Hybrid integral-differential simulator of EM force interactions / / scenario-assessment tool with pre-computed influence matrix in applications to ITER

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- *computing efficiency,*
- *hybrid integral-differential modelling,*
- *interaction matrix,*
- *ITER magnetic system*

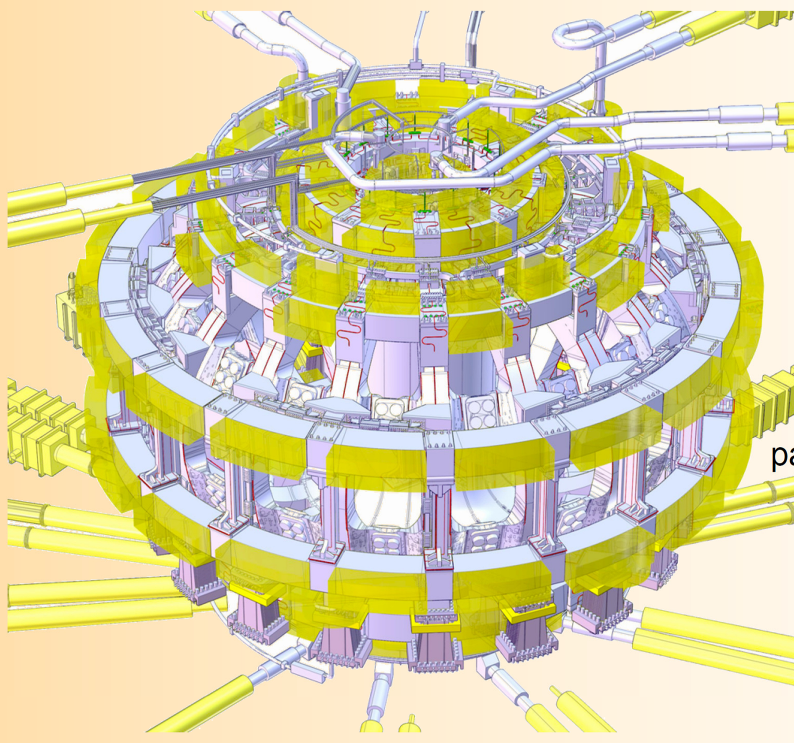


Fig. 1. The ITER magnetc system

Abstract

A necessity to address a wide spectrum of engineering problems in ITER determined the need of efficient tools for modeling of the magnetic environment and force interactions between main components of the magnet system. The assessment of the operating window for the machine, determined by the electro-magnetic (EM) forces, and the check of feasibility of particular scenarios play an important role for ensuring the safety of exploitation. Such analysis-powered prevention of damages forms an element of the Machine Operations and Investments Protections strategy. The corresponding analysis is a necessary step in preparation to the commissioning, which finalizes the Construction phase. It shall be supported by the development of the efficient and robust simulators and multi-physics/multi-system integration of models. The developed numerical model of interactions in the ITER magnetic system, based on the use of pre-computed influence matrices, facilitated immediate and complete assessment and systematic specification of EM loads on magnets in all foreseen operating regimes, their maximum values, envelopes and the most critical scenarios. The common principles of interaction in typical bilateral configurations have been generalized for asymmetry conditions, inspired by the plasma and by the hardware, including asymmetric plasma event and magnetic system fault cases. The specification of loads is supported by the technology of functional approximation of nodal and distributed data by continuous patterns / analytical interpolants. The global model of interactions together with the "meshless" analytical format of output provides the source of self-consistent and transferable data on spatial distribution of the system of forces for assessments of structural performance of the components, assemblies and supporting structures. The used numerical model is fully parametrized, which makes it well suitable for multi-variant and sensitivity studies (positioning, off-normal events, asymmetry, etc.). The obtained results and matrices form a basis for a relatively simple and robust force processor as a specialized module of a global simulator for diagnostic, operational instrumentation, monitoring and control, as well as a scenario assessment tool. The paper gives an overview of the model, applied technique, assessed problems and obtained qualitative and quantitative results.

1. Introduction

The assessment of the EM loads on magnets, of the corresponding operating window and of feasibility of particular scenarios is a necessary step in preparation to the commissioning, which finalizes the Construction phase. It shall be supported by the development of the efficient and robust simulators and multi-physics/multi-system integration of models. The availability of simulators is also one of necessary pre-requisites for entering the pre-nuclear Tokamak Operation phase. In applications for either phase, the key aspect of simulators (models) is their computational efficiency and robustness. The latter can be ensured by the maximum reasonable simplification/optimization of the model and its adequacy to the considered problem/system and to the practical needs.

2. Model and approach

Specifics of the EM system of the tokamak:
- Reduced (quasi-static) approximation applies;
- The localization of currents domain to structural components and their high discretization.

The two strategic directions of optimization:
1. Decomposition of the problem to the modeling of (a) EM transiets and (b) force interactions;
2. Multi-scale and hybrid/composite modeling and analysis.

Approaches to modeling:
- Elimination of information redundancy of numerical models;
- Exploration and specification of 3D EM system in terms of integral parameters;
- Separation of static B and Lorentz forces calculations from the dynamic problem of currents;
- Unilateral bi-component scheme of interacting. Current-to-current logic. Matrix built of solution;
- Assessment of interactions at unit currents (sensitivity matrix approach);
- Pre-computing of the "heavy" geometrical contents;
- Binary model: (I) FE model for pre-computing of matrices; (II) Simplest matrix linear processors.

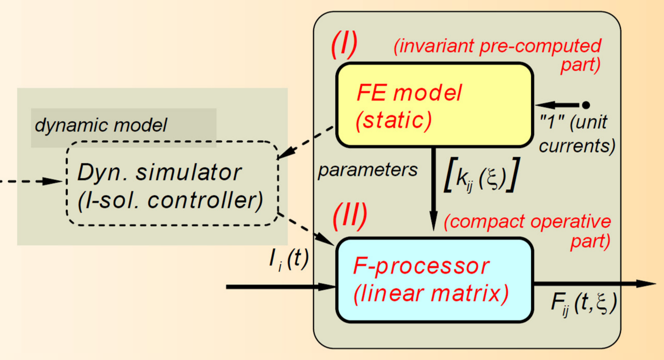


Fig. 2. Breakdown of the problem / models

The geometrical contents of an interaction is completely expressed by:

$$\mathbf{G}_{ij}=\int_{L_j}\int_{L_i}\frac{\mu_0}{4\pi}\frac{1}{r_{ij}^3}\left[\mathbf{dl}_j\times\left[\mathbf{dl}_i\times\mathbf{r}_{ij}\right]\right]=-\int_{L_i}\int_{L_j}\frac{\mu_0}{4\pi}\frac{1}{r_{ji}^3}\left[\mathbf{dl}_i\times\left[\mathbf{dl}_j\times\mathbf{r}_{ji}\right]\right]=-\mathbf{G}_{ji}$$

Then: $\left[\mathbf{F}_{ij}\right]=\left(\left[I_{sourc}\right]\left[I_{probe}\right]^T\right)\circ\left[\mathbf{G}_{ij}\right]$

Here: $\left[I_{sourc}\right]=\left[I_{probe}\right]\equiv\left[I\right]$ *- vector of currents*

$\left[\mathrm{G}_{ij}\right]$ *- a sensitivity or influence matrix*

Here the EM interactions in the tokamak as current-controlled system are considered.

3. Model (I) - for pre-computing of unit interactions between ITER components

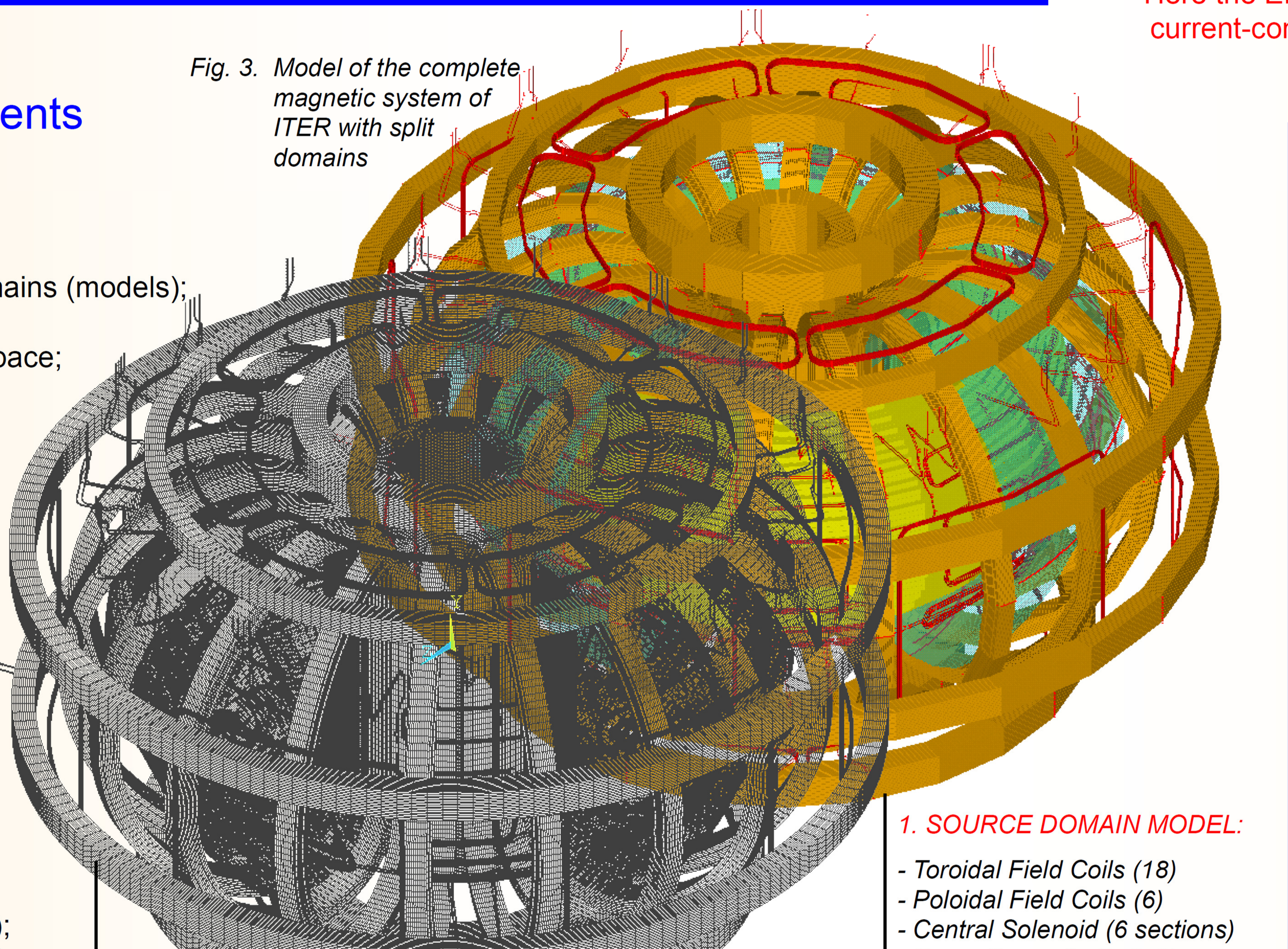
Specification (features and capabilities):

- ANSYS-based;
- Dual definition of currents, split to "source" and "probe" domains (models);
- Hybrid Integral- differential formulation;
- Overlapping of "source" and "probe" domains (models) in space;
- Meshless arbitrarily configured "source";
- Realistic multi-wire (multi-turn) layout;
- Turn-wise (conductor) or cross-sectional output;
  -> Explicit segregation of the own field:
    -> self-inductance effects;
    -> direct assessment of the interaction matrix entries;
- -> "Self-benchmarking" by swapping source<->probe.

The FE model for assessment of matrix terms is optimized for maximum performance (22 hours CPU time for the ITER matrix):

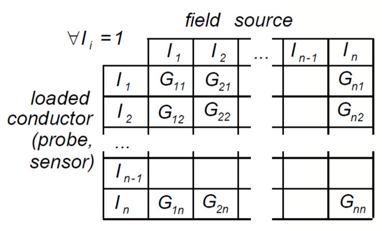
- Incomplete-space (localized) FE field modeling / solution domain, limited to the region of interest (loaded conductor) with no necessity to model a continuous space/media ("air");
- Accounting for symmetries to reduce the number of runs to the number of unique values in the matrix;
- Solving in single steps in static or by harmonic analysis;
- Considering a single pair "source-probe" in a time (per a solution);
- Skipping from obtaining a solution for the current density (Biot-Savart calculations only);
- The fully analytical application of the current in the loaded domain (probe)
- Running at calibrated (unit) current cases for assessment of sensitivity matrix / influence functions as invariant data.

Fig. 3. Model of the complete magnetic system of ITER with split domains



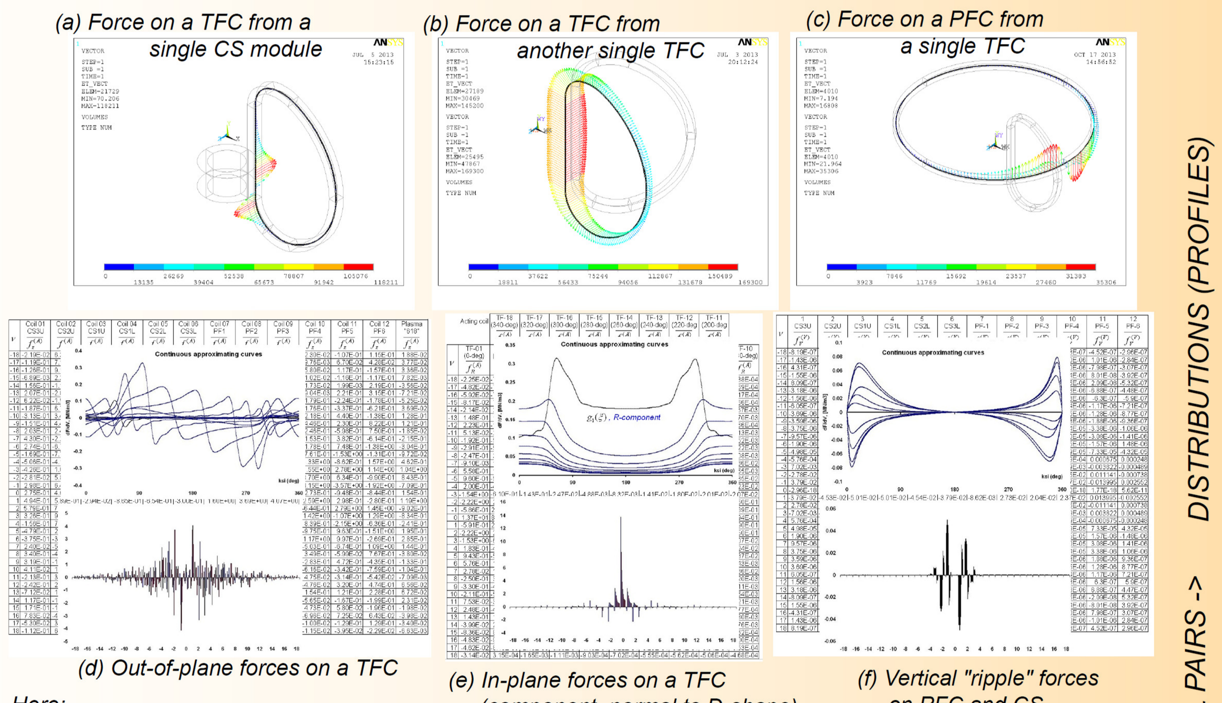
1. SOURCE DOMAIN MODEL:
- *Toroidal Field Coils (18)*
- *Poloidal Field Coils (6)*
- *Central Solenoid (6 sections)*
- *Correction coils (3x2x3)*
- *In-vessel ELM coils (3x9)*
- *In-vessel Vert.Stabiliz. coils (2)*
- *Vacuum Vessel*
- *Plasma**

2. SOLUTION DOMAIN MODEL ("PROBE" / DETECTORS / LOADED COMPONENTS):
- *Toroidal Field Coils (18)*
- *Poloidal Field Coils (6)*
- *Central Solenoid (6 sections)*
- *Correction coils (3x2 top, 3x2 bottom, 3x2 side)*
- *In-vessel ELM coils (9 top, 9 bottom, 9 side)*
- *In-vessel Vertical Stabilization coils (upper, lower)*
- *Vacuum Vessel (toroidal, poloidal passive loops)*



PRE-COMPUTING:
~20 hours, unique run, does not involve scenarios

4. Model (II) - for operative calculation of forces (Influence matrices for ITER magnetic system). Examples: Distributions (profiles) and totals



Here:

$$g(\xi)=\frac{1}{N}\sum_{k=0}^{n\le N-1}H(\nu_k)\left(\cos(\nu_k\xi)+\sin(\nu_k\xi)\right)$$

or

$$g^*(\xi)=e^{(\xi-\pi)^2}\frac{1}{N}\sum_{k=0}^{n\le N-1}H(\nu_k)\left(\cos(\nu_k\xi)+\sin(\nu_k\xi)\right)$$

- continuous analytical approximating function;

$\left[H(\nu_k)\right]$ *- discrete Hartley transform (DHT) coefficients;*

ξ *- toroidal or poloidal angle (counting parameter).*

Fig. 4. Distributed forces of interaction between individual coils (all I=1MA·turn)

<-- INDIVIDUAL PAIRS -->

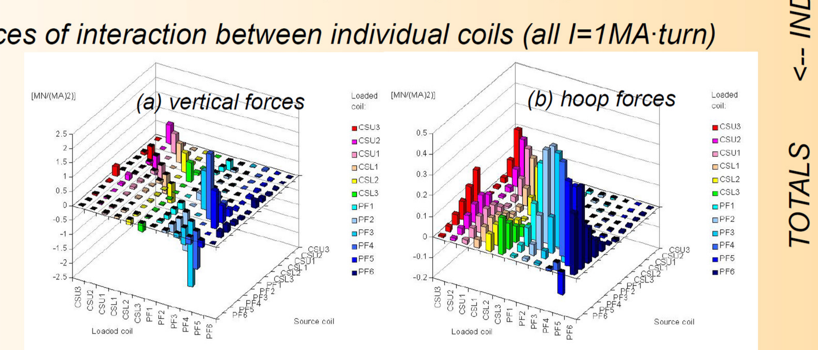


Fig. 5. Forces of interaction in PFC+CS system, [MN], all 1MA·turn

OPERATIVE CALCULATIONS:
Milliseconds (real-time)

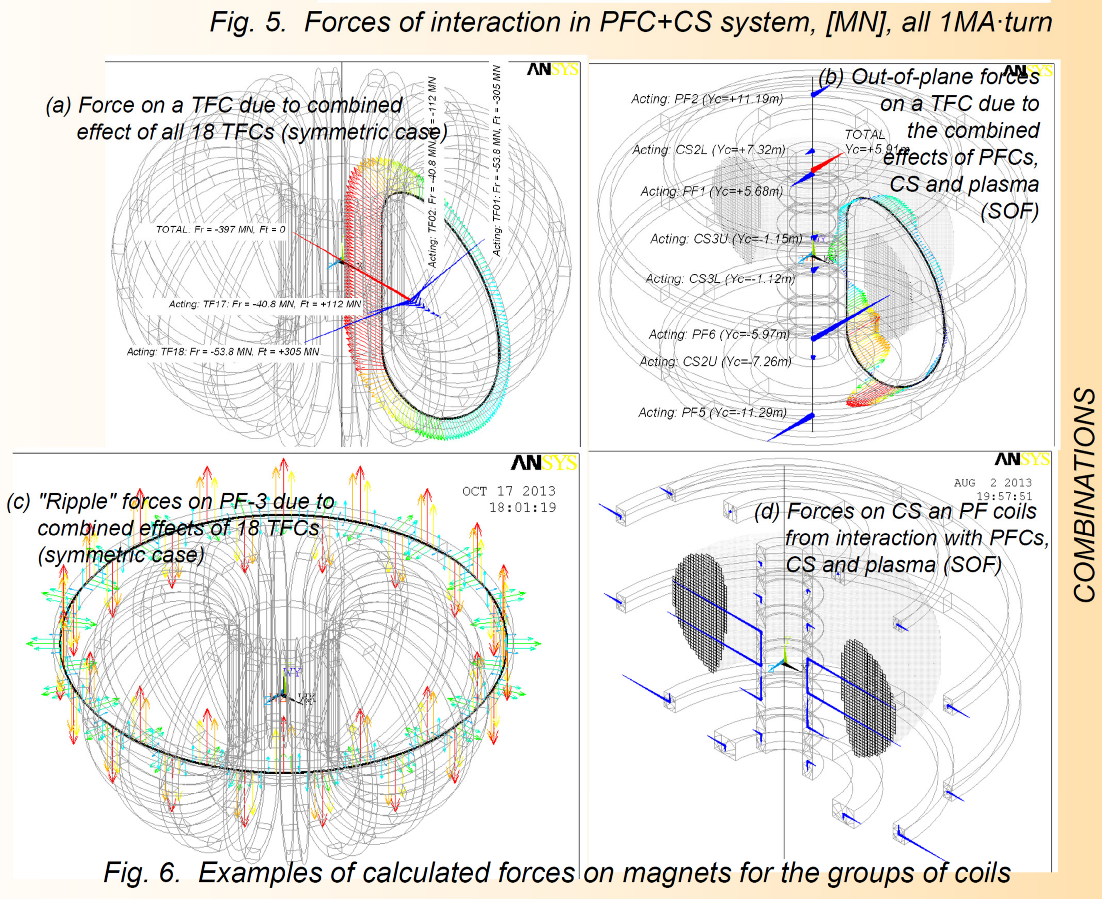


Fig. 6. Examples of calculated forces on magnets for the groups of coils

5. Benchmark of DDD reference design values with new model. Assessment of load ranges, envelopes of reference scenarios (examples)

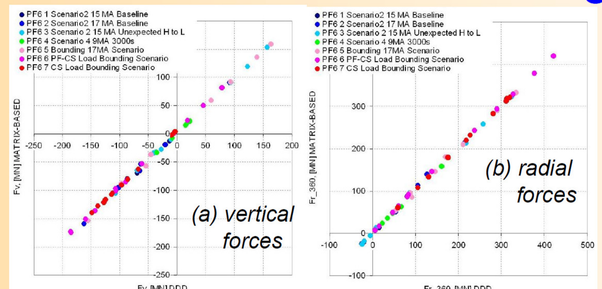


Fig. 7. Benchmark of DDD results (global FE model) against hybrid model. Example: Forces on PF-6, [MN].

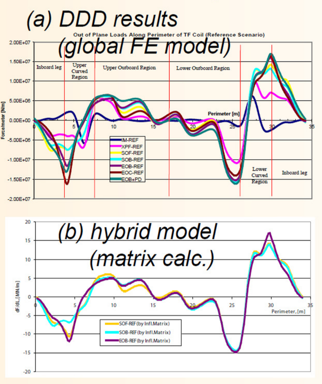


Fig. 8. Calculated profiles of the out-of-plane forces on a TFC.

Table 1. TFC loads benchmark

	Integral parameter	Matrix calc.	DDD [6]
In-plane loads on a TFC from other TF coils (18 acting TFC, at operating conditions)	Radial (centring) force per TF coil F_R, [MN]	397	403
	Vertical force per half TF coil, [MN]	206	205.2
Out-of-plane loads on a TFC from other TF coils (18 acting TFC, at operating conditions)	Net off-plane force $F_z^{(1)}$ on a TF coil from other TFC, [MN]	0 1)	0 1)
	Vertical moment M_y of the out-of-plane forces, [MN*m]	0 1)	0 1)
Out-of-plane loads on a TFC from toroidal currents (CS, PFC and plasma) (total from all currents, at reference timepoint)	Net off-plane force $F_z^{(2)}$ [MN]	-13.1 2) 3)	n/a (0)
	Radial moment M_x of out-of-plane forces, [MN*m]	-77.1 2) 3)	n/a
	Vertical moment M_y of out-of-plane forces, [MN*m]	0 2)	n/a

1) perfectly-symmetric case only (all TFC are at the same current).
2) calculated timepoint: SOF (DINA initial state, model 2010)
3) Vertical position of the centre of forces: +5.91M above the equatorial plane,

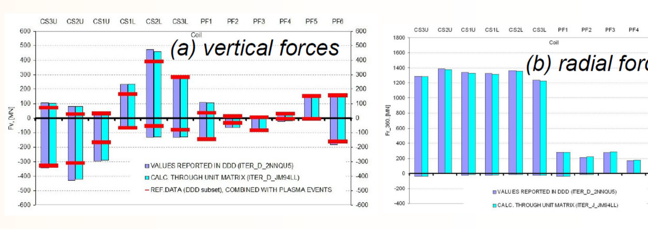


Fig. 9. Envelope forces on CS/PF coils, [MN]. Left bars - DDD, right bars - by influence matrix (red marks - combined with plasma events).

6. Summary

- The efficient method of modeling EM mechanical interaction forces between components of a large tokamak has been proposed and considered for ITER.
- The hybrid model for calculating EM forces on coils and magnets has been developed, according to the proposed method and approach.
- Sensitivity/influence matrices have been produced for the elements of ITER magnetic system, including all coils and magnets.
- The obtained matrices and profiles have been used for the multi-scenario assessment and systematic specification of EM loads on ITER coils and magnets in all considered operating regimes and plasma transients, including full load ranges, maximum loads, envelopes and the most critical cases.
- The reference design values and the ITER Design Description Document (DDD) data have been benchmarked against the new model and systematic results.

- The benchmark of reference design values from ITER DDD (obtained by traditional analyses over the past years) with new results showed their essential consistency.
- The basic principle of considering bilateral configurations, supported by the technology of functional approximation of distributed data by the continuous analytical interpolants, is applicable to asymmetric loading or faulty systems and continuously distributed currents (shells, solids).
- The developed global model of interactions, together with the "meshless" analytical format of output represent a source of self-consistent and transferable data on mechanical loads as input for structural analyses of components, assemblies and supporting structures at any arbitrary scenarios, regimes of operation and transients.
- The obtained results and matrices (transforming the vector of currents to the full set of Lorenz forces) form a basis for a relatively simple and robust linear force processor as a specialized module of a global simulator for diagnostic, operational instrumentation, monitoring and control, as well as a scenario assessment tool.
- The simplicity and computational efficiency of the operative part of the developed hybrid model permits real-time calculations of forces (total and distributed).

- The performed study clearly demonstrated a necessity to restrict the operational space to certain limits, determined by the loading capacity of structures.
- Integration of the force-calculating units / processors / predictors / simulators with Plasma Control System (PCS), other control and safety systems, pulse control allowables, interlock and safety limits must assure a solid margin to the structural limits in order to prevent any risk of magnets and structures overloading. This will insure the investment protection, as well as personnel and environmental safety during the machine operation. The integrated numerical simulators, including mechanical force processors, quantifying the predicted state of structures in a space of operational parameters, should be an implicit part of the system.
- The availability of simulators is one of necessary pre-requisites for entering the pre-nuclear Tokamak Operation phase. In applications for either phase, the key aspect of simulators (models) is their computational efficiency and robustness. The latter can be ensured by the maximum reasonable simplification/optimization of the model and its adequacy to the considered problem/system and to the practical needs.
- The use of hybrid combined models with pre-computed part, similar to the presented model, permits running the operative part in real-time mode, and such functionality can be integrated with the operational diagnostic and control systems of the real machine.

Specific questions of: **- EM loads on Blanket,**
- EM loads on VV,
- use of dynamic simulators,
- hybrid / multiscale modelling of EM problems,
- representation of results and distributed data,
- general strategy and approach
were considered separately in:

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Fus. Eng. Des. 89 (2014) 1826–1831 (ISFNT-11, Barcelona, Spain, 2013)
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