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Calorimetry in Tore Supra. An accurate tool and a benchmark for ITER

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Abstract

In the framework of the Tore Supra-CIEL upgrade, designed for steady-state operation, the calorimetric diagnostic implemented in the cooling water loop has been completely rebuilt. Both the techniques used to increase the diagnostic sensitivity and examples of calorimetric analysis are reported. The interest and relevance of such a diagnostic for ITER or other actively cooled machines are briefly discussed.

Keywords: Tokamak; Active cooling; Calorimetry; Energy balance; Tore Supra

1. Introduction

Tore Supra is the only tokamak to be equipped with a pressurised water loop ensuring the cooling of all the surfaces facing the plasma. This allows us to address the problems of heat removal of stationary long discharge control. This question is of great relevance for the design of future machines. It has been shown [1] that the calorimetric diagnostic implemented in the cooling water system, is an abundant and accurate information source concerning the energy or power deposition on the actively cooled plasma facing components (acpfc). From calorimetry it is possible, first, to estimate the amount of energy extracted from each actively cooled component. Secondly, to analyse the global energy balance for each discharge. Thirdly, to study the splitting of the output energy between convection, radiation or ripple losses. Fourthly, to study the effect of misalignment of plasma facing components on their heat removal capability and further to estimate the local e-folding heat decay length λ_q averaged over the component area. Finally, with reasonable signal to noise ratio, it is possible to estimate the incident power falling on a given component. In ITER, as has already been proposed [2], the calorimetry of the blanket could be used to measure the plasma reactivity, even with a non-negligible time resolution. In this paper, the new Tore Supra calorimetric diagnostic and the first results obtained during the 2001 experimental campaign are reported. After two years installation of the new acpfc and complete rebuilt of the water loop, this campaign has been the first plasma tests of Tore Supra-CIEL upgrade [3]. This is a major step for the long discharge control improvement. The new acpfc are mainly of two types: the inner first wall, IFW, ensuring a complete screening (⩾99%) of the vacuum vessel wall against plasma radiation; and the toroïdal pump limiter, TPL, a high heat flux component designed to extract convected power up to 15 MW. Inner bumpers, antenna screens and limiters, and electrons ripple loss collectors complete the full acpfc set. The TPL is a flat limiter installed at the bottom of the machine. It is made of 12 sectors of 30° toroïdal extension each. During the 2001 campaign, only 3 TPL modules, at 120°, have been installed. Each of them was, on both ends, protected by an inertially cooled baffle collecting the flux entering in the scrape off layer (SOL), to a 7 cm depth. The whole

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acpfc set corresponds to about 128 independent actively cooled elements grouped in parallel sub-nets connected also in parallel to the cooling loop. The various sub-nets are made of a sixth of the TPL, a sixth of the IFW – also including the corresponding inner bumpers, port screens and electron ripple collectors, (ripe) – or the set of screen and limiters of each antenna (ANT) or the antenna guard limiter (AGL).

In the second part of this paper, the diagnostic is presented, the third part being devoted to the calorimetric analysis. Then, the relevance of such a diagnostic for ITER will be briefly discussed.

2. The new calorimetric diagnostic

With the CIEL project, the calorimetric diagnostic has been completely rebuilt, both, to adapt it to the new hydraulic circuits, and to further improve its sensitivity. Calorimetric sensors are of two types: thermometers and flowmeters. Each of the 128 cooled elements is equipped with an output thermometer, while only each hydraulic sub-net is equipped with an internal flowmeter. These are either of differential pressure or vortex types depending on the pipe diameter and have an absolute accuracy of the order of $\pm 2\%$. However a more detailed flow table has been produced, giving the flow distribution in each element measured using a portable ultrasonic flowmeter. Moreover, the analysis of a heat pulse propagation can be used to further check the validity of this flow table [1]. It is found that the global flow balance is reached within an uncertainty better than 5%.

Output temperatures are recorded at the outlet of each cooled element, each sub-net and globally on the main pipe, while input temperatures are only measured in the main pipe and at the inlet of each sub-net. Temperature sensors consist of three wires Pt100 resistors, directly immersed in the coolant. Special care has been taken to get a temperature sensitivity of the order of 2×10^{-2} K and a high accuracy in the estimate of the offset between the input and output temperatures. 16 bit numerical programmable temperature converters are used. Anti-aliasing filters (4 Hz) have been inserted between the converters and the multiplexed optical fibre numerical data transmitters [4]; which send the data to a continuous VME data acquisition board, working 24 h/day with variable sampling rate, specially developed for calorimetry [5]. Fig. 1 shows the behaviour of, T_{out}, and, T_{inc}, the output and the corrected input temperatures, respectively, for the TPL module 2. With $T_{inc(t)} = T_{in(t-\tau)-off}$, where T_{in} is the measured input temperature, $\tau = 10.5$ s is the transit time and off $= 1.865$ °C is the offset. The two spikes correspond to two consecutive 15 s plasma pulses. One can observe that $T_{out} - T_{inc}$ is almost zero everywhere, except during a shot. One can also observe the temperature regulation system reaction and the consecutive oscillation return of hot water pulses, corresponding to the fraction of the input energy not extracted by the heat rejection system, which was only partly available in 2001. These temperature oscillations can be used to check the flow table and the low level of the thermal losses inside the machine.

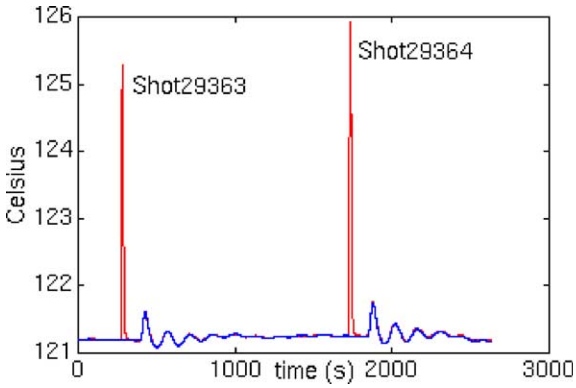

Fig. 1. T_{out} and T_{inc}, output and corrected input temperatures for the TPL module 2.

3. Calorimetric analysis

3.1. Global calorimetric balance

In 2001, the global energy balance analysis had to overcome several difficulties. Firstly, the global output temperature was not available, the balance has then to be made by summing the extracted energy measured at each sub-net, which is a little bit less accurate. It has been necessary to calculate, with a 3D convected heat deposition code TOKAFLU [6], the fraction of energy received by the inertially cooled structures (baffles and their supporting structure). For a $\lambda_q = 10$ mm and 50% of perpendicular heat flux [7] it is found that the inertial structures received 1.4 times the convected energy falling on the actively cooled TPL modules. This energy, not collected by the cooling water system is introduce as a corrective factor $(1.4 + 1)$ in the energy balance equation (1). The radiation collection was also incomplete; the horizontal port screens were missing and the incompleteness of the TLP left part of the vacuum vessel wall in direct view of the plasma. Both the geometry of the installed components and the toroïdal and poloïdal distribution of the plasma radiation deduced from bolometry led to a correction of about 10% of the radiated energy estimated from the IFW calorimetry. In addition to radiation the IFW sub-nets collect also the electron ripple losses which can however be independently measured, the radiation correction factor is then only applied, in Eq. (1) on the radiation part of the energy extracted of the IFW: E_{IFW}–E_{ripe}. Finally, the global energy balance can be written $E_{in} = E_{out}$ with:

$$E_{out} = 2.4E_{TPL} + 1.1(E_{IFW} - E_{ripe}) + E_{ANT} + E_{AGL} + E_{ripe}, \quad (1)$$

$$E_{in} = E_{ohm} + E_{add}. \quad (2)$$

The last difficulty concerns the ohmic discharge balance. As has been previously shown, a way to check the consistency of the calorimetric data is to analyse the ohmic energy balance [1]. Despite the large increase of the temperature sensitivity, the accuracy of the ohmic energy balance remains marginal due to the very large increase ($\times 5$) of the global flow designed for the nominal heat load of the new high performance acpfc. Thermo-hydraulic studies, followed by heat load test on the FE200 facility [8], have shown that for an ohmic shot, a reduction of a factor of 4.5 of the nominal flow gives a critical heat flux margin a factor of 10 higher than the design margin. Fig. 2 shows some examples of global calorimetric balances for ohmic shots made with reduced flow, and for shots with additional lower-hybrid power at the nominal flow. For lower-hybrid shots, the same convected energy enhancement factor $(1.4 + 1)$ is used. This is equivalent to neglecting the weak variation of λ_q with input power [7]. In such conditions, and despite the low level of input energy ($E_{in} < 40$ MJ), a good correlation is found between input and output energies for both ohmic and hybrid shots. The high fraction of missing hybrid power ($\sim$35%) measured with calorimetry in previous campaigns [1] seems not to be found anymore. This could be a first indication of the efficiency of the calibration campaign made on RF power measuring systems. However, these preliminary results have to be confirmed in the 2002 campaign, for which all the present difficulties will be removed. For ICRH power no data are available yet due to electromagnetic pick-up noise on TPL thermometer signals.

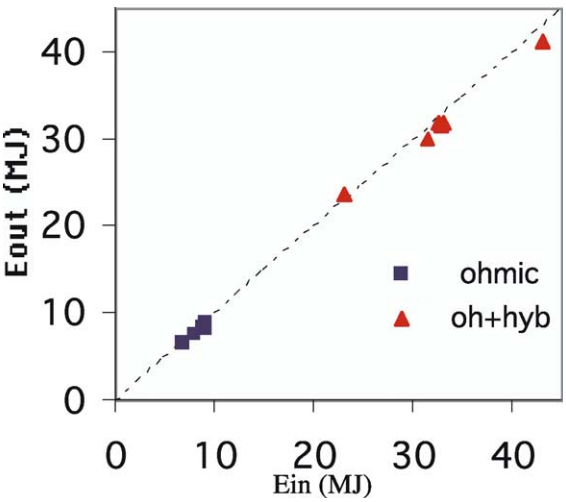

Fig. 2. Global calorimetric balance Campaign 2001.

3.2. TPL trimming and λ_q

The calorimetric measurement accuracy has also been highlighted with the TPL trimming experiments. To optimise the heat flux spread on the TPL area, the latter is mounted on a plane rigid ring supported by six jacks. This allows tuning – with steps of 1 μm – the TPL altitude from −720 mm to −640 mm, and to give to the TPL a total tilt amplitude of about 14.5 mm with respect to the equatorial plane in every toroidal direction. A series of ohmic shots at reduced flow has been made to analyse the effect of trimming on the extracted heat capability of each TPL module. Fig. 3 shows the extracted power behaviour for the three TPL modules (quoted: m2, m4, m6) for four different trimming factors. Fig. 3(a) shows the plasma leaning on the module 4; module 2 and 6 with a position of 3.9 and 7.9 mm inside the SOL respectively. The altitude of each sector, J2, J4, J6, is given in the figure. Fig. 3(b) corresponds to the power repartition for the horizontal trim of the TPL based on

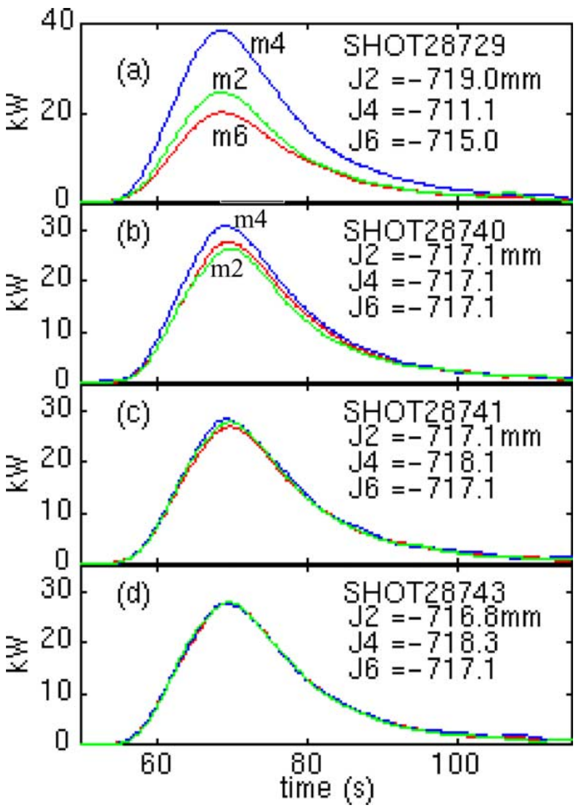

Fig. 3. TPL trimming experiments.

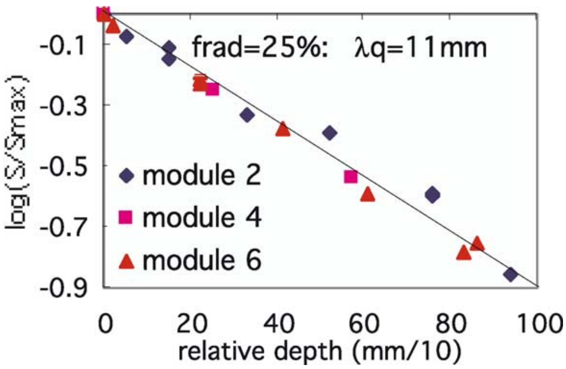

Fig. 4. λ_q calorimetric estimate, averaged over a TPL sector. S is calorimetric energy extracted from each of the 3 TPL sectors corrected from radiation.

data of the optical measuring system, OMS. One observes that the module 4 extracts more energy than the others; the ratios being respectively [0.95 1 0.9]. On Fig. 3(c), module 4 has been moved 1 mm back, and one can still observe some deviation between modules. On Fig. 3(d), sub-millimetric additional trimming variations lead to a complete symmetry of the extracted heat. This shows that the TPL calorimetry at reduced flow is sensitive to trimming variations of the order of 0.2 mm. The very low discrepancy between OMS and calorimetric horizontal trim definition, of the order of 1.2 mm (total amplitude), is compatible with the best OMS estimate of both mechanical and magnetic referentials inside Tore Supra. With this set of data, plotting the extracted energy fraction for each sector, corrected for the radiated fraction, versus the relative depth of each sector in the SOL provides an estimate of λ_q. The radiated fraction – i.e. the radiative contribution to the total energy deposited on the TPL sectors – is assumed to be constant on each sector. Its amplitude is deduced from calorimetric radiated-convected balance constraints by bolometric measurements. For this data set the radiated fraction, frad, is about 25%. One then deduces $\lambda_q \sim 11$ mm. (Fig. 4). Which is in quite good agreement with the estimate deduced from IR and CCD measurements [7].

3.3. Power analysis

The above-mentioned analysis concern energy deposition. However, it also seems viable, using calorimetry, to extract the power evolution with a time resolution lower than the cooling time constant. Analysis shows that the calorimetric thermal power can be fitted using two processes: integration with loss in the component structure (3) and heat diffusion in the coolant (4). For a TPL module, the extracted power exhibits a quasi-exponential decay time τ_c. The diffusion process is equivalent to a gaussian smoothing applied on a characteristic time τ_d. Then the incident power on such a component, P_{in}, is linked to the thermal power measured by calorimetry, P_{cal}, through the following equation set:

$$U(t) = P_{in}(t) + \tau_c \frac{dP_{in}(t)}{dt}, \tag{3}$$

$$P_{cal}(t) = \frac{\sqrt{\pi}}{\tau_d} \int_{-\infty}^{+\infty} U(t') e^{-((t-t')/\tau_d)^2} dt'. \tag{4}$$

In Fig. 5, an example of P_{in} calculation is shown, for TPL module 4 (shot 29273). The total input power is made up of 3 separate, 3 MW, additional power pulses. Fig. 5(a) shows P_{in} (full line) deduced from the model compared with an estimate of the incident flux, P_{bal} (dashed line), deduced from the global energy balance and built from a combination of the ohmic, additional and radiated powers. Fig. 5(b) shows the resulting comparison between the actually measured calorimetric power (dashed line) and P_{cal}, calculated from P_{in}, with $\tau_c = 2.7$ s and $\tau_d = 1.3$ s. These parameters are, of course, dependent on the coolant velocity. Such an example, Fig. 5, gives a time resolution much lower than 1 s. For components that are not properly described using only one cooling time constant, a more detailed modelling is needed.

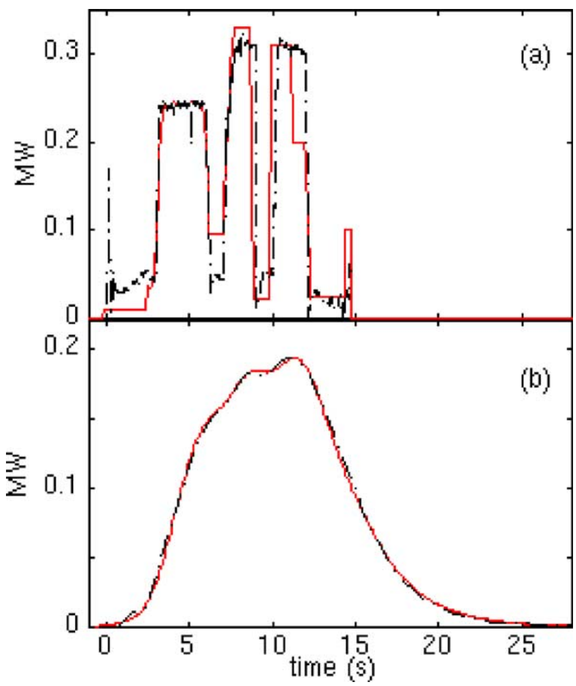

Fig. 5. (a) Comparison of P_{in} (solid line) and P_{bal}, TPL module 4 incident power estimates. (b) Comparison P_{cal} (solid line) and P_{mes} calculated and measured calorimetric power.

4. A calorimetric diagnostic in ITER

The experience in calorimetric measurements, gained these last years, suggests some thoughts about the design of such a diagnostic for ITER. The conflict associated with the coupling of the safety and calorimetry functions assigned to flow and temperature measurements has been clearly identified. Safety functions require the capability to follow parameter behaviours on the largest possible scale, while calorimetry requires the largest possible sensitivity around the working point. This is the reason why on Tore Supra, as on ITER a specific diagnostic is needed [2]. Platinum sensors, less sensitive to neutron irradiation than thermocouples, and differential pressure flowmeters are already used on primary circuits of present nuclear power plants. According to our experience the proposal made to measure the plasma reactivity in ITER by means of the blanket calorimetry seems quite feasible, provided that the neutron multiplication factor be calculated with enough accuracy. To enlarge the sensitivity of this measurement to the physical phase experiments it should be possible to adapt the coolant flow in the blanket to the actual cooling need, as it has been done on Tore Supra for ohmic shot calorimetric analysis.

5. Conclusions

We have tried to show that calorimetry is an accurate and reliable tool allowing validation of the whole set of power measurements. A good global calorimetric balance is essential to any consistent physical analysis. This diagnostic should be considered in any actively cooled device. In particular, to have a good accuracy, it is important to de-couple the calorimetric diagnostic from the operating system (feedback or safety loops) of the cooling water loops.

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