Towards high-power long-pulse operation on Tore Supra

Equipe Tore Supra, presented by ***A. Bécoulet***

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The Tore Supra tokamak was given the main mission to investigate the route towards long pulse plasma discharges. This includes the problem of heat exhaust and particle control (via the development of performant plasma facing components), and in parallel the physics of fully non inductive discharges and its optimisation with respect to the confinement. Tore Supra is thus equipped with a superconducting toroidal magnet (maximum magnetic field on axis 4.5T), a full set of actively cooled plasma facing components (PFC), and a heating & current drive capability based on high power RF systems connected to actively cooled antennas. The encouraging results already obtained, as well as recent progress in PFC, allowed us to envisaged a significant improvement in the heat exhaust capability of Tore Supra. The so-called CIEL-project [1] consists in a complete upgrade of the inner chamber of Tore Supra, planned to be installed during the year 2000. The present paper deals with the experimental and modelling activity linked to the preparation of the long-pulse high-power discharges using the present Tore Supra equipment: heating and current drive scenarios, power coupling, confinement and transport studies, discharge control,... An overview of the results obtained in that field is presented, as well as the progress required in the coming years, and the expected performance, for the CIEL phase, in terms of current drive and confinement.

1. Additional Heating and Non Inductive Current Drive on Tore Supra

The present auxiliary heating system of Tore Supra [2-3] consists of a lower hybrid current drive (LHCD) unit (16x500kW-klystrons, 3.7GHz, 2 multijunction launchers) combined with an ion cyclotron range of frequency (ICRF) system (6x2.2MW-tetrodes, 40-80MHz, 3 double-loop resonant antennas). The maximum power expected to be coupled to the plasma with the present system is in the range of 10-11 MW for ICRF and 5-6 MW for LHCD. Both systems have current drive capabilities (i.e. tuneable phasing), actively cooled antenna structures (lateral bumpers (ICRF+LHCD); Faraday screen, current straps, matching capacitors (ICRF)), and are designed at present for 30s (ICRF) or 210s (LHCD) pulses. Various recent improvements are to be noted as key elements towards a more reliable operation of the system:

- *ICRF operation*: automatic matching based on the tuning of the antenna variable capacitors during pulses, with a minimum time response of the order of 100ms [4]; use of Thomson Tubes Electroniques TH525 tetrodes allowing a higher output power (~2.2MW), as well as a higher dissipated power (up to 2MW) [2].
- *LHCD operation*: VME operation system favouring various real time feedback loops, including one limiting the output power in case of high-Z impurity production.
- *Infrared camera monitoring*: numerical data acquisition and processing of the infrared camera system, allowing a more exhaustive analysis and control of both PFC and antennas.

The progress towards high power long pulse discharges presently follows two main routes. The first one consists in achieving discharges which combine the two RF systems at their maximum power capability. As mentioned above, this aspect of course requires a reliable operation of the generator and antenna systems, involving continuous maintenance and development effort. It also involves the understanding and optimisation of the power coupling. As a matter of examples, one can mention several keypoints, recently documented:

- *acceleration of electrons in front of LHCD multijunction grills*: experiments and modelling on several machines have shown the possible dissipation of LHCD power by the edge electrons, generating damages [5-7]. Minimisation of such effects requires a limitation of the power density at the grill mouth, as well as a careful design of the grill itself (septa shaping, location of guard limiters). Such improvements are being implemented on the present and future Tore Supra [3] launchers to allow a safer long pulse operation.

- *careful ICRF layers optimisation*: due to the Tore Supra aspect ratio, high harmonic cyclotron layers often locate at the very edge of the plasma (low field side) during ICRF operation. This mainly concerns the third harmonic of Deuterium in D(H) minority heating, and the fourth harmonic of Deuterium (second harmonic of Hydrogen) in fast wave electron heating (FWEH) scenarios. Though they do not significantly alter the expected power deposition balance, those layers can be responsible for a strong heat deposition on the antenna Faraday screens when located a few centimetres in front of it (fig1). A careful positioning of such layers, accounting for the important local magnetic field ripple, is thus fundamental for long pulse operation.

The Tore Supra ICRF antennas have demonstrated several time their individual capability of operating at the nominal power of the generator system, namely from 4 to 4.2 MW. The actual antenna limitation is in fact more relevant to a maximum voltage of 40-45kV, located at the extremities of the current strap. Combined operation with several ICRF antennas is of course more constrained. The first effect concerns the increase of the overall power, and thus of the heat load on the antenna structures. This point becomes crucial for long pulse operation and will be discussed mainly in the last section. The second aspect involves the possible "cross-talk" effects between antennas. Power flowing from one antenna can be seen by the other antennas as reflected power, possibly confusing the safety systems based on the reflected to incident voltage ratio. This effect is exacerbated when operating in low single pass damping scenarios, as FWEH or mode conversion heating, which develop strong cavity mode structures. Several solutions are presently envisaged: i) polychrome operation, consisting in associating a different frequency to each antenna. The drawback of this method is that the required frequency split (± 200kHz at least) is not always compatible with the careful control of the edge high harmonic cyclotron layers. ii) the simultaneous management of the three antenna safety systems, which insures that they are switched on and off at exactly the same times. This solution is being implemented. iii) new arc detection systems (optic fibres, detection of sub-harmonic frequencies generated by arcs, ...) replacing the existing safety system. Such a solution still requires R&D. Though no definitive solution has been fully implemented yet, up to 10 MW of ICRF were coupled into the Tore Supra plasmas by the combined operation of the three antennas, both in minority heating scenarios (damping per pass close to 100%) and in FWEH schemes [8] (at 2T, damping per pass of the order of 10%). This performance is close to the present generator capability of the ICRF system. Solving the problem generated by cross-talk effects would however mean more reliability and stability for these high power discharges. This reliability can even become a pre-requisite for certain types of discharges, as the ones operated at high fraction of radiated power (with or without the ergodic divertor) for which a power switch-off leads to disruption, or the ones operated at high-βp for which a power switch-off leads to a fast backward motion of the plasma and thus to major difficulties for recovering.

The combined operation of the two LHCD grills is not altered by such "cross-talk" effects. Maximisation of LHCD coupled power is mainly governed by a careful control of the reflected power of each antenna, i.e. by the optimisation of the edge conditions at the grill mouth (once the antenna conditioning is satisfactory). Up to 5.3MW were obtained energising the two grills simultaneously for 6s. The plasma-grill distance can also be adjusted during the pulse, and controlled by a feedback loop, for instance on the reflection coefficient. Using the same system in a pre-programmed way, the power coupling has been maintained as the plasma-grills distance was slowly increased up to 16cm, in regions where the plasma heat load is negligible.

The ultimate goal is of course to combine both RF systems on the same target plasma. One must here again distinguish between the overall heat load problem (more relevant to long pulses and discussed below), and the problem of compatibility between the constraints. The limitation of the voltage in the ICRF antennas forces to maximise the loading resistance if one wants to maximise the coupled power. This is achieved either by increasing the plasma density (in fact the plasma edge density) and/or by decreasing the antenna-plasma distance. For the Tore Supra ICRF antennas, coupling the full power requires a loading resistance larger than 5 Ω/m, which corresponds to line densities larger than $4\text{-}5.10^{19}m^{-2}$ and antenna-plasma distances of the order of 2-3cm. The edge conditions are of course of importance: recycling conditions, gas, limiter or ergodic divertor configuration,... have an influence on the antenna loading resistance. One finally must keep in mind that a reliable operation requires some antenna voltage margins, in order to cope with transient effects, like giant or monster sawtooth crashes, plasma motions, ... Following this idea, a feedback loop system limiting the antenna voltage to a preset value is under study. On the LHCD side, the optimum coupling conditions are unfortunately opposite: the density at the grill mouth should be maintained close to its (low) ideal cutoff value. Moreover, for a given power density at the grill mouth, the higher the local density the larger amount of fast electrons in the plasma edge, possibly causing damages to the magnetically connected objects. The success is finally sensitive to the chosen scenario and plasma behaviour. The latest performance achieved in this domain (fig2) is a 11.6MW/1.6s discharge (#25419, 32MJ for the overall discharge), consisting of 9.5 MW of ICRF (3 antennas) + 1.8MW of LHCD (1 grill) + 0.3MW of ohmic power. It has been achieved in a He(H) minority heating scenario (B=3.5T, Ip=1.4MA, nl=$6.10^{19}m^{-2}$) where the fundamental hydrogen cyclotron layer is located slightly off-axis on the high field side, in order to limit the sawtooth activity (Te(0)~5keV). The voltages on the ICRF antenna was in the range of 35kV and the coupling resistance of 6Ω/m. The time duration was limited on that discharge by the temperature reached on the main pumped limiter on which the plasma was lying. Note that the diamagnetic stored energy reached the record value for Tore Supra of 1.24MJ (thermal energy confinement time ~85ms).

The second route consists in achieving long pulse discharges in order to progressively qualify new PFC components, in the various integration aspects: power and particle injection and exhaust capabilities, machine operation, diagnostics, data acquisition, feedback loops...., and address the feasibility of steady-state discharges. The pre-requisite of such studies is of course to drive non-inductively a significant fraction of the plasma current, mainly through the intensive use of LHCD (see below). The plasma current has already been sustained on Tore Supra for 2 minutes at the level of 0.8 MA, using 2.4MW of LHCD. The total injected energy (LHCD+ohmic) reached the record value of 280MJ [9]. The slow density increase usually observed after one minute of operation on such discharges confirmed the absolute necessity of a complete particle control system for further progress (i.e. active cooling of each element plus efficient pumping). Fully non inductive discharges were performed for durations up to 75s, using a double feedback control: the loop voltage was imposed to be zero by retroaction on the ohmic system, and the plasma current value was controlled by a feedback loop on the injected LHCD power (Ip=0.6MA, P_{LHCD}=2MW). In order to progressively increase the power level on such discharges, ICRF power has also been superimposed. This allowed us to couple up to 4MW of ICRF (hydrogen minority heating) plus 2.2MW of LHCD during 26s, representing a total input energy of 170MJ. Note that this performance was also favoured by the fact that 1/6 of the Tore Supra carbon inner wall was replaced by more performant PFC components, made of Carbon Fibre Composites (CFC) and intentionally slightly misaligned beyond the remaining 5/6 [10].

The success of the overall programme is of course not independent of the chosen scenarios and of the resulting confinement properties and plasma stability. The required non inductive current is based on Tore Supra on two components. The first one is LHCD, the second bootstrap current. Fully non inductive discharges, driven by LHCD on time durations long enough to reach steady-state under various plasma conditions, allowed us to determine the experimental behaviour of the LH current drive efficiency for the Tore Supra conditions. Besides the predicted dependence in Zeff, it is found to depend linearly on the magnetic field, and to very slowly decrease with density. No clear evidence of a dependence with the volume averaged electron temperature is found. More details on the non inductive current profile behaviour are discussed in the next section, as well as in ref [5]. Extrapolations of such a current drive efficiency clearly show (fig3) that some extra LHCD power and/or alternative non inductive current are required to reach steady-state discharges in the relevant range of $0.5 \leq Ip(MA) \leq 1.5$ and $1 \leq \langle n \rangle (10^{19}m^{-3}) \leq 5$.

Significant effort is thus being made in the bootstrap current generation using the direct coupling of the fast magnetosonic wave to electrons, in the ICRF [8]. This so-called fast wave electron heating (FWEH) scheme involves Landau damping and transit time magnetic pumping of the fast wave on the parallel motion of the bulk electrons. The Tore Supra database now covers a magnetic field range between 1.3T and 3.5T, and an input power range up to 9.5MW. Bootstrap current fractions up to 50% have already been reached for several seconds. The corresponding ICRF frequency is chosen so that the plasma is bounded by the second and fourth cyclotron harmonic layers of the bulk ions (Deuterium or Helium 4). The third cyclotron harmonic layer thus crosses the plasma centre, but the possible competition with the FWEH is insignificant on present discharges as the bulk ion temperature remains low enough. For the first time in a tokamak, the fast wave has also been damped by electrons in a scenario where no competing ion cyclotron damping is present in the plasma (42MHz, 3.9T), confirming without any ambiguity the FWEH process. The power deposition profile is strongly peaked in the plasma centre and the bootstrap current is then driven by the resulting strong electron pressure gradient. The corresponding amount of bootstrap current is found not to depend on the operating magnetic field, and the following ad-hoc expression of the bootstrap current fraction was fitted, adding the TEXTOR and TFTR bootstrap databases to the Tore Supra one [11]:

$$Ibs/Ip \approx 0.5\ \varepsilon^{0.5}\ \beta p\ (\alpha_p/\alpha_j)^{0.5}$$

where ε is the inverse aspect ratio, βp the poloidal beta, α_j the peaking factor of the current density (defined as the ratio between the central current density and the average current density $Ip/\pi a^2$) and α_p the central pressure value normalised to the volume averaged pressure.

Alternative scenarios, combining ICRF and LHCD, are also under consideration. We first investigated some possible "synergistic" current drive effects expected between both waves. The experiment was based on the possibility for the wave mode-converted from the fast wave at a two-ion hybrid layer location (monopole operation) to couple to the fast electrons generated by LHCD. LHCD and ICRF powers have thus been coupled in H-He3 plasmas optimised for ICRF mode conversion heating [12], and various scans in plasma current, density and ion mixture were performed. Operation at zero loop voltage was also studied. More than 60 discharges allowed us to conclude that, in such conditions, no effect on current drive efficiency was noticed, as well as no modification of the fast electron population was seen on the hard-X ray tomography system [13].

The "FWEH-driven" bootstrap current is thus now considered on Tore Supra as the major candidate for supplementing the LHCD non inductive current on high-density long-pulse operation. The characteristic of such a scenario is that the power transfer between the heating waves and the plasma mainly results in a strong bulk electron heating, combined with a significant fraction of non inductive current. The resulting transport is then dominated by the electron L-mode transport, improved by possibly significant magnetic shear modification effects[14], the ion energy content being governed by the collisional equipartition rules. In the present Tore Supra discharges, two kinds of improved regimes have been observed: one mainly observed an enhancement of the confinement linked to the increase of the mid-radius magnetic shear, under the influence of bootstrap current for instance, and/or an enhancement of the central performances due to a flat or slightly reversed central magnetic shear when operating close to 100% LHCD-driven discharges (so-called hot core LHEP discharges). The obtained performance [8] show H-factors up to 1.6 (with respect to the ITERL-97-P thermal scaling law [15]).

2. Current profile modifications and control

In addition to a fully non inductive plasma current, the long-pulse discharges require an active control of the current density profile, both for transport optimisation and MHD stability. It is thus essential to rely on several non inductive current sources, which allow to shape the current profile, as well as on real-time determination of the major (local and global) characteristics of the current profile (central safety factor, minimum safety factor location and value, internal inductance, ...). One can then set appropriate feedback loops on the current sources. This long term work, both technical and physical, is underway on Tore Supra.

Weak (positive or negative) magnetic shear discharges may for instance develop MHD activity of various types, requiring a careful adjustment of the current profile (including bootstrap), pressure profile, etc. For instance, tearing modes have been observed [16] tp limit performance of some Tore Supra long-pulse discharges with a dominant fraction of LHCD non inductive current (so-called LHEP phase)(fig4). In such discharges, the central safety factor is slightly below a low-order rational value (3/2 or 2) associated with a local flatness of the current profile (weak shear region up to r/a~0.3). On the case shown on fig4, the onset of a m/n=2/1 tearing mode is reached after 13s of operation, as the current and pressure profile still slowly evolve. The LHEP phase is abruptly terminated, and the postlude plasma exhibits a strong "sawtooth-like" MHD activity driven by coupled m/n=2/1 and m/n=3/1 modes and preventing recovery of the confinement enhancement associated with the LHEP phase.

An efficient feedback system is thus required in order to extend the duration of such regimes significantly. Improvements in current density profile measurements (through polarimetry diagnostic (from 5 towards 9 channels), development of a MSE diagnostic, VME data acquisition...) are underway. However, one of the key points remains the capability for the heating & current drive systems to efficiently act on the pressure and current density profiles. An example is given on fig5, where a feedback loop was set between the plasma internal inductance (l_i) and the $n_{//}$-spectrum of the LHCD launchers. The injected $n_{//}$ index can freely vary between 1.4 and 2.8. In this experiment, the preset-l_i was required to vary from 1.7 to 1.55 during the discharge. Fig5 shows the corresponding response in terms of LHCD launcher phase and power, as well as the actual l_i-evolution, confirming the possibility of control. But, of course, the relation between the LHCD power deposition profile and the phase of the launchers, as well as between l_i and the current profile, are more sophisticated, and this experiment represents to that respect a proof of principle. The new hard X-ray (HXR) tomography system[5,13] installed on Tore Supra is now extensively used for a more exhaustive fast electron behaviour analysis, both in time (4ms resolution), velocity (8 energy channels) and poloidal (59 lines of sight, 5cm resolution) spaces. One of the first strong conclusions of this analysis (discussed in [5]) is that, in reversed shear ramp-up experiments, the LHCD power deposition profile remains peaked, until the q=1 surface appears in the discharge. Moreover, a correlation between the radial position of the HXR maximum of emission and the q=1 surface location is then observed, revealing a strong connection between the deposition and the current profiles. The present LHCD system can thus hardly sustain high-q_a shear reversal situations, unless the wave accessibility conditions are not fulfilled, as already demonstrated at very low magnetic field [17]. Such conclusions encourage several prospective studies engaged on Tore Supra. These studies both include the present equipment, through the combination with FWEH-driven bootstrap current for instance, as well as on-going developments (installation of an ECRH/ECCD system (see below)) and new possible developments (combination with a vertical LHCD launcher insuring an edge absorption barrier for the LHCD power launched by the main grills located in the equatorial plane).

From the transport point of view, a major interest for Tore Supra remains the possibility of triggering, and sustaining, wide internal transport barriers (ITB) with RF heating and current drive alone. One of the most successful techniques, applied on many tokamaks, consists in coupling the power very early in the discharge, during the plasma current ramp-up, in order to take advantage of the ohmic hollow current profile and slow down its diffusion towards the centre. This technique however suffers from two major drawbacks on Tore Supra: i) when using ICRF additional power, a relatively high density is required (see above) to couple a sufficient amount of power. The time required for reaching such densities is too long compared to the very short current diffusion time scale (a few hundreds of ms in the start-up phase). ii) when using LHCD power, the current deposition profile, as discussed previously and in [5], is peaked at low plasma current. This partially spoils the efforts for sustaining a wide hollow current profile on time scales much longer than the resistive time. An alternative way is thus being investigated at present. It first consists in setting a low (~500kA) plasma current discharge on which ICRF minority heating (and/or LHCD) is established, on a time duration long enough (8-10s) to reach a steady-state. The plasma current and the power are then rapidly ramped-up and a hollow current phase is reached. In that case, one can optimise the resistive skin depth by properly shaping the ramp-up frequency ω=(1/Ip)(dIp/dt). Fig6 shows an example of a fast current ramp-up phase (from 0.5 to 1.2MA) leading to a normalised skin depth 1/a.sqrt(2η/ω) = 0.2 (instead of 0.6 during the start-up phase) (η is the plasma resistivity). The internal inductance drops to ~ 0.6, and the central shear is negative. The next step will consist in increasing the additional power and controlling the reversed shear region by adjusting the power deposition location (off-axis ICRH and/or ECRH heating).

Such a scenario should insure a significant current profile control, in which the electron heating is dominant. The final step consists then in increasing the ion pressure gradient, in order to enhance the rotation shear and improve the transport. This challenge for RF heating systems requires further scenario studies. Those scenarios are presently being investigated. Promising results in this field were obtained in high Hydrogen minority discharges, at relatively high density (80% of the Greenwald limit). In such discharges, ion and electron energy contents are more balanced, and a significant toroidal rotation is induced by ICRF. An improved confinement was observed, during more than 2s, in both ion and electron channels, corresponding to an H factor of 1.6 (with respect to ITERL-97-P)[18]. Other possibilities, involving Helium3 or Impurity minority heating for instance are also under investigations.

3. Towards the CIEL discharges

The power exhaust capability of the so-called "CIEL" plasma facing components will be of the order of 20-25 MW (conducted + radiated), in steady-state (i.e. several hundred of seconds)[1,19-20]. In order to fully benefit of such a capability, the heating and current drive systems follow a long-term improvement programme, including several levels from the generators to the antennas. Among the numerous elements presently under development, one can underline:

- *ICRF operation*: one of the ICRF antennas has been equipped with a new set of lateral protection elements [21] (fig7), using for the first time in this environment the active metal casting technology (CFC tiles bonded on copper alloy water cooled fingers) [22], which is the basis for all the PFC in CIEL. Extensive validation tests were performed under various conditions: ICRF minority heating, FWEH, combination with LHCD, ergodic divertor configuration, antenna-plasma positions, etc. Up to now, those elements showed a quite satisfactory behaviour, as illustrated on fig2, where the antenna temperature is shown during the 11.6MW/1.6s shot (#25419) described above, and compared to another antenna using the conventional carbon tiles lateral protections at the same level of power and radial position. The two other ICRF antennas will be progressively equipped with such protections.

VME data acquisition is also underway for the ICRF system, allowing feedback loops on the antenna position, coupling resistance or limitations of the voltages for instance. An active feedback on the antenna phasing is also being developed [23].

Concerning the future developments, the generators and several antenna elements must be adapted to longer pulses. One of the challenges is certainly the improvement of reliability of the antenna matching elements, presently built with actively cooled variable vacuum capacitors [24].

- *LHCD operation*: a renewal of the LHCD multijunction launchers is underway. The new design [3][25] involves a larger radiation surface (i.e. a lowering of the power density at the grill mouth), as well as the new lateral protections mentioned above for ICRH antennas. The first new grill is planned to be installed and tested in summer 99. New concepts, like Passive-Active Multijunction, insuring a better cooling capability are also being considered, in collaboration with ENEA-Frascati, where the concept will be tested first [26].
- *ECRF*: in collaboration with the Ecole Polytechnique Fédérale de Lausanne, Forschungzentrum Karlsruhe, and Thomson Tubes Electroniques, Tore Supra is implementing a 118GHz/3MW/210s ECRF system. The prototype gyrotron (500kW) is already being tested in Cadarache [27], and the full power is planned to be available for the operation on CIEL. Beyond the extra input power brought by this system, its flexibility in terms of injected angles allows to envisage local heating and current drive effects, strong enough to stabilise performance limiting tearing modes [28], and/or to modify the local current profile significantly, with a capability of setting (slow) feedback loops on the injected angles.
- *Infrared camera monitoring*: both the 360° of toroidal pumped limiter (TPL) and each antenna will be monitored with numerical data acquisition, allowing an active safety control.

The heating and current drive systems, after the necessary upgrades, should typically deliver in steady-state 10-12MW of ICRF, 6-8MW of LHCD and 2-3 MW of ECRF. Zero-D extrapolations of the present database combining LHCD, bootstrap current, the Zeff behaviour in limiter configuration, the confinement and its enhancement with respect to the bootstrap current fraction, gives us the basic steady-state performance of CIEL discharges [8], in terms of (fully non inductive) plasma current versus volume averaged density (see fig8a). They mainly lead to two types of scenarios. The first one takes place at low density: the plasma current is of the order of 1.5-1.7MA (qa close to 3), with a negligible fraction of bootstrap current. The lower density however allows only to control the wall-particle inventory, but not the density profile. Furthermore, the plasma does not radiate a significant fraction of the outcoming power. This regime shows a moderate confinement enhancement. The second mode of operation is more "advanced". It consists in working much closer to the Greenwald limit of density; the plasma current is of the order of 0.8-1 MA (q_a close to 5-6), with a confinement enhancement factor of the order of 2 (with respect to ITERL-97-P). The bootstrap current fraction reaches 50%, and the density level then allows an efficient edge pumping by the Toroidal Pumped Limiter (fig8b), as well as a large fraction of radiated power. Normalised beta values are of the order of 1.5 at 4T, and reach 3 at 2T. Note that this extrapolation is rather conservative, in the sense that it does not rely on further confinement enhancement due to possible hollow current profiles and/or shear flow effects, triggering internal transport barriers.

4. Conclusions

Achievement of high power long pulse discharges is the long term goal of the Tore Supra tokamak programme. It represents a huge integration effort involving all the tokamak technology and physics domains: 100% heat and particle exhaust, fully reliable additional RF power at high level, current profile control, MHD control, possibly in the high performance plasmas. The Tore Supra equipment is progressively evolving in that direction, with first a complete upgrade of the inner vessel components (planned to be installed in year 2000), and second the progressive upgrade of the heating and current drive systems. Scenarios studies (current drive, current profile modifications, long pulse operation, MHD studies, feedback loops, etc.) are also underway. Many encouraging results were already obtained: 2 minute pulses, long fully non inductive discharges, high power shots, high bootstrap fraction plasmas, magnetic shear reversal discharges, etc. At the same time, the understanding and modelling of the corresponding physics is improved: fast electron diagnostic, edge RF physics, MHD, confinement versus current profile, etc. The integration of all these aspects progressively takes place, allowing a more reliable and safe operation.

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Annex: The Equipe Tore Supra

G. Agarici , F. Albajar vinas, J.M. Ané, T. Aniel, G. Antar, J.F. Artaud, A. Azeroual, S. Balme, V. Basiuk, M. Basko, P. Bayetti, B. Beaumont, A. Bécoulet, M. Bécoulet, V. Bergeaud, G. Berger-By, M. Berroukeche, B. Bertrand, Ph. Bibet, J.M. Bottereau, F. Bottiglioni, C. Bourdelle, R. Bregeon, S. Bremond, R. Brugnetti, J. Bucalossi, Y. Buravand, H. Capes, J.J. Capitain, M. Chantant, Ph. Chappuis, E. Chatelier, M. Chatelier, X. Chen, L. Cherigier, L. Chiarazzo, D. Ciazynski, F. Clairet, L. Colas, J.J. Cordier, L. Courtois, B. Couturier, J.P. Crenn, P. Da silva rosa, C. Darbos, B. de Gentile, C. De Michelis, C. Deck, P. Decool, C. Desgranges, P. Devynck, L. Doceul, H. Dougnac, J.L. Duchateau, T. Dudok de Wit, R. Dumont, A. Durocher, D. Elbeze, F. Escourbiac, J.L. Farjon, Ph. Fazilleau, C. Fenzi, M. Fois, D. Fraboulet, P. Francois, Ph. Froissard, L. Garampon, X. Garbet, L. Gargiulo, P. Garin, E. Gauthier, A. Geraud, F. Gervais, Ph. Ghendrih, T. Gianakon, R. Giannella, C. Gil, G. Giruzzi, P. Gomez, M. Goniche, G. Granata, V. Grandgirard, B. Gravil, M. Gregoire, S. Gregoire, C. Grisolia, A. Grosman, D. Guilhem, B. Guillerminet, R. Guirlet, J. Gunn, Y. He, R. Hemsworth, P. Hennequin, F. Hennion, D. Henry, P. Hertout, W. Hess, M. Hesse, G.T. Hoang, J. Hourtoule, P. Houy, J. How, T. Hutter, F. Imbeaux, C. Jacquot, R. Jimenez, E. Joffrin, J. Johner, J.Y. Journeaux, F. Kazarian, L. Ladurelle, D. Lafon, J. Lasalle, F. Laugier, C. Laviron, G. Leclert, F. Leroux, P. Libeyre, M. Lipa, X. Litaudon, T. Loarer, Ph. Lotte, P. Magaud, P. Maget, R. Magne, J. Mailloux, W. Mandl, G. Martin, A. Martinez, L. Masse, R. Masset, P. Massmann, M. Mattioli, G. Minguella, F. Minot, J.H. Misguich, R. Mitteau, I. Monakhov, L. Moncel, P. Monier-Garbet, D. Moreau, J.P. Morera, B. Moulin, D. Moulin, M. Moustier, C. Munnier, R. Nakach, F. Nguyen, S. Nicollet, M. Ottaviani, M. Pain, J. Pamela, G. Pastor, M. Paume, A.L. Pecquet, B. Pegourie, Y. Petrov, Y. Peysson, P. Platz, C. Portafaix, M. Prou, R. Pugno, A. Quéméneur, E. Rabaglino, R. Reichle, J.D. Reuss, G. Rey, F. Rochard, A. Romannikov, B. Rothan, R. Sabot, F. Saint-Laurent, F. Samaille, A. Santagiustina, B. Saoutic, T. Schild, J. Schlosser, J.L. Segui, J. Simoncini, A. Simonin, P. Spuig, F. Surle, M. Tena, J.M. Theis, G. Tonon, R. Trainham, J. Travere, A. Truc, E. Tsitrone, B. Turck, J.C. Vallet, D. van Houtte, D. Voslamber, C. Wachter, G. Wang, J. Weisse, M. Zabiego, X.L. Zou, E. Zucchi, K. Zunino

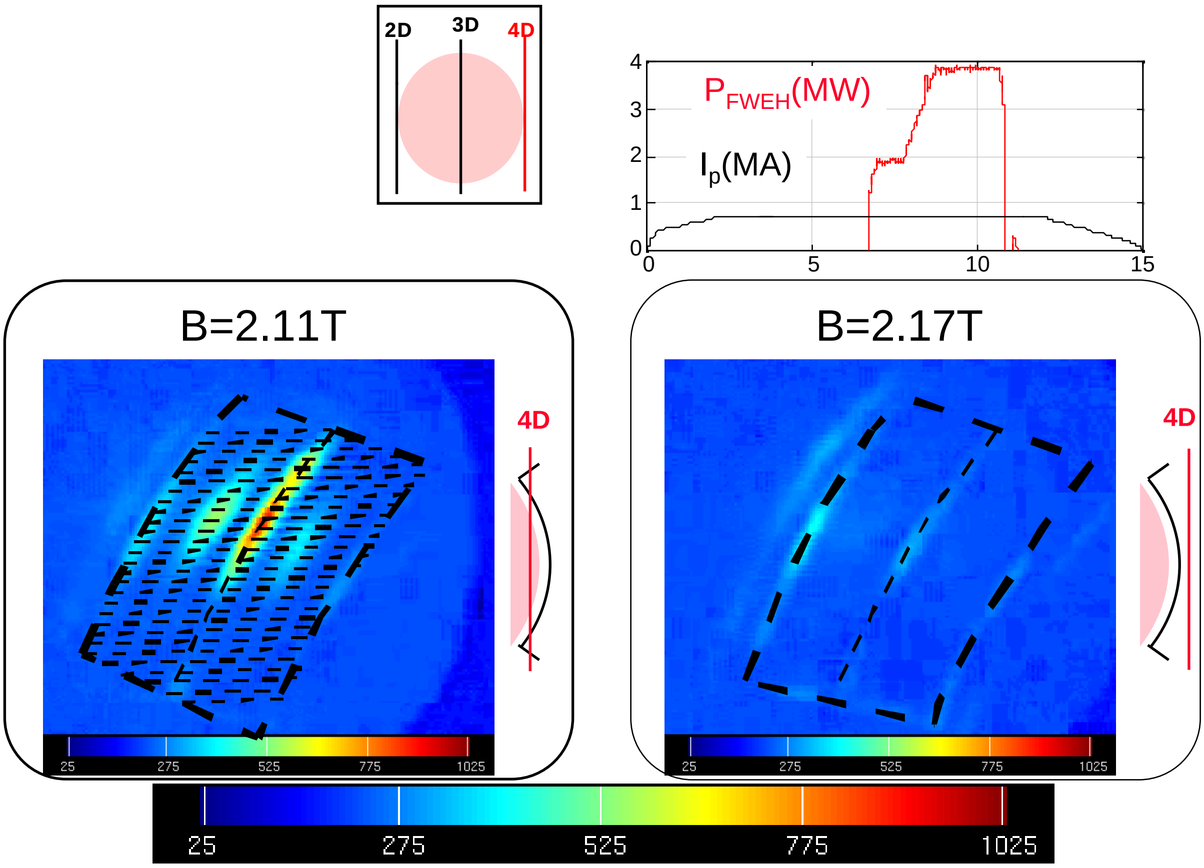

fig1: FWEH experiment (2x2MW with two ICRH antennas, dipole phasing). Influence of the 4D(2H) cyclotron layer exact location on the Faraday screen temperature measured by infrared cameras.

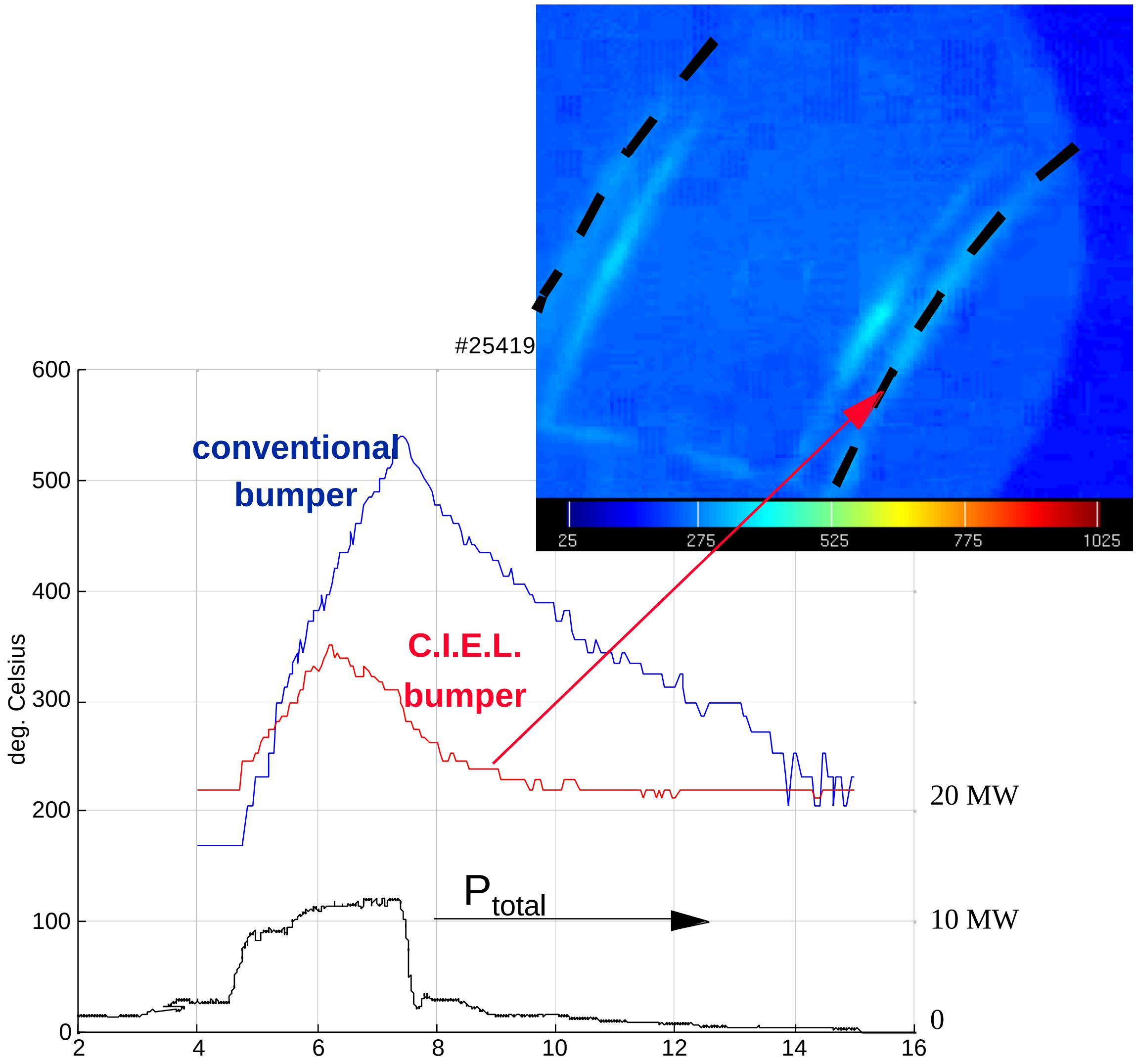

fig2: (#25419) 9.5MW of ICRH (3 antennas)+1.8MW of LHCD(1 grill)+0.3MW of Ohmic. Time traces of the ICRF antenna lateral bumpers temperatures, comparing the conventional ones (carbon tiles) and the new CIEL concept (CFC tiles). An infrared picture also illustrates the new bumper behaviour (on a 25-1025°C scale)

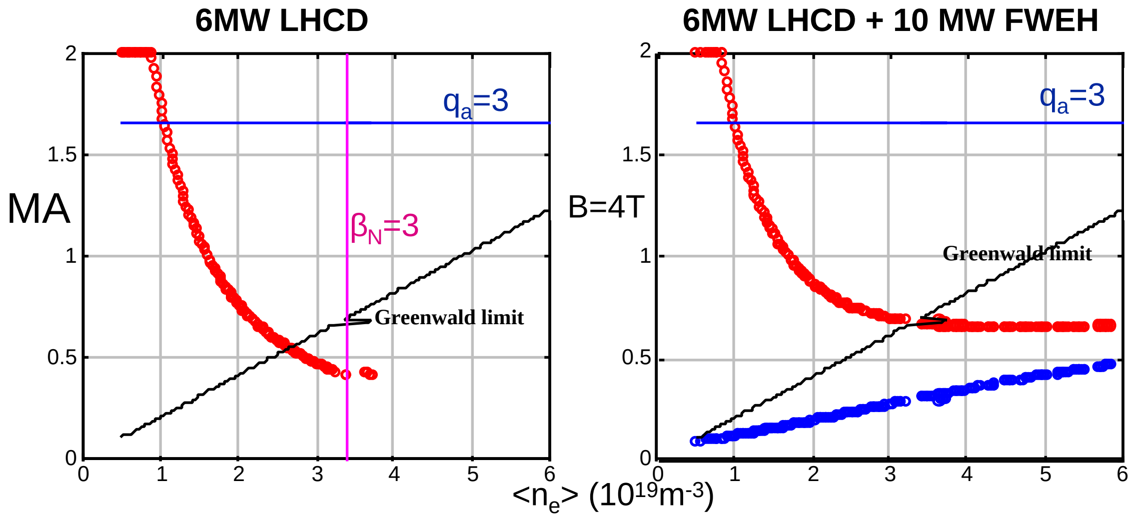

fig3: Fully non inductive plasma current (red) driven by 6MW of LHCD (left), and 6MW of LHCD + 10MW of FWEH (right) (driving bootstrap current (blue)) on Tore Supra versus the volume averaged density. The Greenwald, q_a=3 and β_N=3 limits are also displayed.

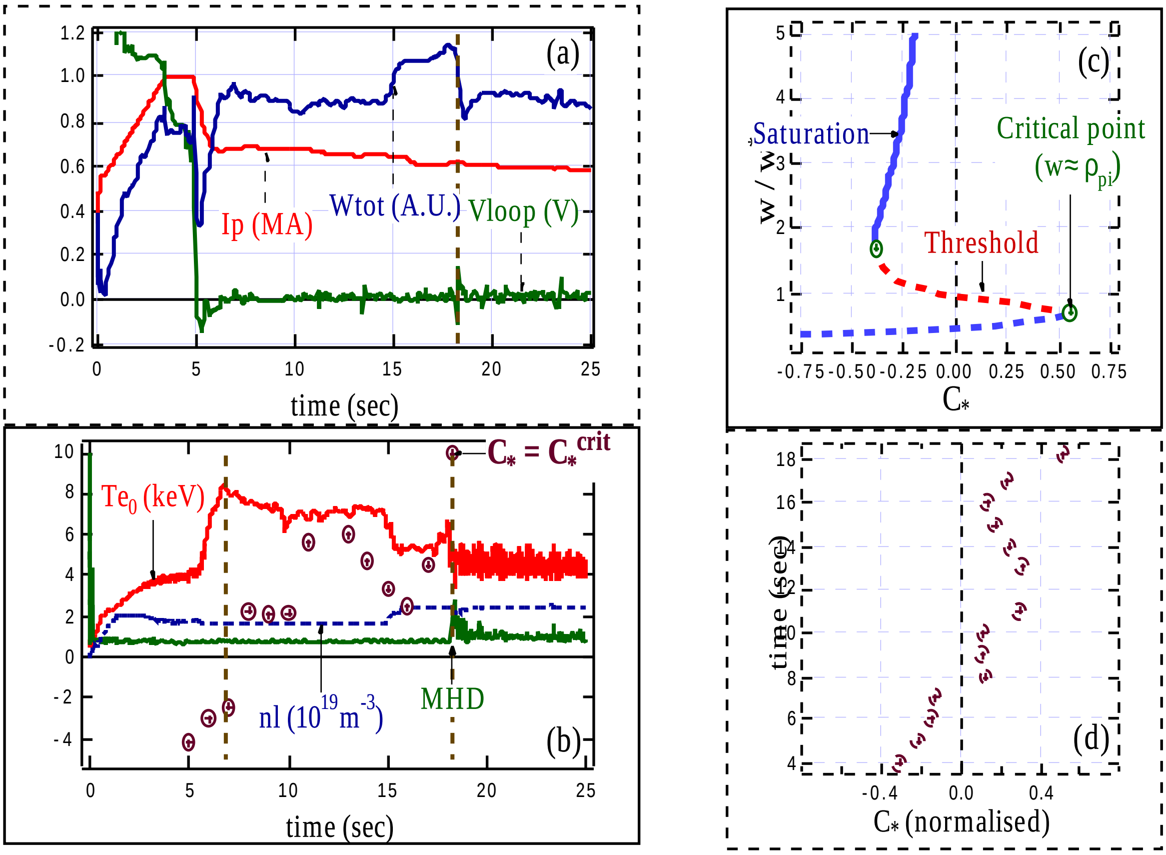

fig4: (a-b) A ToreSupra LHEP-discharge exhibits a transition from improved LHEP-regime towards degraded-regime, with MHD-onset at t=18.2 sec.(c-d) Stability diagram and evolution of the control parameter (see ref [16]) for the considered discharge.

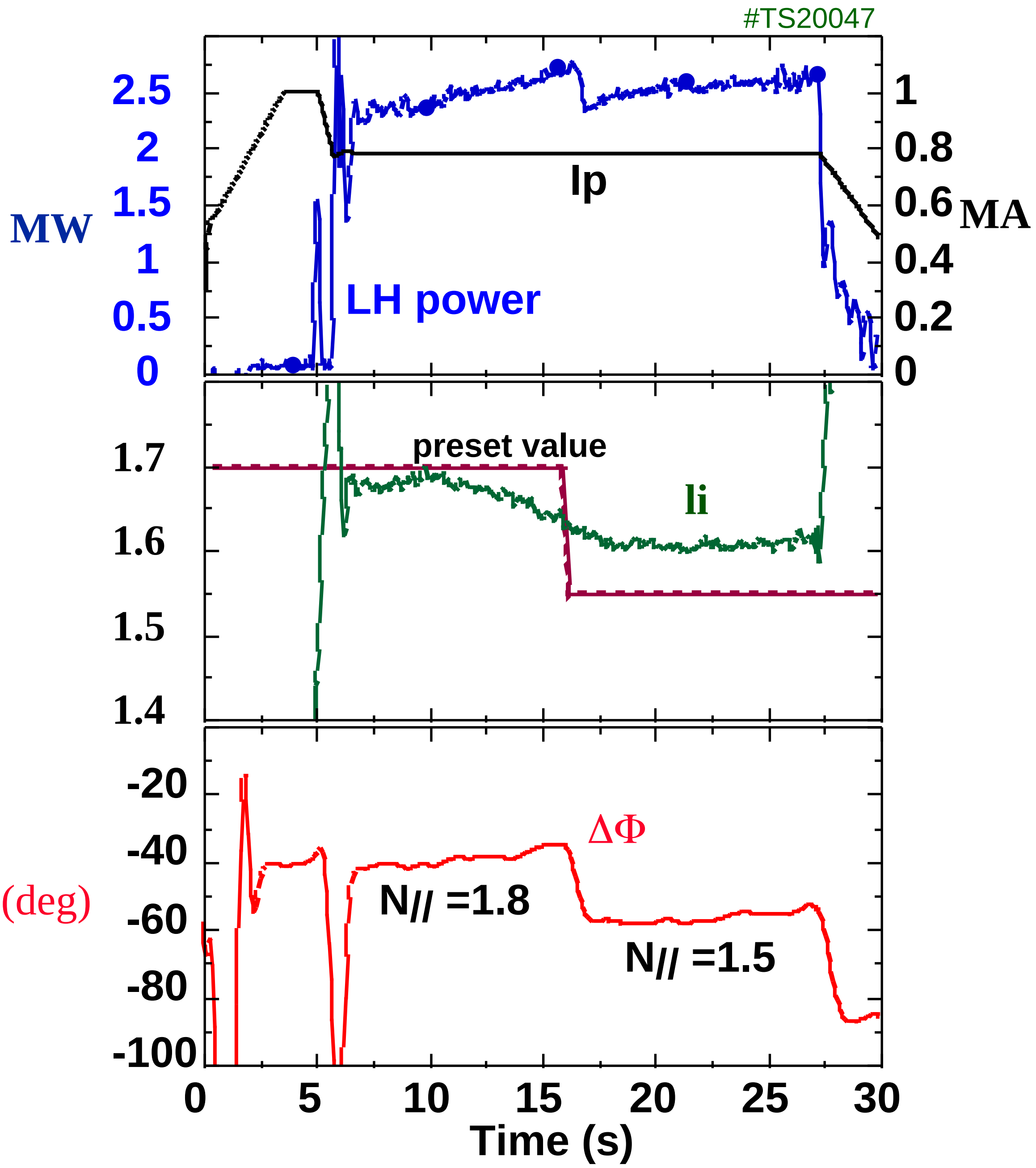

fig5:(#20047) time evolution of a Tore Supra discharge where the internal inductance (li) value is required to follow a preset value feedback controlled on the LHCD parallel index $N_{//}$.

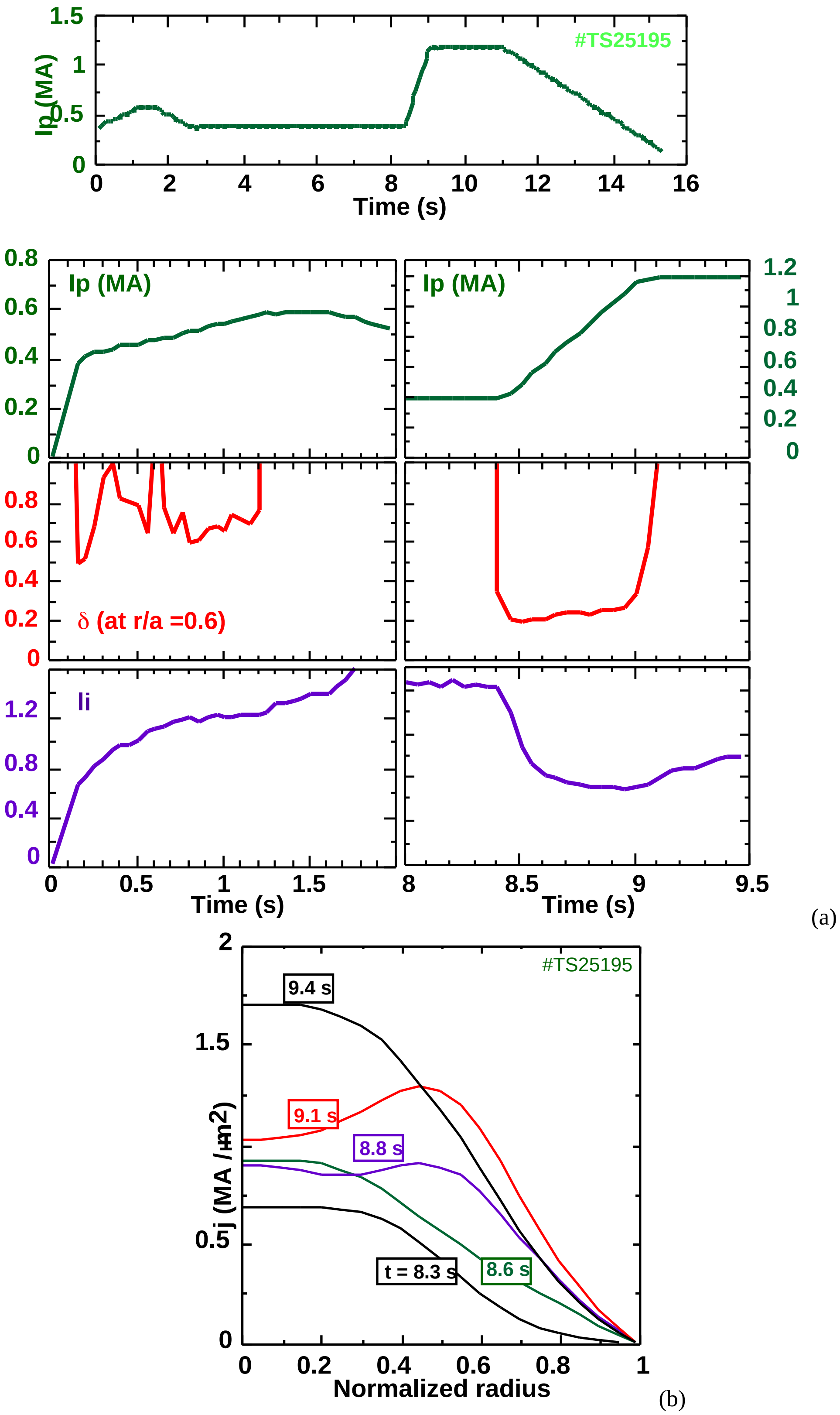

fig6: (a) (#25195) Comparison of two plasma current ramp-up phases. The first one, during plasma start-up (left) leads to a skin depth (computed at r/a=0.6) of 0.6 and a weak effect on li, the second one, after an 8s low current plateau (with 1.6MW LHCD), leads to a skin depth of 0.2 and a significant shear reversal, as confirmed on fig6b. (B) current density profiles during #25195.

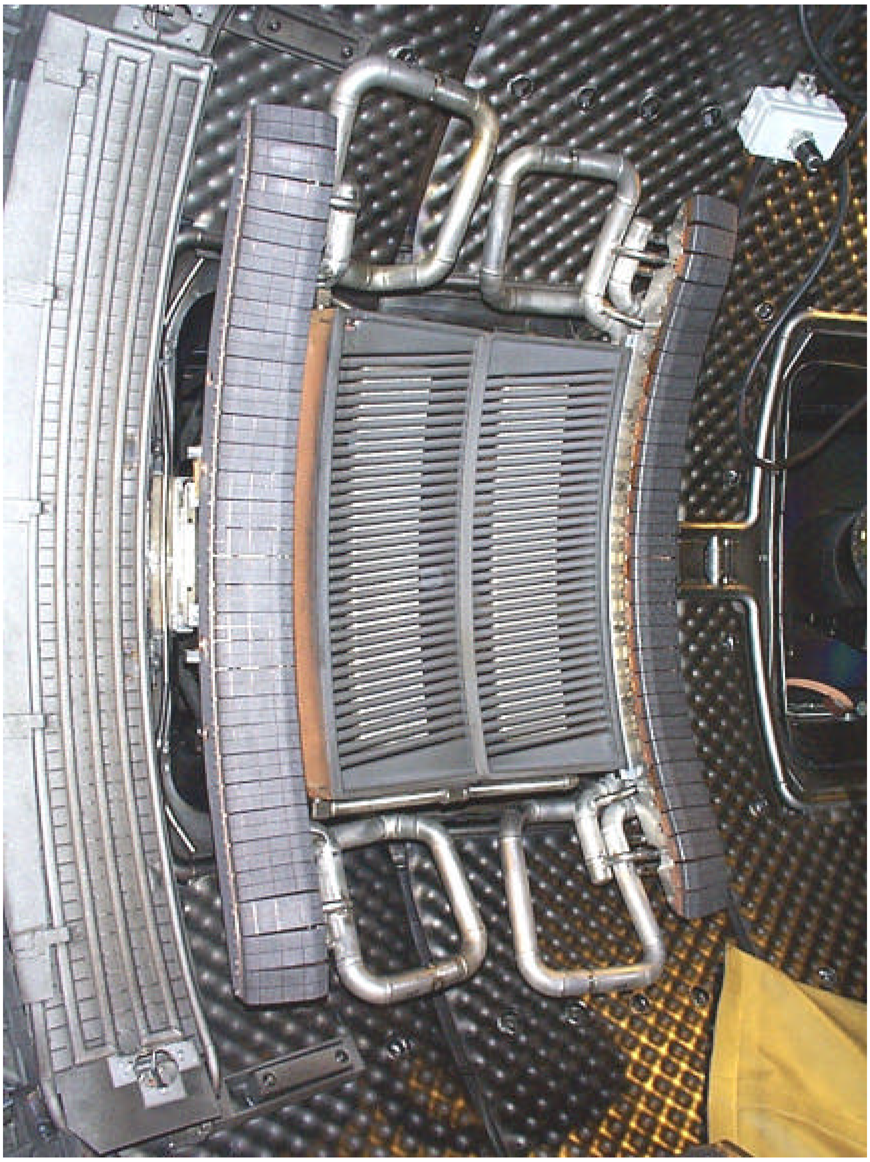

fig7:new lateral bumpers on one of the ICRH antennas.

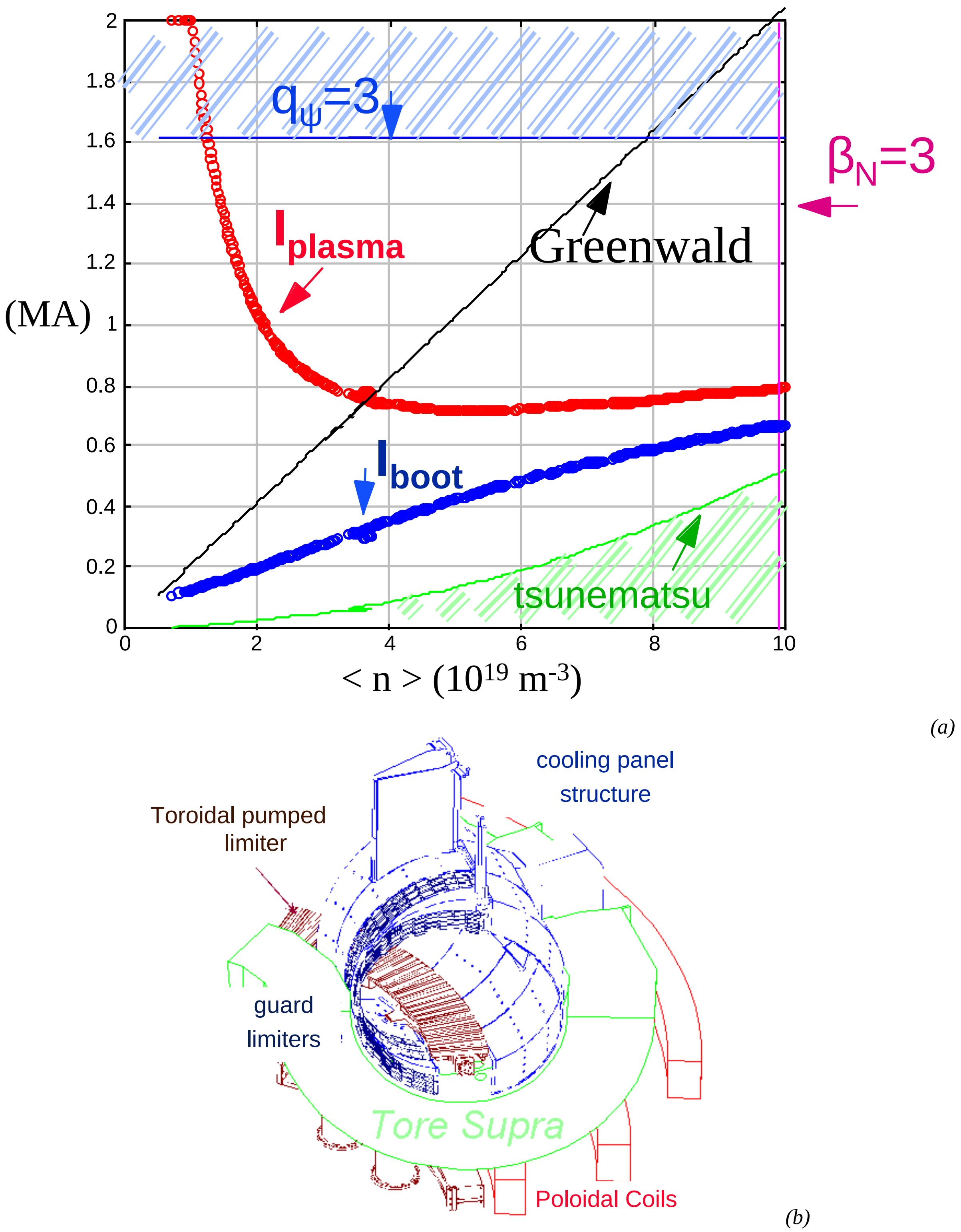

fig8: (a) Fully non inductive plasma current (red) driven by 8MW of LHCD + 10MW of FWEW (driving bootstrap current (blue)+ 2MW of ECRH) on Tore Supra versus the volume averaged density. The Greenwald, Tsunematsu, q_a=3 and β_N=3 limits are also displayed (B=4T).
(b) schematic view of the Tore Supra inner vessel during the C.I.E.L. phase.