Successes & Failures in Design Solutions During the 30 Year Life of ITER (and how we could have improved)

Author: N. Mitchell with contributions from IO, DA and industrial colleagues

Over 30 years ITER has been through many design iterations and multiple novel solutions for the magnets have been tried, in some cases being carried through to successful manufacturing and in other cases being abandoned. Now that ITER operation is approaching, the fusion community is considering possible next steps, to a power producing fusion plant. If we consider the long road ITER has followed, what lessons can be learned for these next steps?

Looking back at the design iteration history of the ITER magnets, there are several key factors driving magnet design, such as superconductors, structural Support, voltage and thermal protection, power supply arrangement and feeders. We can see the new availability of advanced materials and design techniques including high Tc superconductor at low temperature, cable-in-conduit (CICC) development and analytical magnet design. The presentation will look at what ITER did in the early stages in this direction and how a future reactor design could utilise these concepts in the magnets.

Perhaps the most basic lesson is that if a tokamak reactor tries to satisfy the research priorities of many, it can end up as a machine being designed by a committee. This is really the political environment but it can be decisive (as in the case of ITER) in determining the nature of the project. Beyond this, we can look at the many novel technical solutions (those that made it into the final ITER magnets and those that did not) and consider whether we could have been more efficient….and whether we can see any signs of the same mistakes being repeated.

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

ITER Project Timeline

1982 | 1988 | 1988/89 | 1991 | 1993 | 1990s | 1998 | 2001-2006 | 2006-7 | 2007-19 | 2020=>

1982

INTOR activity - beginning of the development of "next generation tokamaks"

Ideas, one co-ordinated design (NET)

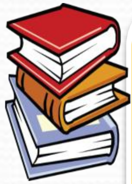
Various EU, JA, RF and US groups participate

1988/1989

Political decision using INTOR basis to launch ITER with the Conceptual Design Activities (CDA) hosted at NET

1989-1991

ITER CDA, four groups participate representing the major fusion research programs (EU, JA, RF, US)



CDA report. One machine with options

1993

ITER EDA agreed. 3 sites. Director abandons CDA, redesigns machine

1990s

Successful realization of

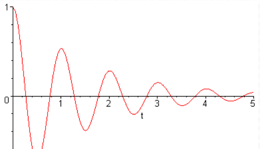
"7 large projects" in parallel with design iterations of a single ITER machine concept during EDA

1998

Budget constraints, "reduced performance design", US leaves

2001 Final Design Report

FDR 1



2001=>6 design improvements

2001-2006

ITER continues, not covered by a formal agreement among the partners. KO, CN join, US rejoins

2002-2005

Negotiations on how to build ITER. In-kind supply invented

2006 Design Review

2006-19

Manufacturing design, industrialisation & qualification, production, buildings erected

2007

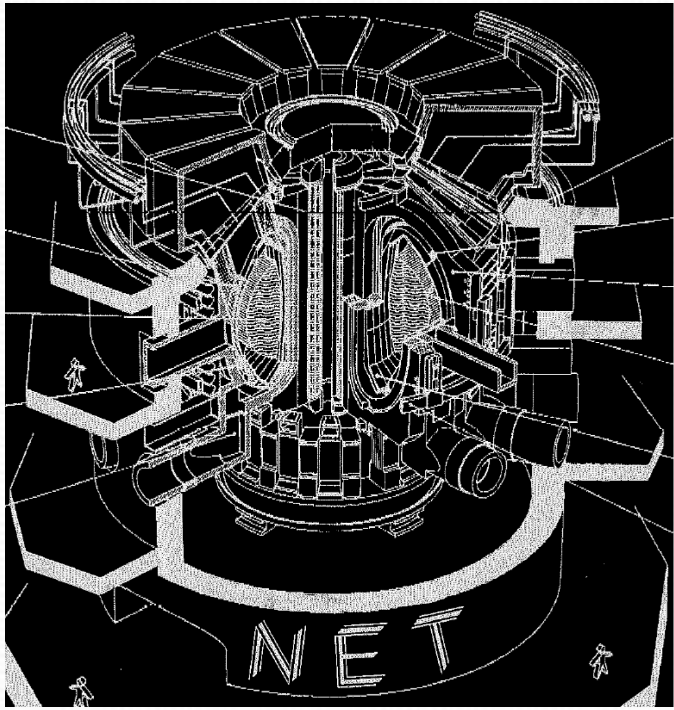
ITER Agreement Project entered the Construction Phase

2020=>

On site assembly of tokamak starts

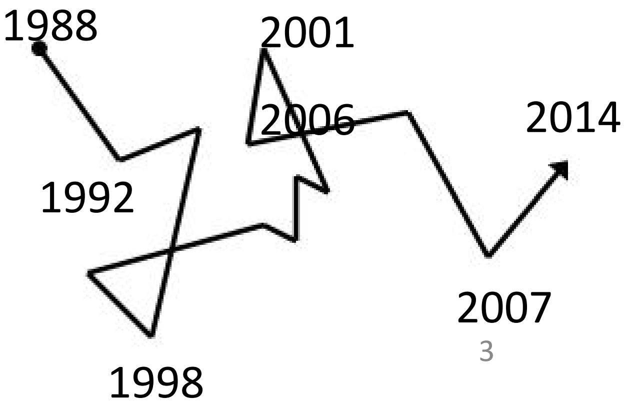
ITER Magnets

- The design roots go back to 1988, the start of the CDA and the NET machine. Present design mostly from 2001 which itself was based on the CDA final design report (1992) which had commonality with the NET project 1988 report (Fusion Technology July 1988--right)



- Changes, sometimes significant, to surroundings and requirements have created something of a random walk over the last 30 years. *We have a design that meets our needs but cannot be said to be optimised. We are where we are…..even if sometimes we don't like it*

- The magnet parameters (field & volume) act as the primary drivers for the overall machine size. *One of the lessons learned from the history of ITER is that giant oscillations can be created between adventurous (but perhaps unrealistic) design choices that produce large promised cost reductions and more sober (but on-paper more expensive) design realism.*



Three Key Choices in ITER Magnets

Question: Looking at the oscillations of the ITER Project as a whole and the tortuous history of the selection/ development of key technologies, may ask “why didn’t you apply a basic engineering approach (i.e. good engineering practice) from the start in 1988 (or even 2001)?”

Answer: “because we couldn’t”. International collaboration in ITER created continuity but also a reluctance to allow decisions to be made based on engineering need. Tendency to end up with sub-optimal & badly integrated engineering solutions, with cost/schedule higher than needs to be because necessary design changes & convergence can take years to implement

Many technology areas in ITER where early ‘choices’ had a major impact

Consider 3 of these as examples for detailed examination, look at what went right….and wrong

Insulation Systems (from 1988) ➔ consider in detail

Superconductors (from 1987) ➔ consider in detail

Repair and Maintenance (from 1988) ➔ consider in detail

Key Choice: 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

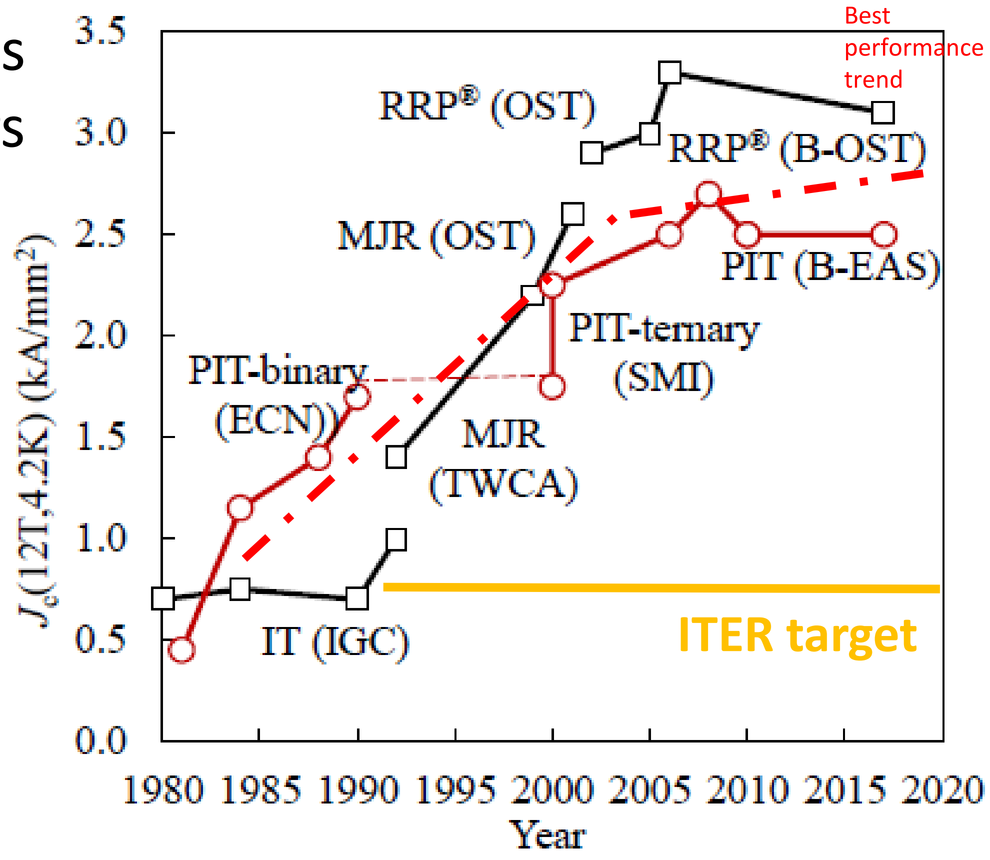
2017-18
TF Recovery Programme #3

2010-14
CS Recovery Programme #2

Crisis Management

Development Drivers for Nb3Sn Strands

- One of the reasons for successful use of Nb3n in ITER was fixing ITER target Jc for nearly 30 years, allowing suppliers to focus on cost and unit length- and price per kg, NOT price per Amp of transport current
- Strong contrast to HEP which has driven high jc development
- Major distraction and source of problems for the use of Nb3Sn has been the constant push to get higher jc by exploiting strain dependence, by jacket material or conductor manufacturing route rather than holistic approach to full engineering problem



Nb3Sn Technology for High Field Accelerator Magnets

Acknowledgement Alexander V Zlobin (Fermilab)

Cable in conduit conductor type used for fusion Nb3Sn from 1970s and became conductor of choice from early 1990s: stability in needs, time to discover MOST issues

Convergence to Final ITER Conductor Design in 1993

Cable in Conduit 1991

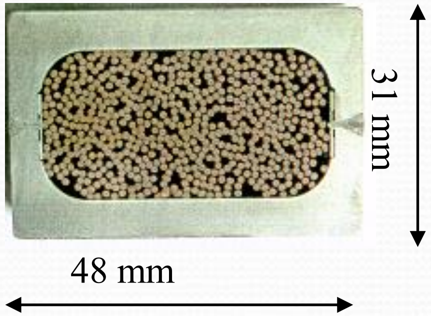
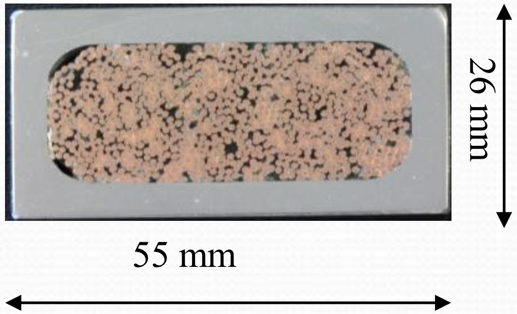
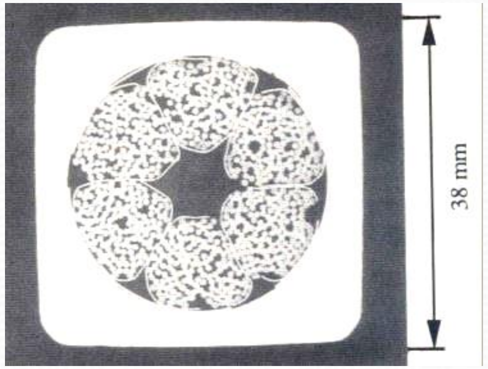


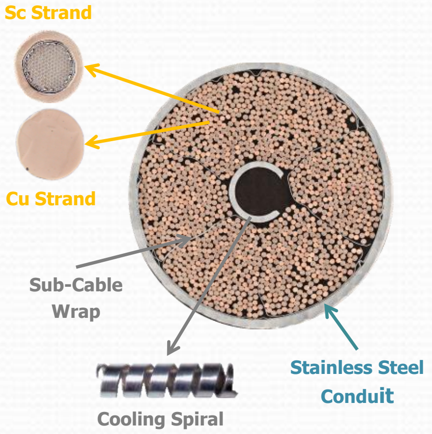
ABB – 1990 Laser welding

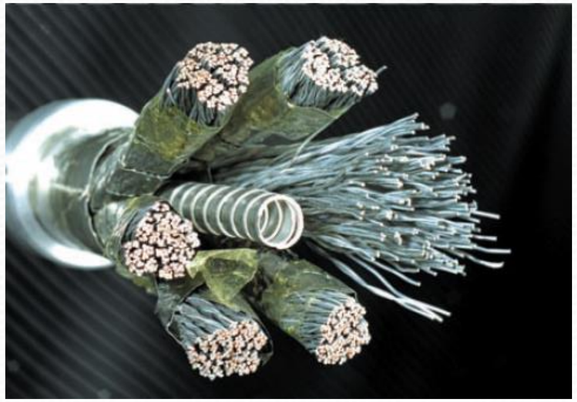


LMI – 1992 Extruded conduit



CEA NbTi – 1992 Central hole





1993 70kA TF

Left open until the 2000s

- Strand coating (Cr vs oil/carbon), interstrand resistance, current uniformity and control of AC losses)

Left open until the 2010s

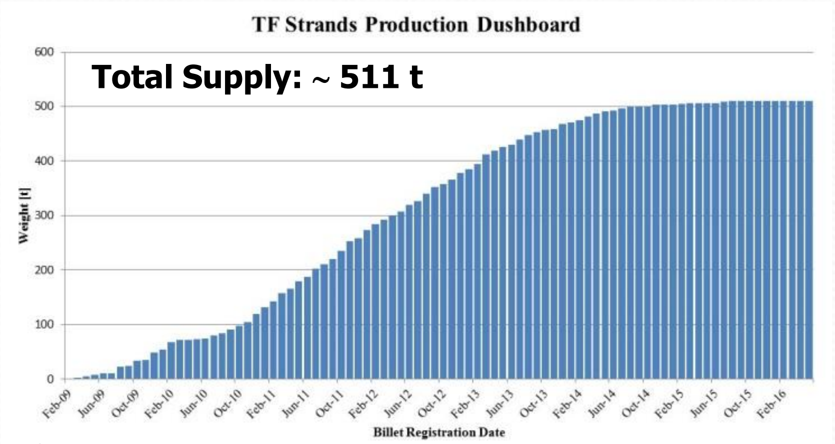
- Cable patterns (and degradation)

CS conductor (short twist pitch)

TF conductor (pseudo long twist pitch)

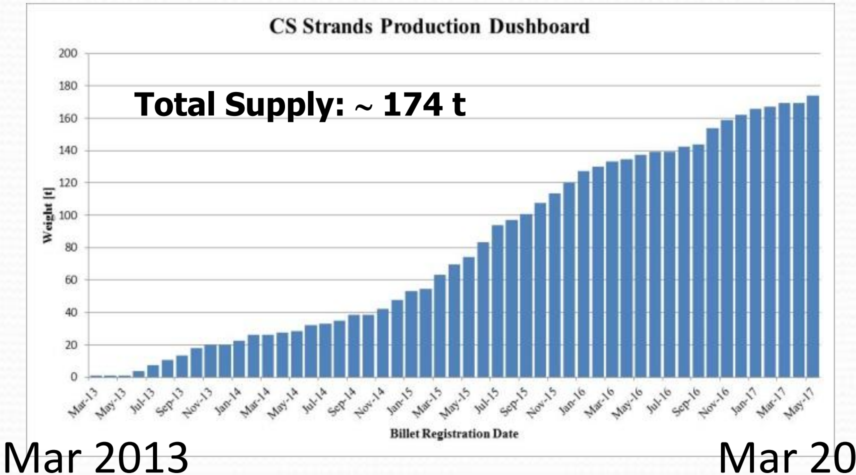
Strand Production

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



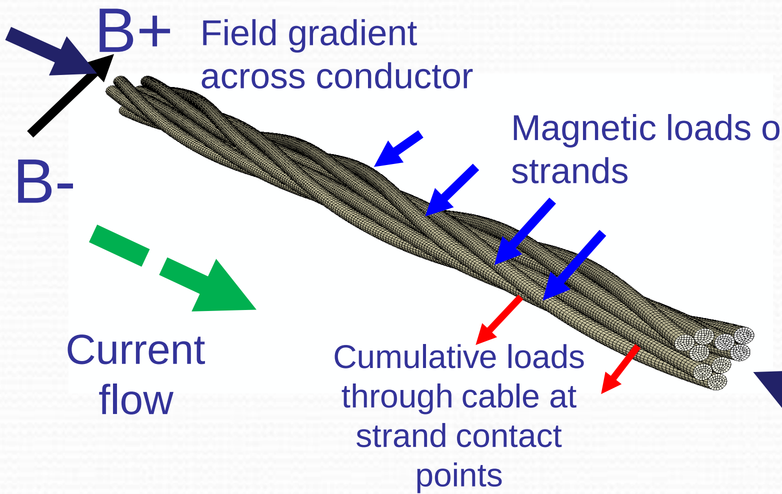
Feb 2009 Feb 2016

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



Mar 2013 Mar 2017

Conductor production ran well…but we discovered that there were undiscovered issues with the cables which we thought we had fixed in 2011



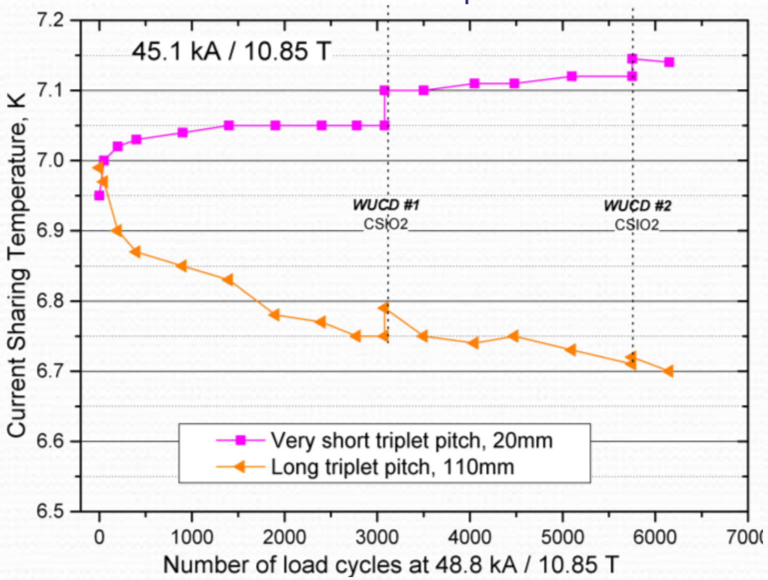
Field gradient across conductor

Magnetic loads on strands

Current flow

Cumulative loads through cable at strand contact points

Thermal loads on strands from jacket



Stand twist pitch has strong impact on mechanical support in the cable. Long twist pitch allows extensive filament fracture to develop

Conductor Conclusions

- A very long convergence process to the final ITER design.
- Large scale testing (insert coils) was critical in this process as it gave undisputable results
- We made mistakes & discoveries, painful corrections during and after manufacturing. Fortunately we built in sufficient margin to cover the worst of these (TF degradation)
- Not everyone agrees that these conductors should be used ‘as is’ for DEMO but they could be
- Amazingly the conductor manufacture did not prove to be a constraint on the ITER construction schedule.
- To take the conductors from the short length (strand and cable) to completion of large scale industrial production took more or less 20 years

So

- Do not expect that a completely new conductor will be much different, for example if based on HTS materials where limited engineering maturity is a concern
- ITER conductors have been well qualified but (apparent) small changes may result in surprises: consider for example the Nb3Sn degradation issue solved by (empirical) cabling adjustments in the CS recovery programme in 2010-14 (earlier slide)
- To minimise these surprises full size testing is critical

Key Choice: 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

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

TFMC unspring transfer to radial plate adopted

2003-2012
Development and industrialization of cyanate ester blend for TF

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

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

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

Coil Bulk Insulation

Impact on Insulation of R&W/I and W/I&R and W&R&I conductor concepts

R=react W=wind I= insulate

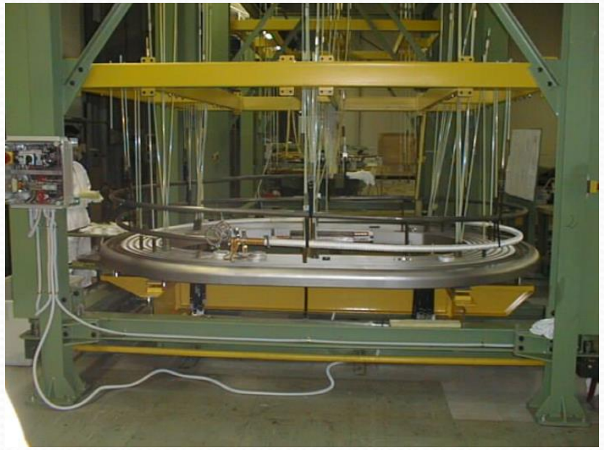
Final selection of W&R&I from 1995

- Early insulation systems <1994 did not integrate dielectric barrier within winding (only as ground reinforcement)
- Relied on stand-off produced by glass filled with epoxy….as long as no cracks
- Glass wrap was compatible with W/I&R coil winding process where the glass went through the Nb3Sn heat treatment
- Despite this from 1988 on TF coil voltages of 20kV to ground and 10kV on terminals were regularly chosen

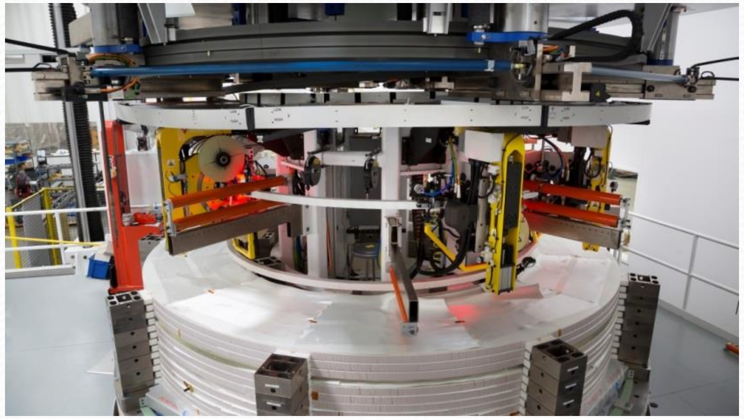
Present experience that these insulation systems would not have worked. Fortunately we did not build them

From 1993 multilayer insulation (familiar in copper coils) was standard

Issues to be addressed are well known and include outgasing of glass to avoid bubbles, resin penetration and cracking. Much more significant in cryogenic coils with thermal cycles and vacuum



Demonstrated on TF MC 1998



Implemented in ITER 2012=>
Top: CS, Below: TF

Requires controlled handling of (delicate) Nb3Sn reacted conductor

Coil Insulation Testing

Quality Testing

❑ Up to 2008, only HV DC testing

❑ From 2008, IO introduced Partial Discharge characterisation and Paschen breakdown testing. Now by far the most critical tests, and used for development as well as qualification and production

❑ Void fraction measurements also improved

Paschen Test on PF6: HV wire exit failure

HiPot Test of CS Mock-Up: arcs between HV wires

CSM3 (& JT60) arc damage after Paschen failure of feeder in test facility

Top left: coil terminal and co-ax joint connection to busbars, as installed
Top right, after arc. Steel clamps are clearly melted

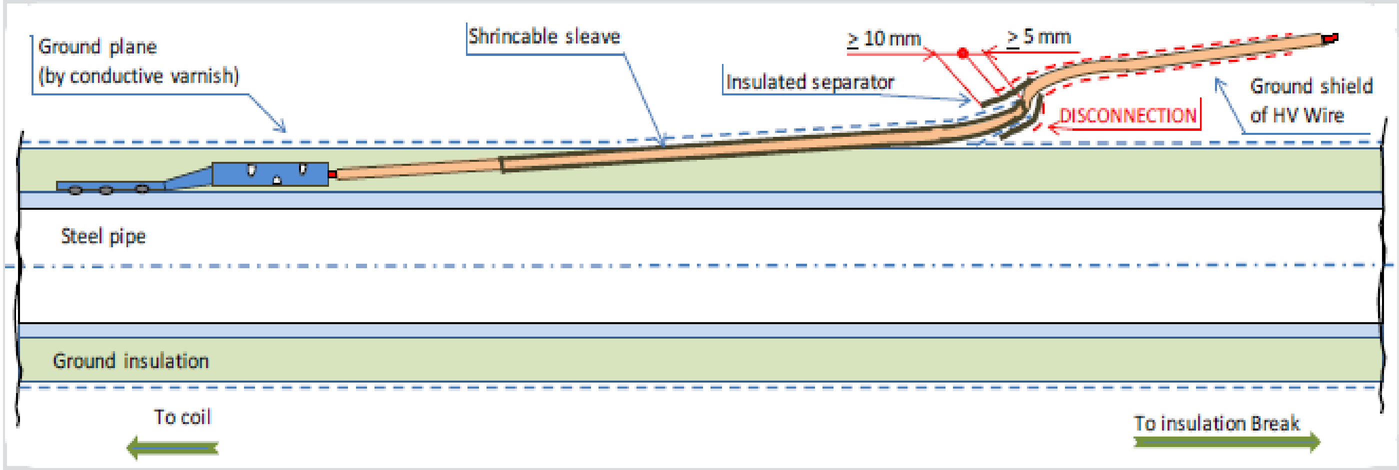
For CS, root cause seems associated with insulation failure on a feeder, not coil

However for both CS3 test and JT60, extent of damage….and propagation of multiple arcs within feeders, structures and instrumentation gives a clear warning about potential hazards of high voltage operation in ‘vacuum’ and need for robust quality controls

Overview of Insulation Non-Conformities During ITER Coil Final Acceptance Tests

- Multiple failures on PF6 at FAT, instrumentation wire exits and hand made insulation
- Multiple failures on CS with dummy in HV wires (wiring layout revised) and on first 2 modules (HV wire exits)
- Several failures on TF coil at FAT, instrumentation wire exits
- Two HV failures in feeder CTBs

Almost all where HV wires (QD systems) exit ground insulation



Generally, recommended design not exactly followed and necessary qualification steps were not fully performed

However this is clearly an area where the manufacturing and possibly the requirements need reviewing

Insulation Lessons to be Learned

Global Messages

- ☐ High voltage insulation of superconducting coils is BY FAR the most challenging problem in the magnets, far more difficult that the superconductivity itself, or helium leaks…as demonstrated by major failures in the manufacturing of every coil system
- ☐ The weakness is not the bulk insulation but the (necessary) wire penetrations and hand made regions
- ☐ Insulation quality testing in operation is basically a destructive proof test. We have developed slightly less destructive tests (Paschen test for example) but its application to an operational machine looks challenging because of the difficulty to locate faults when they occur (we need cameras). Otherwise, we are likely to discover faults only by making the magnets unusable

For DEMO the key messages are

- Reduce the voltage
- Reduce the HV instrumentation or (better) eliminate. Find other non-intrusive QD methods
- Pre-manufacture insulation penetrations and Paschen test with thermal cycles. Helium tight welding is easier than Paschen tight instrumentation insulation
- Prequalify all components on the insulation system especially resins and application techniques and impose that manufacturers use them exactly
- Improve HV testing techniques (qualify, safety factors, include cold Paschen tests, transient tests)

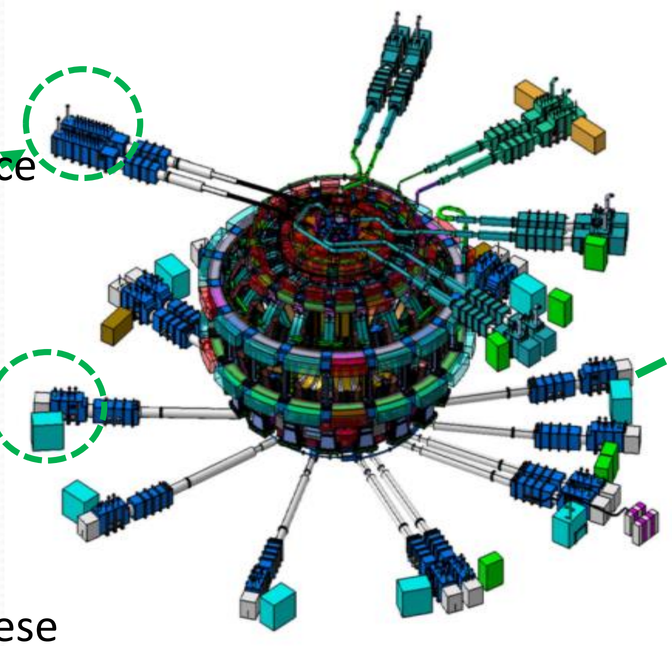
Key Issue: Maintainability & Repairability

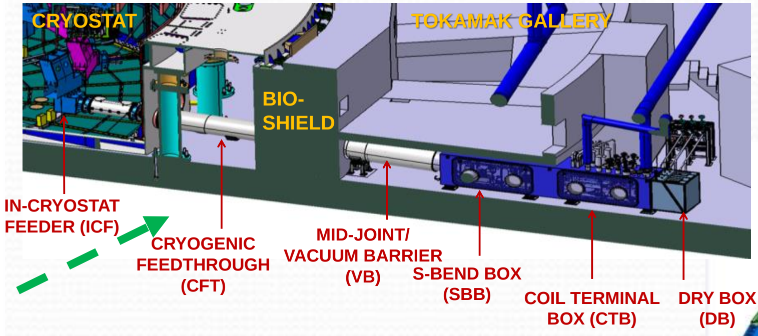
ITER magnets inside cryostat were designed not to require maintenance. All parts that need maintenance, or with limited life, are in the accessible CTBs outside the bio-shield

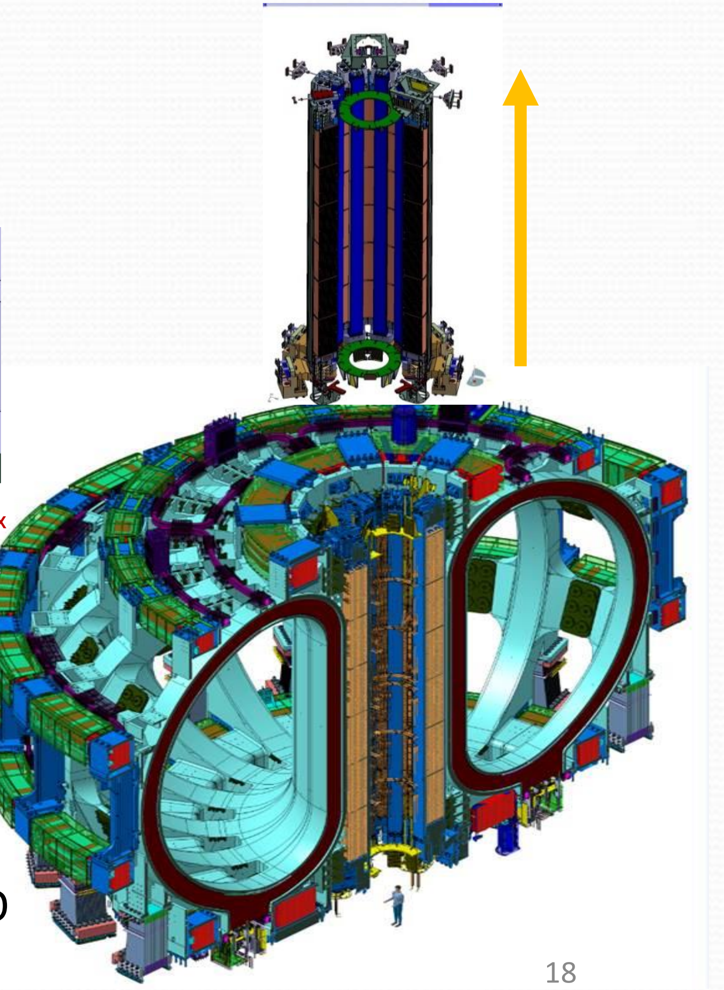
Although the magnets appear as a set of impenetrable rings, recovery options have been included

- ❑ To allow full removal and repair work outside the machine **== CS**
- ❑ With extra redundancy and coil design to allow faulty parts to be bypassed **== PF**
- ❑ With double insulation systems to reduce fault probability **== TF**

Components needing maintenance or replacement (valves, critical Sensors)



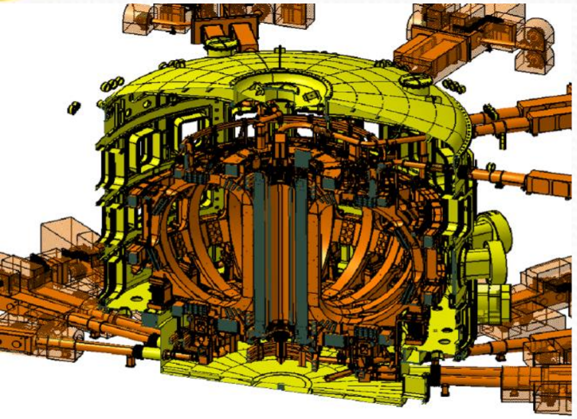




Main issues with these

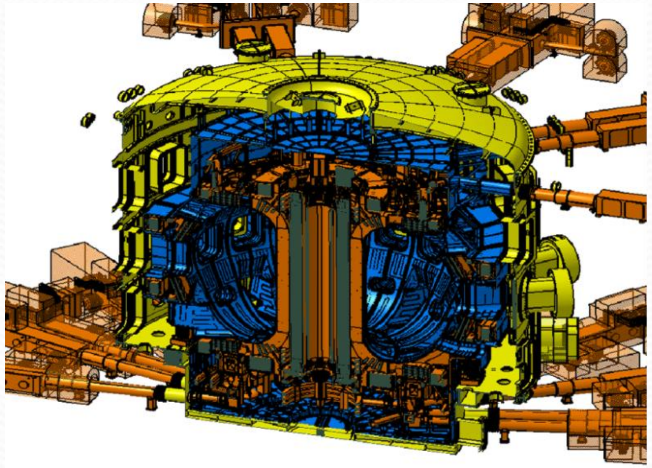
- They have been greatly complicated by the late design development of the feeders
- Limited compatibility with nuclear operations. But provide concepts applicable to a DEMO

Problems of In-Cryostat Working

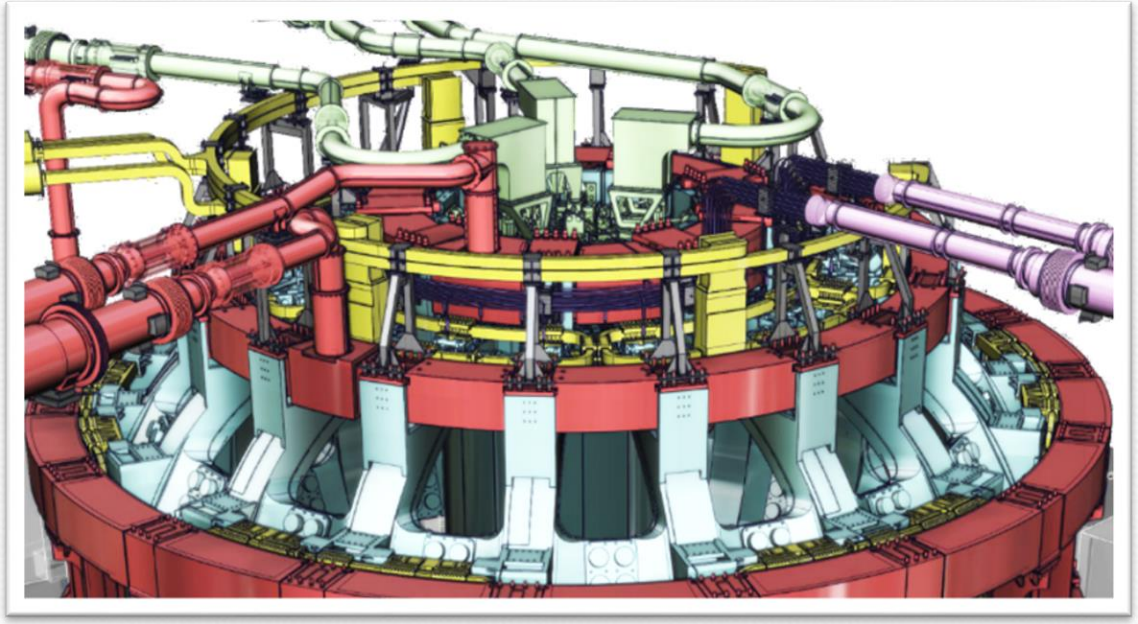


Magnets and Cryostat

Magnets, Cryostat
and Thermal Shield

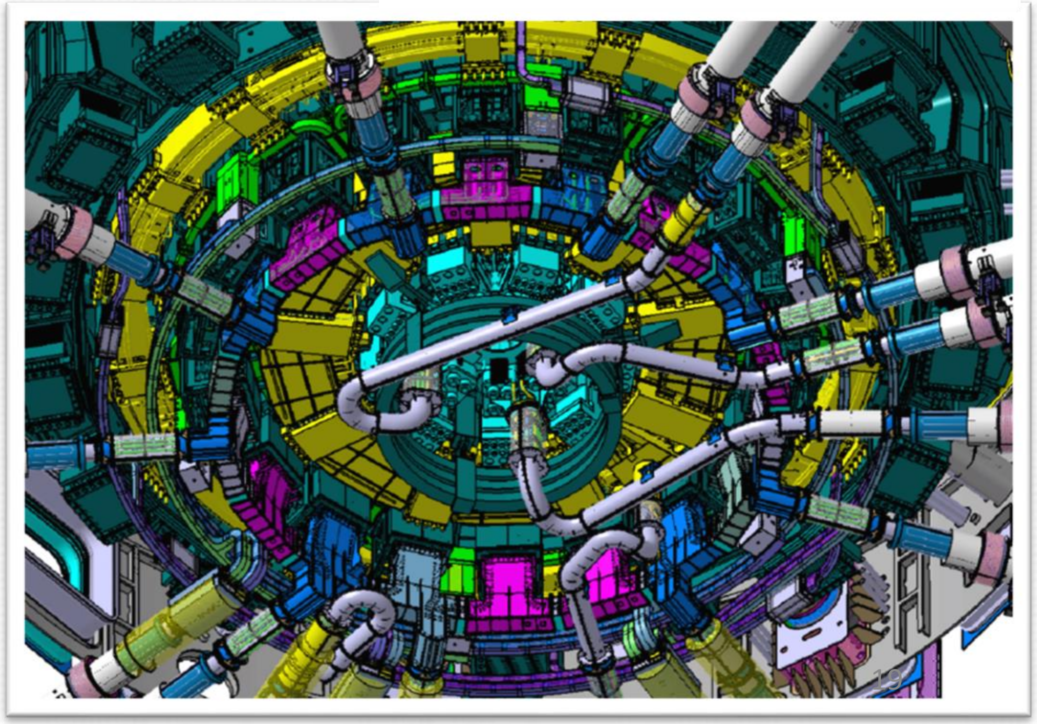


Access to auxiliaries (HV wires, joints etc) is hugely complicated by feeders and TS



Top of the machine

This part of the design could be greatly improved in DEMO **IF allocated priority**

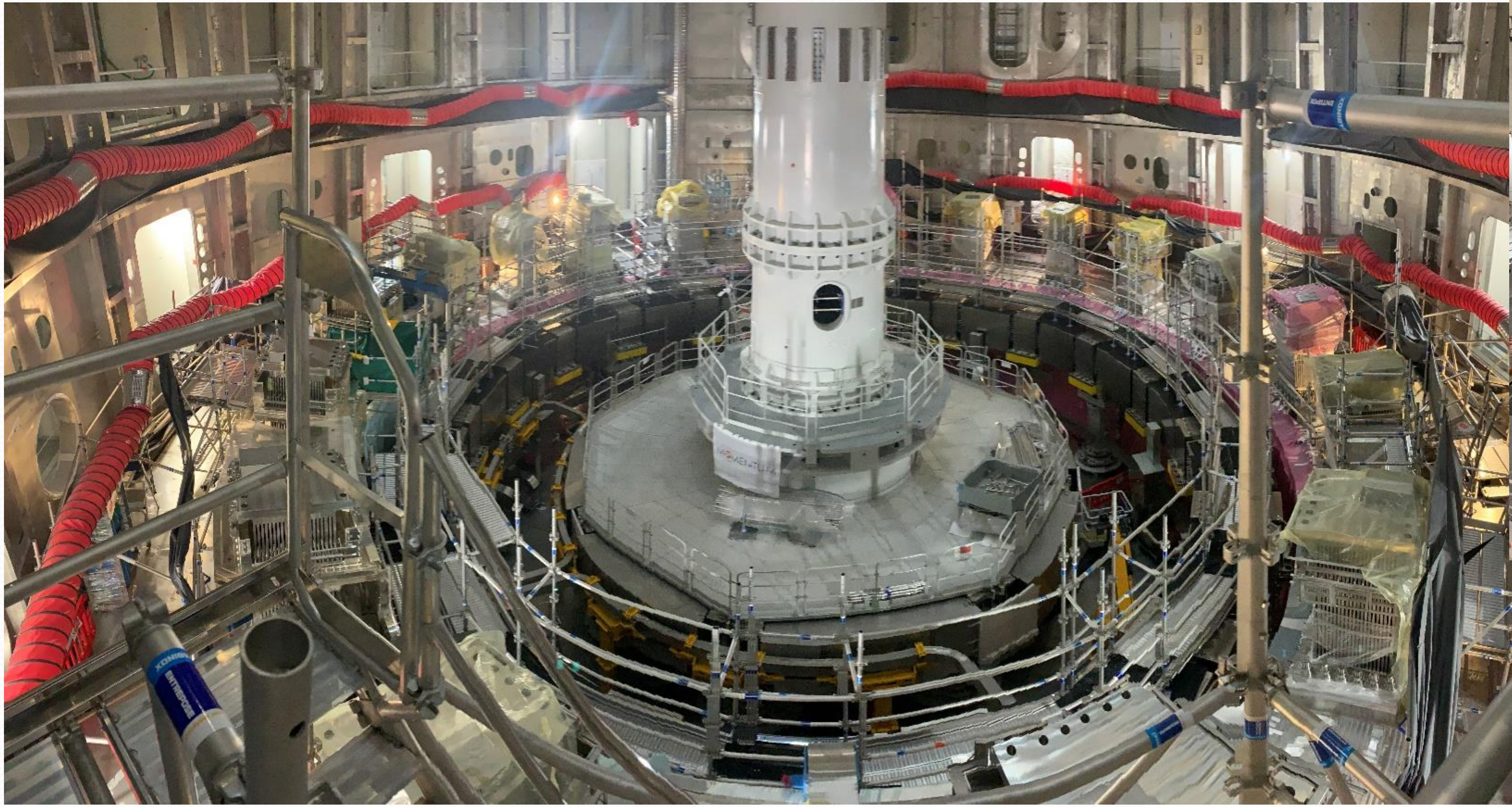


Bottom

Picture of in-cryostat and TF on SSAT as now

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

Nov 2021



June 2020

Conclusions on Repairability

Many lessons can be learned from problems we find in putting ITER together

- ☐ ITER added feeders almost as an afterthought (and changed them to adapt to changes in supports). Result is a maze of equipment that has to be removed and replaced for access to critical coil regions
- ☐ Little effort in feeder design to ease assembly. Poor basic design considerations regarding thermal expansion
- ☐ HV wiring not standardised all the way from coil out, with no pre-fabricated HV insulation lead outs and plug in connectors. ITER all hand made at this level
- ☐ Acceptable level of repair difficulty is a trade off between demonstrated reliability and full acceptance testing

With more effort

- ☐ Demountable coils often proposed, technology complex. For repair, only replacements need to be demountable.
- ☐ Experience on ITER show that coil insulation problems occur in terminal/ joint regions. These could be designed for much easier accessibility (and better nuclear compatibility)
- ☐ ITER originally foresaw that a TF coil could be replaced by cutting a VV segment (twice). This does not look compatible with nuclear safety requirements. More attention to TF coil recovery (in addition to reinforced insulation used in ITER) by adding redundancy
- ☐ Vast amount of HV wiring driven by quench detection systems. Is there scope to reduce voltage and find alternative options for QD

Overall Conclusions

- ITER magnet engineering concepts/solutions need improvement for DEMO (feeders, wiring, access, repair, reliability), with an engineering priority in base machine as the tokamak design driver

- ITER sc base technologies (conductor, insulation, structure) are good building blocks but engineering integration needs improvement and in some areas (voltage, tolerances) we need to consider reducing our demands

- ITER experiences have improved engineering maturity of LTS superconductor 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