Electromagnetic Model of Plasma Breakdown in the JET Tokamak

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* See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, US.

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***Abstract*— This paper deals with the electromagnetic modeling of the plasma current breakdown phase of the JET Tokamak. The first part of the work is devoted to model the presence of the JET iron core up-down asymmetry and the effects of the eddy currents in the reconstruction of the magnetic topology needed for the plasma start. The second part describes the approach used to evaluate the ionized particle connection length inside the vacuum chamber at breakdown. The results obtained were validated using experimental measurements and JET fast camera recordings.**

***Index Terms*— Tokamak, plasma confinement, electric breakdown, electromagnetic modeling.**

I. Introduction

Nuclear fusion is one of the most promising research fields that could help to answer to the increasing demand of energy. In a fusion reaction, light atomic nuclei fuse together to form heavier ones releasing a large amount of kinetic energy, which is the energy source of the sun and the stars. The main requirement to obtain a nuclear fusion reaction is to confine a plasma (ionized gas) at very high temperatures, of the order of ~10^8 K. The most promising device for magnetic confinement is the Tokamak [1], a machine where the plasma is confined in a toroidal vacuum vessel and kept away from the solid walls by applied magnetic fields. The plasma formation is achieved in a tokamak by a Townsend avalanche, which consist in the ionization of a gas, present in the toroidal vacuum chamber at a pressure P, by applying a toroidal electric field E. The electric field E is provided by the variation of the poloidal field current in the central solenoid. Its magnitude is of the order of 1 V/m in the present fusion devices, while in the design of future devices it will be limited to lower values, as for instance in ITER, where the initial electric field will be ~ 0.3V/m [2]. The ionization length λ_i for deuterium in the range E/P of interest is well represented by the eq. (19) in [3]:

$$\lambda_i[m] = (a/P)\cdot \exp(b\cdot P/E) \qquad (1)$$

with $a = 2\times 10^{-3}\, m\cdot torr$

and $b = 1.3\times 10^{4}\, V\cdot m^{-1}\cdot torr^{-1}$.

In order to obtain a successful breakdown it is necessary to maximize the ionizing particles connection length L_c, defined as the particle trajectory covered in the toroidal direction before they hit the vacuum chamber wall:

$$L_c = \frac{1}{4}\frac{a_{null}\, B_\Phi}{< B_z >}, \qquad (2)$$

where B_Φ is the toroidal magnetic field, and a_{null} is the poloidal magnetic field null region dimension with average field B_z. To obtain a successful breakdown it is necessary to reach a ratio $L_c / \lambda_i >> 1$.

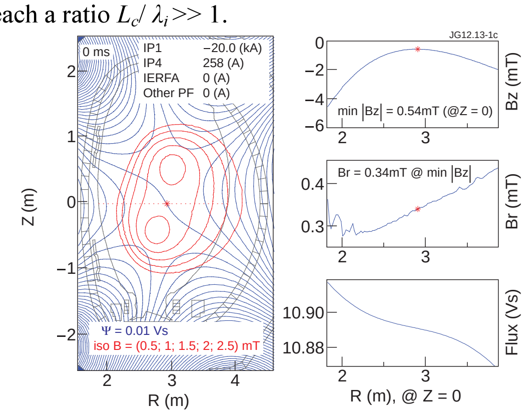

Fig. 1. Static equilibrium reconstruction of the magnetic topology for a JET breakdown configuration with prescribed primary (IP1) and vertical (IP4) circuit currents.

II. Electromagnetic Model of JET

The electromagnetic model used for the breakdown analysis includes an equivalent 2-D axisymmetric model of iron core, the poloidal field (PF) circuits, and conducting structures with 3-D corrections [4]. The model of the JET Iron used takes into account the presence of a gap only in the upper magnetic circuit, leading to a presence of radial field appearing in the static analysis with only symmetric circuits excited [5]-[6]. The conducting structures in the model are: vacuum vessel, restraint rings, mechanical structure and divertor supporting structure. The three poloidal field circuits used at JET during the breakdown phase are: the primary (IP1), the vertical field (IP4), and the radial field (IERFA). The Fig. 1 represents a static reconstruction of the magnetic topology at JET during the breakdown. Several dynamic simulations were run to evaluate the effect of the eddy currents flowing in the passive structures and the electric field produced at breakdown by the poloidal field circuits current variations (Fig. 2).

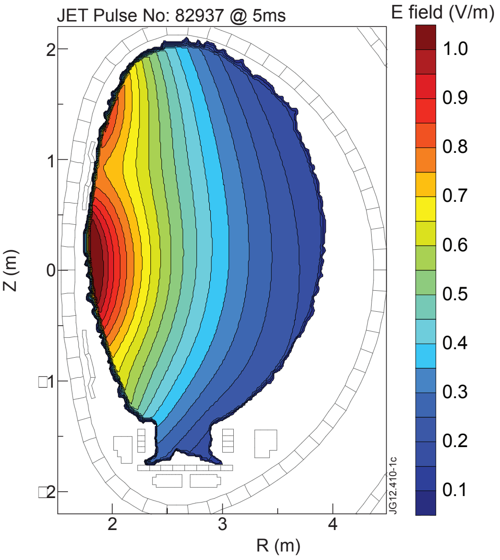

Fig. 2. Electric field reconstruction evaluated by taking into account the effect of the eddy currents, during the JET breakdown for the pulse #82937.

III. STREAMLINE COMPUTATION TECHNIQUES

A field-line-following analysis was performed to study the characteristics of actual complex magnetic field configurations, including the stray magnetic fields in the JET tokamak, to predict the ionizing particle trajectories at breakdown. Streamlines of a vector field are a family of geometric curves that are tangent everywhere to the vector field itself. The streamline can be evaluated by numerical integration of the field in the space:

$$\frac{\partial R}{\partial \Phi} = R \cdot \frac{B_R}{B_\Phi}; \quad \frac{\partial Z}{\partial \Phi} = R \cdot \frac{B_Z}{B_\Phi}; \tag{3}$$

where Φ represents the toroidal angle and (R, Φ, Z) represent the cylindrical coordinates. As for the codes simulating the incompressible fluid flow, it is important to use numerical integration techniques which preserve the volume [7]-[8] and interpolation schemes that preserve the solenoidal properties of the field in the streamline computation on a discrete grid of points. This is particularly relevant if the integration trajectory is very long where non preserving volume techniques may give rise to trajectories converging in fixed points and other phenomena not possible in a solenoidal field. The volume preserving is defined by the capability of the integration technique to keep constant a chosen volume unit over the integration lines of a generic field. This condition can be expressed mathematically by considering a generic divergence-free ordinary differential equation:

$$dx/dt = f(x), \quad (\nabla \cdot f = 0) \tag{4}$$

The integrator is volume preserving if $\det(\partial \psi_{\tau,i} / \partial x_j) = 1$, where $\partial \psi_{\tau,i} / \partial x_j$ represents the Jacobian of the flux. A sensitivity analysis on the streamline calculation error was carried out to evaluate the influence of the time step resolution and the integration degree order by using the explicit and implicit Euler and Runge-Kutta integration methods. The result took into account also the computational time over the precision required, due to the model uncertainties. In the Fig. 3 is represented the connection length map obtained for a typical magnetic configuration during the breakdown at JET, for positive and negative toroidal direction Φ.

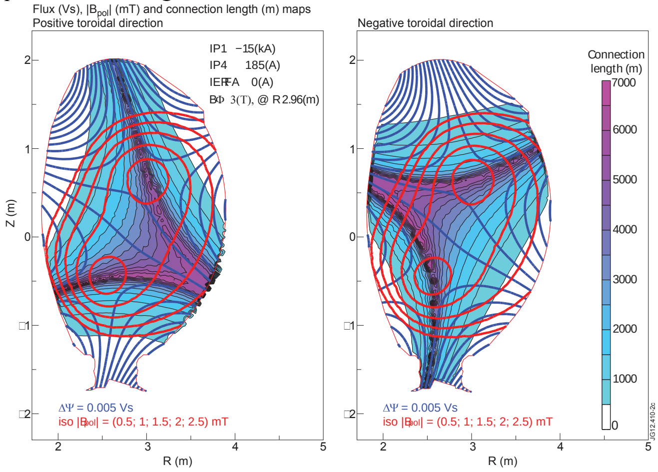

Fig. 3. Connection length maps calculated using a static reconstruction of the JET flux-map at breakdown.

IV. CONCLUSIONS

This paper presents the electromagnetic modeling of the plasma current breakdown phase of the JET Tokamak, including static and dynamic reconstructions of the flux-map. The simulation of the electric field was used to calculate the ionization length. A streamline computation technique was used to evaluate the ionizing particle connection length during the plasma breakdown. Currently a volume preserving technique is being implemented for the streamline calculation and will be used to benchmark the Runge-Kutta method.

V. ACKNOWLEDGMENTS

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Response to referees

We would like to thank the reviewers for their report and suggestions. We will try to give in the body of this file a point to point response, marked in blue.

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CONTRIBUTION DETAILS
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ID: 708
Title: Electromagnetic model of plasma breakdown in the JET tokamak


REVIEW RESULT OF THE PROGRAM COMMITTEE:
This contribution has been accepted.


OVERVIEW OF REVIEWS
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Review 1

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Contribution of the submission
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This paper deals with the electromagnetic modeling of the plasma current
breakdown phase of the JET tokamak.

The method used relies on streamlines computation, taking care of volume
preservation


Evaluation of the contribution
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Quality of Content          (10%): 8
Significance                (10%): 8
Originality                 (10%): 6
Thematic Relevance          (10%): 8
Presentation                (10%): 8
Overall Recommendation      (50%): 9
Total points (out of 100)        : 83


Comments for the authors
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This paper presents a numerical approach which is important in the case dealt
with but also in many other situations. As far as we can consider by reading
the short version of the paper, the approach proposed seems original and needs
to be further developed in an extended version
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Thank you for your comment, we will describe the details of the numerical simulation and the development in the full 4 page paper, as suggested.

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Review 2

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Contribution of the submission

The paper describes the plasma breakdown phase of the Tokamak fusion reactor, in which the chamber of the reactor is filled with a fully ionized plasma. Static numerical simulations of the magnetic fields and dynamic numerical simulations of the electric field, including the effect of eddy-currents in the structural components, are presented.
Furthermore, streamline computations to assess the ion trajectories in the chamber are proposed.

Evaluation of the contribution

Quality of Content	(10%):	8
Significance	(10%):	8
Originality	(10%):	6
Thematic Relevance	(10%):	8
Presentation	(10%):	4
Overall Recommendation	(50%):	7
Total points (out of 100)	:	69

Comments for the authors

The topic of the submission fits well into the aim of the conference. It is interesting to read, although not many details on the applied simulation algorithms and methodolgy are provided. More details should be provided in the conference presentation and the corresponding full paper.

Please revise the units of the variables in equation (1). The righthand-side must be [m]. The argument of the exponential function must be dimensionless.
We modified the equation as it is in the eq (19) of the cited article [3].
Please cross-check units also in equation (3).
We corrected the text that describe the equation.

I would propose to present the results of the sensitivity analysis of the streamline computations, particularely considering your requirement to apply a highly-accurate time integration algorithm.
We have added some details of the sensitivity analysis performed for the specific case, indicating the criteria which were set to choose the integration method. We will give more details both in the presentation and in the full paper.

The paper is written in clear language. However, I propose the following editorial changes:
- Correct usage of small/capital letters in the title.
Corrected according to the provided template.
- Cross-check if the list of authors complies to IEEE publication requirements (the review version contains a reference to a proceedings paper).
This is settled with the editor in the agreement for publication of JET data, and it is a requirement from our laboratory.
- Correct the reference section: the titles of the publications need to be stated for each reference.
Corrected.
Please refer to the template files provided on the webpage of the COMPUMAG conference.

Furthermore, I propose to provide more explanation on relevant details of the JET in the full paper (relevant w.r.t. to the presented numerical simulations).
We agree.
Thank you for your comments.-=-=-=-=-=-=-=-=-=-=-