A new free-boundary equilibrium evolution code, FREEBIE

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Introduction The non-linearly coupled effects between the evolution of the free-boundary equilibrium and plasma profiles observed in many tokamak experiments are the key elements for understanding the detail evolution of a tokamak discharge. The engineering constrains in operating the tokamak, such as the PF coil current, voltage, force and field limits, add additional non-linearity to the plasma control system. Therefore, in order to understand a tokamak discharge in a more complete way, it is essential to self-consistently include all these effects and constraints. In our previous study, this simulation capability has been provided by combining an advanced transport and source modelling code, CRONOS [1-2], and a non-linear free-boundary equilibrium evolution code, DINA-CH [3-4]. Using this combined simulator, several full tokamak discharge simulations have been performed to study the feasibility of ITER operation scenarios, as well as to resolve several issues in operating ITER [5-6]. These simulation studies have improved our understanding on tokamak discharge and operation one step further towards the success of ITER. Nevertheless, the combined CRONOS/DINA-CH simulator has several limitations to be further resolved. First, the non-linearly coupled plasma transport equations are iteratively solved using a partly implicit method. The evolution of the plasma current self-consistently calculated with the evolution of the free boundary equilibrium is coupled with the heat and particle transport using an explicit data exchange scheme and small time-steps. Second, the advanced acceleration scheme used for CRONOS transport modelling is also partly disabled, limiting the computational performance of a full tokamak discharge simulation. This work is proposed to resolve these limitations by developing a new free-boundary equilibrium evolution code, FREEBIE, and coupling it with CRONOS using a fully implicit code coupling scheme.

FREEBIE development FREEBIE has been recently developed in a modular way to be fully compatible with the CRONOS code and its data structure. FREEBIE calculates the dynamic evolution of the plasma equilibrium self-consistently with the evolution of currents in the conducting structures and poloidal field (PF) coils. The free-boundary equilibrium is computed using Green's functions which directly provide the poloidal flux and magnetic field components in the same precision. The computational grid is generated either using rectangular meshes or using Delaunay's method which provides a better description of the plasma shape. Mutual and self-inductances are calculated using Boboz's method [7]. Both single and multi-turn PF coil descriptions have been implemented. The non-linear Grad-Shafranov equation is solved either directly on the given meshes using an adaptive quasi-Newton scheme or using the HELENA code [8]. Simplified iron models [9] based on Green's functions and image current representation are implemented in FREEBIE for tokamaks with an iron transformer, such as Tore Supra and JET. Computational performance has been improved by pre-compiling several time-consuming routines using C language. Two execution modes, 'inverse mode' and 'direct mode', have been developed. In the 'inverse mode', the initial plasma equilibrium is self-consistently calculated with the given plasma boundary and currents flowing in the surrounding conducting structures and PF coils. Minimization of a cost function has been applied to find an initial equilibrium within the given constraints. In the 'direct mode', the evolution of the free-boundary plasma equilibrium

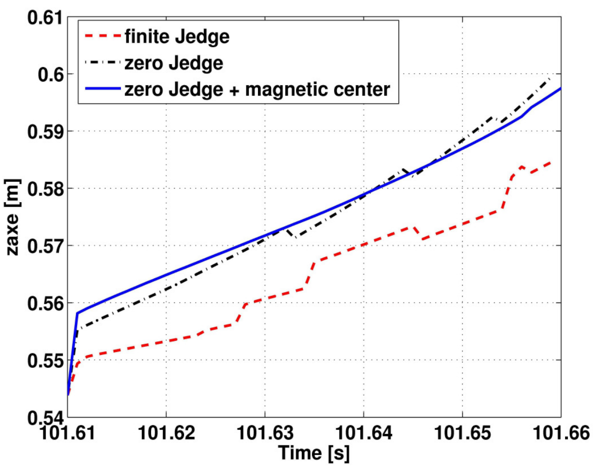

Figure 1. The evolution of the plasma vertical position. Three cases, with finite edge current density, with zero edge current density, and with both zero edge current density and improved magnetic axis determination, are compared.

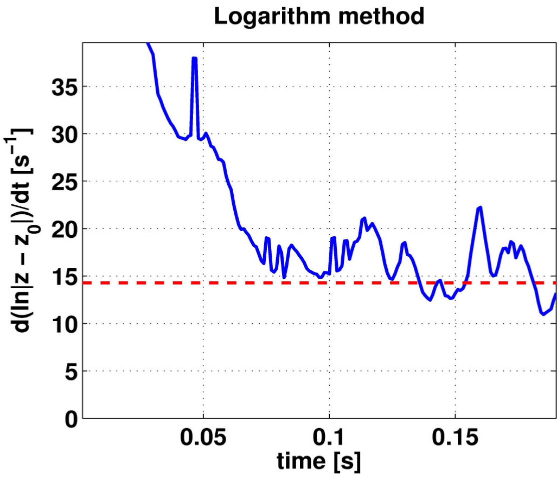

Figure 2. The vertical instability growth rate of 15MA ITER plasma (l_i ~ 0.92 and β_p ~ 0.25) calculated using an exponential curve fitting method (red dashed line) and a logarithmic method (blue solid curve).

is self-consistently calculated with the evolution of currents flowing in the PF coils and surrounding conducting structures. FREEBIE is developed as a stand-alone code and recently coupled with CRONOS using an implicit scheme [10], rather than using the explicit scheme previously applied to the DINA-CH/CRONOS simulator.

FREEBIE validation against ITER plasmas FREEBIE has been significantly improved while performing its first validation against ITER plasmas. Firstly, open-loop simulations of ITER plasma, in which the absence of the feedback control of PF coil currents leads elongated plasma to experience a vertical displacement event (VDE), have been performed and the vertical instability growth rates are compared with the values computed using linear/non-linear plasma response models [11]. In this first step, we have resolved several computational issues. The sudden jumps observed in the evolution of the boundary poloidal flux have been removed by assuming zero current density at the plasma boundary (see figure 1). The algorithm used for finding the magnetic axis has been additionally improved and then we could obtain a smooth evolution of the vertical plasma position as shown in figure 1. With these modifications and improvements, the previously observed unfavourable dependence of the plasma dynamic evolution on the simulation time-step has been almost completely removed and the computational performance has been significantly improved. The vertical instability growth rate of the 15MA ITER plasma has been computed to see if the modelled dynamic evolution of the plasma is physically meaningful. As shown in figure 2, the vertical instability growth rate was about $14s^{-1}$, close to the values reported [11] for similar ITER plasmas. Secondly, the ITER (and TCV) controllers extracted from existing DINA-CH SIMULINK models [4-5] are modified to provide feedback control of PF coil currents. FREEBIE can call a separate stand-alone controller model at every time-step, by providing user-defined delays and additional memories for storing the controller states. Finally, the evolution of the free-boundary equilibrium in the presence of feedback control of PF coil currents has been simulated. We have introduced a minimization of the vertical force on the plasma to stabilize the initial equilibrium and additionally adjusted the initial PF coil currents by trials. The open-loop and closed-loop simulation results are compared in figure 3. We have applied the extracted ITER controller with or without a proportional gain. When zero

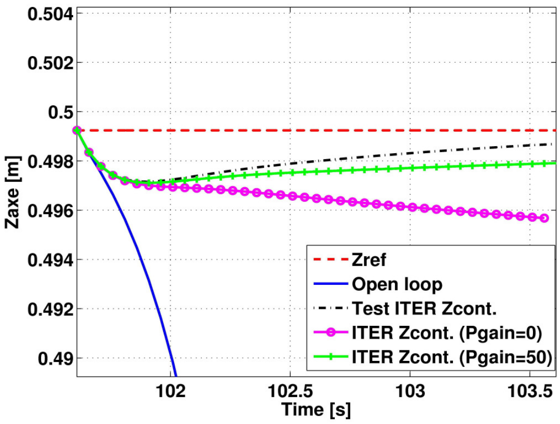

Figure 3. The evolution of the vertical plasma position. Four cases, open loop simulation without feedback control of the PF coil currents, closed loop simulation using a simple vertical position controller which uses user-defined filters and delays (‘Test ITER Zcont.’), and closed loop simulations using the ITER position controller extracted from existing DINA-CH SIMULINK model with/without the proportional gain (‘ITER Zcont.’), are compared.

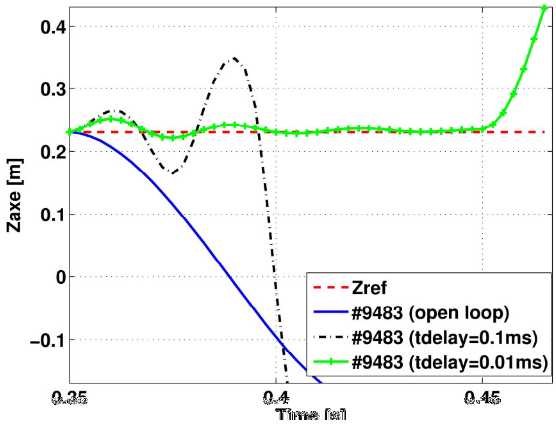

Figure 4. The evolution of the plasma vertical position (TCV #9483). Three cases, open loop simulation without feedback control of the PF coil currents and closed loop simulations using the TCV controller extracted from the DINA-CH model, are compared. The vertical plasma position has been controlled when the time-delay used to avoid algebraic loop is reduced (tdelay = 0.01ms). At t=0.45s, a VDE has been triggered by disabling both the vertical and radial position controls.

proportional gain was used, the evolution of the vertical plasma position was only slowed down (violet colour in figure 3). When we used a finite proportional gain (Pgain=50), the controller was able to recover the reference vertical position (green colour in figure 3). Note that in these simulations only the vertical position is actively controlled while the control of the plasma current, shape and PF coil currents were disabled.

FREEBIE validation against TCV plasmas Validation of FREEBIE against the TCV experiments has been performed step by step. Firstly, we have improved the script routine which imports the pulse data from TCV experiments to be fully consistent with data format used in FREEBIE simulation. Secondly, we have performed DINA-CH simulation of the TCV experiment in which a VDE is triggered at a specified time (t=0.45s). These simulation results were compared with the experiments (see right figure in figure 5). Thirdly, the TCV controller extracted from DINA-CH SIMULINK model has been modified and implemented for FREEBIE simulation. Lastly, closed-loop simulations have been performed. We have found that in some cases there were overshooting and oscillations in the evolution of the vertical plasma position. It has been identified later that FREEBIE does not require the time-delay in the TCV controller, which is additionally used to avoid the intrinsic algebraic loop of the SIMULINK model. Therefore when we have reduced the delay time close to zero, we could obtain the evolution of the vertical position in a feedback controlled manner (shown in green, figure 4). The evolution of the vertical instability growth rates obtained from FREEBIE (left) and DINA-CH (right) is compared in figure 5. These show very similar evolution, and also not far from the experiment (dots in the right figure), especially if we shift the starting time of the VDE in the experiment more close to the VDE start time in the simulation. Note that in these FREEBIE simulations, the plasma current has been assumed to be constant and numerical noises which can introduce additional uncertainty into the dynamic evolution of the plasma has not yet been completely removed. However, recently those noises have been significantly removed with additional improvements of the code.

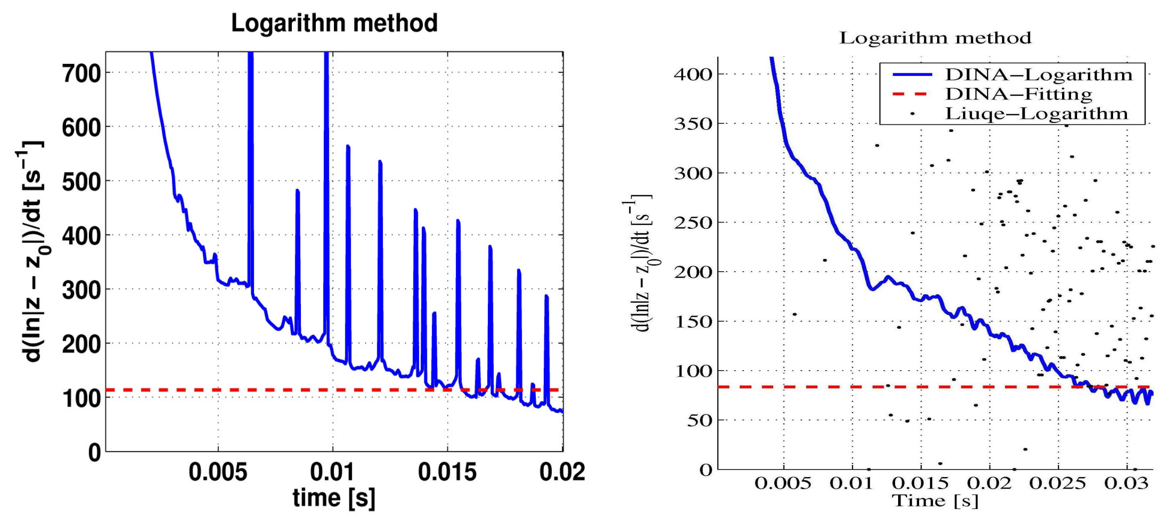

Figure 5. The evolution of the vertical instability growth rate during a VDE triggered at t=0.45s (TCV #9483). The evolution of the growth rate obtained using FREEBIE (left) is similar with those obtained using DINA-CH (right), although the plasma current was assumed to be constant in FREEBIE simulation and numerical noise has not yet been completely removed.

Summary and future FREEBIE has been developed aiming at providing a free-boundary plasma evolution modelling capability to the CRONOS transport code, and it has been validated against the TCV experiments and DINA-CH simulations, although additional simulation studies are necessary to complete the validation in a more rigorous manner. FREEBIE is now coupled to CRONOS and available for interpretative and predictive transport and equilibrium evolution simulation studies [10]. It will help us to study many challenging physics issues and to understand sophisticated physics mechanisms behind the non-linearly coupled plasma behaviours.

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