STRATEGY OF THE TORE SUPRA DIAGNOSTIC SET FOR STEADY-STATE HIGH POWER OPERATION

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1. INTRODUCTION

In most tokamaks as well as in other fusion devices, the set of necessary and useful diagnostics is mainly determined from the plasma parameters to be measured. For next step devices, steady-state high power operation is foreseen, and the diagnostics will increase their role for other missions, such as machine operation or safety control.

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. Such constraints have been examined for ITER[1] for its design, but they have to be applied now to TORE SUPRA which is operational.

TORE SUPRA is a tokamak with superconducting magnetic coils which has originally been designed for long pulse operation. The initial nominal value was 30 seconds when it started in 1988. Nevertheless, this duration has been exceeded when it reached a record pulse of 120 seconds with a controlled total energy of 280 MJ injected and extracted[2]. TORE SUPRA is now facing a major upgrade, with the installation of new internal components[3]. The design is such that the machine would be able to handle a power up to 25 MW for a pulse length of 1000 seconds.

As TORE SUPRA is a machine without tritium, the neutron load is quite low, 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 would give a total energy of 25 GJ in the machine, which has to be injected, controlled and extracted. Compared to the present record of 280 MJ, this is two decades more ambitious in terms of thermal load.

Within this context of high power density for a long time, TORE SUPRA diagnostics have been reassessed, and the priorities were redefined.

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2. CONSTRAINTS

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 not only in terms of maximum power but also of integrated energy. Numerical simulations have been made for windows, mirrors and mechanical supports : by example, for a total radiated power of 10 MW, the thermal flux could reach 32 kW/m^2 on a window facing the plasma at a distance of 80 cm, which cannot be sustained for 1000 seconds without damage. Solutions have been found with intermediate actively cooled mirrors and/or tubes protecting some windows resulting to a reasonable temperature increase (less than 200°C after 1000 s). A test bed facility has been developed to validate these solutions, and drastic control procedures are also made before installation in the vessel, as any single water leak would be very dramatic for the experimental campaign.

Another important point to be considered is the data management system, taking into account the fact that the duration of the discharge is long at human scale, that many kinds of feedback loops have been developed on TORE SUPRA to ensure a good control of the plasma, and that the data has to be accessed in real time by the physicists. For all these requirements, a new data management system has been developed[4], with direct exchange of information at low level between diagnostics, together with real time transfer, real time processing and real time availability and display.

3. TORE SUPRA DIAGNOSTICS

Within this objective of steady-state high power operation, Tore Supra diagnostics have been classified in four groups, depending of their main purpose.

The first group corresponds to diagnostics which are essential to make and sustain a plasma. Without them, no plasma would be possible, and the machine useless. In this group, two important plasma diagnostics have been placed: magnetics and interferometry. Strictly speaking, it would be possible to make a plasma without these diagnostics, but it would be uncontrolled and at low performance (far from our "steady-state high power operation" objective). In addition, some tools (not strictly plasma diagnostics) necessary for the pilots are joined to this group, such as a CCD camera and a mass spectrometer.

Magnetic measurements are necessary for plasma control in terms of shape, position and plasma current. They also provide additional information (stored energy, MHD, ...), which could be classified within an another group of diagnostics (see below). On Tore Supra, the magnetic measurement system has been entirely renewed[5] for an optimized adaptation to the new geometry and with enough redundancy to allow failure of some sensors..

For interferometry, only the central vertical chord is considered as essential, as it is used for the density control feedback. In steady-state operation, a good particle control is essential because the pumping conditions and the recycling on the plasma facing components can vary strongly during the pulse (due to wall saturation and components

temperature change). This diagnostic has been completely rebuilt and Tore Supra is equipped with five vertical chords[6], coupled with polarimetry measurements.

The second group of diagnostics include all those necessary to ensure a safe operation, without creating any strong damage to the machine. If the essential systems listed in the first group are more important, because needed to control a plasma, this second group is strictly necessary for a relevant experimental programme: it is not possible to aim at performing plasmas without the safety diagnostics. Five of them have been placed in this category: neutron monitoring, infra-red thermography of limiters, infra-red monitoring of neutralisers, ripple loss measurements and calorimetry.

Taken as a safety diagnostic, neutron monitoring controls the neutron flux for human and material protection. In addition, it is also used for physics purposes such as ion temperature.

One of the main plasma facing components of Tore Supra in its new configuration is the toroidal pump limiter (TPL), with the ability to stand 15 MW of convected power for 1000 seconds. The safety of this TPL relies on a set of infrared cameras viewing the plasma through endoscopes[7]. This diagnostic is a good example of all constraints : optical components very close to the plasma are maintained at 20°C through a water cooled internal system, while external components evacuate high thermal fluxes through a second layer of water cooling system (200°C, 30 bars). It has to be robust and allow a feedback action on the plasma (shape, position heating). This diagnostic is also used to monitor the additional heating antennas (ICRH and LH) and their thermal protections.

The neutralisation part of this TPL is in a very tight zone, and cannot be observed by IR cameras. A separate diagnostic, based on IR fibers and bichromatic pyrometers[8], is developed to monitor these neutralisers which can locally handle a flux of 20 MW/m^2.

Due to its superconducting toroidal coils which are very compact, the toroidal field encounters a noticeable ripple at the plasma edge. This ripple induces particle losses in the vertical ports which can be high for some plasma conditions. Ripple losses are measured by the intermediate of an array of twelve graphite collectors in a vertical port, each collector being related to a known vertical chord across the plasma by the drift trajectory of the localized particles[9].

Calorimetry, with about 150 temperature and 50 flow measurements, ensures the safety of all actively cooled components. It is also used for analysis of plasma power and energy balance, and is therefore considered as a plasma diagnostic.

Being used for control and safety, all diagnostics of these two groups need to be in the feedback loop system.

The third group of diagnostics include those necessary for a basic monitoring of the plasma. They are not necessary for safely making a plasma, but the plasma would have no interest without measurement of these parameters. In this group, UV spectroscopy, Zeff, Hα, Thomson scattering and bolometry (2 cameras) have been selected. With the combination of the first two groups, electron temperature and density profiles are obtained, with information on radiation, impurities and plasma equilibrium. This provides the basis for energy balance and other standard studies.

Finally, the fourth group of diagnostics include those who give additional and useful information, but which are not essential by themselves. They are linked to specific physics programmes, or used to complete and improve the knowledge of important parameters measured by diagnostics listed above. The choice of the diagnostics of this

group obviously depends on the scientific needs, but with some weighting in priority from other considerations such as what already exists, the budget and manpower for renewing, the technical constraints due to steady-state high power, etc.

After the long shutdown from the end of 1999 to this summer 2001, many if not all diagnostics have been subjected to strong modifications, and only part of them are operational for the 2001 campaign: ECE radiometer, X-crystal spectroscopy (mainly for ion temperature measurement), soft X-ray tomography, hard X-ray tomography, reflectometry, polarimetry, barometry, Langmuir probes (fixed in many places and pop-up in the TPL), reciprocating probe, bolometry (4 additional cameras), Zeff (full profile), neutral particle analyser. Other diagnostics are due for 2002 and 2003 campaigns.

4. CONCLUSION

TORE SUPRA is now facing a very important challenge, with the objective of very long steady-state high power discharges. The associated severe environmental constraints are taken into account, and in particular the thermal load on diagnostic components. In addition, extension in the feedback system and the possibility to access the data during the pulse are implemented.

Therefore, diagnostics have been revisited, and priorities redefined, ordered in different groups: essential diagnostics needed to make and sustain a plasma, safety systems to avoid creating any strong damage, basic diagnostics for a minimal plasma monitoring, and others dedicated to the programmatic purpose.

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