Infrared thermography for real time feedback control in Tokamak Tore-Supra.

D. Guilhem, C. Balorin, G.Caulier, C. Desgranges, P. Messina, M. Missirlian, R.Mitteau, P.Moreau, C. Portafaix, N.Ravenel, H. Roche, A.Saille, P.Spuig

CEA-Cadarache
13108 Saint Paul Lez Durance
France
dominique.guilhem@cea.fr

SUMMARY: Tore-Supra is a Tokamak (Ip=1.5MA, Bt=4T) aiming at doing researches in the field of controlled nuclear fusion. It has a world record with long discharge achievement of 6 min 10s, with the injection and extraction by the active water loop, of ~ 1 GJ. This machine has been constructed with a steady-state magnetic field using super-conducting magnets and water-cooled plasma facing components for high performances long pulse plasma discharges. When not actively cooled, plasma-facing components can only accumulate a limited amount of energy since the temperature increase continuously (T~sqrt(time)) during the discharge until radiation cooling is equal to the incoming heat flux (T>1800K). Such an environment is found in the most today Tokamaks. In the present paper we report the recent results of Tore-Supra, especially the usefulness of the new generation of infrared endoscopes to measure the surface temperature of the plasma facing components.

1. Introduction

Tore-Supra team has developed some experience on real time feed-back control of long plasma pulses (heat extraction capability of 25 MW for 1000 s), and on safety control of heat flux limits of actively cooled components. If these limits are over-passed, a high risk of a water leak is present which is not the case of non-actively cooled machines, even during long pulse operation. The surface temperature from the main components are viewed with infrared cameras. In each camera field of view, windows are set-up on zones of interest and temperature thresholds are defined within these zones. When any of the thresholds are crossed (with some integration time to avoid spurious warning), the main feedback control system switches down additional power. This infrared interlock is used to protect cooled plasma facing components. More sophisticated digital feedback control is actually tested for longer operation, with the steady state as ultimate goal.

2. Tore-Supra a steady-state Tokamak:

Infrared surface temperature maps are essential measurements to run Tokamaks especially Tore-Supra [1], figure-1, having only actively cooled (150°C, 20 bars) plasma facing components [2] to prevent damages and so water leaks.

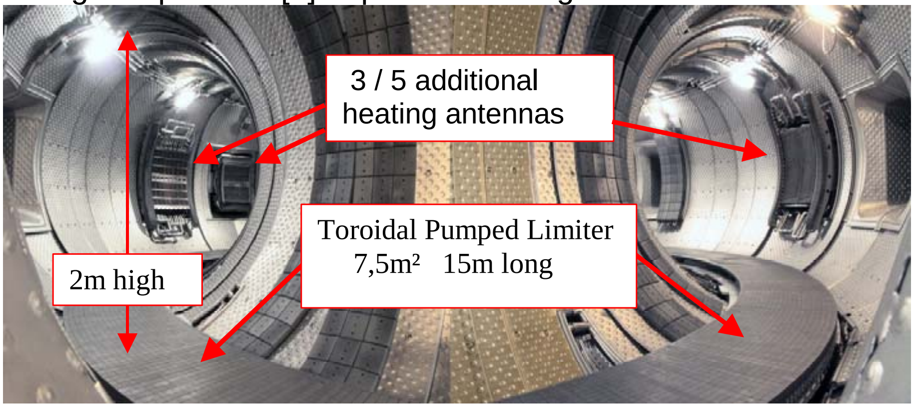


Figure 1. *Overview of the inside of Tore-Supra where one can see the toroïdal Pumped Limiter and 3 of the 5 additional antennas of the plasma heating system*

.

Even when plasma facing components are not actively cooled (as it is today in most Tokamaks), one deduces a lot of informations from such a diagnostic. This ensures reliable shots and most of it, contribute to understand the physic of the interaction of the plasma with facing components.

For Tore-Supra one had to take into account the fact that this diagnostic had to be entirely actively cooled because of the pulse duration. This diagnostic is the first one in the world to be designed for steady state operation, which had strong consequences for the design. We have injected and so extracted so far 1 GJ during a shot lasting more than 6 minutes (2.5 MW of 3.7GHz radio-frequency injected power to drive the plasma current), a world record (December 4th 2003).

3. Infrared thermography system

The infrared thermography system has been designed in order to be able to look at the whole surface of the toroidal pumped limiter (7,5 m², 15m long) and to the 5 additional heating antennas. Note that the optical components (inner part of the endoscope) are cooled by a water loop at 25°C and that the body of the endoscopes (external part of the endoscope) is cooled by another water loop at 150°C, 20 bars (water loop of all the Tore-Supra plasma facing components). Since there is a differential movement of the body of the endoscope from 25°C to 150°C during operation on the machine (due to thermal expansion), we had to take it into account to define the head diaphragm position and diameter. It has been designed for a temperature of 150°C ±50°C. To cover the entire surface of the toroidal pumped limiter and all 5 antennas, a set of 7 infrared actively cooled endoscopes, are spaced around the torus. The measured spatial resolution with less than 5% temperature error (slit response function at 95%) has been measured to be from 7.5 to 9 mm at the 1.8m nominal distance of the endoscope diaphragm. This is to be compared with the width of the smallest element constituting the plasma facing components, 20 mm. Each endoscope is equipped with 3 viewing lines, 2 for 2 sections of 35° (with 5° crossover to chain all 6 cameras together) of the toroidal pumped limiter located at the bottom the machine and one line for one antenna. Each viewing line is made of 2 sapphire windows (Vessel_vacuum / Endoscope_vacuum; Endoscope_vacuum / Atmospheric_air),

1 deflection Si prism, 28 lenses (Φ = 35 mm to Φ = 85 mm) made of Ge, Si and ZnSe, 4 gold plated stainless-steel flat mirrors (or 1 prismatic Si blade for the antenna line). The overall

transmission of each line of view is ~ 0,2. This transmission value is rather low, due to presence of 28 lenses and to 2 sapphire windows, the latest having a transmission < 0,85. On the one hand, the first window close to the plasma is inserted in the endoscope's head which is actively cooled since it will receive a fraction of the plasma radiated power. On the other hand the temperature of the water loop running inside the endoscope's external envelope has to be the temperature of the whole set of plasma facing components between 100°C and 200°C (programmable, usually at 150°C), to prevent the formation of cold points inside the vacuum vessel (which would lead to a bad conditioning of the vacuum vessel). So we have a hot optical element having of rather bad transmission leading to a non-negligible contribution to the signal received by the camera detector. The endoscope's internal part supporting the relay lenses is also actively cooled by another water loop at 25°C. Here the temperature of the 20 lenses is rather low, but since the overall transmission is relatively low < 0,4 his contribution to the spurious signal is also not negligible. To ensure a good absolute temperature measurement of the plasma facing components, even at the lowest temperature ~100°C, one has to take into account of the different stray light getting to the detector. The analysis software developed is taking into account the contribution of each part of the viewing line, calculated from the respective transmission and temperature, which are subtracted from the received radiance before to translate the result in temperature. If one does not follow such a procedure the error bar can be very large especially when the observed object is cold (between shots) at the temperature of the water loop (100°C to 200°C). For this new generation of endoscopes the error bar has been thoroughly evaluated. It is <8%, within the temperature range of interest, 100°C to 1500°C.

4. Interlock and feedback:

This set of endoscope is well suited to prevent overheating of the plasma facing components. We are able to decrease the amount of additional power when overheating is taking place figure-2. Here the threshold was set at 435°C on one of the additional power antenna. When this temperature is reached, the additional power is stepped down until the temperature is again below the threshold limit. This function is set up for security reasons: not to overpass the maximum allowed surface temperature of a component.

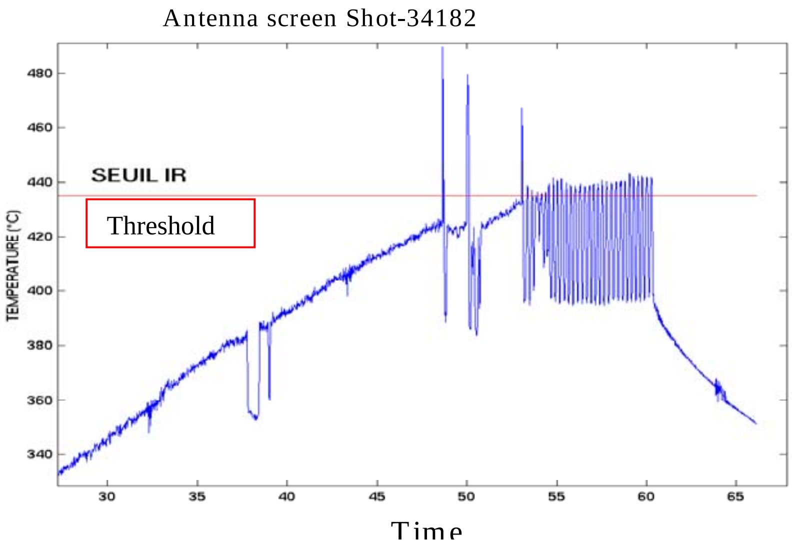
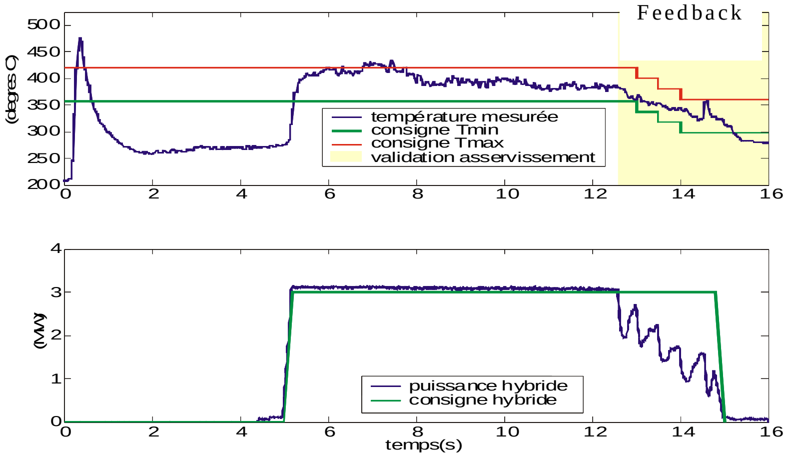


Figure 2. *Example showing the safety system in action. When the surface temperature of one zone of one of the 5 antennas is over-passing the threshold, the additional power is stepped down.*

On the other hand one would prevent to come to such a drastic situation and so we have been able to use temperature measurements from the limiter, to feedback on the level of additional power so that the maximum temperature is between 2 predefined temperatures figure-3. The feedback is active from t=12,5 seconds where one can see that the surface temperature stays within the predefined low and high allowed predefined temperatures envelop. This is ensured by a decrease of the level of additional power injected in the machine by the radio-frequency additional heating system.

3. Conclusion

We have developed a set of 7 actively cooled (steady-state) infrared endoscopes able to measure surface temperatures from 100° to 1500°C with accuracy better than 8%. This set comprise 7 endoscopes is equipped with a total of 9 infrared cameras. It has been shown that the surface temperature measurements are used either for feedback control of the plasma operation (to control long plasma discharges) and also for preventing overheating of the main plasma facing components which would lead inevitably to a water leak inside the machine.



<u>Figure 3</u>. *Feedback control: (top) Infrared surface temperature time trace with maximum and minimum allowed temperature values, validated from t = 12.5s; (bottom) injected power in blue and asked power in green if the feedback was not activated at t = 12.5 seconds.*

<u>References:</u>

[1] “Preliminary results and lessons learned from upgrading the Tore Supra actively cooled plasma facing components (CIEL project)” Fusion Engineering and Design, vol.66-68 (2003) p.59-67 (2003) J.J. Cordier, X. Tore supra team

[2] “Heat flux pattern on the toroidal pump limiter of Tore Supra : first observations and preliminary analysis” Journal of Nuclear Materials, vol.313-316 (2003) p.1229-1233 (2003) R. Mitteau, J. Vallet, A. Moal, D. Guilhem, J. Schlosser, T. Loarer, B. Riou, A. Grosman, A. Geraud, Ph. Ghendrih, E. Tsitrone, B. Pegourie, J.M. Ané