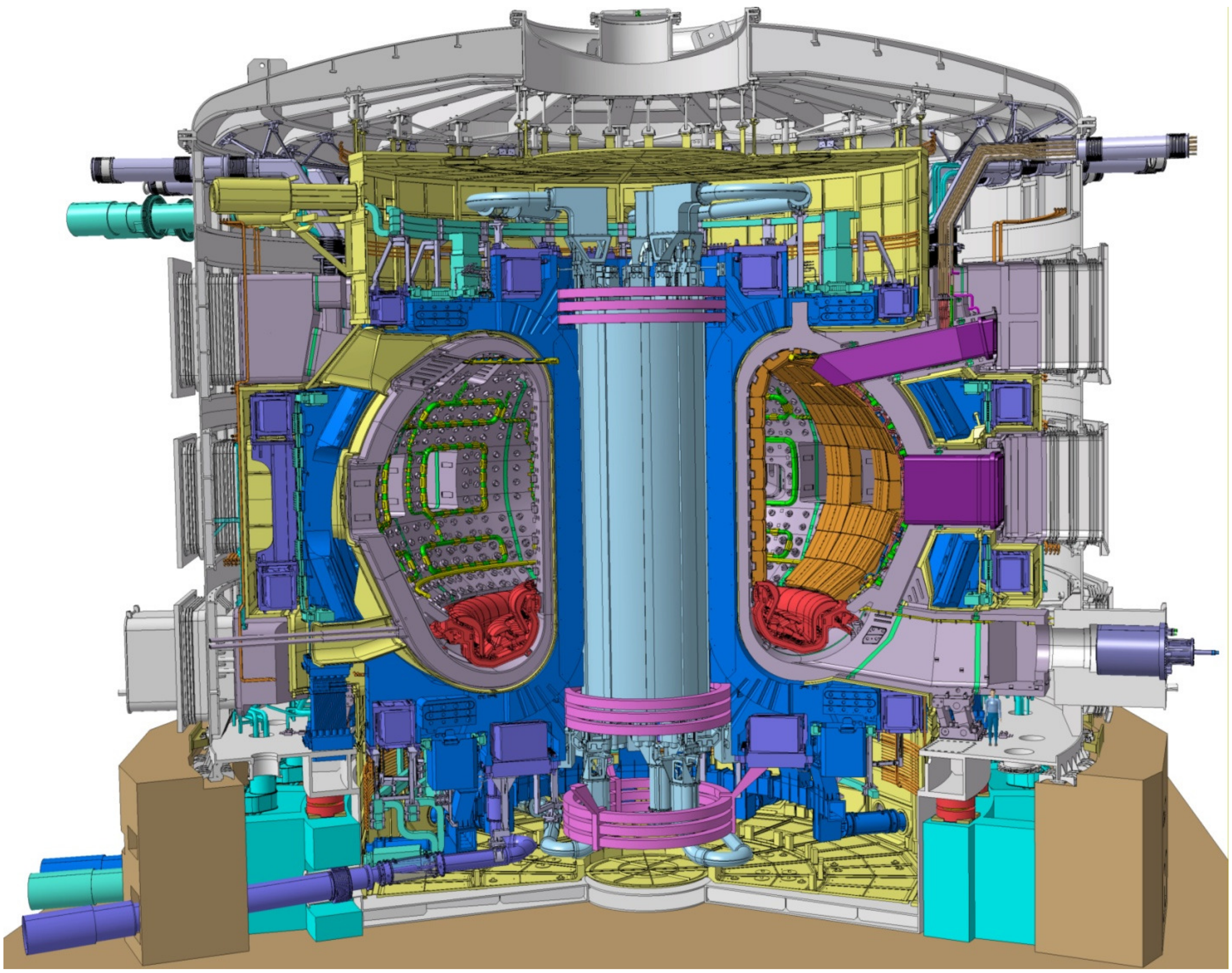
Dimensional Control Systems' 3DCS and ITER, the World's Largest Tokamak Experiment

December, 2012

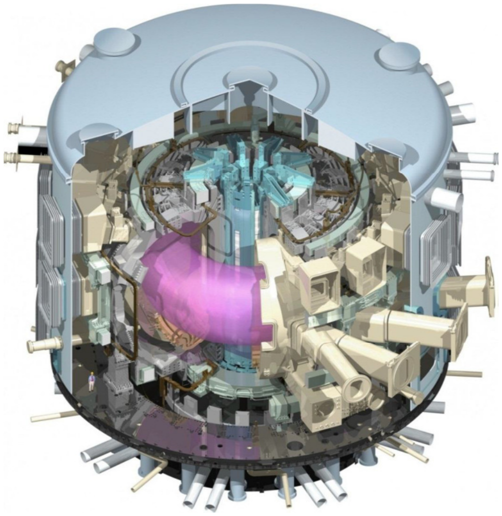


Kristy Erdodi
Benjamin Reese
Tom Halcrow

Dimensional Control Systems' 3DCS and ITER, the World's Largest Tokamak Experiment

The Project: ITER

ITER is a global collaboration – involving China, the European Union (represented by EURATOM), India, Japan, Korea, Russia and the U.S. – formed to test the feasibility of fusion as a potential large-scale commercial energy source for the future.



Fusion is the process the sun uses to create heat and light. It produces no carbon emissions and no air pollution. With hydrogen being the fuel for a fusion-based reactor, it would have the potential to provide a much-needed source of virtually unlimited clean energy.

As a means of testing this source, ITER is currently building the world's largest tokamak device, which will house the fusion reaction. The completed device will be located in Cadarache, France. It is meant to achieve one over-arching scientific goal: deliver ten times the amount of power that it consumes. It will demonstrate that it is possible to capture fusion energy for commercial use.

In comparison to nuclear power plants, the tokamak structure itself also provides benefits in terms of safety. The tokamak cannot explode and does not leak or have poisonous, dangerous by-products. It can be safely shut down if an accident occurs, as long as the heat of the system is contained.

"... In our opinion, the use of fusion energy is a 'must' if we want to be serious about embarking on sustainable development for future generations."

- **Osamu Motojima, ITER Director-General,** *Opening address, Monaco International ITER Fusion Energy Days (MIIFED), 23 November 2010*

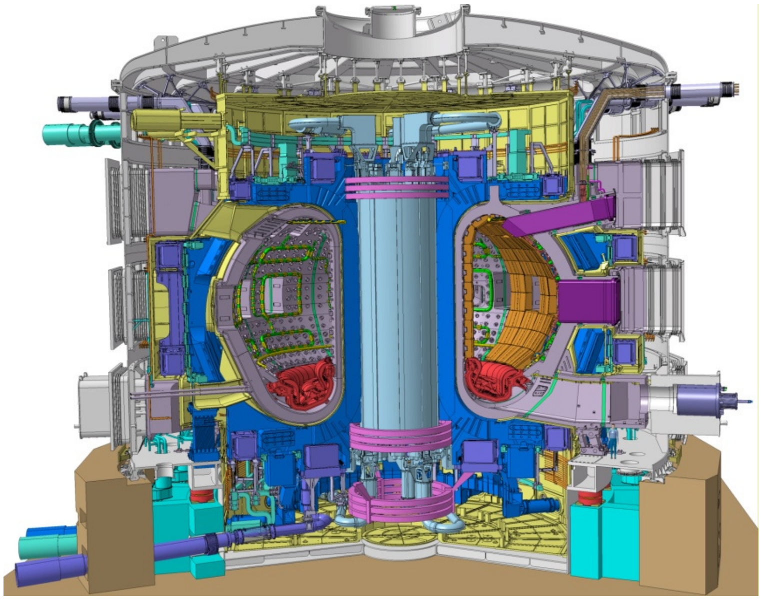
The Software: Dimensional Control Systems' 3DCS

In the design of the tokamak, ITER is using 3DCS Variation Analyst, developed by Dimensional Control Systems, Inc. (DCS), a quality software solutions provider based in Troy, Michigan.

3DCS software is a dimensional tolerance and variation analysis tool for simulating design and manufacturing/assembly processes. As a Dassault Systemes Premier Gold Partner, 3DCS Analyst is available fully integrated into CATIA V5, leveraging the digital prototyping and visualization capabilities of V5. It provides an accurate, efficient and easy-to-use approach to tolerance analysis modeling. In addition, by immediately reflecting design and tolerance changes in the 3DCS tolerance model, the software offers the opportunity for faster development of higher quality products at a lower price.

In terms of the tokamak, 3DCS Variation Analyst is being used for both risk assessment and determining compliance due to alterations in dimensions that result from heat and structural changes. The model being used has over 600 plus parts with more than 15,000 points and 760 functional moves. This is believed to be the first ever application of tolerance analysis for this type of product.

The Tokamak:



In a laboratory setting, the most efficient way to reproduce a fusion reaction includes creating a reaction between two hydrogen (H) isotopes, deuterium (D) and tritium (T). Although this requires temperatures of 150,000,000° Celsius (ten times the heat of the sun), this D-T fusion reaction actually produces the highest energy gain at the "lowest" temperatures.

At such extreme temperatures, electrons are separated from nuclei and a gas becomes a plasma, or hot, electrically charged gas. Plasmas provide the environment in which light elements can fuse and yield energy.

The ITER tokamak will host these reactions, ultimately producing energy from this D-T fusion. The deuterium and tritium mixture will be heated to the necessary temperatures, creating hot plasma. Then the machine will use magnetic fields to contain and control the hot plasma in a vacuum vessel. Superconducting coils surrounding the vessel will accomplish this by working with an electrical current driven through the plasma to keep the plasma away from the walls. This concept of magnetic confinement actually defines the machine as a tokamak.

Following is a timeline of goals for the tokamak:

- **2008:** *Site Leveling*
- **2010:** *Start of Tokamak Complex Excavation*
- **2013:** *Start of Tokamak Complex Construction*
- **2014:** *Arrival of First Manufactured Components*
- **2015:** *Start of Tokamak Assembly*
- **2019:** *Complex Tokamak Assembly, Begin Commissioning*
- **2020:** *First Plasma*
- **2027:** *Deuterium-Tritium Operations Begin*

Concerns in Creating the World's Largest Tokamak

The ITER tokamak requires complex engineering, as its design relies upon many emergent technologies. The challenges of its creation include, but are not limited to, the following examples:

1. This project is meant to serve as a prototype for the mass production of tokamaks (which would make a viable alternative to, or replacement of, current fission based nuclear power plants), it is vital that the machine be manufacturable. That is to say, the model cannot be designed with only the nominal build in mind; no product will be built without variation, and the tokamak is no exception. It must therefore be able to function with tolerances that are large enough to manufacture, but small enough to accommodate the device's structural needs.

2. ITER must also ensure proper assembly of the structure, as unprecedented power, heat and magnetic strength of the fusion reaction and system operation will cause extreme stress to the device's structure. During operation, forces inherent to the device will tend to squeeze and pull parts of the structure in, closing gaps between them. Those gaps must be precise enough to uniformly close, leaving the parts to be largely self-supporting after steady-state operation is reached.

   Especially important components to consider in this precision are the eighteen "D" shaped electromagnets around the outside of the device vacuum chamber, each of which stands 14-meters tall. They require very precise tolerances (+/- 0.5 mm) for the nominal toroidal gap, in order to align and lend structural support when energized. If the gap uniformity is not within specification, the stresses from the process may pull the magnets out of alignment, possibly causing damage to the device.

Tokamak Tolerance Model Status
❖ *600 Single Parts*
❖ *15,000 Points*
❖ *2000 Part Tolerances*
❖ *760 Moves*
❖ *30 Functional/Assembly Requirements*
❖ *6,000 Measurements to Verify Compliances and Perform Impact Studies*
❖ *15 Minutes for a 3DCS Tokamak Analysis, Consisting of 5,000 Runs*

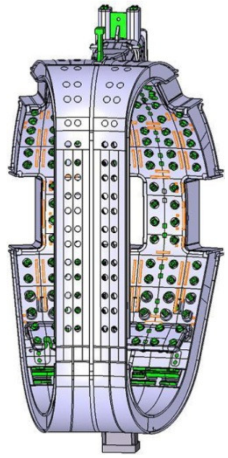
3DCS' Solutions

1. Configuration Management Tool - 3DCS is being used to determine part manufacturability with needed configurations and tolerances. The software does this by running Monte Carlo simulation of

an appropriate number of assemblies and then best fitting that data to find the statistical range of assembly variability, along with the most common configuration of the simulated samples. Presuming the ITER experiment is a success, manufacturers will know what to expect when parts for future tokamaks go into production, which in itself reduces rework, saving their time and budgets.

2. Risk Assessment - 3DCS can also determine "what if" worst-case assembly for the tokamak. By implementing a stack-up analysis, the software can illustrate a possible combined effect on part placement from tolerances over multiple parts. 3DCS randomly generates tolerances for each part in each simulation and then statistically calculates the most likely range of total tolerance effect on the assembly.

<u>A sample of specific uses for 3DCS on the project includes the following:</u>



a. In a circular structure, such as the tokamak, the placement and fit of the final "keystone" piece could be dependent on the tolerance changes of all other parts within the assembly. 3DCS is particularly useful for determining this, as it can statistically calculate the estimated range of that final gap.

b. The area targeted by ITER of significant dimensional concern is the vacuum vessel portion of the plant, which requires an especially complicated and rigorous procedure for assembly. The vessel itself resembles an orange with nine slices. Each of these slices (or sectors) demands extremely strict tolerances, to minimize custom machining and welding for successful assembly.

   3DCS tolerance models were constructed to analyze the "slices" of the vacuum vessel and to validate a complicated plumbing system among them. Most importantly, it is currently analyzing assembly of their internal components of required material thickness against the extreme heat and pressures they will endure, so as to ensure stability.

   Examples of the vacuum vessel key requirements that are being analyzed include:

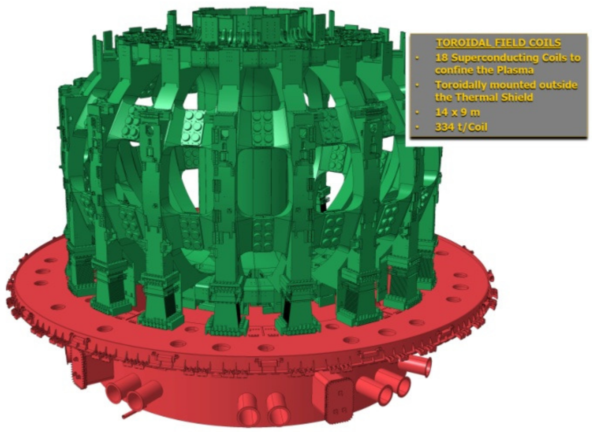
   1. Alignment of sectors in radial and vertical directions
   2. Gap variation between sectors in toroidal direction
   3. Alignment of toroidal field (TF) coils in radial and vertical directions
   4. Gap variation between TF coils in toroidal direction
   5. Gap variation between ports and port plugs in toroidal and vertical directions

c. Because the assembly processes have been seamlessly replicated in the 3DCS tolerance model, the ITER team has been able to explore key concerns that they developed from the start. They were also able to identify problems that they did not yet know existed. In fact, the method of model development and input from supporting ITER engineers revealed that not all aspects of the design and assembly methodology were completely thought out. (Identification of design and manufacturing conflicts commonly results from creating a 3DCS tolerance analysis model.) Additionally, 3DCS allowed engineers who were relying on simple linear stack tolerance calculations to pinpoint potential issues. In all assemblies, the software's "continuous deviation" function continues to assist ITER engineers in recognizing potential failures.

Realistically establishing tolerance requirements in this way provides benefits with respect to function, performance and cost. For example, ITER's initial results of the 3DCS model were the foundation for the re-evaluation of the initial requirements. Such circumstances serve as advantageous because issues are identified in advance, at a time when changes can be made with little or no negative effects on cost or timing.

d. 3DCS is also confirming the engineering team's proposals in certain areas. Many variation results are validating measurement outputs within the expected range of variation.

For example, the first components to be analyzed included a TF coil pair, through a 3DCS variation model. The analysis identified the fit between the individual TF coils in four main areas, determining gap and thickness tolerances. The TF coils' supporting system was also considered for any further analysis of the deviation from the Gravity Supports position interface to the machine pedestal ring. The model results showed that the proposed TF coil tolerances, along with the proposed positioning/alignment tolerances should always allow the TF coils and the pairs to assemble without incident.



ITER is taking advantage of such confirmations, by relaxing the associated tolerances and requirements. These experiences encourage confidence for the affected engineering teams, allowing them to concentrate on additional areas needing greater attention.

"ITER is now finding that many of its engineers now prefer to wait for analysis results before their next move, as the data helps to drive the decision-making process"

- **Jens Reich, ITER Engineer for Tokamak Integration** *to DCS, 2009*

PROJECT STATUS, AS OF 2013:

The decree authorizing ITER to house the project in Cadarache, France became official on November 10, 2012. It was signed by the French Prime Minister and enabled the progression of ITER construction. As of late 2012, many components were in the early phase of production. Of course, the engineers and manufacturers of those components – along with their future counterparts – will continue to take advantage of support from DCS as the project moves forward.