Nonlinear numerical modeling for understanding electron temperature crashes observed in W7-X experiments

Q. Yu[1], E. Strumberger[1], V. Igochine[1], K. Lackner[1], H.P. Laqua[2], M. Zanini[2], U. Höfel[2], W7-X team[2], and S. Günter[1,2]

[1]*Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*

[2]*Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany*

1. Introduction

In Wendelstein 7-X (W7-X) stellarator experiments, electron cyclotron current drive (ECCD) is a possible way to control the island divertor configuration. With slightly off-axis ECCD in co-direction that increases iota and decreases the safety factor, q, the ι-profile can become non-monotonic with two ι=1/q=1 surfaces located in the plasma core region. In these experiments, strong oscillations of the electron temperature, T_e, were observed, similar to that in W7-AS ECCD experiments [4], with a phase of slowly rising T_e followed by a sudden crash in tens of microseconds (μs) [1-3]. Linear stability study was performed for the W7-X equilibria with ECCD using the CASTOR3D code [5]. Double tearing modes (DTMs) and internal kink modes (IKMs) were found [6]. Similar results were also found for the same ι-profiles but with zero plasma pressure and a cylinder geometry from CASTOR3D [6,7].

To study the T_e crashes in W7-X experiments, the modified TM1 code is utilized, to solve nonlinear two-fluid equations using experimental parameters [7-9]. The poloidal equilibrium field is generated by a coil current except for that due to ECCD [7]. Circular equilibrium magnetic surfaces are assumed in TM1, and the shaping of magnetic surfaces and mode coupling due to stellarator geometry are not included. Nevertheless, as low m/n modes (m/n is the poloidal/toroidal mode number) dominate nonlinear mode growth [7], TM1 calculations still capture the major features of the experimental observations.

2. Numerical results

Without ECCD, the q-profile of the considered W7-X discharge is shown by the dotted curve in figure 1 (a). In order to simulate the ECCD effect, non-monotonic q-profiles with two q=1 surfaces in the core region are utilized, shown by the solid red and blue curves. The input parameters for calculations are taken from experimental data with the toroidal field 2.45T, electron temperature 3.18keV and density $2.5\times10^{19}m^{-3}$ at the magnetic axis, the plasma minor radius a=0.502 m, and the aspect ratio R_0/a=11. The perpendicular momentum, particle and heat transport coefficients are assumed to be 0.2m^2/s, and $\chi_{\|}/\chi_{\perp}=10^9$ is taken.

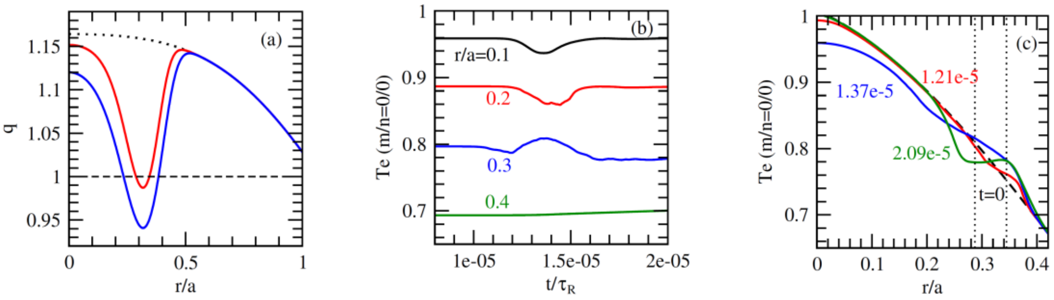

FIG. 1. (a) The solid (dotted) curves are the radial equilibrium q-profiles with ECCD (without ECCD). (b) Time evolution of T_e (m/n=0/0) at r/a=0.1, 0.2, 0.3 and 0.4, with the equilibrium q-profile shown by the red curve in (a). (c) Corresponding radial profiles of T_e (m/n=0/0) at t=0, 1.21×10^{-5}, 1.37×10^{-5}, and $2.09\times10^{-5}\,\tau_R$. The two vertical dotted lines show the equilibrium q=1 surfaces.

Corresponding to the equilibrium q-profile shown by the red curve in Fig. 1 (a), the time evolution of the m/n=0/0 component electron temperature, T_e (m/n=0/0), at the radial location r/a=0.1, 0.2, 0.3, and 0.4, obtained from TM1 calculation, is shown in figure 1(b). When the unstable modes grow up to a sufficiently large amplitude, they first cause a visible change in T_e around the q=1 surfaces at $t=10^{-5}\tau_R$ (blue curve), where τ_R=47s is the resistive diffusion time. The two q=1 surfaces of the equilibrium q-profile are at r/a=0.287 and 0.344. About 90 μs later ($t=1.2\times10^{-5}\tau_R$), T_e decreases in the central region (r/a=0.1 and 0.2) but increases at r/a=0.3 due to the IKM. Shortly afterwards, however, the central T_e recovers.

Corresponding radial profiles of T_e (m/n=0/0) are shown in Fig. 1 (c) at different times. The DTMs first cause a change of T_e around the q=1 surfaces marked by the two vertical dotted lines at $t=1.21\times10^{-5}\tau_R$ (red curve). When the IKM has grown to a large amplitude, T_e drops in the central region ($t=1.37\times10^{-5}\tau_R$, blue). Later at $t=2.09\times10^{-5}\tau_R$ (green), the central T_e recovers, while a local flattening around the q=1 surfaces results from the DTMs. The observed moderate decrease in the central T_e will be referred to as a *partial crash*.

The linear growth rate of higher-m modes is found to be much larger than that of low-m ones. At a later time ($t=1.21\times10^{-5}\tau_R$) right before the drop of the central T_e, the radial profiles of the radial ion velocity of the m/n=1/1, 2/2, 3/3, and 4/4 components are shown in Fig. 2 (a). At this time the m=1 component becomes the dominant, while the higher-m components are localized in the region between the two q=1 surfaces. The mode spectrum in the nonlinear phase changes significantly compared to that in the linear phase [7].

In figure 2 (b), the local radial profiles of the averaged safety factor, $q_{0/0}$, calculated by using only the m/n=0/0 component poloidal field, is shown at t=0, 1.21×10^{-5}, 1.37×10^{-5}, and $2.09\times10^{-5}\tau_R$. The q-profile is first modified around the q=1 surfaces (red curve) by DTMs. During the growth of the IKM, the q value decreases in the central region, accompanying the outwards motion of the plasma core (blue). Finally, only a flattening of the q-profile between the two q=1 surfaces remains due to the DTMs (green). Such a flattening of the q-profile between two resonant surfaces is similar to observations in tokamak experiments and corresponding simulations for m/n=2/1 DTMs [10].

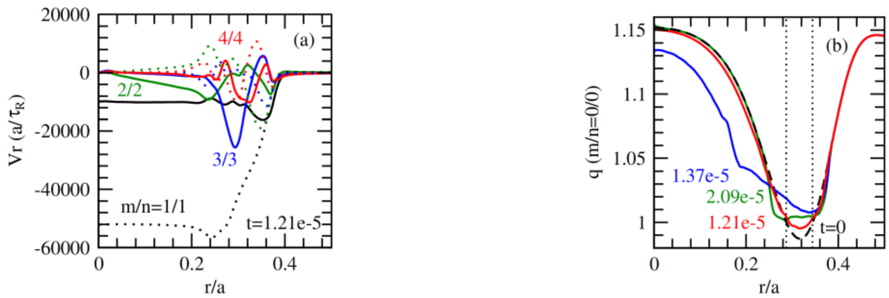

FIG. 2 (a) Radial profiles of the radial ion velocity of the m/n=2/2, 3/3, and 4/4 components right before T_e decreases. The solid (dotted) curve is the real (imaginary) part. (b) Local radial profiles of the averaged safety factor $q_{0/0}$ at t=0, 1.21×10^{-5}, 1.37×10^{-5}, and $2.09\times10^{-5}\,\tau_R$.

For the equilibrium q-profile with a larger distance between two q=1 surfaces, shown by the blue curve in figure 1 (a), the time evolution of T_e (m/n=0/0) at r/a=0.1, 0.2, 0.3 and 0.4 is shown in figure 3 (a). The two q=1 surfaces of the equilibrium q-profile are at r/a=0.234 and 0.384. The electron temperature also first changes around the q=1 surfaces (green and blue curves) due to the fast growth of DTMs. The IKM only grows up at a later time, causing a quick drop in the central electron temperature around $t=1.6\times10^{-5}\tau_R$ and a corresponding increase outside the equilibrium q=1 surfaces (r/a=0.4). The crash time of the central electron temperature is about $6\times10^{-7}\tau_R$=28μs, being comparable to the W7-X experimental results [1-3]. This time scale is also similar to the sawtooth crash times observed in tokamak experiments and corresponding numerical simulation results [8,9].

Figure 3 (b) shows the corresponding radial profiles of T_e (m/n=0/0) at different times. The DTMs first cause the change of T_e around q=1 surfaces at $t=1.56\times10^{-5}\,\tau_R$ (red curve). As the IKM further grows, T_e drops in the central region due to the outward motion of the plasma core ($t=1.58\times10^{-5}\,\tau_R$, blue). The time interval between the red and green curves is only $6\times10^{-7}\tau_R$=28μs. In this short time period, the T_e profile becomes flattened from the plasma center to the q=1 surfaces. Such a strong temperature flattening will be referred to as a *full crash* below. The electron temperature profile becomes hollow due to the outward motion of the hot core. The time evolution of the corresponding radial profiles of $q_{0/0}$ is shown in figure 3 (c). The flattening of the q-profile in the central region after the crash (green curve) is similar to that observed in the simulations for tokamak sawtooth crashes [8,9].

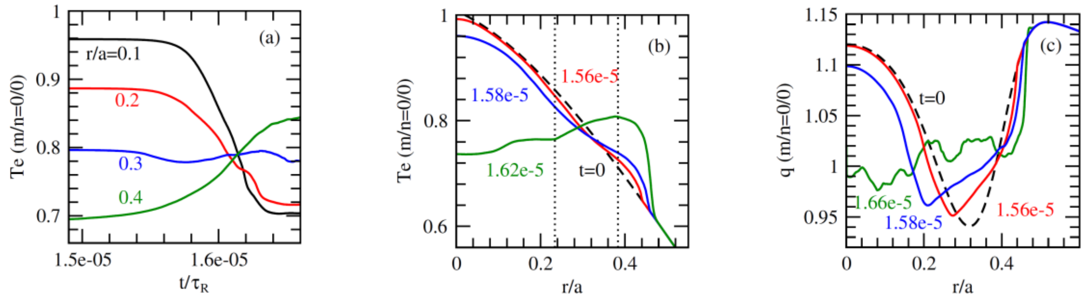

FIG.3 (a) Corresponding to the equilibrium q-profile shown by the blue curve in Fig. 1(a), the time evolution of T_e (m/n=0/0) at r/a=0.1, 0.2, 0.3 and 0.4. (b) Corresponding radial T_e (m/n=0/0) profiles at t=0, 1.56×10^{-5}, 1.58×10^{-5}, and $1.62\times10^{-5}\,\tau_R$. Two vertical dotted lines show equilibrium q=1 surfaces. (c) Radial profiles of $q_{0/0}$ at t=0, 1.56×10^{-5}, 1.58×10^{-5}, and $1.66\times10^{-5}\,\tau_R$.

Further calculations have also been carried out for different equilibrium q-profiles. A large (small) distance between two q=1 surfaces is found to result in a *full (partial) crash* [7].

In summary, to understand the sawtooth-like crashes of the electron temperature observed in W7-X ECCD experiments, numerical calculations have been carried out using TM1 code and experimental data as input. Fast crashes of the central electron temperature are found in calculations, caused by the internal kink mode coupled to double tearing modes. Depending on the distance between two equilibrium q=1 surfaces, two type of crashes with large and small amplitudes seen in experiments [3], are also found in numerical calculations.

Acknowledgements 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 and 2019-2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] Wolf R.C. *et al* 2017 *Nucl. Fusion* **57**, 102020.

[2] Wolf R.C. *et al* 2019 *Phys. Plasmas* **26**, 082504.

[3] Zanini M. *et al*, 2020 *Nucl. Fusion* **60** 106021.

[4] Hirsch M. *et al Plasma Phys. Control. Fusion* **50** (2008) 053001.

[5] Strumberger E. and Günter S. 2017 *Nucl. Fusion* **57**, 016032.

[6] Strumberger E. Günter S. and Wendelstein 7-X Team 2020 *Nucl. Fusion* **60**, 106013.

[7] Yu Q. *et al*, 2020 *Nucl. Fusion* **60** 076024.

[8] Yu Q., Günter S. and Lackner K. 2015 *Nucl. Fusion* **55** 113008.

[9] Günter S. *et al*, 2015 *Plasma Phys. Control. Fusion* **57** 014017.

[10] Günter S. *et al* 2000 *Nucl. Fusion* **40** 1541.