Toward completion and delivery of the first EU ITER magnets

Alessandro Bonito Oliva,

With contributions from P. Aprili, B. Bellesia, E. Boter Rebollo, T. Boutboul, P. Carvas de Sousa, M. Casas Lino, M. Cornelis, P. Gavouyere-Lasserre, R. Harrison, A. Hernandez, M. Jimenez, A. Loizaga, M. Martinez, P. Readman, G. Romano, D. Rossi, C. Sborchia, P. Valente, E. Viladiu, R. Batista, V. Casarin, K. Charalampos, A. Lo Bue, E. Pompa, E. Pozuelo-Segura (F4E)
L. Byung Su, S. Koczorowski, C. Luongo, N. Mitchell, L. Poncet (IO)*

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Fusion for Energy, Barcelona

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

The ITER magnets system

ITER Poloidal Field (PF) Coils

1 Supplied by Russia

5 supplied by F4E

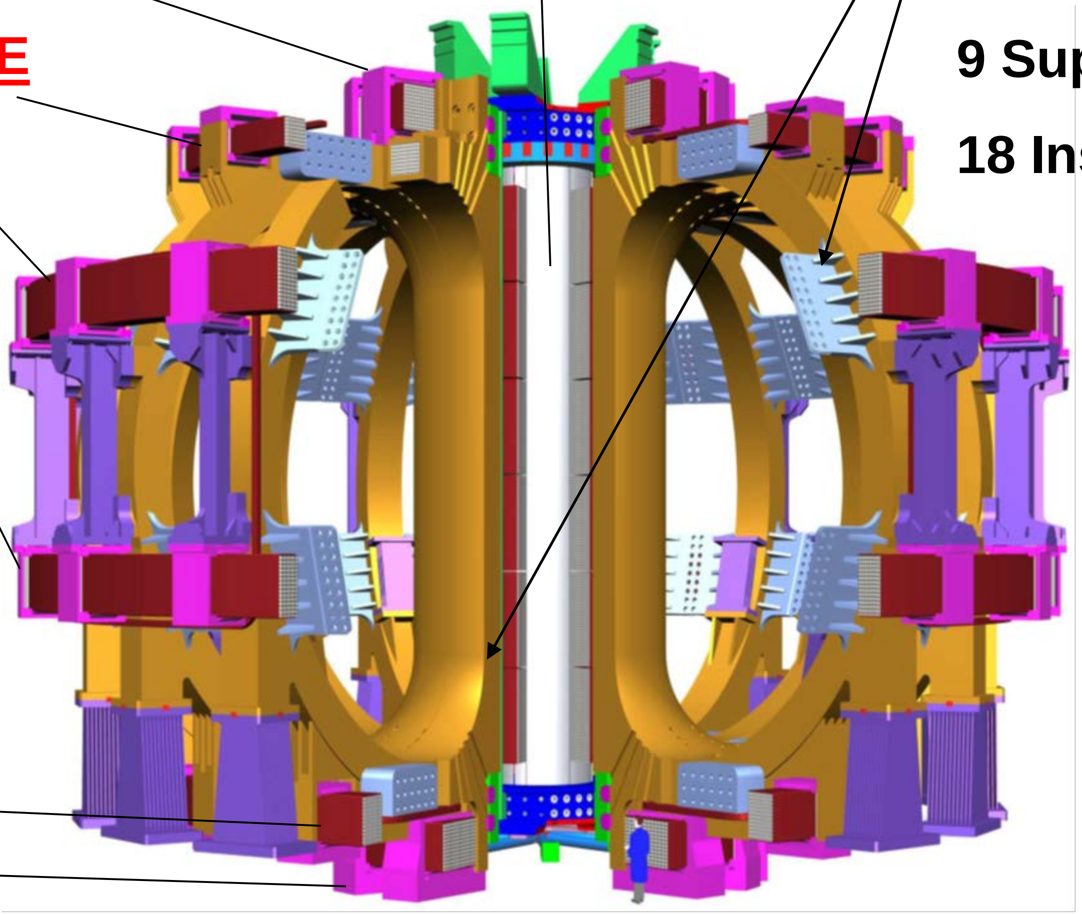
ITER Central Solenoid Supplied by US

ITER Toroidal Field (TF) Coils

10 supplied by F4E

9 Supplied by Japan

18 Installed-1 spare



How did we get from here…

Technical Specification

ANNEX B

to

Procurement Arrangement
1.1.P1A.EU.01

between

the ITER International Fusion Energy Organization for the
Joint Implementation of the ITER Project

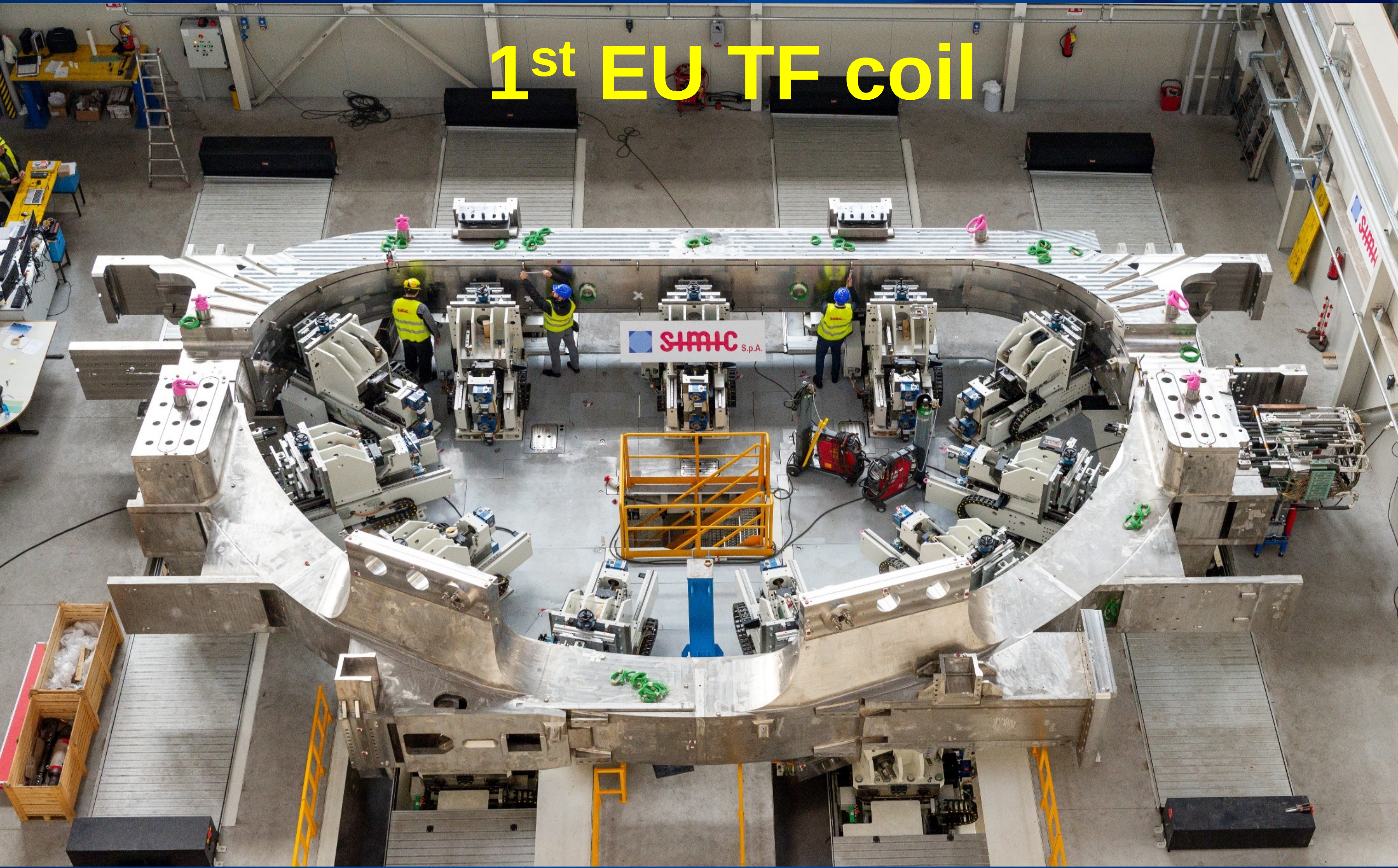
and

The European Joint Undertaking for ITER and the
Development of Fusion Energy

Signed on June 2008 for TF and June 2009 for PF

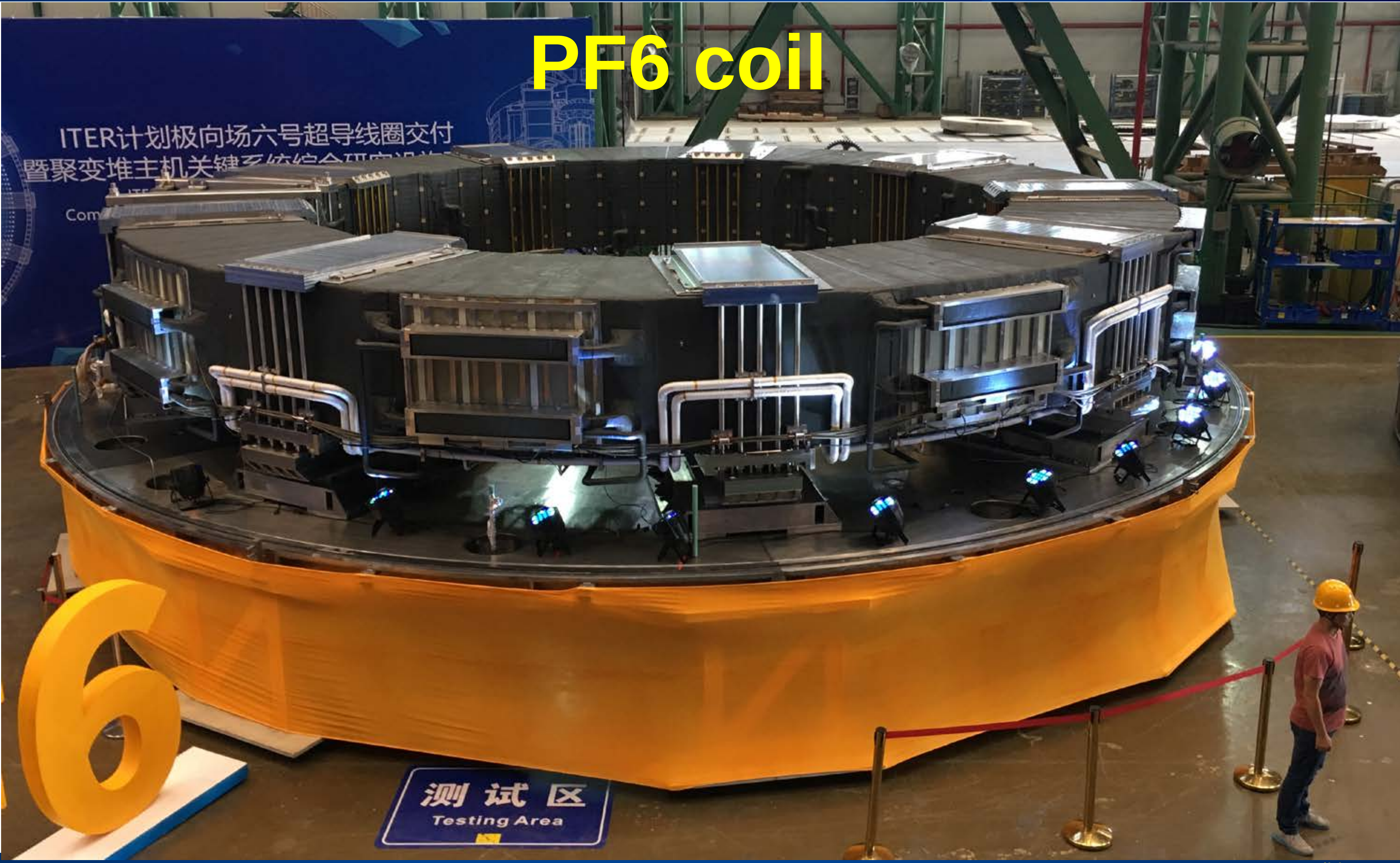
....to here ...

1st EU TF coil



FUSION FOR ENERGY

…. AND to here …



Journey starting point…

- Technical specification (from ITER): the bible !
- A budget … limited !
- An (ITER) assembly schedule ….

Our goal was to manufacture the coils:

1) *Within budget*
2) *With a reliable schedule, respecting ITER need dates*
3) *With a quality consistently matching technical requirements*

Final result depends on number of factors ….

It is not only about technical solutions, but other aspects determine final result:

1. The **<u>procurement strategy,</u>** influencing final costs & possibility to manufacture the coils within budget
2. The **<u>manufacturing strategy</u>** determining robustness of schedule and quality of the final product
3. **<u>Legal arrangements</u>** for the industrial contracts determining scope, responsibilities and interfaces among parties (>20 contracts & > 40 suppliers)

- Without a good solution for each of these dimensions, even with good technical solutions, it is not be possible to succeed.

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And now let's talk about …

EU TF coils

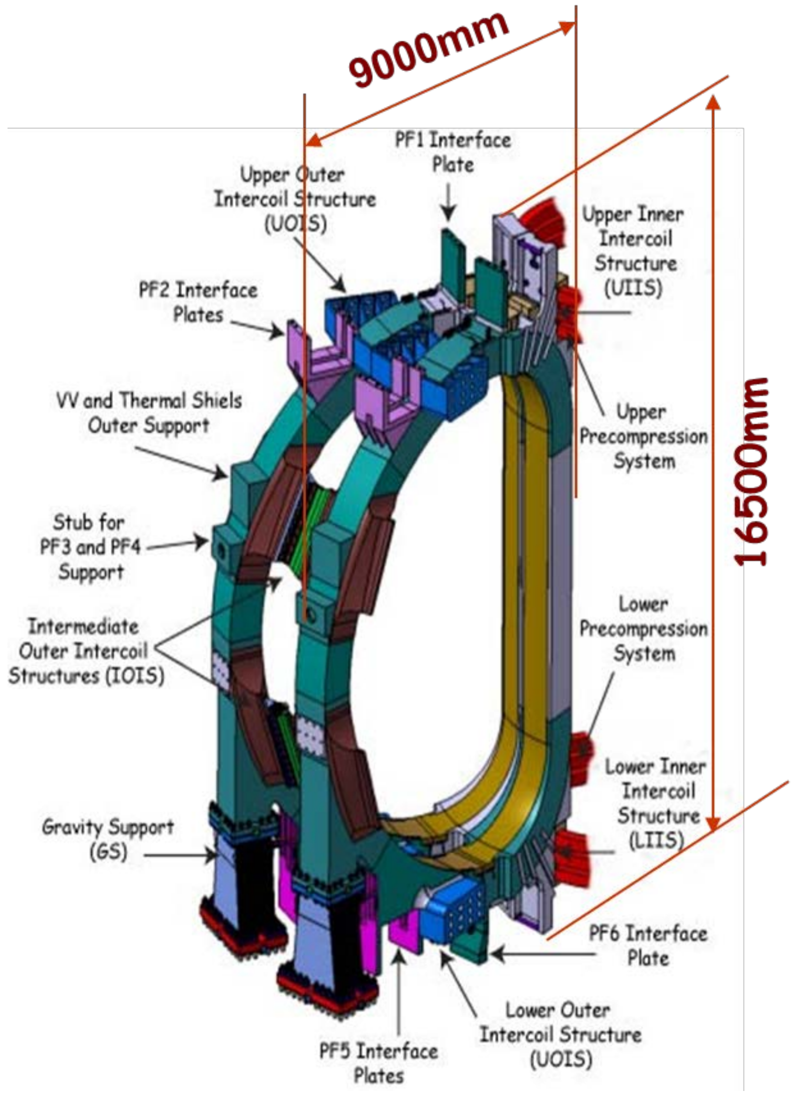
The TF coils: main parameters

Number of TF coils	18
Magnetic energy in TF coils (GJ)	~ 41
Maximum field in TF coils (T)	11.8
Centering force per TF coil (MN)	403
Vertical force half TF coil (MN)	202
TF discharge time constant (s)	11
Total weight of TF coils system	~6540t
TF cases	~190t
TF WP	~110t
Pre-compression system, keys and bolts	~60 t

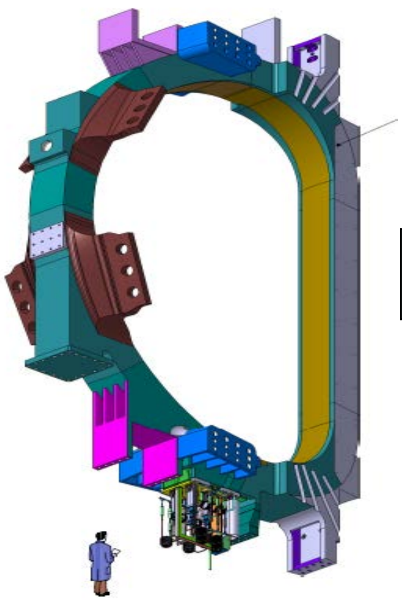
Weight (no precom.): 300t/coil

Peak field 11.8T

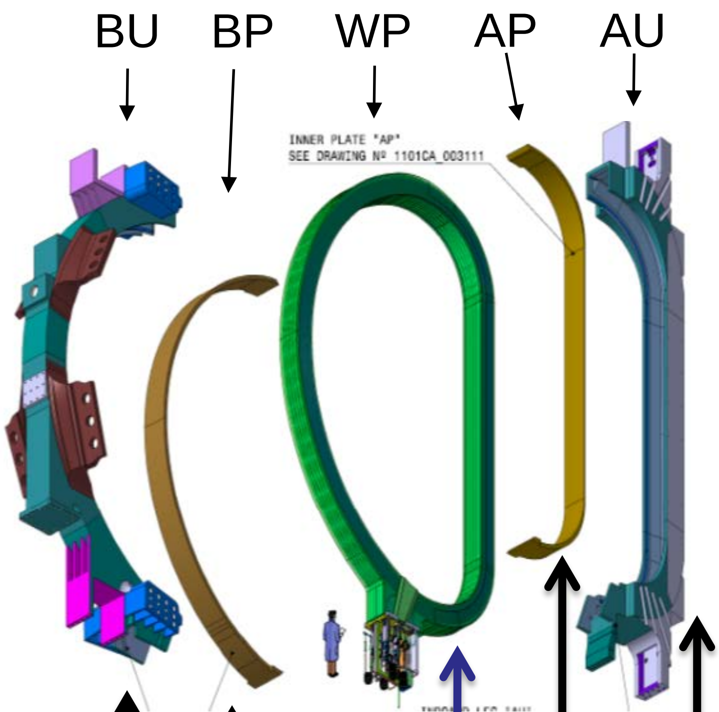
Constant Current 68KA



The ITER TF coils



The ITER TF coil

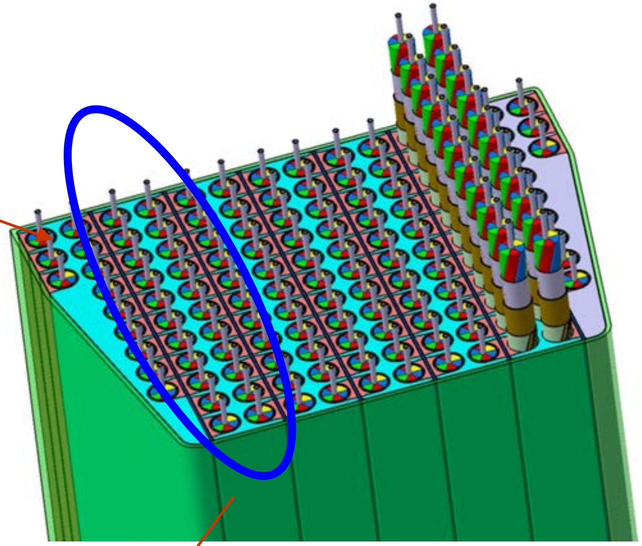


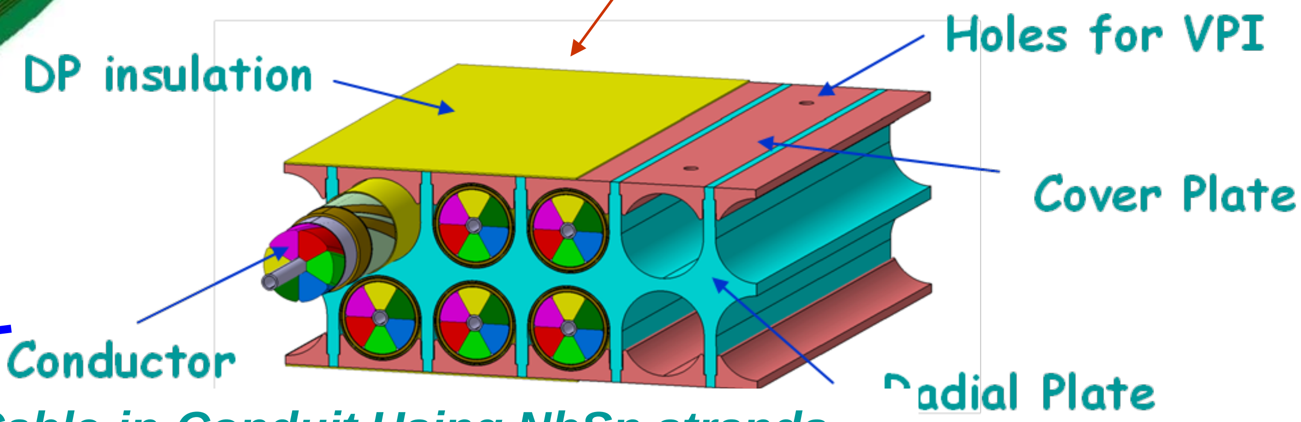
The winding pack

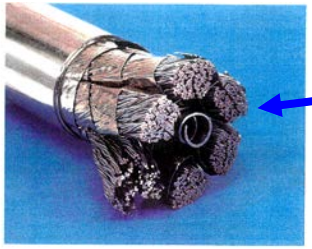
The coil case
Supplied by Japan DA

The TF coil configuration

The winding pack







Cable-in-Conduit Using NbSn strands

The EU TF procurement strategy

Starting point:

- **High technical uncertainty**: feasibility of TF coil never demonstrated at full size scale (only ¼ scale model coil)
- **High financial costs:** several hundreds of M€ involved
- **Very Broad set of skills involved:** from welding and precise machining of very large components, to magnet winding/insulation and cryogenic skills

↓

- **Difficult to find a company with such large broad set of skills & willing to take over such high financial risks**
- **Even if existed, high technical risks would have translated in very high prices, exceeding the budget !**

The procurement strategy

Key points of defined strategy:

- **Reduce technological uncertainty and risks before launching the series production call-for-tenders to reduce bidders' price**

- **Placed initial smaller contracts to demonstrate feasibility and reduce technical uncertainty:**
  - 2 contracts to build radial plates prototypes
  - 1 engineering study for final TF coil construction phase
  - few R&D contracts to develop & qualify TF final welding and its UT technology.

The procurement strategy

Key points of defined strategy:

- **Split full procurement in smaller packages to increase competition at the call-for-tenders**

- **For the series production split the procurement in 3 smaller contracts with:**
  - Narrower and homogenous set of skills
  - Smaller financial liability
  - Clear and minimum interfaces

The production strategy …

- TF and PF coils production involves manufacturing of more than 100 superconducting double pancakes ….
- Reproducibility and reliability of the manufacturing processes are essential for final quality and schedule robustness

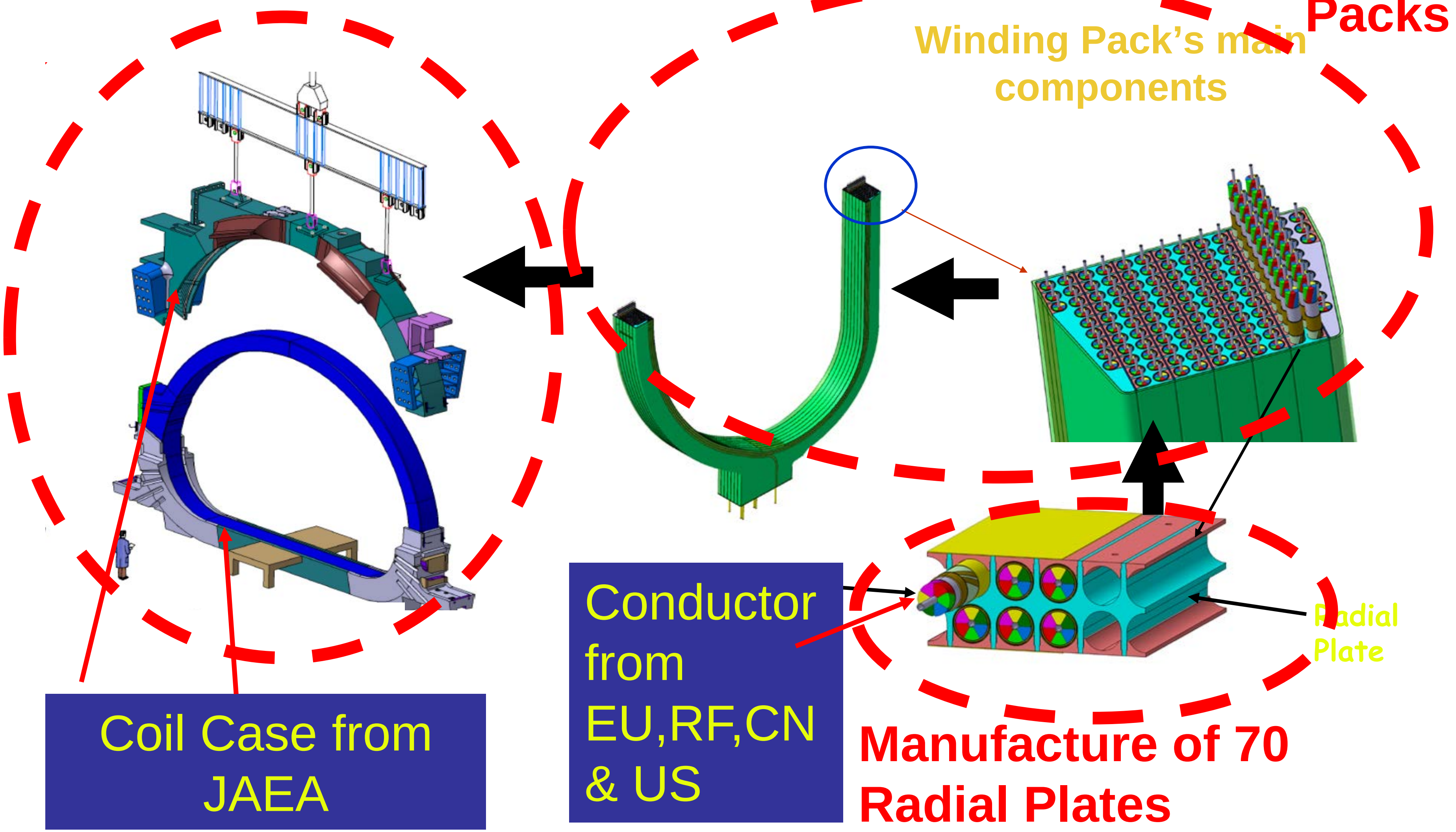
⇩

- Initial decision to invest heavily on automated processes and numerically controlled equipment !
- For TF coils production 90% of the processes are automated.

TF coils procurement split into 3 contracts

Completion of 10 TF coils

Manufacture of 10 Winding Packs



Manufacture of 70 Radial Plates

EU TF Production Contracts

- **Manufacture of the 70 RPs**, awarded to a consortium composed by CNIM (France) and SIMIC (Italy) in 2012.
- **Manufacture of 10 WPs**, awarded to a consortium composed by ASG (Italy), Iberdrola (Spain) and Elytt (Spain) in 2010.
- **Completion of 10 TF coils**, awarded to SIMIC (Italy) with support of BNG (Germany) in 2014.

All contracts within initial budget

Main Steps and Status of the TF coils production

The manufacture of the 70 radial plates

The radial plate

The 70 Radial plates: the main manufacturing steps

6 segments of ITER grade 316LN are forged for each RP (Courtesy by Thyssen)

Forged segments are pre-machined (5mm over metal) at CNIM

Forged segments are butt-welded (NG GTAW or LV EB) into larger sectors at SIMIC

Sectors are welding by NG GTAW or LV EB (in photo GTAW welding-SIMIC))

Final machining with portal machine on nominal trajectory at 20+/-1C (at CNIM)

Weld 3

The Manufacture of the Radial Plates by SIMIC and CNIM

All 70 RP have been successfully completed and delivered !

Celebration for the completion of last RP with representatives of companies involved.

The manufacture of the 10 TF winding packs

Production of the 10 WP :Steps and status of the DP production

All 70 DPs completed !

Steps of the WP construction at ASG (with Elytt and Iberdrola contribution)

All 10 units completed

Stacking of the DPs

All 10 units completed

Application of ground insulation

7 units completed

Application of semiconducting painting, piping and instrumentation

7 units completed

Impregnation

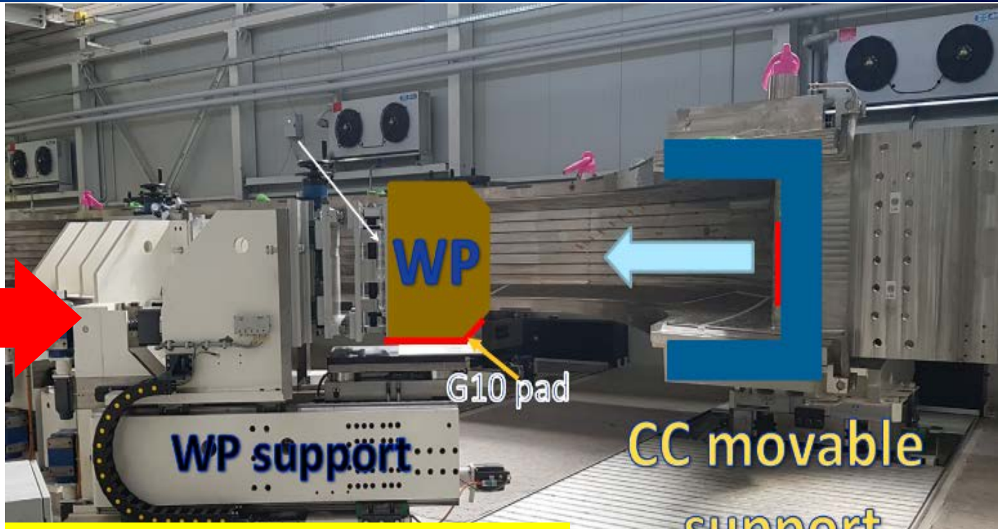
This has been the result of the work of more than 25 organizations ….

Celebration for the completion of the 1st WP with the representatives of the main organizations which contributed to its construction

Steps of the TF completion at SIMIC (with BNG contribution)

4 WPs cold tested

Thermal Cycle to LN Temperature + HV insulation test and leak check



Insertion of WP inside CC

1st TF welding completed & 2nd in progress

Closure weld with GTAW

2 TF insertions completed

Insertion completed

Next Steps of the TF completion at SIMIC (with BNG contribution)

In progress on 1st TF coil

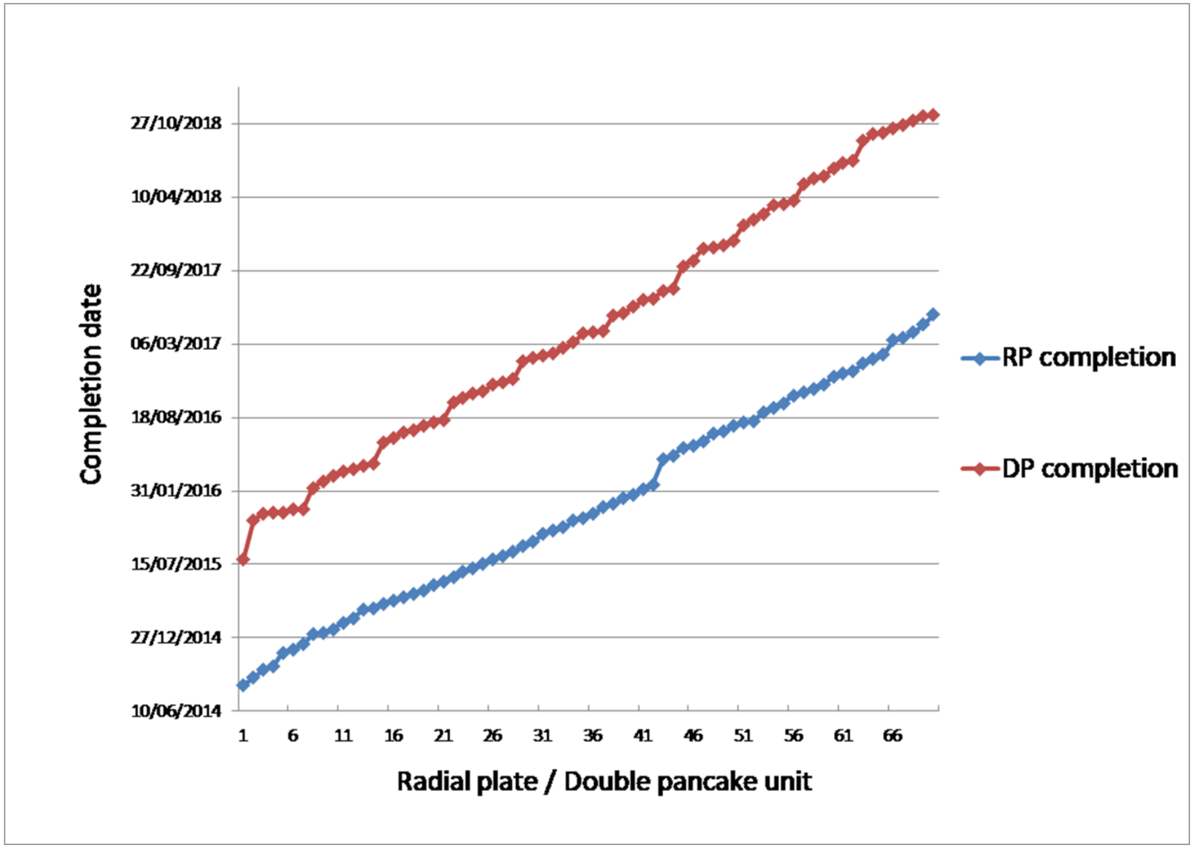
- Filling of gap between WP and CC with epoxy resin
- Resin "reinforced" with dolomite (calcium magnesium carbonate, 41% by volume)
- During the gap filling the TF coil is tilted with a 5º angle

Starting soon on 1st TF coil: to be completed by year end

- Final machining of interfaces (10mm over-metal)
- Use Large Portal Machine capable to handle whole TF coil
- Final DI con laser scanner

Main results obtained so far on EU TF Coils

Achieved production rates on RPs and DPs



- In average 1 RP every 14 calendar days and 1 DP every 17 calendar days !
- Result obtained thanks to:
  - Strong automation of the processes (only 10% manual)
  - Optimization of number of tools working in parallel on different units

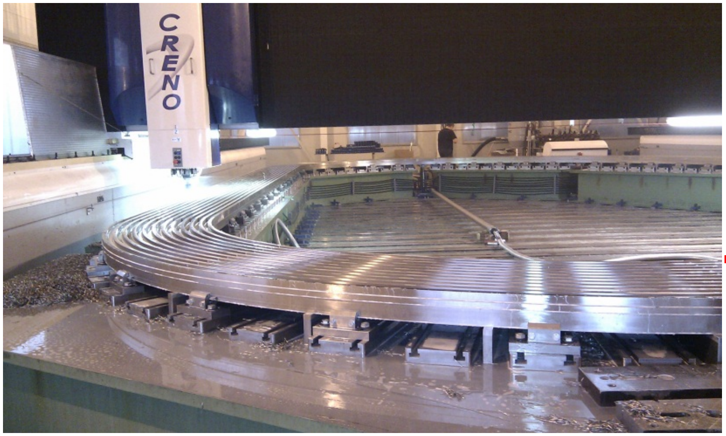
Achieved accuracy on conductor and radial plate trajectories

The biggest challenge: to transfer the conductor into radial plate groove

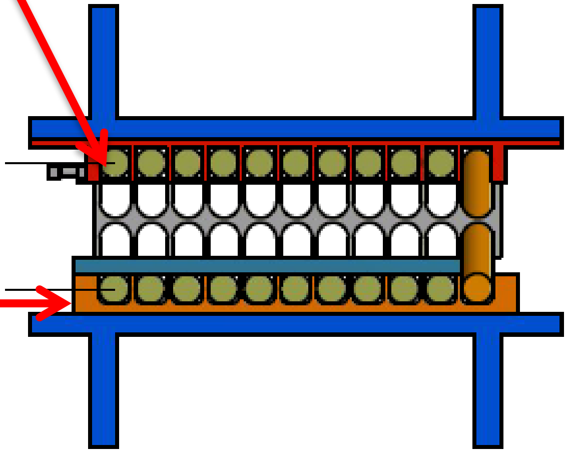
Winding of double pancake according to nominal trajectory

Heat Treatment causes a length change ΔL

The conductor is inserted inside the radial plate grooves along its trajectory 700m long

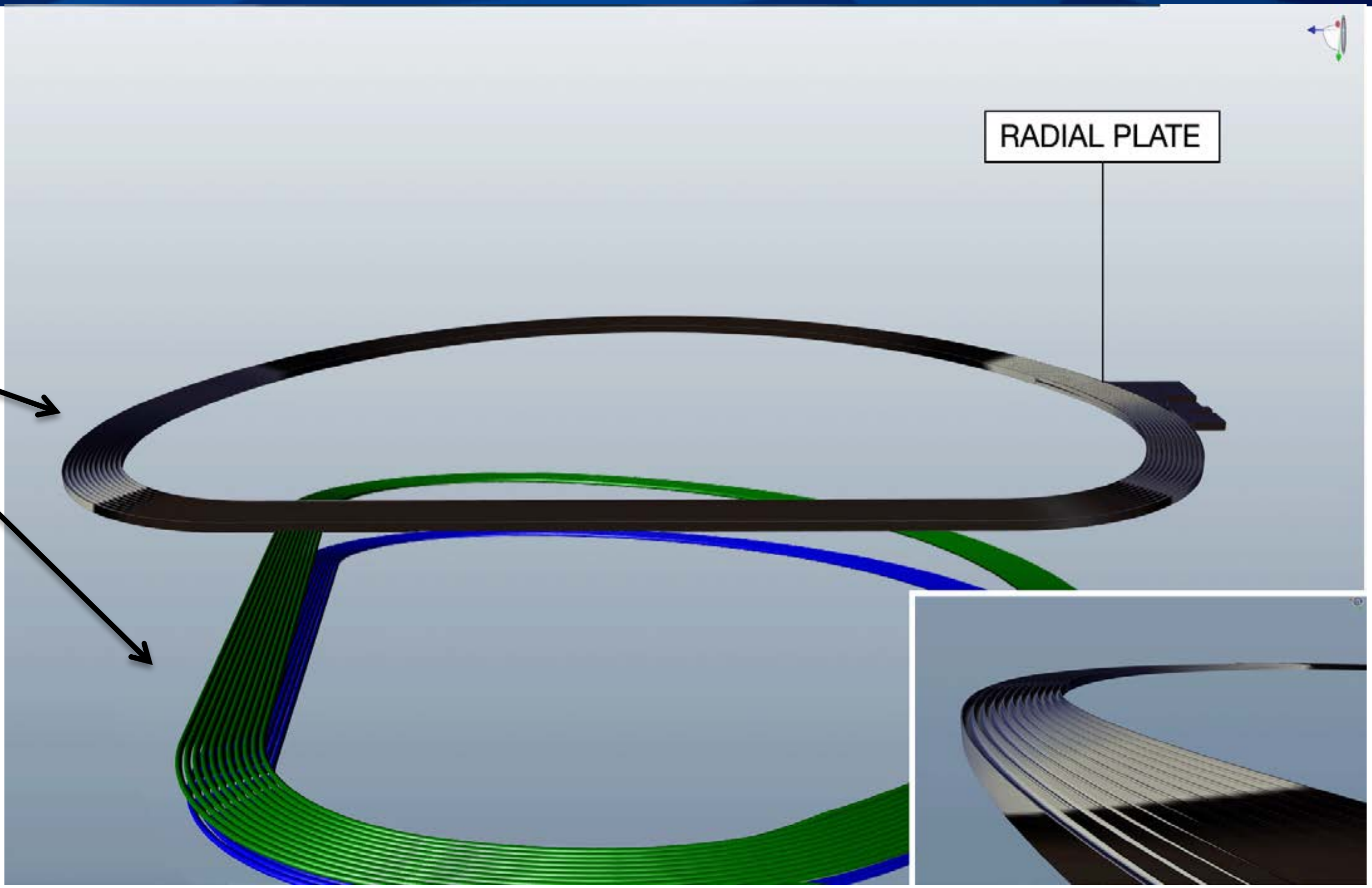


Machining of the radial plate grooves according to a nominal trajectory



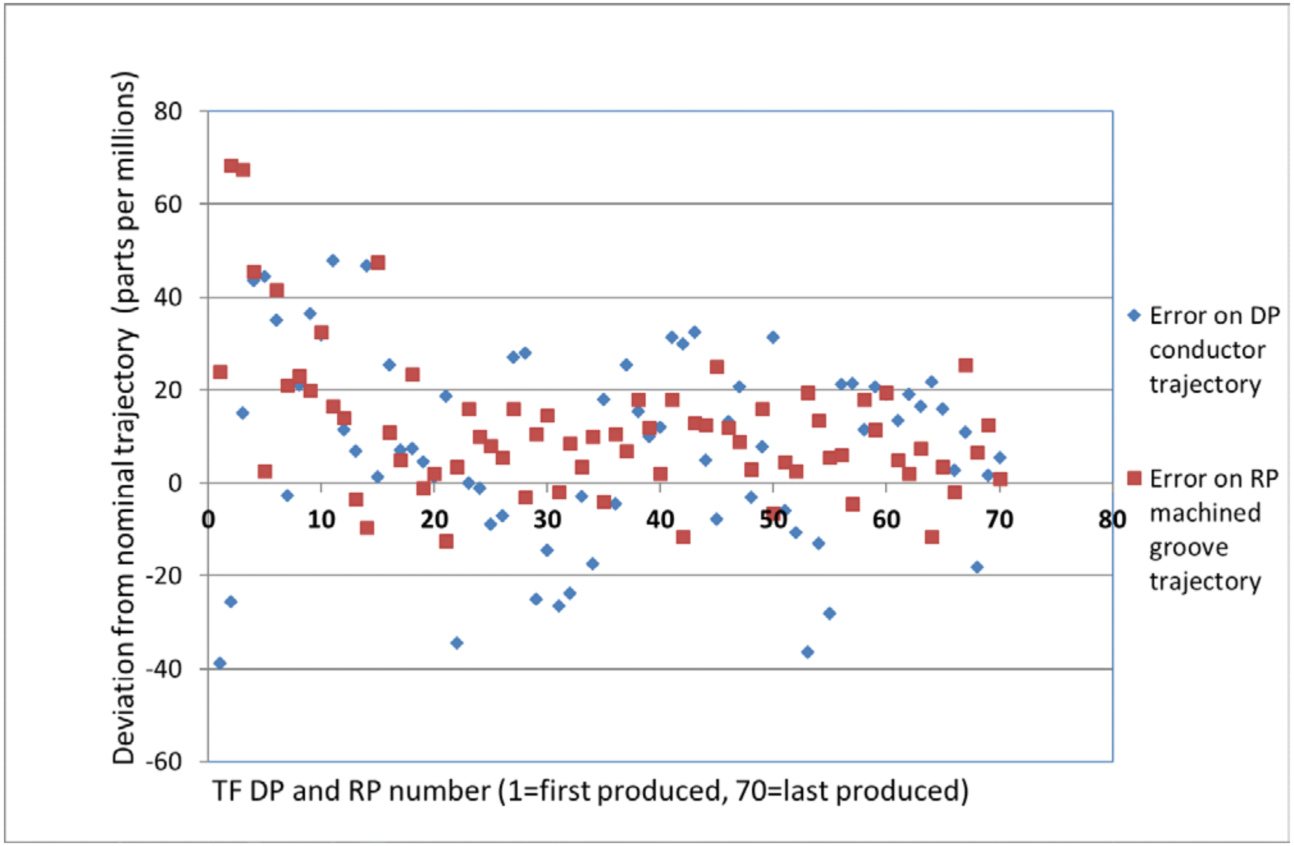
THE INSERTION OPERATION

The double spiral is inserted from both sides of the radial plate



The trajectory of the conductor (and of the radial plate groove) MUST STAY within +/-100ppm (80ppm) of the nominal trajectory along the 700m long groove !

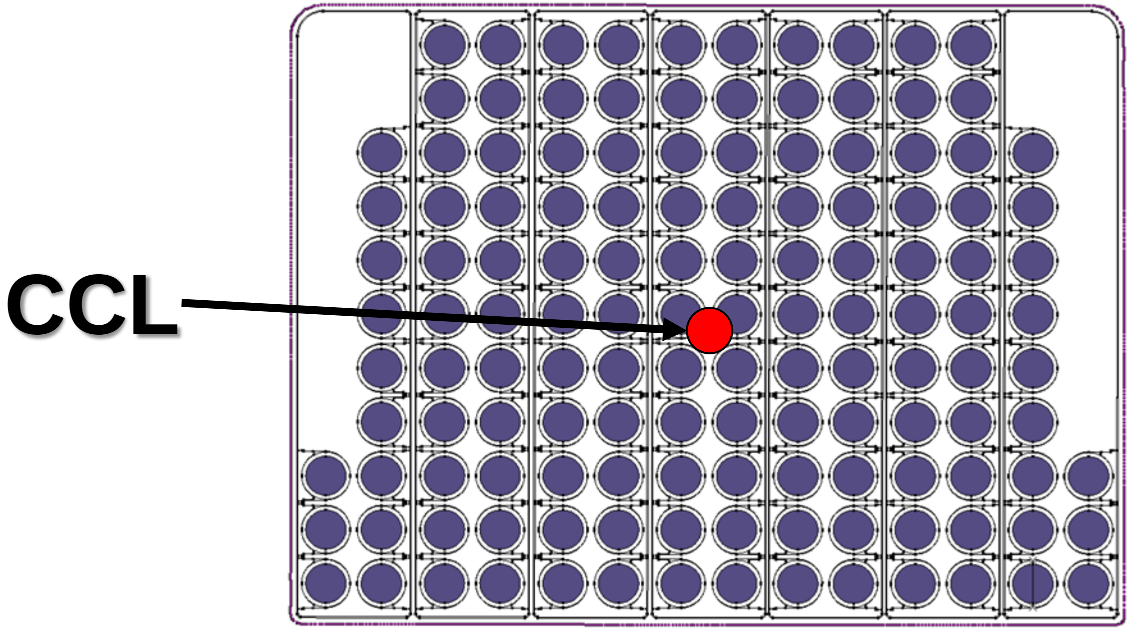
Results on conductor and radial plate groove trajectories on 70 DPs and RPs



- All WELL within required accuracies !
- Strong learning curve on RPs
- On DPs, deviation dominated by scattering among conductors on heat treatment length-change.

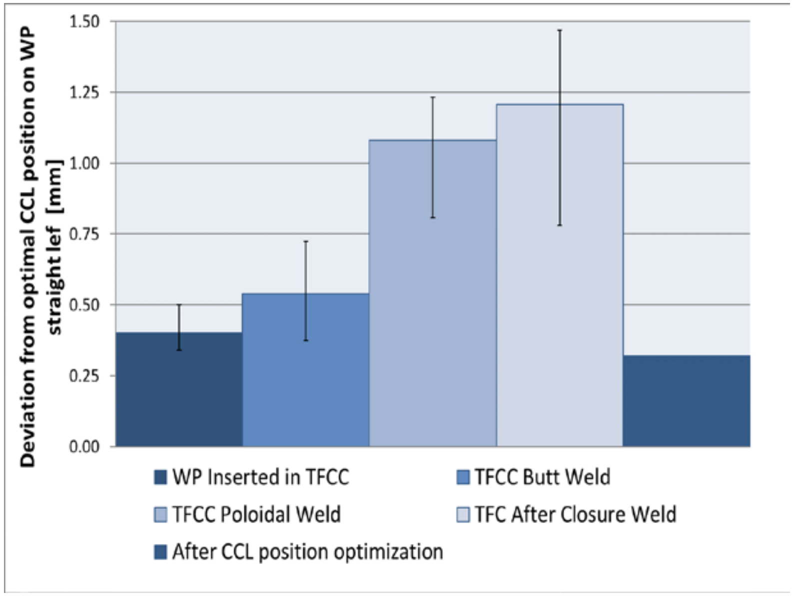
Achieved accuracy on current centerline position

The Current Center Line (CCL)



- The CCL is the geometrical barycenter of the conductors inside a WP
- **The accuracy of its position with respect to plasma drives magnetic field homogeneity in the plasma**
- Accuracy of its position depends on:
  - Accuracy of conductor trajectory
  - Flatness and dimensions of the DPs
  - Accuracy in DP stacking
  - Accuracy of position of WP inside the coil case
  - Deformation of the TF coil during closure welding.

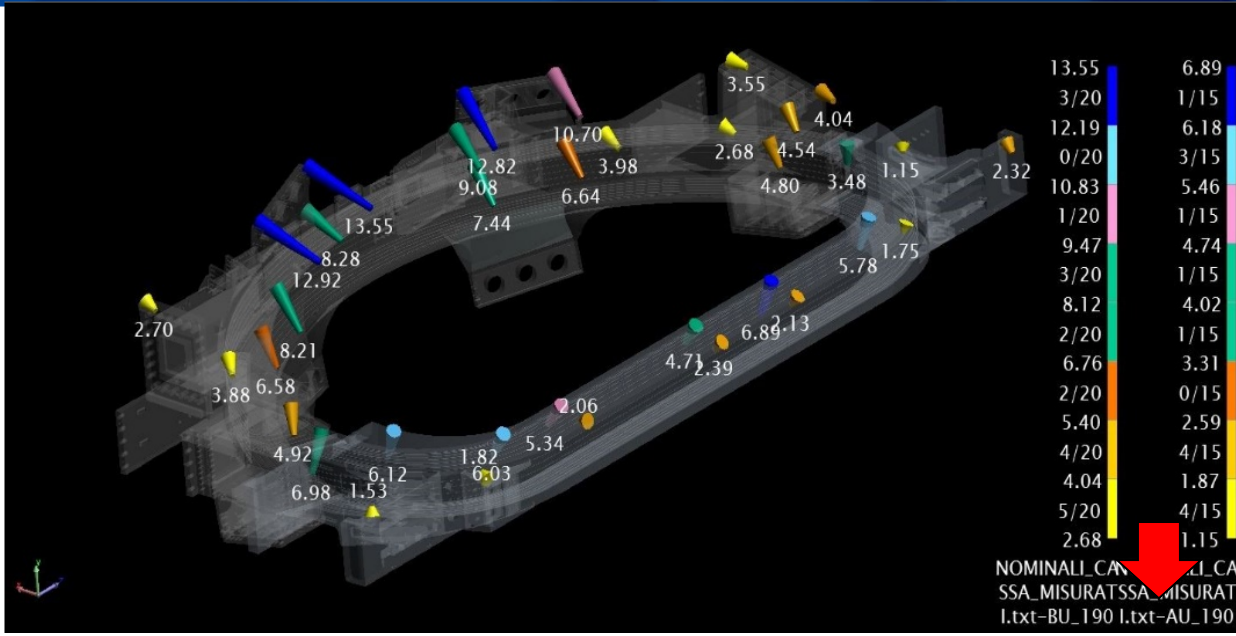
The CCL final accuracy on 1st TF



- The TF straight leg is the coil area which contributes most to the magnetic field homogeneity
- Final accuracy on target position is 0.3 mm : an excellent result

TF coil deformation during final welding

Deformation on first EU TF coil after closure welding

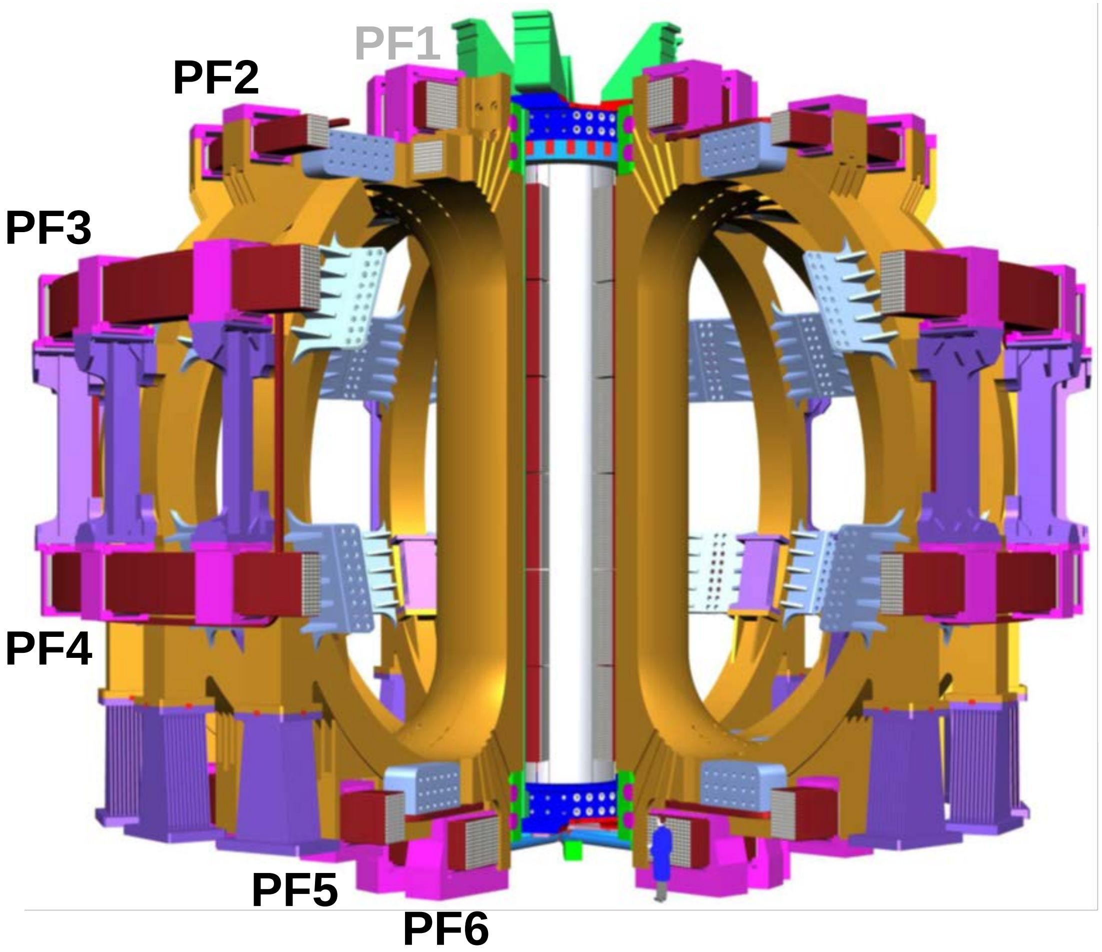


- TF important interfaces manufactured with 10mm over-metal
- Welding distortions below 10mm can be corrected by machining
- All distortions (but one) below 10mm: fully recoverable
- Only distortion on TF wings is few mm above 10mm (same on JADA coils): easily recoverable by utilizing simple shims
- After final machining, the 1st EU TF coil will be fully suitable to be installed in the Tokamak !

And now let’s move on to the …

EU PF coils

The PF coils



PF DIMENSIONS (MM)

	Outer diameter (m)	Height (m)	Weight (t)
PF2	17.2	0.7	342
PF3	**24.8**	1.0	384
PF4	24.6	1.0	349
PF5	17.6	1.0	342
PF6	10.3	1.1	**399**

PF procurement strategy

Driving factors:

- PF3 & PF4 too large to be transported: to be built in Cadarache
- PF5 & PF6 to be delivered simultaneously: 2 production lines
- Not enough space in Cadarache to install 2 production lines

Key decisions

- Production line built in Cadarache
- Manufacture of PF6, with smallest diameter, outsourced
- PF2-PF5 built in Cadarache

- Because of a number of concurrent factors, it has not been possible to apply same procurement strategy used for TF (vertical splitting of procurement).

The PF factory in Cadarache

Winding

Electrical jointing

DP impregnation 1

DP impregnation 2

DP stacking

PF coil impregnation

PF coil cold test

PF coil final assembly

PF procurement configuration

PF2-PF5 Procurement split in 6 smaller contract:

1) Engineering Integrator and Manufacturer for final phase, awarded to ASG (Italy)
2) Manufacturer for the Double Pancakes, awarded to CNIM (France)
3) Winding tooling, awarded to Sea Alp consortium (Italy)
4) Impregnation tooling and other tooling, awarded to the the consortium Alstom-Elytt-Seiv
5) Cold test facility, awarded to Cryotec Impainti (Italy)
6) Management of the building and facilities, awarded to Dalkia-Veolia (France)

All contracts signed between 2013 and 2016.

PF6 Procurement assigned on 2013 through international agreement to:

Chinese Academy of Science (CAS) Institute ASIPP, located in Hefei (China)

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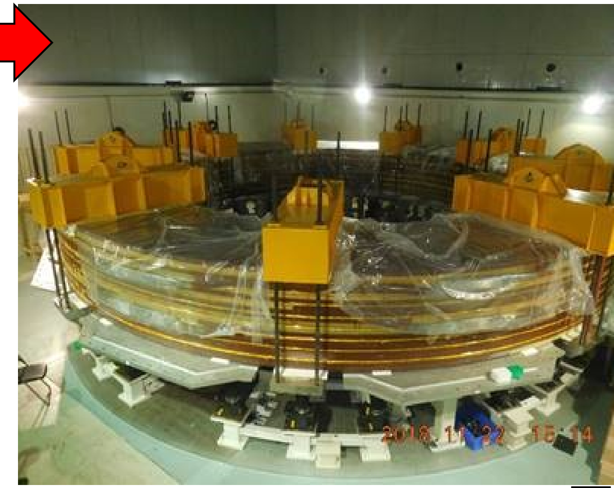
PF manufacturing process

Double pancake winding and insulation

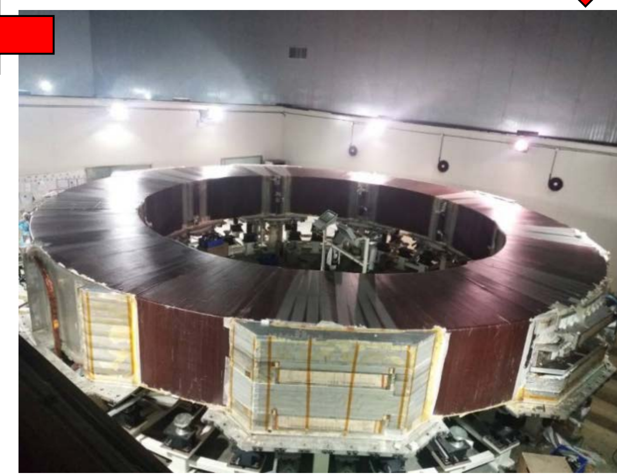
Double pancake Impregnation



Double pancakes stacking and WP insulation

PF thermal cycle to LN T + HV insulation test and leak checks

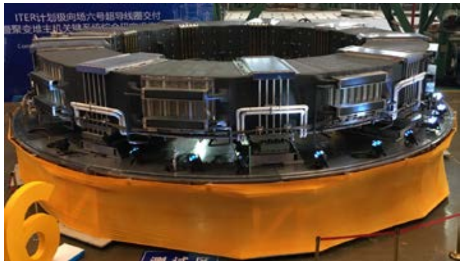
Hydraulic circuit and clamps assembly



Winding Pack Impregnation

PF manufacturing status

PF6 status

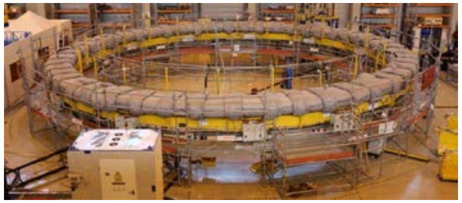


- Completed within the next weeks
- Shipping to ITER foreseen soon!

PF5 status

- Stacking of DPs completed.
- Ground insulation on going.

PF2 status



- Winding of 4 DPs completed.
- Impregnation of 2 DPs completed.

PF3-4 status

- Starting of PF4 (middle 2020).
- It will require a reconfiguration of the tooling to adapt larger coil radius.

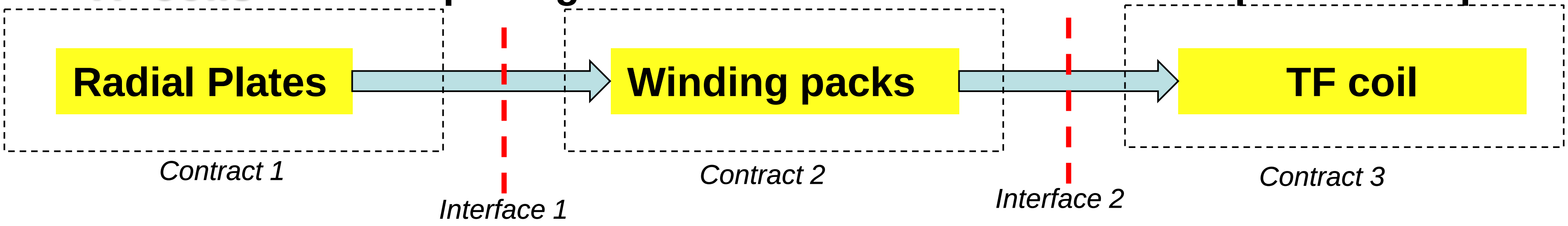
And finally …

some lessons learned

Lessons learned

Vertical vs **horizontal splitting of procurement**

For TF coils vertical splitting: each contract covers a different production phase



- Each supplier solely responsible for scope of its own contract
- 2 clear interfaces, no co-activity in contracts
- Each interface involving only 2 suppliers

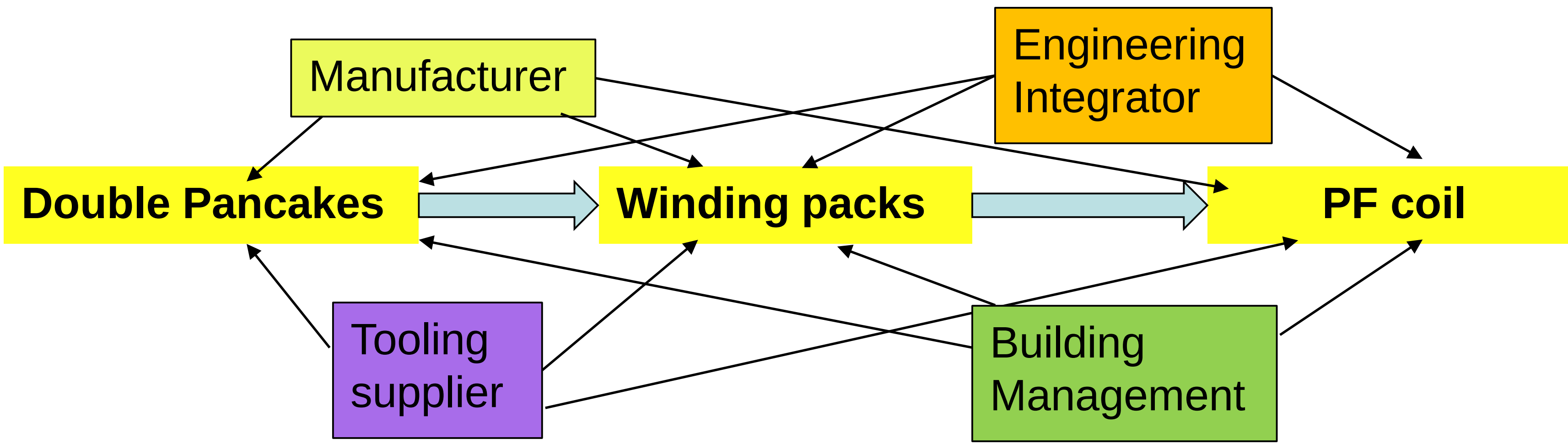
To avoid gaps of responsibilities, acceptance by F4E of a component only after acceptance by the receiving supplier

This scheme has been quite effective over the years !

Lessons learned

Vertical vs **horizontal splitting of procurement**

For PF coils horizontal splitting: all contracts cover each production phase



- On each task involved at least 4 suppliers.
- Multiple and complex interfaces for F4E to manage

This scheme has been very complex and difficult to manage

Conclusions

The first PF and TF coils will arrive in ITER in the next few months ….

They have been 11 years of very hard work:

- *Continuous interaction with:*
  - *more than 40 suppliers*
  - *ITER Organization*
  - *6 different Domestic Agencies*
  - *more than 800 people from industries and laboratories involved in the production*
- *Fixing mistakes and tackling unexpected issues as they arise: cannot keep hundreds of workers on hold waiting for your decision …*

These years have been everything but boring !

Conclusions

… **but, hard work and development of good technical solutions are not sufficient…**

An essential key to our success has been the strategic thinking spent upfront to analyze and to define the proper implementation strategy …

"No problem can withstand the assault of sustained thinking."
Voltaire

Additional papers on EU TF coils present at this conference

Fri-Mo-Or26-02 - B. Bellesia et al.
Progress on European ITER Toroidal Field Coil Procurement: Cold Test and Insertion Work Package

Fri-Mo-Or26-03 - M. Jimenez et al.
Current Centre Line integration in the manufacturing process of the ITER Toroidal Field Coils

Mon-Af-Po1.17-03 - E. Pompa et al.
Comparison of FEM Predicted and Measured values of the TF coil closure welding distortion

Mon-Af-Po1.17-02 - C. Boffo et al.
Cold Testing of ITER Toroidal Filed Winding Packs

Thank you