36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-2.171 (2009)

# Time-dependent Simulations of Hybrid Operation Modes Including Neoclassical Tearing Mode Activities in KSTAR

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## 1. Introduction

Establishment of long-pulse high-performance scenarios is one of key issues for economically viable fusion power plants. Hybrid operation modes are being developed with such an aim in present tokamak devices. They exhibit higher fusion performance compared with conventional H-mode scenarios in long-pulse duration even without a delicate feedback control of plasma profiles. The ITER employs the hybrid mode as one of its operation scenarios with a goal of maximising the neutron fluence in order to demonstrate availability and integration of essential fusion technologies in extended pulse length.

In this paper, predictive modelling of hybrid modes is performed to investigate the potential of hybrid modes in KSTAR with the ASTRA code employing a transport model. The neoclassical tearing mode (NTM) activities, which limit further improvement of fusion performance of hybrid modes, are taken into account by solving the modified Rutherford equation (MRE) coupled with plasma transport and their behaviours are investigated in time-dependent simulations. Furthermore, suppression of the (2,1) NTM activity by applying EC current drive (CD) is demonstrated for hybrid scenarios in KSTAR.

## 2. Simulation of Hybrid Scenarios in KSTAR

The predictive simulation is executed with the ASTRA code. The NBI heating package is embedded in ASTRA to calculate the NBI heating and CD. TORAY-GA is implemented to calculate the EC heating and CD. A model developed by Sauter is used for calculation of bootstrap current and the GLF23 transport model is employed to calculate the anomalous heat transport. Time-dependent simulations are performed based on a typical hybrid scenario, so-called improved H-mode, at ASDEX Upgrade (pulse 17870) [1,2] from which initial conditions and boundary conditions of the simulations are taken. Experimental density ($n_e$) and toroidal velocity ($v_{tor}$) profiles are used and the poloidal rotation is assumed to be neoclassical in the simulations. The radiated power is calculated including bremsstrahlung, cyclotron and line radiation due to carbon contamination. The effective ion charge ($Z_{eff}$) is assumed to be constant at 2.0. The plasma current is 1 MA and the toroidal magnetic field is 2.1 T, same as the ASDEX Upgrade discharge. NBI is used as a sole external heating and current drive source. The first beam source with power of 2.7 MW is applied at 0.3 s during the current ramp-up phase to raise the electrical conductivity and delay the penetration of the inductive current towards the centre of the plasma. At 2 s, when the current flat top phase

begins, the second beam source with power of 2.7 MW is applied to increase the fusion performance. After 2 seconds, when the plasma reaches close to stationary conditions, the third beam source with power of 2.7 MW is fired to maximise the fusion performance, where a real hybrid mode can be realised. The time evolution of plasma current ($I_p$), NBI heating power ($P_{NB}$), $\beta_N$, central $q$-value ($q_0$), volume averaged ion and electron temperature ($<T_i>$ and $<T_e>$), and electron density ($<n_e>$) is presented in figure 1 (a).

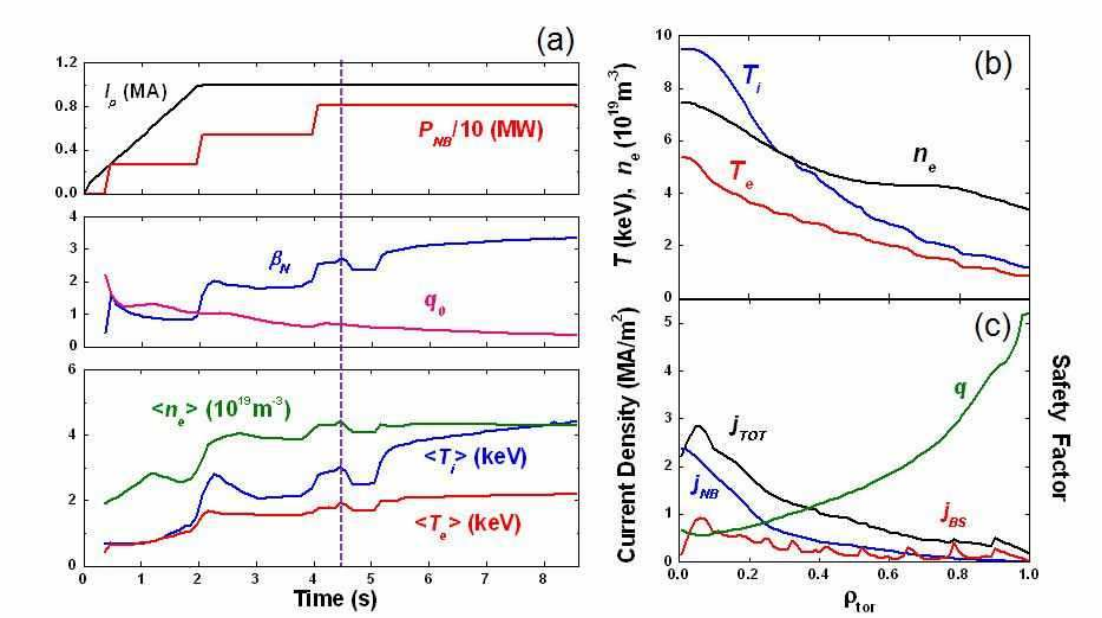


*Figure 1. (a) Time evolution of main plasma parameters in KSTAR hybrid mode. Ion and electron temperature, electron density profile (b), total, NB driven, bootstrap current and q profile (c) at 4.5 s*

As shown, $\beta_N$ is improved above 3.0 as observed experimentally in hybrid modes. However $q_0$ is dropped below unity that is inconsistent with experiments. As reported in Ref. 2-4, 1.5-D transport codes without considering the effects of MHD activities generally allows $q_0$ goes below one. In the simulation, a sudden drop of $\beta_N$, $<T_i>$ and $<T_e>$ is observed around 4.5 s as a result of NTM activities detected in the experiment. They influenced electron density and boundary conditions of the plasma temperature in simulations. The kinetic profiles are plotted in figure 1 (b) at 4.46 s prior to the event. The current density profiles are shown in figure 1 (c) together with the $q$-profile. As shown, bootstrap current results in slightly reversed shear configuration at the centre. Owing to a strong current drive at the centre by NBI, $q_0$ goes further down below unity. In addition to lower $q_0$, the typical flat shape of $q$-profile is not reproduced in the simulation. Similar results are reported in Ref. 1, 2, 4. This could result from exclusion of influence of MHD activities on current diffusion.

## 3. Simulation of Neoclassical Tearing Modes and Their Control in Hybrid Scenarios

The NTM effects are additionally taken into account to predict hybrid scenarios in KSTAR. The solver of MRE is coupled with ASTRA to calculate the time evolution of widths of islands self-consistently. The MRE implemented in ASTRA is as follows [5];

$$\frac{\tau_R}{r_s}\frac{d\omega}{dt} = \Delta'_0 r_s + \delta\Delta' r_s + a_2 \frac{j_{bs}}{j_{\parallel}} \frac{L_q}{\omega}\left[1 - \frac{\omega^2_{m\arg}}{3\omega^2} - K_1 \frac{j_{ec}}{j_{bs}}\right].$$

In the equation, all the variables are calculated with ASTRA self-consistently, except $a_2$ which is inferred from the saturated island width obtained from ISLAND [6]. Flattening of profiles by islands is considered in simulations by increasing heat conductivity deliberately in electron and ion channels as shown in figure 2 (a); $\chi_i = \chi_e = 40$ inside the islands, otherwise, $\chi_{i,e} = \chi_{i,e}^{NC} + \chi_{i,e}^{GLF}$. Perturbation in bootstrap current due to the flattening can be seen in figure 2 (c). No flattening is forced in density profiles.

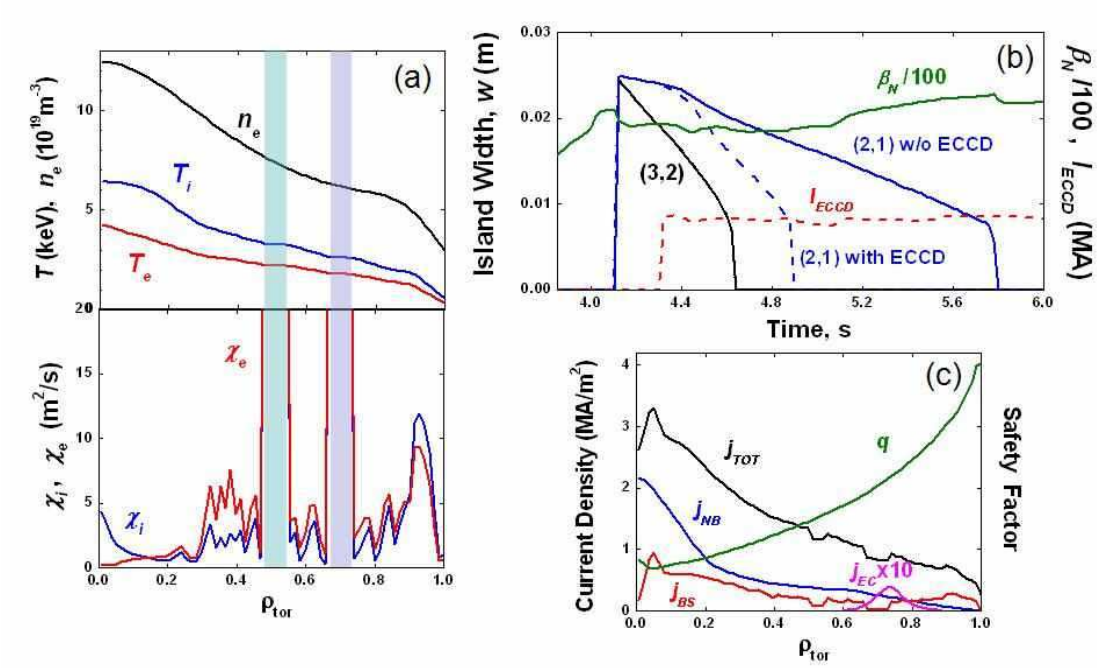


*Figure 2. (a) Flattening of temperature profiles at island locations due to deliberate increase of heat conductivities. (b) Time evolution of islands' widths, $\beta_N$, and EC driven current. (c) Total, NB driven, EC driven, bootstrap current and q profile (c) at 4.4 s.*

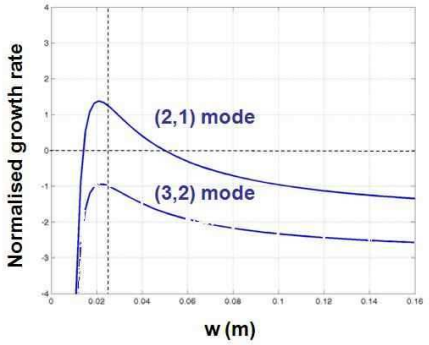


*Figure 3. (3,2) and (2,1) NTM stability calculated at 4.1s*

For the simulation of hybrid scenarios with NTM's, plasma current and toroidal field are assumed to be 1.5 MA and 2.T, respectively that are adjusted for EC resonance frequency of 170 GHz in KSTAR. Other simulation settings are the same as section 2. The simulation starts at 3.8 s. The third NB is applied at 4.0 s which increases $\beta_N$ above 2.0 high enough to trigger NTM's. Here, both (3,2) and (2,1) modes, the most frequently observed NTM activities in hybrid scenarios, are considered in the simulation. After the NTM's are triggered, $\beta_N$ decreases but recovers again as islands shrink (see figure 2 (b)). The initial widths of seed islands to trigger NTM's are postulated to be 2.5 cm at 4.1 s for both (3,2) and (2,1) mode. Time traces of the island widths are shown in figure 2 (b). The

black and the blue solid curve present the island width of the (3,2) mode and the (2,1) mode, respectively. As shown, this hybrid regime is supposed to be stable against both modes as they can be suppressed with no help of external current drive source to stabilise them. The (3,2) mode is stabilised quickly in about 0.5 second, good in agreement of stability diagram calculated with fixed parameter values taken at 4.1s (see figure 3). The (2,1) mode survives longer for 1.7 seconds, but without further growth of islands. This is somewhat contradictory to figure 3. The stability diagram predicts the (2,1) mode to develop with a positive normalized growth rate and to saturate with a island width of 5 cm. This discrepancy can be explained by the fact that variables being used in calculation of the MRE such as $j_{bs}$, $j_{\|}$, $L_q$ and $\omega_{marg}$ are continuously evolving interaction with islands in the time-dependent simulation but not in figure 3. As usual, the NTM activities appear in dynamic situations, e.g. the plasma beta improves, thus fixed values cannot be used to calculate the MRE to predict behaviour of islands. It emphasizes the necessity of time-dependent simulations coupled with transport for predicting the NTM behaviour. The effect of ECCD is investigated by applying ECRH with power of 1 MW at 4.3 s. The antenna is located at $R$ = 2.785 m, $Z$ = -0.14 m. The EC driven current is presented as the red dashed curve in figure 2 (b). The (2,1) mode is stabilised by ECCD in 0.6 second represented by dashed blue curve in figure 2 (b). The EC driven current is intended to be localised very close to the island location to compensate the loss of bootstrap current as shown in figure 2 (c). The poloidal angle is 107° and the toroidal angle is 193° in the simulation. Here, it is noteworthy that the $j_{ec}$ profile is changing in time as the plasma condition is varying during the simulation.

## 4. Summary

The predictive modelling of hybrid modes is performed with the ASTRA code employing the GLF transport model in KSTAR. Fusion performance relevant to experimental values is reproduced. The NTM effects are taken into account by coupling the solver of MRE to ASTRA for computing time evolution of widths of islands, self-consistently. The effect of ECCD is also investigated. Both the (3,2) and (2,1) modes are supposed to be stable in this regime, but ECCD can improve the stabilising effect. Contradiction to the stability of the (2,1) mode calculated using fixed parameters at single time point suggests the importance of integrated simulation of NTM corporated with time-dependent transport phenomena.

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