ITER Central Solenoid Module Fabrication

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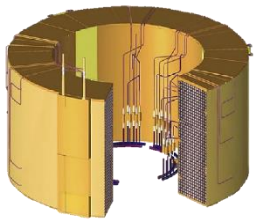


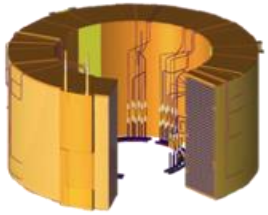
ITER Central Solenoid is the Heartbeat of ITER

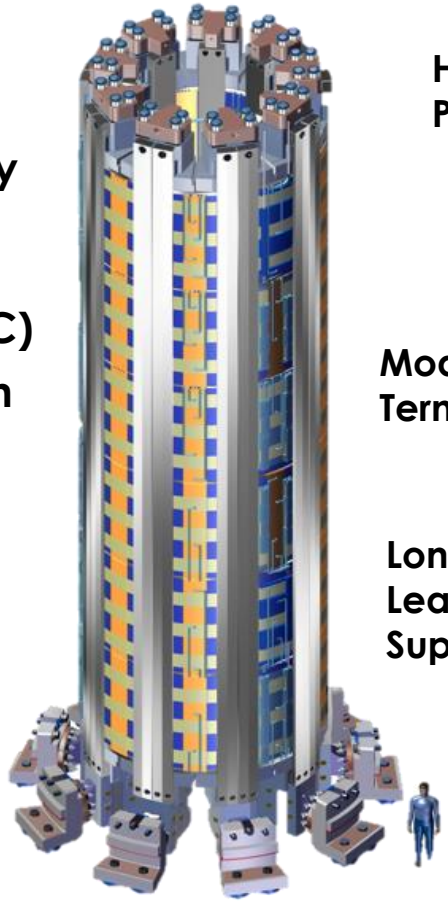
ITER Central Solenoid

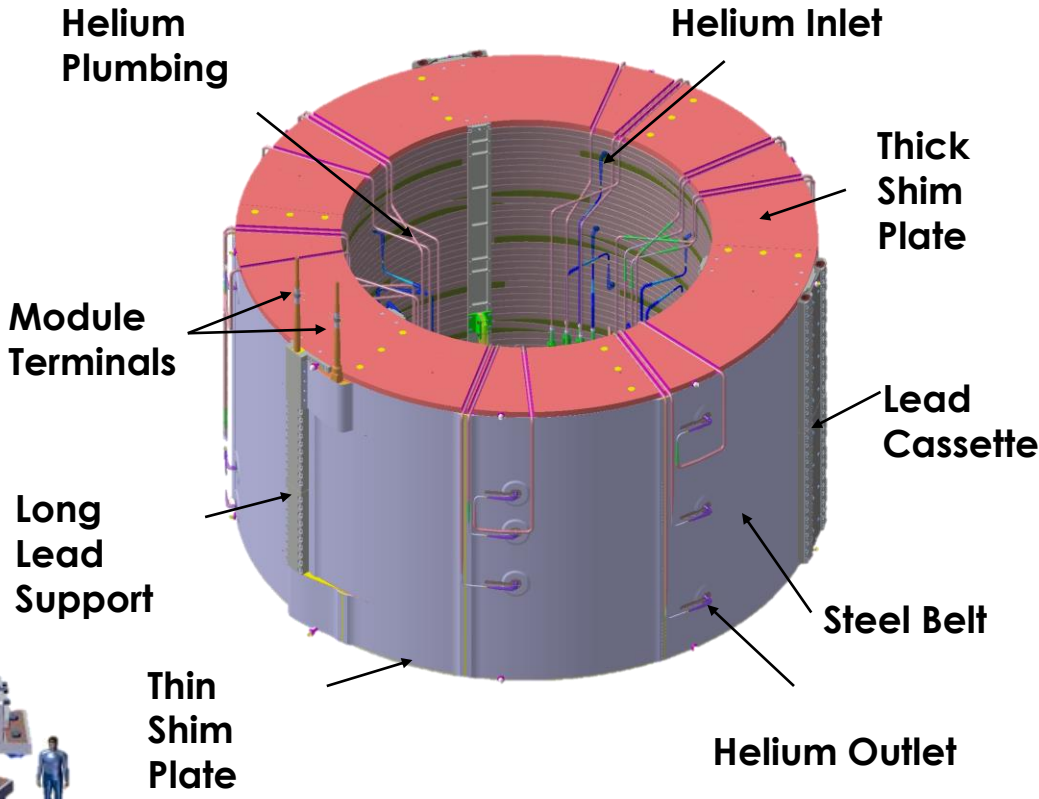
Six modules
17 m tall
4.2 m diameter
13 Tesla
5.5 GJ of stored energy

CS Module

Conductor Nb_3Sn (CICC)
Outer Diameter of 4.1 m
Height of 2.2 m
Weight 110 tonne
Inductance 0.77H
Stored energy 1GJ
Peak Current 45 kA







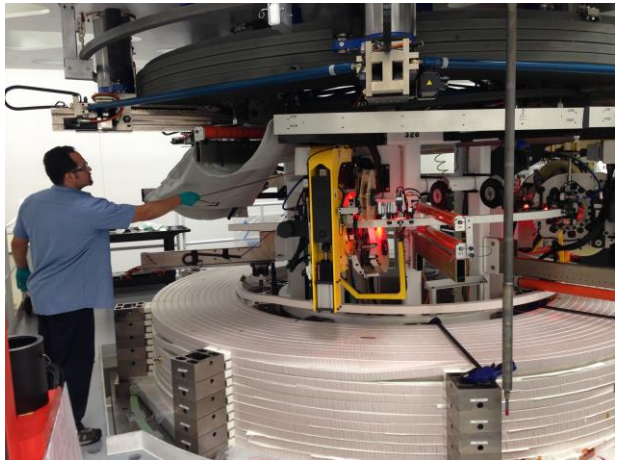
ITER Central Solenoid Module Fabrication Must Be Exacting
Quantity of Production Material is Limited

First production module in joining station

Manufacturing design completed in partnership with US ITER

Complex fabrication process

- **Qualified procedures**
- **Trained staff**
- **Non-superconducting qualification coil completes validation of processes and procedures**
- **Testing and verification during production performed to ensure success**
  - **Non-destructive examinations**
  - **Electrical testing**



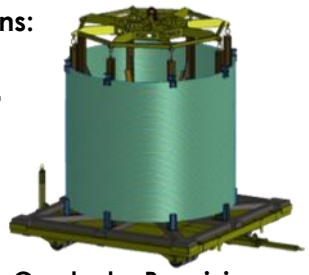
Qualification Coil during insulation process

ITER CS Requires Complex Manufacturing Process

Ten process stations developed, built and tested

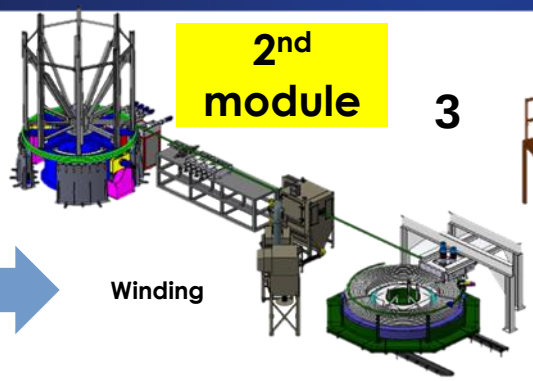
Stations:

1



Conductor Receiving Inspection

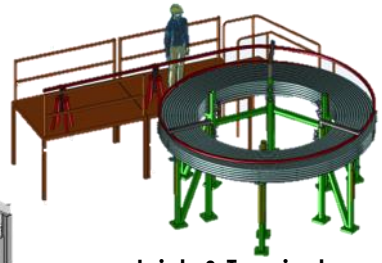
2



2nd module

Winding

3



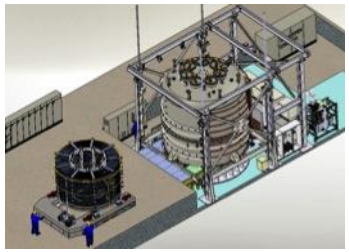
Joints & Terminals Preparation

4

1st module

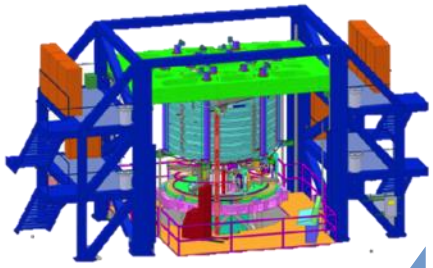
Stack & Join/Helium Penetrations

5



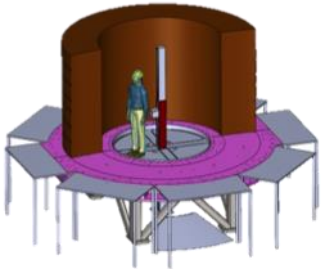
Reaction Heat Treatment

6



Turn Insulation

7



Ground Insulation

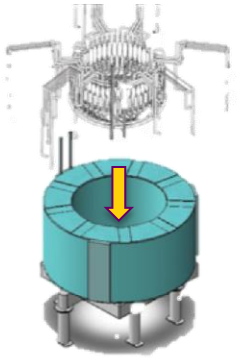
8

Qualification coil

Vacuum Pressure Impregnation

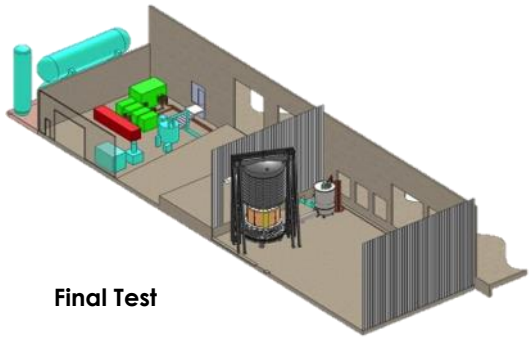
Turnover Tool

9



Helium Piping

10



Final Test

First module ships in 2018

Seventh module in 2021

Unique Technical Developments/Capabilities Required to Fabricate Central Solenoid Modules

- **Winding**
- **Coil and Bus Joints**
- **Welding of special stainless alloy**
- **Insulation of 110 tonne module**
- **Testing of modules at 48.5kA**

6000m^2 purpose built facility for manufacturing CS modules

Special Tooling Developed to Wind Coils to Tight Tolerances
Turn Radius Held to within 0.5mm

- Seven segments wound for each module
- Convert 900 m spool of JA produced conductor into six layers of 14 turns each

IO Annual Work Plan milestone, one month early:

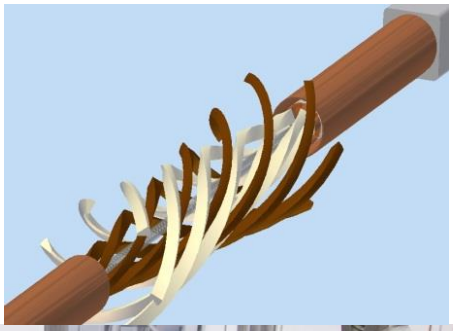
Winding first production module

Six layer coil segment

Joining of Superconductors required to complete CS
Two joint types designed and developed

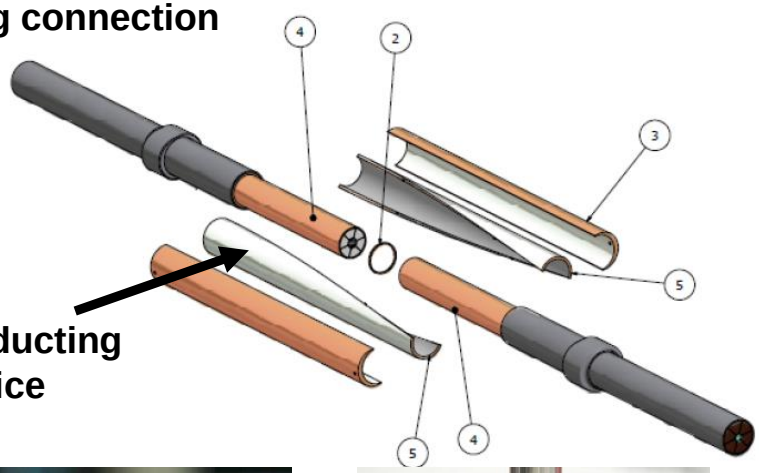
Intra-module

Laced sintered joint; six joints inside winding pack per module

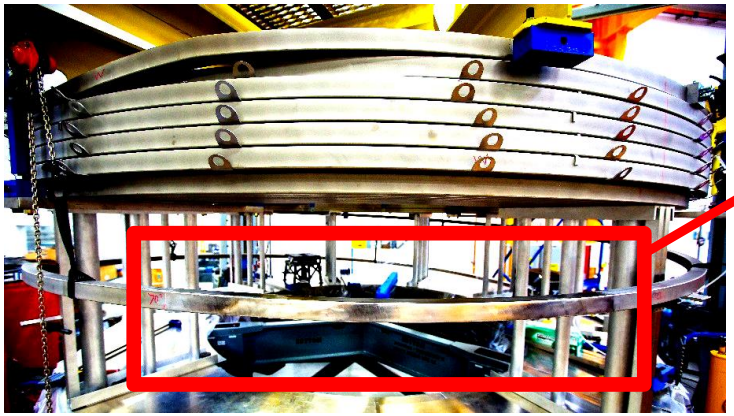


Module to bus bar

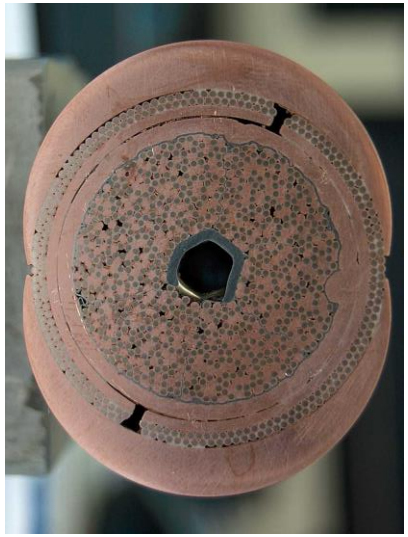
Coaxial joint with superconducting strands making connection



Superconducting strand splice



Completed Joint



Critical Welding of Specialty Stainless Steel Alloy
Qualified weld processes and operators required

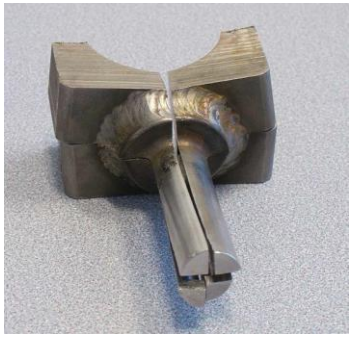
- **Joints designed to protect superconducting cable while achieving full joint penetration**

Non-Destructive Examinations developed to verify production welds

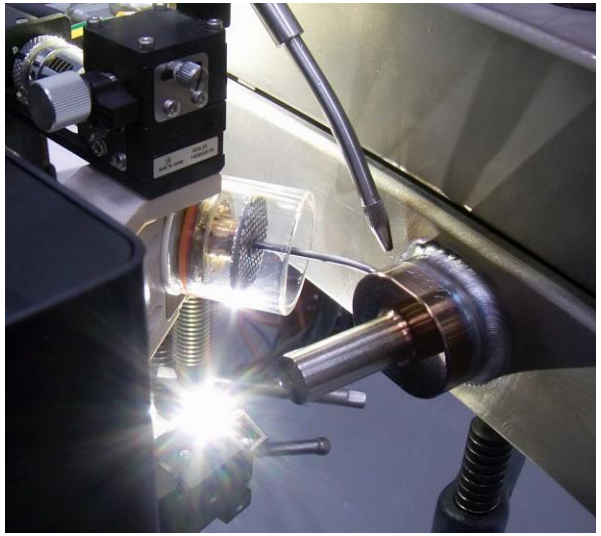
- **In-situ radiography**
- **Ultrasonic inspection**
- **Dye Penetrant Inspection**
- **High pressure helium leak checks**

- **Reproduce weld processes with high success rate is necessary**

Hundreds of weld samples produced



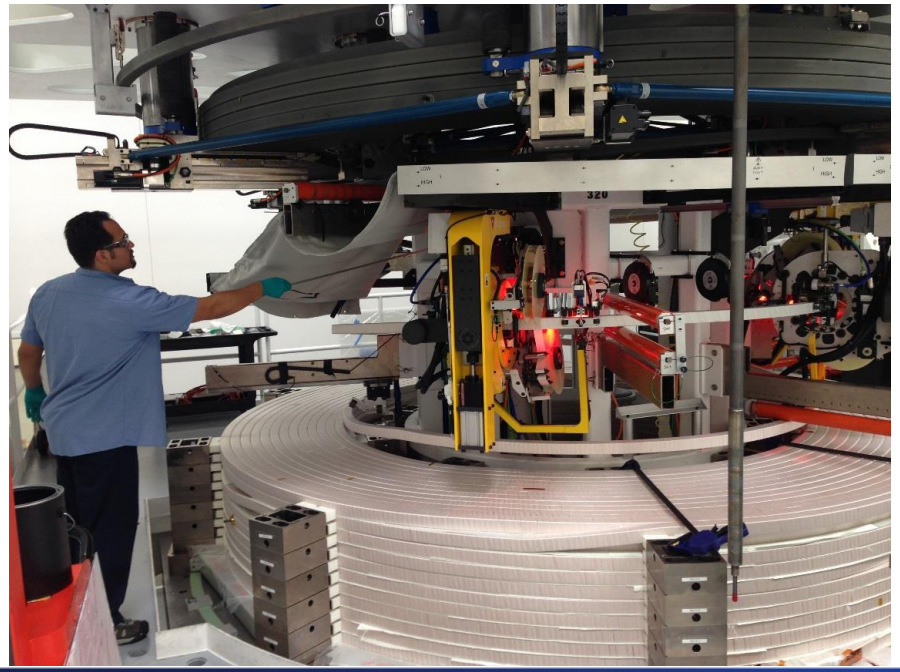
Machine welds performed where feasible

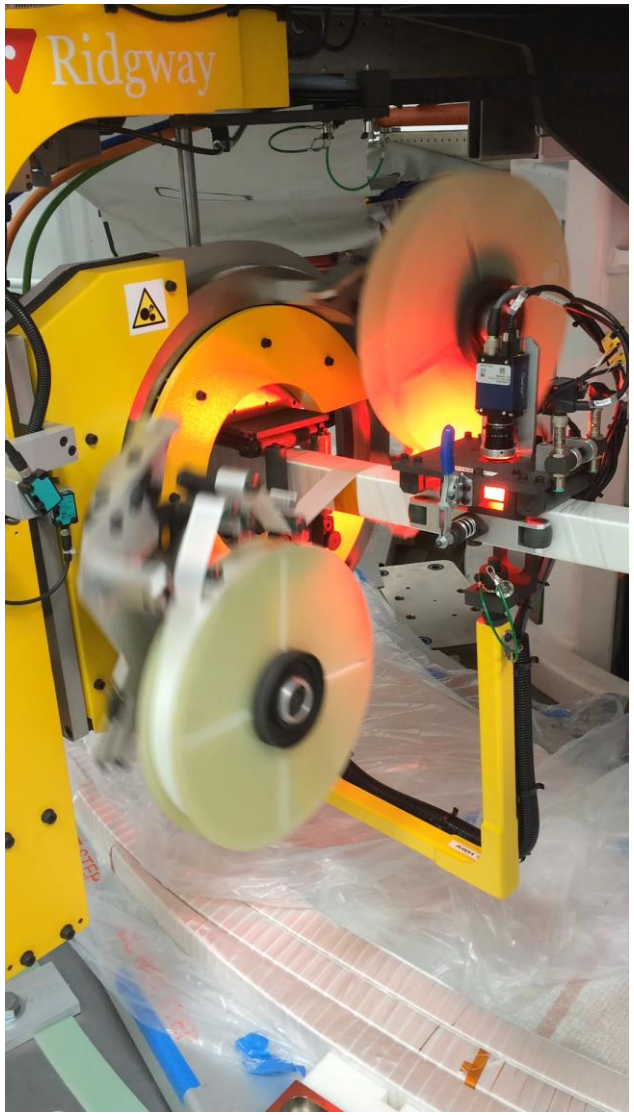


Insulating Coil After Heat Treatment of Nb_3Sn is Challenging

Superconductor strain is limited to < 0.1%

- 1.4kV of insulation required between turns
- Coil separated, six layers of insulation applied and rebuilt as wound
- 300km of tape applied to 6km of conductor
- Helium inlets/outlets requires special process and materials
- Quench detection voltage taps applied





30kV of Insulation to Ground Required for Module
Special Materials and Processes Developed

- Fiberglass, polyamide sheets used for bulk insulation
- Over 200 penetrations per module must be insulated to pass Paschen test
  - 160 wires, 39 helium pipes, 2 leads
- Special insulation areas designed, mocked up and tested electrically to five times test requirement

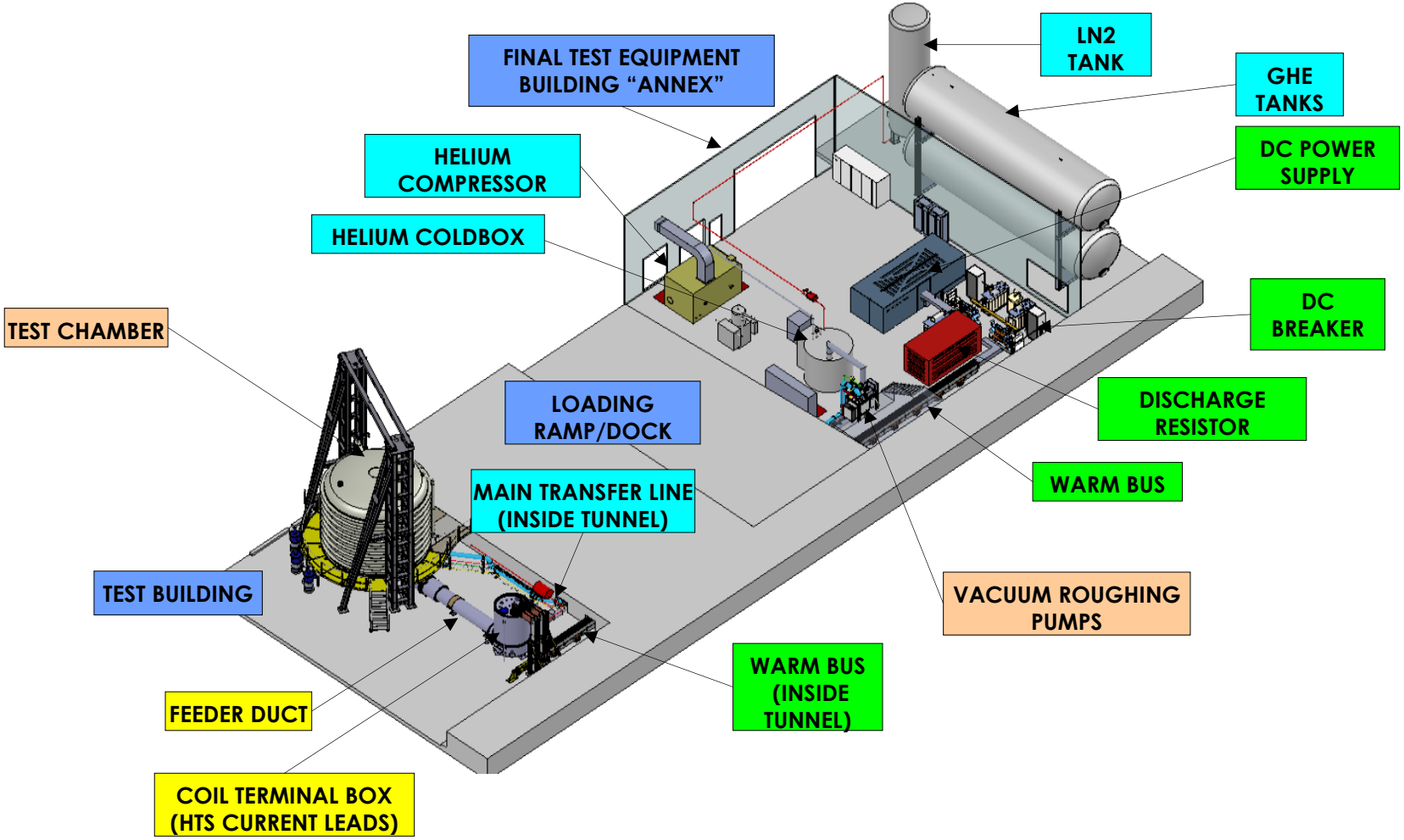
Sheets of ground insulation being applied to qualification coil

Quench detection wires exit along helium pipes

Quench detection wires and pipe after insulation

CS is only ITER Coil to Undergo Factory Full Current Test

Equipment to Protect the Modules During Test is Critical



- Quench detection system provides signal of adverse condition
- DC Switch and energy dump system disipates 1GJ of stored energy

All Systems Installed for Full Current Cold Test of Modules

Integrated Testing of Systems in Progress

0.130 Ω Dump Resistor

900W Liquid Helium Cryo System

0.5 MW DC Power System

Redundant 50kA DC Breakers

ASIPP provided HTS Feeder and Cryostat

Extensive Testing For All Modules Prior to Shipping
Testing confirms design and manufacturing

Test Step	Copper Qual. Coil	Module 1	Modules 2-7
Initial Room Temperature Tests			
Global leak test at 3MPa	√	√	√
Paschen test (at RT)	√	√	√
Cold Tests			
Cool down CSM from 300K to 4K	√	√	√
1 charge/discharge cycle of module (0kA-48.5kA-0kA)	3000 A	√	√
Joint/Terminal resistance measurement		√	√
Current sharing temperature measurement #1 (10 double layers)		√	
AC loss measurements (Fast Discharge τ=6 sec)		√	
10 charge/discharge cycles of CSM (0kA-48.5kA-0kA)		√	
Current sharing temperature measurement #2 (10 double layers)		√	
Global leak test at 3MPa (cold)	√	√	√
Final Room Temperature Tests			
Global leak test (3MPa, RT)	√	√	√
Paschen test at RT	√	√	√
30 kV Hi-Pot test	√	√	√

Development of All Critical Tools and Processes Completed and Production of ITER CS Modules has Started

- Unique tooling successfully installed and tested
- All major equipment built and installed in facility
- 70% of stations fully tested and operators trained with qualification coil
- Six of ten process stations cleared for module production

<u>Production Status of CS Modules</u>

- Copper qualification coil will be resin impregnated in December and manufacturing completed in early 2017 followed by cool down to 4.5K and low current testing
- Module 1 has been wound and five of six intra-module joints completed
- Module 2 is currently being wound
- Module 1 scheduled to ship in 2018; Module 7 in 2021