EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(03)03-01

A. Bécoulet, the Tore Supra Team and JET EFDA Contributors

Hybrid and Steady-State Operation on JET and Tore Supra

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Association EURATOM-CEA sur la Fusion, CEA Cadarache 13108 St Paul-lez-Durance cédex, FRANCE
** See annex of J. Jacquinot et al, (19th Fusion Energy Conference, Lyon 20002).*
*** 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).*

Preprint of Paper to be submitted for publication in Proceedings of the
15th Topical Conference on Radio Frequency Power in Plasmas
(Moran, Wyoming, USA 19-21 May 2003)

ABSTRACT.
Producing fusion energy requires to simultaneously sustain in a tokamak environment fully non inductive regimes at the highest Q-values and a "significant" fusion performance level under MHD-stable conditions, while insuring a satisfactory confinement of the fast alpha particles. This ambitious goal is being investigated on many devices worldwide, particularly focusing on the role played by the current density profile. The paper reports on the recent experimental progress of both the JET and Tore Supra devices towards i) long to very long pulse operation relying on a careful use of lower hybrid current drive under various current profile tailoring conditions (namely so-called "hybrid" peaked current density profiles and so-called "steady-state" hollow current density profiles) and ii) discharges performed with real-time controlled pressure and/or current density profiles. Such discharges are detailed and interpreted using the CRONOS integrated modelling suite. Its fully predictive capability, including real time control features, is used to provide keys to future experiments.

1. INTRODUCTION

Recently, the International Tokamak Physics Activity (ITPA) Group on Steady-State Operation and Energetic Particles proposed a classification of the tokamak discharges which aim at long pulse operation, in present and next step devices. This classification is based on the commonly admitted result that the current profile tailoring is the key issue for this type of discharges. Thus, regardless to the absolute long pulse technical capability of the concerned devices, two major target discharges were defined. The first one, so-called "hybrid" regime, relevant to the extended burn phase of ITER, consists in discharges where i) some inductive flux is saved mostly by a non inductive additional H&CD source and ii) the central current density profile is tailored in order to avoid the main q=1 MHD sawtoothing activity. The resulting q-profile, depicted in Fig.1(a), is monotonic, with an edge value not larger than ~5 and a central value in the vicinity of 1. The second target regime, called "steady-state", is more ambitiously preparing the fully stationary operation of devices like ITER. The baseline is to take full advantage of the self-consistent bootstrap current in order to set-up a regime with the capability of providing actual stationarity to the plasma core. The resulting plasma current density is broadened by the large contribution of the bootstrap current (say above 50%), even leading to a magnetic shear reversal in the plasma core. The regime thus operates at vanishing loop voltage, with large values of the normalized beta. Here again, considerations on overall MHD stability and fast ion confinement bound the central q-value around a typical value of 3, and the minimum q-value in the range 1.5-2.5. Though the value of the magnetic shear inversion radius is not specified for this target, the recent results by many devices on the existence of internal transport barriers (ITBs) in such regimes tend to push towards the largest possible values. The typical "steady-state" target q-profile is depicted in Fig.1(b).

Referring to this classification, the ITPA then encourages each tokamak device to document the "hybrid" and "steady-state" scenarios in terms of existence, stability and performance, investigating in the largest density / plasma current / configuration parameter space. Obviously, the performance has to be sustained over the longest pulse duration allowed by the devices. The development and implementation, in parallel, of real-time control algorithms is strongly supported as part of the optimisation process.

The present paper locates the Tore Supra and JET devices in this respect, underlining the key role often played by lower hybrid current drive (LHCD), either when bringing a dominant non inductive additional current source and/or when tailoring the current density profile prior to the high power phase. Section 1 illustrates the “hybrid” and “steady-state” regimes with recent discharges from both devices, and discusses the present related performance and limits; section 2 presents some specific issues linked to the real time control at vanishing loop voltage operation; it finally proposes an alternative procedure of real time algorithms, performance oriented, that are presently developed using the predictive capability of the CRONOS[1] integrated modelling suite.

2. HYBRID AND STEADY-STATE TARGETS

The Tore Supra experimental programme is focused on long pulse plasma operation, progressively integrating all the technology and physics aspects of a multi-megawatt tokamak discharges lasting over hundreds of seconds. The constraint on the scenarios makes the vanishing loop voltage a pre-requisite. The circular limiter configuration of the device ($R = 2.42$m, $a = 0.72$m) prevents from investigating the ITER-relevant geometries or the compatibility between the edge barrier and a plasma core with a strong current density profile shaping. On the other hand, Tore Supra’s long pulse radio-frequency power capability (LHCD, ion and electron cyclotron resonant heating (ICRH, ECRH) systems) allows to produce and study such “hybrid” and “steady-state” current profiles over time durations much larger than the resistive current diffusion time, and under vanishing or controlled-zero loop voltages. The most investigated regime so far is the low density fully non inductive discharge in which a dominant fraction (~80-90%) of the plasma current is driven thanks to LH waves, the small remaining fraction being provided by the bootstrap effect. The typical current drive efficiency obtained in these fully stationary discharges ($\eta_{vloop=0} \sim 0.7\times10^{19}$ A/W/m^2) allows long pulse operation with the following typical parameters: $I_p = 0.55$ MA, $B = 4$ T, q_a~9, $P_{LHCD} = 3$ MW, $n_{//inj}$~1.8, $n_{e0} = 2.5\ 10^{19}\ m^{-3}$. The propagation/absorption conditions[2] of LHCD are such that the resulting current profile is centrally peaked (l_i~1.6), naturally producing an “hybrid-like” target. It is to be noted that the LHCD system is presently being upgraded (both through new 700kW klystrons, and a new antenna[3]) and will bring the operating point closer to q_a~5 in the near future. The present longest discharge of Tore Supra[4] (Pulse No: 30414) reached 4minutes 25s, thanks to 0.75GJ injected. The regime has also been consolidated adding up to 3 MW ICRH (D(H) central minority heating) at somewhat higher density (Fig.2).

Accessing a steady-state target is somewhat more complex. For a machine like Tore Supra, the constraint of 50% of bootstrap current requires the poloidal beta value to exceed 1.5. Such values were obtained applying a high power level (>6MW) of ICRH in the so-called Fast Wave Electron Heating (FWEH) mode[5]. The scenario was performed at $B = 2.15$T, and a wave frequency of 48MHz. In that case, the only ion cyclotron resonance present in the plasma is the 3rd harmonic of deuterium, with a negligible absorption compared to the direct absorption of the wave by the electrons under the combined electron Landau damping and transit time magnetic pumping effects. The resulting discharges exhibit the expected 40-50% of bootstrap current, a significant confinement enhancement factor ($H_{ITER97\text{-}L} = 1.6$), thanks to a highly enhanced electron stored energy (more than twice the Rebut-Lallia-Watkins zero-D prediction). It is to be noted that, so far, no signature of shear reversal or ITB has been observed in such discharges. Here again, the on-going upgrade of the ICRH capability of Tore Supra, through CW sources and an improved antenna concept more resilient to variations of load will help investigating further this route in the coming years[6]. Meanwhile, hollow current profile targets are produced and studied, at lower bootstrap current fractions, using the RF heating and current drive systems. Two main routes are followed on Tore Supra for the production of such reversed magnetic shear discharges. The first one follows the conventional proven recipe of many tokamaks, relying on a fast plasma current ramp-up phase, which naturally produces a transient hollow current profile[7]. In the present case, a low current stationary plasma is first produced (I_p<400kA for 8-10s), and the plasma current is then rapidly ramped-up, at a typical rate of 1.6MA/s, while additional ICRH power and density are raised. Target q-profile relevant of the "steady-state" are then temporarily produced over 1 to 2 seconds, as reconstructed from magnetics and polarimetry data. The regime is only transiently produced as the inductive current fraction remains dominant. It is to be noted that an ITB on electron temperature is then observed, the normalized radius for the foot of the barrier being as broad as 0.5-0.6. One must also point out that the superposition of LHCD power to this sequence in order to prolong the high performance phase failed so far, as LHCD is then deposited mostly centrally and counter-acts the reversed shear configuration. More successful in terms of duration are the attempts to reverse the magnetic shear directly from a monotonic situation using LHCD alone and/or a combination of LHCD and Electron Cyclotron Current Drive (ECCD) power. The initial situation is similar to the hybrid long pulse operation, but i) the LHCD deposition profile is broader due to a proper choice of parameters[2] (higher-$n_{//}$ launched spectrum, larger plasma current, Ö) and/or ii) a local perturbation is applied off-axis on the current density profile by counter-ECCD[8]. In such situation(s), a so-called Lower Hybrid Enhanced Performance (LHEP) mode is triggered, exhibiting an ITB on electron temperature. Due to the modest volume occupied by this barrier, which foot point lies between 0.2 and 0.3 in normalised radius, it is difficult to conclude on the related shear reversal, but through 1-D current diffusion reconstructions which give good confidence in its presence. The on-going increase of the available long pulse ECRH capability of Tore Supra allows us to expect producing broader ITBs with more off-axis ECCD deposition[9]. The massive role played by LHCD eases the stationarity of the phenomenon. LHEP targets lasting more than a minute (LHCD only), and/or as long as the ECCD pulse, have already been observed this way, routinely. Interestingly, the transition between the hybrid target and a hollow current density profile may lead to a stationary solution oscillating at very low frequency[8][10] (observed at a few Hz for more than 100s). Such oscillatory behaviour is presently identified as an interplay between the current density profile evolution and the associated local transport properties, and viewed as an incomplete transition towards the core ITB.

Complementarily, the JET device allows to investigate both "hybrid" and "steady-state" targets integrating ITER-relevant configuration aspects and compatibility with an H-mode edge. JET also provides an alternative set of additional heating and current drive systems. Though high power phases include large fractions of positive neutral beam power, the ICRH and LHCD systems of JET appear to also play key roles in setting-up the regimes[11]. The development of the “hybrid” target is pursued in the frame of the so-called “JET/Asdex-Upgrade identity” experiments [12][13]. In both machines, the additional heating power waveform is carefully timed so that the current density is tailored with the identical “hybrid” features described in introduction. The core region exhibits a rather flat q-profile, clamped in the vicinity of q = 1 by a regular fishbone activity which prevents the current profile from further peaking. The plasma current, still dominated by ~70% of ohmic current, typically contains 20% of bootstrap current and 10% of neutral beam current drive, responsible for this core current density flattening. Though differences may occur, the comparison between the two machines is carried out extensively, including the match of the ρ^* and edge q-values at various triangularities. The present JET performance reaches H_{89}. $\beta_N > 5$ at 1.4MA/1.7T (q_{95}~4, δ up to 0.45), the compatibility with an H-mode edge is satisfactory and the possible limitation due to the role of the central fishbone activity on fast ion confinement seems presently modest.

JET provides also major contributions to the viability of the “steady-state” target. The reversed magnetic shear configuration is provided routinely by imposing LHCD power during the fast plasma current ramp-up phase (~0.4MA/s). A careful dosing of the power and the ramp-up rate gives access to a large range of current profile targets from monotonic to extremely hollow (so-called “current hole” configurations[14]). The target current profile is then carefully adjustable, very close to the stationary solution obtained during the high power phase, which combines bootstrap current, NBCD and LHCD. This way of proceeding allows JET to access and study the steady-state targets despite the limited high power pulse duration. Steady-state discharges mixing 50% of bootstrap current to 25% of NBCD and 25% of LHCD have been maintained up to typically 10 seconds. This represents about one current diffusion time for JET. H_{89}. β_N values in such discharges reach 4 at present[15] (Fig.3).

It is noticeable that such discharges are always associated so far with ITBs: ITBs on electron temperature are present from the prelude LHCD phase, ITBs on electron and ion temperature, but also on plasma density and toroidal velocity then develop when the high NBI+ICRH+LHCD power phase is triggered. As a common feature to all these developments, steady-state targets in JET are carefully designed to last, and not to explore the performance limits (fusion, MHD, ...). To that respect, they do not really bring new information, but on long time scale phenomena. The most noticeable result here concerns the high-Z impurity behaviour. It has been demonstrated [16] that impurities follow the neo-classical expectation, i.e. accumulate in the plasma core all the more that the density gradient is large and the temperature gradient is weak. Core radiative collapses have even been observed in long lasting strong ITBs, though it must be noted that the regime recovered after such collapses, as the current density profile was still under control.

3. CONTROLLING THE REGIMES, IN VIEW OF STATIONARY OPERATION

A careful control of the various profiles is thus necessary for the viability of these regimes. An intensive work is being conducted on both devices in the direction of a real-time control of the advanced discharges.

To alleviate the high-Z impurity accumulation on long pulse discharges with ITBs, JET uses for instance a real-time feedback loop between the measured characteristic gradient length of the ITB and the input power. The ITB is detected[17] and then followed in location and strength through the maximum value of the local ion Larmor radius at the sound speed ρ_{se} ($\rho_{se}^2 = m_i T_e / e Z_i^2 B^2$) normalised to the local electron temperature gradient length (deduced from electron cyclotron emission measurement). The best actuator appears to be the ICRH power.

To better match the requested current profile targets, JET is also equipped with a real-time determination of the q-profile, based on real-time equilibrium reconstruction constrained by polarimetry data, and soon by MSE data. The control algorithm is a model-based control [18] which presently uses a pre-determined matrix link between five values along the safety factor profile and the LHCD power actuator. It insures a least square minimisation between the actual q-values and five prescribed ones. The matrix can either be computed from models or deduced from previous open-loop experiments. Successful prescribed monotonic or reversed q-profile have been obtained and maintained this way, combining current ramp-up and LHCD power. It is important to note that the model based algorithm can accepts much more sophisticated actions through any desired link between measured q-profile, pressure profile, ... values and LHCD, ICRH, NBI, ... actuators. Such algorithms are under intense development and tests presently on JET[19].

Tore Supra has also a long tradition of real time control developments and operation[20]. One can remind the routine operation at constant primary flux consumption combined with a plasma current feed back control by the LHCD power, which allows most of the long pulses, feedback loop between the internal inductance and the LHCD antenna phasing, which allows a certain control on the current profile width, Ö But Tore Supra is also equipped with an increasing series of feedback loops relevant to a safe long pulse operation, i.e. very accurate plasma shape controller (R and Z to be controlled within millimetres, triangularity within percents), feedback loops involving radiated power, local surface temperature of plasma facing components (infrared measurements), water cooling flows, ... The electron cyclotron emission and the hard-X ray tomography signals will also be available in real time during the coming campaign, allowing determination of the electron temperature and lower hybrid current profiles during the pulses.

The success of advanced tokamak physics is intimately linked to our capability to access key information and to react in real time on the major plasma parameters, including some radial profiles. The difficulty to develop performant algorithms can be summarize under three major bullets:

i) The relevant physics addresses detailed profile characteristics, and thus imposes to access and treat a very large amount of information in real time. Some of this information is even hardly accessible by diagnostics and/or requires long computation time.

ii) The actuators mostly act on global parameters and/or upon several profiles simultaneously. One must also note their few number and the tendency to become "weaker" in the large size next step devices (lower power densities).

iii) Our present level of predictability is low, in the sense that the routes towards the desired stationary targets are still difficult to model satisfactorily.

Thus, it appears crucial to consider in the control algorithms a part of self-optimisation from the discharge itself. In fact, the real time control process is then conceived more like an online help to decision, rather than like a permanent constraint along the discharge. One can then envisage to run a tokamak discharge the following way (note that this is naturally relevant of long duration discharges):

i) Global plasma/machine parameters are prescribed: would it be the toroidal magnetic field, the plasma shape, ...

ii) Global constraints are imposed: in the case of a stationary discharge, for instance, the primary flux consumption might be imposed to zero. The discharge must then run constantly under these constraints. Note that one might envisage to suppress this constraint during given phases of the plasma scenario, if necessary. Constraints concerning the safety of the subsystems are also to be included.

iii) The series of actuators is identified: one mostly recognizes here the additional power systems, with their usual parameters of power, phase, ..., but also the gas fuelling (puff, pellets, ...) and pumping or, on limited time duration, the primary flux consumption. Each actuator is given an operating window.

iv) The physics limits are pre-programmed: this part plays a key role in the self-optimisation process. These limits have either a zero-D character (as the density limit, the maximum radiated power fraction, ...), or a more sophisticated one-D character (as the MHD stability domain dependent upon the actual pressure and current density profiles, the transport enhancement conditions,...).

v) The algorithm is then in charge of running the plasma discharge satisfying an optimisation condition, say the maximisation of the fusion power, or of the stored energy for instance. After a plasma initiation phase, a snapshot of the discharge is thus taken from the real time data, and the actual value(s) of the quantity(ies) to optimise is stored. The algorithm then guesses whether a given step in one of the actuators is compatible with the physics limits. This guess might be strict ("the plasma density when increased by one step will remain below the Greenwald density limit" for instance) or more fuzzy ("the plasma density when increased by one step will still remain "far enough" from the Greenwald density limit", "far enough" to be quantified). Of course, the more constraints and prescribed limits, the more sophisticated the decision step will be. All the physics and knowledge are located at that step, would they come from first principles or from fits or various learning processes. If a green light is given by the controller, the action is taken ("the density is increased"), the discharge evolves following the constraints and the controller waits for a new state to establish. The duration here might either be pre-programmed or determined by the controller itself. It is essentially determined by the characteristic time of the (local) current profile relaxation. The following snapshot of the discharge is taken from the real time data, and the quantity to optimise is compared to its previous value. If better, the same actuator is used again under the same procedure, if worse the controller comes back one step and restarts the procedure on the following actuator.

The controller then progressively brings the plasma discharge from its initial state to the "best" situation in terms of fusion power, or stored energy, and on a safe route (if not always the fastest). The procedure described here above somewhat decorrelates the plasma engineering procedures from i) the physics governing the discharge and ii) the choice of constraints and limits. For instance, even if several local optima exist, possibly depending upon current density or velocity shear profiles for instance, the controller will cope with such a situation, if it is properly taught. The procedure also gives room to a given device to follow its own learning curve, along a given discharge and/or from discharge to discharge.

As a matter of illustration, such a real time central controller has been implemented in the CRONOS suite of code[21]. The code is not used as an interpretative tool for an existing discharge, but as a "virtual tokamak" enabling us to adjust the engineering part of the controller, and test the best strategy in terms of steps in the actuators, delays between snapshots, Ö The Tore Supra device is chosen, as this first demonstration will be proposed for an actual experiment.

The global parameters are fixed as follows: circular shape R = 2.40m, a = 0.72m, $B_T = 3.9T$. The constraint forces to operate at constant primary flux ($V_{loop} = 0V$). Only two actuators are selected: i) the LHCD power, bounded between 0 and 7MW, with steps of 0.3MW, and ii) the line averaged density (actuated by gas fuelling and pumping), bounded between 0 and $10^{20}m^{-3}$, with steps of $2\times10^{18}\ m^{-3}$. A single zero-D limit condition is pre-programmed: the density must not be expected to overcome 95% of the Greenwald limit. The optimisation condition is chosen to be the maximisation of the fusion power. The algorithm was developed with three different delays between snapshots (0.5, 1 & 2s), resulting in three different routes. The controller was then able to bring itself the discharge from a low density – low current hybrid discharge to the highest combination of density/power/ current compatible with the imposed limits and constraints, as expected in such a simplistic demonstration case. It is interesting to note that once the vicinity of the optimum point is reached, the algorithm carries on oscillating in terms of actuators, in a stationary way. The time requested to reach the optimum region ranges from 20 to 100 seconds depending on the delay between snapshots (Fig.4).

Of course, when transposing this type of algorithm to larger ignited stationary discharges, constraints and limits will significantly increase and gain in complexity, actuators will change, physics will change, but the procedure should basically remain the same. From now on, it can be developed and tested on existing long pulse devices, with the help of integrated codes, as the CRONOS suite.

CONCLUSION

Besides the considerable technological actions needed to bring tokamaks from the plasma performance exploration to the stationary production of fusion energy, the integration of physics aspects linked to stationarity requires a dedicated effort. Various regimes are candidate, either to an extended pulse length regime or to a truly steady-state solution. Many devices, like JET and Tore Supra, are dedicating an increasing experimental time to generate and study stationary plasma targets. This issue is intimately linked with the capability to diagnose the discharge in real time, and then to react through the relevant actuators in order to drive the plasma towards the desired operating point, and/or to sustain this operating point. Real time feedback controls are now routinely used on Tore Supra and JET, from simple one-to-one actions to more sophisticated non-diagonal model-based controls, mixing physics quantities to control and actuators. The safety of the devices (plasma facing components, disruptions, Ö) are progressively also included in the algorithms. Finally, it is proposed to use real time controls also as an online help to decision in a self-optimisation process, rather than as a permanent constraint along the discharge.

ACKNOWLEDGEMENTS
It is a great pleasure to acknowledge many fruitful discussions among the members of the ITPA Group on Steady-State Operation and Energetic Particles, in particular with Drs Claude Gormezano, Tim Luce and Shunsuke Ide.

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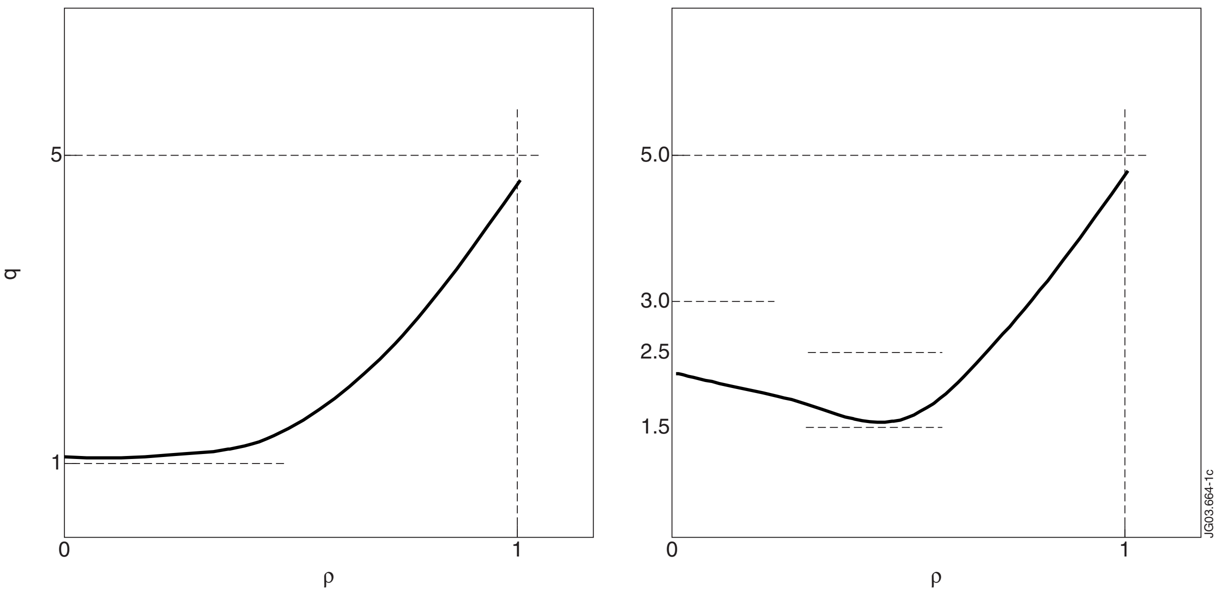

Figure 1: Typical safety factor profile for a) the hybrid target and b) the steady-state target

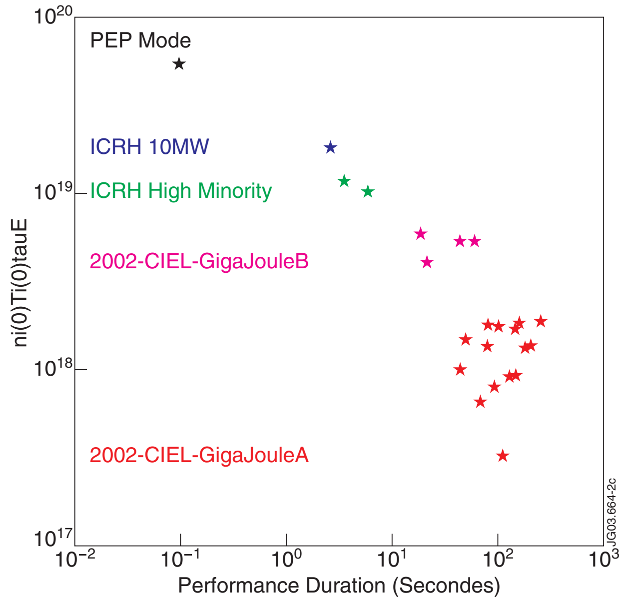

Figure 2: Tore Supra: $n_i(0)T_i(0)\tau_E$ (keV.s.m^{-3}) as a function of the performance duration (s).

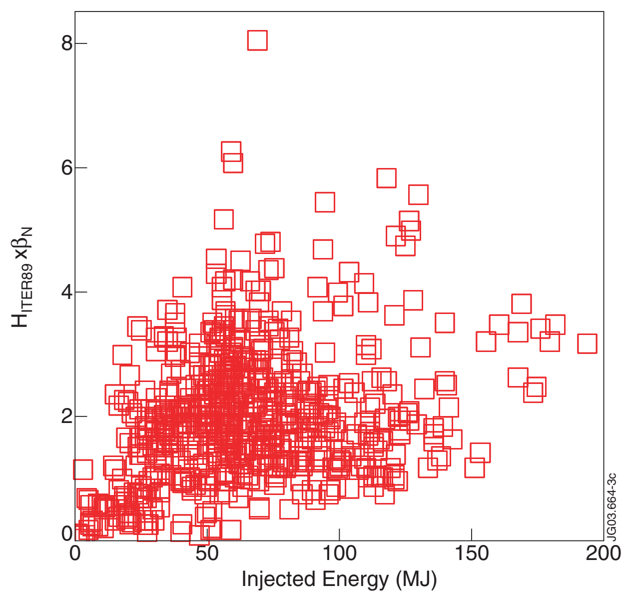

Figure 3: JET: present performance (H_{ITER89} β_N versus injected energy) in steady-state target discharges.

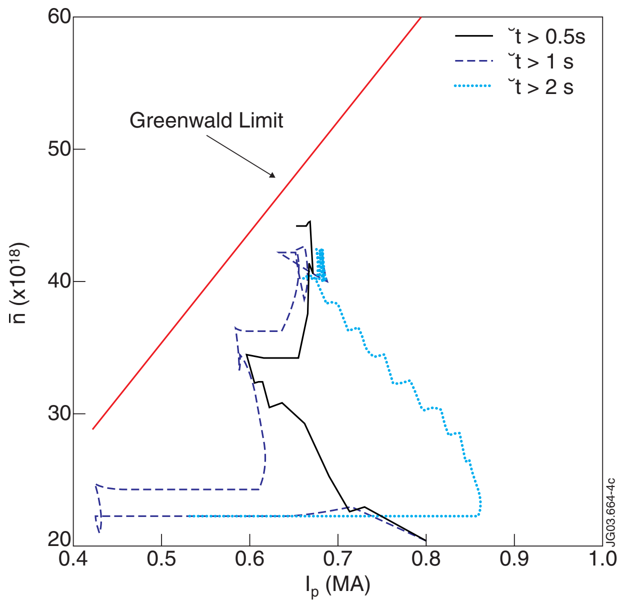

Figure 4: Tore Supra: Self optimisation trajectories in the line averaged density / plasma current operating space, for three different delays imposed between snapshots.