Contribution of Efremov Institute to Design and Structural Analyses of ITER

Presented by A. Alekseev

21 July 2011

IO, Cadarache, France

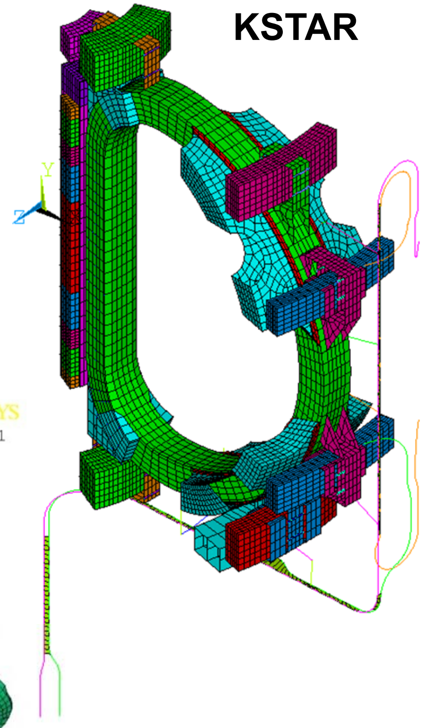
Outline

What has been done, what we do now and what could be done in future

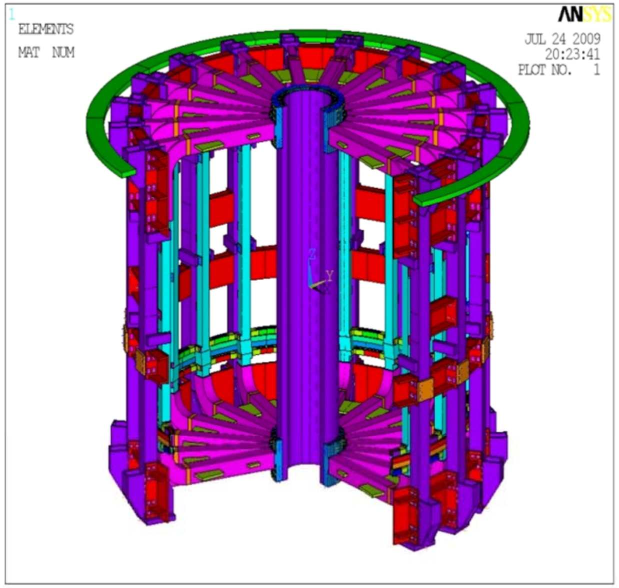
- Introduction, EDO activities
- Magnet system
  - TFC, PFC and CS Global and local analyses, normal operation
  - Fault conditions
  - Impact of tolerances
  - Magneto-elastic stability of PFC and CS
  - Insert Coils
  - Structural Design Criteria
- Vacuum Vessel
  - Global models and detailed design and analysis of Upper Port
- In-vessel Components
  - Divertor
  - First Wall
  - Operational Instrumentation
- Power Supply System
- Seismic Analysis
- Summary

Introduction

- Working on ITER from the very beginning
- Our speciality is to work on engineering aspects of fusion devices
- Not only ITER
  - T-15
  - GLOBUS-M
  - KTM
  - KSTAR
  - W7-X
  - T-15MD,
  - etc

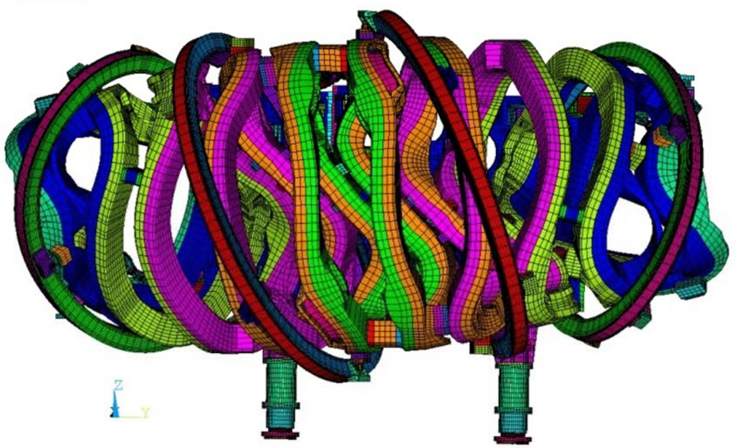


KSTAR



KTM

W7-X



Efremov Design Office Activities

- ➢ EDO was organaized in 1995, worked until 2002
- ➢ By mutual agreement between the ITER Director and Efremov Institute DG.
- ➢To support JCT at the Naka JWS in design and analysis during EDA
- ➢ Main fields of activity
  - Design of Magnet Structures (CS pre-compression structure, PF supports, TF Inter-coil connectors, cooling passages, etc)
  - Design and Analysis of Vacuum Vessel Thermal Shield
  - Thermo-hydraulic Analysis of Magnet System: Cool-down and Operational Conditions
  - Structural Analysis (Global and Local Models: windings, joins, mechanical connectors, keys, supports, etc., Fatigue analysis, Structural Analysis under Cool-down, Magneto-elastic stability analysis, Structural analysis of assembly & manufacturing tolerances impact, Development of the Structural Design Criteria, etc)
  - Design and Analysis of the current & cryolines
  - Safety Analysis (Effect of Exceptional PF Coil Currents on PF and TF Coil Stresses. TF Coil fault structural analysis)
  - Power Supply System Analysis (Analysis of electrical transients within CS and PF coils, Ground system analysis)
  - Error Field and Correction Coils Analysis
  - etc

FRD 2001, Magnet DDD, Structural Analysis, List of Annexes

Annex [1]: Non-linear 3D Global structural Analysis of ITER-FEAT Toroidal Field magnet System, N11 RI 27 00-06-29 F1, C.T.J. Jong

Annex [2]: Structural Analysis of the TF Structures of the ITER-FEAT magnet System, Work Topic 3.3, TFC Global Model, PR 206, 11/12/2000, Efremov Design Office.

Annex [3]: ITER-FEAT TF Coil Cross Section Analysis, G 73 MD 38 00-09-01 W0.1, M. Verrecchia, 01-09-2000, ITER-JCT-Garching.

Annex [4]: 3D Structural Analysis of the Tolerance Impact on the Wedging Zone Stresses, Work Topic 3.4, PR 199, 01/12/00, Efremov Design Office.

Annex [5] Structural Analysis of the Pre-Compression Ring, Work Topic 3.3, PR205, 08/12/2000,Efremov Design Office.

Annex [6] Structural Analysis of the Pre-Compression Ring with the Pressure Plate Split, Work Topic 3.2, PR227, 24/05/01, Efremov Design Office.

Annex [7]: Structural Analysis of the Poloidal key with Poloidal Strain re-calculated from the JCT Global model, Work Topic 3.2, PR 228, 22/05/2001, Efremov Design Office.

Annex [8]: FEM Structural Analysis of overall Gravity Supports, JA Home Team, Task No: N 11 TD 84.02 FJ

Annex [9]: Stress analysis of the flexible plate supports for the vacuum vessel, IDoMS G 16 MD 306 01-1-22 W0.2, F. Elio – ITER-JCT Garching.

Annex [10]: 2D Stress Analysis of the Support and Pre-compression Structure of the CS with the Incoloy 908 Conductor jacket, PR 230, Work Topic 3.4, 25/05/2001, Efremov Design Office.

Annex [11]: Preliminary 2D Stress Analysis of the Support and pre-compression Structure of the CS with the SS Conductor jacket and Aluminium Alloy Tie-Plates, PR 231, Work Topic 3.4, 25/05/2001, Efremov Design Office.

Annex [12]: Structural Analysis of Overall CS Coil (Option Design) Support System; Sec.4.4 in Final Design Report by JA-HT with Task No. N 11 TD 84.02 FJ

Annex [13]: Stress Analysis for CS coils at aligned location with Strip type conductor and Armour type conductor under ITER-FEAT Condition

Annex [14]: Stress Analysis for CS coils at misaligned location with Strip type and Armour type conductor under ITER-FEAT Condition.

Annex [15]: Structural Analysis of ITER-FEAT Poloidal Field Magnet System – Design of Support, RF Home Team.

Annex [16]: 3D FEM Structural Analysis of PF3/PF4 Clamp Structures (Connected Type Support), JA Home Team, May 2001

Annex [17]: Stress Analysis of PF3 Coil, JA Home Team, Task No: N11 TD 84.02 FJ

Annex [18]: Stress Analysis of PF6 Coil, JA Home Team, Task No: N11 TD 84.02 FJ

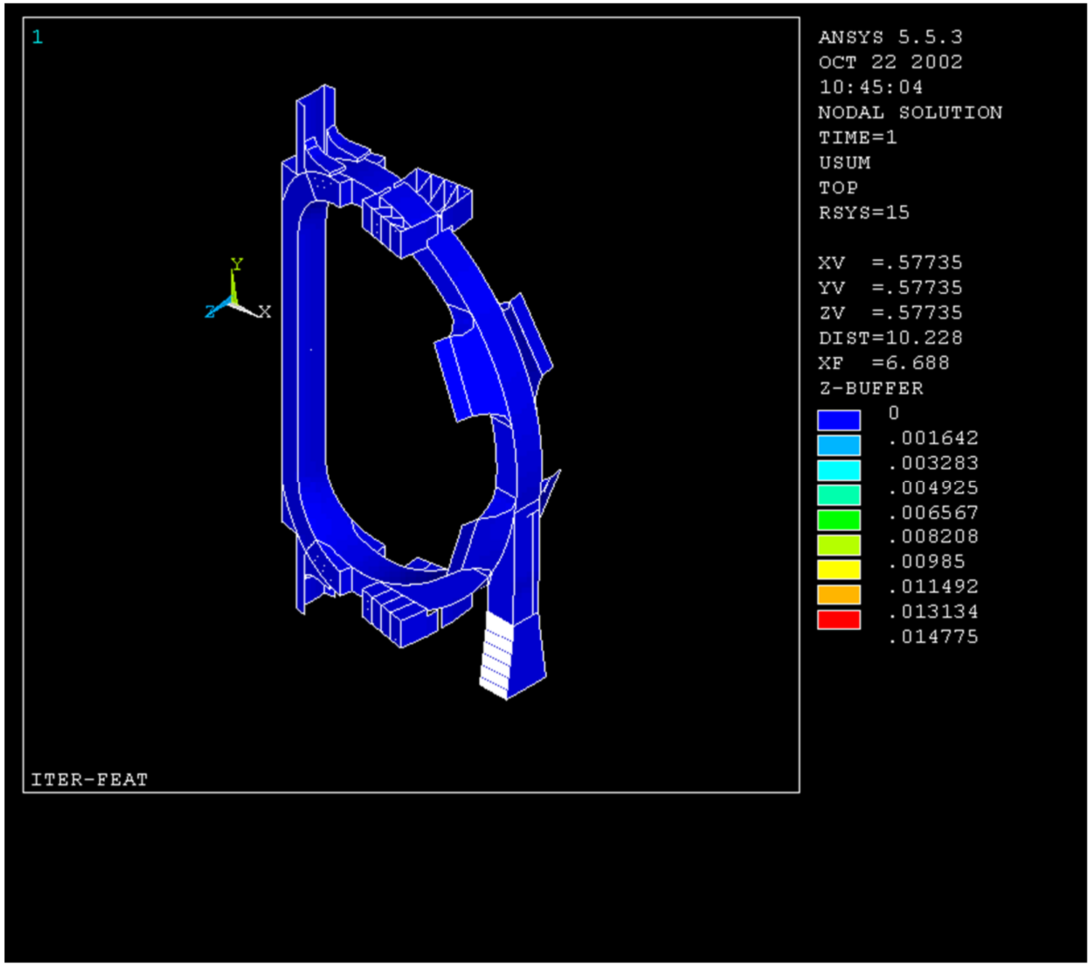
Annex [19]: Bottom Correction Coils, Design of Supports and Structural Analysis, RF-Home Team, St. Petersburg, May 2001

Annex [20]: Study of the Multi-pulse Frictional Stability of the TF-coil System under Out-of-plane loading, A. Panin, RF-Home Team, 17 November 2000

10 of 20 annexes were developed by the RF Team

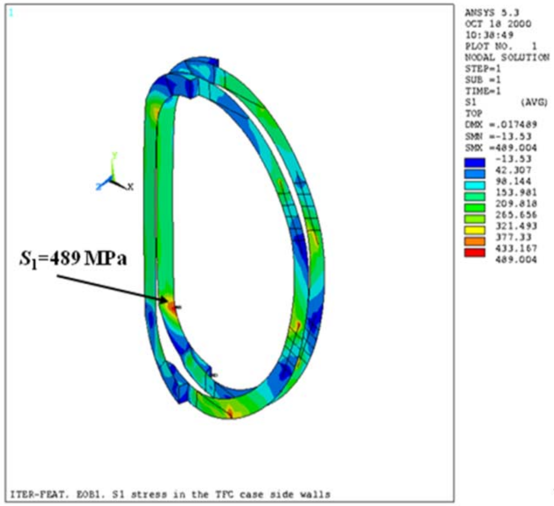
TFC. Global modeling

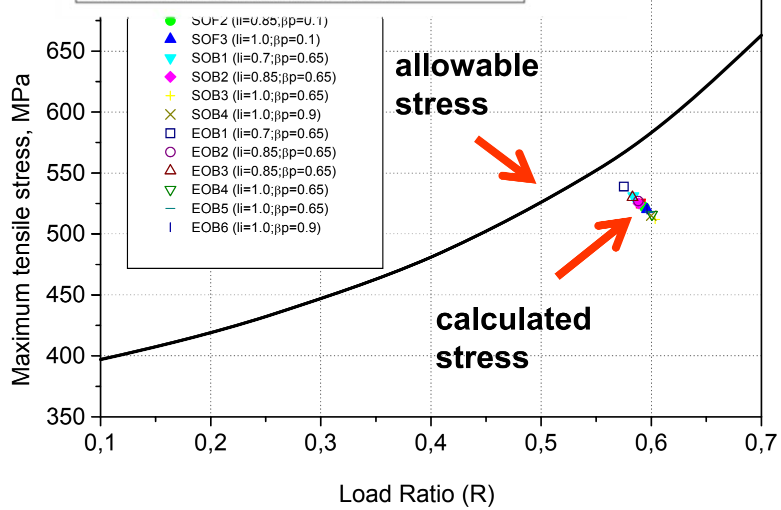
TFC displacements under EM loading (m)



The Design is based on Structural analysis

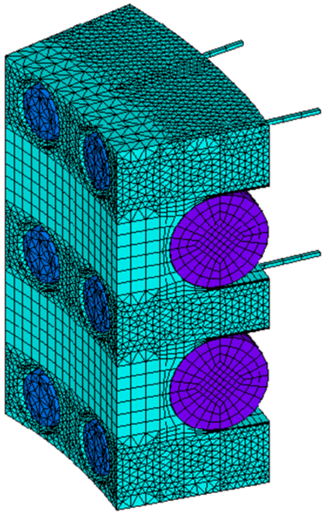
First principle stress in TFC case (MPa)



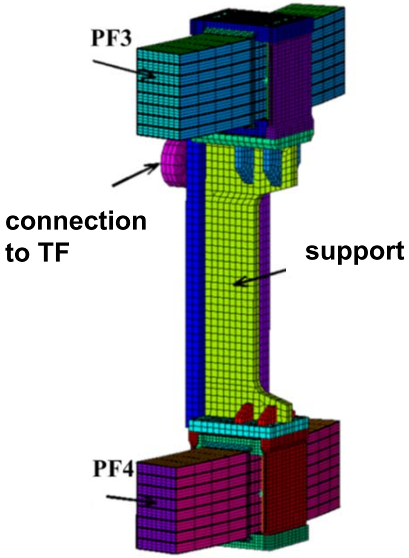


Local modeling

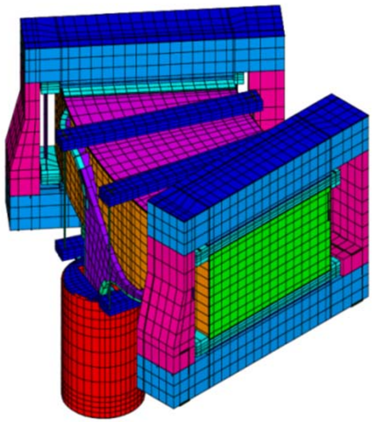
Pre-compression Rings



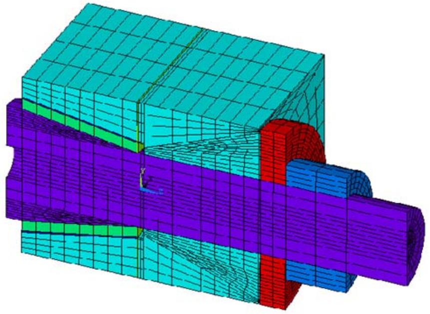
PF3 и PF4



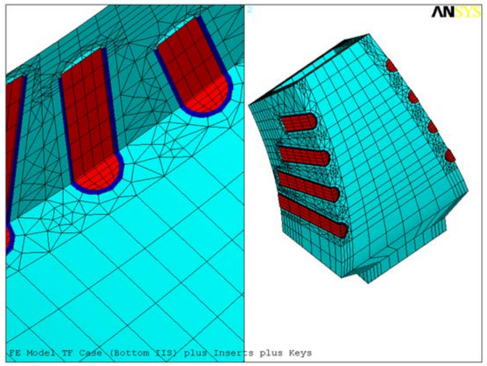
PF6



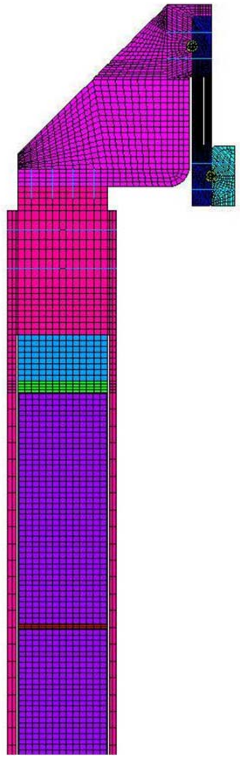
Conical Bolt



Poloidal Keys



CS (fragment)

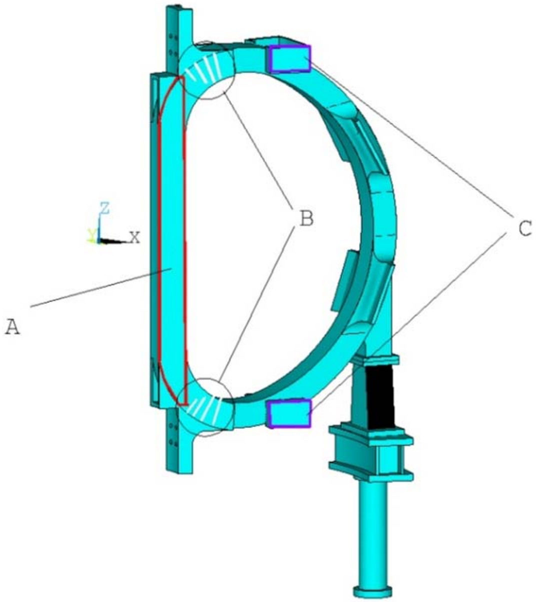


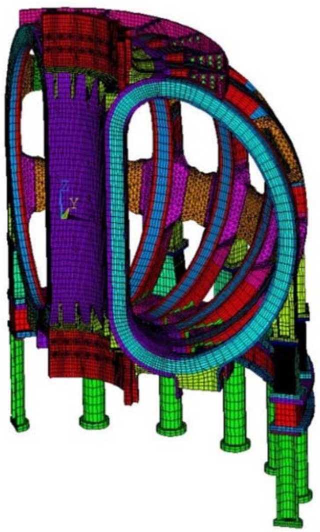
Impact of tolerances on TFC (2009)

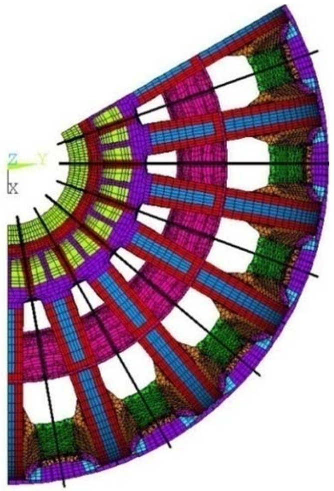
Deviations from nominal dimensions cause additional stresses in the TFC and structures

- ❑ Small tolerances on manufacturing and assembly - small stresses, but high cost
- ❑ Too much relaxed tolerances may result in unacceptably high stresses

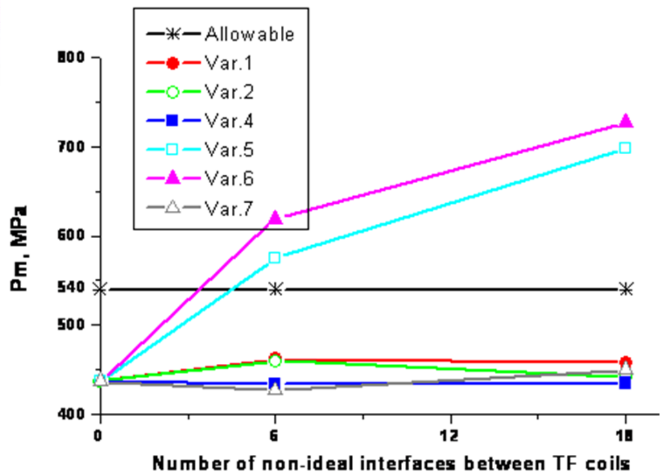
Structural assessment of the impact of geometrical deviations has been performed to specify reasonable tolerances







Membrane stress in weld of Inner Leg



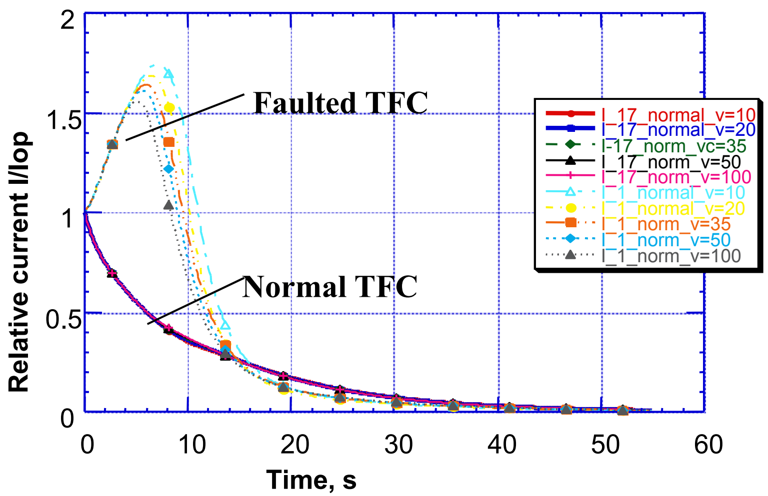
A – wedging area, nominal gap 2 mm

C – OIS flanges, nominal gap - 0 мм

B – poloidal keys, nominal gap- 0 мм

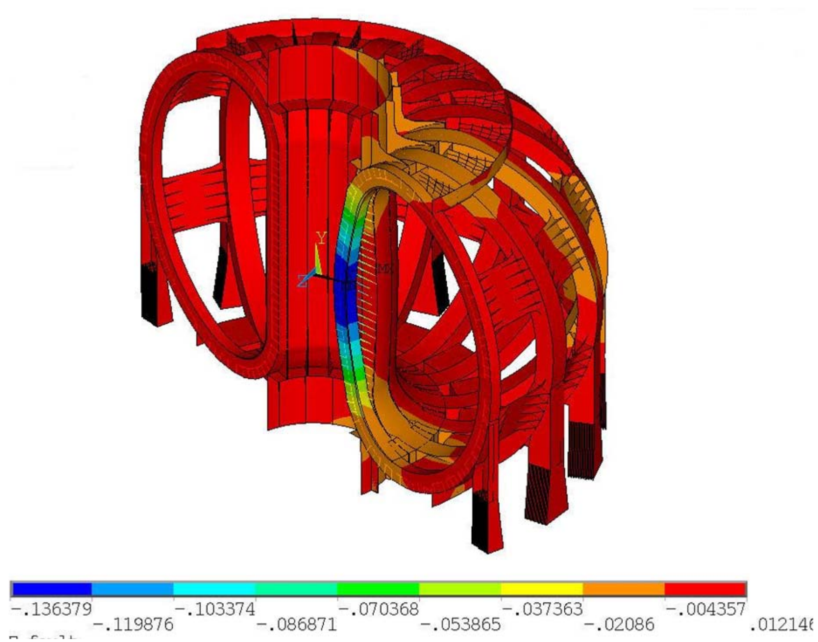
Fault conditions

➢ **Short Circuit in one TF Coil under fast discharge**



Evolution of currents in TF Coils

Elasto-plastic analysis



Radial displacements, $\mu = 0.1$, м.

Elastic analysis results

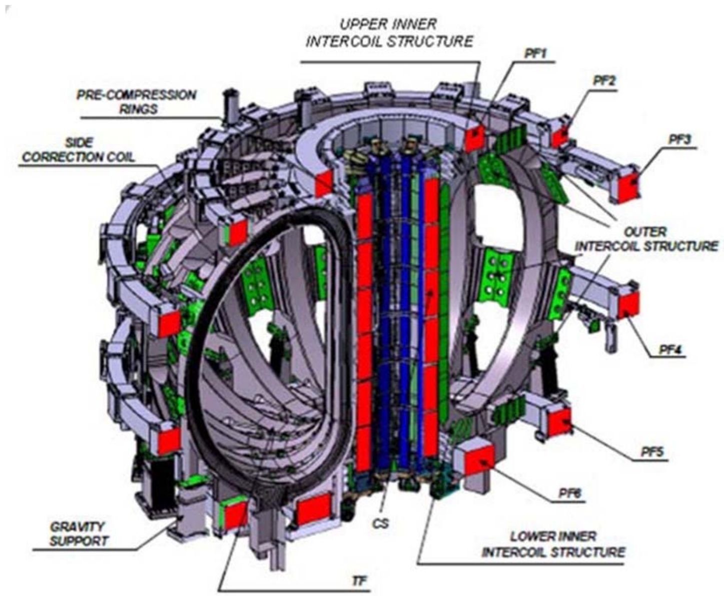
Friction Coefficient		0	0.1	0.2	Allowable stress MPa
Radial displacements, mm (min/max.)		-126/16	-57/13	-12/12	
Maximum stress intencity MPa	membrane	673	349	251	900
	membrane + bending	1724	797	423	1350

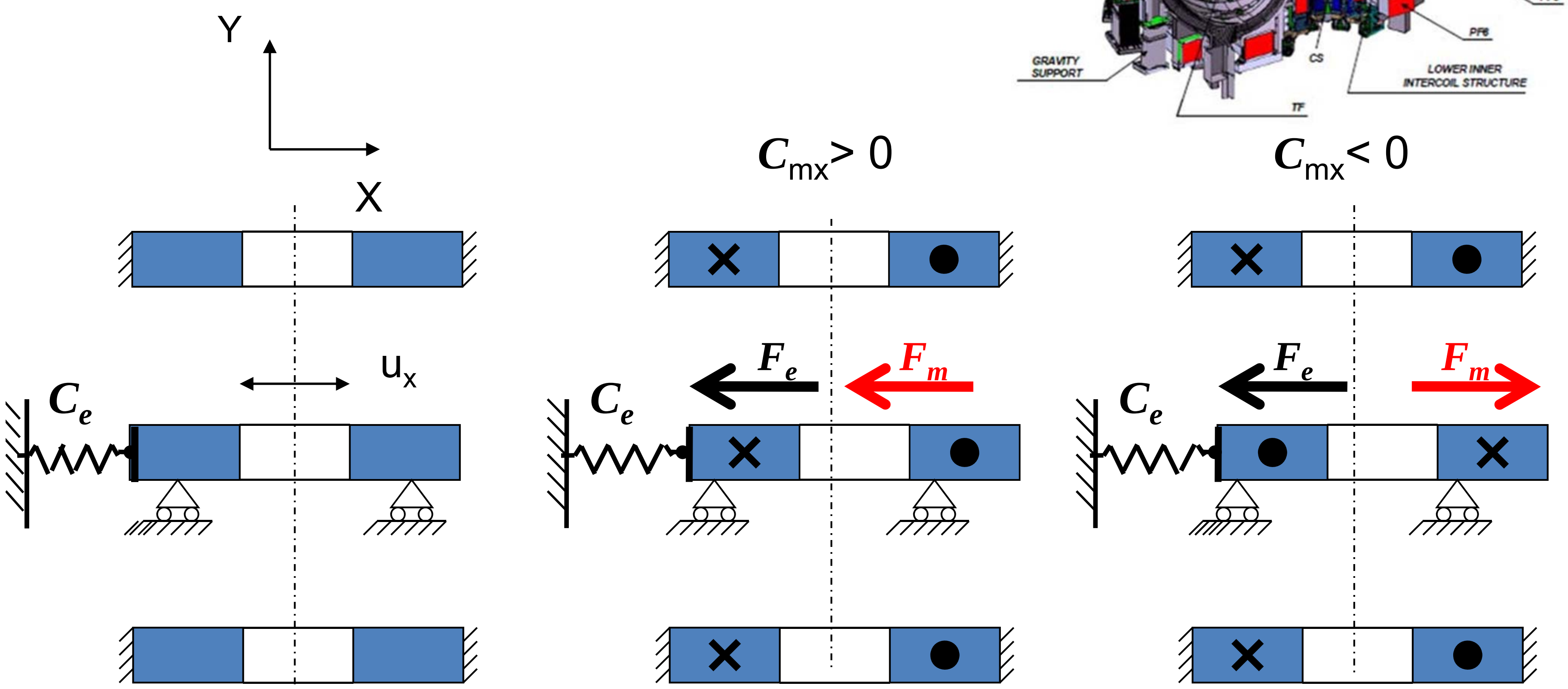
⇨ **- stresses are within allowable limits**

⇨ **- Load bearing capacity of the structures remains;**

- Displacements of TFC are not dangerous for the VV

Magneto-elastic stability of PFC and CS (1)





The coil position is stable, if $C_e + C_m > 0$

Magneto-elastic stability of PFC and CS (2)

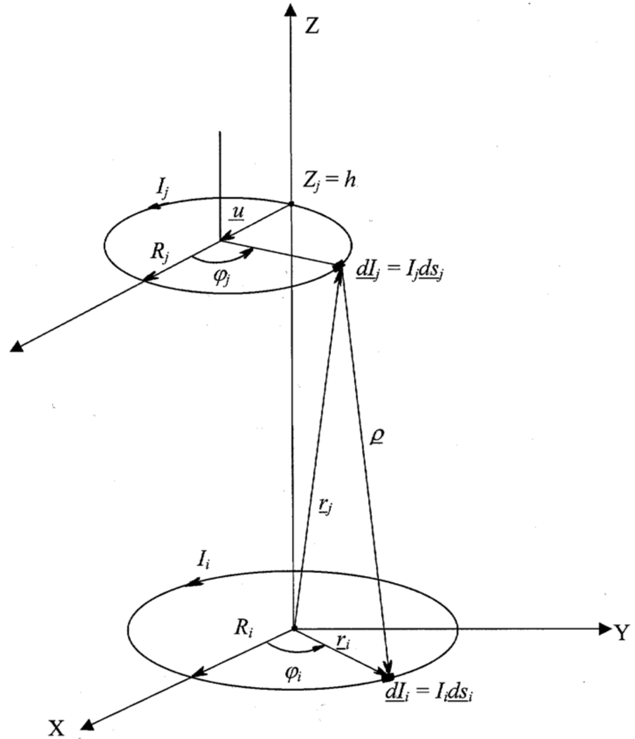
Force of interaction of two coils caused by displacement: $u=u_i-u_j$

$$F_{ij} = -c_{ij}^{PF}\left(u_i - u_j\right),$$

here c_{ij}^{PF} - mutual magnetic stiffness *i*-coil and *j*-coil

$$c_{ij}^{(PF)} = \frac{\mu_0}{2} I_i I_j R_i R_j \int_0^{\pi} \frac{\left((z_i - z_j)^2 - 2\left(R_i^2 + R_j^2\right)\right)\cos\psi + R_i R_j\left(3 + \cos^2\psi\right)}{\left(R_i^2 + R_j^2 - 2R_i R_j \cos\psi + \left(z_i - z_j\right)^2\right)^{5/2}} d\psi.$$

$$\left(i \neq j,\quad c_{ij}^{(m)} = c_{ji}^{(m)}\right)$$



Combined matrix of magneto-elastic interactions for all PF and CS coils can be built

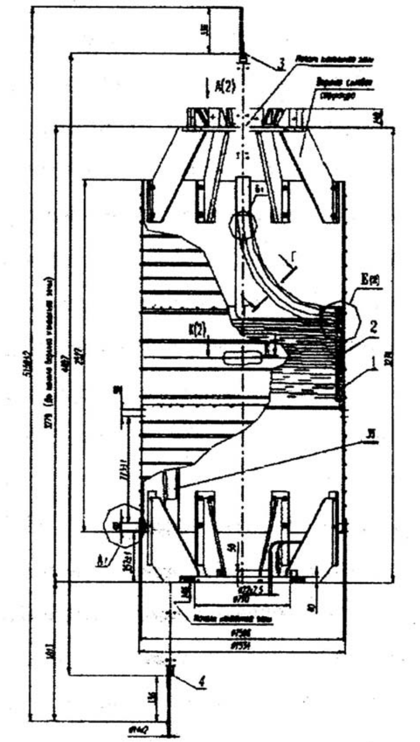
$$\mathrm{A} = \mathrm{A}_{PF}^{(m)} + \mathrm{A}_{CS}^{(m)} + \mathrm{A}_{SP}^{(e)}.$$

The system will be stable, if matrix **A** is stable (positive-defined)

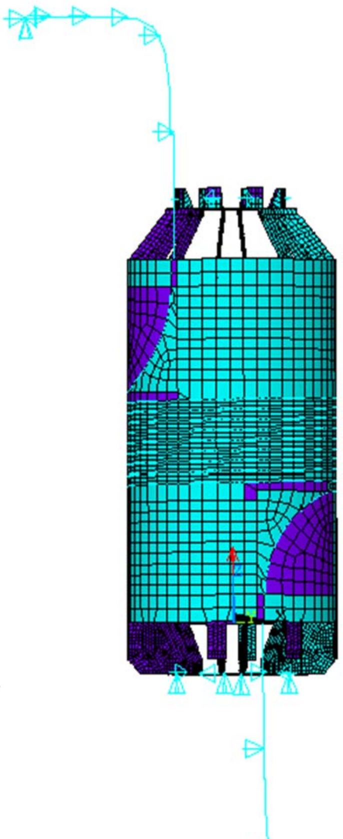
Analysis was performed for ITER (1998), support stiffness was verified. The technique for magneto-elastic stability analysis has been developed and included in the ITER Magnet Structural Design Criteria

Insert Coils in the CS MC (Naka)

Toroidal Field Conductor Insert Coil (2001)

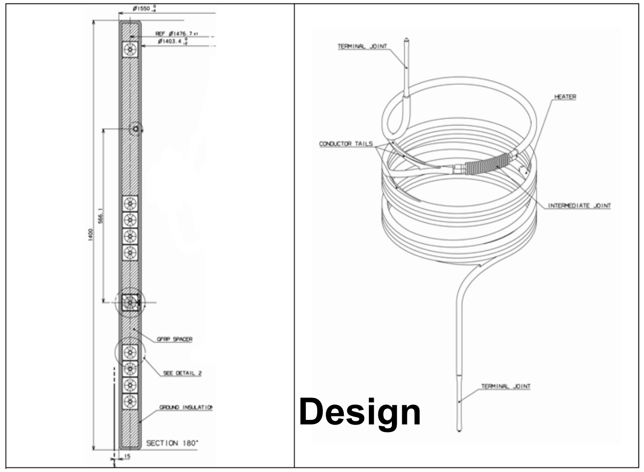


Design

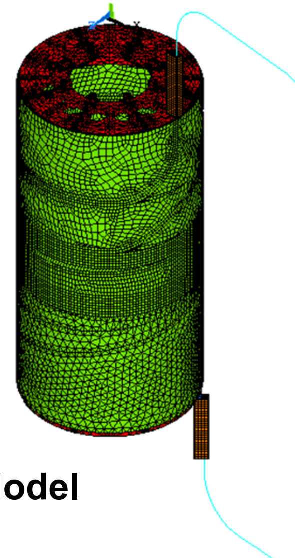


FE Model

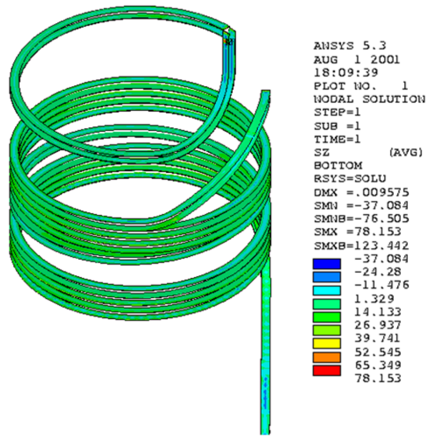
Poloidal Field Conductor Insert Coil (2008)



Design



FE Model



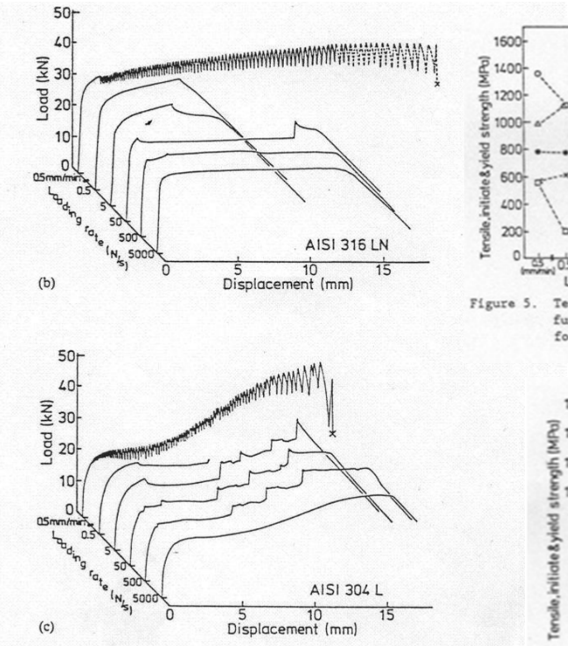
Stress across insulation layers

Structural Design Criteria for ITER Magnet

- Structural Criteria may have a critical impact on the design
- At present time there is no Structural Code in force for the superconducting magnet systems, like ASME, RCC-MR, etc
- The ITER magnet has a set of specific features in design and operating conditions which require the special structural criteria

Specific features of the ITER magnet require special Criteria (1)

- The magnet system operates at cryogenic temperature, around 4K. Structural materials show specific plastic deformation, which in particular depends on the load rate at this temperature. Compared to high temperature, yield and ultimate strength are increased, but fracture toughness decreases. Fast fracture mode and fatigue assessment based on crack propagation become more important than plastic yielding.



Load-displacement curves obtained at various loading rates. a) for AISI 310, b) for AISI 316LN, c) for AISI 304L.

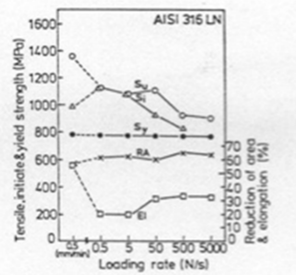


Figure 5. Tensile properties as a function of loading rate for AISI 316LN.

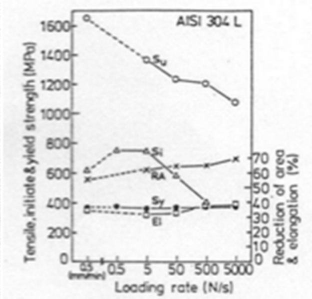
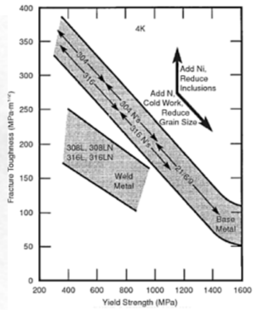


Figure 6. Tensile properties as a function of loading rate for AISI 304L.



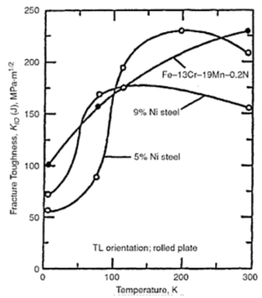


FIGURE 3.11. Fracture toughness of two ferritic steels (Fe–5Ni, Fe–9Ni) and one austenitic steel 13Cr–19Mn–0.2N) w temperatures.

Criteria should be based on S_y and K_{IC}

The criteria should prevent global plastic deformations and fast fracture

T.Ogata, K. Ishikawa, R.P. Read and R.P. Walsh.
Loading rate effects on discontinuous deformation.

Specific features of the ITER magnet require special Criteria (2)

- The main primary loads are static and cyclic electromagnetic forces. Magneto-mechanical interaction of the coils may be a source of structural instability.
- The stress-strained state of the magnet and supports caused by the loads differs considerably from structures consisting of pressure vessels, pipes and their supports. Electromagnetic loads cause 3D stress systems, with the additional complexity of contact interfaces. Hence, FE analysis is required.
- Large material thicknesses, up to ~0.2m with welds
- Bolts and fasteners are applied at room temperature, but operate at low temperature when the structural limits are much higher. This differs from the operation conditions of the high temperature fasteners.
- The superconducting windings are complicated anisotropic structures, in which the non-metallic material, especially for bonding, plays a significant structural role. The structural limits could be defined by the electrical functionality also.
- In-service inspection of the magnets is not possible. Leak-before-break is not a design option.
- No previous experience with such a design.

These features are not addressed in the existing industrial codes (ASME, RCC-MR, KTA, etc)

ITER Magnet Structural Design Criteria (2008)

A. Alekseev, C. Jong and N. Mitchell

Part I: Main Structural Components and Welds

- Toroidal Field (TF) coil cases
- Outer Intercoil Structures (not bolts and keys)
- Feeder Ducts

Part II: Winding Packs, Conductors, Insulation and Filler

- TF winding pack and case-winding filler.
- Poloidal Field (PF) winding packs
- Central Solenoid (CS) coil winding packs
- Correction Coils (CC) coil winding packs

Part III: Bolts, Keys, Supports and Special Components

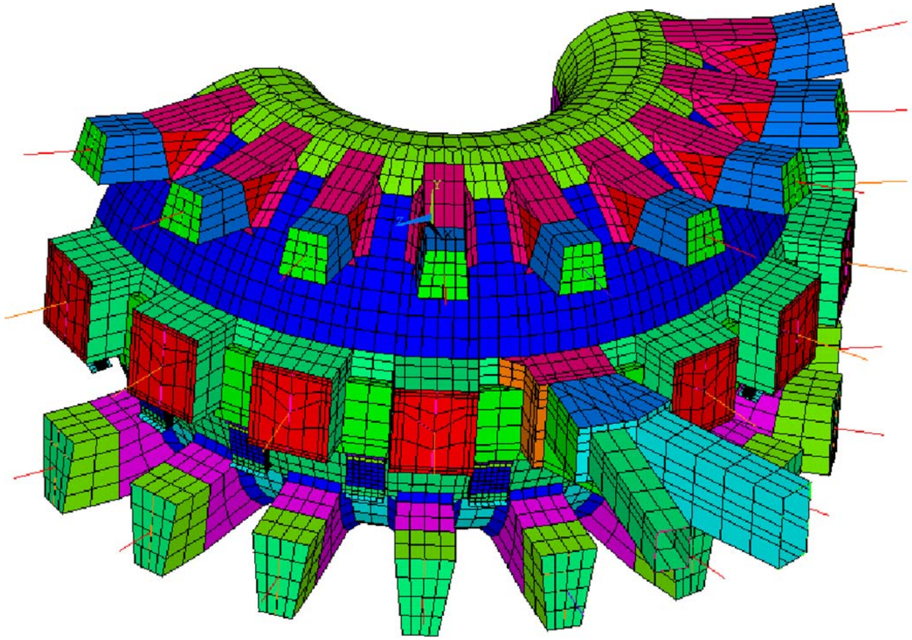
- CS pre-compression system (top and bottom flanges and vertical tie plates)
- CS coil interface plates (between coils)
- Inner Poloidal Keys
- OIS bolts and keys
- Pre-compression rings (PCR)
- Supports between PF and TF coils and between CS and TF coils
- Supports for Correction Coils
- TF coil gravity supports

Part IV: Cryogenic Piping

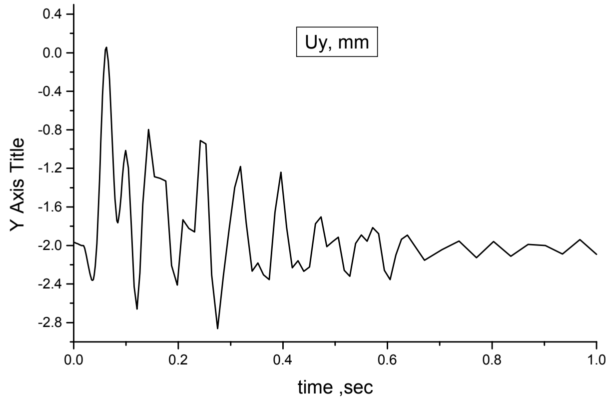
Total volume: 137 pages, including 7 appendixes

Vacuum Vessel

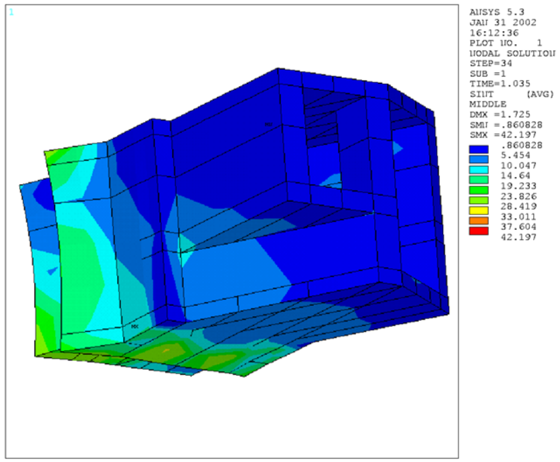
Global Dynamic Analysis



FE model of a half of the VV
with NBI port structures

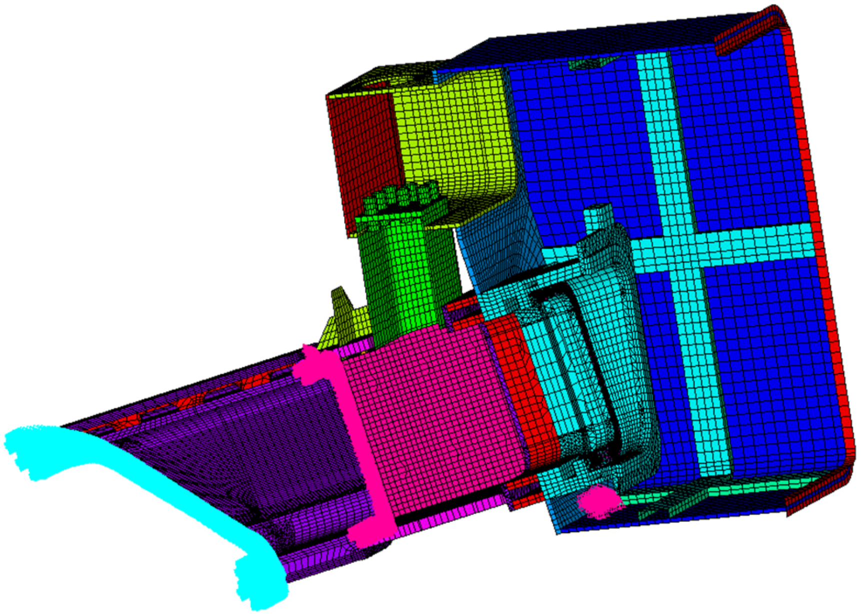


Time history of the vertical displacement
Uy (mm) of the DNB duct at CPD 27 ms

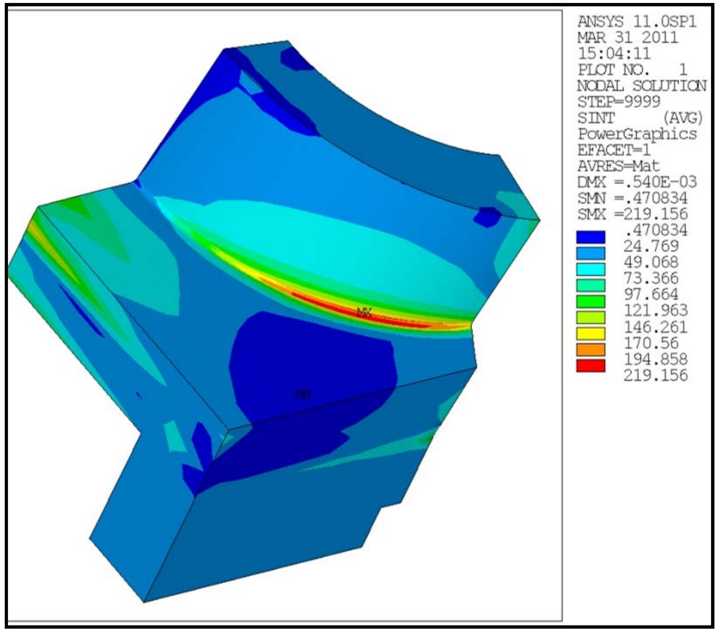


Total stress intensity in the NBI port
at CPD 27 ms, time 35 ms

Design and analysis of the VV Central Upper Port.
(PROCUREMENT ARRANGEMENT 1.5.P2B.RF.01.0)



Finite element model of the Port (one half) with boundary conditions.



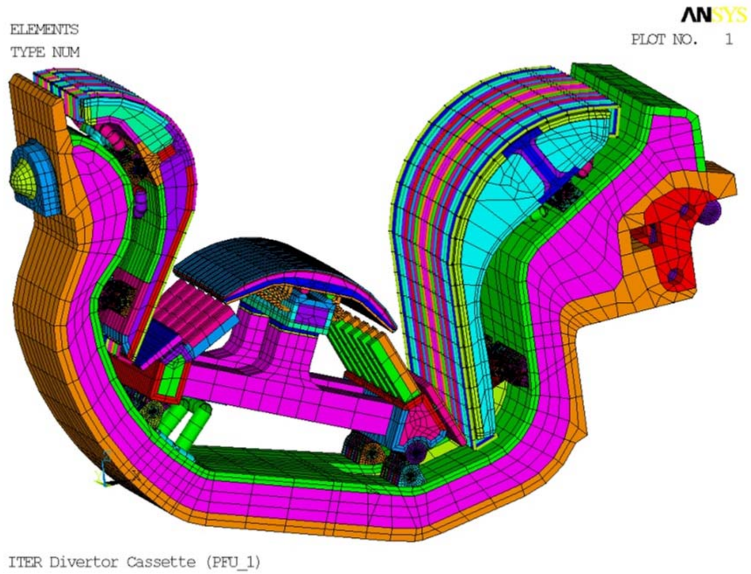
Local stresses in the zone of Chimney connection with single-wall part of the Stub Extension under EM loads

In-Vessel Components

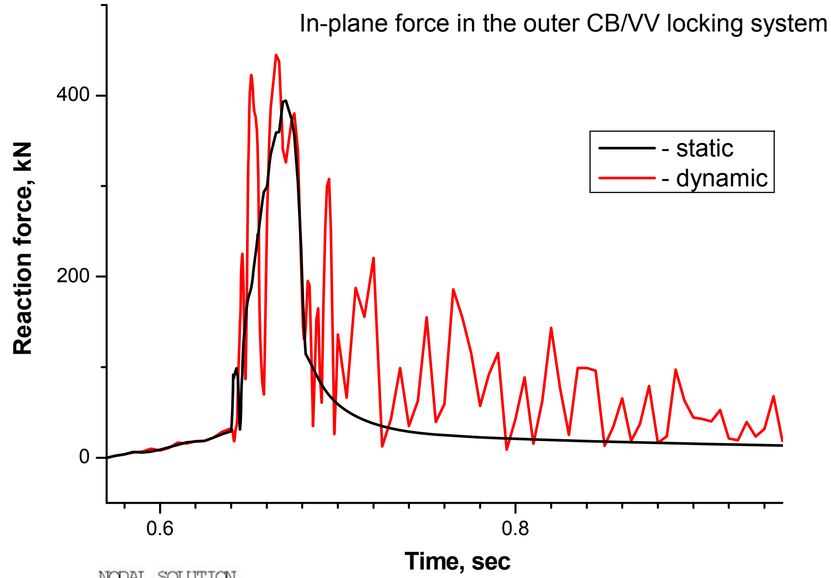
Design and analysis of the ITER Divertor

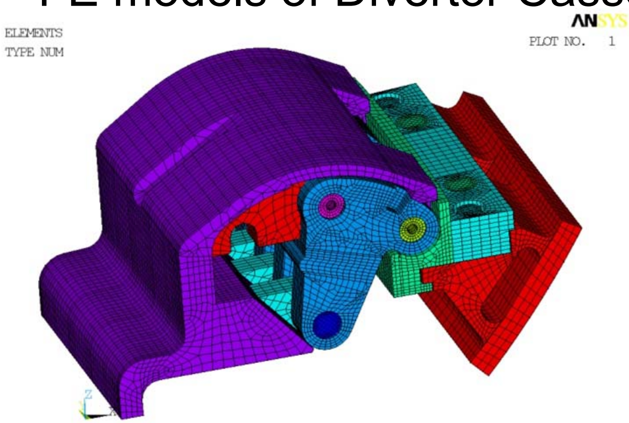
1. Dynamic analysis of the Divertor cassette (CB, IVTs, OVTs, Dome and their supports), 2006-2007.
2. Local analysis of the Divertor Cassette (CB supports, cooling pipes and manifolds, plasma facing units with supports, multilink supports etc.), 2008-2009.
3. Dynamic analysis of the Dome. Local analysis of the Dome critical places (plasma facing units, multilink supports, cooling pipes, structural pipes, manifolds), 2009-2010.

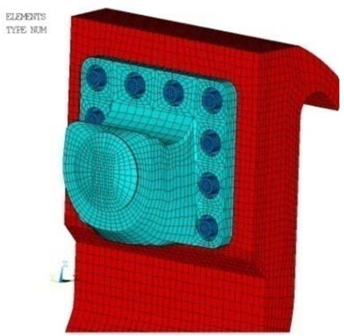
Divertor Cassette dynamic analysis

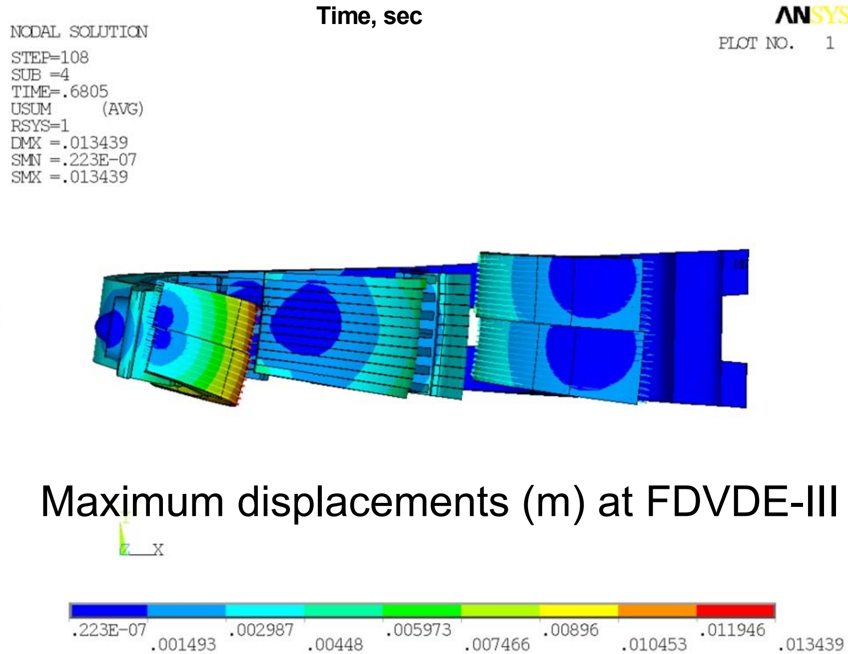


FE models of Divertor Cassette







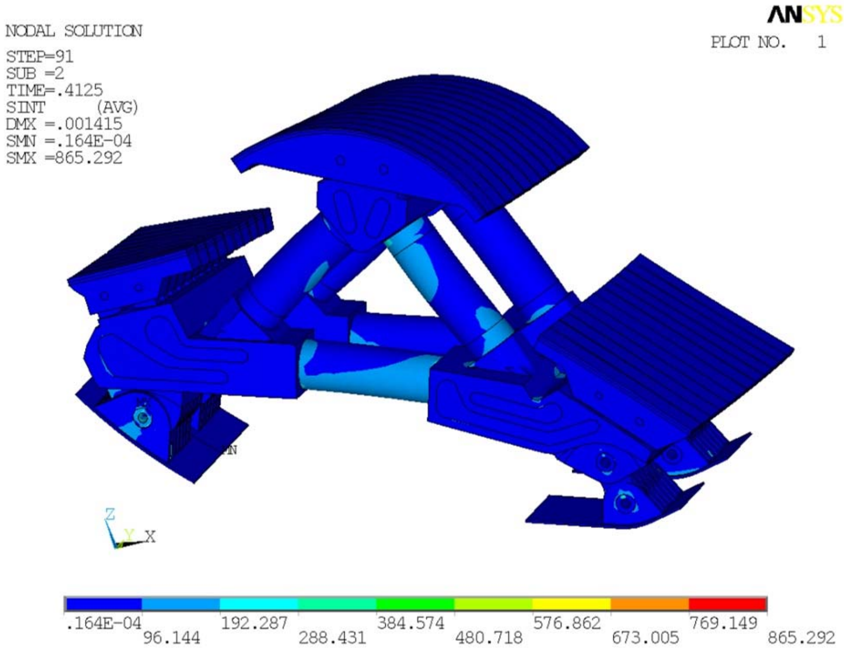


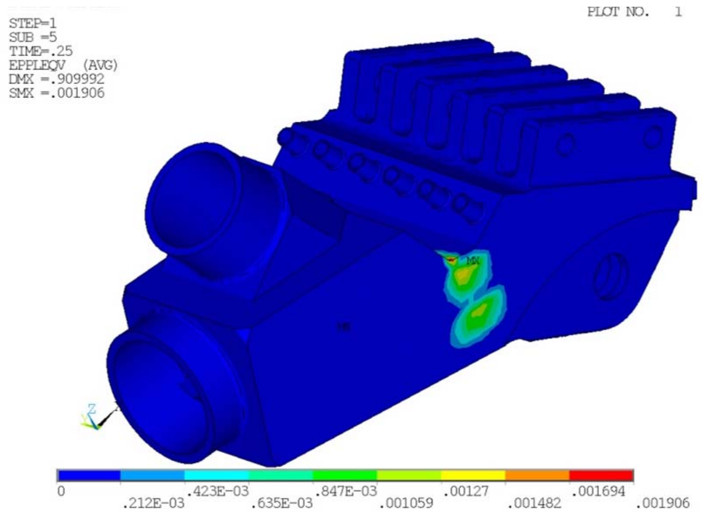
Maximum displacements (m) at FDVDE-III

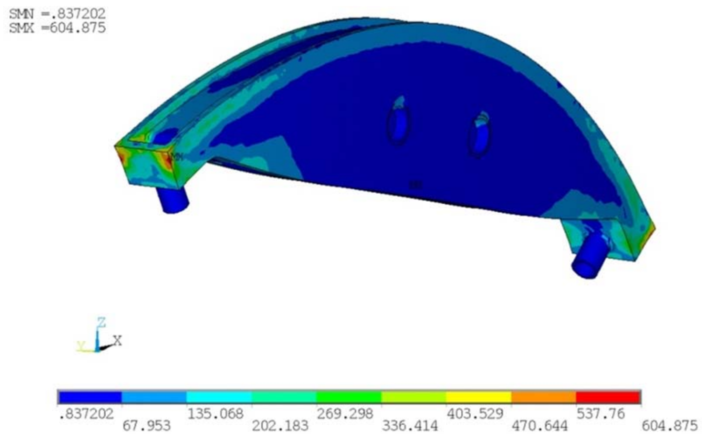
Divertor Dome analysis

RFDA is the supplier of the Dome to ITER. Design changes have been introduced by RFDA into Dome during (1) preparation of manufacture and (2) to eliminate structural problems revealed by previous analysis.

Design changes introduced by RFDA have been verified by analysis







Mechanical tests for Divertor

- **Qualification of HIP bonded 316L(N)/XM-19 steel joint materials (PA 1.7.P2C.RF.01. QTP01)** :

  Tensile tests, Fatigue tests, KCV impact tests

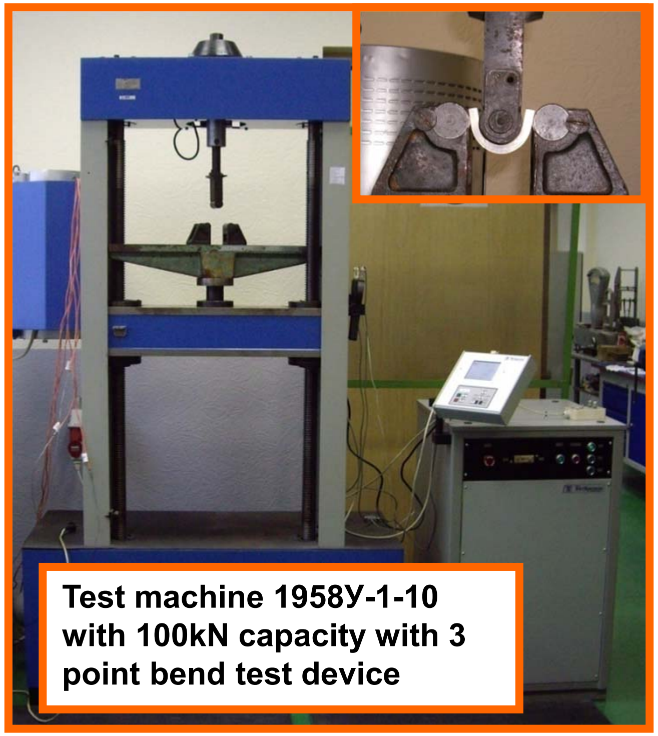
- **Weld procedure qualification test:**

  Tensile tests, Bend tests, Corrosion test

- **Qualification for CuCrZr/316L(N)-IG explosion bonded joint (1.7.P2C.RF.01.0)**

Test machine INSTRON 8802 with 250kN capacity

INSTRON SI-1M pendulum pile driver with 450 J energy store and U type pendulum

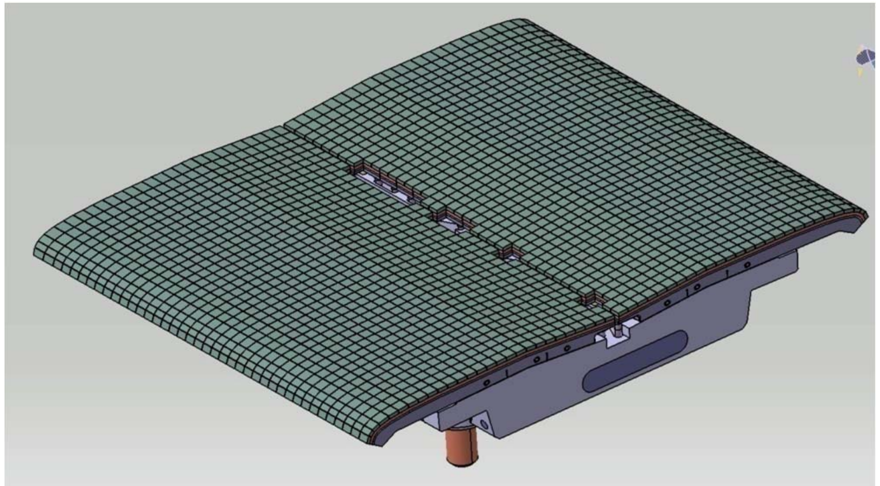


Test machine 1958У-1-10 with 100kN capacity with 3 point bend test device

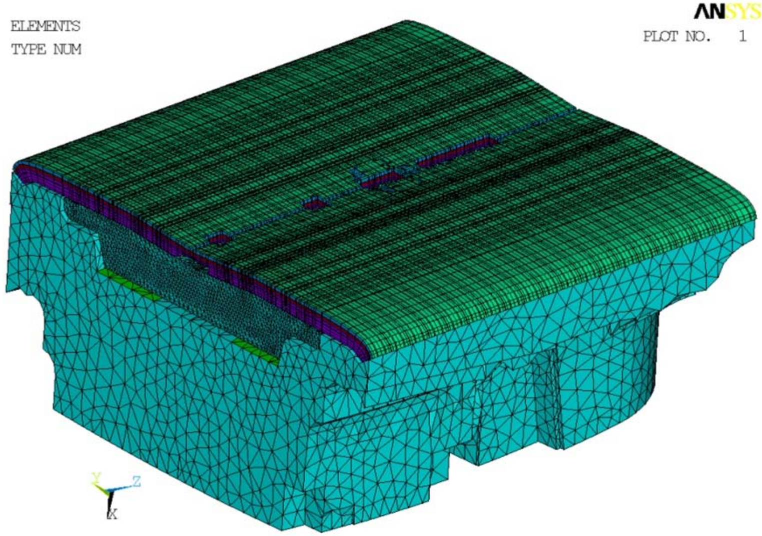
Design and analysis of FW

- In frame of BIPT activity
- Design and analysis of the Enhanced Heat Flux FW under EM and Heat loads

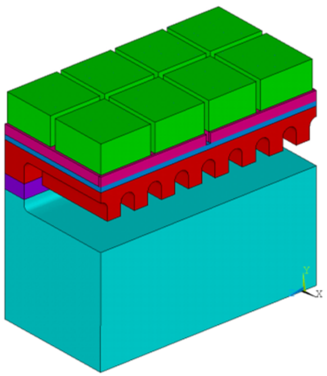
FW 14 design

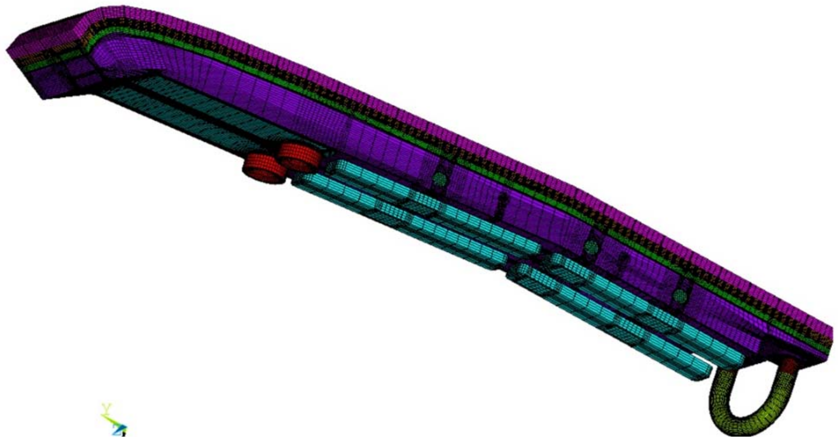


Global model



Local models





Operational Instrumentation

Why operational (engineering) instrumentation is needed?

- The Safety Margins in ITER SDC-IC are basically taken from ASME and RCC-MR Codes. These Codes are for vessels, pipes, etc. loaded by **Dead Weight, pressure** and temperature mainly. **These load are known with a very high accuracy.**
- Main specific of the ITER is that the **main primary loads are EM loads caused by Plasma Disruptions**. There are many uncertainties in the input data for determining the EM loads. The calculation of the EM loads itself is a very complicated problem**.**
- **If the design satisfies the SDC-IC, it will provide the same level of safety, as other codes, if the EM loads are determined with the same accuracy as, say, the dead weight.**

Obviously, this is not the case

What to do?

- Change Design Criteria

  not realistic, many people will be against it, there is no real basis (experience) to justify new criteria, this is a task for future

- Provide sufficient safety margins against EM loads in design of IVC

  more realistic, but requires a lot of analysis, use of **conservative** EM loads, cross-checking, difficult to specify "reasonably conservative" loads, excessive conservatism may kill the project

- Use operational instrumentation

  it provides: verification of numerical models, monitoring of temperatures, currents, magnetic fields, displacements and stresses where it is possible.

The ITER will increase performance gradually, there will be indications if something goes wrong.

The ITER is an experimental machine, it is important to get as much as possible engineering information at the operating conditions. It will be very valuable for future developments.

Goals of Operational Instrumentation

- Collecting information required for the validation of the numerical models, especially during the hydrogen phase of ITER operation

- Estimation of EM loads acting on the In-vessel components during plasma disruptions with help of EM, mechanical measurements and numerical modeling

- Monitoring the electromagnetic, mechanical and temperature state of In-vessel components. Collect the data and estimate the residual life-time of the structural components

Main Systems of Operational Instrumentation

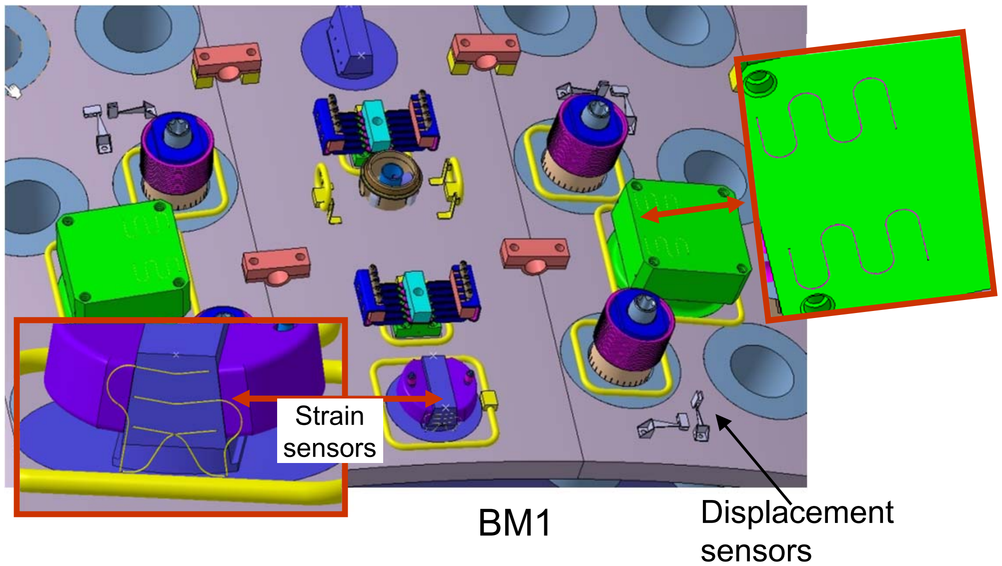
- Electromagnetic Monitoring System (EMS)
- Mechanical Monitoring System (MMS)
- Temperature Monitoring System (TMS)

Progress of Operational Instrumentation

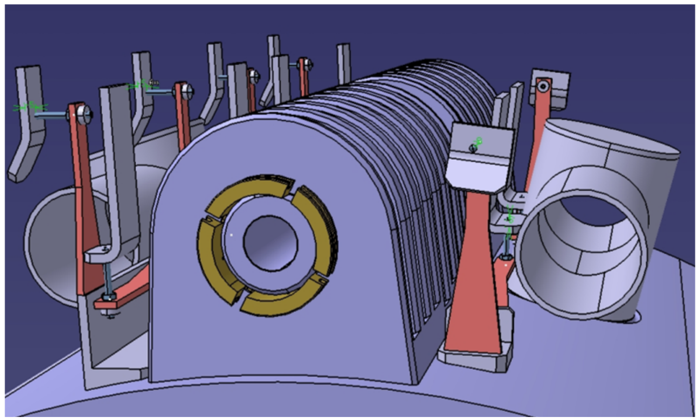
➢ Conceptual Design of the EM and Mechanical Monitoring Systems for the EM Test Blanket Module (2007)

➢ Conceptual and Detailed Design of the Divertor Operational Instrumentation (2008)

➢ Conceptual Design of the Blanket Operational Instrumentation (2011)

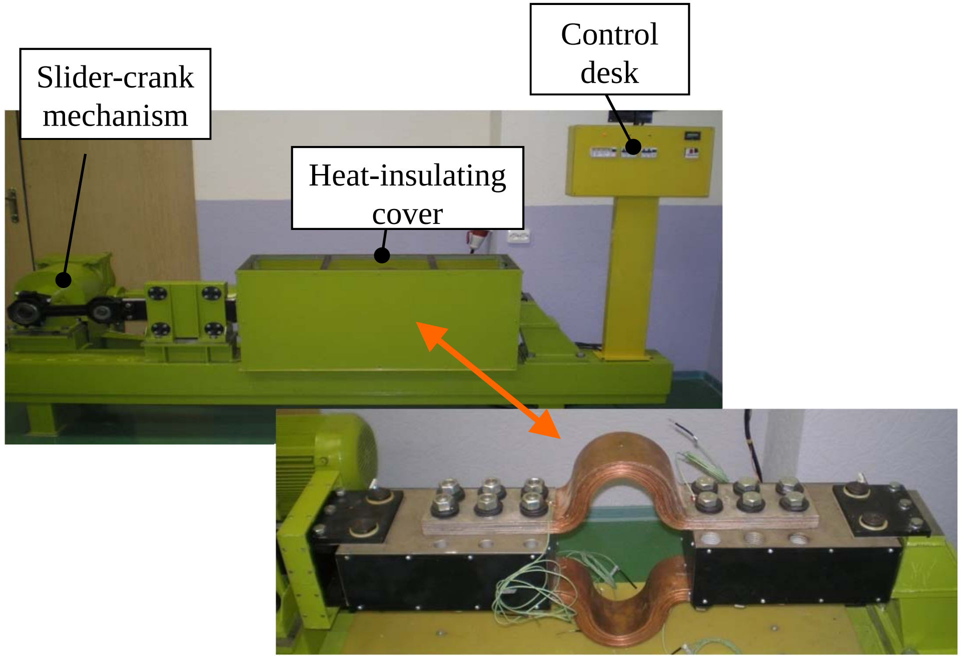


BM1



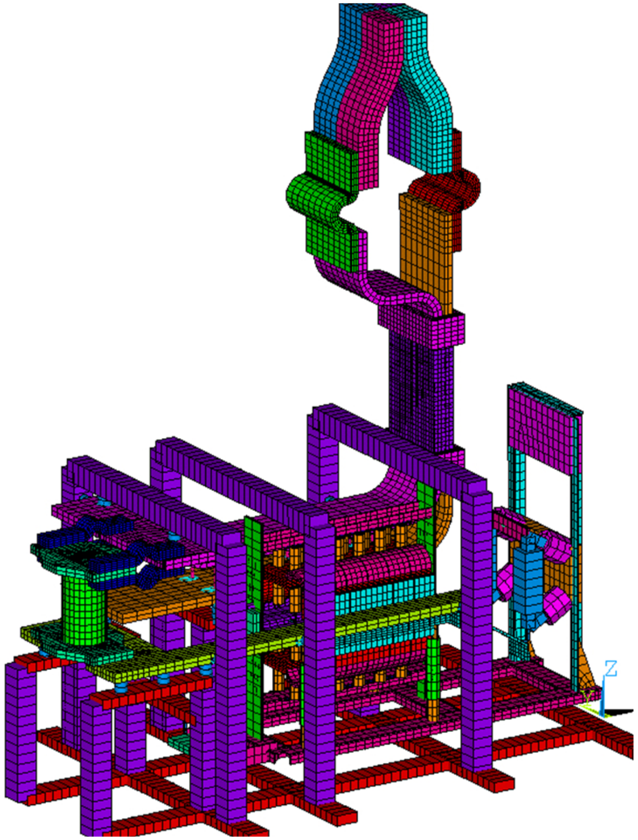
Power Supply System

- Design, analysis and testing of the coil busbars, compensators, supports
- Design , analysis and testing of the PS equipment: fast discharge resistors, switchers, etc.
- Seismic qualification of the SIC equipment



Busbar thermal compensator cyclic testing at specially designed cyclic test machine (PA 4.1.P3.RF.01)

(Temperature T= 80ºC , displacement Δ=25.4 mm, number of test cycles N = 32 200.)

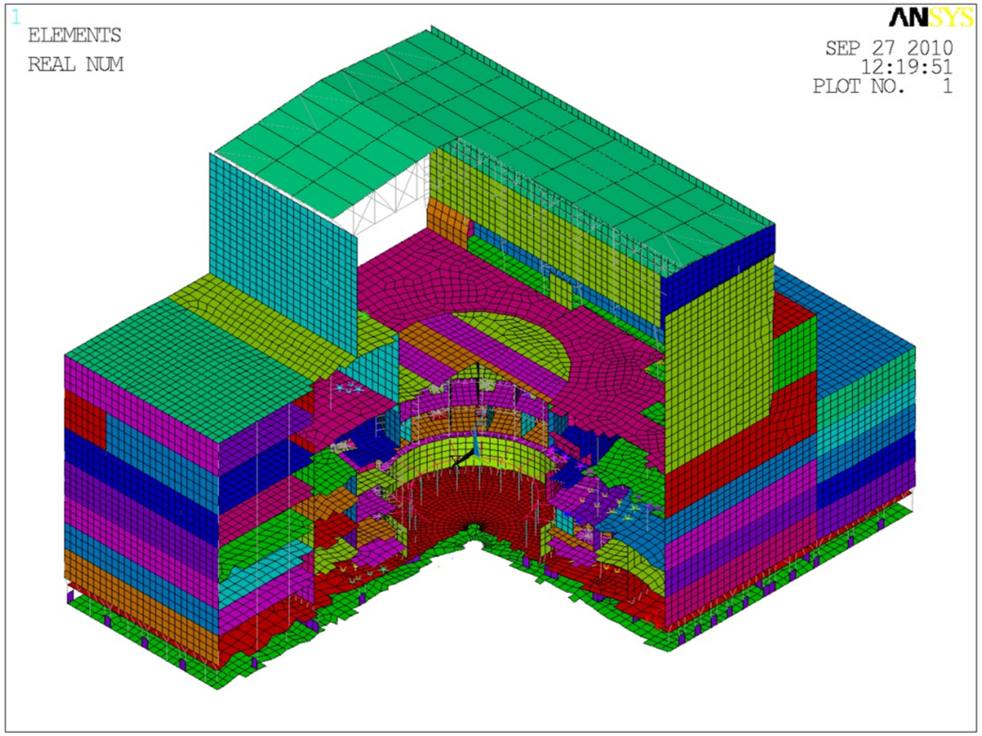


FE models of the High current switchgear

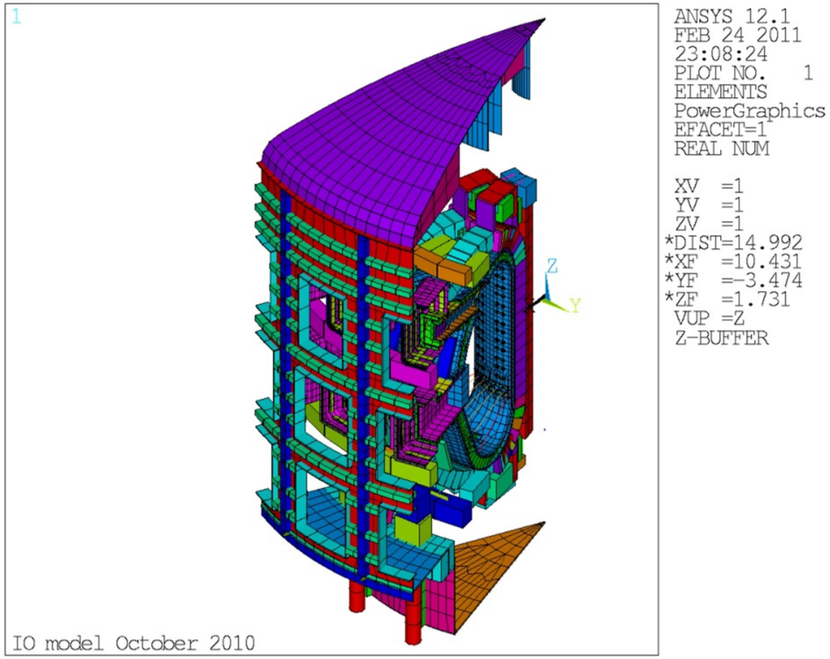
Seismic Analysis

➢ Seismic analysis of the ITER Building to find accelerations and Floor Response Spectra (FRS), which are the input for equipment seismic analysis

➢ Seismic analysis of the Tokamak machine to find accelerations, displacements, loads on main supports, and In-Structure Response Spectra



Finite-element model of the Building



"One-sector" method has been developed and used , which allows to use only one-sector model instead of full 360-degrees torus

Results of our Seismic Analysis are in ITER documentation

PD - Plant Description *(ITER_D_2X6K67 v1.1)*
Project Integration Document PID January 2007 ITER_D_2234RH Version 3.0
Load Specifications for Buildings 2ERTXQ_v1_6
Seismic Tokamak Loads upon the Building (2LM7MV v3.1) (current)
Seismic Loads on the Vacuum Vessel (2LB3GH v4.0) (current)
Seismic Loads on the Magnets in seismic events. (2LLLP3 v2.0) (current)
and many others.

Summary

➢ For more than 20 years of working for ITER we have considerably contributed to the design and analysis of all ITER systems

➢ Our specialists have unique experience in solving a wide range of engineering problems of tokamaks and other fusion devices: from design to analysis and structural criteria

➢ We do our best applying our skills to the successful development and realization of the ITER project