# ALGORITMIZATION CONCEPT FOR QUASI-MAGNETOSTATIC SIMULATION IN TOKAMAK-TYPE MACHINES

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**Abstract**
Algoritmization of eddy-current problem is discussed in the context of analysis of electromagnetic transients for large tokamak-type machines. A computational technique is proposed to effectively simulate spatial and temporal distributions of eddy currents and related EM loads. The computational algorithm offers general formalism that makes it applicable for a range of electrophysical devices.

**Key words**
Simulation, EM transients, tokamak, eddy current, finite element, magnetic shell

## 1 Introduction

One of key issues in the design and operation of large tokamak-type machines, such as ITER [http://www.iter.org], is prediction and analyses of distributed eddy currents and electromagnetic (EM) response of the structures, in terms of related EM, mechanical and thermal loading. The loads are expected to reach critical levels. At the final stages of the machine design, virtual commissioning and then actual implementation, dynamic simulations by means of simulator-codes are of fundamental importance to ensure successful operation. Devoted simulators have to adequately reflect the complexity of the tokamak EM behavior to enable reliable and accurate prediction. Attention therefore must be concentrated on systematic enhancement of the simulation accuracy and development of various simulators. Focusing on the ITER application, specific features to be taken into consideration include:

- a variety of field sources, the main one being the plasma motion,
- a wide range of operational scenarios,
- inductive coupling of the components,
- diversity of sizes and geometry of conducting structures;
- presence of a number of insulating gaps and electric contacts.

EM response of the ITER structures is simulated using relevant models of various degrees of refinement. To provide the desired computational accuracy, it is insufficient to use only simple models, such as axisymmetric plasma models in MHD and transport-modeling plasma simulations, to evaluate distributed eddy currents, fields and EM loads. However, spatial and temporal distributions of the plasma and coil currents derived from the MHD and plasma transport computations, for instance, with the code DINA, serve as inputs for simulation EM transients in passive structures. Evaluation of eddy currents and associated EM loads almost invariably demands solving of a non-stationary problem, in contrast to a stress analysis that often may use a static solution due to a short characteristic time of the process. Duration of EM transients usually extends greatly the periods of physically significant fluctuations of parameters, such as thermal quench of the plasma current. This fact together with typical stiffness of a system of ordinary differential equations [Gear, 1971] makes solving a required non-stationary Cauchy problem unfavourably extensive. Our practice in EM analysis suggests that numerous multivariate parametric computations to support design activities, standard for tokamak-type devices, are inefficient if a sole global model is used. A special technique is required to enable cost-and time effective computations. Evidently, for the best efficiency, the technique must allow for a number of ITER features. A computational algorithm and a set of complementary models are described that were developed in the course of works to support ITER design activities. The presentation reflects continuous experience in EM computations requested and supervised by the ITER Organization.

## 2 Modeling strategy

A number of factors makes it possible to simplify the EM modeling in the ITER application.

1. In Maxwell's electromagnetic theory, EM phenomena are associated with a set of differential equations [Tamm, 1989], [Sommerfeld, 1949]. These equations define relations between the vectors of electric field intensity **E,** field strength **H**, electric flux density **D** and magnetic flux density **B,** the density of free charge ρ, and conduction current density **j**. If the field varies slowly and polarization processes are developed concurrently, which is characteristic for EM transients in ITER [ITER Technical Basis, 2002], [Glukhih, Belyakov, Mineev, 2006], then the quasi-stationary formulation is applicable [Tamm, 1989]. Therefore, fields from varying currents and relevant interaction forces can be calculated at any time point as instantaneous values using equations for steady-state current. The variable currents are closed and have the same values at any portion of a single-path circuit.

2. A variety of field sources can be represented via a set of currents. Almost all the currents can be modeled as simple coils with a constant cross-sectional current density or current filaments. These coils (filaments) are configured through circles or a set of arcs. Such description allows utilization of conventional procedures and high-precision computer codes for field simulations, including those developed by the authors [Amoskov, Belov, Belyakov et al., 2003]. An important issue is the halo current, special techniques have been developed to model it [Neubauer, Belov, Gapionok et al., 2011].

3. At any reference point, conducting materials are assumed to have a constant electrical conduction dictated by the operating temperature.

4. Non-linear effects of steels used in the ITER machine, have a relatively weak impact on eddy currents induced in passive structures [ITER Technical Basis, 2002], [Glukhih, Belyakov, Mineev, 2006]. For this reason a constant magnetic permeability in localized regions is applicable at least at the initial stage.

5. Assumptions *3* and *4* make it possible to use the superposition principle. Spatial distributions of conduction and magnetic permeability are iteratively corrected when solving the coupled problem through the following steps: (i) MHD calculations with, for instant, the DINA code [Sugihara,, Shimada, Fujieda et al., 2007], (ii) simulations of EM transients – (iii) simulations of transient thermalhydraulics and heat diffusion - (iv) stress analysis - (v) return to step (i) if necessary.

6. Homogeneous and isotropic media can be modeled using relations $\mathbf{D} = \varepsilon_a \mathbf{E}$, $\mathbf{B} = \mu_a \mathbf{H}$, where $\varepsilon_a$, $\mu_a$ are, respectively, absolute permittivity and absolute permeability, which are constant and independent on **E** or **H**. For the current density the same degree of

approximation is determined by Ohm's law written at the reference point of the stationary medium in a form $\mathbf{j} = \sigma\mathbf{E} + \mathbf{j}^e$ [Koshlyakov, Gliner, Smirnov, 1970], where σ is the constant conductivity, $\mathbf{j}^e$ is the volume density of an external current. The parameter $\mathbf{j}^e$ is introduced to correlate with possible effect of a pre-determined external field from current $\mathbf{j}^e$ associated with a known process. In the Cartesian coordinates, **H** and **E** can be expressed in the differential formulation [Tamm, 1989], [Sommerfeld, 1949], [Koshlyakov, Gliner, Smirnov, 1970] without simplifying assumptions of low $\varepsilon_a \partial\mathbf{E}/\partial t$ in the conducting regions and zero conductivity σ in dielectrics:

$$\Delta\mathbf{E} - \varepsilon_a\mu_a \partial^2\mathbf{E}/\partial t^2 - \mu_a\sigma\, \partial\mathbf{E}/\partial t = \frac{1}{\varepsilon_a}\mathrm{grad}\rho + \mu_a \partial\mathbf{j}^e/\partial t \qquad (1)$$

$$\Delta\mathbf{H} - \varepsilon_a\mu_a \partial^2\mathbf{H}/\partial t^2 - \mu_a\sigma\,\partial\mathbf{H}/\partial t = -\,\mathrm{rot}\,\mathbf{j}^e$$

(here Δ is the Laplacian).

As an alternative formulation, the vector potential A and scalar potential φ are introduced [Tamm, 1989], [Koshlyakov, Gliner, Smirnov, 1970], [Kneppo, Titomir, 1989], [Biro, Press, 1989], [Carpenter, 1967], also the well-known «T-Ω» method is applicable [Frenkel, 1956], [Albanese, Martone, Miano, Rubinacci, 1985], [Belov, Doinikov, Duke et al., 1996]. In the considered case of homogeneous media, this yields partial hyperbolic differential equations:

$$\Delta\mathbf{A} - \varepsilon_a\mu_a \partial^2\mathbf{A}/\partial t^2 - \mu_a\sigma\,\partial\mathbf{A}/\partial \mathrm{t} = -\,\mu_a\mathbf{j}^e, \qquad (2)$$

$$\Delta\varphi - \varepsilon_a\mu_a \partial^2\varphi/\partial t^2 - \mu_a\sigma\,\partial\varphi/\partial \mathrm{t} = -\,\rho/\varepsilon_a\,.$$

The left sides of the field and potential formulations are similar, while the right sides are different.

In this case differential equations allow formulation of independent problems in terms of field components and the scalar potential. With the use of parallel computing, the set of problems can be resolved in one step of the algorithm.

Reasoning from the similarity of the left sides of both formulations, we can draw primary conclusions:

- the run time is the same for calculations both in terms of fields and potentials,
- nominally, with the field formulation the computational resources involved are half as much again those of the potential formulation;
- in the field formulation, the need for calculation of derivatives of a given external current is associated with an additional error. However, this error is controllable and can be reduced to acceptable value by means of thorough preparation of input databases;
- the field formulation gives a relatively smooth solution because it does not employ numerical differentiation. Solution in the potential formulation is often based on grid methods (finite-element or finite-difference representations) and can require additional smoothing procedures; the problem becomes more complicated for calculations of mechanical loads.

7. In any grid method, discretization of the Cauchy problem on spatial coordinates gives a system of linear (or linearized) ordinary differential equations (SLODE) in terms of field or potential. The constant coefficients of SLODE are dictated by electric and magnetic properties of the structural materials. The right sides of the equations are determined by temporal and spatial distributions of field sources. The equations are accompanied with initial and boundary conditions. If a pulsed current law (trial pulse action, time dependent pulse functions) is given for one source, the EM response is derived in a form of an eddy current distribution throughout the finite elements. Going successively over other sources, we can form an array of solutions called the trial pulse action table (TPAT). Variations of current sources determined through MHD and plasma transport simulations (with DINA or similar codes) may be expanded in terms of pulse functions. Let $w_1(t)$ and $w_2(t)$ be partial solutions for the respective SLODE right-side terms $f(\mathrm{t}) = f_1(\mathrm{t})$ and $f(\mathrm{t}) = f_2(\mathrm{t})$. Using superposition, we obtain the particular solution for the right side $f(t)=\alpha f_1(t)+ \beta f_2(t)$ in a form:

$$w(t)=\alpha w_1(t)+ \beta w_2(t) \qquad (3)$$

8. Conductive components of the ITER vacuum vessel (VV), cryostat, and thermal shield (TS) have near symmetrical configuration, except for 3 irregular ports. A calculated domain can be reduced to a 20- or 10-degree sector relying on the axial or mirror symmetry. Models of irregular ports were built separately [Amoskov, Arslanova, Belov et al., 2012]. The EM transients are grouped reasoning from the types of symmetry of the toroidal and poloidal currents. In combination, individual solutions result in generalized distributions of the current density, EM forces and heat loads in any sector within a domain expanded to 360 degree [Amoskov, Arslanova, Belov et al., 2012].

9. To predict eddy currents in the passive structures, the magnetic shell approximation [Carpenter, 1967], [Kameari, 1981], [Belov, Doinikov, Duke, et al., 1996] is applicable to model thin conducting structures arranged arbitrary in space.

On the basis of these simplifying approximations related to the ITER features, a special computational technique has been developed (also see [Belov, Doinikov, Duke et al., 1996]). The computational algorithm is shown schematically in Fig.1.

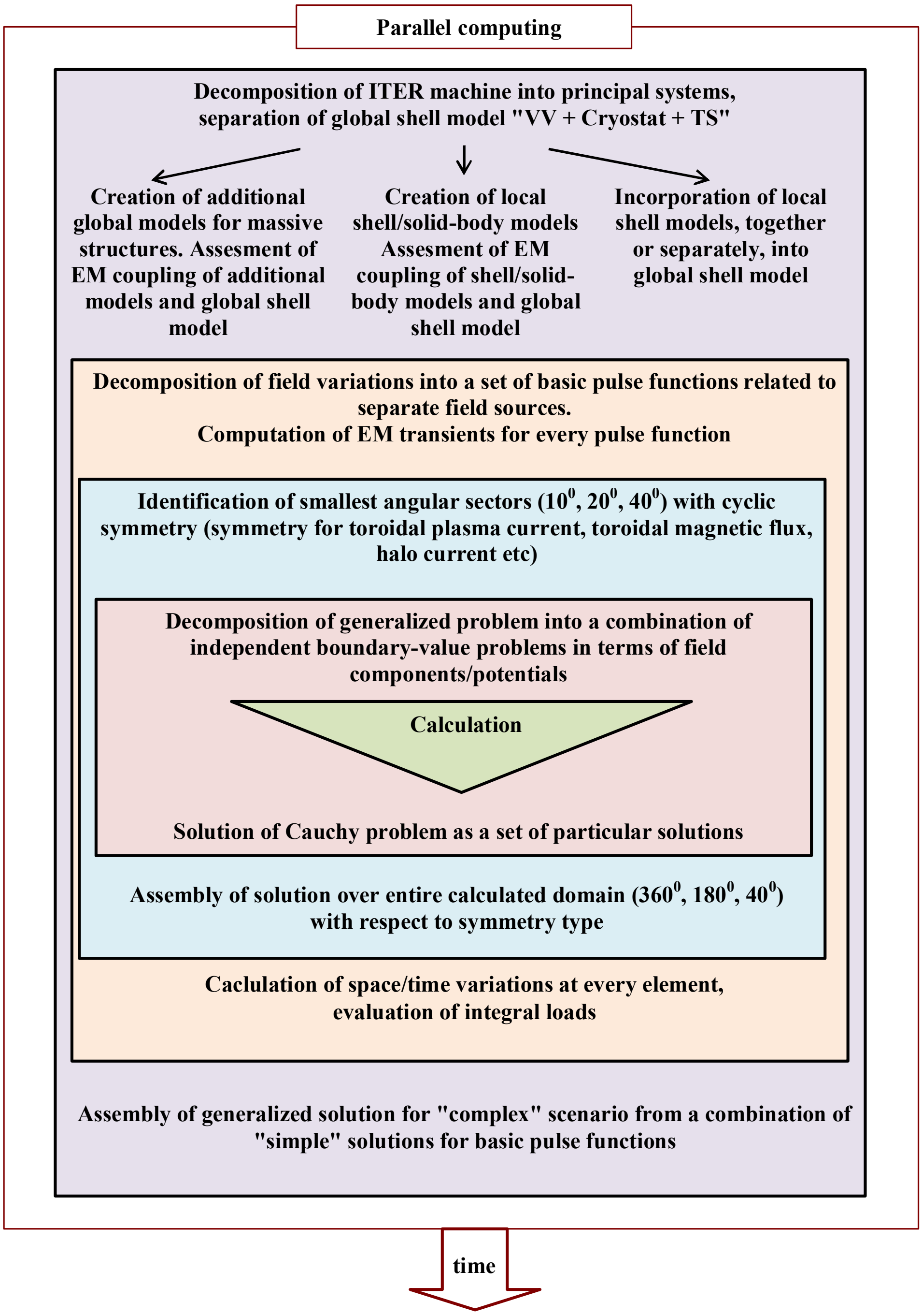


Figure 1. Algorithm for EM computations using parallelism

Briefly, the main steps imply:

- decomposition of complex current variations into a combination of separate current sources in terms of given analytical functions;
- dichotomy of the eddy current problem in the context of a complex configuration of conducting components, the use of local models to accommodate EM response of different structures, appropriate choice of the shell or solid-body approximation so that to ensure the optimal computational cost for modeling EM transients in different structures;
- selection of solution procedures enabling reduction of a calculated domain due to relevant boundary conditions at a distant external boundary (boundary conditions of infinity) and symmetry, description of generalized EM effect via superposition of poloidal and toroidal fields where applicable.

## 3 Description of current sources

The computer code KLONDIKE [Amoskov, Belov, Belyakov et al., 2003] enables simulation of practically all current sources in ITER (see [Amoskov, Arslanova, Belov et al., 2012] for details), particularly:

- CS, PF, and TF coil currents, complemented correction coil currents and ELM coil currents, if necessary;
- plasma current;
- toroidal field variations due to the β drop;
- halo current.

Computed data form a database of field maps associated with the spatial and temporal variations of these currents. By virtue of the described approximations, the error of field simulations is governed by the accuracy of the eddy current calculation.

Fig. 2 illustrates schematically the model of the ITER magnet system and plasma.

A possible modelization of spatial and temporal distributions of the halo current is implemented in the TYPHOON model. The halo current is assumed to close through the plasma periphery. The surfaces where the halo current passes are modeled via relevant shells. The shells are meshed with finite elements that assumed immune to eddy currents. The full current throughout the shells varies in time according to the halo current evolution. This description corresponds to the ideal current source.

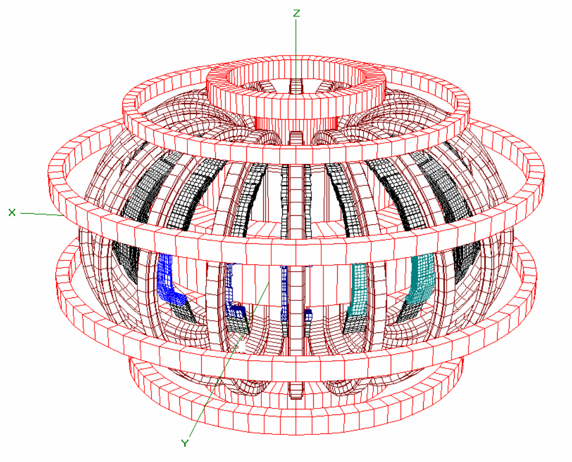


Figure 2. Model for ITER magnets and plasma

Fig. 3 taken from the paper [Neubauer, Belov, Gapionok et al., 2011] illustrates such modeling applied to the EM analysis of the diagnostic system for the ITER core charge exchange recombination spectroscopy (cCXRS).

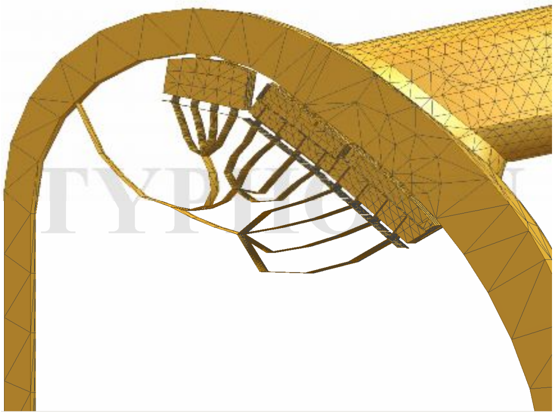

Figure 3. Upper segment of VV with shells for FE representing Halo current, side view.

The system is constructed as a plug of the upper VV port #3. The poloidal halo current passes near the blanket shield module of cCXRS port plug and blanket modules ##9-11 are modeled with 12 shells. Two most loaded scenarios, Fast Upward Vertical Displacement Event (FU VDE) and Slow U VDE, have been simulated. For every shell a time law was prescribed for a relevant share of the halo current flow using DINA results. The region near blanket modules ##6, 7 is modeled with a single shell because its remoteness from the investigated structures. The model takes into account the loads generated by the flow of halo current on conducting structures.

## 4 Software tools for simulation of eddy currents and EM loads

The following computer codes have been applied to investigate EM transients in ITER.
TYPHOON [Belov, Doinikov, Duke et al., 1996] is intended to model conducting multi-connected walls arbitrary located in 3D space via the magnetic shell approximation [Carpenter, 1967], [Frenkel, 1956], [Albanese, Martone, Miano, Rubinacci, 1985]. Using an integral-differential formulation, a single unknown is determined within the shells in terms of the vector electric potential taken only at the nodes of a 2D finite-element (FE) mesh. This approach offers an advantage of easy shell adding/removal due to localized re-meshing in contrast to 3D solid body-models that require the mesh to be re-build over the entire volume.
TORNADO [Amoskov, Arslanova, Belov et al., 2012] is used to model massive structures. The 3D FE representation and electric vector potential are employed.
3DHE utilizes a two-vector field formulation and grid approximations.
ANSIS simulations have been used in test runs in order to validate accuracy and quality of the developed models.

## 5 Computational models

The VV, Cryostat, and TS, being the principal components of ITER [Ioki, Barabash, Choi, 2011], are known to have strong electromagnetic impact on each other and surrounding structures. All these components can be classified as thin-walled structures, that makes the magnetic shell approximation applicable for modeling their electromagnetic behavior. A set of detailed computational models has been developed (see [Alekseev, Arslanova, Belov et al., 2012] for more details) that covers integrally the system "VV + cryostat + TS". Both regular and NB VV ports has have been included in the models. As compared to a 3D model based on an equivalent approximation, the shell model requires imply much lesser computational cost. Figs 4-7 illustrate FE meshing used for VV, Cryostat, and TS models.

Now the models for the system "VV+Cryostat+TS" closely reflect recent design options. The validity of models has been proved in benchmark computations and comparison with analytical estimates.

The models provide desired computational accuracy under full spectra of EM loads (during normal plasma operating conditions, scenarios of plasma disruption and magnet system discharge).

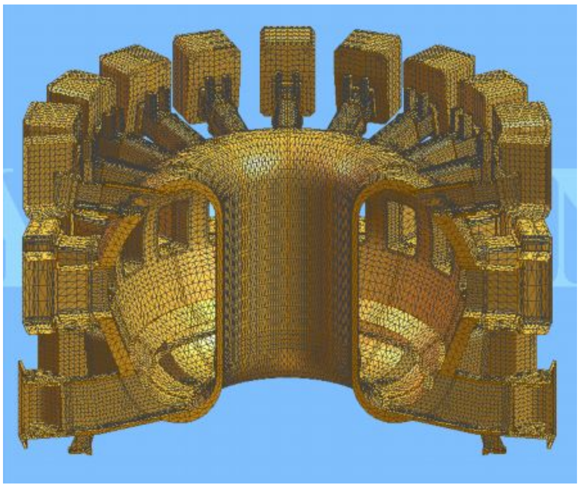

Figure 4. FE model of ITER VV

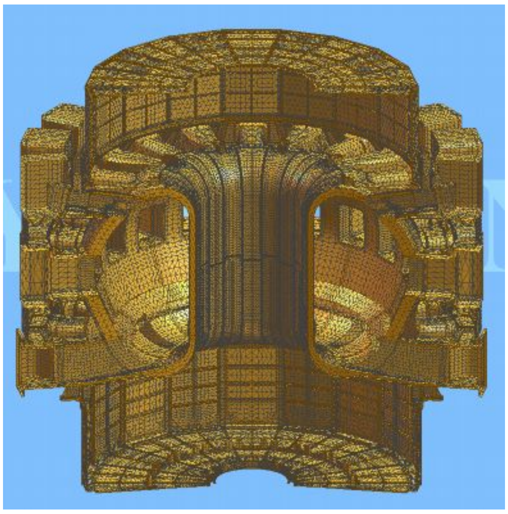

Figure 5. FE model of ITER VV and TS.

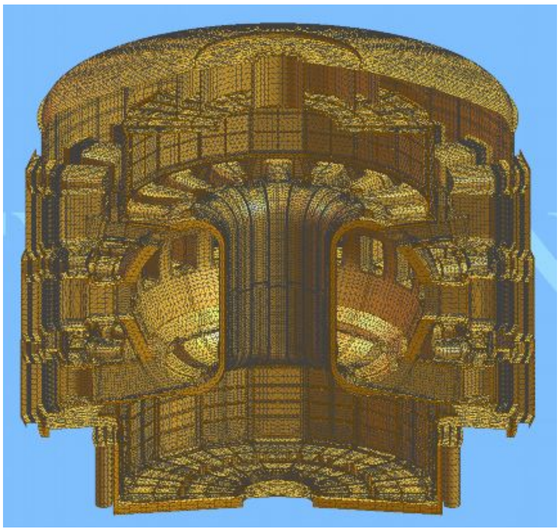

Figure 6. FE model of ITER VV+ cryostat +TS

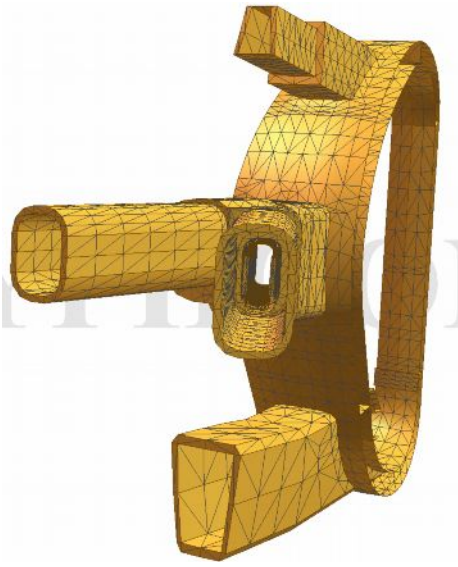

Figure 7. 20-degree sector of VV model. Heating neutral beam liner with cooling pipes is incorporated into heating/diagnostic neutral beam (H/DNB) equatorial port. Outboard view.

There are several ways to integrate additional components into the existing global shell model. One way is to merge additional shell models with the primary global model. This technique was utilized to model cryopumps installed in the lower VV ports, see Fig. 8, 9 (taken from [Antipenkov, Day, Amoskov, 2010])

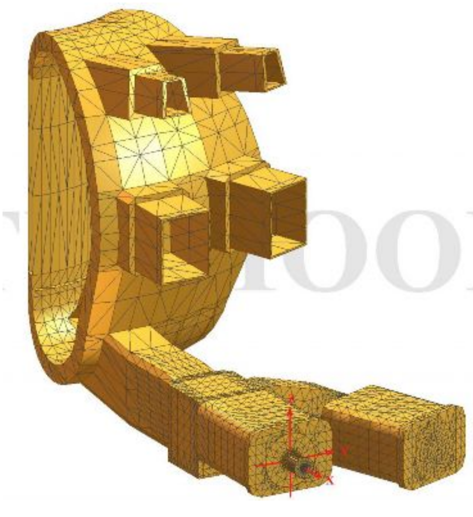

Figure 8. FE model of VV and cryopump. Rear view.

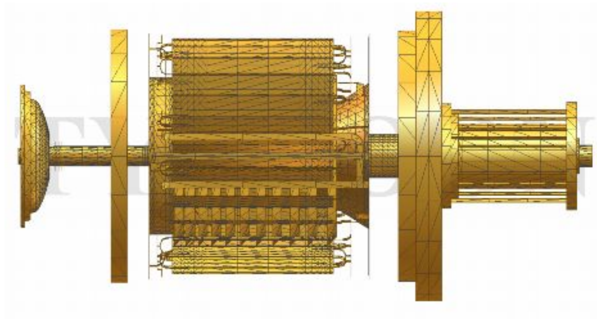

Figure 9. FE model of torus cryopump. The carrier tube of housing and carrier tubes of 80K radiation shield are not shown.

Figs. 10, 11 show the model used in the EM analysis of the generic upper port diagnostic plug (GUPP) installed inside the ITER vacuum vessel upper port. The shielding effect of blanket modules #9-11 has been analyzed on EM loads on GUPP. The specified plasma event Fast Upward VDE linear 36ms has been studied using the data from the DINA code. The simulations have been performed assuming the model (machine) implies only regular sectors, 20-degree periodicity (instead of 40-degree) of the lower ports is taken into consideration [Rozov, Raffray, Lamzin et al., 2012]. However, such modeling leads to increase in mesh sizes that could be computationally infeasible. An alternative is to use a combination of inductively coupled global models [Alekseev, Andreeva, Belov et al., 2012]. Convergence of the computational process is provided by the above approximations.

Figure 10. FE model of sector (1/36) with blanket modules #9-11. Inboard view

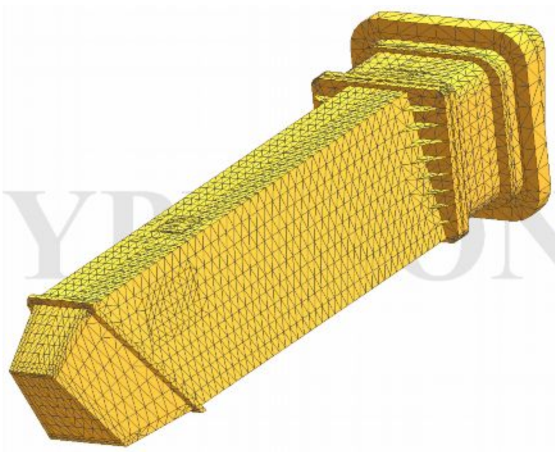

Figure 11. FE model of generic upper port plug located in VV upper port. Isometric view.

This approach is most efficient if the additional component (second global model) has relatively low EM effect on the primary structures. A correction coefficient is determined in the solution with the additional model and may be iteratively adjusted. This makes it possible to arrange parallel computations. Evidently, both shell models and 3D solid-body models can be coupled in such a manner to the primary global shell model "VV+Cryostat+TS". An example is illustrated in Fig.12: additional components are TS manifolds modeled via thin shells.

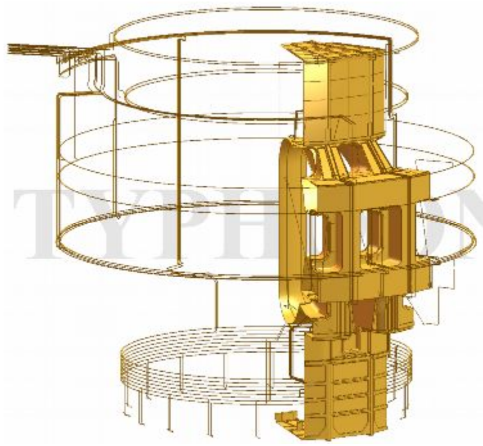

Figure 12. ITER "VV+cryostat +TS" first global model and TS manifolds second global model.

The ITER in-vessel components related to the blanket [Merola, Loesser, Martin et al., 2010], divertor or diagnostic system are massive though small in volume as compared with VV. Generally, they are modeled with the use of 3D FE meshes. For brevity, we focus on the modeling of the blanket modules (BM) to demonstrate the characteristic way of treatment. Other in-vessel and out-vessel components distinguishing non-essential modeling specifics are excluded from consideration.

Simulation of anticipated EM loads on BMs is accomplished through the following procedure:

- merging of a simplified shell model for a selected BM and neighboring modules with the global shell model "VV+cryostat+TS" to form an integrated global model GM1;
- building a global 3D solid-body model GM2 to describe only the selected BM in details with simplified description for the neighboring modules, if required;
- TYPHOON simulation of EM transients on GM1, evaluation of EM loads from calculated eddy currents and field sources external with respect to GM1 over a set of reference points in the GM2 calculated domain. Note that fields from eddy currents obtained in the simplified shell model of BM are excluded from the fields calculated at the GM2 reference points;
- TORNADO simulation of EM transients on GM2 with respect to external for this model fields evaluated from the preceding TYPHOON simulation with GM1;
- assessment of inductive impact of GM2 on GM1. Modification of GM1 by means of removal of the BM and neighboring modules if iterative correction of the prediction is required; assessment of EM response of the modified GM1 on GM2 eddy currents

The simplified shell model of BM is used at the first step to ensure accurate description of EM transients. The simulation procedure may be adjusted so as to cope with specifics of modeled massive structures in the most efficient way. Figs. 13, 14 show an example of FE meshing for a blanket module #16. Simulations for BM#14 have demonstrated that a discrepancy in evaluation of the principal EM forces and moments with the detailed 3D solid-body model and simplified shell model is within 10% to 15% for all scenarios considered.

These results comply with estimates obtained with the use of the simplified approach [Rozov, Raffray, Lamzin et al., 2012], [Rozov, Belyakov, Kukhtin et al., 2012]. However, assured prediction of spatial distributions and evolutions of eddy currents and associated EM loads in BM requires a detailed 3D solid-body model.

Smart utilization of global and local models based on different approximations provides complementary and cross-checked results of simulations. The developed models have been validated within common internal procedures and in comparative computations with other codes [Belov, Doinikov, Duke et al., 1996], [Neubauer, Belov, Gapionok et al., 2011], [Rozov, Raffray, Lamzin et al., 2012], [Beliakova, Belov, Gapionok et al., 2009], [Amoskov, Arslanova, Belov et al., 2012], [Rozov, Belyakov, Kukhtin et al., 2012].

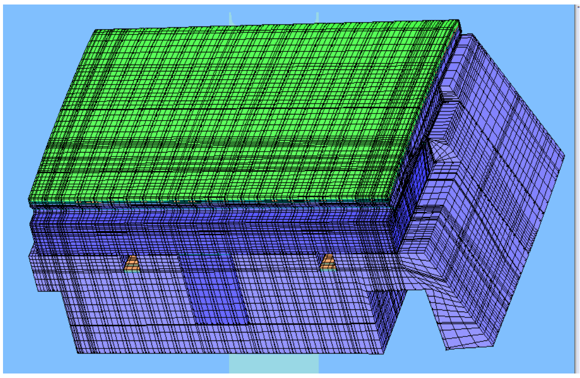

Figure 13. FE model of BM#16. View from first wall.

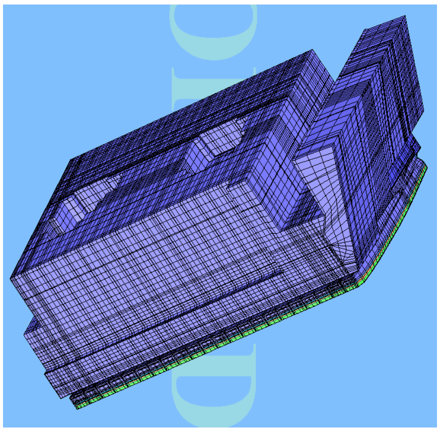

Figure 14. FE model of BM#16. View from shield block.

Accuracy of predictions has been proved against results of experiments on the operating tokamak GLOBUS-M [Amoskov, Belov, Belyakov et al., 2005]. A comparison with analytical estimates [Amoskov, Arslanova, Belov et al., 2012], [Belov, Doinikov, Duke et al., 1996] identifies the available computational accuracy for the ITER application.

The proposed computational algorithm foresees a possibility to use a local 3D solid-body model for eddy current analysis. A closed boundary of a finite calculated domain is selected. The boundary conditions are given in terms of fields or potentials associated with eddy currents calculated from to the global shell model "VV+cryostat+TS", other local models or independent current sources.

This technique has been justified in solving a set of model problems with computer codes TYPHOON, TORNADO, ANSYS.

## 6 Conclusions

A versatile modeling technique has been developed to efficiently predict EM loads in ITER conducting structures. The technique offers generality that makes it applicable to a range of complex electrophysical devices.

A flexible combination of different models enables computation of spatial and temporal variations for eddy currents and generated EM, thermal and mechanical loads with a desired accuracy. The input data are derived from results of MHD simulations, particularly with the code DINA. The output databases are stored in formats suitable for subsequent thermal hydraulic and stress-strain computations.

The technique employs combined computations with a set of original codes (developed by authors), that provides modeling synergy and cross-checking within common procedures. Integration with other codes including conventional commercial programs is feasible that can improve reliability and efficiency of predictions.

The proposed technique summarizes our more than 15-year practice of computations within the framework of the ITER project. The models have been developed and validated in the course of activities requested and supervised by the ITER Organization. The simulated results have been included in the project documentation. Developed computational models enable cost-and time effective computations at the further stages of works.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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