Overview of the ITER Magnet System and European Contribution

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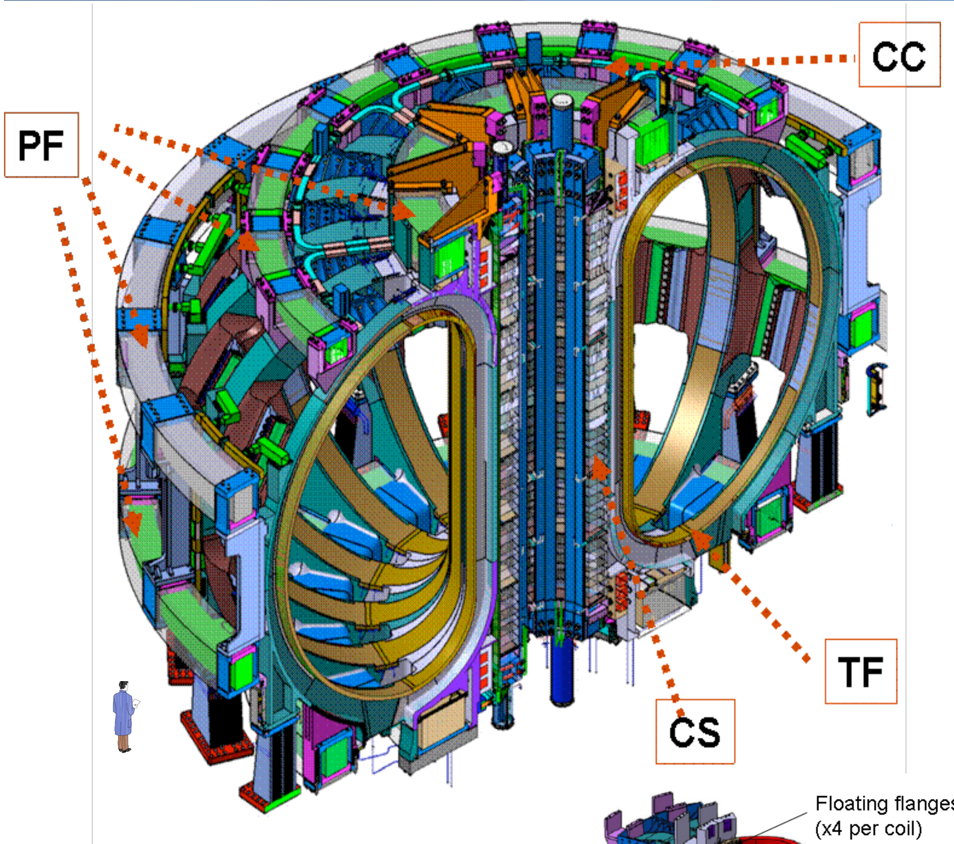
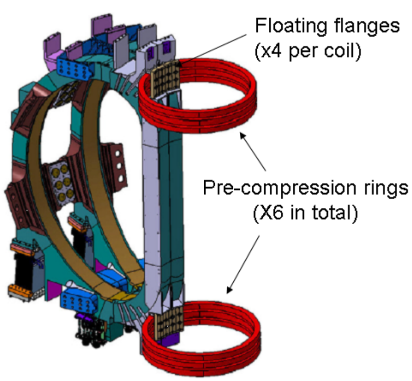
FUSION FOR ENERGY

- Introduction
- ITER Magnet System Design
- EU Magnet Procurement
- Conductors
- Toroidal Field Coils
- Poloidal Field Coils
- Summary

The ITER Magnet System





48 Superconducting Coils:

- 18 Toroidal Field coils
- 6 Central Solenoid (CS) modules
- 6 Poloidal Field (PF) coils
- 9 pairs of Correction Coils (CC)
- + Feeder lines

System	Energy GJ	Peak FieldT	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

Courtesy of ITER

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Main Design Issues

- **Large stored energy** → impact on conductor design and insulation voltages

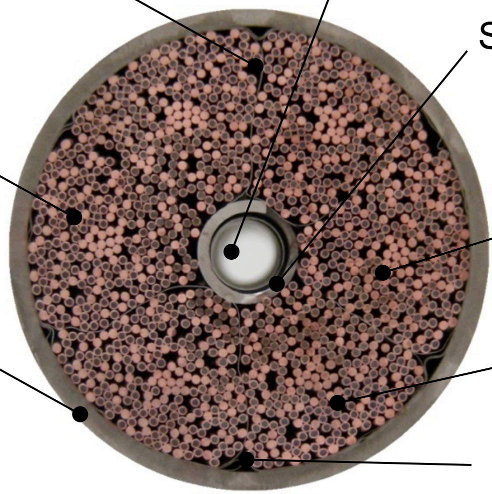
- **Large current and forces:**
  - → **Conductor degradation** under electro-magnetic load (Nb_3Sn)
  - → **Stringent mechanical requirements** on conductor jackets
  - → **Large steel fabrication** (welding, forging, etc.) with **tight tolerance requirements**

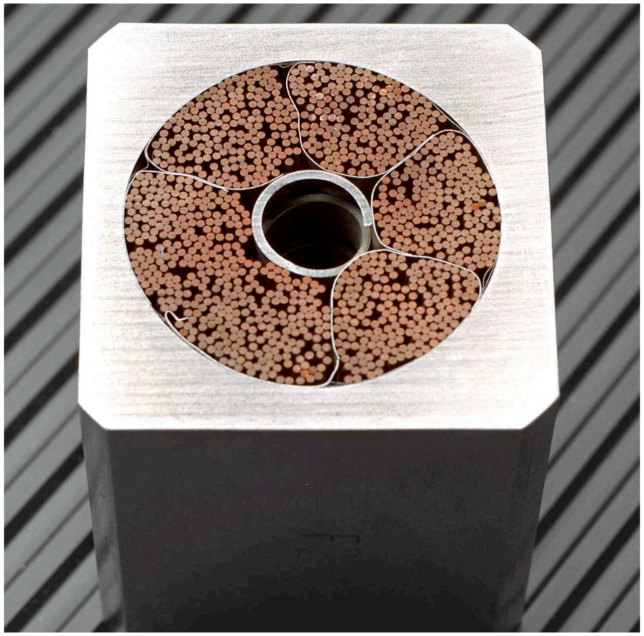
- **Large nuclear heating** on conductor → impact on cooling requirements

- **Neutron irradiation** → impact on insulation selection

- **High electric voltage (in vacuum)** → impact on insulation selection and quality control procedures

Conductor Design

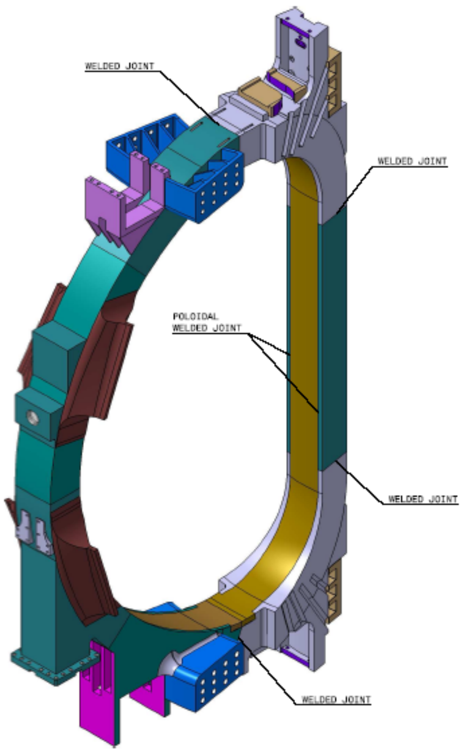


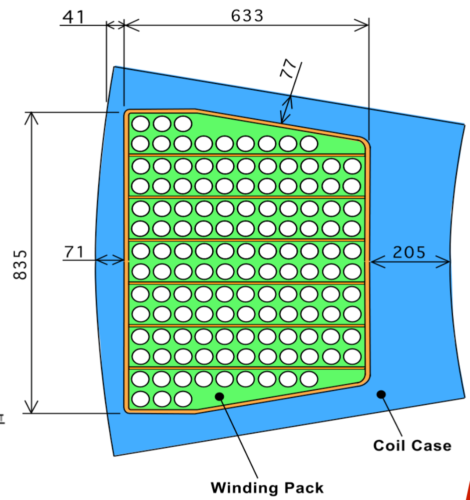


- All four magnet systems (CS, TF, PF and CC) are using the same concept
- Strand type (Nb_3Sn or NbTi) defined by max. field and Cu for thermal stability
- Number of strands defined by nominal current, typically 1400 strands in 6 bundles made of triplets (2 S/C + 1 Cu)
- Supercritical He flows in voids
- Conductor operating conditions:
  - → 5K with margin of 0.7K for Nb_3Sn @ 11.8-13.0 T
  - → 5K with margin of 1.5K for NbTi @ 4.0-6.4 T
- Outer conduit material and shape (steel, round) defined by magnet design

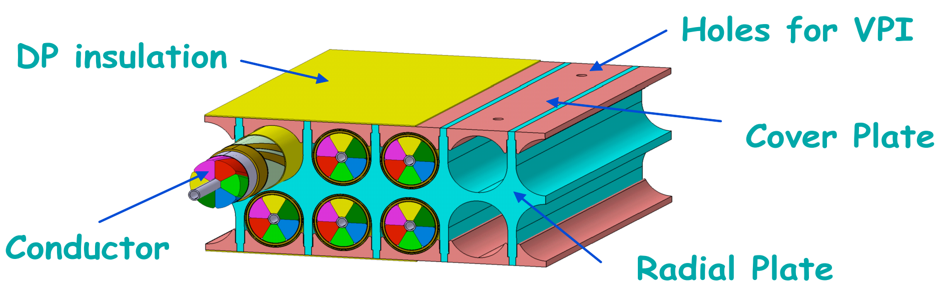
Toroidal Field (TF) Coils

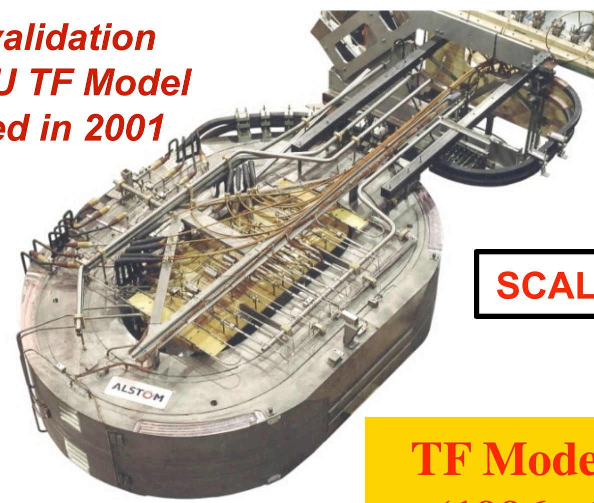
Number of coils	18 (+1 spare)
Total stored energy (GJ)	**~41**
Max. conductor field (T)	11.8
Superconductor	**Nb_3Sn**
Operating current (kA)	**68**
Operating temperature (K)	5
Number of turns	134
Height (m)	12.6
Weight (t)	~310
Centering force per coil (MN)	~400
Discharge time constant (s)	11
Max. voltage (kV)	7





Design validation through EU TF Model Coil tested in 2001





SCALE 1:3

TF Model Coil (1996 - 2002)

Central Solenoid (CS) Coils

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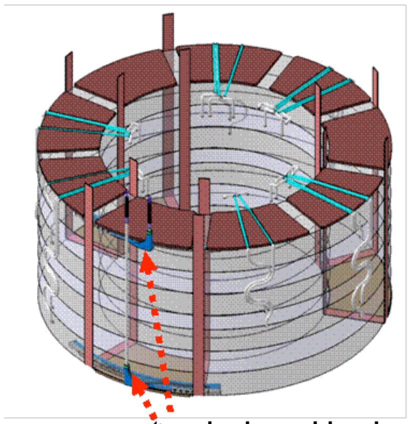
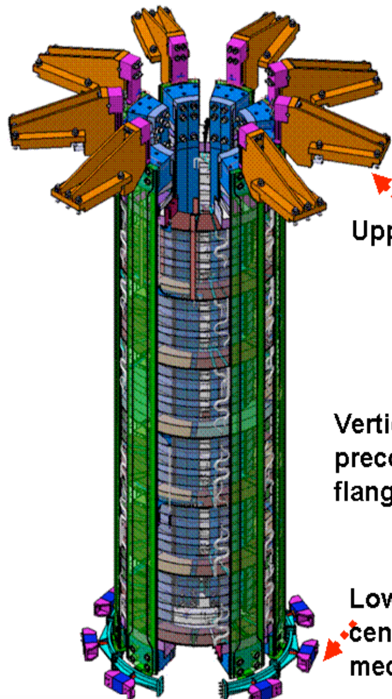
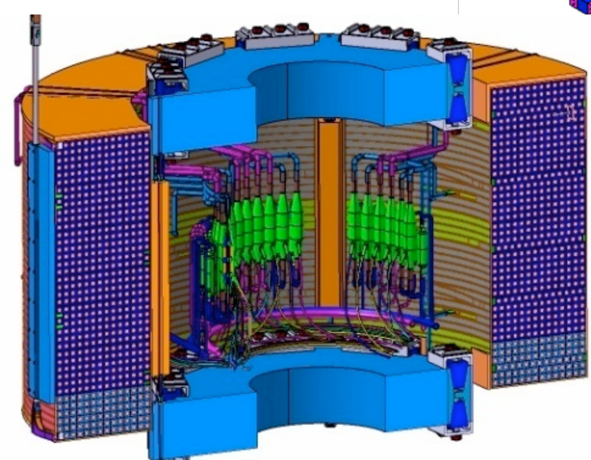




Number of modules	6 (+1 spare)
Total stored energy (GJ)	**~6.4**
Max. conductor field (T)	**13**
Superconductor	**Nb_3Sn**
Operating current (kA)	**45**
Operating temperature (K)	5
Turns per module	535
Total weight of coil assembly (t)	**~980**
Max. voltage to ground (kV)	**20**

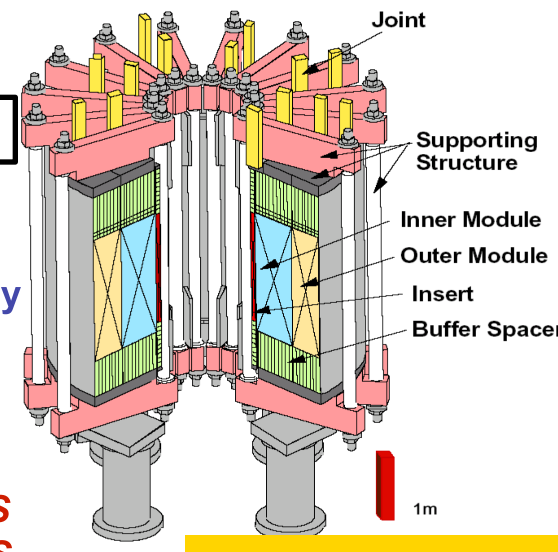
Single CS Module



CS stack composed of 6 independently powered modules wound in hexa-pancakes

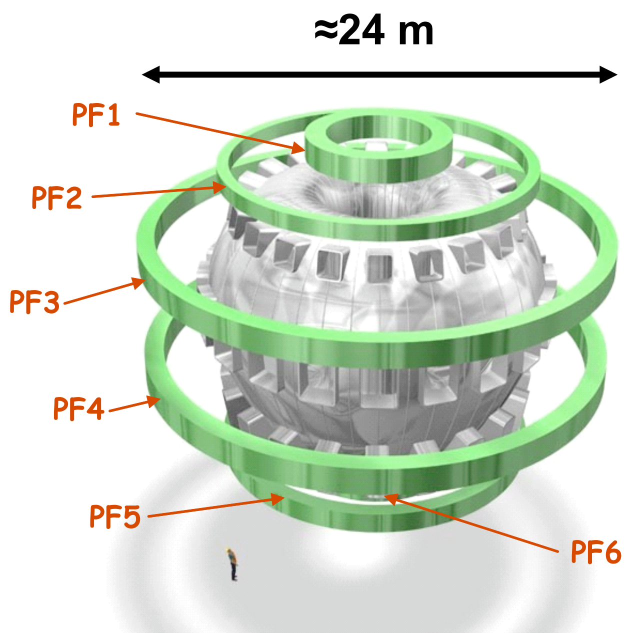
- ***Detailed design phase in progress***
- ***Design validation through JA-US CS Model Coil tested in 2000, but new CS Insert required to confirm conductor performances under tensile hoop load***

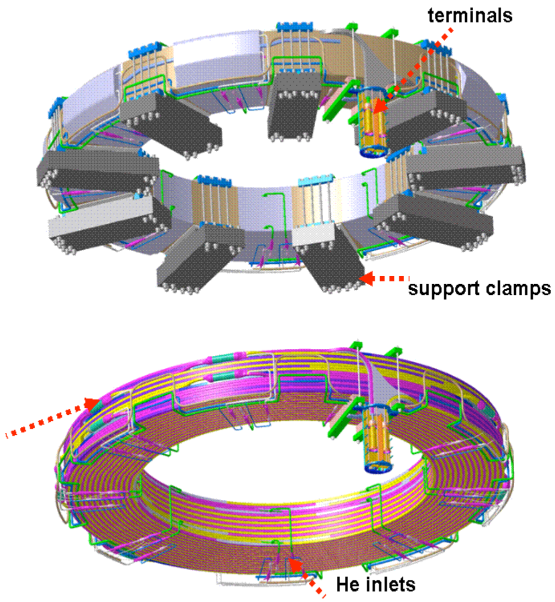
SCALE 1:1



CS Model Coil (1994 - 2000)

Poloidal Field (PF) Coils





- **6 PF coils independently powered, wound in double pancakes**
  - Confine and shape the plasma
  - PF1 & PF6 control plasma vertical displacement

- Conductor field limited to 6.5 T → NbTi, three grades of conductors depending on max. field
- Coils are large (24 m diameter) but use of NbTi simplifies construction

Design validation through EU PF Insert Coil tested in 2008

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ITER Magnet Complex Sharing

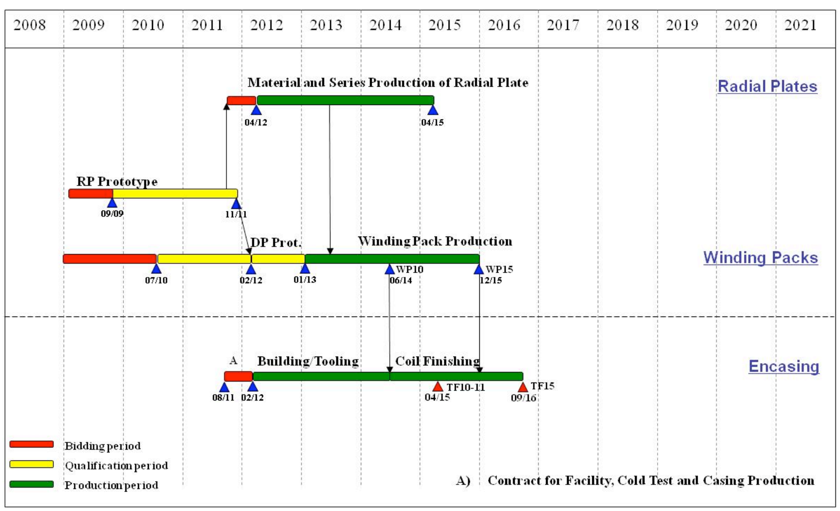
Component	IO	CN	EU	KO	JA	RF	US
TF Conductors		7%	20%	20%	25%	20%	8%
TF Windings + Insertion			10 coils		9 coils		
TF Case Sections					19 sets		
Pre-compression Rings			9 rings				
TF Gravity Supports		100%					
CS Conductors					100%		
CS Coils + Structure							7 coils
PF Conductors		69%	13%			18%	
PF Coils			5 coils			1 (PF1)	
PF Supports		100%					
CC Conductors		100%					
CC + Supports		18 coils					
Magnet Feeders		100%					
Instrumentation	100%						

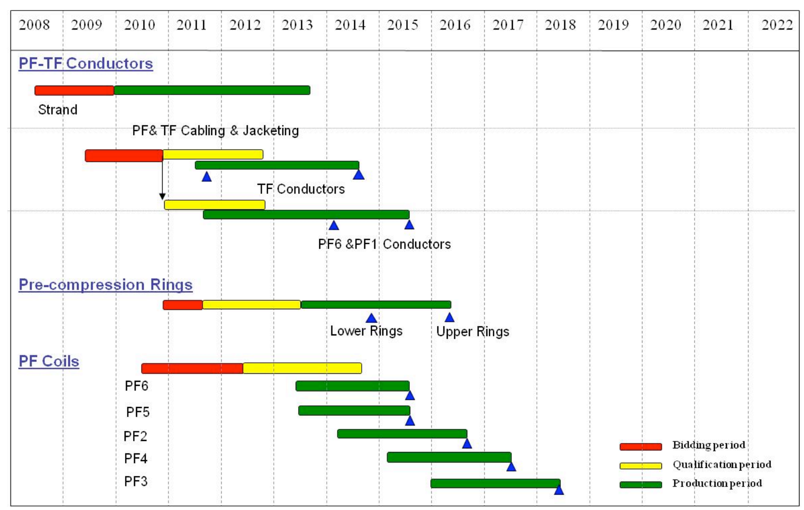
20 Procurement Arrangements (PA) signed between ITER and Domestic Agencies from 2007 till 2011 – 5 of them signed by EU

Challenging Schedule

Following the qualification and pre-production phases (typically one to two years), the following delivery rates need to be achieved:

- **95 tons of advanced Nb_3Sn strand in 3 years** ➔ **up to 3.3 tons/month**
- **27 TF & 34 PF conductor unit lengths in 3.5 years** ➔ **up to 2 conductors/month**
- **70 TF radial plates & double pancakes in 3 years** ➔ **up to 2 RPs/month**
- **10 TF coils in 2 years** ➔ **up to 5 coils/year**
- **55 PF double pancakes in 3 years** ➔ **up to 1.5 DPs/month**
- **5 PF coils in 3 years** ➔ **up to 2 coils/year**



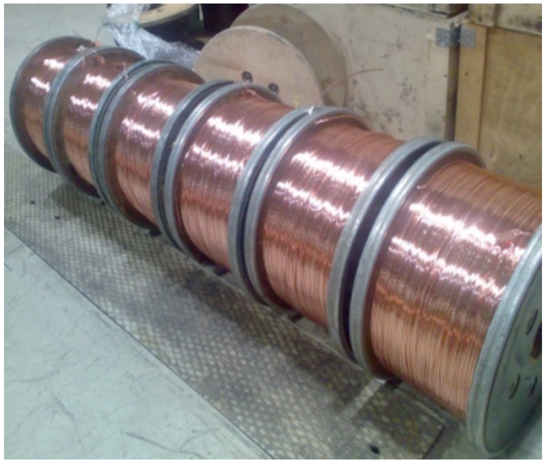


EU Magnets Procurement 1/4

EU to supply TF/PF Conductors, 10 TF Coils, 5 PF Coils & 9 PC-Rings

Contracts placed in 2008-2009 - Strand

- **Cu strand for TF conductors (62 tons, Luvata Finland, completed in 2010)**
- **Nb_3Sn strand for TF conductors (total 95 tons, 60% OST USA – 40% Bruker EAS, BEAS Germany)**
- **TF conductor qualification testing (completed at SULTAN in 2009)**
- ***Bilateral agreement with Russia to receive NbTi cables for PF6 in exchange of jacketing services for RF conductor lengths***



Spools of non-plated Cu strand (Luvata)

Nb_3Sn strand drawing machine (OST)

Part of Nb_3Sn strand testing machine (BEAS)

EU Magnets Procurement 2/4

Contracts placed in 2008-2009 – TF Coil Structures

- **Side radial plate prototype** for TF Coils (CNIM, France)
- **Central radial plate prototype** (different manufacturing method) for TF Coils (SIMIC, Italy)
- TF coil casing closure welding qualification (CSM/ISQ, Italy/Portugal)

Side radial plate prototype mock-up machining (CNIM)

Central radial plate prototype (SIMIC)

Central radial plate mock-up section welding set-up (SIMIC)

EU Magnets Procurement 3/4

Contracts placed in 2010 – Conductors and TF Coils

- **Strand characterization of TF Nb_3Sn samples (Durham Univ., UK)**
- **PF conductor testing in SULTAN (CRPP, CH)**
- **Cabling & Jacketing of TF conductors & Jacketing of PF conductors (ICAS - Italian Consortium for Applied Superconductivity, ENEA/ Criotec/Tratos)**
- **Supply of 10 TF winding packs (Iberdrola/ASG/Elytt, Spain/Italy)**
- **Engineering study of TF winding pack cold test and insertion (BNG, Germany)**

EU Magnets Procurement 4/4

Contracts in tender in 2011-2013 – Coils and Rings

- **Supply of NbTi strand characterization**
- **Full-scale supply of TF radial plates**
- **TF winding packs cold test (if approved by ITER Council) and insertion into cases for 10 TF coils**
- **Supply of 5 PF coils (PF2 to PF6)**
- **Cold test of 5 PF coils (if approved by ITER Council)**
- **Supply of 9 Pre-compression rings**

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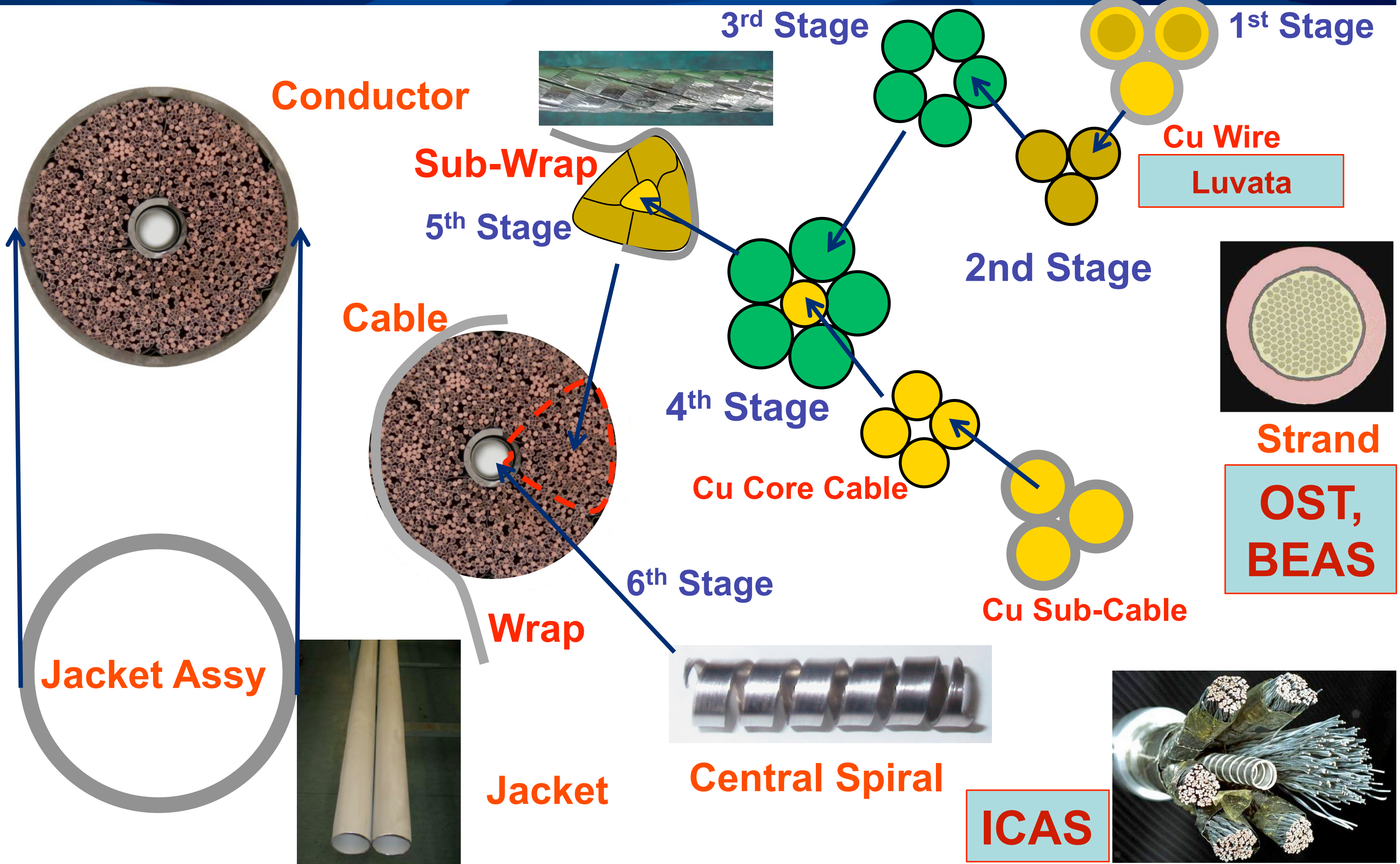
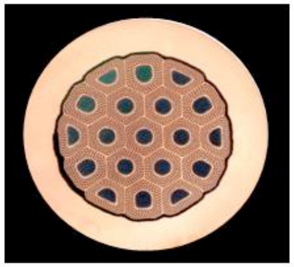
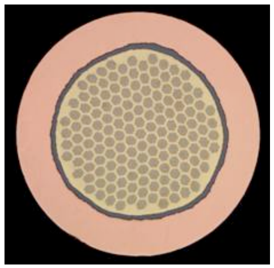
Conductor Manufacture



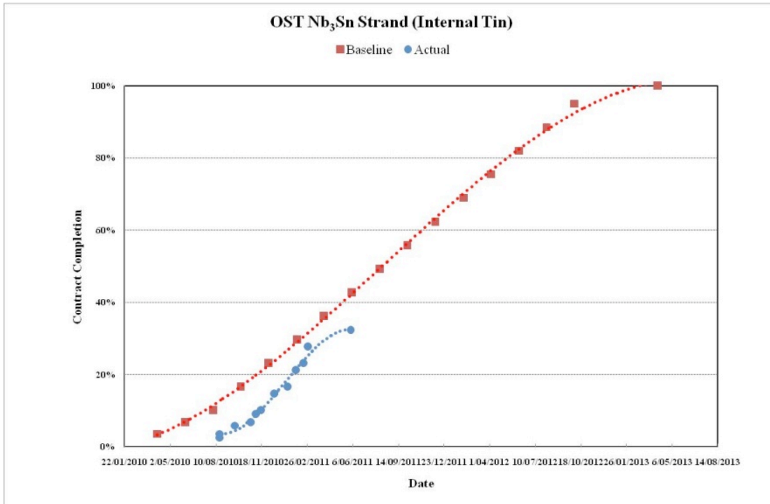
Status of Strand Manufacture



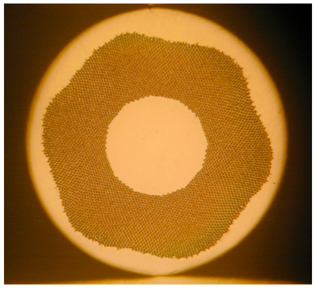
OST (USA)	Nb_3Sn (ITD)
Total	58.2 t
Start	Aug 2009
End	Oct 2012



Bruker EAS (Germany)	Nb_3Sn (BR)
Total	37.1 t
Start	Dec 2009
End	Jan 2013



Comparison between nominal and actual delivery rates of OST strand



ChMP (Russia)	NbTi
Total	45 t
Start	Oct 2009
End	Apr 2014

Supplier	Luvata Pori (Finland)	OST Carteret (USA)	Bruker EAS (Germany)	ChMP (Russia)
Type of strand to be produced	Cu-OFE, Cr plated	Nb_3Sn - Internal Tin Diffusion route, Cr plated	Nb_3Sn -Bronze route, Cr plated	NbTi, Ni plated
Strand manufacturing status	62 t (completed in September 2010)	18.2 t	2.6 t	14 t

Cabling & Jacketing

Cabling Facilities at Tratos

Jacketing Facility at Criotec

Test Facilities for Conductors: SULTAN & EDIPO, CRPP (CH)

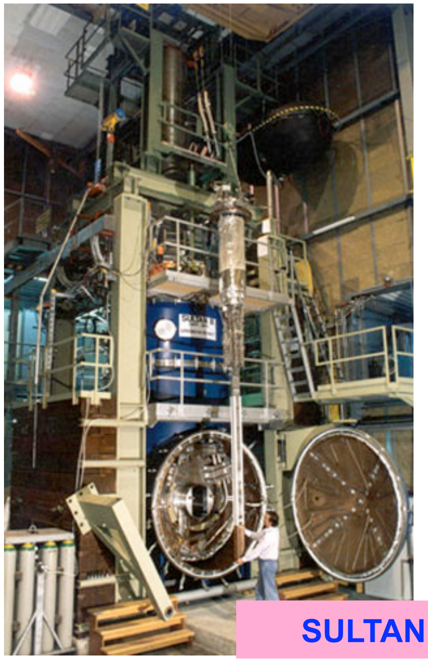
SULTAN (SUpraLeiter Test ANlage)

• Split solenoid coil: it allows tests of <u>short conductor samples</u> (~3 m) in various magnetic field orientations up to 12 T, 100 kA current

➔ <u>Length of High Field area = 450 mm</u>

• Operated by CRPP in Villigen (Switzerland)

• Unique in the world: all ITER conductors are qualified at SULTAN

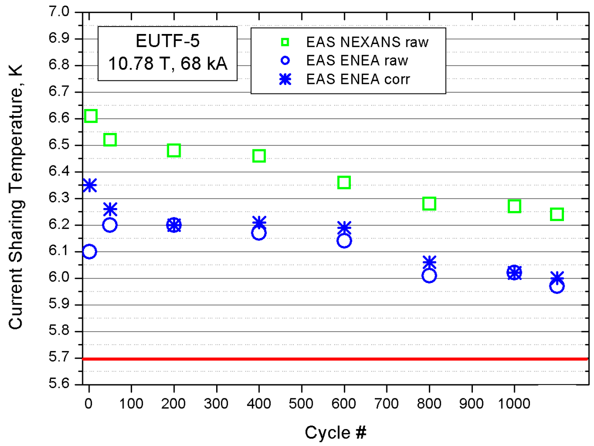


SULTAN

EDIPO (European Dipole)

• High field, large bore dipole procured by F4E and completed by BNG in May 2011, under assembly at CRPP

• Operation to be started in early 2012 to test the same samples at a higher field (13 T) & <u>longer length of High Field area = 1200 mm</u>



Qualification of EU Sample with Bruker EAS Strand

EDIPO

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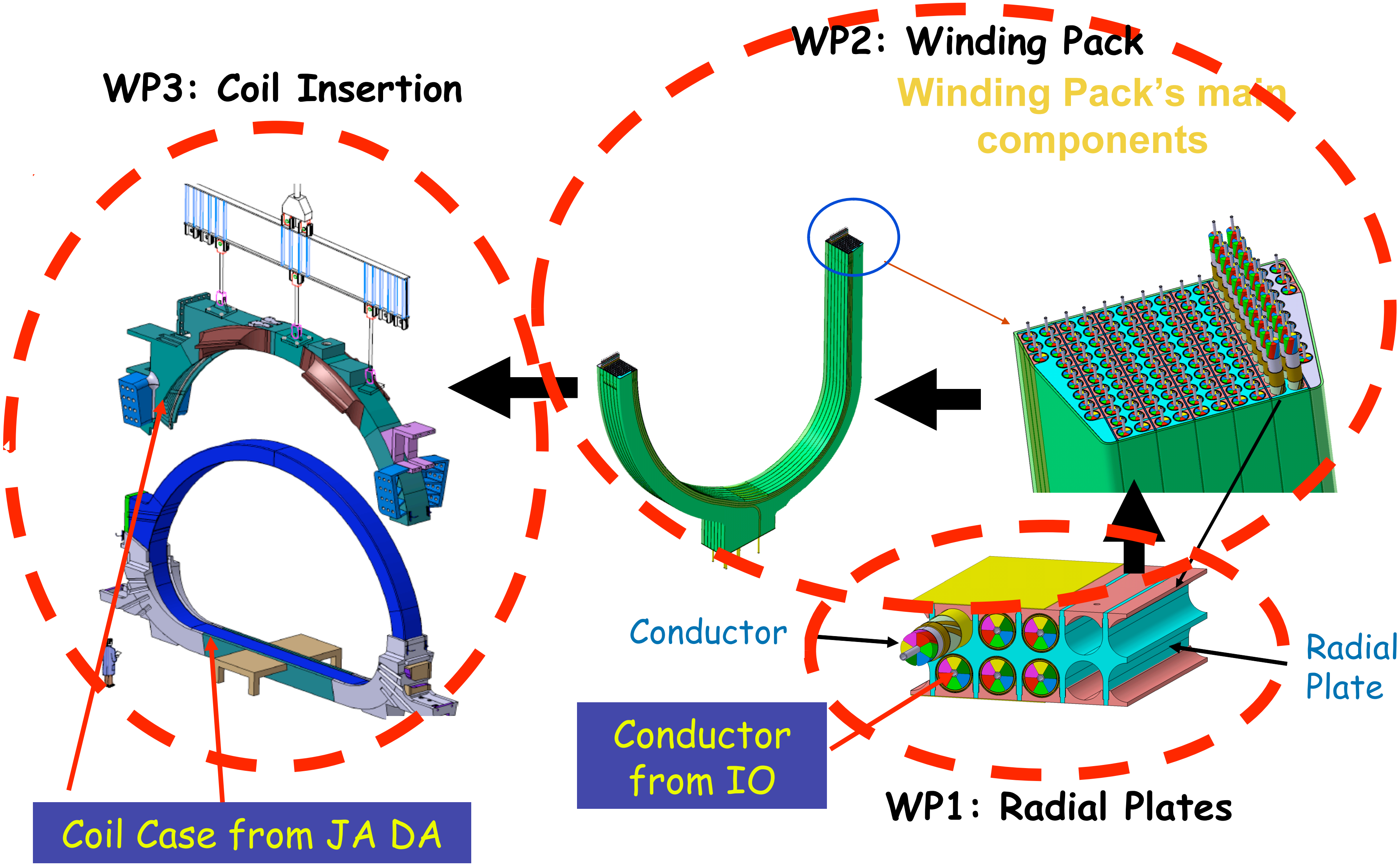
EU Procurement Strategy for TF Coils

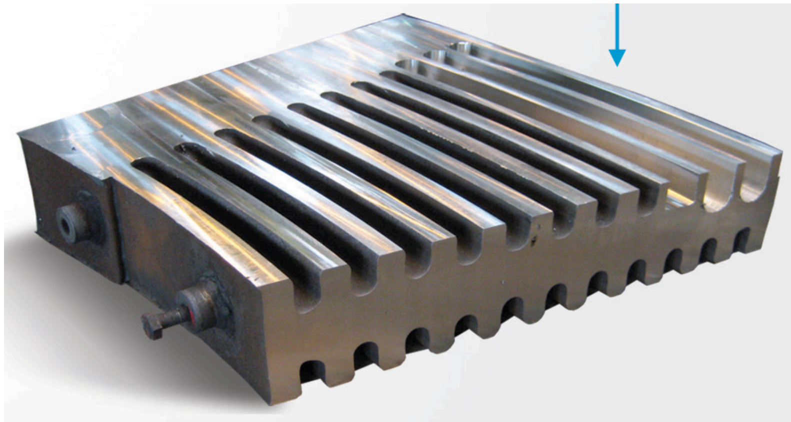


Radial Plate Prototypes

• Regular Radial Plate Prototype:
- 16 segments produced by powder HIPping
- mechanical properties under investigation
- welded together by narrow-gap GTAW
- flatness tolerance of 3mm achieved on rough-machined segments
- final machining to achieve 1mm overall flatness in progress with a large portal machine
- completion foreseen in July 2011

• Side Radial Plate Prototype:
- 7 segments produced by forging and final grooves pre-machined in each segment
- high strength and fracture toughness
- flatness tolerance of 1mm achieved on separate segments
- welded together by local EBW
- final local machining at welded regions only
- completion foreseen in September 2011

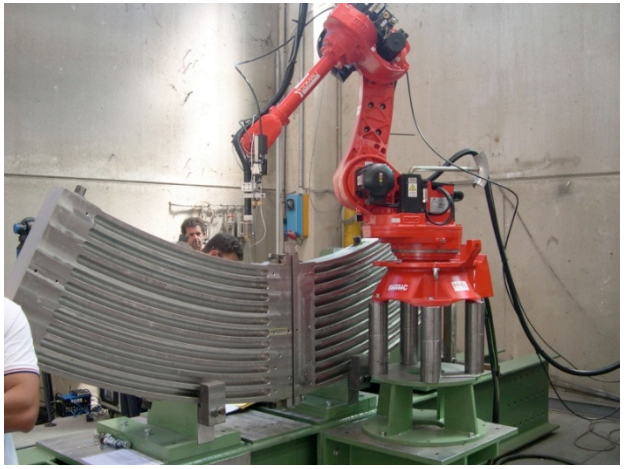
Manufacture of Radial Plate Prototypes



Radial plate segment produced by powder HIPping (SIMIC)

Machined side radial plate segment (CNIM)

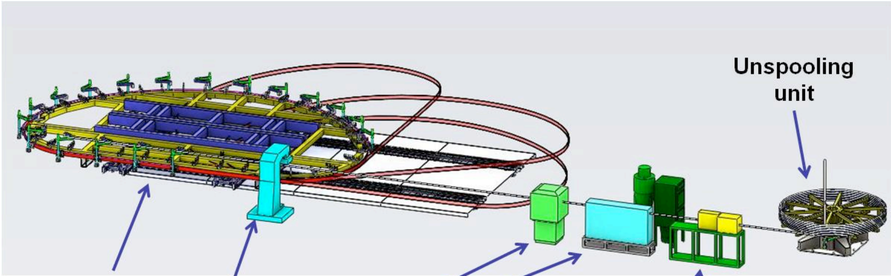
Local vacuum Electron Beam Welding machine (CNIM)



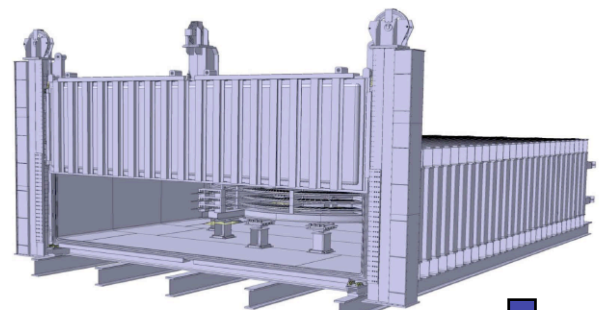
Assembly of radial plate with GTAW welding (SIMIC)

Large portal machine for full radial plate (SIMIC)

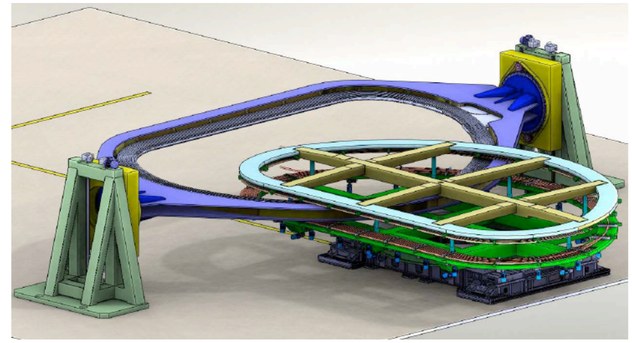
TF Double Pancake (DP) Manufacturing Steps



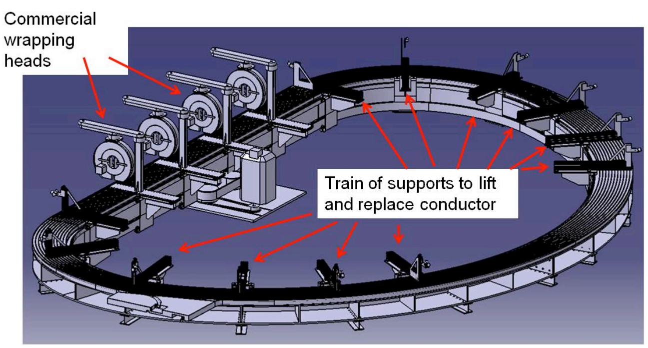
Winding



Heat Treatment of 2-3 DP

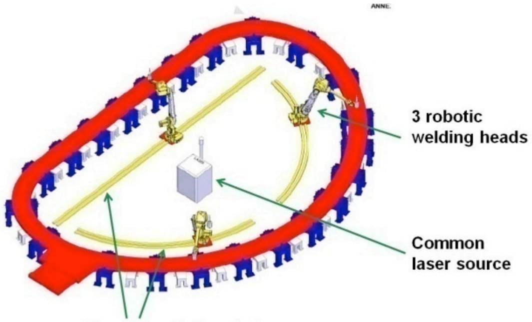


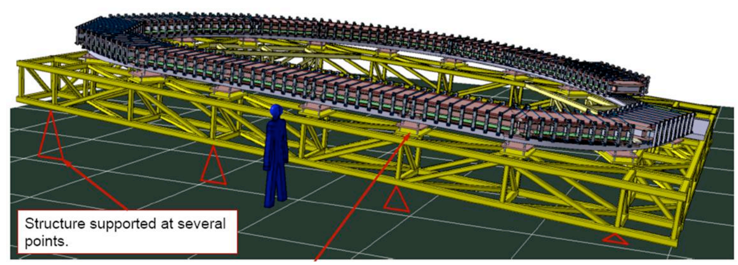
Transfer into Radial Plate



Turn Insulation

Cover Plate Laser Welding

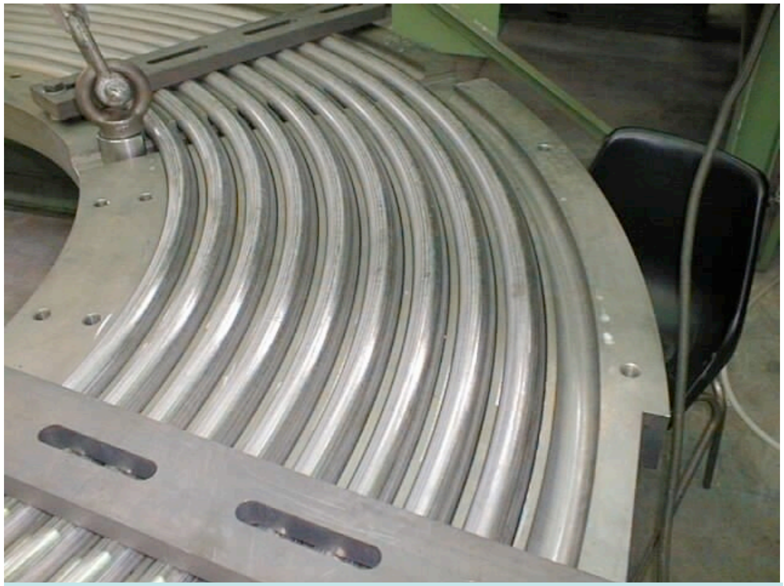




DP Vacuum Pressure Impregnation (VPI)

A Big Challenge: the conductor change in length during HT

In the TFMC the measured change in length was +0.05%



Before HT: Gap on EXTERNAL side of groove

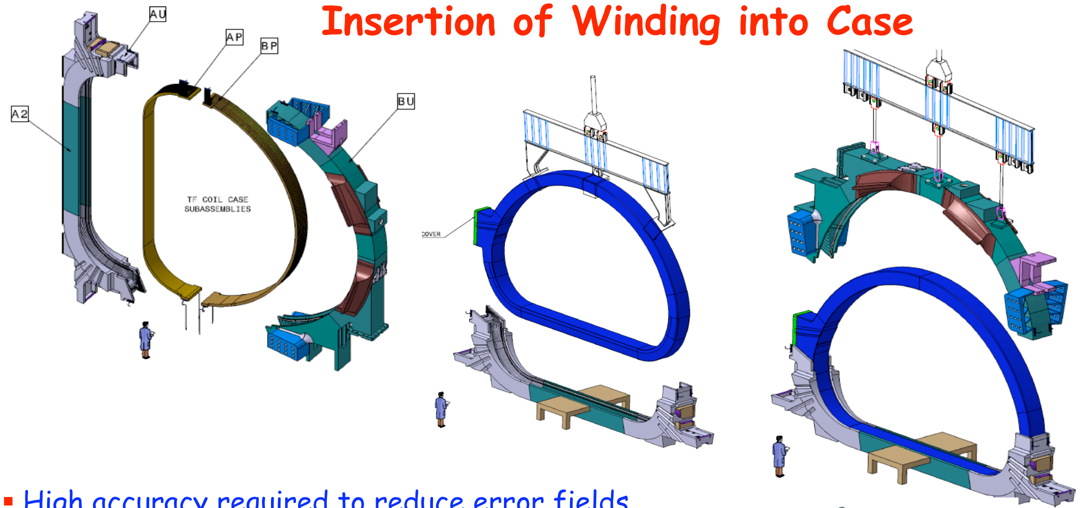
Heat Treatment

After HT: Gap on INTERNAL side of groove

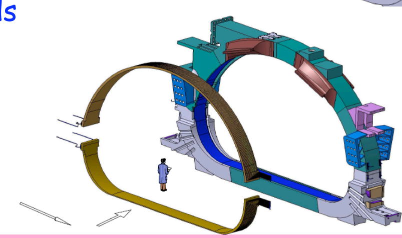
Extrapolating to the full size TF coils = expansion of 7 mm !

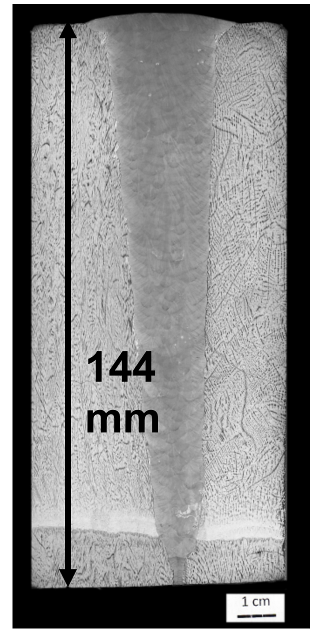
Insertion of TF Winding in Case

Insertion of Winding into Case



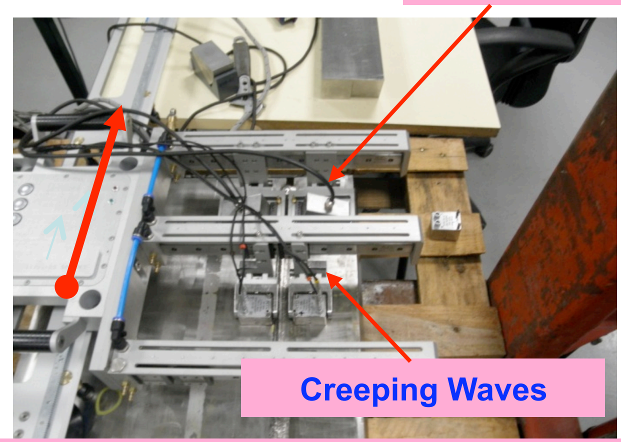
- High accuracy required to reduce error fields
- Reduce machining of huge components
- Fitting gaps carry stress penalty





Thick Hybrid Laser + GMAW Weld (CSM)

Phased Array



Creeping Waves

Ultrasonic Inspection of Welded Joint (ISQ)

EU Mock-up Forged Section (2002)

JA Forging Qualification

Pre-compression Ring Qualification

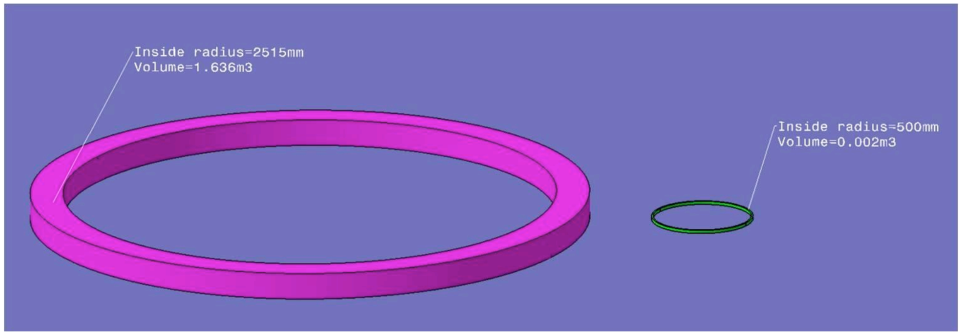
- R&D work carried out at ENEA Frascati to qualify the base material properties (tensile, ultimate, relaxation, creep, thermal contraction, etc.)
- 1/5 scale mock-ups manufactured and tested at RT under similar static load/hoop stress conditions as in the full-size rings after pre-loading during ITER assembly

Ring mock-up before test

Test ring assembly into test machine

… and ring mock-up after test

Scale-up from test ring to full-size ring



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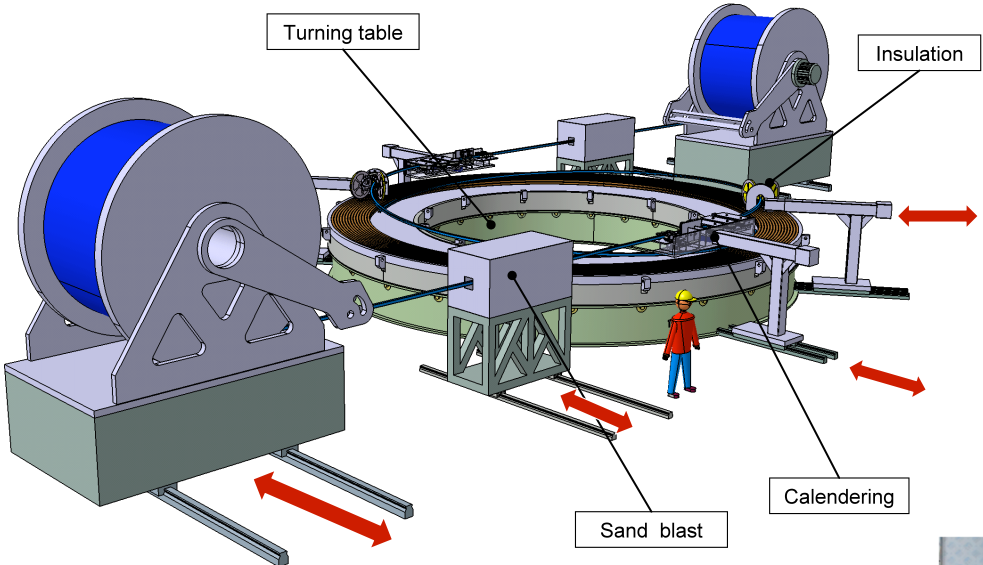
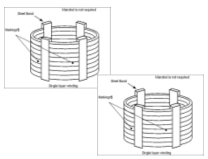
PF Coil Fabrication



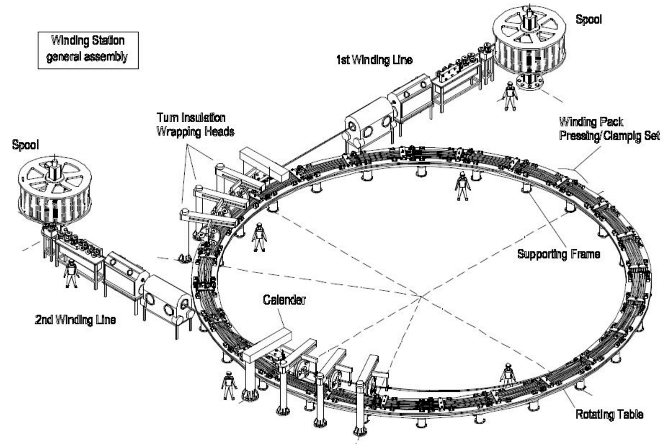
One possible winding scheme shown:
EU call-for-tender for manufacture of PF2-PF6 in progress, supply contract to be placed in 2011

Winding tooling prepared by RF DA for PF1 double pancakes: insulating and impregnation equipment & devices have been designed and procurement is in progress

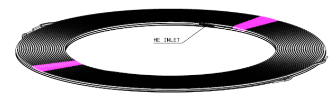
PF Coil Fabrication



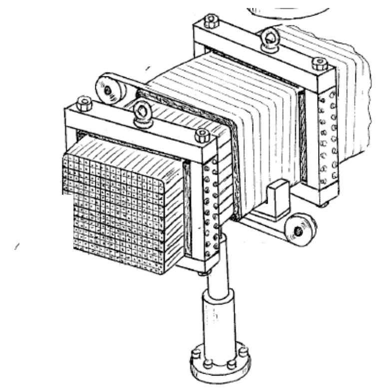
CICC Preparation



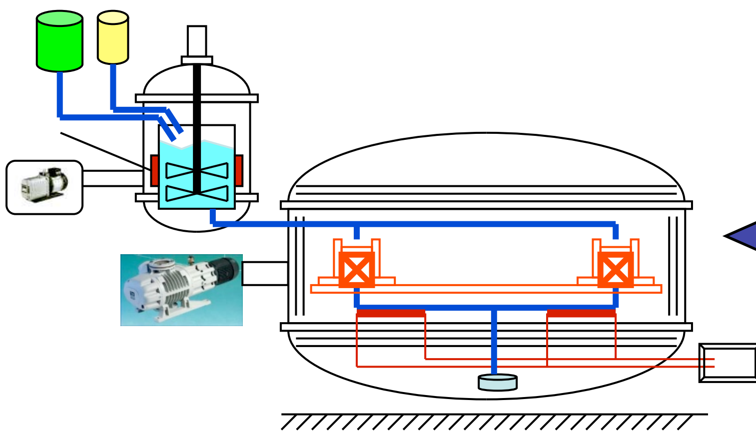
Winding & Insulation



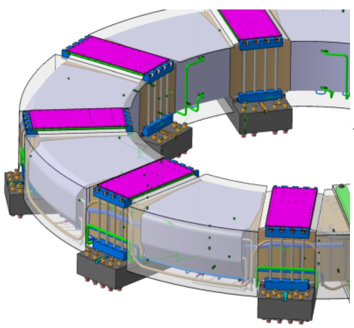
DP Impregnation



DP Stacking & Ground Wrapping

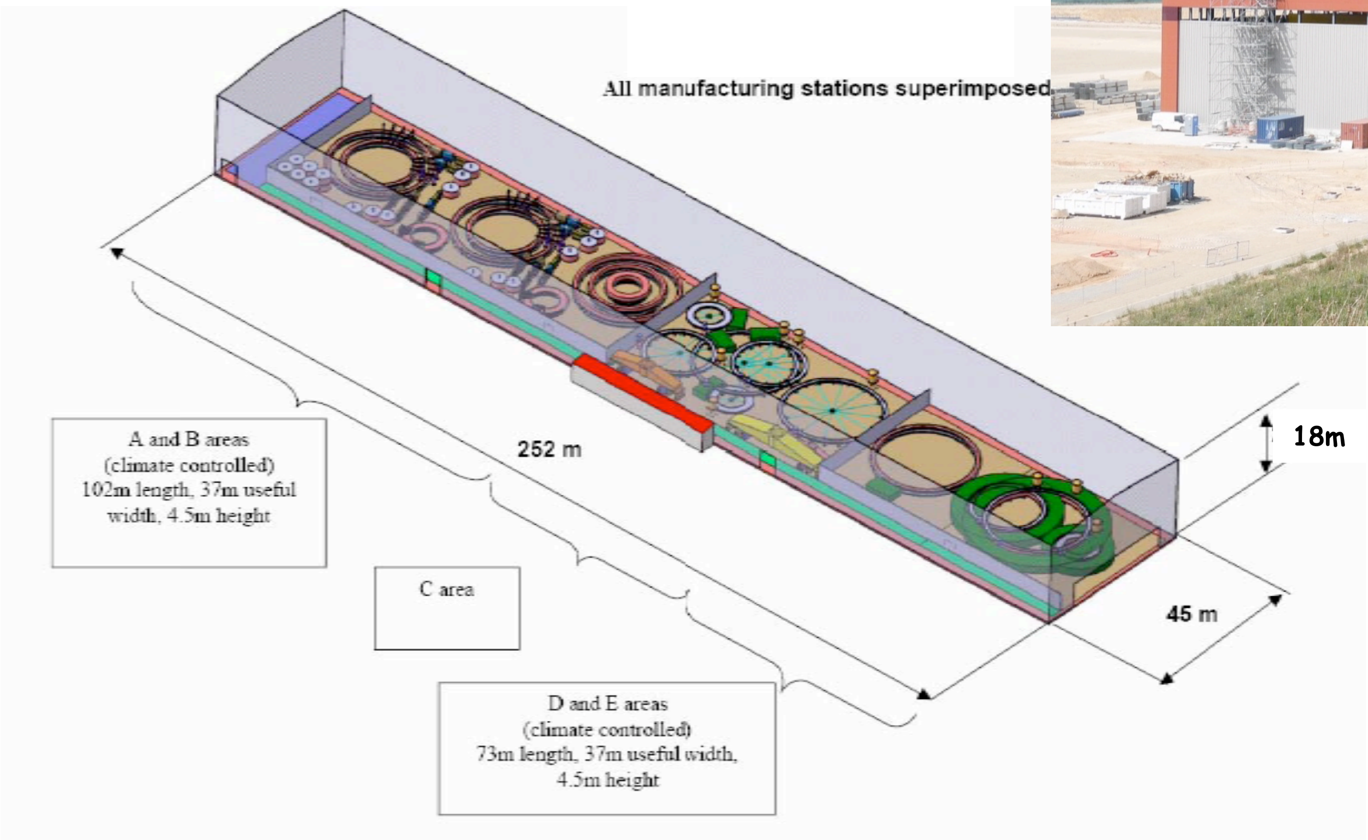


Final VPI



Assembly of Clamps & Covers

PF Coil Manufacturing Building in Cadarache



FUSION FOR ENERGY

- Introduction
- ITER Magnet System Design
- EU Magnet Procurement
- Conductors
- Toroidal Field Coils
- Poloidal Field Coils
- Summary

Summary

- Procurement phase started at the end of 2007 with the signature of first Procurement Arrangement for TF Conductors
- Supported by many years of design and R&D work ➔ Model Coils and Insert Coils
- Several technical issues never experienced before on coils of this size are still open and must be tackled in the first stages of manufacture
- Main challenges:
    i. organization of in-kind contribution
    ii. management of large and complex procurement contracts
    iii. stringent QA requirements
    iv. tight, success-oriented, manufacturing schedules
    v. risk & cost containment

Thank you for your attention

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