Understanding the dynamics of inductive plasma initiation in the TCV tokamak

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Introduction

The dynamics of the plasma initiation in TCV (Tokamak à Configuration Variable) [1] are revisited with the goal of improving the reliability and efficiency of conventional plasma initiation scenarios and develop new scenarios such as a simultaneous breakdown at two locations for the creation of doublet shaped plasmas.

Plasma initiation requires many successful physical processes which are often characterized by phases, such as the breakdown phase, the plasma burn-through phase and the plasma current (I_P) ramp-up phase. The initial breakdown has an unstable nature (avalanche) and may be modeled with a Townsend-like model. Following the Townsend model, breakdown occurs when the ionization rate (ν_{ion}) exceeds the loss rate (ν_{loss}) of electrons. During this initial breakdown phase, loss of electrons is mainly caused by their motion along the magnetic field lines in the presence of the stray poloidal magnetic field (B_p) generated by currents in the ohmic (OH) and poloidal field (PF) coils and by the eddy currents generated in the vacuum vessel (VV) and other surrounding conducting structures. To reduce the loss of electrons, the poloidal field is minimized by creating a null in the poloidal field. TCV uses the code MGAMS [2] to pre-calculate the PF coil currents that produce a quadrupole null in the poloidal field at the intended location of breakdown. The electron loss rate is approximated by

$$\nu_{\text{loss}} = \frac{u_{||}}{L_{\text{eff}}}, \text{ with } L_{\text{eff}} \approx \frac{3}{2}\frac{B_\phi}{|\nabla B_{\text{p}}|_{npt}},$$

where L_{eff} is the average or effective connection length, B_ϕ the toroidal magnetic field, and $|\nabla B_{\text{p}}|_{npt}$ the gradient of the poloidal field at the null point. The breakdown in TCV is initiated by increasing the effective connection length at an optimal neutral gas pressure (~10^{-2} Pa) while the loop voltage is close to its maximum value (~10 V). Active I_P feedback control and plasma radial position control commences 10 ms after the nominal breakdown time.

Magnetic field reconstruction leading up to breakdown

During the breakdown phase, the particularly low resistivity (~55 $\mu\Omega$) of the TCV vacuum vessel results in vessel eddy currents of the order of 200 kA which significantly modify the poloidal field distribution. The vessel currents are modelled using toroidal current filaments. The circuit equation for the vessel filaments is,

$$0 = R_{vv} I_v + M_{vv} \frac{dI_v}{dt} + M_{va} \frac{dI_a}{dt}. \tag{1}$$

Here R_{vv} denotes the VV filament resistances, M_{vv} the mutual inductance between the VV filaments, M_{va} the Greens function between the VV filaments and the PF coils and I_v and I_a the currents in the vessel filaments and PF coils, respectively. While MGAMS only estimates I_v taking into account the time derivatives of the OH coil currents, the accuracy of the vessel and coil current estimation and, hence, of the reconstruction of the poloidal field can be increased by also using the time derivatives of the other PF coil currents as well as magnetic measurements [3]. The measured quantities are related to the currents in the system and their derivatives according to the specific properties of the considered sensor,

$$\mathbf{m} = \mathbf{M}\left[I_a, I_v, \dot{I}_a, \dot{I}_v\right]. \tag{2}$$

The vector of measurements $\mathbf{m}$ is composed of 38 flux loop measurements, 38 loop voltage measurements, 38 poloidal field measurements, 16 PF coil current measurements and 2 OH coil current measurements. $\mathbf{M}$ is the coupling matrix between the currents, the current derivatives and the measurements. The TCV VV is typically divided into 38 toroidal vessel current filaments. This model is only valid up to the breakdown time, since the plasma current is not taken into consideration. With the currents and their derivatives considered as independent variables in equations (1) and (2), the link between these quantities is explicitly added by imposing,

$$\dot{I}_a = \frac{dI_a}{dt};\ \dot{I}_v = \frac{dI_v}{dt}. \tag{3}$$

In eq. (3), $\dot{I}_a$ is the vector of the fitted coil current derivatives, I_a is the vector of the fitted coil currents, $\dot{I}_v$ is the vector of the fitted vessel current derivatives and I_v is the vector of fitted vessel currents. A least square solution for I_a and I_v of equations (1) and (3) is obtained for each time step until the breakdown time. An iterative process enforces consistency between the fitted current derivatives and the derivatives of the fitted currents. I_a and I_v, obtained by solving only eq.(2) without the current derivatives, are used as an input for computing the current derivatives from equation (3) and a new solution is found using the full system of equations.

In many TCV discharges the reconstructed field is found to differ significantly from the intended breakdown configuration. The main source for this discrepancy are different vessel currents, which can be interpreted as an experimental vessel filament resistance [4].

A fast framing visible camera has been used to validate the magnetic reconstruction of the poloidal field distribution at the time of breakdown. The tangential measurements with a spatial resolution of 512 x 1024 pixels, an exposure time of 66.8 μs and a sampling frequency of 5 kHz are inverted assuming an axisymmetric emissivity distribution [5]. Assuming that neutral gas pressure and electric field are constant throughout the VV, the loss rate should only depend on the magnetic geometry and the breakdown should occur in the vicinity of the poloidal field null with the largest L_{eff} .

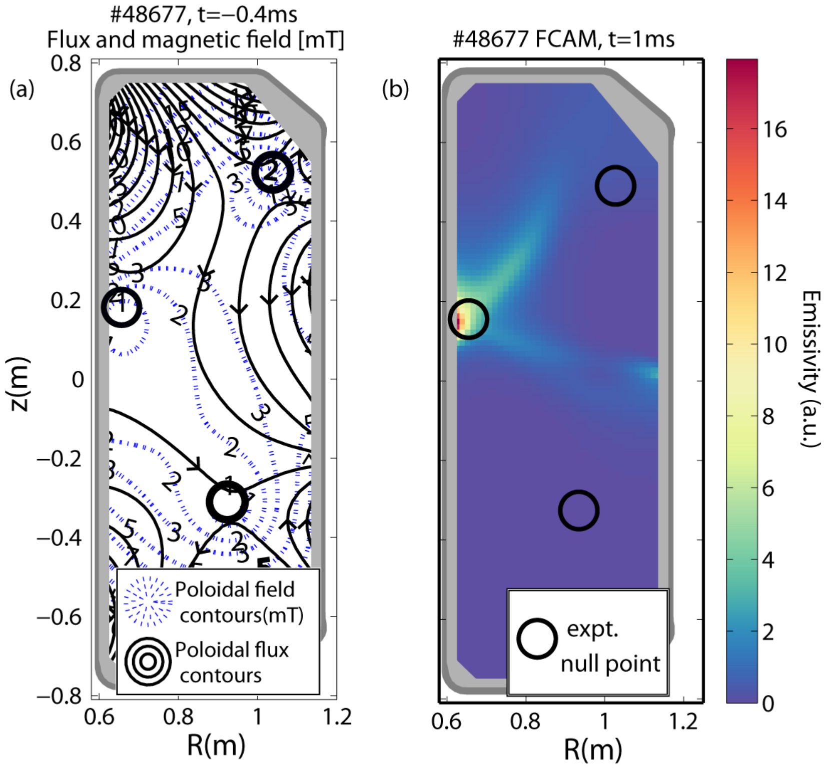

Figure 1: *Comparison of (a) the reconstructed magnetic field configuration and (b) the inverted fast framing camera image obtained using the GTI package [5].*

At the time of breakdown of discharge 48677, the null point with the largest L_{eff} is located at R=0.620 m, Z=0.153 m, figure 1(a), which is in good agreement with the highest emissivity located at R=0.624 m and Z=0.150 m, figure 1(b), corroborating the accuracy of the magnetic reconstruction.

Methods to improve the plasma initiation in TCV

Correcting the position of the field null and improving the stray field compensation by removing the offsets in the reference waveforms of the coil currents leads to a higher L_{eff} and, hence, an earlier breakdown. However, an earlier breakdown increases the likelihood of failure in the burn-through phase. This is caused by an experimental open loop I_P ramp rate that is significantly larger than the derivative of the plasma current control reference leading to strong oscillations once the I_P feedback control is activated, figure 2.

Several methods were proposed to avoid this mismatch in I_P by decreasing the initial I_P ramp rate. Experiments showed that an increase in the quadrupole field leads to a delayed breakdown reducing the mismatch in I_P. Another method to reduce the mismatch in I_P is the reduction in V_{loop} which leads to a monotonic rise of the plasma current, figure 2. However, reducing V_{loop}

is expected to limit the range of neutral gas pressure for successful breakdown. Hence, an increase of the I_P reference to match the experimental I_P ramp rate was proposed as an alternative solution and proved to be effective to avoid the mismatch in the plasma current.

Implementation of a proportional controller for the I_P feedback control from t=0 s onwards was unsuccessful to avoid the mismatch in I_P and, hence, an optimization of the I_P controller is required to effectively control the initial I_P ramp rate.

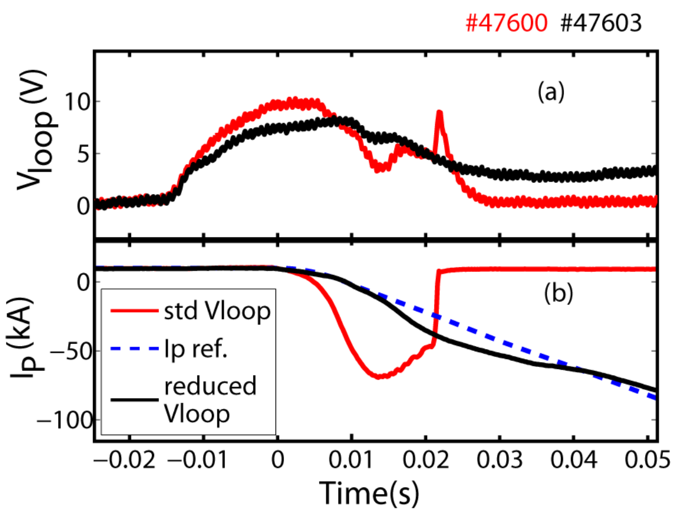

Figure 2: *Effect of (a) reduced loop voltage (b) on the I_P evolution.*

Conclusion

The reconstruction of the poloidal field at the time of breakdown using the coil currents and magnetic measurements identified an imprecise vessel model in MGAMS as the main reason for the discrepancy between the intended and experimental breakdown location. An improved magnetic configuration, however, aggravates a mismatch between the experimental plasma current and its control reference and leads to a control oscillation, which has been identified as the main cause for the plasma current extinction during the plasma burn-through phase. The increase in the quadrupole field and reduction in the loop voltage are effective in decreasing the rise in I_P. Based on the improved understanding of the dynamics of plasma initiation in TCV, improving I_P feedback control system should reduce the mismatch between the experimental and planned I_P ramp rate and, thereby, improve the reliability of the plasma initiation in TCV.

Acknowledgment

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