IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P2 given at the virtual ASC 2020, October 27, 2020.

Construction Status of ITER and Lessons from the Manufacturing for Application of Superconductivity in Fusion Reactors

Neil Mitchell, ITER Organisation with contributions from many colleagues in the IO and Domestic Agencies

Applied Superconductivity Conference Oct 2020

Virtually located

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1. **What are tokamak magnets**

2. **Brief Status of the ITER Magnets**

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4. **Next step in fusion…. timelines and possible machines, big and little**

5. **Ancestors of SC fusion machines……history of SC in fusion…foundations for ITER**

6. **ITER Experiences and New Priorities for DEMO**

- Development of ITER conductors (and analogy with next step now with HTS)
- Development of ITER structural materials
- Development of ITER insulation

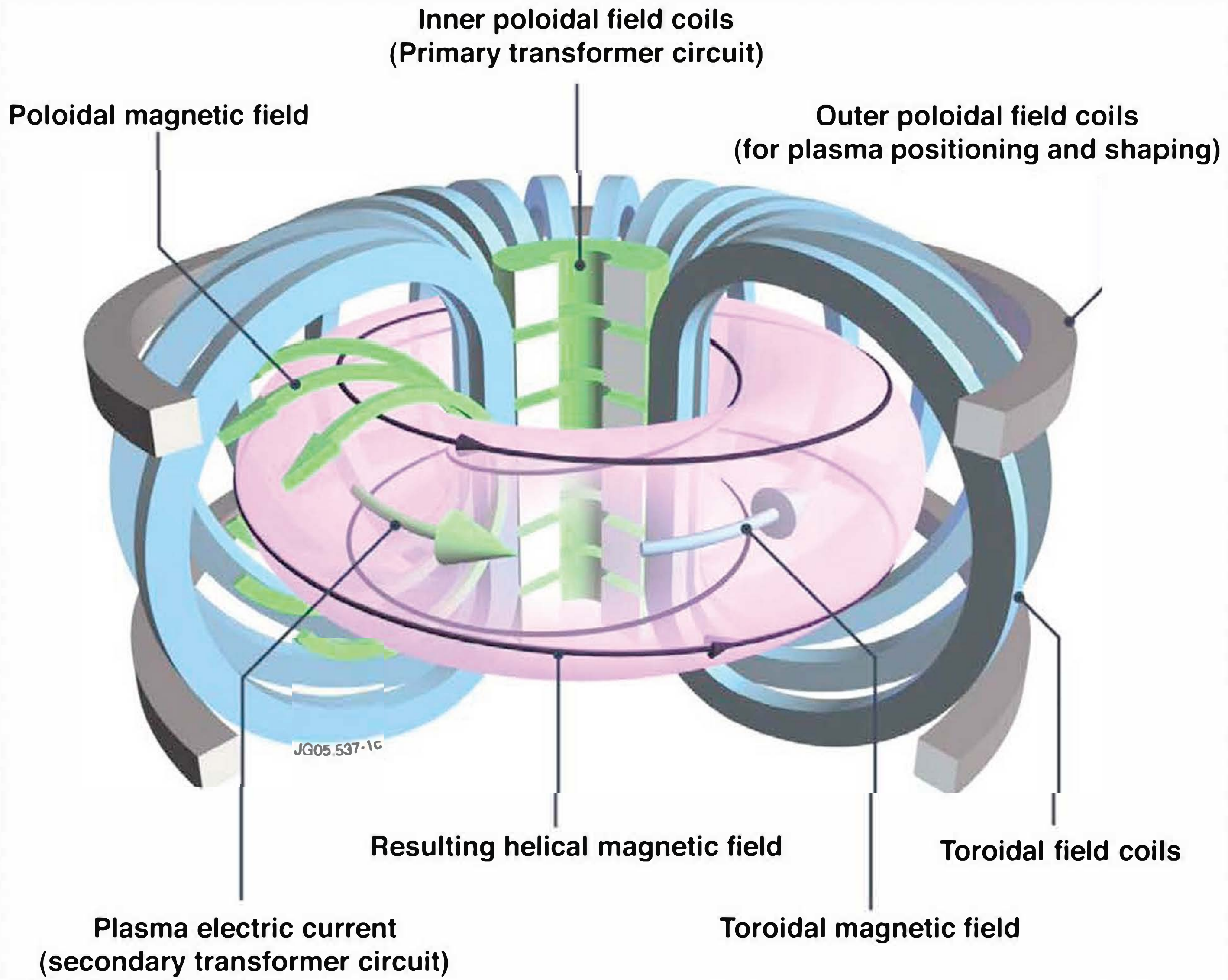
Safety and its role in DEMO compared to ITER, Maintenance & Repair

7. **Lessons for the future and foundations for the next step**

- Importance of integrated design, not just focusing on one idea. For next step tokamaks give more weight to basic engineering considerations like repair
- Build on ITER, improve engineering but be cautious to try to start again with new basic technologies
- Exploit collaboration, set stable industrial targets, give visible intermediate targets for the magnets

1. What are the ITER Magnets

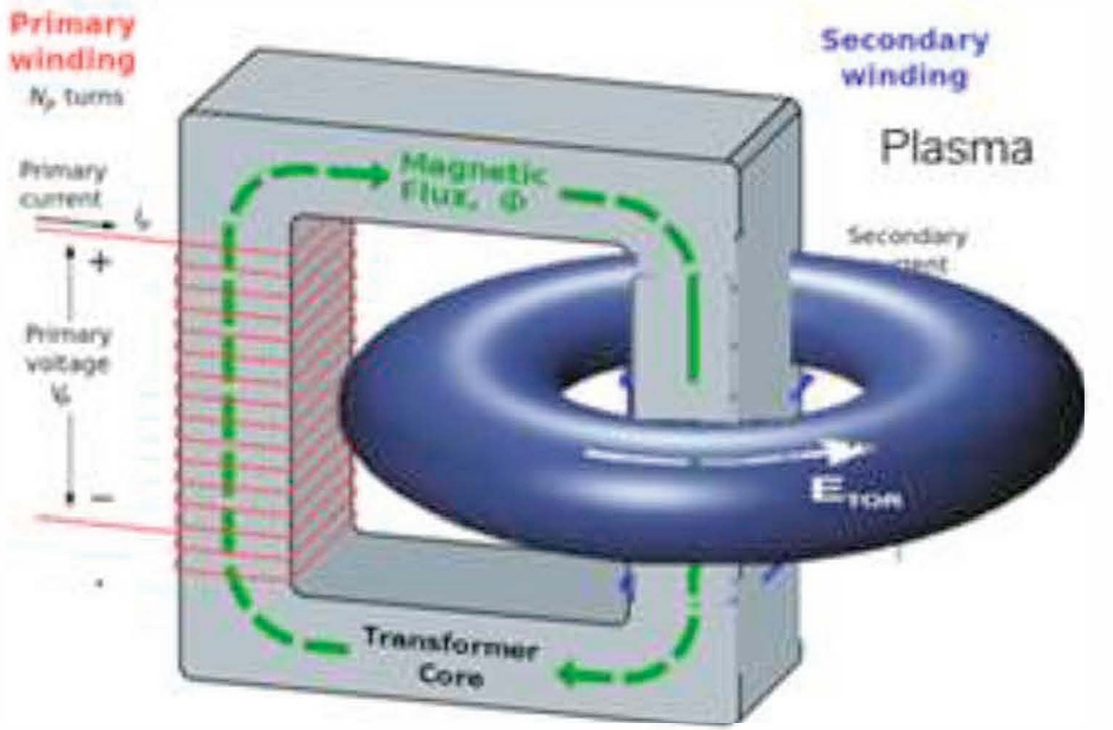
ITER is a superconducting Tokamak



Designed to achieve 500MW fusion power

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

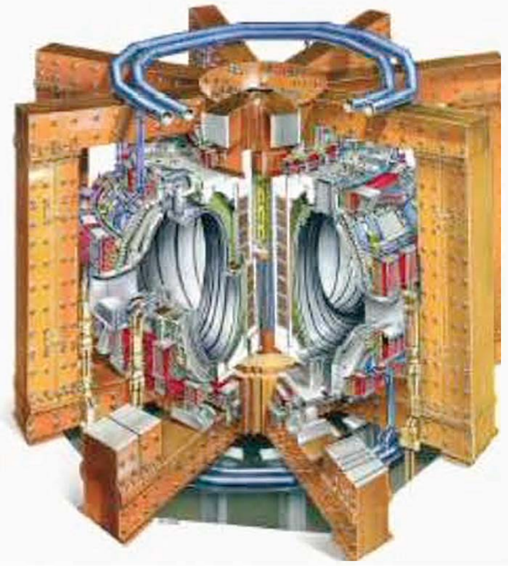
Creating the Plasma Current



- 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

Some tokamaks use an iron core to improve coupling to plasma

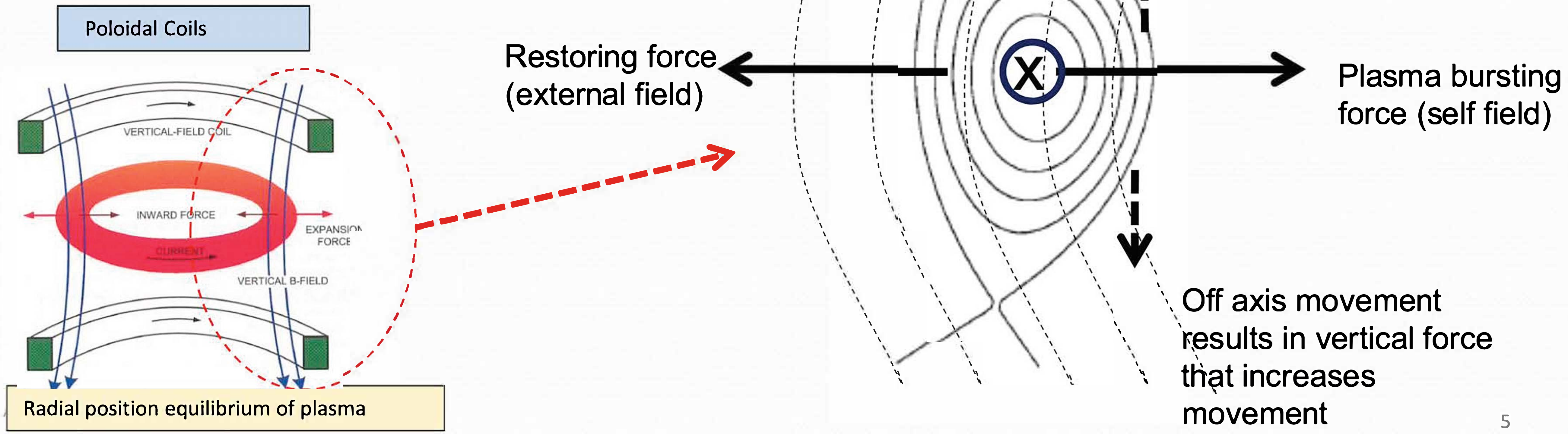
Tore Supra
V_{plasma} 25 m^3
P_{fusion} ~0
t_{plasma} ~400 s



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

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.
- Active stabilisation required (AC operation of some coils)



Restoring force (external field)

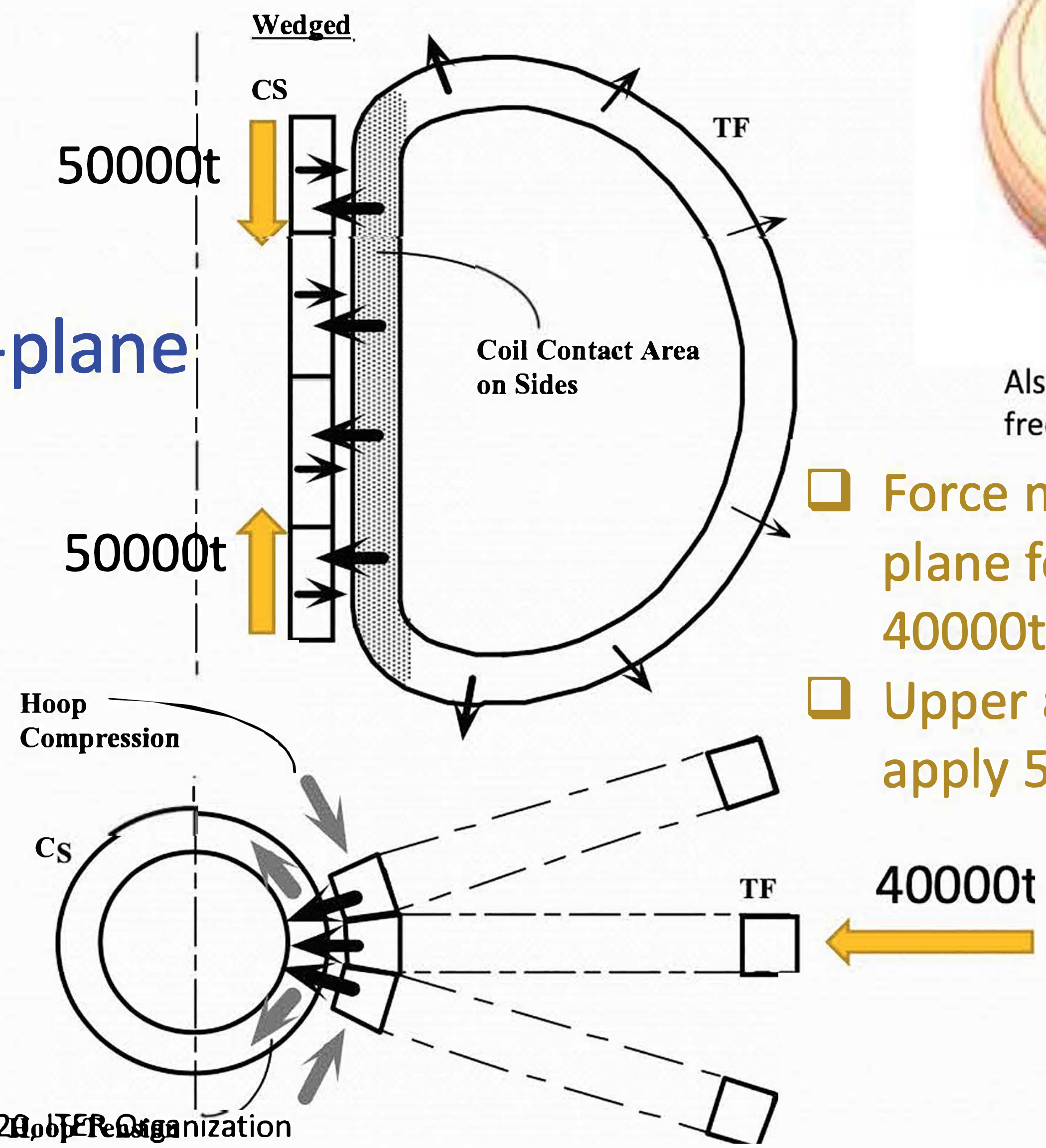
External field curved to elongate plasma

Plasma bursting force (self field)

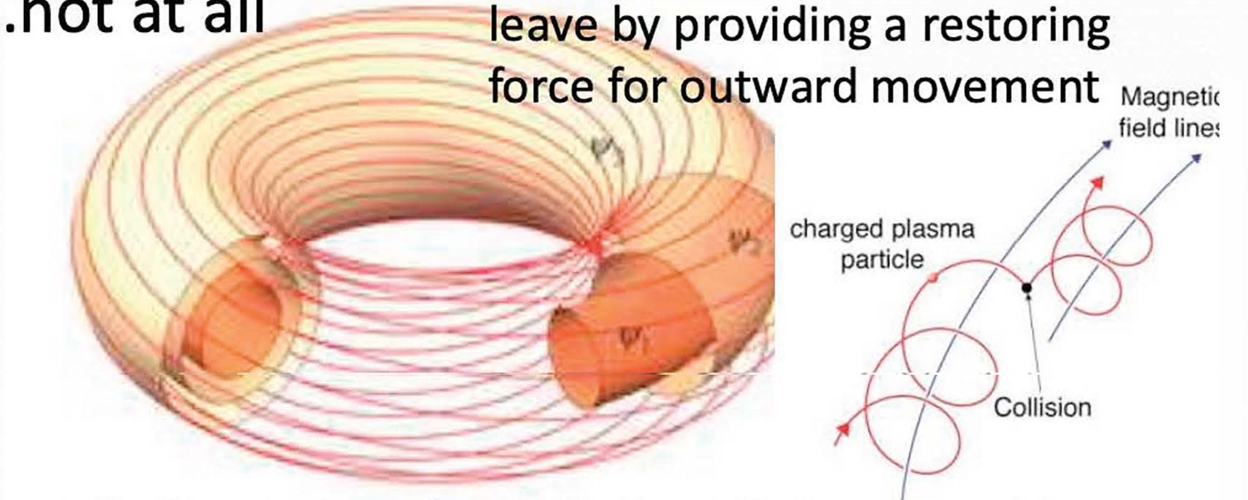
Off axis movement results in vertical force that increases movement

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



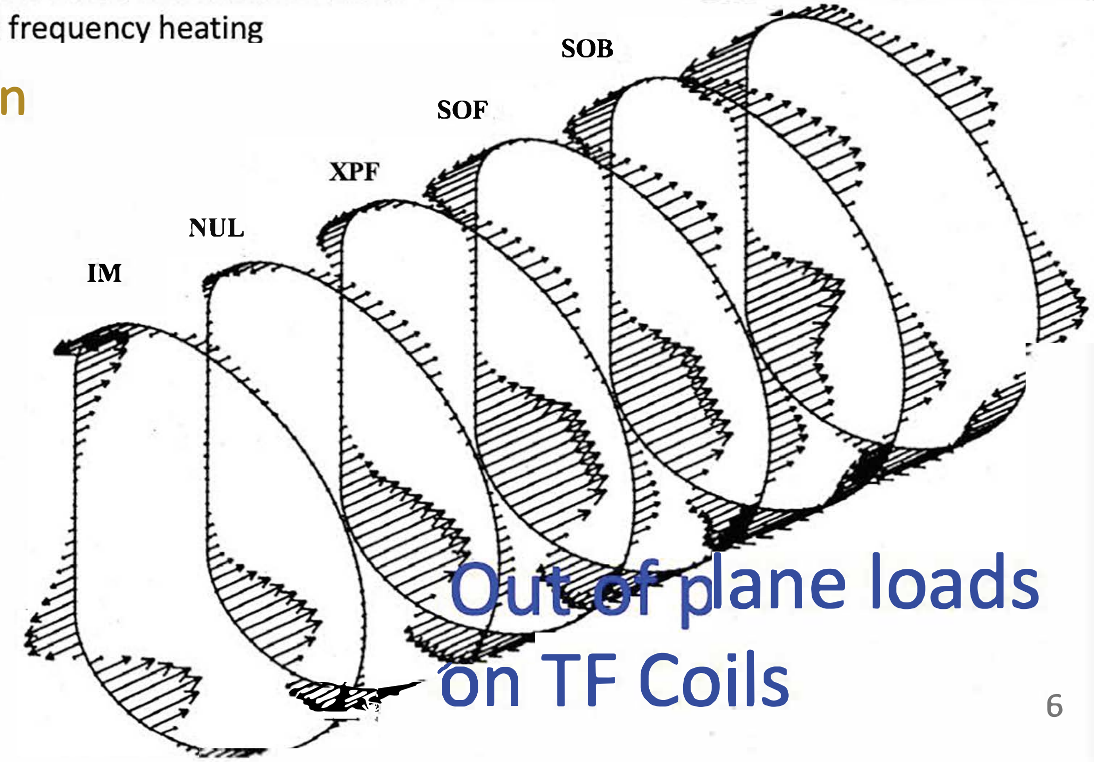
In-plane



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

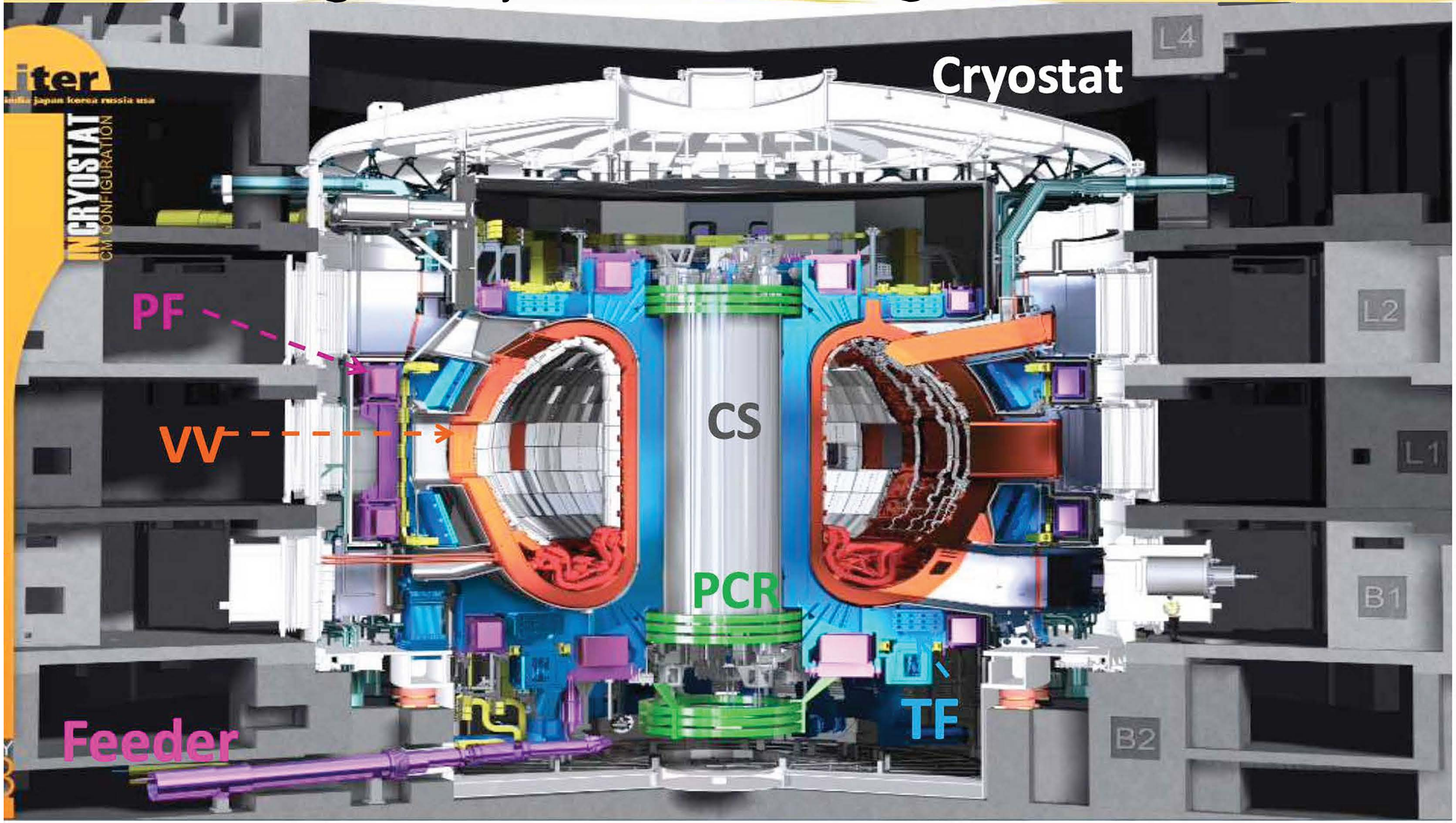
Also forces moving particles to orbit. These orbits have characteristic frequencies that can be coupled to radio frequency heating

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



Out of plane loads on TF Coils

Overall Magnet System and Neighbours



2. Brief Status of the ITER Magnets

Manufacturing Status (Sep 2020)

Very approximate overview

Conductors: 100% complete

TF Coil Windings: 80% complete

TF Structures: 95% complete

PF Coils: 65% complete

Feeders: 50% complete

Supports: 75% complete

CS coils: 60% complete

Transport of 3rd and 4th TF coils (TF13, TF11) July/August 2020

Sea to Fos-sur-mer

Special road transport to site (3-4 nights)

Major activity since January 2020
Transport magnets to the ITER site

Transport of PF6 June 2020

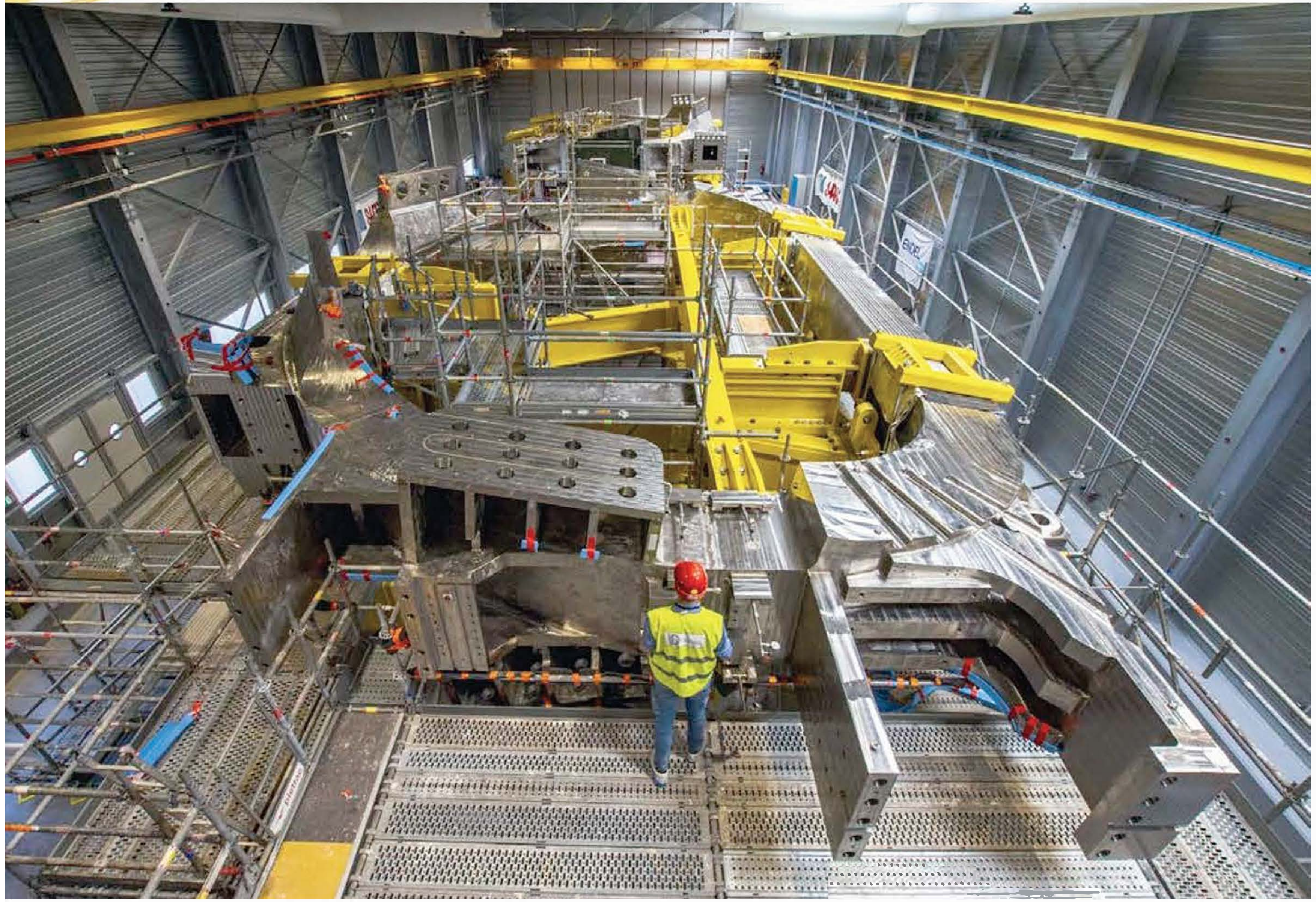
PF Coils at ITER Site

PF6

PF5 (far left), PF2 (middle), test cryostat, PF6 (far right)

PF5

TF Coils at ITER Site



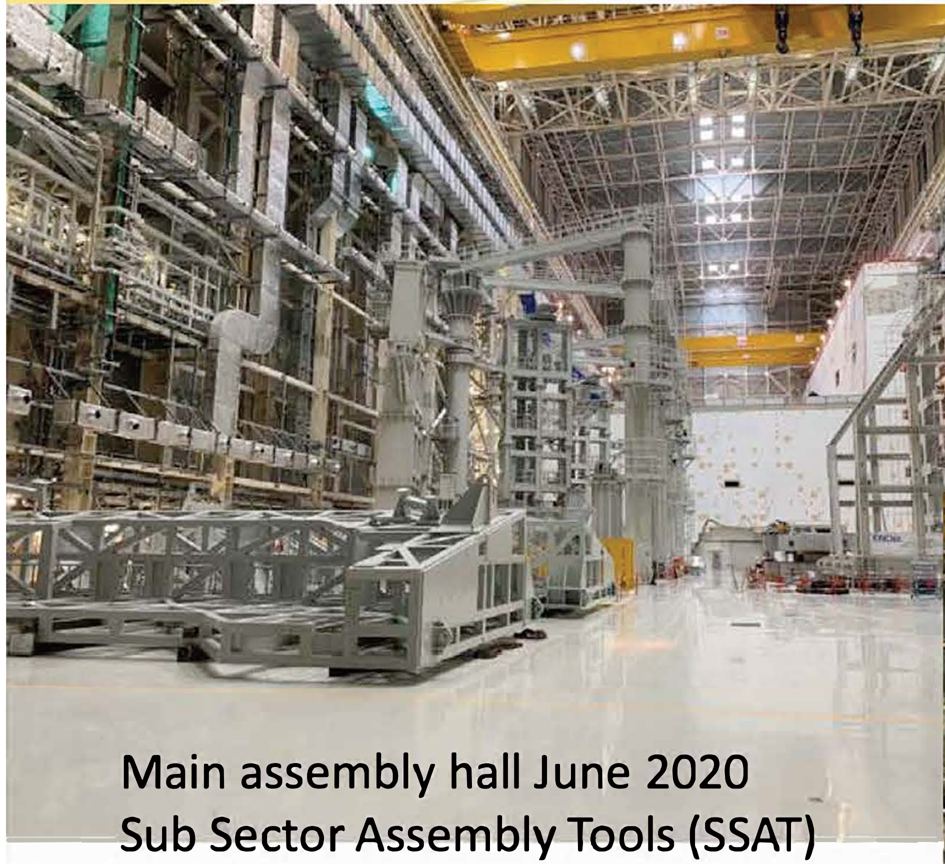
TF13 & TF12 under preparation for installation Aug 2020

Feeders and Supports

TF Gravity Support before shipping from China

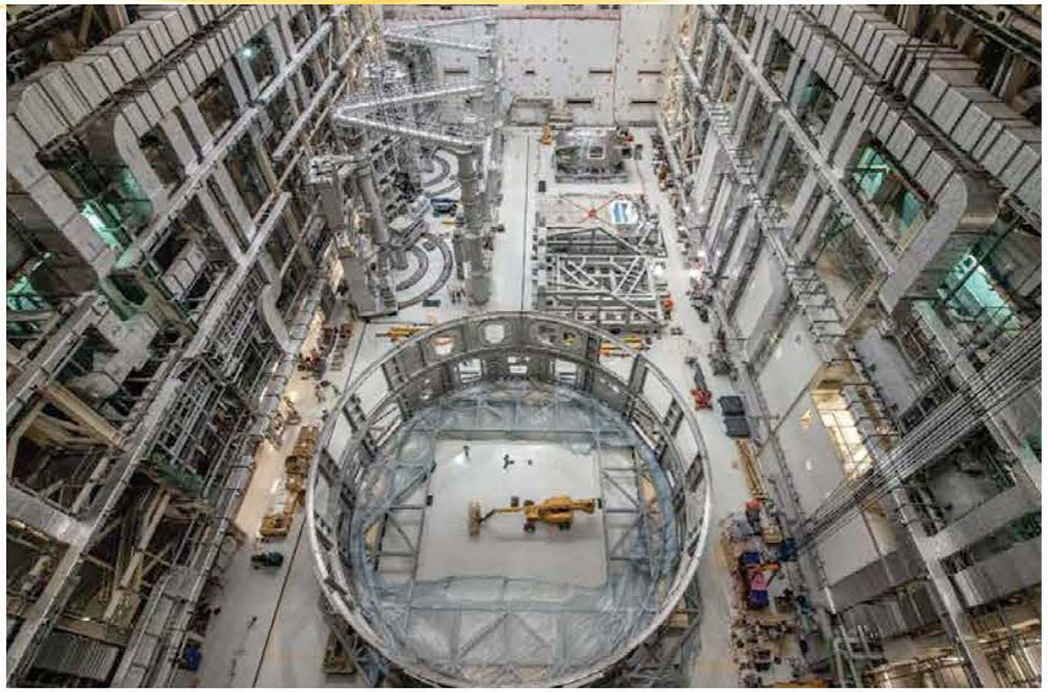
TF12-13 Cryostat Feed Through preparing for SAT after arrival from China

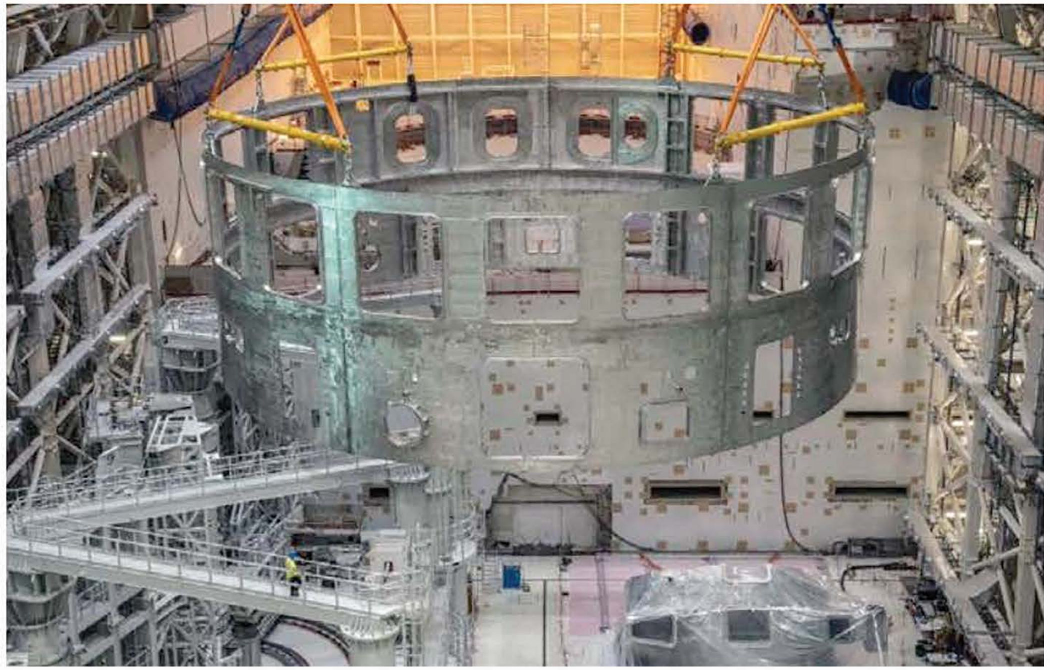
Assembly Hall and Tooling (and Lower Cryostat Cylinder Lift) Aug/Sep 2020



Main assembly hall June 2020
Sub Sector Assembly Tools (SSAT)
Each for mounting 2 TF coils and 1 VV sector

Main
assembly hall
Top right VV6
Bottom Lower
Cryostat





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

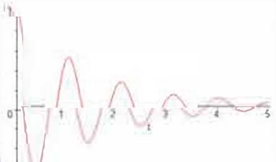
Successful realization of "7 large projects" in parallel with design iterations of a single ITER machine concept during EDA

1998

Budget constraints, "reduced performance design"

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

Lessons Learned?

3. Magnet (and superconductor) utilisation drivers: conductors, structures and insulation

ITER is now well on the way to completion and operation:

Where next?

What are the drivers that will allow applied superconductivity to be in a position to deliver what is needed for a fusion reactor?

The 3 key technologies for the future are the same as they were for ITER

- ☐Conductor (determines field limits)
- ☐Structures (to support magnetic forces)
- ☐Insulation (to allow fast discharge at high voltage limit copper for protection)

Factors to use them are (1) integration (2) *engineering* maturity.

Several examples in ITER of great integrated technology with poor engineering maturity (➔ problems)

Also, don't miss the design usability factors

- Safety & Decomissioning
- Repairability/Reliability

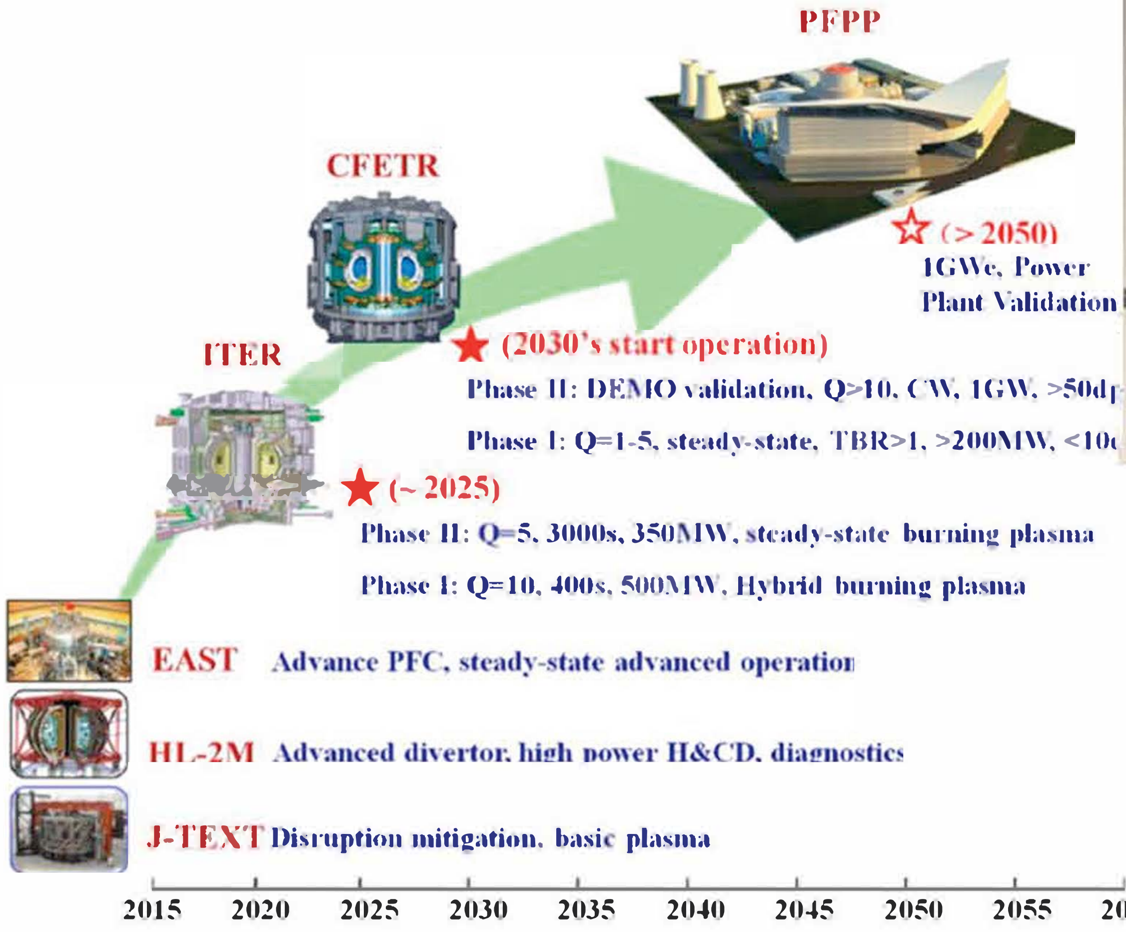
These will be key factors in the future (more than for ITER)

4. Next step in fusion…. timelines and possible machines, big and little

Big machines: build on ITER

Little machines: new technology

Roadmap of China magnetic confinement fusion Development (**Yuanxi Wan et al**).



PFPP

★ (> 2050)
1GWe, Power Plant Validation

CFETR

★ (2030's start operation)
Phase II: DEMO validation, Q>10, CW, 1GW, >50d
Phase I: Q=1-5, steady-state, TBR>1, >200MW, <10

ITER

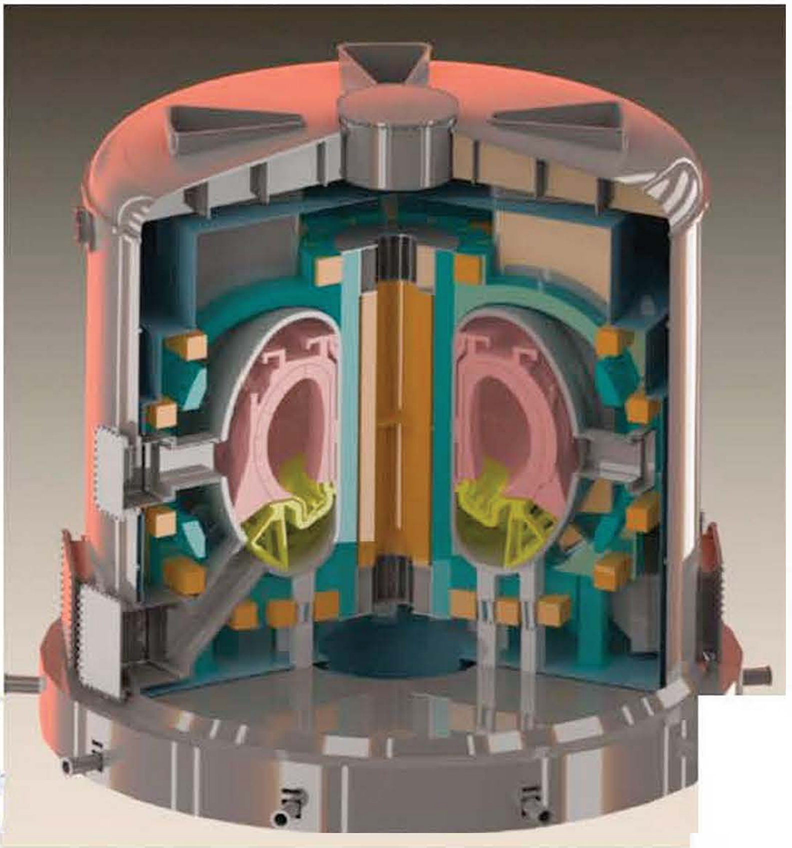
★ (~ 2025)
Phase II: Q=5, 3000s, 350MW, steady-state burning plasma
Phase I: Q=10, 400s, 500MW, Hybrid burning plasma

EAST Advance PFC, steady-state advanced operation

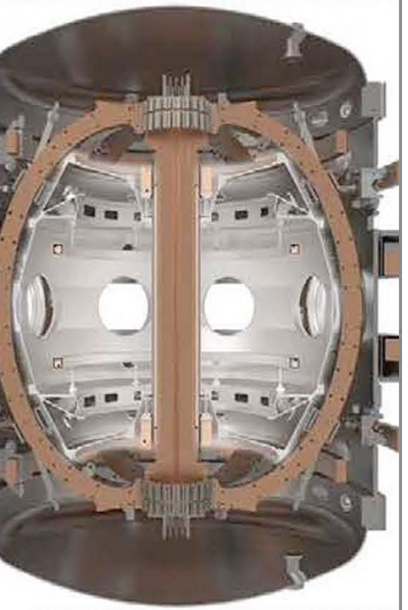
HL-2M Advanced divertor, high power H&CD, diagnostics

J-TEXT Disruption mitigation, basic plasma

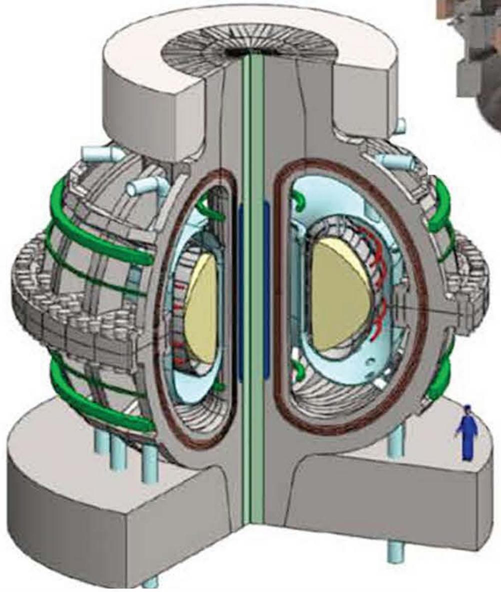
CFETR



ST40 from Tokamak Energy: HTS



ARC from CFS: HTS



5. Ancestors of SC fusion machines…history of SC in fusion…foundations for ITER

Looking at history over last 40 years

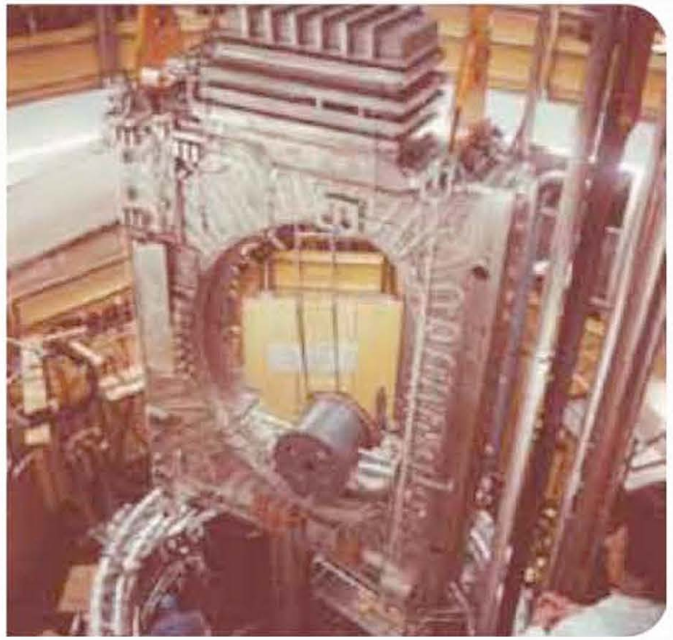
- Focus is dominated by superconductor where there are sometimes strategic considerations for the future
- Insulation and structural materials are treated as secondary considerations, specific for the step but not strategic
- Innovations that would improve/simplify reactor design are not considered

Focus on mostly on material, sometimes on integration, little on design usability

Early Conductor Testing

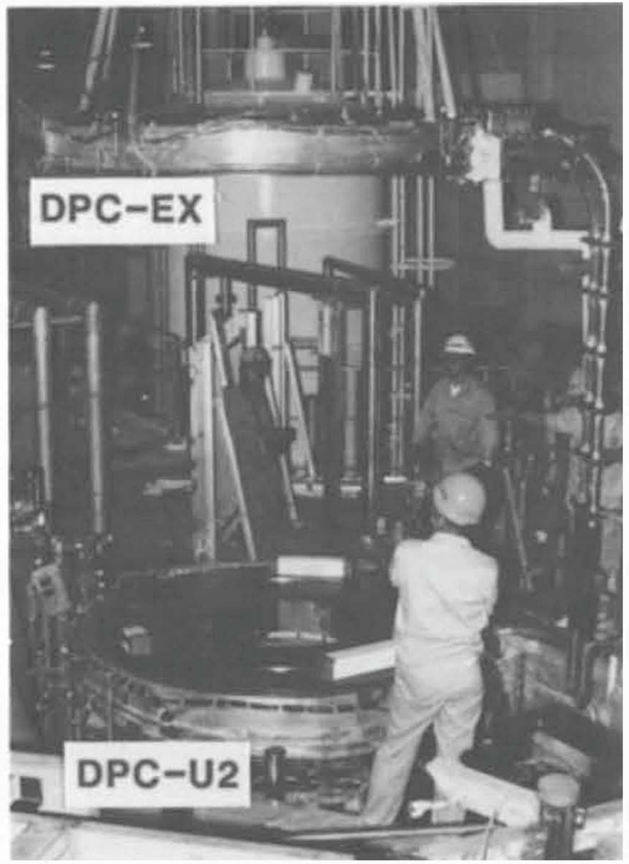
First test of ‘ITER relevant’ conductors was the IAEA Large Coil Task, a collaboration US-JA-EU in the late 70s and 80s…and this included a Nb3Sn CICC

This Nb3Sn Westinghouse coil had all the features seen in the ITER TF conductors (good & bad…)



TF model coil and pulse coil in LCT

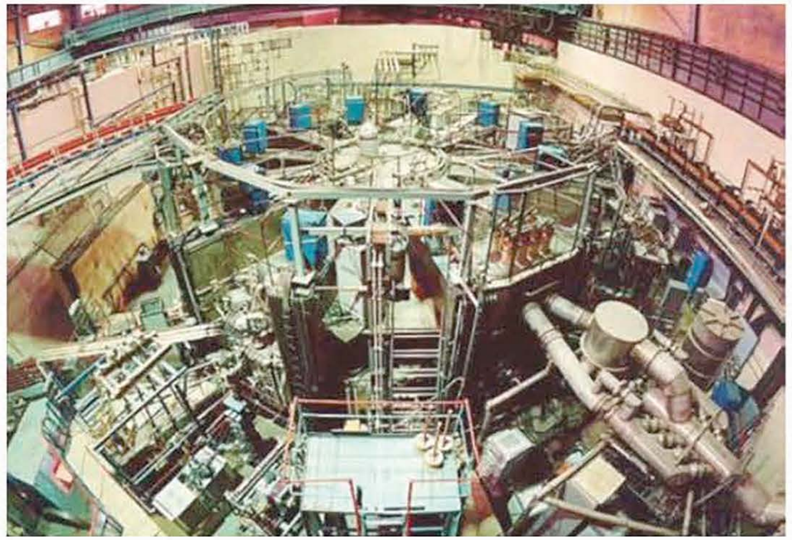
Photo. 2 Six LCT coils installed in vacuum tank : October 1985



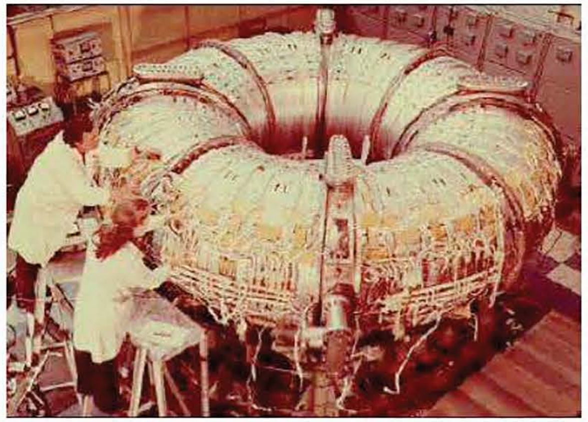
Almost at the same time, US-JA tested model pulsed coils

Generation 1: 1970s design

TRIAM-1M Kyushu University 1986 Nb3Sn superconductor in its 16 D-shaped TF coils, cooled by pool boiling liquid helium

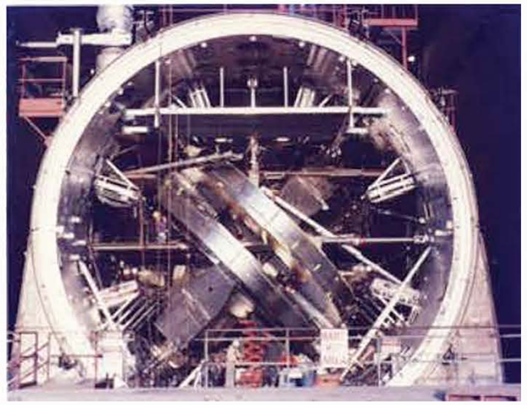


T15, Kurchatov, 1988, largest Nb3Sn TF coils

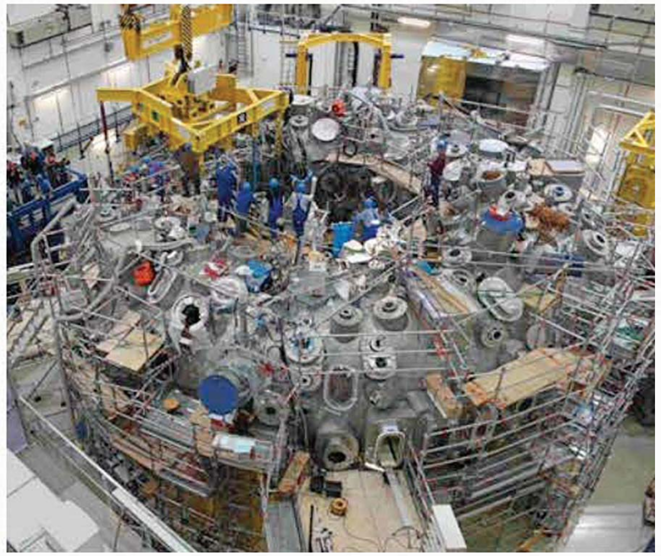


T-7 Kurchatov 1979 NbTi TF

Mirror Fusion Test Facility (MFTF) NbTi and Nb3Sn, Complete 1984.

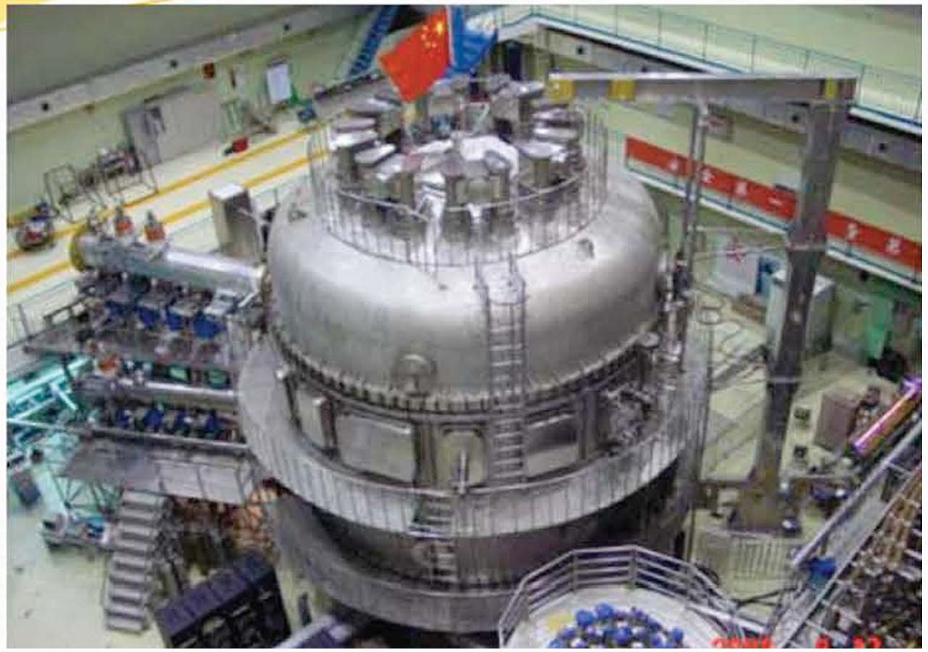


Tore Supra, CEA Cadarache France 1988 NbTi TF coils run at a temperature of 1.8K

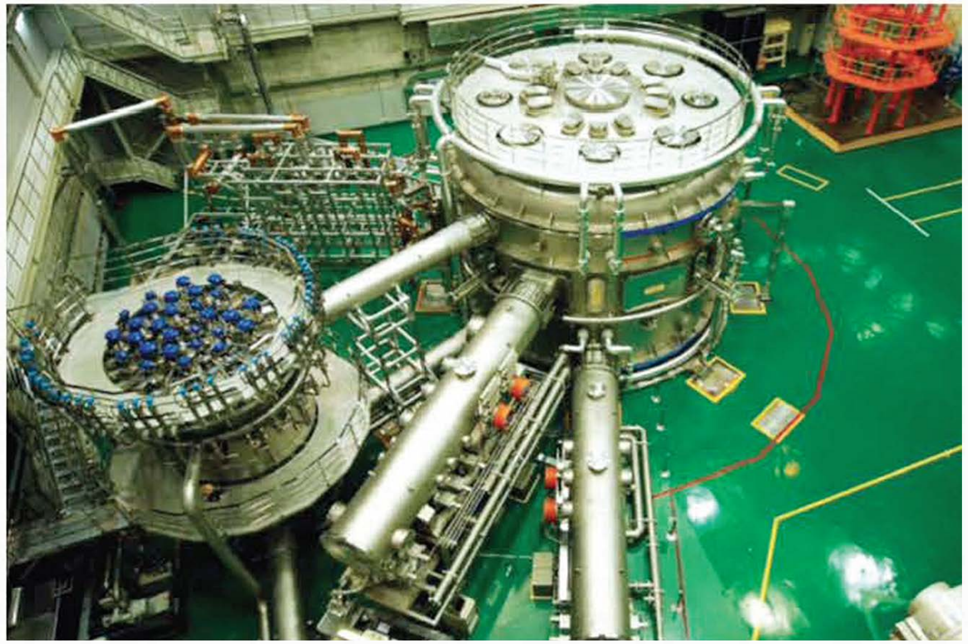


Wendelstein 7X Stellerator 2015 NbTi (designed 1980s)

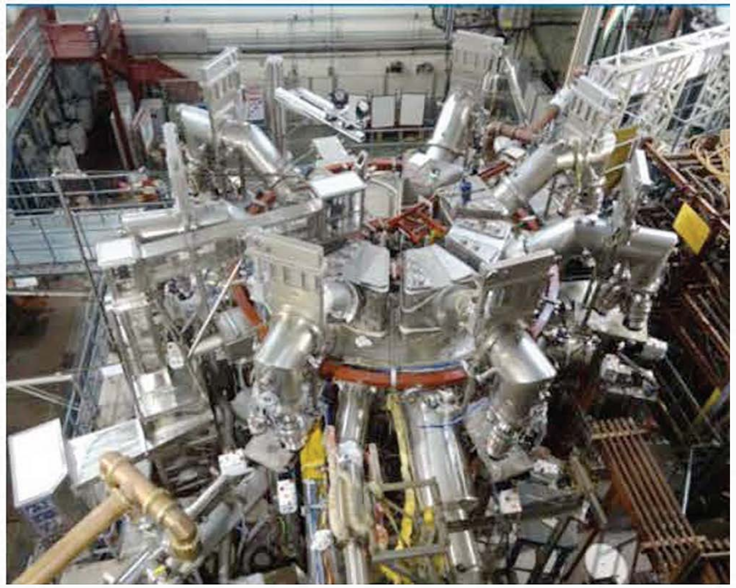
Generation 2: 1990s design



EAST – China. First fully superconducting tokamak. 2006 ASIPP, NbTi

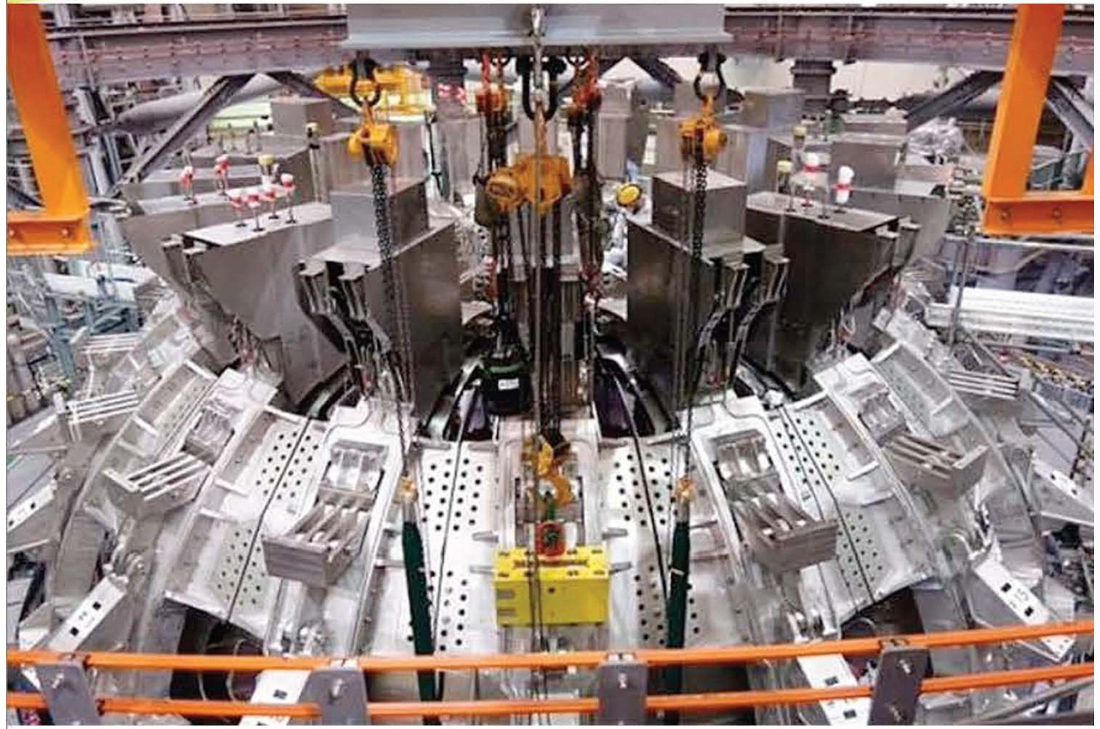


KSTAR –South Korea, 2008, All superconducting TF and PF coils (30 in total, **26 coils are made of Nb3Sn** and 4 of NbTi).



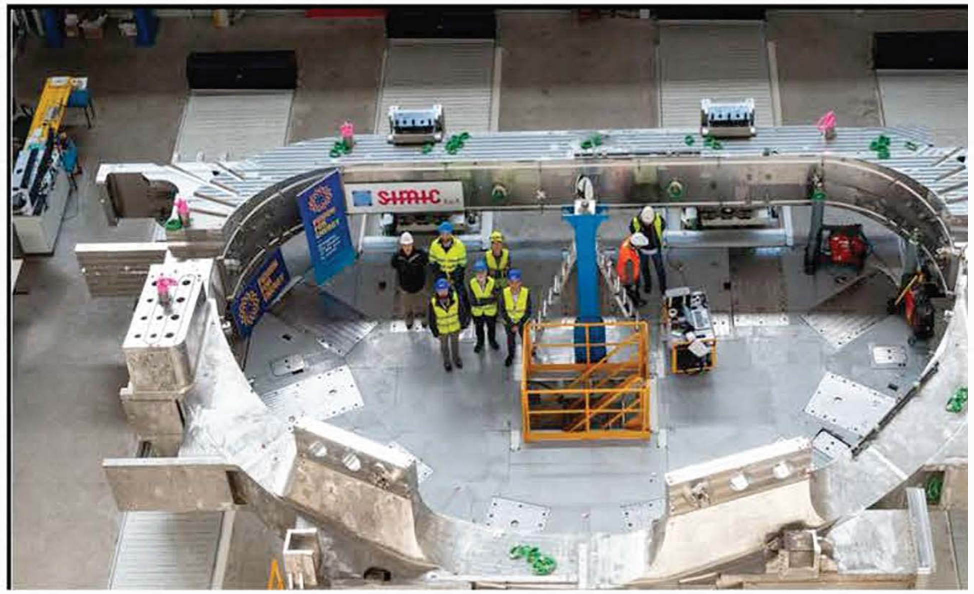
SST-1, India, 2013, NbTi TF and PF coils

Generation 3: 2000s design



JT60-SA, Japan, final TF coil being placed. Mostly NbTi (TF, PF) and Nb3Sn CS

ITER



TF coil Jan 2019 Nb3Sn

PF Coil Feb 2019 NbTi

CS coil USA Apr 2019 Nb3Sn

How much 'new technology' superconductors appeared in the 3 generations?

Clear from the pictures above & table below that EVEN IN 2000s, dominant SC technology is NbTi from 1970s.....

What does NbTi offer that Nb3Sn does not?

All 3 generations of machines use NbTi with the exceptions of the Nb3Sn below

Facility	Year of commissioning	Weight of Nb_3Sn t
T-15	1987	15
KSTAR	2008	23.5
JT60SA	2020	11.5
ITER	2025	> 650

Hypothesis: NbTi is a 'good' engineering material, Nb3Sn is not

- ☐ Cost uncertainty (and dependence on very few suppliers)
- ☐ Lack of depth of experience: frequent occurrence of the unexpected....many variables to be controlled, maturity still developing
- ☐ Lack of a common fully integrated magnet solution: conductor + coil + machine....risk for engineering integrator

ITER experience provides a basis to move forward a step. Coil/conductor technology brought to maturity and relevant building blocks for future machines

6. ITER Experiences and New Priorities for DEMO

Three Key Innovations in ITER Magnets

Insulation Systems (from 1988) *SUCCESS*

Superconductors (from 1987) *SUCCESS*

Structural Metals (from 1991) *AFTER REDIRECTION, SUCCESSFUL*

The challenges of these systems had a common theme:

- ☐ Significant impact on overall machine size and cost if not implemented
- ☐ Concerns with technological maturity
- ☐ 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)

6.1 Key Technology: 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)

Internally cooled conductors with solid insulation systems soon became a baseline

Arguments over React & Wind vs Wind & React, and on Shape, went on for many years and still carry over to DEMO

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

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

React &Wind, monoliths discarded

Base building block: cable

1994-2001
Multiple coil concepts, stable conductor design

2002
Extent of Nb3Sn degradation issue in Nb3Sn CICC recognised

Strand suppliers fail

1993-2002
CS and TF Model Coil Projects

1995-98
Extent of Incoloy cracking issue recognised

Base building block: jacket

2003
ITER decides strand/cable copper distribution and jacket material

Incoloy, Ti discarded

2007-2015
ITER conductor production

Industrialisation

2006-08
TF Recovery Programme #1

2010-14
CS Recovery Programme #2

2017-18
TF Recovery Programme #3

Crisis Management

Strategy for Convergence of the ITER Conductor Design

One step at a time. Converge at one level while fighting to avoid divergence on subsequent steps

- ☐ *As with future fusion reactors in 2020, in 1988 many seductive promises 'choose this strand/cable/conductor and build a fusion reactor tomorrow'*
- ☐ *In ITER we made the same promises (by necessity) while arguing to focus budget into one programme and avoid technical divergence*

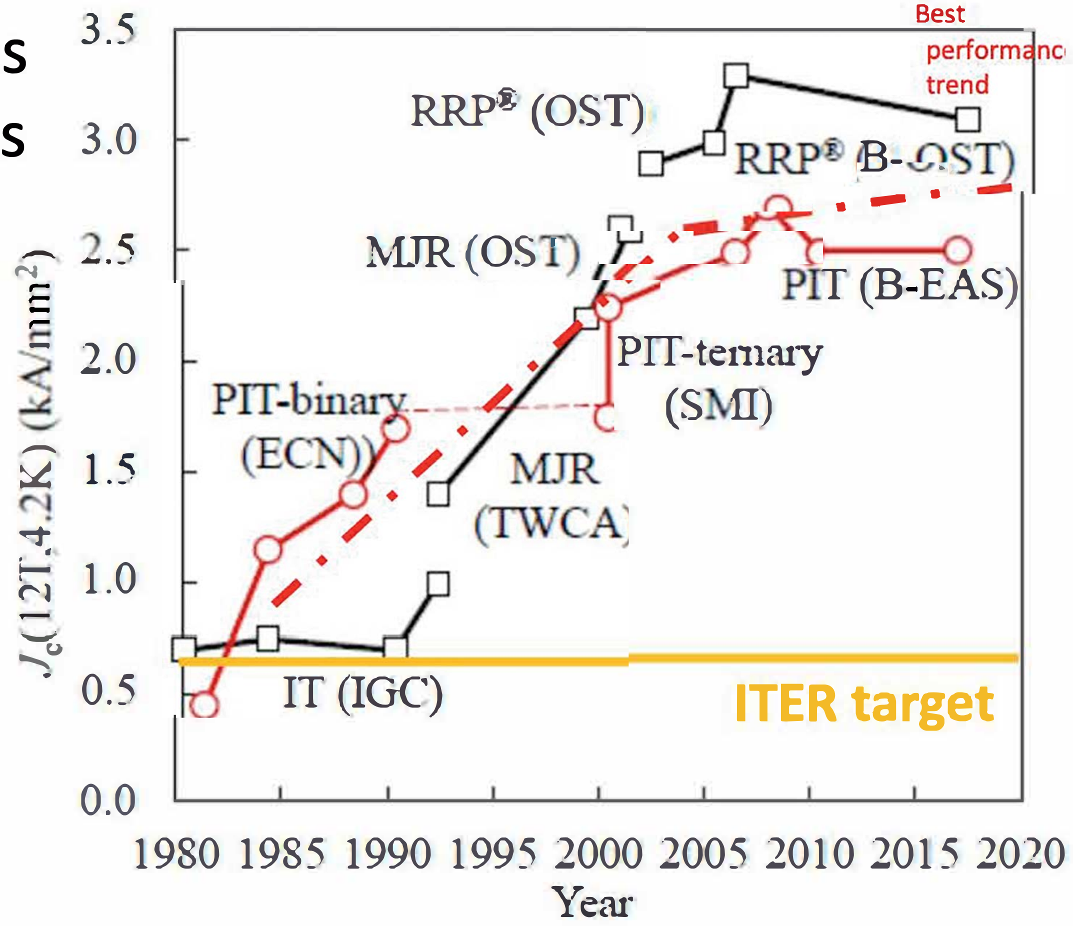
Many steps helped us

- ☐ International collaboration (for 15 years only 4 partners.....today, with 7, it would be far more difficult), some shared resources and some common objectives: INTOR then CDA then EDA......always voluntary but everyone saw the advantages. This was in particular the key to CONTINUITY but also an obstacle to CONVERGENCE
- ☐ Common shorter term high visibility intermediate targets/demonstrators: LCT, ITER model coils, ITER FoK qualifier
- ☐ Continuous integration of multiple industries.....although national interests stopped application of competitive tendering and supplier reduction early on, multiple quasi-qualified supplier availability (for strand, conductors, coils) key to ITER procurement in 2007-2020
- ☐ Things often went wrong....managed to stay 'on message' and recover, not panic

Funding has been critical. Over 35 years the ITER program has been the focus. Now we need to look to DEMO

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

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Strand Developments

- In 1987 even basic Nb3Sn strand fabrication was difficult. Few suppliers, low yield, 'individual' strands not standard material. ITER launched multiple contracts of ~200kg with common target, 4 production routes (jelly roll, bronze, IT, PIT). This led to the ITER model coil production starting 1995-6, ~24t by 1999

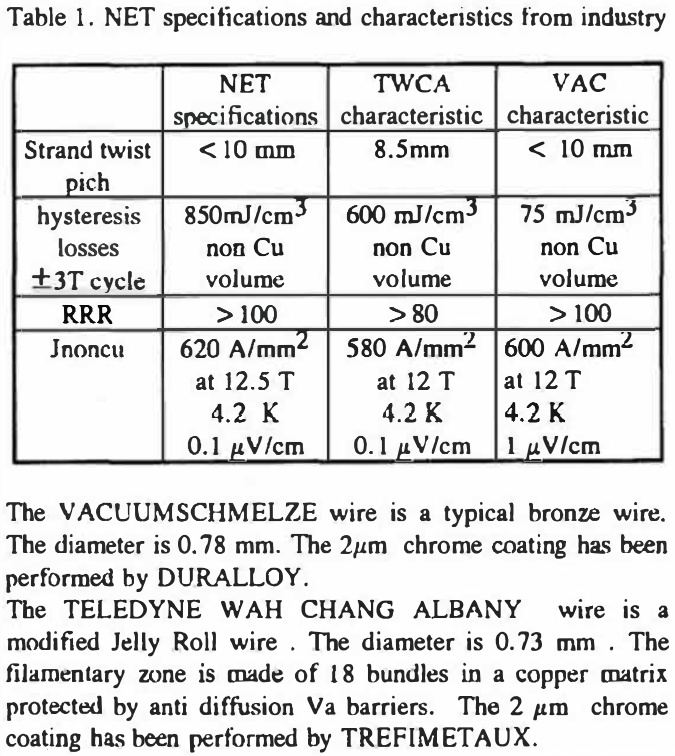
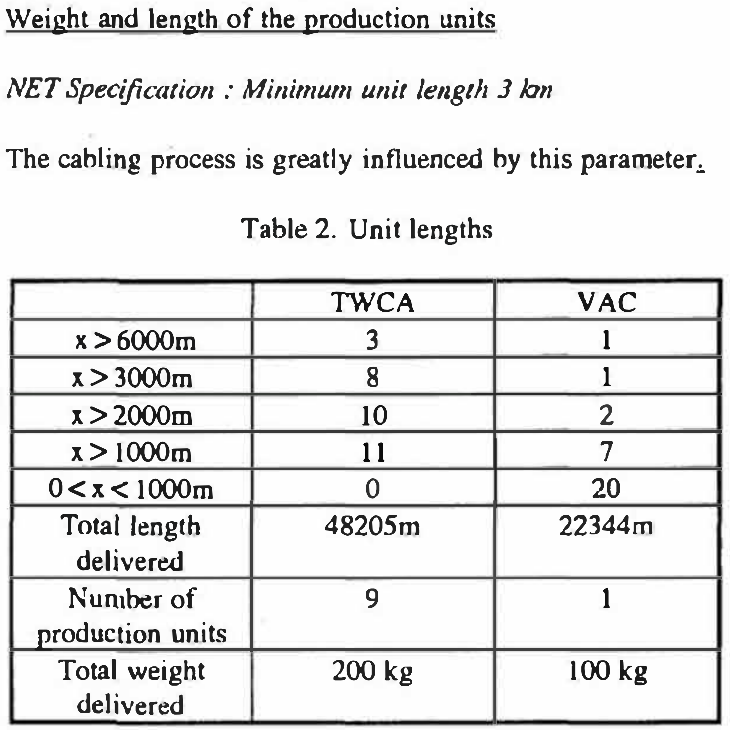


Table 1. NET specifications and characteristics from industry

	NET specifications	TWCA characteristic	VAC characteristic
Strand twist pich	< 10 mm	8.5mm	< 10 mm
hysteresis losses ±3T cycle	850mJ/cm^3 non Cu volume	600 mJ/cm^3 non Cu volume	75 mJ/cm^3 non Cu volume
RRR	> 100	> 80	> 100
Jnoncu	620 A/mm^2 at 12.5 T 4.2 K 0.1 μV/cm	580 A/mm^2 at 12 T 4.2 K 0.1 μV/cm	600 A/mm^2 at 12 T 4.2 K 1 μV/cm

The VACUUMSCHMELZE wire is a typical bronze wire. The diameter is 0.78 mm. The 2μm chrome coating has been performed by DURALLOY.
The TELEDYNE WAH CHANG ALBANY wire is a modified Jelly Roll wire. The diameter is 0.73 mm. The filamentary zone is made of 18 bundles in a copper matrix protected by anti diffusion Va barriers. The 2 μm chrome coating has been performed by TREFIMETAUX.

1993 (work carried out 1990-1992)



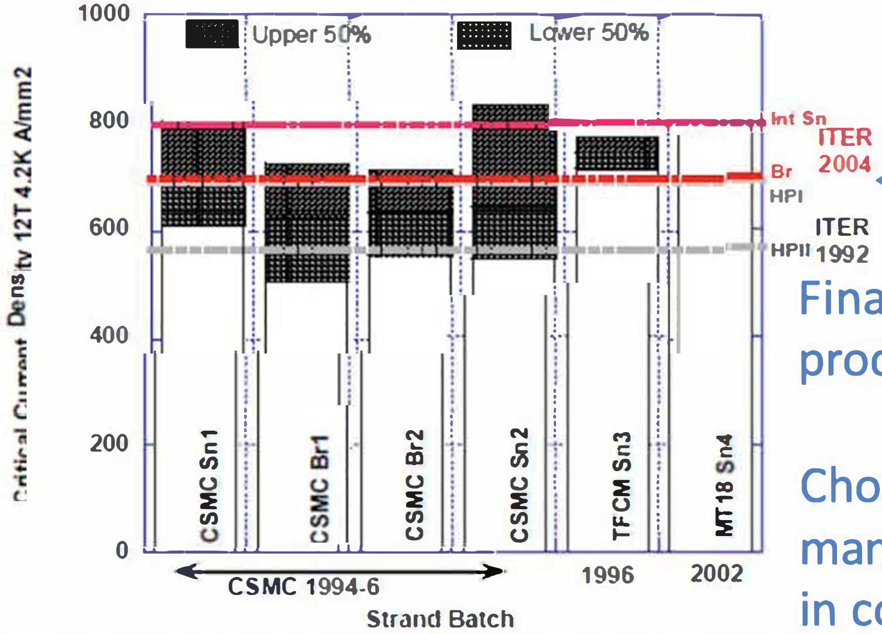
Weight and length of the production units

NET Specification : Minimum unit length 3 km

The cabling process is greatly influenced by this parameter.

Table 2. Unit lengths

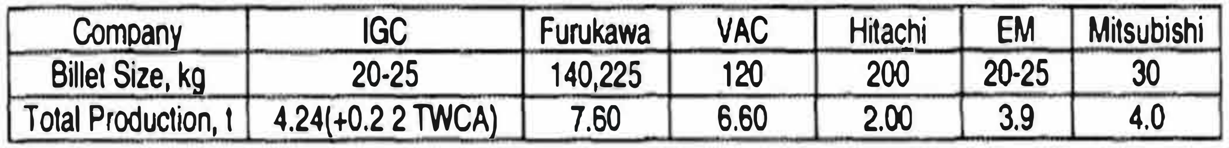
	TWCA	VAC
x > 6000m	3	1
x > 3000m	8	1
x > 2000m	10	2
x > 1000m	11	7
0 < x < 1000m	0	20
Total length delivered	48205m	22344m
Number of production units	9	1
Total weight delivered	200 kg	100 kg



Final 2007 production criteria

Chosen to keep all manufacturing routes in contention

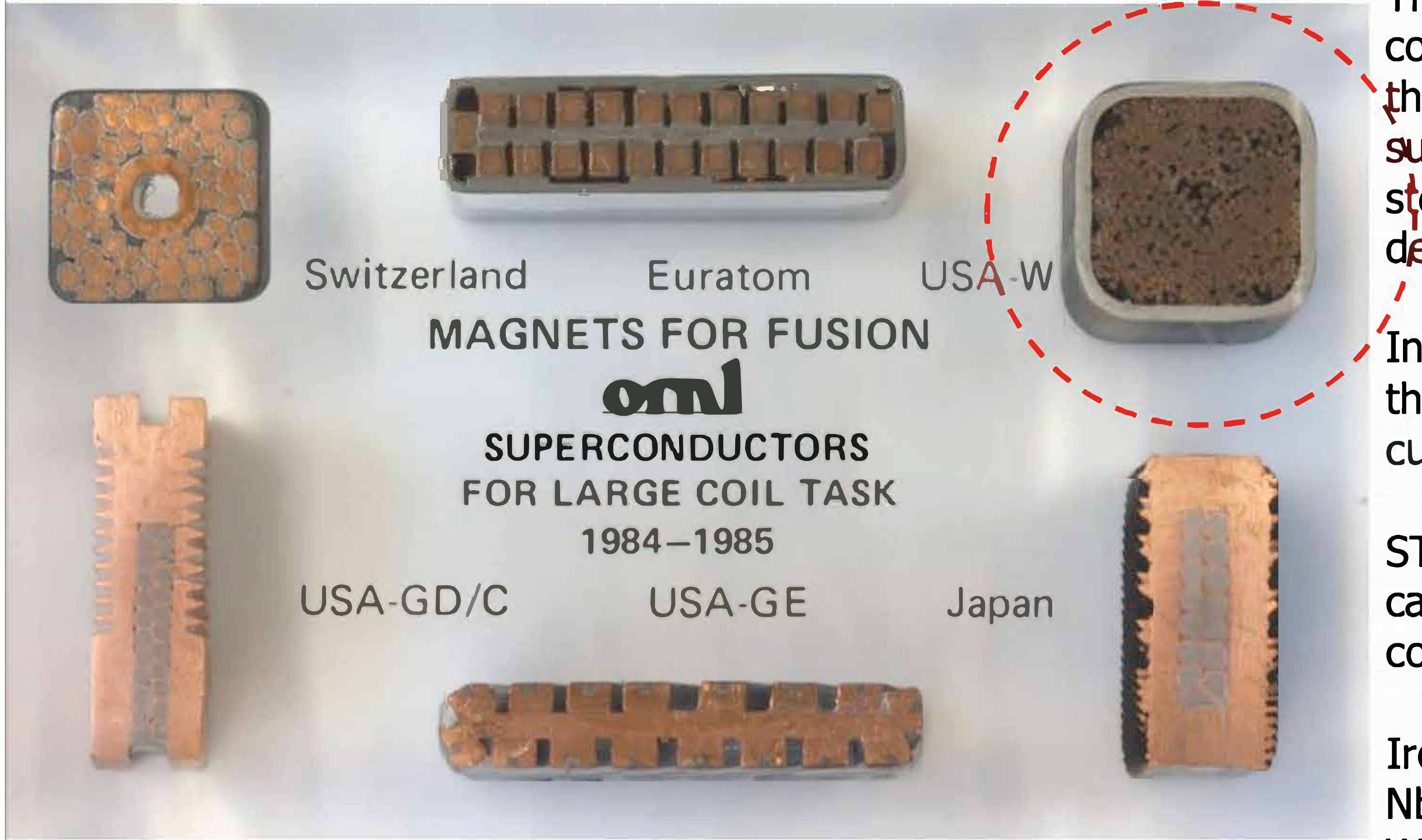
Final production for the ITER model coils 1999



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

Early focus on strand usability
Unit length requirements
IEEE Trans App Sup v3 n1 1993, Duchateau et al

LCT Coils and Conductors



The LCT project started in 1977 and was completed in 1988. By mid 1980s it was clear that some of the coil technologies (although successful in LCT) were not relevant for next step fusion machines but many different developments started/continued

In the early 80s Nb3Sn react and wind was the lead coil concept. Limited size (and current) to keep low strain on Nb3Sn

STRAIN as a cause of LOSS of critical current capacity was dominant focus of 1980s conductor design, along with R&W vs W&R

Ironically nearly 40 years later our base Nb3Sn conductor is quite similar to the USA-Westinghouse…..*and has the same resistive behavior (low n) that was seen as a cause for failure in the 1980s*

How we designed conductors (Nb3Sn/NbTi) in the 1980s and now

The issues in 1980s…..

- Stekly criterion and limiting current
- Quench and Hot Spot
- Thermal strain and the jacket material
- React and Wind vs Wind and React (impact of strain)

The conductors we designed work well now, but not really for the reasons that we thought 30 years ago……

What we didn't know then (or couldn't quantify and therefore ignored)

- *Nb3Sn filament fracture except as binary limit (below, no impact, above, no current)*
- *Current non-uniformity (inherent to any superconductor) and its effects on stability during pulsed (or even near steady state)…several noted failures in NbTi*

The issues in the 2020s….

- Current (non)-uniformity and role of strand coatings
- Design and operation with (slightly) resistive (low n) Nb3Sn strands and (linked) very different stability behaviour of NbTi and Nb3Sn
- Complexity of Nb3Sn strain systems in conductors (and up to now) inability to predict

Convergence to Final ITER Conductor Design in 1993

Cable in Conduit 1991

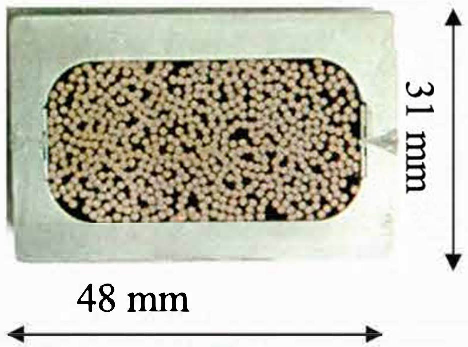
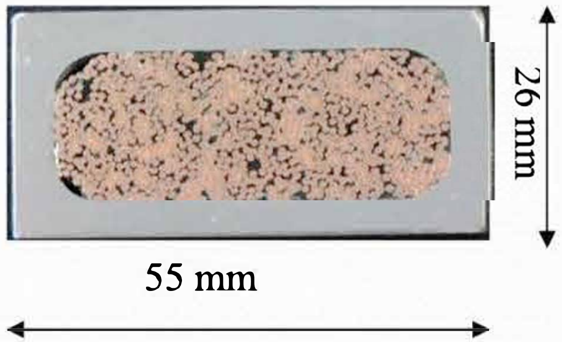
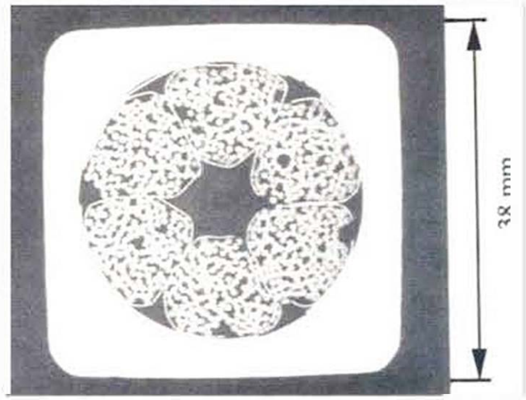


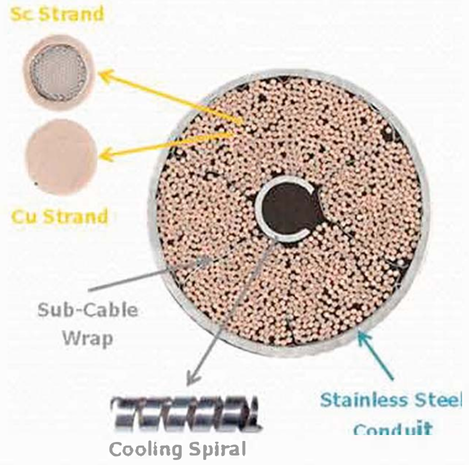
ABB – 1990 Laser welding

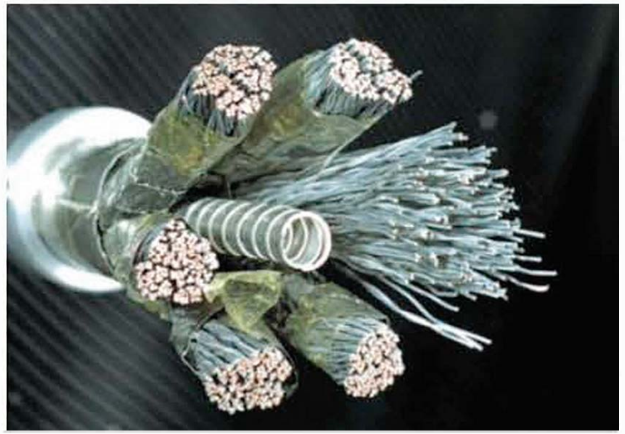


LMI – 1992 Extruded conduit



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)

Conductor Conclusions

- ☐ A very long convergence process to the final ITER design.
- ☐ We made mistakes & discoveries, painful corrections during manufacturing
- ☐ 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

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)

6.2 Key Technology: Structural Metals

Structural Metals critical to carry magnetic forces

In a typical tokamak they can be distributed

- In the conductor jacket
- In the coil cases

As a general rule

☐ Putting structural material in a conductor jacket mean more material at high voltage with all the insulation problems

☐ With Nb3Sn conductor jacket material becomes tangled with Nb3Sn formation process

☐ Putting material in coil cases brings the issues of fatigue crack growth and fast fracture resulting from the (inevitable) defects, plus the 'conventional' (but still novel) problems of reliable low distortion low defect welding

☐ Despite many attempts to avoid/reduce, ITER relies on huge quantities of stainless steel

Worth noting (perhaps) that Stainless Steel was invented 2 years AFTER the discovery of superconductivity

Structural Metals Development Diagram

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

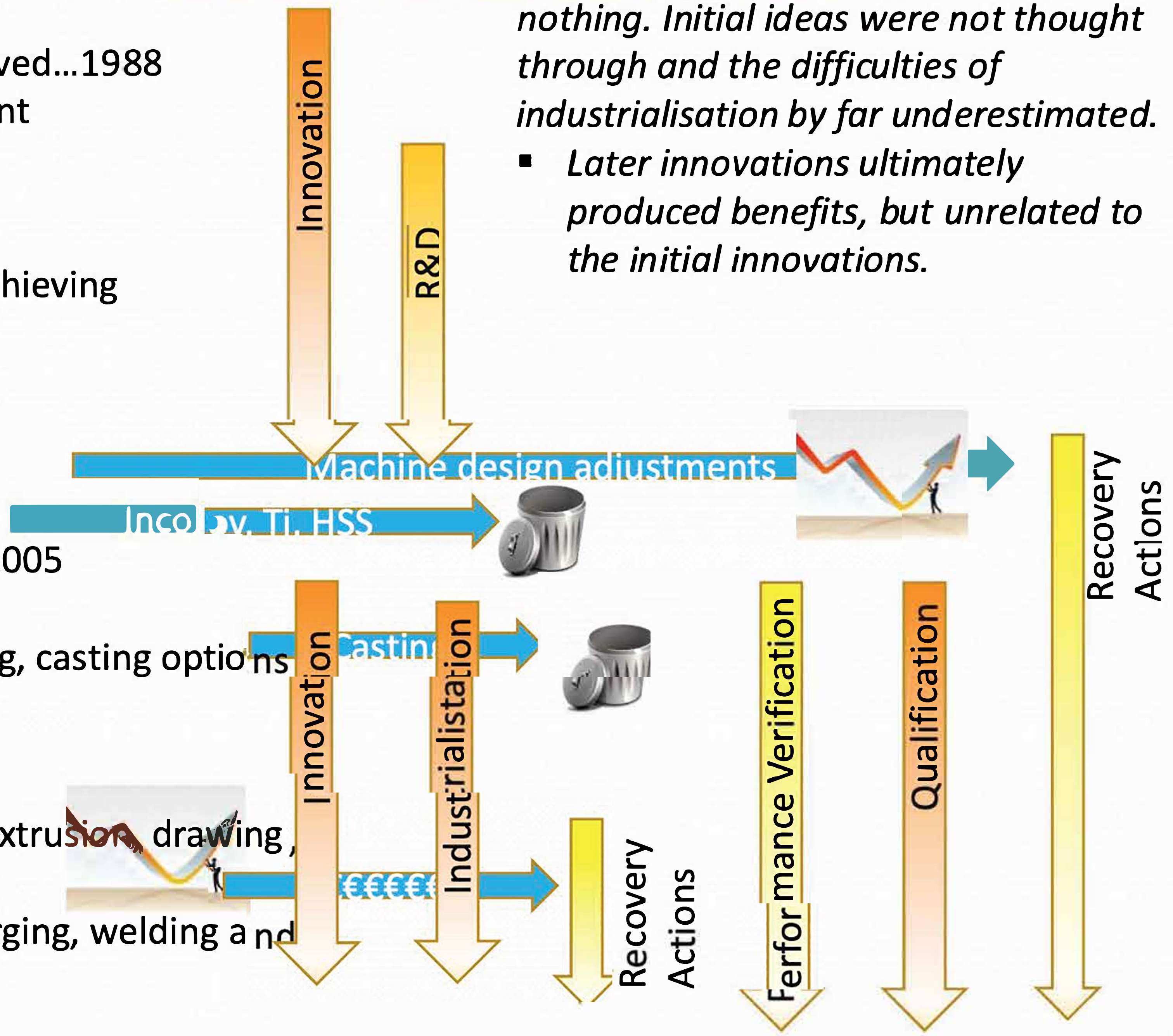
Large scale manufacturing trials and industrialisation

Further adjustments to achievable parameters 2008=>

- Manufacturing design of jacket material production (extrusion, drawing , inspection)…recovery actions on low Carbon 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.*

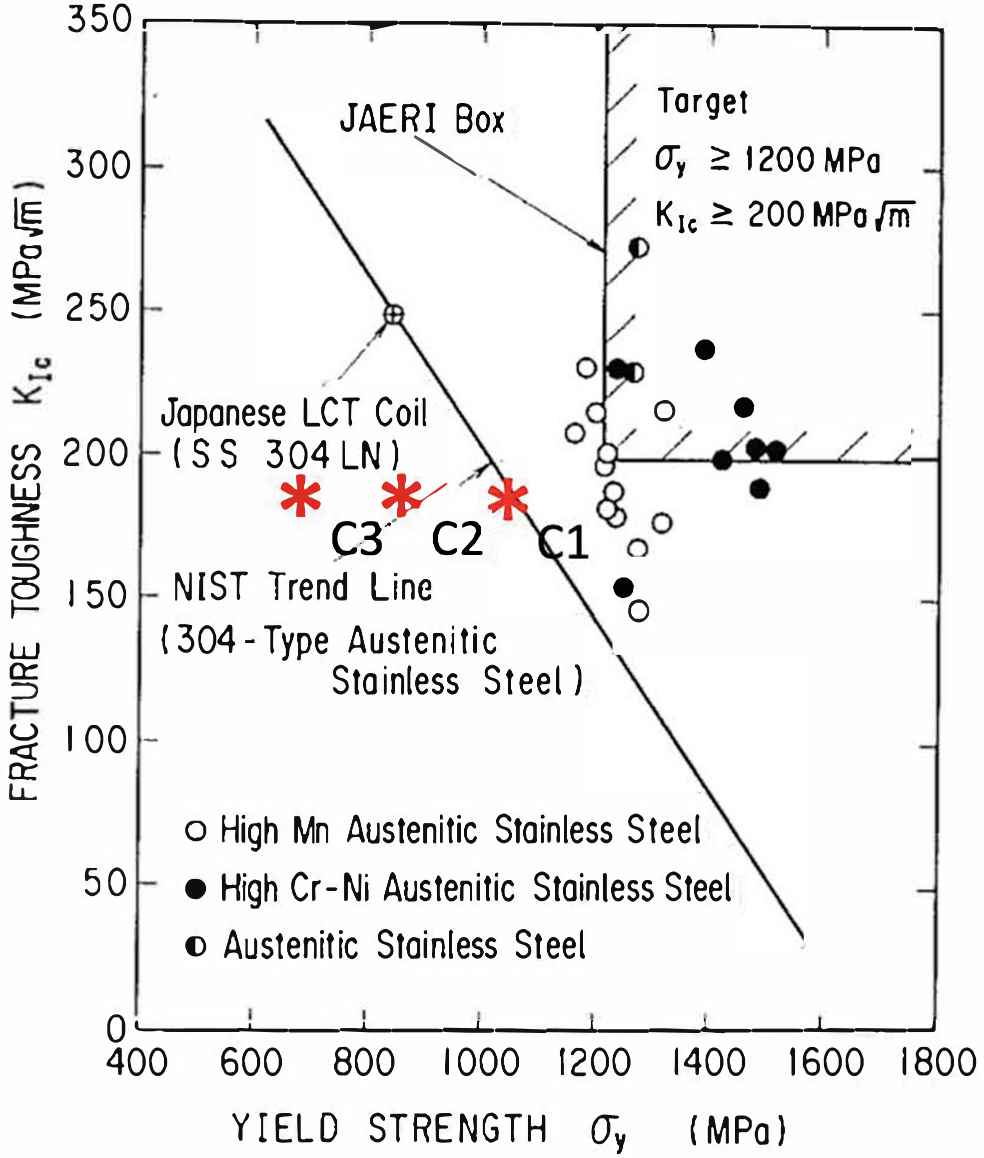


Structural Metal Performance

Base Materials for Structures

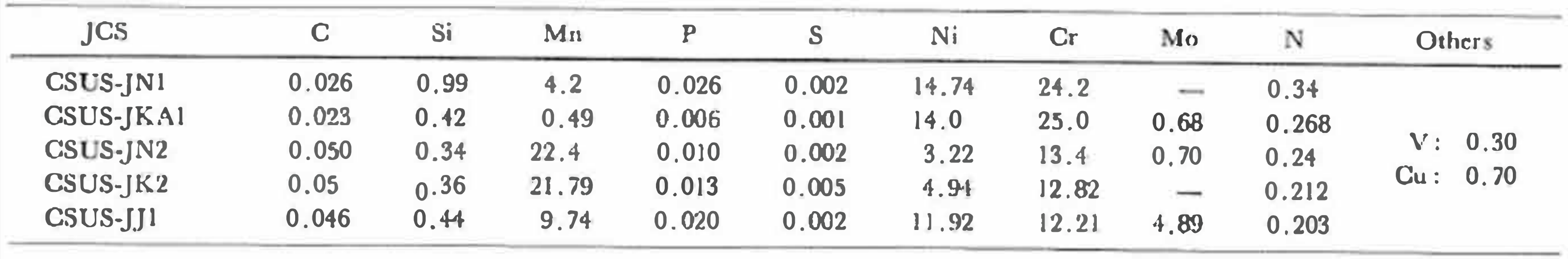
- Basic material research launched in 1988 as perception that higher structural metal properties could bring saving in overall machine cost
- Programme launched in JA, EU, RF
- Success claimed in laboratory scale research but universal failure on industrial scale.
- Problems of production of highly compositon specific alloys underestimated
- Issues such as welding, forging, corrosion neglected
- By 2008 only JJ1 remained (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	

Structures and Field Accuracy

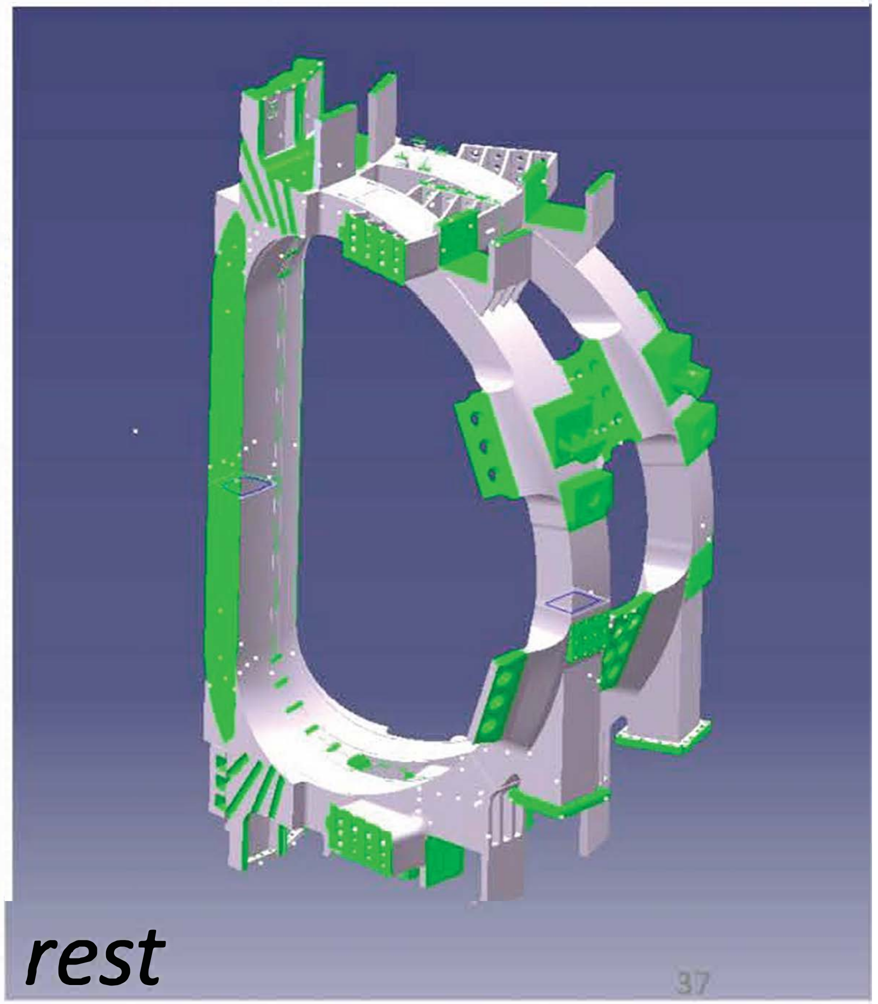
Example of Tolerances: Structures

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

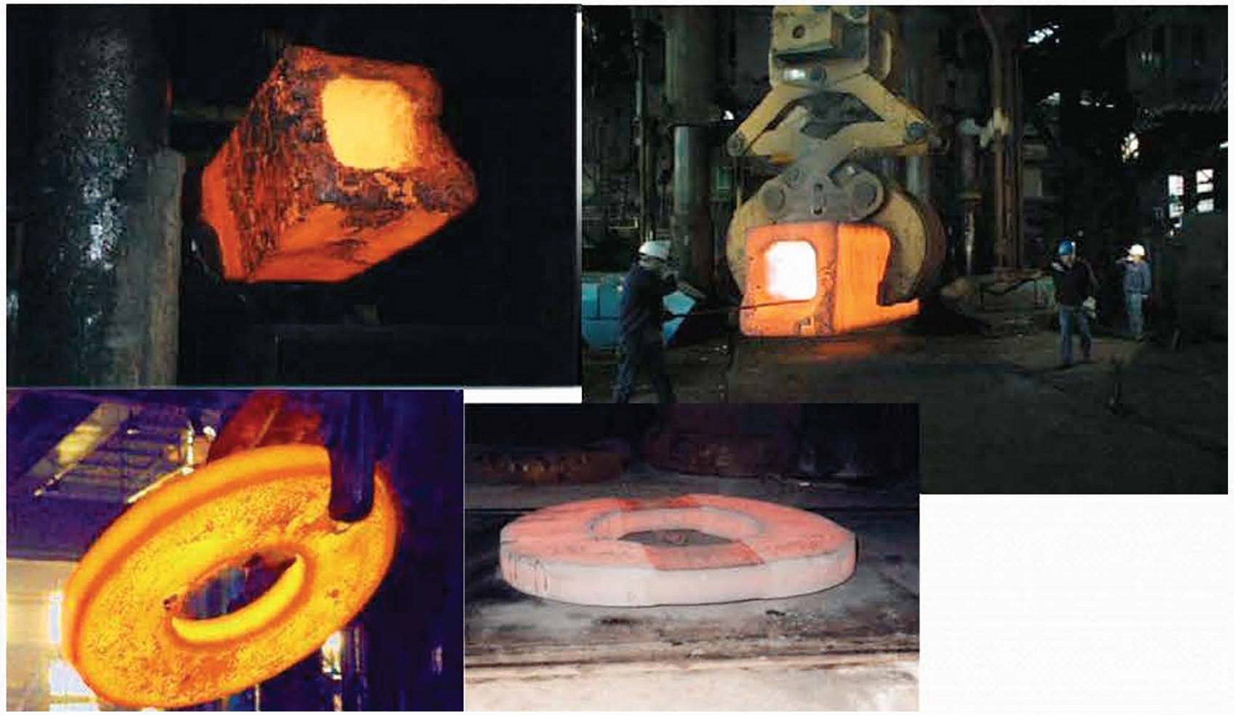


Multiple TF coil interfaces (green)

TF coils & structures are the core which drive the rest

Forming 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

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

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

Exotic 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

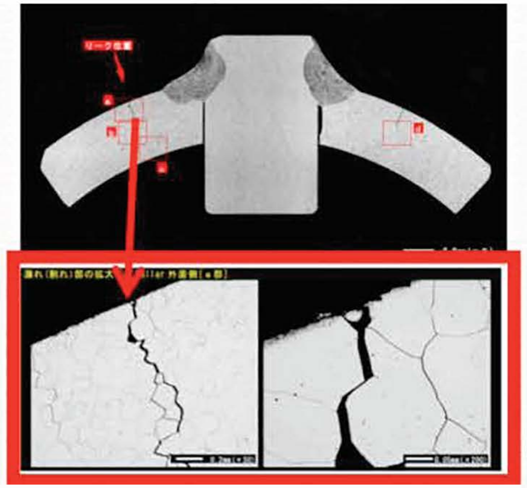
Candidates Incoloy 908 and Ti. SS was neglected

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



Less Exotic Structural Metals

Base Materials for Conductor Jackets

“Conventional”

Late development of SS jackets

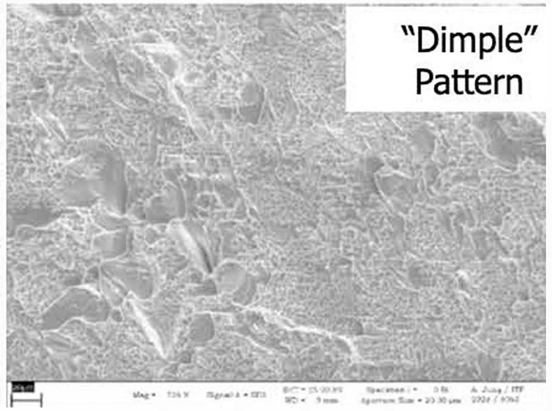
- Nb3Sn heat treatment leads to carbon precipitation and embrittlement of SS enhanced by cold work of jacket
- For TF needed to develop low carbon steel. Worked with industrial partners to optimise production process and control cold working
- For CS JADA continued with JK2LB and eventually achieved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

ization

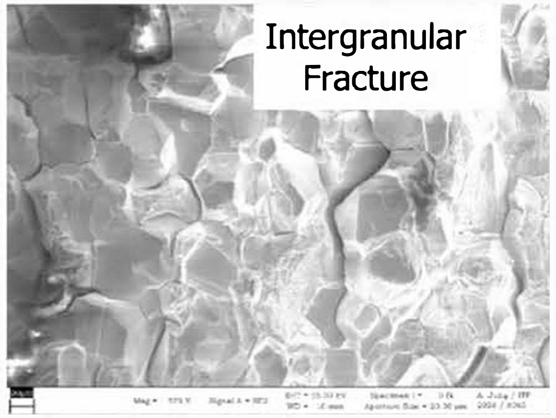
- **4 TF jacket suppliers** (1 in EU SMST, 1 in JA KSST, 1 in KO POSCOSS and 1 in CN JIULI) **have been qualified** and produced tubes for all **6 DAs**.
- Tubes extruded in ~12m lengths and butt welded

Tensile Tests at Low Temp. (< 7K)

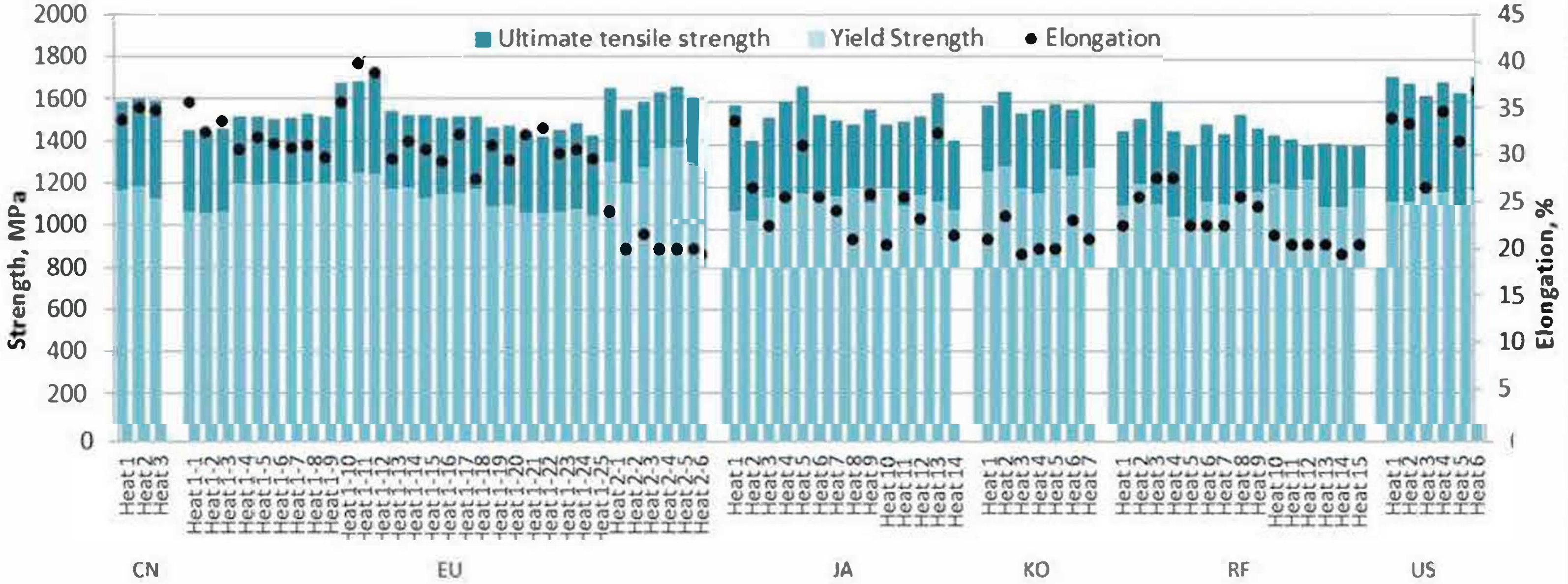
Courtesy of K. Weiss (KIT)



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)

Structural Metals Conclusions

Despite the failure to improve the limiting structural performance, ITER program has led to major INDUSTRIAL developments in the SUPPLY of LARGE ACCURATE SS structural pieces

This manufacturing development for ITER (even if unexciting) is part of achieving engineering maturity of the steel structures for a future DEMO

The conductor jacket program resulted in materials (SS for TF, PF, JK2LB for CS) that work for ITER but have undesirable manufacturing sensitivities

6.3 Key Technology: Insulation

The magnet operational voltages (and therefore the insulation requirements) are driven by

- Conductor current
- Conductor thermal protection (fast discharge in the event of quench)
- Number of coils (especially TF) in series, number of feeders and power supplies

Generally, going as high as technologically possible with reliability brings benefits elsewhere

- ☐ Conceptual studies from 1970s considered organic and inorganic options, focusing especially on radiation resistance
- ☐ Polyimide (Kapton) first produced by DuPont in late 1960s. Under consideration for Fusion in 1970s
- ☐ Most of early work was focussed on irradiation performance (and early resins were not very good)
- ☐ Early tokamak coil insulation was often glass-epoxy. JET used mica in PF coils as an early example of dielectric barrier, rather than physical separation
- ☐ Glass-resin relies on physical separation to provide voltage resistance, and can be severely weakened by voids

Insulation systems are always multi-function, as, unavoidably, the insulation has to transmit the magnetic forces (if only by compression)

Coil Insulation Development Diagram

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:

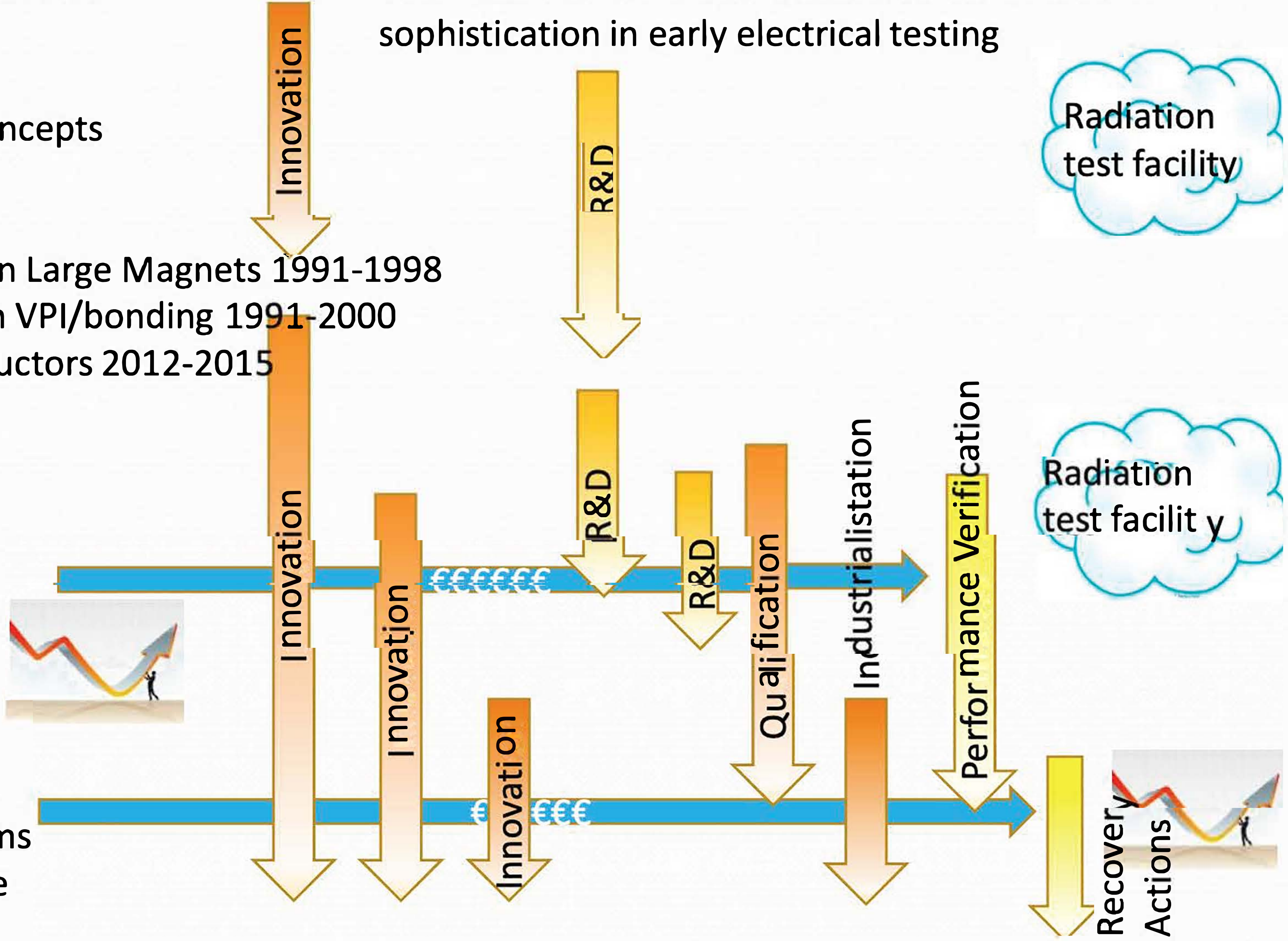
- H&S, pot life, mixing, curing

Detail (from 2010)

Recovery actions in:

- Infilling and terminal regions, auxiliary systems
- Instrumentation lead outs from ground plane

Quality verification



Coil Insulation and Nb3Sn

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

R=react W=wind I= insulate

- Glass wrap was compatible with W/I&R coil winding process where the glass went through the Nb3Sn heat treatment. Dielectrics (Kapton) were not
- Despite this from 1988 on TF coil voltages of 20kV to ground and 10kV on terminals were regularly chosen using just epoxy-glass

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

Final selection of W&R&I from 1995

Requires controlled handling of (delicate) Nb3Sn reacted conductor

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

Coil Insulation & Nuclear Radiation

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

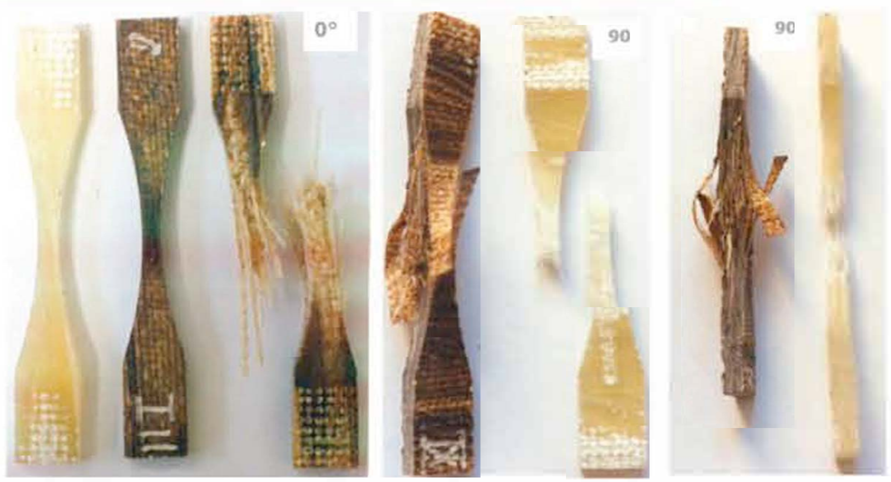
ATI

Radiation Limits of Coil Insulation

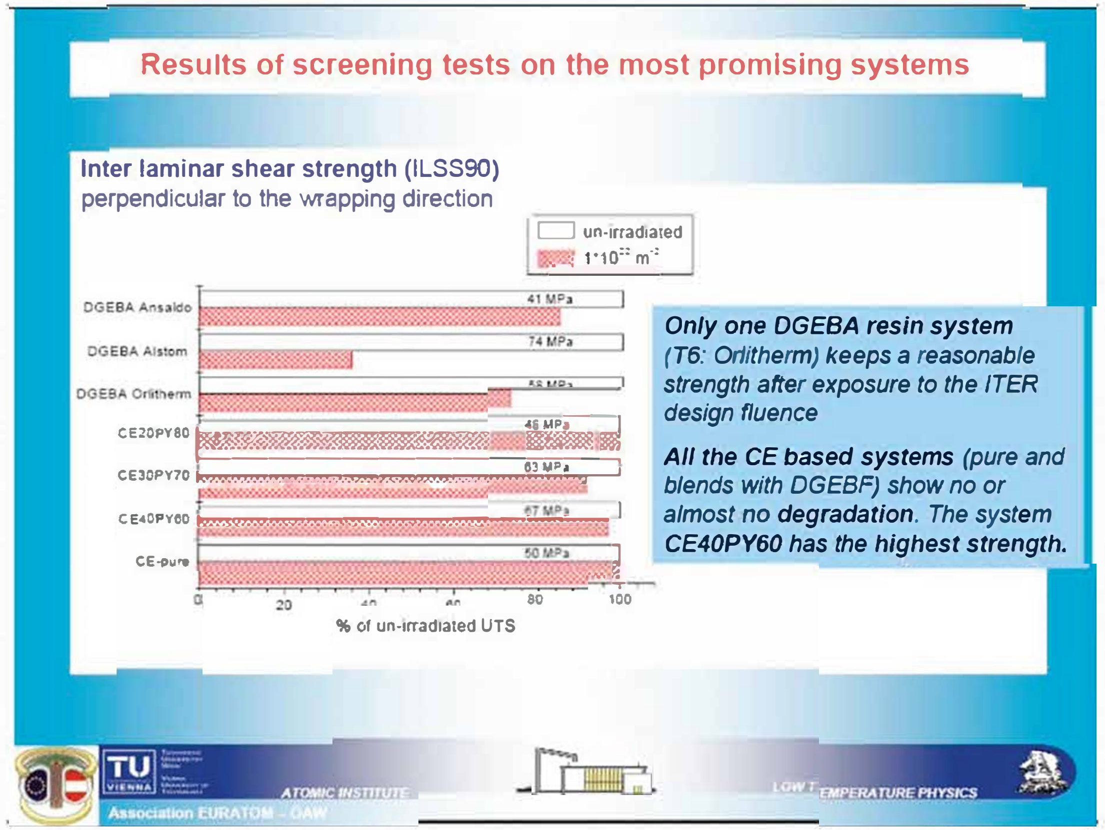
Insulation Irradiation Results

- 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)

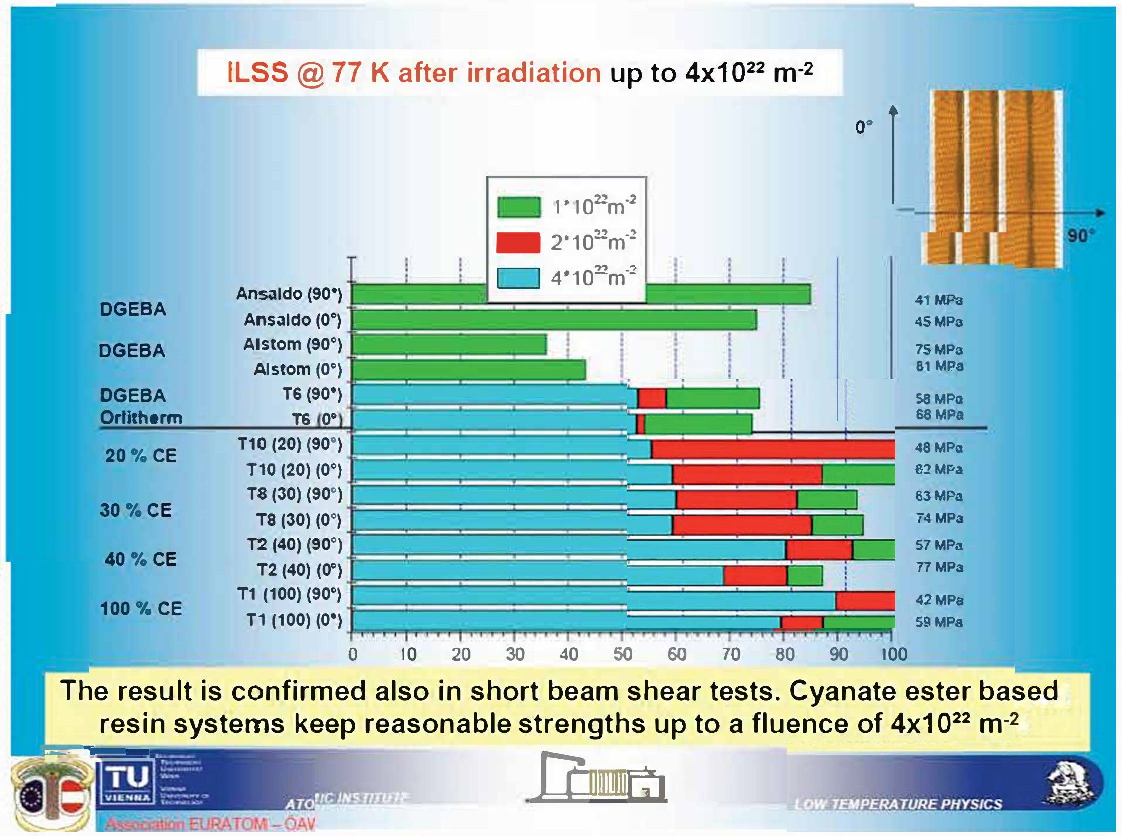


Results of screening tests on the most promising systems

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 4x10²² 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 4x10²² m⁻²

Radiation resistant resins

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

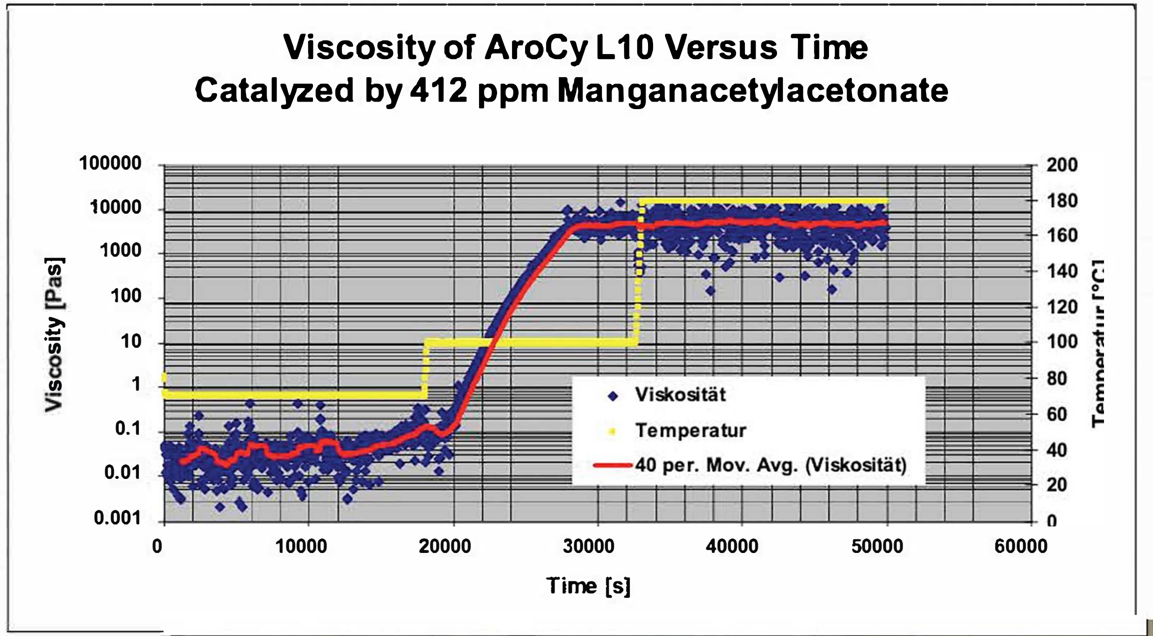
- Pot life (time to impregnate large winding at low viscosity before glassification)
- Exothermic curing
- Health issues (and regulation of perceived health risks) on composite chemicals (especially catalysts)
- Mixing and outgassing

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.

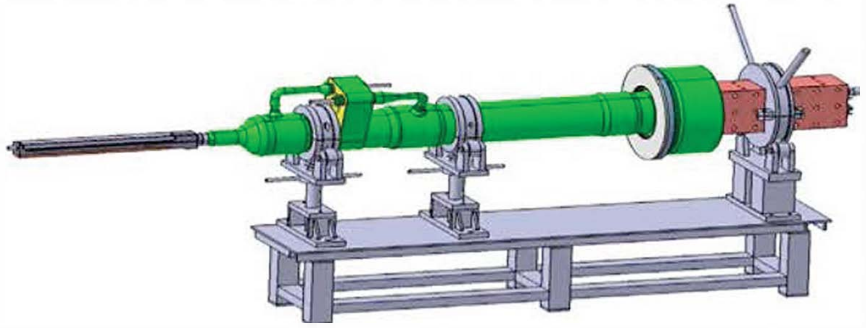


Lab-scale thermal runaway of cyanate ester

Coil Insulation Application

Art of applying polyimide

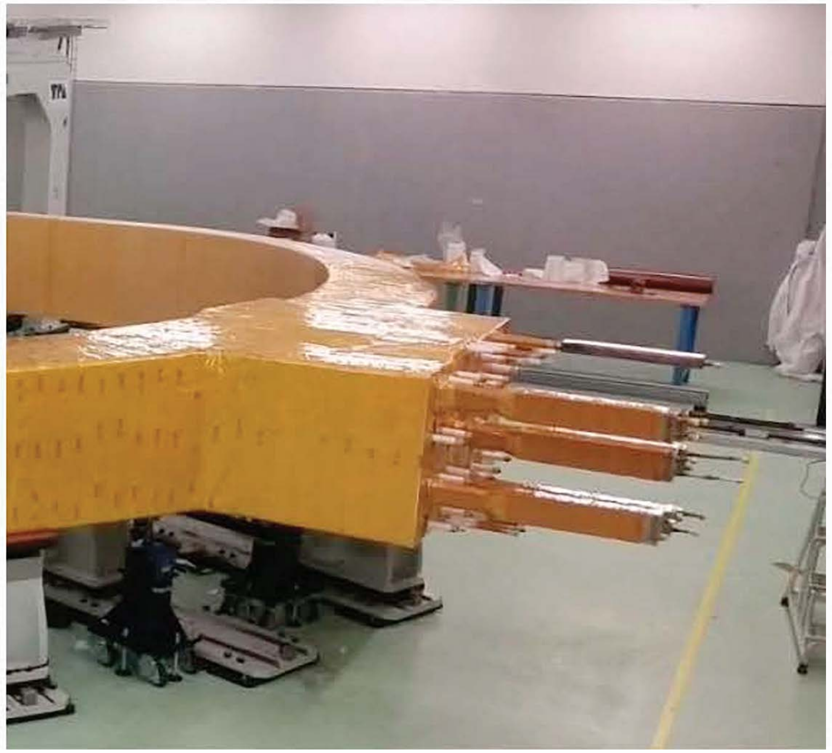
- Inflexible and therefore curved surfaces have to be smoothed
- Complicated patterns of lay-up



- 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.

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



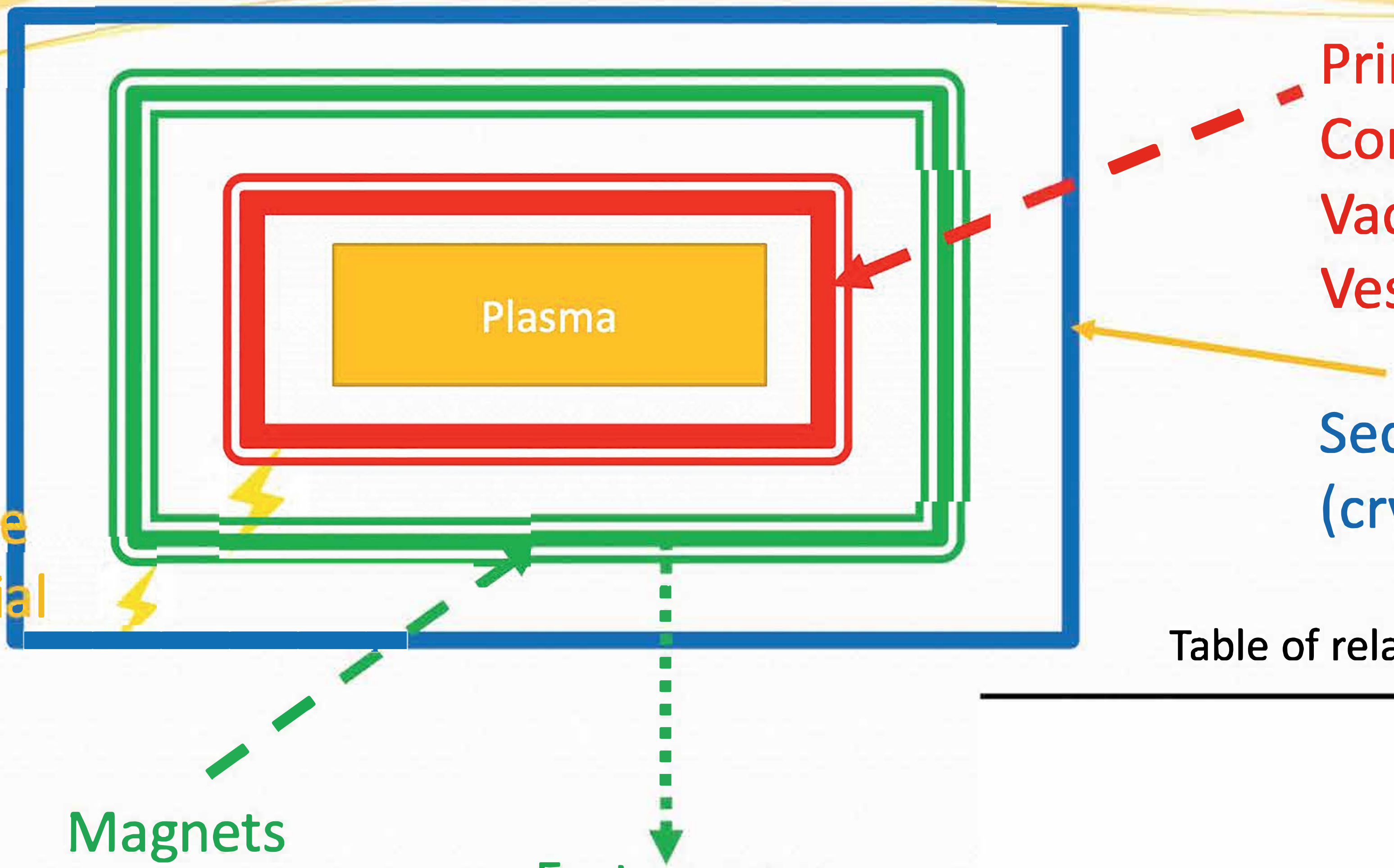
Insulation Conclusions

ITER has introduced major innovations in high voltage cryogenic magnet technology, all now proven in large scale applications

- ☐ Robust insulation systems capable of OPERATION up to 20kV
- ☐ Associated technology for feeder and local insulation
- ☐ (finally) techniques for integrating high voltage instrumentation
- ☐ Radiation tolerant resins
- ☐ Effective quality control processes (Paschen testing)

- This is reactor-ready technology. Implies similar requirements on magnet shielding in DEMO as ITER
- Room for improvement in standardisation of HV exits from insulation and reduced hands-on artisan work at coil surface: better basic engineering

6.4 Key Issue: Why magnet safety will be a concern in DEMO



Primary Containment Vacuum Vessel

Secondary containment (cryostat/building)

Damage potential

Magnets

Fast energy extraction

Table of relative VV vulnerability to magnet failures

JET	16	1.5	0.02
JT60SA	0	1	0.007
ITER	500	50	0.01
CFETR	1000	140	0.13
ARC	525	18	0.21

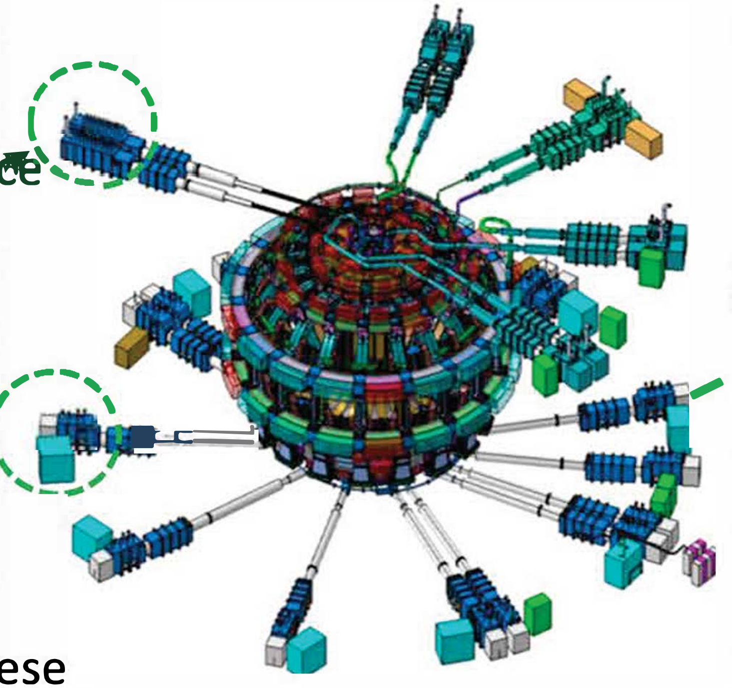
Trend to more compact DEMO-generation tokamaks with higher field greatly increases relative ‘damage ability’ of the magnets

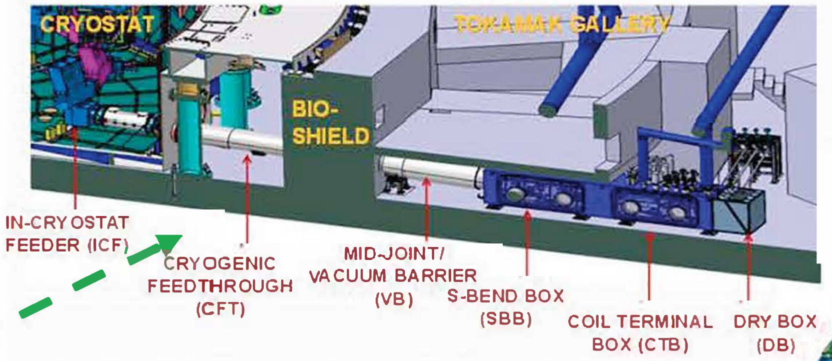
6.5 Key Issue: Maintainability, Repairability & Reliability

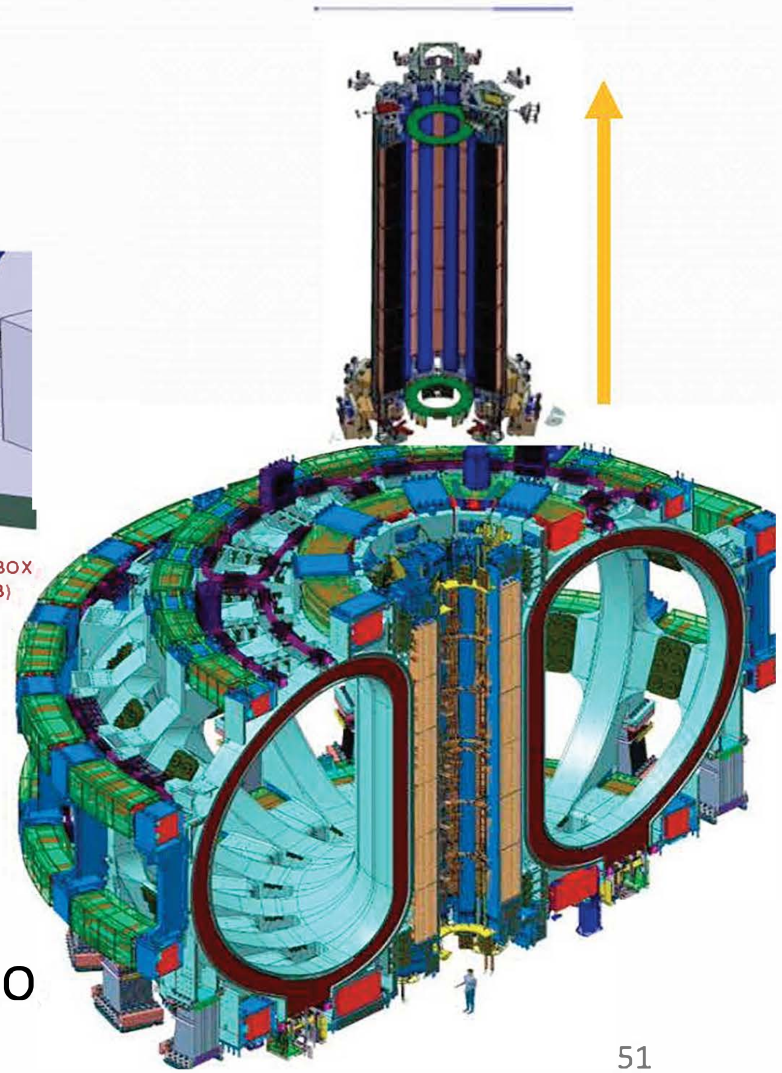
ITER magnets inside cryostat were designed not to require maintenance. All parts that need maintenance, or with limited life, are in the accessible CTBs outside the bio-shield

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)







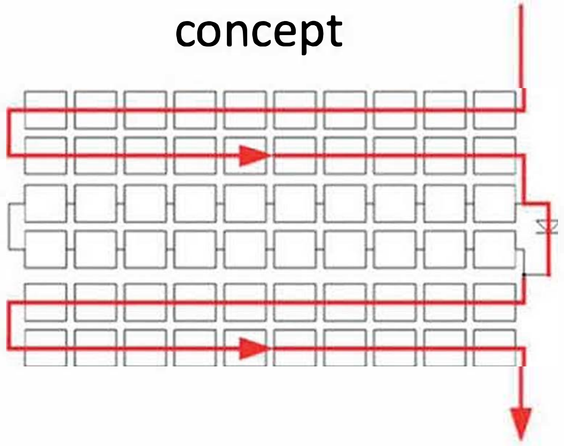
Main issues with these
- They have been greatly complicated by the late design development of the feeders
- Limited compatibility with nuclear operations. But provide concepts applicable to a DEMO

PF Coil Design with Redundancy and Recovery

Key feature: Joints on the winding packs are accessible from outside. Faulted double pancake can be bridged

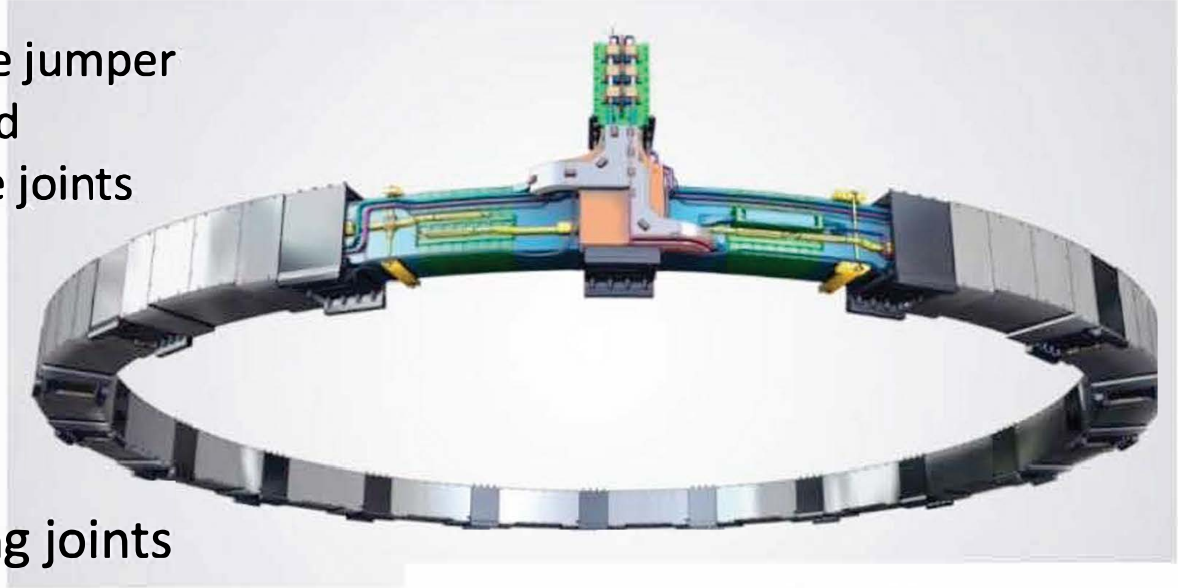
Does not repair but allows recovery

concept



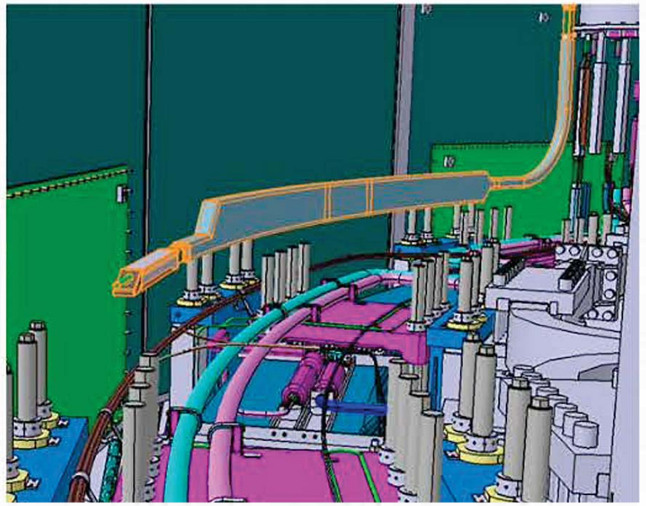
External bridge
added around
failure

Coil showing possible jumper locations (yellow) and existing interpancake joints (green)

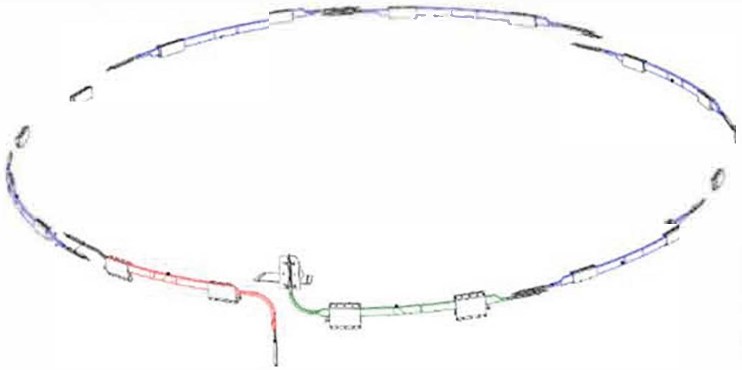


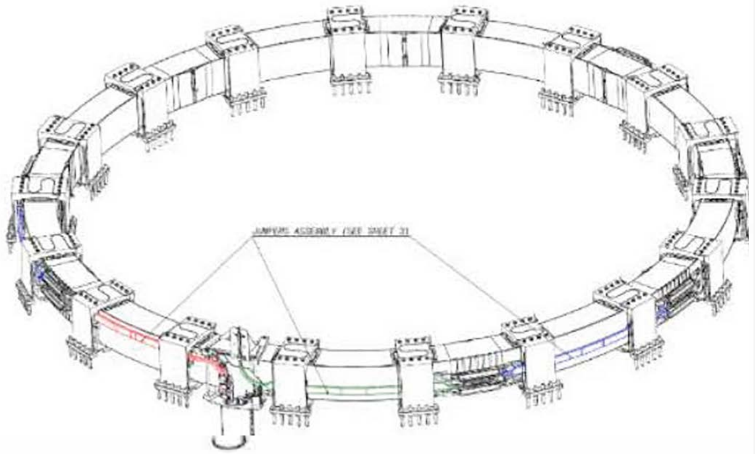
Steps to recover

- Place jumper in position
- Remove insulation and open existing joints
- Connect jumper to bridge DP



Jumper (orange) in position to bypass top pancake on PF coil

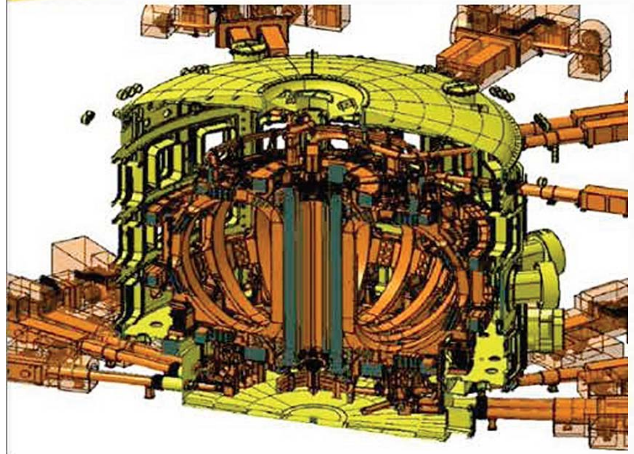




Potential jumper positions around a PF coil to bridge any DP

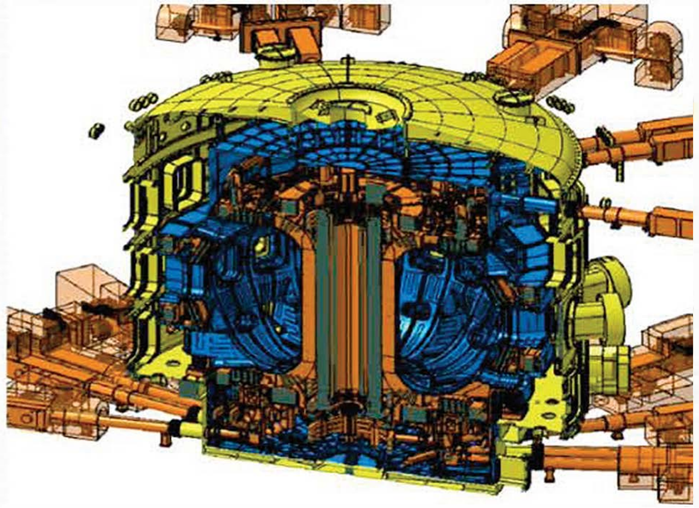
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk1P2 given at the virtual ASC 2020, October 27, 2020.

Problems of In-Cryostat Working

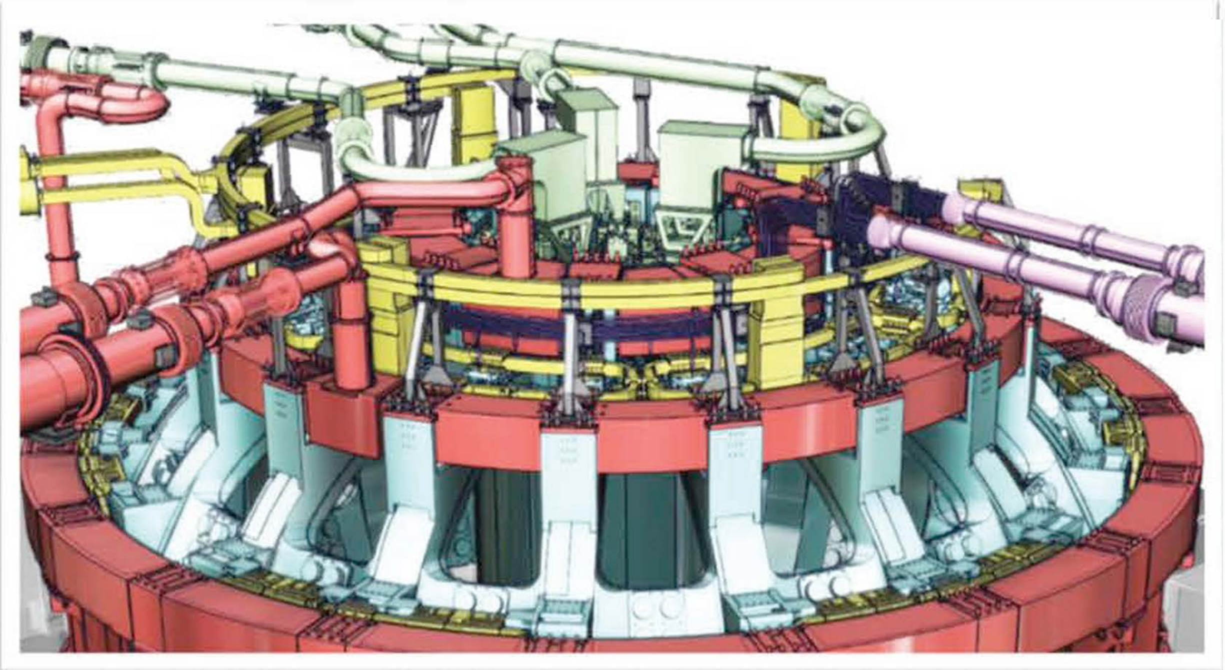


Magnets and Cryostat

Magnets, Cryostat
and Thermal Shield

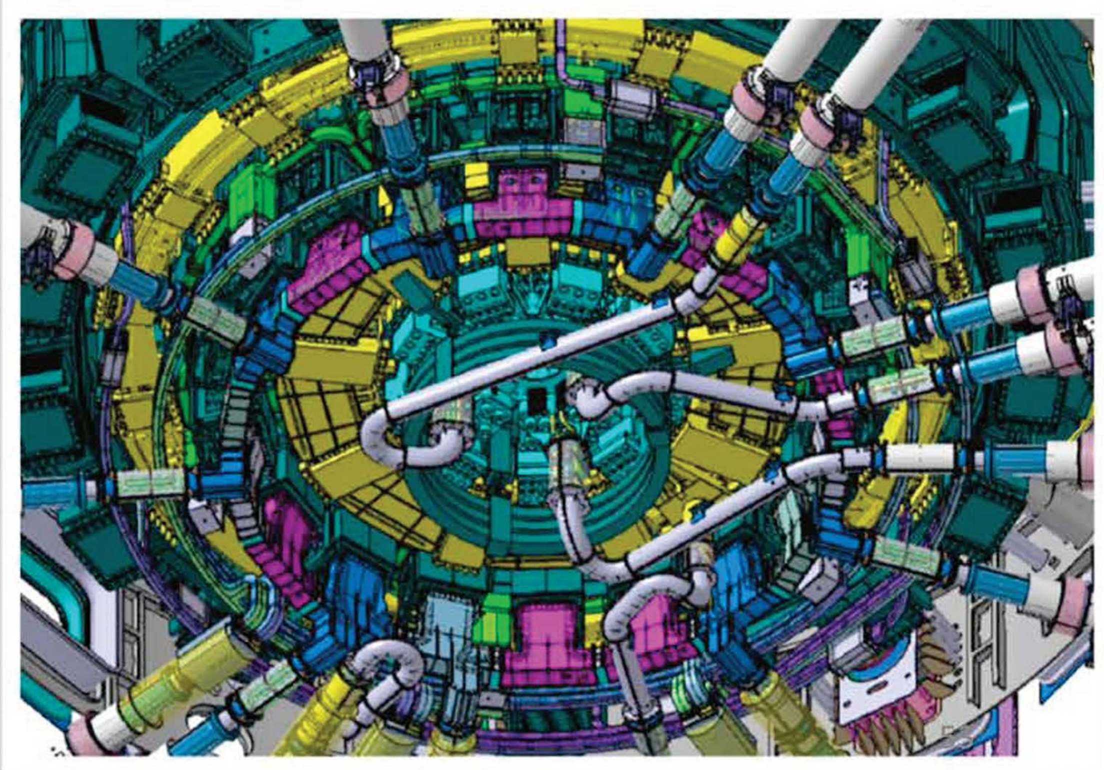


Access to auxiliaries (HV wires, joints etc) is hugely complicated by feeders and TS



Top of the machine

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



Bottom

Conclusions on Repairability

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

- ☐ Inbuilt back-ups (spare pancakes) included in PF, could have been considered in TF
- ☐ ITER added feeders almost as an afterthought (and changed them to adapt to chances 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 (subject of ITER research in 1990s)

7. Lessons for the future and foundations for the next step

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 engineering solutions, with cost/schedule higher than needs to be because necessary design changes & convergence can take years to implement

- ITER magnet engineering concepts/solutions need improvement for DEMO (feeders, wiring, access, repair, reliability), engineering priority in base machine as tokamak design driver
- ITER sc base technologies (conductor, insulation, structure) are good building blocks
- ITER type collaboration is valuable for continuity, can hinder design convergence
- ITER experiences have improved engineering maturity of superconductor technologies but there is more to do if new technologies are used for DEMO

From ITER onwards: DEMO conceptual design

Message

- Build the machine around good basic engineering principles, not around specific technological features
  - ☐ Priority to the real cost drivers, not imaginary ones
  - ☐ Integration
  - ☐ Simple and proven manufacturing routes
  - ☐ Technology that is mature (this includes those used for ITER)
- Instead of (as for ITER) starting at the plasma and working out, start at the outside of the cryostat and work inwards (through the coils to the plasma) and outwards (to the bioshield and building)
- Avoid (as for ITER) minimising notional machine cost (essentially prioritising compaction) at the cost of overcrowding, demonstration of reliability, lack of ability to adapt later and difficulty to repair

From ITER onwards: For new technologies (if this is the decision)

Message

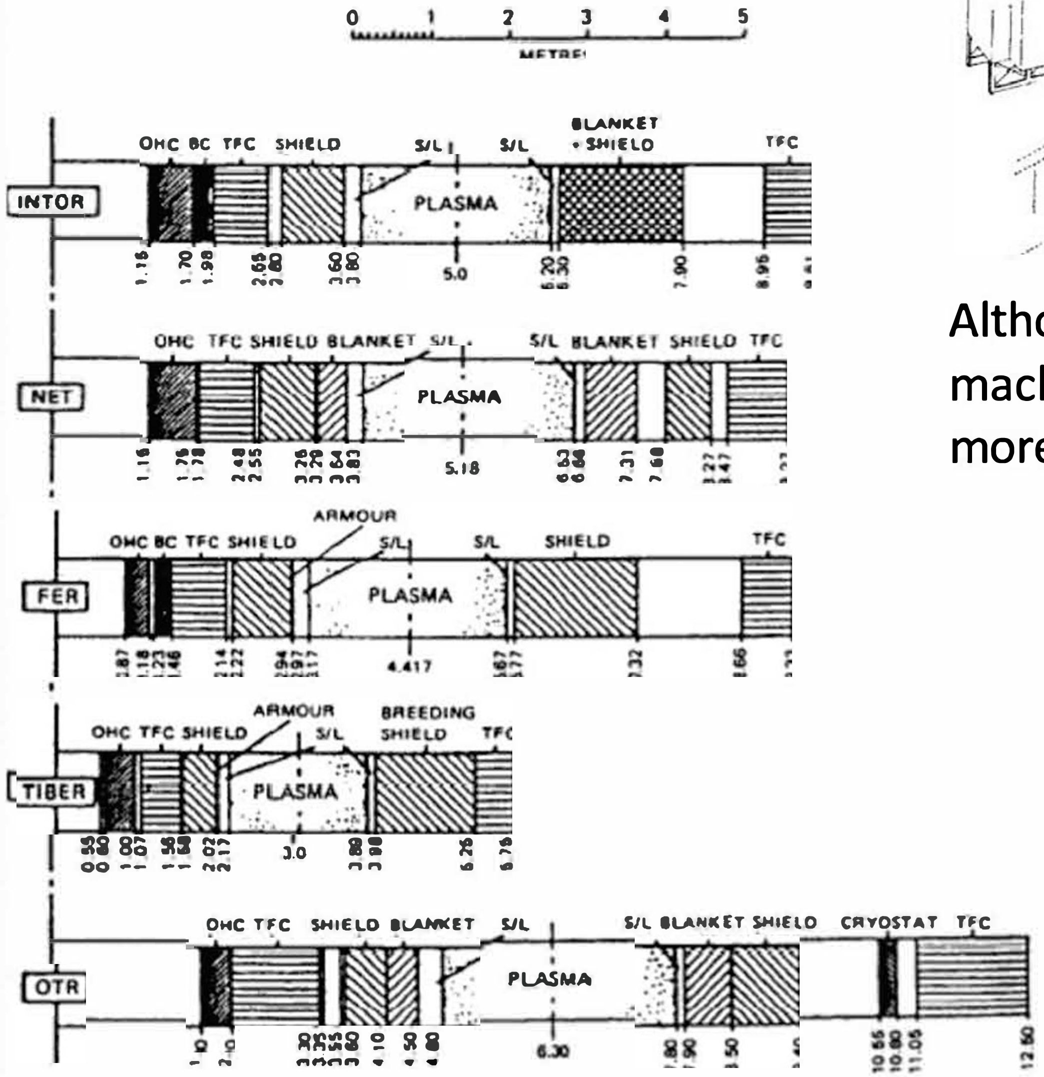
- Set base design that allows as wide a range of suppliers as possible to make a contribution, encourage economies but don't penalise innovation
- Avoid R&D driven priorities: individual research projects can develop dangerous 'take it all or leave it' selling techniques. Industrial capabilities and interests do not match those of research institutes
- Focus on what is needed to encourage industrial development, not on what is needed to control it. Test facilities, intermediate projects with multiple industrial participants
- Cost is important but can be misleading. Simple estimates focus on a few critical components and miss the background engineering and integration associated with the different technologies (which in ITER are dominant). For ITER, strand price appeared impractical at early stage but eventually the conductor was one of the few ITER components that was supplied at or below the original cost estimate.
- The SC magnet community needs to take an initiative to provide intermediate goals for 'SC Technology in Fusion'

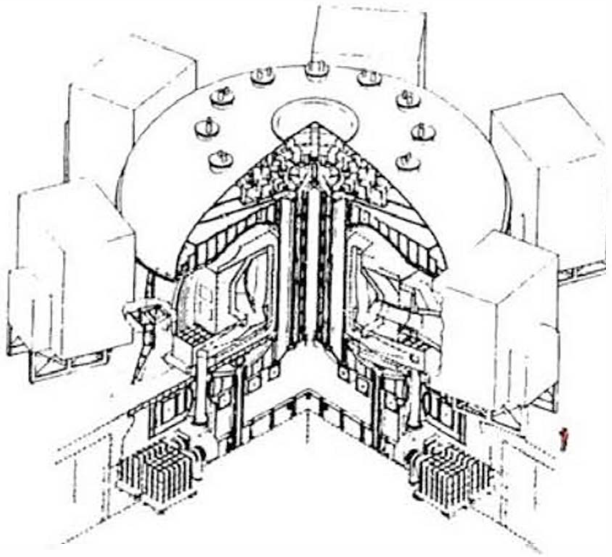
Some Proposals for a future framework: Machines

Machines

- ☐ INTOR allowed early comparison of technologies and system engineering without forcing choices. Decoupled plasma physics from technology and technology from engineering design
- ☐ Acknowledged as important background to ITER
- ☐ Could a new version of INTOR, half a century on, be useful? INTOR brought politically opposed factions together at the working level…this time perhaps differences are commercial not political but effect is the same….dissipation of resources in opposing each other rather than fighting a common problem

INTOR Final Report 1988
National Machines

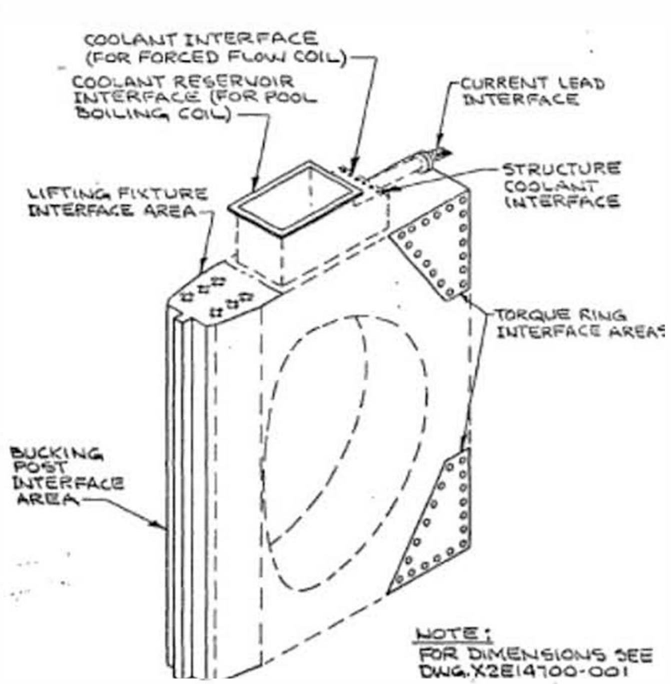




Although implied to be a single machine, INTOR was never more than a benchmark

Some Proposals for a future framework: Intermediate Projects as Demonstrators for New Technologies

- Similar methods to those already used for ITER could stimulate DEMO engineering
  - For new technology, to engage industry and develop maturity
  - For basic engineering improvements (repair, reliability)
- Agree common base building blocks (conductor, materials) to reduce risk to industry in investing. Get above the strand/tape level and look at composite conductors…set outline designs that allow internal innovation. Much easier to define/agree as a building block than the wires and tapes. Then bring the blocks together for large scale demonstration
- Agree common demonstrators that also provide future test facilities……SULTAN from 1980s and CSMC in 1990s were good examples. Building and maintaining large test facilities requires a community effort to provide users and balanced load
- Scope for innovation in quench detection and thermal protection: encourage with demonstrator projects



Do not need much detail: Proposal for the 6 TF coils in the Oak Ridge LCT Facility 1977