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# Development of the “Hybrid” Scenario in JET

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**ABSTRACT.**
In the last campaigns, JET has extended the hybrid scenario with q profile close to unity in the plasma core to different $q_{95}$ (from 5 to 2.7), larger normalised pressure ($\beta_N$) up to 3.6, density up to the Greenwald density and also long duration up to 20s. In contrast to other machine the confinement improvement has not exceeded 1.2 with respect to the H98y2 scaling law. Differences in critical temperature gradient length in terms of rotational shear and magnetic shear might explain this difference. Recent experiments have transiently reached an improvement factor of H = 1.4 by raising the magnetic shear in the outer half of the plasma. In addition, the stability at high $\beta_N$ has been address experimentally using MHD spectroscopy using error field correction coils and indicates that hybridlike q profile are ideally stable at JET.

## 1. INTRODUCTION

In the recent 2006-2007 campaigns, JET has made a detailed experimental exploration of the plasma scenario, now known as “the ITER hybrid scenario”. In ITER, this scenario is a standard H-mode regime operated at slightly lower plasma current (13.5MA instead of 15MA), with an H factor of 1 and aiming at reaching a fusion gain factor of typically Q=5 for a duration exceeding 1000s because of the smaller demand on the ohmic coils.

The hybrid scenario has been first explored in ASDEX Upgrade [1, 2] and in DIII-D [3, 4]. In both devices, improved confinement time ranging from 1 to 1.7 with respect to the H98y2 scaling [5] have been observed, providing this scenario with a promising route to ITER long pulse operation at an even higher gain factor (up to 10). The maximisation of confinement and stability properties is the main attraction of the hybrid scenario. However, the origin of the reduced transport is not clearly identified yet, although candidates like the central magnetic shear and flow shear stabilisation are under consideration. Differences in confinement in the pedestal region have also been reported between the different devices [6].

In the first JET experiments on the “hybrid” scenario, in 2003-2004 [7], no substantial increase of confinement has been observed in comparison to the H98y2 scaling (HH~1.2). During more recent campaigns (2006 and 2007) experiments in JET, focused on extending the “hybrid” scenario in terms of the edge q profile range ($q_{95}$), normalised pressure ($\beta_N$) and density. Systematic comparisons of these discharges with its reference baseline H-mode scenario have also been carried out at same toroidal field strength (1.7T) but different plasma current Ip ranging from 1.4MA to 2MA. Again, in all these experiments, no increased confinement increase has been observed (HH~1.1). In the more recent experiments led in 2008, different families of q profile and magnetic shear have been explored so as to increase the external magnetic shear while keeping the flat shear in the plasma core.

In this process JET has produced transiently an H factor up to 1.4 suggesting that there is a possible route to improve the confinement in JET by tailoring the target q profile. In this paper the exploration of the hybrid scenario confinement properties at JET are first presented. In a second part, the recent experimental developments on MHD stability (role of the 3/2 NTM and $\beta$ limit) in JET hybrid plasma on confinement are described. In view of the scenario implementation in a future Be/tungsten wall, scenario integration work has also been carried out and led to the integration of a 20s duration pulse (more than 3 resistive time) with HH = 1.1, $\beta_N$ = 2.5 strike point sweeping and active flux control.

## 2. CONFINEMENT IN HYBRID DISCHARGES

During the 2003-2004 campaign [7] experiments have been limited to a given $q_{95}$ ($q_{95}$ = 4), relatively short duration (~4s not exceeding the resistive time), moderate density with respect to the Greenwald density limit (~0.5-0.6) and a total $\beta_N$ of 2.8 (i.e. typically below the estimated no wall limit given by the product 4×li). Extending this parameter space in terms of $q_{95}$, density at higher $\beta_N$ in a large machine like JET was an essential goal in the JET 2006-2007 programme for the development of this scenario closer to the parameters of ITER at lower normalised Larmor radius $\rho^*$ and collisionality $\nu^*$.

Figure 1 show the extension of the hybrid scenario achieved in 2006-07 with respect to 2003-04 data in terms of $\beta_N$ and $\rho^*$. The mode of operation to establish the scenario in JET is to use the plasma current ramp-up heated with 0 to 2MW of LH power to broaden the q profile before the main heating (NBI) power is applied. This scenario has been operated at high triangularity ($\delta$ = 0.45) different $q_{95}$ ranging from 2.7 to 5, at lower $\rho^*$ for larger diamagnetic $\beta_N$ (fast particle energy content represent typically 30 to 40% of the total diamagnetic energy) have been achieved. However, in all this parameter space it appeared that the confinement has not shown any sign of improvement above 1.1 with respect to H98y2 scaling in contrast to what other devices have recently reported [5]. DIII-D has reported improvement factor up to 1.5 [4] and AXDEX Upgrade 1.7 [1].

For this reason, a systematic comparisons of these discharges with a reference baseline H-mode scenario at same toroidal field strength (1.7T) and different plasma current Ip ranging from 1.4MA to 2MA. This comparison has been achieved with a plasma shape at high triangularity of $\delta$ = 0.45 up to normalised pressure $\beta_N$ of 3.0. Stationary conditions have been achieved for about one resistive time with the figure of merit for fusion gain ($H_{89.}\beta_N/q_{95}{}^2$) reaching up to 0.7 at $q_{95}$ = 2.8 for both the "hybrid" scenario and its equivalent H-mode. The distinction between the two scenarios has been made operationally by applying current penetration control (using current ramp-up together with lower hybrid current drive to produce broad current profiles with low core magnetic shear and $q_o$ close to unity) in the first case and with a fully diffused q profile in the second. Figure 2 shows the superposition of the two scenarios at 1.7T and 2.0MA with the same input power and same plasma density. From the 4×li parameter trace itself, it is apparent that the q profiles are different when the neutral beam heating is applied (~16MW). q profile reconstruction using kinetic profiles and MSE measurements and consistent with MHD markers (sawteeth and 3/2 mode activity) does confirm that the initial q profiles at the start of the heating are very different (q>1 in the case of the preformed q profile and q<1 in the case of the fully diffused target) (figure 3). This difference does not lead to any marked change in thermal energy confinement between the hybrid scenario with and a reference

H-mode. Furthermore, the comparison of kinetic profiles (electron and ion pressure) does not show any local difference (outside the error bars of the measurements) between the two scenarios. After 6s of the main heating pulse (i.e. after about one resistive time) the q profiles of both scenarios look almost identical. From this comparison, it appears that the modifications operated on the q profile in the current ramp-up (weak magnetic shear in the plasma core within r/a~0.4) may not be relevant in changing the transport in the plasma core. The results of this comparison is also consistent with the analysis made on 2003 data [7] showing that the normalised critical temperature gradient length in hybrid discharges does not differ from that of the standard baseline scenario.

The confinement increase in hybrid scenario may originate from different sources. In DIII-D, it has been reported that varying the NBI torque using co- and balanced neutral beam injection could change the E×B flow shear and lead to an increase of the heat transport and as a result a drop of confinement from HH=1.5 to 1.0 [8]. In ASDEX upgrade [9], the change in magnetic shear at mid-radius (producing a higher s/q and modifying the threshold of ITG modes) is put forward as a possible candidate to explain the observed improved confinement.

JET generally operates with a lower normalised toroidal rotation ($V_\varphi/R$) than the other devices. Typically this parameter is not greater than $0.6\times10^5 s^{-1}$ in JET, whereas DIII-D and ASDEX Upgrade are operating the hybrid scenario with $V_\varphi/R$ of the order of ~$2\times10^5 s^{-1}$ and $1.5\times10^5 s^{-1}$ respectively. It is also interesting to note that $V_\varphi/R$ at JET is of the same order as the value achieved in DIII-D with balanced beam injection where HH~1. This suggests that the E×B flow shear in co-injection might be larger in these machines than it is in JET. This is consistent with a recent experimental study supported by gyro-kinetic computation with GS2 in JET [10] that indicates that the toroidal rotation and its shear could increase significantly the normalised temperature gradient length R/LTi and therefore could lead to an increase of the overall confinement. Identity experiments with the other devices could help in solving this issue and provide the necessary extrapolation to ITER.

Except for specific experiments such as those with ripple [11], it is not possible in JET to separate experimentally torque and heating flux since the neutral beam are all in the co-direction. On the other hand the current profile can be significantly modified to investigate more radical change of the q profile than in previous experimental campaign and test the impact of the s/q parameter on confinement. The critical temperature gradient length has been predicted to increase as s/q increase for positive magnetic shear s [12]. In the 2008 campaign, experiments have explored strong variation of the q profile produced using strong current ramp down (0.6MA/s) after an initial current ramp up (from 0.3 to 0.5MA/s). This has the effect to reduce the inductive flux in the outer half of the plasma (r/a>0.5) and results in a sharp steepening of the magnetic shear in this region.

The initial experiments have been executed at low triangularity ($\delta$ = 0.2) and at current from 1.4 to 1.7MA. The beam power (15 to 20MW) is applied right at the end of the current ramp down in an attempt to freeze the preformed current profile. This experiment has shown some success in reaching transiently an H-factor just above 1.4 for about 2s and suggests that modifying the s/q parameter at the plasma edge might play a role in the production of higher confinement. According to EFIT reconstruction with Motional Stark effect diagnostic s/q is indeed increased by up to 30% at r/a = 0.75 for the same plasma rotation and $T_e/T_i$. However the change in magnetic shear also leads to a change in tearing stability. This has to be taken into account in the analysis. At this stage, it is also not clear whether the pedestal confinement is affected. Experiments are planned in the near future to extend this high confinement phase for durations exceeding several resistive time.

## 3. STABILITY OF JET SCENARIO WITH Q PROFILE CLOSE TO 1

As in ASDEX-Upgrade [9], the JET scenario with preformed q profile exhibits better confinement with prominent 1/1 fishbone activity than when 3/2 or 4/3 Neoclassical Tearing Modes (NTMs) are present without sawtooth activity. The 3/2 island is thought to play a particular role in the current evolution of the hybrid scenario in DIII-D [13]. At the same time, since NTMs are pressure driven modes, the access to high normalised pressure requires the optimisation of the q profile in order to avoid the sawtooth crash on q = 1 inducing a seed island on the mode rational surface. To investigate the effect of the target q profile on the stability of the hybrid scenario a scan of the LH power has been carried out. Varying the LH-power in preheat has the effect to modify the poloidal flux diffusion in the current ramp-up before t = 4.0s when the main heating (NBI power) is applied. This is confirmed by EFIT q profile reconstruction using MSE measurements. In this way, the optimum target q profile can be determined. The LH power was varied from 0 to 1.2MW in the prelude phase keeping the same current ramp-up (0.25MA/s). Discharges with an LH-power below 0.5MW do not show any significant 3/2 mode but sometimes intermittent sawteeth accompanied with fishbones n = 1 activity. On the other hand discharges with LHpower above 0.5MW show strong 3/2 activity and a degraded confinement by typically 15% on average, but no sawtooth activity.

These data are summarised in figure 4 showing the confinement degradation related to the presence of the 3/2 mode. This result first suggests that higher values of $\beta_N$ can be reached when the q profile is just touching the q = 1 surface. It also indicates that the 3/2 NTM is triggered when the stability parameter $\Delta'$ becomes positive in the q profile formation phase with LH. This is also consistent with the latest ASDEX Upgrade results [9] showing the difference in confinement between the late heating timing (with fishbone activity) and the early timing (with m = 3 n = 2 MHD activity). Secondly, this study helps in quantifying the effect of the presence of a 3/2 mode on confinement. Applying the confinement degradation expected for an island located at 3.45m [14], the island size produced in this discharges are of the order of 10 to 15cm which is consistent with the MHD measurement of the island size using magnetic pick-up-coils.

In addition, dedicated experiments with preformed target q profile above unity and toroidal field strength of $B_T = 1.5T$ have extended the scenario operations at higher total normalised pressure (up to $\beta_N = 3.6$). This value is also well above the estimated no-wall ideal limit of $4\times l_i$. This high normalised pressure is not limited by the onset of 2/1 NTM mode as this was reported in other experiments [15]. In the high power phase these discharges are showing a small amplitude 3/2 mode activity but no sawteeth indicating that the q minimum of the q profile in the core is below 1.5 and above 1.

The proximity to the no-wall limit has been diagnosed in these plasmas using the Resonant Field Amplification (RFA) [16] of an externally applied helical magnetic field. It has been suggested that this technique might be used as an indication of the no-wall beta limit and it has been recently applied in particular to the JET advanced tokamak scenario [17]. Figure 5 shows the plasma response of the radial magnetic field to an applied perturbation with the JET Error Field Correction Coil (EFCC) coils in AC mode with a probing frequency of 20Hz. At about 28-29s this response increases and looks consistent with $\beta_N$ exceeding the estimated ideal limit of 4li. The difference in $\beta$ between the measured RFA limit and the calculated no-wall limit for a global pressure-driven kink mode also depends on the details of the q and pressure profiles, plasma shape and other parameters. Modelling the effect of resonant field amplification due to the response of low-n MHD modes for different type of q profiles using the MARS-F code has shown that the RFA onset of this signal is systematically lower than the predicted nowall $\beta$ limit by ideal MHD theory [18]. From this it would appear that the no-wall limit with hybrid-like q profile in JET in highly shaped plasmas is actually higher than the 2.8 estimated by the 4xli limit consistent with the achieved $\beta_N$ in this discharge.

It should be noted that in this type of discharges, the high level of fast particle energy content (30 to 40%) in JET could be suspected to play a role in the experimental determination of the no-wall limit. However, calculation with the HAGIS code for the external kink mode indicates that the fast ions have small impact on the prediction of the no-wall limit.

## 4. SCENARIO INTEGRATION APPLIED TO HYBRID.

One important objective in establishing an integrated advanced reference scenario for ITER is to demonstrate that the combination of non-inductive currentused can preserve the initial (optimised) q profile for duration exceeding several resistive time. Using the optimised target q profile (i.e. without significant 3/2 NTM activity), the scenario has been maintained for 20s (~3 resistive times), using active boundary flux control and strike point sweeping for power spreading onto the divertor targets.

Figure 6 illustrates the 20s long scenario with q~1 achieved in JET. This discharge is operated at a plasma current of $I_p$ = 1.3MA and a toroidal field $B_T$ = 1.5T with a high triangularity (~0.4) ITER-like magnetic configuration and $q_{95}$ = 3.5. The current ramp-up is pre-heated by Lower Hybrid Current Drive (LHCD) up to a level of 1.2MW as explained in a previous section. Neutral Beam Injection is injected at the time the current plateau is reached for duration of 20s at a level of about 10MW. Because of power supply hardware limitations it is not possible to use all beams at the same time for more than 10s. Therefore, in this experiment, the 14 beams available were divided into two groups of 7 beams, each covering 10s of the pulse. With this set up a record of 186MJ of NBI energy has been injected in the plasma. As a consequence, beam diagnostics such as charge exchange spectroscopy (for ion temperature and rotation measurements) and MSE (for the q profile) are only covering respectively the second and first 10s of the pulse.

The pulse shown in figure 6 reaches a normalised pressure $\beta_N$ of 2.5 for almost 20s. The resistive time is of the order of 5.5s. This discharge therefore lasts for more than three resistive times. It is operated at 70% of the Greenwald density, an ion temperature of 4keV and electron temperature of 3.5keV with type I ELMs. There are some signs of infrequent sawtooth crashes in the plasma core with an inversion radius of 20 to 25cm and preceded by long n=1 precursors lasting up to 0.5s indicating that the q profile is close to unity. There is no sign of 3/2 MHD activity. This pulse has a thermal H factor of 1.1 with respect to the ITER scaling H98y2 [7], making a fusion merit factor $G = H_{89.}\beta_N/q_{95}^2$ above 0.4. The discharge stays below the estimated ideal wall limit (4li~3).

Current balance analysis has been inferred from the CRONOS [11] codes. The main non-inductive current components are the bootstrap current reaching a level of 500kA (40% of the total current) and the beam current with a level of 150kA (10 to15% of the total current).

In order to make this pulse compatible with long duration, several new key plasma control features have been simultaneously integrated. The new JET shape controller recently installed and validated for accurate control of the plasma boundary has been integrated with boundary flux control and also includes a strike point sweeping facility specifically designed to spread the heat load on the divertor target [19]. During the 20s pulse, both boundary flux control and sweeping have been applied at a rate of 0.15Wb/s. The strike points are swept with peak to peak amplitude of 7cm and a frequency of 4Hz on two tiles of the divertor. Measurements with the infrared camera show that the maximum temperature measured by the infrared camera on the outer divertor tile is lowered by 25 to 30% close to thermal equilibrium conditions. The broadening of the foot print on the tile results in a lower power load density from typically $5MW/m^2$ to $3.5MW/m^2$. On average, no significant confinement losses related to the sweeping of the strike points are observed. However, to ensure compatibility with an all-metal wall this scenario will require line average density higher than the beam shinethrough limits. The hybrid scenario has also been extended to higher density using gas fuelling in the X-point private flux diverted area.

In dedicated experiments the density could be raised up to the Greenwald density limit at $\beta_N$~2.7 at $I_p$ = 1.7MA while keeping an HH factor 0.93. In addition to extending the parameter space for the JET scenario to higher $\nu^*$ and different density peaking at higher thermal pressure, these experiments together with radiative layer experiments [20] are important developments for the future implementation of the hybrid scenario with the Berylium and tungsten wall in JET which will be installed in 2009-2010. However, establishing the physics basis for steady state hybrid scenario achieving a confinement in excess of 1 remains the main objective in future JET hybrid scenario experiments

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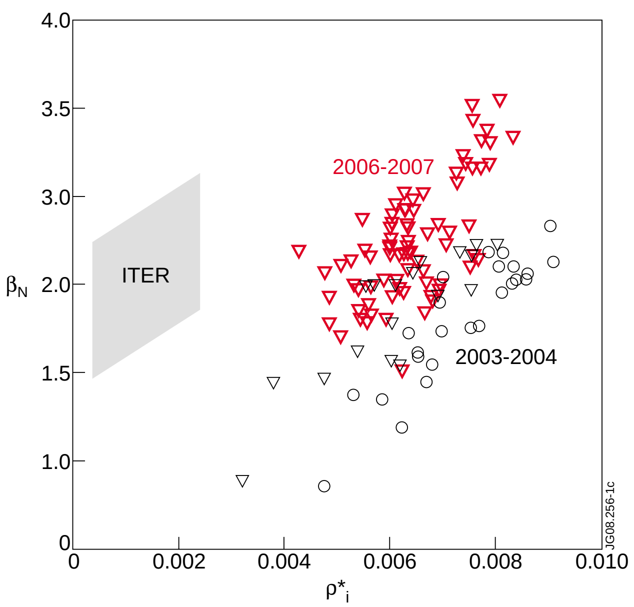



*Figure 1: Recent extension of the "hybrid" scenario in JET in $\beta_N$ and $\rho^*_i$ for $\delta$ = 0.2 (circles) and $\delta$ = 0.45 (triangles).*

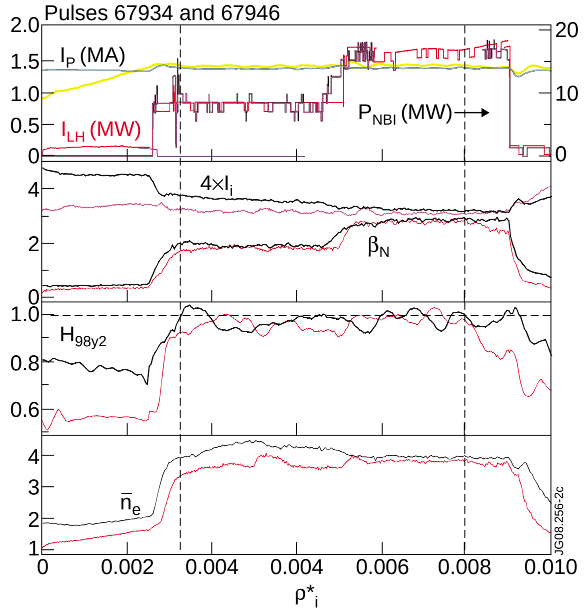
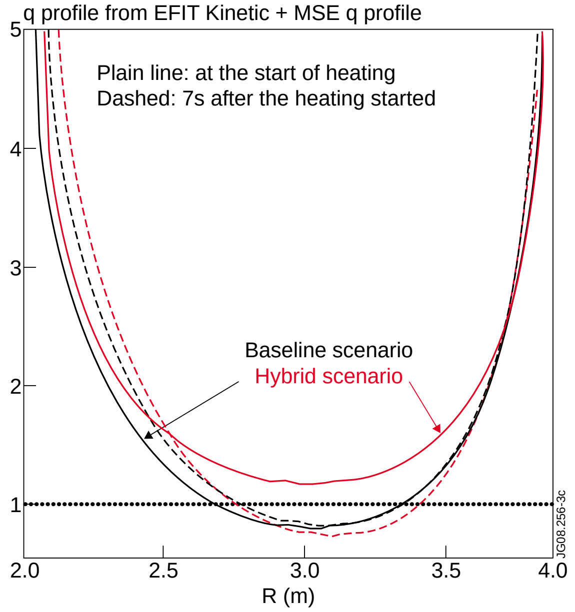



*Figure 2: In red, typical JET hybrid scenario. Overlaid in black: baseline comparison H-mode without initial q profile tailoring shifted in time by 15.5s. No difference is observed at 12s between the two discharges even though the hybrid is initially starting with a very different q profil (at 5s). Doted lines indicate the time of the q profiles shown on figure 3.*



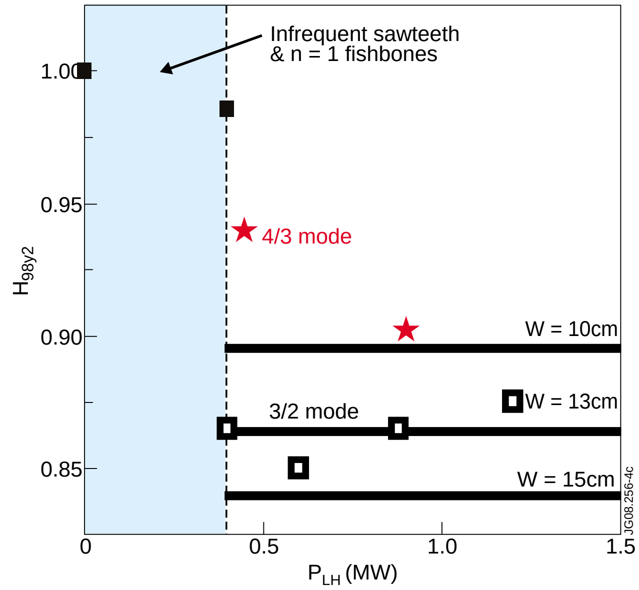
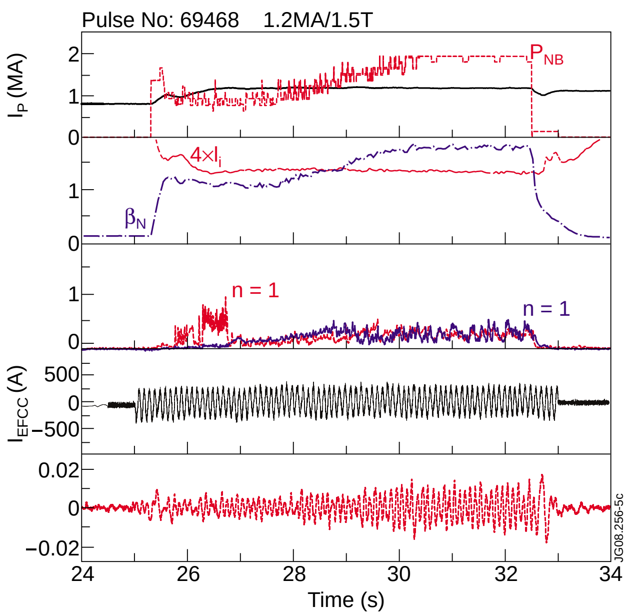




*Figure 3: Comparison of the q profiles of the hybrid and baseline scenarios. After 7s of heating (dashed), the q profiles are identical within the error bars of the reconstruction.*

*Figure 4: Confinement degradation caused by 3/2 and 4/3 islands. The horizontal lines are showing the typical confinement level arising from the presence of a 3/2 island of 10, 13 and 15cm located at 3.45m as calculated using the formula from reference [14].*



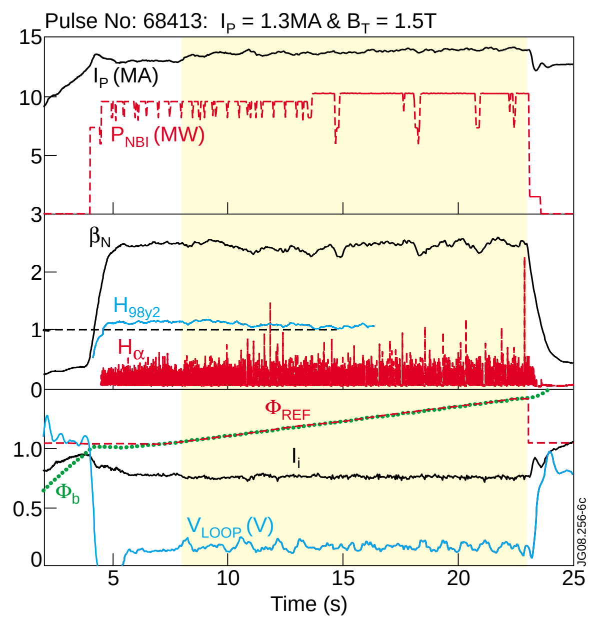




*Figure 5: MHD spectroscopy applied to the scenario with q≥1 reaching $\beta_N$=3.6. Resonant field amplification is observed at around 29s at the minimum of the ratio: RFA amplitude / $\beta_N$.*

*Figure 6: Typical 20s pulse with boundary flux control (and floating $I_p$)and strike sweeping. The control window is indicated by the shaded area. Note that the total plasma current increases slightly during the flux control window indicating that sum of inductive and non-inductive current exceeds 1.3MA.*