# Start of the ITER Central Solenoid Assembly

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# Summary

- ITER Central Solenoid
- CS Overview
- CS Module manufacturing status
- Special tooling and process qualification
  - Lifting tool
  - Bus bar joint assembly
  - Pre-compression
- CS Assembly status

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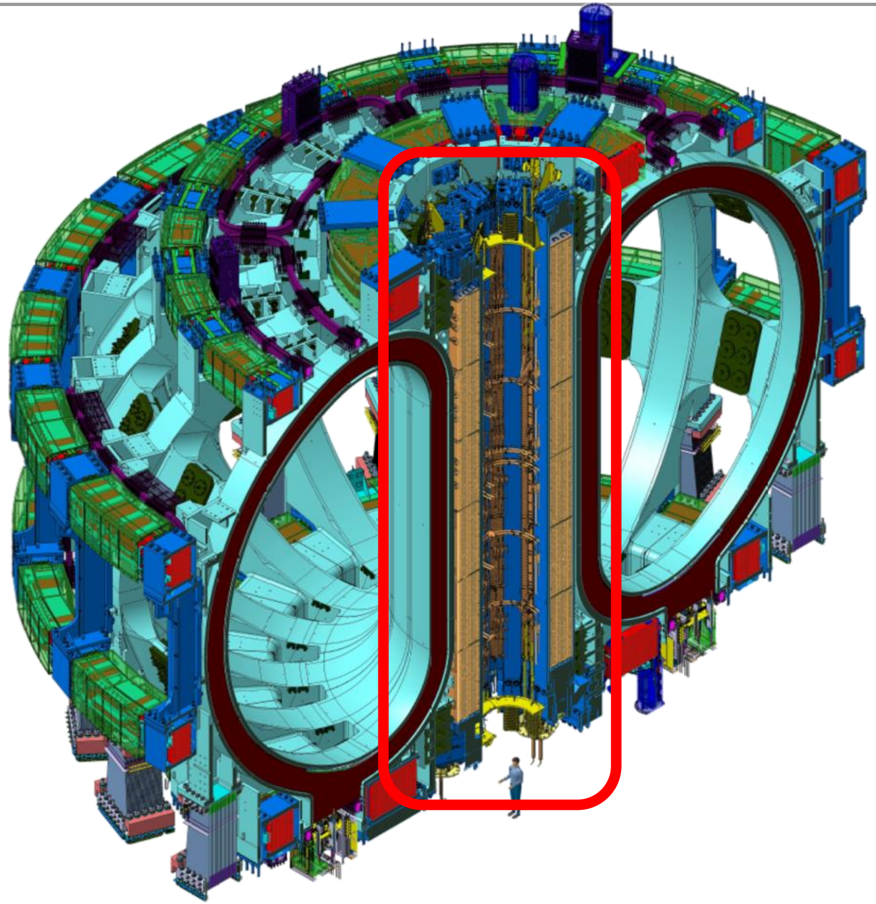
# ITER Central Solenoid

- **Function**
  - Induce **15 MA** of plasma current
  - Shape the plasma → 6 modules

- **Steps**
  - Design
  - Qualification
  - Manufacture
  - Assembly
  - Installation
  - Commissioning
  - Operation

This talk



# ITER Central Solenoid

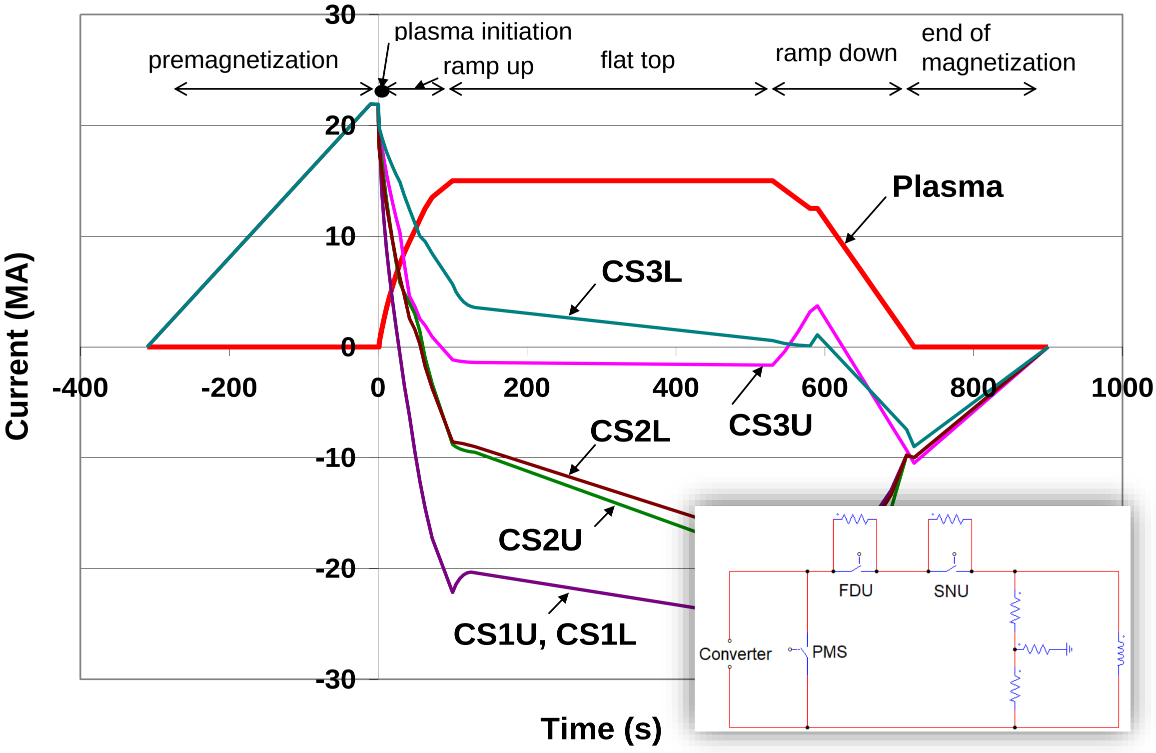
## Key parameters

- *Electrical*

| Parameter | Unit | Value |
|---|---|---|
| Maximum operating current | kA | 45 |
| Peak field | T | 13 |
| Peak module nominal voltage at initiation | kV | 10 |
| Peak current decay | kA/s | 5 |
| Ground insulation voltage test | kV | 30 |
| Expected Iter life cycle number | | 60000 |

- *Mechanical*

| Parameter | Unit | Value |
|---|---|---|
| Module weight | tons | 120 |
| CS weight with structure | tons | 1000 |
| CS height | m | 15.5 |
| CS maximum outer diameter | mm | 4312 |
| Axial pre-load | MN | 210 |




Time current evolution in CS coils and plasma

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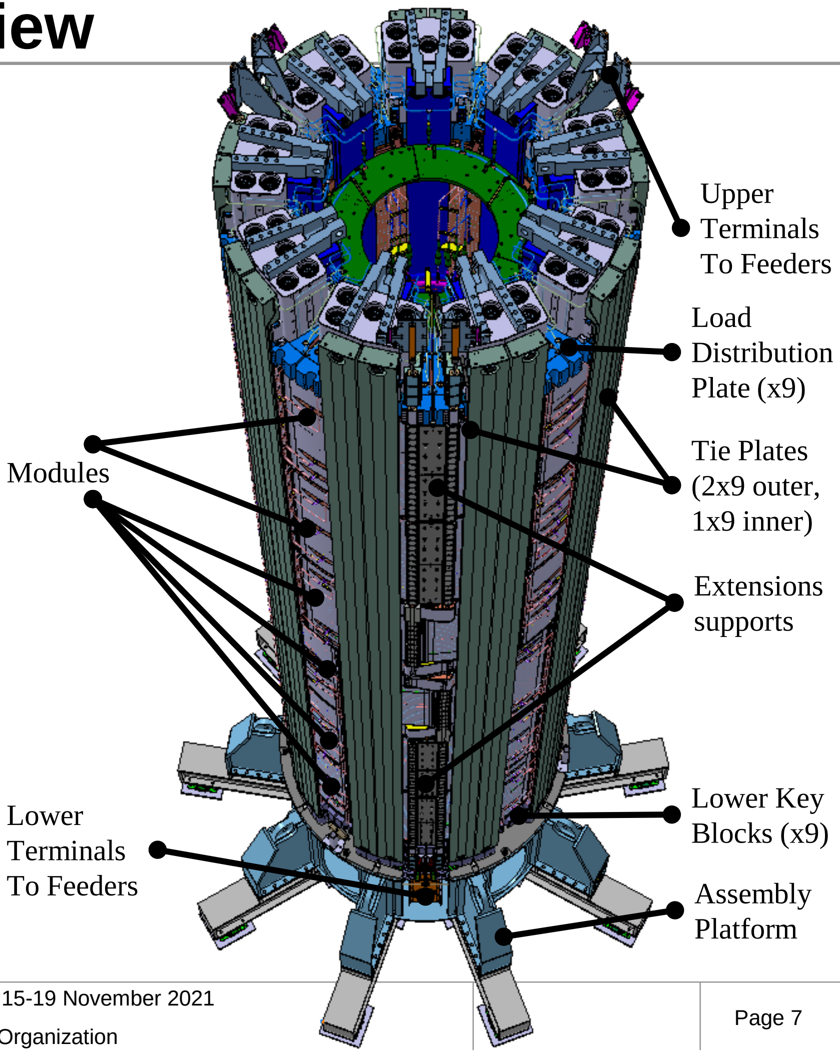
# CS Overview

- Lower Key Blocks (LKB): 9 LKB ensure the mechanical interface in between CS and lower TFC gravity supports.
- Upper Key Blocks (UKB): 9 UKB ensure the mechanical interface in between CS and upper TFC structure through centering rods.
- Tie Plates (TP): Each sector is equipped with three TP (two at the Outer Diameter (OD), and one at the Inner Diameter (ID)). TPs are locked to LKB and UKB.
- Multi Jack bolts Tensioners (MJT): Each UKB is equipped with 5 MJT screwed into the UKB and pushing on the LDP (see next bullet) to apply the pre-compression load.
- Load Distribution Plate (LDP): 9 LDP are stainless steel plates that distribute the load from MJTs uniformly on the modules stack upper surface.



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# CS Module Manufacturing status

- 7 modules at different manufacturing staged
  - CSM1&2 modules delivered at IO
  - CSM3 pending status following issue during FAT
  - CSM4 in preparation for FAT
  - CSM5 VPI in progress
  - CSM6 in turn insulation station
  - CSM7 ready for heat treatment

| | Fabrication of CS Module | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Part 1 | | | | | Part 2 | | | Part 3 | | | CS Module Manufacturing % |
| | Receiving Inspection | Winding | Joint& Terminal Prep | Stack&Joint/ He Pen | Heat treatment | Turn Insulation | Ground Insulation | VPI | Piping | Final Test | Packing& shipping | 77.66% |
| | 0.05 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.05 | |
| Module 1 | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100.00% |
| Module 2 | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100.00% |
| Module 3 | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 99% | 91% | 0% | 93.94% |
| Module 4 | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 84% | 0% | 0% | 83.36% |
| Module 5 | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 53% | 1% | 0% | 0% | 70.37% |
| Module 6 | 100% | 100% | 100% | 100% | 100% | 91% | 17% | 0% | 1% | 0% | 0% | 55.96% |
| Module 7 | 100% | 100% | 100% | 100% | 28% | 0% | 20% | 0% | 2% | 0% | 0% | 39.99% |

Module 1
At IO SAT station

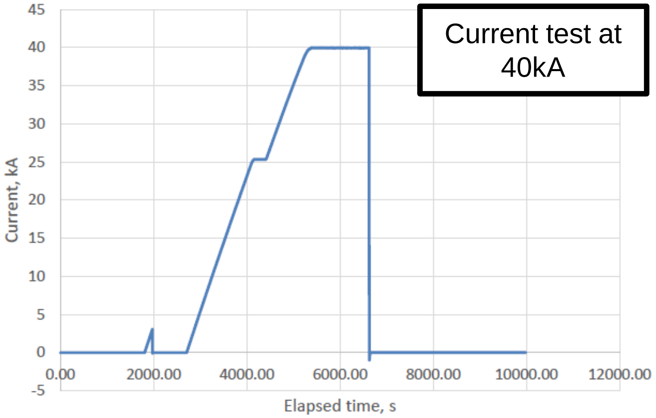
Module 4

Module 7

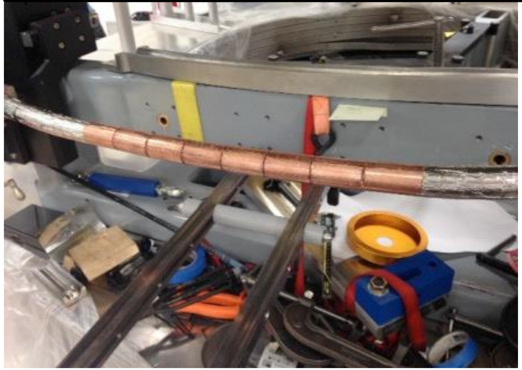
# CS Module Factory Acceptance Outcomes

- All modules are submitted to an extensive test program that includes
  - Paschen (15kV), Hipot (30kV) before and after cool down
  - Leak check
  - Cryogenic tests at 4.5K
    - Hydraulic test
    - Joint resistance
    - Mechanical (strain and deformation)
    - Current cycling up to 40kA and AC loss

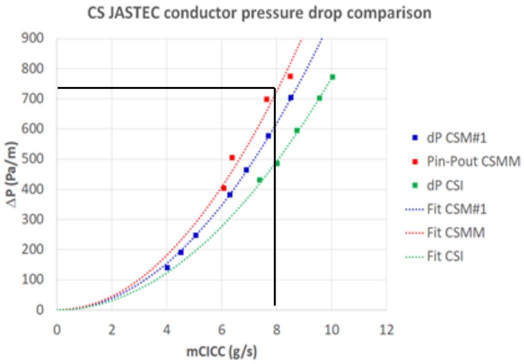
Current test at 40kA



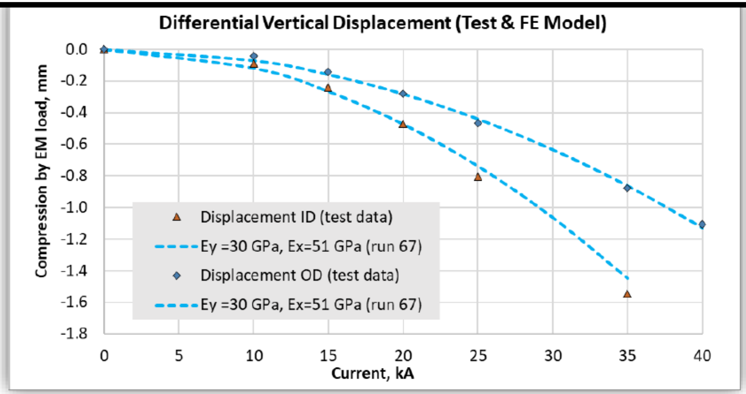

Inter-pancake joint resistance below 1nΩ (Required <4.1nΩ)



Pressure drop below 1 bar at 8g/s

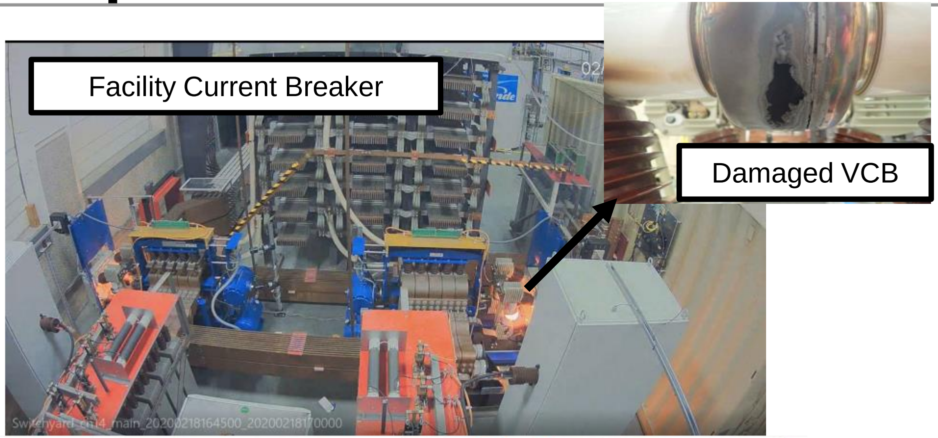


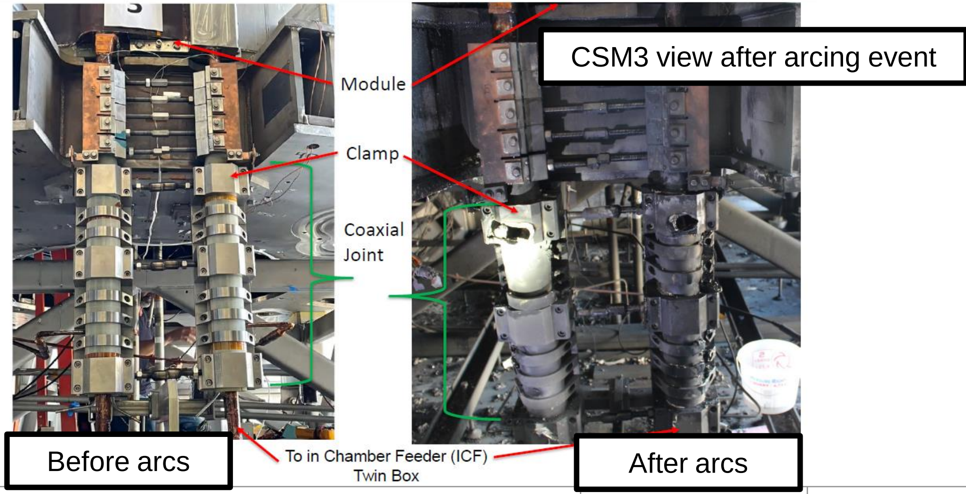

Vertical stiffness (30GPa) lower than expected (54GPa) but acceptable



# CS Module Factory Acceptance Outcomes

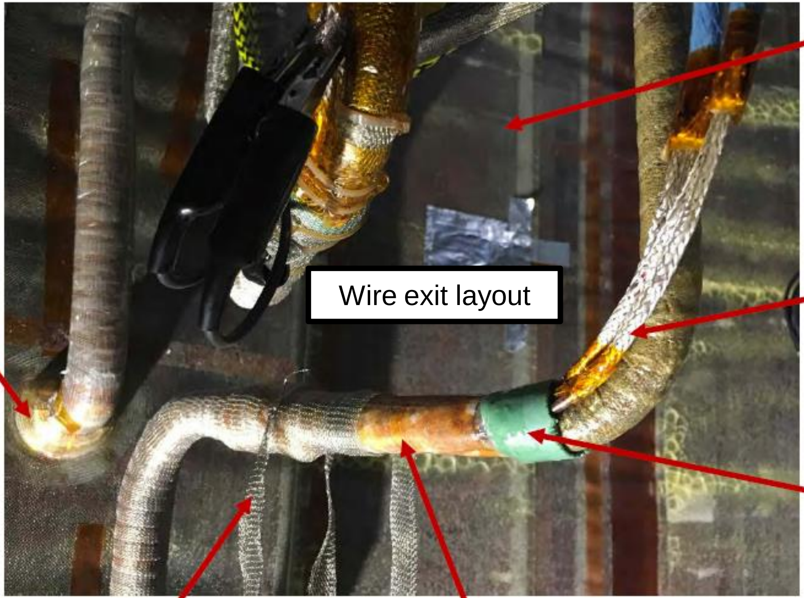
- Three main issues linked to the test facility
  - During CSM1 tests, Vacuum Breaker was damaged during a manual fast discharge at 10kA due to lack of sufficient charge voltage in DC breaker capacitance to extinguish the arc.
  - During CSM2 tests, DC power supply was damaged due to transient voltage in a specific operating mode.
  - During CSM3 tests, module and facility experienced multiple arcs at terminal and busbar area during a planned manually triggered fast discharge at 15kA. <u>The event is still under investigation.</u>



# CS Module Factory Acceptance Outcomes

- Main outcome related to module
  - HV tests has shown that the design of the polyimide quench detection wire exit from the ground insulation is critical. Several wire insulation cracks experienced on CSM1 and CSM2 (similar experience on TF and PF).
  - Issue solved with re-design.



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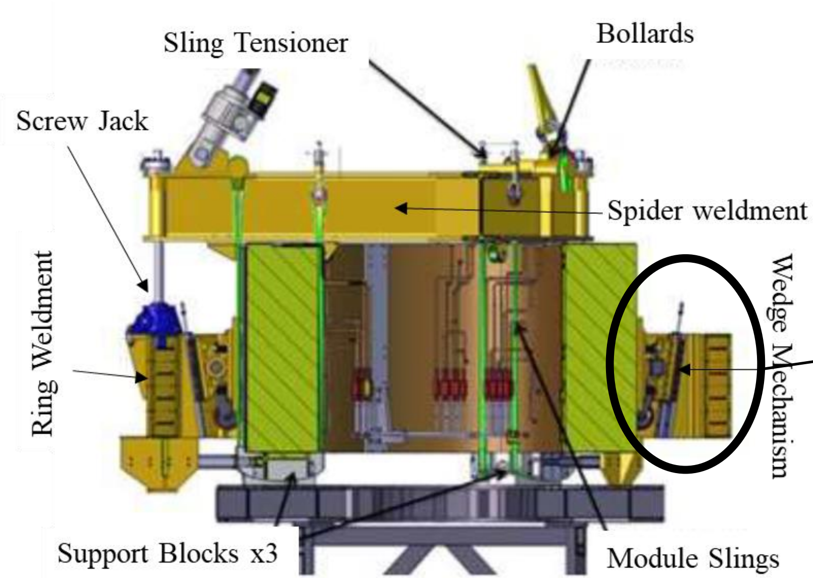
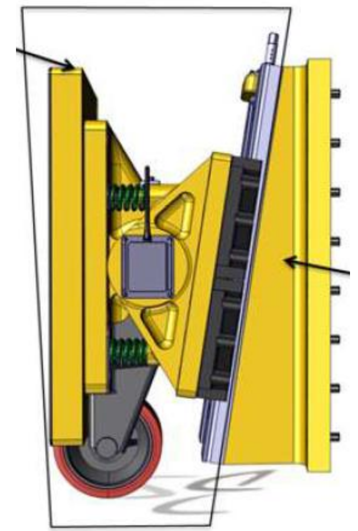
# Lifting tool

- Each module is about 120 tons for a diameter of 4,1 m and 2,2 m height.
- Due to the rather small distance in between inter-module pancakes, about 8 cm, it was not possible to foresee grooves in the inter-module insulation plate to insert slings or bars.
- The lifting tool was designed to grab the module from its outer diameter using wedged mechanism with a friction pad interface; slings between spider weldment and ring weldment provide 100% redundancy for lifting

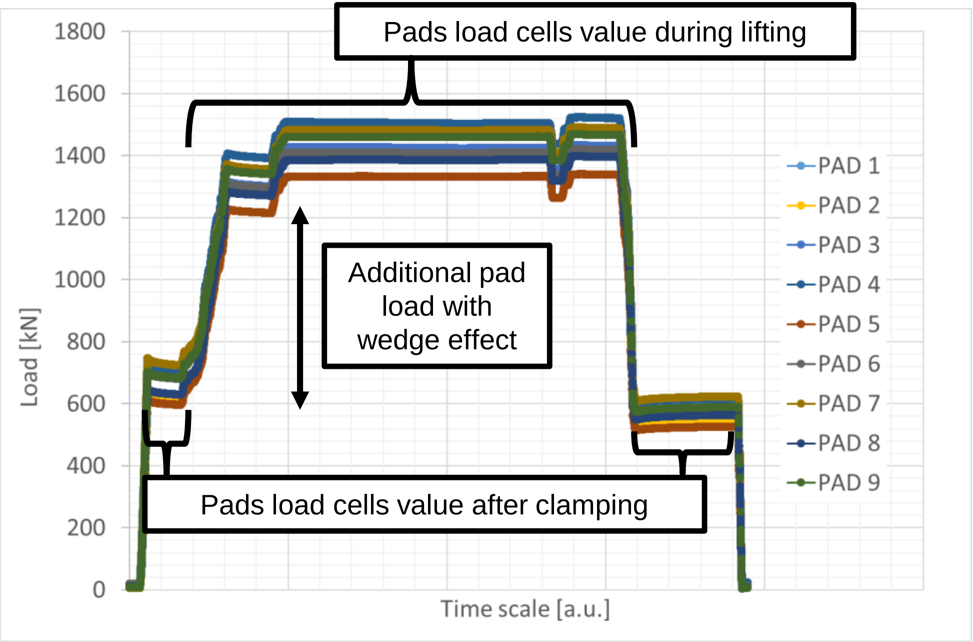


# Lifting tool

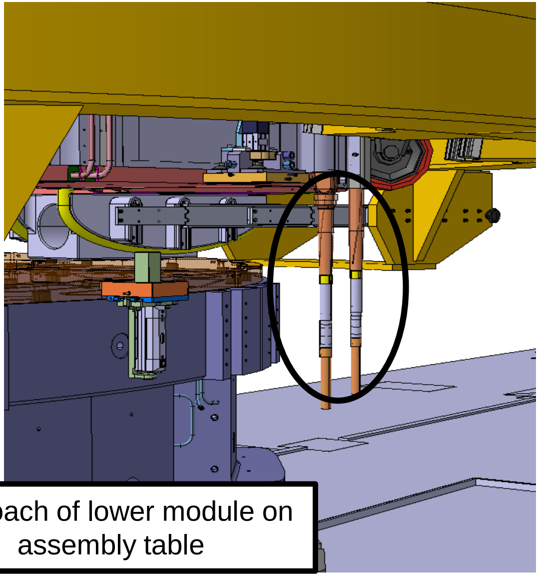
- As part of the tool certification, a load test at least 150% of the nominal load (120 tons) was performed in August 2021. This test has shown that the key installation difficulty is to center the module at a millimeter accuracy inside the ring weldment so that the wedge mechanism components do not interfere with the module support.

Lifting test with 185 tons test load

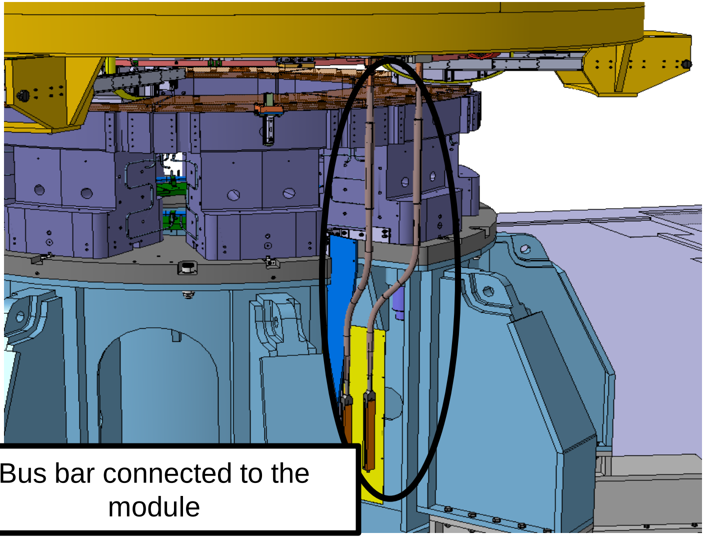


# Coaxial Joint Bus bar assembly

- The joint in between module and busbar has to be done in vertical position during stacking. Several constraints make this joint design and assembly process difficult
  - Vertical assembly at height
  - Lack of clearance in final bus bar clamps
  - Short terminal length (170mm)
  - Joint can be dis-assembled to change a module



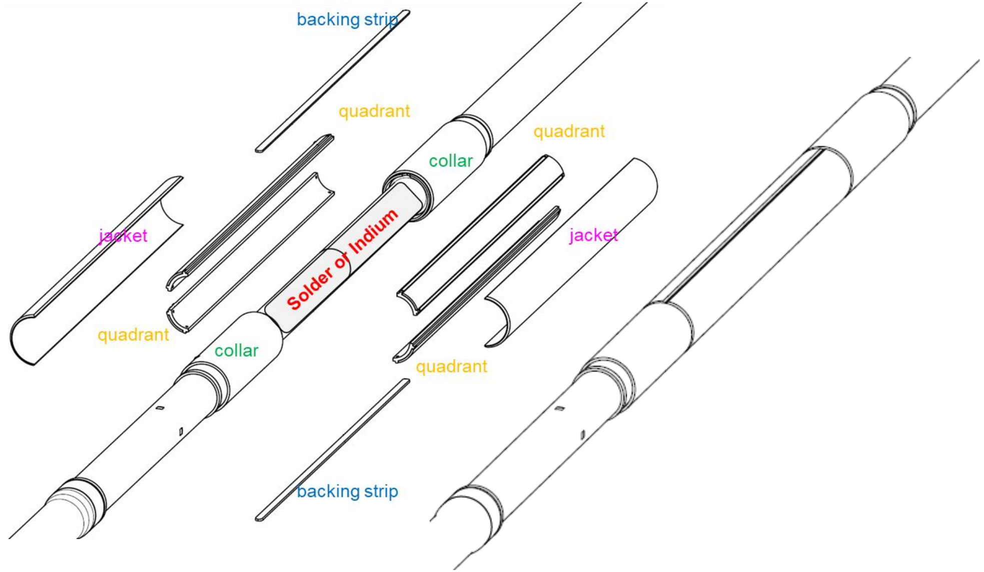
Approach of lower module on assembly table



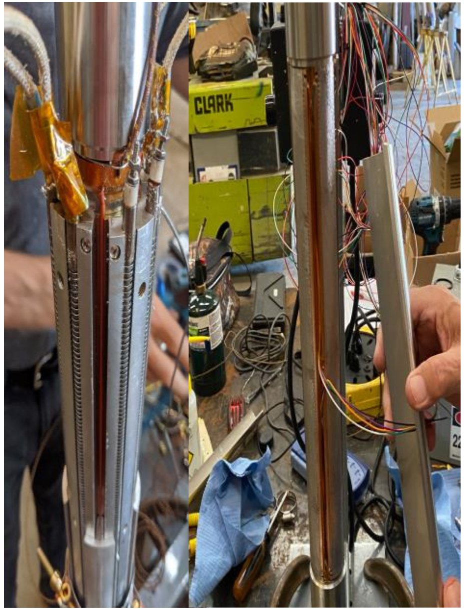
Bus bar connected to the module

# Coaxial Joint Bus bar assembly

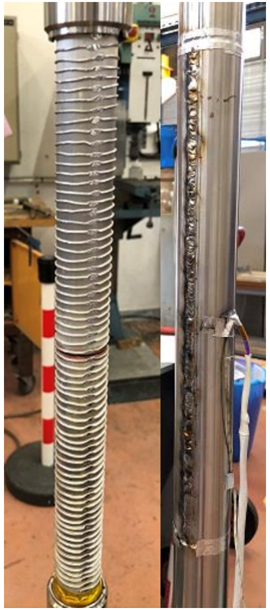
- Due to the dimension constraints (joint to fit in a 44mm diameter cylinders), a butt joint connected with superconducting unions was selected.
- Two options were tested for the electrical connections of unions to terminal: fast soldering and indium compaction.




Solder



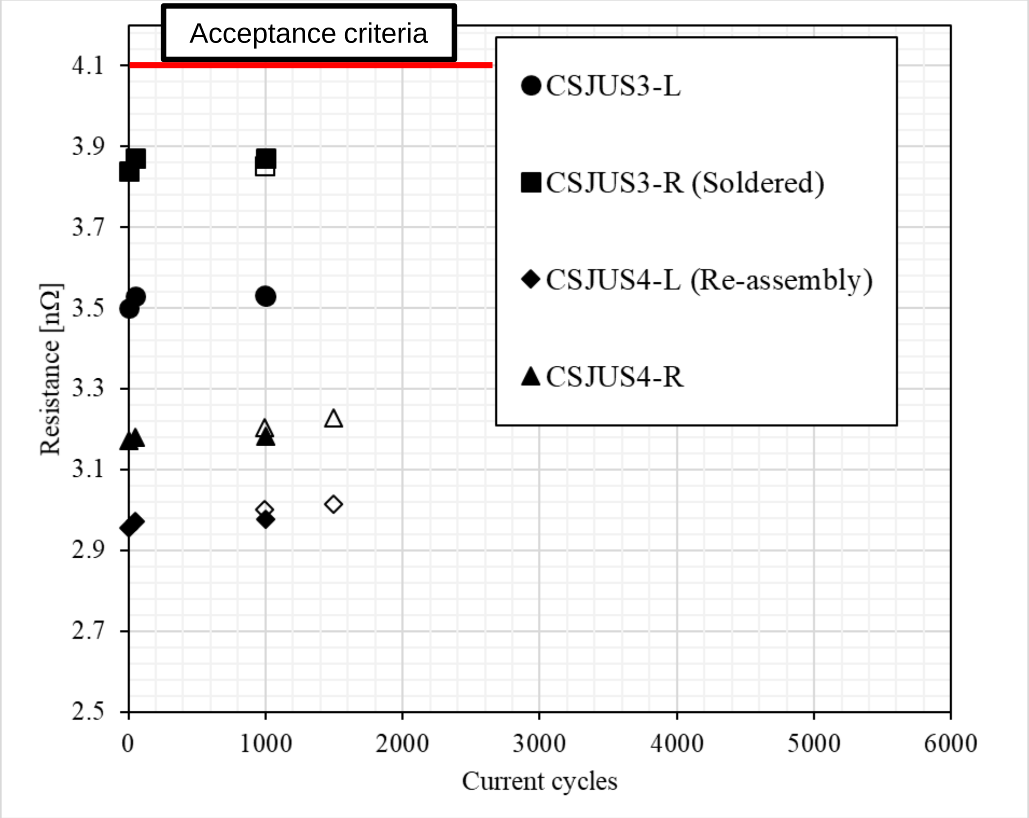

Indium



# Coaxial Joint Bus bar assembly

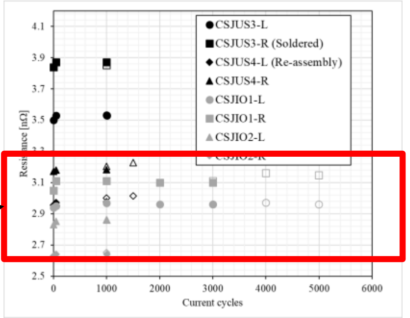
- Cryogenics tests shows no significant difference in between solder and indium assembly:
  - Indium process then selected as much simpler and less risky to implement in assembly conditions (difficulty to solder in vertical position, risk of solder leak inside the cable)
- 3 indium joints were then manufactured to qualify the process for assembly and re-assembly.

- Qualification samples cryogenic testing outcomes:
  - Resistance below requirement (4.1 nΩ)
  - No sensitivity to EM cycling
  - No sensivity to WU/CD cycling



# Coaxial Joint Bus bar assembly

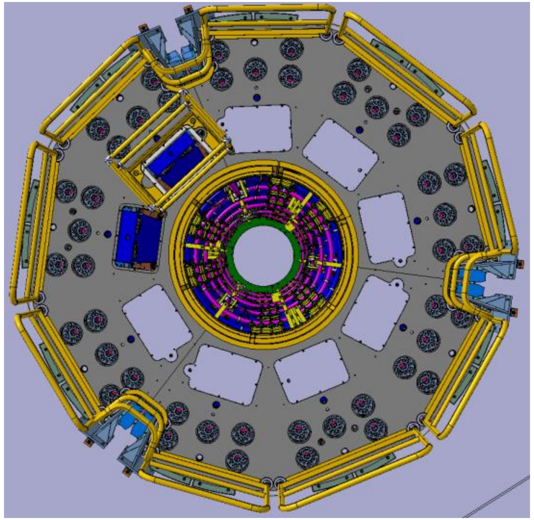
- Four new joints was then manufactured to qualify operator from the company awarded to complete the CS assembly.
- Joints were made using final assembly tooling procured by USDA and with a mockup simulating final assembly conditions.
- Two teams were trained and qualified; results were even better than qualification samples.



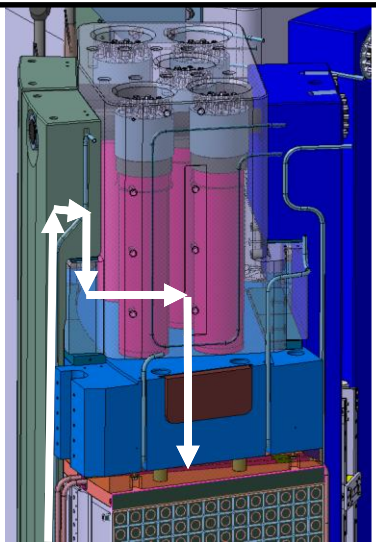

# Pre-compression

- The CS required a pre-compression load of 210 MN to ensure contact in between modules along plasma scenarios.
- Baseline process foresees to apply the pre-load by tightening 45 superbolts.
- A mockup was procured by USDA to verify the tightening process
  - Full scale in cross-section
  - Reduced scale in length (same deformation than stack under nominal preload)

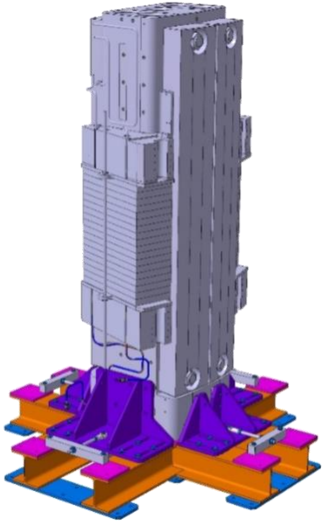
CS stack top view with 45 superbolt

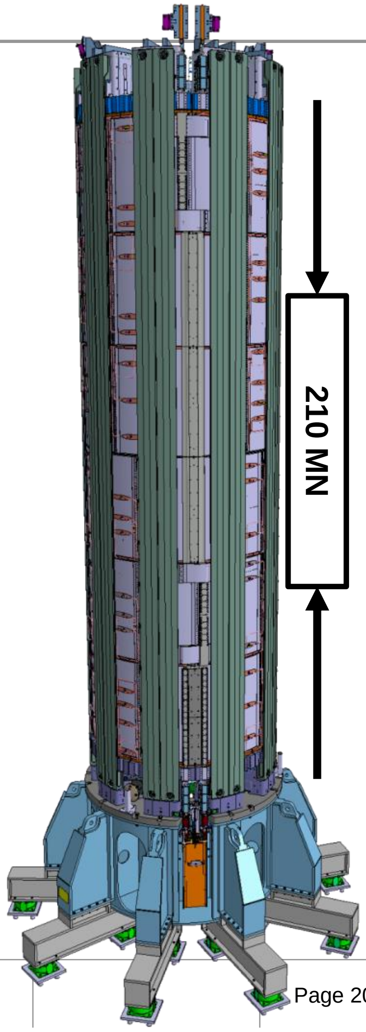


Zoom on UKB with pre-load load path



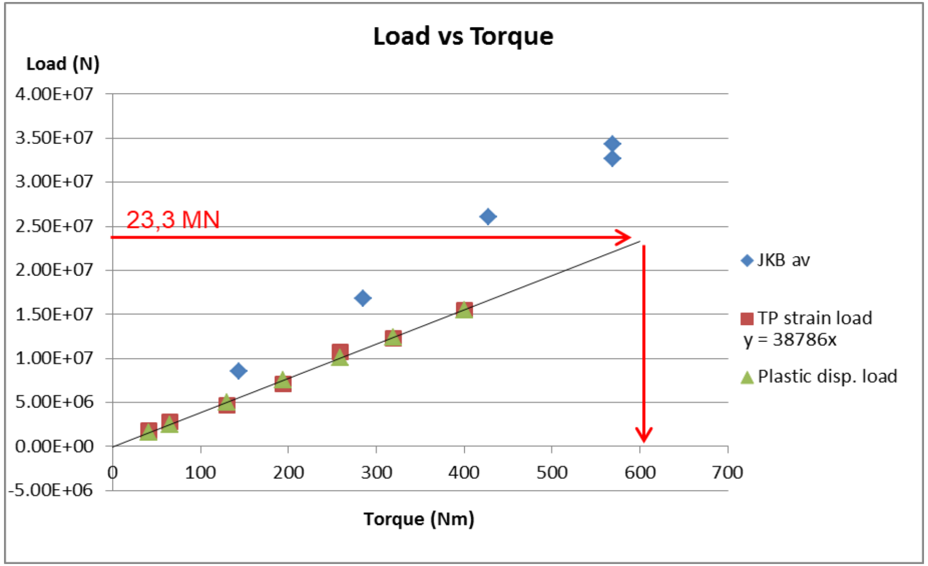
Sector MockUp

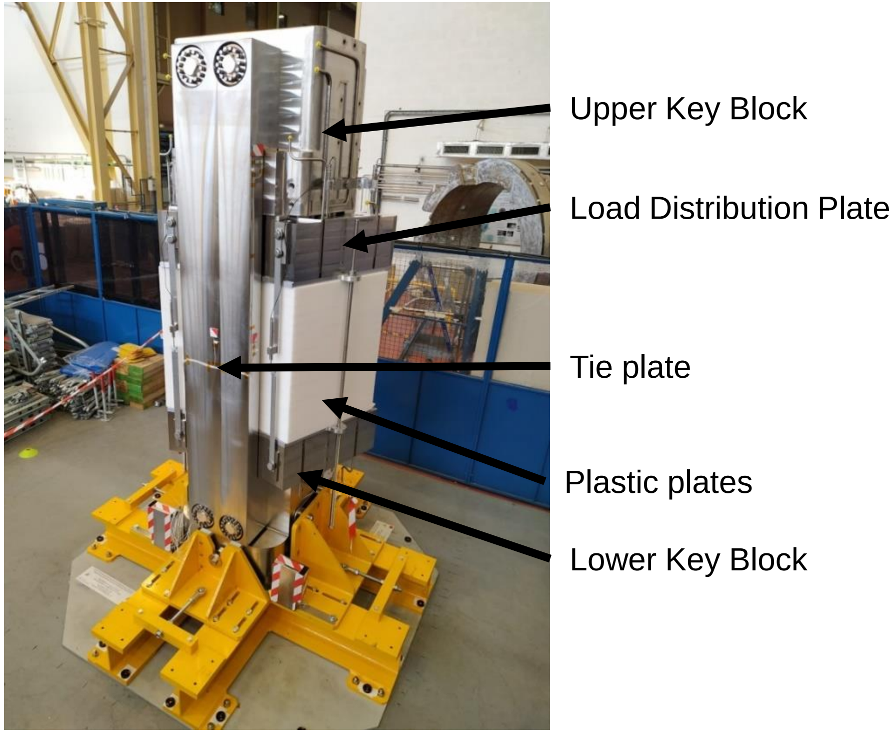




# Pre-compression

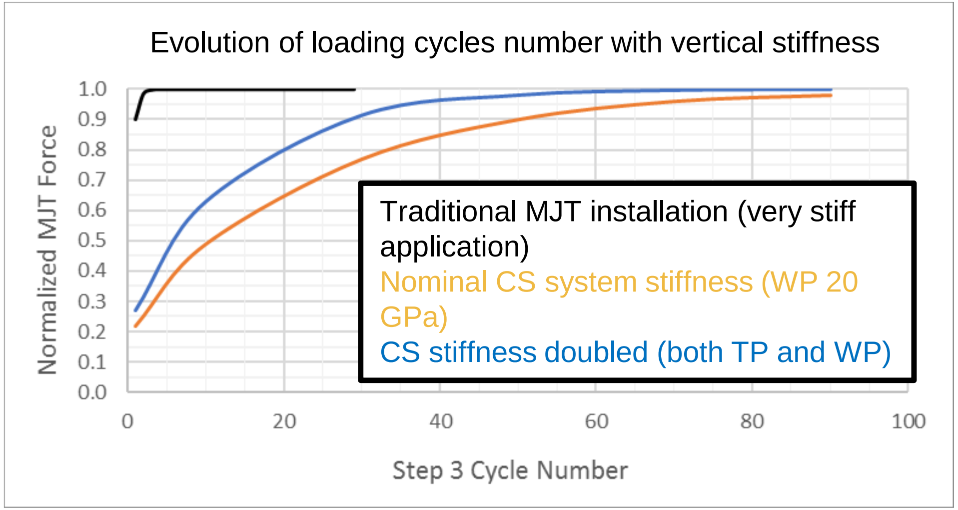
- The mockup test raised the following issue:
  - The pre-load was not achieved with the tightening process defined by superbolt suppliers
    - Additional torqueing stabilization steps required

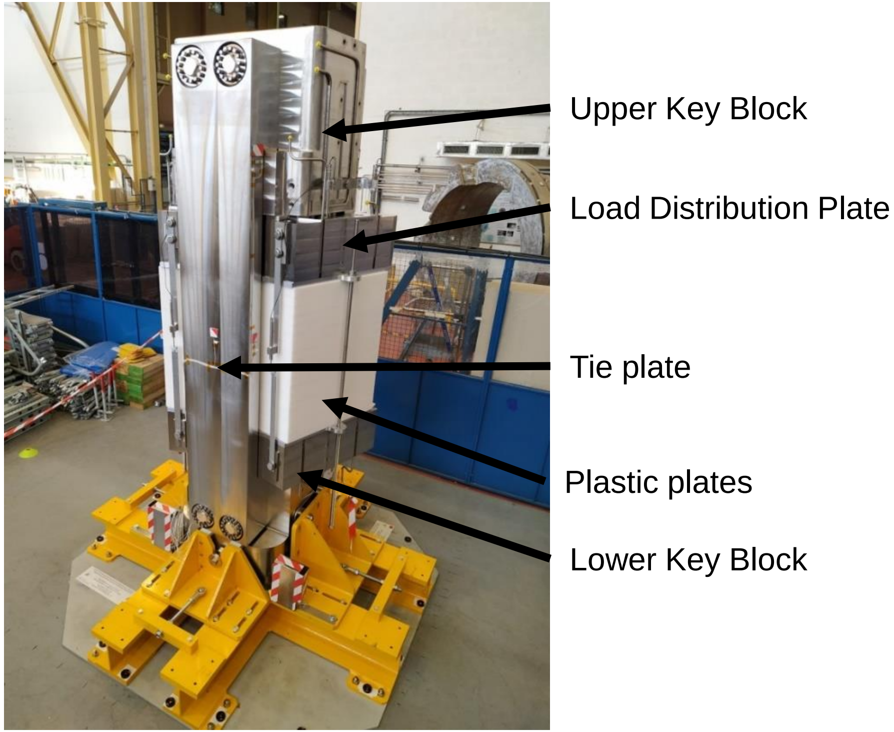


# Pre-compression

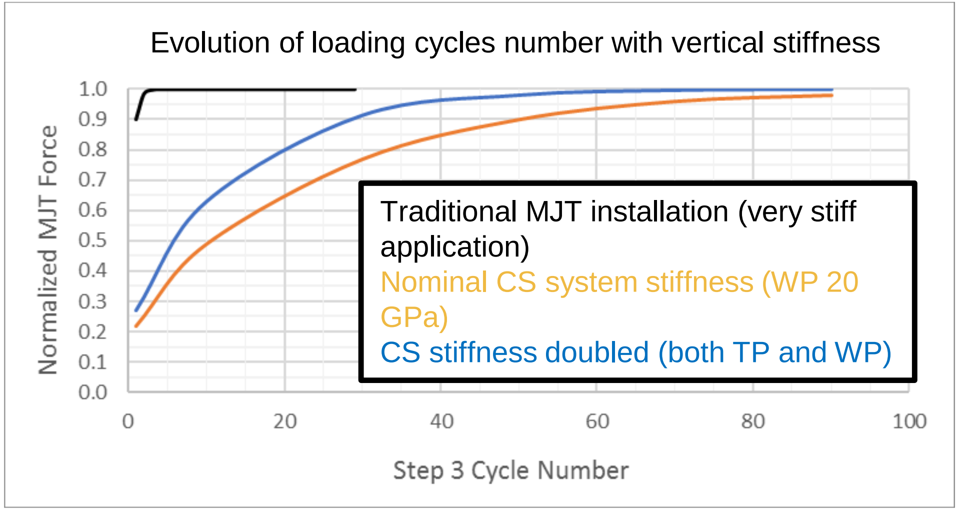
- The mockup test raised the following issue:
  - The pre-load cannot was not achieved with the tightening process defined by superbolt suppliers
    - Additional torqueing stabilization steps required
- Analysis  shows that the process is very sensitive to stack stiffness. 1.7 M cycles estimated to load the CS.

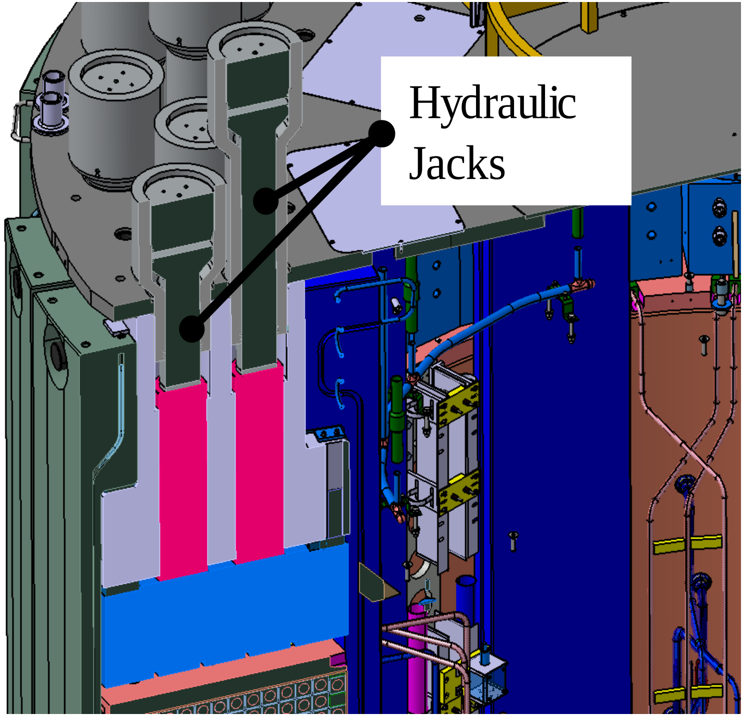


# Pre-compression

- The mockup test raised the following issue:
  - The pre-load cannot was not achieved with the tightening process defined by superbolt suppliers
    - Additional torqueing stabilization steps required
- To reduce assembly time and mitigate technical assembly risks, it was decided to procure custom hydraulic tighteners to replace superbolts. .



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# CS Asssembly status

- Two modules delivered in IO
- All special tooling developed by USDA are delivered to IO
    - Lifting tool, Bus bar assembly tool, Assembly platform, Drilling tool
    - Training on-going
- All structural parts required to start assembly are delivered
- Assembly has started with installation of the platform in the assembly hall

Assembly platform in Assembly Hall


Lifting tool prepared for training

# Thank you for your attention