Stabilization of Burn Conditions in an ITER FEAT like Tokamak with Uncertainties in the Helium Ash Confinement Time

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Abstract. In this work we demostrate using a two-temperature volume averaged 0D model that robust stabilization, with regard the helium ash confinement time, of the burn conditions of a tokamak reactor with the ITER FEAT design parameters can be achieved using Radial Basis Neural Networks (RBNN). Alpha particle thermalization time delay is taken into account in this model. The control actions implemented by means of a RBNN, include the modulation of the DT refueling rate, a neutral He-4 injection beam and auxiliary heating powers to ions and electrons; all of them constrained to lie within allowable range values. Here we assume that the tokamak follows the IPB98(y,2) scaling for the energy confinement time, while helium ash confinement time is assumed to be independently estimated on-line. The DT and helium ash particle confinement times are assumed to keep a constant relationship at all times. An on-line noisy estimation of the helium ash confinement time due to measurements is simulated by corrupting it with pseudo Gaussian noise.

1. Introduction

In a burning regime a reactor plasma must be heated mainly by the energetic particles produced by fusion. In DT fueled reactors in particular the α-particles produced will deposit, during slowing down, most of their energy to the plasma electrons. The highly energetic alpha particles are expected to destabilize MHD modes known are Alfven eigenmodes. The strong nonlinear coupling among the energy deposition profile of the alpha particles, the new MHD instabilities, the bootstrap current and the plasma boundary, will make transport properties significatively different from those observed in current tokamak experiments.[1] Hence, active control of particle densities and plasma temperature will be essential in order to regulate the power density and to suppress fluctuations in plasma parameters due to turbulence and/or changes in confinement modes.

Here we report the results of a burn control study of an ITER FEAT-like tokamak by means of radial basis artificial neural networks with Gaussian nodes in the hidden layer and sigmoidals in the output layer using a two-temperature volume-averaged 0-D

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model,[2] assuming the particle density is homogeneous throughout the plasma core, with electrons and ions having the same radial profile but different peak temperatures. In contrast with previous works[3] alpha particle thermalization time delay is taken into account in this model. It is assumed that the energy confinement time of the reactor follow the IPB98(y,2) scaling and that the helium ash particles confinement time τ_α, is independently estimated "on-line". Their current estimated value contains noise due to turbulence and/or intrinsic measurement uncertainties, and is fed, together with the electron and ions temperatures, the electron density and the helium ash fraction, into the RBNN controller. The control actions are implemented through the concurrent modulation of the refueling rate S_f, the neutral He-4 injection rate S_α, and the auxiliary heating power density deposited to the ions and the electrons, $P_{\text{aux},i}$ and $P_{\text{aux},e}$, respectively, which can take values only within appropiate minima and maxima.

2. Model

The fusion reactor model considered here describes the time evolution of a quasineutral plasma composed of electrons, 50:50 D-T fuel, helium ash, a small amount of Be and Ar impurities, whose densities are n_e, n_{DT}, n_α, n_{Be} and n_{Ar}, respectively. The total thermal energy is determined assuming Maxwellian distribution of the particles: the electrons with a temperature profile $T_e(r,t)$, and all the ions with the same radial profile $T_i(r,t)$. The plasma heating takes place mainly by the thermalization of the alpha particles produced by the fusion reactions together with an external RF electron and ion heating, with a small contribution of joule heating. Bremsstrahlung is the only radiation loss mechanism considered. We assume that both the density and the effective charge of the impurities particles remain constant at all times. The simple model used here, before volume average is taken, is represented by the following coupled set of equations

$$\frac{\partial}{\partial t} n_{DT} = S_f - \frac{1}{2} n_{DT}^2 < \sigma v > - \nabla \cdot \vec{\Gamma}_{DT} \quad , \tag{1}$$

$$\frac{\partial}{\partial t} n_\alpha = S_\alpha + \frac{1}{4} f_{\text{frac}} \int_0^\infty dt' \xi_{\text{th}}(t') n_{DT}^2(t-t') \langle \sigma v(t-t') \rangle - \nabla \cdot \vec{\Gamma}_\alpha \ , \tag{2}$$

$$\frac{\partial}{\partial t}\left[\frac{3}{2} n_e T_e\right] = P_{\text{aux},e} + \frac{1}{4} f_{\text{frac}}\, f_e\, Q_\alpha \int_0^\infty dt' \xi_e(t') n_{DT}^2(t-t') \langle \sigma v(t-t') \rangle - A_b Z_{\text{eff}} n_e^2 T_e^{1/2} + \eta j^2 - \frac{3}{2} n_e (T_e - T_i)/\tau_{\text{ei}} - \nabla \cdot \vec{\Gamma}_{\text{E},e} \tag{3}$$

and

$$\frac{\partial}{\partial t}\left[\frac{3}{2}(n_{DT} + n_\alpha + n_{\text{Be}} + n_{\text{Ar}}) T_i\right] = P_{\text{aux},i} + \frac{3}{2} n_e (T_e - T_i)/\tau_{\text{ei}} - \nabla \cdot \vec{\Gamma}_{\text{E},i} + \frac{1}{4} f_{\text{frac}}\, f_i\, Q_\alpha \int_0^\infty dt' \xi_i(t') n_{DT}^2(t-t') \langle \sigma v(t-t') \rangle \quad ; \tag{4}$$

Here $\vec{\Gamma}_{\text{DT}}$, $\vec{\Gamma}_\alpha$, $\vec{\Gamma}_{\text{E},e}$ and $\vec{\Gamma}_{\text{E},i}$ are the DT and α particle fluxes and the electron and ions energy fluxes due to transport, respectively. The coefficients A_b, η and j correspond respectively, to the bremsstrahlung radiation losses, the neoclassical resistivity and the toroidal plasma current density. $Z_{\rm eff}$ is the effective charge densiy; and $\tau_{\rm ei}$ is the relaxation time between the energy densities of the electrons and the ions. The energy carried by the fusion alpha particles is $Q_\alpha = 3.5$ Mev; $f_{\rm frac}$ is the effective fraction of alpha particles not anomalously lost during thermalization; f_e and f_i are the fraction of the alpha particles energy Q_α, deposited to the electrons and to the ions, respectively. The thermalization of the alpha particles produced by fusion is not assumed instantaneous but time dependent with a distribution density function given by $\xi_{\rm th}(t)$ for an alpha particle produced at $t = 0$. Similarly, the energy lost to the electrons and the ions during the thermalization process are also taken to be time dependent following the distribution functions $\xi_e(t)$ and $\xi_i(t)$, respectively.

The dynamical equations used in this work are the volume-averaged of the above equations, assuming a time dependent but homogeneous particle density throughout the plasma with temperature radial profiles of the form[4]

$$T(\vec{r}, t) = T_0(t)[1 - (r/a)^2]^{\gamma_t} , \tag{5}$$

with T_0 the peak or central temperature, and a the tokamak's minor radius. The radial profile parameter will be taken $\gamma_t = 1.85$ for both the electrons and the ions. Transport losses are taken into account in the 0-D model through the energy confinement time τ_E, as well as by the D-T and the helium ash confinement times τ_p and τ_α, respectively.

The nominal operating state is assumed to be $n_0 = 1.01 \times 10^{20}$ m^{-3} for the electron density; and $T_{\rm e0}^{(n)} = 23.6$ keV together with $T_{\rm i0}^{(n)} = 23.0$ keV, for the central temperatures of the electrons and the ions, respectively. The helium ash fraction nominal value is $f_0 = 0.045$. The relative fractions of the Be and Ar impurities are assumed i $f_{\rm Be} = 0.02$ and $f_{\rm Ar} = 0.0012$. The ionization charge will be assumed $Z_{\rm Ar} = 17$, and $Z_{\rm Be} = 4$. The coefficient $f_{\rm frac}$ is assumed constant and equal to 0.9. The above values of the plasma parameters will constitute the operating point for the ITER-FEAT like tokamak reactor used in this work.[5,6] Here, we will assume that energy and particle scaling laws are independent, but the DT and alpha particle confinement times have a constant relationship, $\tau_p = 0.6\tau_\alpha$.

In practice, actual control actions are always constrained between a maximum and a minimum value, thus we shall impose in the model described in Eqs. (1)-(4) that

$$\begin{gathered} 0 \leq S_f^{\rm total} \leq 2.3 \times 10^{22}\ {\rm sec}^{-1} \ , \quad 0 \leq S_\alpha^{\rm total} \leq 5.7 \times 10^{20}\ {\rm sec}^{-1} \ , \\ 0 \leq P_{{\rm aux},e}^{\rm total} \leq 95.2\ {\rm MW} \qquad {\rm and} \quad 0 \leq P_{{\rm aux},i}^{\rm total} \leq 92.8\ {\rm MW} \ \ ; \end{gathered} \tag{6}$$

these limits contain the required values for steady state operation for the range of confinement times considered here. The plasma core volume is assumed 837 m^3.

Assuming quasineutrality we have , $n_e = n_{DT} + 2n_\alpha + Z_{\rm Be}n_{\rm Be} + Z_{\rm Ar}n_{\rm Ar}$; and after taking volume average in Eqs. (1)-(4), we obtain a coupled set of nonlinear differential equations for the time dependence of the electron density n_e, the helium ash fraction $f_\alpha = n_\alpha/n_e$, and the peak electron and ions temperatures, T_{e0} and T_{i0}. Transport losses are taken into account in the resulting equations through τ_E, the energy confinement time, as well as by the DT and helium ash confinement times τ_p and τ_α, respectively.

As pointed out in the Introduction, during the thermalization process, approximately 85% of the energy of the fusion alphas is absorbed by the electrons and only 15% by the ions. Thus, in this work we take $f_e = 0.85$ and $f_i = 0.15$. On the other hand, for the nominal operating plasma parameters of the ITER-FEAT design, the time required by the alphas to reach the threshold energy of 0.5 MeV, below which the energy is deposited mainly to the ions, for the nominal operating plasma parameters of the ITER-FEAT design is approximately 0.18 seconds; afterwards its energy is mainly deposited to the ions, taking an additional 0.06 seconds approximately to completely thermalize to the volume average plasma temperature of approximately 8.0 keV.

In order to stabilize the system around a given state, the neural network must provide appropriate values for the control variables, according to the current state of the system. In all the simulated transients used in the training and testing of the neural network in this and the next sections, we use a fourth order Adams-Moulton integration scheme with two corrector-predictor steps, using a constant time step of length 0.02 sec. The control actions are updated every 0.06 sec; in other words, the values of the control variables in Eqs. (6) remain the constant for three consecutive time steps and then updated, feeding to the RBNN the current values of the electron density, the fraction of helium ash, the ion and electron peak temperatures and the energy and helium ash confinement times.

3. Simulation Results

We present here an example of a typical transient behaviour with the resulting network controller, obtained after training the RBNN using a backpropagation through time algorithm.[7] The tokamak reactor is assumed to follow the IPB98(y,2) scaling law,[8] i.e.

$$\tau_{\mathrm{IPB98}} = 0.056 I^{0.93} R^{1.97} B^{0.15} M^{0.19} \epsilon^{0.58} \kappa^{0.78} n_e^{0.41} P_{net}^{-0.69} \quad ; \tag{7}$$

and the ratio $r = \tau_\alpha/\tau_E$ will be assumed to randomly fluctuate following a Gaussian distribution with mean value value $\bar{r} = 4.5$ with standard deviation $0.04 \times \bar{r}$; while its "on-line" estimation will also be a Gaussian stochastic variable with the same mean value but with standard deviation $0.08 \times \bar{r}$. In the transient shown below we choosed the following initial conditions $n_e = 1.15 \times n_0$ for the electron density; $f_\alpha = 0.80 \times f_0$, which corresponds to a helium ash density of 8 % below its nominal value; and an initial peak electron and ion temperatures of $T_e = 1.15 \times T_{0e}^{(n)}$ and $T_i = 1.15 \times T_{0i}^{(n)}$, respectively. In Figures 1 and 2 we show the behaviour of the normalized electron density, helium ash fraction, the electron temperature and the ions temperature, as function into the transient. In Figures 3 and 4 we show the time behaviour of the control variables, normalized with respect their maxima allowable values, as function ito the transient. It is observed that the RBNN controller is able to supress these fluctuations within

12 seconds into the transient. In Figure 5 (left) we show the time behaviour of the IPB98(y,2), Eq. (7), for this transient; and in Fig. 5 (right) the random fluctuations of the "on-line" estimation of the ratio τ_α/τ_E, along the duration of the transient.

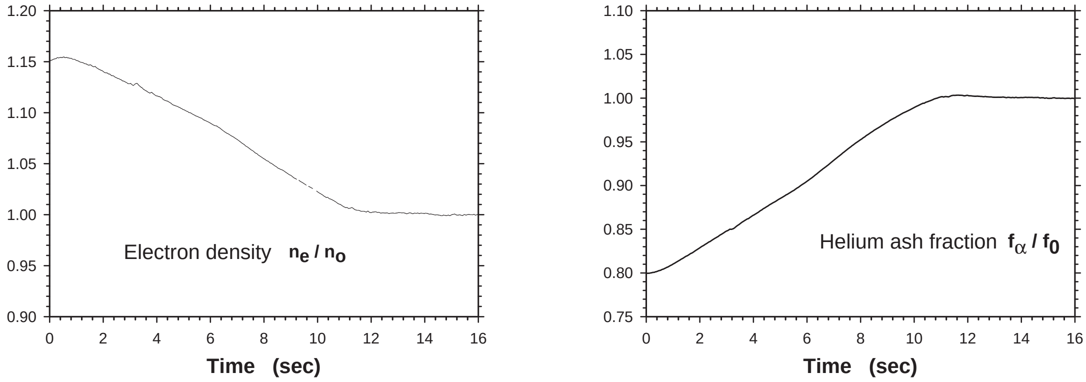

Figure 1. Behaviour of the electron density (left) and the helium ash fraction (right) as function of time corresponding to the transient described in the text.

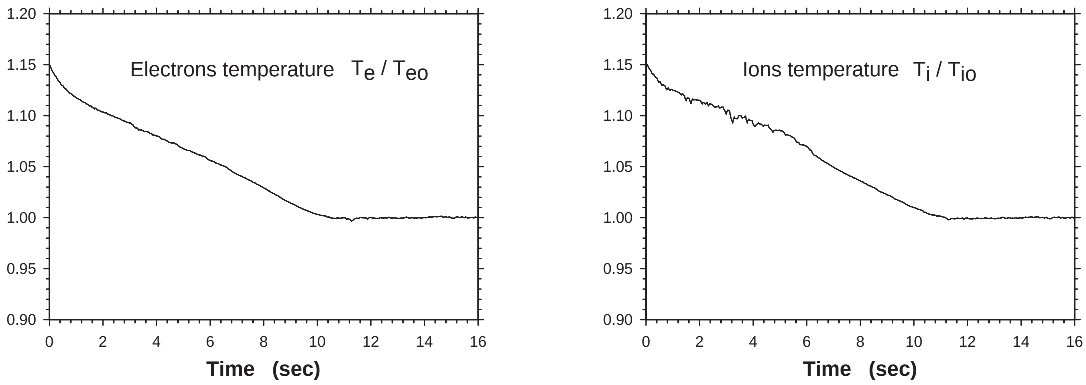

Figure 2. Behaviour of the electron and ions temperatures, left and right respectively, as function of time corresponding to the transient described in the text.

4. Conclusions

We have shown that burn control of an ITER-FEAT like tokamak with uncertainties in the helium ash confinement time can be succesfully achieved with radial basis neural networks. Assuming the reactor follows IPB98(y,2) scaling law, and using a 0-D two temperature volume-averaged model we illustrate by means of a typical transient that the RBNN controller is robust with respect to noisy "on-line" measurements of the ratio τ_α/τ_E. A complete report of these results including "on-line" measurement noise in the estimation of the energy confinement time is under preparation.[9]

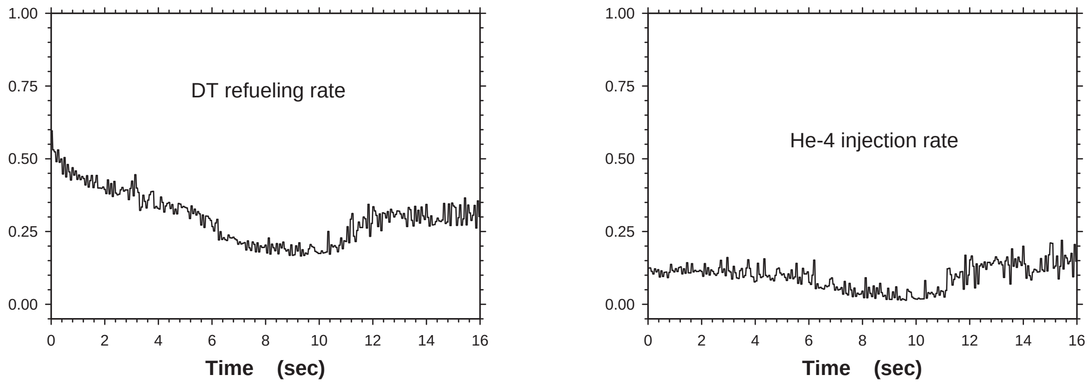

Figure 3. Normalized behaviour of the DT refueling rate (left) and neutral He-4 injection rate (right) as function of time corresponding to the transient described in the text.

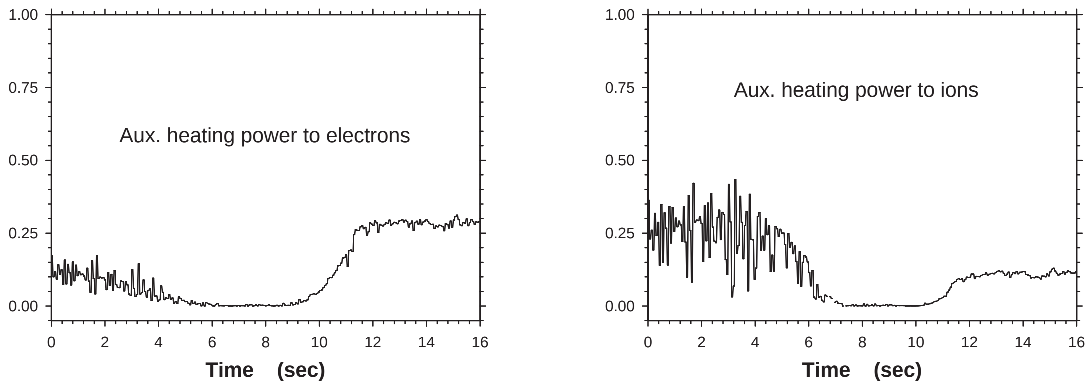

Figure 4. Normalized behaviour of the auxiliary heating power to electrons (left) and to ions (right) as function of time corresponding to the transient described in the text.

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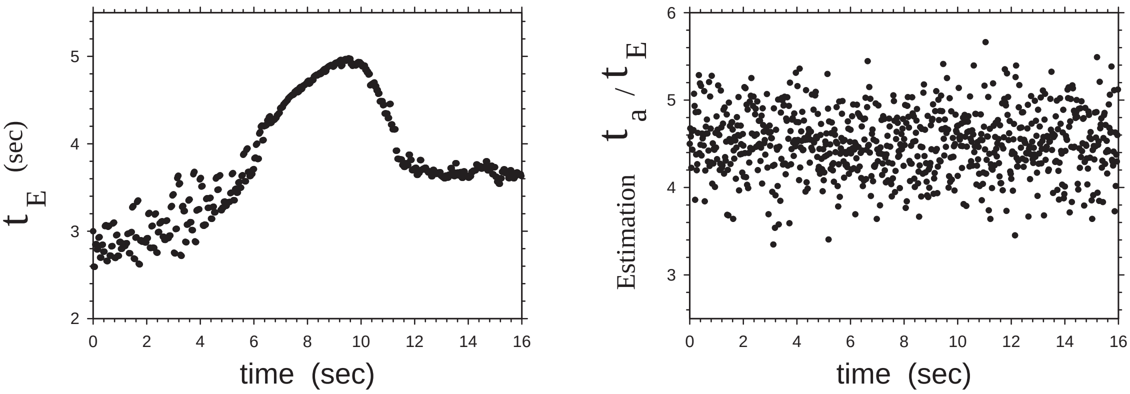

Figure 5. Energy confinement time τ_E as obtained from Eq. (7) for the IPB98(y,2) scaling (left) and the noisy "on-line" estimation of the ratio τ_α/τ_E, (right) used by the RBNN to update the control variables for the transient discussed in the text.

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