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Analysis of electromagnetic loads on EU-DEMO inboard and outboard blanket vertical segments

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ABSTRACT

An analysis of the EM loads acting on a DEMO reactor configuration based on Multi Module Segment (MMS) design is presented in this work as part of the ongoing EU DEMO studies. Lorentz's forces and moments, both on the single module as well as on the complete blanket segment, are calculated for both the European HCPB and HCLL concepts. The system is analyzed considering a major central disruption scenario with a linear current quench of 42 ms using the ANSYS finite element software. The results are also compared to linear analyses to underline the effect of the non-linearity of the ferromagnetic materials.

1. Introduction

Plasma disruptions and vertical displacement events (VDEs) in tokamak reactors are design drivers for the in-vessel components' attachments as the induced loads constitute a sever issue for the mechanical structure.

Off-normal operations in tokamak reactors result in the induction of eddy currents in the electrically conductive components that, coupled with the large magnetic field, impose strong electromagnetic forces (Lorentz's forces) to fusion reactor components. In addition the presence of ferromagnetic material in the blanket structures induces Maxwell's forces as interaction between the magnetized material and the external magnetic field. The related electromagnetic (EM) loads can have a significant impact on the design of the reactor's components, thus having an impact on the parameters related to the structural integrity of the reactor itself. In particular, in a DEMO reactor configuration based on Multi Module Segment (MMS) design, the magnitude of the EM loads both on the single module as well as on the complete blanket segment are expected to be a design driver in the definition of the number of modules per each blanket vertical segment. This definition is the basis of the blanket conceptual design development.

A DEMO reactor configuration based on a model elaborated by EFDA in 2012 on the basis of PROCESS system code optimization [1,2] is here considered. The reactor has been designed to consolidate the present knowledge and technology into a reference design. Under the main global assumption of a net electric output of 500 MW and a thermodynamic efficiency of 33%, a 9 m major radius machine with aspect ratio of 4 has been defined. The complete Blanket System is divided in 16 toroidal 22.5° sectors. Each sector is then divided into 5 segments: 2 inboard (IB) segments (11.25°) and 3 outboard (OB) segments (7.5°). Each segment consists of a number of modules which are connected to a strong manifold structure.

In this paper, an assessment of the EM loads acting on the single module as well as on the complete blanket segment is made considering a major central disruption scenario. The Eddy currents, electromagnetic forces and moments are computed using the ANSYS finite element software.

2. The FEM model

A 22.5° sector model of DEMO has been developed on the basis of a 2D sketch of the poloidal–radial cross-section. Such sketch defines: (1) the space allocation of the blanket segments; (2) the

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Table 1
Inboard and outboard module radial dimension.

Component name	Inboard (mm)	Outboard (mm)
FW	30	30
CAP	30	30
BZ	200	450
BP	30	30
BPint	150	140
BP	40	40

vacuum vessel (VV); and (3) the poloidal field (PF), central solenoid (CS) and toroidal field (TF) coils.

2.1. Blanket segmentation

The radial segmentation of the IB and OB blankets has been defined on the basis of the data reported in previous works for a similar reactor configuration [3,4] and adapted to the current geometry. The modules' structure is based on the CAD model provided by the Test Blanket Module (TBM) group at INR-KIT, whose main characteristics are reported in [5]. It has been developed on the basis of the EU TBM to be tested in ITER [6] and it features a common architecture in both the two European concepts: Helium Cooled Pebble Bed (HCPB) and Helium Cooled Lithium Lead (HCLL).

The blanket module is generally divided into: (1) a U-shaped first wall (FW); (2) two side walls (CAPs); (3) a breeding zone (BZ) with an internal stiffening grid for the cooling of the breeding units (BU) and (4) a box manifold whose back plate (BP) is attached to the segment's manifold. Each sub-component presents a complex internal structure (pipes, holes and cooling channels) that would result in a too high level of detail for the model here considered. In order to reduce the dimension of the FE model mesh and, consequently, the computational time, the blanket module has been schematized as in Table 1.

The material composition associated to the modules' inner and outer components are defined in Section 2.2.

The FE model of the inboard and outboard manifold is based on the model proposed in [5], properly scaled in order to fit the reference DEMO sketch. The internal structure has been reduced to a single channel with non-constant poloidal cross-section that follows the shape of the manifold.

Following the rule of constant radial thickness for each component, a base 3D reactor model has been built. For what concern the poloidal segmentation, an averaged value of 1 m length for the module's first wall poloidal dimension has been considered. Using this constrain, 9 and 10 modules have been defined for the IB and OB blanket respectively. The modules are insulated by a 20 mm gap (defined as air/vacuum) both in toroidal and poloidal direction. Each module is connected to the manifold along a central attachment that provides a single electrical connection. The manifold is, in turn, electrically connected to the VV at one single point corresponding to the location of the upper vertical port. A side view of the cross-section of the final 3D model is depicted in Fig. 1, while a zoomed view of the module is shown in Fig. 2.

2.2. Materials properties

At present, the reference structural materials for DEMO blankets and VV are the Reduced Activation Ferritic Martensitic (RAFM) steel EUROFER97 [7,8] and the Stainless Steel 316 (SS316 [9]) respectively. Differently from SS316, EUROFER97 is a ferromagnetic material that shows a nonlinear *B*–*H* characteristic curve with high saturation magnetic flux density (>1.9 T at room temperature).

The magnetic and electrical properties of materials associated to the solids in the FE model have been defined as macroscopic parameters averaged on the considered spatial region according to

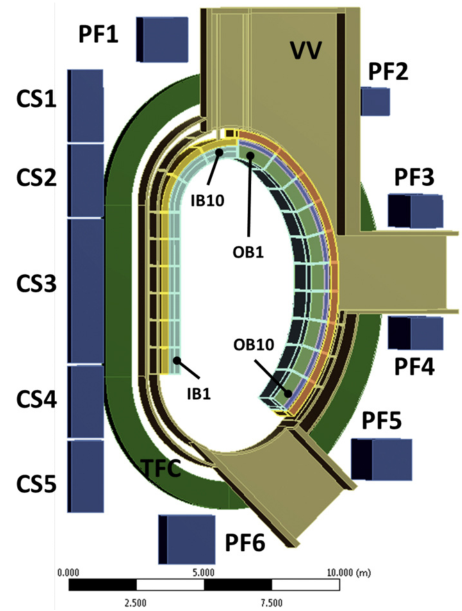

Fig. 1. Cross-section of the FEM model.

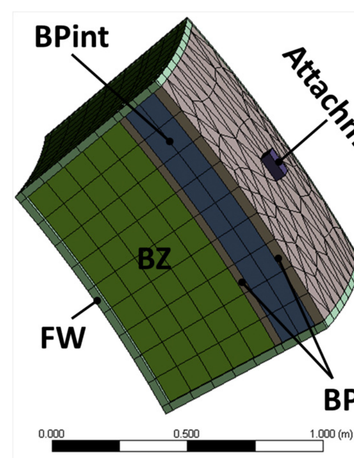

Fig. 2. 3D view of the schematization of a blanket module.

the percentage of conductive material as made in [10]. Since these properties are temperature dependent, an approximated reference temperature has been defined for each component. The values are reported in Table 2. The composition is defined by the percentages of the pure materials involved. The missing part consists of nonconductive materials (air, vacuum, water, etc.).

Two different materials, named BZ-HCPB and BZ-HCLL in Table 2, have been defined to perform a preliminary investigation on the effect of PbLi [11] in the EM loads acting on each module (see Section 4.2). Since the magnetic permeability of PbLi is almost equal to the permeability of vacuum, the two materials show the same *B*–*H* behavior and differ only in the electrical resistivity.

2.3. Elements type

The models have been developed using the SOLID236 element type. This element uses the *Edge-based magnetic vector potential* formulation to solve the problems of discontinuous normal component of magnetic vector potential, allowing discontinuities in the materials properties at interfaces (different permeability, ferromagnetic materials). Details are given in [12].