A control-oriented model for breakdown and burn-through in TCV and its application

T. Ravensbergen[1,2], F. Felici[2], H. Reimerdes[3], J. Sinha[3]

[1] *DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, the Netherlands*

[2] *Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

[3] *École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland*

The need for tokamak start-up modelling and control

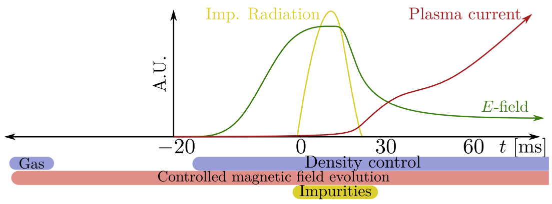

Figure 1: Schematic overview of tokamak start-up

The pulsed nature of experimental tokamak fusion devices implies the hot plasma needs to be formed over and over again. This justifies better understanding and optimization of this particular transient phase, such that a higher reliability and reproducibility can be achieved. From a physical point of view, plasma start-up in tokamaks can be divided into four different regimes, indicated in Figure 1: first, a neutral gas is injected and a favorable magnetic topology is created inside the vacuum vessel, having a large region with a purely toroidal magnetic field. Then the gas is ionized via collisions with electrons, which are accelerated and confined by an electric and magnetic field respectively. After a successful breakdown, the newly formed plasma is contaminated by impurity particles originating from the tokamak inner wall, which radiate away a large portion of the applied heating power. However, upon ionization, these impurities radiate less intensely, calling for sufficient heating of the plasma. When this is achieved, the plasma can be further heated and fueled, such that the fusion-relevant conditions are reached.

Modern model-based control can assist in optimizing plasma start-up, but needs a fast but reliable model to do so. Even though different models [1] and controllers [2] exist, they have not yet been extensively used to improve start-up *after* breakdown, especially in the presence of changing impurity dynamics. Here, a so-called *control-oriented model* is derived by combining and reproducing existing models, and extending them with a link to electromagnetics and plasma force balances, yielding a self consistent description of the whole start-up process. As such, inputs to the model are solely the gas fueling and coil currents, being the actual control inputs for the plasma. The remainder of this paper is structured as follows. First, a short overview of the control-oriented model is provided. Then, we compare this model to experimental data from the TCV tokamak, after which it is used to design and simulate controllers.

Physical modeling of plasma start-up

Modeling the plasma start-up requires dedicated models for all of the above distinct physics regimes. Each phase is characterized by the species that are taken into account, as well as the number and complexity of the necessary equations. The switching between regimes is dictated by triggers: The breakdown or Townsend avalanche can occur when the number of ionizations per second is higher than the electron losses. This poses the first distinct switch to a new modeling phase. At some point in the breakdown, the electron-ion collisions start to dominate, calling for another switch. Then, once the impurities are burnt-through, the ramp-up phase can start. From a physics point of view this phase be described by the same governing equations as the burn-through, up until a point where the approximations and assumptions in the model, for example dominating volume effects, do not suffice any more. In Figure 2 the modeling approach is summarized. Neutral atoms are denoted by 0, electrons by e, ions by i, and impurities by z. In the following, the different regimes are discussed briefly.

Pre breakdown and breakdown phase

The phase before breakdown is characterized by the absence of a plasma. It is assumed that a constant known pre-fill pressure p_0 is present in the vessel, and the effect of the coil currents and voltages, and their mutual coupling on the magnetic field on a discretized grid of the vessel cross section and coils is described by circuit equations. Then, the number of ionizations and electron losses per second are calculated via the well-known Townsend model $\dot{n}_e = n_e(\nu_{ion} - \nu_{loss})$ on each location of the vessel cross-section. The connection length is approximated by aB_{phi}/B_{pol}, with minor radius a instead of computationally heavy field-line tracing. Then, when the ionizations exceed the losses by a certain (approximately known) amount in a location of the vessel cross-section, the breakdown phase is entered. The plasma location is then immediately initialized on this location. Then, the plasma location is evolved by a simple force balance, which assumes a mass-less circular plasma with a flat density profile:

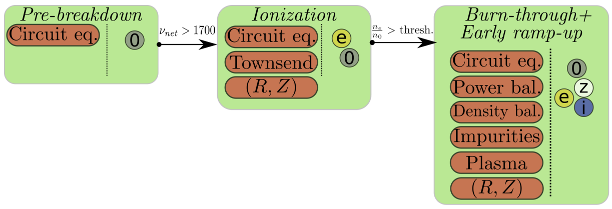

Figure 2: Model blocks and switching triggers

$$\frac{\mu_0 I_p^2}{2} F(R, B, I_p, n_i, n_e, T_i, T_e) + 2\pi R I_p B_z = 0 \qquad I_p B_r = 0 \tag{1}$$

The Townsend avalanche model is only valid when dominating collisions are neutral electron collisions. As ionization proceeds, however, the dominating one will be electron-ion collisions. Therefore, from a certain constant degree of ionization, the burn-through phase is entered.

Burn-through phase

In the final and most complex regime of plasma start-up, the equation set is expanded with electron and ion power and particle balances, including simple 0D descriptions (with some 1D effects). The following features of the model in this phase are relevant. The plasma is modeled as a rigid cilinder having a fixed current distribution on the cross-sectional grid. Semi-empirical descriptions for charge exchange, ionization, impurity radiation and equilibration are employed [3]. Furthermore, the essential paradigm shift from open to closed field lines with rising plasma current is captured by a simple model, proposed by [1]. This yields a self consistent description of the confinement time as a function of I_p and the magnetic fields, where we assume equal particle and energy confinement times for all species. The particle balances consist of a simple two reservoir model (ions and neutrals) that take ionization, confinement loss, recycling, and gas fueling into account in a heuristic fashion. Quasi neutrality is assumed to calculate the electron density from the impurity fraction and ion population. The total model then takes gas fueling, coil voltages, and the impurity fraction as input. For benchmarking purposes, also the loop voltage, plasma position, and radius can be taken from experiments.

Comparison with TCV data

Next, the model is compared to reconstructed start-ups in TCV. As the plasma is still cold, Thomson scattering is not yet available, and many other diagnostics are not as reliable as for hotter and bigger plasmas. Nevertheless, by selecting a particularly successful ramp-up, having an almost constant plasma current ramp rate, a comparison can be pursued. In Figure 3 various time traces are shown, with dashed lines indicating measurements or reconstructions, and solid lines the modeling efforts. Clearly, the model shows reasonable agreement, especially considering the simplified impurity model.

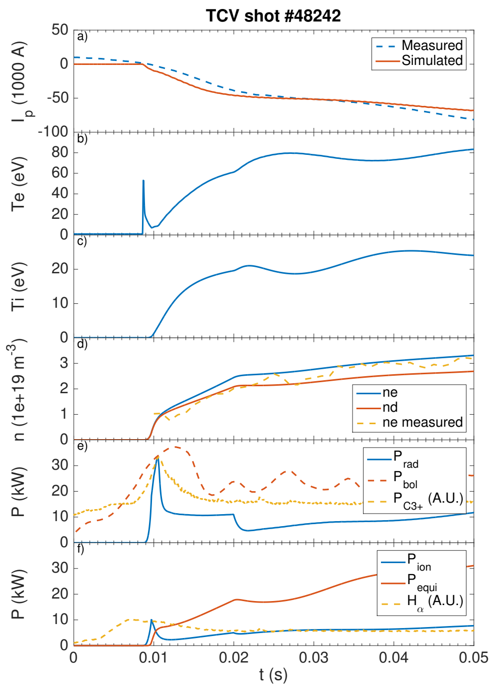

Figure 3: Model comparison with TCV #48242

Start-up optimization and control

The aim of successful start-up control is to first have a breakdown at a pre-configured location and time, after which just enough heating needs to be applied to sustain the burn-through phase. As such, these two control tasks are also separately treated. As the time scales of the whole process are very short and diagnotics not reliable or fast enough to be used in a feedback loop, feedforward control is the often used. To remove the need of meticulous tuning of coil current time traces, the advanced *Iterative learning Control* (ILC) approach is applied to automate and optimize the tuning of said signals [4]. ILC is particularly suited for repetitive control tasks, as is extensively applied in high tech motion systems, e.g. wafer steppers [5]. For this application, the coil voltages are first iteratively updated between (simulated or real) start-ups such that a breakdown is achieved at a desired location and point in time, even though a significant model mismatch in the vessel resistivity is present. Then, the burn-through problem is separately treated by another ILC algorithm such that the error in three variables of interest: plasma current, location and density is reduced. As a different wall conditioning can significantly change the breakdown dynamics, we only try to achieve targets in the three variables at the end of the burn-though, whose timing we fix. In simulations, the updated time traces are applied to a model having not only a different vessel resistivity but also different impurity dynamics (for each shot). Even though these model mismatches are present, the ILC algorithm is able to achieve convergence in the tracking error of all three variables at the end of the burn-through phase, see Figure 4. The convergence is not monotonic however, due to the changing impurity influx. The resulting time trace comparison is shown in Figure 5.

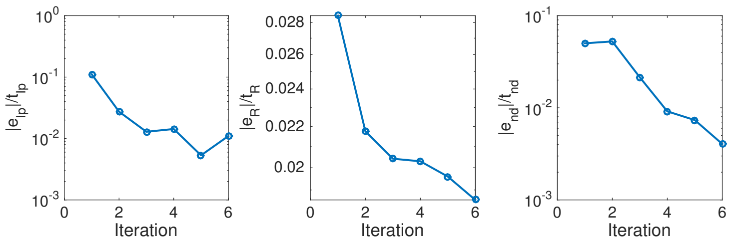

Figure 4: Convergence of the ILC algorithm in the three variables of interest

Conclusions

A control-oriented description op plasma start-up has enabled model-based control of breakdown and consecutive burn-though by application of the advanced Iterative Learning Control (ILC) method. This method iteratively updates the coil voltage time traces between shots or simulations to reduce the tracking error in breakdown location and timing, and subsequently the early plasma current, density, and position. In simulations, this has shown to be promising even in the presence of changing impurity dynamics from one discharge to the next.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

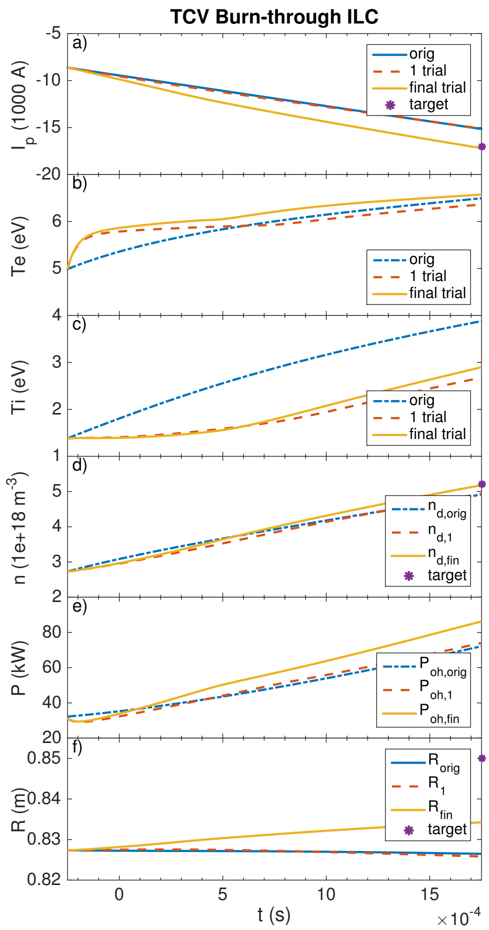

Figure 5: Time traces before and after ILC algorithm

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