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ABSTRACT.

The interplay occurring between the magnetic shear, the plasma rotation and the bootstrap current profile, to get and sustain an Internal Transport Barriers (ITB), makes mandatory the presence of an active control of both current density and the pressure profile. So far the most used strategy to obtain high performance ITB has been the optimization of the current density profile early in the discharge by combining the skin effect with a pre-programmed off-axis non-inductive currents. The stepping up of the Neutral Beam (NBI) during this phase provides the necessary input of external momentum and auxiliary heating. On JET it has already been shown the possibility of a closed loop real-time control of parameters characterizing the pressure profile in ITB discharges [1]. Moreover preliminary experiments [2] have shown the possibility to control a set of families of target safety factor profile (q). Here we will report the results of controlling the q profile in two different plasma configurations: with and without an ITB. In the first scenario only the Lower Hybrid (LHCD) is used to control three different classes of target q profile in absence of the ITB. In the second scenario a combination of the NBI, of the Ion Cyclotron Resonant Heating (ICRH) and of the LHCD is used to control the current density profile in an ITB configuration. The goal was achieved by using a technique [3] which is well adapted to the control of a distributed parameter system such as a set of radial profiles and that it is based on a Truncated Singular Value Decomposition (TSVD) of a model integral operator (diffusion-like).

1. SCENARIO WITHOUT ITB.

The most used technique to produce an ITB consists in obtaining the necessary q profile during the plasma current rise, either by relying in the current diffusion or by conditioning it with some external non-inductive current drive. Our first experiment was the control of the q profile evolution during this phase (before the ITB onset) by using the LHCD. The limited available LHCD power constrained the experimental parameters: $I_p = 1.3MA$, $B_T = 3.1T$. The q profile was described by five reference constant values at five different normalized plasma radius: r/a = .2 - .4 - .5 - .6 - .8. Three different kinds of experiments were successfully attempted. In the first a monotonic q profile was chosen as reference; in the second a reversed profile was controlled starting from a plasma scenario with an already reversed q; finally, in the third experiment a reversed q profile was actively achieved and sustained starting from a monotonic q profile. Figure 1 shows the three different reference profiles and the evolution of the real q profiles at different times. These profiles were obtained by using a real time inversion of the polarimetry measurements. The control was switched on a different timing in the three scenarios, but in all the cases the experiment was lasting more than a resistive diffusion time and the experimental profiles were frozen to the reference one for several seconds.

2. SCENARIO WITH ITB.

The next logic step is the control of a q profile during a well established ITB configuration. In Fig.2 it is shown the time evolution of a few important quantities for the used scenario. In the experiment all the three available heating systems were used to control the q profile, as defined by 5 constant values at different plasma radius (r/a = .2, .4, .5, .6, .7). The plasma current is not constant during the time, but it is preprogrammed to decreases from 1.8 to 1.5MA between t = 7s and t = 11s; after that, and before the end of the discharge, a plateau of 2 seconds was available to study a quiescent phase. This evolution was chosen to guess the role played by the applied loop voltage in the current density evolution. Other quantities characterizing the experiment were: $B_T = 3T$, $\langle n_e \rangle \approx 3\times10^{19}$ m^{-3}, $T_e \approx 7$ keV, T_i ranging between 10 and 13KeV, and β_p varying between .7 and 1.1. At t = 7s the NBI power was programmed to step down (Fig.3) of 5MW to allow more margin in terms of power available for the active controlled phase; finally the controller was switched on at t = 7.5s. As can be noted by the neutron yield behavior, the sudden NBI decrease causes a strong reduction of the ITB strength that becomes just marginal in the following of the discharge. The Loop Voltage drops to a value quite close to zero between t = 8s and t = 13s, showing that discharge is not far from a fully non-inductive regime.

Actually a simulation performed with JETTO code shows that about 70% of the plasma current is driven non inductively; in particular 30% + 30% of the current is driven by the bootstrap effect and by the LHCD. The used control matrix of gains was got by a series of dedicated discharge, were the transfer function of all the actuators (NBI, LHCD, ICRH) was obtained stepping down, individually, the power of any system. In Fig.3 are reported the reference waveforms for the three actuators, as requested by the controller, and the real powers coupled with the plasma. All the system powers are actively modulated to follow the plasma evolution, and must be underlined the correct agreement in between the requests and the delivered powers. In Fig.4 are shown, versus time, the q experimental values, the reference values and JETTO simulations at three different r/a: .2, .4, .6.

JETTO code was used to simulate the current diffusion by taking all the experimental temperature and density profiles. A constant $Z_{eff} = 3.5$ was used, as provided by the bremsstrahlung. The simulation was able to describe quite well the behavior of all the macroscopic quantities such as the Loop Voltage and the Li. As shown by the figure the simulations was also able to reproduce the experimental q data at all the times and plasma radius. However it also showed that the plasma did not achieve a fully steady state phase. A further simulation, lasting up to t = 27s, performed by freezing the last available experimental kinetic profiles, has shown that to achieve a relaxed parallel electric field profile, on a time scale of the order of 15 s, it should be necessary to repeat the experiment either at higher LHCD (≈4MW), or with an ITB strength similar to the one of the early phase of the discharge. The next step in this experiment at JET will be to try the simultaneous control of pressure and current profile in an ITB plasma scenario.

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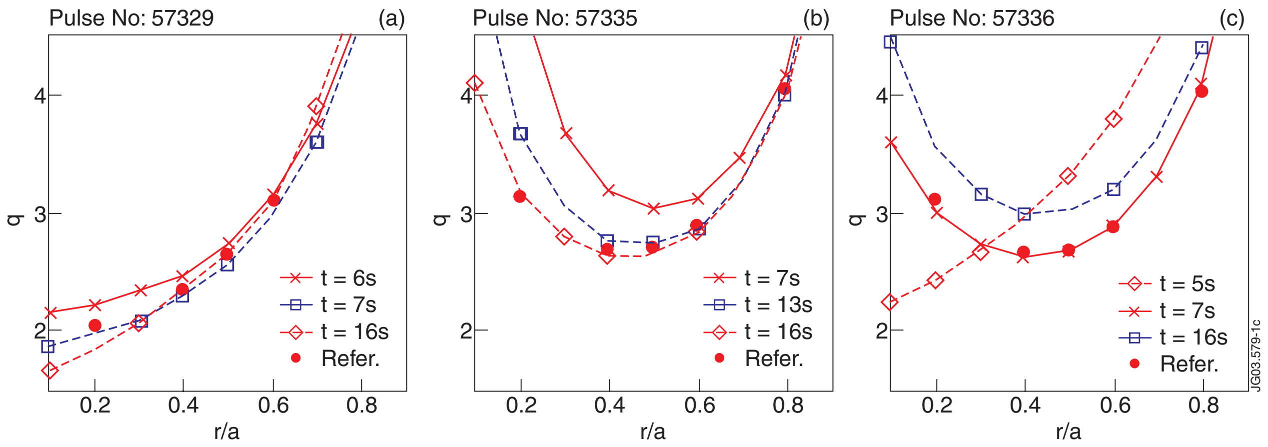
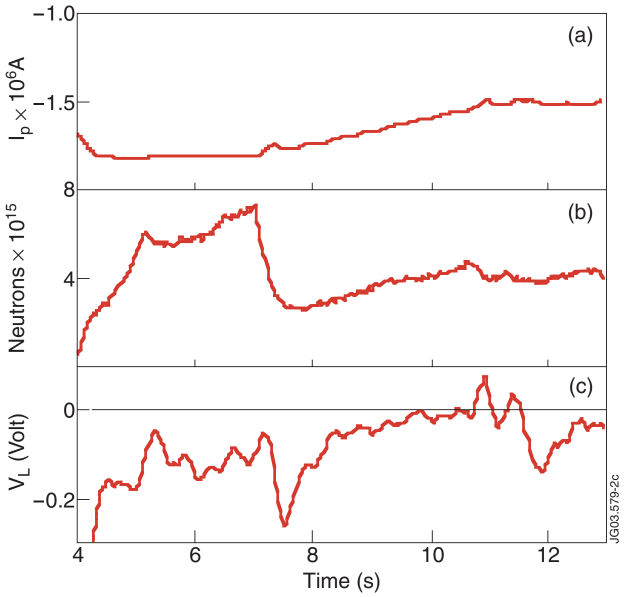


Figure 1:Reference q profile and experimental ones, obtained in closed loop. a) Monotonic q profile; b) Reversed q profile; c) Reversed q starting from a monotonic q profile



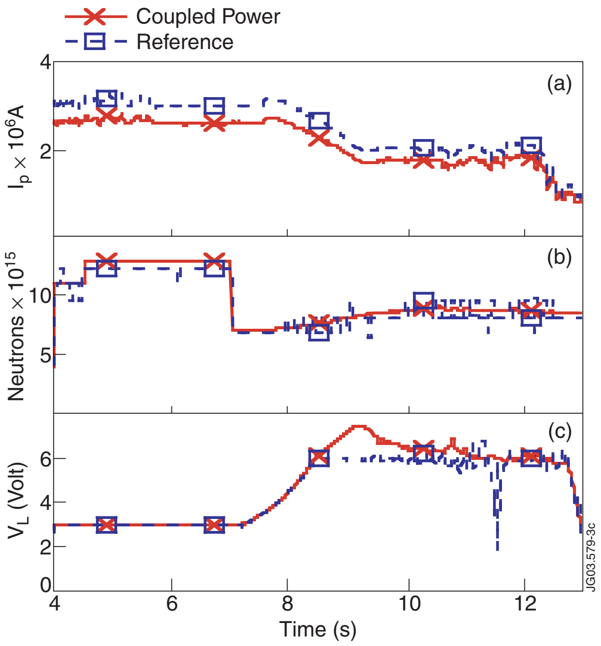


Figure 2:Pulse No: 58474: time evolution of the plasma current (a), the neutron yield (b) and loop voltage (c).

Figure 3:The Reference waveform as requested by the controller and the coupled ones for the LHCD (a), NBI (b) and the ICRH (c).

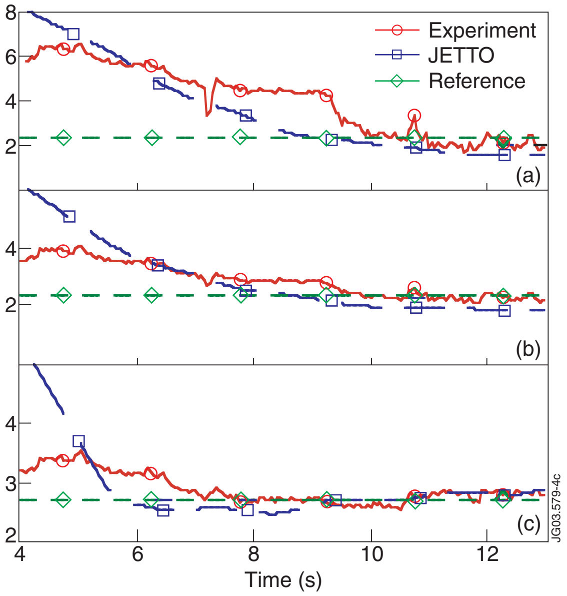


Figure 4: Time traces of reference q, the experimental values and JETTO simulation for radius a/r=.2, .4, .6.