Footprint of the Magnetic Configuration in ECH Plasmas of the TJ-II Flexible Heliac

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Abstract. The configurational flexibility of the TJ-II Heliac has been upgraded with the commissioning of a mode of operation that allows changing the magnetic configuration dynamically: the currents feeding the different coil sets can be ramped during the discharge, which allows for, e.g., moving up or down the offset of the rotational transform profile. In these experiments the Ohmic transformer is also activated so as to counteract the induced currents. This capability can be used to investigate the effect of low order rational values of the rotational transform, $\iota/2\pi$, in transport magnitudes, like the effective diffusivities, without altering considerably the magnetic shear. The experiments in plasmas created and sustained with Electron Cyclotron Resonance Heating show, in agreement with previous experience from the TJ-II, that such low order rational values of $\iota/2\pi$ do not deteriorate the effective heat diffusivity.

1. Introduction

One of the distinctive capabilities of the Heliac concept is its large magnetic configuration space, where the plasma volume, rotational transform, magnetic well and other characteristics can be varied over ample ranges. The largest machine of this kind presently in operation is the TJ-II Heliac, a device operating since 1997 [1]. Most of its plasmas are produced in configurations with rotational transform above $t= \iota/2\pi=1$ with very low magnetic shear. In the first experimental campaigns, only Electron Cyclotron Heating (ECH) plasmas were available, which were partly exploited with focus on magnetic configuration effects. Thus, results have been published on, for instance, (i) the effect of t on global confinement [2]; (ii) the influence of magnetic well in fluctuations [3]; (iii) the general response of the plasma to small ohmic [4,5] or ECH driven [6] currents; (iv) the properties of magnetic resonances with respect to fast particle confinement [7]; (v) the role of such resonances in the plasma core [8,9,10] or bulk plasma [11]; and (vi) the effect of magnetic shear on transport [12,13]. All this experience indicates that the effect of the magnetic configuration on confinement should be conveniently described in a context of rotational transform and magnetic shear [14]: In ECH, low density (up to $\sim 10^{19}$ m^{-3}) plasmas, the results from the TJ-II show that lowest order magnetic resonances, like t = 3/2, can be present in low shear plasmas with confining properties not worse than those without major resonances. This is in apparent contradiction with long-time assumed concepts, also supported by the experiment [15], of confinement degradation due to the presence of low order resonances in low shear machines. A main difference between results of the TJ-II Heliac and of other low shear devices (e.g. Wendelstein VII-AS) is precisely the rotational transform, a factor between roughly 3 and 6 larger in the TJ-II. Another important aspect to keep in mind is that the low order resonances are indeed deleterious for transport, also in the TJ-II, when the resonant region occupies a large portion of the plasma, which calls for local transport studies that should include the knowledge of the ι-profile.

Particle and energy balance methods using TJ-II diagnostics with spatial resolution yield effective diffusivities (which can be considered as inverse gradient scale-lengths) that are noticeably, although not dramatically, smaller in and around the location of low order magnetic resonances. This is the case in steady state discharges, where the analysis has been mainly based on Thomson Scattering data and on the information of vacuum magnetic structure [11]. The results are further supported in experiments with Ohmic induction, in which the evolving electron temperature profiles can be obtained from Electron Cyclotron Emission (ECE) signals [16]. The evolution of the rotational transform can be obtained after calculation of the evolving induced plasma current assuming negligible internal currents, a fair assumption in TJ-II ECH plasmas. In this way, the same qualitative behaviour is found as in steady state discharges: despite the poorer spatial resolution of the ECE diagnostic, regions of larger electron temperature gradients are coincident with the positions of lowest order resonances as they move throughout the plasma volume. Only when the induction process is likely to be causing an extended plasma region with low order rational value of the rotational transform does the confinement deteriorate. However, this happens in a transient manner that allows the discharge to recover straight away [14,16].

Uncovering the effect of low order magnetic resonances in stellarator plasmas is very important due to evident implications in the design of a reactor device. TJ-II plasmas are presently entering a new phase with stationary Neutral Beam Injection heated plasmas: the knowledge gained on the role of magnetic resonances and the new capabilities of the machine with respect to its configurational flexibility extend our possibilities to understand and control the physics of stellarators as magnetic confinement devices. The present work is mainly devoted to prove that the new operation mode of the TJ-II Heliac produces plasma discharges with variable configuration in a controlled manner. In Sec. 2 we describe the technique used to produce the plasmas. In Sec. 3 we present a cross-checking of diagnostics from which we deduce that the configuration change during the discharge is similar to a continuous sequence of plasmas with rotational transform not too different from the corresponding static configurations and, in Sec. 4, we show how such dynamic configurations affect electron temperature gradients.

2. Variable magnetic configuration experiments

The hydrogen plasmas here shown are produced in the TJ-II Heliac (B = 1 T, major axis radius R=1.5 m, average minor radius $a \approx 0.2$ m) with lithiumized walls [17] and heated by two ECH lines launching approximately 300 kW each of on-axis heating with high power density. The line-averaged densities are 0.5—0.8 x10^{19} m^{-3} and electron temperatures peak around 1–2 keV. The magnetic configuration can be varied with suited values of the currents in the different coil sets. In particular, the central conductors (Circular Conductor, CC; and Helical Conductor, HC) of the device can shape the Last Closed Flux Surface (LCFS) giving rise to a variety of configurations where magnitudes like the confining volume, the magnetic well, or t can be changed significantly. Recently, this flexibility has been improved with the possibility of changing the currents in the coil sets during the discharge; in other words, with the possibility of changing magnetic configuration during the discharge.

In the experiments that follow we perform dynamic rotational transform scans. Several profiles of vacuum t are shown in Fig. 1. The current in HC ranges from 4.4 kA (bottom profile) to 5.2 kA (top). Instead of performing discharges in each of the corresponding magnetic configurations, the dynamic configuration experiments are designed to vary the magnetic configuration in a single discharge. With proper ramps in the coil sets (mainly HC in this particular case), we can have these vacuum t-profiles at discrete times during one discharge, as noted in the labels on the right of Fig. 2. The timescales must be appropriate for the experiment. The normalized rate of change of the configuration should not exceed the inverse skin times. In our case, the longest skin times are ~ 100 ms and correspond to the hottest plasma core; the relative change in rotational transform is $\Delta\iota/\iota \sim 0.1$ (see Fig. 1) and therefore we can perform a scan like the one shown in Fig. 1 in dynamical configuration discharges that are longer than, roughly, 20 ms. To follow the passage of magnetic resonances through the plasma, say two major resonances like 8/5 and 5/3 in Fig. 1, an appropriate time for the duration of the discharge is ~ 200 ms.

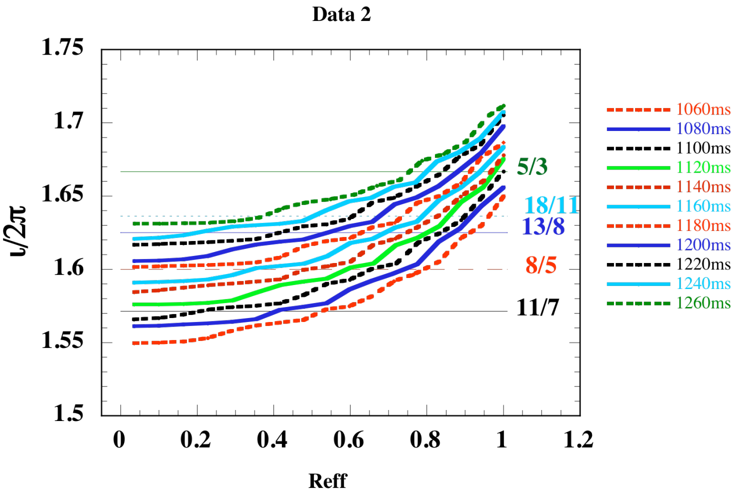

FIG. 1. Rotational transform profiles for several vacuum magnetic configurations obtained by changing (mainly) the current in the helical conductor. Several magnetic resonances move inwards in radius as the edge t increases. In a dynamic configuration experiment, these vacuum configurations coincide with discharge times like those labeled on the right.

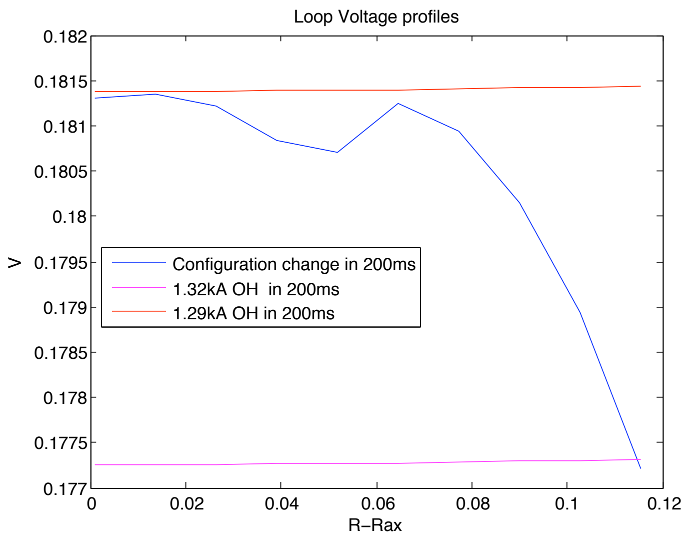

FIG. 2. Calculated radial profiles of loop voltage due to a linear change of magnetic configuration with HC varying from 4.4 to 4.8 kA in 200 ms; and two values of loop voltage due to linear ramps in the OH coils.

The changing poloidal magnetic flux in dynamic configuration discharges induces toroidal plasma currents that will be stronger the faster the change. This flux change can be compensated quite well in the plasma region with the Ohmic transformer. Figure 2 shows the radial profile of the induced loop voltage as a function of the distance from the magnetic axis for a configuration change in which the current in HC varies from 4.4 to 4.8 kA in 200 ms. We also plot the induced voltages for two linear ramps in the currents of the OH coils. Noting the scale of the ordinate we can assume that the geometry of the coil sets of the TJ-II allows for good compensation of flux change between HC and OH coils. Observe also that the calculations have been done including the rate of change in the currents of *all* the coils, although in these experiments only HC varies substantially.

The main set of diagnostics in these experiments consists of Rogowskii loops for the net plasma current, a poloidal set of Mirnov coils, ECE and Thomson Scattering for the electron temperature, micro-wave interferometer for the line density; reflectometer, Soft X-Ray chords and Thomson Scattering for the reconstruction of electron density profiles and, at the plasma edge, a Langmuir probe and a magnetic probe to obtain the fluctuating density, floating potential and radial component of magnetic fluctuations.

3. Description of the discharges

Figure 3 corresponds to a discharge with IHC, the current in HC, changing linearly in such way that the vacuum configuration is coincident with the standard configuration (IHC=4.4 kA) at t = 1060 ms, see left arrow. In a normal experiment IHC would have a flat top (1000–1300 ms) during the discharge. The line density is kept around $0.6{\cdot}10^{19}$ m^{-3}. The evolution of the plasma current is similar to that of control ECH discharges, i.e., an initial negative value that stabilizes later in values of the order of 1 kA. Without OH compensation, the net plasma current is always negative and reaches values (not shown) close to -3 kA. Except for the plasma currents, other magnitudes like the density and temperatures normally take some 30 ms to stabilize after the ECH switch-on. Two different ramps have been designed to have configurations in, respectively, a “slow” scan with IHC=4.4 kA at t=1060 ms and IHC=4.8 kA at t=1260 ms; and a “fast” scan with IHC=4.4 kA at t=1060 ms and IHC=5.2 kA at t=1260 ms like the one of Fig. 3. At such times (shown with arrows in figure 3) the vacuum magnetic configuration is theoretically coincident with calculated configurations of the TJ-II operational space, which allows a first interpretation of diagnostic signals.

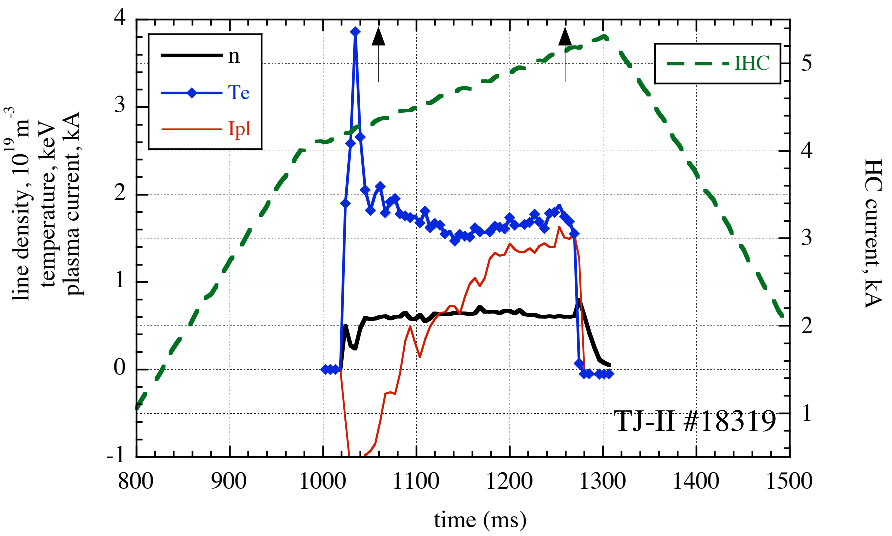

FIG. 3. Time traces of line density (thick line), core electron temperature (diamonds), net plasma current (thin line) and current in the helical conductor (dashes) for TJ-II discharge #18319. The arrows indicate times at which the vacuum configuration is coincident with configurations of the TJ-II flexibility diagram.

Fig. 4 shows the result of analyzing the mode number corresponding to the poloidal array of Mirnov coils for a slow (left) and a fast (right) configuration scan like the one in Fig. 1. IHC and time are linearly related. In order to obtain the poloidal mode numbers, the time traces from the coils are processed using the Singular Value Decomposition (SVD) filtering technique. The obtained values are crosschecked against additional methods like the Lomb periodogram or the comparison with filament-based simulations [18]. Mode numbers coincide with low order rationals as they enter the plasma: a mode with m=5 is detected by the diagnostic up to IHC ≈ 4.5 kA (t ≈ 1085 ms). According to the vacuum calculations, the n=8/m=5 resonance should be occupying the region $\rho \approx 0.7$ at that time. Almost immediately after, when IHC ≈ 4.5 kA at t ≈ 1090, the n=5/m=3 resonance touches the plasma. This is detected by the Mirnov coil set with an associated mode number m=3 (and m=6, very likely a harmonic that can only be followed for a short time). The m=3 mode persists until IHC ≈ 5.2 kA at t ≈ 1260 ms, when the position of the resonance is also $\rho \approx 0.7$. Note the similitude between the slow and fast scans in terms of MHD activity.

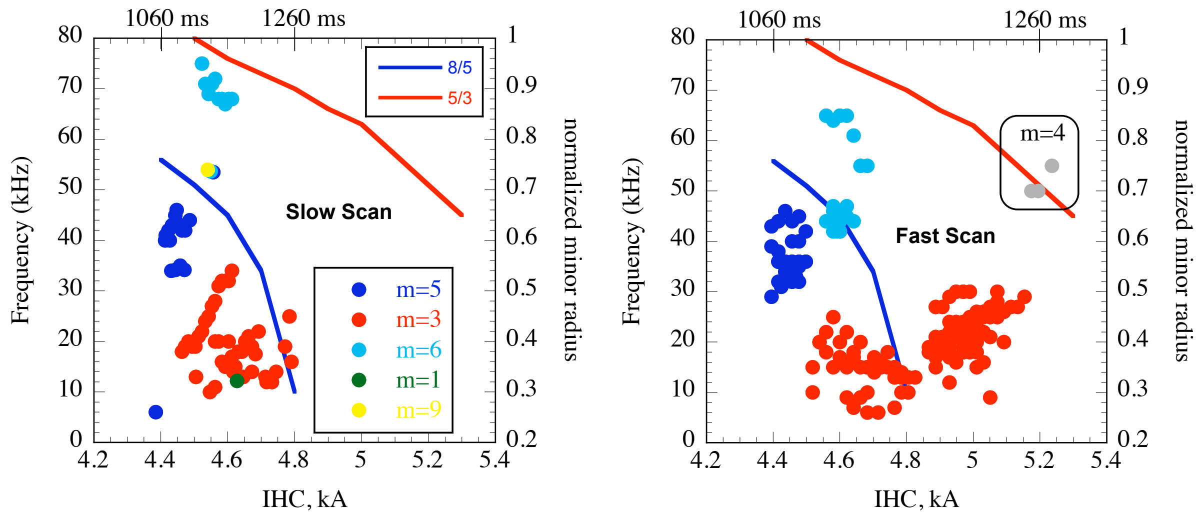

FIG. 4. Frequencies and poloidal mode numbers as a function of the currents in the helical conductor in slow (left) and fast (right) scan discharges. The corresponding times of the discharges are shown above.

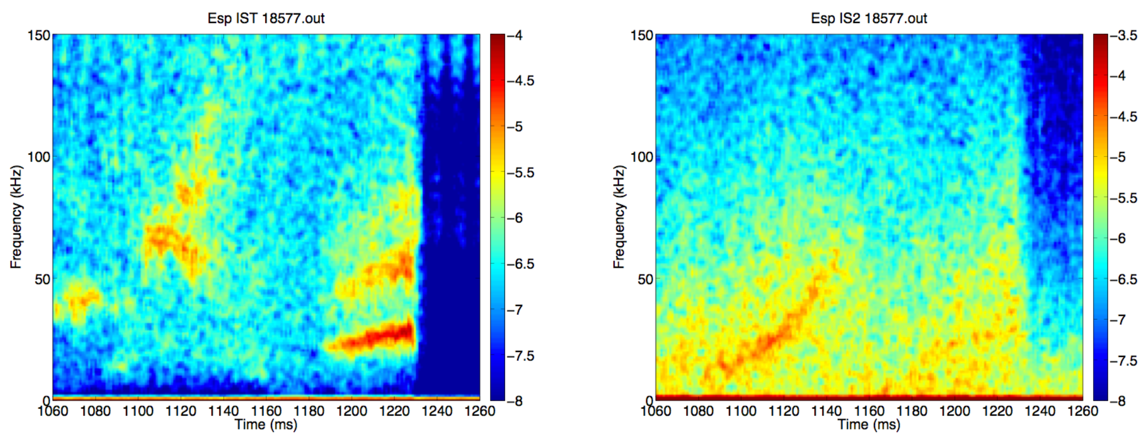

FIG. 5. Spectrograms of the signals of a magnetic probe ($\rho \approx 1.05$, left) and the saturation current of a Langmuir probe ($\rho \approx 0.95$, right) for the fast scan discharge TJ-II #18577. The discharge is terminated at $t \approx 1230$ ms due to ECH density cut-off limit.

A magnetic probe (Fig. 5, left) located very close to the LCFS detects also a ~40 kHz mode at the beginning of the experiment. The m=3 mode of Fig. 4 is, however, only weakly detected by this probe while higher frequencies, associated to m=6 according to Fig. 4, clearly appear. It is important to recall here that the magnetic probe in Fig. 5 is oriented so as to detect the radial component of the variations in magnetic field, while the Mirnov set is poloidally oriented. The m=3 mode, on the other hand, is clearly felt by the Langmuir probe located just inside the LCFS (Fig. 5, right). Note that the frequency is also increasing. Since the measurement of the ion saturation current is local, the disappearance of the signal means that the corresponding perturbation has moved inwards from the probe location, that is, the 5/3 resonance moves inside $\rho \approx 0.95$ when IHC ≈ 4.7 kA, t ≈ 1140 ms. According to the vacuum calculations, the position of the 5/3 resonance should by then be $\rho \approx 0.93$. At t ≈ 1185 ms (IHC ≈ 4.9 kA) another ~ 25 kHz mode is detected by the magnetic probe. After 5/3, the only low order rational that enters the plasma according to the vacuum calculations is 17/10, practically at that time. It is, however, much more likely that the radial component of the m=5/3 magnetic perturbation becomes noticeable to the probe at that time (note similar frequencies in Fig. 4 –right). We have shown TJ-II discharge #18577 for the data from probes because the signals are cleaner –the density is also higher– although it reaches the ECH cut-off density before the end of the experiment, at t = 1230 ms. Other discharges show similar spectrograms. The signals in the floating potential are in all cases similar to the ion saturation current. The results from figures 4 and 5 indicate that the resonances near the edge plasma approach the vacuum values. Nevertheless, it is possible that a residual parallel electric field (see Fig. 2) is causing currents to flow near the plasma periphery, a region of low temperature and thus low conductivity and short skin time, which would modify the edge rotational transform. Indeed, in Fig. 4 (right) an m=4 mode is detected. This may correspond to the resonance 7/4, for whose appearance at the LCFS we would need IHC = 5.6 kA in vacuum. It may also be an error in the identification of the mode number.

4. Effect on T_e-profiles

Previous experience in TJ-II ECH plasmas [11,14,16] indicates that the electron temperature gradient is sensitive to the presence of magnetic resonances, i.e., low order rational values of the rotational transform. If there is a finite albeit small magnetic shear, such gradients are found a bit steeper in the presence of the resonance. This can be checked also with the variable configuration experiments. The evolution of electron temperature profiles is taken from ECE data, although the diagnostic was not absolutely calibrated for these discharges and we have tuned it using a fit to Thomson Scattering profiles. The density profiles, necessary to calculate an effective diffusivity, are taken from a reconstruction based on SXR chords up to $\rho \approx 0.65$. The profiles are continued with data from the reflectometer. The metrics of the different configurations (see Fig. 1) are practically the same and we have taken the vacuum configuration that would correspond to t = 1160 ms, that is, the mid of the discharge.

Fig. 6 is a contour map with the time evolution of the effective electron heat diffusivity profile. The corresponding discharge (#18587) is similar to the one shown in Fig. 3 except for a fast event near t = 1180 ms. It is important to realize that these experiments are designed to keep the rotational transform profile with low shear, ideally the vacuum one. According to the previous figures, the plasma response to the changing configuration and the bootstrap current cause small deviations in the rotational transform with respect to the vacuum one, but even deviations no larger than a 10% in ι can alter considerably the magnetic shear. We have performed about 30 discharges with dynamic configuration scans and several of them show fast events associated with strong magnetic perturbations, drops in H_α light and radiation bursts, like the one shown in Figs. 6 and 7 at $t \approx 1180$ ms. These events can be a consequence of having null magnetic shear in finite regions inside the plasma, which may have a strong impact in the radial electric fields and rotation, aside from consequences in confinement. Although not shown, the detailed temporal evolution of the low frequency spectrum of a Mirnov coil and several edge bolometer signals during this event exhibits a high intensity mode at 20 kHz. This mode splits into two modes with approximate frequencies of 15 and 25 kHz. Preliminary analysis of the soft X ray emissivities and the analysis of different bolometer chords indicate that the event is associated to a poloidal mode m=8 and is located in $\rho \approx 0.65$. Further work is needed to elucidate in this and other phenomena found in experiments with variable configuration.

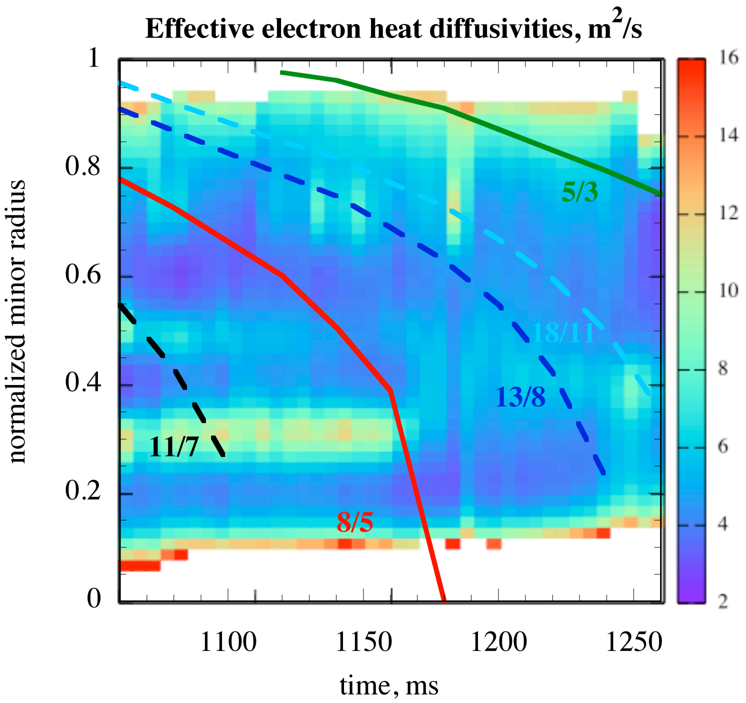

FIG. 6. Contour map of the effective electron thermal diffusivity (~1/L_{Te}) during a fast configuration change experiment. Lowest order magnetic resonances of the calculated vacuum rotational transform are traced with lines. White areas correspond to out of range data.

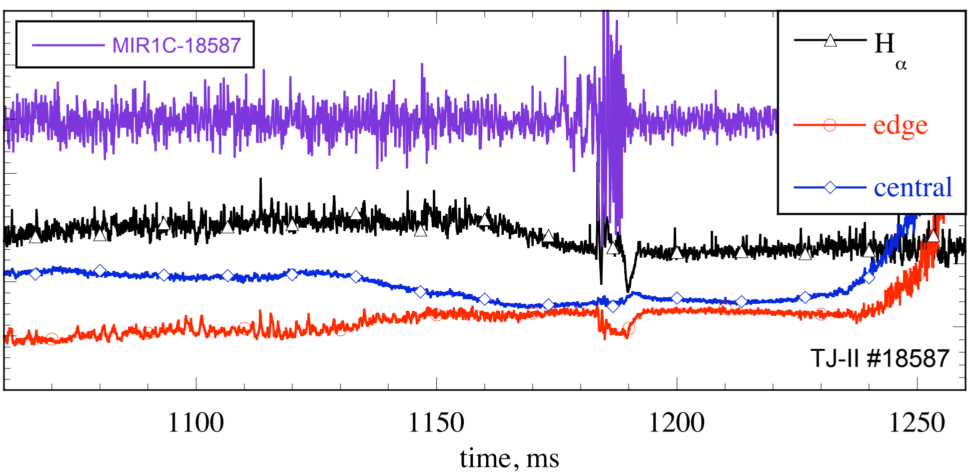

FIG. 7. From top to bottom: time traces (arbitrary units) of Mirnov coil, H_α monitor, and edge and central bolometer chords for TJ-II discharge #18587.

Finally, it is worth noting that the fact that several resonances cross the plasma minor radius does not destroy confinement. Moreover, if the calculated vacuum position of the resonance 8/5 is, as expected, close to the real one, then the electron temperature gradients in Fig. 6 seem to be somewhat larger in its presence. This is in agreement with previous experience in the TJ-II. Apparently, exceptional conditions of very small magnetic shear over finite regions allowing for the opening of large islands can provoke transient events like the one just described. Otherwise, the resonances in these plasmas are not a threat for confinement.

5. Summary

The TJ-II Heliac can produce discharges with variable magnetic configuration. In this work we show rotational transform scans where the “footprint” of low order resonances can be followed dynamically without altering much, as it happens in discharges with Ohmic induction, the magnetic shear. The effect of the resonances on the plasma profiles is found compatible with the results found in previous experiments: major resonances can be sustained in low shear conditions and seem to be associated to lower effective diffusivities, while in conditions plausibly related with zero shear in a finite region, there are transient magnetic events that strongly deteriorate confinement.

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