Steady-state, fully bootstrap-sustained discharges in the TCV tokamak

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1. Introduction

The attainment of a high bootstrap current fraction in stationary conditions is a crucial element of the Advanced Tokamak route to nuclear fusion [1]. These scenarios are typically characterized by an internal transport barrier (ITB), with a tight internal feedback loop governing the current profile, which is largely driven by the pressure gradient but in turn strongly affects the confinement and thus the properties and location of the high-gradient region [2]. As the bootstrap current fraction approaches 100%, the external control on the current profile vanishes and a total self-consistency of this feedback loop becomes necessary. This is usually referred to as "bootstrap current alignment" and the question of whether the plasma can support a stable, perfectly aligned state is both scientifically non-trivial and highly relevant to the Advanced Tokamak programme.

We have recently succeeded in answering this question affirmatively in the TCV tokamak by producing discharges in which the current is entirely self-generated by the plasma in conditions of intense electron cyclotron resonance heating (ECRH). These discharges are stationary on the time scale of a TCV pulse (1-2 s), which is significantly longer than a typical resistive current redistribution time (~150-300 ms) and orders of magnitude longer than the confinement time (~3-6 ms).

2. Experimental scenario

High-power ECRH is applied perpendicularly to the magnetic field, thus providing no current drive, during the initial plasma current ramp-up. A small toroidal wave number is given to the waves in order to render the wave vector truly orthogonal to the total magnetic field at the resonance (including the small poloidal field component), within the launcher orientation accuracy. Strong electron barriers (eITBs), with confinement improvement up to a factor of 6 over L-mode, are generated by the transient negative central magnetic shear induced by slowing down the current penetration [2]. The Ohmic transformer current is clamped to a constant value immediately after breakdown, cutting off the external plasma current source. Under the appropriate conditions, the plasma can then evolve unaided towards a stationary and quiescent state, i.e. a stability point of the internal bootstrap feedback loop. Enabling the system to reach this state requires a careful tuning of the timing of both the external coil currents and the EC power sources, to minimise the impact of MHD modes that occur during the initial phase and can either quench the barrier too rapidly or terminate the discharge altogether. In particular, preventing

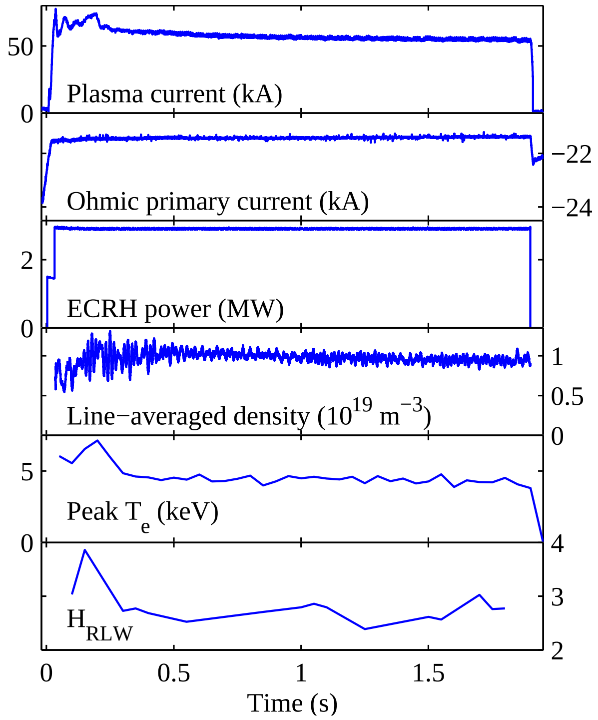

Fig. 1 *TCV discharge 34428. There are no external current sources from 0.02 to 1.9 s. A stable current of 55 kA (to within 2%) is supplied by the bootstrap mechanism from 0.9 to 1.9 s. The confinement enhancement factor in the bottom box is scaled to the TCV L-mode confinement scaling (the Rebut-Lallia-Watkins scaling [3]).*

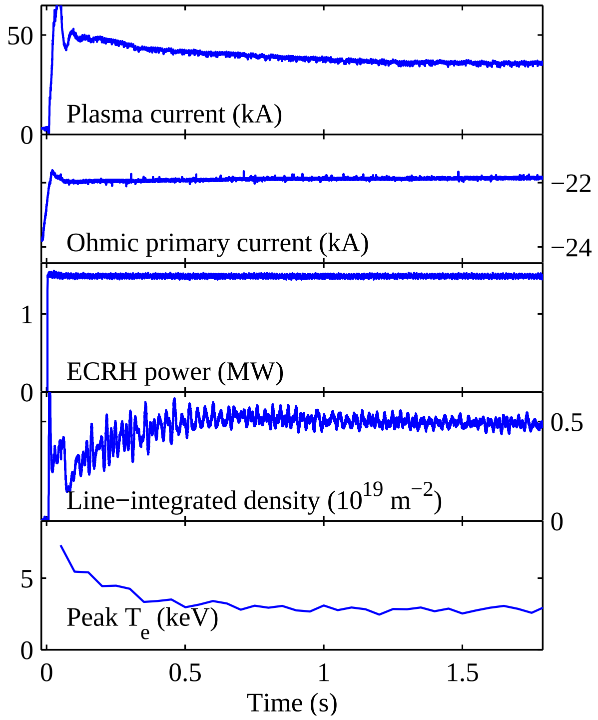

Fig. 2 *TCV discharge 34421. A stationary, purely bootstrap current of 35 kA is sustained from 1.2 to 1.8 s with half as much power as in the case of Fig. 1. The external current input is cut off at 0.02 s.*

the surface loop voltage from becoming negative (injecting a negative Ohmic current) has proven crucial in this initial phase. We have experimented with different power deposition profiles, and it was found operationally that the most reliable and stable configuration is obtained by applying all the power close to the plasma centre. The toroidal magnetic field on axis is 1.43 T and the ECRH frequency (second-harmonic X-mode) is 82.7 GHz.

Typical examples include a 55 kA discharge sustained for 1 s by 2.7 MW heating (see Fig. 1) and a 35 kA discharge sustained for 0.6 s by 1.35 MW heating (Fig. 2), both at a line-averaged density of ~$1x10^{19}$ m^{-3}. This self-organized state is characterized by a narrow eITB with a reduced confinement enhancement of the order of 2.5–3. The normalised temperature profile is shown in Fig. 3 in comparison with a standard Ohmic profile and a typical TCV eITB profile (the latter from a separate experiment described below). The corresponding bootstrap current profile can be seen in Fig. 4. When MHD modes do occur and after they degrade the confinement, striking examples of spontaneous bootstrap overdrive are sometimes observed, with the plasma current increasing autonomously as a result of a confinement recovery (Fig. 5).

We have also explored the possibility of achieving a 100% bootstrap fraction by annulling the total EC-driven current in pre-existing stationary conditions. Standard stationary non-inductive eITBs [2] are first generated by off-axis co-ECCD; counter-ECCD is then added gradually until the total driven current density is nominally zero everywhere. In some cases a quasi-stationary state is indeed established. If the spatial profiles of the co- and counter-ECCD distributions are exactly matched, this configuration differs from the pure-heating one only in the much broader power deposition profile (Fig. 6) and the greater suprathermal electron population that is always observed with ECCD [5]. Unlike the no-ECCD scenario, these discharges retain a rather broad barrier (see Fig. 3), with a confinement enhancement factor of the order of 4-5. This results in significant MHD activity, causing oscillations and jumps both in the confinement and in the total current. The example shown in Fig. 7 displays a quasi-stationary phase starting at ~1.7 s, followed again by a spontaneous current ramp from bootstrap overdrive.

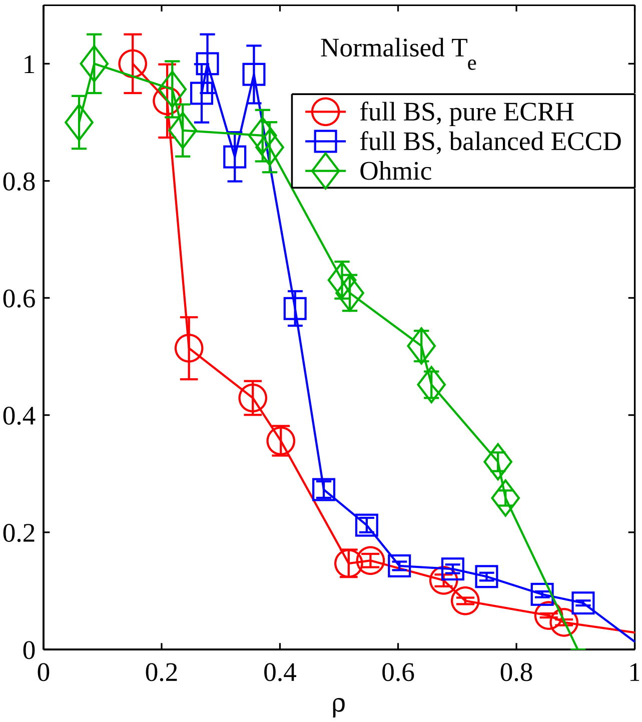

Fig. 3 *Normalised electron temperature profiles for TCV discharges 34428 (narrow eITB with no ECCD and 100% bootstrap; red), 34175 (broad eITB with balanced co- and counter-ECCD and 100% bootstrap; blue) and 34508 (Ohmic; green).*

3. Discussion and conclusions

The achievement of a 100% bootstrap fraction implies the removal of the degree of freedom provided by external current profile control. For steady state to be possible, a state supporting exact bootstrap alignment must exist and must additionally be a stable equilibrium point of the internal bootstrap feedback loop, i.e. an outward displacement of the current density peak must cause the point of steepest pressure gradient to lag on the inboard side, and vice versa. Multiple stable equilibrium points may of course exist in the many-dimensional tokamak parameter space and may be accessible over different operational paths. In TCV two distinct such scenarios have been identified, one involving central heating, no current drive and a narrow eITB, and the other characterized by distributed heating, balanced co- and counter-current drive and a broader eITB. The parameter space is however far from being exhausted, and in particular the effects of density and of plasma shape have not been studied systematically thus far.

For the purposes of the Advanced Tokamak programme, while an existing body of research has already proven that robust steady-state configurations can be achieved with the current being predominantly self-generated by the plasma [1,2], the present results provide a positive

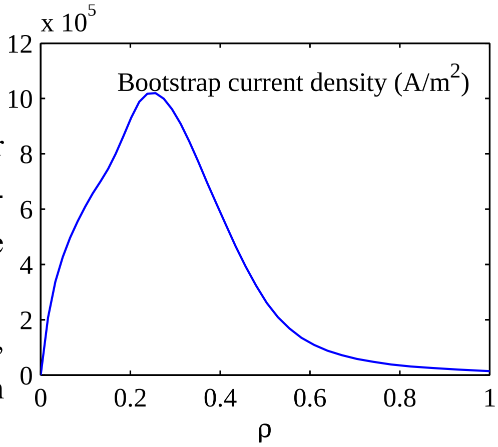

Fig. 4 *Bootstrap current density profile calculated from measured density and temperature profiles by Thomson scattering (TCV discharge 34428).*

answer for the first time to the important additional physics question of the possibility of *purely* bootstrap-driven stationary tokamak discharges.

Acknowledgment

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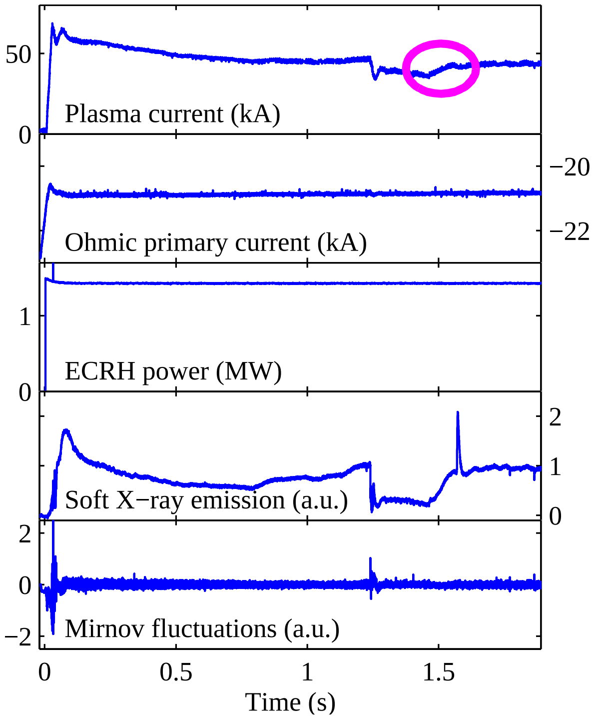

Fig. 5 *TCV discharge 34429. After the MHD event at 1.25 s and the internal disruption it causes, a phase of bootstrap overdrive follows at 1.5 s, with a spontaneous current increase in the absence of external current sources.*

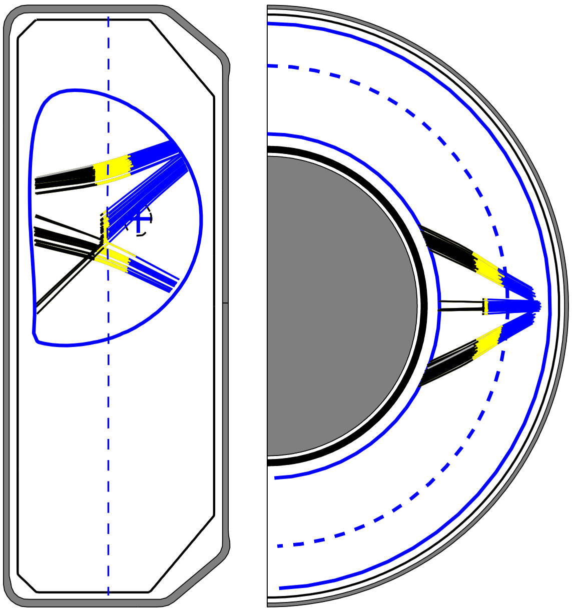

Fig. 6 *Ray trajectories calculated by the ray-tracing code Toray-GA [4] for TCV discharge 34175 at time 1.8 s (poloidal and toroidal views). Co- and counter-ECCD beams are matched pairwise. The wave is absorbed primarily in the yellow region.*

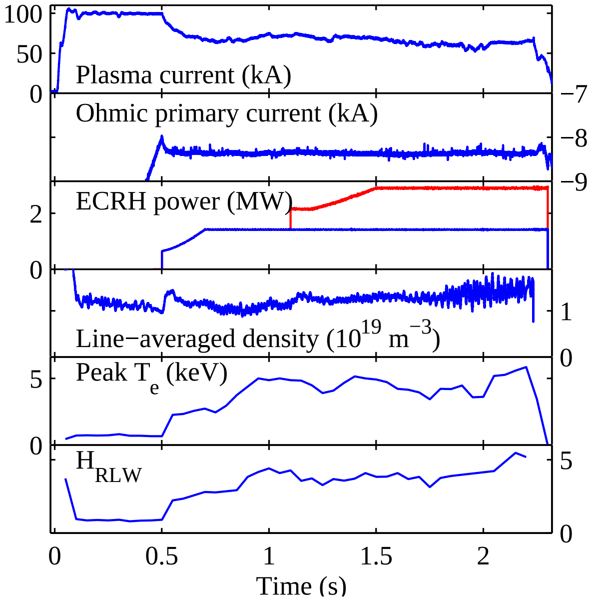

Fig. 7 *TCV discharge 34175. The ECRH power traces correspond to co- (blue) and counter- (red) current drive. The confinement enhancement factor in the bottom box is relative to the TCV L-mode confinement scaling. The total nominal driven current after 1.5 s is zero.*