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Diagnostic Development for Steady-State High Power Operation

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Abstract

The next generation of fusion experiments will operate for much longer pulse lengths, introducing several new requirements for diagnostics compared to existing experiments. With the installation of its upgrade named CIEL (a French acronym for Internal Components and Limiter), TORE SUPRA has now to take into account most of these requirements, which can be developed in two parts. The first one deals with the thermal load on diagnostic components and the need to optimise the geometry and develop specific protections with active cooling. The second set of requirements concerns the need for more complex control loops in order to maintain optimised modes of plasma operation for longer periods. This requires higher reliability and stability of calibration of the relevant diagnostics. There are also increased requirements for real-time data analysis and on-line displays to keep physicists informed of the state of the experiment and for intelligent systems to warn operators of potential dangerous plasma conditions. These and other requirements, and the way they are being dealt with on TORE SUPRA are presented.

Keywords:
diagnostic, plasma physics, tokamak, high power operation, steady-state

1. Introduction

Measurements in high temperature fusion plasmas require specific techniques, most of them being remote, without contact with the plasma or only at the extreme edge of the plasma. Remote methods are based on plasma emission, either from particles escaping the plasma, or from radiation within a broad electromagnetic range. These methods can be either passive (i.e. relying on the natural plasma emission), or active (the plasma being locally excited by waves or particles). Many kinds of diagnostics have been developed and are in operation in fusion devices. Although remote, i.e. the detection system is often at a safe distance of the plasma, they require interfaces with the plasma through components which can be close to it.

High power operation induces possible high thermal and neutron fluxes on diagnostic components close to the plasma. Having high power together with steady-state operation adds a new constraint: not only the thermal flux, but the integrated thermal load on components has to be considered.

Developments of diagnostics for steady-state high power operation have been studied for ITER, taking into account the thermal load, the neutron load and remote maintenance.

If ITER is still a machine under design, TORE SUPRA is a machine in operation now facing a major upgrade, with the installation in the year 2000 of the CIEL components [1]. The design is such that the machine would be able to handle a power of 25 MW for a pulse length of 1000 seconds. As TORE SUPRA is a

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machine without tritium, the neutron load is not a difficulty, and there is no need for remote handling. The main consequence of high power operation for long durations is that the total integrated energy has to be considered. A power of 25 MW for 1000 s gives a total energy in the machine of 25 GJ, which has to be injected, controlled and extracted. Compared to the present record of 280 MJ hold by TORE SUPRA, the new goal is two decades more ambitious in terms of thermal load.

Steady-state operation induces a strong need of real time control and feedback, in order to maintain optimised modes of plasma operation for longer periods, which leads to real time data proccessing. In addition, the management of large amounts of data has to be properly organised, in terms of transfer, storage and on-line display.

In this paper, the problem of thermal load on components is presented and discussed in section 2, followed by the data management in section 3.

2. Thermal Load

The CIEL components of TORE SUPRA have been designed with the requirements of 15 MW convected on the toroidal pumped limiter and 10 MW radiated. As this radiation level is not likely to be with perfect poloidal and toroidal symmetries, it has been chosen to multiply this number by a 2.5 factor to design the components facing the plasma, as if there were 25 MW radiated. The external surface to be considered is about 100 m^2, therefore the average flux density at the plasma edge is of the order 0.25 MW/m^2. To avoid overheating, most of the components facing the plasma have to be actively cooled.

The diagnostic components presently designed to be actively cooled in TORE SUPRA are mirrors, waveguides, endoscopes, and some fibre supports if they are not shadowed. During boronisation or other possibly deteriorating actions, protective shutters will be placed in front of mirrors or windows. These shutters will be made in high temperature standing materials (CFC or else) which allows an active cooling.

If actively cooling the components facing the plasma is an attractive solution, it implies circulating water for a proper thermal exchange efficiency. In the case of the IR endoscope (Fig. 1) used for controlling the surface temperature of the toroidal pumped limiter and heating antennas, there is an inner cooling system at room temperature to keep the optical components at constant temperature and ensure a good transmission of the image properties, and an outer one at higher water temperature and pressure to remove the heat flux coming from the plasma [2].

For all the actively cooled components, it is absolutely excluded that water would leak and pollute the vessel, because this would stop the machine for weeks if not for months. It is therefore necessary to tend towards zero defect, starting from the very first phase of the design through all the stages of the construction. No component can be installed inside the vacuum vessel without going through well defined control procedures.

On ITER, by the use of dog-leg mirrors, no window would be directly facing the plasma, because of the thermal load, but above all because of the neutron flux and fluence. This neutron consideration does not apply on TORE SUPRA, and if the windows can handle the thermal flux, it is easier to avoid dog-leg mirrors, especially when many windows are necessary. Windows will be placed at the extremity of tubes which reduce the thermal load. An example of such a configuration is shown on Fig. 2, with a set of six windows for the

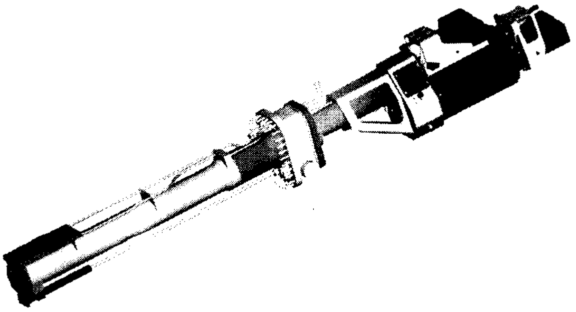

Fig. 1 Actively cooled endoscope for IR survey of the toroidal pumped limiter and heating antennas.

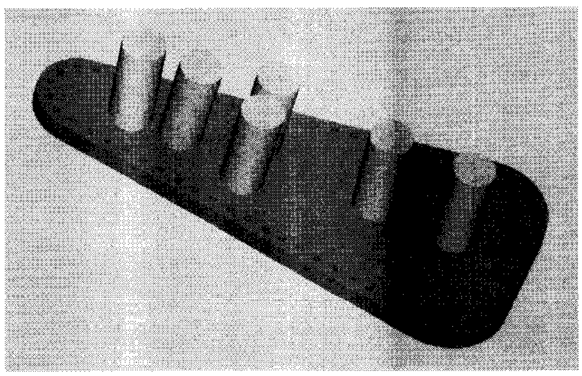

Fig. 2 Windows and tube extensions for a vertical port of the interfero-polarimetry diagnostic.

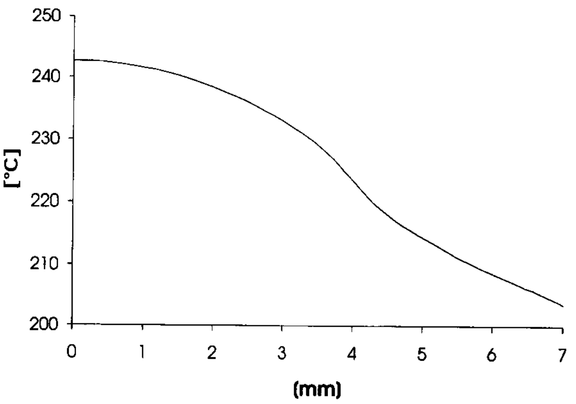

Fig. 3 Radial temperature profile as calculated for the endoscope sapphire window, after an exposure for 1000 s on a plasma radiating 0.2 MW/m².

vertical interferopolarimetry diagnostic.

Numerical calculations of the temperature increase have been made for different configurations, and with a proper tube extension, the temperature of the windows does not exceed 250°C for the highest value after 1000 s. Similar temperatures are obtained for the endoscope shown on Fig. 1, where the window is closer to the plasma, but it has a smaller diameter (Fig. 3). Calculations have also been made to optimise the mechanical stress on windows and supports due to the temperature gradients.

The new concepts have to be validated before these control tests. For the windows, a test bench is being prepared to validate these thermomechanical calculations. In the tokamak, the plasma radiation will be for its main part in the UV range, and therefore absorbed at the surface of the window. As it is not easy to simulate such a high UV flux for a long time, the test bench will use an IR radiation and the window will be coated with an absorbing material to simulate the energy deposition at the surface.

3. Data Management

The second set of requirements on diagnostics for steady-state high power operation concerns the data management, because long pulses cannot be managed just as an extension of more conventional plasma discharges. First of all, steady-state needs more complex control loops in order to maintain optimised modes of plasma operation for very long periods.

Many feedback loops have been developed for TORE SUPRA, to control the plasma for steady-state discharges. As most of the tokamaks, plasma current, plasma position and lineic density are controlled by the poloidal field system and gas injection. There are also feedbacks intrinsic to systems such as the additional power controlled by the reflexion coefficient in the antennas.

A system of three controls on three parameters has been specifically designed for stationary discharges: the plasma current, the loop voltage and the internal inductance are controlled by the magnetic flux (itself controlled by the poloidal field coils), the lower hybrid power level and the lower hybrid phase. This allows not only to control the current value (I_p) but also its distribution (through the internal inductance li) for a better performance and stationarity [3].

As the lower hybrid system is required to operate for a long time, impurities generated by the copper antenna have to be controlled. A feedback loop on the Cu level in the plasma directly controls the maximum allowed power for the LH system. Another important feedback system is a control of the surface temperature of components such as the limiter, the neutralisers or the antenna protections. The data from the IR cameras imaging these components through the endoscopes (Fig. 1) will be processed in real time, with the possibility to control the average temperature over a predefined surface, or a maximum temperature to react if hot spots arise [4].

Another useful feedback which has been developed on TORE SUPRA is the gas injection controlled by the edge electron temperature. If T_e goes below a threshold (usually set to 14 eV), the injection is stopped to avoid a disruption [5].

Going further, the operator might want to be able to react if an unpredicted feature appears. The present operational active control on TORE SUPRA is a STOP order with a controlled procedure: the additional heatings are stopped and the plasma current is decreased as fast as possible keeping an active control of the plasma position. There are still discussions for more control, which could be expressed by "does the operator need a joystick?". But it seems preferable to develop automatic active controls with a good understanding of the different underlying mechanisms.

If not properly handled, long discharges may imply a very large amount of data. Although capabilities of computing and storage systems increase continuously, it seems better to develop strategies of acquisition than storing huge amounts of data which would never be analysed. Since its first plasma in 1988, the acquisition systems of all TORE SUPRA diagnostics are able to use different strategies, triggered depending of the events detected. In case of a transient event, such as a pellet injection, the beginning of additional heating, a sawtooth crash, etc, a diagnostic can increase its acquisition rate during a time window. On the other hand, the acquisition rate can be reduced when a long discharge is programmed, and when the plasma is in a stationary phase.

As real time processing allows to reduce the amount of raw data, it is nevertheless necessary to store a part of this raw data to a posteriori control the validity of the real time processing. The amount of raw data stored has to be considered in function of the foreseen future needs, and can be changed following the reliability evolution of the real time processing.

Finally, it is necessary for all diagnostics to consider the validity of the calibration: would a calibration (offset removal, etc) made at the beginning of the discharge still valid after 1000 s? If a periodic recalibration is being made during the plasma discharge, would there still be measurements during that calibration? It is also possible to cross-calibrate diagnostics using real-time data transfer between them. By way of example, it has been considered for ITER to recalibrate the plasma edge position obtained from magnetic measurements by using reflectometry. Although this cross-calibration proposal can be tested on TORE SUPRA in very long discharges, it is not necessary as new integrators have been designed for magnetic measurements and successfully tested.

4. Conclusion

Steady-state high power operation of fusion plasmas implies severe constraints on diagnostics. Compared to shorter high power pulses, thermal load on components for long durations has to be accounted in terms of integrated energy and not only of maximum power. To handle that energy, up to 25 GJ in TORE SUPRA, most components have to be actively cooled, with drastic control procedures before installation in the vessel, as any single water leak would be very dramatic for the experimental campaign. For components which cannot be easily cooled, such as windows, the geometry around them has to be optimised to limit the thermal load. The second important point to be considered is that the duration of the discharge is long at human scale. Many kinds of feedback loops are necessary and have been developed on TORE SUPRA, to ensure a good control of the plasma. Moreover, the data has to be managed in real time, with real time transfer, real time processing and real time availability and display.

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