Lessons Learned from the ITER Magnets: Materials Development and Materials Industrialisation

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ITER Magnet Division and CTTA

Acknowledgements to: Arnaud Devred, Alex Vostner, Vladimir Tronza, Byung-Su Lim, Yuri Ilin, Julia Garel, Cesar Luongo, Sebastien Koczorowski, Kazuya Hamada and many many more colleagues in IO, F4E, QST, US-IPO and their suppliers in particular ASG, SIMIC, MHI, GA, ASIPP, KIND & HHI

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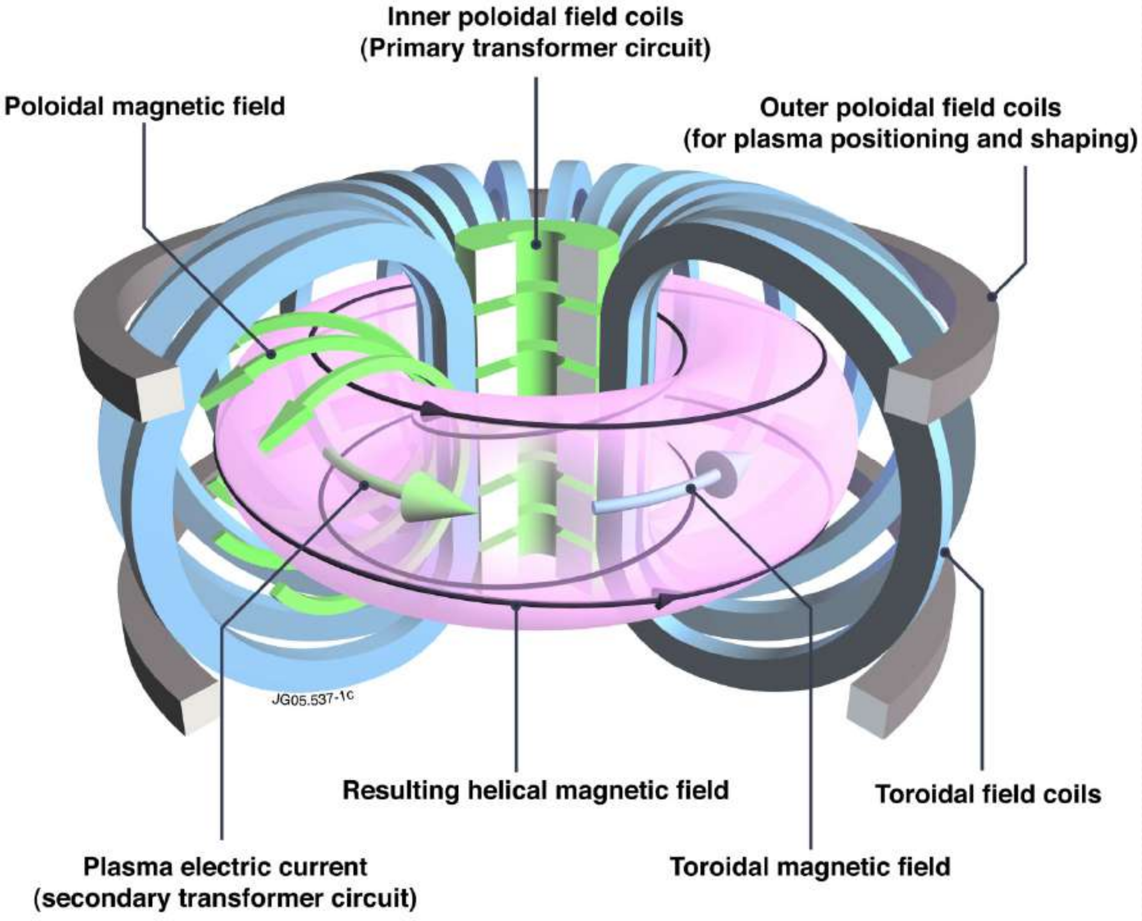
Manufacture of the ITER magnets started in 2008 with the superconducting strands, and over 10 years has progressed through the completion of the conductor supply to reach the stage of full scale industrial production of the final coils, with final first-of-kind items nearing delivery and the remainder soon following.

Looking at the material development before 2008 and the industrialisation post 2008 provides illustrative lessons on the extent to which novel materials could be rapidly brought into mainstream production cost effectively. The most critical materials have been:
Insulation Systems
Superconductors
Structural Metals
High Strength Composites

Also worth looking at: Superconducting joints, W&R&I technology (future paper…)

1. What are the ITER Magnets

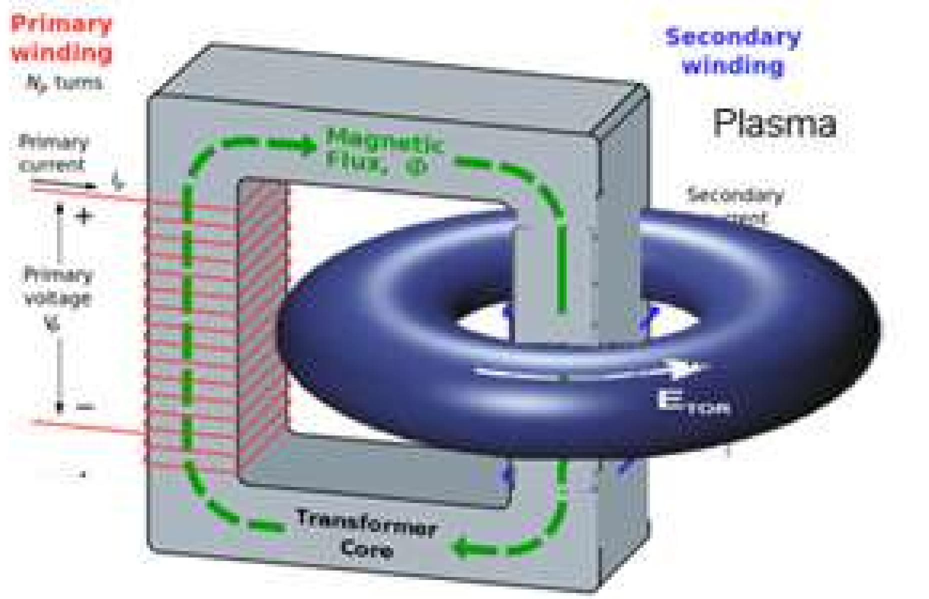
ITER is a superconducting Tokamak



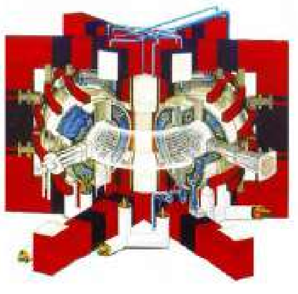
Designed to achieve 500MW fusion power

Plasma carrying a current up to 15MA confined by
- ☐ Toroidal Field Coils
- ☐ Central Solenoid Stack
- ☐ Poloidal Field Coils

Creating the Plasma Current

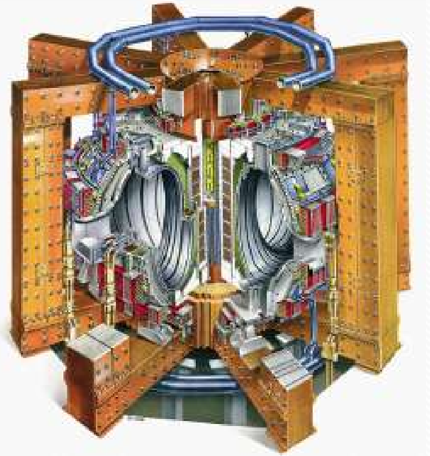


Some tokamaks use an iron core to improve coupling to plasma



Tore Supra

V_{plasma}	$25\ m^3$
P_{fusion}	~0
t_{plasma}	~400 s



JET

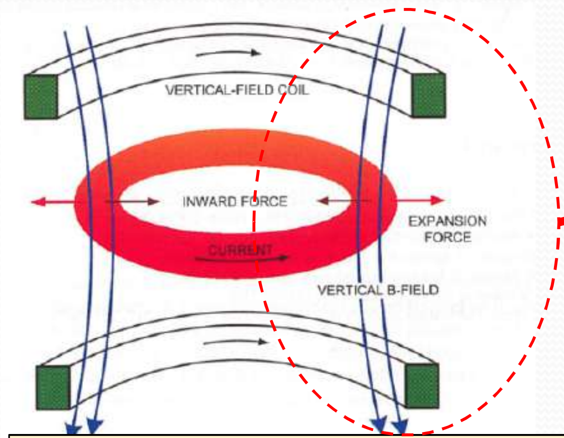
V_{plasma}	$80\ m^3$
P_{fusion}	~16 MW 2s
t_{plasma}	~30 s

- Break down the plasma (applied electric field and/or ECRH) as a secondary 1 turn coil in a conventional transformer
- Primary winding is largely CS supported by PF
- As well as creating conditions to drive current, need a field configuration that allows plasma to form

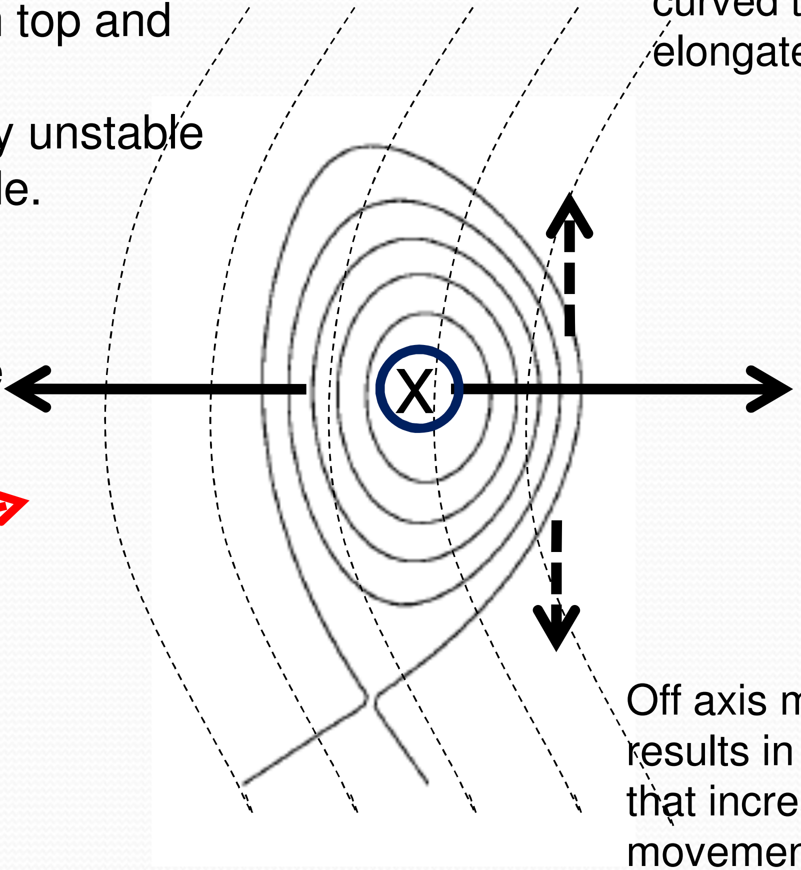
Plasma Shaping

- Circular plasma current loop tends to expand as if under internal pressure. Has to be kept in position by field to push it back
- Diverter shape created by ‘pulling’ plasma from top and bottom
- BUT elongated tokamak plasmas are inherently unstable in the basic axisymmetric (n=0) solid body mode.

Poloidal Coils



Radial position equilibrium of plasma



External field curved to elongate plasma

Restoring force (external field)

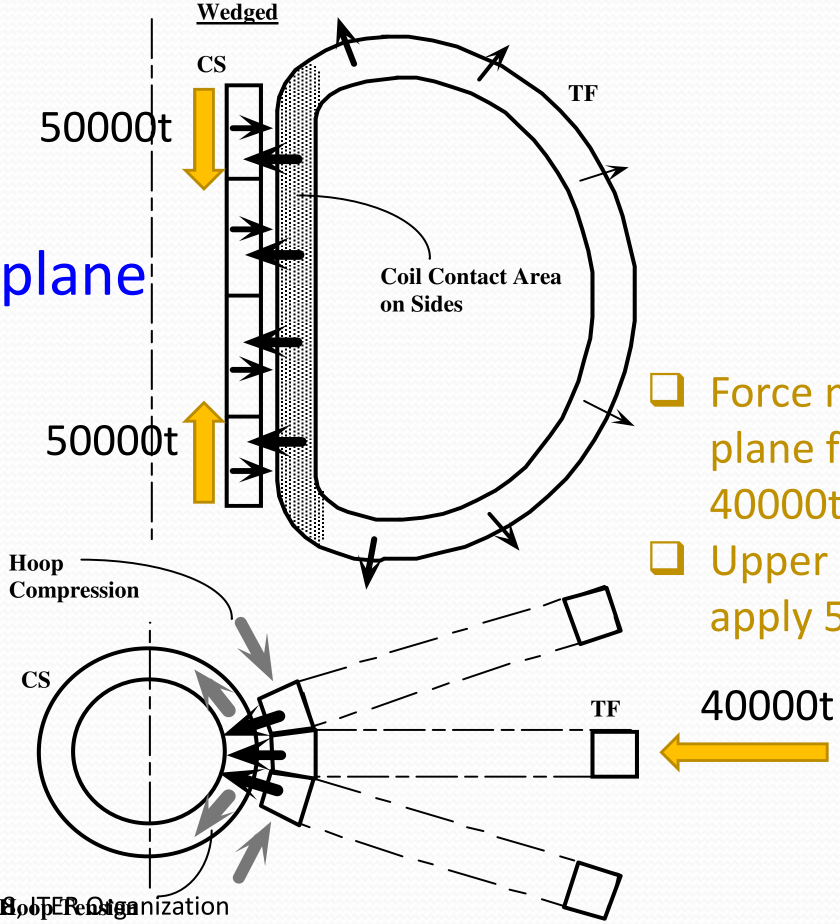
Plasma bursting force (self field)

Off axis movement results in vertical force that increases movement

Role of Toroidal Field Coils and Resulting Loads

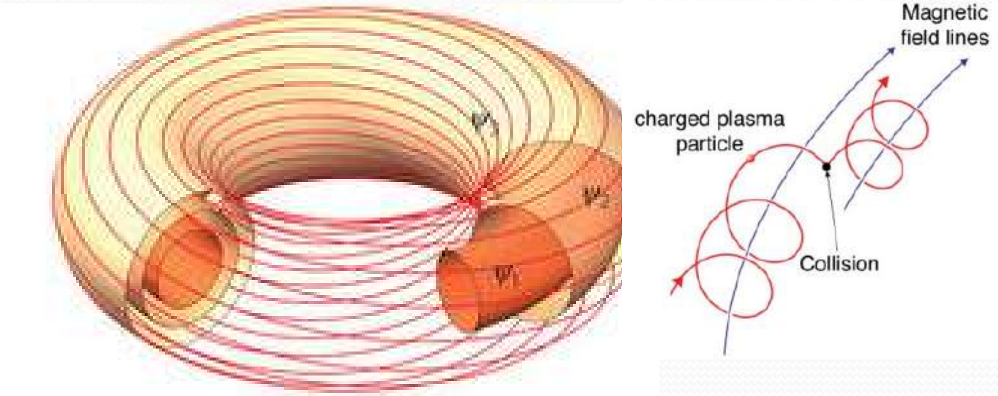
Because of poloidal fields, structures have to react a complex 3D force pattern.....not at all like a pressure vessel

In-plane

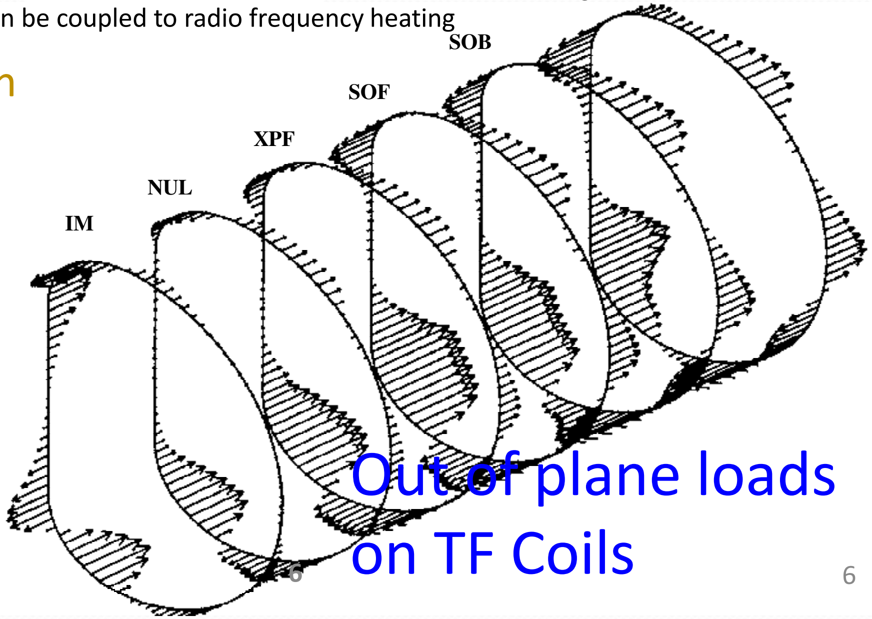


- ❑ Force magnitudes are huge…in plane force on each TF coil is 40000t
- ❑ Upper and lower parts of CS apply 50000t at the centre

Toroidal Field makes it more difficult for charged particles to leave by providing a restoring force for outward movement

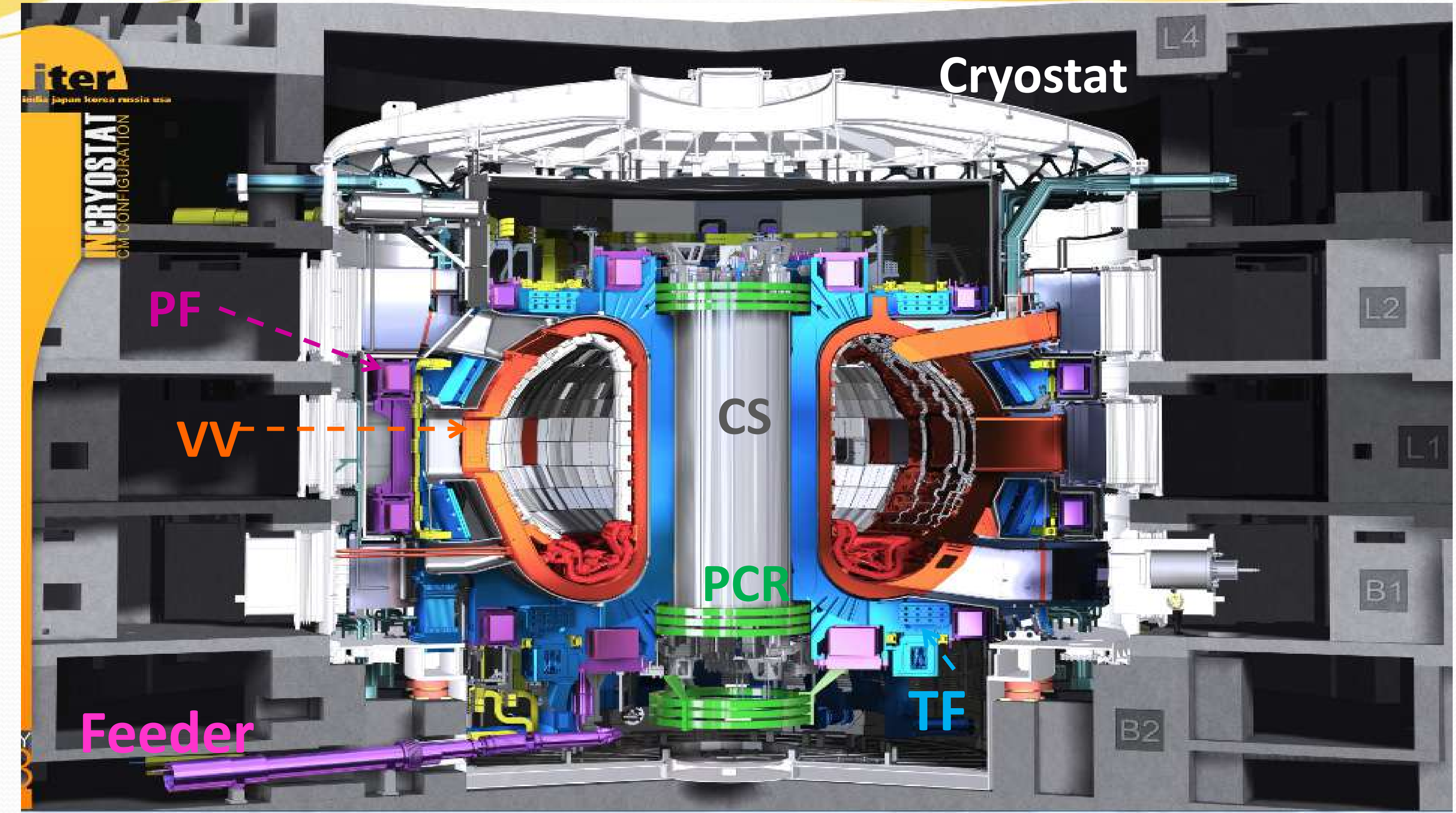


Also forces moving particles to orbit. These orbits have characteristic frequencies that can be coupled to radio frequency heating



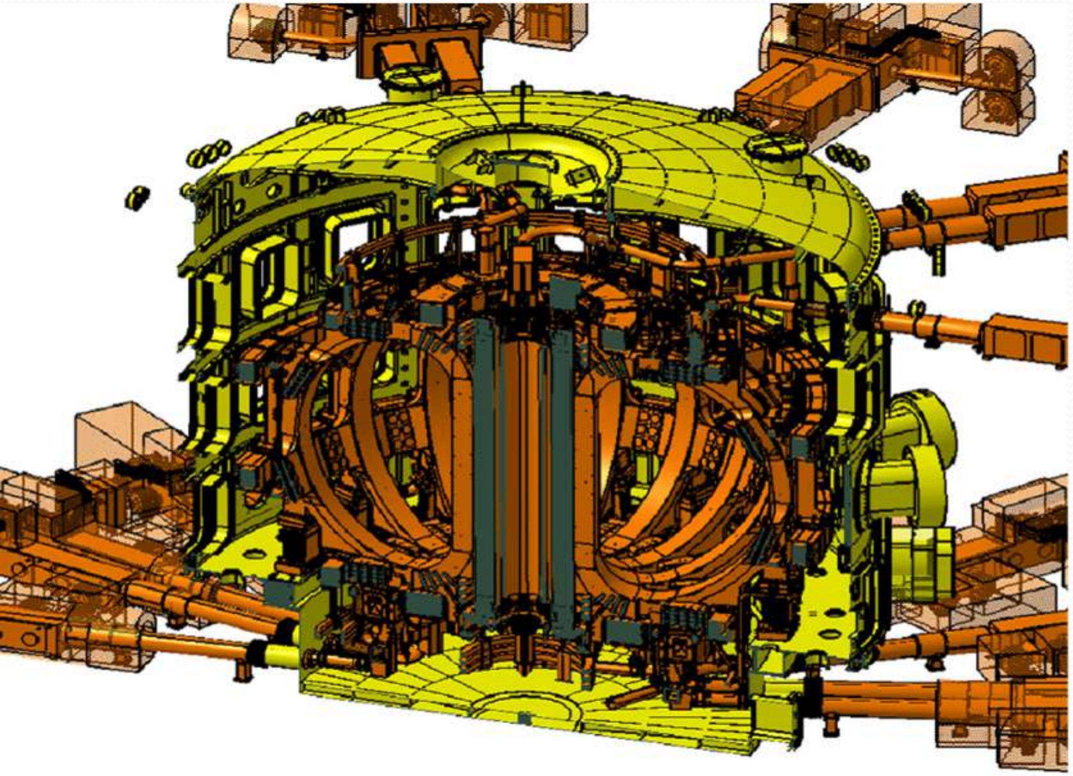
Out of plane loads on TF Coils

Overall Magnet System and Neighbours

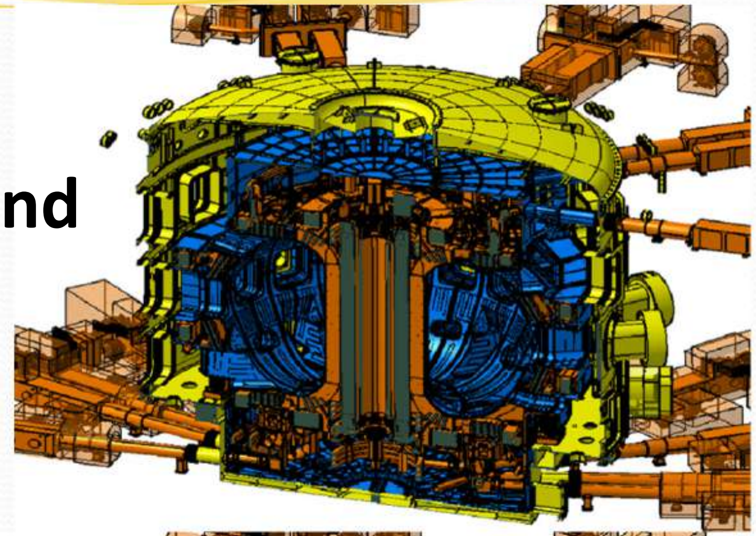


Superconducting Magnet In-Cryostat Environment

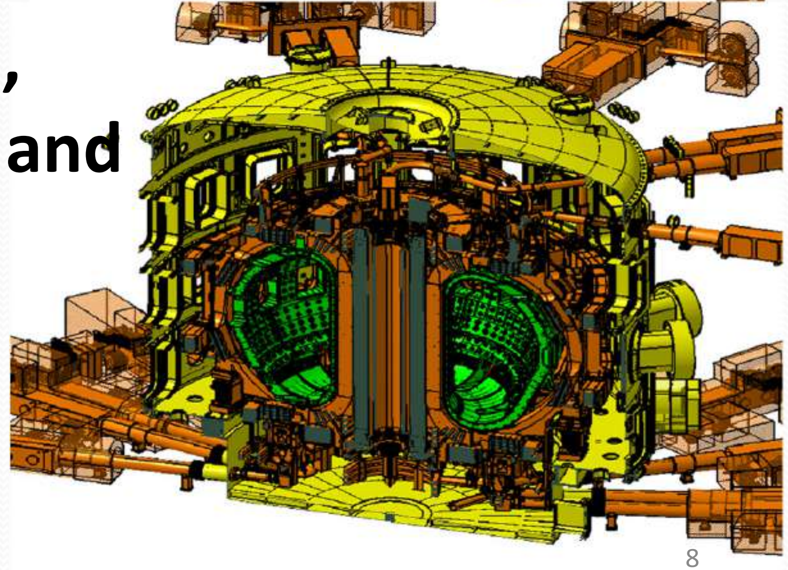
Magnets and Cryostat



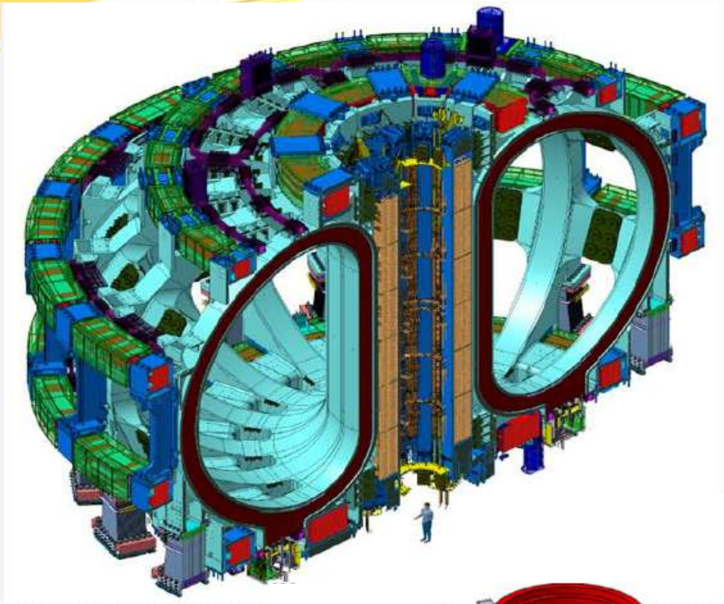
Magnets, Cryostat and Thermal Shield



Magnets, Cryostat and VV

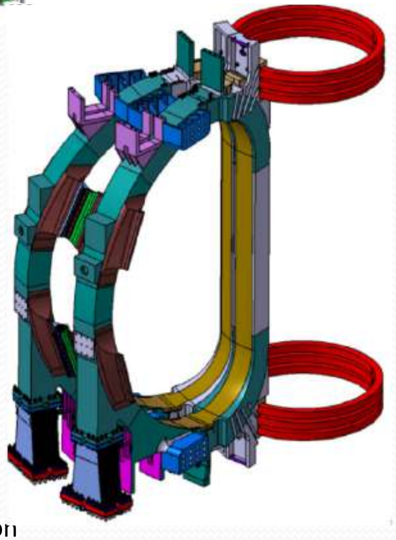


ITER Magnet System – Superconducting Coils

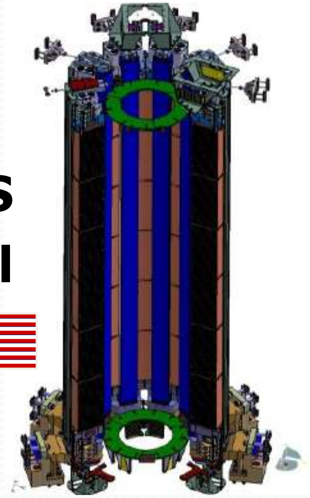


- The ITER sc magnet system is made up of
  - **18 Nb_3Sn Toroidal Field (TF) Coils,**
  - **a 6-module Nb_3Sn Central Solenoid (CS),**
  - **6 Nb–Ti Poloidal Field (PF) Coils,**
  - **9 Nb–Ti pairs of Correction Coils (CCs).**

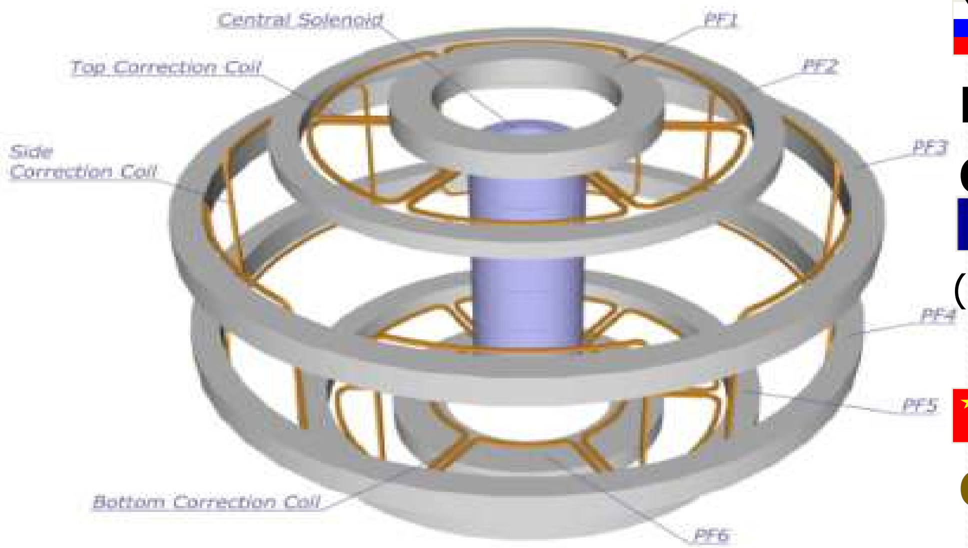
ITER SC Magnet System



Pair of TF Coils



CS Coil



(PF1)

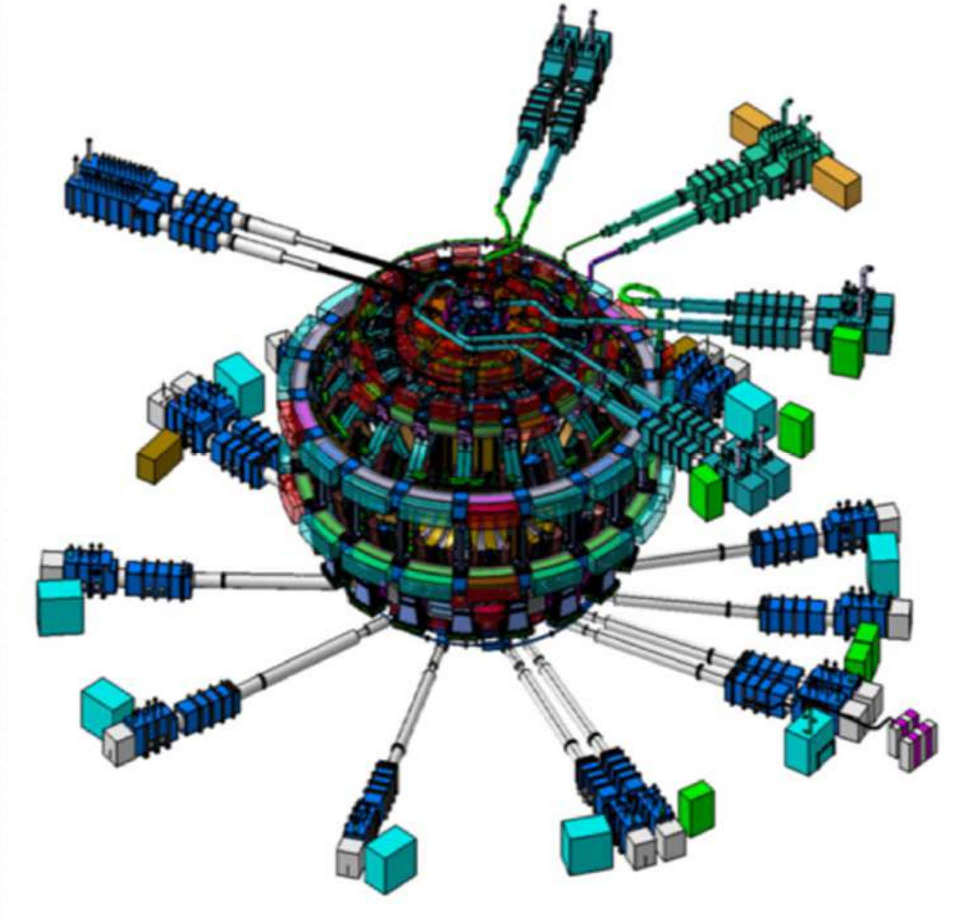
PF Coils

(PF2-6)

CCs

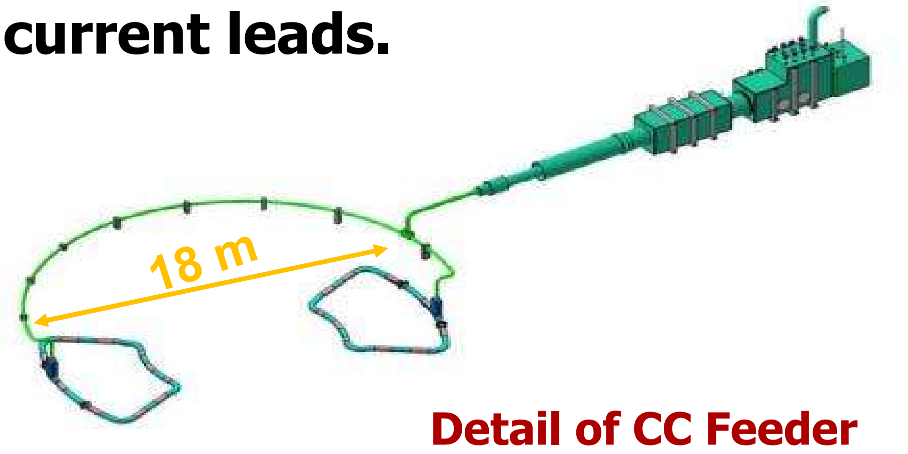
ITER Magnet System – Superconducting Feeders

- 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.**

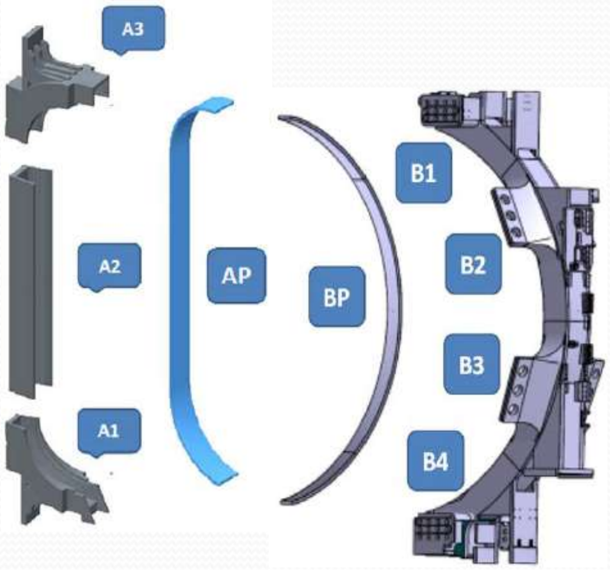


Detail of CC Feeder

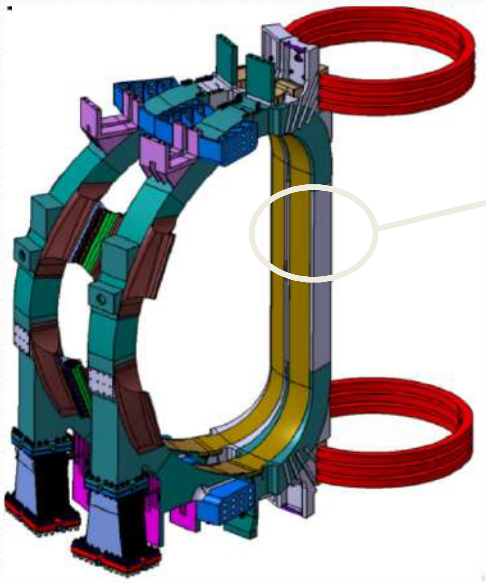
68 kA Trial Lead Developed by ASIPP

Main Features of ITER TF Coils

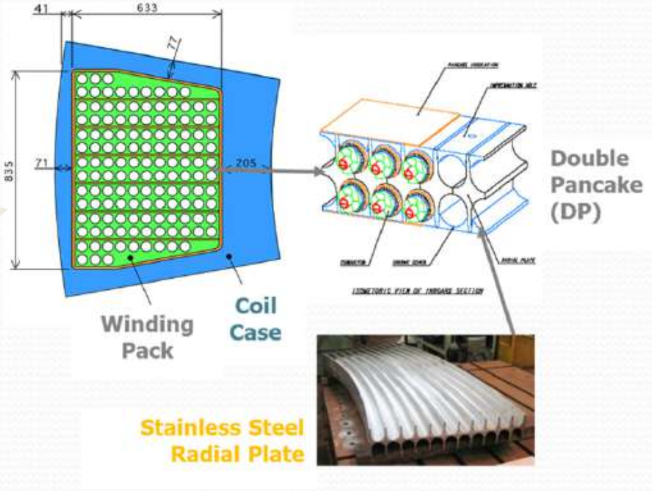
- The TF coil is made up of a winding pack **(WP)** inserted inside a thick **coil case** made of welded, stainless steel **segments.**



TF Coil Structure



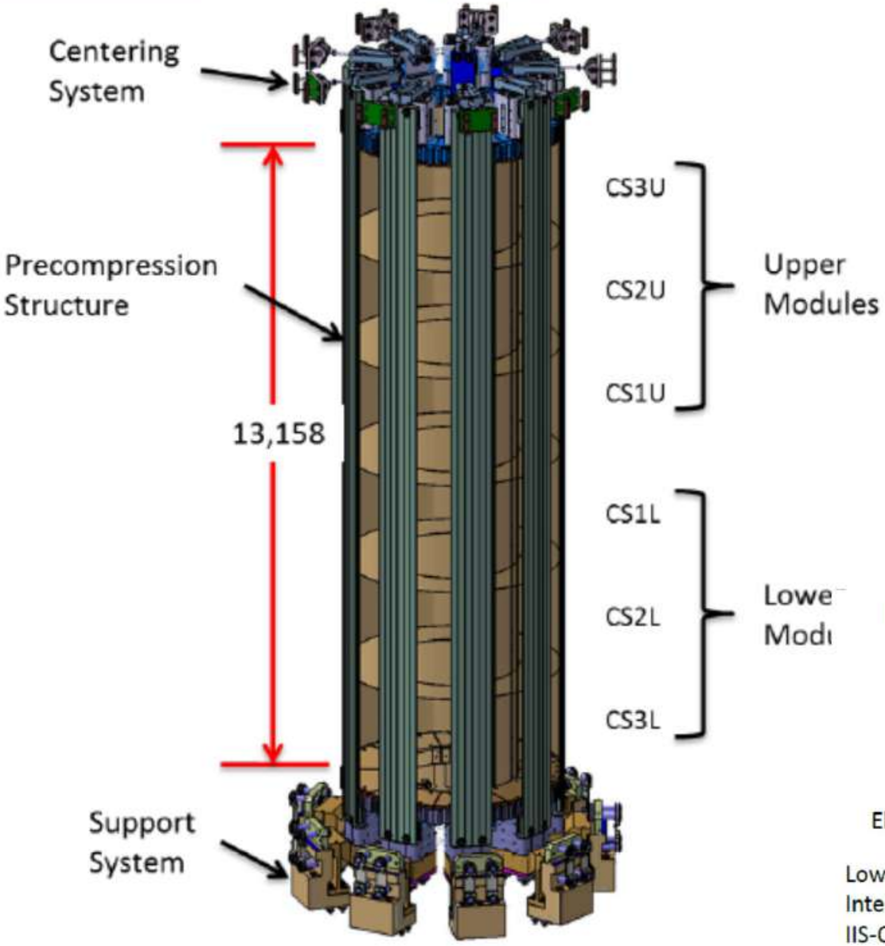
Pair of TF Coils

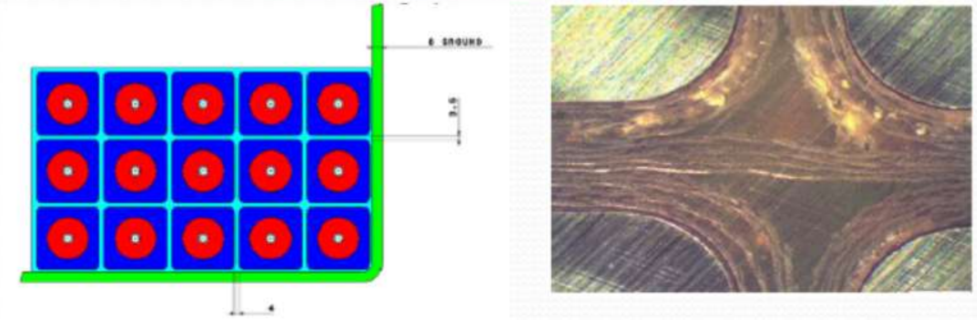


TF Coil Winding Pack

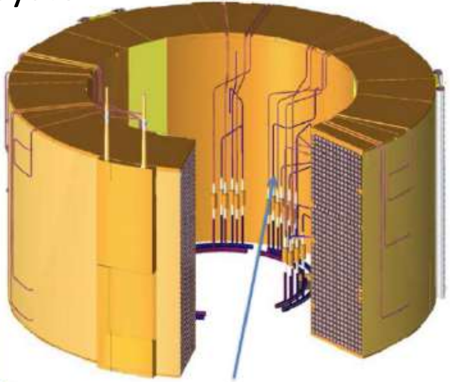
- Each **winding pack (WP)** comprises **7 double pancakes (DPs)**, made up of a **radial plate** with precisely machined grooves into which the **CICC** is transferred upon heat treatment completion.

CS Coil Features



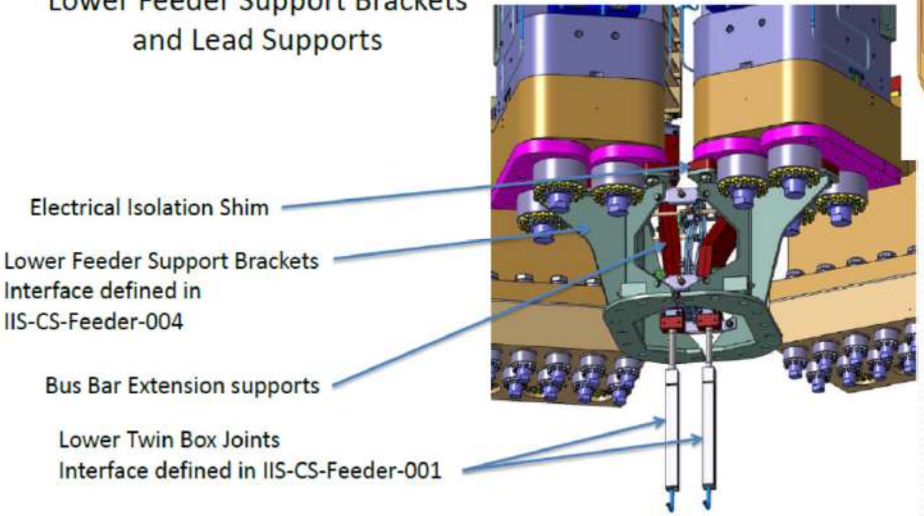


Conductor in winding and insulation system



Module Helium Distribution

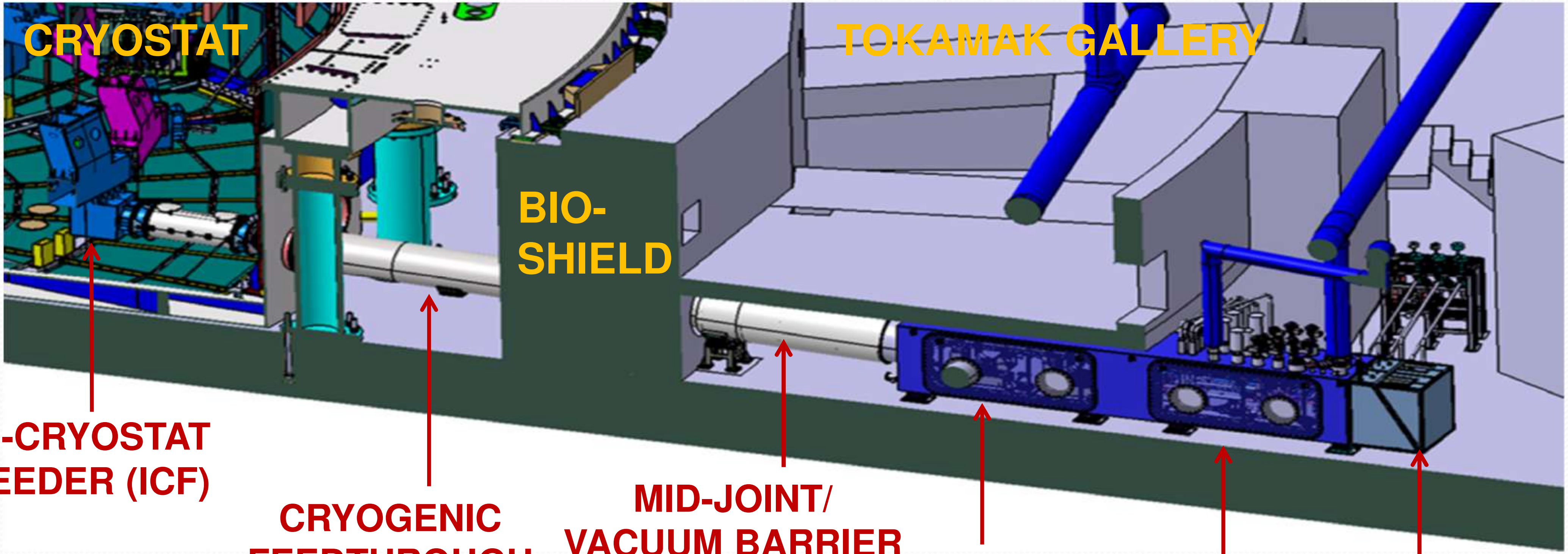
Lower Feeder Support Brackets and Lead Supports



6 hexapancake wound coils using Nb3Sn conductor

ITER Magnet Feeder Layout

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



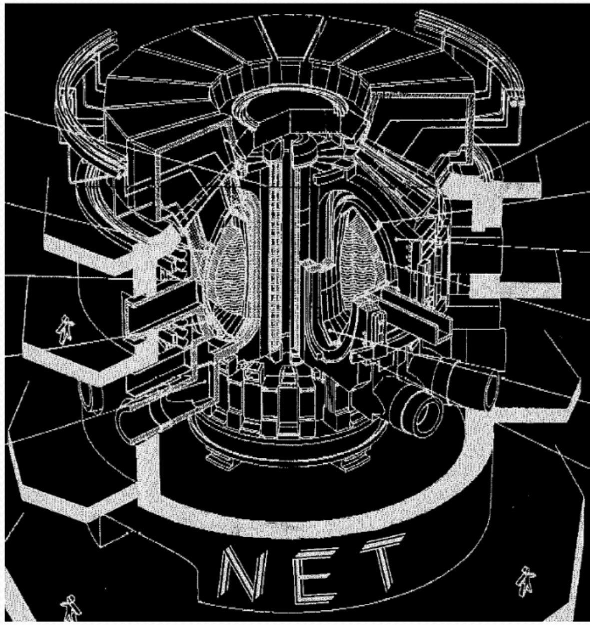
Courtesy of C.-Y. Gung (ITER-CT), E. Niu (CN-DA) & K. Lu (ASIPP)

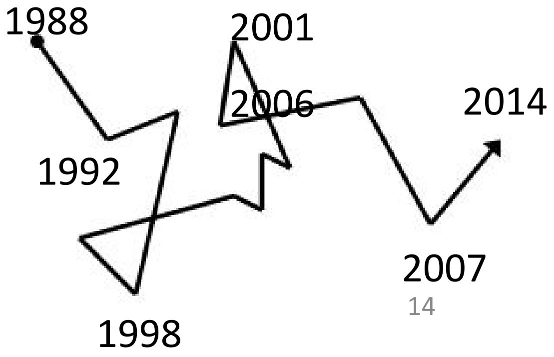
2. ITER Magnet History and Innovations

- 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)

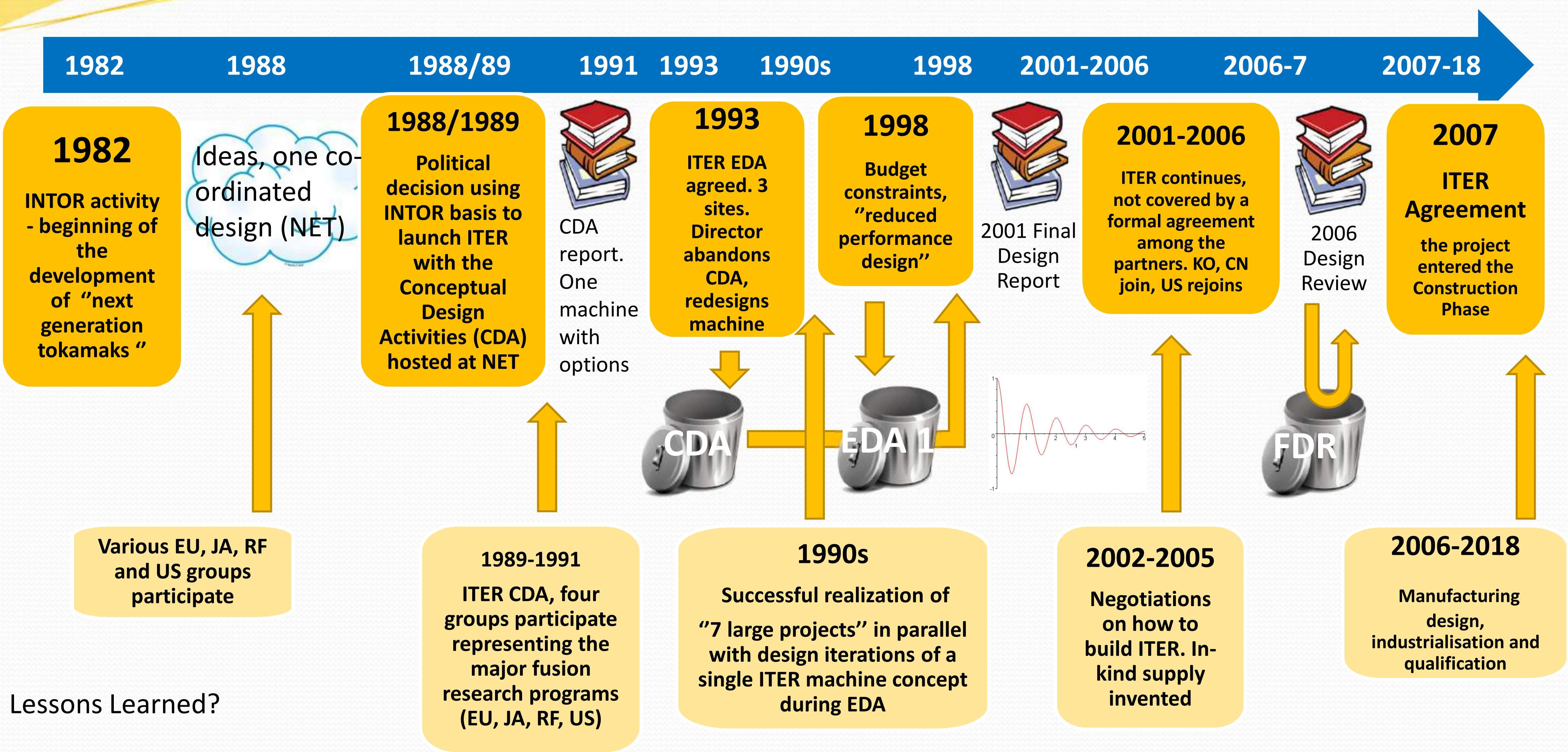
- Changes, sometimes significant, to surroundings and requirements have created something of a random walk over the last 30 years. *We have a design that meets our needs but cannot be said to be optimised. We are where we are*…..

- 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) innovations that produce large promised cost reductions and more sober (but on-paper more expensive) design realism.* ***Key is to get the right balance***





ITER Project Timeline



1982 1988 1988/89 1991 1993 1990s 1998 2001-2006 2006-7 2007-18

1982

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

Ideas, one co-ordinated design (NET)

1988/1989

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

CDA report. One machine with options

1993

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

1998

Budget constraints, "reduced performance design"

2001 Final Design Report

2001-2006

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

2006 Design Review

2007

ITER Agreement

the project entered the Construction Phase

Various EU, JA, RF and US groups participate

1989-1991

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

1990s

Successful realization of

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

2002-2005

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

2006-2018

Manufacturing design, industrialisation and qualification

Lessons Learned?

Magnet Design: Challenges

Having worked out what the magnets had to do, and argued about the basic components/concepts, we then had to design them

The top engineering innovation issues were (in 1991)

- high fields (12-13T) and current densities for industrial scale superconductors
- tight manufacturing tolerances
- very high voltages for a cryogenic environment
- severe multidirectional loading requirements
- high frequency AC operation
- spectacularly complicated interfaces

Issues with magnets in fusion are the familiar engineering ones that arise when components move out of the research field:

- ➢structural and electrical fatigue considerations imposed by the lifetime usage
- ➢focus on reliability and repairability.
- ➢€€€€€

How to Plan

INNOVATION? Quantify REALISTICALLY the benefits…..and RISKS

LESSON 1 from ITER

IMPLEMENT:

- **a planned, phased development program**
- **qualification**
- **industrialization**

INNOVATION:

- Requires **DEVELOPMENT**
- Possible implementation of **SOPHISTICATED TECHNOLOGIES**
- Is likely to be **CHALLENGING/EXPENSIVE….**risk recognition and MITIGATION

Plan and cost adequate testing and TEST FACILITIES

therefore:

- ***RECOGNIZE*** *the steps required*
- ***IMPLEMENT*** *a dynamic responsiveness*
- ***DIFFERENTIATE*** *between branch points where a change and additional resources are needed and those where a branch should be cut*

EXPECT AND ALLOW FAILURE!

The successful implementation of an innovation

LESSON 2 from ITER

EARLY ANALYSIS of the full route through to the implementation

- Innovations come with ***BENEFITS*** and **DISADVANTAGES**

IDENTIFICATION and EVALUATION of the full implications of an innovation

Most difficult: subjective, difficult to quantify, requires broad engineering knowledge
Plagued by short-termism: those who decide are often not those who have to do

COST of development AND implementation

RISK if it fails fully or partially

TIME for development

Increased PERFORMANCE

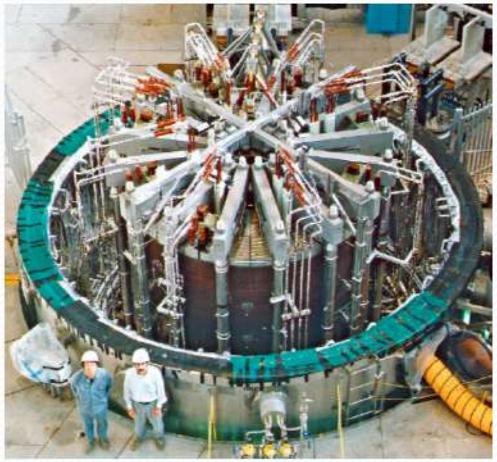
Overall COST saving

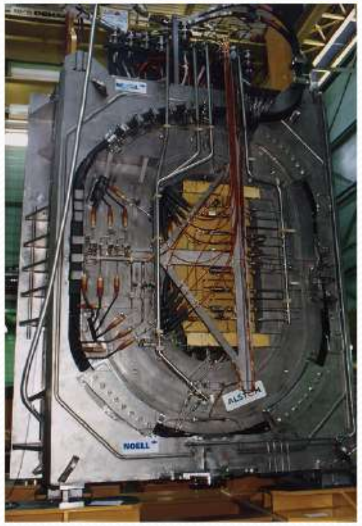
A limitation to one industrial supplier constitutes a high risk and potentially high cost

At the start, engage multiple suppliers and keep competition. Not only price, also ensures critical reviews

3. Industrial Development: Planning & Learning Lessons

Key (but not unique) facilities CS and TF model coils





Four Key Innovations in ITER Magnets

Insulation Systems (from 1988)

Superconductors (from 1987)

Structural Metals (from 1991)

High Strength Composites (from 1999)

The challenges of these systems had a common theme:

- ☐ Significant impact on overall machine size and cost if not implemented
- ☐ Early decision to choose what performance requirements to use for the baseline design, difficult to change later because of wide ranging impact on overall design
- ☐ Need to select the R&D targets at levels that are reasonable, promise a cost effective manufacturing route and maintain the positive advantages for the machine.

For each example we can look back and see how the Innovations were Implemented, using more-or-less successful process of learning lessons (….eventually)

With hindsight, it is possible to develop and trace a logic that was not there at the time

Key Technology: Superconductors

Strategy of Conductor Development

Decide strand concept……..1987

Develop conductor test facilities 1988-1991 (FENIX then SULTAN)

Decide strand parameters….1991, more or less fixed for 20 years

Nb3Al persisted as R&D activity until 2002, obvious unsuitability after 1996

Consider composite conductor options

Choose conductor concept….more or less fixed for 20 years

Argue about conductor concept for first 10 years

Consider conductor details

Strand stability and copper…fixed 2003

Conductor jacket material….fixed 2003

Cable configuration…fixed 2003, iterate 2006, iterated 2010

Industrialisation (from 2007)

Engage multiple strand suppliers (limited by ITER politics)

Couple strand and cabling (reduce interface), extensive IO support on cabling

Special jacketing lines (ITER politics dictated more than needed)

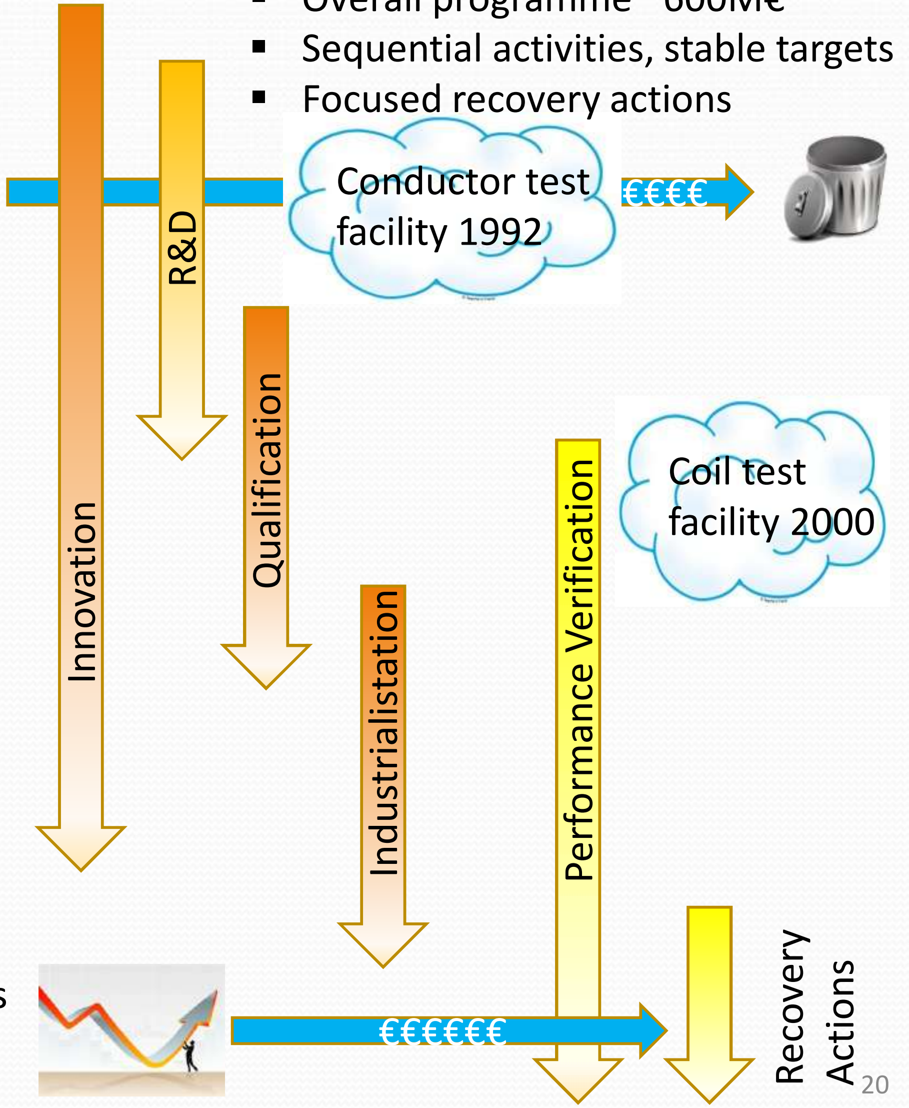
Continuous Performance Checks

CS conductor problems 2009 => solved 2013 (Crash Program 2)

TF conductor problems 2006, adjusted 2008 (Crash Program 1), further issues 2017, solved 2018 (Crash Program 3)

Classic example of successful innovation.

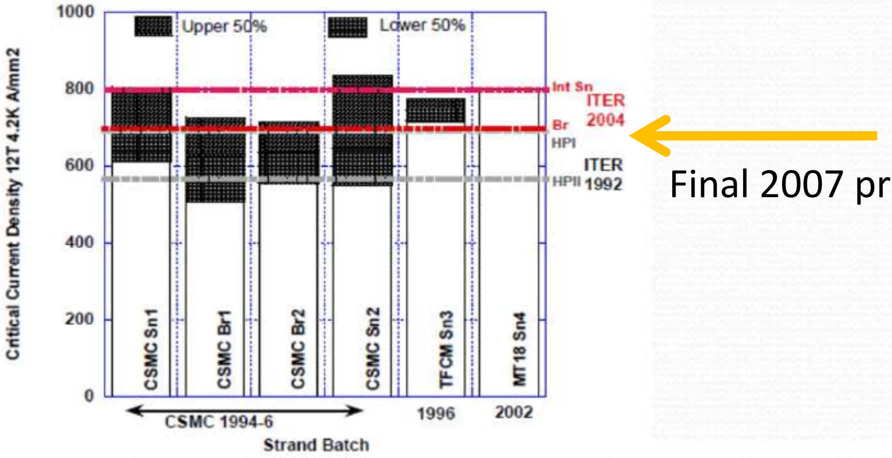
- Overall programme ~600M€
- Sequential activities, stable targets
- Focused recovery actions



Key Technology: Superconductors

▪Step I: Base Material Development

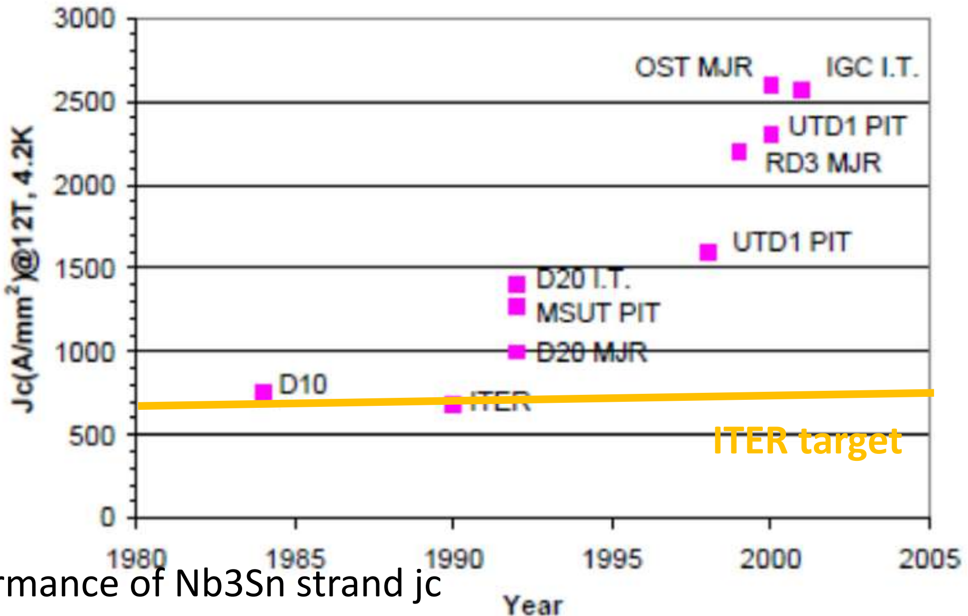
- In 1987 even basic Nb3Sn strand fabrication was difficult. Few suppliers, low yield, ‘individual’ strands not standard material. Launched multiple contracts of ~50kg with common target, 4 production routes (jelly roll, bronze, IT, PIT)
- ITER target kept well below “technology frontier”. ITER model coils gave first steps in industrialisation
- 7 companies produced a few tonnes each by 1998, one (TWCA, jelly roll) dropped out



Final 2007 production criteria

Company	IGC	Furukawa	VAC	Hitachi	EM	Mitsubishi
Billet Size, kg	20-25	140,225	120	200	20-25	30
Total Production, t	4.24(+0.2 2 TWCA)	7.60	6.60	2.00	3.9	4.0

Improvements in Strand Performance During/Since Model Coil Construction, Range of Critical Current Compared to Specification (HPI and HPII are the original bronze/ internal tin specification, Br is bronze route, Sn is internal tin, MT18 is a published reference). Also Bochvar institute provided strand for TF insert coil ~1t



Top Performance of Nb3Sn strand jc

Acknowledgement R. M. Scanlan et al

Key Technology: Superconductors

- Focused on industrial qualities: unit length, wastage, NDT processes and inherent process cost
- Contracts >1988 had incentives to improve usability: Larger billets, lower breakage
- Unit length increased from a few 100m in 1988 to ~1km in 1993 to >5km in 2008

ITER TF Production (courtesy Alex Vostner). 2 Bronze Suppliers (unit length ~21km) and 2 Internal Tin (unit length 9-13km)

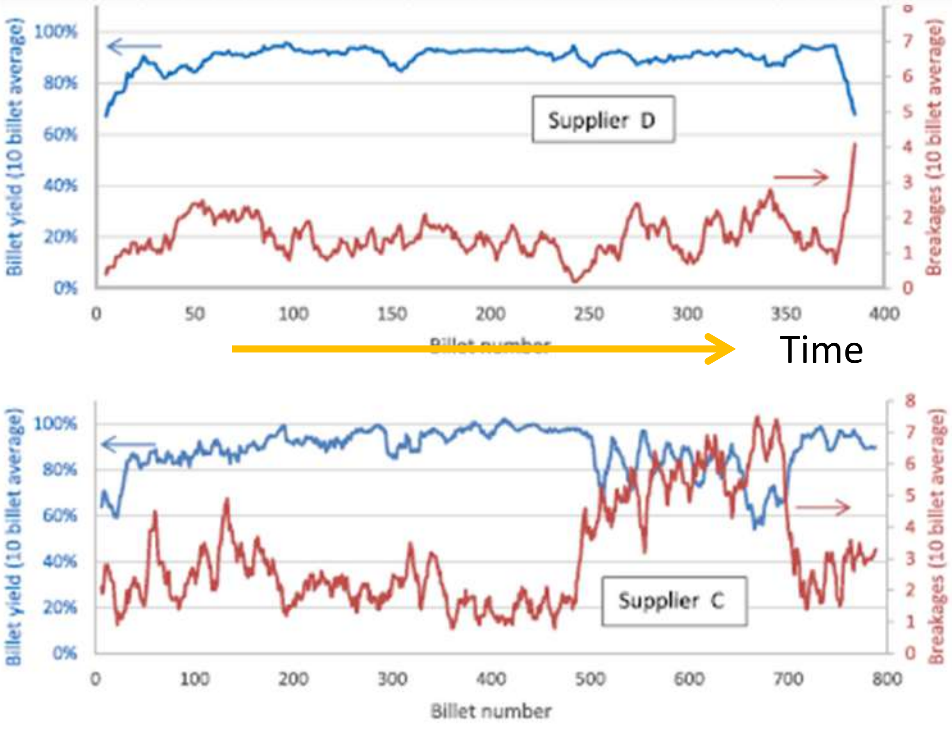
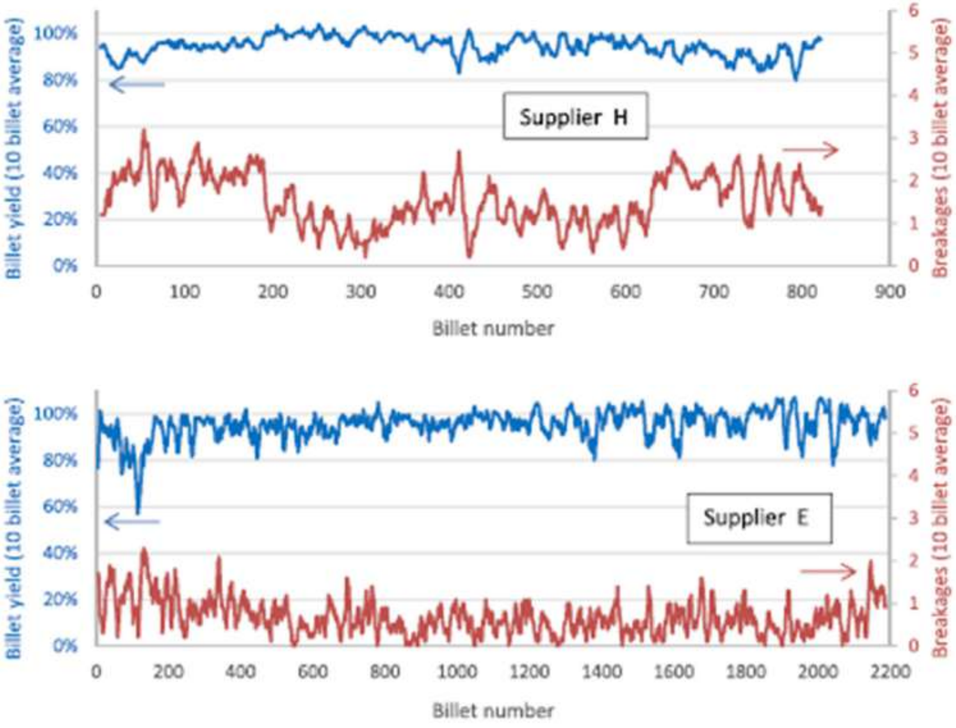


Figure 3. Billet yield development with production time for two selected BR suppliers.



Internal Tin billet after re-stacking

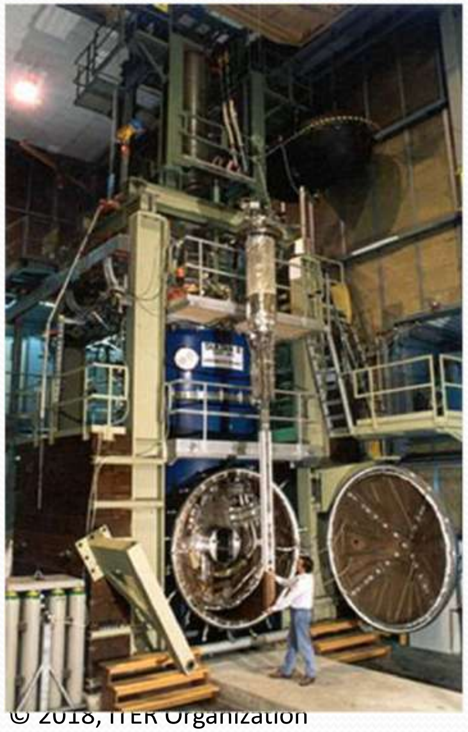
Figure 4. Billet yield development with production time for two selected IT suppliers.

Yield is based on piece length wastage (breakage) not billet usability

Key Technology: Superconductors

▪Step II: Composite Conductor Selection

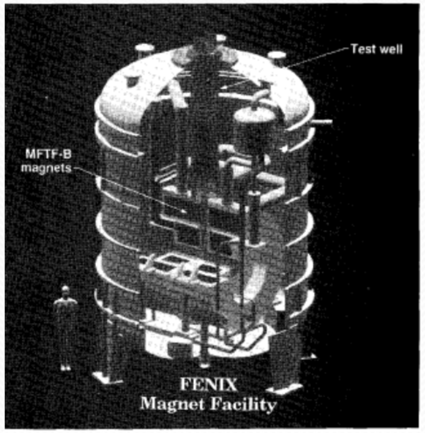
- Differences in use of basic material (strand). Substantial difference in coil manufacturing (react and wind vs wind and react)
- Key element to choice of conductor was current capacity (reduces voltage and/or copper for protection)
- Test facilities for conductor samples were critical: SULTAN was constructed in 1980s and became available as split coil test facility in 1992. Still running 2018



Key for testing: SULTAN facility for conductor testing with open end cap showing conductor sample hanging vertically in front, 1990s

FENIX conductor test facility constructed at LLNL 1988-1990

- Used MFTF-B choke coils (Nb3Sn)
- First large test facility
- Very noisy high current power supply limited useful results



ITER TF Conductor Concept selected (by decree) 1993 Significant iterations on the details (Nb3Sn strand quantity, void fraction, twist pitch). For example Nb3Sn strand weight for the TF with temperature margin, standardised to a strain of -0.5%

1998	822t	1K
2001	351t	1K
2004	369t	2.25K

In 2003-4 recovery for degradation implemented

Key to 2003-4 changesCu:nonCu ratio

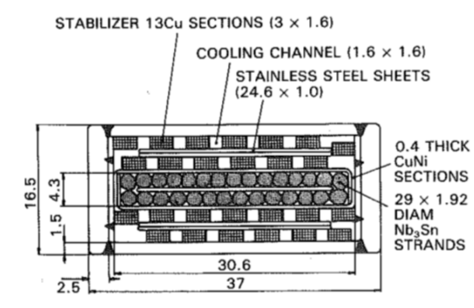
Key Technology: Superconductors

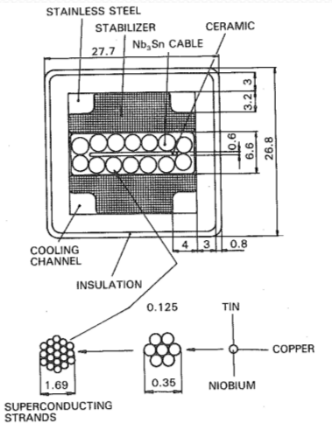
- Ancestry of ITER Composite Conductors

DPC Nb3Sn cable in conduit 1985

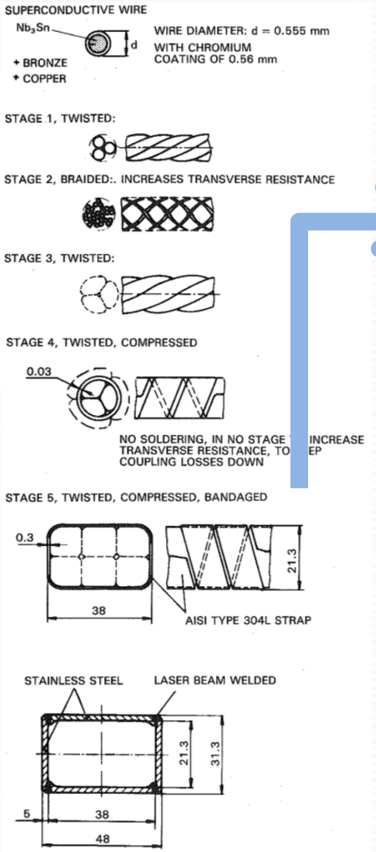
NET TF Conductor Options 1988

20kA R&W





40kA W&R



Cable in Conduit 1991

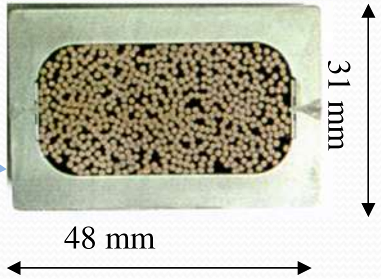
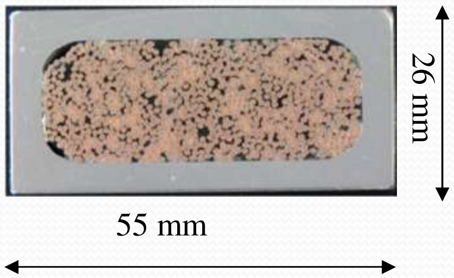
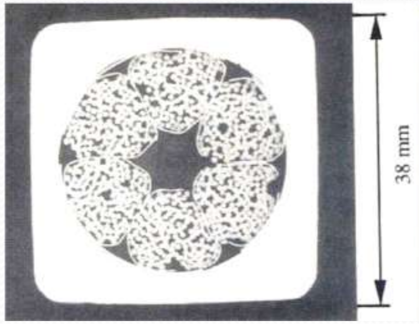


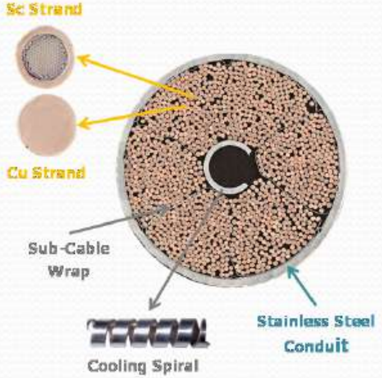
ABB – 1990 Laser welding

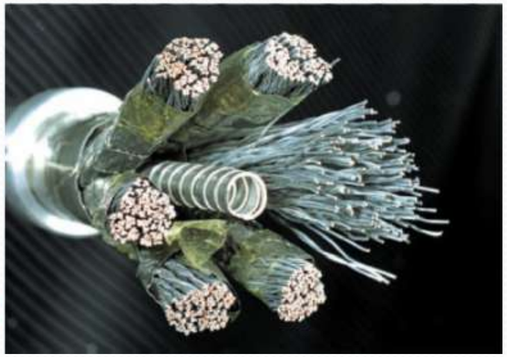


LMI – 1992 Extruded conduit



CEA NbTi – 1992 Central hole





1993 70kA TF

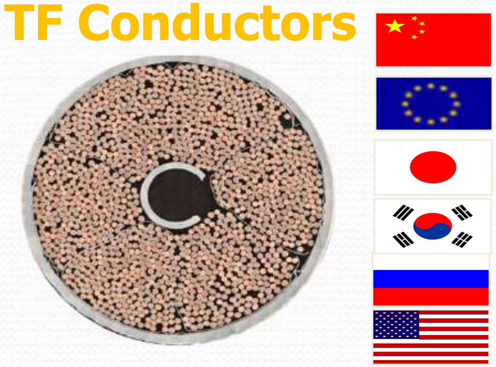
Not discussed:
Strand coating (Cr vs oil/carbon), interstrand resistance, current uniformity and control of AC losses)

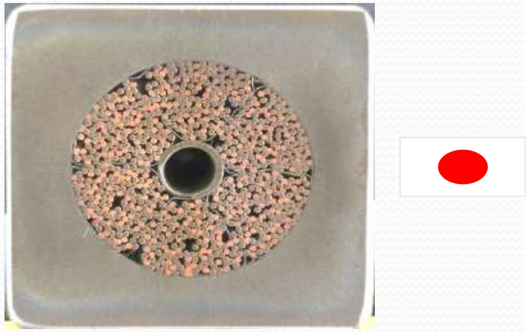
Key Technology: Superconductors

Nb_3Sn

88 km, 825 t
215 kIUA
(334 M€)

TF Conductors

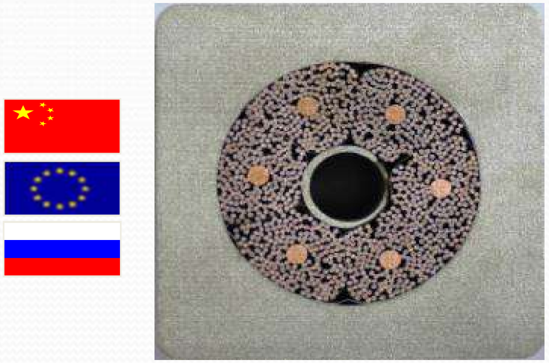




43 km, 745 t
90 kIUA
(140 M€)

CS Conductor

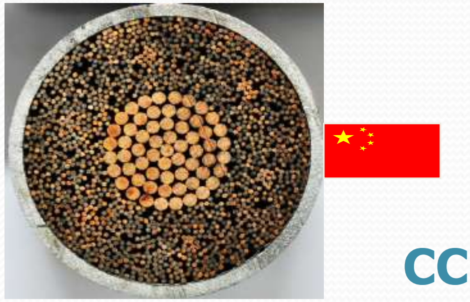
PF Conductor



Nb–Ti

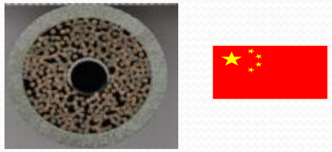
65 km, 1224 t
81 kIUA
(126 M€)

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



MB Conductor

CC Conductor



CB Conductor

ITER Conductor Supply 2011 on

Key Technology: Superconductors

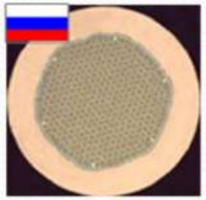
▪Step III: Industrial Base for strand

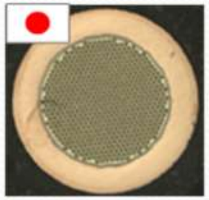
▪Even by 2007, minimal industrial base when we started (ITER scale up was about 1 order of magnitude over 4 years in world production)

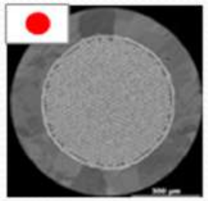
▪Raw material supply (Nb alloys, barriers) an early concern, eventually no issue

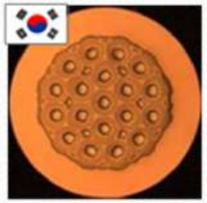
▪ITER procurement specification set to encourage multiple suppliers; staged ramp up, repeated gates to demonstrate performance. Support from IO in problem resolution in 2-3 cases


BAS (Br)

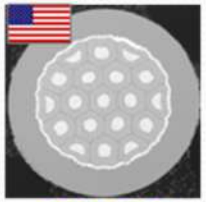

ChMP (Br)

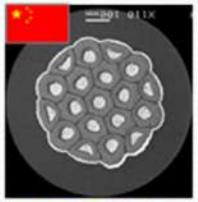

Hitachi (Br)


Jastec (Br)


KAT (IT)

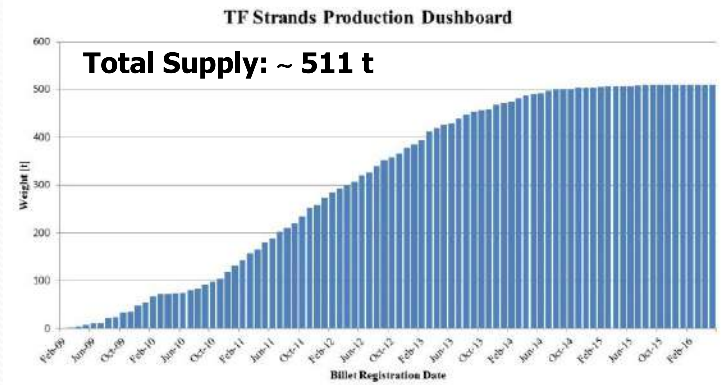

Luvata (IT)


OST (IT)


WST (IT)

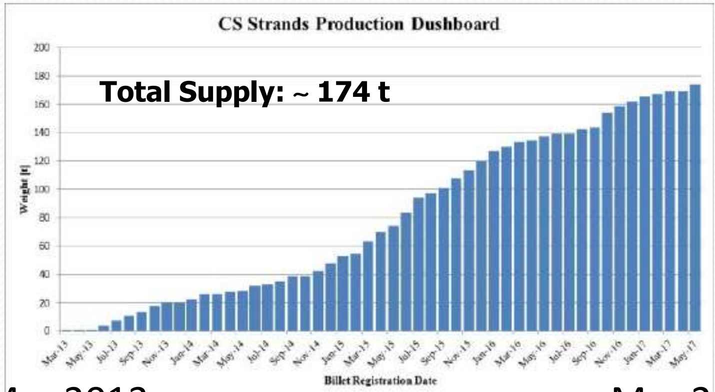
Data Compiled by D. Kaverin as of 31 May 2017 (ITER-CT)

- Nb_3Sn for TF: ~100% complete.



Feb 2009 Feb 2016

- Nb_3Sn for CS: ~100% complete.



Mar 2013 Mar 2017

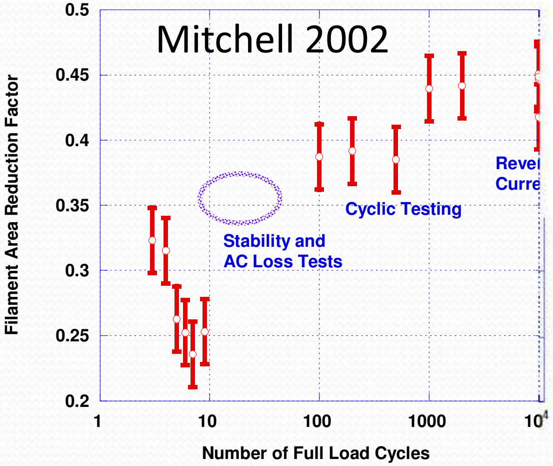
Pre-ITER world production estimated at **~15 t/year;** ITER achieved **~100 t/year for ~5yrs.**

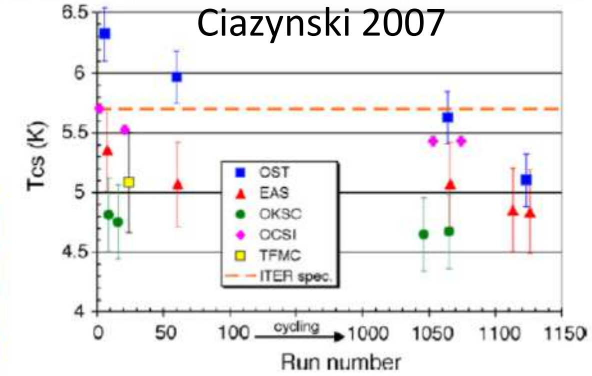
Key Technology: Superconductors

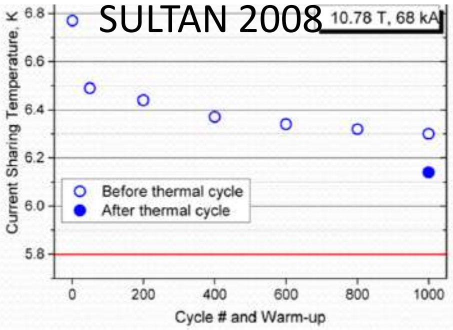
▪Step IV: Recovery Programmes

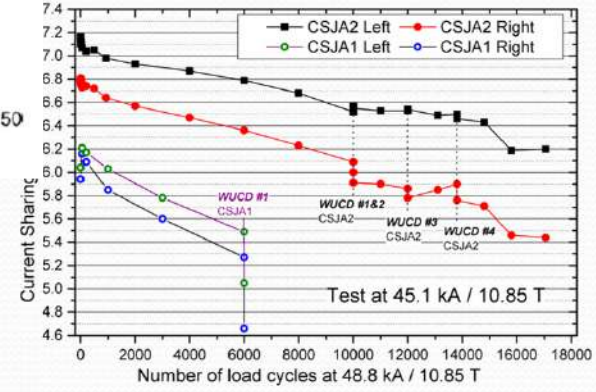
▪By necessity (budget, schedule) industrial qualification went in parallel with full integrated performance testing. Result was unexpected issue with filament fracture that had to be addressed three times

I. Degradation discovered 2002-3. Details of cable design adjust 2003, then 2006-7, issue thought to be solved
II. Testing of CS conductor 2010 showed issue not solved, cable redesign for CS, too late for TF
III. Thermal-mechanical coupled degradation found in TF, testing showed stabilisation within margins

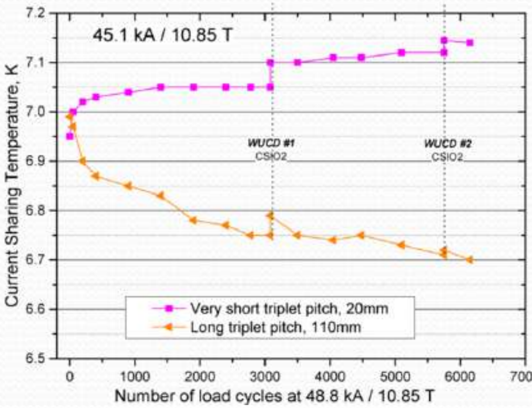

Mitchell 2002


Ciazynski 2007


SULTAN 2008



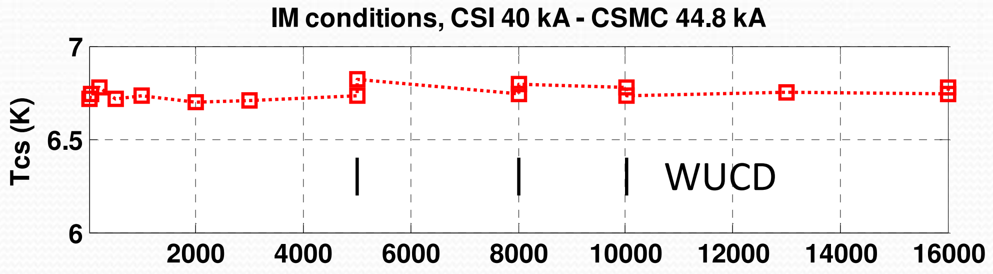
SULTAN 2010



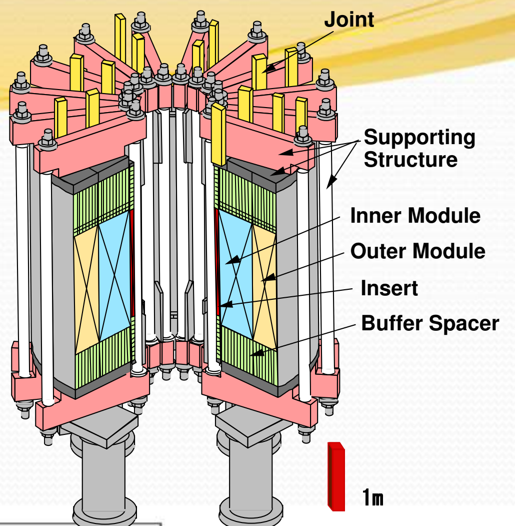
SULTAN 2012

Key Technology: Superconductors

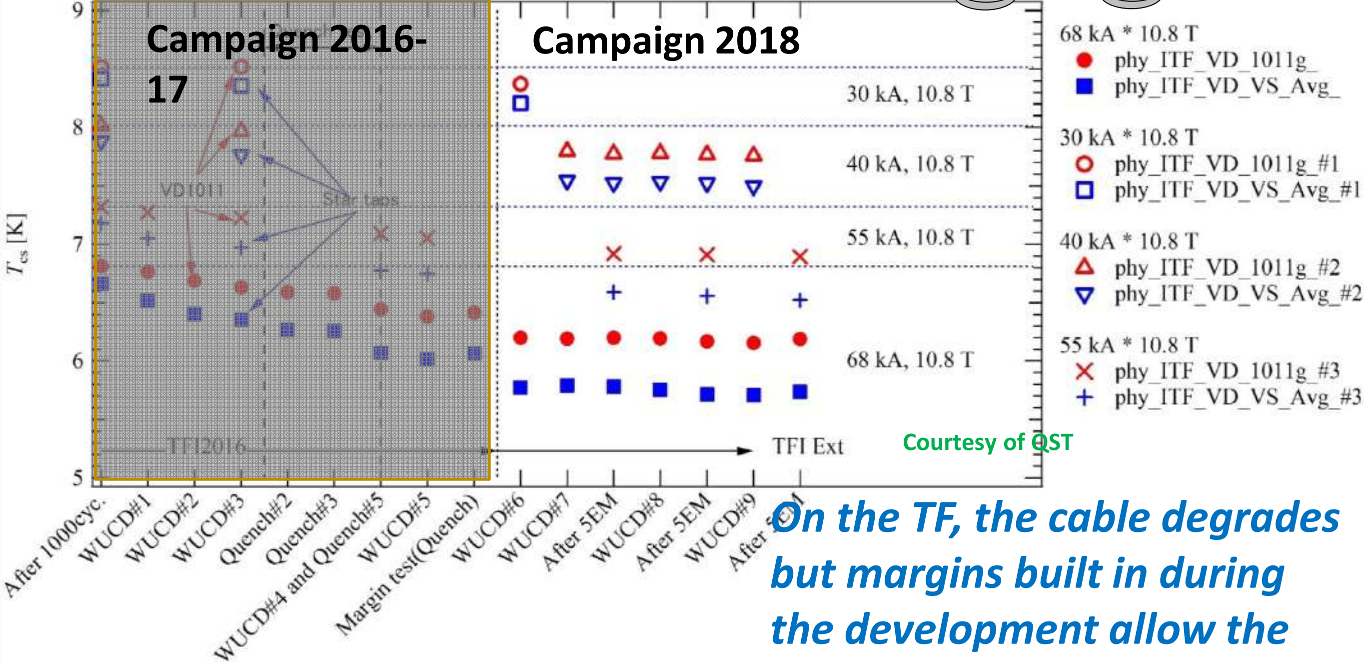
Final Recovery Programs: Second set of Model Coil Tests 2015 and 2018



CS Insert Test



TFI extended test results



Courtesy of QST

On the CS, a new cable configuration based on a short twist pitch triplet avoids all degradation

On the TF, the cable degrades but margins built in during the development allow the degradation to be absorbed

Development of Nb3Sn Superconductors for ITER

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 DG decides conductor concept, circular CICC

1994-2001
Multiple coil concepts, stable conductor design

2002
Nb3Sn degradation issue in Nb3Sn CICC recognised

2003
ITER DG decides strand/cable copper distribution and jacket material

2007-2015
ITER conductor production


R&W, 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

1993-2002
CS and TF Model Coil Projects

1995-98
Incoloy SAGBO issue recognised

2006-08
TF Recovery Programme #1

2010-14
CS Recovery Programme #2

2017-18
TF Recovery Programme #3

Key Technology: Coil Insulation

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

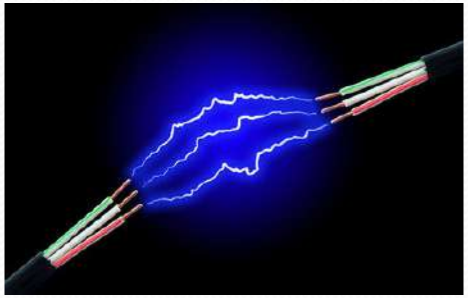
- Solid (VPI) glass-epoxy with kapton insulation as standard
- For example JET ground voltage is 20kV, test voltages about 40kV

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



Now glass-kapton-epoxy is standard, ITER developed and uses glass-kapton-cyanate ester blend to give improved bonding and radiation resistance

INSULATION TECHNOLOGY AS CRITICAL AS SUPERCONDUCTING

Key Technology: Coil Insulation

Ultimately successful but close links to coil and conductor concepts created several restarts: insulation was considered as a secondary technology….. repeated innovation needs & late industrialisation. Lack of sophistication in early electrical testing

Strategy of Insulation Development

Solid insulation concept & discard pool boiling……..1988

Define drivers 1988-1991

  Radiation

  R&W/I and W/I&R and W&R&I conductor concepts

Base Manufacturing Issues

Viability/Risk of Vacuum Pressure Impregnation on Large Magnets 1991-1998

Voltage Reinforcement (dielectrics) and impact on VPI/bonding 1991-2000

Insulation forming with pre-pregs on feeder conductors 2012-2015

Resin Issues

Radiation Hardness 2002-2008

VPI compatibility 2000-2005

Industrialisation 2005-9: Recovery actions due to:

  H&S, pot life, mixing, curing

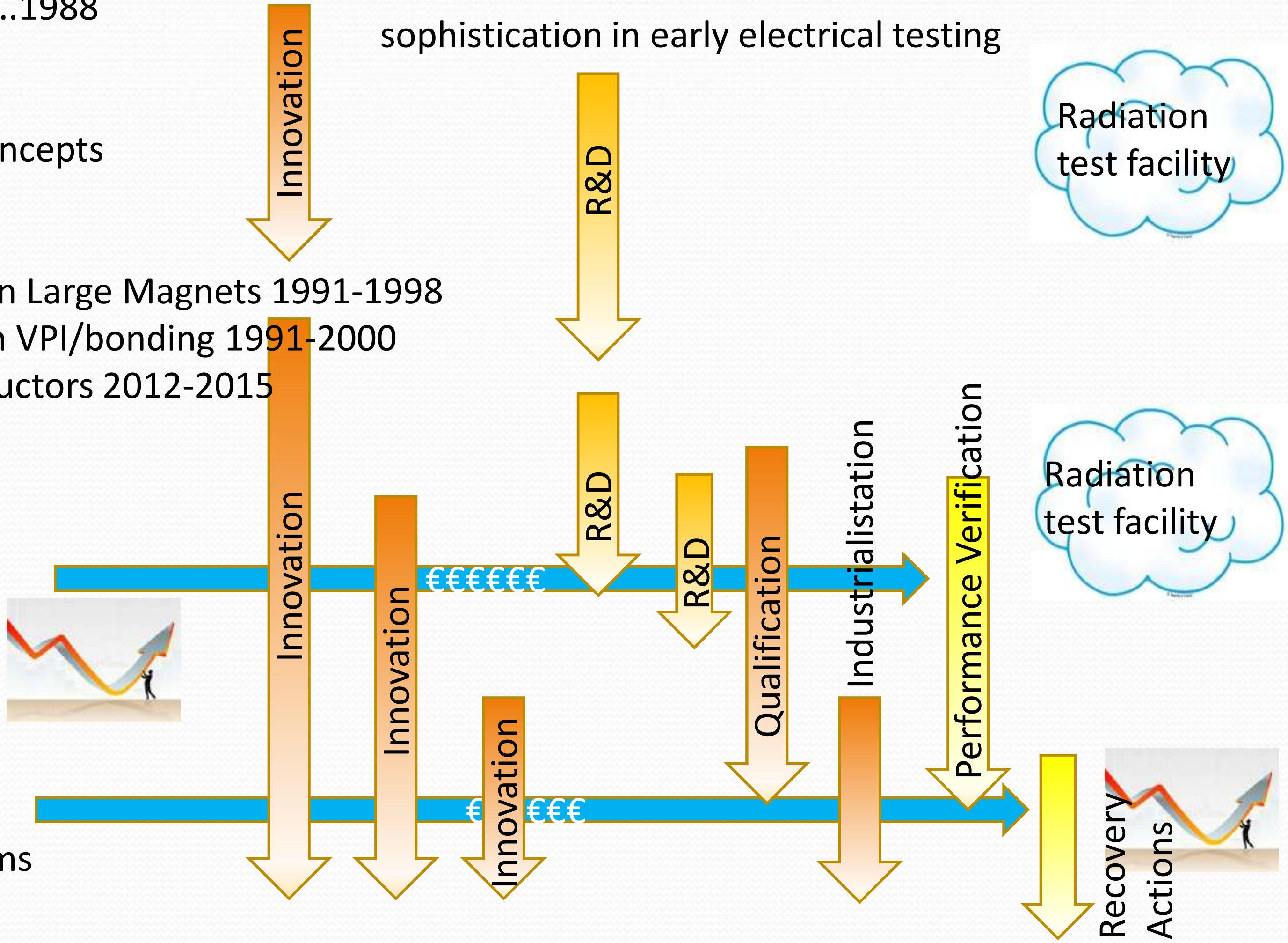
Detail (from 2010)

Recovery actions in:

  Infilling and terminal regions, auxiliary systems

  Instrumentation lead outs

Quality verification



Key Technology: Coil 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

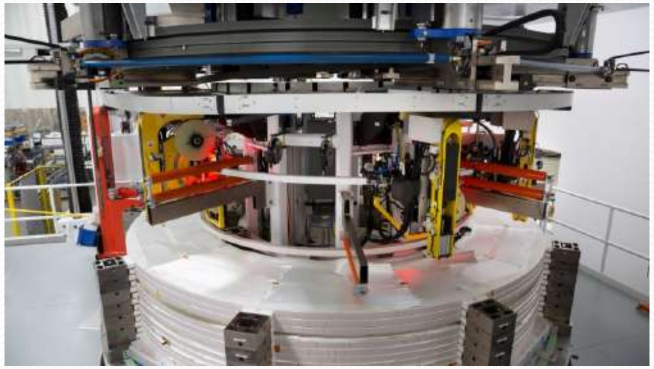
- Early insulation systems <1994 did not integrate dielectric barrier within winding (only as ground reinforcement)
- Relied on stand-off produced by glass filled with epoxy….as long as no cracks
- Glass wrap was compatible with W/I&R coil winding process where the glass went through the Nb3Sn heat treatment
- 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

Key Technology: Coil Insulation

Test Facilities for Irradiation

Required shielding for coil insulation is a key parameter driving the machine build. Establishing limits is difficult

- Irradiation in test reactor is not same spectrum as tokamak
- Big variations in resistance with minor changes in composition
- Impact of degradation difficult to quantify

First facility at Garching (up to mid 1990s)

- Small samples
- Succeeded to carry out irradiation and testing <80K by installing a special facility above the reactor
- Ended when reactor shut down

Second facility at Atom Institute Wien ATI (2001 to 2010) Triga

- Larger samples
- Room temperature only

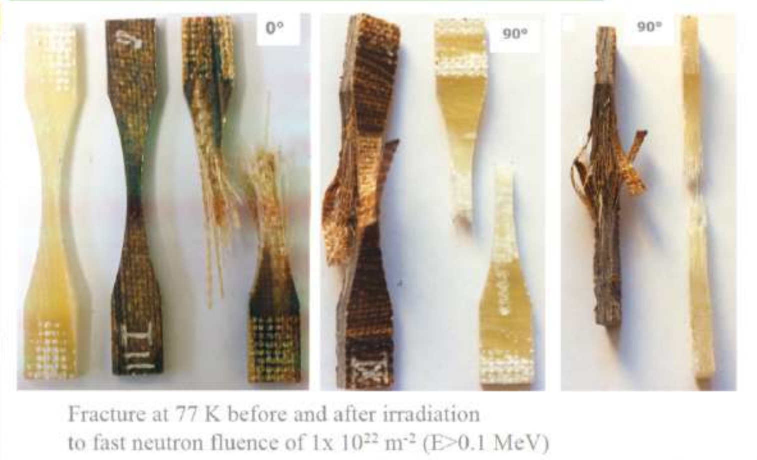
Garching

ATI

Key Technology: Coil Insulation

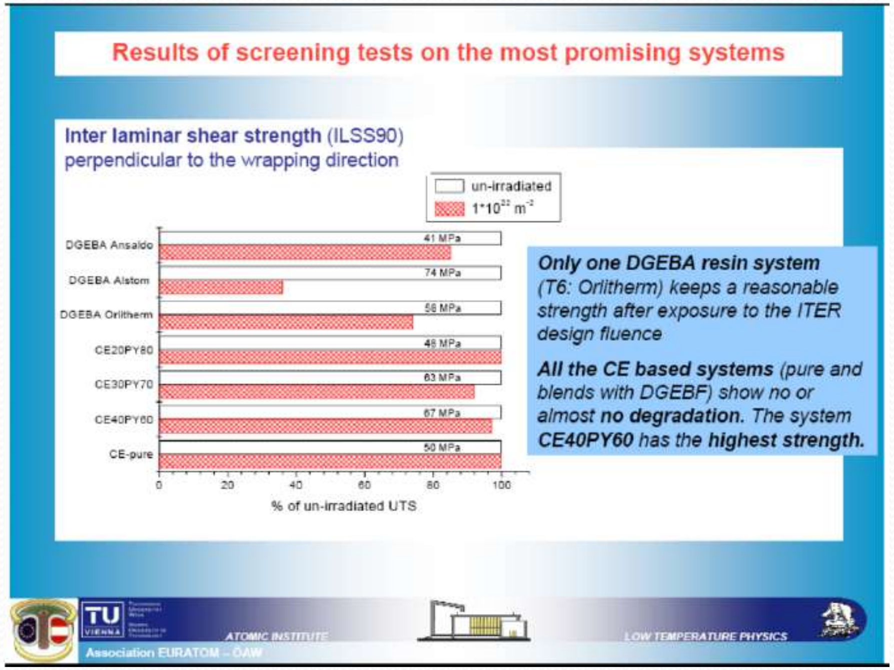
Insulation Irradiation Results

- Up to 2003 all coils impregnated with epoxy resin typically DGEBA
- At ITER fluence level (10MGy or $1*10^{22}$ neutrons/m^2) marginal
- Cynate ester proposed in 2002 (CDT/TU Wien) as possible improvement
- Due to cost Cynate Ester – Epoxy blend investigated, 40% CE identified as acceptabl up to $4*10^{22}$ neutrons/m^2



Tensile Tests of Unirradiated and Irradiated ALSTOM ITER Samples

Fracture at 77 K before and after irradiation to fast neutron fluence of $1x\ 10^{22}\ m^{-2}$ (E>0.1 MeV)

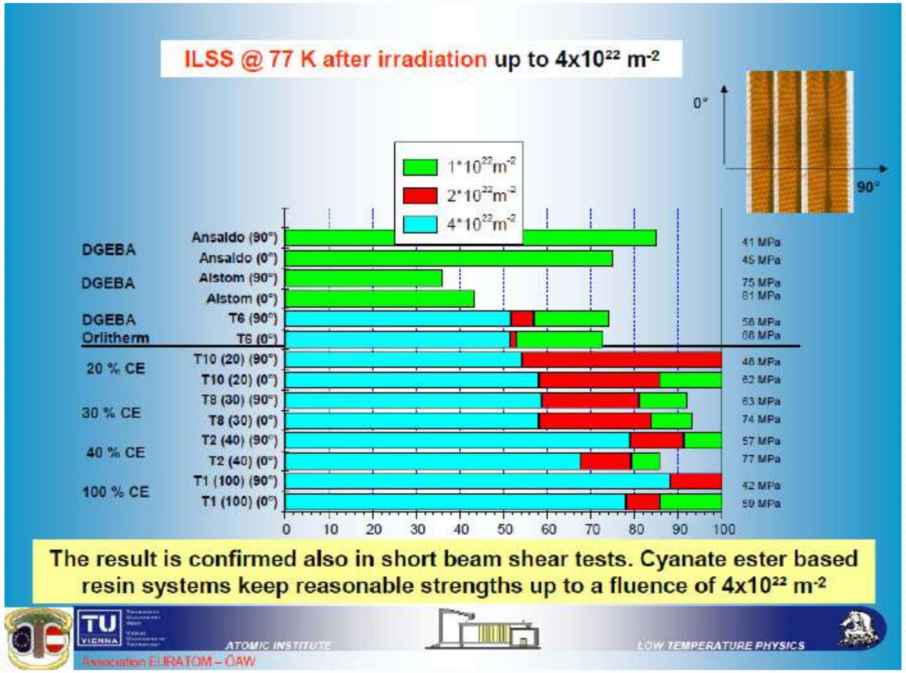


Results of screening tests on the most promising systems

Inter laminar shear strength (ILSS90) perpendicular to the wrapping direction

Only one DGEBA resin system *(T6: Orlitherm) keeps a reasonable strength after exposure to the ITER design fluence*

All the CE based systems *(pure and blends with DGEBF) show no or almost* ***no degradation.*** *The system* ***CE40PY60*** *has the* ***highest strength.***



ILSS @ 77 K after irradiation up to $4x10^{22}\ m^{-2}$

The result is confirmed also in short beam shear tests. Cyanate ester based resin systems keep reasonable strengths up to a fluence of $4x10^{22}\ m^{-2}$

Key Technology: Coil Insulation

Resin Systems

- ☐ Initially (too) focused on radiation resistance
- ☐ Used industrial standard resins and until 2005=> did not look properly at electrical issues

Only from 2009 addressed issues of

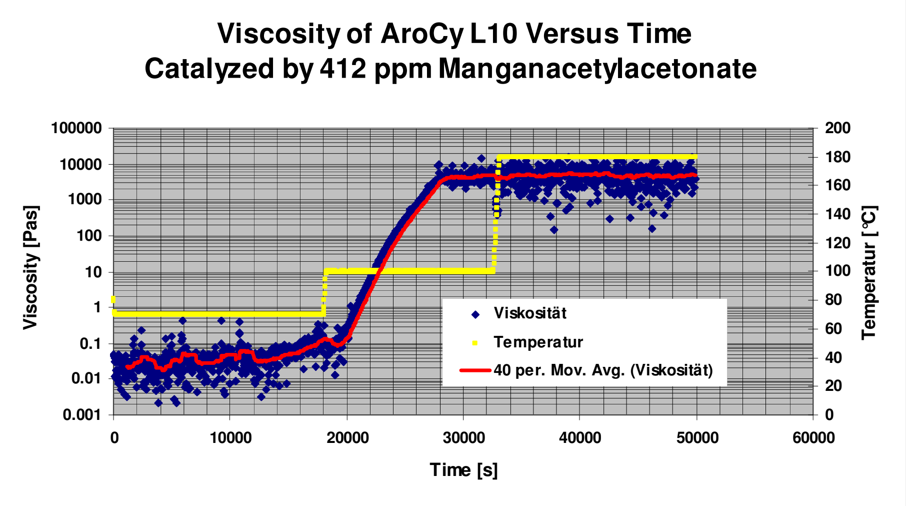
- ▪ Pot life (time to impregnate large winding at low viscosity before glassification)
- ▪ Exothermic curing
- ▪ Health issues (and regulation of perceived health risks) on composite chemicals (especially catalysts)
- ▪ Mixing and outgassing

EXAMPLE: Industrialisation of Cyanate Ester blend produced several recovery actions

Cyanate Esters Polymerization ….. Catalysts

- Pot life / speed of reaction strongly depends on catalyst type / concentration
- Catalysts must be added as homogeneous (filtered) solution to avoid any local high catalyst concentrations that could lead to uncontrollable reactions
- Polymerization is a highly exothermic reaction. Safety precautions!
  - ☐ Metal catalysts (typical concentrations 20-300 ppm)
  - ☐ Co, Zn, Mn, Cu ...
  - ☐ Soluble organic salts/complexes are used e.g. acetylacetonates, octoates, naphtenates
  - ☐ Solutions in liquid alkyl phenols

Pot-life extended in 2009 to more than 100h by exchanging the Mn-catalyst by a Co-catalyst.


Viscosity of AroCy L10 Versus Time
Catalyzed by 412 ppm Manganacetylacetonate

Lab-scale thermal runaway of cyanate ester

Key Technology: Coil Insulation

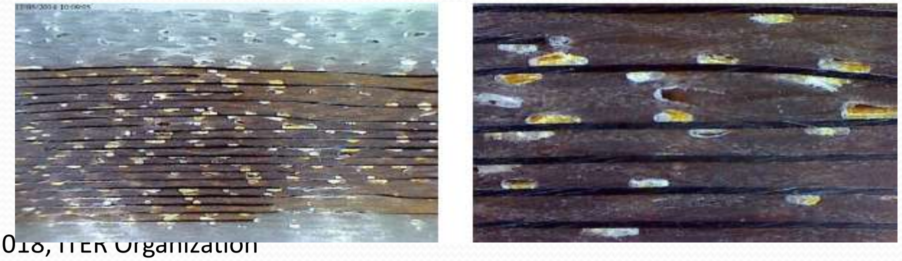
Auxiliary Insulation Systems

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

Silicon wrap to compress during curing

Acknowledgement ASIPP

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

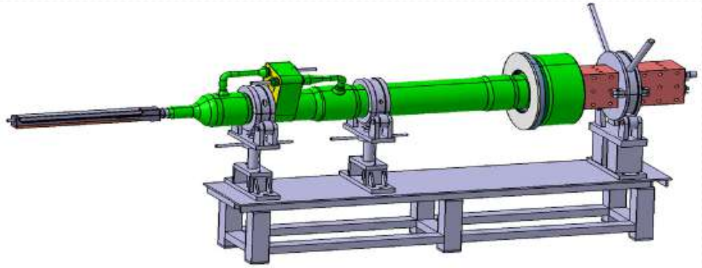


The final selected materials produce largely void-free specimens (right)

Key Technology: Coil Insulation

Art of applying polyimide

- Inflexible and therefore curved surfaces have to be smoothed
- Complicated patterns of lay-up



- The HTS current leads offer a challenging geometry to wrap due to changes in section and presence of helium pipes at right angles.
- Strategy is to lay up the GK tapes on the cone section.
- Root area of the pipes is first smoothed with green putty before application of the GK tapes.

Feeder Wrapping

TF coil terminal region

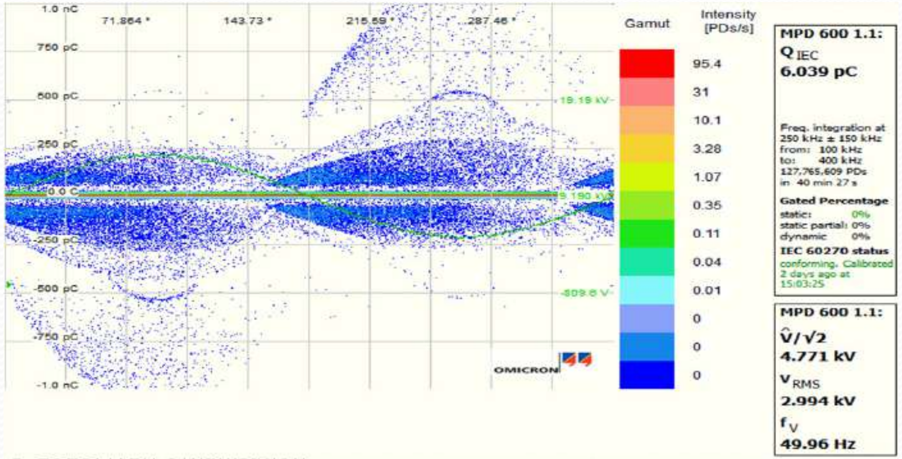
Origami style cutting of sheets to fit curves

Principles well known but in ITER (with vacuum) failure to overlap adequately (and cure without resin rich areas) leads to cracks and Paschen failures

Key Technology: Coil Insulation

Quality Testing

- ☐ Up to 2008, only HV DC testing
- ☐ From 2008, IO introduced Partial Discharge characterisation and Paschen breakdown testing. Now by far most critical tests, and used for development as well as qualification and production
- ☐ Void fraction measurements also improved
  - Insulation test of current lead
    - ➢ PD test results show stable but relatively high absolute values.
    - ➢ Ground screen termination was improved on next prototype.



MPD 600 1.1:
Q_{IEC}
6.039 pC

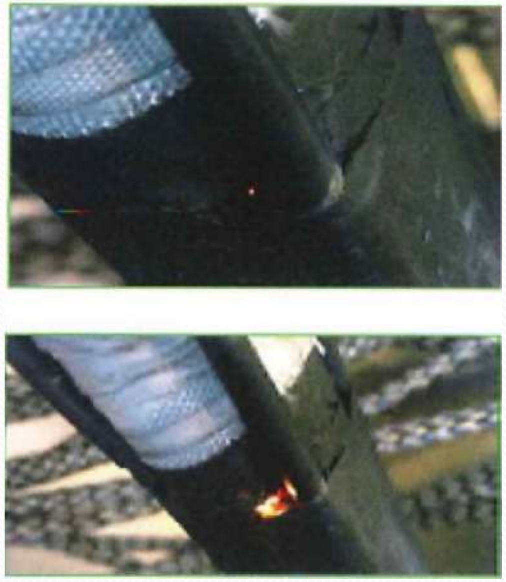
Freq. integration at
250 kHz ± 150 kHz
from: 100 kHz
to: 400 kHz
127,765,609 PDs
in 40 min 27 s

Gated Percentage
static: 0%
static partial: 0%
dynamic 0%

IEC 60270 status
conforming. Calibrated 2 days ago at 15:03:25

MPD 600 1.1:
$\hat{V}/\sqrt{2}$
4.771 kV
V_{RMS}
2.994 kV
f_V
49.96 Hz

Paschen Tests on TF Terminal Region (first production coil): yellow arc indicates the breakdown



Acknowledgement F4E/ASG and Sandro Bonito-Oliva and US-IPO/GA Wayne Reiersen and John Smith

CS Lead Breakout (mock-up) before discharge (left) and during discharge (right), breakdown at <5kV, 10 mbar

Key Technology: Structural Metals

Strategy of Metals Development

Identify areas where structural metals could be improved…1988

Define targets for properties of laboratory development

Innovations in conductor jacket material …1991

Adopt properties into design 1991

Base design around ideas (and therefore commit to achieving innovations)

Research and development

Gradual descoping of innovations:

- Reject all jacket material innovations….fixed 2003
- Reject all structural material innovations….fixed 2005

New industrial innovations 1996->

- Working/processing of common materials, forging, casting options

Large scale manufacturing trials and industrialisation

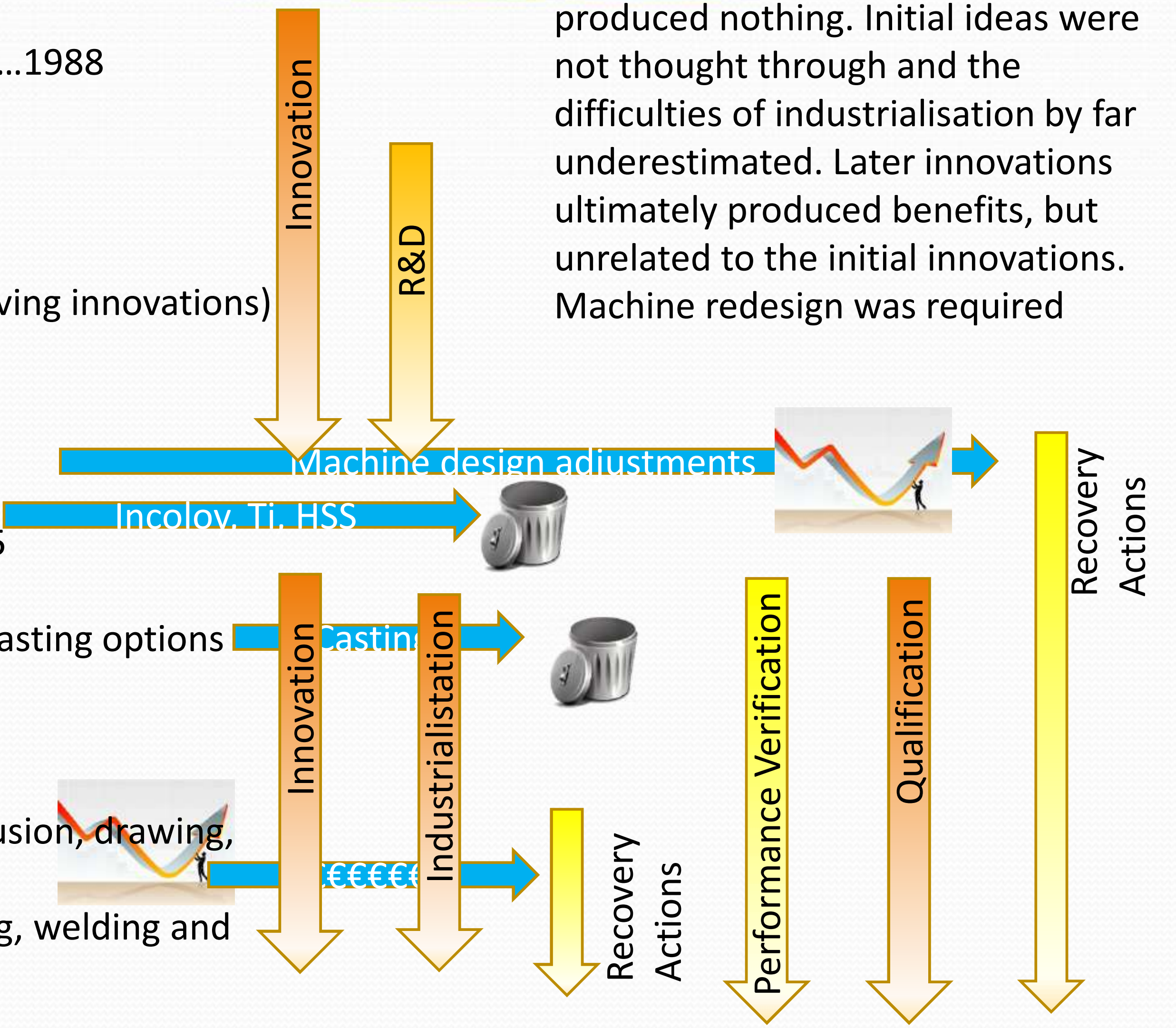
Further adjustments to achievable parameters 2008=>

Manufacturing design of jacket material production (extrusion, drawing, inspection)…recovery actions on low C SS

Manufacturing design of coil structures: innovative forging, welding and machining

Relaxation of tolerances

Almost classic example of a programme where early innovations produced nothing. Initial ideas were not thought through and the difficulties of industrialisation by far underestimated. Later innovations ultimately produced benefits, but unrelated to the initial innovations. Machine redesign was required



Key Technology: Structural Metals

- Accuracy and adjustability of magnetic fields critical to plasma performance
- Coil set built for one function must minimise fields that affect other functions
- Impossible to build and fit everything in ITER magnets to <1mm tolerances. Difficult & expensive to achieve <5mm overall
- Difficult to establish coil tolerances (or field accuracy) on many existing tokamaks
- Generally ‘a few mm’….regardless of size
- Only recently (last 10 years) is field quality (➔ tolerances) a design issue

Major effort with ITER coils to identify and minimise critical manufacturing manufacturing/assembly tolerances but NOT to demand unnecessary accuracy

Key Technology: Structural Metals

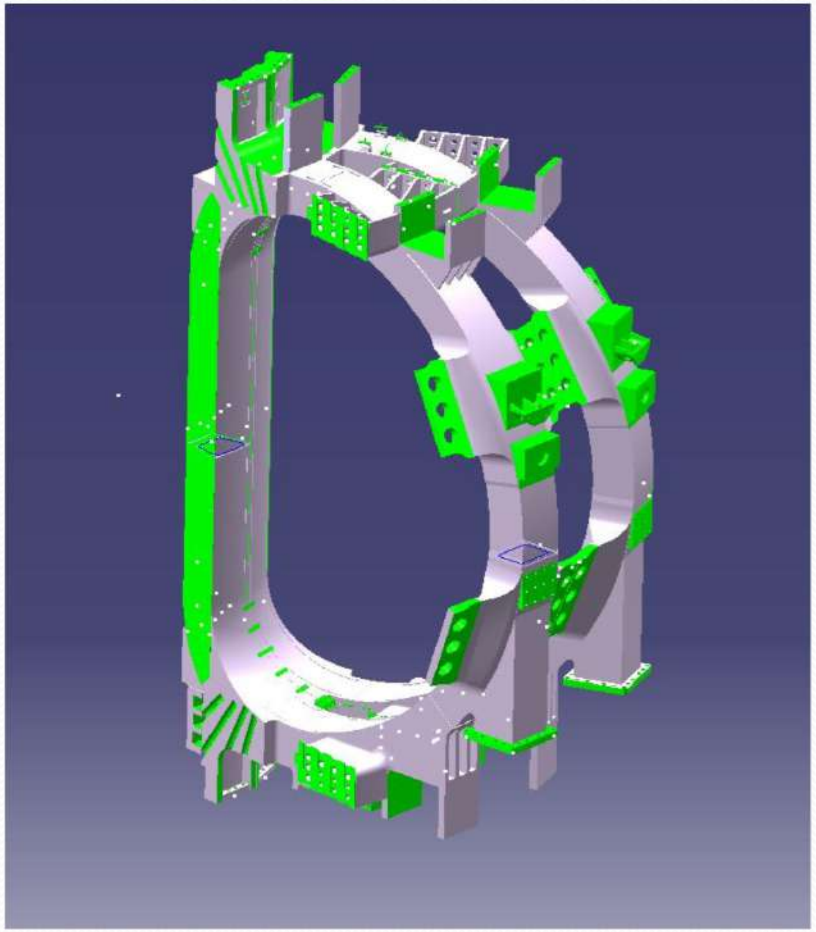
Example of Tolerances: Structures

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 typically +/- 1-2mm locally +/-0.5mm
- Installation requirements/capability typically +/- 2mm
- Measurement errors and component deformations under gravity
- Cumulative build up during manufacturing & assembly…. tolerances depend on other components
- For some interfaces we can adapt to +/-10mm



Multiple TF coil interfaces (green)

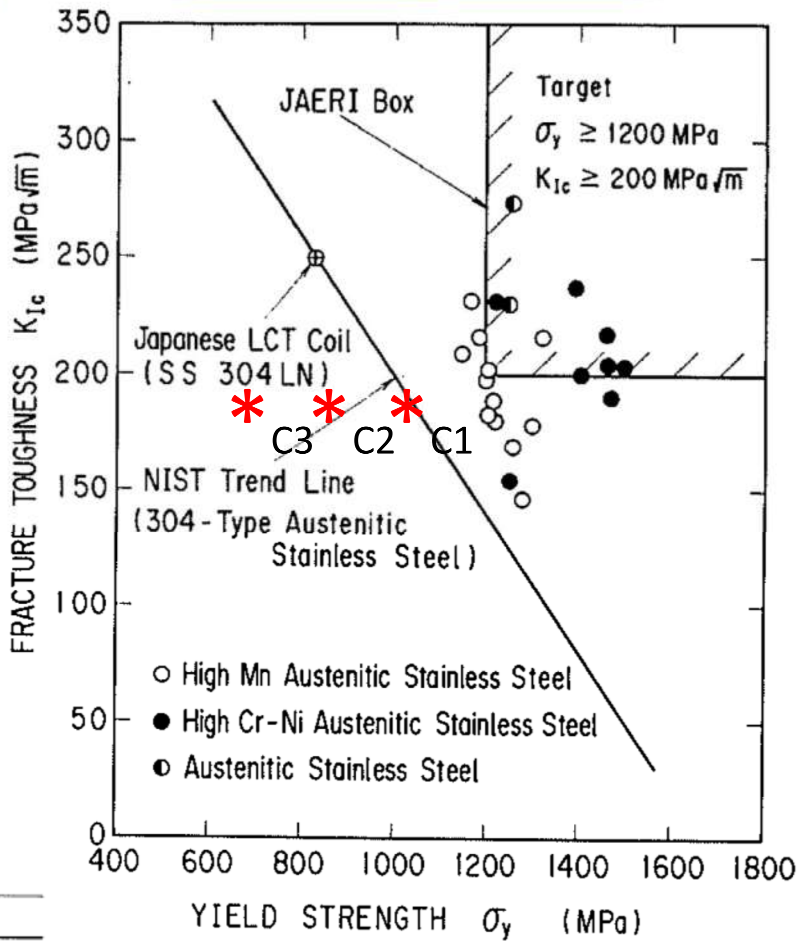
TF coils & structures are the core which drive the rest

Key Technology: Structural Metals

Base Materials for Structures

- Basic material research launched in 1988 as perception that higher structural metal properties could bring saving in overall machine cost
- Programme launched in JA, EU, RF
- Success claimed in laboratory scale research but universal failure on industrial scale.
- Problems of production of highly compositon specific alloys underestimated
- Issues such as welding, forging, corrosion neglected
- By 2008 only JJ1 remains (TF coil nose) at C1 level and steel properties at same level as obtainable industrially in 1980s

* indicates the 3 ITER material grade specifications used in 2009 C1, C2, C3



The relation between fracture toughness and yield strength of the JCS at 4 K. 1988

Table 1. Chemical compositions of the JCS.

JCS	C	Si	Mn	P	S	Ni	Cr	Mo	N	Others
CSUS-JN1	0.026	0.99	4.2	0.026	0.002	14.74	24.2	—	0.34	
CSUS-JKA1	0.023	0.42	0.49	0.006	0.001	14.0	25.0	0.68	0.268	
CSUS-JN2	0.050	0.34	22.4	0.010	0.002	3.22	13.4	0.70	0.24	V: 0.30
CSUS-JK2	0.05	0.36	21.79	0.013	0.005	4.94	12.82	—	0.212	Cu: 0.70
CSUS-JJ1	0.046	0.44	9.74	0.020	0.002	11.92	12.21	4.89	0.203	

Key Technology: Structural Metals

Base Materials for Conductor Jackets I

“Exotics”

Considerations on requirements (in 1991)

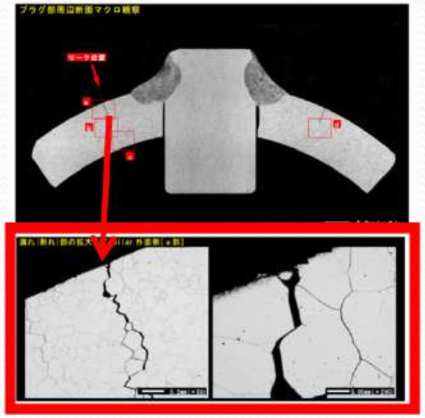
- Perception that metal contraction coefficient from 600C to 4K should match that of Nb3Sn to avoid critical current degradation
- The thermal contraction significance in CICC optimisation vastly over-estimated (still seen in new cable development in 2018) *leading to incorrect cost impact assessment*
- Many other issues drive cable in jacket performance (In particular degradation)
- *Environmental issues ignored: corrosion*
- Production issues vastly under-estimated but became obvious in period 1998-2002

Candidates Incoloy 908 and Ti. SS was neglected

Corrosion 1

Typical SAGBO cracking in Incoloy 908, in CS Model Coil jacket sections (K. Hamada and JAERI)

Corrosion 2



CS JK2LB conductor samples 2012-13 - corrosion leaks originating from halides present in solder flux accidently contaminating the metal surface

Key Technology: Structural Metals

Base Materials for Conductor Jackets

"Conventional"

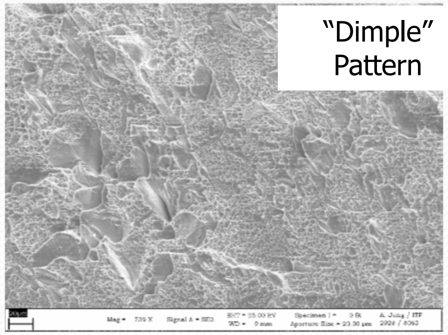
Late development of SS jackets

- Nb3Sn heat treatment leads to carbon precipitation and embrittlement of SS enhanced by cold work of jacket
- For TF needed to develop low carbon steel. Worked with industrial partners to optimise production process and control cold working
- For CS JADA continued with JK2LB and eventually achieved success after several material composition adjustments
- JK2LB remains highly sensitive to halogen stress corrosion

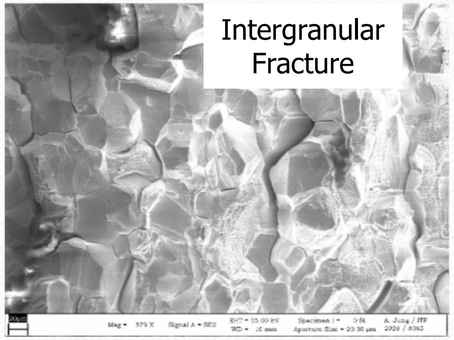
- **4 TF jacket suppliers** (1 in EU SMST, 1 in JA KSST, 1 in KO POSCOSS and 1 in CN JIULI) **have been qualified** and produced tubes for all **6 DAs**.
- Tubes extruded in ~12m lengths and butt welded

Tensile Tests at Low Temp. (< 7K)

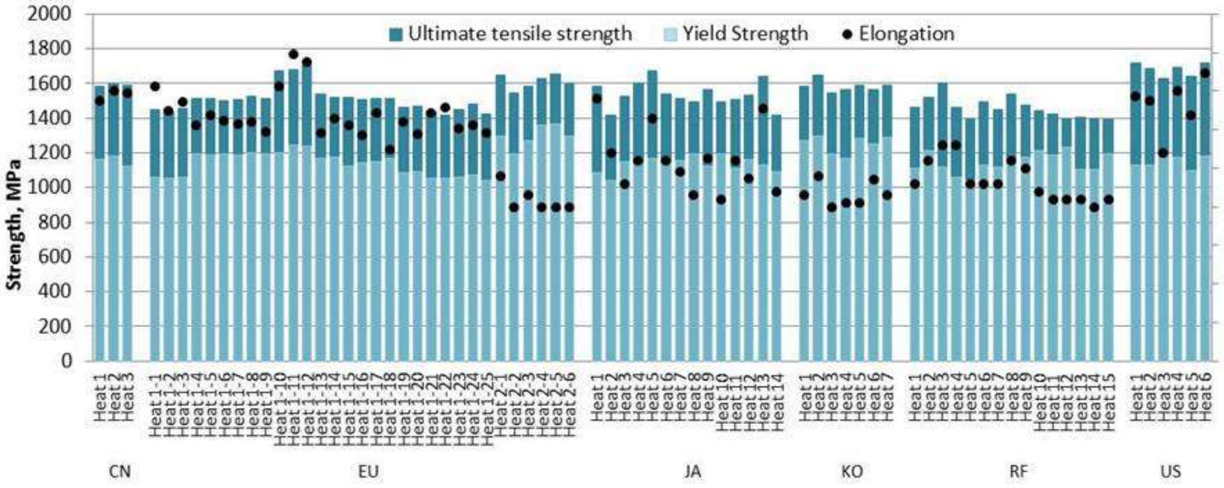
Courtesy of K. Weiss (KIT)



Sample exhibiting fully ductile fracture (Max. elongation > 20%)



Sample exhibiting embrittlement (Max. elongation < 15%)



TF Jacket Production Elongation Data (4.2 K)
Compiled by D. Kaverin (ITER-IO)

Key Technology: Structural Metals

1996-2000 Various forged sub-sections of the ITER TF coil case, showing the complexity of the forged forms. Top: seamless TF case, bottom, seamless radial plate for TFMC

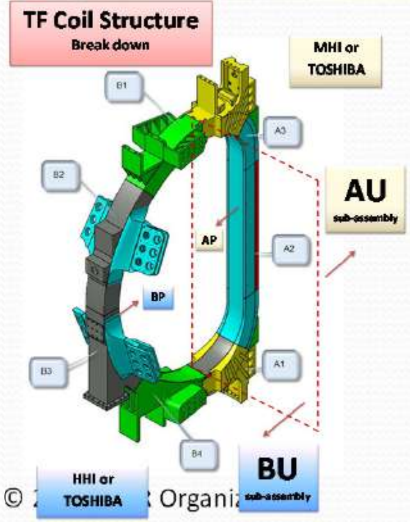
Trials on TF Structures: curved hollow section of coil case. Ultimately too complex but the know-how obtained by the company (Kind) was used to produce almost all the forgings for the TF coil cases and VV under contracts with EU, KO and JA

Forging Challenges: Size (for CS tie plate, longer than reheat furnace), shape complexity to reduce machining, narrow temperature window for forging high strength steel

2015-16 Offset forging of a 12m CS tie plate

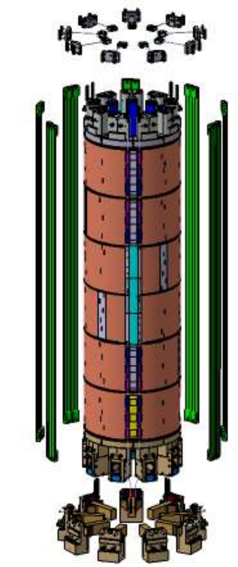
Trial Casting of Components: rejected because of poor properties (low modulus, low strength)

Key Technology: Structural Metals



CS tie plate 2017

Various forged sub-sections of the ITER TF coil case in 2016-17, showing the complexity of the forged forms.



Key Technology: High Strength Composites

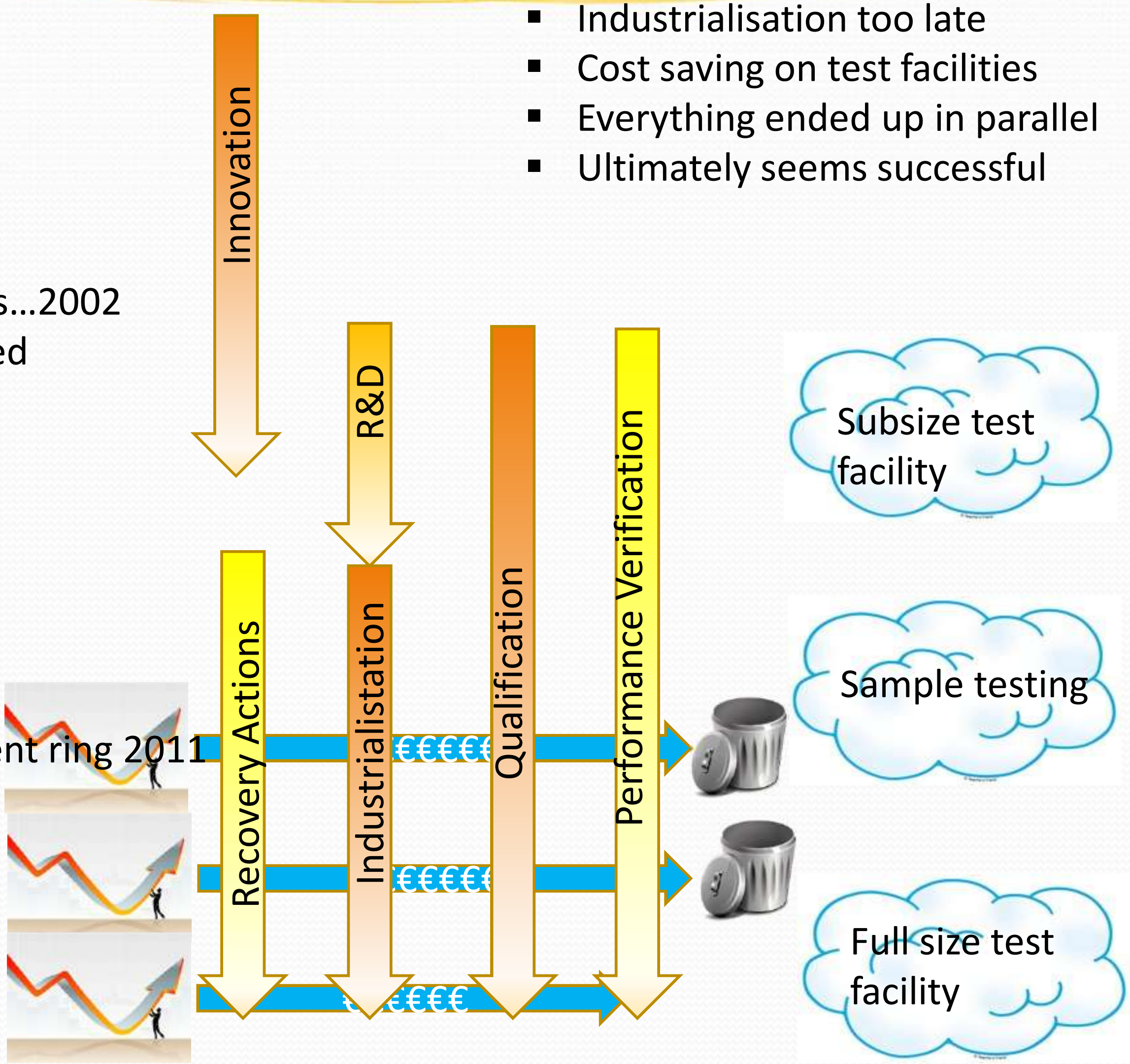
Classic case of poor implementation of innovation
- Industrialisation too late
- Cost saving on test facilities
- Everything ended up in parallel
- Ultimately seems successful

Strategy of Use
Decide on Pre-compression ring concept…….2000…too vague
Decide performance parameters….overestimate

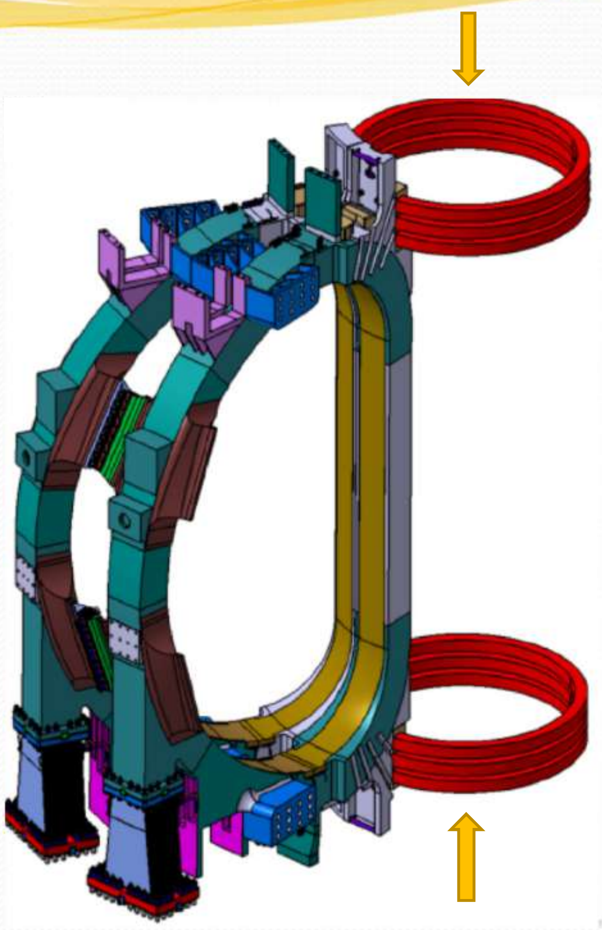
Consider options
Choose winding concept…..wet winding of monofilament glass…2002
No industrial input, attractive as subsize tests can be performed

R&D and qualification
Change winding concept…VPI of monofilament glass…2004-5
Construct 1/5 scale test facility 2005-6
Wind 1/5 scale samples in laboratory, successful test 2006-7

Industrialisation (from 2009)
No industrial suppliers prepared to offer full scale monofilament ring 2011
Change concept to AFP, new process, 2012
Process not down-scalable to 1/5 test facility, go to full scale
AFP manufacturing issues 2015
Change main line concept to pultruded process, 2017
Construct full scale test facility 2017
Full size pultruded ring test end 2018 (?)



Key Technology: High Strength Composites



Critical component introduced in ITER in 1999-2001 to preload TF coils and compress shear keys

Relies on specific properties of strength, modulus and thermal contraction.

Practically only one solution: structure made with glass fibre

Classic example of a high risk innovation: limited opportunity for risk mitigation if it does not work, limited possibilities to find alternatives

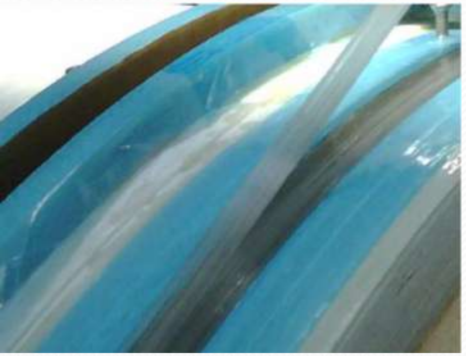
Cost saving did not allow proper risk mitigation. Too small testing, very late industrial involvement. In the end cost more than a structured programme from the start

Classic example of a (too) late recovery plan based on R&D to produce a ‘Plan B’ that seems successful linked to implementation of full testing

Key Technology: High Strength Composites

Pre-PA R&D at ENEA: 2003-2009

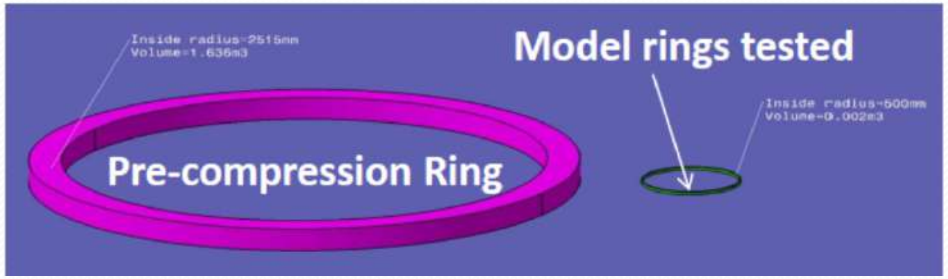
Wet Winding



VPI

Ring before and after testing

1/5 scale test facility



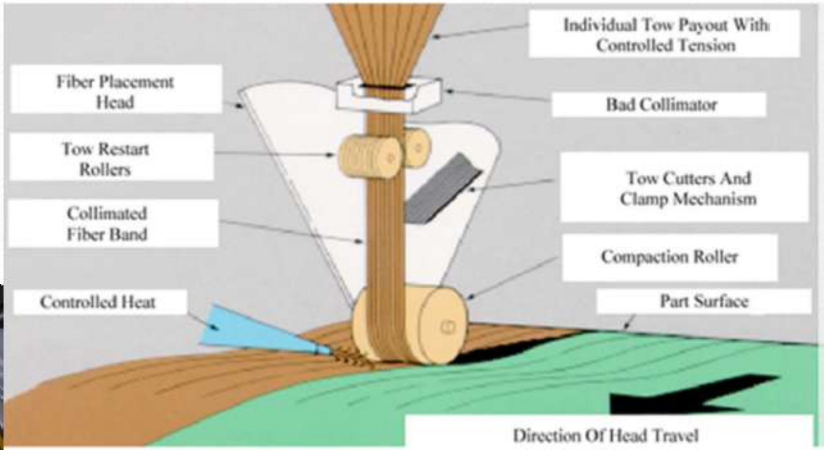
1/5 scale test facility 2009

Key Technology: High Strength Composites

AFP Automated Filament Placement Method

Fibers' Wrinkles: waves on fibers with **pitch of few mm**

- **Fibers' Undulations**: waves **slightly taller** and with **pitch of tens of mm**



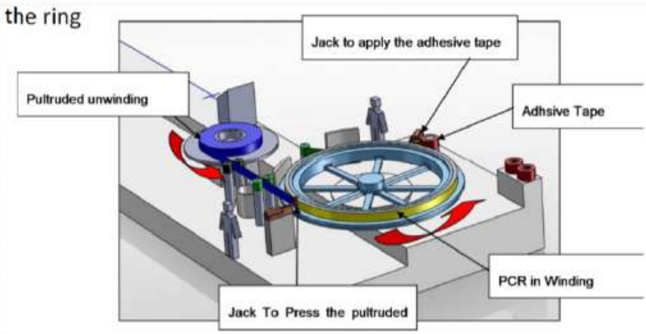
Full diameter prototype ring after curing, showing wrinkles

Pultruded Route

Full size 1/3 thickness prototype July 2018

Full size test facility Jul 2018

Winding line completed



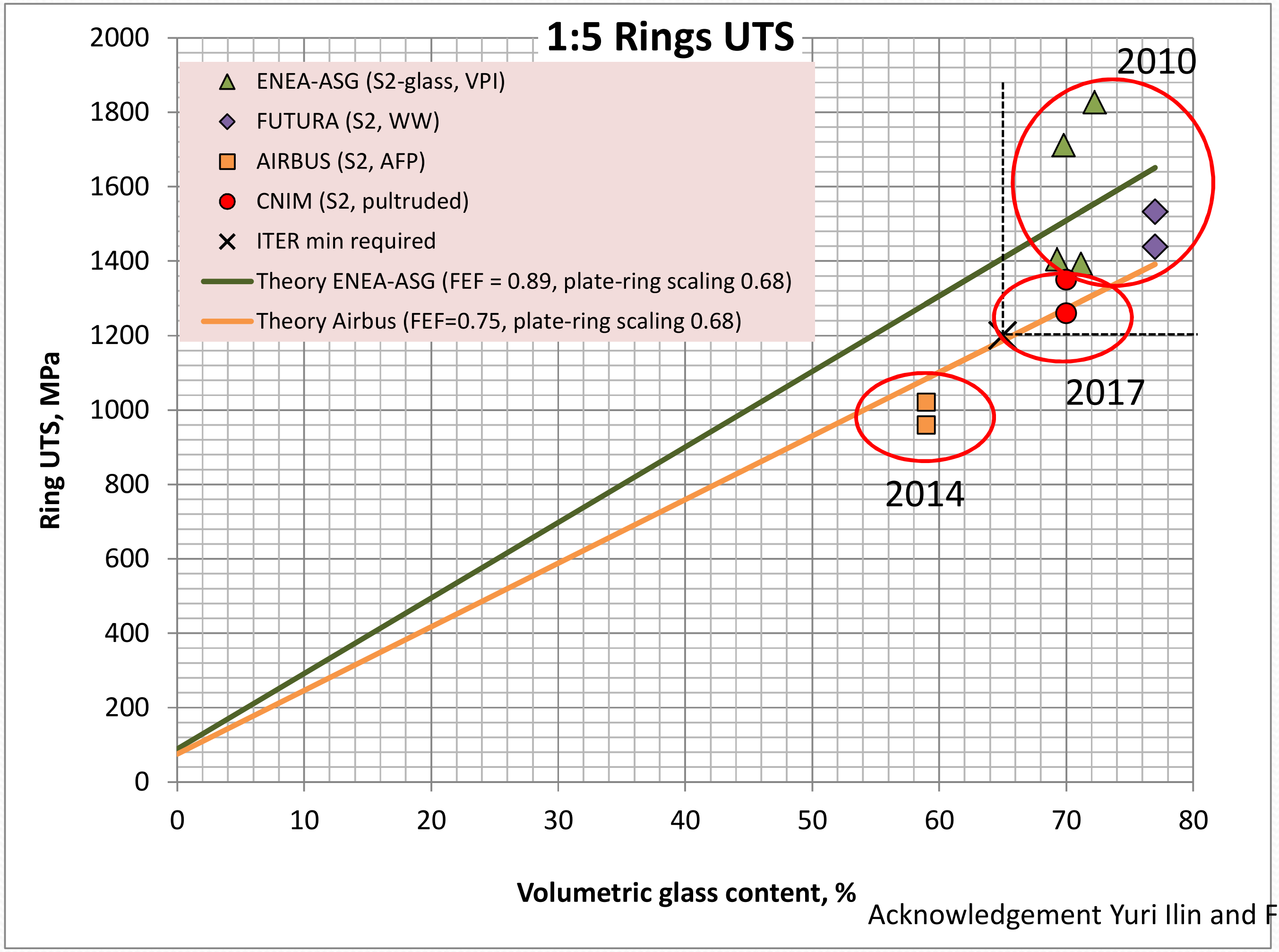
Acknowledgement F4E, A. Bonito-Oliva, T. Boutboule, CASA and CNIM

Key Technology: High Strength Composites

Summary of recovery actions

Tests of 1/5 scale rings to failure

UTS= ultimate tensile strength



Acknowledgement Yuri Ilin and F4E

What Lessons were learned?

Innovation will happen at many levels in a project….great ideas everywhere
ITER top level: Series of innovations in tokamak concepts provoked big oscillations in the technological development
Medium level: 4 innovations were ultimately successful but followed paths of highly variable roughness

What Lessons do we expect to learn from all this? We are not going to repeat exactly the ITER experience

Generalise the specific examples to write rules/guidelines on how to start a basic research project in an international environment (which in the present world is omnipresent)…essentially try to carry out a root cause analysis

1. Always carry out a FMEA assessment based on the full, partial or complete failure of a great idea. A risk analysis is not the same….failure is black and white, risk is shades of grey. A FMEA should identify the necessary escape routes…
2. When assessing a proposed innovation, confirm that the innovation is really the key issue in the area it affects. Good example here is the structural materials….laboratory scale R&D created a series of red herrings that took years to straighten out. If it is not, what is? And can it be improved?
3. Successful engineering implementation is much more difficult than a small R&D programme. If an innovation is selected, plan, plan, plan! You need industrial suppliers and (while recognising the key part industrial collaboration can play) never ever create a monopoly supplier situation
4. Successful innovation is a long grind, with many forks. You cannot follow them all, but nor can you cut off the branches too early. Plan frequent reviews, adapt, ensure wide input, get in early with recovery plans, and ruthlessly discard when the end of the road seems to be reached.

3. Brief Status of the ITER Magnets

Manufacturing Status (July 2018)

Very approximate overview

Conductors: 99% complete

TF Coil Windings: 60% complete

TF Structures: 50% complete

PF Coils: 25% complete

Feeders: 25% complete

Supports: 60% complete

CS coils: 50% complete

Worksite Progress: Feb. 2015 – July 2018

Feb 15

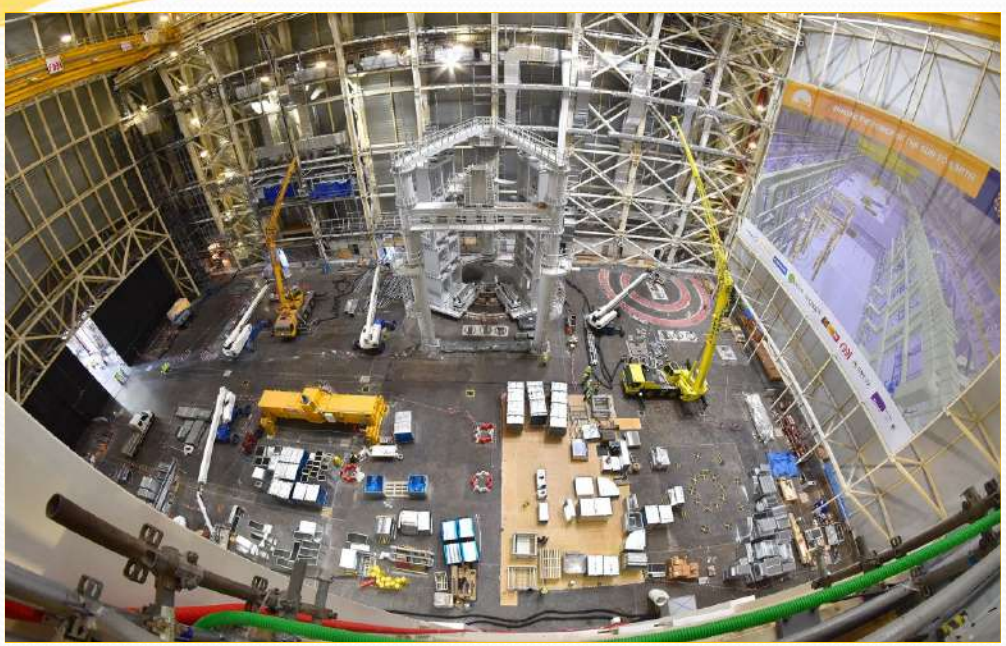
July 18

Nov 17

April 18

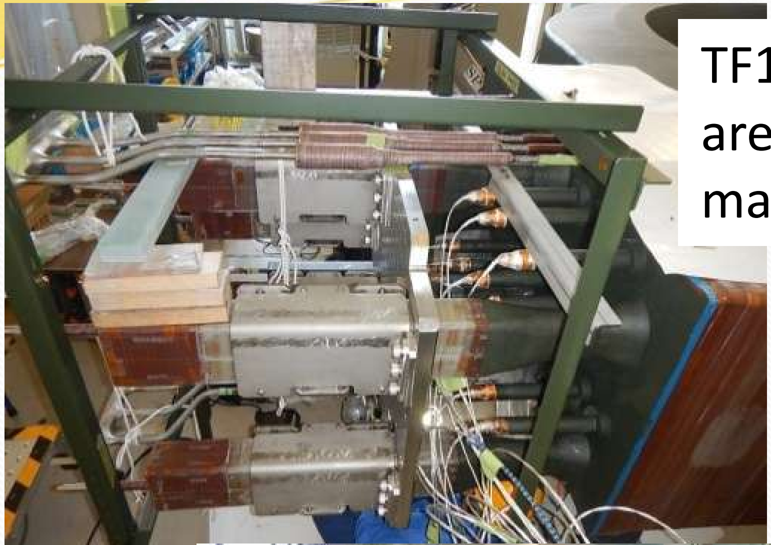
More than halfway to First Plasma:

Assembly Hall



Before being integrated in the machine, the components will be prepared and pre-assembled in this 6,000 m2, 60-metre high building.
The Assembly Hall is equipped with a double overhead travelling crane with a total lifting capacity of 1,500 tons.
To the right, the installation of the first sub-assembly tool (SSAT-1) is nearing completion

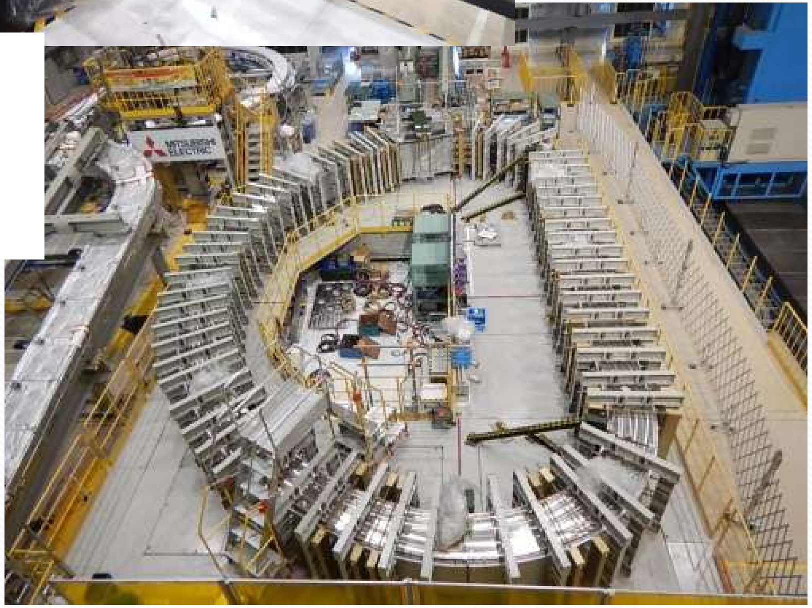
JA TF coils – Manufacturing progress at MHI Kobe



TF12 terminal area (under manufacturing

TF13 DP joint assembly

TF12 WP



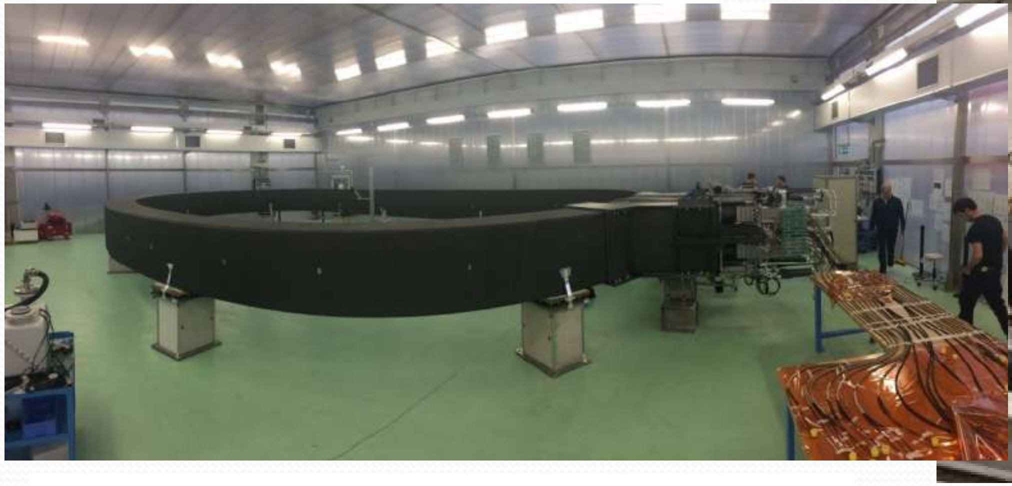
TF13 WP in VPI mould

Acknowledgement:
N. Koizumi, QST
team and MHI

EU TF coils – Progress at ASG La Spezia

Completed TF06 WP

Completed TF09 WP



WP instrumentation under test

Completed TF11 WP

Acknowledgement F4E and ASG

TF Coil Structure BU-AU fitting tests at MHI Japan & HHI Korea

Fitting achieved to better than 0.5mm at interfaces

Left: TF09 fitting, HHI, January 2018

Right: TF12 fitting, MHI, Aug 2018

Acknowledgement QST, MHI & HHI

Case-WP Insertion Assembly Rig at SIMIC

- The 1st Assembly Rig has been tested and commissioned in 2017
- Results showed that the parts can be moved with a precision better that 0.2mm
- First set of structures has undergone a trial fitting in July 2018
- First winding pack insertion starts in September 2018

Acknowledgement F4E & SIMIC

Supports at various locations in China

- Lots of PF clamps in various stages of completion at HTXL China
- TF GS complete and components for 3-4 more near completion

Water jet machining PF5 clamps

TF GS plates

PF clamps rough forgings

Behind: PF clamps (left), TF GS plates (right), PF6 plates and blanket shielding blocks (front)

Balancing a PF5 clamp

First complete TF Gravity Support (July 2017)

Acknowledgement CNDA, SWIP & HTXL

PF5 Status (ITER Site)

- **Five PF5 real Double Pancakes (DPs) windings have been completed. The third series production DP6 has been started.**
- **First VPI on DP7 finished. VPI on DP8 and DP6 is on-going.**

PF5: 2nd DP(DP8) Winding Completed

PF5: Dummy DP VPI Under Preparation

Acknowledgement F4E

PF6 Status in Hefei, China

- All DPs windings have been completed.
- Completed resin impregnation (VPI) for six DPs.
- Coil stacking underway

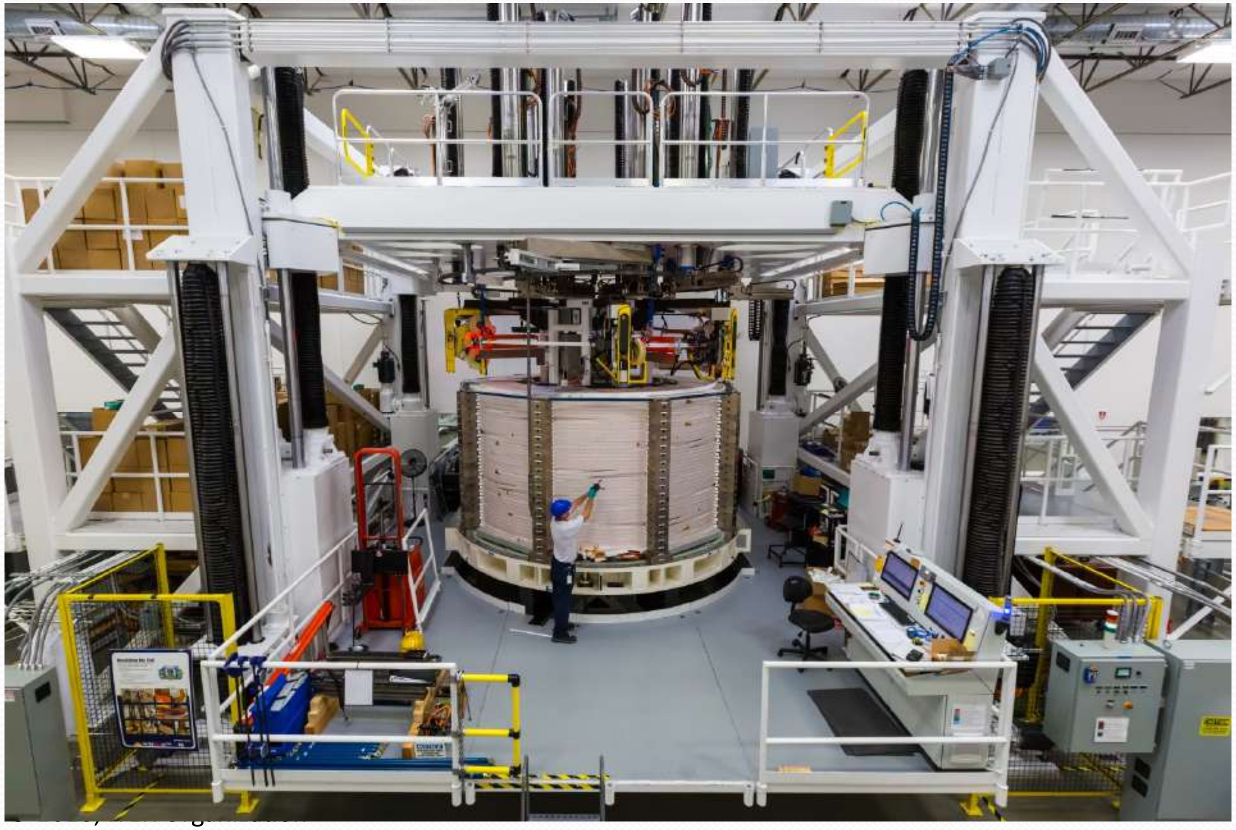
PF6 DP stacking, July 2018

Acknowledgement F4E & ASIPP

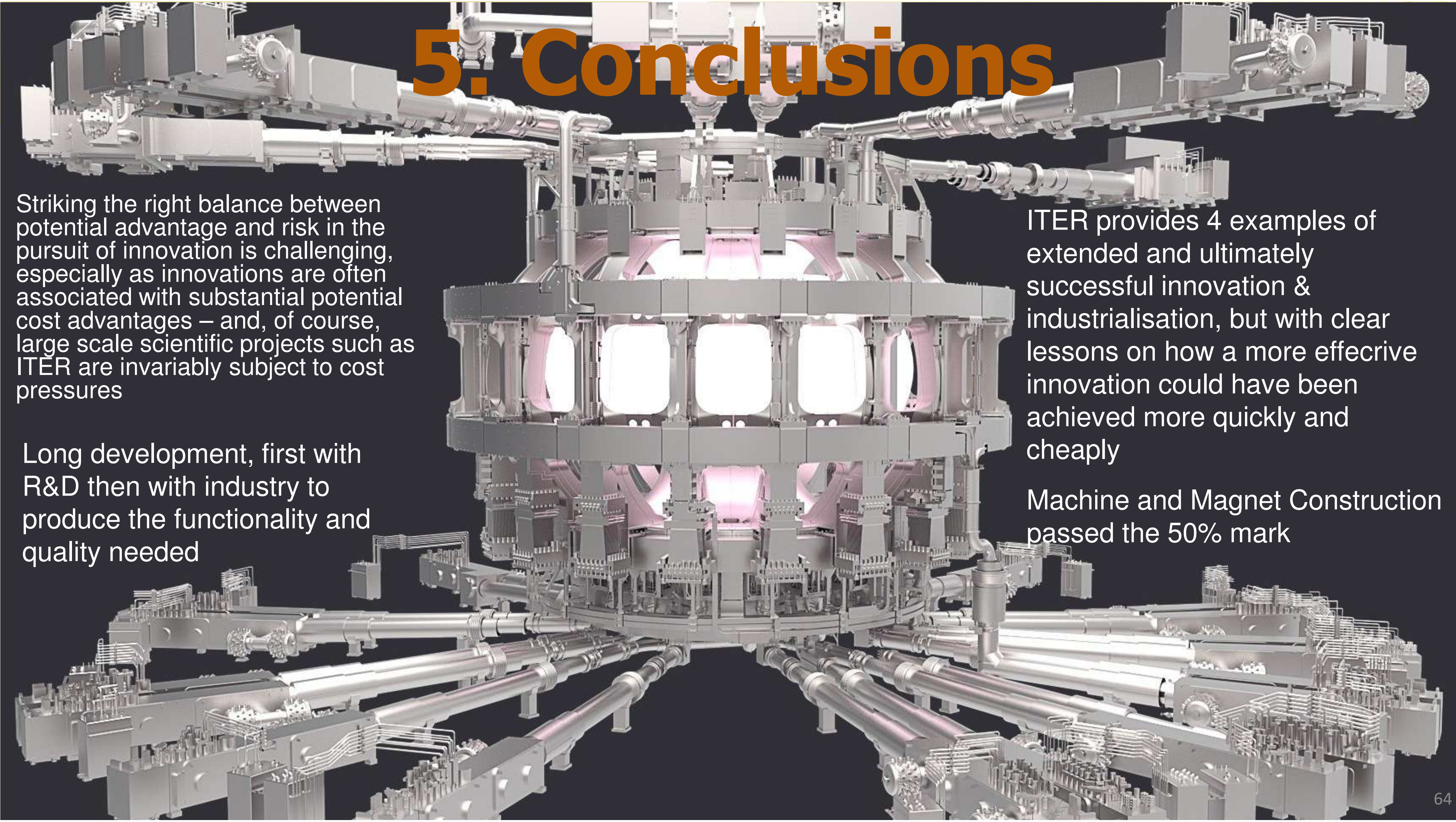
CS Coil at GA San Diego

- Left: CS module 1 on turn insulation station after heat treatment. Right: Module 1 entering mold (Aug 18). Resin impregnation in September 2018
- Winding of 4nd module is completed; winding of 5th module has started.
- Modules 1, 2 & 3 are heat treated

Acknowledgement US-IPO, GA)



5. Conclusions



Striking the right balance between potential advantage and risk in the pursuit of innovation is challenging, especially as innovations are often associated with substantial potential cost advantages – and, of course, large scale scientific projects such as ITER are invariably subject to cost pressures

Long development, first with R&D then with industry to produce the functionality and quality needed

ITER provides 4 examples of extended and ultimately successful innovation & industrialisation, but with clear lessons on how a more effecrive innovation could have been achieved more quickly and cheaply

Machine and Magnet Construction passed the 50% mark