Island healing and CERC formation in the TJ-II stellarator

F. Castejón, T. Estrada, D. López-Bruna, and F. Medina
Laboratorio Nacional de Fusión. CIEMAT. Avenida Complutense 22, 28040 Madrid, Spain

e-mail: francisco.castejon@ciemat.es

Introduction

It has been shown that the introduction of a rational value of the rotational transform in the core of TJ-II plasmas heated by EC waves creates an enhanced heat confinement zone [1]. This regime is characterized by presenting a peaked temperature profile together with a hollow density one. The explanation given for the appearance of such phenomena is based on the fact that the particle flux through an ergodic area or an island chain is proportional to the parallel velocity of the particles. This means that the presence of islands or ergodic zones will imply the increase of electron flux in comparison with the ion one, thus enhancing the positive electrostatic potential and giving an increase of radial electric field in the plasma core.

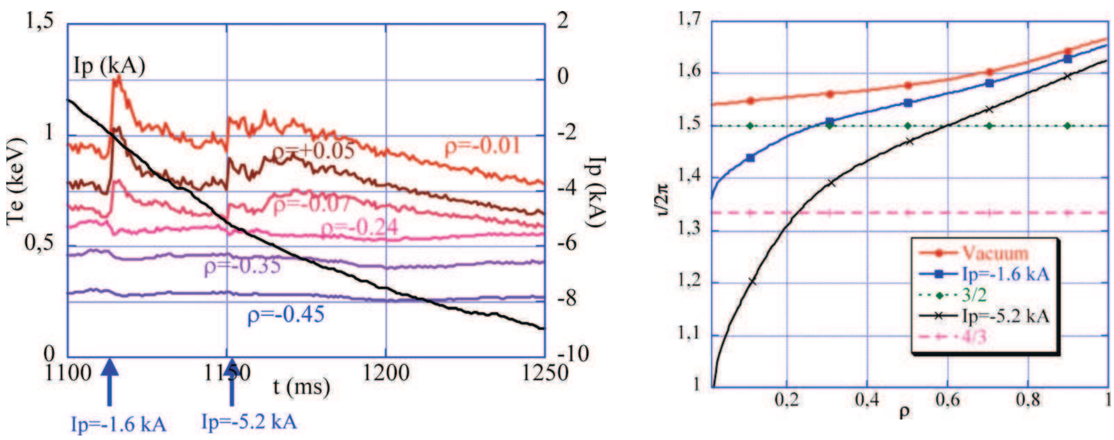

Figure 1. Temperature given by ECE measurements (left) and rotational transform profile (right) evolution during an OH-induced current experiment in TJ-II. The rotational transform profiles are shown for the times when the CERC is triggered.

This regime is commonly called CERC (Core Electron Root Confinement) in the stellarator literature [2], and has been observed in stellarators without rational values of the rotational transform, including TJ-II [3], triggered by the large electron flux due to the high absorbed power density in electron cyclotron heating (ECH) regime. The main advantage of provoking a CERC by using a resonance is that the power per particle threshold needed to trigger the CERC is much lower in this case, thus allowing one to have higher density plasmas.

CERC based on rationals has been achieved by locating the resonances either using the TJ-II configuration flexibility, driving currents with ECH, or inducing currents using the OH coils. The phenomenon has been observed for several values of the mode number, although there are several rationals for which CERC is not triggered in the plasma [4]. Figure 1 shows the ECE-measured temperature and the rotational transform profile evolution. It is seen that the CERC is triggered when the rational value reaches the plasma core ($\rho < 0.3$).

Island Healing

In many cases, the presence of the rational is estimated but cannot be detected as a flattening of electron temperature or pressure profiles. The electron cyclotron emission (ECE) diagnostic might not detect small magnetic islands, since its radial

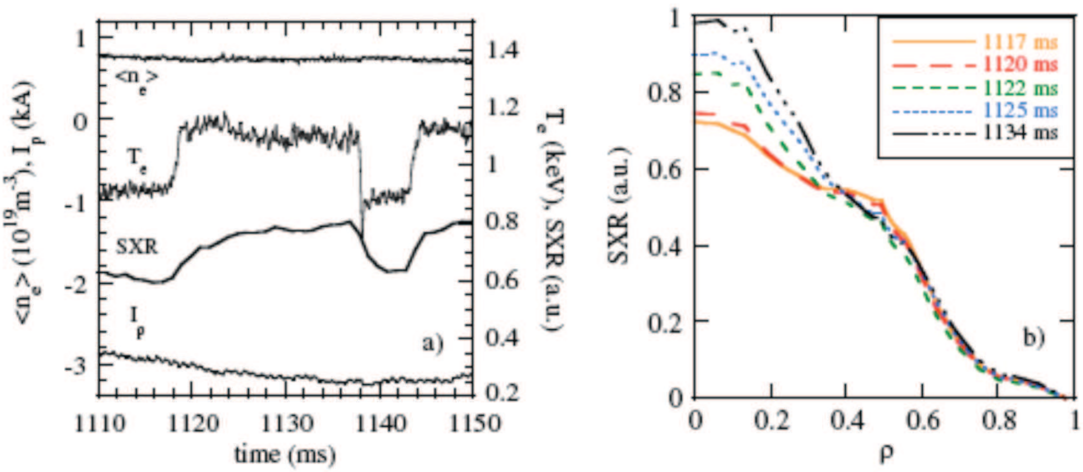

Figure 2. Time evolution of plasma current, line density, central temperature and SXR signal (left). Time evolution of electron temperature profile as measured by ECE (right).

resolution is of the order of 1.5 cm. Therefore, we can conclude that if no flattening is observed it is due to the fact that the island chain is not developed. CERC without temperature flattening has been observed for m/n=3/2, 4/3, and marginally for 5/3, while the onset of CERC could not be observed for higher order resonances.

The same experiments were performed with the 4/2 natural resonance [5], moving inward the rational surface with a moderate amount of OH current. In this case, the results are different: a flattening appears in the temperature profile close to the estimated position of the rational, as measured by ECE system. The evolution of SXR emission profile is observed in Figure 2, where it can be seen that the flattening is shrinking up to small values. The island healing is produced just simultaneously to the CERC onset. The evolution of the m=2 structure can be followed by SXR measurement, showing that it almost disappears when CERC is established. The flattening in ECE channels was accompanied by the presence of coherent modes measured by the Heavy Ion Beam Probe (HIBP) [6], which happens also for 3/2 resonance. Those modes are located well inside the plasma column ($\rho \approx 0.3$) so they cannot be detected by Mirnov coils, which are suited for modes located at $\rho > 0.6$. The coherence of HIBP with the ECE measurements is extremely high, showing that the plasma temperature is vibrating in phase with the potential. When the CERC is finally formed, the HIBP signal is stabilized and the flattening disappears. The modes are destabilized when the CERC disappears and a flattening is observed again.

Explanation

The behaviour of magnetic islands in the TJ-II plasma core can be understood by considering the non-liner theory of tearing modes. The generalized Rutherford equation [7] can be taken as a starting point for this dynamics and, as a result, the island width time evolution. The latter is governed by the following equation [8]:

$$A_1 \frac{dw}{dt} = \eta\left(\Delta' - A_2 c_b \sqrt{\varepsilon}\, \frac{p' q}{q' B_p w}\right) = \eta\left(\Delta' - A_2 c_b \sqrt{\varepsilon}\, \frac{|p'| \iota}{\iota' B_p w}\right)$$

Where A_1=0.823, A_2= 6.34, $c_b \approx 1$, $\iota = 2\pi / q$ is the rotational transform, and all the quantities are evaluated at the resonant radius. The first term corresponds to the rational discontinuity and must be estimated numerically taking into account the actual magnetic configuration and the island chain structure. The second term is proportional to the pressure gradient. This term is negative in TJ-II stellarator due to the sign of ι' and, therefore, tends to stabilise the tearing mode and to reduce the magnetic island width. The stabilising effect becomes more and more intense as the pressure gradient is increased and as the island is narrowed, which is experimentally observed. The magnetic instabilities detected by HIBP also disappear when the island is shrunk. As has been stated above, the increasing pressure gradient is due to the electron heat confinement enhancement caused by the positive ambipolar electric field created by the presence of the rational. Finally, the stabilising term becomes dominant and the island width becomes too narrow to be detected.

The fact that the other studied resonances that have been previously introduced inside the plasma column do not cause detectable profile flattening can be due to the fact that this modes are stable for the present TJ-II conditions or the width is too small to be detected by ECE. An analysis of the linear NTM stability similar to the one developed in Ref. [9] must be performed to clarify this point.

Conclusions

It is well-known that CERC regime (or electron temperature internal transport barrier) can be created in TJ-II stellarator by positioning low order resonances inside the plasma core. The resonances, which can be introduced inside the plasma by tailoring the rotational transform profile, create an ambipolar positive electric field that enhances the electron heat confinement, giving rise to a steep pressure gradient. According to the non-linear theory of tearing modes, this pressure gradient has a stabilising effect due to the sign of the magnetic shear in stellarators. The CERC formation is accompanied by island healing and magnetic turbulence stabilization.

References

[1] F. Castejón et al. Nuclear Fusion 44 (2004) 593
[2] M. Yokoyama et al. Nuclear Fusion 47 (2007) 1213
[3] F. Castejón et al. Nuclear Fusion 42 (2002) 271.
A. Fujisawa et al 1999 Phys. Rev. Lett. 82 2669
H. Maassberg et al 2000 Phys. Plasmas 7 295
[4] F. Castejón et al. Plasma Phys. Control. Fusion 47 (2005) B53
[5] T. Estrada et al. Nuclear Fusion 47 (2007) 305
[6] T. Estrada et al. Plasma Phys. Control. Fusion 47 (2005) L57
[7] P. H. Rutherford. Physics of Fluids 16 (1973) 1903
[8] Q. Yu, S. Guenter and K. Lackner. Physics of Plasmas 1 (2004) 140
[9] H. P. Furth, P. H. Rutherford, and H. Selberg. Physics of Fluids 16 (1973) 1054