Plasma start-up in the TCV tokamak

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In this paper, we (1) present the inductive plasma start-up in the TCV tokamak, (2) investigate the importance of the poloidal magnetic field configuration at the ionization time and (3) show the recent results on electron cyclotron heating (ECH) assisted breakdown with second harmonic.

During the inductive plasma start-up, a population of free electron is accelerated by the toroidal electric field induced by the ohmic coils. Neutral particles are ionized by impact ionization and the number of free electrons increases. An avalanche mechanism is triggered until the gas is fully ionized.

Fig. 1 shows time evolution of a typical TCV inductive plasma start-up. The neutral gas ionization occurs when the toroidal electric voltage reaches ~ 10 V (Fig. 1(b)), corresponding to an electric field of ~ 3V/m. The ionization phase is well detected by the H_α detector signal shown in Fig. 1(c). During the ionization phase, the magnetic field lines are open and the accelerated electrons are mainly lost along the magnetic field lines. When the magnetic field produced by the plasma current is high enough, a closed magnetic field line configuration is established and the plasma ramp-up phase starts. The transition between the two phases can be deduced from Fig. 1(d), where the signal from a Langmuir probe located at the low field side (LFS) of TCV is shown. During the ionization phase the open magnetic field lines intersect that probe and an increase of the ionic saturation current

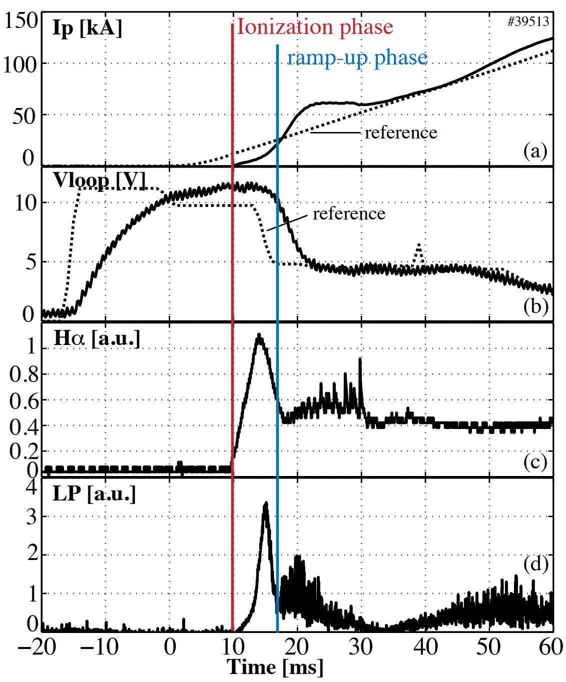

Figure 1: Breakdown scenario: temporal evolution of (a) plasma current, (b) toroidal electric voltage, (c) H_α signal from the top of TCV and (d) ion saturation current from a Langmuir probe located at the LFS of TCV.

is observed. When the ramp-up phase starts, no plasma can directly reach that region and the saturation current drops.

In the TCV tokamak, the flexibility given by the 16 independent poloidal field coils (PFC) provides the capability to generate a wide range of magnetic field configurations at the ionization time. The magnetic field given by the current induced in the vacuum vessel (larger than 200 kA) is compensated and a poloidal magnetic field quadruple (null-point) is created inside the vacuum vessel. The magnetic properties of the null-point impact the early breakdown dynamic. A magnetic field reconstruction is used to estimate the magnetic field inside the vacuum vessel. To that purpose, the currents in the system (PFC, vessel currents modeled with 38 toroidally symmetric filaments) and their current derivatives are fitted to optimally reproduce the measured magnetic field and poloidal flux. Each measurement is weighted according to its uncertainty [2] .

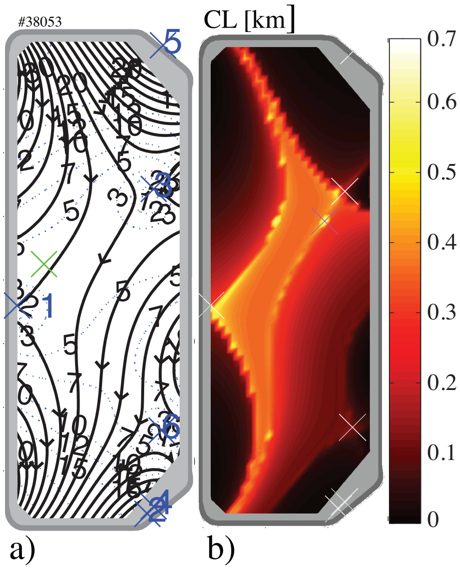

Figure 2: (a) Magnetic field reconstruction and (b) connection length at the ionization time for a typical TCV breakdown.

An example of a magnetic field reconstruction for a typical TCV breakdown in given in Fig. 2. The green cross in Fig. 2(a) represents the preprogrammed breakdown position. The solid curves are flux surfaces and the dashed curves show the magnetic field amplitude. The blue crosses represent the position of the null-points. In the null-point region, the poloidal magnetic field is smaller than 1 mT and its location and shape depend on the individual discharge. Fig. 2(b) shows the spatial distribution of the connection length between intersections with walls for the same breakdown configuration. The connection length is larger in the null point regions, where the poloidal magnetic field vanishes.

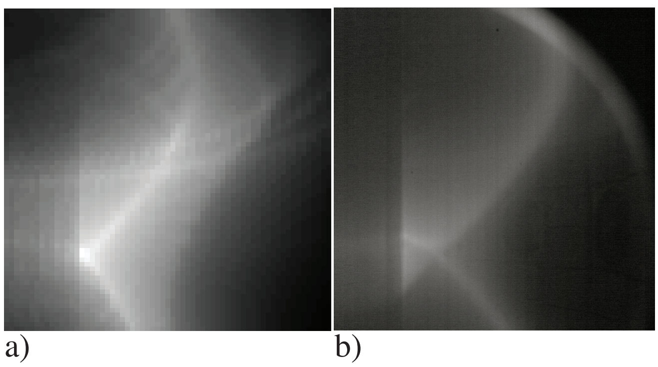

Figure 3: (a) 3D visualization of the connection length distribution at the breakdown time (t = 5.2ms) and (b) frame from the fast tangential visible camera at t = 7ms (shot #38053).

The magnetic field reconstruction can be visualized with with a fast tangential visible camera installed on TCV. Fig. 3(b) shows a frame recorded at the breakdown time of the shot in Fig. 2. In

Fig. 3(a) the image of a virtual camera positioned and oriented as is the fast visible camera with a light source proportional to the connection length is represented. The good agreement between the two images validates the magnetic field reconstruction. The ramp-up phase is studied adding a single toroidal filament model of the plasma current. At each time step the filament position giving the best fit is obtained. In general, the following behavior is observed: the plasma current starts close to the null point with the longer connection length and then moves towards the pre-programmed plasma position.

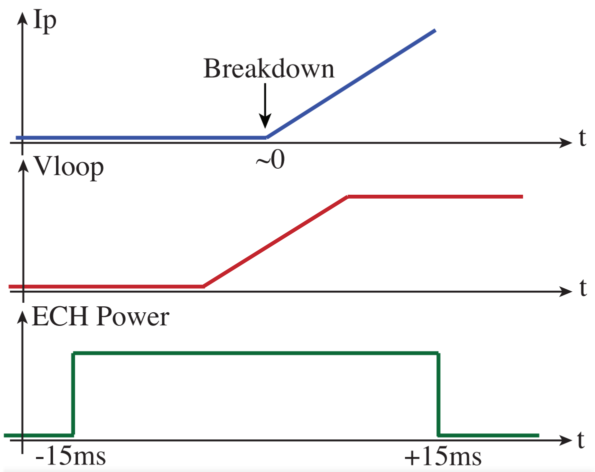

Figure 4: ECH assisted breakdown scenario.

A statistical analysis based on the the magnetic properties at the breakdown time has been done collecting data from about 20000 shots. For each shot, the null points at the breakdown time are automatically detected and the matrix of the magnetic field derivatives is computed at these points:

$$\nabla \mathbf{b} = \begin{pmatrix} \partial_R b_R & \partial_Z b_R \\ \partial_R b_Z & \partial_Z b_Z \end{pmatrix} \tag{1}$$

The size of the magnetic field null is defined as:

$$\rho[\mathrm{m}] = \frac{10^{-3}}{\varepsilon} \tag{2}$$

where ε is the absolute value of the eigenvalues of $\nabla \mathbf{b}$ and its orientation as the angle in the counterclockwise direction of the eigenvectors. The size of the null point ρ is proportional to the connection length CL ($\rho = 8 \times 10^{-8}\ CL$). Null points with long connection length ($>$ 1.6 km) manifest a probability of breakdown failure reduced by a factor 2. No significant correlation is observed between the null point orientation and the breakdown failure probability.

Recently, new experiments have been dedicated to investigating the physics of the assisted breakdown with second harmonic ECH. The typical scenario is shown in Fig. 4. The ECH power is injected in the vacuum vessel 15 ms before the expected breakdown time and kept on for 30 ms. No evidence of pre-ionization is observed, in contrast to what is reported in [1]. For high injected ECH power, the breakdown occurs earlier and with smaller values of toroidal electric field (Fig. 5(a,b)). Moreover the reliability of the breakdown is clearly improved when the breakdown is assisted with ECH, with a drastic reduction of the number of failures to breakdown. A variation of the breakdown dynamic is observed when the toroidal angle of the injected beam is changed. The fastest burn through of H_α are obtained with an ECH incident angle of 90 deg, even if no drastic variation of the breakdown time is observed (Fig. 5(c,d)). Finally, the effect of the ECH polarization on the breakdown is investigated. The most prompt ramp-up is obtained with the X-polarization, as shown in Fig. 5(e,f).

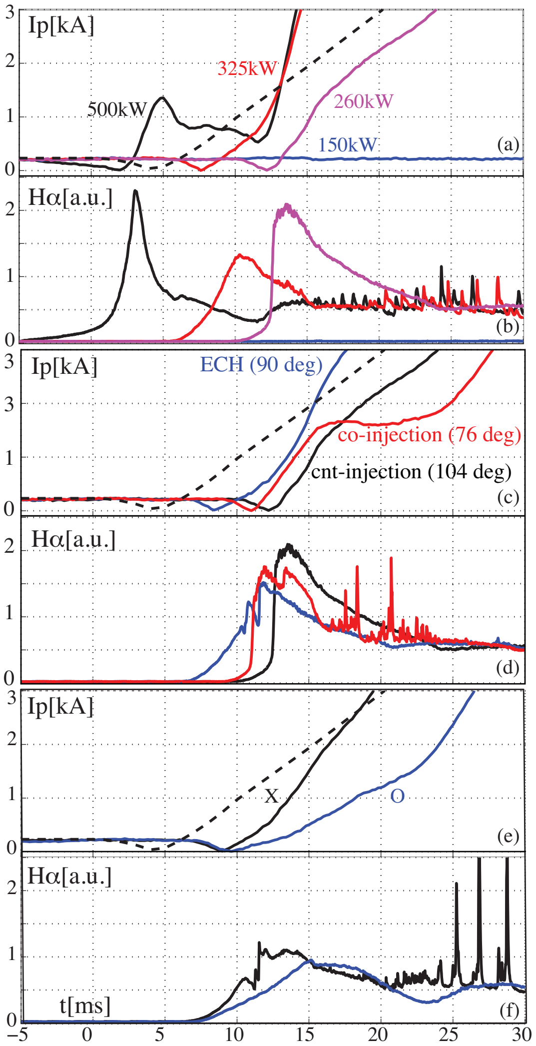

Figure 5: Temporal evolution of the plasma current and the H_α signal as a function of the (a,b) injected ECH power, (c,d) ECH incident launch angle and (e,f) beam polarization.

Further experiments are planned to investigate the effects of the poloidal magnetic field in the resonance region of ECH assisted breakdowns using the fine field control possible with the magnetic model previously discussed.

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References

[1] G. L. Jackson et al, Nucl. Fusion **47**, 257 (2007)

[2] F. Piras et al, Plasma Phys. Control Fusion (to be submitted)