Overview of the ITER project, and our variable experiences in the development of some critical components of the magnets

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ITER IO, France

Abstract

ITER has now reached the stage where about half of the large magnet components have arrived on site and many more are nearing completion at manufacturing locations distributed throughout the ITER partners. Although we still have several years of challenging on-site assembly ahead, the acceptance tests and first-of-a-kind assembly are teaching us a lot about the magnet quality and possible improvements for future tokamaks.

The webinar will summarise the present status of manufacturing and assembly. Then I will chose 3 areas, critical to magnet and tokamak performance, to describe in more detail

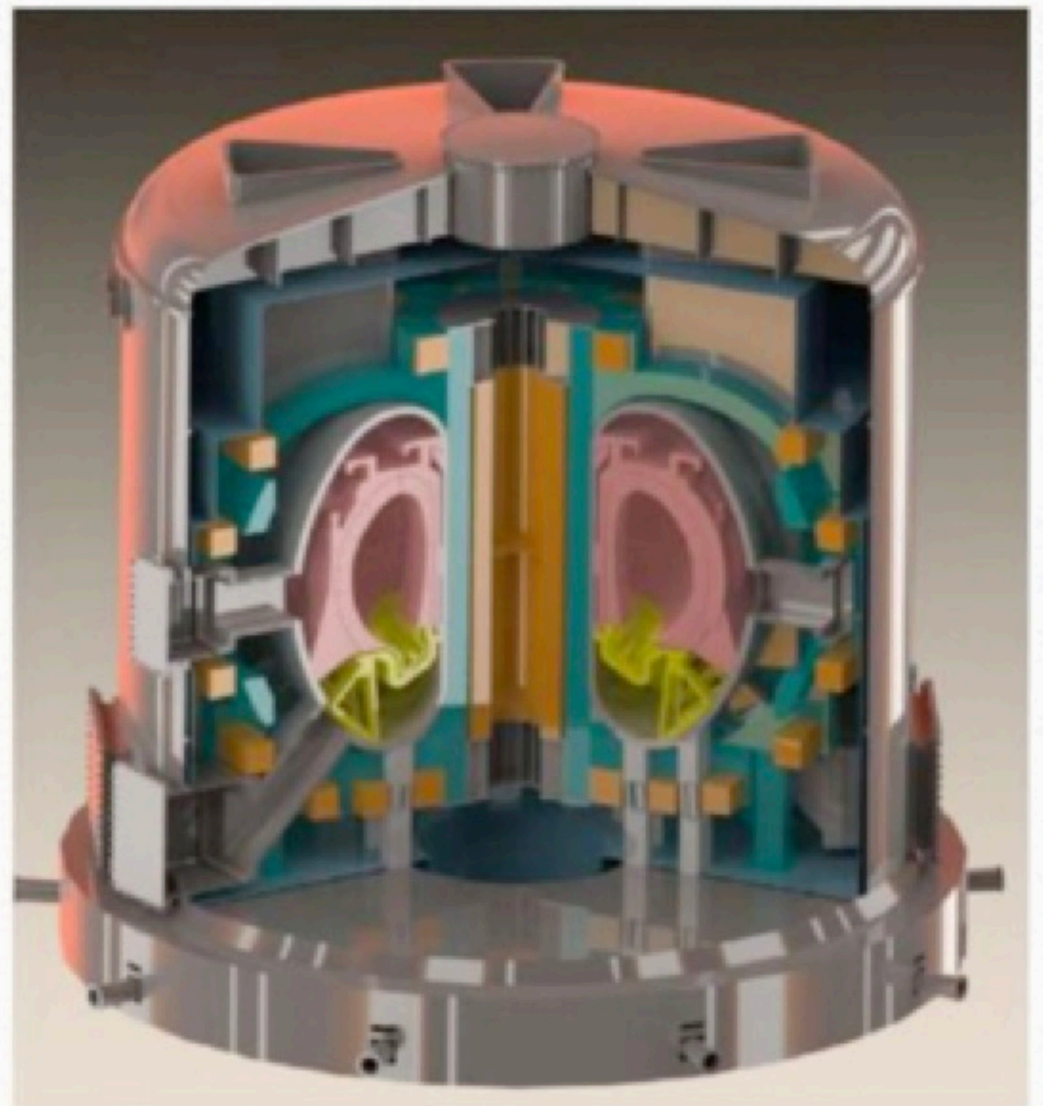
1. Development of Nb3Sn strands for fusion applications started in the 1980s and the selection of the material for the Toroidal and Central Solenoid Coils in the first phase of ITER 1988-1991 was a key driver of the overall tokamak parameters. The development, qualification and procurement, both before and after the decision to use it, gives us an unusual opportunity to look at the implementation of a novel technology in its entirety, with the expected and unexpected problems we encountered and how they were solved—or tolerated.
2. High voltage insulation in superconducting magnets is a frequently-overlooked area that demands many new technologies. It is the area in the ITER magnets that has created the most quality issues on magnet acceptance and is clearly an area where more engineering attention is required.
3. The need for improvements in overall integration of the magnets into the tokamak, and in particular maintainability and repairability, is being demonstrated as we assemble components into the cryostat. The assembly is proceeding well in terms of quality but at the same time, the complexity shows that for a nuclear power plant, we need improvements.

Drivers for the Future After ITER

- ❑ Progress in magnetic fusion plasma confinement: SIZE
- ❑ Progress in HTS: SC TECHNOLOGY
- ❑ Experience in nuclear tokamak construction: ENGINEERING INTEGRATION

Leads us to two clear groups

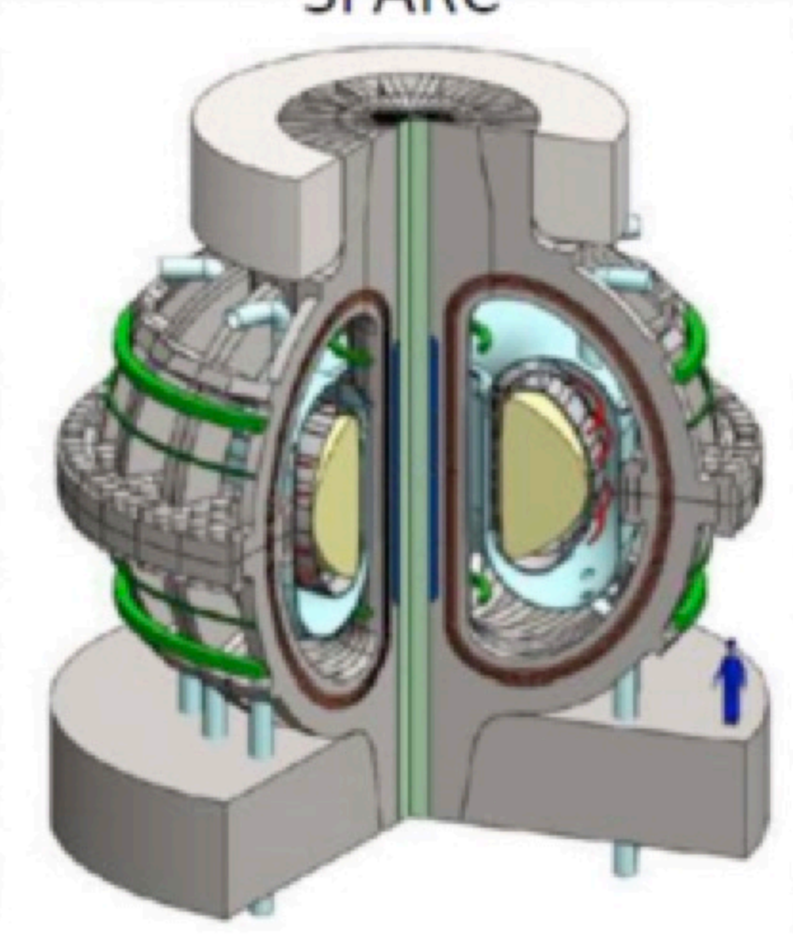
1) “DEMO” projects, e.g. in China, Europe, Korea, Japan, which are the natural follow-up of ITER. *The focus of design and R&D for these projects is about the improvement of the reliability, the reduction of risk in operation, the quality assurance procedures and the effectiveness (i.e. the cost) of the design and manufacturing approach.*
2) Use of new materials/concepts, especially HTS magnets, which are definitely not in the footprint of ITER. In contrast to the activities described above, *here the main object is to achieve proofs-of-principle and demonstrations for novel technology approaches which offer (potentially!) a better match to customer (utility) needs*



CFETR

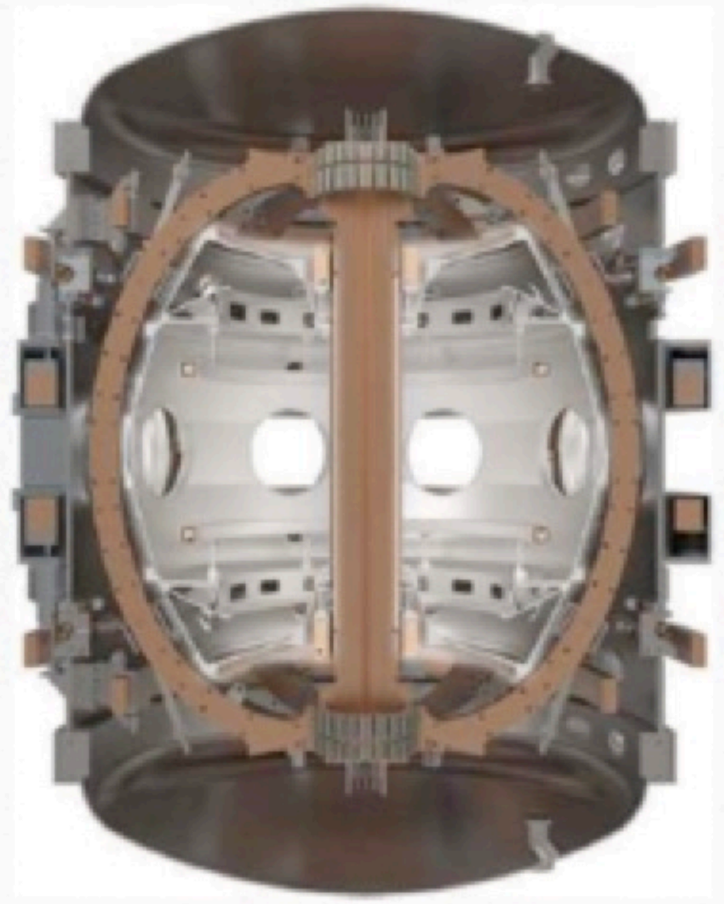
ITER like

SPARC



Compact machines

STEP

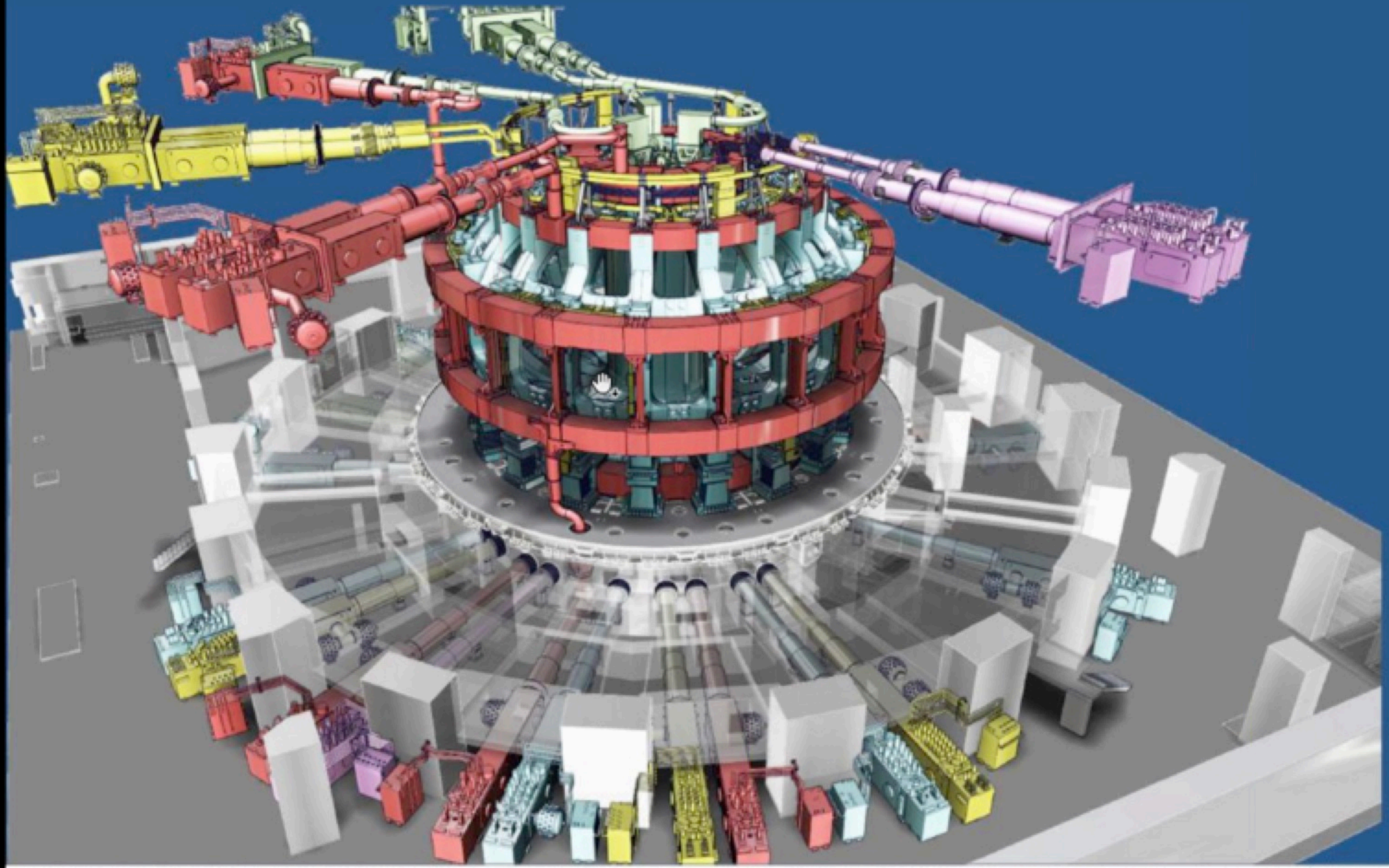


Overview of ITER and the Magnets

Status of ITER Magnet Manufacture and Assembly

- ❑ ITER Site
- ❑ ITER Tokamak and Manufacturing
- ❑ Transport
- ❑ On site Assembly

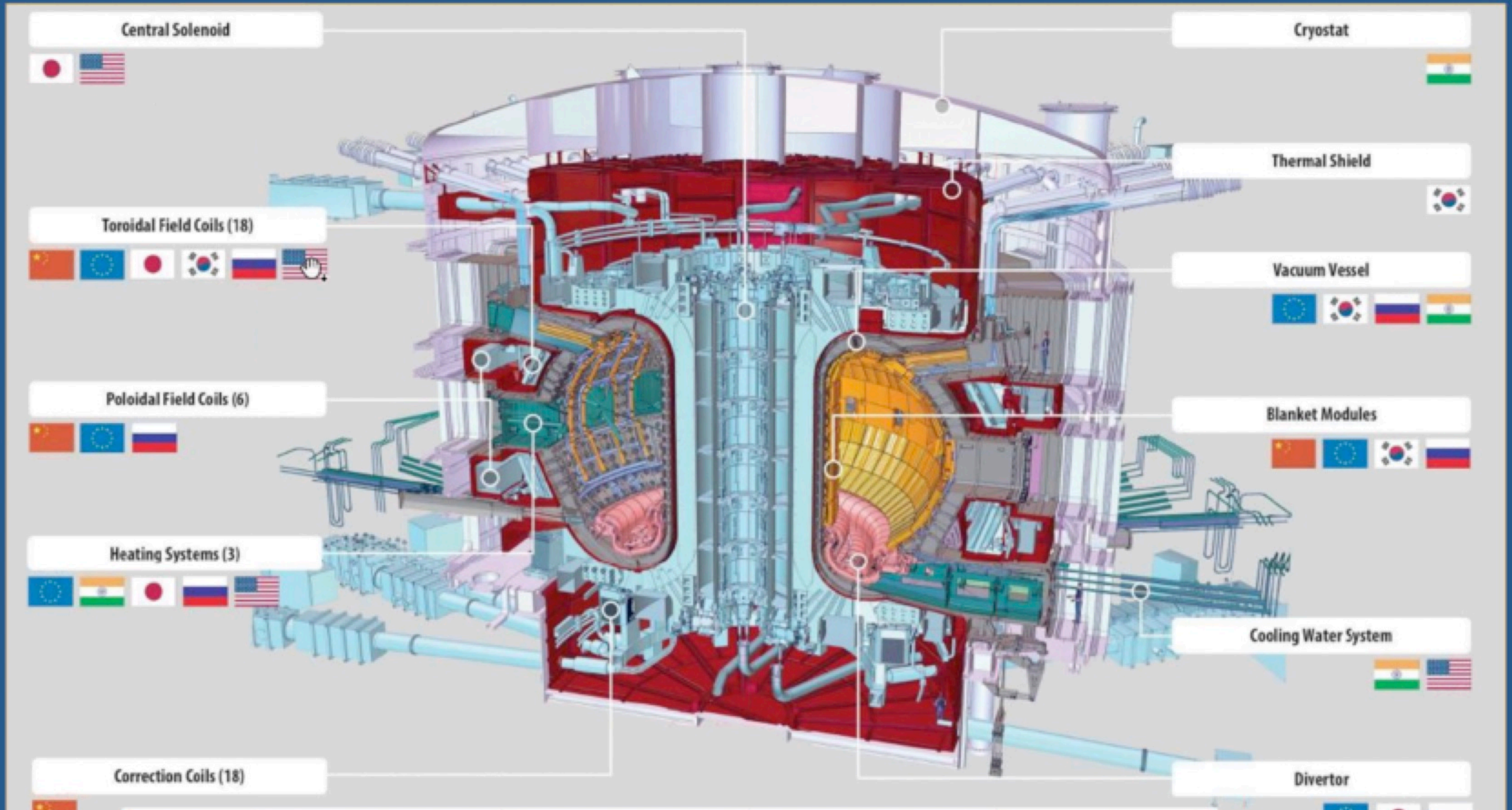
The magnets and the feeder system



Manufactured from niobium-tin (Nb3Sn) or niobium-titanium (Nb-Ti), the magnets become superconducting when cooled with supercritical helium in the range of 4 K (– 269 °C).

10,000 tons of magnets, with a combined stored magnetic energy of 51 Gigajoules (GJ), produce the magnetic fields that initiates, confines, shapes and controls the ITER plasma.

Main Manufacturing Sharing



The ITER Members share all intellectual and industrial property

Manufacturing Off- and On- site

Overview on deliveries

2 CS modules and the majority of the CS structures are on site

2 PF coils have been installed, 2 are at FAT stage and 2 are in manufacturing

10 TF coils are on site, 2 are in the process of installation. 5 are in the final stages of manufacturing

6 Correction coils (the BCC) are on site, 2 have been installed. 6 others (the TCC) are in the final stages of manufacturing and 6 (the SCC) are in manufacturing

TF Coil Status, Nov 2021

Coil type		Sectors	Status
F	TF12	6	Onsite, installed in first sector on SSAT2
A	TF13		Onsite, installed in first sector on SSAT2
B	TF08	7	Prepared, stored in B73.3
C	TF09		Prepared, stored in B73.3
D	TF10	8	Arrived in France
E	TF11		Under preparation in B73.2
D	TF16	5	Will ship from Japan in November
E	TF05		Under preparation in B73.2
B	TF02	4	Arrived in France
C	TF03		Onsite, stored
F	TF06	3	Onsite, stored
G	TF07		
D	TF04	2	In transit from Italy
E	TF17		
B	TF14	1	
C	TF15		
F	TF18	9	
A	TF01		
	Melco		
	TSB	KO	
	SIMIC	EU	

Some particular experiences during the magnet manufacturing

- ❑ TF with radial plates and wind-react-insulate and external case (QST & F4E)
- ❑ CS with hexapancakes and wind-react-insulate (US-IPO)
- ❑ Huge PF coils (F4E, ASIPP & Efremov)

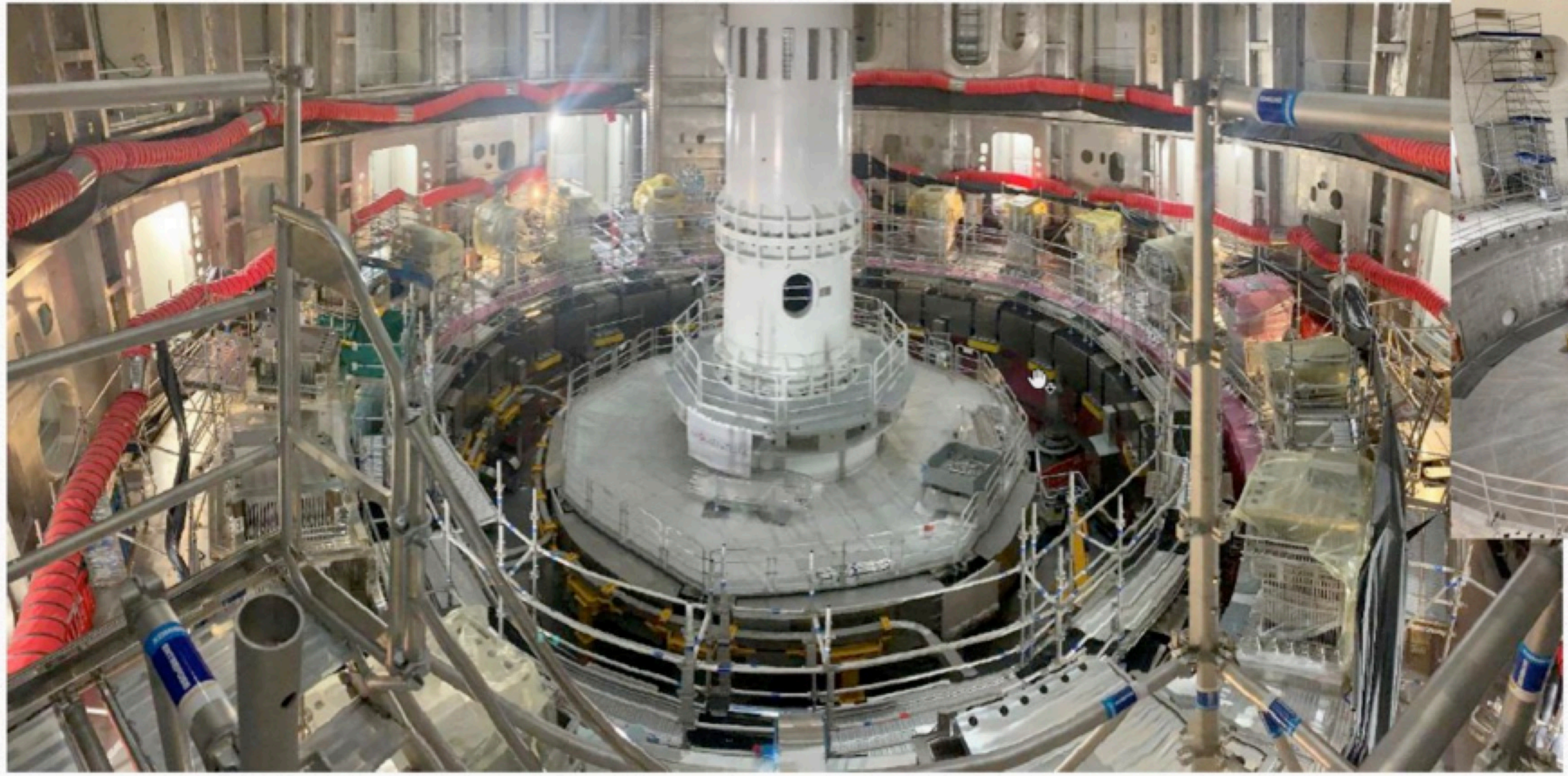
All worked well despite many doubts and arguments before we started

On site Assembly

Picture of in-cryostat changes over 15 months

Components are in ‘parked’ position until TF installed but we can already see the congestion

Nov 2021



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Focus on 3 Specific Issues where ITER Experience may be Relevant for DEMO

- ❑ Superconductors
- ❑ High Voltage Insulation
- ❑ Repair, Maintenance and System Integration

ITER Conductors

ITER conductors were always considered from the basis of 3 potential options

- NbTi superfluid
- NbTi
- Nb3Sn

But within these options there were many concepts for integrating the superconducting material into a conductor and then the conductor into a coil.

NbTi superfluid was soon eliminated due to the likely thermal loads and voltage restrictions (of He baths)

To achieve compact machine, only option was Nb3Sn. In 1988 & 1993, far from being an industrial product. But 'compact' machine perceived as low cost so Nb3Sn chosen

Internally cooled conductors with solid insulation systems soon became a baseline

ITER Conductor Programme Timeline

1987 — 1992 — 1998 — 2001 — 2007 — 2018

1987
NET and MIT start collaboration on Nb3Sn strands and CICC composite conductors

1988
ITER CDA decides ~1mm strand as base building block

1988-91
CDA- Multiple conductor design options

1993
New EDA decides conductor concept, circular CICC

1994-2001
Multiple coil concepts, stable conductor design

2002
Extent of Nb3Sn degradation issue in Nb3Sn CICC recognised

2003
ITER decides strand/cable copper distribution and jacket material

2007-2015
ITER conductor production

Industrialisation

React &Wind, monoliths discarded

Strand suppliers fail

Incoloy, Ti discarded

1979-85
US lead in Nb3Sn strands through LCT coil, MFTF-B, US-DPC coils: Airco & Teledyne

1989-91
Construction of first composite conductor high field test facilities: FENIX (LLNL) and SULTAN III

1987-91
NET, Kurchatov, MIT, JAERI fabrication of trial strands

Base building block: cable

1993-2002
CS and TF Model Coil Projects

1995-98
Extent of Incoloy cracking issue recognised

Base building block: jacket

2006-08
TF Recovery Programme #1

2017-18
TF Recovery Programme #3

2010-14
CS Recovery Programme #2

Crisis Management

ITER Insulation System

What is an insulation system?

In a superconducting fusion magnet system there are typically 2 systems, High Voltage (HV) and Ultra Low Voltage (ULV)

HV system has at least 7 components which have to be integrated (this is often forgotten…..at bottom level, something like 50% of ITER insulation problems have been caused by failure to consider ALL the integration issues)

1. Bulk within magnet (usually VPI)
2. Bulk on feeders
3. Locally applied by hand (outside VPI mold)
4. Instrumentation
5. Ground plane
6. Insulating breaks in coolant supply and return lines
7. Patches for repairs

What levels of voltage could be 'reasonable'

Copper coiled tokamaks built to high voltage requirements on PF system since 1970s

- Solid (VPI) glass-epoxy with kapton insulation as standard
- For example JET ground voltage is 20kV, test voltages about 40kV

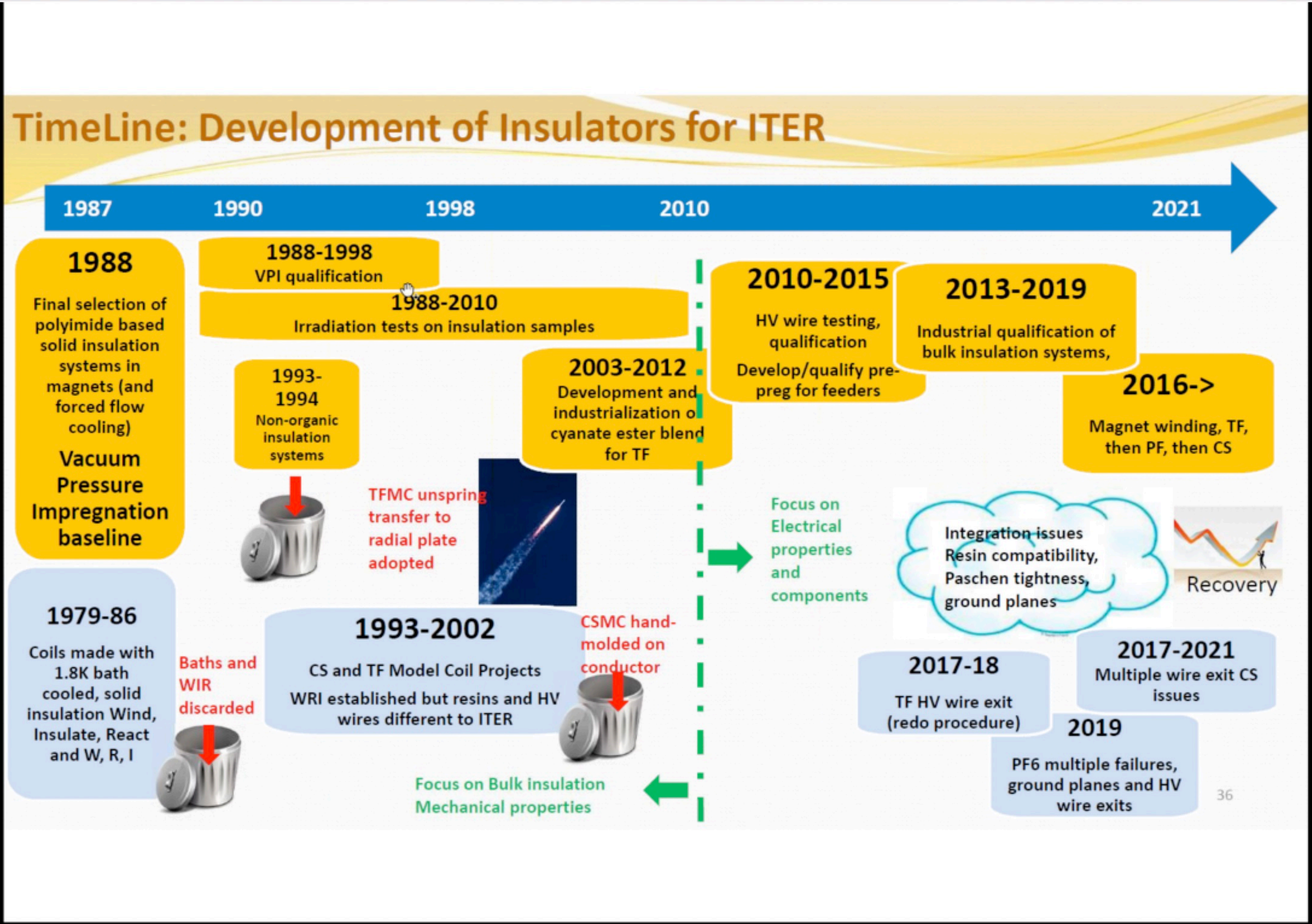
} But not in vacuum!

Early s/c tokamaks low energy & did not need to address high voltage issue, generally copper coils for pulsed CS/PF and steady s/c for TF (Tore Supra, T-7, T-15).

Now s/c voltage gradually increase

- ITER CS model coil factory tested at 30kV
- KSTAR tested at 15kV after installation
- EAST tested at 6kV after installation


Mitche


TimeLine: Development of Insulators for ITER
1987
1990
1998
2010
2021
1988
Final selection of polyimide based solid insulation systems in magnets (and forced flow cooling)
Vacuum Pressure Impregnation baseline
1988-1998
VPI qualification
1988-2010
Irradiation tests on insulation samples
1993-1994
Non-organic insulation systems
2003-2012
Development and industrialization of cyanate ester blend for TF
TFMC unspring transfer to radial plate adopted
2010-2015
HV wire testing, qualification
Develop/qualify pre-preg for feeders
2013-2019
Industrial qualification of bulk insulation systems,
2016->
Magnet winding, TF, then PF, then CS
Focus on Electrical properties and components
Integration issues
Resin compatibility,
Paschen tightness,
ground planes
Recovery
1979-86
Coils made with 1.8K bath cooled, solid insulation Wind, Insulate, React and W, R, I
Baths and WIR discarded
1993-2002
CS and TF Model Coil Projects
WRI established but resins and HV wires different to ITER
CSMC hand-molded on conductor
Focus on Bulk insulation Mechanical properties
2017-18
TF HV wire exit (redo procedure)
2017-2021
Multiple wire exit CS issues
2019
PF6 multiple failures, ground planes and HV wire exits
36

Overall Conclusions

- ITER sc base technologies (conductor, insulation, winding, structure) offer many good qualified building blocks, *not only for ITER-like machines*

- Engineering integration needs improvement (simplification, selection of fewer building blocks!) and in some areas (voltage, tolerances) we need to consider reducing requirements. *Minor reductions could bring large advantages in manufacturing, reliability and integration!*

- ITER development experiences have improved engineering maturity of LTS superconductors and High Voltage technologies but there is more to do if new technologies like HTS are used for DEMO…and ITER took 20 years to bring LTS to maturity. *Lessons to be learned for HTS!*

- ITER magnet engineering concepts/solutions need improvement for DEMO (feeders, wiring, access, repair, reliability), with an engineering priority in the base ex-vessel machine as the tokamak design driver. ITER has led with many technologies, now we need to improve their integration. *This applies, ITER like or not!*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