Building the ITER Magnets

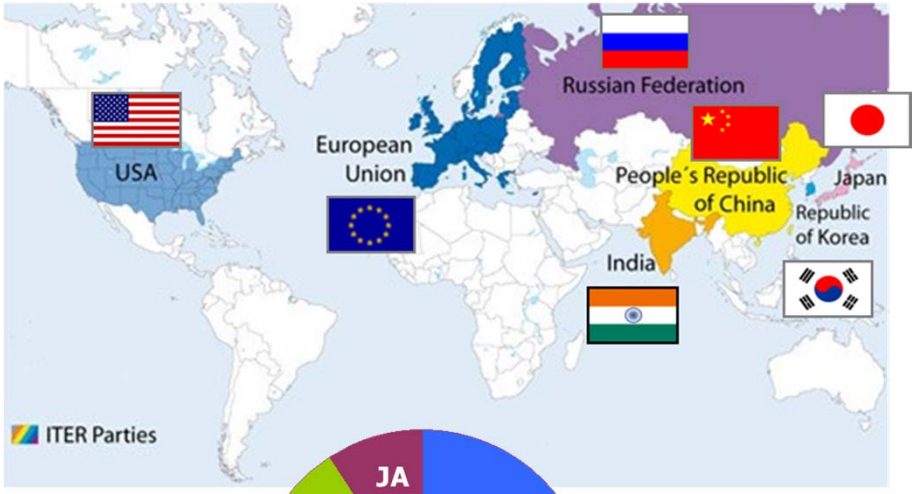
Neil Mitchell
ITER IO

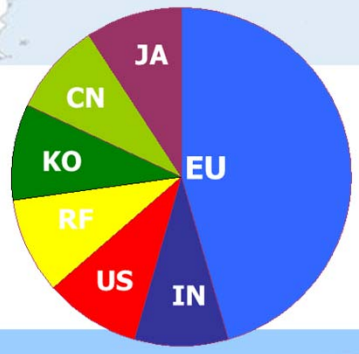
Cadarache
22 April 2013

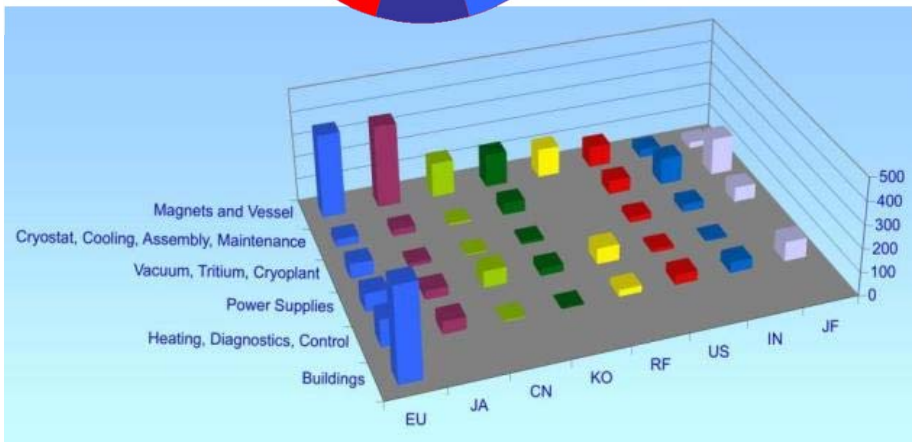
ITER Parties & ITER Agreement

china eu india japan korea russia usa

- ITER is supported by 7 Parties (CN, EU, IN, KO, JA, RF and US) that represent more than half of the world population.
- The 7 ITER Parties have agreed on a sharing of the construction costs
  - 5/11th for the EU and 1/11th for each other Party,
  - 90% of in-kind contributions and 10% of cash contributions (directly handled by ITER IO).
- The breakdown of who contributes what is at the component level and is set out in the ITER Agreement.







ITER Site Construction – 1

china eu india japan korea russia usa

Model of ITER Site 2006

ITER Site Construction – 2

china eu india japan korea russia usa

ITER Headquarters Building
(4 storey; 16,000 m^2)

ITER IO Staff: ~550
Contractors: ~300

- The ITER site was selected on 28 June 2005.

- It is located in Cadarache, ~40 km north of Aix-en-Provence.

PF Coil Winding Building
(17 m high;252 x 45 m)

Tokamak Building
Pit and Seismic Isolators
(17 m deep;120 x 90 m)
B2 slab started

CONTENT

china eu india japan korea russia usa

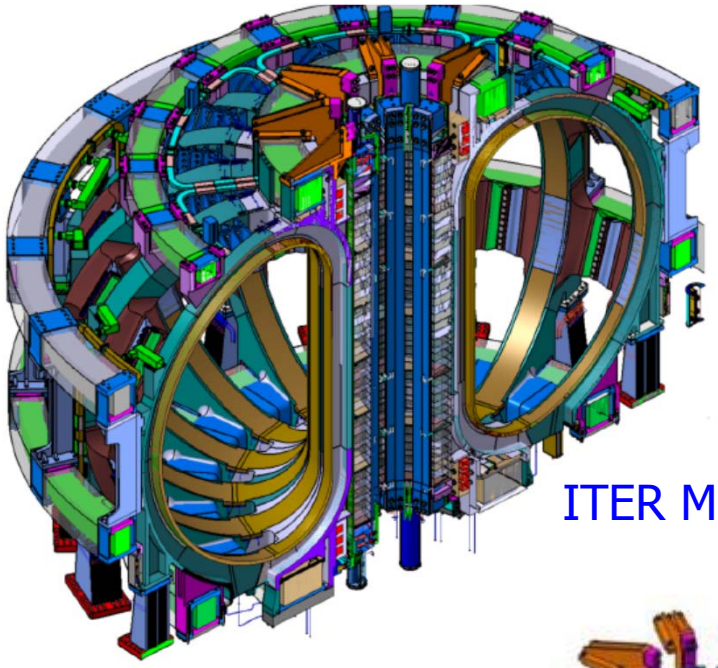
- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils, Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

CONTENT

china eu india japan korea russia usa

- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

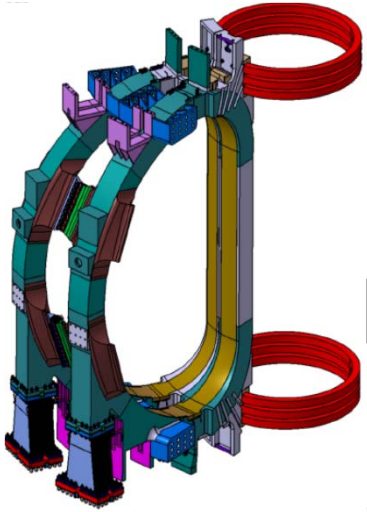
ITER Magnet System – Overview



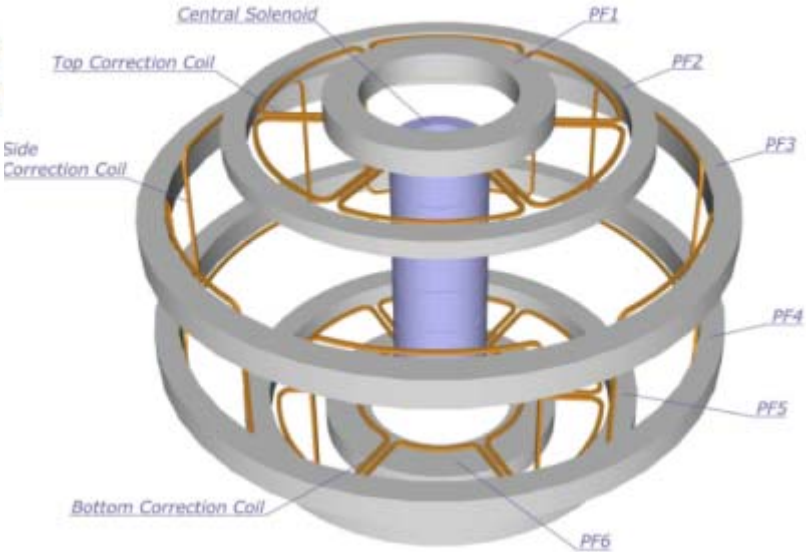
- The ITER magnet system is made up of
  - 18 Toroidal Field (TF) Coils,
  - a 6-module Central Solenoid (CS),
  - 6 Poloidal Field (PF) Coils,
  - 9 pairs of Correction Coils (CCs).

ITER Magnet System

Pair of TF Coils



CS Coil



(PF1)

PF Coils

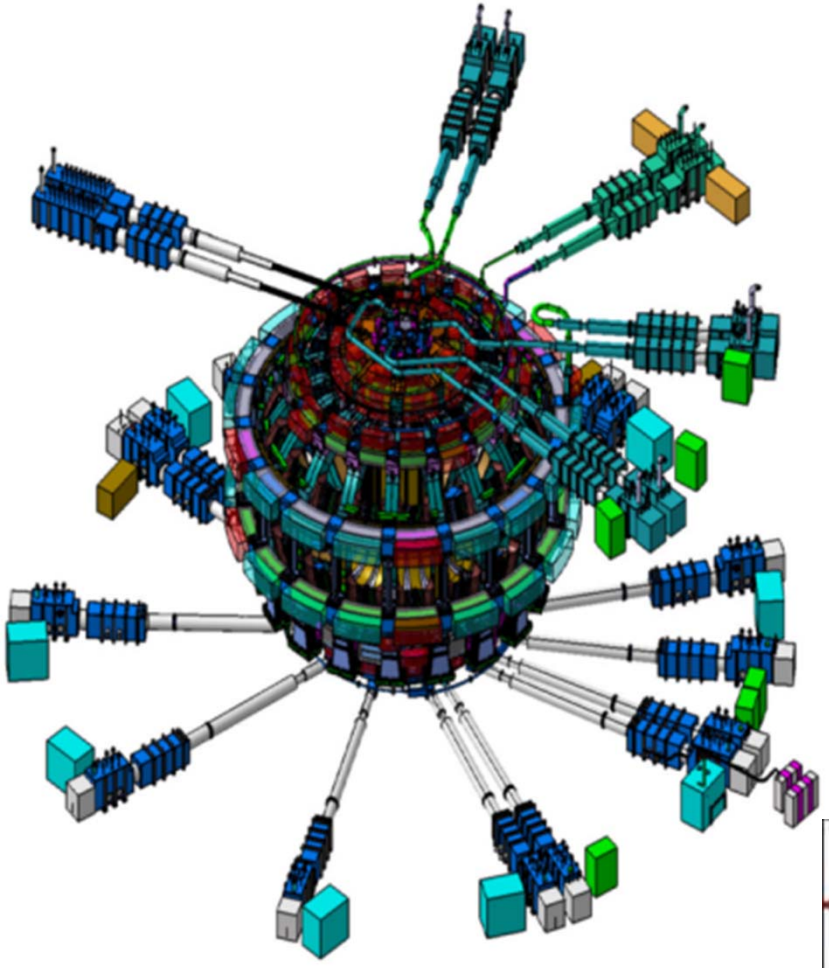
(PF2-6)

CCs

ITER Feeder System – Overview

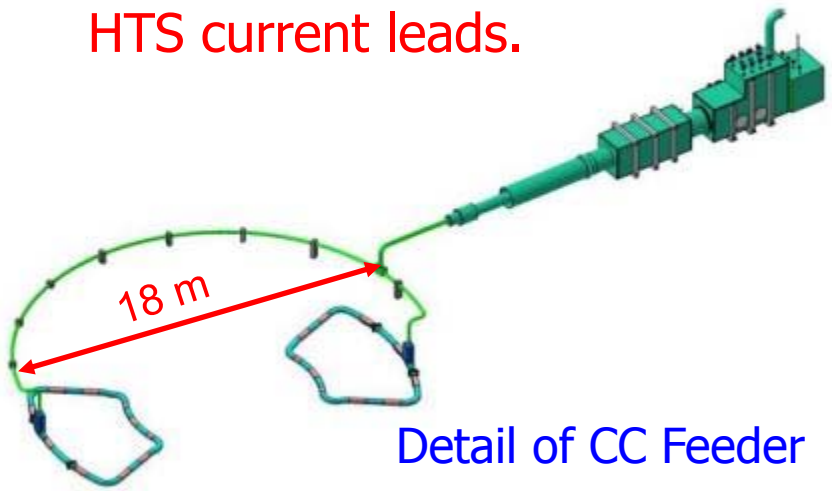
china eu india japan korea russia usa

- The magnets are supplied in current and cryogenic fluids by 31 Feeders.



ITER Feeder System

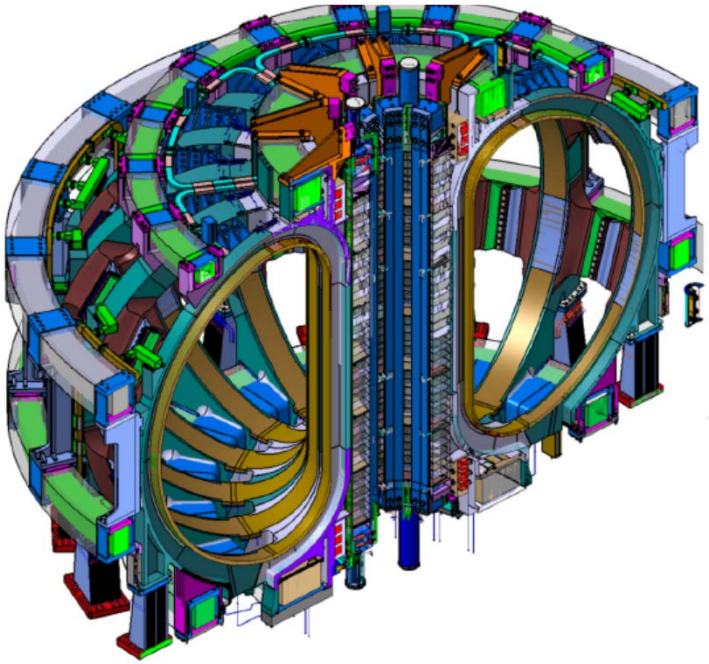
- The magnet Feeders include
  - NbTi CICC busbars,
  - Ag-Au(5.4%) BiSCCO 2223 HTS current leads.



Detail of CC Feeder

68 kA Trial Lead Developed by ASIPP

Stored Energy of ITER Magnet System



ITER Superconducting
Magnet System Energy
~51 GJ

Charles de Gaulle Airplane Carrier Energy
~38000 t at ~180 km/hr
(fast discharge equivalent to stopping it in ~20s,
a braking distance of 500m)

ITER Magnet Supply: 10 PAs

iter china eu india japan korea russia usa

CS with US (General Atomics)

Pre-compression rings: EU (EADS CAS)

PF1: RF (Efremov)

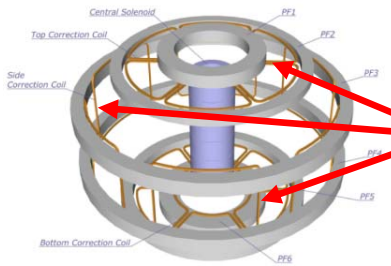
9+1 TF coils with EU (Iberdrola/ASG/Elytt Consort.)

9 TF coils with JA (MHI)

PF2-6: EU (*not decided*)

Magnet Supports: CN (SWIP)

19 TF coil cases: JA (MHI/Hyundai Consort.)



9 pairs of CCs: CN (ASIPP)

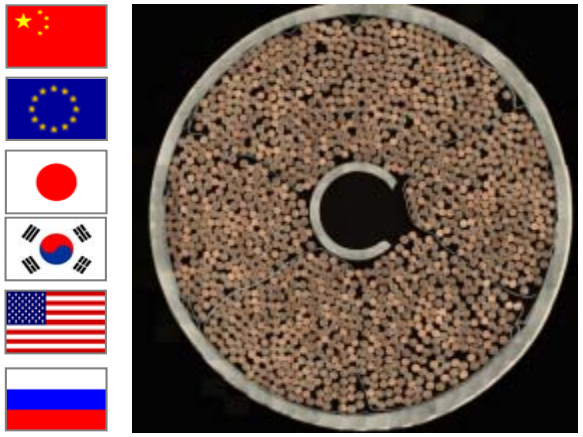
31 Magnet Feeders: CN (ASIPP)

ITER Conductor Supply: 11 PAs

iter china eu india japan korea russia usa

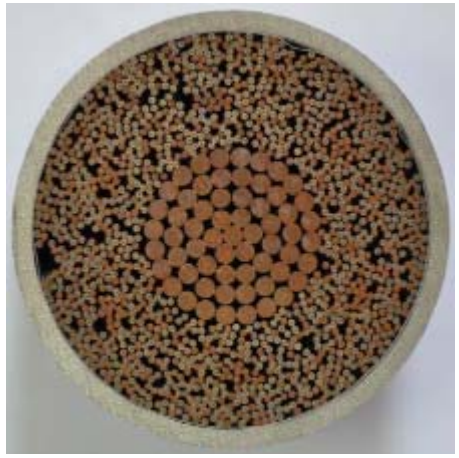
Nb_3Sn

TF Conductor



(dummy)
CS Conductor

PF Conductor



MB Conductor

Nb–Ti

CC Conductor

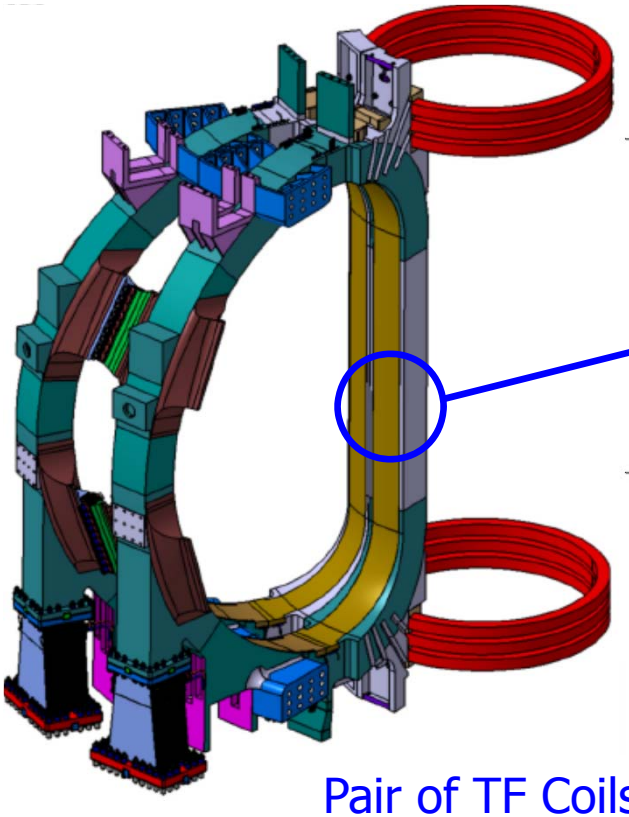
(dummy)
CB Conductor

CONTENT

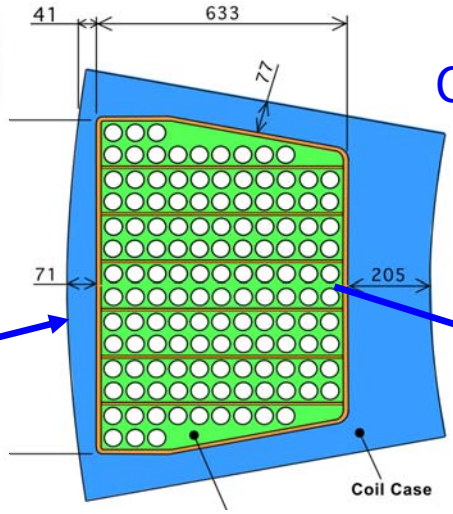
china eu india japan korea russia usa

- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

Main Features of TF Coils -1

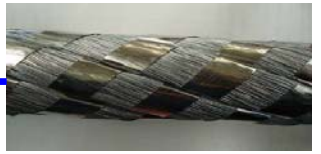


Pair of TF Coils

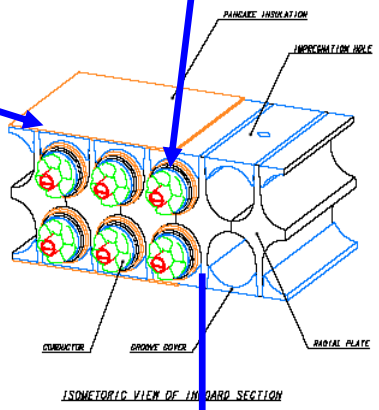


Winding Pack

CIC Conductor



Nb_3Sn Rope-Type Cable



Double Pancake

Stainless Steel Radial Plate

- Main assembly steps: wind, react, transfer and impregnate.

Main Features of TF Coils -2

Manufacturing Challenges

Nb3Sn strand and conductor

- Nb3Sn required, brittle and has to be formed after winding by heat treatment of about 600C for 200hrs
- Has to achieve a high critical current and controlled AC loss

Fitting conductor into radial plates

- High tolerances on RPs (tenths of mm over 15m)
- High tolerances on winding and control of conductor distortion during Nb3Sn heat treatment

Massive structures with small tolerances (few mm)

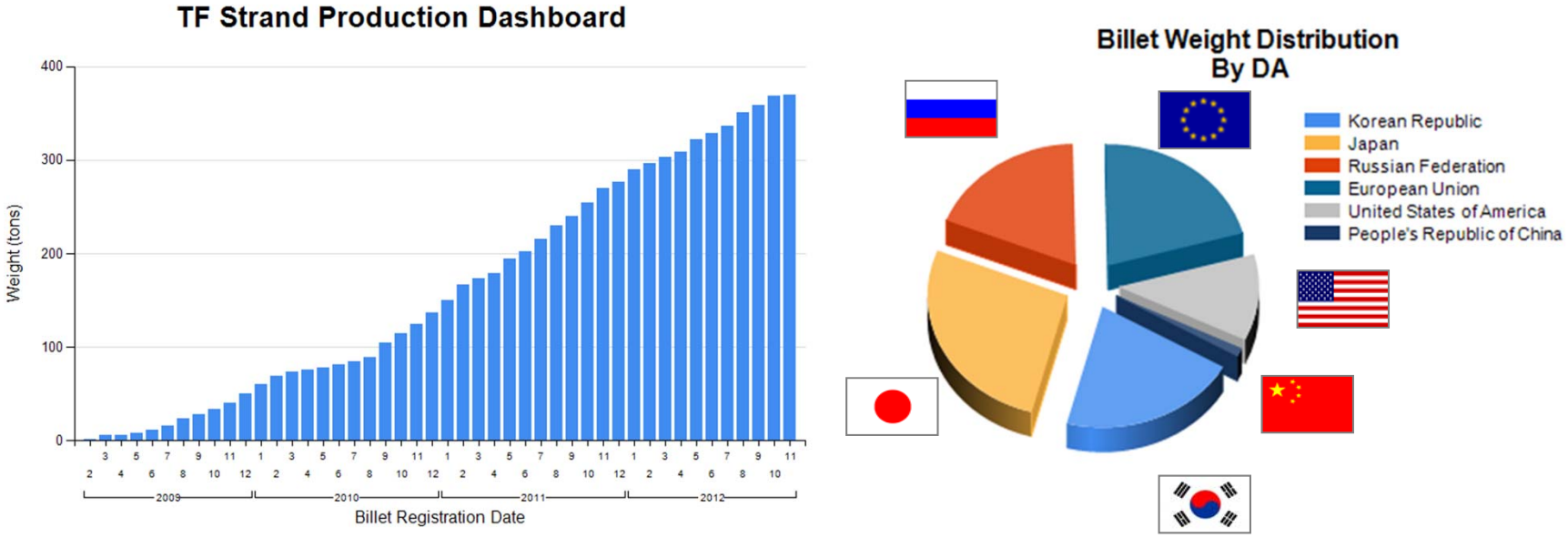
Assembly of RP to winding and fitting winding pack into case

LOGISTICS DUE TO MULTIPLE SUPPLIERS!!!

ITER TF Strand Production

china eu india japan korea russia usa

- As of today, nearly ~409 tons (85,000 km) of Nb_3Sn strands have been produced; this corresponds to ~90% of total amount needed.
- It is the largest Nb_3Sn strand production ever – pre-ITER world production was ~15 t/year.

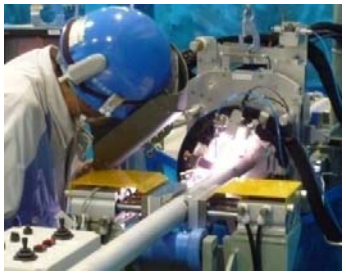


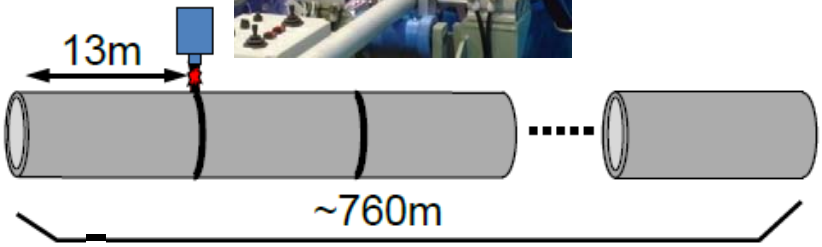
Dashboard of Billet Registration in Conductor Database
(Courtesy of I. Pong and G. Bevillard, ITER-IO)

ITER Conductor Manufacture

Jacket Inspection

Orbital Welding

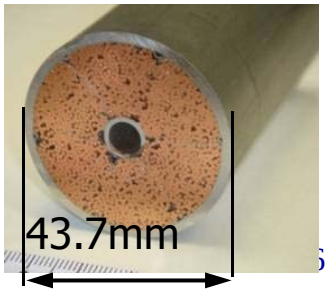


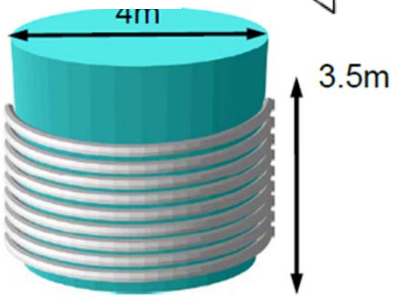


Jacketing Line

Cable Insertion

Compaction





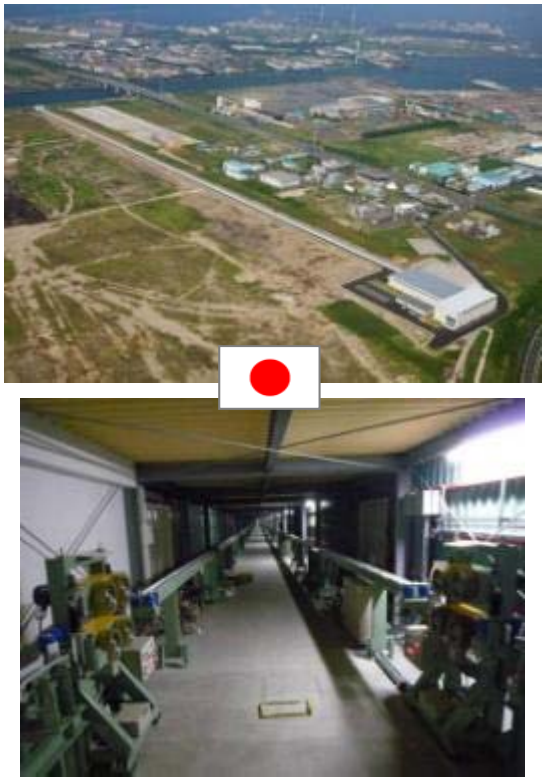
Spooling

Final Tests

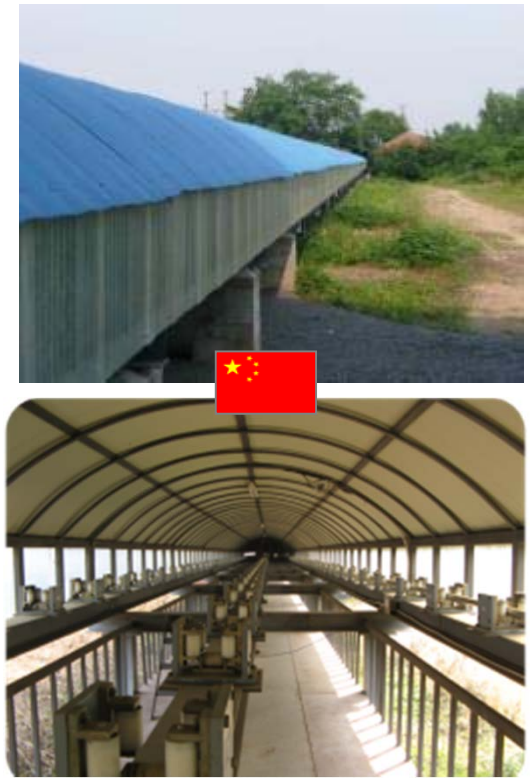
(Courtesy of JAEA)

ITER Jacketing Lines – 1

- 5 DAs (JA, CN, RF, EU and US) have built dedicated 800-1000 m long jacketing lines, while KO is subcontracting jacketing work to EU supplier.



JA Jacketing Line at NSE



CN Jacketing Line at ASIPP

RF Jacketing Line at IHEP

ITER Jacketing Lines – 2

iter china eu india japan korea russia usa

- JA, CN, RF and EU/KO have completed commissioning; US is expected to be ready early next year.

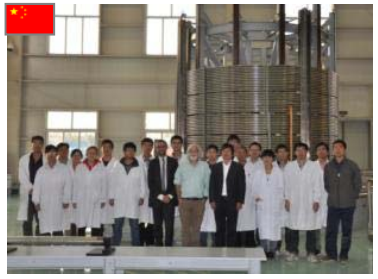
EU Jacketing Line at Criotec

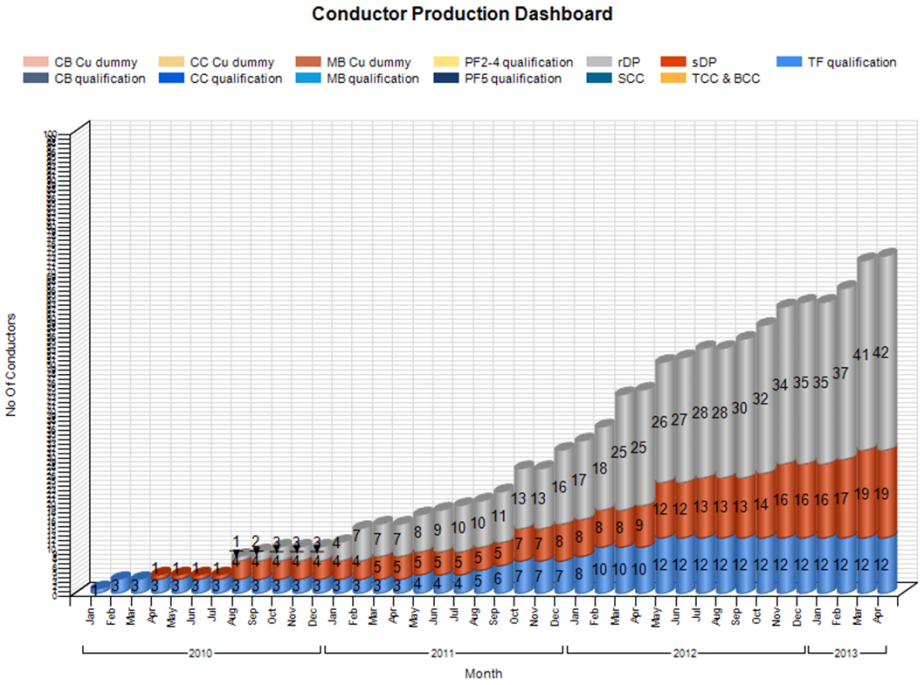
US Jacketing Line at HPM

ITER TF Conductor Production

iter china eu india japan korea russia usa

- In addition to 12 x Cu and sc qualification ULs, a total of 42 x 760 m rDP ULs and 19 x 415 m sDP ULs have been manufactured by JA, KO, RF, F4E and CN; this corresponds to ~8 TF Coils.



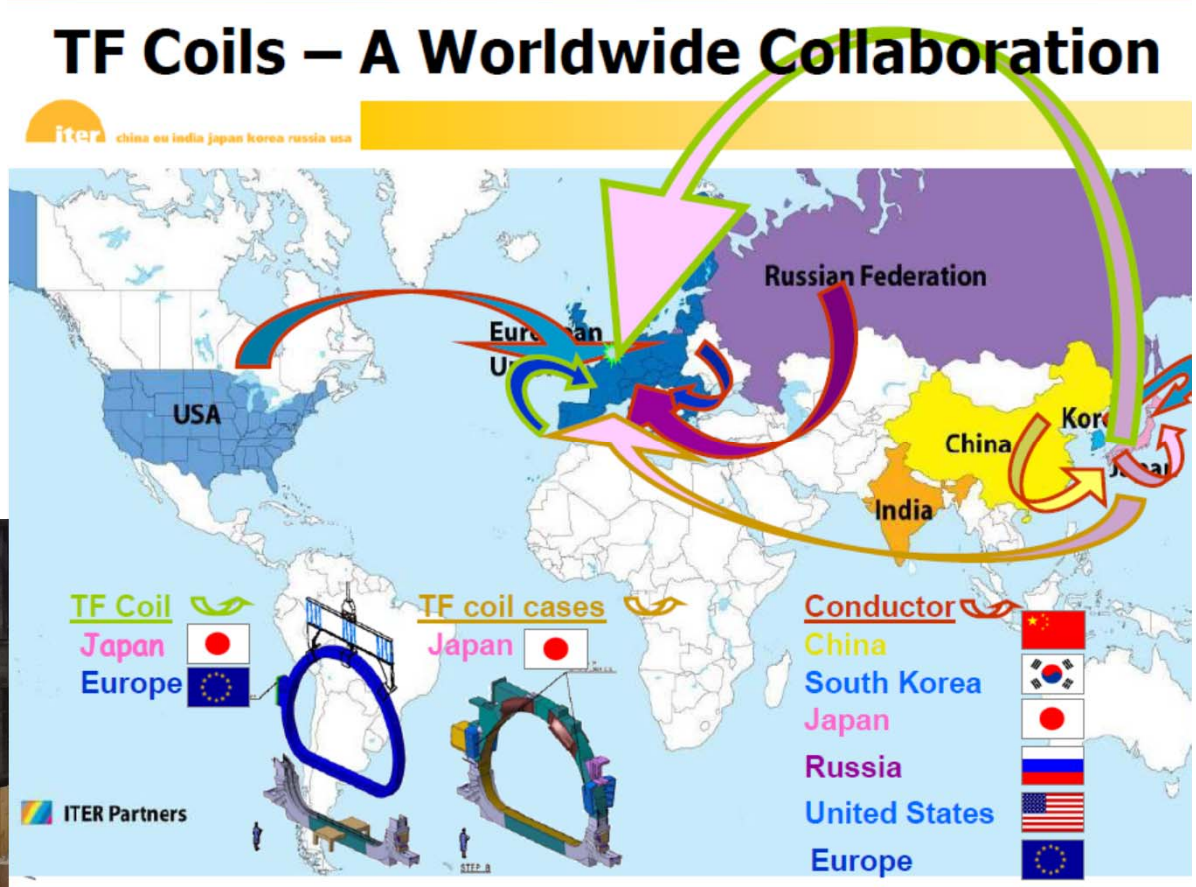


Dashboard of TF Conductor Registration in Conductor Database

(Courtesy of G. Bevillard, ITER-IO)

ITER TF Conductor Shipping Nightmare

Conductor is being stored in large warehouses in Japan and (soon) in Europe

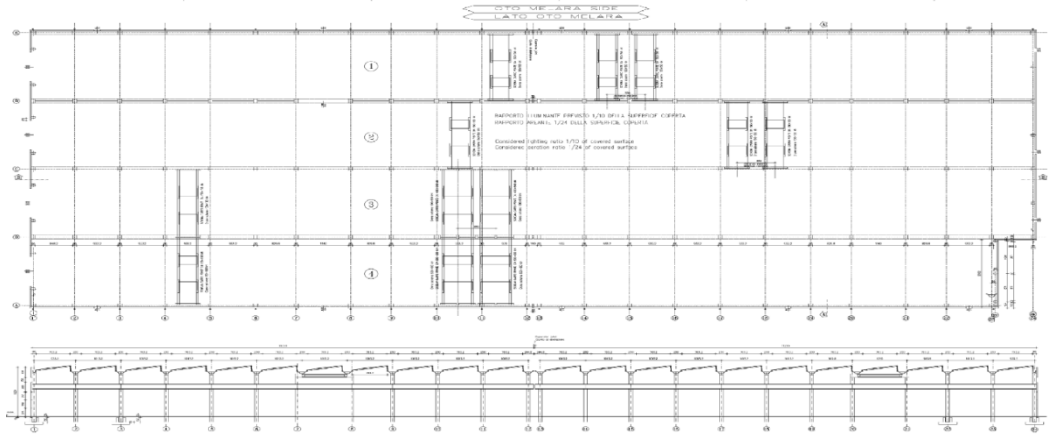


For TF conductor, the rate of supply exceeds usage

Progress on TF Coils: Facilities in EU and JA

china eu india japan korea russia usa

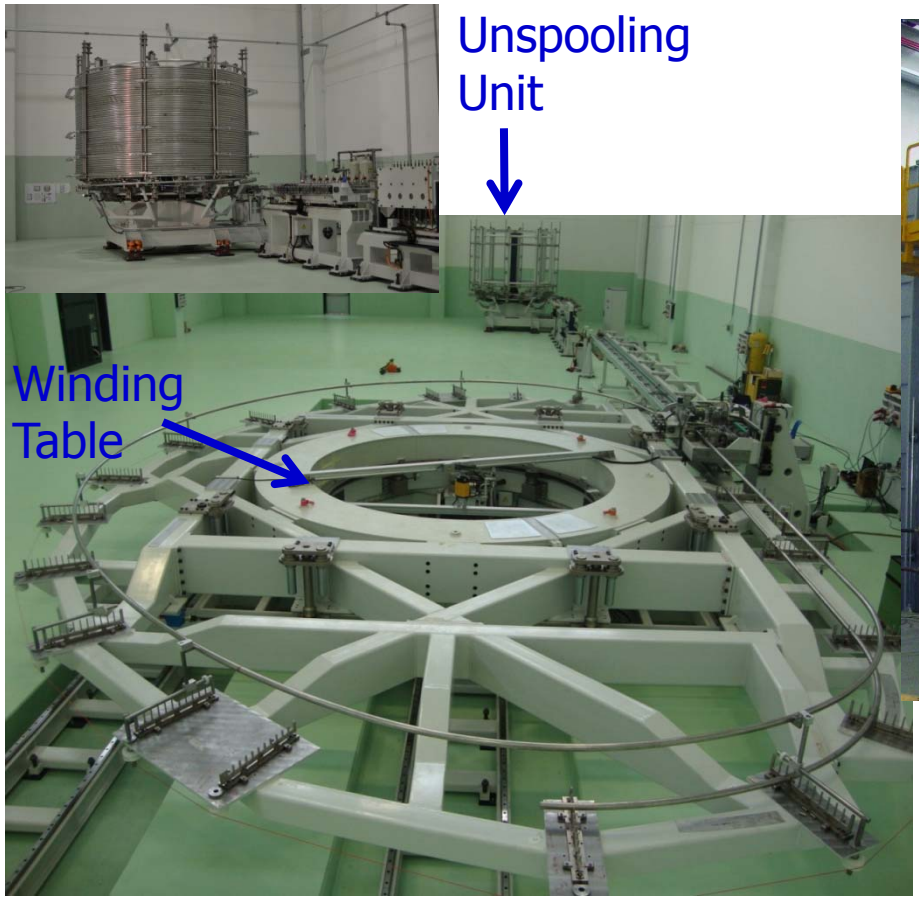
Construction of Facilities (ASG and MHI)
La Spezia 80x220m (in 4 bays) completed



Kobe conversion of existing buildings starting

Progress on TF Coils: EU – Tooling 1

- EU is commissioning the winding line



Winding line at ASG

Heat Treatment Oven at ASG

(Courtesy of
A. Bonito-Oliva, F4E)

Progress on TF Coils: EU – Tooling 2

(Courtesy of
A. Bonito-Oliva, F4E)

Wrapping tooling for turn insulation of double pancake during assembly at Elytt (Bilbao, Spain)

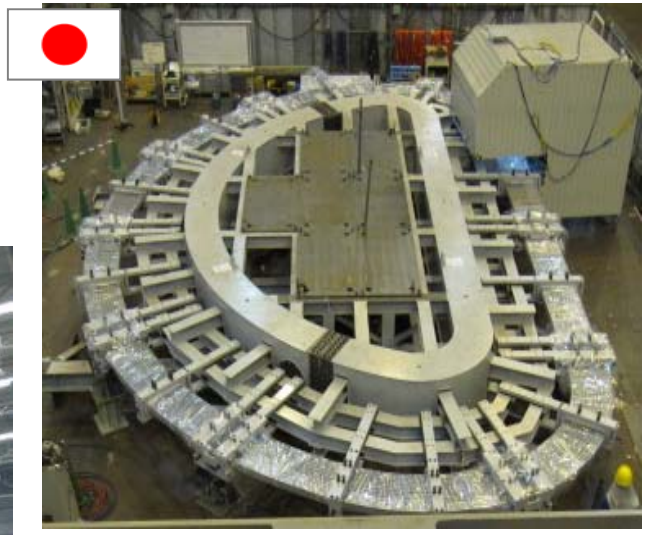
Progress on Radial Plates

- EU has manufactured 2 full size Radial Plate (RP) prototypes: one sDP and one rDP, while JA manufactured 1 full size rDP RP prototype.

Full-Size sDP RP Prototype in EU

Courtesy F4E

Full-Size rDP RP Prototype in EU

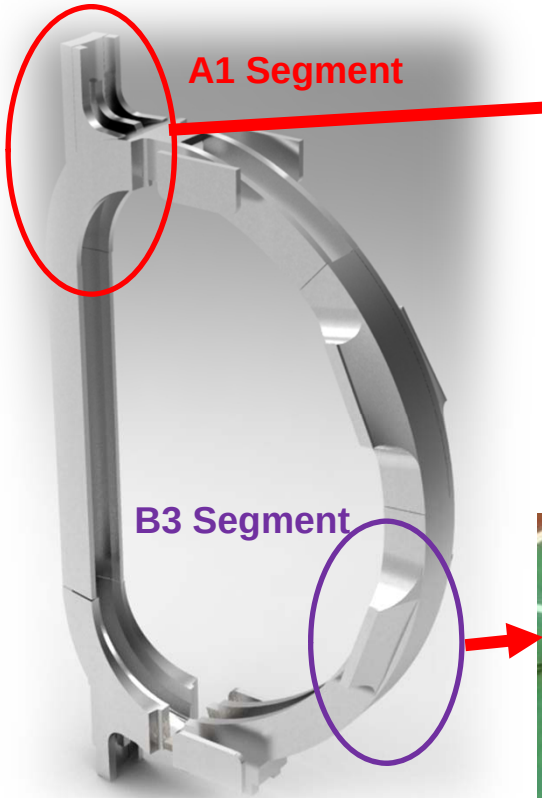


Full-Size rDP RP Prototype in JA

EU has just awarded contract for full supply of 10x7 RPs

Progress on TF Structures: JA

china eu india japan korea russia usa



JADA has just placed contracts with MHI/ HHI for 1 complete set of structures and 6 sets of materials

Pre-compression Ring Flange

Inter-coil Structure - Forging

Manufacturability study of large TF coil components by Toshiba and its sub-contractor KHI

Pictures courtesy JAEA & Contractors Toshiba & KHI

CONTENT

china eu india japan korea russia usa

- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

PF and Correction Coils

iter china eu india japan korea russia usa

Manufacturing Challenges

- NbTi conductor with thick jacket, high quality welding for fatigue tolerance
- High voltage
- Large dimensions

- For CC, high tolerance on large dimensions and weak winding, welding and winding accuracy critical

PF Conductor Status – 1

- EU & RF are responsible for the PF1&6 conductors, which rely on Nb–Ti strand 1, while CN is responsible for the PF 2-5 conductors, which rely on Nb–Ti strand 2.

Nb–Ti Strand 1 developed by VNIINM (1.6:1)

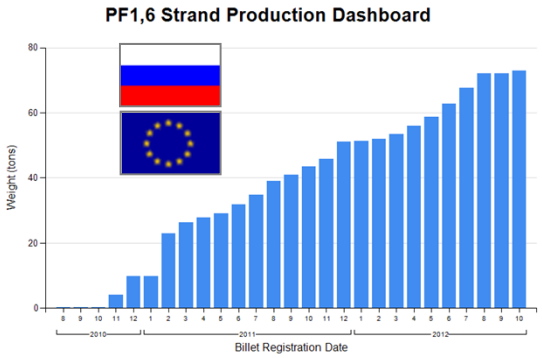
Nb–Ti Strand 2 developed by WST (2.3:1)

PF Conductor Status – 2

china eu india japan korea russia usa

- RF/F4E have registered ~95 t of Nb–Ti strand 1 into Conductor Database (production complete) and RF is in full cable production for F4E.

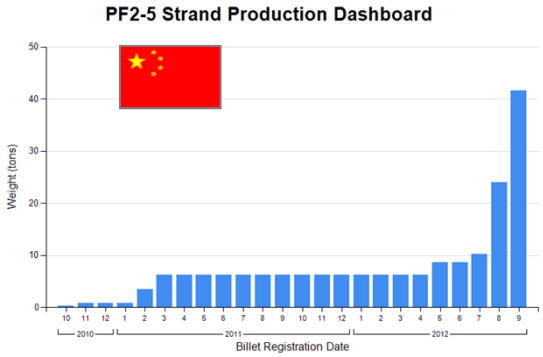
PF1-6 Registration



PF1&6 Cable Delivery at Criotec

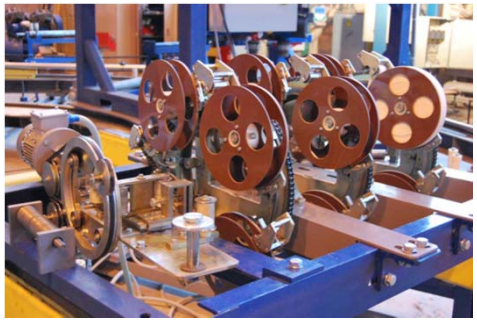
- CN has registered ~40 t of Nb–Ti strand 2, completed PF tube/welding qualification and has manufactured 800 m PF5 Cu dummy.

PF2-5 Registration

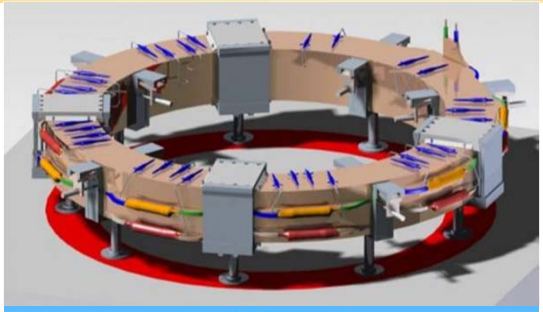


Compaction & Spooling of PF5 Cu Dummy at ASIPP

PF1 Coil Development at Efremov

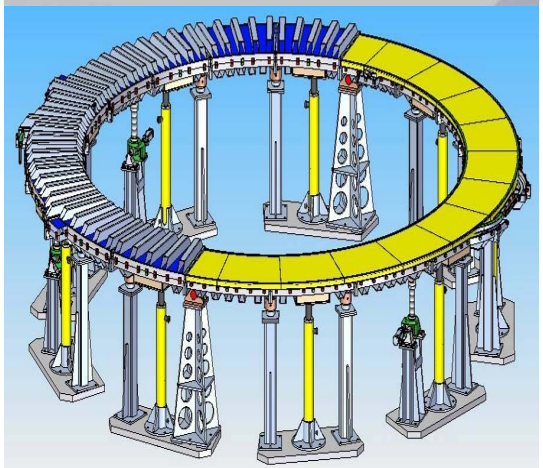


- Efremov has procured main tooling for PF1 coil manufacture.



Insulating machine

Vacuum chamber for impregnation and baking



Bending equipment

Winding table

Equipment for resin mixing

(Courtesy of I. Rodin, Efremov)

PF2-6 Coil Development by F4E

china eu india japan korea russia usa

Building on Cadarache site completed in 2011
240mx45m

Coil main contractor not yet selected. F4E has just re-launched Call for Tender

Correction Coil Winding Development in CN

china eu india japan korea russia usa

Winding facility constructed by ASIPP in Hefei. Tooling commissioning underway

Coil handling jig

2x 4kW Yb robot lasers for case welding being commissioned

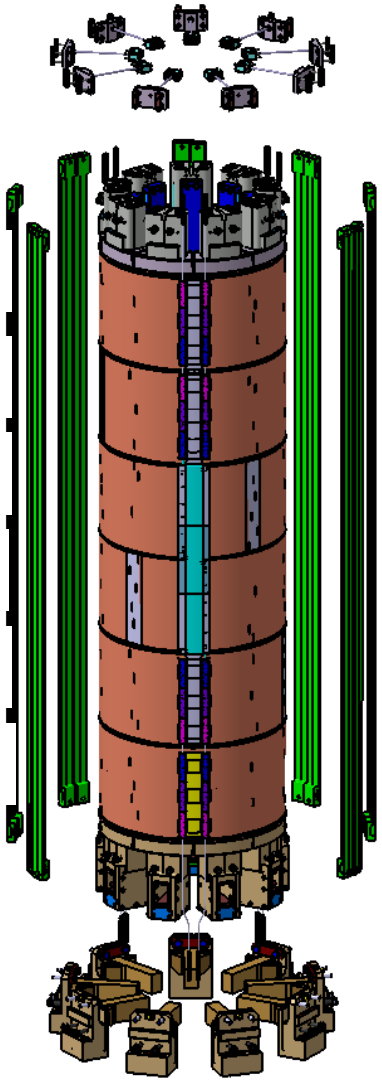
Courtesy ASIPP

CONTENT

china eu india japan korea russia usa

- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

CS Coils



- In comparison to the TF coils, which are operated in a steady state, the CS and PF coils must drive inductively 30,000 x 15 MA plasma pulses with a burn duration of 400 s.
- During their life time, the CS coil modules will have to sustain severe and repeated electromagnetic (EM) cycles to high current and field conditions.

CS conductors are to be procured in kind by Japan; they are 100% funded by EU (Broader Approach) and will be delivered to the USA for coil manufacture.

Strand Filament Breakage-1

china eu india japan korea russia usa

Nb3Sn is a brittle compound formed during manufacture by a 200hr heat treatment at 650C. ITER conductors require an 'open' structure to allow cooling. Also allows strands to bend under the magnetic loads

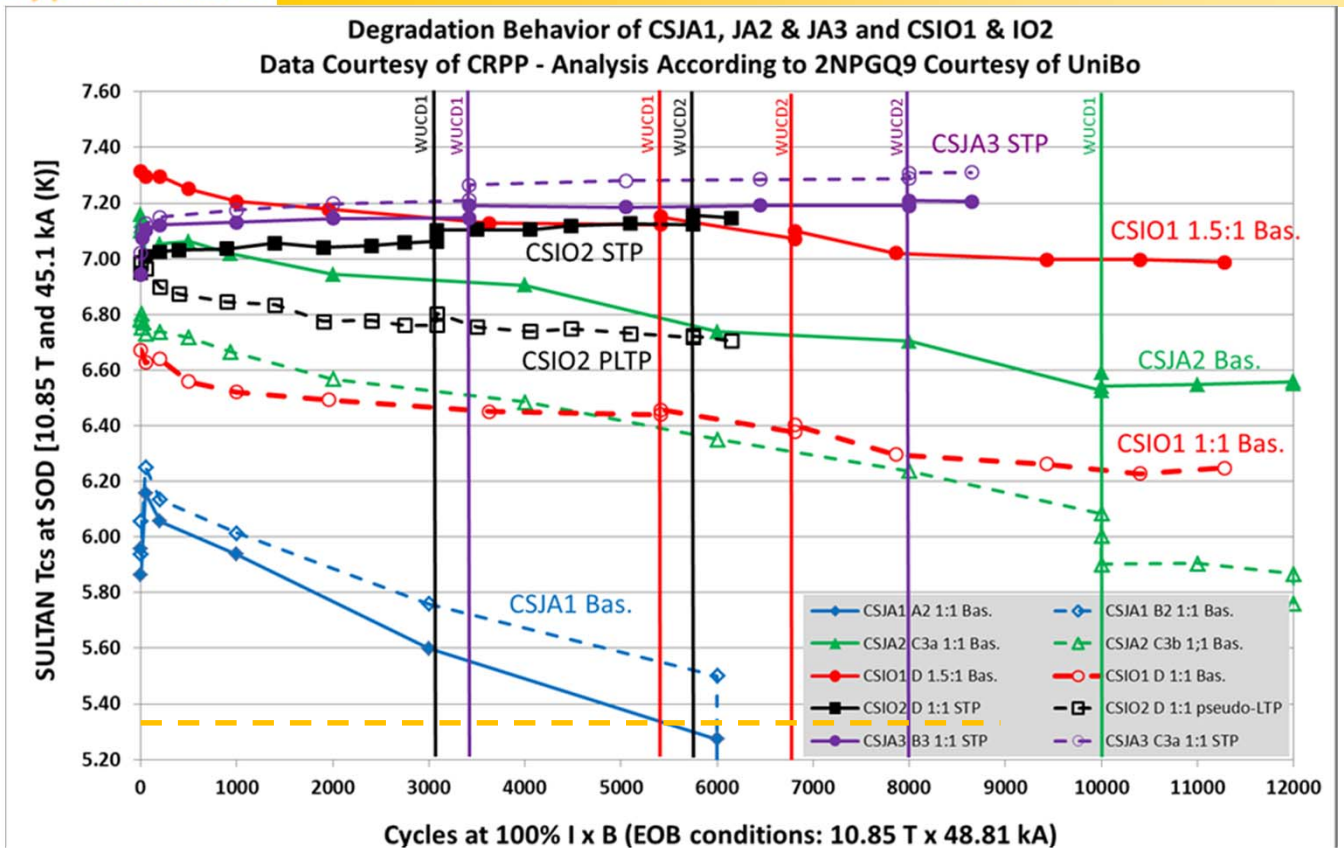
Performance problems were found in the CS conductor. Degradation of current sharing temperature with cycling to unacceptably low values in full size SULTAN conductor tests

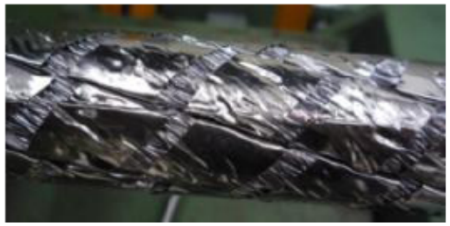
Extensive programme of analysis, sample fabrication, and diagnostic investigations

Solution: adjustment of cable pattern and void fraction to provide support: CSJA1->CSJA2->CSIO1->CSIO2->CSJA3

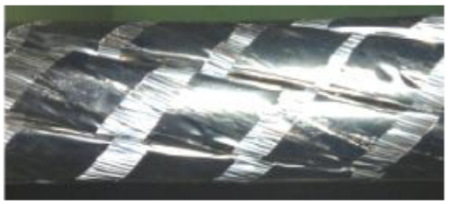
Bad.....better.....good

CS conductor Sultan Test Results





Short Twist Pitches (CSIO2)

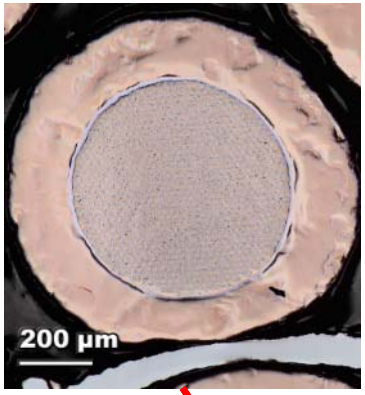


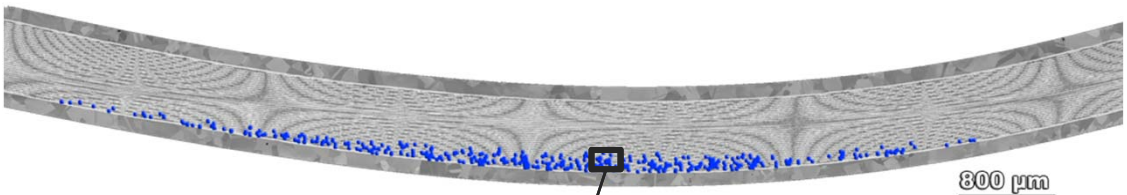
Standard Twist Pitches (CSIO1)

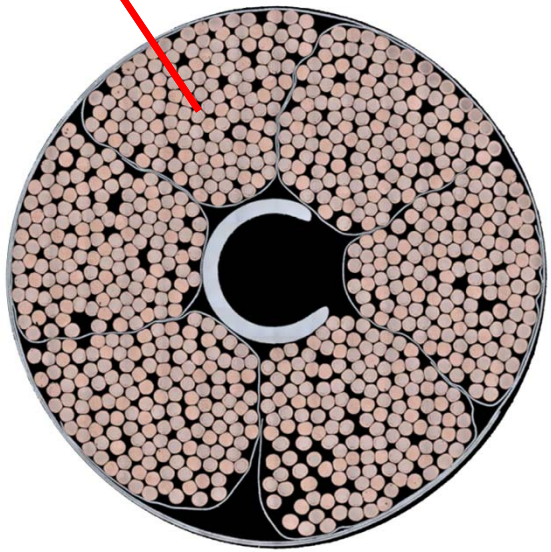
Long Twist Pitches (CSIO2)

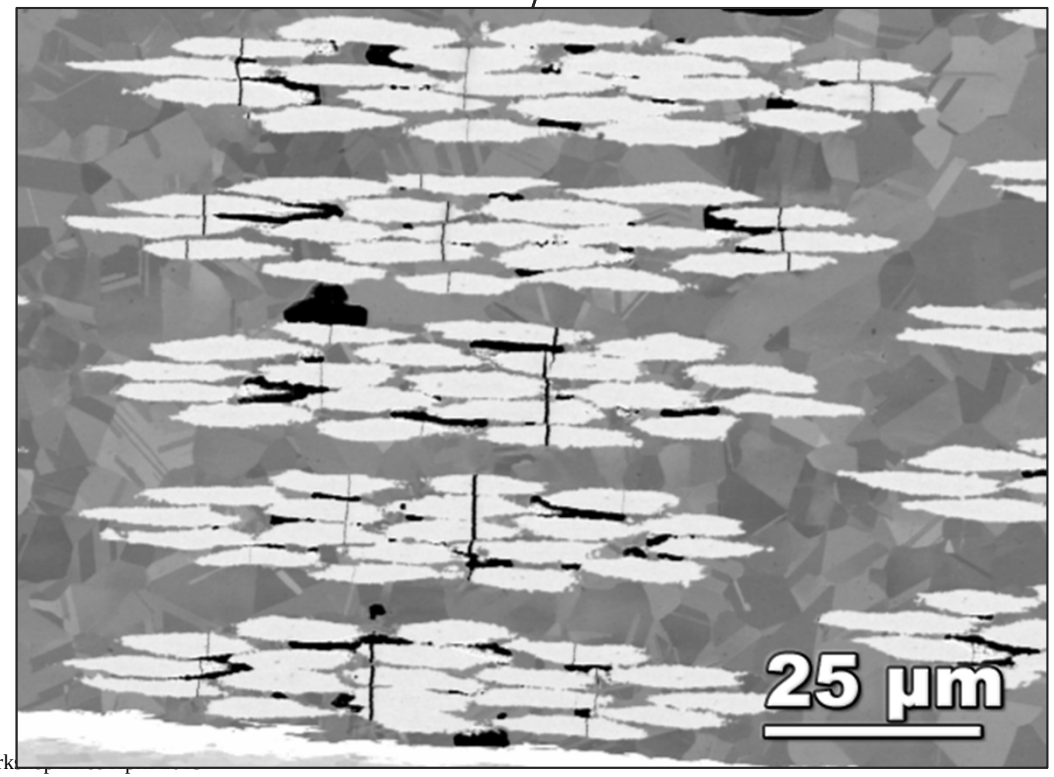
(Courtesy of L. Muzzi, ICAS)

Strand Filament Breakage-2









Courtesy of FSU

CS Coils

iter china eu india japan korea russia usa

Manufacturing Challenges

- Coils wound as Hexa-pancakes. Critical issues are tolerances, joints and high voltage insulation.
- Busbars have to be led down the outside of the coil…support and flexibility are critical, tolerance sensitive, issues
- Support structure has high fatigue stresses and requires high mechanical performance at RT due to pre-load

Upper plate showing He outlet piping and dowel locations

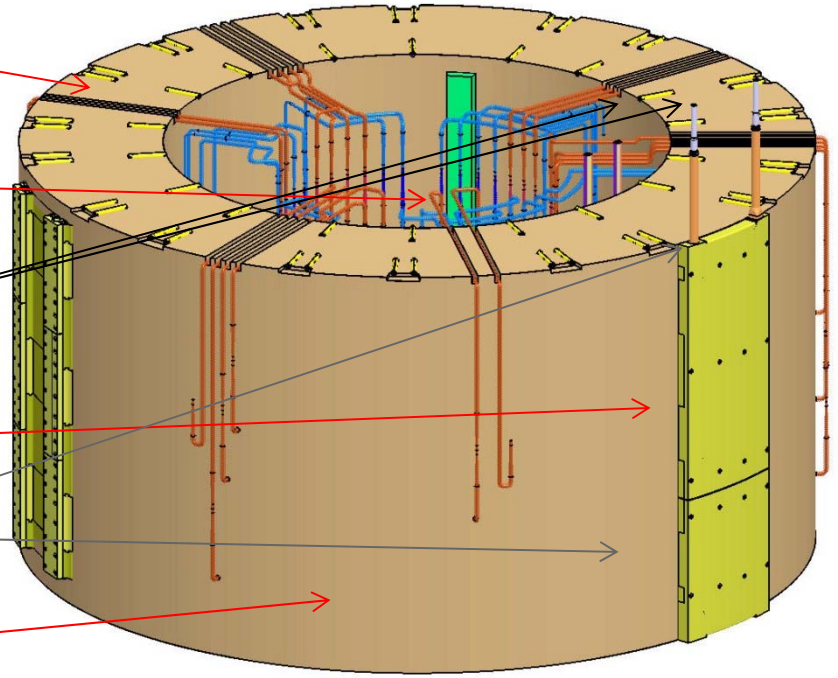
He manifolds with voltage taps and isolators

Terminals

Cassettes

Break out

Lower plate showing dowel locations



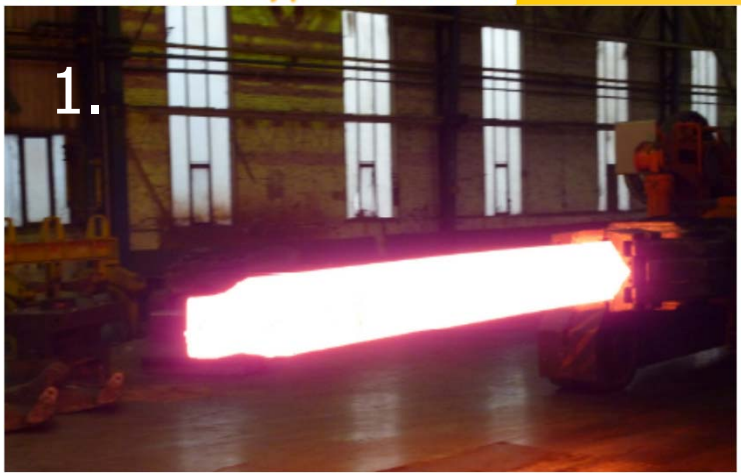
CS Coil Winding Facility

Renovation of part of 20000m2 facility just completed by GA in Poway, San Diego
Tooling deliveries during 2013

Clean area installation

Courtesy of US-IPO and GA

CS Structure- Trial Tie-Plate Forging



(Kind Germany)

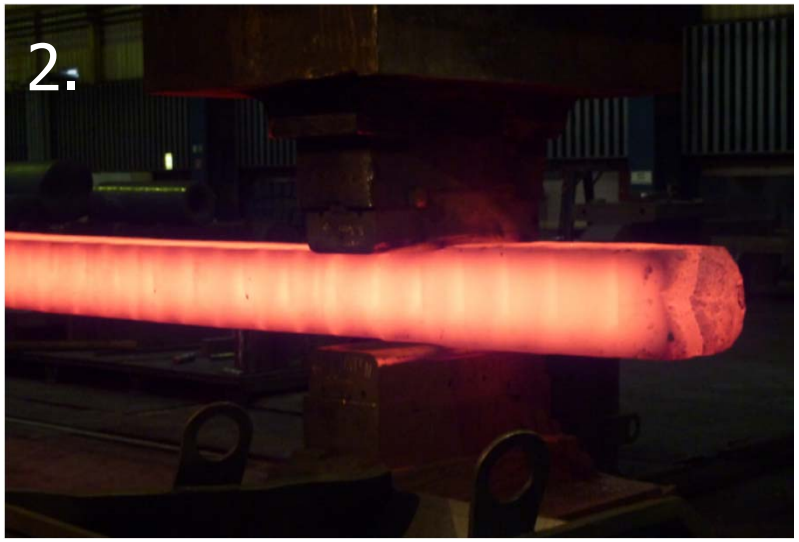


Plate longer than oven

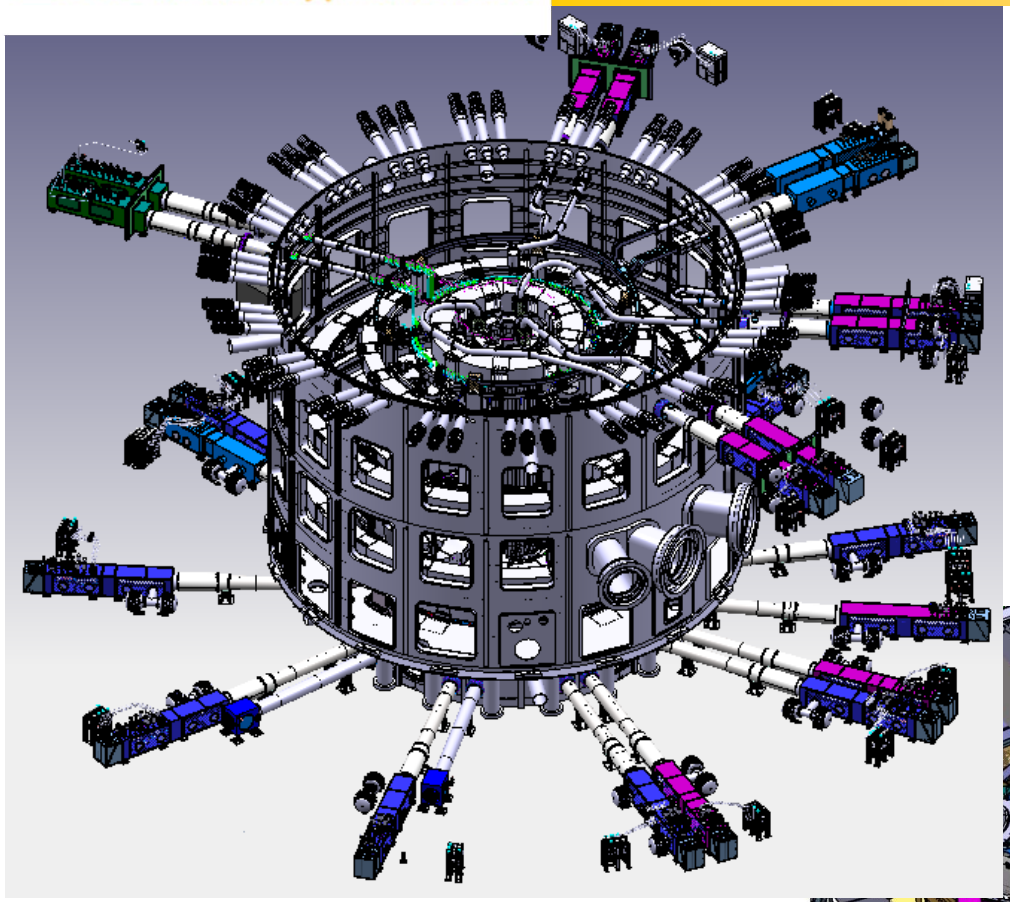
Courtesy of US-IPO

CONTENT

china eu india japan korea russia usa

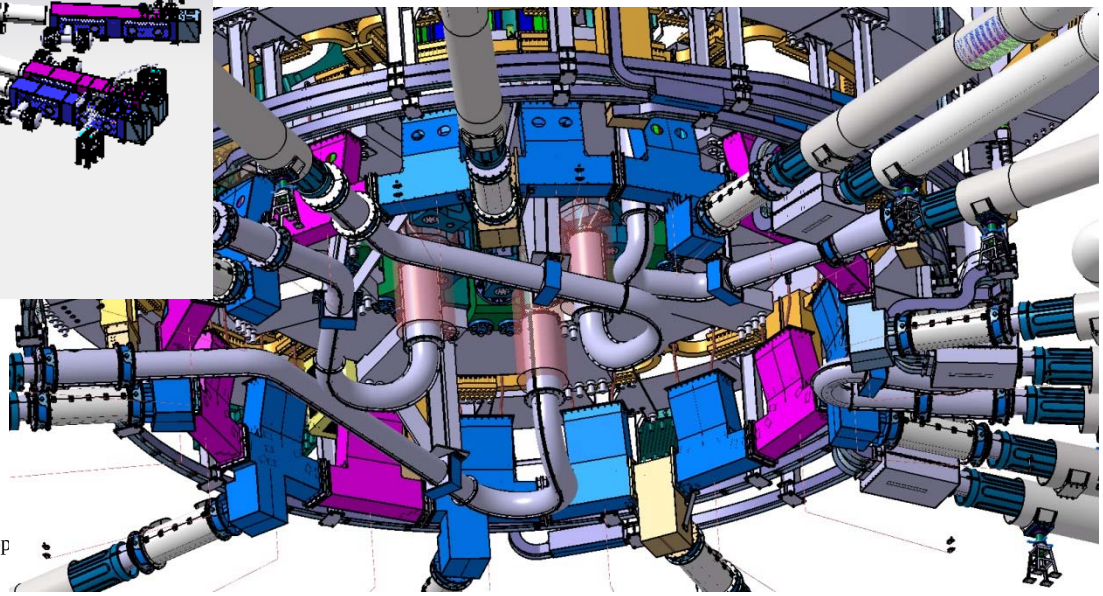
- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

Feeders



Provide current, He and instrumentation supplies to coils and structures

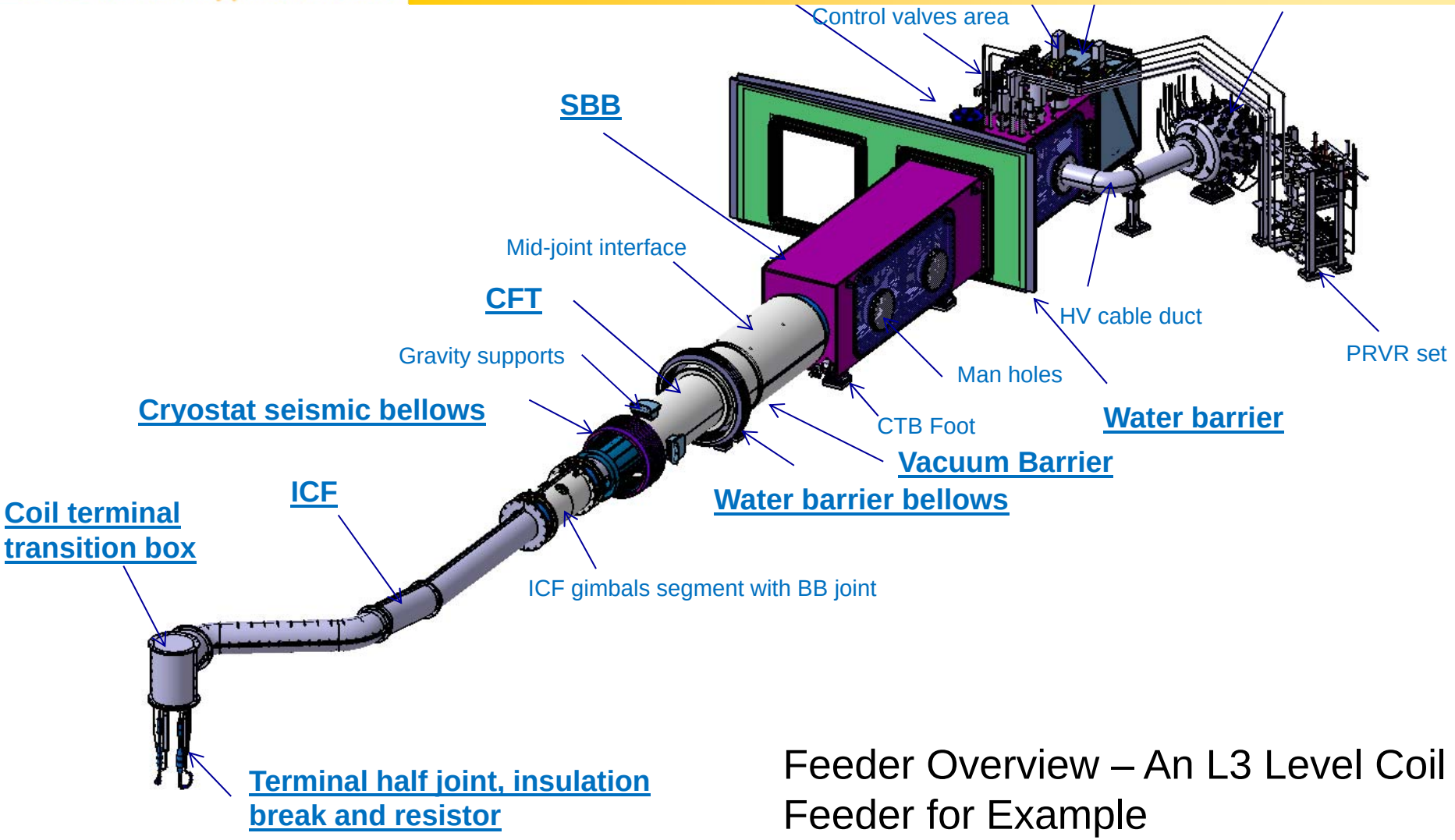
S/C busbars that interface to RT busbars



Highly complex integration

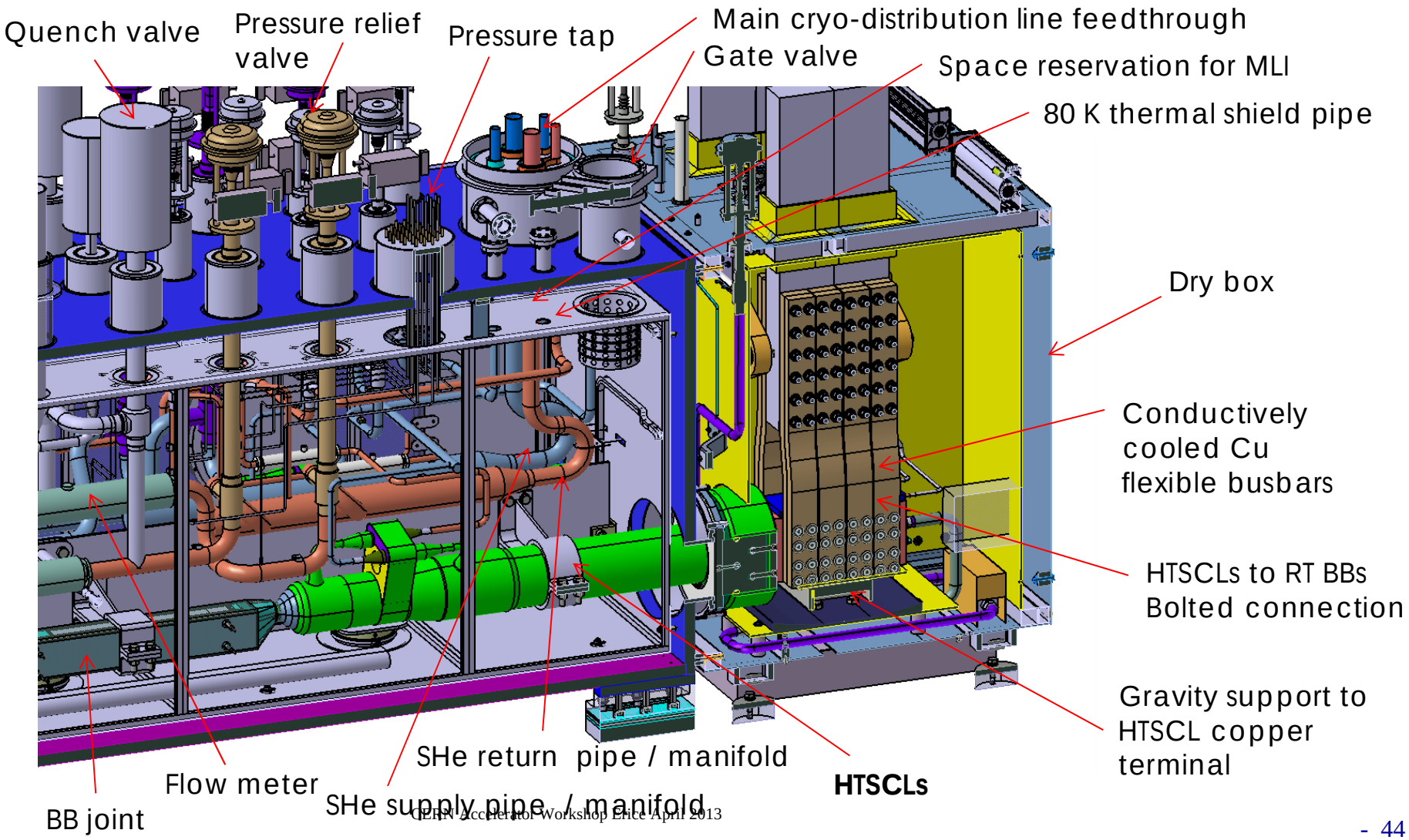
More complex than appear

Feeders Overview



Feeder Overview – An L3 Level Coil Feeder for Example

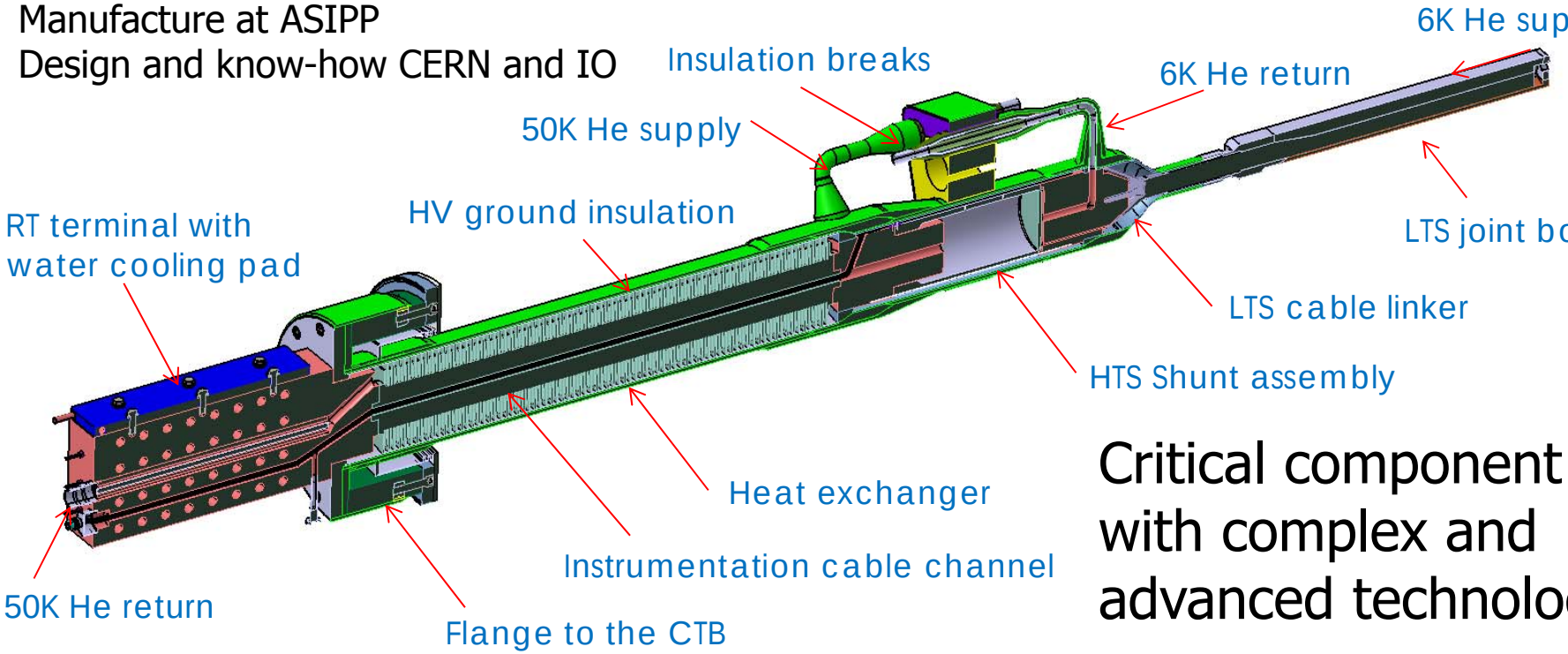
Feeder CTB Close-up



Feeder HTS Leads - 1

china eu india japan korea russia usa

Manufacture at ASIPP
Design and know-how CERN and IO



Critical component with complex and advanced technology

Brazing joint

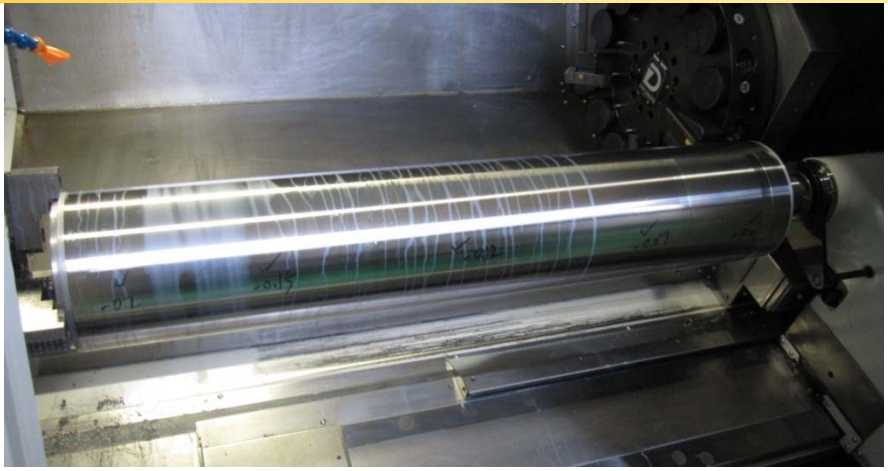
Machining of the grooves

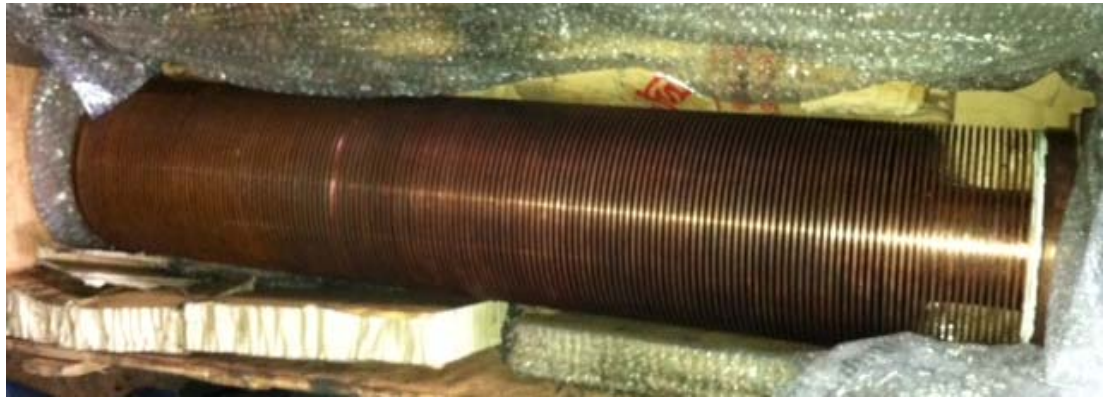
HTS Elements

Feeder HTS Leads - 2

Early (2008) Pre-prototype HTS leads under test at ASIPP

Feeder HTS Leads -2





Machining of copper fin Heat Exchanger and steel container to tolerances within few micro m

Feeder Manufacturing Facilities Complete

china eu india japan korea russia usa

Off-site ASIPP workshop for:

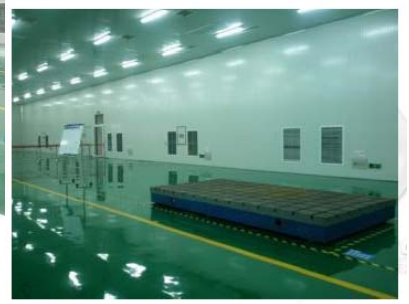
- Feeder insulation
- HV test
- Pipe bending
- Integration assembly

In Hefei

Workshop for insulation

HV Test area

Tubing bending area



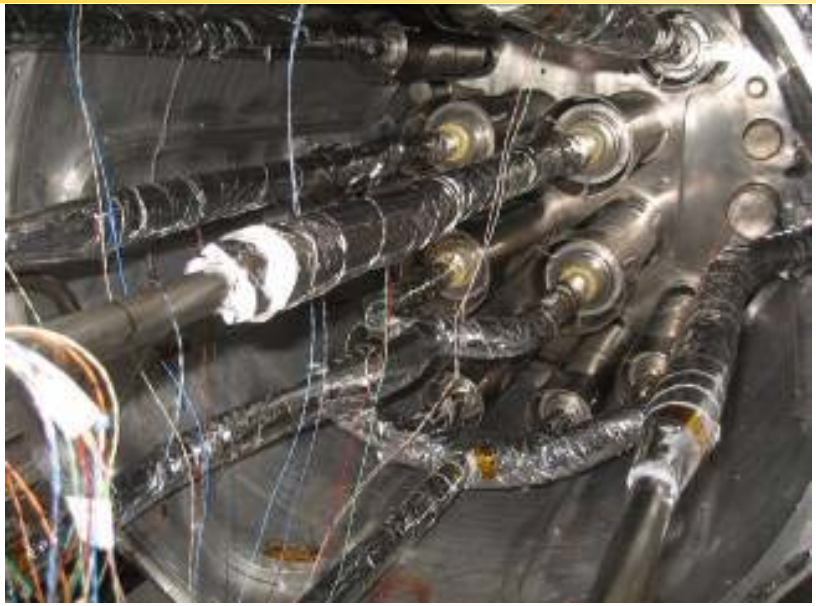
First 1000m² clean room of 8 class of ISO14644 for Feeder assembly

Assembly area

- 48 -

Feeder Prototypes and Mock-ups Complete

Vacuum barrier

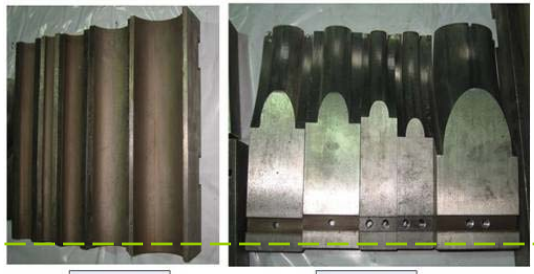


Thermal shield

Feeder Tooling is under fabrication

Positioning jig for the welding of thermal shield

Tools for pipe bending



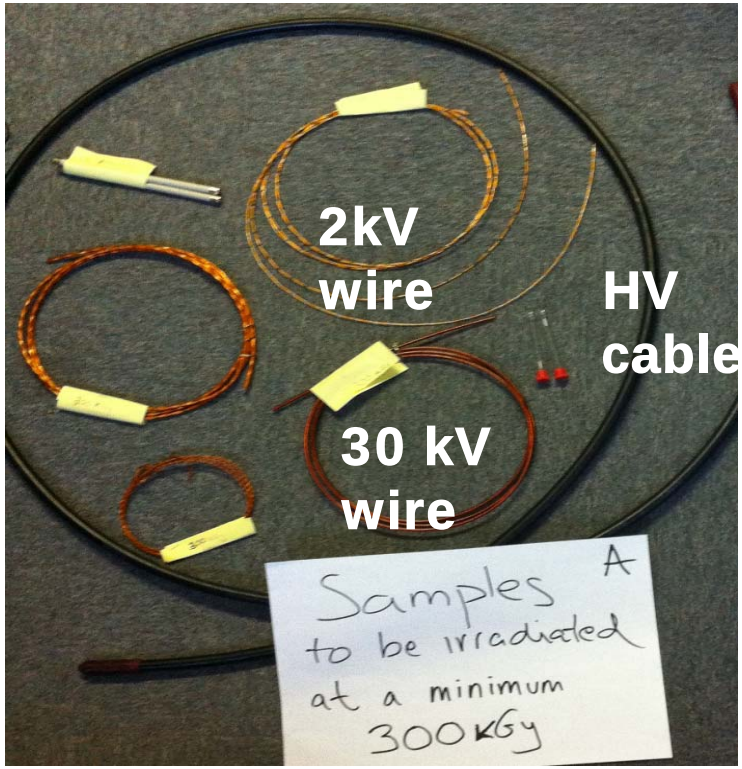
Large number of components
Many geometric variations
Difficult assembly

More than 50 tools for pipe bending

Instrumentation

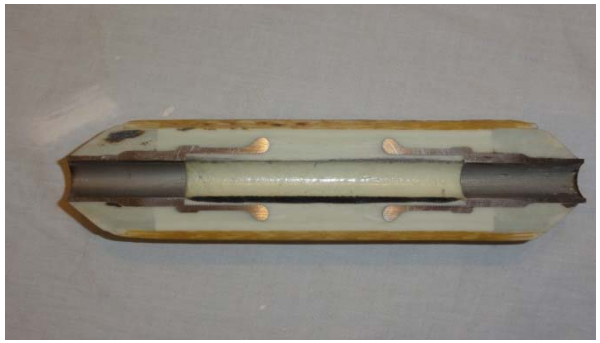
iter china eu india japan korea russia usa

Procured directly by IO. Covers HV cables, sensors, wires, insulating breaks. IO runs laboratory in CERN for testing

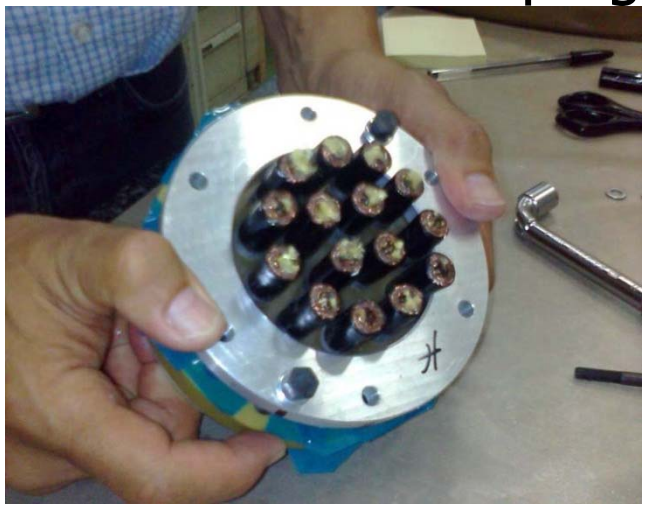


High voltage cables (for irradiation testing)

Section through 30kV insulating break for He pipe



15 cable vacuum plug



CONTENT

china eu india japan korea russia usa

- ITER Magnet System
- TF Conductor & Coils
- PF Conductors & Coils , Correction Coils
- CS Conductor and Coils
- Feeders and Instrumentation
- Conclusions and The Future

Conclusions and The Future

china eu india japan korea russia usa

- ITER relies on an unprecedented collaboration of 7 Parties around the world; 24 years after its inception, ITER has entered the construction phase. Technical challenges are being overcome.
- TF conductors are well into production, with over 90% of the required Nb_3Sn strands already completed. PF strand production is over 50% complete and conductor production has been launched in RF and CN
- TF coil winding facility commissioning is well underway in Europe and facility preparation and tooling fabrication is starting in Japan.
- Facilities for feeder production in CN are complete and manufacturing trials are underway
- A technical solution has been found for the CS conductor. CS coil winding facility is nearing completion in US and tooling manufacture is underway