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CIEL in *Tore Supra*: How to Master Power and Particles on very Long Discharges

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Abstract

In order to prepare the next generation of tokamaks, a new goal has been assigned to Tore Supra. Initially designed for handling 15 MW of power over 30 s operation, the original generation of plasma facing components will be replaced by a set of new, high technology components, constituting the so-called "CIEL" project (French acronym for "Composants Internes Et Limiteur"), with the ultimate aim of injecting 25 MW over 1000 s in the plasma. An overview of the developments associated to the various components and of the main technological challenges is given. Installation of CIEL in Tore Supra will last about 18 months; the new configuration will be operational mid of 2001.

Keywords:

Tore Supra, Plasma Facing Components, infrared, long discharges

1. Introduction

After 11 years of operation, during which many new results have been obtained, as PEP or LHEP modes [1] (regime where pellet injection or lower hybrid enhances confinement), record energy coupled to the plasma (280 J, during two minute shot), comprehensive studies on improved confinement regimes (internal transport barriers, reversed shear), etc., *Tore Supra* is now being dismantled in order to renew the whole plasma facing component environment. Former results, even if obtained for relatively long discharges, must be confirmed for almost steady state operation.

It is the goal of this new environment, called CIEL (French acronym for "Composants Internes Et Limiteur", inner components and limiter) to provide stable and reliable plasma facing component configuration to extend former studies. They have shown in particular the importance of the wall preparation, its behavior for very long discharges (more than one minute), and the overall power exhaust capability, in particular for the convected power. A total of 25 MW power extraction becomes possible for 1,000s discharges, with a pumping exhaust of 4 Pa·m^3/s [2].

The development of a new generation of high heat flux components makes possible an increase of about one order of magnitude thermal removal capability. CIEL main object, so-called toroidal pump limiter benefits of these developments, and enables a power exhaust of 15 MW of convected power. The remaining 10 MW of radiated power will be evacuated by a set of panels enabling even a potential radiation up to 25 MW for 1,000s, or peaked radiation up to a factor of 3. Figure 1 below shows the main components of CIEL:

- A flat Toroidal Pump limiter (TPL) located at the bottom of the inner vessel;
- A set of 6 poloidal bumpers, located on the high field side of the machine;

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- Stainless steel panels covering the whole surface of the inner vessel, designed to evacuate up to 25MW, and providing a stable temperature environment;

- 12 so-called neutralization cassettes located under the limiter, in its throat, and connected via ducts to pumps.

Other components, as infrared endoscopes located in the upper ports are not visible on the drawing. They ensure the safety of the limiter, and are a nice tool to measure power deposition on it.

Cooling loop enhancement is also necessary.

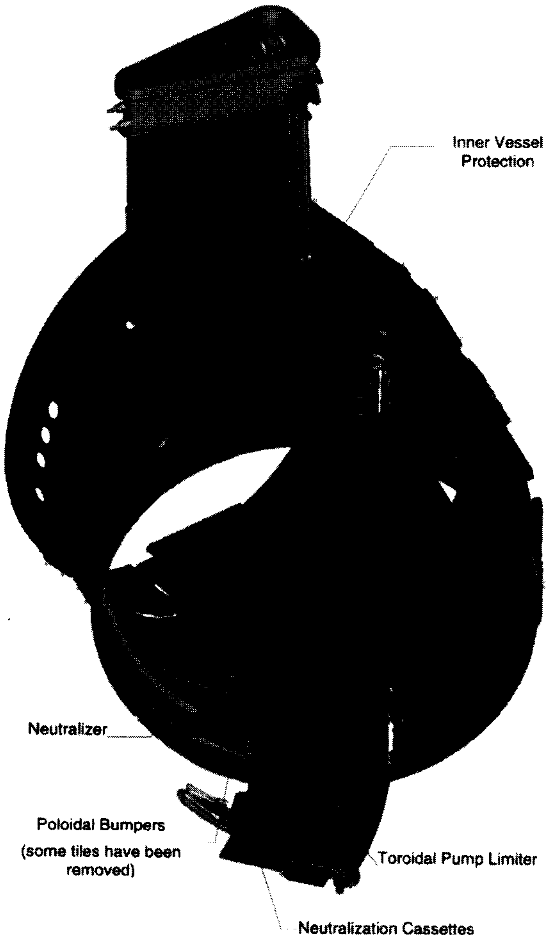

Fig. 1 Overview of CIEL Components

2. Heat Extraction

Two generations of actively cooled components have been already intensively used in *Tore Supra*:

- the first one, based on the brazing of carbon tiles on stainless steel pipes, showed some limitation, in particular with respect to runaway electrons which destroyed some tiles, and their heat exhaust capability;

- a new generation was then installed on the high field side of the inner vessel, based on carbon fiber composite tiles, much more robust than the first ones, but always cooled down via stainless steel heat sink.

In the meantime continuous development led to the possibility to braze CFC tiles on copper layer, with a gain of one order of magnitude in the thermal flux removal capability with respect to stainless steel. This new generation has been already successfully used on antenna bumpers for two years of experimental campaign.

After 10 years of successful operation of the ergodic divertor inside *Tore Supra*, a limiter configuration has been chosen, in order to provide a simple and stable environment to the plasma. It will replace the main limiter used before (inner wall bumper), which had some remaining gaps between the cooled structures, because of its poloidal and toroidal geometry (wider distance at the top and bottom than in the equatorial plane).

On the other hand, actively cooled stainless steel panels will be used in the new geometry, this cheap technology being compatible with the flux to extract. Only slight optimization, in particular with respect to water flow rate has been made, as explained hereafter.

2.1 *Toroidal Pump Limiter*

A flat limiter configuration procures a flexible way for plasma shaping, control and HF additional heating coupling; simple feedback control on the local shape in the throat can be used to optimize heat deposition and pumping. The Toroidal Pump Limiter covers 7.5 m^2 of the bottom area of the inner vessel and has been designed to sustain a convective power of 15 MW in steady state.

This horizontal disk, tangent to the plasma, is linked to a supporting structure (Fig. 2), used as a reference plane and manifold [3]. It allows the accurate positioning of the limiter leading edge, can be moved vertically and is electrically isolated from the vacuum vessel by ceramic rings, allowing a biasing up to ±1kV. A remarkable manufacturing accuracy, measured by two different techniques, has been obtained: ±0.2 mm of flatness, ±0.3 mm of circularity and ±0.2 mm of circularity between the external and inner crowns.

The head of the limiter (horizontal disk) is composed of high heat flux components, called fingers, manufactured by the Austrian company Plansee. These fingers are cooled by pressurized water (40 bar at 150°C) provided by the TPL structure. Flux performance of these elements has been measured on a special facility, an electron gun called FE200: up to 15MW/m^2 on the flat part of the finger and 11 MW/m^2 on the leading edge with safety. They are composed of a sheath of 6 mm carbon fiber composite linked to a thin copper layer by a technique called "Active Metal Casting" [4]. This copper layer is itself welded by electron beam on the body, made of CuCrZr alloy. A final systematic check by means of infrared camera on a specific test bed is carried out to measure individual thermal transfer from finger surface to inner water channel, and guaranty the overall performance of the TPL.

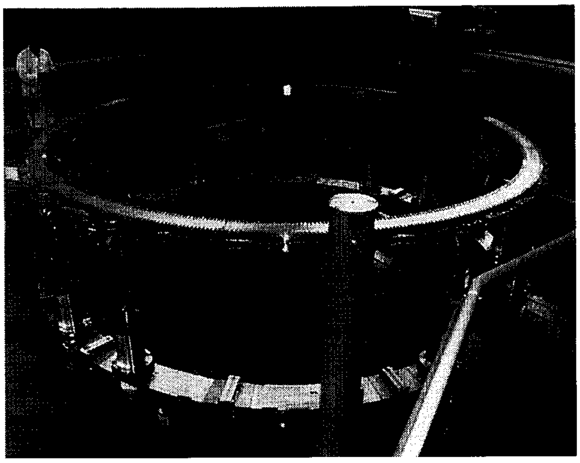

Fig. 2 TPL Supporting Structure

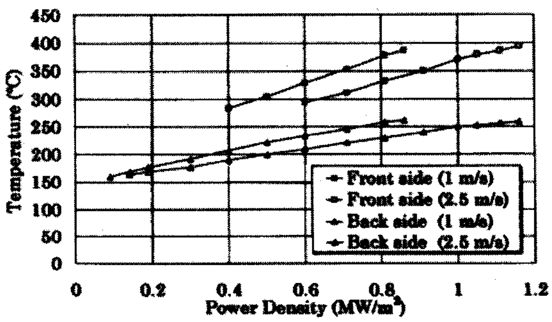

Fig. 3 FE200 Test of Inner Wall Panels

2.2 *Inner Wall Protection Panels*

Protection of the inner vessel against radiated power is devoted to a set of stainless steel panels. *Tore Supra* has already experienced this kind of panels, but it was necessary to replace them by a new generation for the following main reasons:

- Suppression of all slots between panels, resulting in a transparency lower than 1%;
- In order to optimize water flow rate, the thickness of panels was decreased from 12 (present configuration) down to 8 mm. Thus the manufacturing technology is also different: pre-embossed plates were welded, while the first generation consisted in hydroformed panels.

Figure 3 shows the experimental results of test under flux of one panel on FRAMATOME-CEA installation FE200 (water velocity: 1 and 2.5 m/s). Even with a low water velocity of 1 m/s, up to 0.5 MW/m^2 can be applied with a maximum temperature of 300°C. This flux corresponds to an overall radiated power of 25MW, with a peaking factor of almost 2.

2.3 *Bumpers*

Transient events (disruptions, runaways...), as well as permanent radiated power will be absorbed by a set of 6 pairs of poloidal bumpers (Fig. 1). Their technology, developed in the framework of a NET contract, is based on the concept of thick CFC tiles cooled on a CuCrZr heat sink via a sheath of carbon paper, called papyex, and springs. The latter ensure a constant pressure, whatever the surface temperature of the CFC tiles. Their thickness and shape are calculated to spread the flux on a large surface, with a deep penetration of the runaways, without any risk of damage for the cooling structure. The temperature is less than 600°C for the maximum radiated power (25 MW) after 1,000 s.

2.4 *Cooling Loop Modifications*

CIEL project also includes modifications of the cooling loop, which ensures Tore Supra's baking at 230°C and heat removal at about 150°C. A total amount of 1,000 t/hours is indeed necessary for all CIEL components, but also RF antennas, plasma facing diagnostics, etc. The upgraded loop primary circuit (40 bar – 230°C) will extract 25 MW overall power for 1,000 s discharges.

2.5 *Particle Control*

In steady state, one cannot rely on wall pumping, and an active pumping must be provided. Control of the edge density will be made by means of neutralizer sets, located below the limiter, and connected to the pumps. Pellet injectors will mainly fuel the plasma, at a frequency of 10 Hz.

A total pumping capacity of 4 Pa·m^3/s seems to be enough to maintain a constant density, whatever the scenario.

2.6 *Neutralization Cassettes*

Below the TPL throat are located 12 cassettes as shown in Fig. 1. Four fingers (same technology as for the flat part of the TPL) are assembled in a V-shape so that each quadruplet of neutralizers is at the shadowing limit of the next toroidal one.

A bellows under the cassette plate is connected to the vertical port of *Tore Supra* and enables evacuation of neutralized species towards the pumps.

Figure 4 shows also optical fibers and the final mirror that monitors finger surface temperature.

Gases are then pumped via cylindrical ducts located under *Tore Supra*. After neutralization on the fingers, thermalization in the box below the plate, molecular recombination occurs all along the pipe towards the pumps. EIRENE code has been intensively used to compute and dimension all these elements. As a result, Fig. 5 shows the necessary flux to extract versus deuterium pressure at the bottom of *Tore Supra's* lower vertical port. The calculation is made assuming 10 ports available under the machine (two of them are occupied by traversing diagnostics: Thomson scattering and interfero-polarimetry). Data are given with a gas temperature of 300 K.

2.7 *Cryomechanical Pumps*

The principle of the cryomechanical pump is based on the relation between volume and temperature at a given pressure. When the section is infinite, the resulting gain in the pumping speed is with the ratio of the temperatures (i.e. a factor 3.3 for 80 K pump, including a 10 K gradient between the gas and the pump, with respect to room temperature). But when the section shrinks, it converges to the square root of the temperatures, as shown in the Fig. 6 below, which plots the gain vs. the product of the radius R and the pressure Pc above the pump. *Tore Supra* typical operation, is also shown.

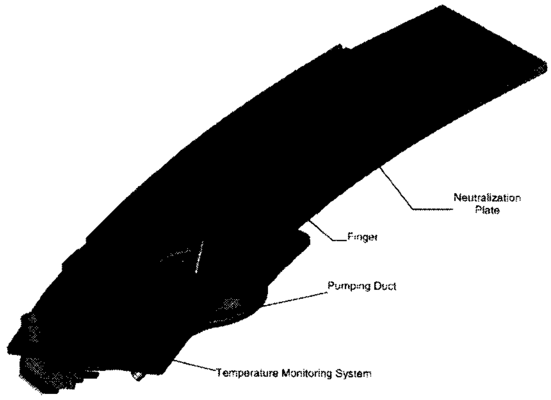

Fig. 4 Schematic of Neutralization Cassette

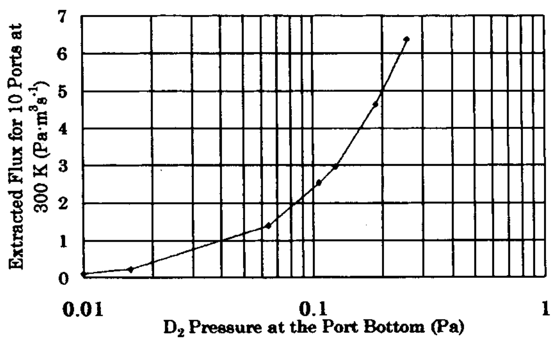

Fig. 5 Computed Flux vs. D2 Pressure

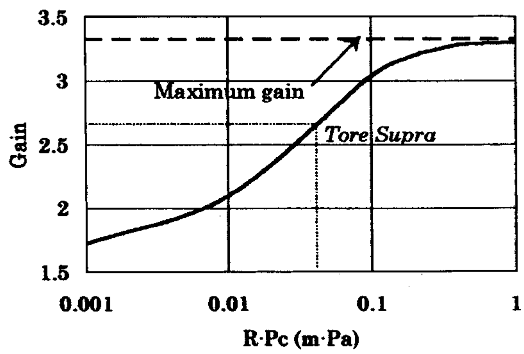

Fig. 6 Possible Gain vs. Pressure and Radius

3. Temperature Monitoring and Safety

3.1 *TPL Surface Infrared Monitoring*

Power deposition measurement on the TPL is a very important challenge (15 MW – 1000 s is the design value). The most commonly used model is based on the conventional exponential decay out of the scrape-of layer, with a characteristic length called λ_Q. Present power deposition analysis on the so-called Inner Wall Protection, in spite of very important recent progress, leads to surprisingly very small heat decay length λ_Q, and needs to be better understood. The flat geometry of the TPL will help a lot in the construction of a model and its understanding. Recently this model was improved by including self-shadowing of the limiter on itself, as shown in Figure 7 [5].

On the other hand, the safety of such an expensive instrument must be particularly robust and enable also a feedback action on plasma itself (position, shape), or even to its heating.

All these functions will be devoted to a set of 6 infrared cameras, analyzing and combining 12 images of the 360° of the TPL. 6 endoscopes are thus located in the upper vertical ports of the machine, every 60°. Each one has 3 lines, 2 of them looking to the TPL surface, a third one towards one RF antenna. Spatial resolution is foreseen to be better than 9 mm. A specific line will have even a better resolution (4 mm), to make detailed power deposition physics analysis.

As shown in Fig. 8, the endoscopes are full plasma facing components and must withstand, not only the radiated power, but also electrons lost in the magnetic ripple. They are composed of the following elements:

- A head in CuCrZr alloy, actively cooled as the other plasma facing components at 150°C in operation; this head is protected during boronizations by a rotatable protection.
- The whole body of the endoscope is also cooled at the same temperature.

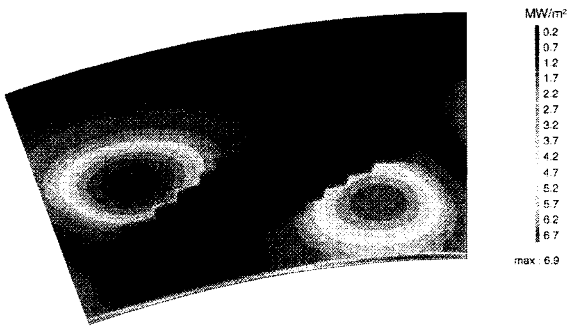

Fig. 7 Computation of Power Deposition on the Toroidal Pump Limiter

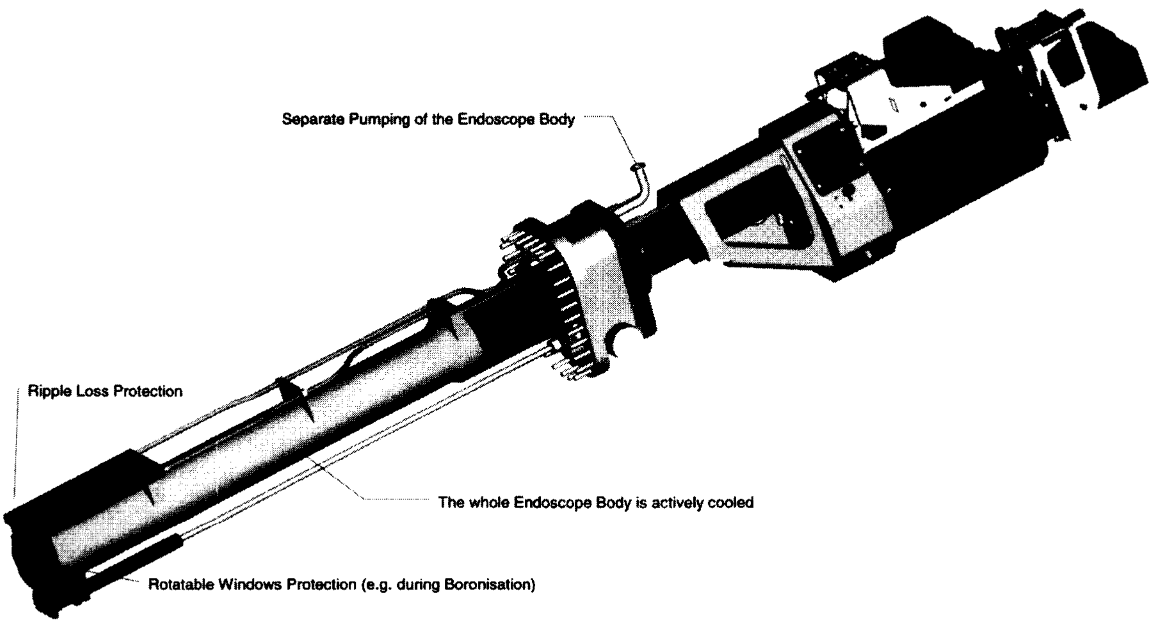

Fig. 8 Overall View of one Endoscope and its Cameras

- The inner lenses, which propagate the images, are cooled with another loop at 20°C, to avoid image contamination by higher temperatures, and maintain a good transmission coefficient (some of the materials become opaque at high temperature).

- Two infrared cameras, one devoted to the TPL measurement, the other one to the antenna monitoring.

3.2 *Neutralizer Infrared Monitoring*

Computations performed in the frame of an "advanced scenario" with a total power of 25 MW coupled to the plasma show that the thermal flux which hits the front face of the most exposed neutralizer finger reaches locally 20 MW/m^2, in spite of a specific shaping to spread this flux.

In order to monitor this critical component, the following original concept is in study. A triplet of fiberglass will look at the edge of the neutralizer. Then, after separation of the signal, a bi-chromatic pyrometer will allow absolute temperature measurement. The bundle of 12 times 3 signals will be separated by means of a beam-splitter. The resulting signals will pass through two narrow interferential filters. The comparison and ratio between the two signals will give the surface temperature, whatever the transmission. Preliminary experiments carried out in the laboratory show that blackbody emission intensity (the foreseen wavelength range is 0.8–2 μm) is much higher than molecular rays, and should not be affected by them. But a non-Lorenzian distribution has been observed, leading to some difficulty in the interpretation of the measured signal. Thus an absolute measurement is also implemented.

4. Conclusion

CIEL project, the extraction part of the more global project "Tore Supra Continu" has been launched in February 1996. After 3 years of design and manufacturing, all components are now in the phase of completion and final acceptance tests. Removal of existing components, in particular the ergodic divertor modules, has started in December 1999 and CIEL installation is scheduled during the three last quarters of 2000. The new machine should be ready for conditioning beginning of 2001, and the first plasma is expected mid-2001.

The upgrade of the injection part, second half of "Tore Supra Continu" is now in study, as well as the necessary upgrade of plasma facing diagnostics (windows, valves...). Because of the limitation of present heating systems, a first objective of 1 GJ (e.g. 4 MW – 500 s) can be set for the first years of CIEL operation, 2001, 2002.

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