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ABSTRACT

This paper presents the breakdown studies carried out in the framework of JET Enhancement Projects for Plasma Control Upgrade (PCU) and Enhanced Radial Field Amplifier (ERFA), to obtain plasma formation with different sets of coil turns in the radial field circuit. The electromagnetic conditions to reach the plasma breakdown in the JET machine are strongly dependent on the properties of JET iron core and the effects of the eddy currents driven by the transient electric field on the present passive structures. The study has been carried out by using a linearized dynamic model of JET provided by 2D axisymmetric finite element code CREATE-L. The dynamic simulations have been compared with the experimental data. A new fast visible camera has been installed and has been used for the first time at JET for studies of plasma breakdown. The images show, coherently with the model, that the avalanche evolves dynamically towards a region where the stray field is perpendicular to the first wall.

1. INTRODUCTION

The plasma formation is obtained in a tokamak fusion device from an electric breakdown of gas in a toroidal vacuum chamber. It has been known for many years that it is necessary to make a hexapolar magnetic field null on JET tokamak to meet the conditions for Townsend avalanche (electric field and gas pressure). The electromagnetic conditions to obtain plasma breakdown in JET are strongly dependent on the properties of the iron core and the effects of the eddy currents driven by the transient electric field on the present passive structures.

This paper presents the breakdown studies, carried out in the framework of JET Enhancement Projects for Plasma Control Upgrade (EP-PCU) and Enhanced Radial Field Amplifier (ERFA), to obtain plasma formation with different sets of coil turns in the radial field circuit. The study has been carried out by using a linearized dynamic model of JET provided by 2D axisymmetric finite element code CREATE-L [1]. In the first section of this paper the JET machine modeling activity is presented. The second part of this paper is devoted to the static and dynamic electromagnetic analysis of JET breakdown conditions in order to evaluate the sensitivity of reconstructed magnetic flux map to the currents in the poloidal field (PF) circuits and to take into account the effects of the eddy currents in the passive structure. The results of the model reconstruction, obtained during the experimental commissioning of the new ERFA system [2-3], will be presented in the last part of the paper and will be compared with the recordings of the new JET fast visible camera [4], used for the first time during the plasma breakdown phases.

2. JET ELECTROMAGNETIC MODELING

The electromagnetic model used for the breakdown analysis includes an equivalent 2-D axisymmetric model of iron core, poloidal field (PF) circuits, and conducting structures with 3-D corrections [5]. The model of the JET Iron used takes into account the actual presence of a 3 mm gap in the magnetic circuit located at the vertical position $z = 4.45\ m$, and not *at* $z=-4.45\ m$, leading to a presence of radial field appearing in the static analysis with only symmetric circuits excited. The conducting structures

included in the model are: Vacuum Vessel (VV), Restraint Rings (RR), Mechanical Structure (MS) and divertor supporting structure Mark 2 (MK2). The MK2 structure, the only up-down asymmetric element considered in the model, plays a fundamental influence on the field null position during the breakdown phase. The resistivity value of MS has been refined via a best fit of the simulations with the experimental data. The overall resistivity of the whole MK2, composed by the base plate plus two vertical elements, and of the VV and RR are in agreement with [6]. The circuit equations are coupled to electromagnetic and Magneto-Hydro-Dynamic (MHD) equations, in order to take into account the plasma presence, via Finite-Element Method (FEM) using the CREATE-L perturbed equilibrium approach [1]. A dynamic state space model is obtained by solving and linearizing the non linear problem around the equilibrium point. The model is manipulated via change of state variables in order to use the PF circuit currents, I_{PF}, as driving inputs. The equations of the model are hereafter reported:

$$\begin{cases} \dot{\phi}_e = A_{\varphi e}\,\phi_e + B_{\varphi e}\,I_{PF}; \\ y = C_{\varphi e}\,\phi_e + D_{\varphi e}\,I_{PF}. \end{cases} \tag{1}$$

The unknowns of the model are the currents and the poloidal magnetic flux y, the state variables are the fluxes linked with the conducting structures Φ_e, while $A_{\Phi e}$, $B_{\Phi e}$, $C_{\Phi e}$, $D_{\Phi e}$ are the new state space dynamic matrices. A number of models have been evaluated for the different proposed ERFA system configuration, with a different number of coil turns, denoted at JET as P2R and P3R, connected to the vertical stabilization system amplifier. A subset of configuration has been chosen, based on theoretical and modeling analyses, for testing during the experimental commissioning with the new amplifier [3] with the following *P2RU-P3RU-P2RL-P3RL* (U=upper, L=lower) coil configurations and inductance [7]:

1: *standard* configuration *16-20-16-20 (≈20mH)*;
2: *reduced* configuration *8-20-8-20 (≈12mH)*;
3: *asymmetric* configuration *16-20-8-2 (≈10mH)*.

3. STATIC ELECTROMAGNETIC RECONSTRUCTION

Preliminarily static electromagnetic reconstructions have been carried out on the sensitivity of the model to the PF coil currents. The attention has been focused on the three circuit currents used at JET during the breakdown, named IPRIM (primary), IP4T (vertical field) and IFRFA (fast radial field) (suffix I=current). The latter is used during breakdown after 39.99s to compensate the radial field produced by the passive currents flowing in the MK2 structure via a feedback control that takes into account a proportional factor named Base Plate Proportionality (BPP). A sensitivity analysis is carried out showing the dependence of the variation of current in the poloidal field system on the set of 18 Internal Discrete Coils (IDC) and on the flux map reconstructions. Different effects of the field null position using several breakdown recipes have been evaluated, for instance required P4T circuit current value for the static vertical field (Fig.1). It has been also evaluated for the first time

the radial field due to the presence in the magnetic circuit of a 3mm gap located at z = 4.45m, and not at z=-4.45 m. This contribution is included in the model static analysis with only symmetric circuits excited and its magnitude is of the order of ≈0.2 mT in standard operational condition. The static flux maps have compared with other equilibrium code such as Proteus [8] finding a fair agreement, within the models difference limits (i.e. different iron model). An estimation of the residual magnetization on the 18 IDC has been assessed for a plasmaless experiment, with no TF coils energized. The inductive discrete coil integrators are set to zero at JET when the iron is partially magnetized. The relations that link the jth ΔI_{PFexp} experimental currents to the kth IDC $\Delta Bpol$ with the equilibrium value $Bpol_{eq}$ have been used :

$$Bpol_{eq,k} = Bpol_{mag,k} + \sum_{j=1}^{num\,PF} I_{PF\,exp,\,j} \cdot \frac{\Delta Bpol_k}{\Delta I_{PFj}}$$

Solving the term $Bpol_{mag,k}$ it is possible to estimate the residual magnetization for each IDC. The values are in the range of 0.1÷1 mT for the iron completely saturated and the up-down asymmetry is due to a gap in the upper part of the magnetic circuit.

4. DYNAMIC ELECTROMAGNETIC RECONSTRUCTION

The dynamic reconstructions have been implemented by driving the CREATE-L (1) plasmaless model with the current of the PF circuits used at JET during the breakdown phase, described in section 3. A number of models have been produced and used for several breakdown configuration simulations, such as different primary circuit pre-magnetization, influencing the iron magnetization, and coil turn configurations for the radial field circuit, such as the subset of standard, reduced and asymmetric configurations, presented in the section 2. The simulation output considered were: a set of desired magnetic coils (typically the 18 IDC), the eddy currents flowing in the passive structures, and the flux-map.

4.1 MAGNETIC COIL RECONSTRUCTION

The simulation of the 18 IDC are in fair agreements with the experimental measurements, also in reproducing qualitatively the effect of eddy currents influence on the probes during fast transients, with a quantitative discrepancy on some sensors up to a factor ≈2 on some IDC (i.e. number 8 and 11). Imprecise Toroidal Field (TF) compensation has been observed for some IDC, and in particular on those coils number 8 and 11 up to few mT, comparing the experimental measurements of pulses with and without TF currents.

4.2 EDDY CURRENT RECONSTRUCTION

The dynamic simulations of the JET full flux loop voltage FLD3 are in good agreement with the experimental signal (Fig.2). This probe is sensitive to the eddy currents flowing in the nearby MK2 structure. This measurement, divided by a number that takes into account the MK2 resistivity, is used in a feedback scheme by the control system, via the FRFA circuit and the proportional factor

BPP described in section 3, during the breakdown phases in order to counteract the effect of MK2 passive current on the field null position. The effect of the other conducting structure passive currents, namely RR, VV and MS, on the magnetic measurements has been simulated in order to benchmark the model predictions (i.e. the influence on the magnetic measurements IDC described in 3.1).

4.3 FLUX MAP RECONSTRUCTION

A procedure to obtain a JET equilibrium flux-map by taking in account the contribution of the currents flowing in the passive structures, using the CREATE-L model, has been realized and tested. Different reconstructions have been carried out with several breakdown recipes, as for instance the influence of different vertical field current (IP4T) slopes on the field null radial position. This has been done also to take into account the control delay in answering to the pre-programmed current slope. An important part of the analysis have been computed by including in the dynamic simulation the new Enhanced Radial Field Amplifier (ERFA) voltage limits, raised from 10kV to 12kV [2], and the three combination of coil turns, mentioned in section 2, to be used during experimental commissioning. In this activity, the field penetration inside the chamber in breakdown conditions has been evaluated, i.e. other PF circuit currents set to zero, after 2ms when a step of 12kV of the ERFA circuit is applied. The field configurations inside the vessel are very similar for the standard and reduced turns (up-down symmetric) apart from a scale factor. Outside the vessel the field is different. For the up-down asymmetric turns the main effect is the generation of an additional vertical field (Fig. 3).

5. FAST VISIBLE CAMERA

A new fast visible camera has been installed at JET and has been used for the first time for studies of plasma breakdown. The camera acquisition rate spans from 50 to 250000 frames/s, with a maximum resolution of 1000×1000 pixels and operates in the spectrum of visible light. Some tuning activity has been carried out for a number of experimental pulses in order to setup the new condition for the breakdown. The frame rate has been set to 500 frame/sec, which is fast enough for breakdown studies and permits exposure times adequate for the low light conditions of the preliminary plasma formation phase. The optical system used for these recordings casted an image size on the detector of around 300×300 pixels for the whole half-torus, providing a spatial resolution of about 1cm/pixel.

6. RESULTS OF EXPERIMENTAL BREAKDOWN RECONSTRUCTIONS

During the commissioning of the ERFA system some experimental session has been dedicated to the plasma breakdown. Several breakdown recipes, with different slopes of P4T current rise, pre-magnetization, base plate proportionality, have been run for the different chosen coil configurations. The dynamic flux maps do not take into account the plasma current (in any case small) contribution. The comparison of the simulations with all the camera recordings are in good agreement for different breakdown configurations. The new images show that the ionization cloud appears after the model suggests that the initial transient hexapole null has been superseded by two quadrupole nulls.

In these conditions the inboard null could well be preferred for plasma formation for the higher electrical field and shorter path of the ionized particles. It is suggested that the avalanche evolves dynamically towards a region that leans on the part of the first wall where the angle between the force on the plasma and the normal unit vector is larger than 90 deg (fig.4).

In the poloidal plane such a region is delimited by the points where the stray field is perpendicular to the first wall. From the new camera recordings is possible to see that the plasma is then pushed down in the divertor region, presumably by the radial field produced by the current flowing in the passive structures, of the same sign of the plasma current, and then, for a successful breakdown, it comes up toward the outer wall (Fig. 5). .

CONCLUSIONS

This paper presents the breakdown studies carried out in the framework of the JET PCU and ERFA Enhancement Project and optimized the turns chosen on the four coils of the radial field coils of JET. A modeling activity has been carried out using a refined CREATE L state space model in order to analyze the electromagnetic conditions of JET breakdown including the impact of the new radial field system. The model has been used to make predictions of the required static and dynamic vertical field and radial field bias required for breakdown. This work identified for the first time the radial field due to the up-down asymmetric gaps in the iron core and the relative influence on the field null. An estimation of the iron magnetization effect on the induction coil measurement has been evaluated. The reconstructions have been positively compared with the experimental evolution of the field and passive currents estimations signals being able to follow the dynamics of the first few ms during the plasma formation. The dynamic flux map reconstructions have been positively compared with the new fast visible camera recordings, used for the first time at JET during the breakdown, showing that it is possible to reliably predict and in principle optimize the region of plasma formation. The images show, in agreement with the model, that the avalanche evolves dynamically towards a region where the stray field is perpendicular to the first wall.

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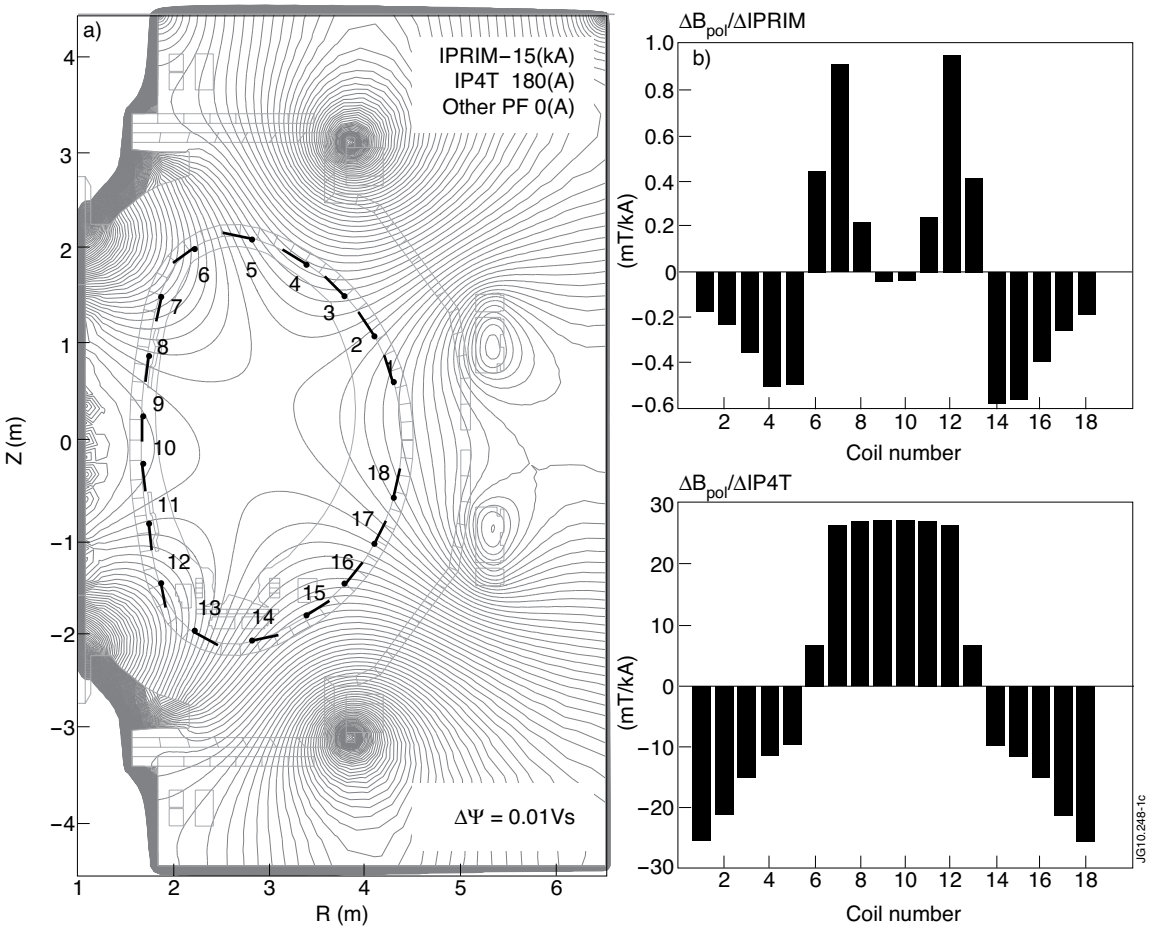

Figure 1(a) Flux map static reconstruction for a prescribed pre-magnetization current IPRIM and vertical circuits IP4T. In the images are also indicated the position and orientation of the up-down symmetric 18 IDC. (b) Sensitivity of the primary and vertical circuit on the 18 IDC, named Bpol. It is possible to notice the presence of a radial field due to the presence of a gap in the magnetic circuits with only PF symmetric circuits excited.

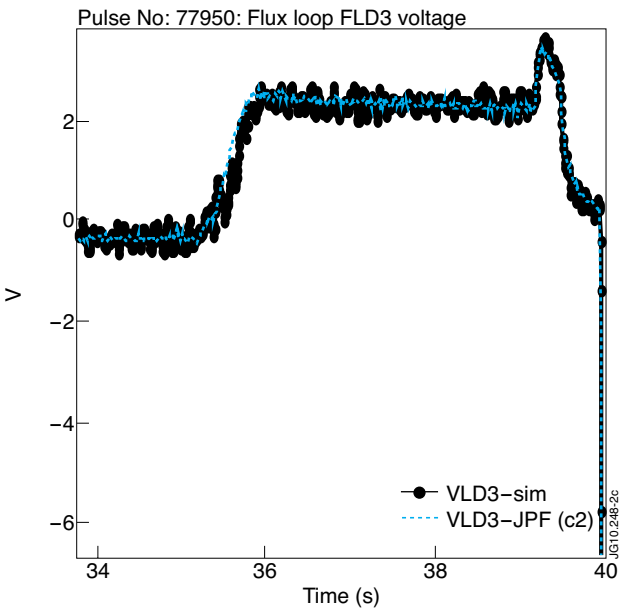

Figure 2: JET Pulse No: 77950. The comparison of the simulated and experimental voltage of full flux loop FLD3 (JET database signal jpf/77950/da/c2-vld3) results in a good agreement in the time range of interest (from 33s, TF current rump up, up to 40.02s plasma formation). This signal is used at JET by the control system in order to counteract the radial field produced by the eddy currents flowing in the MK2 structures during breakdown phase.

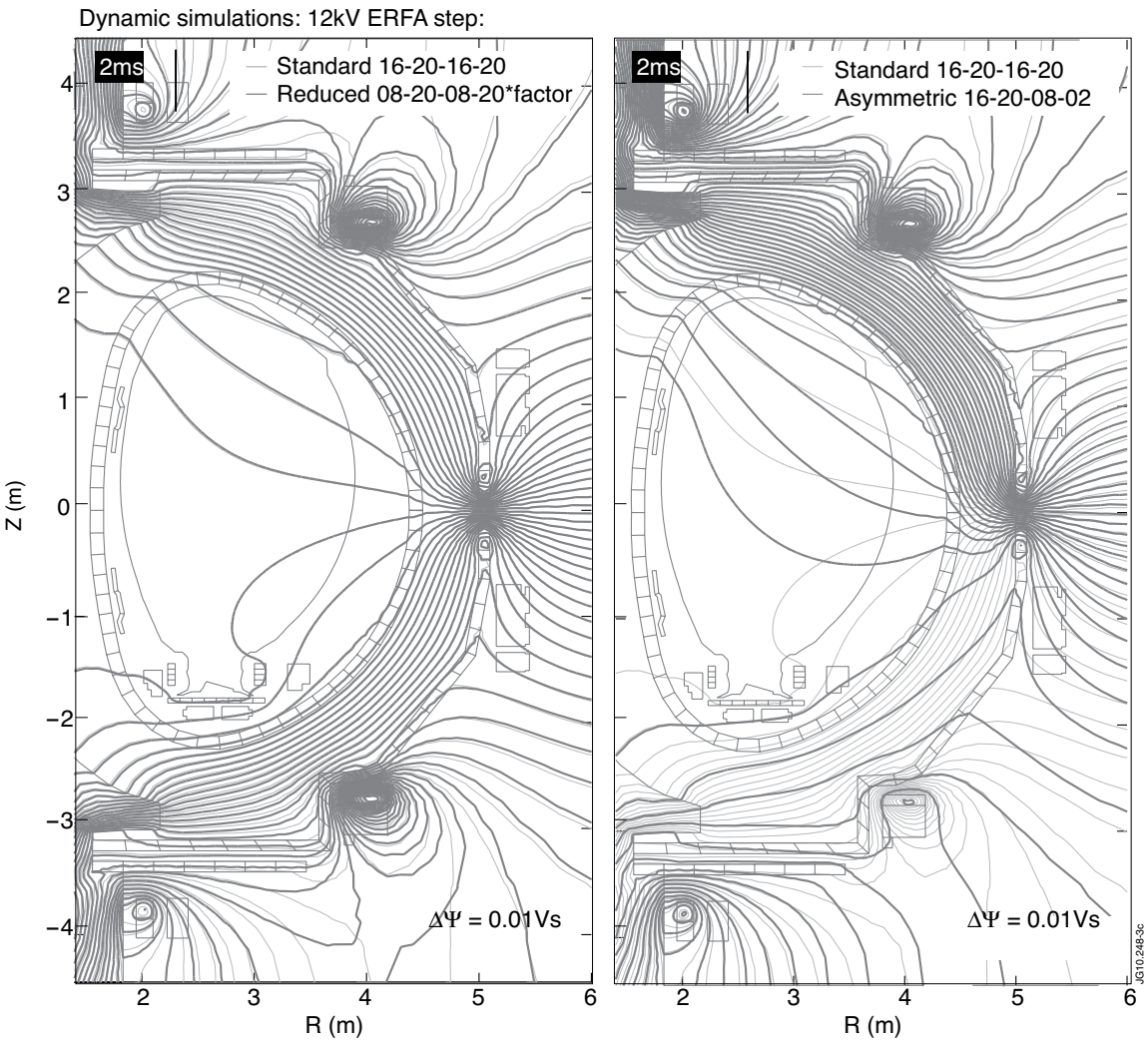

Figure 3: Simulation using as input a step of 12kV on ERFA circuits and evaluating the flux penetration after 2ms. For the reduced configuration a scale factor is sufficient to obtain field paths equivalent to the standard one inside the chamber, while is possible to notice the different magnetic topology outside the vessel. For the asymmetric option a further vertical field correction is needed.

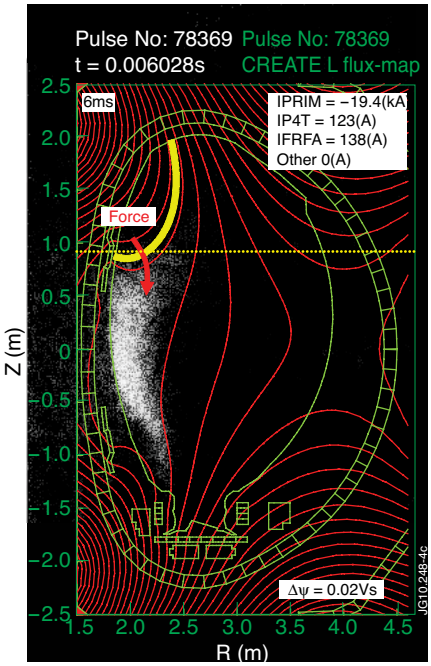

Figure 4: Comparison between the dynamic flux map reconstructions at 40.006s with the first available camera recording at the same instant for the JET Pulse No: 78369. The plasma is pushed against the internal wall and included in the region where $B_{tg} = 0$.

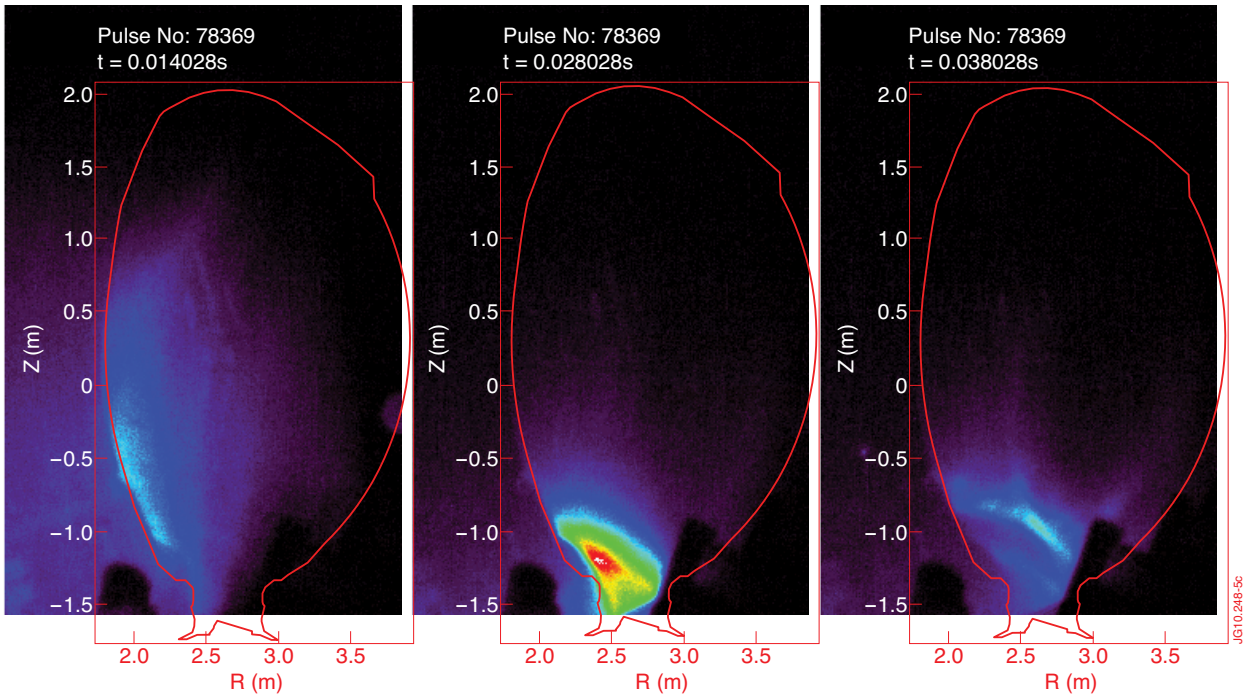

Figure 5: Camera recording for the JET Pulse No: 78369. The ionization cloud appears against the inner wall and then is presumably pushed down in the divertor region by the radial field produced by the current in the passive structures. Finally, for a successful breakdown, the plasma should be pushed up toward the outer wall.