Full Bootstrap Discharge Sustainment in Steady State in the TCV Tokamak

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Abstract - The Advanced Tokamak scenario, one of the modes of operation being considered for ITER, relies on the attainment of a high bootstrap current fraction. This scenario is typically characterized by an internal transport barrier (ITB). An internal feedback loop then governs the current profile, which strongly affects the confinement and thus the properties and location of the high-gradient region, where in turn the bootstrap current component is localized. The bootstrap current fraction can reach 100% only if the bootstrap current profile can be exactly and stably aligned with the high-gradient region it engenders. Recent work on the TCV tokamak has shown that such an alignment is indeed possible. We have produced discharges in which the current is entirely self-generated by the plasma in conditions of intense electron cyclotron heating (ECH, up to 2.7 MW), by employing two different methods. In one scenario, high-power, second-harmonic ECH waves are launched with no current drive component, during the initial plasma current ramp-up. A strong ITB is generated by the transient negative central magnetic shear that develops in the current penetration phase. The Ohmic flux swing is zeroed immediately after breakdown, cutting off the external plasma current source. The plasma can then evolve spontaneously towards a stationary and quiescent state, characterized by a narrow ITB with a confinement enhancement of 2.5-3 over L-mode. The discharge remains stationary over 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). Following a different approach, we have also succeeded in achieving a 100% bootstrap fraction by annulling the total EC-driven current in pre-existing stationary conditions. Standard stationary non-inductive eITBs 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. In this case the barrier remains broad with a standard confinement enhancement factor of the order of 4-5.

1. Introduction

In toroidal magnetically confined plasmas, a current parallel to the magnetic field is internally generated by the pressure gradient. This “bootstrap” current is a neoclassical effect, resulting from the finite orbit widths of trapped electrons [1]. The tokamak concept, the current best candidate for the exploitation of nuclear fusion for commercial energy production, requires a strong toroidal current, which is conventionally supplied by a pulsed transformer. It is only natural then that the theoretical realization of the existence of the bootstrap current [2,3] led immediately to its being put forward as a possible mechanism for steady-state tokamak operation, without recourse to external current sources. In the context of neoclassical theory, however, it was concluded that a completely bootstrapped tokamak was an impossibility [3]. This conclusion stems from the fact that the bootstrap current does not generate poloidal flux, a manifestation of Cowling’s antidynamo theorem [4]. The bootstrap current, rather, acts as a spatial amplifier, requiring a modicum of current density on the magnetic axis, which can then be magnified considerably away from it in the presence of a sizable pressure gradient. Neoclassically, the trapped particle population vanishes on axis, implying that the bootstrap current itself must vanish there. The seed on-axis current must be generated by other means. In actuality, this constraint may be little more than academic, as the small central seed current required could easily be supplied by non-inductive rf current drive even in a fusion reactor. It is however entirely possible that additional effects may grant existence to a purely bootstrapped tokamak: these include finite “pota-

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to” orbits near the magnetic axis [5] and flux-generating microtearing-mode turbulence [6], both of which can cause effective nonclassical diffusion of current towards the plasma center.

A more significant obstacle to the achievement of a perfectly bootstrapped tokamak could be expected to arise from the collapsing of the degree of freedom represented by an external current source, whether Ohmic or non-inductive. The current density profile has a strong influence on the plasma confinement, which determines the pressure profile, which in turn determines the bootstrap current density. If the latter constitutes the *entire* current density, it follows that the pressure-current system must be completely self-consistent. Whether this is possible depends on the exact details of the physics governing plasma confinement. In view of this, even a small external current, whether co- or counter-directed, could well be tailored to compensate for a misalignment between the current and the pressure gradient.

The absence of external current sources therefore adds further constraints to the inescapable requirements of MHD equilibrium and stability. This suggests that either a 95% or 105% bootstrap fraction could be more readily achievable than 100% and still constitute a viable route to a steady-state fusion reactor. It is clear however that the question of whether a stationary, fully bootstrapped tokamak discharge is possible remains fundamental and is rich in physics implications.

Following the experimental demonstration of the existence of the bootstrap current in an octupole device [7], pioneering experiments on the CDX-U and DIII-D devices [8,9] succeeded in demonstrating the spontaneous generation of pressure-driven parallel currents in the absence of external current sources. In these experiments, plasma breakdown was achieved by electron cyclotron heating (ECH) alone, and the magnetic topology was observed to evolve to closed, nested flux surfaces. In the fusion program, scenarios featuring a high bootstrap current fraction have fallen primarily within the purview of research on the so-called Advanced Tokamak (AT) concept [10-13]. The AT route to nuclear fusion focuses on the attainment of steady state and therefore requires a high degree of current self-sustainment to moderate the amount of rf power required for current drive. This in turn mandates sufficiently high pressure gradients in the plasma core, which in practice can only occur in the presence of internal transport barriers (ITBs). An ITB results naturally in a hollow bootstrap current profile, and negative central magnetic shear is generally understood to cause improved confinement and to sustain the ITB in turn [14-16]. Notable results have been reported in particular from the JT-60U tokamak, where bootstrap overdrive has been demonstrated both by Ohmic transformer recharging and by zeroing the loop voltage in the presence of counter-current drive [17].

Stationary conditions aid greatly in the determination of the bootstrap current fraction unless accurate measurements of the plasma inductance are available. The surface loop voltage can be written as $V_s=R_pI_{p,ind}+d(L_{int}I_{p,tot})/dt$, where R_p is the plasma resistance, $L_{int}=\mu_0R_0l_i/2$ is the internal plasma inductance, R_0 is the plasma major radius, l_i is the normalized internal inductance per unit length, and $I_{p,tot}$ and $I_{p,ind}$ are the total plasma current and its inductive component, respectively. If conditions are not stationary, a zero or negative loop voltage cannot be construed to imply noninductive sustainment or overdrive ($I_{p,ind}\leq 0$) unless both the total current and the internal inductance are known to be non-decreasing. If the externally applied loop voltage V_{ext}, rather than the measured surface voltage, is made to be zero or negative, a similar consideration applies since $V_{ext}=V_s+L_{ext}d(I_{p,tot})/dt$, L_{ext} being the external plasma inductance.

To answer the question of the attainability of “exact” bootstrap current alignment and 100% bootstrap fraction, true steady state is required. Not only must the bootstrap current profile align exactly with the high-gradient region it engenders, this 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. Any misalignment will play itself out over a resistive diffusion time scale. Additionally, all external non-inductive current drive sources must be accurately controlled to ensure their overall contribution is naught. Achieving these conditions would also provide for a quantitative validation of the neoclassical bootstrap current theory [1,18] in a reactor-relevant scenario.

Recent work on the TCV tokamak [19] has succeeded in demonstrating the feasibility of a steady-state, fully bootstrapped tokamak. We have produced stable discharges in which the current is entirely self-generated by the plasma in conditions of intense ECH [20]. This is the culmination of several years of research on electron barriers (eITBs), during which the bootstrap current fraction was steadily enhanced up to its current value of 100% [21-23]. 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).

The ECH system employed in these experiments consists of 6 second-harmonic X-mode (X2), 82.7-GHz gyrotrons, delivering 0.45 MW each to the plasma through 6 independent launchers that can be steered in real time to adjust the deposition locations and parallel wave numbers [24]. The vacuum toroidal field in all cases is 1.43 T.

The remainder of the paper is organized as follows. Section 2 describes the steady-state discharges performed in the absence of current drive, whereas section 3 reports on an alternative scenario with balanced co- and counter- electron cyclotron current drive (ECCD). Conclusions are offered in section 4, which concludes the paper.

2. Bootstrapped tokamak without current drive

2.1. Operational scenario

To test the possibility of full bootstrap sustainment in the absence of any external current sources, the following experimental strategy was employed. Strong ECH, up to 2.7 MW, is applied in the plasma core during a current ramp. This is a widely utilized technique for generating transient ITBs [15]. The drastic resulting increase in the core temperature and thus in the conductivity slows down the current penetration and induces a hollow current profile. Confinement is dramatically enhanced in the negative magnetic shear region and an ITB is formed. Since our objective was to achieve a current that could be sustained by neoclassical effects alone, which was expected to be in the 30-80 kA range, we could not begin the heated ramp from an established equilibrium condition. Rather, we enacted this scenario during the initial current ramp-up following plasma formation. ECH is applied typically in two power steps, from 0 to 15-25 ms after the initial breakdown, with the first step occurring as early as the preionization time preceding the start of the inductive current ramp-up. The injection angles are adjusted to render the beam exactly perpendicular to the total magnetic field at the point of absorption, within experimental accuracy, in order to minimize ECCD. At 6 ms after breakdown, the current in the transformer primary coil is clamped to a constant value, shutting off the external current source altogether. From this point onward, 100% first-pass power absorption is achieved.

As current penetration is occurring along with the initial formation of closed flux surfaces and during the plasma expansion and shaping phase, this technique is fraught with difficulties, primarily engendered by the strong pressure and current gradients leading to often virulent MHD instabilites. These instabilities can accelerate current penetration, degrade the barrier quality, and often lead to disruption. Steering a course that maintains a sufficient ITB quality required a lengthy empirical adjustment of parameters, discharge after discharge. The primary parameters are the timing of the ECH power waveforms, the deposition locations, the imposed loop voltage at breakdown, and the plasma density. In particular, a deposition as central as possible was generally found to be best (see Fig. 1). This has the additional advantage of facilitating the zeroing of the current-drive component, as the poloidal field vanishes on axis. The aiming accuracy of the ECH launchers is $\pm 0.2^{o}$ in the poloidal plane [24], and of the order of $\pm 0.5^{o}$ in the toroidal direction, which corresponds to variations in ECCD of the order of 2-4 kA. More sig-

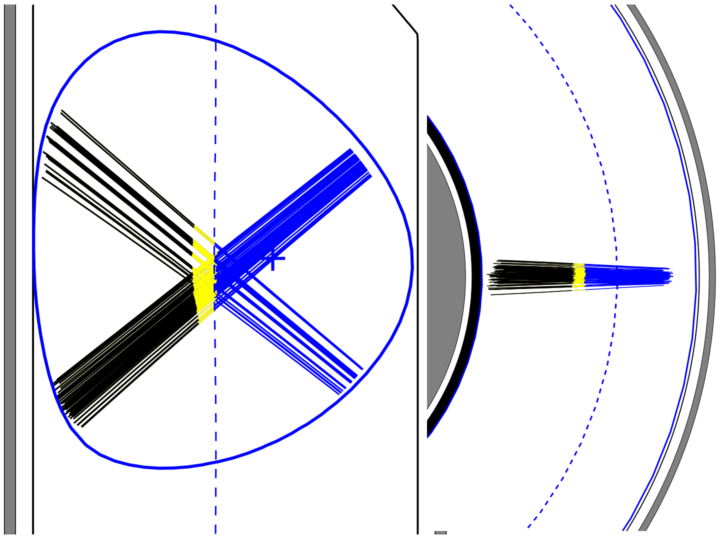

FIG. 1. Ray trajectories calculated by the ray-tracing code Toray-GA [25] for TCV discharge 34428 at time 0.035 s (poloidal and top views). The beams are launched by four upper and two lower launchers. The wave propagates in the blue region and is absorbed primarily in the yellow region, located at ρ*<0.25. The cross represents the magnetic axis.*

nificant are the uncertainties in the plasma equilibrium reconstruction, in the launcher angle calibration, and in the ray-tracing calculations that are the first step for ECCD estimation; as a result, the ECCD component is known to within an accuracy of the order of 5-8 kA.

Crucial to the avoidance of the most aggressive MHD modes is tailoring the current rise to prevent the surface loop voltage from changing sign (see Fig. 2), i.e. to avoid negative current injection. While a slight current overshoot appears inevitable, keeping V_s non-negative has proven possible. To this end, the current ramp is not piloted by feedback operation of the Ohmic transformer, as is usually the case; rather, the latter is driven with a purely feedforward voltage up to the time of clamping (breakdown + 6 ms), after which the coil current is kept constant by feedback control of the voltage based on the measurement of the coil current itself. The typical loop voltage at breakdown is 4.5-5 V, as opposed to the 10 V employed usually. Finally, while the role of the density in navigating through the formation phase is less clear, a lower density seems generally advantageous for mode avoidance. Line-averaged densities of 0.7-1.0x10^{19} m^{-3} are typical for these discharges.

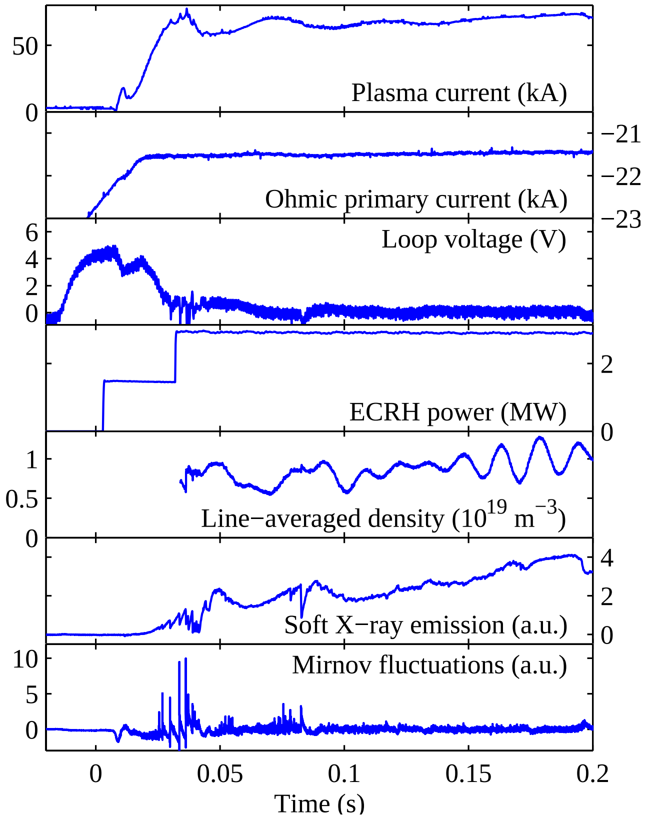

FIG. 2. Early evolution of discharge 34428. MHD modes are visible as bursts in soft X-ray emission and magnetic probe signals.

2.2. Results

During the current ramp phase an eITB is formed, at a location between ρ=0.25 and 0.45 (ρ being a radial flux-surface coordinate equal to the normalized enclosed plasma volume), resulting in an energy confinement enhancement over L-mode (H factor) between 2.5 and 6. (The upper values are typical of eITBs sustained in steady state by off-axis co-current drive and central ECH on TCV [23].) The barrier then moves inward and the high-confinement region shrinks over a resistive time scale of 0.2-0.3 s. The end state is characterized by a narrow eITB at ρ~0.25 with a reduced H factor of the order of 2.5-3.5. The pressure profile shapes of these different eITB profiles and of a reference Ohmic discharge are shown in Fig. 3. In view of the natural evolution of the plasma, the achievement of an initial H higher than 3 appears unnecessary, simply delaying the attainment of steady state. Circumstantial evidence indicates that by lowering the target density the initial confinement is lower and the establishment of an overly broad barrier can be avoided (see Fig. 4). Nevertheless, in practice the time required for the discharge to fully stabilize is the same, approximately 1 s. No systematic parameter scans however have been performed thus far and it is possible that a more rapid relaxation can be achieved.

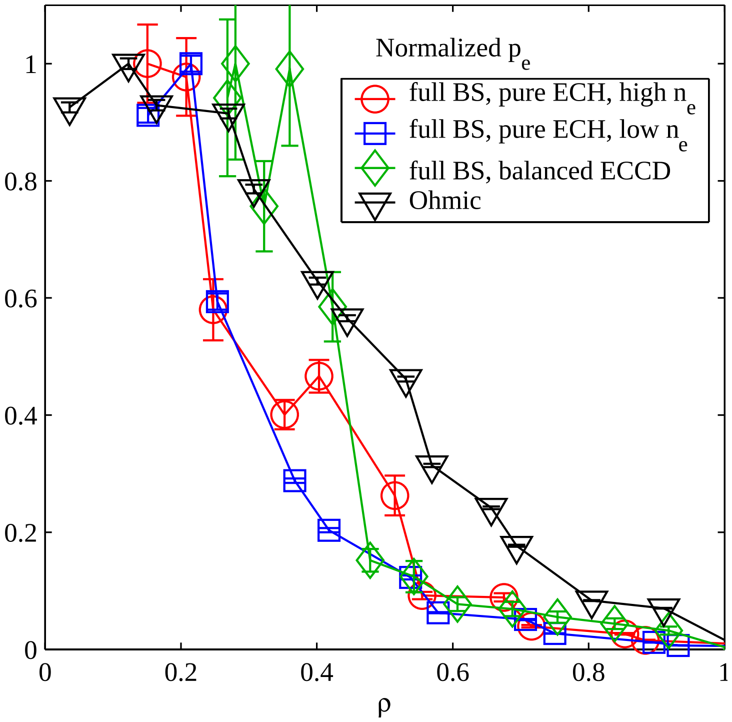

FIG. 3. Normalized electron pressure profiles for TCV discharges 34428 (narrow eITB with no ECCD and 100% bootstrap, line-averaged density ~1x10^{19} m^{-3}; red), 34533 (similar with density ~0.8x10^{19} m^{-3}), 34175 (broad eITB with balanced co- and counter-ECCD and 100% bootstrap, also representative of a typical TCV eITB; green) and 33476 (Ohmic; black).

Once the plasma becomes stationary, it remains in steady state for the duration of the discharge, limited only by the 2-s maximum length of the gyrotron pulse. Two representative cases are shown in Fig. 4: a 55 kA discharge sustained for 1 s at a line-averaged density 1x10^{19} m^{-3} and a 71 kA discharge sustained for 0.8 s at 0.8x10^{19} m^{-3}. Even though the location of the barrier is the same (Fig. 3), the low-density case displays better confinement (peak pressure 13.7 vs. 8.1 kPa). The current is stable to within 2%. For the time scales of TCV these discharges are steady-state for all practical purposes. The one parameter that is difficult to control within less than a few percent is the density, which is slowly drifting in the cases shown. Similar results have been obtained at lower power: the maximum current driven at half power (1.35 MW) is 35 kA [20]. For comparison, the maximum steady-state currents driven by ECCD on TCV are 210 and 160 kA at 2.7 and 1.35 MW, respectively [27].

2.3. Bootstrap current validation

The current density profile is not directly measured at present on TCV. Hence validation of the bootstrap current model is limited to the value of the total self-driven current. For the discharges shown in Fig. 4, the formulas from Ref. 18 yield 43 and 52 kA, respectively, vs. measured values of 55 and 71 kA. Uncertainties in the underlying measurements result in an uncertainty of the order of 20% in the calculated bootstrap current. The plasma current measurement has an absolute uncertainty of ~2 kA, to which must be added the 5-8 kA uncertainty in the estimation of the residual ECCD current. However, even with due consideration of these uncertainties, from the limited data set available at present it appears that the bootstrap current may be larger than theoretically predicted. The effective diffusion due to potato orbits [5], not included in Ref. 18, and to turbulence [6] may be partly responsible for the discrepancy.

2.4. MHD activity

As discussed in subsection 2.1, MHD modes are always destabilized during the current rampup under strong heating. The modes appear on edge magnetic probe signals as rapid bursts (see Fig. 2) at frequencies below 20 kHz, with predominant toroidal wave number *n*=1, typically

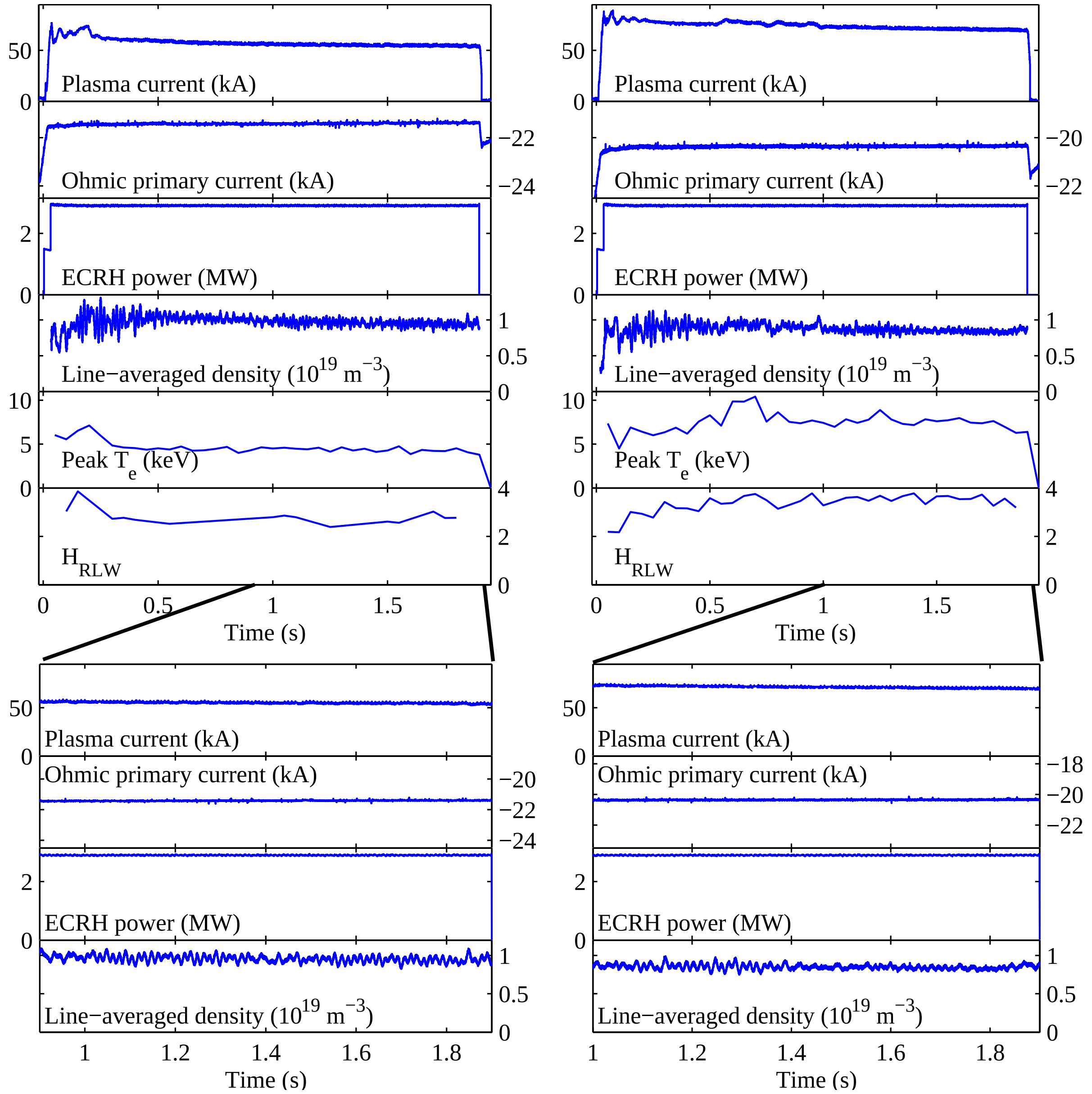

FIG. 4. TCV discharges (a) 34428 and (b) 34533. There are no external current sources from 0.02 to 1.9 s. A stable current of (a) 55 kA, (b) 71 kA (to within 2%) is supplied by the bootstrap mechanism from (a) 0.9 s and (b) 1.1 s to 1.9 s. The energy confinement enhancement factor H_{RLW} is scaled to the TCV L-mode confinement scaling (the Rebut-Lallia-Watkins scaling [26].

only lasting a few cycles and causing transient reductions in confinement. Kink modes may be expected to be destabilized during the ramp at a succession of rational safety-factor values, owing to the strong pressure and current gradients at play. The highly dynamic nature of the scenario lends only limited reproducibility to the mode history, favoring an empirical approach to develop practical “recipes”, described in subsection 2.1, to prevent the most virulent modes that lead to a major disruption. As a counter-example to Fig. 2, Fig. 5 demonstrates the disruptive effect of allowing the loop voltage to change sign.

3. Bootstrapped tokamak with balanced co- and counter-current drive

A second strategy was also employed to demonstrate the possibility of full bootstrap discharge sustainment. Strong, stable eITBs with H>4 are routinely generated in TCV by a combination of off-axis co-ECCD and central heating without any inductive current [21-23]. In these scenarios the bootstrap current fraction is typically between 60 and 80%. By adding off-axis counter-ECCD beams to balance the co-ECCD component exactly (Fig. 6), the total driven current can be annulled, leaving only the bootstrap component to sustain the eITB. If the ECCD cancellation is exact, these discharges differ from the ones without ECCD only in the much broader deposition profile and in a stronger suprathermal electron population. In these discharges the barrier does not shrink as in the scenario described in section 2, rather it remains broad as shown in Fig. 3. This often results in MHD activity causing oscillations and drifts both in confinement and in the total current. Nevertheless, in some of these cases a quasi-stationary state is reached [20], such as in the example shown in Fig. 7, from ~1.7 s; note that later in the discharge an internal plasma reorganization causes a spontaneous current increase. Thus far we have not reached steady-state conditions comparable to the scenario without ECCD, but the research investment in the balanced-ECCD strategy has been more limited up to now.

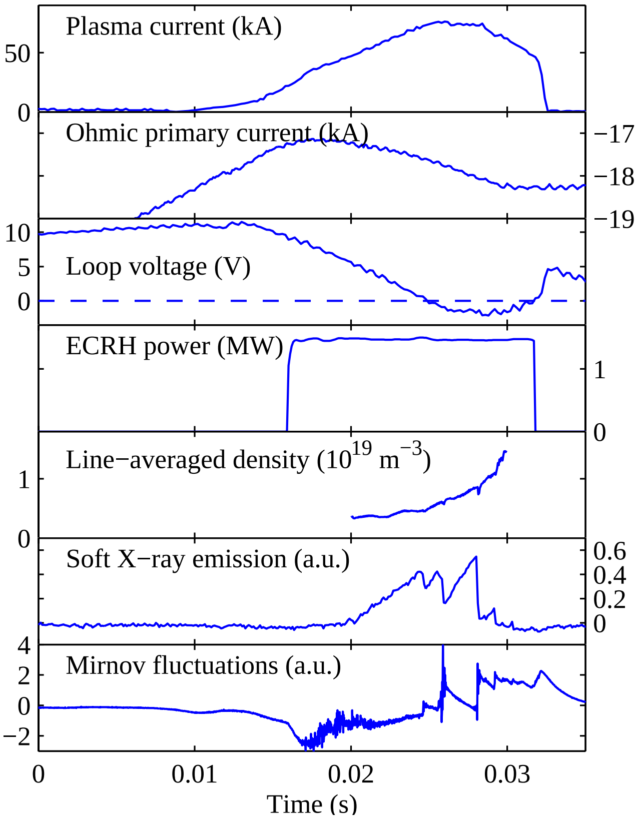

FIG. 5. *TCV discharge 34233. The loop voltage changes sign at 0.025 s, and the ensuing MHD modes disrupt the plasma.*

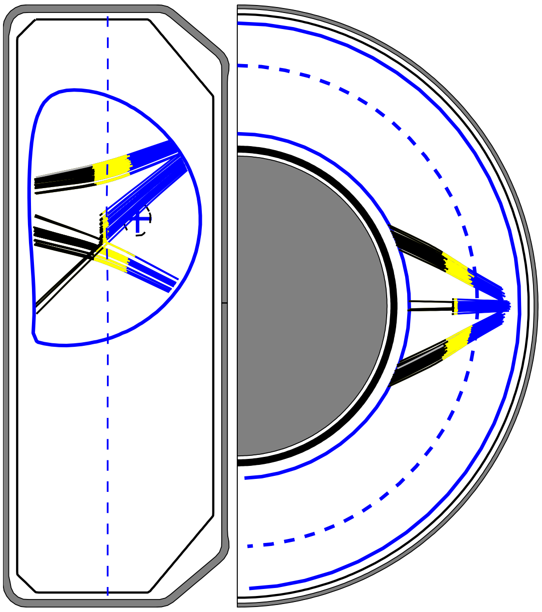

FIG. 6. *Ray trajectories calculated by the ray-tracing code Toray-GA [25] for TCV discharge 34175 at time 1.8 s (poloidal and top views). Co- and counter-ECCD beams are matched pairwise. The waves are absorbed primarily in the regions shaded in yellow.*

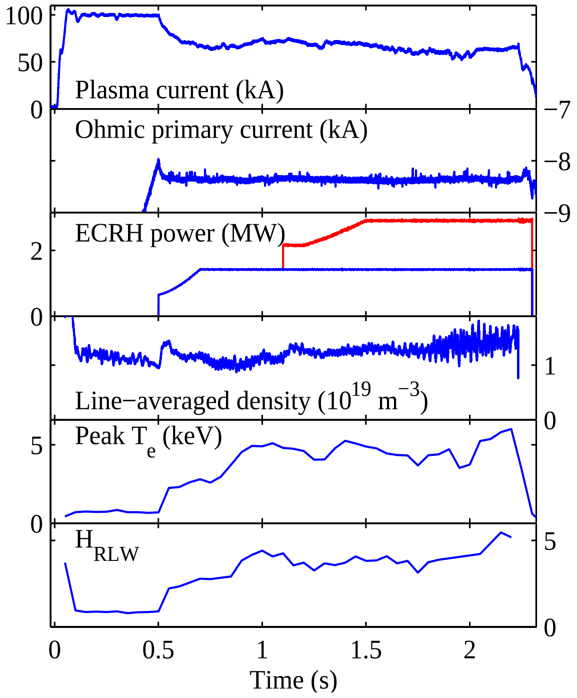

FIG. 7. *TCV discharge 34175. The ECH power traces correspond to co- (blue) and counter- (red) current drive. The total nominal driven current after 1.5 s is zero.*

4. Conclusions

Fully bootstrapped, steady-state tokamak discharges have been obtained for the first time in the TCV tokamak, in scenarios featuring electron internal transport barriers. This demonstrates that a stable and self-consistent equilibrium state is possible in the absence of external current sources. While more extensive parametric studies remain to be performed, there are preliminary indications that the magnitude of the bootstrap current exceeds purely neoclassical predictions.

Acknowledgments

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