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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th International Conference on Controlled Fusion and Plasma Physics, Sorrento, 2000), IAEA, Vienna (2001)*

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ABSTRACT
The need of a better understanding of the origin, distribution, and scaling of halo currents flowing through plasma and vacuum vessel during Vertical Displacement Events (VDE) is one of the critical issues for the ITER project. JET can play a key role in this study, provided that new and more detailed information becomes available. This fact motivated the design of a set of additional sensors specifically aimed at improving the diagnostic capability of halo currents at JET. This new system is described in the paper. It consists mostly of Rogowski coils and of a small number of toroidal field pick-up coils. The former will measure directly the current flowing through the tiles of the first wall. The latter will allow the estimation of the total poloidal halo current where the insertion of Rogowski is technically difficult and provide complementary data for a better characterization of the phenomenon. The system is a compromise between the maximization of the spatial resolution in both toroidal and poloidal direction and the actual JET capability of adding new in-vessel probes and new conduits needed to bring the signals outside the vessel. The main system issues are briefly reported, then the modifications of the in-vessel components, necessary to house the probes, will be described together with the technological solutions adopted to improve the measurement quality. Electromechanical analysis is performed on modified tiles to allow the measurement of the current flowing through them. Its results are also presented in the paper.

1. INTRODUCTION

Vertical instability of elongated plasma is a well known problem, first theoretically predicted [1], then experimentally observed on many different devices (for a review of experimental and theoretical observations about vertical instabilities and their effects, see for example [2] and references therein). During Vertical Displacement Events (VDE), currents flowing through plasma and vacuum vessel are present. Such halo currents induce severe mechanical stresses that are a major concern for present and future fusion experiments.

The need of better understanding the origin, the distribution, and the scaling of halo currents is one of the critical points for the ITER project.

At present an international Halo Current Database has been built with data from JET, JT-60U, ASDEX-U, DIIID, C-MOD, COMPASS-D [3], and, more recently, MAST. Several issues on halo currents are still open, such as the upper bound of the maximum halo current that can be expected for an ITER class tokamak, and the detailed in-vessel distribution of halo currents. The existence of toroidally localized peaks (or “filaments”) of current was suggested by some measurements [4], and the detailed knowledge of their structure is needed to calculate the forces acting on the in-vessel structures. The main n=1 character of the in-vessel current asymmetry and its relation with the possible development of an m=1, n=1 “external” kink instability during the termination phase of a VDE are still the subject of MHD equilibrium and stability modeling [5]. Rotation of the halo current asymmetry is observed, but not on all machines, and in general non-rotating asymmetries are observed in larger machines [4, 2].

All those studies have an obvious impact in the definition of some design recommendations for ITER. In particular the improvement of the Halo Current Database and the understanding of the present scatter of the data were recommended. JET can play a key role in this study, provided that new and more detailed information became available. New JET data are essential to address the subjects of size scaling of the peak halo current, toroidal and poloidal asymmetries, and lateral mechanical loads.

2. THE MEASUREMENT SYSTEM

2.1 EXPERIMENTAL PURPOSES

The main characteristics of the halo currents can be identified on the following list:

- halo current scaling with plasma current;
- current density distribution and localization (width of the halo zone);
- poloidal and toroidal current asymmetries, their nature and correlation with other plasma parameters (e.g.
  filaments, correlation with kink instabilities).

In JET the halo currents features and correlation have been obtained by a set of toroidal pick up coils placed close to the vessel and the divertor, acting as partial rogowski coils, and through mushroom tiles placed in the external upper part of the vessel instrumented with shunts [6, 7, 8]. To increase the understanding of the phenomena a new set of halo probes, to be installed in the first wall, is envisaged.

In order to perform a complete analysis, sensors should be located in the places where the halo currents are more frequent, i.e. in the lower part (divertor zone) and upper part of the vessel.

The project hereinafter described deals only with the system of sensors placed behind some tiles fixed to a structure in the upper part of the vessel: the dumplate. Each tile in one poloidal section could be provided with a small rogowski coil. This will lead to instrument eight tiles in the dumplate with eight rogowski coils in the same toroidal position covering the whole poloidal extension of the dumplate. Four measurement sections are foreseen in four toroidal locations equally spaced along the vessel (figure 1); they could allow both a measurement redundancy and a better analysis of the halo current structure and the detection of its possible rotation.

2.2 IMPLEMENTED SOLUTION

A reduced measurement system has been proposed taking into account the constraints related to the management of all the diagnostics actually present or foreseeen in the experiment and to the requirements of mounting by means of Remote Handling system (RH).

The diagnostics will be installed at four octants (Fig. 1), each with a direct in-vessel conduit to route the wiring to a feedthrough available at the second inner upper port of the C rigid sector of the vessel. The system will include:

- 8 Rogowski coils and 1 or 2 toroidal field coils in octant 3;

- 8 Rogowski coils in octant 5;
- up to 6 Rogowski coils in octant 7;
- up to 6 Rogowski coils in octant 1.

The reduced number of the probes is due to the limited channels availability.

Each set of sensors (Fig.2) consists of: the rogowski coils, a base plate (supporting both the sensors and a conduit along the poloidal direction up to a RH plug), and the toroidal conduits (22.5 degrees long, going from the location of the sensors at the dump plate inter-octant gap to the feedthrough).

The base plate (1 mm thick of Inconel 600) will be fitted between the tiles, suitably encarved to house the coils, and the dump plate. The fixing systems of the tiles will provide therefore also the fixing of the base plate to the dump plate. The narrow room available at the inter-octant gap between dump plates (Fig. 3) will be fitted with the poloidal conduit and the transitions from Mineral Insulated Cables and fibre glass braid insulated cables (cfr. section 3).

The installation of such an assembly will require an ad hoc procedure and tooling for RH and the removal of the interested tiles, nevertheless no modifications on the fixed structures of the dumplates are necessary. The installation of RH sockets and toroidal conduits to the wall will require procedures similar to the ones adopted for other similar diagnostics already installed in JET [9].

3. TECHNICAL SOLUTIONS

3.1 SENSORS

A common specification for both current and toroidal field sensors is the operating temperature. The rear of the tiles is designed to support up to 700 °C; this is the worst condition and is assumed conservatively as a constraint for the design of all the sensors. Available space bounds the size of the sensors and consequently the amplitude of their output signals together with their signal to noise ratio.

Rogowski Coils have to be placed in order to concatenate the current flowing through each the considered tile of first wall. To obtain this, the tiles to be instrumented need to be modified to have a single electrical connection with their supporting structure, around which the rogowski coils will be placed. It corresponds to insulate by plasma spraying some well-identified points of contact from tile to structure. Impurity redeposition during experimental operation could cause this insulation to degrade slightly, but this should lead only to a small error in current measurement, as the current toroidal location of instrumented tiles in the dump plates available feedthrough and 22.5° conduit to be designed existing IUIWP instrumented tiles (shutdown 2001) will continue to flow mainly through the principal electrical connection.

The rogowski coils will be made by winding a special very thin (0.6 mm outer diameter) Mineral Insulated Cable (MIC) on a MACOR (machineable ceramic) support. Coils will be protected with an Inconel case; the case will act as an electric shield too. An external coil thickness of 10 mm (maybe less) can be obtained, and the sensor should withstand up to 900 °C, provided that it is not directly exposed to plasma, as it can be assumed in this application. The minimum winding section will be about 100 mm^2 , so relatively small signals will be produced by the coils.

A transition from MICs to more flexible copper wires is required from JET Operator, as usually foreseen for other magnetic probes. The presence of a transition box near each coil, in a region where large varying fields are present especially during disruptions, could introduce interference in the low level rogowski signals. A particular care is applied to the orientation of the unavoidable areas in the transition boxes so as to reduce the disturbance effect.

Properly oriented pick-up coils could be used to measure the toroidal field. They could be realized with the same rogowski coil technology. The probe position in this case can be chosen more freely with respect to the rogowski case, so larger probes are allowed, with a better signal-to-noise ratio.

3.2 MECHANICAL ANALYSIS ON TILES

As stated above the instrumented tiles has to be modified to well define the halo current path towards the vessel, furthermore a groove has to be realized to allow the installation of the rogowski coils behind the tiles (figure 4). This machining could significantly modify the stresses in the CFC tiles. A static electromechanical analysis is performed considering the maximum foreseen halo current flowing through the tiles. Two extreme cases are considered: the structure of the smaller instrumented tile, its structure is considered the weakest, after the machining; and the larger one, which could collect the larger current and presents the larger cantilevered portion. The analysis are been carried out both on the not modified tile and on the instrumented one. The obtained results have been compared.

A three dimensional Finite Element Model (FEM) have been developed with a relatively high number of elements and nodes (about 65000 and 90000 respectively). The model includes the tile excavated where the bolt and the groove are located. Each tile is attached to dump plate by means of a bolt, which is pulled down by the pre-load force of 3260 N applied by springs.

The analysis has been divided in two stages: firstly the distribution of the current density on the tile has been studied, then the results of the electrical calculation was post-processed to obtain the loads for the mechanical analysis.

The loads applied to the model for the electric analysis have been valued according to the following formula [10]:

$$I_h = I_{p0} \,.\, f \,.\, TPF \cdot \frac{w_{tor}}{2.\pi.R} \cdot \frac{w_{pol}}{w_{halo}}$$

where I_{p0} is the conservative plasma current, R is the distance of the component from the centre of the machine, w_{pol} and w_{tor} are the poloidal and toroidal width of the component wetted by the halo current, w_{halo} is the typical poloidal width of the halo footprint, TPF is the Toroidal Peak Factor and f is the ratio average poloidal halo current to initial plasma current.

According to this estimate, the total current applied to the model on the upper face of the tile exposed to the plasma is 33 kA for the smaller tile and 48 kA for the larger one.

Then the loads for the structural analysis are evaluated by taking into account the interaction between the current density and the magnetic field on the single element. Finally the obtained forces are distributed on each node of the model. The applied component of the magnetic field is supposed to be: 4 T toroidally, 1.2 T poloidally and 0.4 T radially.

The distribution of the halo current and the considered field cause the loads both is pushing the tile downward, by the pre-load force, and rotating it clockwise.

The maximum amplitude of the stresses for the tiles without and with groove are summarized in table 1 where σx, σz and σy are the stresses in the poloidal and toroidal and radial direction respectively, while σ1 and σ3 are the principal tensile and compressive stress. These stresses are localized along the thread of the bush, cannot be adequately represented in this FE model without increasing enormously the number of the elements. Nevertheless the results can be considered satisfactory because they have to be valuated comparing the stress amplitudes of the not modified tile with those ones of the instrumented tile. The analysis show as the smaller tile is not affected by the presence of the groove, on the contrary the stresses seem to decrease because of a different distribution of the halo current, while in the cantilevered tile the stresses increase slightly (table 1).

	Small tile		*cantilevered tile*	
	Tile without groove (MPa)	*Tile with groove (MPa)*	*Tile without groove (MPa)*	*Tile with groove (MPa)*
σ*1*	*11.4*	*10.6*	*10.3*	*11.6*
σ*3*	*1.9*	*1.9*	*1.4*	*1.9*
σ*x*	*11.1*	*10.3*	*9.1*	*10.7*
σ*y*	*7.7*	*6.2*	*6.4*	*8.3*
σ*z*	*4.6*	*4.5*	*4.9*	*4.4*

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Table 1: Distribution of the stresses on the tiles.

The analysis results allow to continue the project by a good safety margin but mechanical tests on prototypes will be done to confirm them.

4. CONCLUSIONS

The designed system is placed in an important location inside the vessel, it should allow a more detailed study of the distribution of the halo current during vertical instabilities moving upward. It could be considered a significant improvement of the present diagnostic dedicated to the halo current study allowing a limited, but considerable, increased resolution both along the poloidal and toroidal directions. Its use, together with the already installed and still operative rogowski coils, toroidal field probes and shunts, should bring to a better understanding of the halo current phenomenon in JET and should allow a better definition of the ITER operating conditions.

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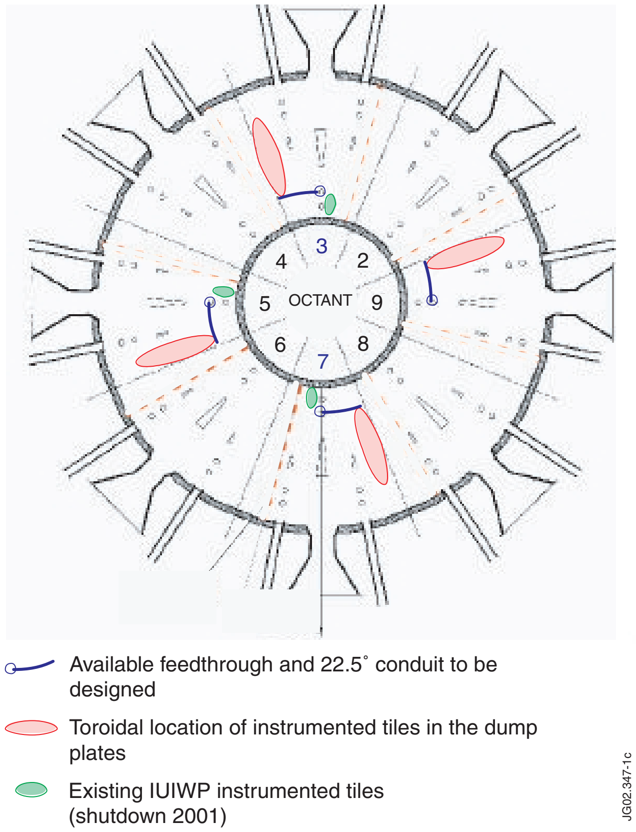

Fig. 1: Toroidal location of the 4 proposed set of halo sensors.

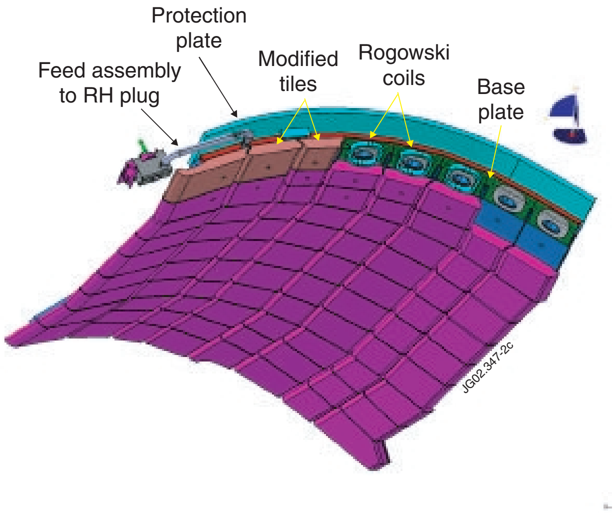

Fig. 2: Set of halo sensors at one octant.

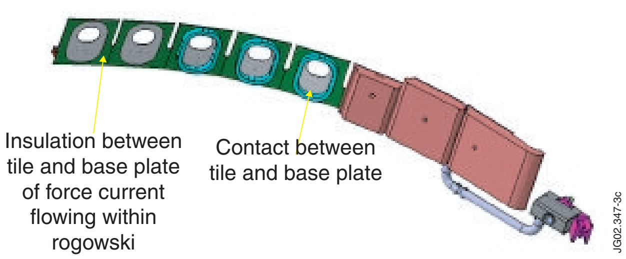

Fig. 3: Structure of the sensor assembly.

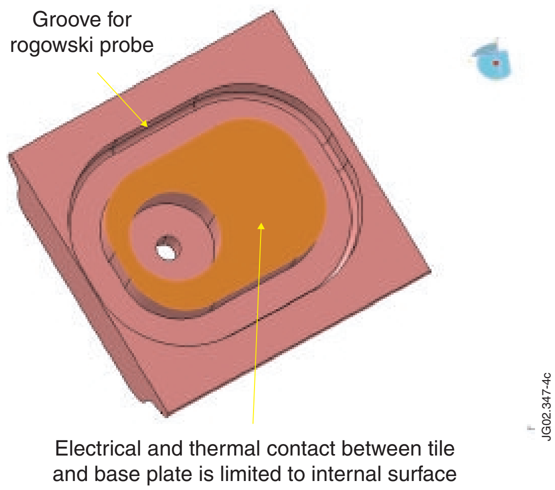

Fig.4: Example of modified tile.