ITER, the magnets and the road to first plasma

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In 2020-21 ITER passed the point at which the delivery of components to the site was driving the schedule for the achievement of the first plasma. From now on, the schedule is driven by the process of assembling the components on site.

The presentation will look back at the main steps in the design finalisation and manufacturing of the main magnet components between 2007 and 2022, and their relation to the project critical path. From 2020 magnet components have been accumulating on site at the same time as the tokamak machine assembly has started.

After reviewing the main assembly achievements over the last 2 years, we will look at the scope, challenges and room for improvements for the future decade, until we achieve an operational tokamak

ITER Early History 1982-2007

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

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", US leaves

2001 Final Design Report

2001-2006

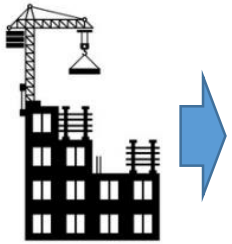
ITER continues, not covered by a formal agreement among the partners. KO, CN join, US rejoins

2006-7 (concept) Design Review

2007

ITER Agreement

the project entered the Construction Phase



What was the machine in 2007

Cryostat walls and lid, gravity supports and feeder layout completely different from 2022

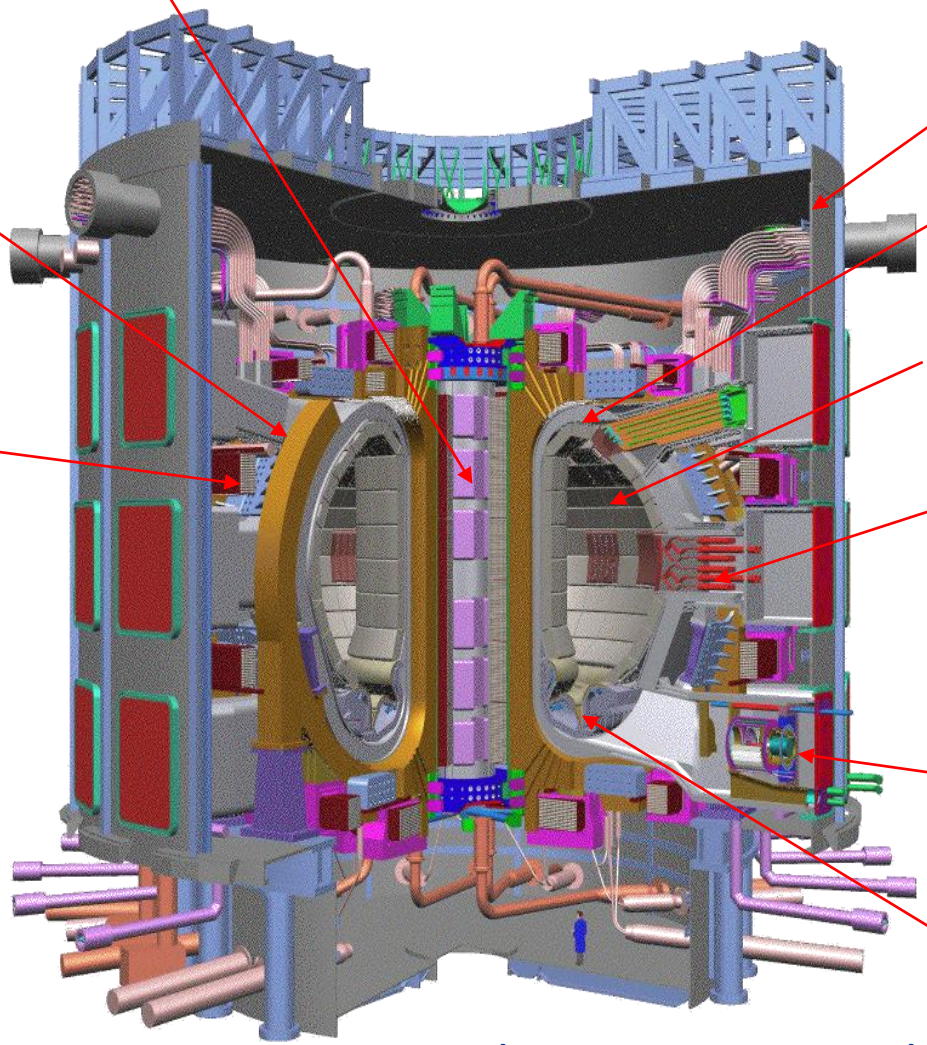
➔ Even in 2007 after 'review', design far from complete

➔ Buildings and balance of plant far from design finalisation

The 2006-7 Design Review should have been an opportunity to improve the integration and depth of the design.

- ❑ On the positive side a number of changes introduced in the period 2002-6 were 'legalised' (HTS leads a prime example)
- ❑ But also nearly 2 years were spent arguing concepts that were eliminated in the 1990s and in the 2001 FDR
- ❑ Missed opportunity to improve manufacturability

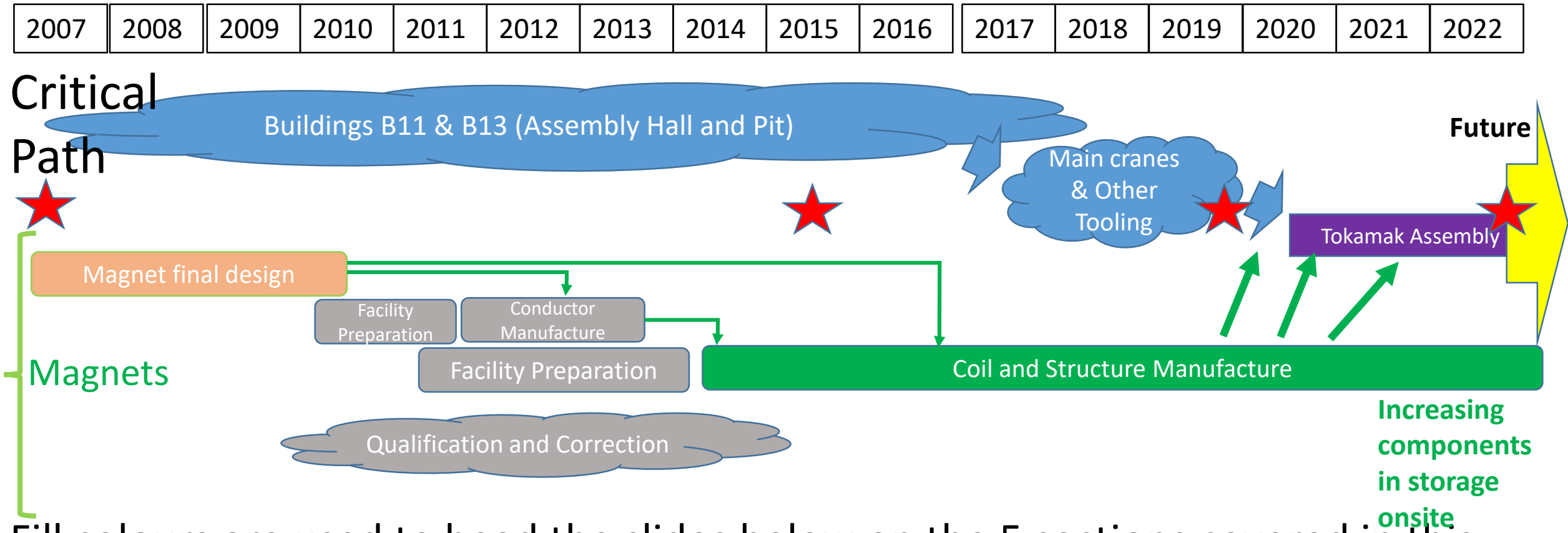
In magnets we argued and there were no changes. VV was diverted for 2 years by an alternative concept before rejecting it



Machine mass: 23350 t (cryostat + VV + magnets)

- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

Schedule Drivers 2007-2022 and Presentation Overview



Fill colours are used to head the slides below on the 5 sections covered in this presentation

★ Indicates rebaselining / re-organisation

- ❑ Always pressure from project to the component suppliers but actual critical path has been buildings and now assembly
- ❑ In last 2 years component delivery rate >> assembly rate, and this looks like it will continue to be the case

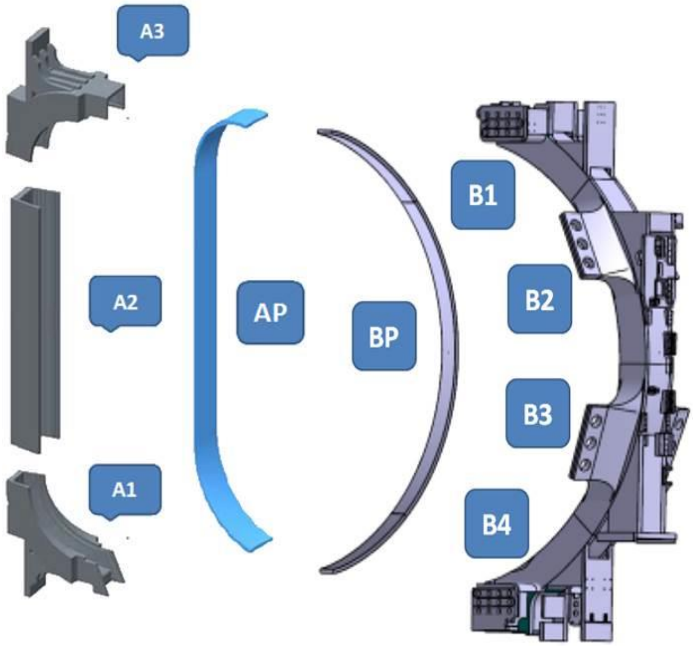
Magnet Final Design as Eventually Realised in the Period 2008-10

- We successfully demonstrated in 2003-6 that the in-cryostat parts of the magnets are not 'safety important' components
- This avoided the creation of an ANB (Authorised Notified Body) for the magnets and avoided the addition of another party (without superconductor/HV knowledge) in what was already a complex negotiation with the Domestic Agencies (DA) in manufacturing routes and qualification for FOAK components
- The magnets apart from the feeders and gravity supports do not have physical interfaces to the rest of the machine and we could integrate efficiently within the magnets. The integration experience of feeders and in-vessel coils shows the importance of minimising and simplifying formal interfaces in technically bureaucratic projects

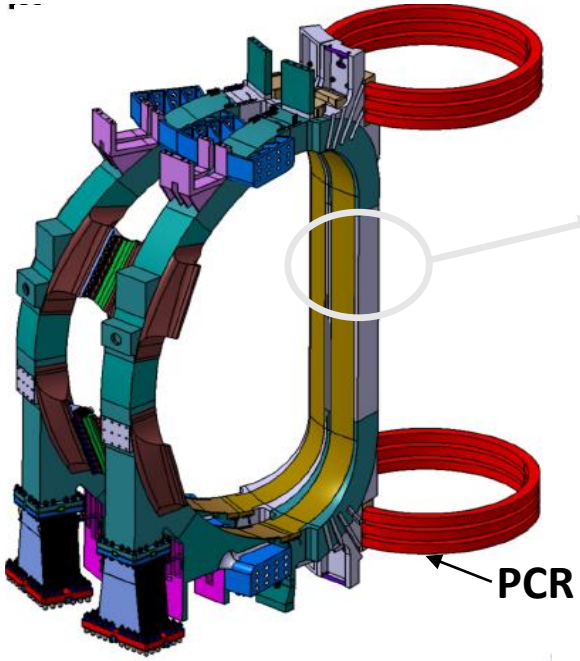
Other ITER components (critically the VV, but also the buildings) found many unanticipated issues in both completing the manufacturing design and responding to the regulator

TF Coils Features

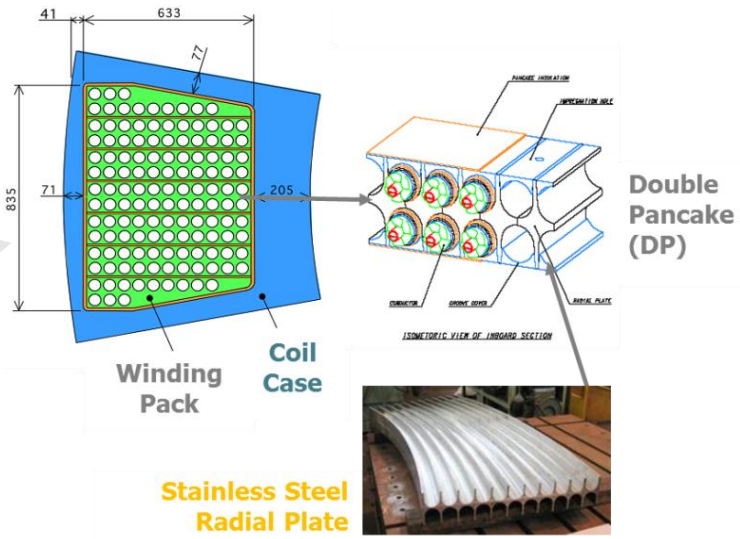
- The TF coil is made up of a winding pack **(WP)** inserted inside a thick **coil case** made of welded, stainless steel **segments.**



TF Coil Structure



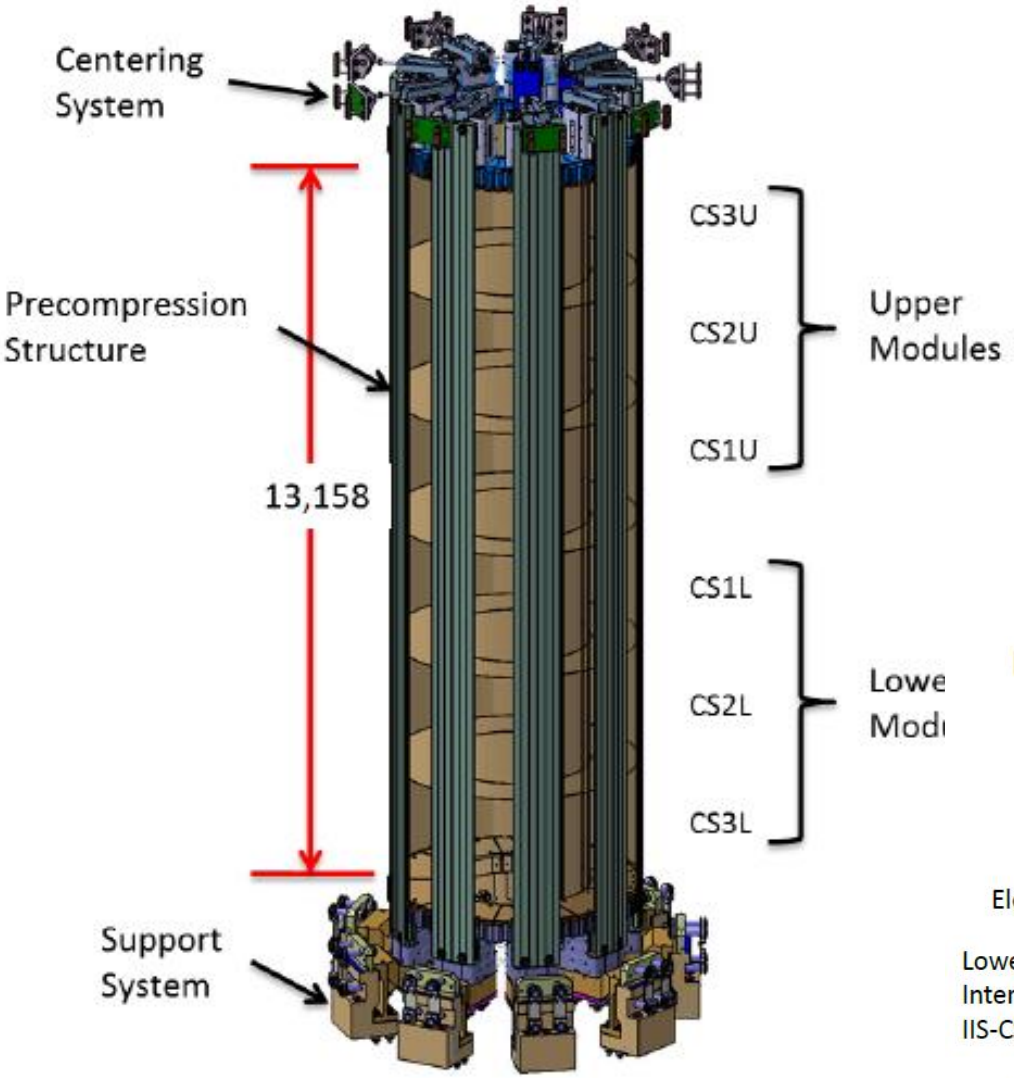
Pair of TF Coils



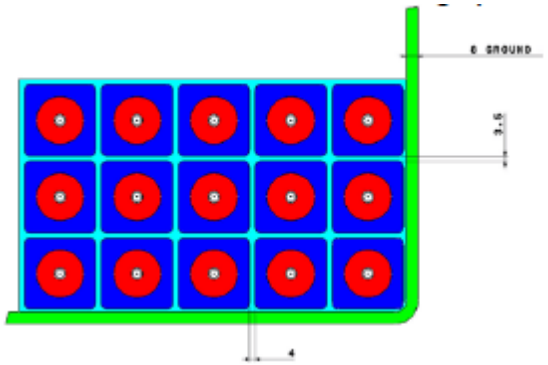
TF Coil Winding Pack

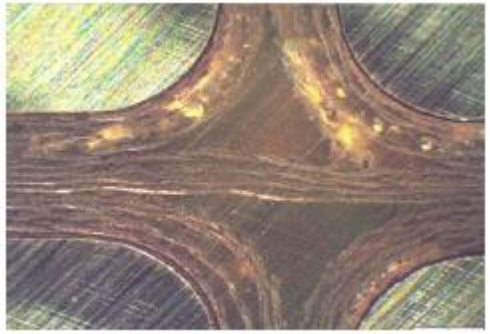
- Each **winding pack (WP)** comprises **7 double pancakes (DPs)**, made up of a **radial plate** with precisely machined grooves into which the **CICC** is transferred upon heat treatment completion
- The 18 TF coils are held together by a set of 2x3 composite **pre-compression rings (PCR)**

CS Coil Features

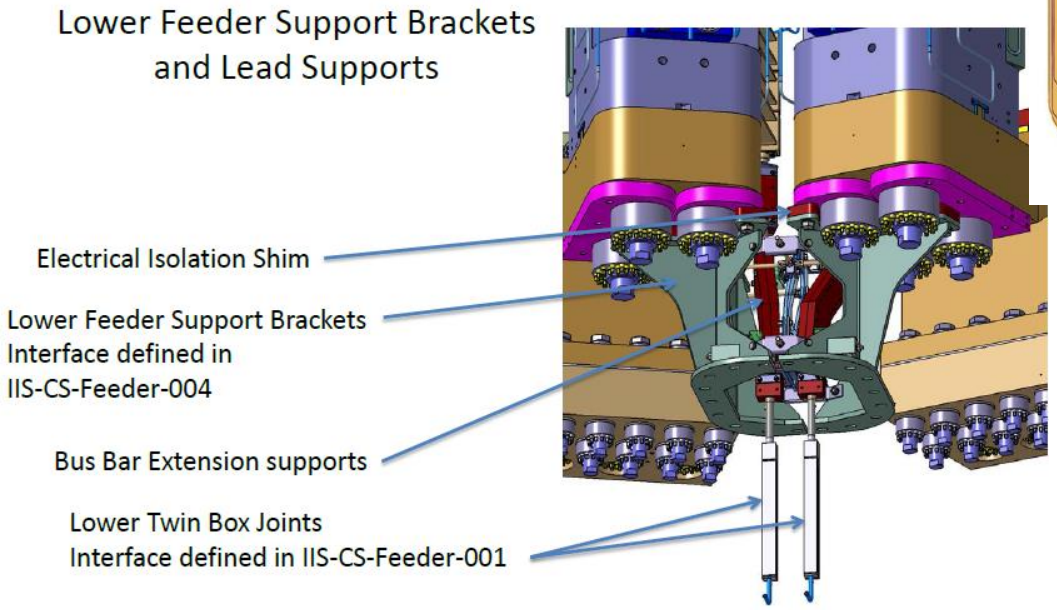


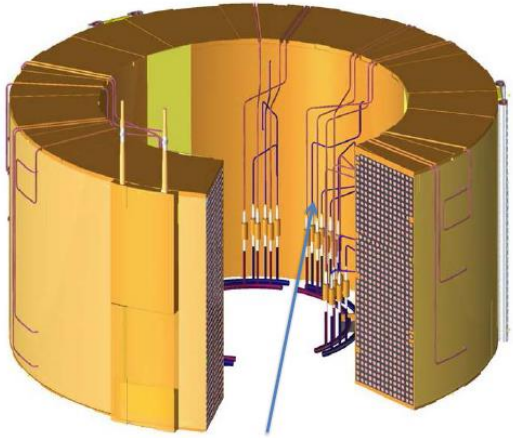
6 hexapancake wound coils using Nb3Sn conductor





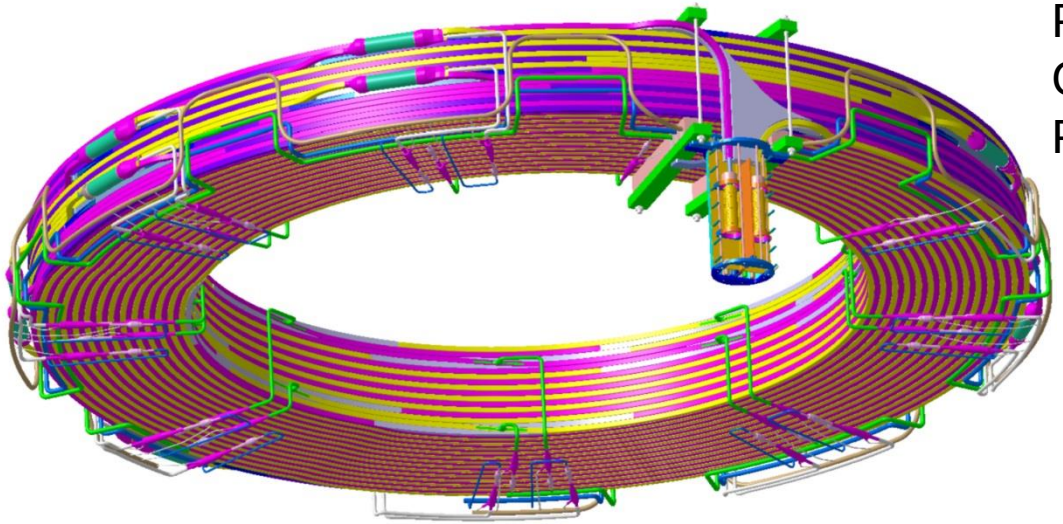
Conductor in winding and insulation system





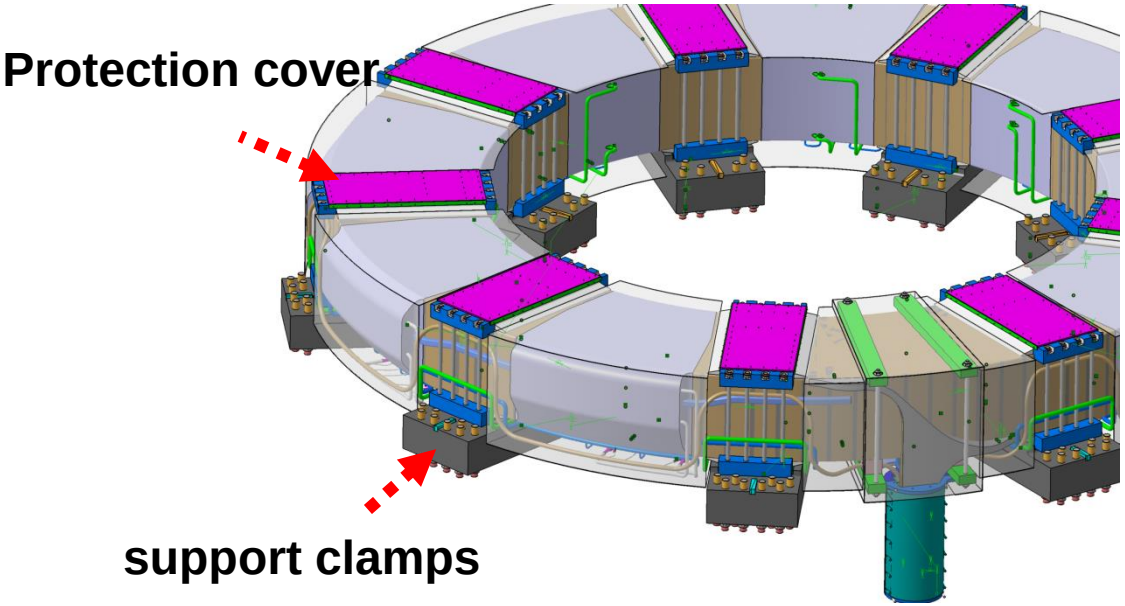
Module Helium Distribution

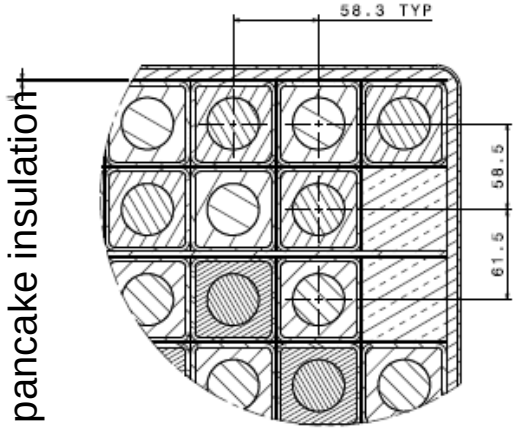
PF Coil Features

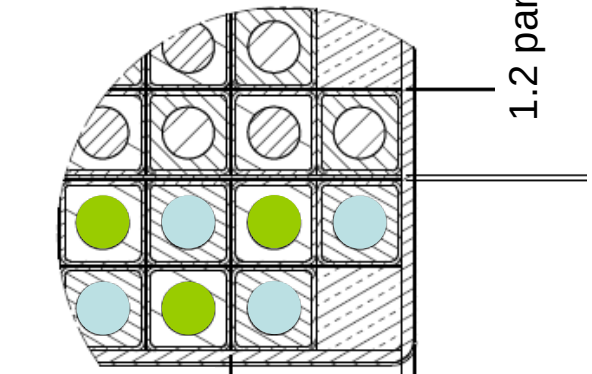


Pancake insulation, shims, bounding layer – fiberglass
Ground insulation – interleaved polyimide and fiberglass
Protection wrap – G10 plate

6 conventional double pancake wound coils using NbTi conductor

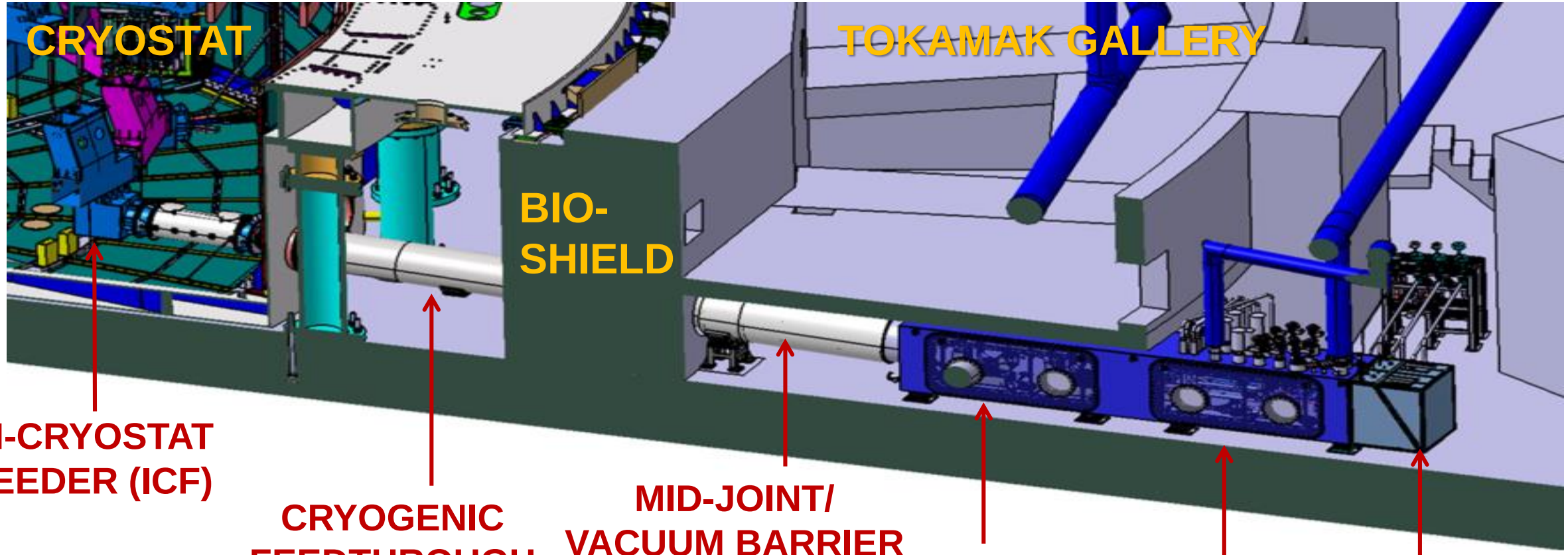






ITER Magnet Feeder Layout

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



IN-CRYOSTAT FEEDER (ICF)

CRYOGENIC FEEDTHROUGH (CFT)

MID-JOINT/ VACUUM BARRIER (VB)

S-BEND BOX (SBB)

COIL TERMINAL BOX (CTB) AND HTS LEADS

DRY BOX (DB)
(HTS current leads exit)

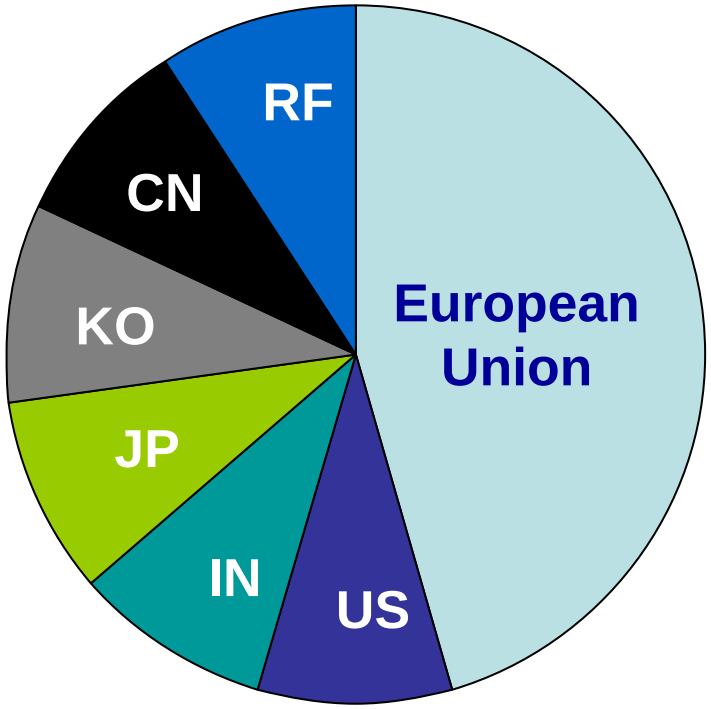
Courtesy of C.-Y. Gung (ITER-CT), E. Niu (CN-DA) & K. Lu (ASIPP)

2007 ITER Agreement & Construction Sharing

Procurement of ITER is mostly 'in kind' with components supplied by one of the parties in the project

How the overall NOMINAL costs are shared:

EU 5/11, other six parties 1/11 each. Overall contingency of 10% of total. Total amount: 3577 kIUA (5.365 B € / 2008)



Magnet Nominal & Real Costs

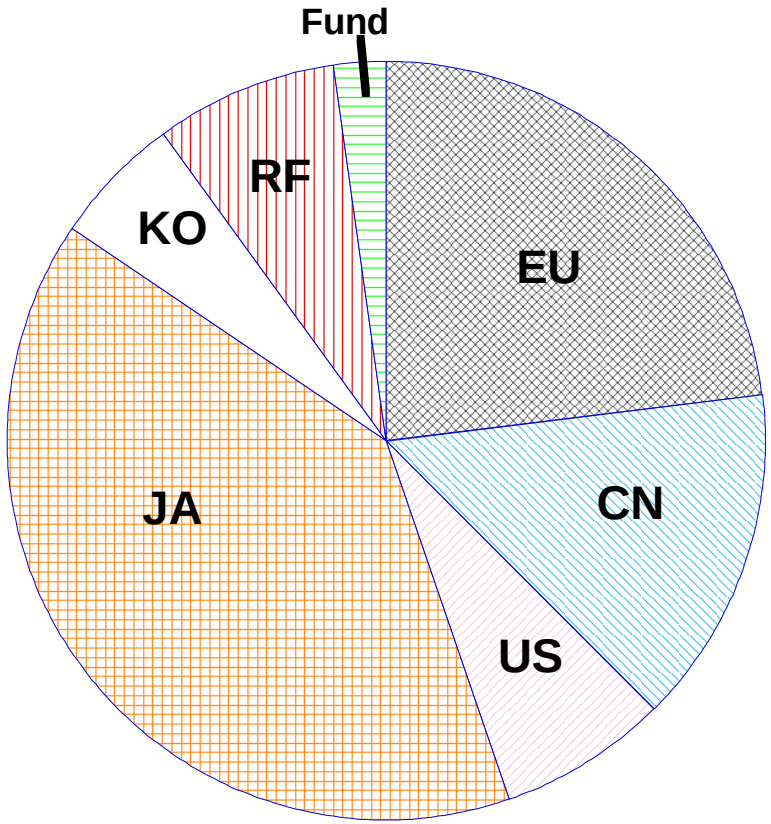
Notional Costs of Magnets is 802kIUA (1.3Beuro)

However actual costs are not known in public and difficult to estimate but are likely, and conservatively, in range of 4-5Beuro of which ~95% is spent (Jan 2022)

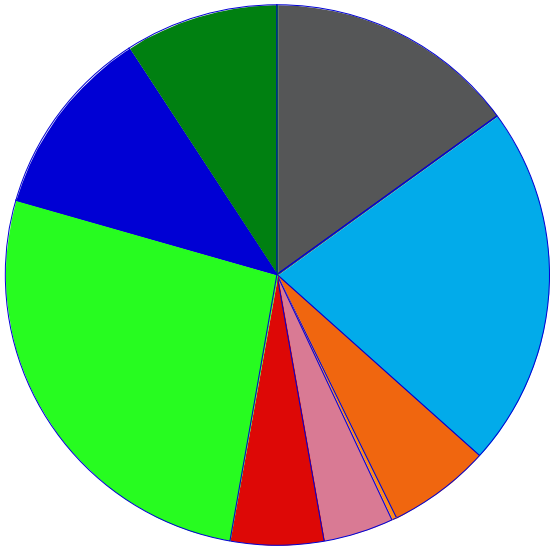
Significant part of the overspend due to inefficiencies of ITER sharing

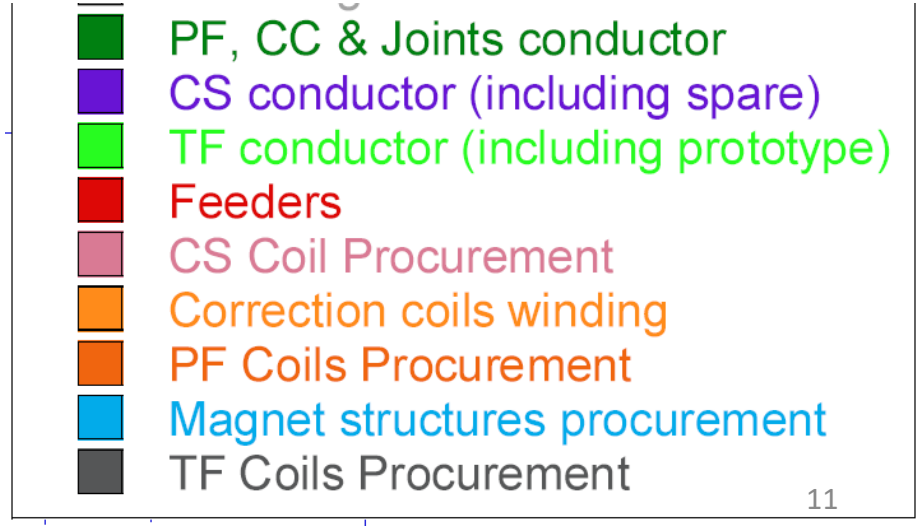
For example:

- We constructed 5 conductor jacketing lines (10-30Meuro each), 1-2 would have done
- We constructed 3 TF winding and casing lines, 1 would have done
- Much First of a Kind duplication



Relative Total Contribution of Different Components
Total 802IUA





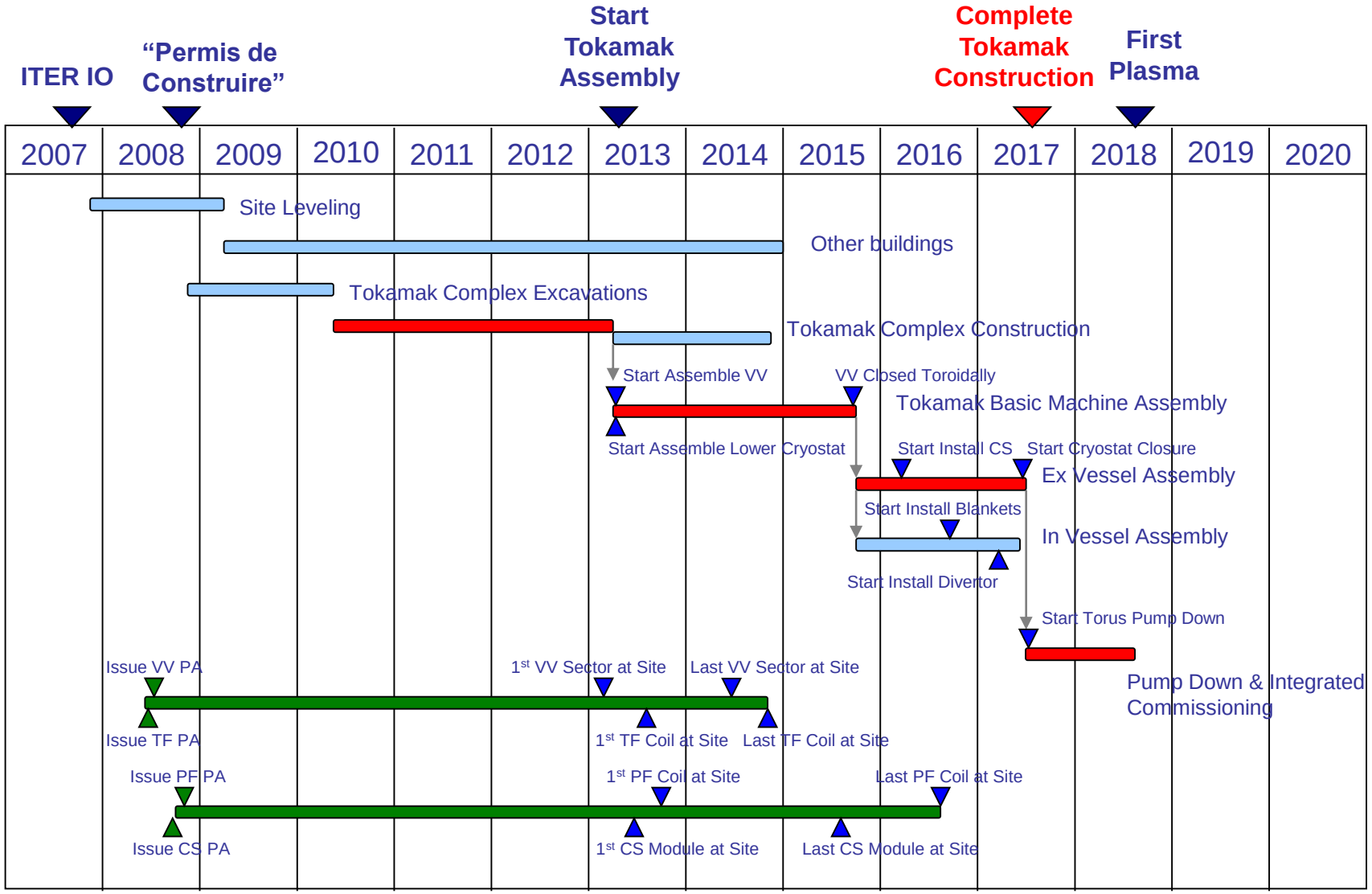
Reference Integrated Project Schedule mid 2008

Very little depth, very optimistic

First weakness was buildings. Start of Lower Cryostat Assembly foreseen q1 2013, actually q2 2020…driven by building readiness

Manufacturing was also highly optimistic but (just) shadowed by building completion

Assembly not integrated and durations look highly optimistic (x2 on duration) compared to what is now being achieved



Due to the Building Delays, Tokamak (Magnets, VV, Cryostat, Assembly) were able to gain about 6 years for design finalisation and manufacturing. For magnets & cryostat, it was enough. Not for VV nor Assembly

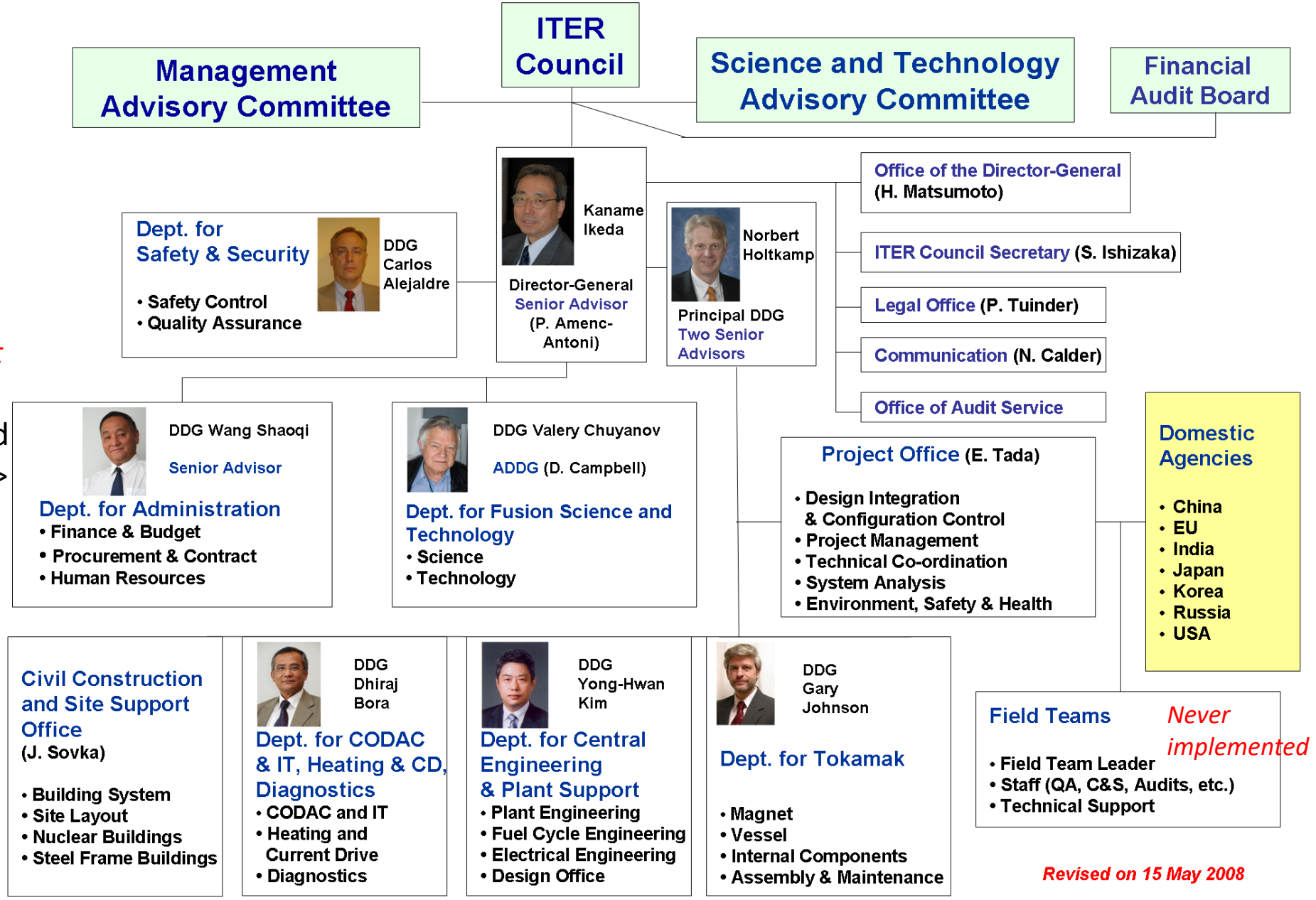
ITER Organization 2008

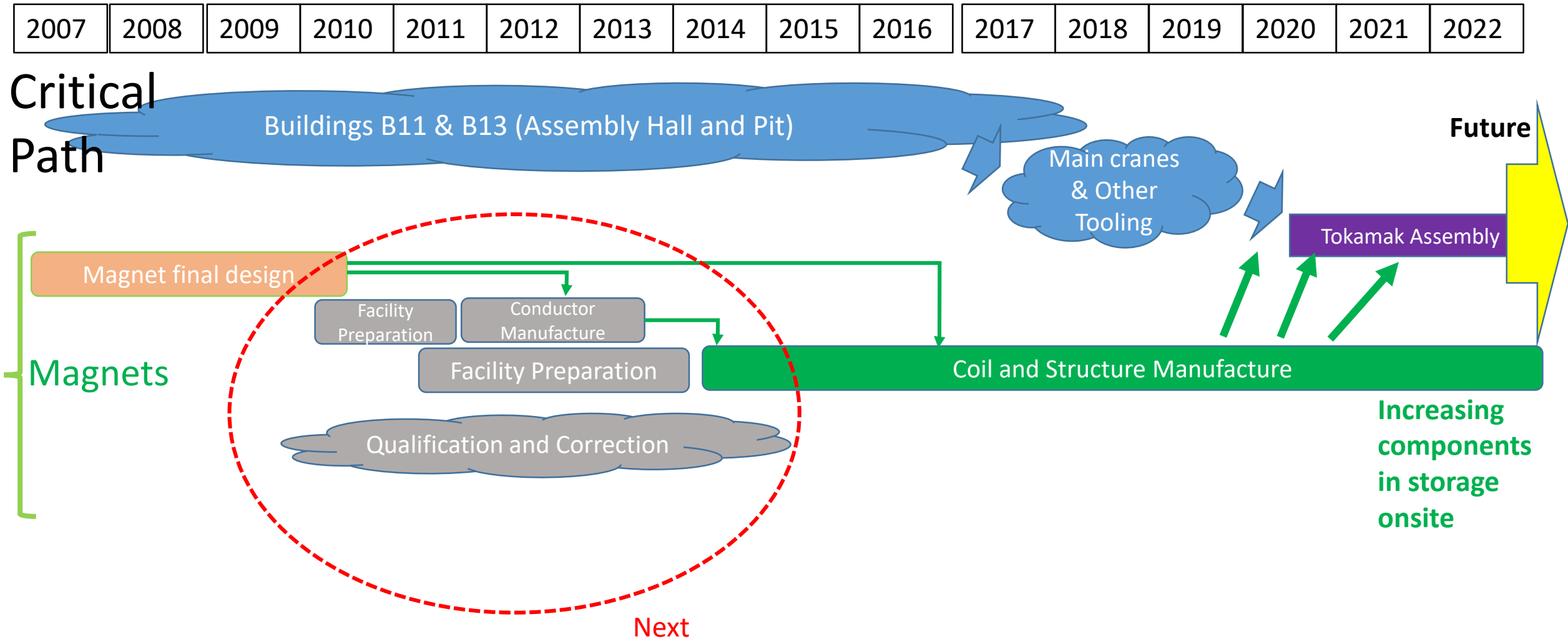
At this point the familiar ITER silo approach was introduced

Authority given at top level to administration, manufacturing, assembly, operations and transverse functions like integration. Result was confused responsibility. *No Field Teams which created poor QA oversight*

This organisation also introduced the concept of Manufacturing => Assembly => Operations, with the attitude that suppliers deliver (perfect) components to the ITER site, construction then puts them together and hands over to Operations. And it all should work first time….

We still have this concept




2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Critical Path
Buildings B11 & B13 (Assembly Hall and Pit)
Main cranes & Other Tooling
Future
Tokamak Assembly
Magnet final design
Facility Preparation
Conductor Manufacture
Facility Preparation
Coil and Structure Manufacture
Magnets
Qualification and Correction
Increasing components in storage onsite
Next

Next Problem 2011-2015 How to Manufacture It

Following 2007 Design Review there was Large Political Pressure to launch component procurement and on-site construction

Soon became obvious that Buildings were a major issue (for F4E), also regarding their integration to the Tokamak Machine

This gave us some time to sort out magnets
Clear that superconductor was going to be a major risk so in magnets we focused on it starting with strand
We launched 3 major development activities in parallel

- ❑ Strand (and conductor)
- ❑ Insulation
- ❑ Large structural components

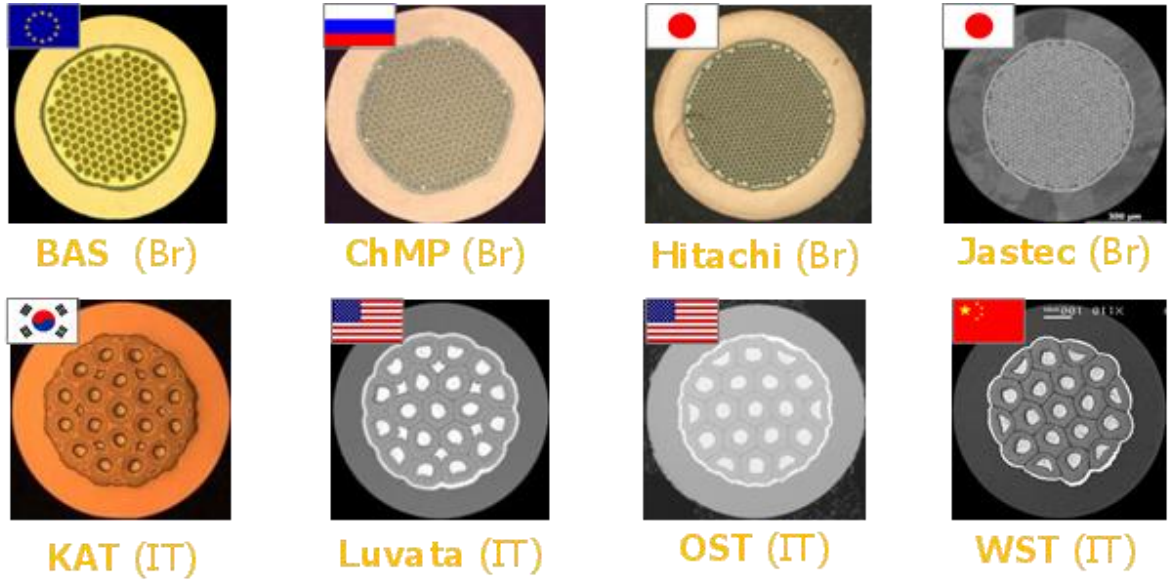
We also constructed (or adapted) major industrial facilities (conductor jacketing lines, TF, PF & CS winding plants)

Significant achievement that no coils were delayed due to conductor supply and that most conductors were available several years in advance

Following slides show some examples

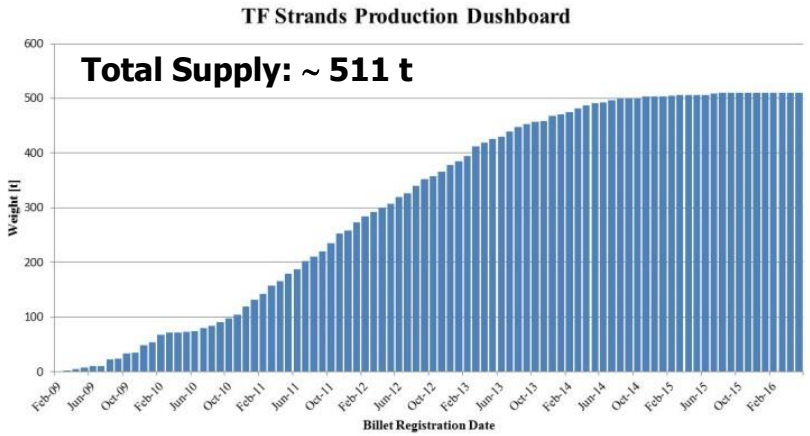
Superconductors

- 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)
- 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



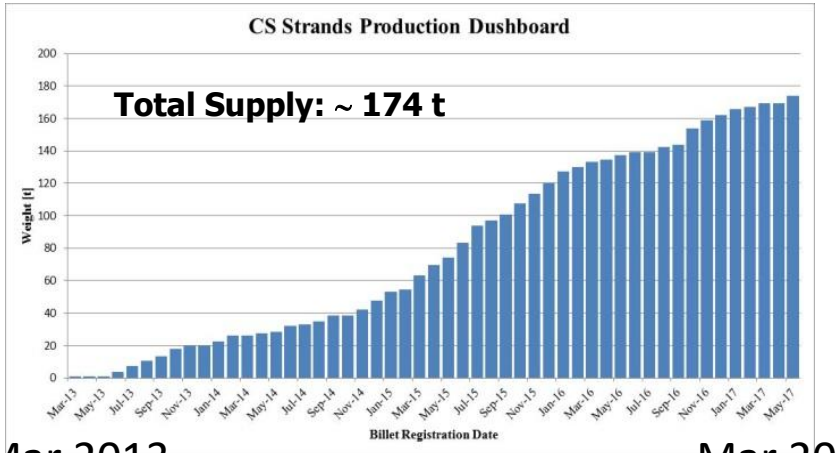
Data Compiled by D. Kaverin as of 31 May 2017 (ITER-CT)

- 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.

Conductor Issue. Degradation of large Nb3Sn CICC

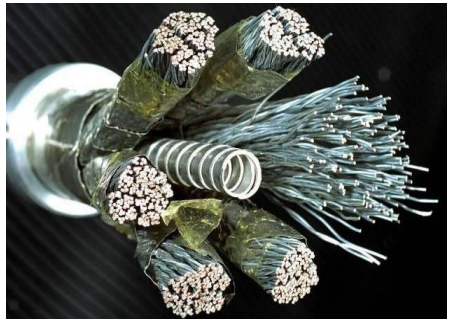
The Design Challenge

- ❑ Nb_3Sn is a brittle compound that easily fractures under tension
- ❑ Wires contain 1000s of filaments. Form cable from wires then heat treat to make Nb_3Sn.
- ❑ Wires separated to allow Helium at 5K to flow and limit AC losses
- ❑ But wires must be strongly supported for magnet/thermal loads

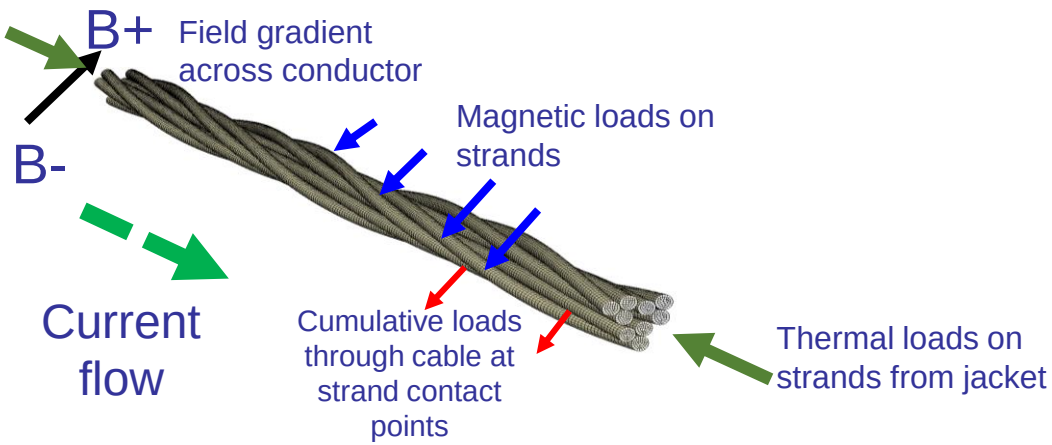
=> Filaments crack, current has to bypass. Challenge is to avoid *too many* filament cracks

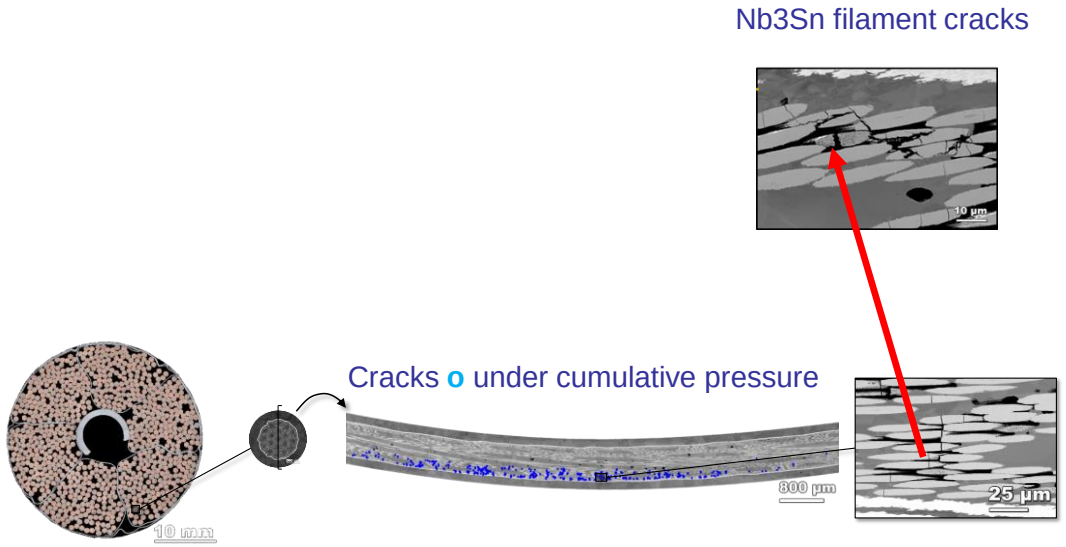
Solution required several iterations starting 2006 and finishing 2012

- *Applied to CS (short twist pitch)*
- *Too late for TF, but able to demonstrate sufficient margin*



'Exploded' ITER Cable





Structures and Field Accuracy

Dimensional errors have a major impact

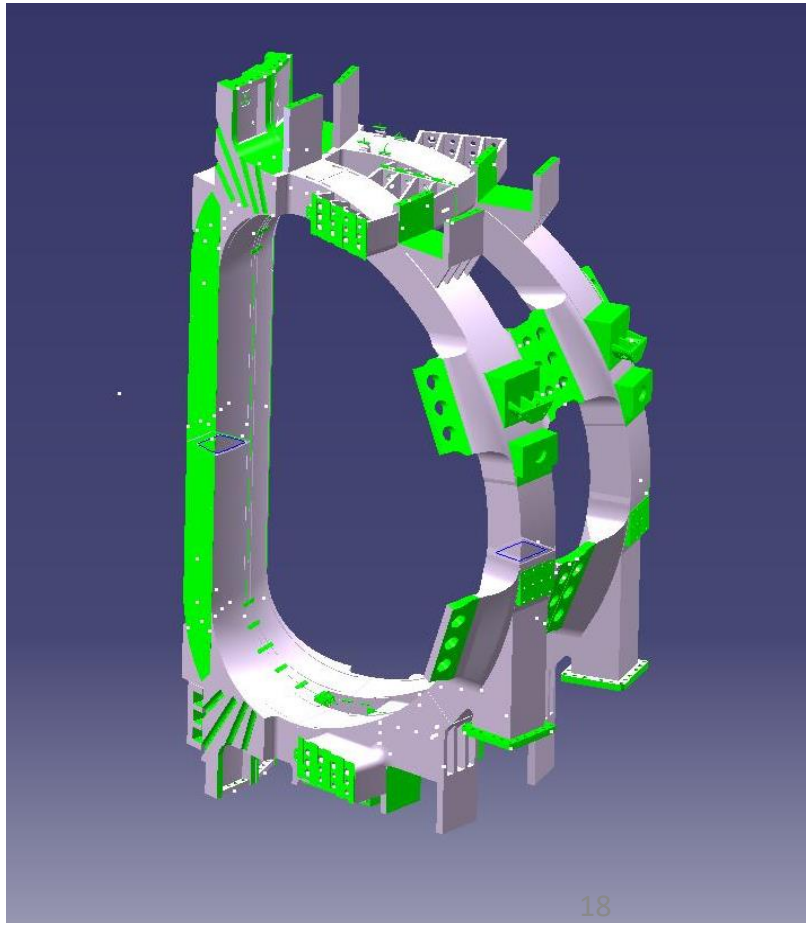
- Fitting of components during assembly so that load paths still match design intention
- Inability to place component in available space
- Field errors (very limited or no ability to correct post-assembly)

What drives tolerances

- Manufacturing capability up to +/- 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

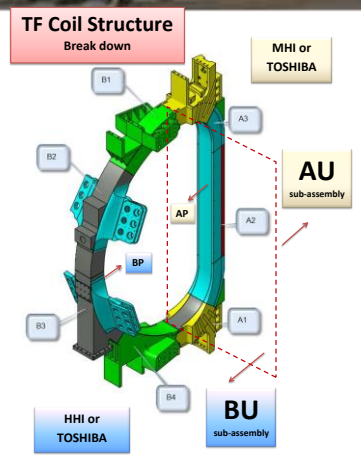
Development of manufacturing routes (forging and welding) 2007-2015

Multiple TF coil interfaces (green)



Structure Manufacturing

CS tie plate 2017



Trials on TF Structures: one company (Kind) produced almost all the 316LN forgings for the TF coil cases and VV under contracts with EU, KO and JA. MHI and HHI developed welding and machining

Radiation resistant resins

Resin Systems

Evident from 2007 that TF magnet shielding (VV, blanket) inadequate…dramatically confirmed in 2022 as x3 above 2007 baseline…and we had to move to **cyanate ester based resins**

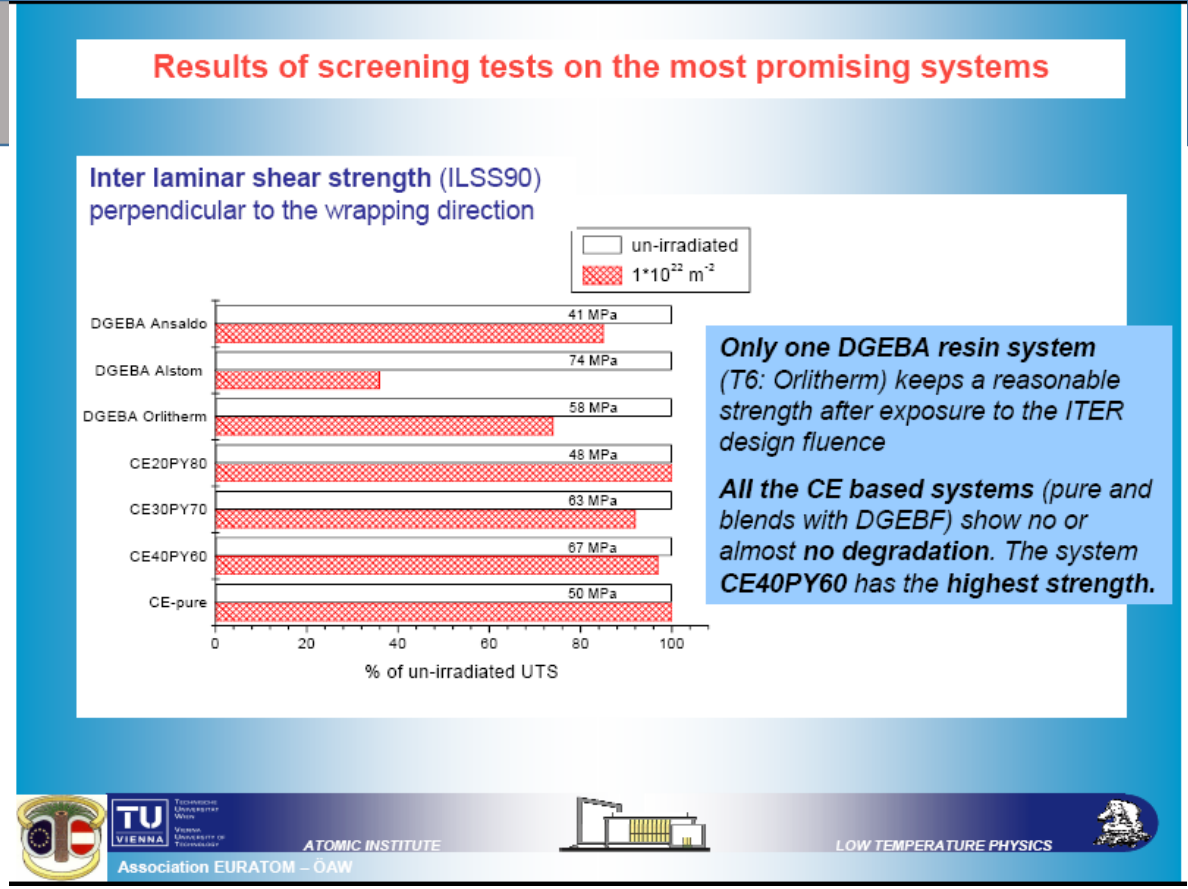
From 2009 addressed issues of

- 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

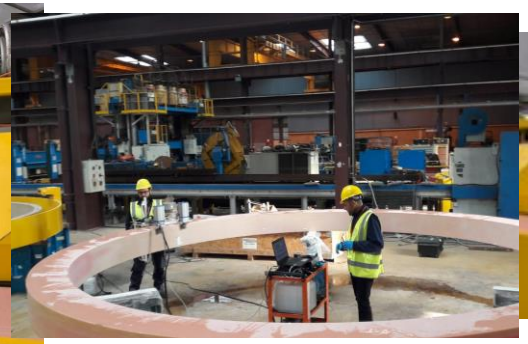
Industrialisation of Cyanate Ester blend produced several recovery actions

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

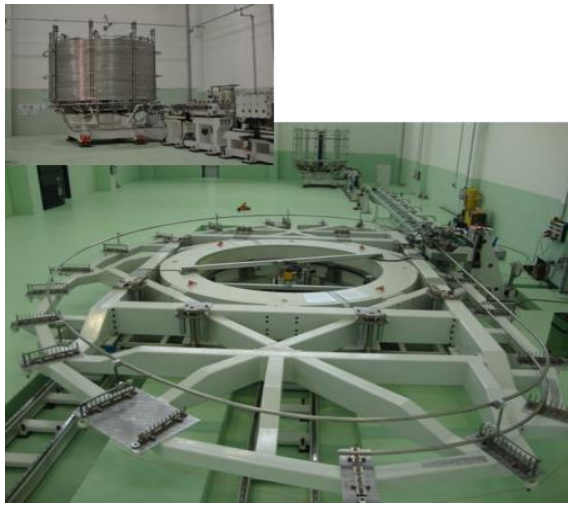


Development of manufacture, qualification and test of composite pre-compression ring



Examples of Construction of Production Facilities

TF Winding Facility La Spezia 2011



Radial plate SIMIC 2011

PF building 2012

VNIIKP Jacketing line 2009

Rebaseline and Refinance 2015-16

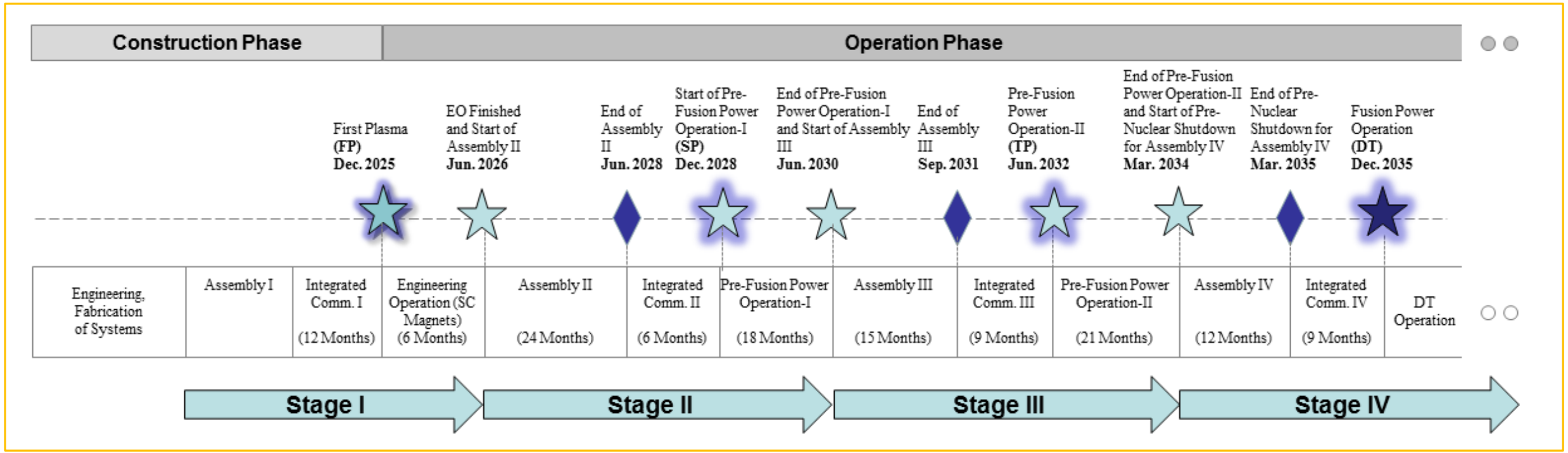
By 2014 it was obvious that FP in 2019 was far from realistic, as was the budget

Rebaselining in 2015-16 focused on

- An assembly review
- Requesting DAs to give firm commitment to deliveries of TF coils, Cryostat and VV…..and Buildings
- Re-organisation to put weight on construction

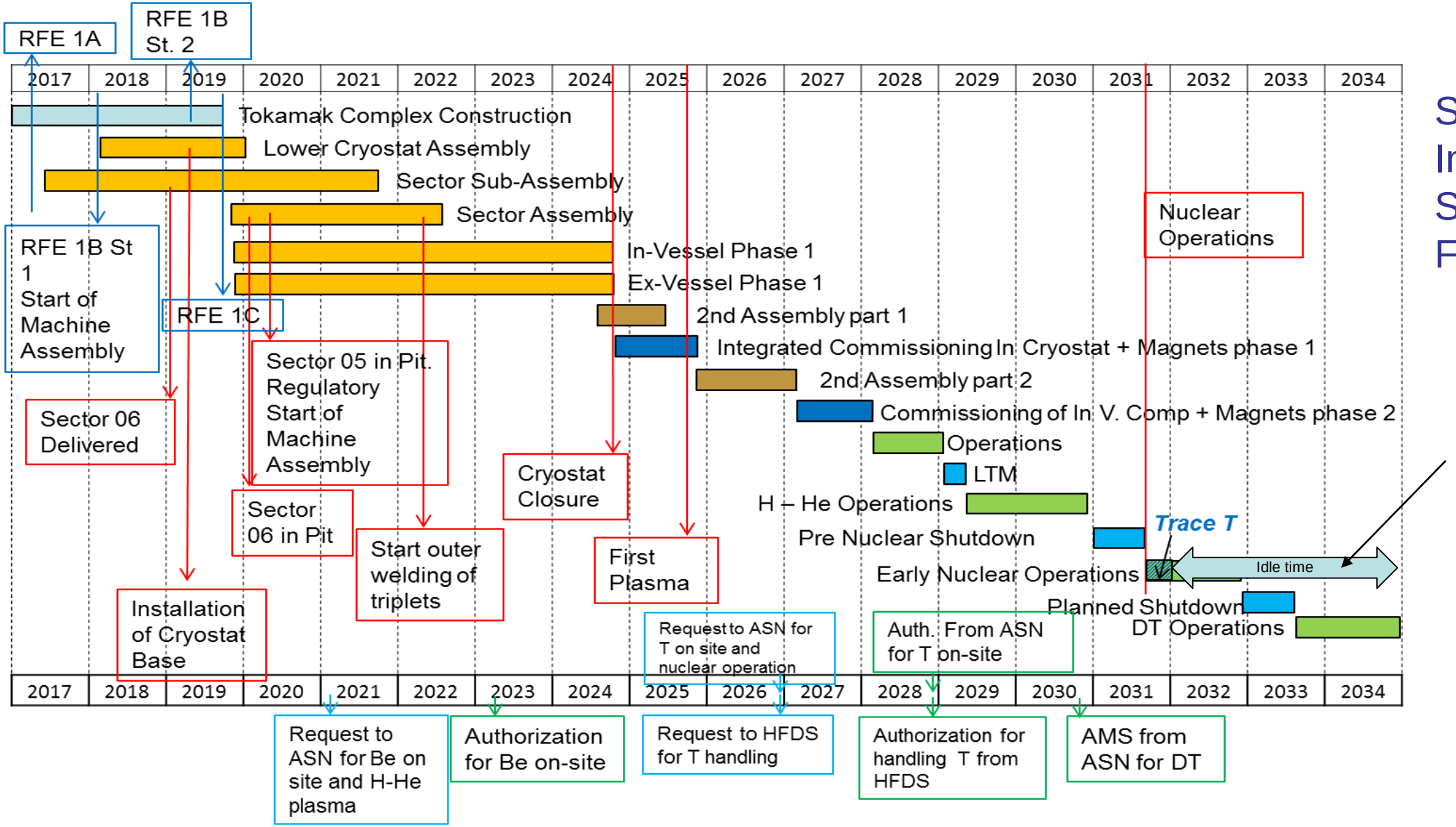
For magnets, coil fabrication really started in 2015 once conductor, radial plates and winding facilities were available

Staged approach to DT plasma Overview



In 2015 the staged approach to nuclear operation was introduced. First time clarity on the 10 year gap between FP and full 15MA nuclear operation

Rebaselined (2015) Level-0 Schedule



Same as Integrated Schedule up to First Plasma

Funding impact

2015 proposal for construction re-organisation

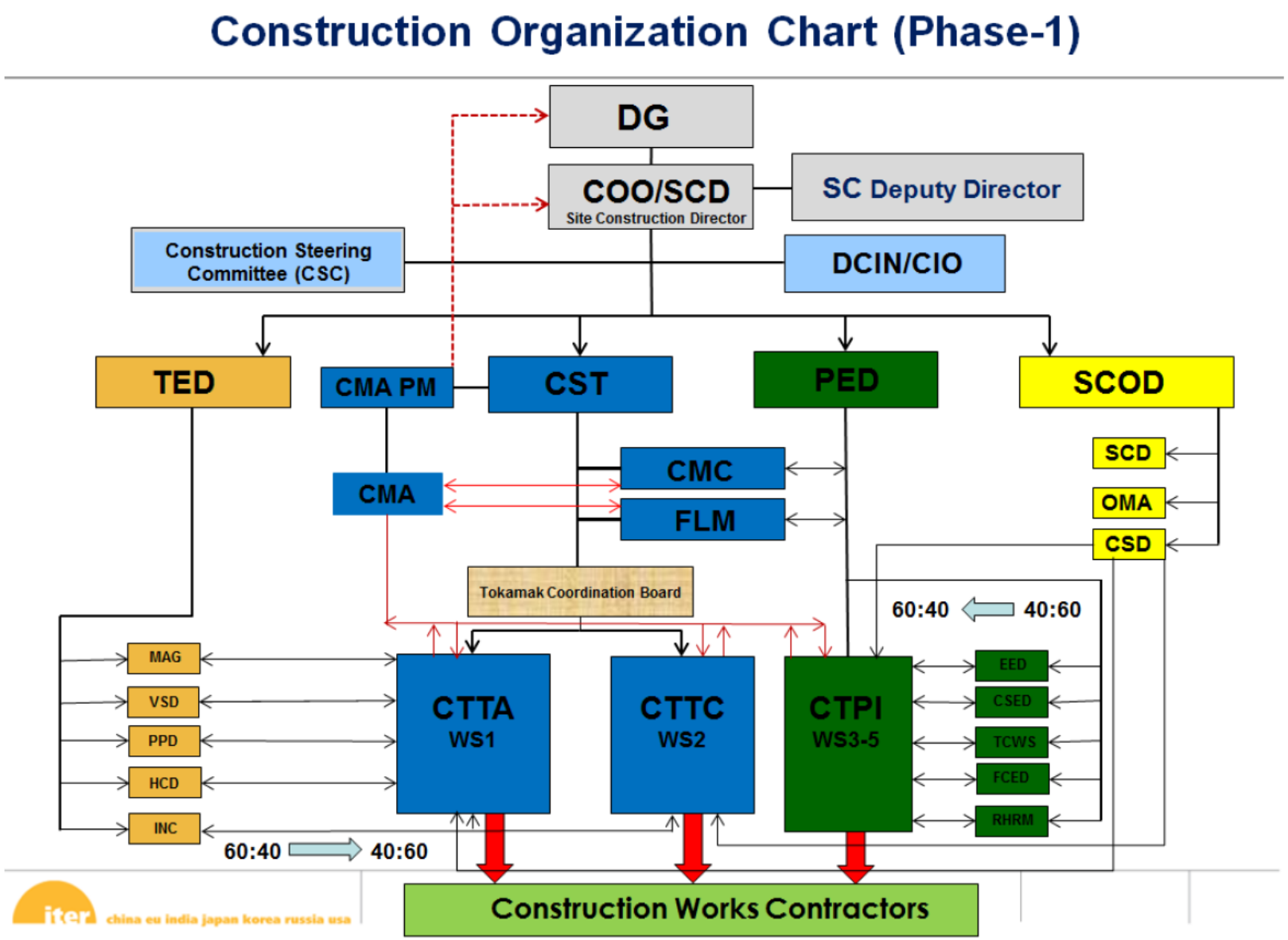
More or less as implemented from 2016 until end 2019

Note (odd) role of CMA (Construction Manager as Agent)..normally would be between contractors and IO parts

The PBS (under TED) matrixed to the construction organisation CTTA

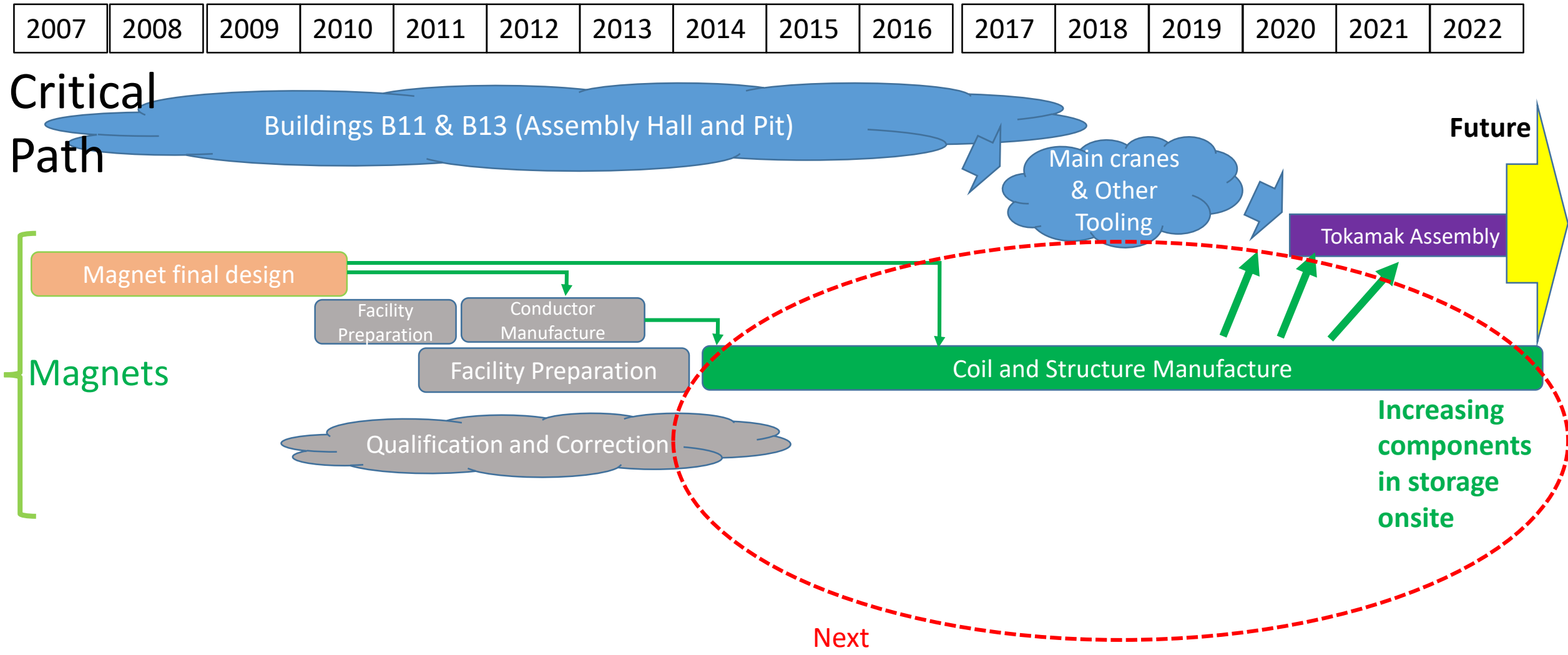
Further development in

- ❑ Complexity
- ❑ Diffuse responsibility
- ❑ Project management by transverse functions

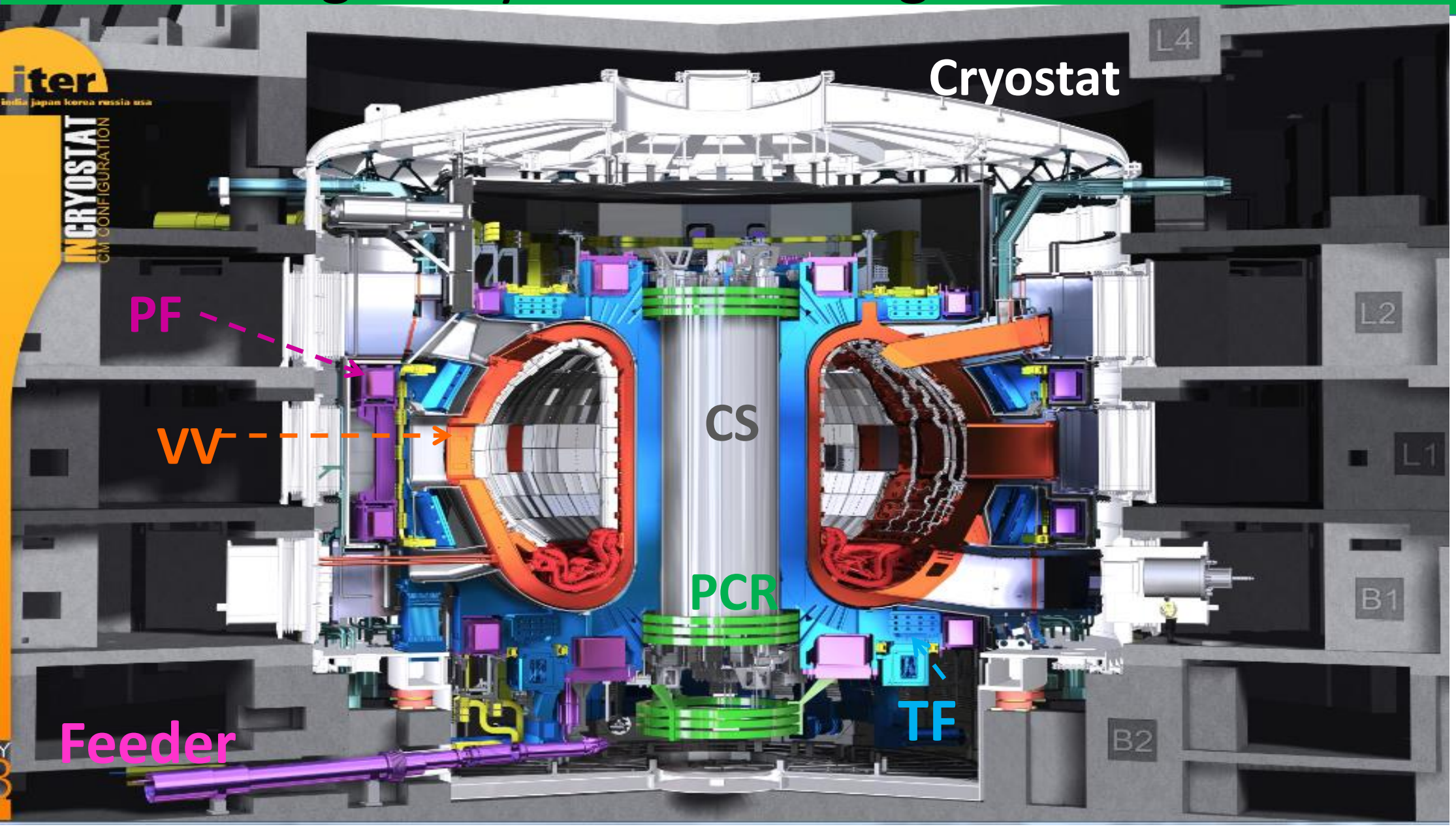


IO could not properly implement and run a matrixed organization

Manufacturing gets underway and components flow to site



Overall Magnet System and Neighbours 2017



Status of the ITER Magnets in 2022

Manufacturing and Assembly Status (April 2022)

Very approximate overview (% based on work to be done, cost or labour hours)

Manufacturing

Conductors: 100% complete

TF Coil Windings: 100% complete

TF Structures: 100% complete

TF Casing: 80% complete

PF Coils: 80% complete

Feeders: 70% complete

Supports: 90% complete

CS coils: 80% complete

Assembly

Overall (SSAT, in pit, galleries: 8% complete)

Major activity since January 2020: Transport magnets to the ITER site

Sea to Fos-sur-mer

Special road transport to site (3-4 nights)

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

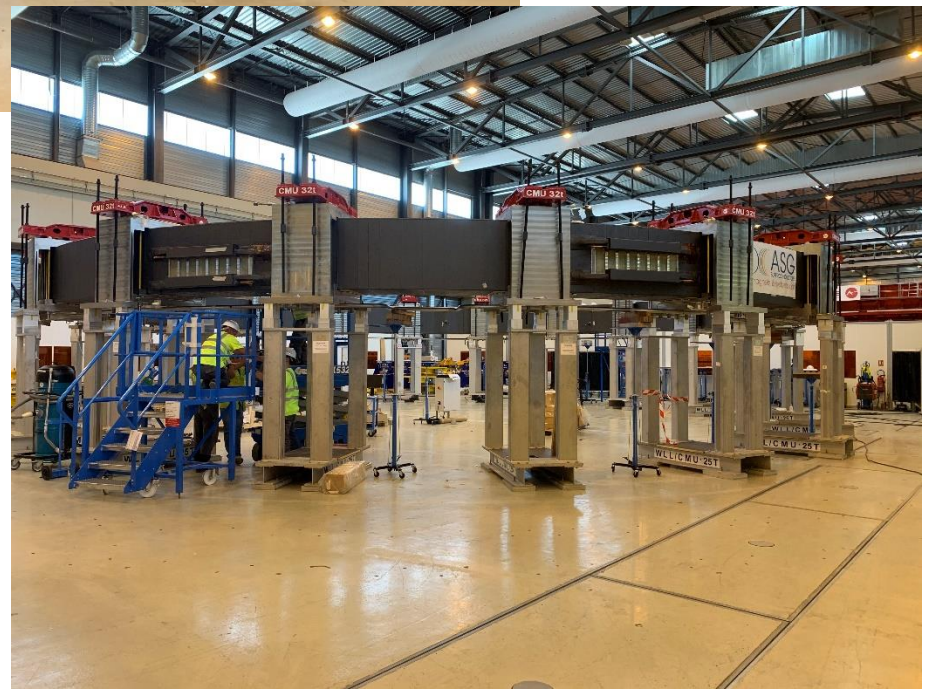
Transport of PF6 June 2020

PF Coils at ITER Site

PF6

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

PF5

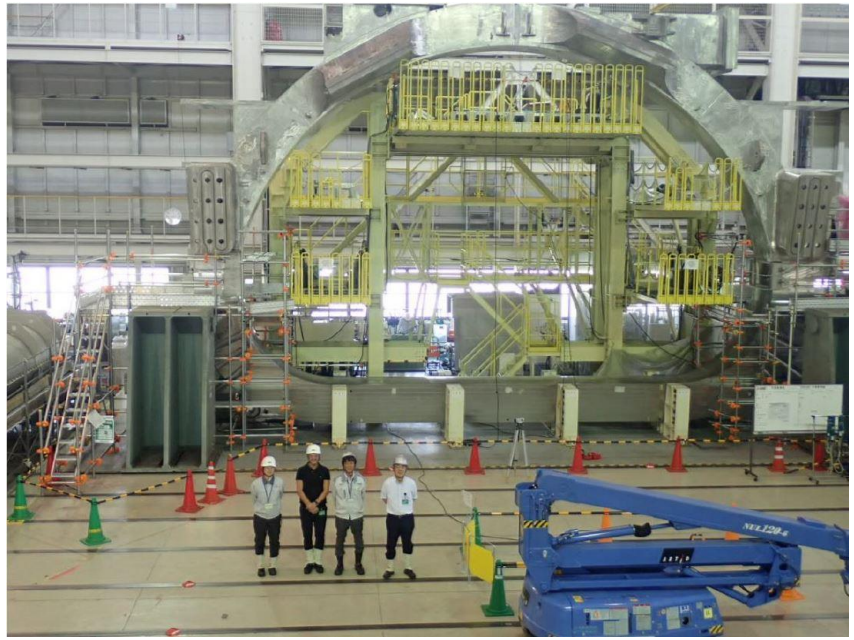


TF winding pack

TF coil terminal region

Horizontal TF WP insertion (EU)

TF structures fitting test

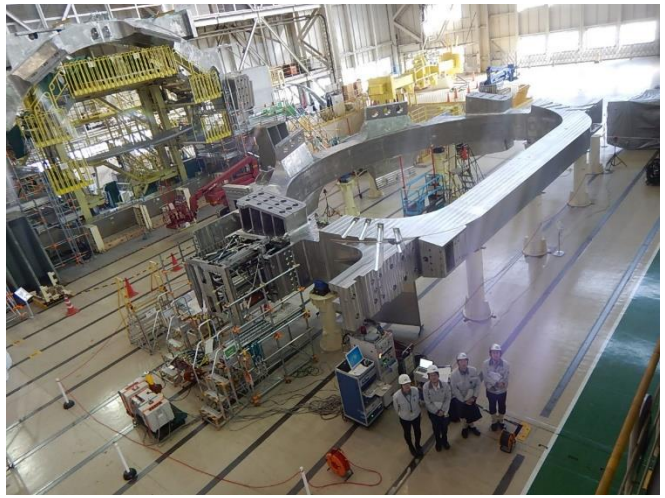


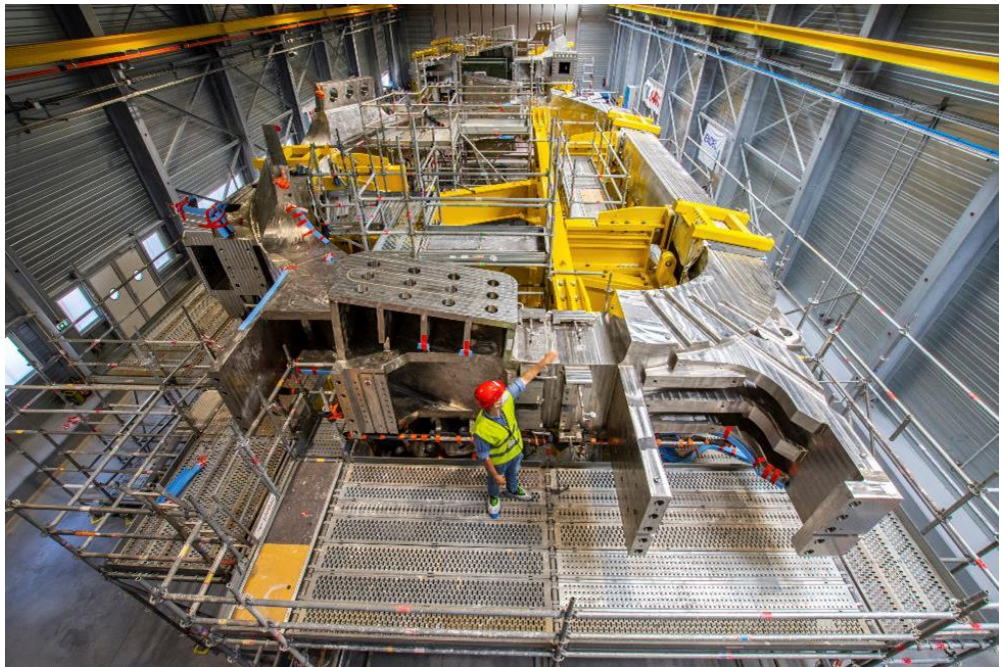
Vertical TF WP insertion (JA)

Completed TF Coils

Visible

- ❑ Terminal region
- ❑ PF6 flanges
- ❑ IOIS, IIS, OIS





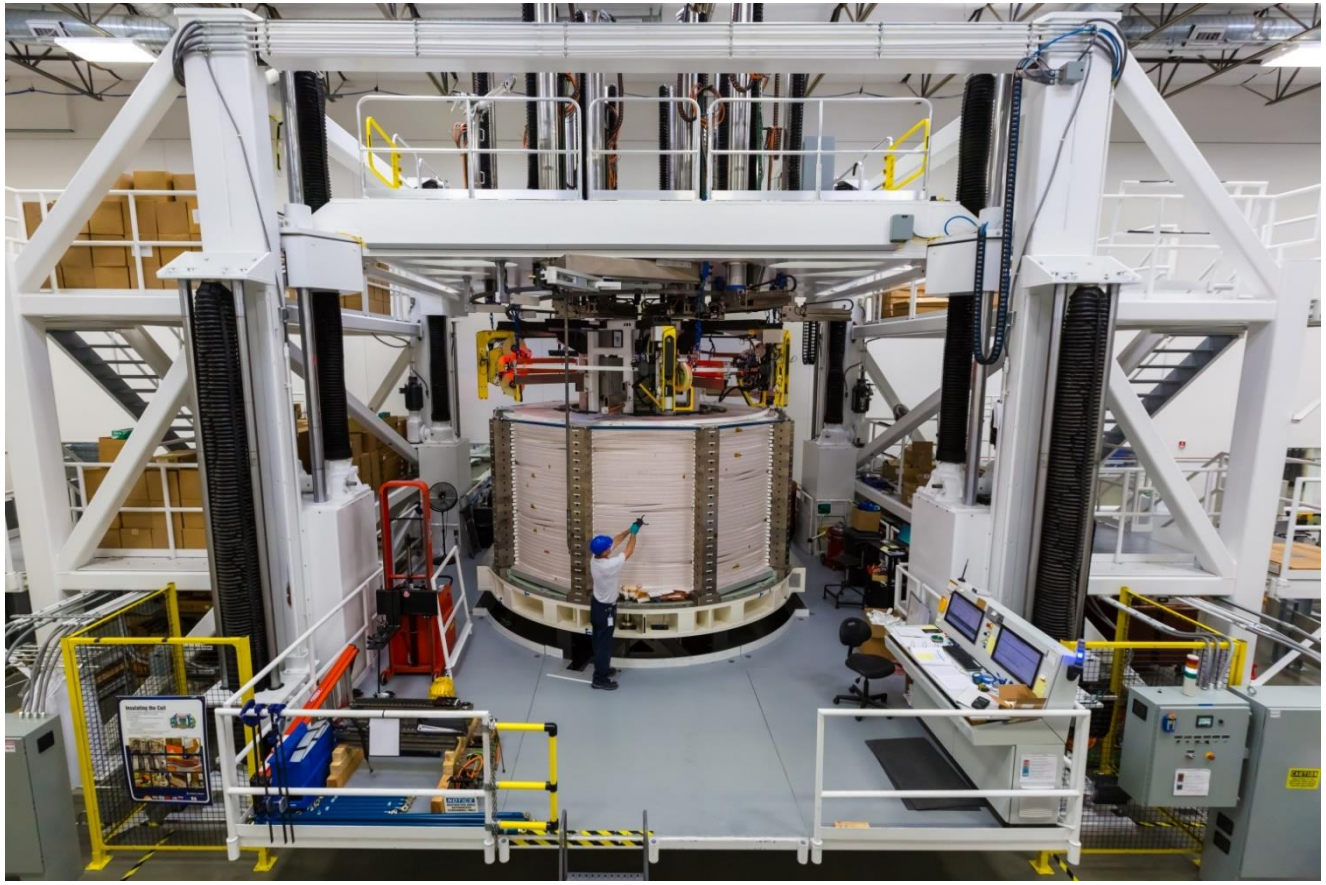
Feeder CTBs (SAT at ITER site and Fabrication at ASIPP+ suppliers Hefei)

Left: warm and cold ends of CC HTS lead

Right: S bends

CS Coil at GA San Diego

Left: CS module 1 on turn insulation station after heat treatment. Right: Module 1 entering mold (Aug 18). First resin impregnation in September 2018



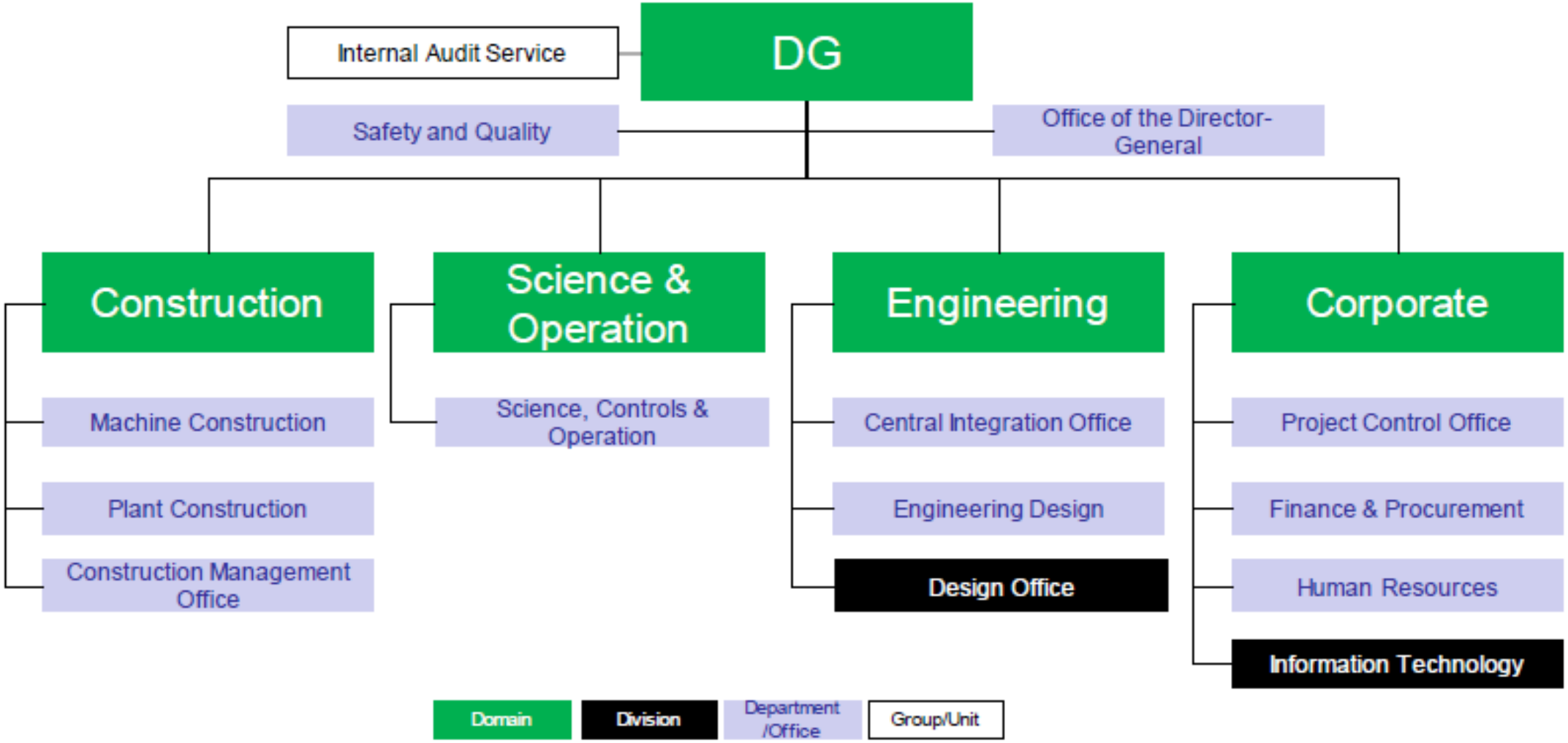
CSM2 before impregnation

Modules & conductor at GA plant

2019 Another Re-Organisation

Components (VV, Magnets, Buildings etc) no longer any organisational role, all lumped into Construction and organized by assembly step/contract

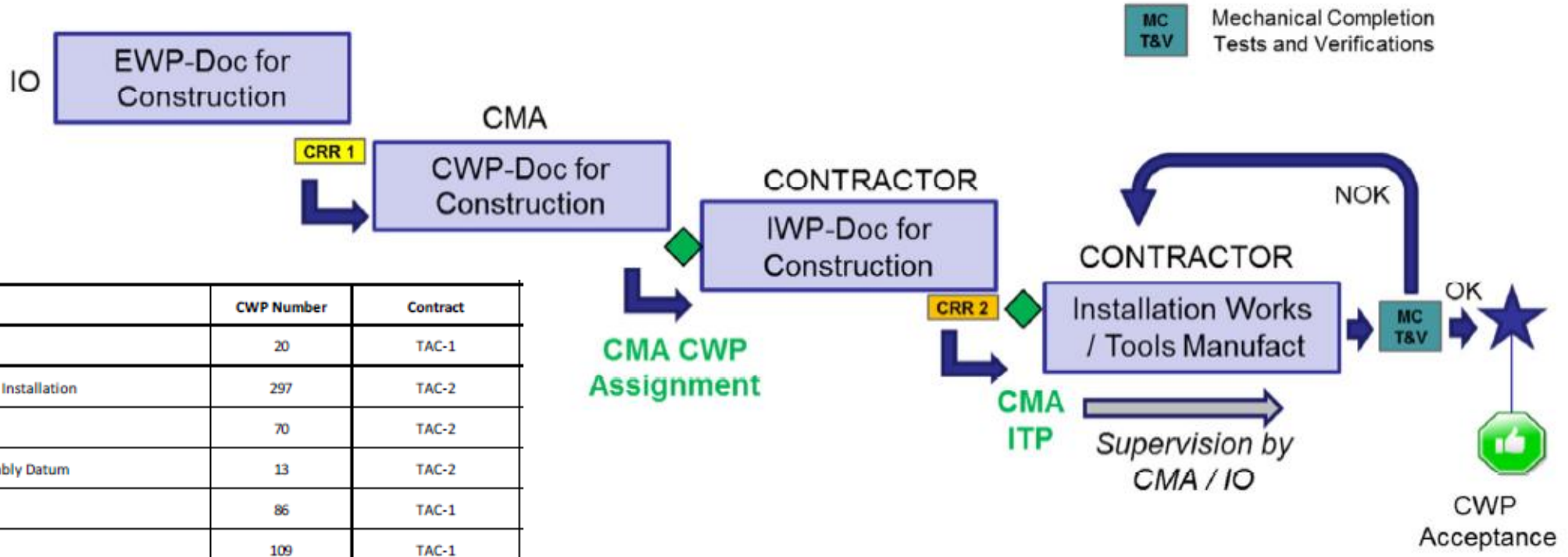
Compared to 2016, head of construction (COO) no longer has special role (replaced by "Domain Head")



Organisation and Specification of ITER Construction

- Grouping of Engineering Work Packages (EWP) and handover to CMA
- EWP prepared by Construction Team in close collaboration with IO engineering departments

- EWPs are the base of work execution, subdivided into Construction Work Packages (CWP)
- CMA and the contractor in charge of the development of Installation Work Packages - IWP



Scope Definition	CWP Number	Contract
A1 - Lower Cryostat Activities	20	TAC-1
A2 - Sector Sub Assembly and Installation	297	TAC-2
A3 - Sector Assembly	70	TAC-2
A4 - Establish Tokamak Assembly Datum	13	TAC-2
Feeders Installation	86	TAC-1
A5L - Ex Vessel Lower Region	109	TAC-1
A5S - Ex Vessel Side Region	155	TAC-2
A5U - Ex Vessel Upper Region	104	TAC-1
A6I - In-Vessel Assembly (First Plasma Scope)	155	TBA
A7 - CS and Cryostat TS Pre-Assembly and Assembly	32	TAC-1
	1041	

There are about 1000 “unique” CWPs for ITER Basic Machine Assembly

These provide the technical specification for the construction, as well as construction follow-up, price quote/payment, etc.

Teams per Area & Contractor Organization

Following teams were created for the Assembly of the Tokamak core machine:

Ex-Vessel Delivery & Assembly (EVDA)

All in-Cryostat activities (ex-Vessel) in the Tokamak pit

Contractor: Consortium CNPE (TAC-1) and Consortium CNIM/MAN (A0)

Sector Module Delivery & Assembly (SMDA)

Sector sub-assembly in the assembly hall and sector assembly activities in Tokamak pit

Contractor: Consortium DYNAMIC (TAC-2) and VV welding contract (ENSA)

Support to the Assembly & Installation execution by other entities like “Contract Management as Agent” (CMA) as well as by a Construction Management Office (CMO) and Machine Assembly & Integration for horizontal work arrangements.

- Site Coordination/Supervision/ Contract management support
- Assembly tools
- Metrology and as-built data management
- Leak & electrical check

© 2021, ITER Organization

WORKSITE

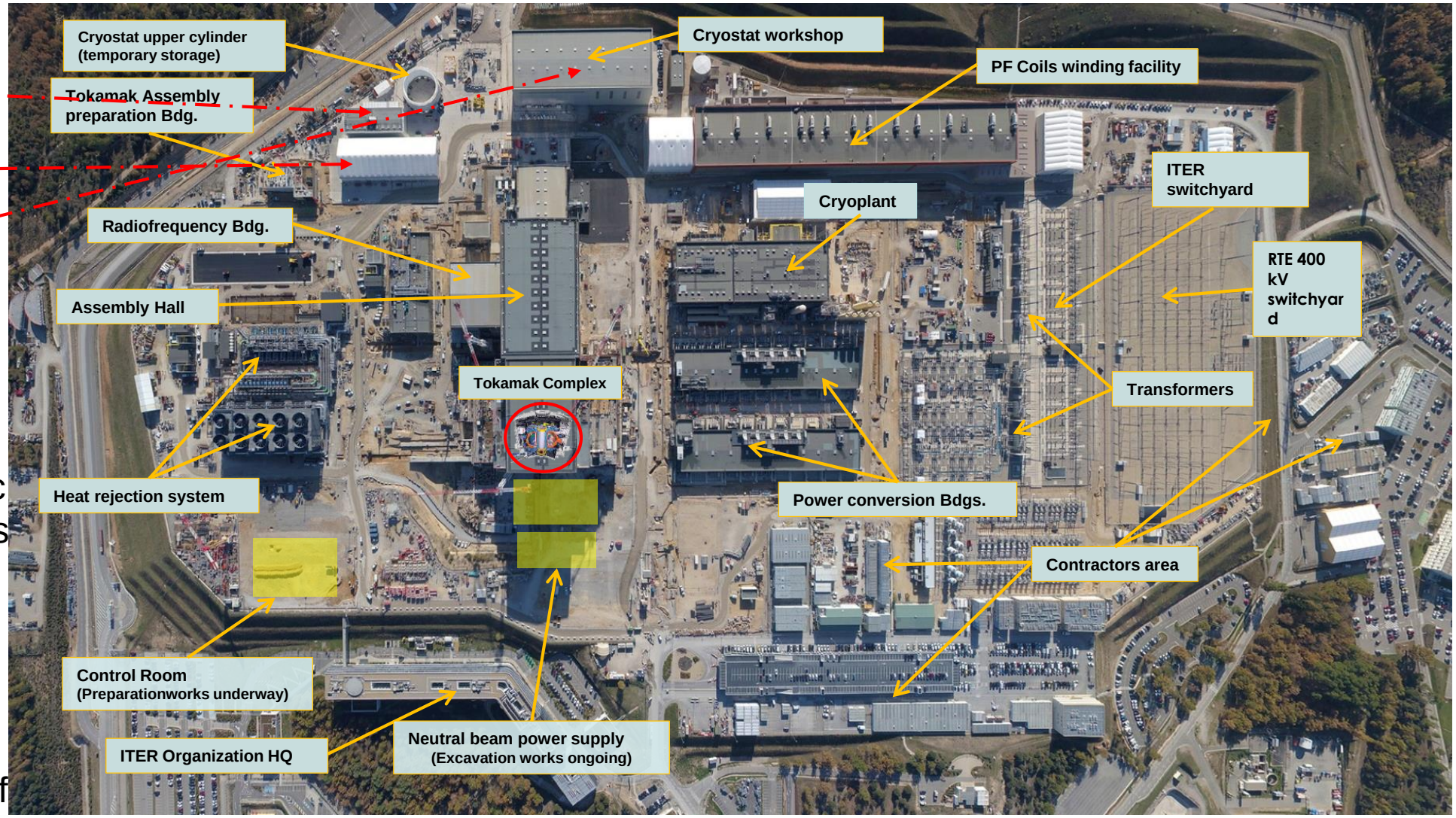
TF preparation

Feeder, CS SAT

Occasional tests

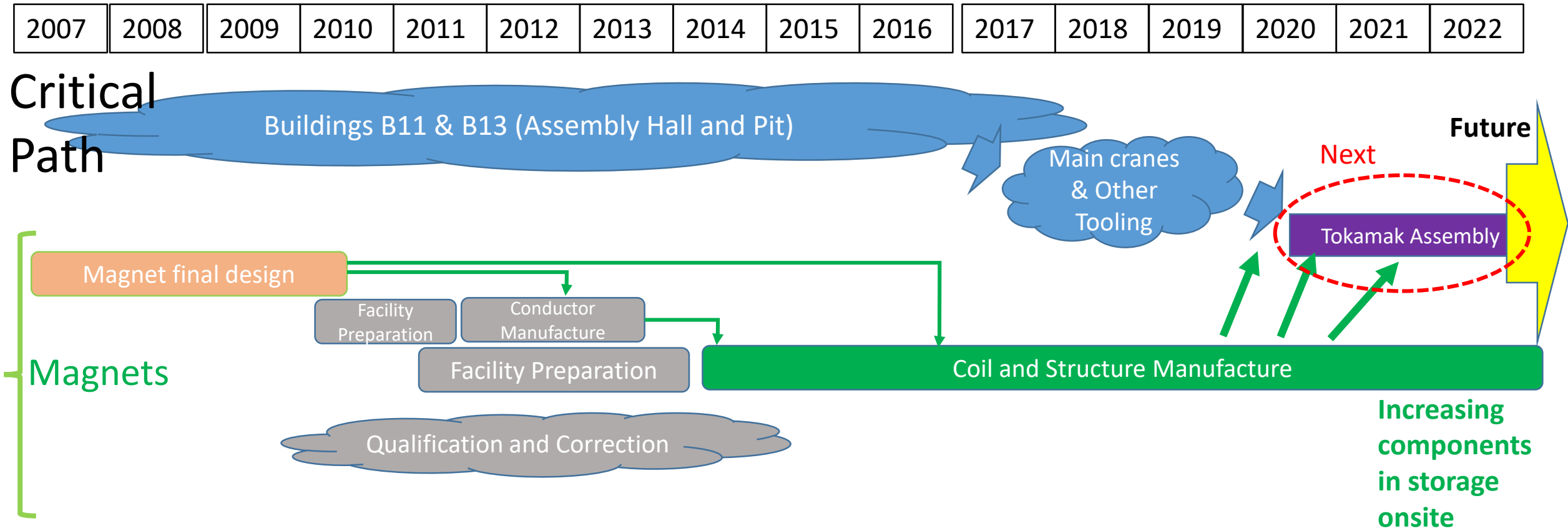
Site congestion is one of tokamak issues

- Tokamak complex is over occupied
- For magnet have ad-hoc use of adjacent buildings but these were only agreed in 2017 and arrived too late to be properly integrated in planning
- Lack of understanding of tokamak priorities by centralised organisation

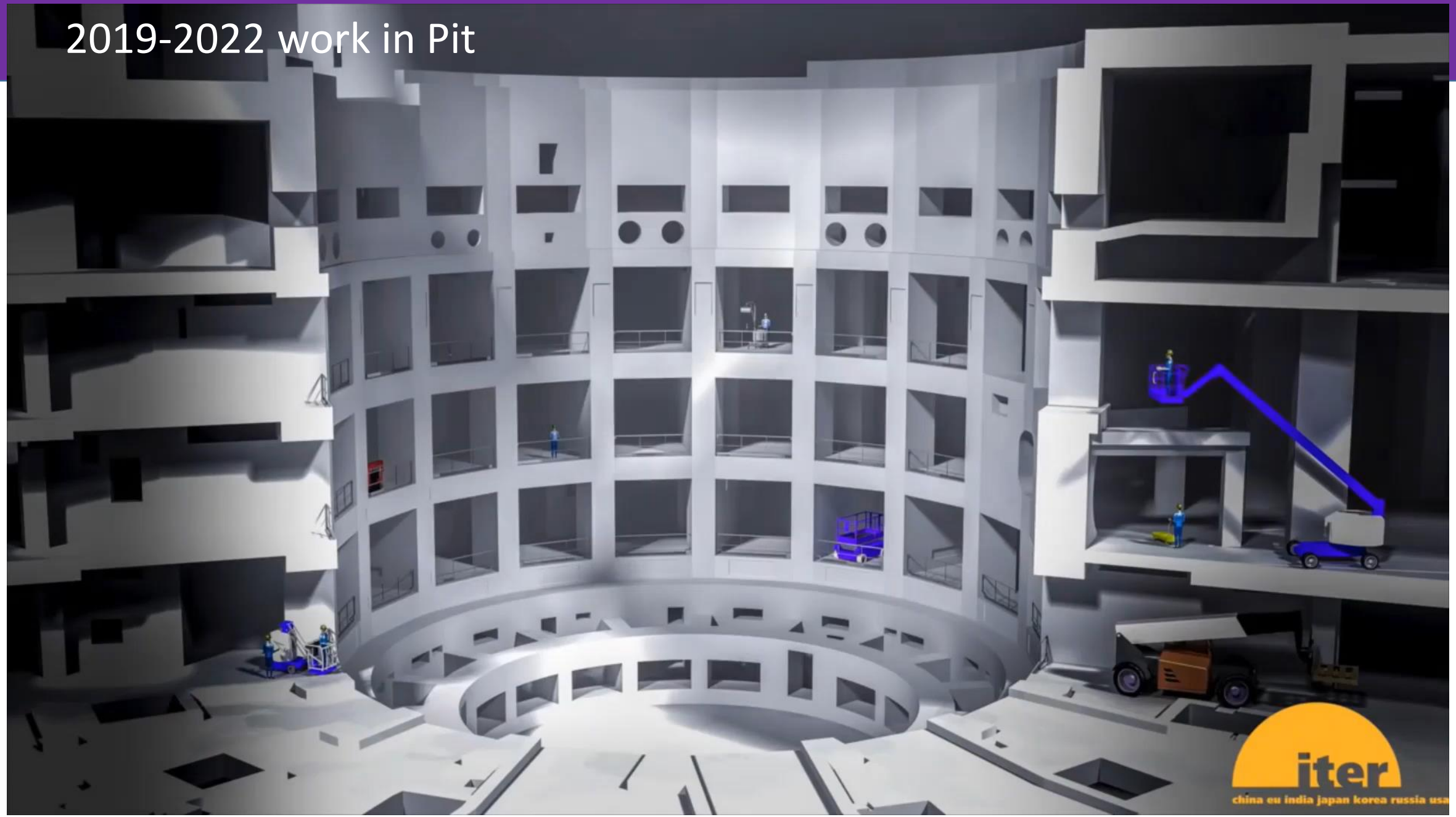


37 PBS SYSTEMS and 65+ BUILDING/AREA taken 2020

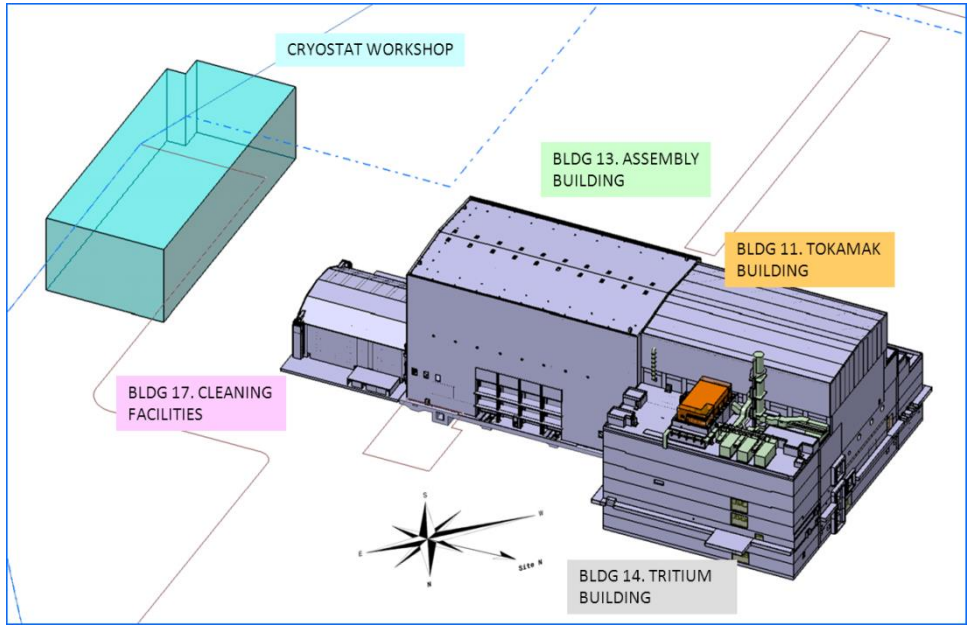
Assembly Onsite

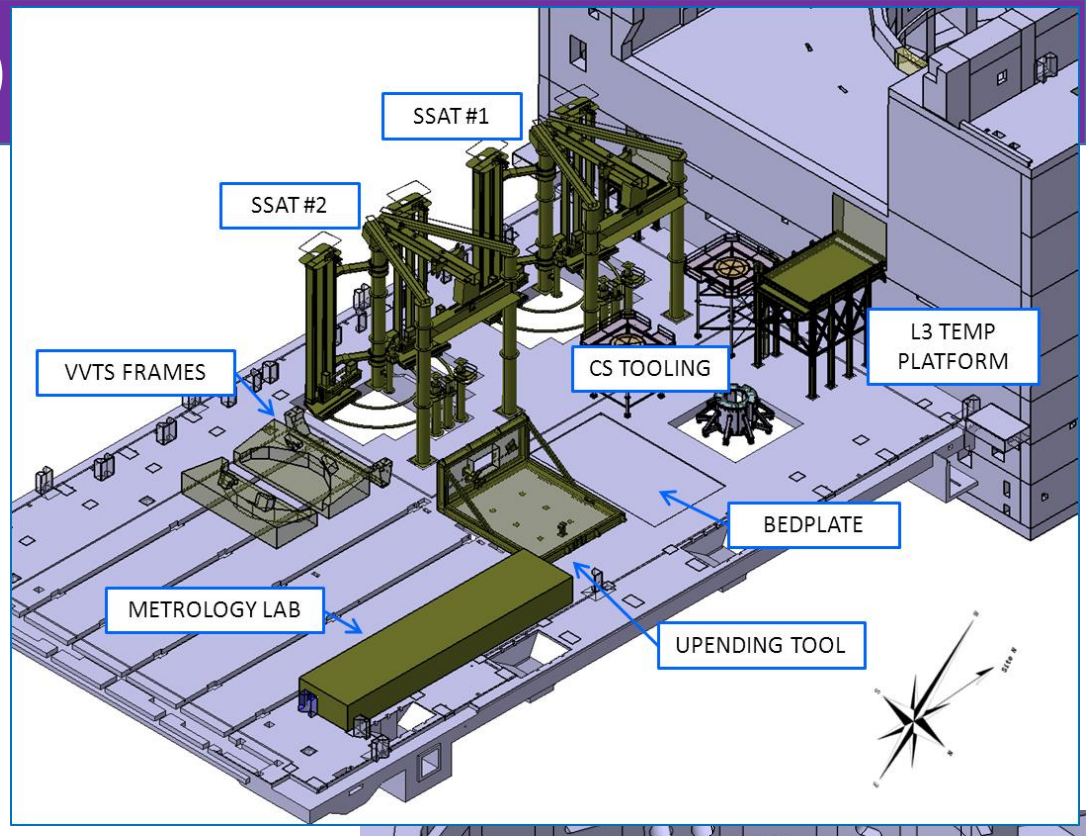


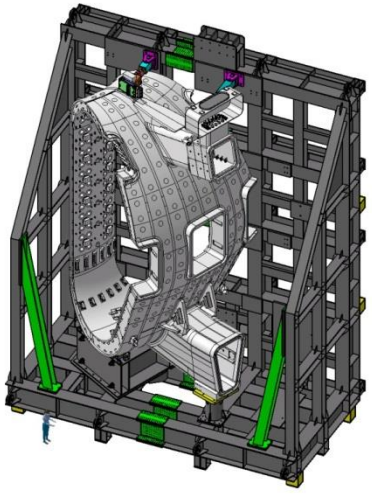
2019-2022 work in Pit

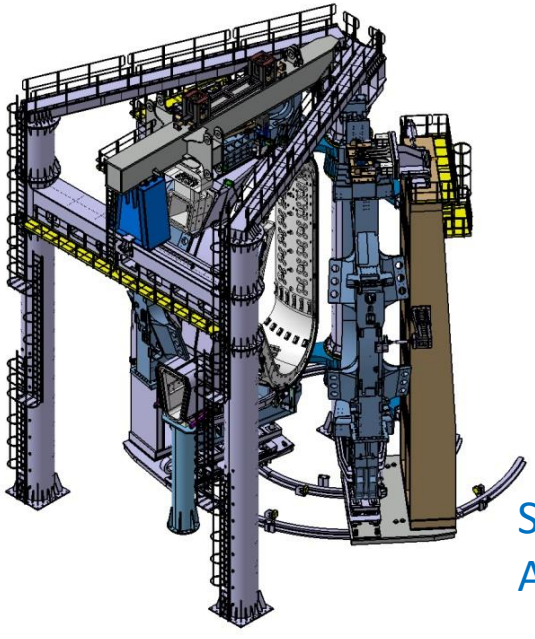


2019-2022 Work in Assembly Hall (Sub Sector Assembly)



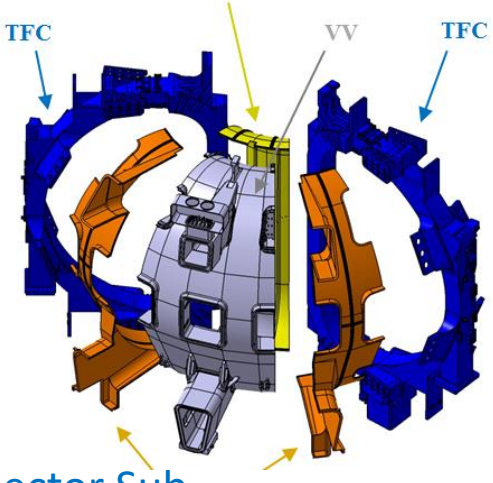




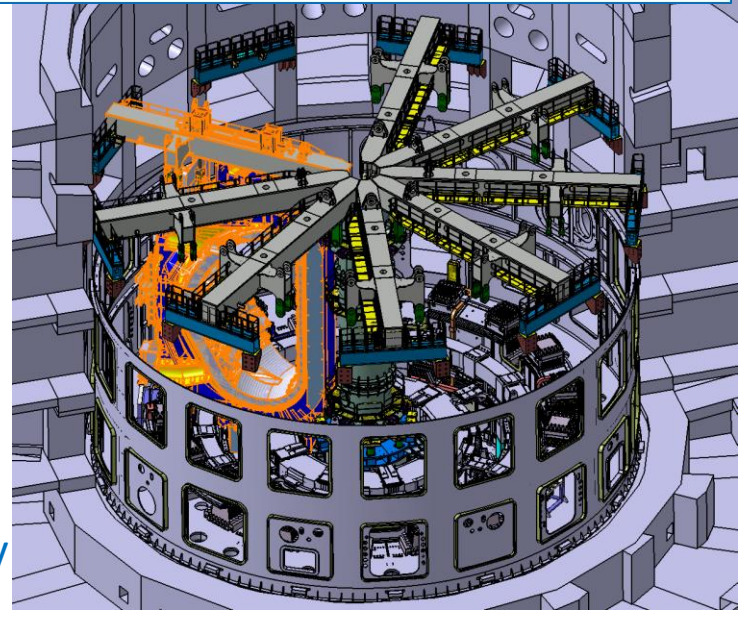


Upending Tool

TF and TS rotate over VV



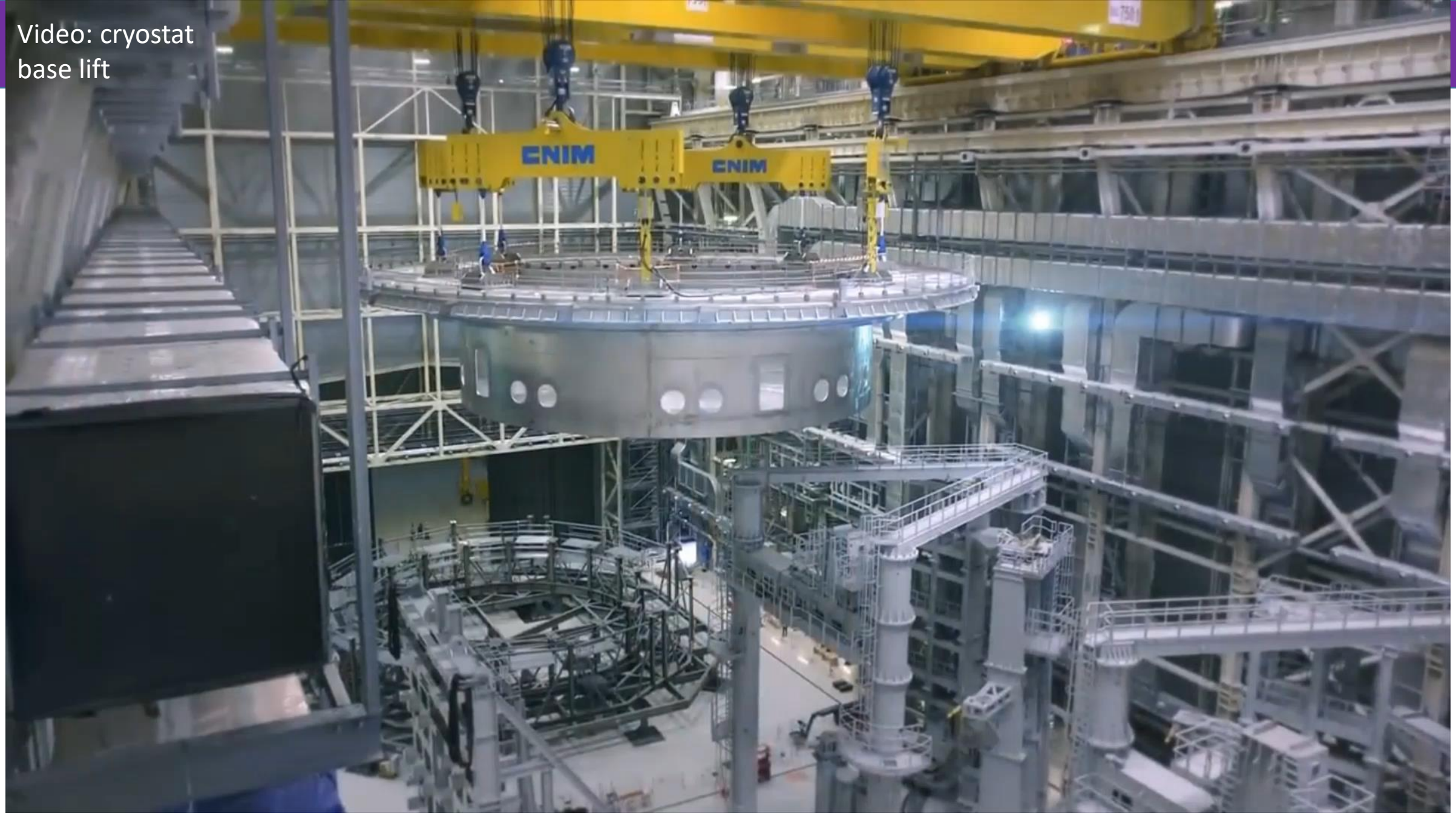
Sector Sub Assembly Tool



Sector Assembly

Pictures of 2020-21 Machine Assembly

Video: cryostat base lift

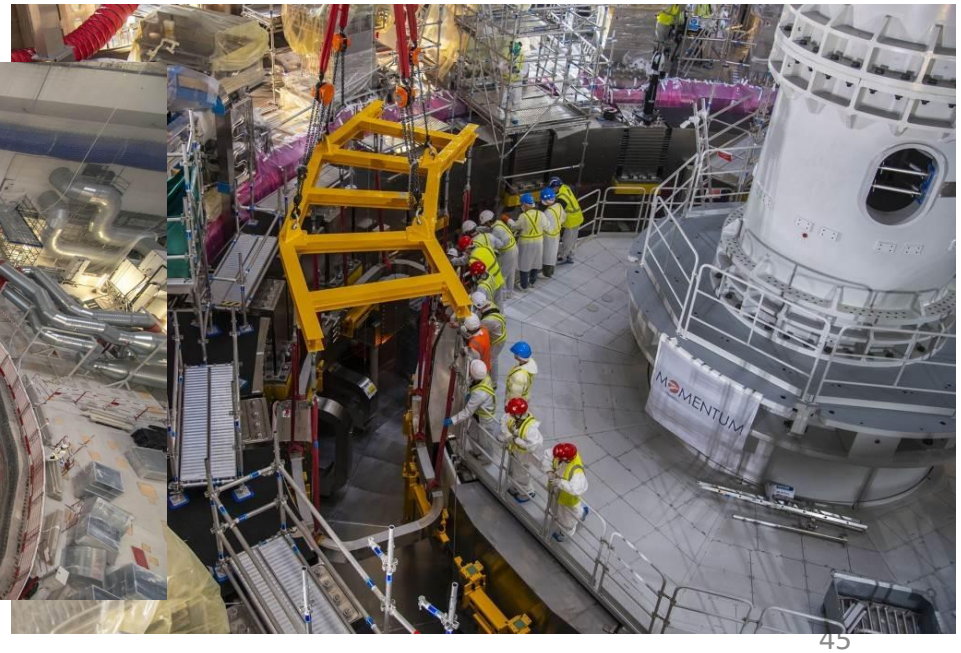


Video: Cryostat lower section lift

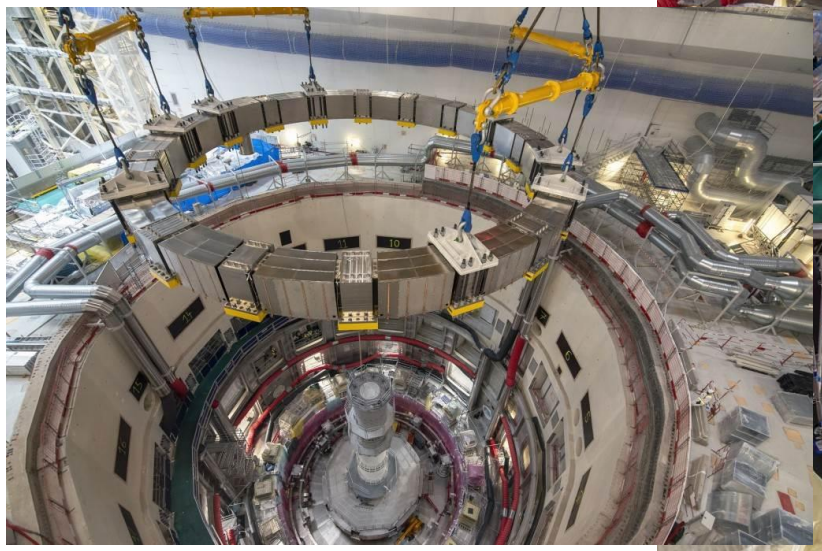
PF & CC Coils Entering Cryostat 2021

PF6

CC



PF5

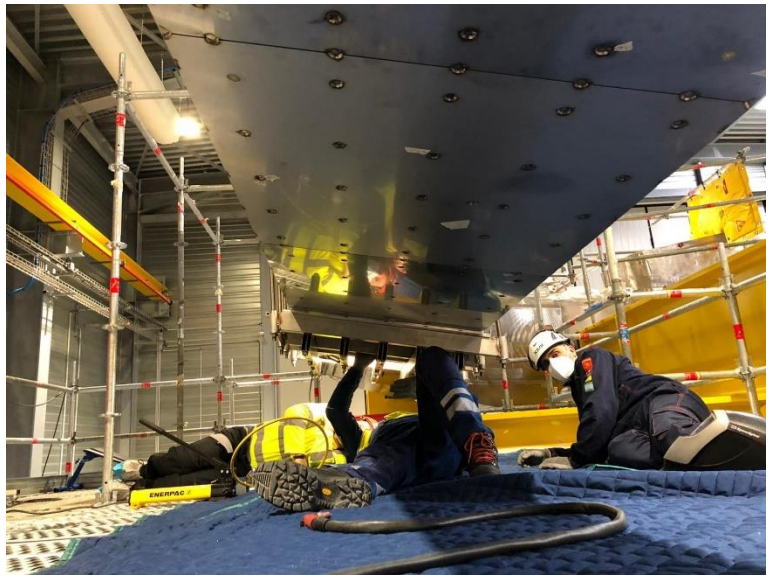


TF Pre-Assembly Preparation

Temporary building 73.2 available in 2019 after much pressure. Houses 2 TF coils under preparation prior to upending

Reception, unpacking, dimensional inspection

Initially facility managed by IO with TAC-2 contractor carrying out the work



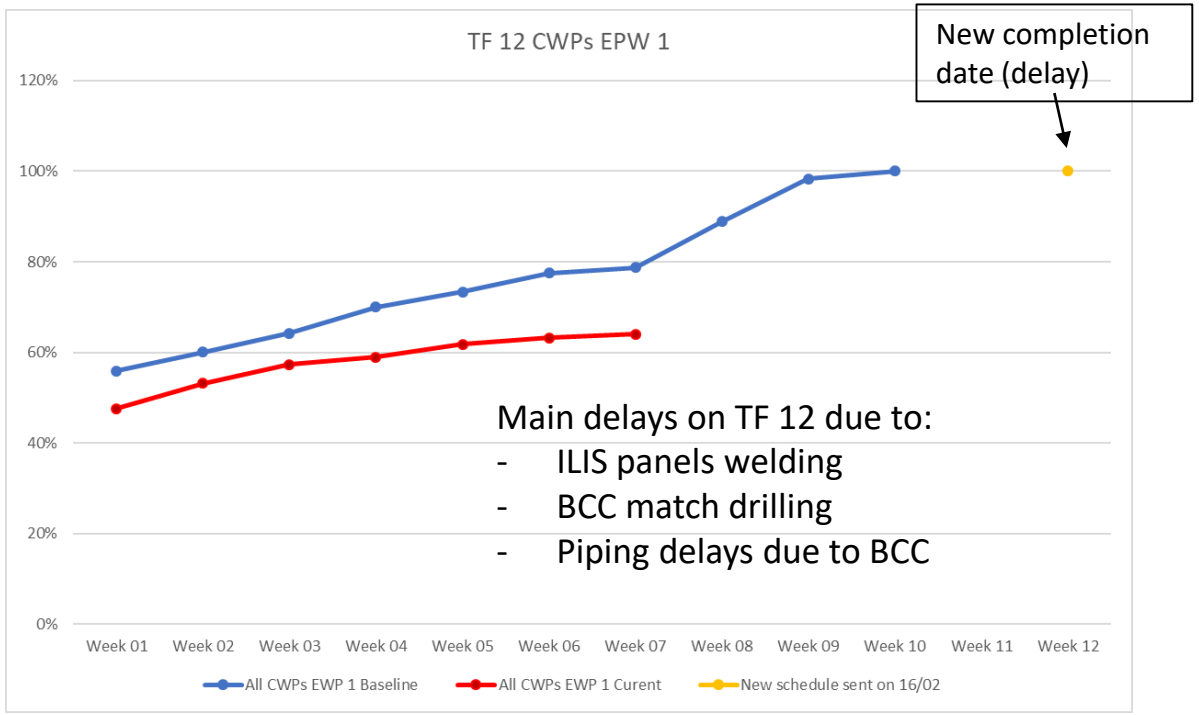
ILIS panel installation

Installation/weld of TF external cooling pipes

Introduction of Factory Mode for TF Preparation in Building 73.2

Original Organisation, First TF Coil

Based on DYN schedule issued on 16/12/2020

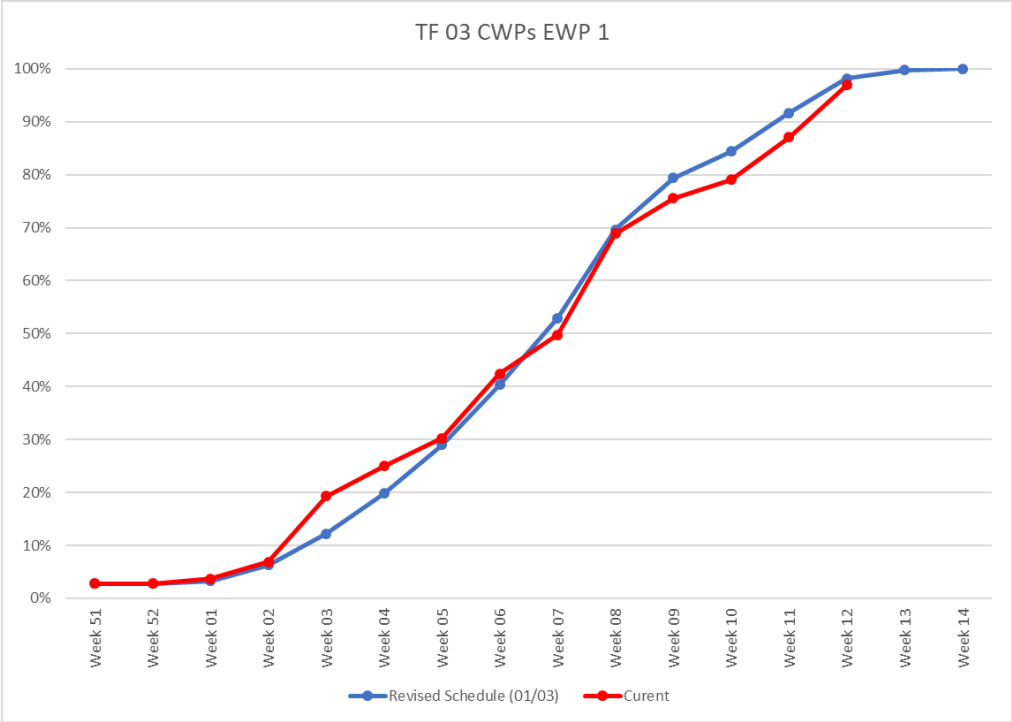


Main delays on TF 12 due to:

- ILIS panels welding
- BCC match drilling
- Piping delays due to BCC

Around 8 months in total

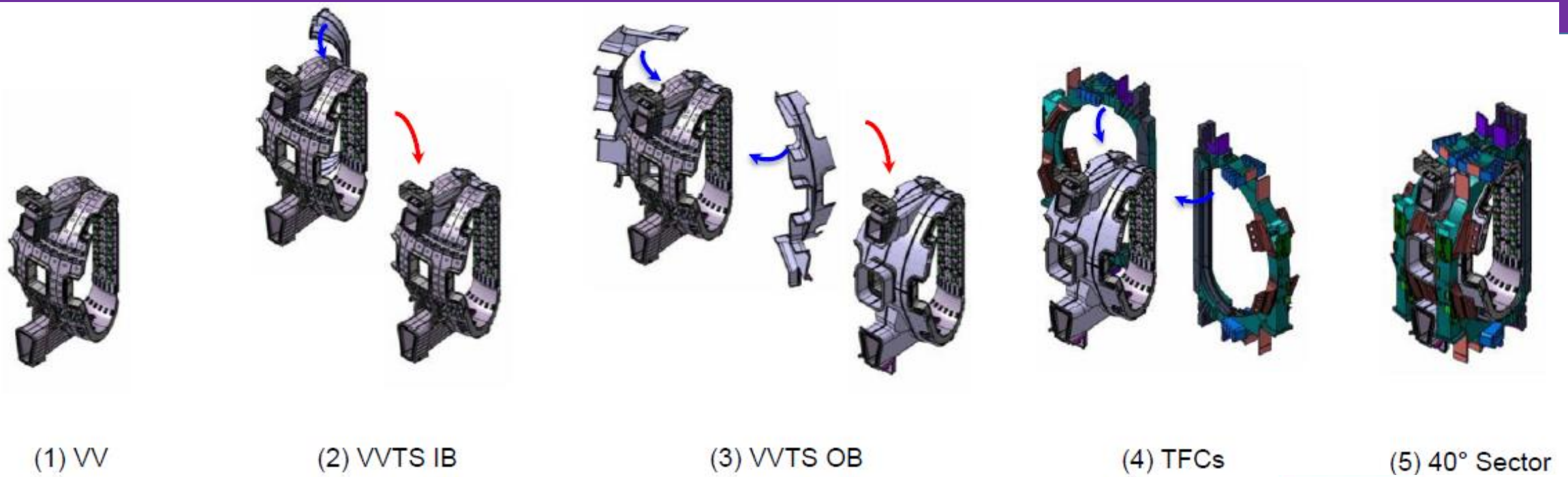
Factory Mode, 7th TF Coil TF03



Close to target of 3.5 months

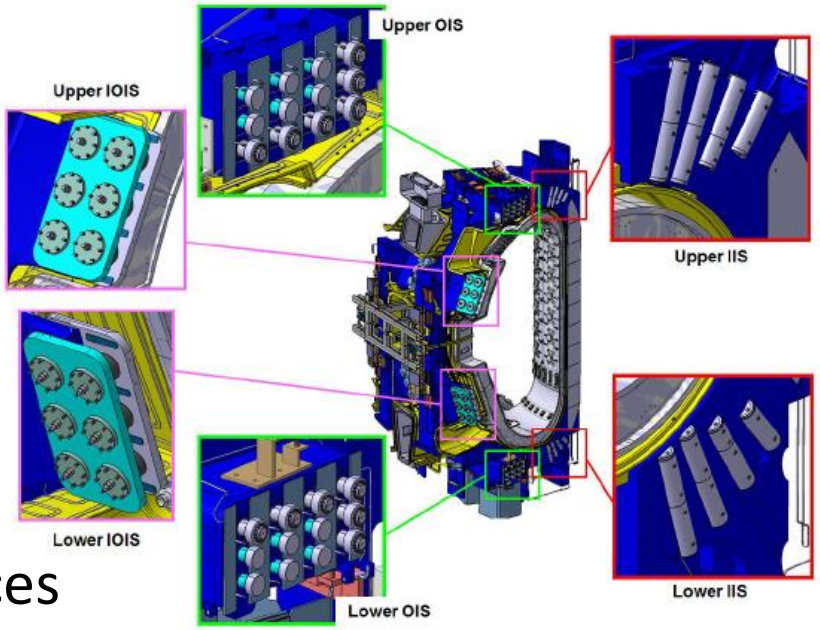
One way to significantly improve the situation with first TF coil was to assign the TF Coil preparation scope in B73.2 to a single consortium member to run the work in “factory-mode”, with other consortium members in a lead-follower arrangement, and called upon on as-needed basis. SIMIC was the member of the consortium that has demonstrated the capacity to perform the TF coil work with the best level of preparation. Basically, B73.2 turned into a factory which is a seamless continuation of TF coil manufacturing. Decouple its schedule from B13 (TF prep not a bottleneck)

Steps in Assembly of 1/9 Sector including 1 VV sector and 2 TF coils



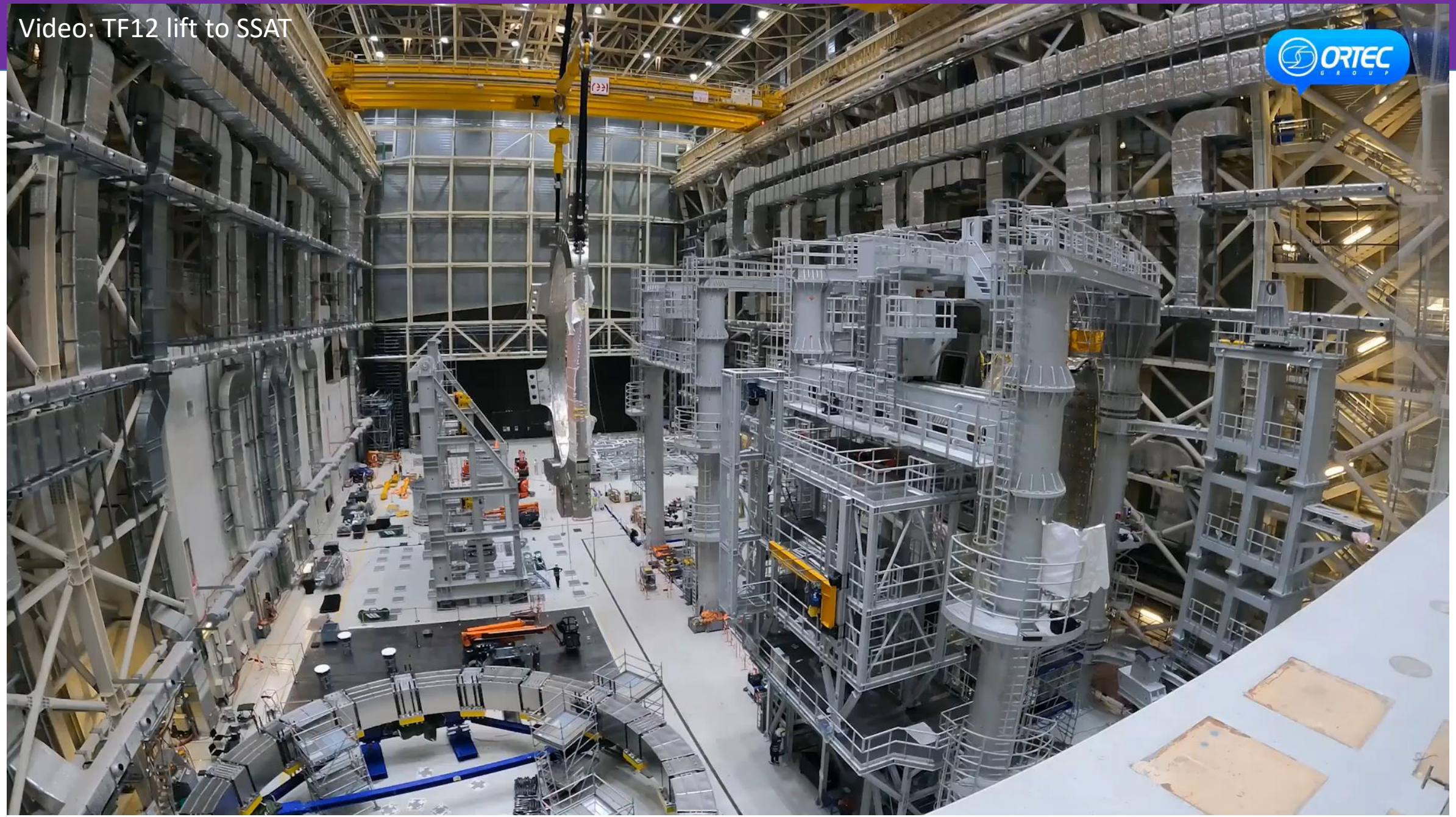
SSAT adjustability: Radial: ±0.2 mm; Vertical: ±0.2 mm;
Inner/Outer toroidal: ±0.2 mm
Weights: Each TF 320t, VV 420t, Thermal Shield (TS) 40t

Most critical alignment is the inner leg 'wedge' with a gap of 0.5-2mm



TF-TF Interfaces

Video: TF12 lift to SSAT



TF alignment In Sector

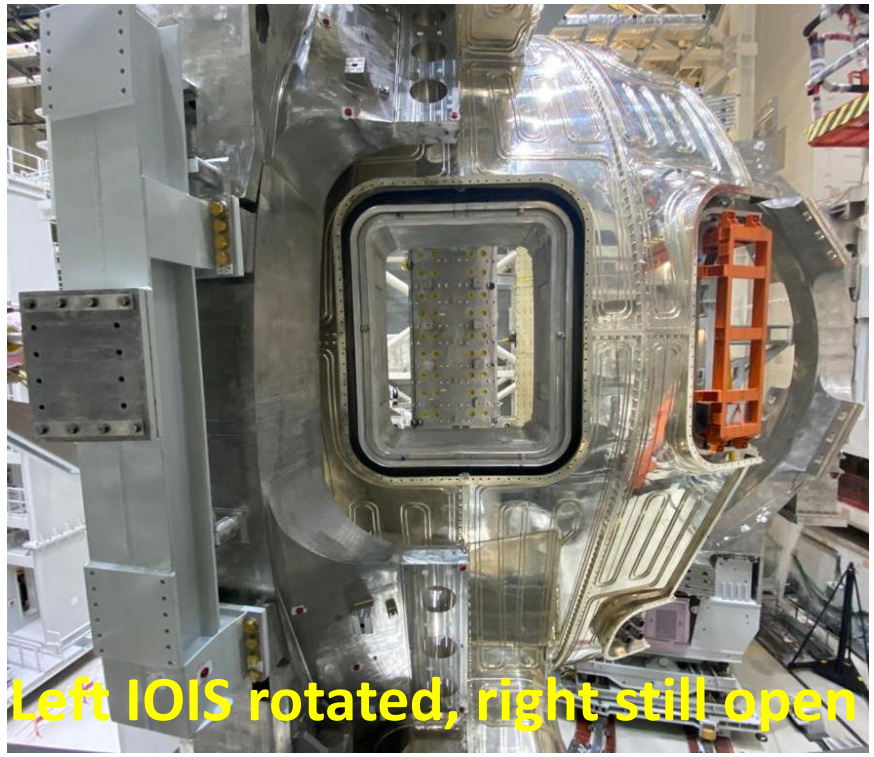
Alignment accuracy is critical for plasma error field control and also so that the inner legs of all 18 TF coils will fit without interference

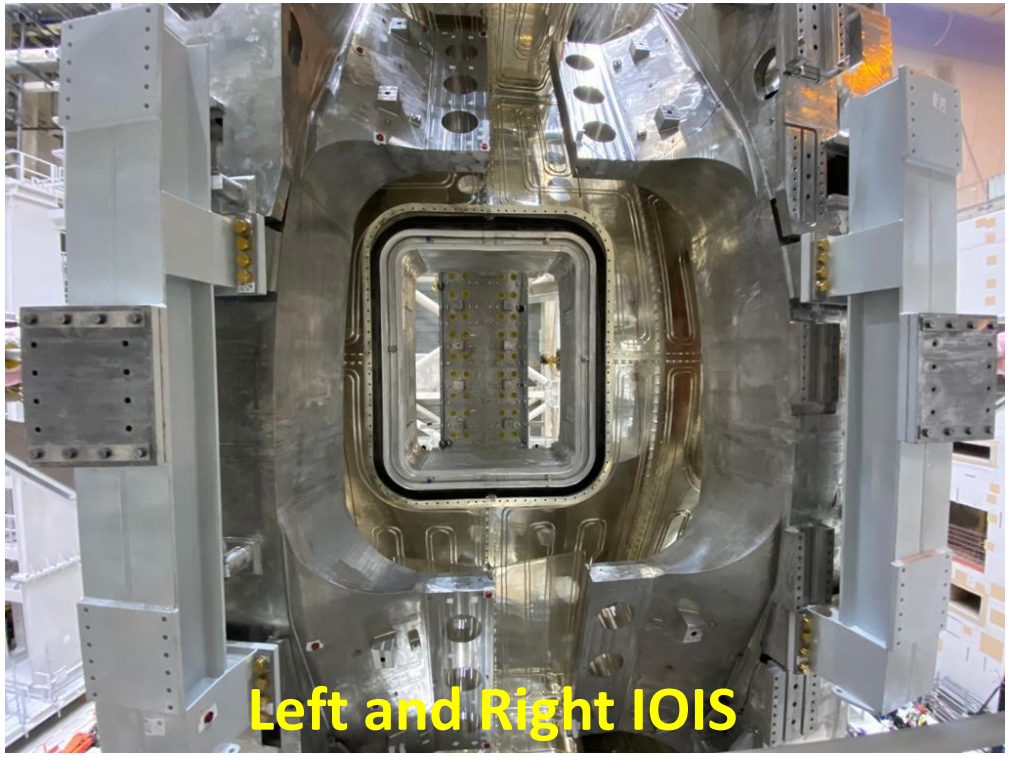
Example of diffuse responsibility, with multiple, not well-coordinated players involved. Technically successful, but slow

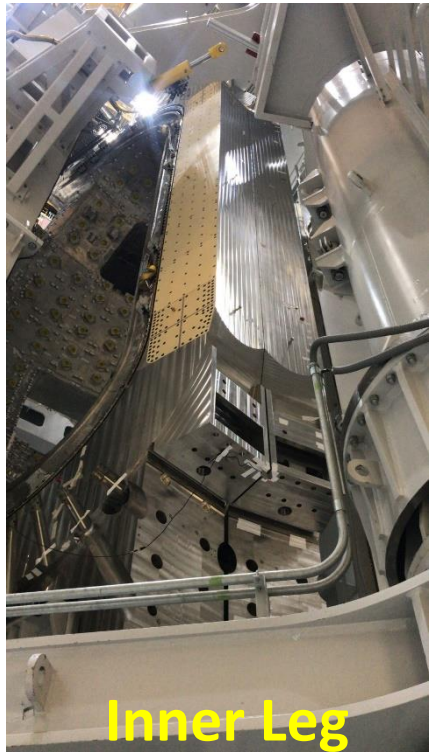
One sector so far aligned

- Tolerances achieved
- Concerns about mechanical stability during lift (mostly due to the fact that to "save schedule" not all intercoil structures connected – in the end, irrelevant due to other delays

TF coil rotation and alignment



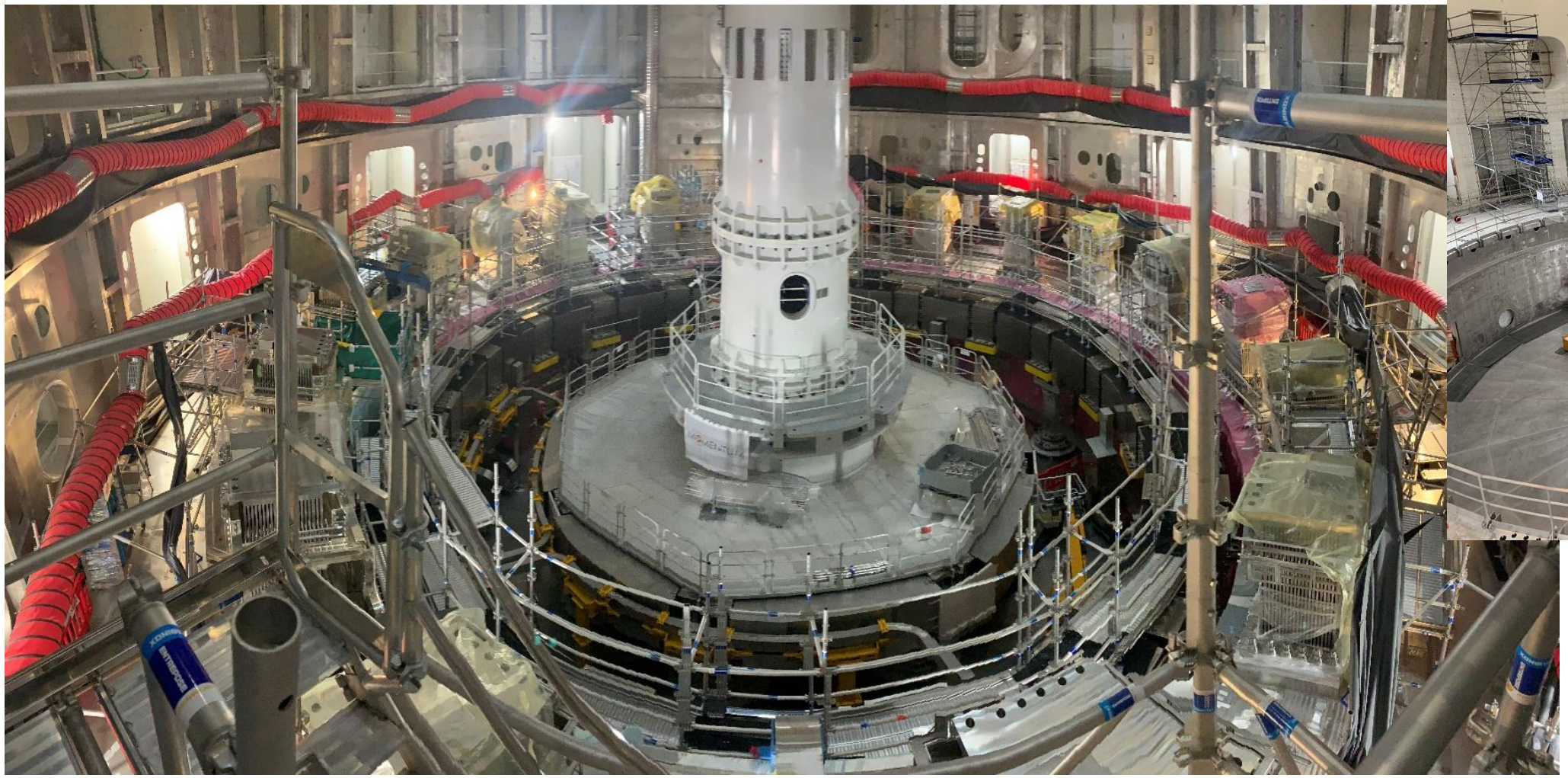




Picture of in-cryostat changes over 15 months

PF and CC components are in ‘parked’ position until TF installed

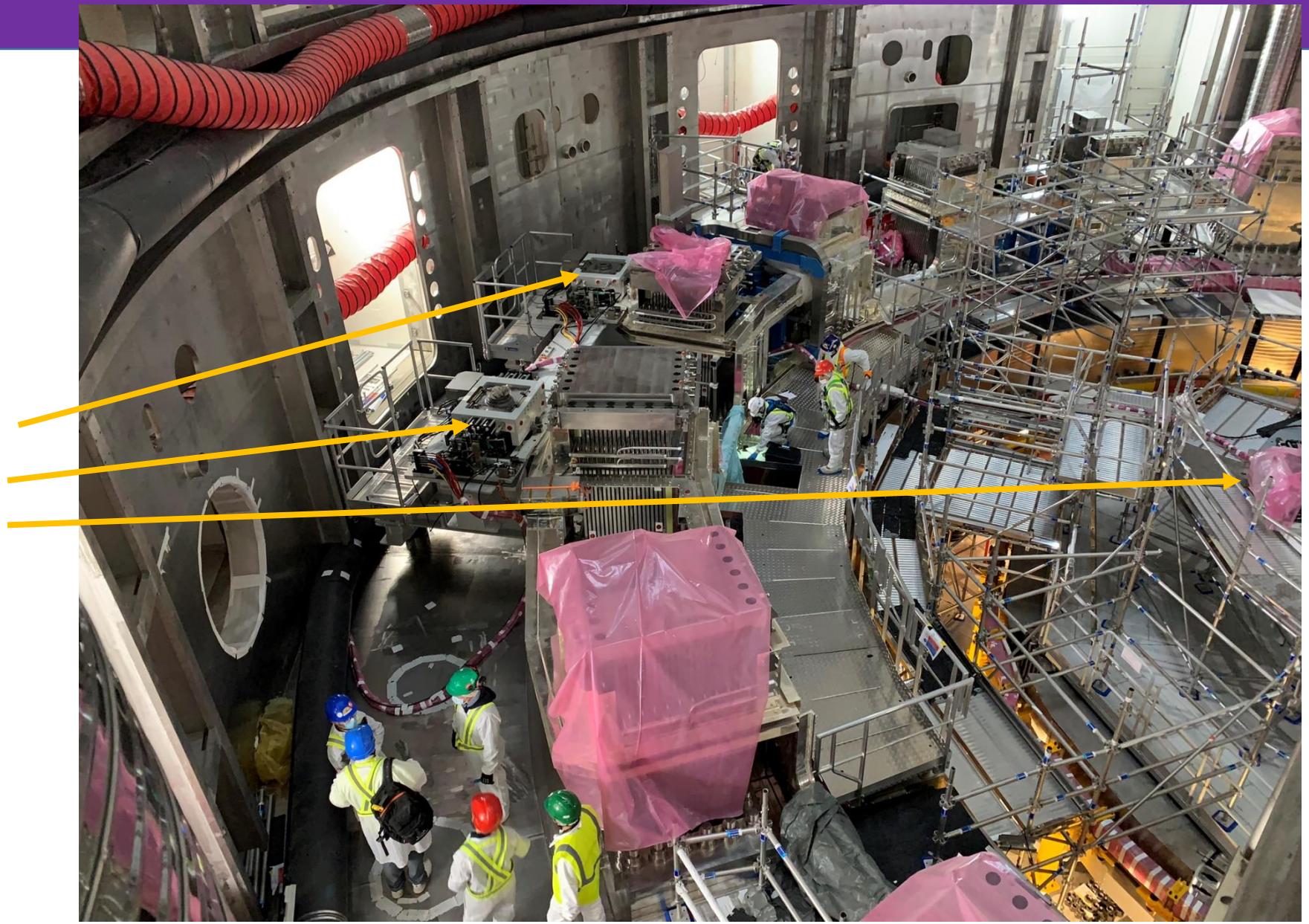
Nov 2021



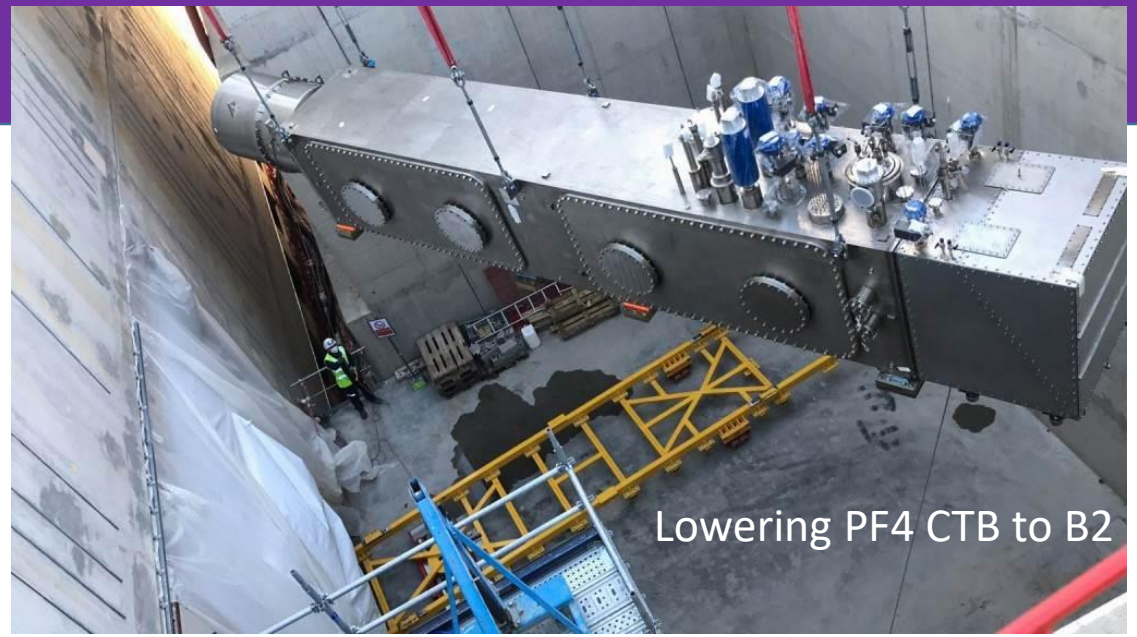
June 2020

Sector Installation in Pit

Pit and TIPI units (for position adjustment of TF coils) ready for Sector 6 lowering March 2022



Feeder Assembly


Lowering PF4 CTB to B2

Preparing first feeder joint T12/13 CTB to CFT

CTB & SVB on B2

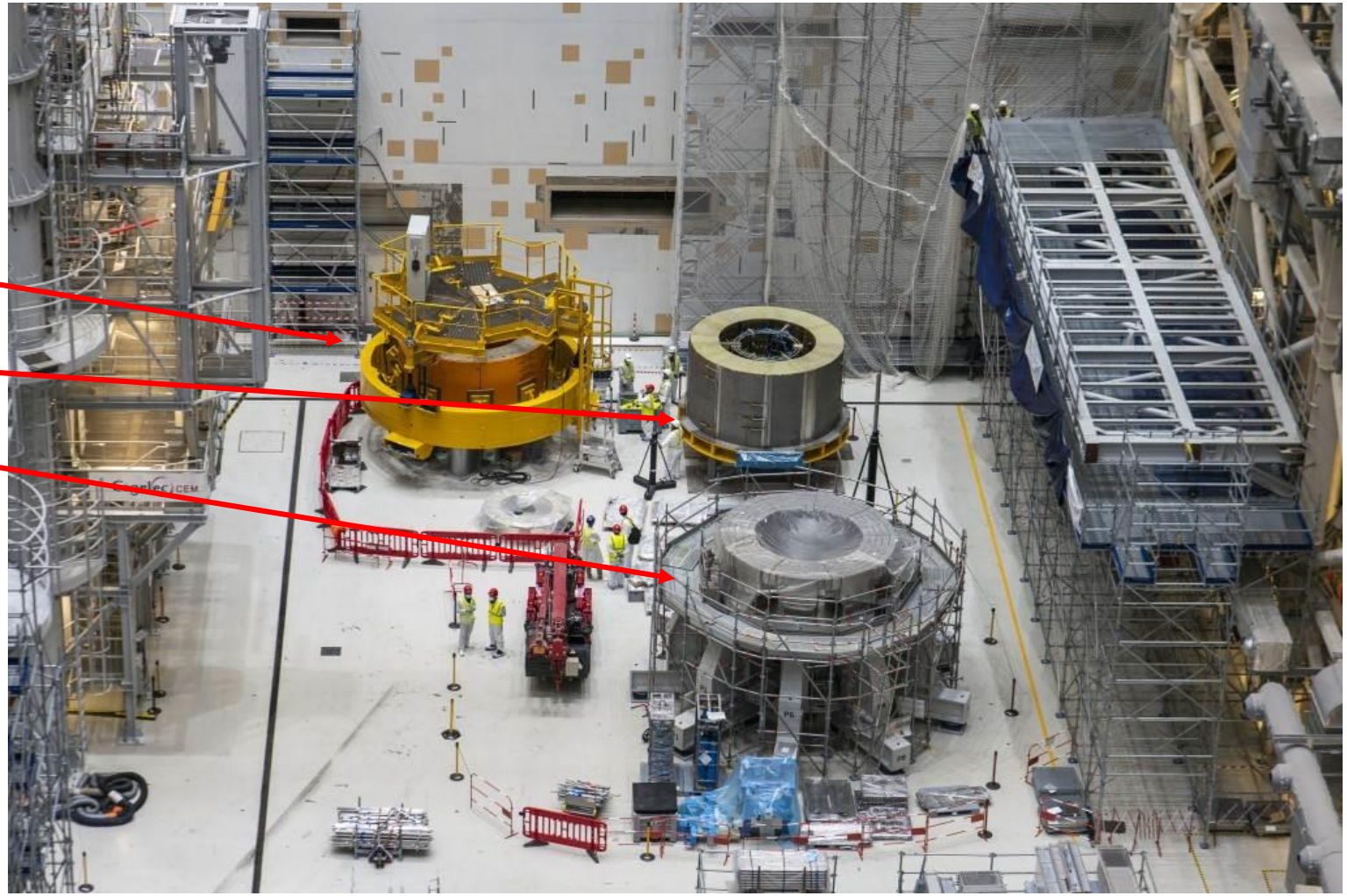

CFT in position at L3

CS assembly area

CS Lifting Tool

CS Module 3L

CS assembly platform and keyblocks

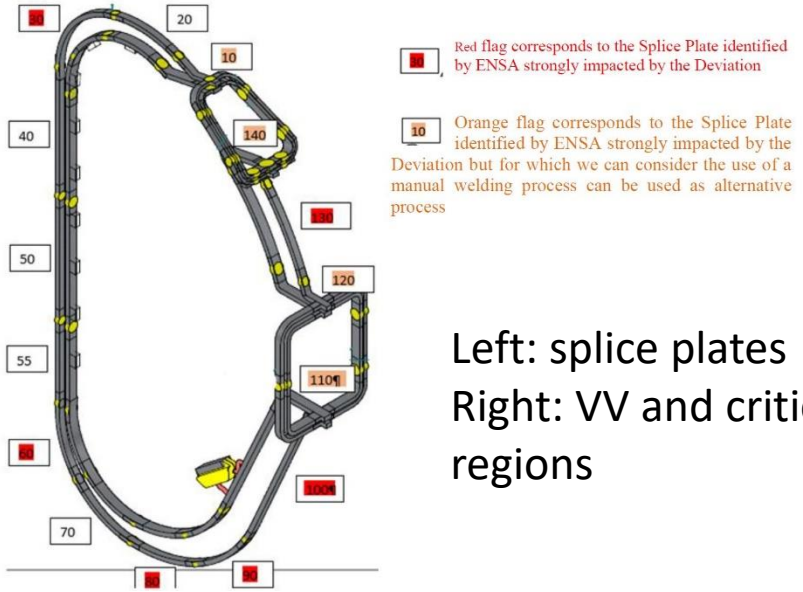


Two examples of Recent Major Quality Problems with Delivered Components (2022)

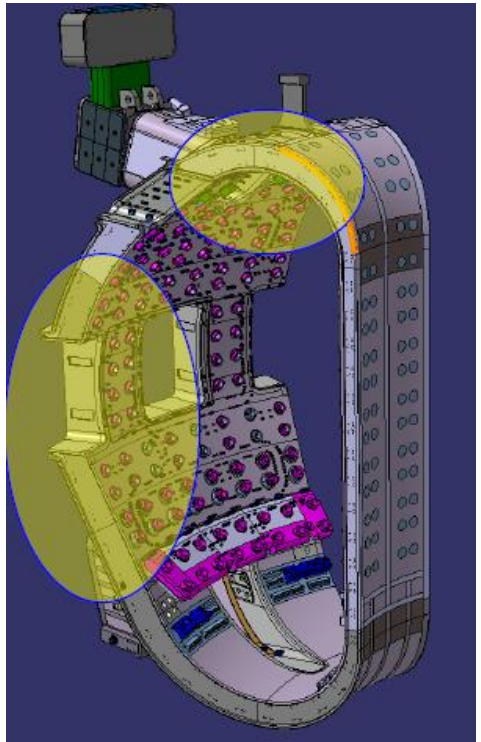
VV bevel out of tolerance (ASN issue)

VV 9 sectors joined by welding inner and outer shells in pit

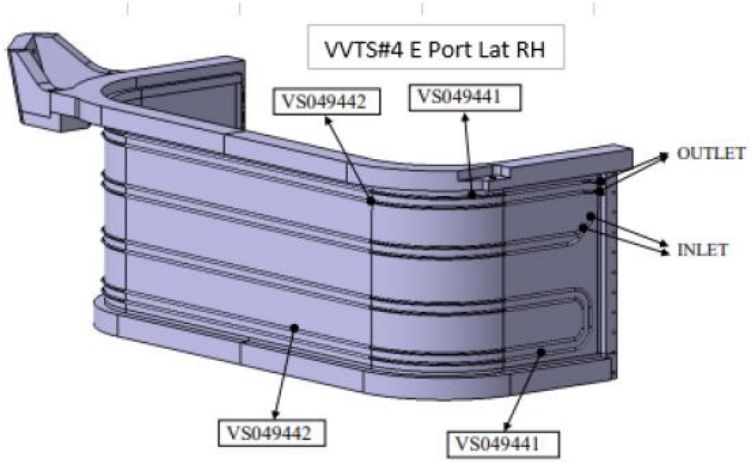
- Between 2 sectors there is a splice plate
- Multipass weld that was intended to be automatic and was accepted by ASN on this basis
- Now root pass at least has to be manual, new qualification needed and new welding contract



Left: splice plates
Right: VV and critical regions

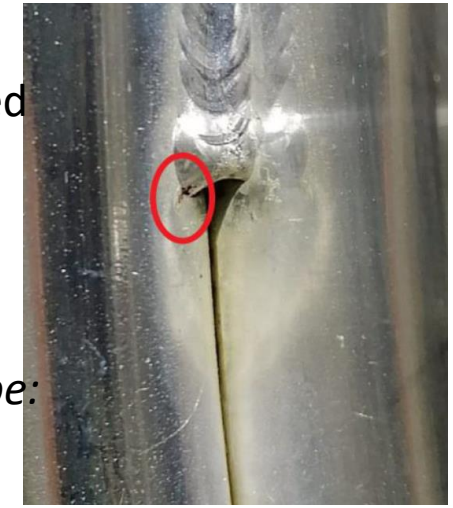


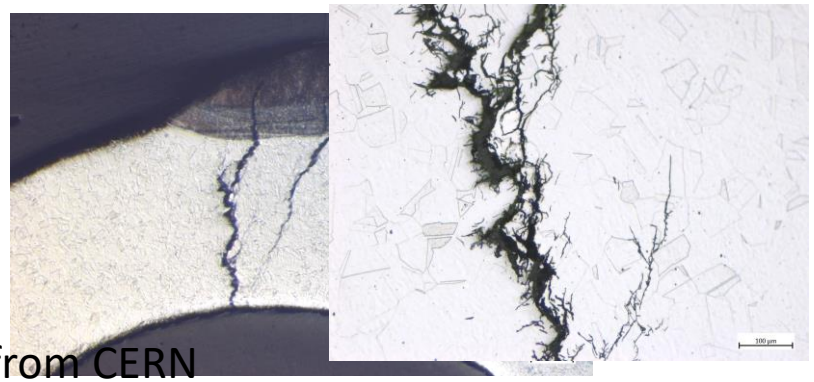
VV Thermal Shield Stress Corrosion



Transgranular branched crack

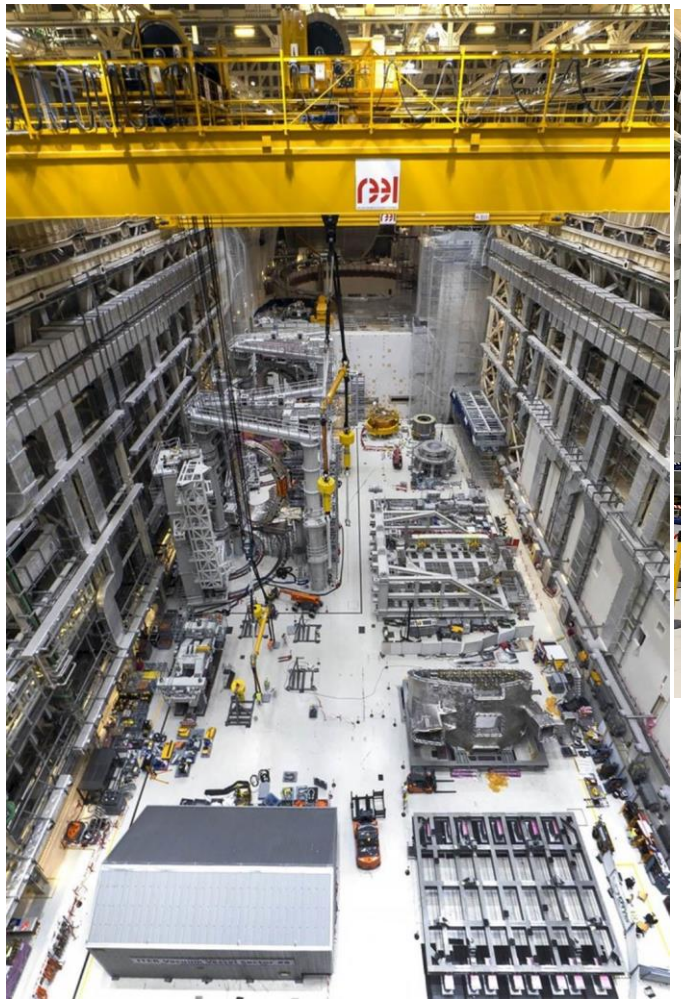
- Stress corrosion cracking caused by poor rinsing of process chemicals containing halogens and stress induced by weld shrinkage.
- *Concern how widespread can be: 3 occurrences found by leak checks*





Pictures from CERN

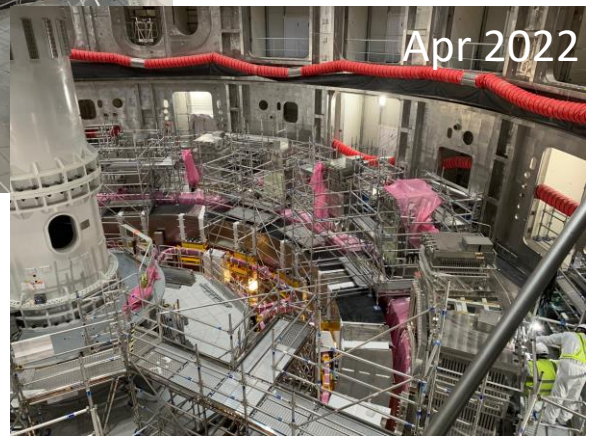
Problems encountered during assembly with *organizational* root cause (3 examples from many)



April 2022

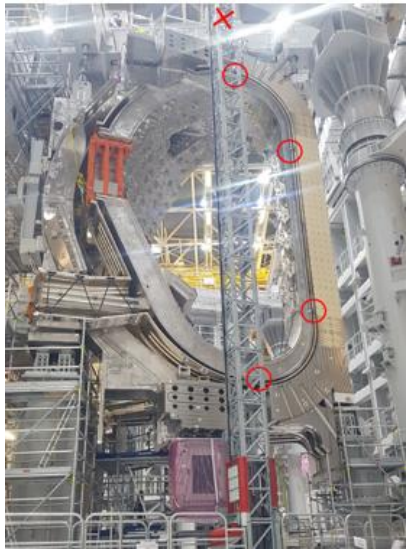
Back SSAT has customised access platforms, front has scaffolding

Scaffolding only being designed now!



Pit scaffolding resting on coil protection covers (high risk to HV components). Removed Feb 22, put back Apr 22!

Large debris between TF coils, TS and VV…largely inaccessible
Also metallic debris
April 2022



Despite Impressively Large Technical Progress, Gradual slippage of Baseline Assembly Schedule during 2019-2022 period

Looking at the 2015 schedule, 2 milestones illustrate the slippage

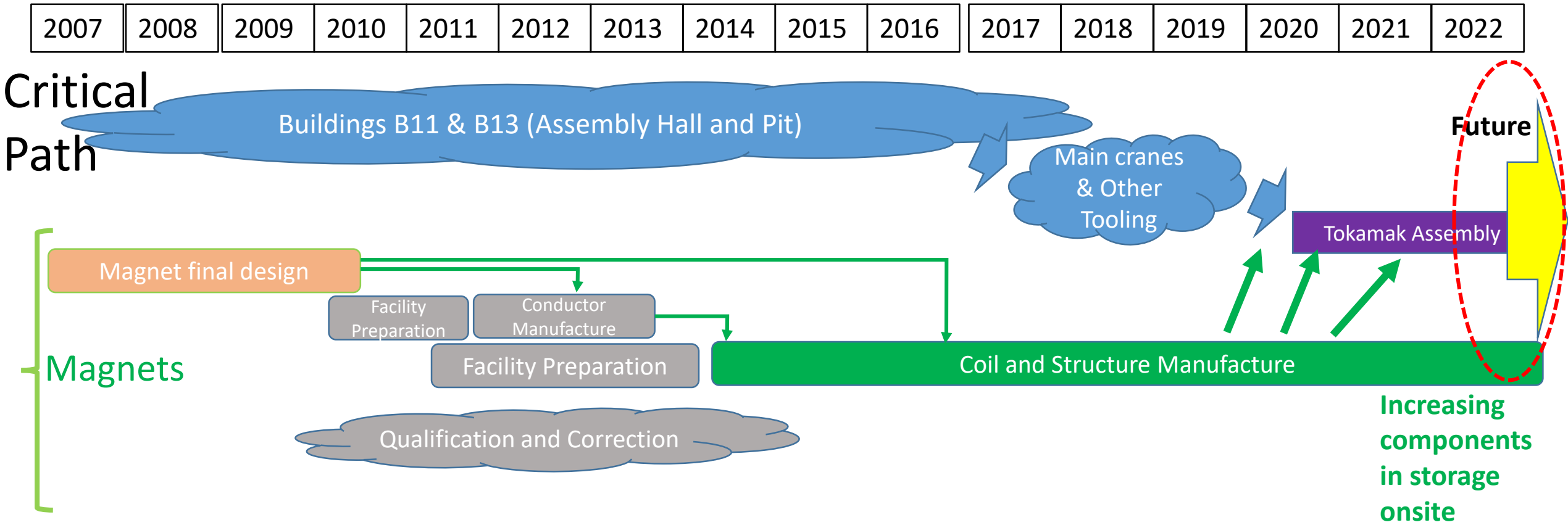
- Cryostat base installation due ~q1 2019, actual q2 2020
- First sector in pit due ~q1 2020, actual q2 2022 (and some work de-scoped from SSAT to Pit as well)

Latest schedule shows close to 4 years delay, **difficult (with IO history) to present this as stable**

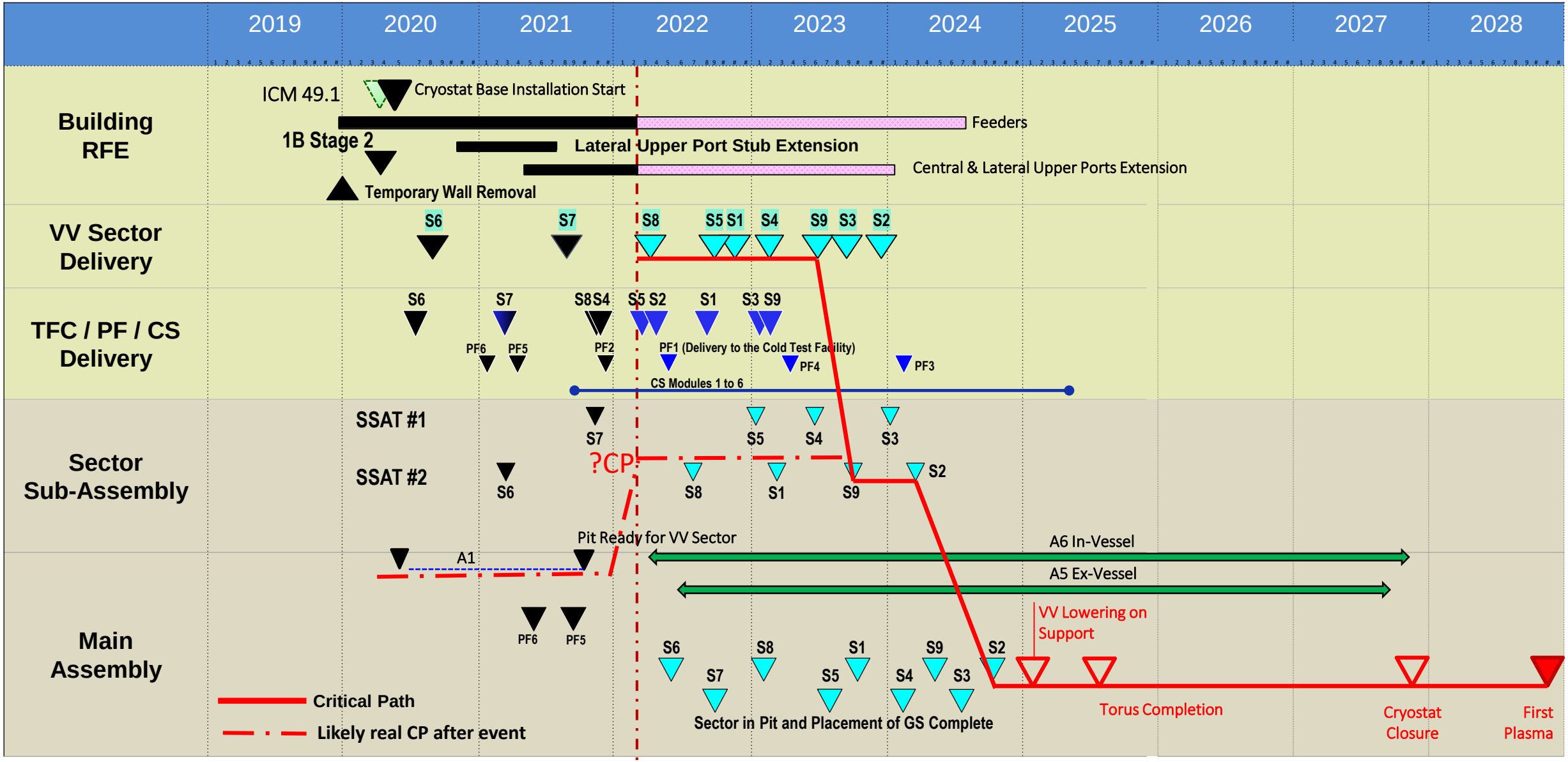
Cost overruns are becoming significant (> 50%), and often not reducing after FoK is passed

Overall, assembly is ~ 8% complete. Large components are being prepared and brought together in the Assembly Hall and Pit. However the installation of these components (VV welding, TF inter coil key installation, feeders, PF coils) has yet to start, and this installation work is complex and carried out in a difficult environment; while manufactured large components continue to arrive onsite with limited and inappropriate space to store

Where do we go from here? (and how)



C-DWS Ref#8.2: Critical Path



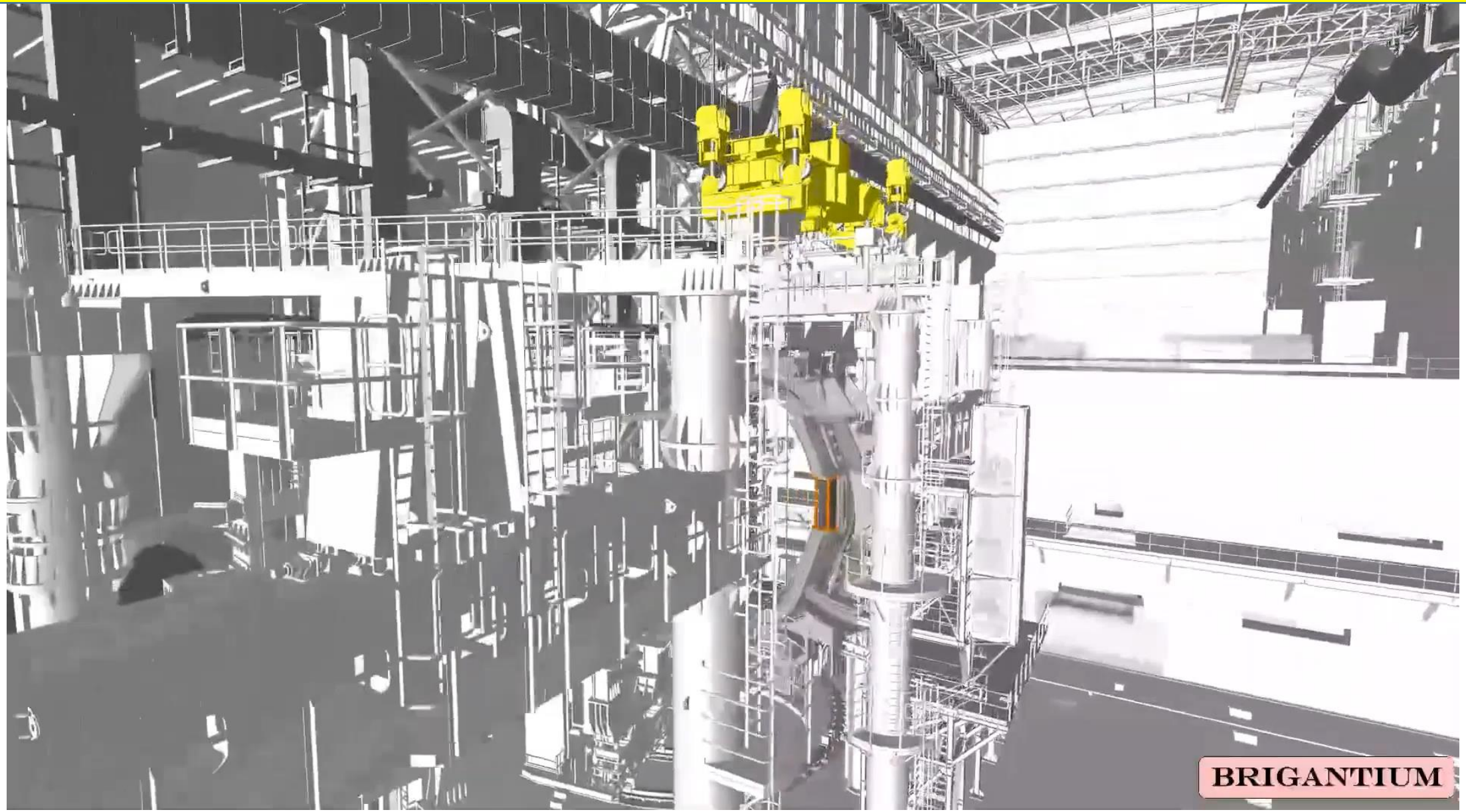
Possible Root Causes of Delay

- Congestion in main Assembly Hall and Main Crane Bottleneck
- Complex and heavy construction organisation, diffuse responsibility, slow response to change
- Lack of detail & foresight in preparation of work instructions
- Contract organisation poorly adapted to take advantage of learning curves after FoK
- Quality problems in some deliveries, on site repair

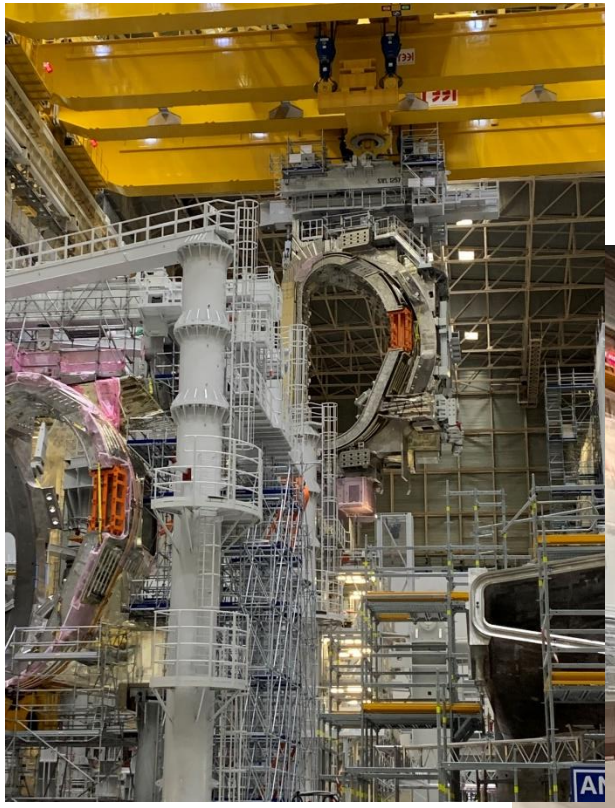
- See back-up slides

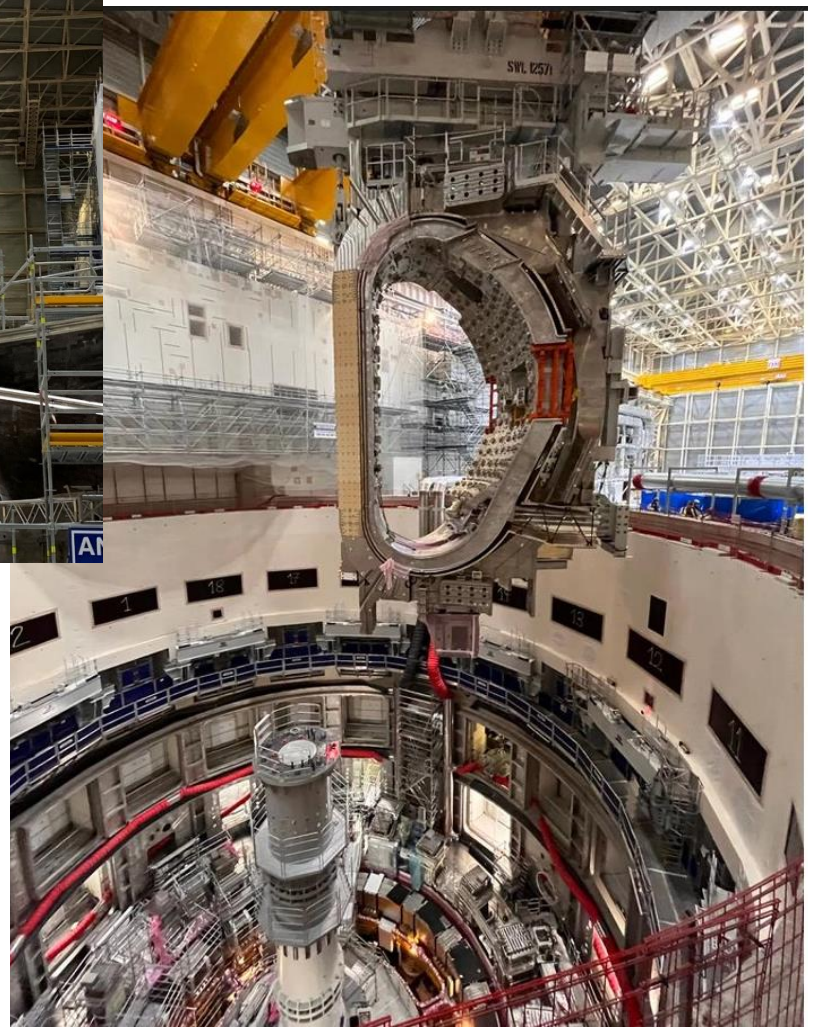
To achieve FP this decade will be a challenge if improvements are not made

Sector Module (1/9 of torus) Transfer to Pit



Sector Module (1/9 of torus) Transfer to Pit: Update 11 May





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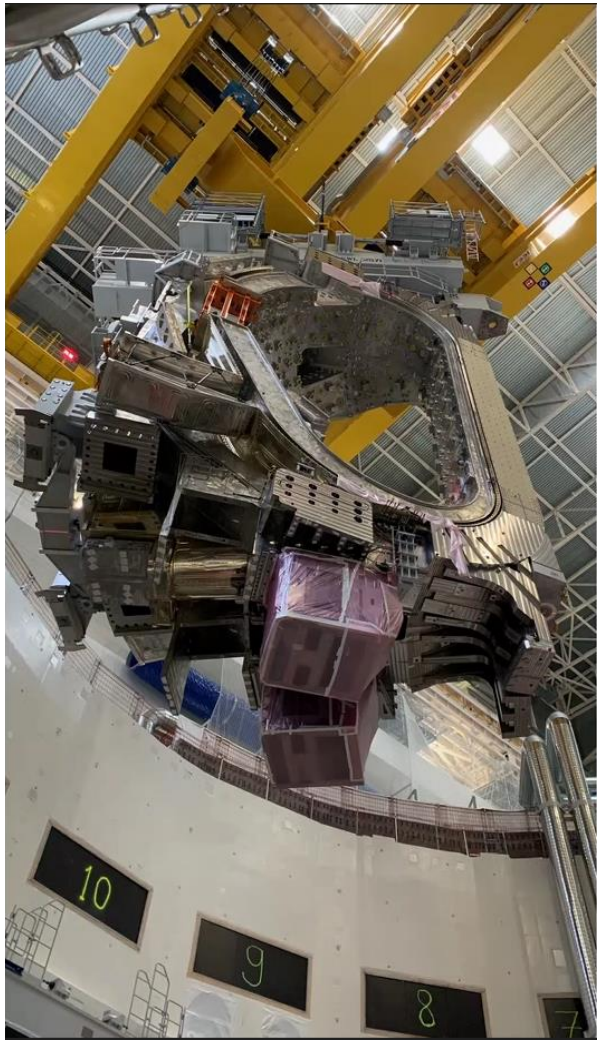
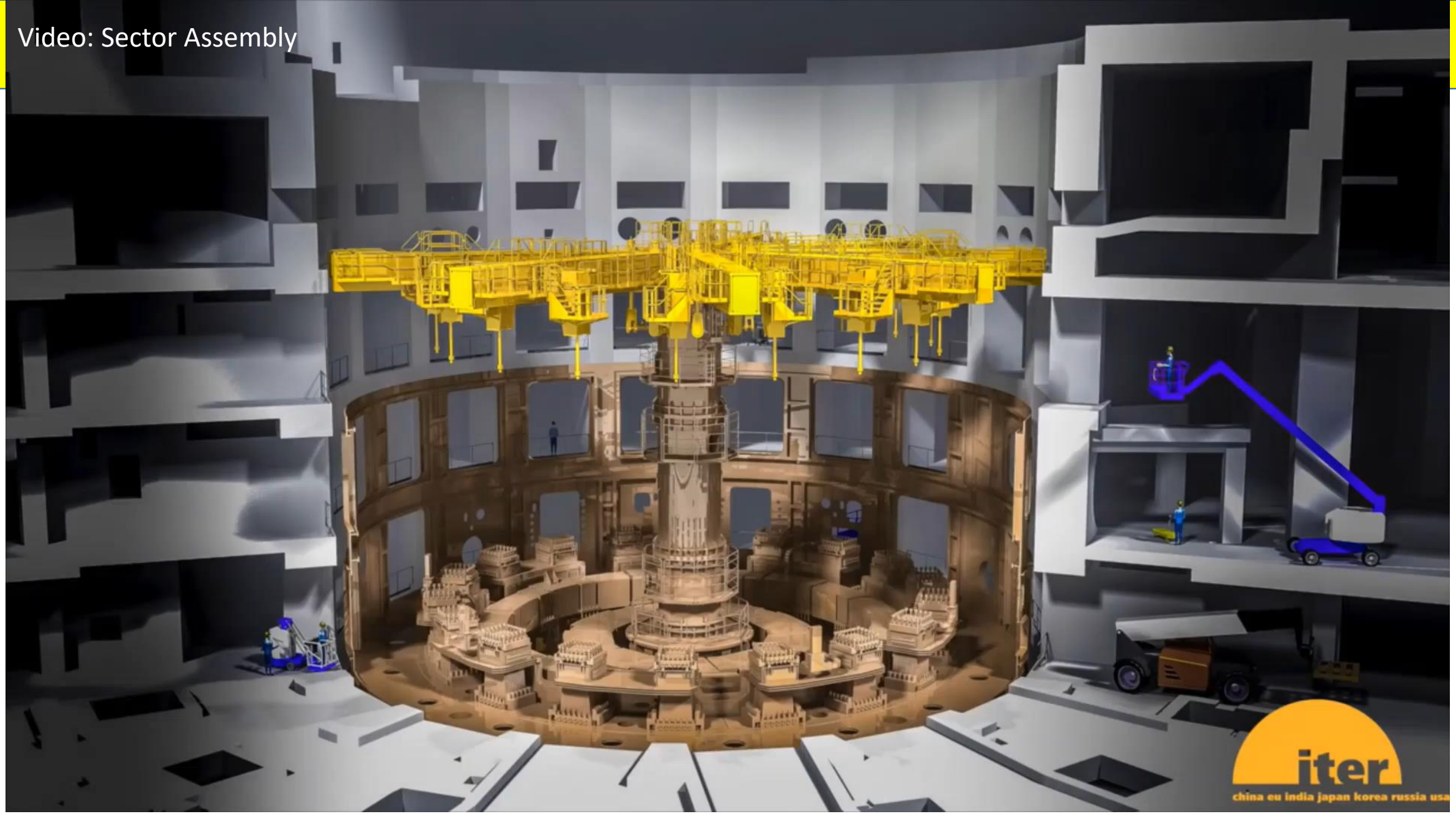


Video: Sector Assembly



Challenges 2022-25

The key in this period is the sector alignment and linking in the pit. Schedule driver is predicted as the VV welding (where VV non conformities on dimensions have been revealed very late (apparently after arrival on site) and have forced revision of automatic welding procedures and warnings from ASN). However this is not the only concern

- ❑ Significant descoping from Assembly Hall to Pit of FoK processes (TF intercoil keys is an example)
- ❑ Congestion inside pit known as issue, maybe not fully resolved
- ❑ Several quality issues (repairs) to be fixed in Pit, as well as realization that onsite inspection of components by IO needs to be ramped up substantially to cover for poor quality at suppliers (resources and processes not anticipated)
- ❑ Many magnet components manufactured several years ago, aging and deteriorating in poor assembly hall/pit environment, or even in non-optimal storage facilities, is a concern

Video: Ex cryostat assembly

Challenges 2025-2028

Covers CS, PF coil final installation, feeders, HV cables, instrumentation

- In-vessel assembly has to go in parallel once VV closed, not shown and contract still to be placed
- Ex-vessel has many activities on or near critical path, much scope for knock-on effects and need of a robust risk mitigation plan for when inevitable delays occur

- ❑ Congestion in-vessel and in pit access remains a concern
- ❑ Lack of detail on issues (not fully thought through) which in the confined space of the cryostat is likely to mean that delays in any one will severely impact others
- ❑ Missing/optimistic items (completion of instrumentation, PCR pre-loading)
- ❑ Almost all steps are FoK and many processes are only conceptual, not qualified
- ❑ Tooling not developed for many of the in-cryostat operations…small, but many
- ❑ Due to long storage of sensitive components in poor environment, we can expect to carry out major quality checks (and quite possibly cleaning/repairs) once commissioning starts

Scope for improvement: see backup slides

Conclusions

Despite the delays & costs the ITER tokamak manufacturing and assembly has been a remarkable high technology success story.

- There are some significant problems in quality of delivered components but at a basic technology level (weld quality, tolerances etc) which should have been avoidable.
- The ITER organisation and project management has been challenging. To overcome assembly challenges some re-focusing and adjustments could be considered. The project has a unique structure mixing stakeholders and executors which do not always share a common purpose

At present both costs and schedule are 'not stable'.

- ❑ Costs are being escalated through project management failings (insistence on schedule baseline, ineffective contractor controls, poor risk management, quality problems at suppliers, lack of hands-on technical supervision, byzantine project controls) ➔ this can be fixed, first
- ❑ Schedule is a second step, a consequence of first. Once we have a *stable and effective* project organisation, we can look for realistic opportunities. But it is no use looking for miracles…