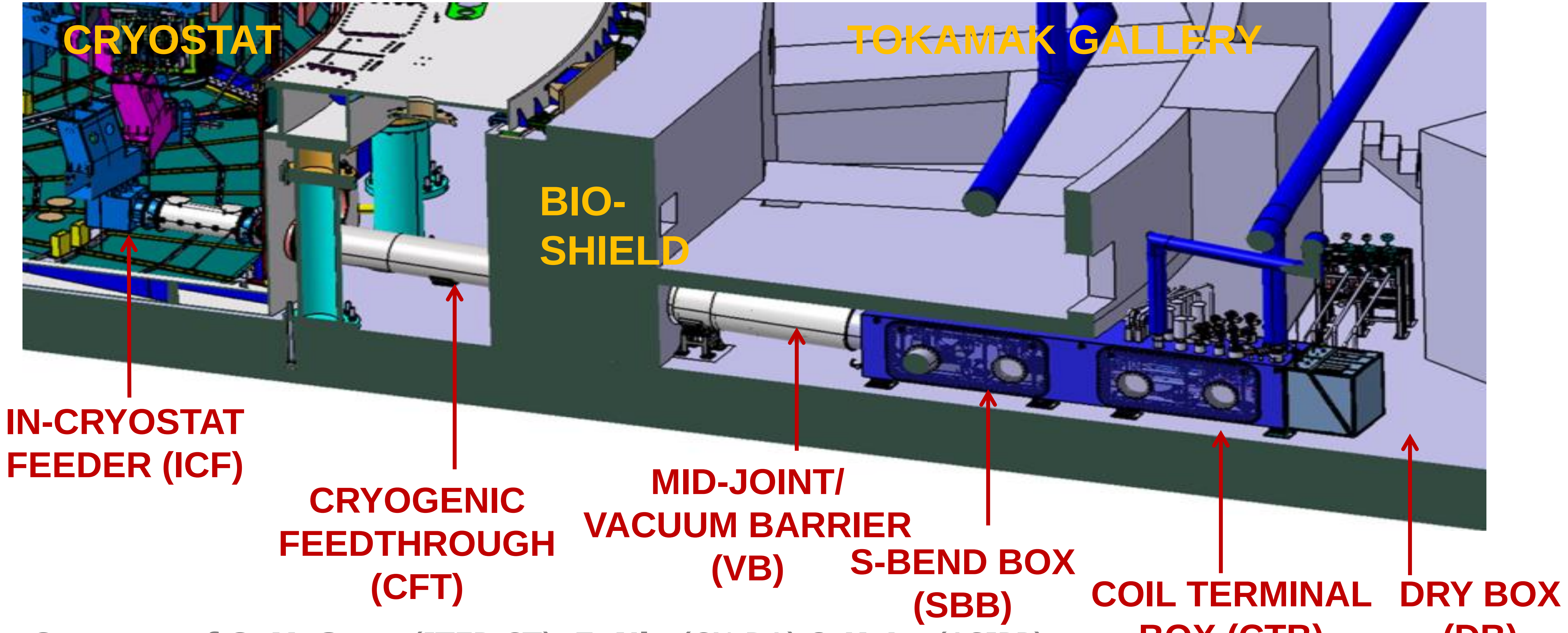
Commissioning turn over station with dummy module

Courtesy USIPO & GA

- **USIPO supplier** has completed stacking and heat treatment of **first** (out of 7) **CS Coil Module** and is proceeding with turn insulation (each module is made up of 6 hexapancakes and 1 quadropancake).
- Winding of **2^{nd} module** is completed; winding of **3^{rd} module** has started.

ITER Magnet Feeder Layout

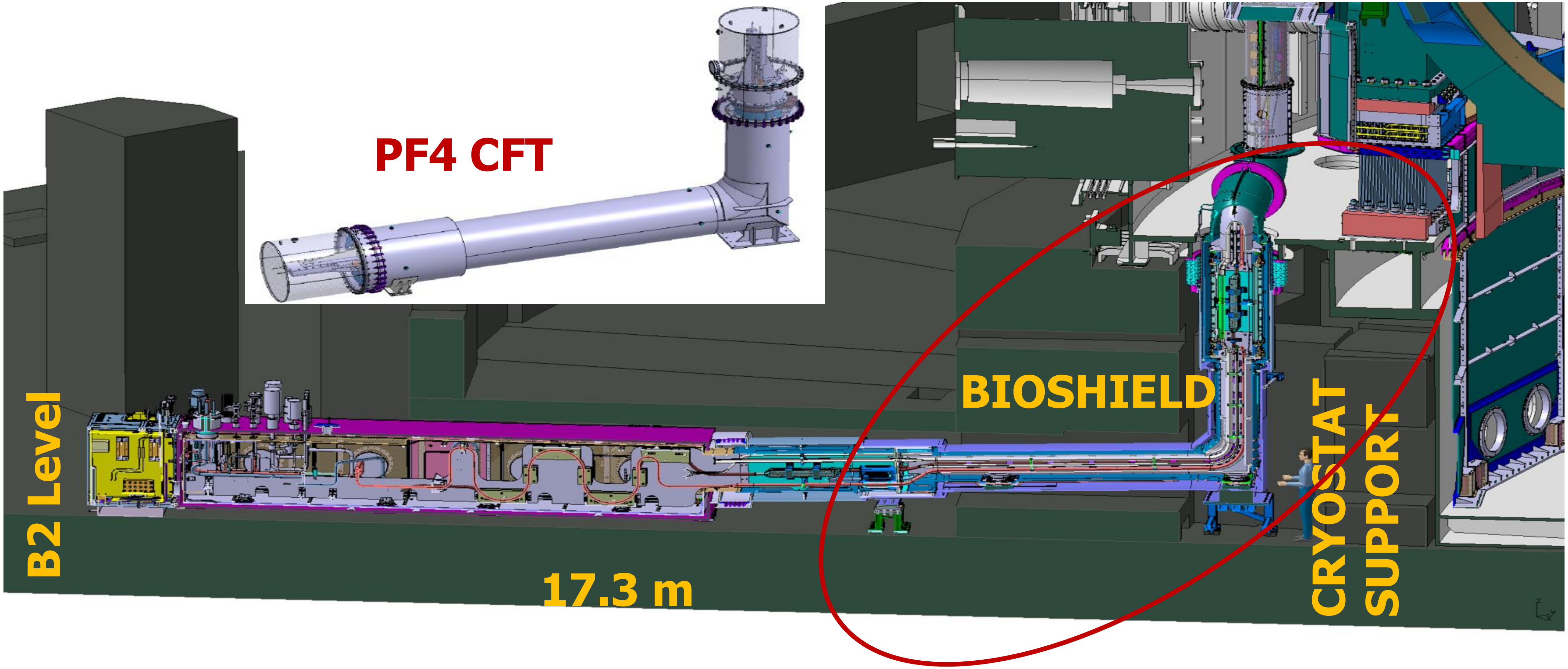
- **The magnet feeders** are deeply integrated into to the tokamak.



Courtesy of **C.-Y. Gung** (ITER-CT), **E. Niu** (CN-DA) **& K. Lu** (ASIPP)

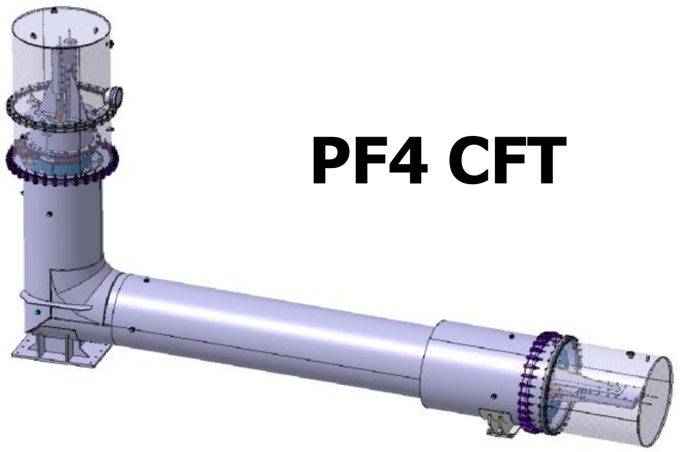
PF4 Cryostat Feed-Through

First magnet component to be installed in tokamak pit will be **PF4 Cryostat Feed Through (CFT),** which is a captive component.



PF4 Cryostat Feed-Through (Aug-Sep 2017)

- Manufacture is completed at ASIPP and shipping to IO is underway



PF4 CFT

Complete

Containment Duct Assembly

Thermal Shields ready for Assembly

Internal Pipes

Horizontal Vacuum Duct Machining

Courtesy of C. Liu (ASIPP)

Main Challenges of the Coil Procurement (2001-2017)

- ❑ Conductor Degradation
- ❑ Tolerances on TF Coil Geometry
- ❑ High Voltage Insulation

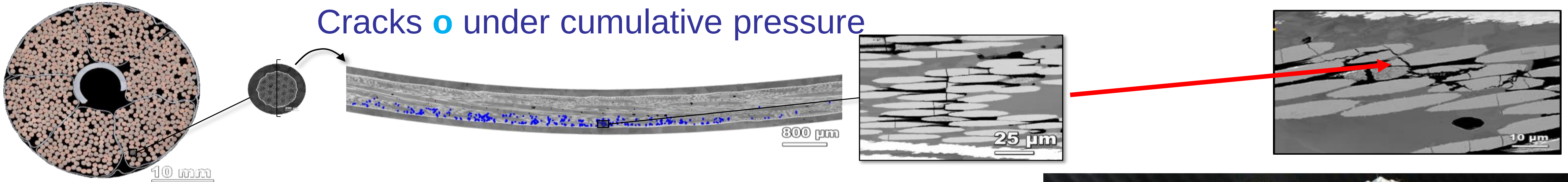
Conductor Issue. Degradation of large Nb3Sn CICC

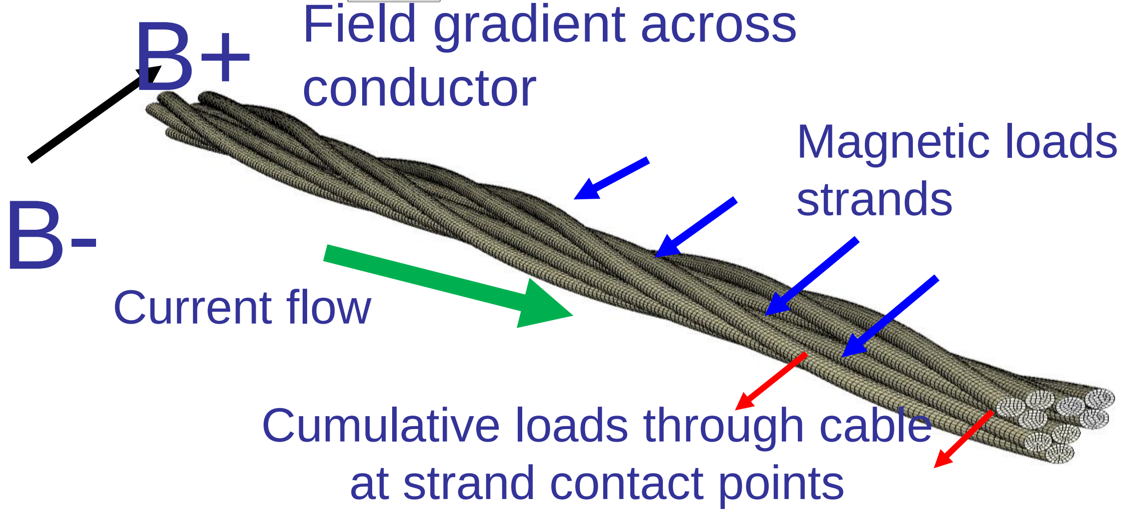
The Design Challenge

- Nb_3Sn is a brittle compound that easily fractures under tension
- Form cable from wires then heat treat to make Nb_3Sn.
- Wires separated to allow Helium at 5K to flow and block AC losses
- Wires must be strongly supported mechanically

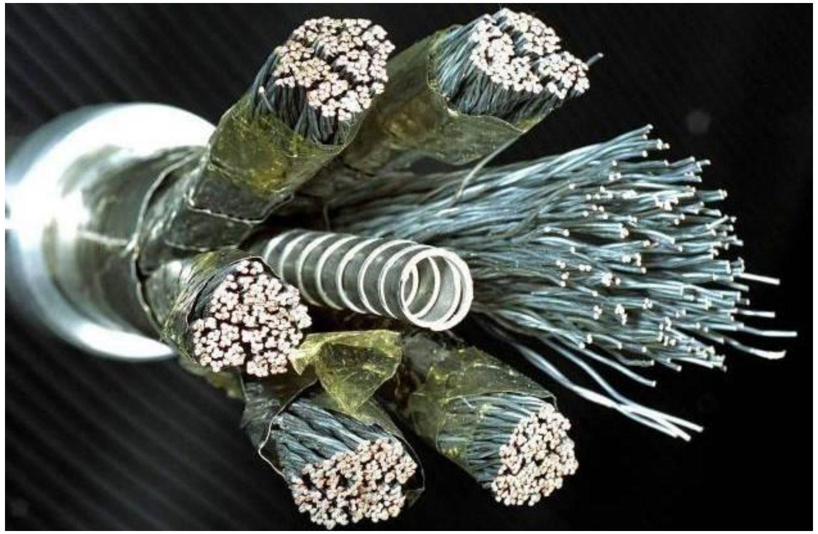
=> Challenge is to avoid filament cracks

Nb3Sn filament cracks





‘Exploded’ ITER Cable

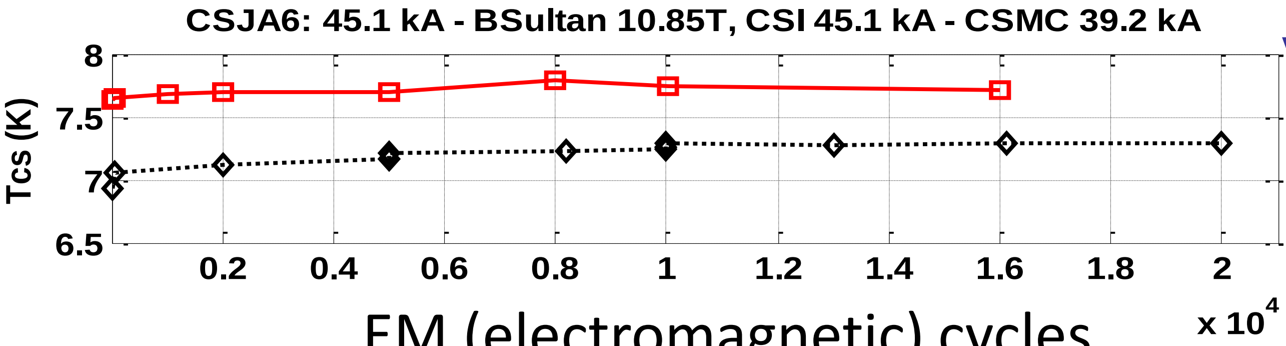


Demonstrating the degradation can be overcome

- ❑ Short (~3m) conductor lengths tested *for all 8 strand types*
- ❑ Tests of "insert coils" with a conductor length of ~50m, a diameter of about 1.5m and a height of about 2m.
- ❑ 'inserted' into the bore of a very large superconducting coil

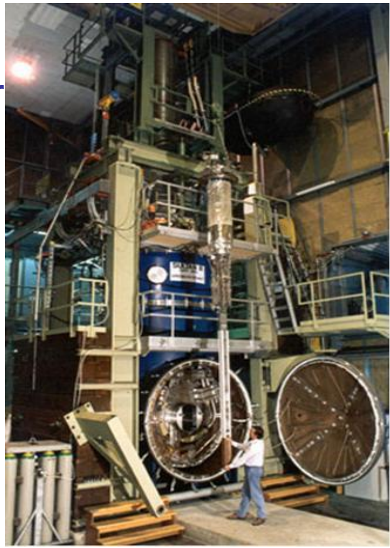
- ➢ Close synchronisation with the industrial development of Nb_3Sn wire and cable
- ➢ Coil tests, in 2000-2002, led to adjustments in the wire and conductor design.
- ➢ Coil tests in 2014-2017 have confirmed the performance of the Central Solenoid conductor *but leave open some issues on the Toroidal Field (TF) conductor.*

CS Insert test results confirm stable behavior as a function of EM and thermal cycling



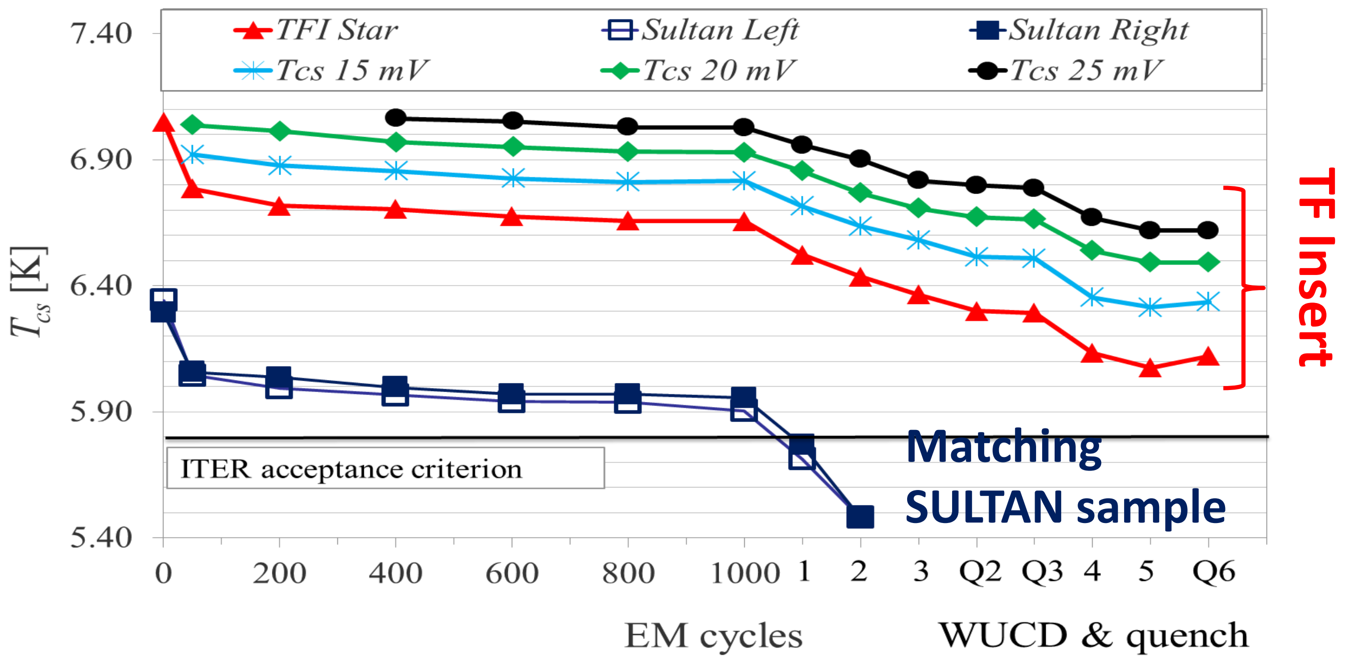
EM (electromagnetic) cycles

SULTAN facility with open end cap showing conductor sample hanging vertically in front



Latest TF Insert Results

- TF conductor successfully resists the magnetic forces, with an acceptable level of performance loss
- Triggering of repeated WUCD degradation by EM cycles in the TFI is more persistent than expected
- Anticipated fracture of Nb_3Sn material, conductors ***were designed with margin***.
- TFI tested under much more severe set of conditions than in ITER



- Conservative extrapolation of results to ITER itself shows ***sufficient margin***
- Higher level of degradation than foreseen, EM triggers extra WUCD degradation.

Steps to manage degradation through better understanding

- Extension of the present TF insert test
- Extra programme of conductor testing
- Thresholds exist for EM-WUCD interaction: use tests to identify, adjust operation to reduce number of 'triggers'
- If needed, new insert coil to exactly replicate the TF conductor operating life.

Structural Issue. Tolerances on structures

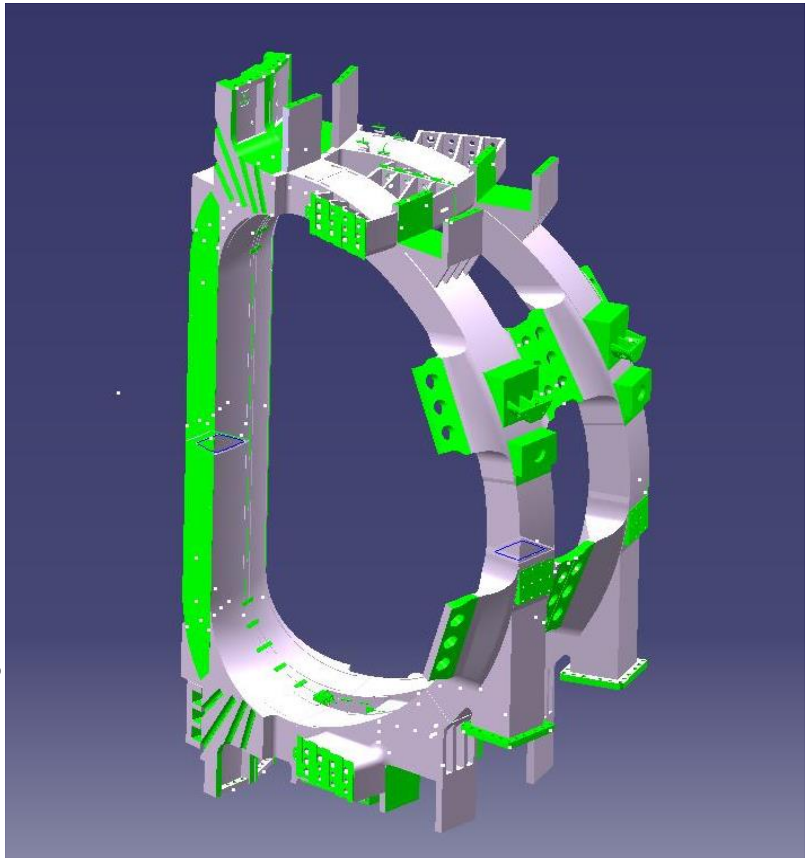
Where dimensional errors have an impact

- Fitting of components during assembly so that load paths still match design intention
- Inability to place component in available space
- Field errors

What drives tolerances

- Manufacturing requirements/capability
- Installation requirements/capability
- Measurement errors and component deformations under gravity
- Cumulative build up during manufacturing & assembly…. tolerances depend on other components

TF coils & structures are the core which drive the rest



TF coil interfaces (green)

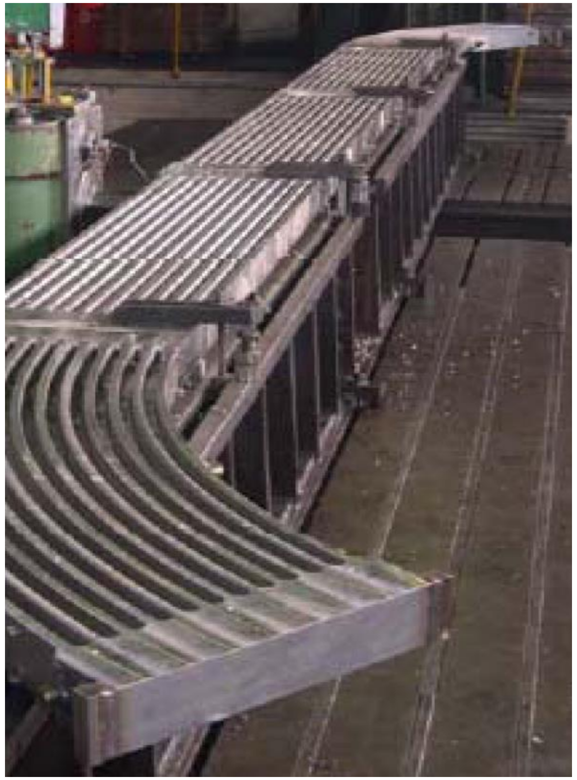
Structural Build-up of TF Coils

Key is manufacturing of accurate radial plates to hold the conductor

- Decouple geometric uncertainties of conventional bonded WP due to insulation from WP final geometry
- Eventual solution (after many trials) is to assemble plates from sections, with squared ends, and then local machine groove continuation

Below: radial plate section
Right: assembly of sections

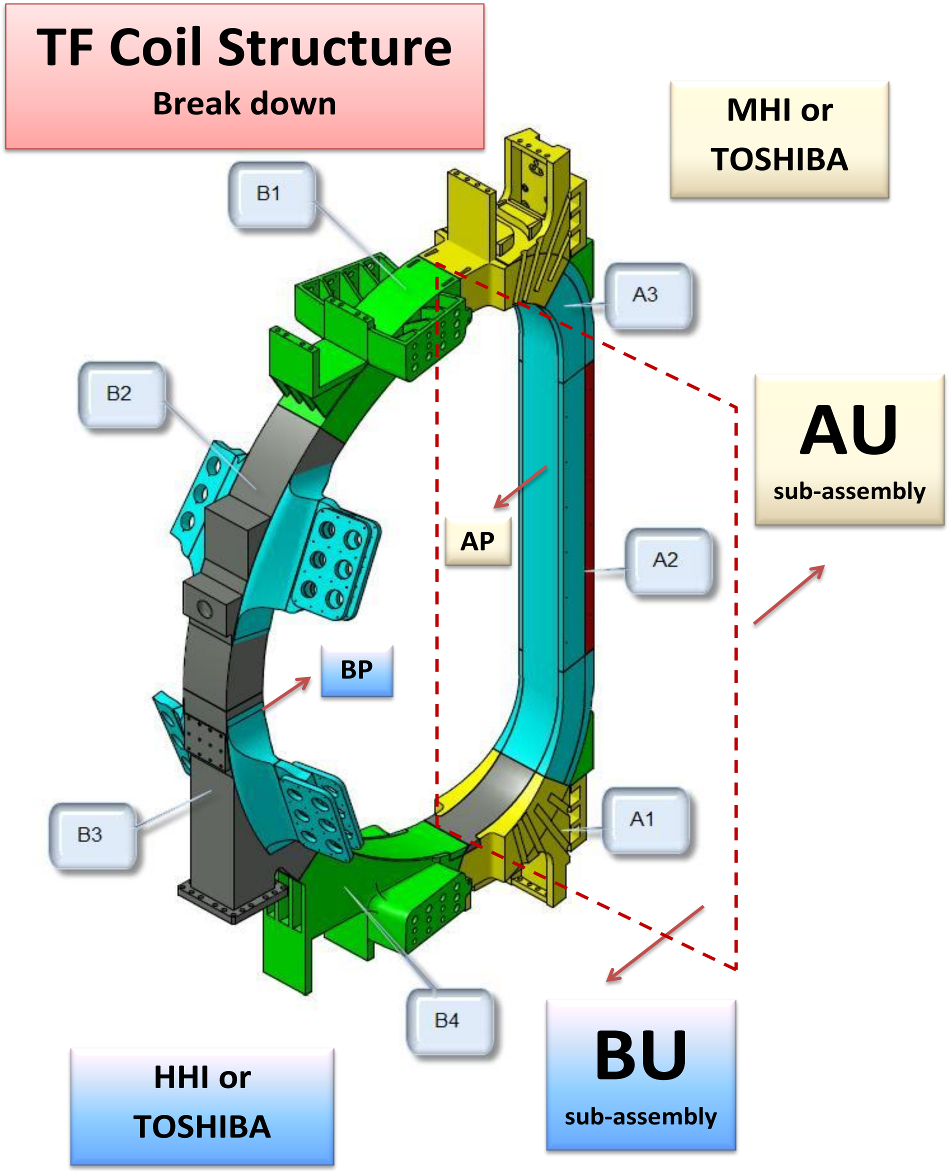
Courtesy of F4E



Completed radial plate

Accuracy <1mm in flatness and inner/outer profiles

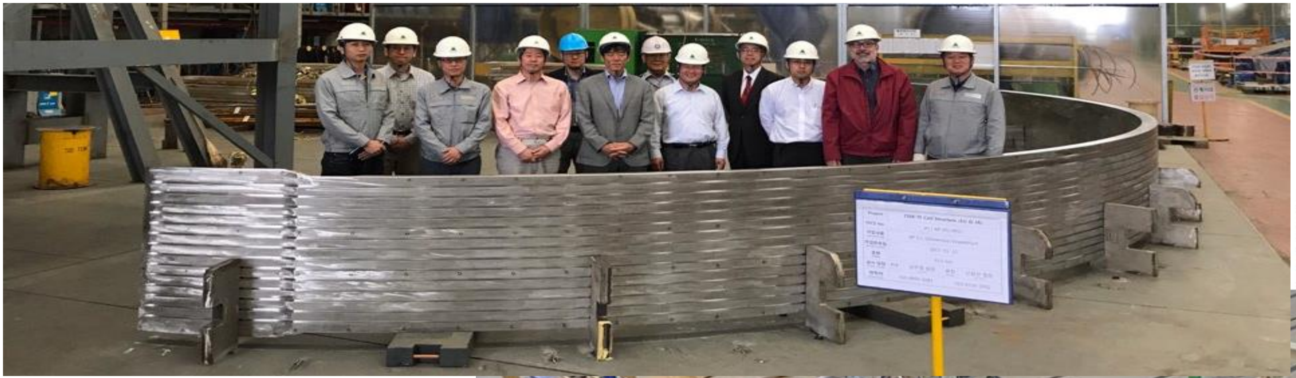
TF Coil Structures



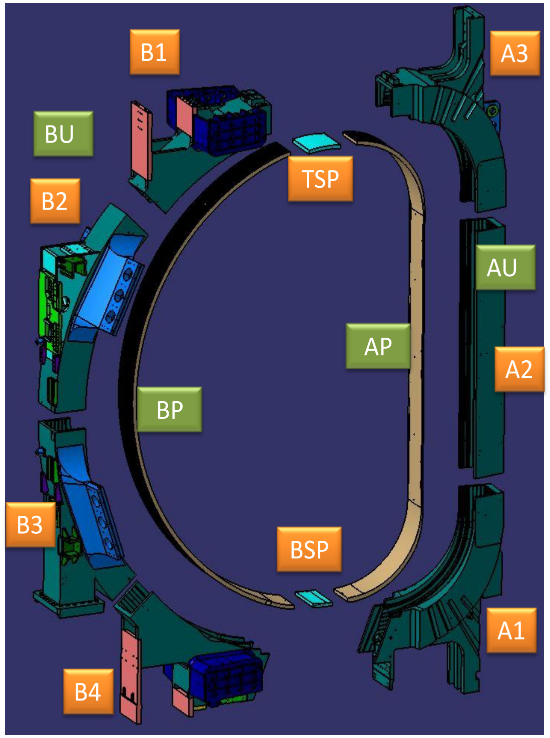
Courtesy of R. Gallix and M. LeRest (ITER-IO)

- TF structure calls for mass production of ~ **4500 tons** of large, high-strength, **316LN steel** components.
- Components are made of TIG welded assemblies of **forged plates up to 200 mm** and require **tight deformation control** to achieve final shape.
- Three suppliers have been selected: **MHI** and **Toshiba** (Japan) and **HHI** (Korea).
- **Series production** of AU, AP, BU and BP sub-assemblies are underway at all 3 suppliers.

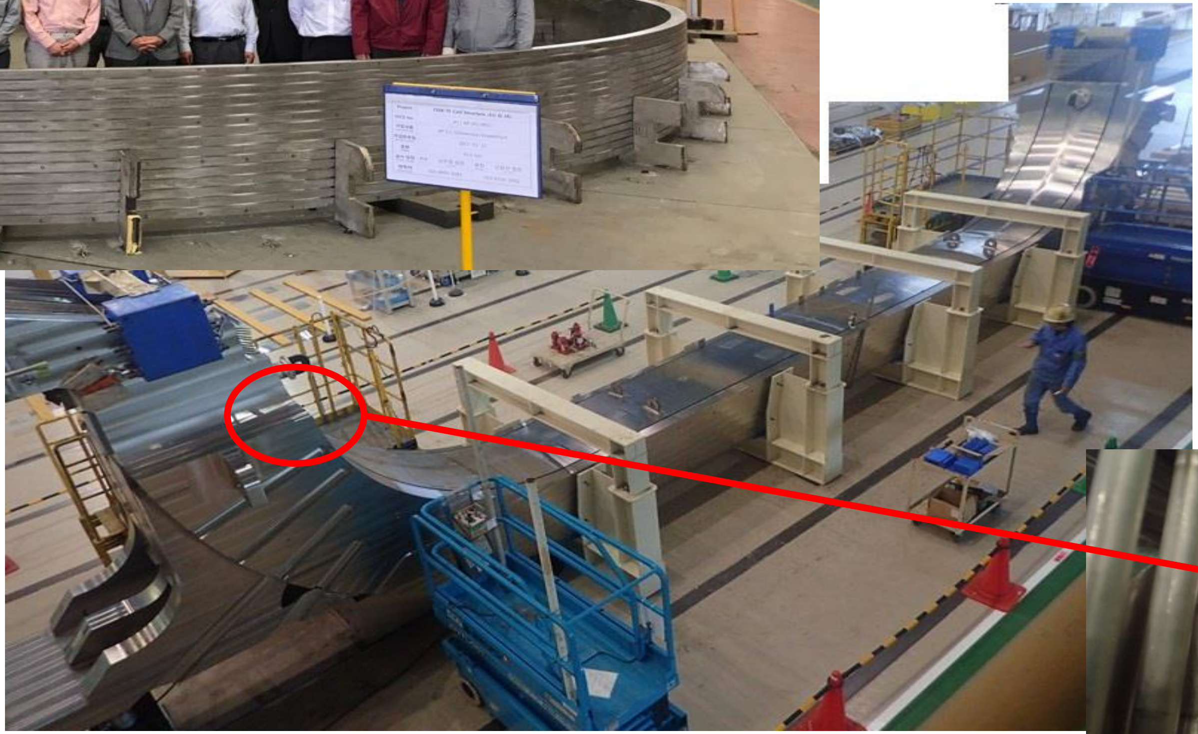
Large Structure Manufacturing



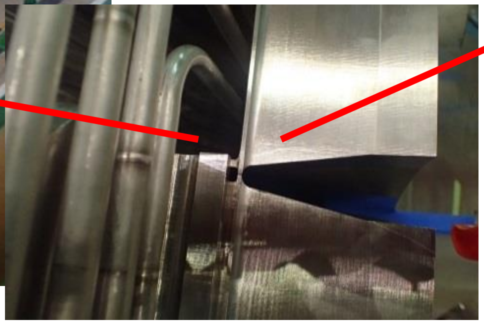
Completed BU and BP sections

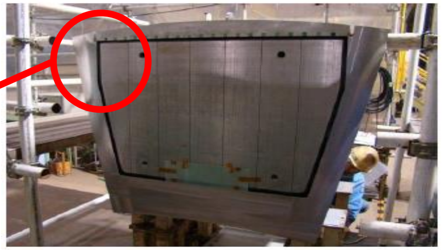


Fitting test of AP on AU



~50mm





Picture of mock up (b) during manufacturing

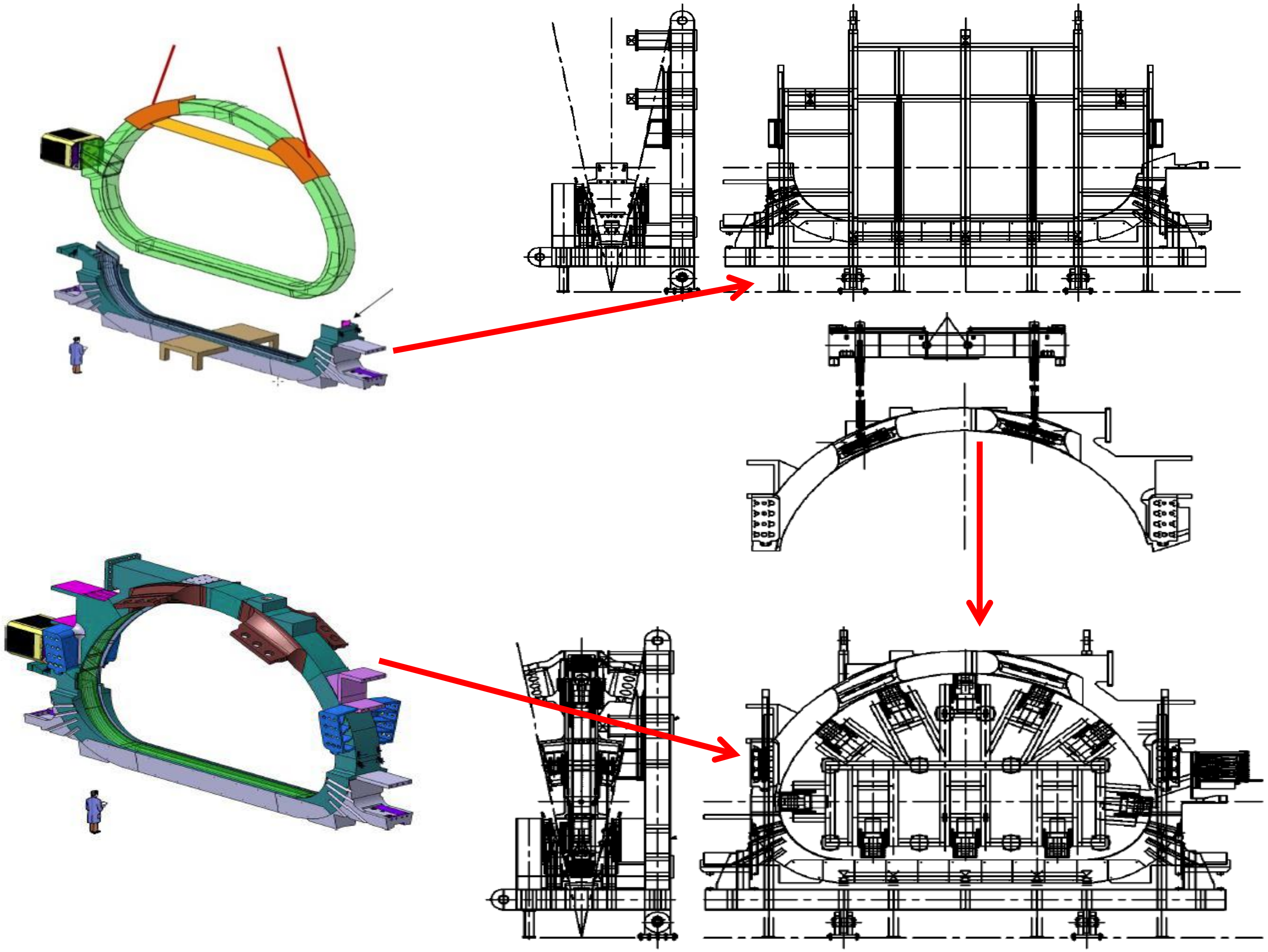
Typical machining accuracy 0.5-1mm

Courtesy QST, MHI and HHI

Last Step: Fitting the TF Winding Pack into the Case

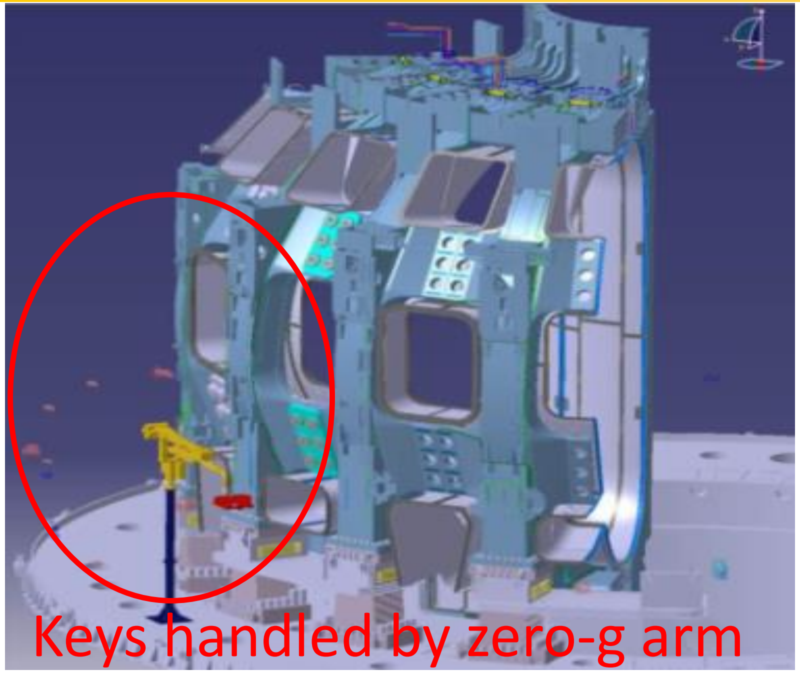
Vertical insertion route

- Lower WP into nose section
- Lower BU outer section onto WP
- Weld AU to BU: *control distortion*
- Insert AP and BP (spring into place)
- Weld AP to AU and BP to BU: *control distortion*
- Fill gap between winding pack and case
- Machine case



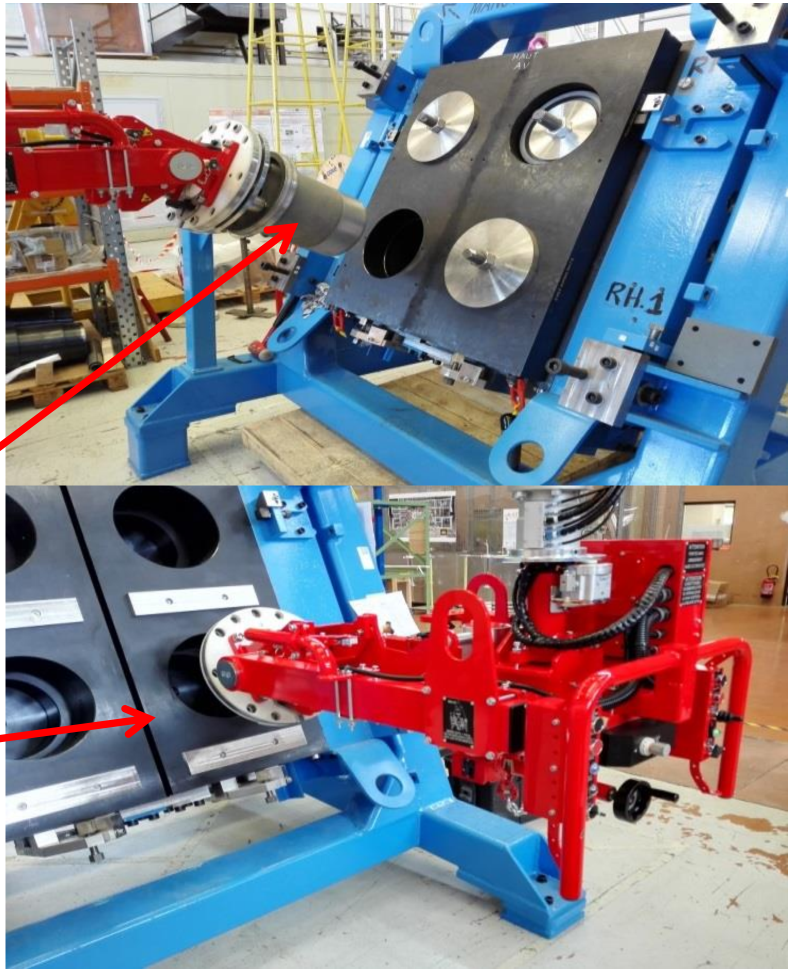
Target tolerance on interface surfaces <2mm

Development of Insulated Adjustable Keys and Bolts

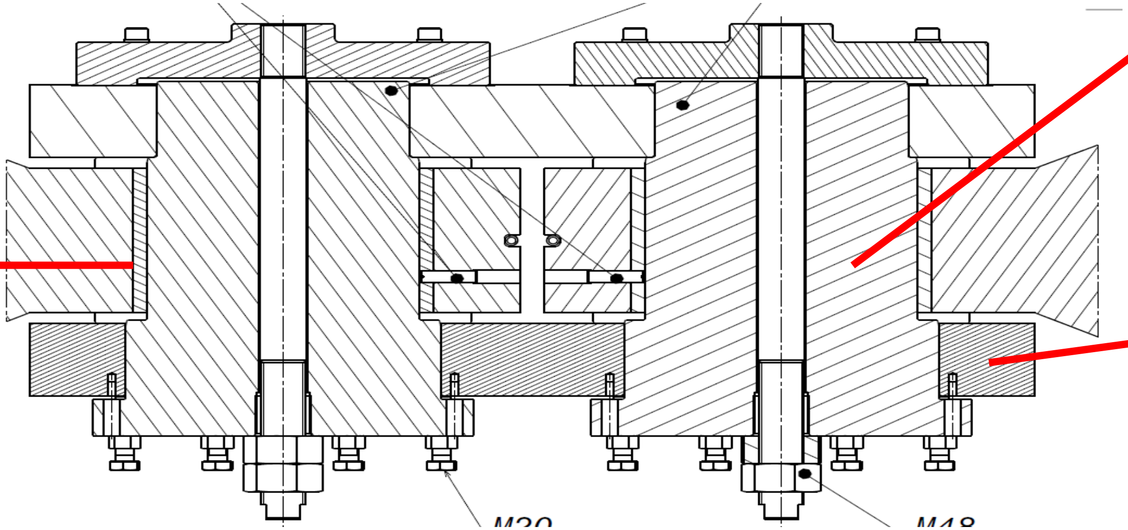


Example IOIS: Using adjustable sleeves, coil misalignment of 12mm can be accepted

Mock-up trials, full size



Adjustable sleeve



Electrical Issue. High voltage insulation

Challenges

- Unprecedented voltage levels for s/c coils, typical design range 20-30kV driven by coil energy and limits to s/c cable size
- Cryogenic (differential expansion) and vacuum (Paschen breakdown) environments
- Nuclear environment for some of the coils,

Solutions

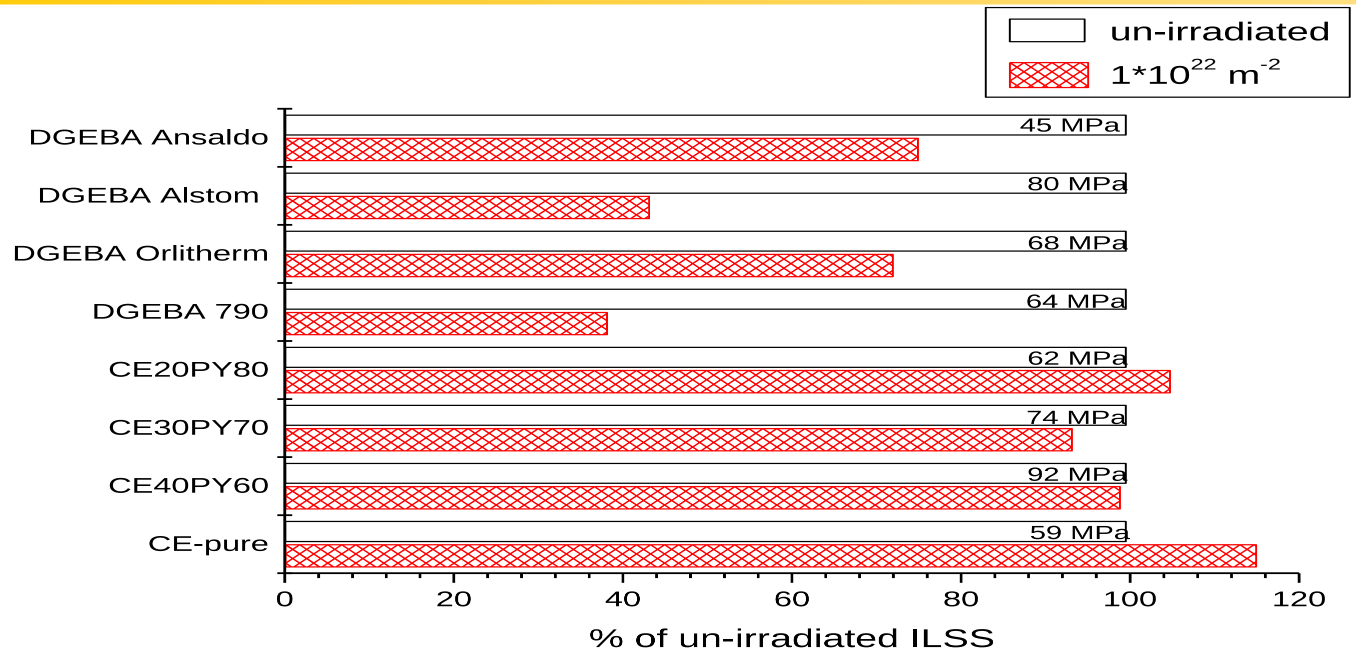
- Solid insulation systems, low void content
- Polyimide based electrostatic barriers
- Robust ground screens
- Detailed procedures developed and tested for weak points such a signal wire lead-outs

TF coil test voltages

Acceptance and Manufacturing Test Voltage Levels

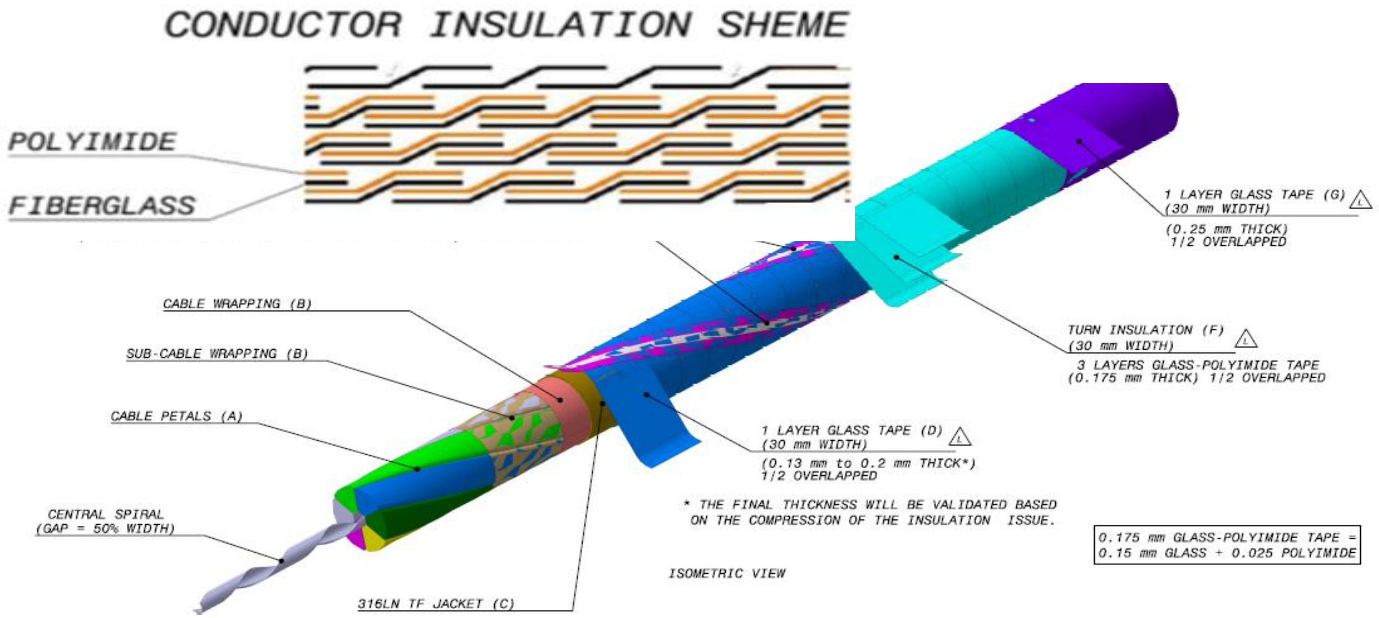
	DC Acceptance Test kV	AC Acceptance Test kV	DC Manufacturing Test kV	AC Manufacturing Test kV	Paschen Manufacturing Test kV
Turn to RP	>2.2	0.4	>2.2	>0.4	2.2
DP to DP	>3.4	0.8	>3.4	>0.8	3.4
WP to ground	>19.0	2.5	>19.0	>2.5	8.0

Solid Insulation in the Coils



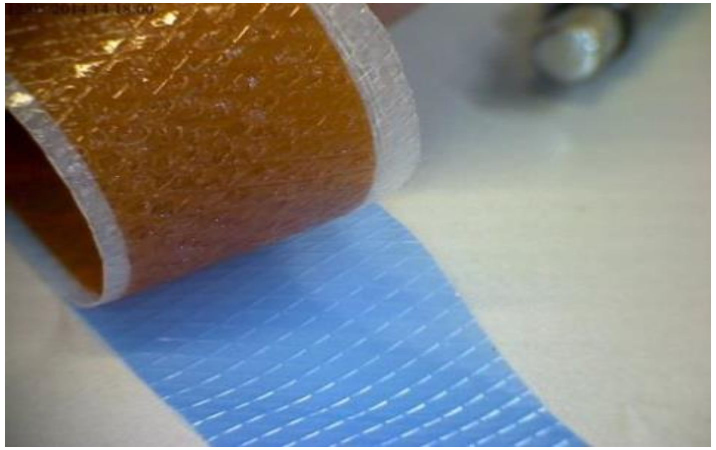
Blend of cyanate ester and DGEBA resin gives x2 improvement on radiation resistance

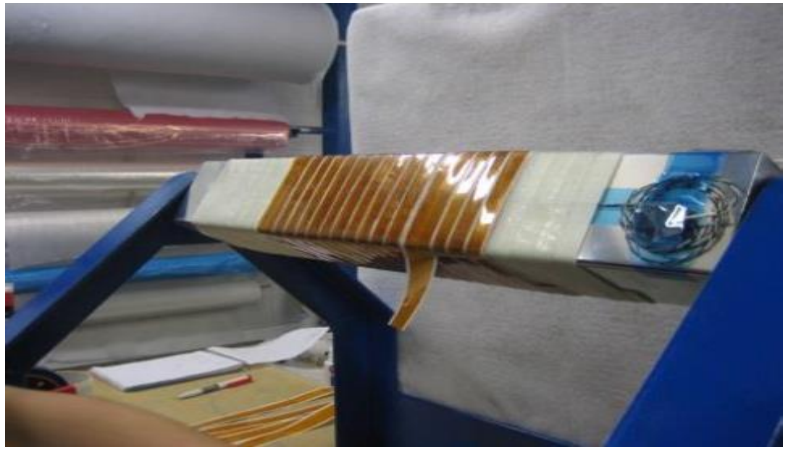
- ❑ Developed 2005-2008
- ❑ Many challenges in industrialisation
- ❑ Exothermic reaction in curing can become uncontrolled
- ❑ Some catalysts considered endocrine disruptors or calcinogens
- ❑ Etched polyimide film has increased shear strength

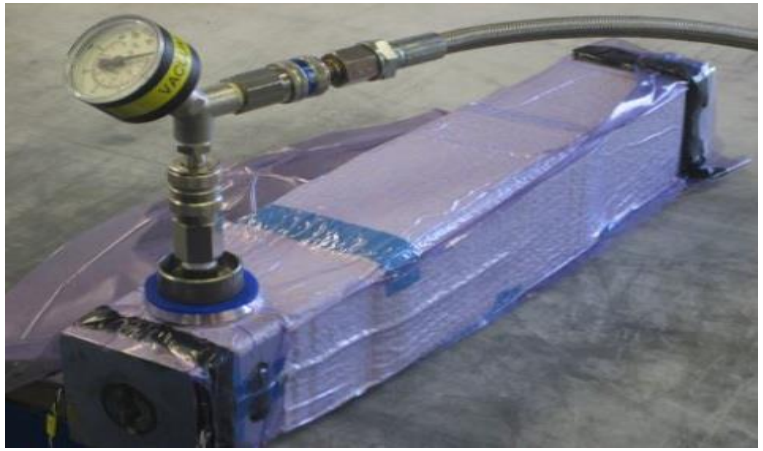


Hand wrapped insulation in feeders and on joints

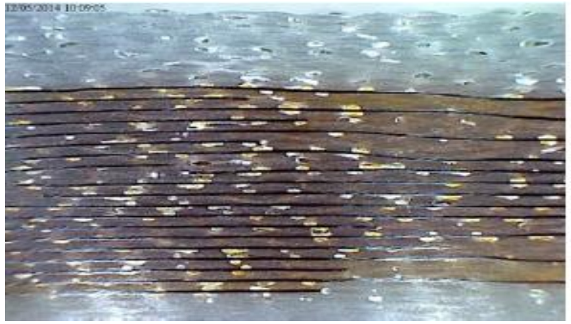
- Insulation specimens manufactured with pre-preg from different suppliers. Processing conditions optimised
- Pre-preg surface conditions important for bonding and voids
- Pressure important to reduce void fraction to 2-3%

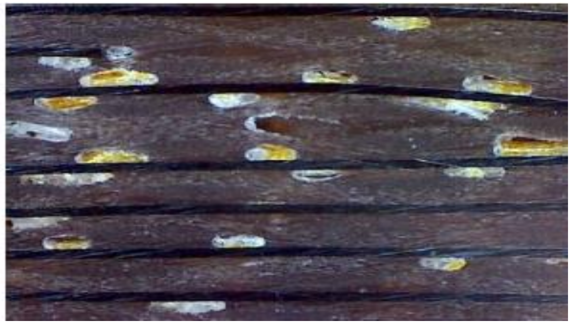




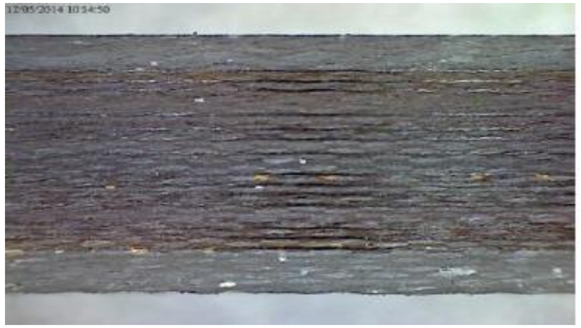


Some material / process combinations result in insulation with significant voids, leading to poor electrical performance

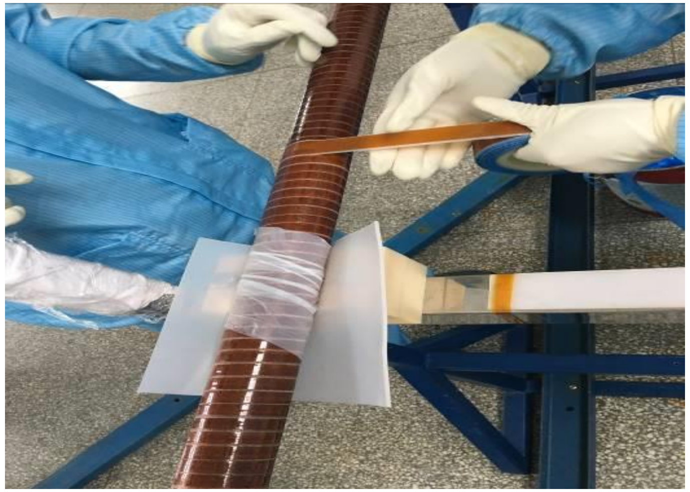




The final selected materials produce largely void-free specimens



Insulation Manufacture – Feeder Busbars & Joints


Feeder Wrapping


Ground screen


Silicon wrap to compress during curing

The joints have a complex outer geometry.
Insulation will be made during machine assembly
Insulation is cured in a vacuum bag.

CONCLUSIONS

On the magnets, we are gradually getting through the problems of 'First of a Kind' production

We can expect a busy 1-2 years of 'second level' manufacturing problems but we expect these to be containable

Of the 3 main challenges in the last 10 years

- Insulation is solved
- Tolerances have one last manufacturing step to solve and then we have to address *the machine assembly problems*
- Conductor degradation needs to be properly understood but we have routes to manage it if necessary