LRP 718/02 January 2002

Control of Neoclassical Tearing Modes by Sawtooth Control

O. Sauter, E. Westerhof, M.L. Mayoral et al.,
Task Force M, Task Force H and contributors
to the EFDA-JET Workprogramme

A shorter version of this report has been
accepted for publication in
Physical Review Letters (2002)

ISSN 0458-5895

Control of Neoclassical Tearing Modes by Sawtooth Control

O. Sauter[1], E. Westerhof[2], M. L. Mayoral[3,4], B. Alper[3], P. A. Belo[5], R. J. Buttery[3], A. Gondhalekar[3], T. Hellsten[6,7], T. C. Hender[3], D. F. Howell[3], T. Johnson[6], P. Lamalle[8,7], M. J. Mantsinen[9], F. Milani[3], M. F. F. Nave[5], F. Nguyen[4], A. L. Pecquet[4], S. D. Pinches[10], S. Podda[11], J. Rapp[12], Task Force M, Task Force H and contributors to the EFDA-JET Workprogramme†

1) Centre de Recherches en Physique des Plasmas, Ass. EURATOM-Confédération Suisse, EPFL, 1015 Lausanne, Switzerland.
2) FOM-Rijnhuizen, Ass. EURATOM-FOM, TEC, PO Box 1207, 3430 BE Nieuwegein, NL, 3) EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX143DB, UK, 4) DRFC, CEA Cadarache, Ass. EURATOM/CEA, France, 5) Centro de Fusao Nuclear, Instituto Superior Tecnico, Lisboa, Portugal, 6) Association EURATOM-NFR, Royal Institute of Technology, Stockholm, Sweden, 7) EFDA-JET Close Support Unit, Culham Science Centre, Abingdon, UK, 8) LPP/ERM-KMS, Ass. EURATOM-Belgian State, TEC, Brussels, B, 9) Helsinki University of Technology, Association EURATOM-Tekes, Finland, 10) Max-Planck-IPP, IPP-EURATOM Ass., Garching, Germany, 11) CRF, Ass. EURATOM-ENEA sulla Fusione, Frascati, Italy, 12) Institut für Plasmaphysik, EURATOM Ass., TEC, Jülich, Germany, †See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001)

Abstract

The onset of a neoclassical tearing mode (NTM) depends on the existence of a large enough seed island. It is shown in the Joint European Torus that NTMs can be readily destabilised by long period sawteeth, such as obtained by sawtooth stabilisation from ion cyclotron heating or current drive. This has important implications for burning plasma scenarios, as alpha particles strongly stabilise the sawteeth. It is also shown that by adding heating and current drive just outside the inversion radius, sawteeth are destabilized, resulting in shorter sawtooth periods and larger beta values being obtained without NTMs being destabilised.

One of the main objectives of fusion plasma physics research is to optimise $\beta = p/(B_0^2/2\mu_0)$, the ratio of the plasma pressure to the magnetic pressure, where B_0 is the main confining magnetic field. In tokamak discharges, the maximum achievable β is limited by macroscopic unstable modes well described by the ideal magneto-hydrodynamic fluid theory. This limit is relatively high in standard high confinement scenarios (H-mode), with a monotonic safety factor q. The value of q is determined by the helical winding of the magnetic field line around the torus, being the ratio of toroidal to poloidal turns of the field line. It has been found in the last few years [1] [2] that pressure driven modes can be destabilised at β values much lower than the ideal limit. These tearing modes form islands near resonant surfaces corresponding to rational q values, in particular the $m = 3/n = 2$ and 2/1 surfaces, where m and n are the mode numbers in the poloidal and toroidal directions. Once a seed island is formed and is sufficiently wide to locally flatten the density and/or temperature profile, it reduces the self-generated bootstrap current which further destabilises the mode [1]. The main detrimental effect of these modes is a loss of energy and particle confinement which can significantly reduce both the central temperature and density and may thus adversely affect the performance in the baseline ELMy H-Mode scenario, envisaged for reactor-like plasmas [3]. We shall concentrate in this paper on the 3/2 mode, even though the 2/1 mode leads to larger confinement degradation. However the 3/2 mode is usually destabilised at lower beta values, near values envisaged in reactor-like plasmas, whereas the 2/1 mode was not destabilised in the scenarios presented here.

It is well known both theoretically and experimentally that a finite seed island is required before the island can be further destabilised by the perturbed bootstrap current [2]. This is due to stabilising terms which are important at small island size, typically when the island is of the order of the ion poloidal Larmor radius, that is of a few centimeters. Several stabilising mechanisms have been proposed, but which is dominant is not relevant for the results presented here. However their existence is responsible for the necessity of creating a finite seed island. The trigger mechanism for this seed island is usually associated with a sawtooth crash or its pre- or postcursor, but can be due to other perturbations like edge localised modes (ELMs) or fishbones for example. Therefore a possible way to avoid NTMs is to keep the seed islands smaller than the critical seed island width. This has been tested indirectly using scenarios with $q > 1$, such as to avoid the main internal perturbations, the sawtooth activity [4]. However these scenarios are inherently transient as it would require too much current drive to keep $q > 1$ in the center of a standard scenario in a reactor-like tokamak. A new and better scenario would be to maintain the sawtooth activity, which is deemed useful in a reactor for avoiding ash accumulation in the centre, but at a level such that the seed islands induced at $q = 1.5$ and 2 are small. In this letter, we shall first demonstrate that by controlling the sawtooth period (τ_{saw}), due to sawtooth stabilisation, the β values at which NTMs are observed can be changed by more than a factor of 2. Then it is shown how the performance can be increased by destabilising the sawteeth, thus keeping the τ_{saw} short. Therefore a new scheme is proposed for ELMy H-mode burning plasmas: prevent NTMs by controlling the main perturbations causing the seed islands.

In the Joint European Torus (JET), it has been demonstrated that sawteeth can be affected by waves in the ion cyclotron range of frequencies (ICRF). Using a fundamental H minority scheme, a large population of fast ions is created, which has a stabilizing effect on the internal kink mode and leads to long τ_{saw} [5a]. Moreover, depending on the ICRF antenna phasing, the fast particle pressure inside q=1 and thereby τ_{saw}, can be differently modified due to the ICRF-induced pinch of the resonating trapped ions [5b]. In recent experiments, this mechanism has been utilized with $4.5MW$ of ICRF power applied at a frequency of 42MHz (Fig.1). The discharge with +90° phasing (co-current, dark line), leads to longer τ_{saw}, $630ms$, than the discharge with $-90°$ phasing (counter-current, grey line), $200ms$. As the resonance layer is positioned near the sawtooth inversion radius (R_{inv}), the Ion Cyclotron Current Drive (ICCD), which can modify locally the current profile and consequently destabilize or stabilize sawteeth, also plays a role [5c, 6a-b]. In addition, for the discharges shown in Fig. 1a, a similar ramp of neutral beam injection (NBI) power is imposed in order to determine the onset beta value of the 3/2 NTM mode (Fig. 1b). The ICRF and NBI power, normalised beta (β_N), soft X-ray emission (SXR) and neutron rates are well matched, that is the profiles are similar. However at $16.5s$ a 3/2 NTM is destabilised in the discharge 51794 which has long sawtooth periods. The mode is triggered exactly at the sawtooth crash, at $\beta_N = 1, P_{NBI} = 5MW$ and $P_{RF} = 4.5MW$. On the other hand, the case with shorter sawtooth periods does not trigger NTMs even at full power, $\beta_N \approx 2, P_{NBI} = 16MW$ and $P_{RF} = 4.5MW$. τ_{saw} can be controlled by moving the fundamental H resonance position. In this way, increasing τ_{saw} from $240ms$ to $720ms$, changing B_0 from $2.23T$ to $2.6T$, with +90° phasing, while keeping the q profile fixed, it was shown that NTMs are destabilized at low $\beta_N (\sim 1)$ when $\tau_{saw} \geq 600ms$ at this medium field [7]. Note that these modes were actually observed and described as a consequence of sawtooth stabilisation already in 1988 [5a]. This also explains why discharges dominantly heated by ICRF have much lower β_{Nonset} than NBI only discharges. In some specific NBI only cases, when the power ramp is such as to create a long first sawtooth period, NTMs can also be destabilized at low beta at the crash. These experiments demonstrate the direct effect of controlling the sawtooth activity on the NTM onset. In previous standard JET experiments, NTMs were never destabilised even at full NBI power ($17MW$) for $I_p >$ 1.7MA, $B_0 >$ 1.7T. This was thought to be due to lack of power. However through sawtooth control, NTMs can now be triggered at low β_N. As a further test, $5MW$ +90° ICRH was added to a high magnetic field discharge with $3.3T$, $3.3MA$, and $5.4MW$ NBI power. A $1.6s$ sawtooth free period is induced after which crash a 3/2 NTM is triggered at $18.74s$. Figure 2 shows that a large seed island of $6cm$ is directly triggered, close to the saturated width at this low β, thus the island width remains almost constant. In standard scenario at low field, seed islands are typically of 2-$5cm$ [2]. The island width is obtained from edge magnetic measurements [1] calibrated with ECE measurements. However this can only be measured when a mode is triggered. Fig. 2 shows also that although the precursor n=1 is large around 15-$17s$ no mode is triggered while the crash at $18.74s$ has no significant precursor activity. Similarly the crash of the central chord SXR at this sawtooth is not much larger than at the previous crash. The only correlation observed so far in these experiments is the sawtooth period itself. However there is not a linear correlation with the seed island triggered. Further experimental and theoretical studies are necessary to quantify this relationship.

We have shown that by sawtooth stabilisation one can easily trigger NTMs, as soon as beta is larger than the critical beta limit, and in these cases the seed island is formed directly at the sawtooth crash. This is confirmed by the strong correlation between the sawtooth crash time and the NTM onset, as opposed to cases with short sawtooth period [8]. This is the main result of this paper and is particularly important for burning plasma discharges: the alpha particles are predicted to strongly stabilise the sawteeth, in the same way as the ICRF fast particles do in these JET cases [9]. Therefore NTMs in reactor-like plasmas might be destabilised at low beta, near the marginal beta limit. Thus it will probably be necessary to destabilise the sawteeth in ITER-like discharges to avoid large seed islands. Due to the large contribution of the alpha particles, the only possibility to reduce τ_{saw} will be through local current drive. Using a model based on Ref. [9], we are able to simulate the effect of fast particles [10] and of localised current drive (CD) and electron power deposition as shown in detailed experiments in TCV [11]. However it is out of the scope of this paper to quantify the amount of local counter-CD needed to significantly reduce τ_{saw} in such scenarios. In addition, as the exact physical mechanism by which the seed island is formed during the crash is not known, it is not possible to predict what is a short enough sawtooth period. However we have already tested if beta onset can be increased in present discharges using scenarios aimed at destabilising the sawteeth. This is a more difficult task, as in present low field discharges τ_{saw} are of medium size, about 200-300ms. In this case the sawtooth crash is only one of the trigger mechanisms, others being pre-, post-cursors and ELMs [2] [8].

A reference discharge is chosen for which NTMs are destabilised with NBI only. This is achieved by choosing a low magnetic field case (1.2-1.4T), which requires the use of second harmonic H (ω_{2cH}) minority ICRH to drive localized current (ICCD) and affect the sawteeth. Scanning the ω_{2cH} resonance position across R_{inv} shows that τ_{saw} has a minimum when the resonance position is just outside R_{inv} [6]. Using this method the magnetic field ($B_0 = 1.2T, I_p = 1.2MA$) to couple at this position on the high field side (HFS) can be found. This is exploited in the results shown in Fig. 3 where two cases with and without ICRF are compared, but with the same total power waveform. The NBI only discharge, 52712, triggers a 3/2 NTM at $\beta_N \approx 2.7, P_{tot} = 8MW$ (typical for this field and current), much earlier than the one with ICRF which reaches a maximum $\beta_N \approx 3.8$ without 3/2 modes. Actually a 5/4 mode is triggered at $t = 25.0s$, then a 4/3, at 26.0s and finally a

3/2 mode at $t = 26.2s, \beta_N \approx 3.6$ in the ICRF case. Note that during the high β phase the local magnetic field decreases due to diamagnetic effects and the resonance position moves away from the optimum position for sawtooth destabilisation, as will be discussed later. Also fishbones are usually present when $\beta_N \geq 3$ [8], so it is not clear if sawtooth activity or fishbones have triggered these NTMs. However it should be noted that the discharge is very close to the ideal beta limit, $\beta_N \approx 4l_i \approx 4$, and therefore much higher than the value at which a stationary standard ELMy H-mode discharge would be in burning plasmas [3].

The peculiar time evolution of the island width and the related confinement degradation needs clarification. While the NBI power is further increased, Fig. 3, the island width decreases at about $24.5s$ and saturates to a lower value. Consequently the confinement degradation is reduced and β_N recovers, reaching similar values as the other case which has no 3/2 NTM (around $25s$). This effect is termed "self-healing" and occurs as the NBI power increases (at $P_{NBI} \approx 15MW$, $\beta_N \approx 3.3$). A similar behaviour has also been observed on ASDEX Upgrade (AUG). It is found that bursts of 4/3 modes can frequently interrupt the 3/2 growth and therefore lead to a smaller average island width (FIR-NTM) [12]. In our case there is also a strong burst of a 4/3 mode at $24.5s$, which triggers the sudden reduction of the island width while allowing the mode frequency and rotation to increase. Then smaller bursting 4/3 modes persist. Therefore it is probably the combination of the coupling to the 4/3 mode and the increased rotation with increased NBI power, as confirmed by a rapid mode frequency increase at $24.5s$, which enables this "self-healing" to occur and the saturated width to settle at a lower island size. However the neutron rate does not fully recover, due to its higher sensitivity to central plasma parameters and the presence of the 3/2 mode, albeit at a small amplitude.

The sawtooth period near t=$22s$ in Fig. 3 is smaller for the NBI+ICRH case, $130ms$, than for the NBI case, $300ms$. As NBI fast particles also stabilise sawteeth [10], we have repeated the case 52712 but with the same NBI power waveform as 51994 instead of the same total power. In this case a NTM is triggered at $\beta_N \approx 2.1$ and $\tau_{saw} = 180ms$. This comparison with same NBI or same full power is important as rotation also plays an important role. In particular smaller differential rotation between $q = 1$ and $q = 1.5$ surfaces, leads to lower β_{Nonset} [13]. This can contribute to the lower β_{Nonset} values usually observed in ICRF dominated scenarios. Therefore, it is only by a careful choice of the resonance position, such as to destabilise the sawteeth, that we have been able to actually increase β_{Nonset} with the application of ICRF waves. This is also well illustrated in Fig. 4, where a detailed shot to shot magnetic field scan with constant q profile, has been performed in order to find the best resonance position. Two groups of discharges can be identified: three shots which have no NTMs up to $\beta_N \approx 3.6$, similar to the HFS case 51994, and in the other discharges a 3/2 NTM is triggered at $\beta_N \approx 3$ or lower. From the time evolution of the resonance position of ω_{2cH}, the first group corresponds to cases for which the resonance is just outside the sawtooth inversion radius during the ramp. τ_{saw} cannot be determined in H-modes, because of ELMs activity and fishbones, but τ_{saw} is minimum for 52083 ($180ms$) and maximum further inside 52079 ($300ms$) at 23.5s. The width of this "good" region is about $20cm$, and the position corresponds to the region where the minimum τ_{saw} is found, as mentioned earlier [6]. The width in magnetic field, $\Delta B_0 \approx 0.1T$, confirms that an accurate control is needed, in agreement with the simulations of the localized ICCD profiles [6c]. Using the sawtooth model of [9], one can simulate the effects of fast particles [10] and localised current drive [11]. In particular the sensitivity presented in Fig. 4 corresponds to the effect of localised current drive and electron power deposition as observed in detailed electron cyclotron heating experiments on TCV [11]. This confirms the relation to the control of the sawteeth.

In conclusion, we have clearly demonstrated experimentally the direct relation between sawteeth and NTM onset and thereby the possible control of NTMs by control of the sawtooth period. We have shown that by increasing τ_{saw}, 3/2 NTMs are triggered at the sawtooth crash, at very low β_N values down to $\beta_{Ncrit} \approx 0.5-1$. This has important implications for burning plasmas which are predicted to have long sawtooth periods due to strong stabilisation by alpha particles. The dependence on τ_{saw} has been confirmed by slowly increasing the period from $240ms$ to $720ms$. The dependence of β_{Nonset} on the period is not linear and the critical value is at about $600ms$ at $B \approx 2.4-2.8T$ in JET. Further detailed analyses and experiments are needed to quantify and understand this effect. A possible explanation is that a longer τ_{saw} allows the shear at $q = 1$ to become larger at the crash [10], leading to a larger magnetic perturbation due to the reconnection process. As β_{Ncrit} is low in standard JET ELMy H-mode discharges [7], it is only by controlling the maximum size of the seed islands that NTMs can be avoided. This has been further confirmed as β_N values close to the ideal limit have been reached before triggering NTMs by accurately positioning the ICRF resonance such as to destabilise the sawteeth. Sawteeth are useful for avoiding impurity accumulation, therefore sawteeth destabilisation is the most promising ELMy H-mode scenario. The following step is to demonstrate that sawteeth can be controlled even with a large stabilising contribution from fast particles, like alpha particles resulting from the fusion reactions [9]. Localised ICCD or counter electron cyclotron CD, of the order of $1 - 2\%$ of the plasma current [11], should enable a reduction in the sawtooth period.

ACKNOWLEDGMENTS

We are grateful to the UKAEA for the efficient operation of the JET tokamak. This work was performed under the European Fusion Development Agreement and was supported in part by the Swiss National Science Foundation, in part by EURATOM and in part by the UK Department of Trade and Industry.

REFERENCES

[1] O. Sauter *et al*, Phys. Plasmas. **4**, 1654 (1997) and references therein.

[2] R. Buttery *et al*, Plasma Phys. Contr. Fus. **42**, B61 (2000) and references therein.

[3] ITER Physics, Nuclear Fus. **39**, 2137 (1999).

[4] R. J. La Haye *et al*, Nucl. Fusion **40**, 53 (2000).

[5] D. J. Campbell *et al*, Phys. Rev. Lett. **60**, 2148 (1988); L.-G. Eriksson *et al*, Phys. Rev. Lett. **81**, 1231 (1998) ; V. P. Bhatnagar *et al*, Nucl. Fusion **34**, 1579 (1994).

[6] M.-L. Mayoral *et al*, Proc. 14th Topical Conf. on RF Power in Plasmas, Oxnard, 2001; F. Nguyen *et al*, ibidem [7], P2.081; M. Mantsinen *et al*, ibidem [7], P2.083, submitted to Plasma Phys. Contr. Fus.

[7] O. Sauter *et al*, Proc. 28th EPS Conf. on Cont. Fusion and Plasma Physics, Madeira 2001, Europhys. Conf. Abstr. (2001) Vol. 25, Oral 08, P5.001 (http://epsppd.epfl.ch).

[8] P. Belo *et al*, ibidem [7], P5.004.

[9] F. Porcelli *et al*, Plasma Phys. Contr. Fus. **38**, 2163 (1996).

[10] C. Angioni *et al*, submitted to Plasma Phys. Contr. Fusion.

[11] O. Sauter *et al*, Phys. Plasmas. **8**, 2199 (2001).

[12] S. Guenter *et al*, Phys. Rev. Lett. **87**, 275001 (2001)

[13] R. J. Buttery *et al*, ibidem [7], P5.011.

FIGURES

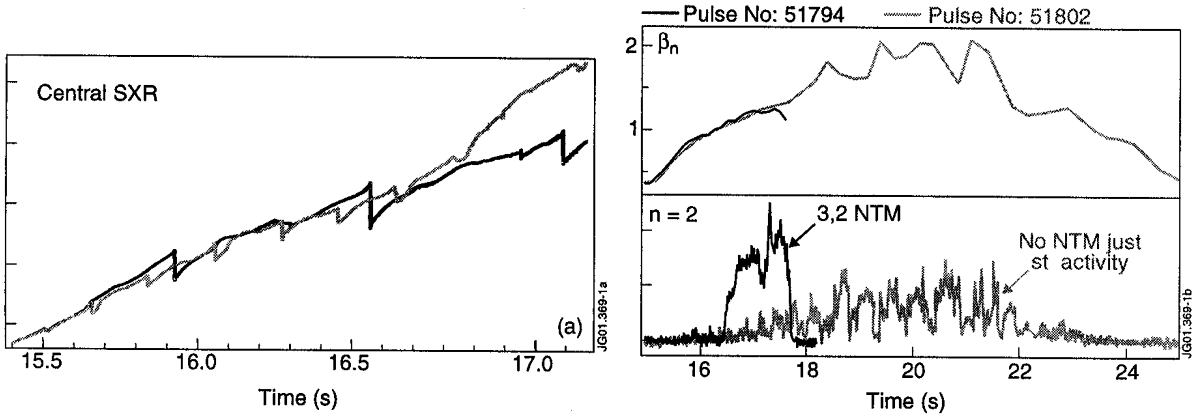

FIG. 1. Two similar discharges with $2.4T, 2.4MA, 4.5MW$ ICRF, same P_{NBI} ramp. Only the antenna phasing has been changed: $+90°$, #51794 (long ST, dark line) and $-90°$, #51802 (short ST, grey line). (a) SXR emission. (b) β_N and $n = 2$ MHD activity. In #51794, a NTM is triggered at the first crash when $\beta_N > \beta_{Ncrit}$.

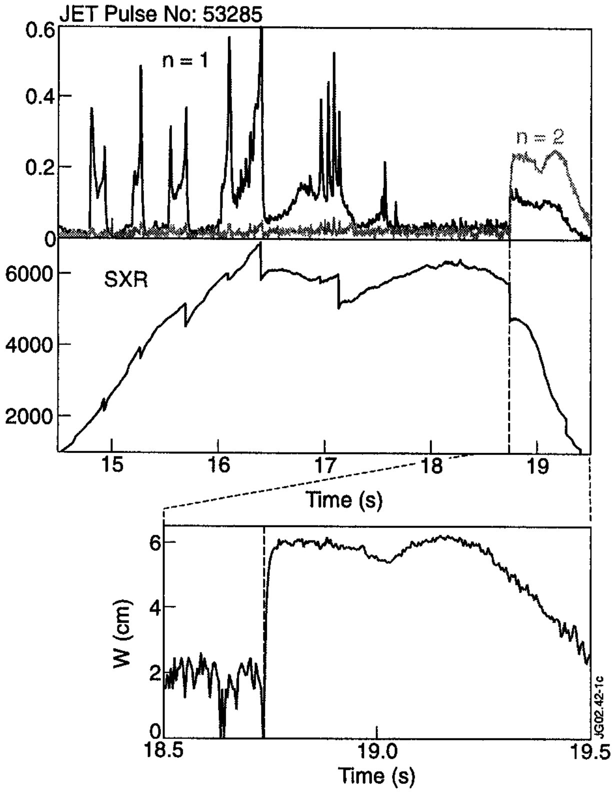

FIG. 2. High field case, $3.3T, 3.3MA, \beta_N \approx 1$. The 3/2 mode is triggered at the crash after a $1.6s$ sawtooth period. The island width (from $[\delta B_\theta(n = 2)]^{1/2}$) is directly formed at about $6cm$.

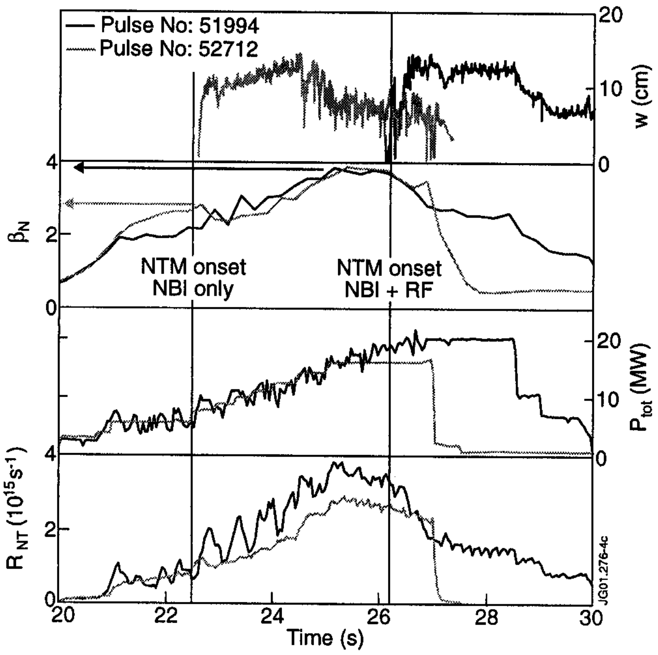

FIG. 3. Low field case, $1.2T, 1.2MA$. Two discharges with same total power waveform, one with NBI heating only, 52712 (grey line), and one with NBI+ICRF ($4.5MW$) heating with the resonance position just outside R_{inv}, 51994 (dark line). The island width w, β_N, total power and neutron rate are shown.

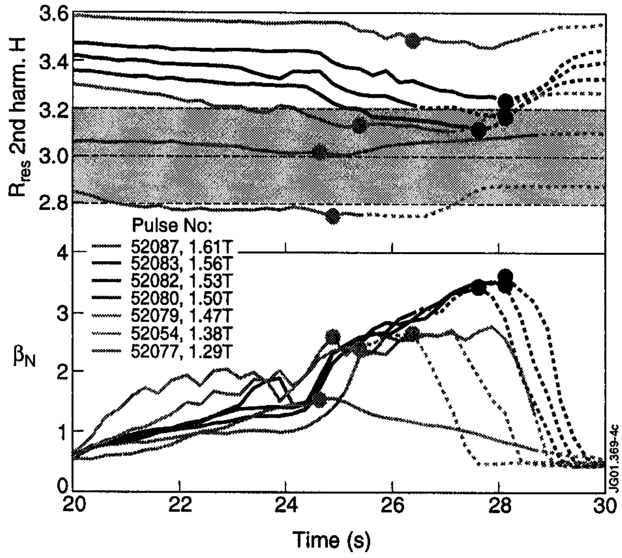

FIG. 4. Resonance position and β_N evolutions for discharges with only B_0 changed from shot to shot with I_p/B_0 constant. The dots mark the NTMs onset and the dashed portions when $P_{ICRH} < 1MW$ (due to bad coupling). The shaded area sketches the region inside R_{inv}.