*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-5.126 (2007)*

# Development of 20s long hybrid scenarios on JET

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**Abstract**

This paper reports the results of recent experiments carried out at JET achieving a stationary hybrid scenario lasting 20s with $\beta_N \approx 2.5$ and $H_{89} \approx 2$. Up to 186 MJ have been injected in the plasma via Neutral Beams, with a significant fraction (up to 50%) of current density driven non-inductively. Emphasis is given to the plasma control features (boundary flux control, strike points sweeping and total plasma current control) that have allowed this achievement.

## 1. Introduction

In recent years, the so-called hybrid scenario has been proposed as an alternative H-mode to the conventional ELMy H-mode for ITER operation. This scenario is characterized by a central value of the safety factor close to 1 and a low central magnetic shear. Sawteeth activity is low or absent, thus preventing large Neoclassical Tearing Modes (NTM) to be triggered.

Several experimental devices have validated the performance of the hybrid regime, such as DIII-D [1], ASDEX-U [2], JT-60U [3] and JET [4]. In this last case, the pulse duration achieved (≈ 5 s) was smaller than the resistive time, thus preventing a thorough test of the scenario for durations comparable with the current diffusion time and for assessing plasma-wall interactions. This paper reports the main results of dedicated experiments carried out at JET during 2006 campaigns, using a stationary hybrid scenario lasting 20s.

Stationary scenarios pose challenging control issues, requiring simultaneous and sometimes competing active control of plasma performance, stability and loading on the in-vessel components. Hence, during these experiments a number of control features specific for

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[*] See appendix of M. L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006).

stationary discharges have been successfully implemented, such as boundary flux control, strike points sweeping, and total plasma current control through external non-inductive current drive systems.

## 2. Experimental set-up and main results

The magnetic configuration used is a high-triangularity ITER-like with plasma current of 1.3 MA, toroidal field 1.5 T and q95=3.5 (Fig. 1). A Lower Hybrid (LH) pre-heat is performed during the plasma current ramp-up. A scan of LH power levels (from 0 to 1.2 MW) allowed to modify the target q profile, showing that [5] for LH power below 0.5MW no significant 3/2 NTM is present, but intermittent sawteeth activity can occur, while for LH power above 0.5MW no sawteeth occur, but strong 3/2 NTMs may appear, leading to a degraded confinement (typically 15%). Neutral Beam Injection (NBI) is used during current plateau (Fig. 2), for a duration of 20s at a level of about 10MW, leading to a record of 186MJ of NBI energy injected in the plasma. A careful timing of the beams was required in order to deal with NBI power supply limitations.

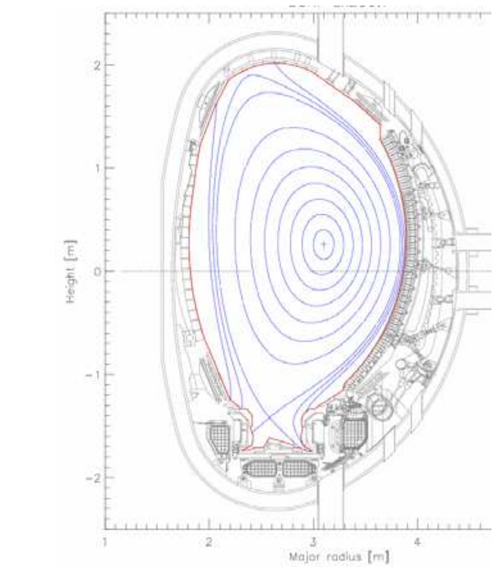


Figure 1. Magnetic configuration

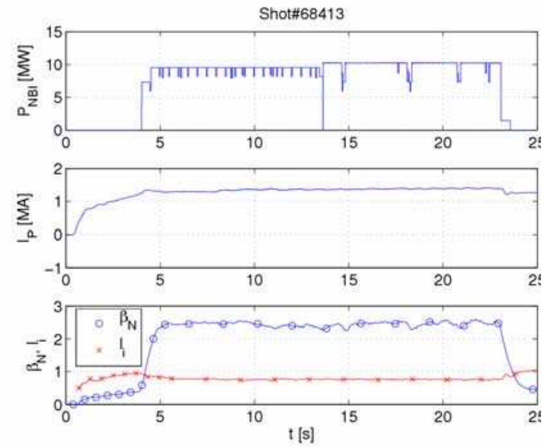


Figure 2. Time behaviour of plasma current, NBI power, $\beta_N$ and $l_i$

A current balance analysis [5] carried out with the CRONOS code [6] suggests that the q profile is in fact stationary thoughout the 20 s plateau, and has shown that the bootstrap current can be as much as 500 kA (40% of the total plasma current), while the current directly driven by NBI amounts to around 150 kA (more than 10% of the total).

The normalized beta $\beta_N$ stays around 2.5 (below the ideal wall limit) for almost 20 s (Fig. 2), which is more than three resistive times [5] and more than 70 times longer than the confinement time, with a thermal H factor equal to 1 with respect to the ITER scaling H IBP98(y,2) [7].

## 3. Control features

The new JET eXtreme Shape Controller (XSC) [8] recently installed and validated for accurate control of the plasma boundary also in presence of huge variations of poloidal $\beta_p$ and internal inductance $l_i$, has been integrated with several new key plasma control features, in order to make these experiments compatible with long duration.

First of all, the first wall must deal with the power deposited on plasma facing components. In particular, mitigating local power on the divertor target is less of an issue when using carbon tiles, but can be essential with beryllium or tungsten tiles because of their lower melting temperature. To this purpose, a strike points sweeping technique (described in details in [9]) has been tested for 13s of the 20s long hybrid scenario. The strike points have been swept with a peak to peak amplitude of 7cm and a frequency of 4Hz, with no significant confinement losses and a slight influence on ELM frequency [5]. The local temperature at the target has been measured with the new infrared camera, showing that sweeping causes a decrease of the maximum temperature on the outer divertor tile of about 100° C [5, 9].

During 15 s of the plateau of the 20s experiments reported in this paper, plasma boundary flux was controlled to a desired value (estimated on previous reference pulses), as detailed in [10], by means of a SISO (single-input-single-output) loop acting on the current in the transformer circuit, using a Proportional-Integral (PI) controller whose gains have been tuned by standard design techniques on the basis of the linearised CREATE-L model [11].

When the transformer current is used to control the boundary flux, the plasma current is in principle left floating. Hence, a further feedback loop has been added, that controls the plasma current using the NBI power as actuator. To this purpose, another SISO PI controller has been designed, on the basis of a first-order linear response model relating plasma current variations to NBI power variations. The parameters of such model (a static gain of the order of 25 kA/MW and a time constant around 300ms) have been empirically tuned before the actual experiments using the results obtained on a different plasma configuration. These values have been roughly confirmed also by the experiments carried out on the stationary hybrid scenario.

In order to allow the NBI power to exceed 10MW, this additional control loop has been attempted on a shorter pulse of 10s. Figure 3 shows four examples of plasma current control, with the NBI power used; a controlled increase of plasma current of more than 15% was achieved. It should be noted that in one single case the desired plasma current value of 1.6 MA was not achieved, due to the fact that the NBI did not release all the required power.

This work was supported in part by Italian MiUR (PRIN grant #2006094025) and CREATE.

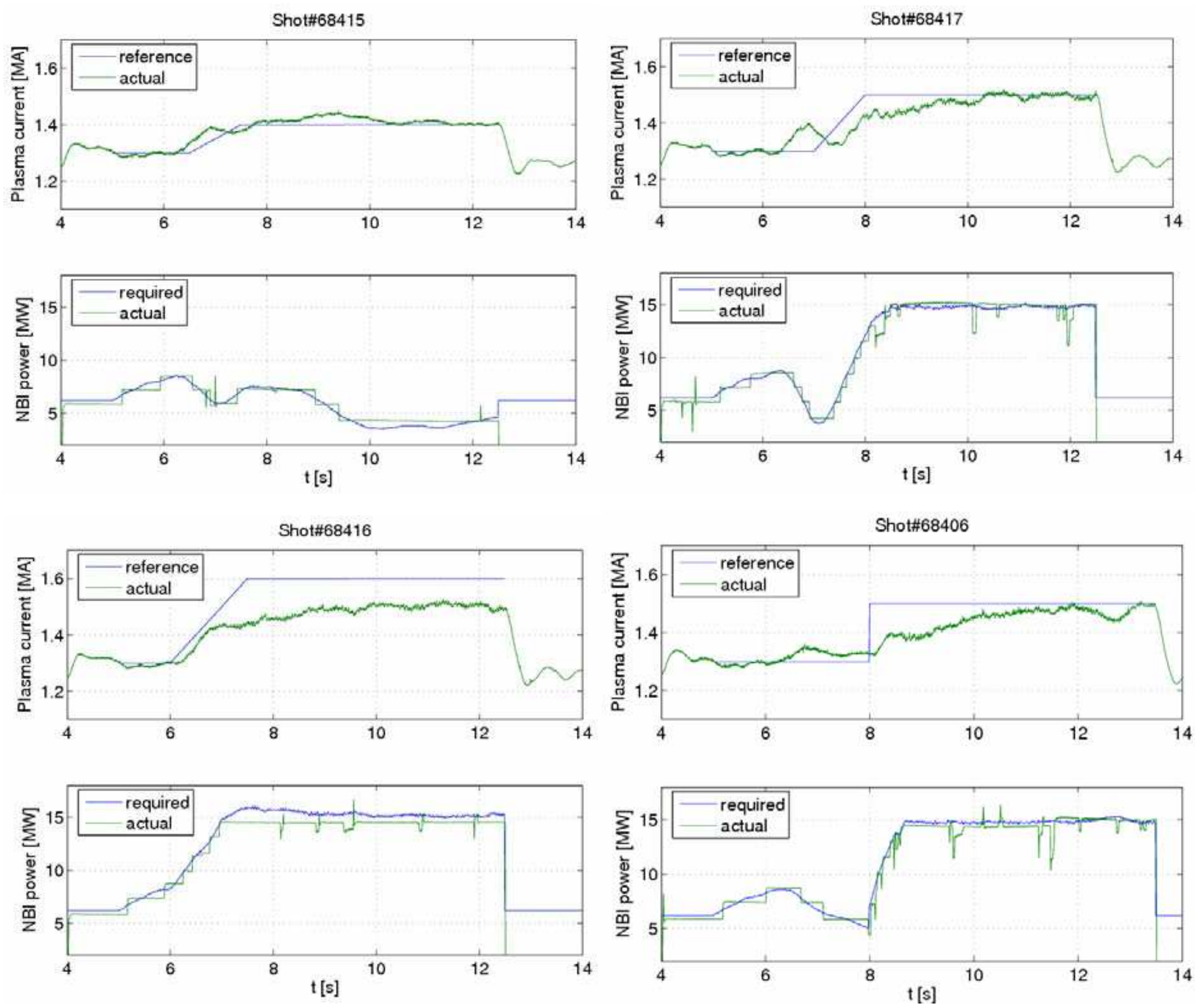


Figure 3. Examples of non-inductive plasma current control: plasma current (required and measured) and NBI power (requested and delivered) for shots# 68406, 68415, 68416, 68417.

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