Inductive Current Perturbations to Steady-State eITBs

T.P. Goodman, R. Behn, A. Bottino, S. Coda, E. Fable, M.A. Henderson, P. Nikkola O. Sauter, C. Zucca

Centre de Recherches en Physique des Plasmas,

Association EURATOM-Confédération Suisse, EPFL, CH-1015 Lausanne, Switzerland

Abstract

Dedicated experiments in which co- or counter- inductive-current *perturbations* were added to an electron internal transport barrier (eITB), created in a plasma fully sustained by non-inductive electron cyclotron current drive (ECCD), show that the barrier location remains stationary while the barrier strength can be either decreased or increased, respectively, at constant EC power input and fixed aiming. There is negligible power and momentum input from the inductive perturbation. GLF23 simulations show that the growth rate of trapped electron modes can be greatly reduced in the core region near the minimum of the weakly reversed q profile used to describe the eITBs. These results show that eITBs can be formed by changing the current profile alone

Introduction

In TCV eITBs are created during the current flat top of a plasma discharge. Target plasmas are created at t=0s and formed during ~100ms to a shape with κ~1.5, $\delta \sim 0.2$, $I_p \sim 100$kA and $q_{95} \sim 5$-6 and $n_e \sim 10^{19}\mathrm{m}^{-3}$. The L/R time of these low temperature plasma (Te ~ 1keV) is ~ 0.23s with roughly 35% of the total inductance coming from the internal inductance of the plasma. At t=0.4s, 70kA of co-ECCD is driven at ρ~0.4; 20ms later, the current in the Ohmic transformer is feedback controlled to a constant value thereby removing the external inductive EMF. Although the power is absorbed off-axis, cross-field diffusion of the heated electrons transports co-current to the center of the plasma column [1]. The measured driven current $I_{cd} = I_p - I_{bootstrap}$ is 1 to 3 times the value calculated with the (linear) TORAY-GA ray-tracing code. EC power is then injected into the plasma and absorbed at a location closer to the plasma center than that of the off-axis EC beams. This is referred to here as "central" deposition even though it is not necessarily near the magnetic axis. The beam(s) can be injected with a toroidal angle to produce Doppler-shifted absorption, thus ECCD. The driven current can be either in the same (co-) or opposite (cnt-) direction as the initial inductive current.
With this methodology we routinely produce eITBs in TCV which last up to 2000 times longer than the electron energy confinement time τ_{Ee} [2] even when τ_{Ee} is already ~3-5 times longer that expected from TCV L-mode scaling (Rebut-Lallia-Watkins scaling). We quantify the improved confinement using an $H_{RLW} \equiv \tau_{Ee} / \tau_{RLW}$ factor. An $H_{RLW} = 4$ ($H_{ITER\text{-}98\text{-}L}$~1.6) has been obtained in steady-state [3, and references therein].
In this contribution we discuss the confinement and barrier properties in a series of experiments in which perturbative inductive current is added to pre-existing eITBs in either the co- or counter- direction.

Background

In eITBs the barrier is characterized quantitatively using the maximum in $\rho *_T \equiv \rho / L_T$, the same quantity used for ITB detection on JET [4], where ρ is the ion Larmor radius calculated at the sound speed and L_T is the electron temperature-profile scale length.

The three basic parameters of the EC system which control the current profile, thus the barrier, in non-inductive steady-state discharges are the injected powers P, the toroidal injection angles ϕ, and the deposition locations of the individual EC beams in minor radius $\rho_{co,cnt}$. The electron density n_e can also be changed thereby altering the current drive efficiency. Previous experiments have shown [5] that increasing ρ_{co} at constant input powers and toroidal angles causes the barrier to expand, encompassing more plasma volume. At the same time, the strength of the barrier increases (i.e. the maximum value of $\rho *_T$, proportional to the temperature gradient, increases). On the other hand, increasing the central counter-ECCD by means of the toroidal injection angle, increases the barrier strength while increasing the central co-ECCD reduces the barrier strength. In both cases the barrier location remains roughly unchanged. Combining these 2 control parameters, ρ_{co} and ϕ, allows independent control of both the barrier location and strength.

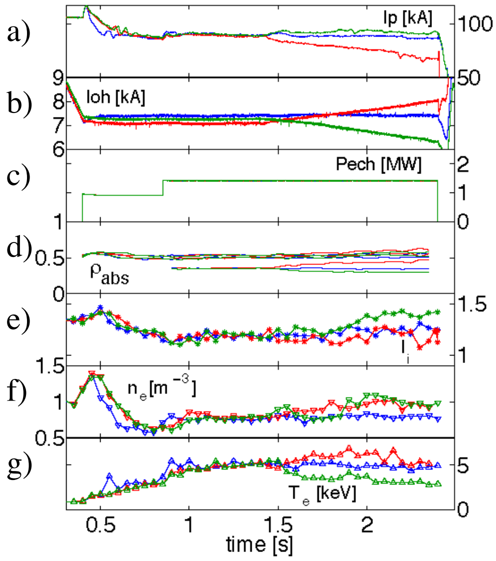

Fig. 1 Time traces of (top to bottom) plasma current, transformer current, EC Power, EC deposition radius, internal inductance, electron density and electron temperature, for 3 shots in which co- (green), zero (blue), and counter- (red) current is driven by very small loop voltage in an established non-inductive eITB discharge (see text).

Experiment

Feedback control of the tokamak transformer current ramp-rate $\Delta I_{OH}/\Delta t$ (i.e. the source of the external loop voltage) provides an additional actuator. In TCV, negative (positive) transformer current ramp rates produce co- (counter-) current, defined as for ECCD. During normal I_p feedback, this ramp-rate is adjusted by the feedback loop to produce a desired I_p regardless of changes in conductivity. In the experiments described here the transformer current I_{OH} is feedback controlled to a given value or ramp-rate and the I_p evolves according to the imposed EMF, plasma conductivity, internal ECCD sources, and the

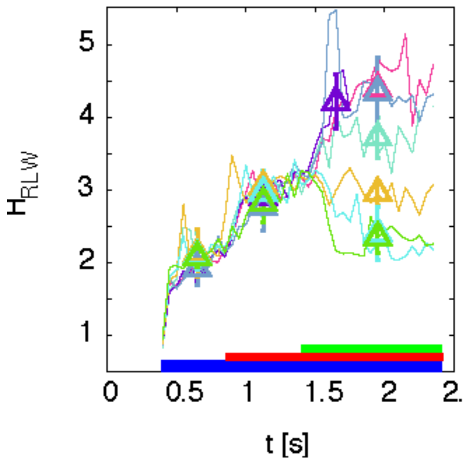

Fig. 2 H_{RLW} factors for a series of shots in which inductive current perturbations are added at 1.4s. Confinement degrades with co-inductive current and improves with counter-inductive current relative to the heated eITB level of $H_{RLW} \sim 3$.

bootstrap current generated by the confinement-dependent pressure gradient. The ramp rates are fixed at values up to an order of magnitude smaller than those resulting from typical *Ip* feedback. The additional power input to the plasma by the EMF source is negligible (a few kW) while the driven current can be significant. This is therefore a perturbative current drive method from the point of view of power input; whereas, adding central ECCD always implies adding significant EC power simultaneously (typically 500kW).

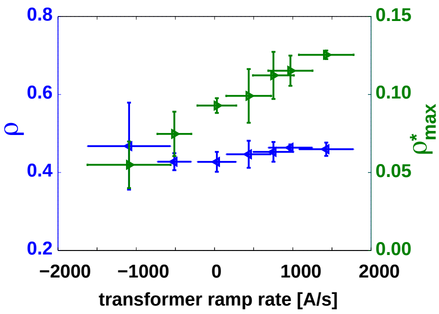

Fig. 3 The barrier strength (green) and location (blue) for a the same 7 shots as figure 2. A ramp rate of 1000A/s corresponds to a loop voltage of 64.5mV in steady-state. These results are very similar to previous scans of the ECCD launch angle. Thus, the H_{RLW} increases due to an increase in the barrier strength resulting from a decrease in the central current density and an increase in the bootstrap current off-axis near the barrier. The barrier location remains roughly constant.

Three shots from a scan with inductive current perturbations are shown in Fig. 1. A standard 100kA (1a) non-inductive eITB is formed by off-axis co-ECCD at 0.4s followed by central EC heating at 0.85s. An inductive current perturbation is added 0.55s later at 1.4s (1b). The absorption locations (1c) are also seen to move in ρ even though the launch angles are fixed. Furthermore the internal inductance l_i (1d) is altered indicating a change in current profile. The central n_e (1f) increases for both co- or counter- induced currents whereas T_e (1g) increases with counter- and decreases with co-current, as the confinement changes. Although the EC actuators are fixed, the changes in temperature, density and absorption location can affect the co-ECCD.

A scan of the transformer current ramp rates has been made from –2000A/s to +1000A/s, corresponding to a steady-state loop voltage, V_{loop}, scan from –129mV to 64.5mV. The H_{RLW} factors for a series of 7 shots are shown in figure 2. Co- inductive current degrades confinement while counter- inductive current improves confinement and the H_{RLW} factor.

Figure 3 shows that with more counter inductive current it is mainly the barrier strength that increases, while the location remains fixed. We conclude that this is due to the current profile becoming more hollow on-axis. This effect on the barrier is the same as found for central ECCD scans and confirms that the confinement improvement seen in those earlier scans is due primarily to the modification of the current profile caused by the ECCD rather than the slight changes in deposition location due to differences in the Doppler-shifted absorption.

As the EMF interacts strongly with the entire electron distribution function, whereas the ECCD interacts mainly in a restricted region of velocity space, the inductive current drive efficiency is high. With co- induced current I_p is maintained but, as the current profile peaks l_i increases. Driving counter-inductive current, the plasma current slowly drops and q_{95} is increasing during the shot. The inductive current contribution can be readily calculated from the loop voltage and conductivity profile assuming flat *Zeff* and steady-state conditions (i.e. flat V_{loop} profile) using quantities averaged from 1.95s to 2.35s (i.e. 0.55s to 0.95s after the start of the applied *EMF*). However, as I_p is slowly changing, especially for counter inductive currents, a back *EMF* is still present. The database of shots indicates an inductive contribution to I_p of approximately ~0.54kA/mV for co-inductive current and ~1.0kA/mV for counter-inductive current; clearly the inductive current is particularly overestimated in the counter case and a more detailed analysis is required.

Using a χ_e profile calculated from the measured T_e profile and TORAY-GA EC power deposition profiles taken at 1.4s to define the transport, preliminary ASTRA simulations have been made. An abrupt change in V_{loop} causes a current perturbation which penetrates quickly to the barrier location then more slowly to the plasma center with a characteristic exponential time constant of ~0.26s. After 0.55s the V_{loop} at the plasma center has attained only 2/3 of the steady-state value but the current profile is nevertheless centrally peaked. Future work will include the associated modifications of the transport in the simulations to better follow the experimental situation.

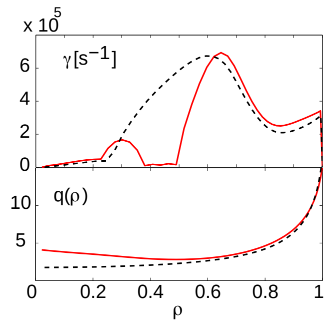

Fig. 4 GLF23 simulations of the growth rate of the most unstable mode as a function of the minor radius for a monotonic (black dashed) and reversed-q (red-solid) profile. Changing only the current profile is sufficient to stongly reduce the growth rate in the plasma core (ρ<0.6) near the q_{min}.

The eITB forms due to the non-monotonic current profile generated by the current profile tailoring. Linear gyrokinetic simulations with the in-house LORB5 code show that the TEM is the most unstable mode. They confirm that there is little influence by the ions. In addition, they show that changing only the q profile can change significantly the TEM growth rate, reverse shear being strongly stabilizing in the region of q_{min} and of the reverse shear.

Figure 4 shows the results of simulations using the GLF23 transport model to calculate the linear growth rates for 2 current profiles – one producing a monotonic q-profile and the other a reversed-q profile. The TEM mode is found to be stabilized for the reversed-q case with a growth rate more than an order of magnitude lower than the monotonic case in the plasma core.

TCV results show that eITBs can result merely from a change in the current profile. In the absence of momentum injection or additional power input, the barriers can be strengthened or weakened while maintaining their position by current profile tailoring alone.

This research was partially funded by the Swiss National Science Foundation.

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