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Heating and Current Drive System for Tore Supra Steady-State Operation

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Abstract

A major upgrade of the Tore Supra heat and particle exhaust capability, known as the CIEL project [P. Garin *et al.*, this conference] and installed during the year 2000 shutdown, will raise the heat exhaust capability to 25 MW (convected + radiated) steady-state, and the pumping capability to ~4 Fa.m^3/s, and will allow Tore Supra to investigate high power steady-state plasma operation, with target discharges up to 25 MW–1000 s. Consequently an upgrade of the wave based heating and current drive system is studied (ICRH, LHCD, ECRH/CD), in order to reach this target, in terms of input power and current drive capability, but also in terms of current and pressure profile control, in order to address relevant "advanced tokamak" physics, including steady-state discharges balancing LHCD and bootstrap current, and possibly exhibiting internal transport barriers. The optimization of antennas for such high power long pulse operation is also discussed.

Keywords:

Heating and current drive steady-state operation ICRH LHCD ECRH

1. Introduction

The Tore Supra tokamak has been operating successfully its superconducting toroidal magnet for almost 12 years (R_0 = 2.37 m, a = 0.80 m, B < 4 T, circular cross-section). Successful long pulse operation has been achieved during the past years, using radio-frequency (RF) systems, namely ion cyclotron resonant heating (ICRH) and lower hybrid current drive (LHCD). Among the performances reached by Tore Supra up to now, one must underline long pulse discharges reaching 2 minutes, long pulse zero loop-voltage discharges reaching 75 s, combined heating long pulse discharges reaching 4 MW coupled during 60 s, and high power short pulse discharges (up to 10 MW–2 s ICRH, 5.3 MW–6 s LHCD, and 12 MW–2 s combined) [1].

Recently, the new electron cyclotron resonant heating (ECRH) power plant (working at 118 GHz) obtained its first results with the prototype gyrotron, both on dummy loads (up to 400 kW/15 s, setting a new world record) and on plasma (up to 350 kW/2 s). The series of 6 gyrotrons is under construction, raising the plant capability up to the target of 2.5–3 MW for 210 s in the coming years.

Following the major upgrade of the heat and particle exhaust capability of Tore Supra (CIEL project, [2]), the present paper reviews the proposed plan for the wave based heating and current drive (H/CD) upgraded systems, motivated by physics R&D, including the definition of the various steady-state target plasmas (low density/high current/L-mode or high density/low current/improved confinement discharges) and a discussion on the delicate problem of long term power coupling issues when using wave H/CD methods.

2. Requirements and Constraints for Scenario Studies

The H/CD system upgrade and the corresponding physics scenario analysis are obviously constrained by both technological and financial considerations, out of the scope of this paper. They are also influenced by the specific CIEL power and particle exhaust structure, as well as by the strong magnetic ripple of the superconducting Tore Supra tokamak. The present study has thus followed the rules listed here:

- the plasma loop voltage is zero volt; i.e. the plasma current is fully non inductive. This allows to envisage steady-state operation. However transient positive or negative loop voltage can be envisaged.
- the steady-state injected power is in the range 20–25 MW. The regimes presented here thus correspond to the maximum heat removal capability expected on Tore Supra.
- the H/CD methods envisaged are ICRH/CD, LHCD and ERCH/CD. The magnetic ripple of Tore Supra prevents to envisage a massive input of neutral beam injection (NBI) power. Only one neutral beam injector (1.5 MW, 80–100 keV) is kept to provide probe fast neutrals for diagnostics (MSE, NPA, CXRS, ..). Seven ports are devoted to H/CD systems: one port for the already installed ECRH antenna bringing 2–3 MW in the plasma, six ports to be shared by 3 MW-cw ICRH antennas and 4 MW-cw LHCD multijunction grills. Attention must be paid on long term coupling issues, as well as on fast ion and electron ripple losses.
- $R = 2.4$ m, 0.69 m $< a < 0.72$ m. The optimisation of heat and particle exhaust by the 360° bottom limiter gives the new plasma configuration.
- finally, the system optimization must offer sufficient flexiblity for current and pressure profile modifications, in order to study advanced tokamak physics on long term operation.

To fulfill those constraints, the scenario study has been performed using two distinct approaches: a zero-dimensional (0D) approach based on the present Tore Supra H/CD database, and a more sophisticated one dimensional (1D) self consistent computation including power and current deposition codes on plasma equilibria together with transport simulations and MHD stability predictions, in order to access the final steady-state regimes. The 0D model is used mainly to determine the operating space versus the power balance between H/CD systems and guide the hardware choice, though the 1D model investigates the inner consistency, including the present H/CD and transport models.

3. Determination of the Optimum Power Balance

Among the possible current sources, only LHCD and the bootstrap effect can provide enough current to insure a zero loop voltage operation at significant plasma current values. Non inductive current drive effects provided by the ICRH or ECRH systems are thus only considered as local correction effects. Both LHCD and bootstrap current are sufficiently well documented in the Tore Supra database, including zero loop voltage operation, to allow us to fit their behaviour, together with the electron and diamagnetic stored energy, in a coupled confinement-current prediction code [3]. Note that the only confinement improvement terms concern the well-documented enhancement due to the increase of the mid-radius magnetic shear resulting from a significant bootstrap current fraction [3]. No further improvement due to a possible internal transport barrier (ITB) triggering was considered in the zero-D approach, though observed sometimes [4]. Finally, in cases using ICRH minority heating, the presence of a fast ion population is included in the total diamagnetic energy as well as in the global energy confinement time.

Using this model, the optimum balance between ICRH and LHCD was investigated, assuming that ECRH brings 2–3 MW of heating power. The magnetic field is 3.8 T and the ICRH scheme is minority Hydrogen in Deuterium. The plasma current is bounded between Ip = 0.5 MA (below which operation is delicate in Tore Supra), the edge q-value of 3 and the Greenwald density limit. Similarly, the volume averaged density is bounded between $\langle n \rangle = 1.5 \times 10^{19}\ \mathrm{m}^{-3}$ (lower limit for an efficient and reliable ICRH coupling) and the Greenwald limit within the constraint that the edge q-value is limited to 3. The resulting operation space, in terms of plasma current versus volume averaged density is shown on figure 1, in the situation of 3 LHCD grills (12 MW-cw) and 3 ICRH antennas (9 MW-cw).

Fig 1. allows to define two categories of non inductive target plasmas:

- high current-low density plasmas (quoted as "CIEL1" in Fig. 1). These discharges are L-mode type with low (< 20%) bootstrap current. A volume averaged electron temperature of 4.6 keV is expected, Zeff ~ 2.4 (deuterium plasmas) and $\beta_N \sim 1.2$. The relatively low density however will probably not allow to take full advantage of the limiter pumping capability, thus possibly leading to a non steady-state operation in terms of density control.

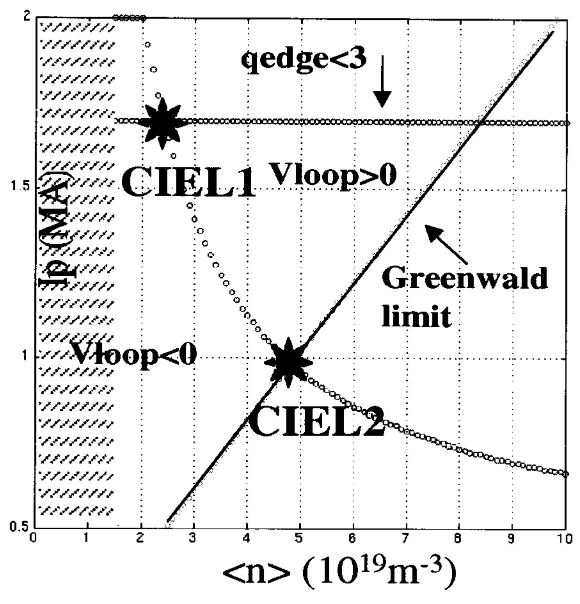

Fig. 1 Operating space at 3.8 T, 12 MW LHCD, 9 MW ICRH, 2 MW ECRH. The grey area refers to the ICRH coupling low density limit.

- Low current-high density plasmas (quoted as "CIEL2" in Fig. 1). These discharges, operating at the Greenwald density boundary, exhibit a high (~45%) bootstrap fraction together with a confinement enhancement (an H factor of 1.8 with respect to the ITERL97-tot predictive law is expected). A volume averaged electron temperature of 2.2 keV is predicted, Zeff ~ 1.7 (deuterium plasmas) and $\beta_N \sim 2.2$. Note that the confinement times of CIEL1 and CIEL2 are finally very similar (~0.07 s), though the plasma current of CIEL2 is almost half of CIEL1. CIEL2 will allow to study the stability of "advanced" regimes on long term operation. The high density is also more compatible both with the particle pumping capability and a higher fraction of radiated power (~40%) required at that high level of injected power.

On the top of those two regimes, several other options are open, mainly due to the flexiblity in terms of ICRH frequency (40–80 MHz):

- lowering the magnetic field down to 3 T or 2 T, one can access the operating domain of the ICRH direct fast wave electron heating (FWEH), and study regimes free of fast ion in the discharge. The antenna phasing capability and the corresponding FWCD effect will also allow us to study the role of the central current density.
- varying the plasma composition, either in terms of Hydrogen minority concentration, or seeding the discharge with a low Helium3 concentration, one can operate in ICRH regimes with low temperature ion tails, favouring bulk ion heating and considerably reducing the ion ripple losses. This is considered as a "safe" option with respect to ripple problem. Mode conversion heating and current drive will also be possible.
- prescribing the loop voltage to positive or negative values allows both to study the influence of the edge current profile on the confinement and MHD properties. Note that negative loop voltage regimes (at the same given input power) also allow to investigate transiently higher β_N-values.
- a high field side multiple-pellet injector (10 Hz, 1000 s) is also envisaged to fuel the plasma. This option would modify the density profile, as well as the bootstrap current profile.

This situation in terms of power balance appears to be the best compromise, for less LHCD power would not allow to open up the whole range of plasma current at zero loop voltage ("CIEL1") and more LHCD power would reduce the performance of the non inductive operation at high density high bootstrap fraction ("CIEL2").

4. Implications of Edge RF Physics

Before starting the 1D analysis of the two main target plasmas, one must discuss the extra constraints on the physics R&D exercise generated by the very high wave power involved.

Concerning IRCH, locating the power deposition imposes to position the (hydrogen) ion cyclotron resonance layer somewhere in the plasma by tuning the proper generator frequency. This frequency tuning has however two major boundaries, which become real constraints when dealing with long term high power injection:

- first, the ion cyclotron resonance layer must locate in the so-called "ripple good confinement area", i.e. ICRH must drive fast ions which banana tips stay in the plasma core region, where no trapping in the ripple magnetic well is possible. In a machine like Tore Supra, this mainly means that the ion cyclotron resonance layer must remain on the high field side of the magnetic axis to prevent strong ripple losses. Moreover, low current low collisionality operation may also enhance the ripple stochastic diffusion effect, which must be carefully estimated.

- second, no ion cyclotron resonance layer, including high harmonic ones, must exist in the immediate vicinity of the antenna front [1]. Though they do not significantly alter the expected power deposition balance, those layers are responsible for significant heat loads on the antenna Faraday screens when located a few centimetres in front of it, subsequently causing damages in long pulse operation.

A careful experimental campaign has been conducted on Tore Supra in 1999, in the exact CIEL configuration, to build up a database of the best compromise for ICRH - minority heating.

A second major issue for high power long term ICRH coupling is the presence of RF sheath effects [5] at the antenna front level (Faraday screen, lateral bumpers, ..). These RF sheaths generate convective cells in front of the antenna, creating both density depletion in certain areas and density rise in other regions. The most damagable effect is the last one as those sheaths may accelerate ions which hit the antenna front and cause damage, as observed already on the Tore Supra present antennas [6]. A complete model, including RF field radiated by the antenna (three dimensional) [7] and a one dimensional RF sheath model in the (poloidal/ radial) two dimensional geometry is underway [8]. The purpose is to help the new long pulse antenna design to minimize such effects, achieving 9 MW-cw coupled to the plasma by three double-loop resonant antennas (40–80 MHz, phase tunable).

In parallel, the LHCD multijunction grills suffer from accelerating edge electrons in front of their mouth. The high-$n_{\parallel}$ component of the spectrum was recognized as responsible for this effect which, in case of high power density, may cause severe damages to grills and connected limiters [9-11]. Minimization of such effects requires a limitation of the power density at the grill mouth (< 25 MW/m^2), as well as a careful design of the grill itself (septa shaping, careful location of guard limiters). Such improvements have been implemented and successfully tested on the new Tore Supra [12] launcher installed on Tore Supra in 1999. Two extra launchers of that type are planned to be installed, insuring 12 MW-cw in the plasma.

Of course, all those high power density elements are equipped with high performance bumper protections, exhausting the conducted-convected power coming from the plasma, as well as RF losses. Such bumpers have been designed and already tested on plasma for both LHCD and ICRH, using the same technology as the CIEL limiter high flux plasma facing components [13].

4. Self-Consistent 1D Scenario Modelling

The results from the 0D simulations have been used as first guess of a self-consistent 1D model, where plasma equilibrium, ICRH deposition profile, LHCD, transport and bootstrap current are coupled in various codes run sequentially up to convergence. The following codes have been coupled and used:

- toroidal geometry equilibrium and transport: ASTRA [14]. The transport model is the so-called Mixed Bohm/gyro-Bohm model, including a magnetic “shear function”, insuring an electron transport reduction in the low magnetic shear region [4].
- ICRH deposition: PION [15].
- LHCD: DELPHINE (ray tracing + Fokker Planck) [16].
- Bootstrap current: NCLASS [17].
- ECRH/CD and neoclassical tearing modes stabilization codes [18,19].

Though not fully reported here, MHD analyses are also coupled, mainly using the MISHKA code [20].

4.1 The CIEL1 case

The low density/high current CIEL1 case is mainly an L-mode discharge driven by LHCD current, the extra pressure being given by minority ICRH. As shown on Fig. 2, and due to the high electron temperature, the ray propagation is single pass (at least for rays with $n_{\parallel} > 2.3$ in that case). The current profile tayloring is thus easily doable, using different spectra on different launchers (“compound spectrum”). On- and off-axis current drives are accessible mixing power between $n_{\parallel} = 2.3$ and $n_{\parallel} = 2.9$. Moreover, as the plasma current is essentially a lower hybrid non inductive current, driven by fast electrons, the feedback control of the steady-state current profile by the hard-X ray measurements can be seriously envisaged. It is performed on Tore Supra by a tomographic system of two cameras, using CdTe detectors, with excellent time, space and energy resolution [21].

On the question of ICRH deposition, the only point concerns the H-minority heating, for which PION predicts a very energetic fast ion tail (fast ion slowing down time ~1.6 s), leading to a significant fraction of power lost by direct orbit losses. This aspect could force us to split the ICRH power on several frequency (“polychromatism”), and/or to use more extensively the

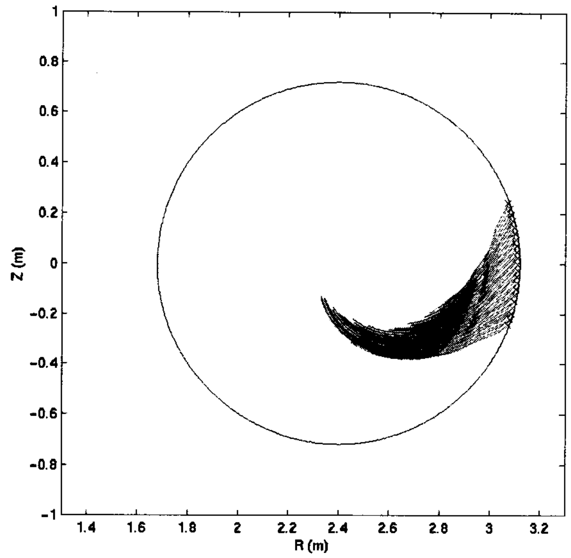

Fig. 2 CIEL1: example of LH rays propagation in the actual Tore Supra equilibrium. The launched spectrum is centred on $n_{\parallel}$ =2.6 (60 rays).

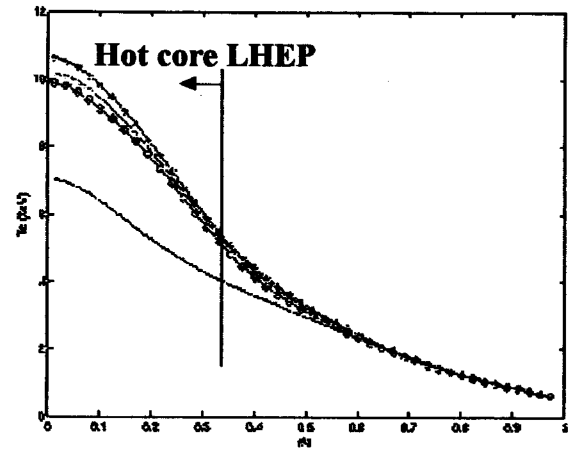

Fig. 3a CIEL2: Electron temperature profile (keV) versus r/a. (–) first guess, (--) 2nd iteration, (-x-) 3rd iteration, (-o-) 4th iteration.

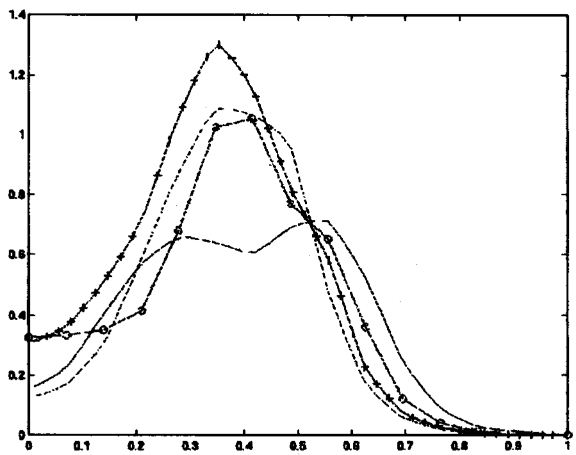

Fig. 3b CIEL2: LHCD current profile (a.u.) vs r/a. (–) first iteration, (--) 2nd iteration, (-x-) 3rd iteration, (-o-) 4th iteration.

Helium3 minority scheme.

4.2 The CIEL2 case

On the contrary, in the high density/low current CIEL2 case, the LHCD absorption is less direct, and requires 1.5 to 2 passes and a significant $n_{\parallel}$-upshift to take place. This means that the LHCD deposition is much more sensitive to the exact pressure and overall current profiles, fully justifying the self-consistent procedure described here above. Fig. 3 shows the 4 iterations performed with ASTRA and DELPHINE on such a steady state/high density case. Note that the ICRH deposition was kept constant for these iterations, as the self-consistency in this case is a minor effect. Fig. 3a and Fig 3b show the electron temperature profile, and the LHCD current deposition profile, respectively. The bootstrap fraction is 45%. The first guess comes from 0D considerations. One can see that, due to the off-axis LHCD deposition (compound spectrum $n_{\parallel}$ = 2 and $n_{\parallel}$ = 2.9) and bootstrap current, the central magnetic shear is low enough to trigger an electron ITB (known on Tore Supra as "hot core lower hybrid enhanced performance" [4]), whose first effect is to strongly enhance the central pressure, and thus increase the central bootstrap (2nd–3rd iterations). This current profile rearrangement slightly increases the central shear, tending to weaken the ITB and to peak the LHCD deposition (smaller $n_{\parallel}$-upshift). An equilibrium state is reached rapidly (4th iteration and beyond).

The influence of the externally imposed LHCD spectrum is illustrated on fig. 4, showing the resulting converged steady-state q-profile for two quite different injected compound spectra. The multi-pass LHCD damping, the significant (uncontrolled) bootstrap fraction together with the self consistent process linking current profile and transport significantly reduces, for CIEL2, the freedom of tayloring the final state. Fig. 4 indicates that the electron ITB (i.e. the shear inversion radius) will occur in the range $0.3 < r/a < 0.4$.

Further investigation involving in particular a better

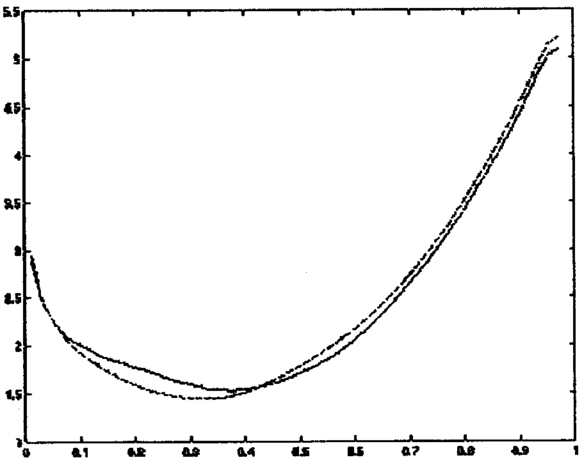

Fig. 4 CIEL2: safety factor profile vs r/a. (–) compound spectrum $n_{||}$ = 2 & $n_{||}$ = 2.9, (--) compound spectrum $n_{||}$ = 2.3 & $n_{||}$ = 2.6.

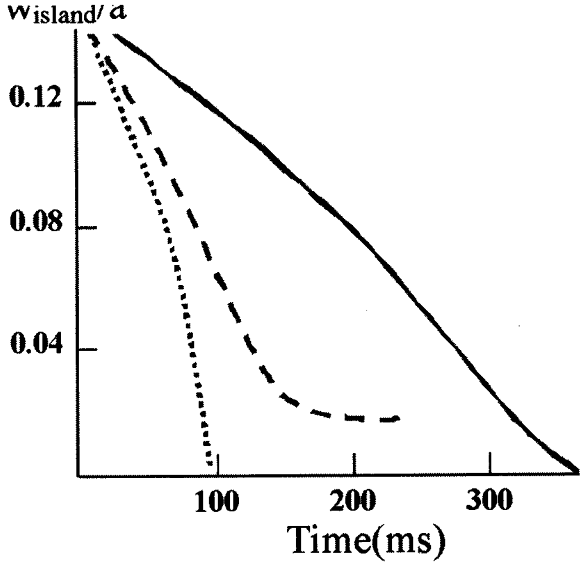

Fig. 5 CIEL2-2T: (3,2) mode island width normalized to minor radius vs time. Stabilization by ECCD (–) 0.9 MW, (--) 2.5 MW, (...) 2.5 MW modulated.

control of the bootstrap current profile using off-axis ICRH, and/or magnetic shear modification by local ECCD is envisaged. As an example, 2.5 MW of ECCD (on a Ip = 0.9 MA, <n> = 2×10^{19} m^{-3} plasma) can drive up to 120 kA at mid-radius , which is sufficient to displace the minimum q location of $\Delta\rho \approx 0.15 - 0.2$.

4.3 MHD considerations

MHD analyses are performed a posteriori using the 1D simulation output. Though not fully performed yet, one can however give some interesting conclusions.

First, concerning disruptive MHD (linear stability of kink, ballooning and interchange (ideal and resistive) modes), the CIEL1 equilibrium is found to be operating far from the limits, and only seriously affected by the possible sawtooth activity (enhanced by the presence of fast ions), if the target q-profile contains a q = 1 surface. Let us recall that this giant or monster sawtooth activity also affects the wave power coupling by repetitive strong perturbation of edge conditions. The ICRH system is however designed using pre-matching stubs in order to cope with those sudden transients of coupling.

The CIEL2 scenario is found to operate close to both the high-n ballooning and low-n kink limits. The stability to low-n kink modes is actually improved by the presence of the close fitting wall. Taking the wall into account moves the stability limit about 50% above the target beta. Then, in the absence on any significant momentum source, the CIEL2 scenario is found to operate close to the stability limit of the resistive wall mode (RWM) [22], which could be observed in long-pulse discharges.

Next, the beta-limit imposed by the resistive-interchange mode or the so-called *infernal* modes [23] is known to be an issue for scenarios where the safety factor profile is flattened or reversed in the core, when a strong pressure gradient exists close to or inside the minimum of the safety factor profile. The CIEL2 model equilibria above are found to be stable to such modes. However, the sensitivity of the infernal modes (less importantly, the resistive interchange modes) to the details of the profiles imply that such modes may occur in discharges with similar features. Should this happen, the current and pressure profile control capability of the heating and current-drive system would allow some fruitful analysis of the associated operational limit, in reproducible steady-state discharges

Concerning "softer" events, CIEL1 and CIEL2 seem to be mostly immune to neoclassical tearing modes (NTMs). However, should this occur, the ECRH/ CD system is able to stabilize such modes (2,1) or (3,2). As an example, fig. 5 shows the time evolution of such an (3,2) island, pre-established in a CIEL2-2T discharge and submitted to either 0.9 MW, 2.5 MW or 2.5 MW synchronized with the island rotation. In all cases, the stabilisation of the island is achieved in 300 ms.

Finally, in scenarios with high input power from the ICRF system, it is worried that the excitation of Alfvèn Eigenmodes by high-energy ions could degrade the heating performance. However, it is important to note that the capability to analyze such high-frequency modes is limited on Tore Supra, for high-frequency magnetic measurements are hindered by the existence of some upper cut-off frequency (typically 40 kHz) imposed by the iron-shell which protects the pick-up coils installed in the vacuum chamber.

5. Conclusion

The installation of new inner-wall components in Tore Supra, being able to exhaust up to 25 MW of power in steady-state is claiming for a significant upgrade of the H/CD capability of the machine, both in terms of power, but also in terms of current drive capability, and reliability at each level. Besides the pluri-annual technological efforts put in the upgrade of the H/CD subsystems (generators, lines, antennas, ...), a physics R&D activity is underway to better integrate all the physics requirements and constraints on such long term operation plasmas (up to 1000 s). A strong effort has been put on the edge RF physics to help the antenna design activity to optimize the long pulse power couplers. On the plasma scenario side, the strong zero-loop voltage constraint, together with Tore Supra specificities, lead us to base the non inductive current on a mixture of LHCD and bootstrap current, setting two type of target plasmas: the low density/high current L-mode plasmas, mainly driven by LHCD, and the more "advanced" high density/low current improved confinement plasmas, based on a balanced LHCD/ bootstrap mixture, operating close to the Greenwald limit. A top up of 3 MW of ECRH/ECCD power will allow local H/CD effects, helping broadening the current profile and/or stabilizing possible NTMs. A multiple-pellet injector will provide the plasma fuelling. A complete 1D self-consistent set of codes has been assembled to investigate the final states of such discharges, including MHD stability. A self-consistent time dependent model is now under development which will help us to study the routes to such final states, including the transient ohmic effects, and the perturbations due to pellet injection. Developing the corresponding feedback loops is also one major scope of this on-going analysis.

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