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Heat exhaust control with active cooling in Tore-Supra: towards steady state operation

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Abstract

Tore-Supra is presently the only fusion device in the world that has incorporated in its design active control of heat and particles in a realistic environment for high power long pulse steady state operation. A first generation of plasma facing components, installed in the early experimental phase of the machine, has been tested and has provided much information on physics and technology, as well as the operational difficulties of its 'early childhood.'

Keywords: Fusion technology; Energy deposition; Low Z wall material; Steady state regime

1. Introduction

The achievement of steady state in fusion devices implies that power is removed continuously. in most existing machines, pulses are short enough to enable temporary storage of the energy delivered by the plasma in internal components then removal during the dwell time between shots. This is at the expense of wall temperature excursions which are often a limitation to the plasma performances. In contrast, Tore-Supra has incorporated the capability of cooling the plasma facing components with a time constant shorter than the pulse duration. Fig. 1 gives the example of the inner first wall behaviour for very long shots with the comparison of steady state and semi inertial regime. The Tore-Supra tokamak ($R = 2.4$ m, $a = 0.75$ m) has been defined in 1980 to achieve and control long pulse powerful discharges [1,2]. The toroidal field superconducting coils (NbTi) allow steady state operation at 4 T over the full day. The maximum power generation implemented for the additional heating of the plasma could be as high as 25 MW. This power is extracted at steady state through the plasma facing components by a cooling water loop. Depending on the local plasma wall interaction, different levels of heat loads have been associated with different specific technologies.

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2. Technical issues

In order to achieve steady state on the plasma facing components and to cope with the baking requirements, the water loop was designed to operate in the vacuum vessel under a pressure of 3.5 MPa, a maximum temperature of 230°C and with a pumping power allowing velocities up to 10 m/s in the high heat flux components. Therefore Tore-Supra was the first tokamak to operate with a large water loop (400 t/h) in the vacuum vessel.

Final choice of graphite at the beginning and then Carbon Fiber Composites (CFC) as the preferred materials for plasma wall interaction was a challenge for the proper assembly on water cooled components. indeed brazing of such material to metallic structure was only available as laboratory specimens. Therefore the extrapolation to large components was a great challenge.

The thermohydraulic and thermomechanic design of components able to sustain a steady state 10 MW/m^2 heat flux was also a challenge due to the lack of assessed engineering knowledge.

3. Long pulse operation

Operation began in 1988 and since then 20000 discharges have been realised including results dealing with physics issues and also with technological aspects of long

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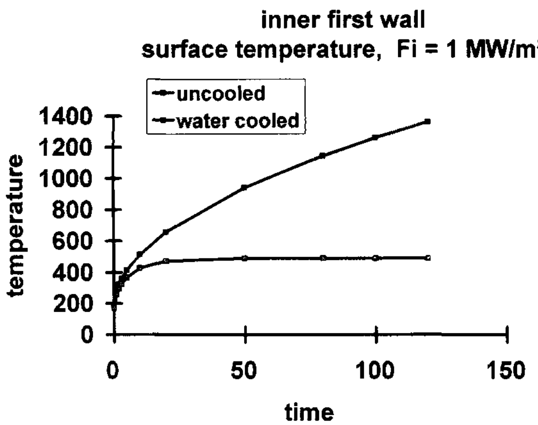

Fig. 1. First wall thermal behaviour.

pulse tokamak discharges. Regarding heat exhaust, a good performance was obtained in March 1996 with a record of 280 MJ of LHH injected in the plasma during a 120 s discharge (see Fig. 2). During this shot, all the actively cooled components where running at steady state low power regime as shown on the calorimetric measures on Fig. 3.

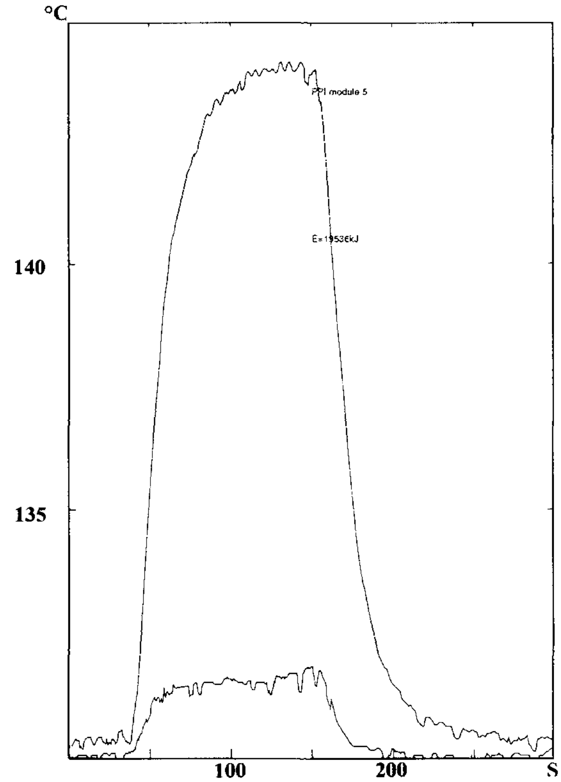

Fig. 3. Calorimetric measurements on a module of the inner and outer first wall.

4. Heat exhaust systems, the inner first wall

The inner bumper of Tore-Supra [3,4] is a modular brazed graphite wall capable of sustaining up to 1 MW/m^2 continuously. This inner bumper covers 360° in the toroidal direction and 150° in the poloidal direction. It was initially intended to remove a maximum power of 12 MW. The cooling structure is composed of square cross-section stainless steel tubes each with a circular inner channel as shown on Fig. 4. The pressure of the cooling loop is 3.5

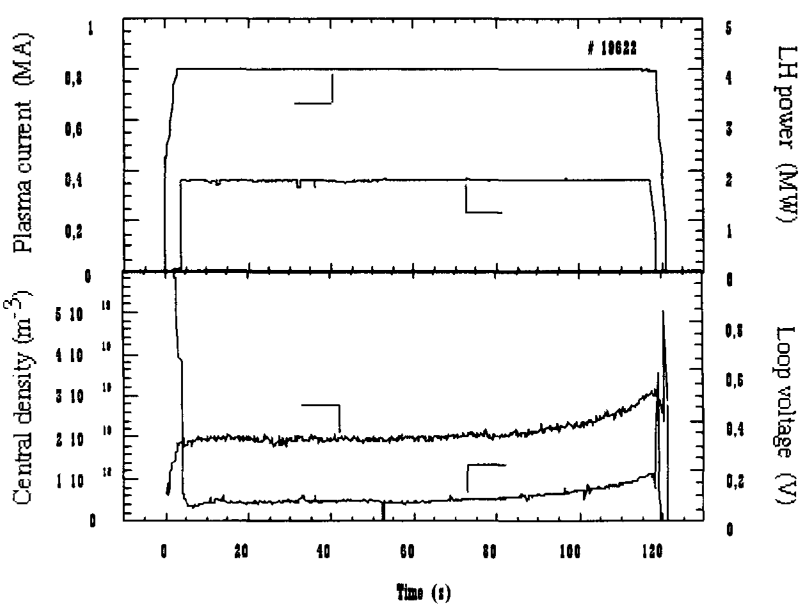

Fig. 2. 120 s discharge in Tore-Supra.

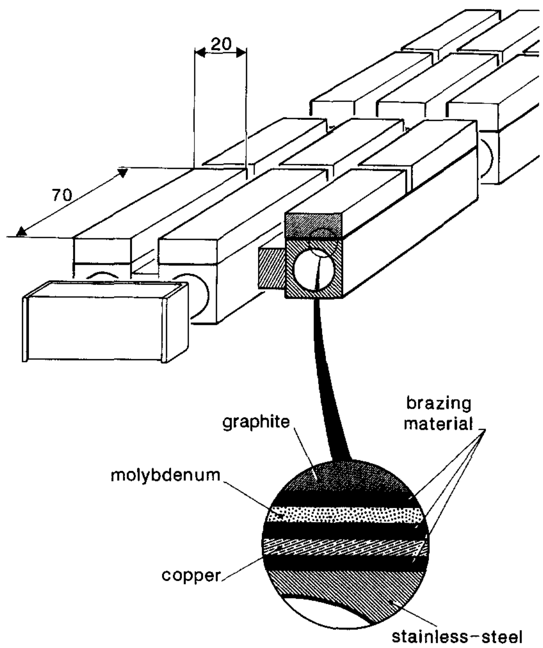

Fig. 4. Inner first wall cross-section.

MPa, the water temperature 150°C and the velocity 3.5 m/s. The total area of graphite (5890 PT from Le Carbone Lorraine) is 12 m^2 (8600 brazed flat rectangular tiles). The tiles are 10 mm thick. They are brazed on the stainless steel sink through a multilayer brazing joint. A 0.5 mm Mo sheet (with a thermal expansion close to that of graphite) was used in contact with graphite, to reduce stresses in it. Also, an OFHC copper 0.5 mm thick compliant layer was placed in contact with stainless steel to compensate the brazing mismatch of the thermal expansion between these materials.

5. Experimental results

The number of identified damaged tiles has grown with time from 2% in 1988 up to 7% in 1994, probably due to the degradation of preexisting defects. This supports the idea that an extremely rigorous quality control must be implemented from the beginning of the fabrication until the installation in the device, with accurate non destructive tests of the brazed joint. This aspect of the problem is discussed further where the fabrication of a 'second generation' inner wall for Tore-Supra is described.

A large number of shots has been taken with the plasma leaning on the inner wall. The time constant for thermal equilibration of the inner wall is roughly 15 s, and among the 20,000 shots presently achieved on Tore-Supra, only a very small number has significantly exceeded this duration. Therefore, while heat deposition and plasma wall interaction have been obtained, experience on fatigue of wall components is limited.

One of the most encouraging results on Tore-Supra with regard to power exhaust is the one minute discharge obtained with 3.2 MW of LH power, corresponding to 150 MJ of heat exhausted by the inner wall [5]. The average wall temperature remains rather low, in the range 200–300°C due to active cooling and the peak power flux density is roughly 0.3–0.4 MW/m^2. However, pre-existing localised braze flaws and/or tile cracks produce overheated localised spots (surface temperature in excess of 2000°C). These high temperature areas are small and do not lead to plasma contamination by carbon, even over long discharges. Indeed, no 'carbon bloom' (i.e., large flux of C entering the plasma bulk) has been observed, in contrast to other non-actively cooled machines, but the input power has to be increased further to make proper comparisons.

An evolution of the hot spot location has been observed with the IR camera, corresponding to a deterioration of the tile status. Small cracks, parallel to the surface, probably degenerated into larger ones and ended, in many cases, in detachment and falling of a tile, which often generated a plasma disruption. The most severely damaged tiles have been eliminated by this process.

When disruptions occur, the plasma moves rapidly inward due to the plasma pressure loss, and runaway electrons (in the range 50 MeV in Tore-Supra) created during this phase, impact in the equatorial plane of the inner wall [6]. Tile cracks do appear in this plane, particularly where the wall is misaligned with respect to the toroidal field configuration. A radioactivity signature of this phenomenon is observed. A full description of the phenomenon is difficult; the initial path of runaway electrons is tangential to the wall and they penetrate deep in carbon, so a 3D calculation is necessary to predict the damage to brazed joints.

6. Improvement on the inner first wall

The decision to replace a 40° toroidal sector of the inner wall was made in early 1994. The choice of 40° was dictated by the need to show significant progress beyond the first generation inner wall in both concept and manufacturing before making a decision to replace the full 360°. Many modifications were introduced in this new sector. Carbon fiber composite was chosen (N11 from SEP) as the facing material based on the expectation that its higher thermal conductivity and good mechanical properties would eliminate crack propagation in tiles under thermal stress. A more modular inner wall, that would ease the replacement of any part, was designed with heat sink elements consisting of CFC tiles (6.5 cm long, 2 cm wide, 1 cm thick) brazed onto three parallel rectangular stainless steel cooling tubes (3° 20′ wide along the toroidal co-ordinate), welded together and oriented in the poloidal direction.

The CFC tiles were laser treated to enhance the adherence of the brazed joint, a process developed by Metallwerk-Plansee in Austria, the contractor for this new inner wall piece. The tiles were brazed onto a 2 mm thick copper compliant layer using a TiCuSil filler metal. Exacting detail for the braze procedure was specified in common agreement with the brazing company. A minimum brazing factor of 90% of the intended braze area between CFC and copper and 75% between copper and stainless steel had to be guaranteed. No flaw larger than 3 mm was tolerated. The flatness of individual tile areas had to be less than 0.5 mm. The reproducibility of the CFC–Cu braze joints quality was guaranteed by systematic fracture shear stress tests, by destructive metallographic tests on reference pieces accompanying each braze cycle, by X-ray radiography of each tile attachment at Plansee and finally by thermographic measurements at Cadarache for the manufacturing series (hot water tests).

This final systematic verification of the thermal continuity of the braze joints for all individual tiles was performed by CEA, with transient thermographic measurements. This supplemented the initial X-ray radiographic procedure and provided an independent control of the brazed joint integrity along the sequences of the assembled sectors before they were installed in the machine. A hot water test stand was set up at Cadarache. IR measurements of the tile surface temperatures during thermal transient heating were made with a water flow (95°, 4 m/s) in the heat sink cooling channels. The surface temperature of each test element was compared to the surface temperature of a reference element previously tested at the e-beam facility and connected in parallel on the hot water circuit. The highest temperature difference between the test tile and the reference one was determined and compared to a specified limit. Calculations show that this measurement method depends more on braze defect length than braze void area. A minimum observable defect size of 30% for the CFC/Cu interface and ≅ 10% for the Cu/SS one was achieved with the 1–2°C thermal resolution of the IR camera. For final acceptance of the elements, a maximum tile surface temperature variation of 6°C between the reference module and the tested module was considered acceptable; this corresponded to a brazing factor of 75% in the SS/Cu interface.

7. Modular pump limiters

A set of modular pump limiters has been installed on Tore-Supra with the aim of achieving simultaneous heat and particle exhaust. Indeed, density control can be achieved only if an efficient particle exhaust takes place,

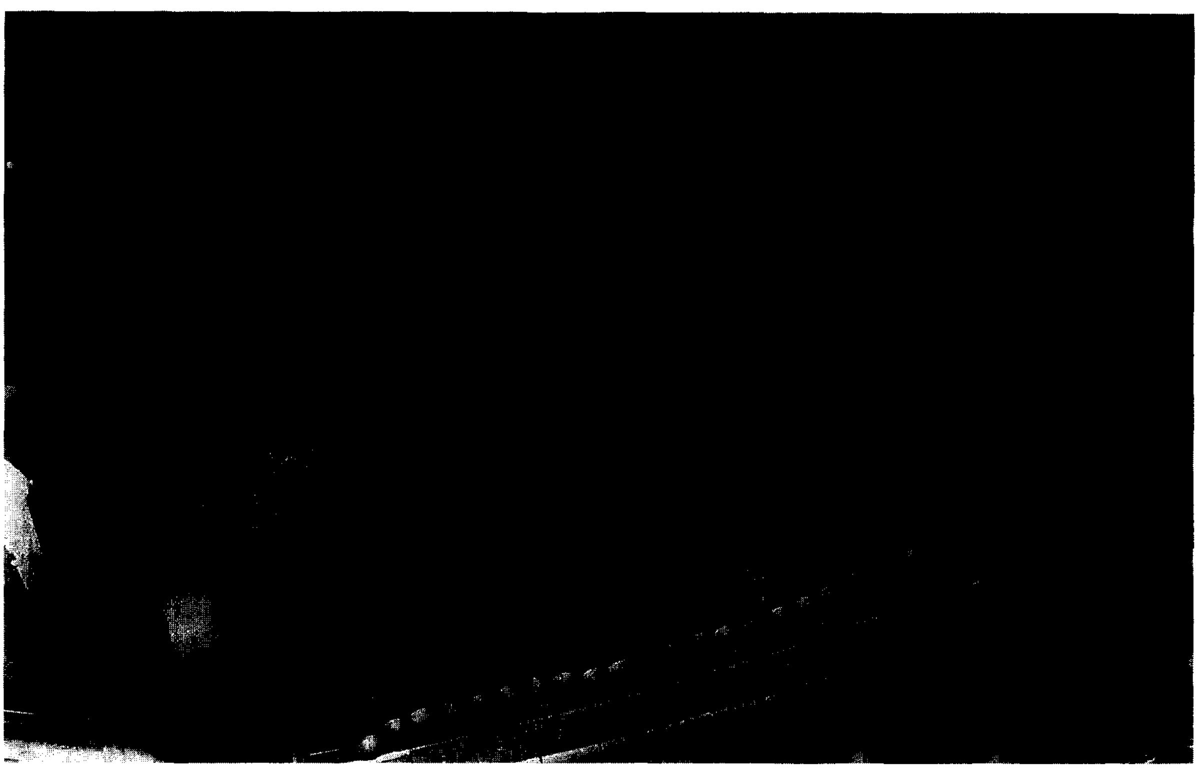

Fig. 5. Bottom pump limiter.

an important feature as far as helium exhaust or plasma stability and transport are concerned. Two different solutions have been considered.

In the first approach, six bottom limiters (0.4 m × 0.4 m) (Fig. 5) with the following features were built: 'Y shaped' counter flow tubes; hardened copper tubes (Cu–Cr–Zr), 12 mm in diameter covered with brazed graphite 3 mm thick; swirl tapes in the tubes to enhance heat transfer and semispherical caps of CFC (A05 from Le Carbone Lorraine) on the leading edges [7]. A maximum heat flux density of 10 MW/m^2 at the leading edge, considered as the most critical zone, was estimated, for 700 kW removed by each limiter. The braze material was TiCuSil. As in the case of the inner wall, the quality of the brazed joint has been the most concerning achievement and it has not been possible, at the time of this realisation (1988), to achieve sufficiently reliable bonding of all the carbon tiles. Tests on the electron beam facility (EBTS) at Sandia National Laboratories (Albuquerque) showed however that average heat flux density of 4 MW/m^2 and peak values of 8 MW/m^2 could be removed from well bonded parts on the tubes sides whereas the leading edge caps could withstand up to 14 MW/m^2 at a surface temperature of 1500°C.

In a second approach, an outboard pump limiter (low field side) was built by Sandia through a CEA-US DOE agreement [8,9]. The limiter (0.6 m × 0.5 m) had 14 water-cooled copper tubes, poloidally oriented, covered with about a thousand brazed pyrolitic graphite tiles (Fig.

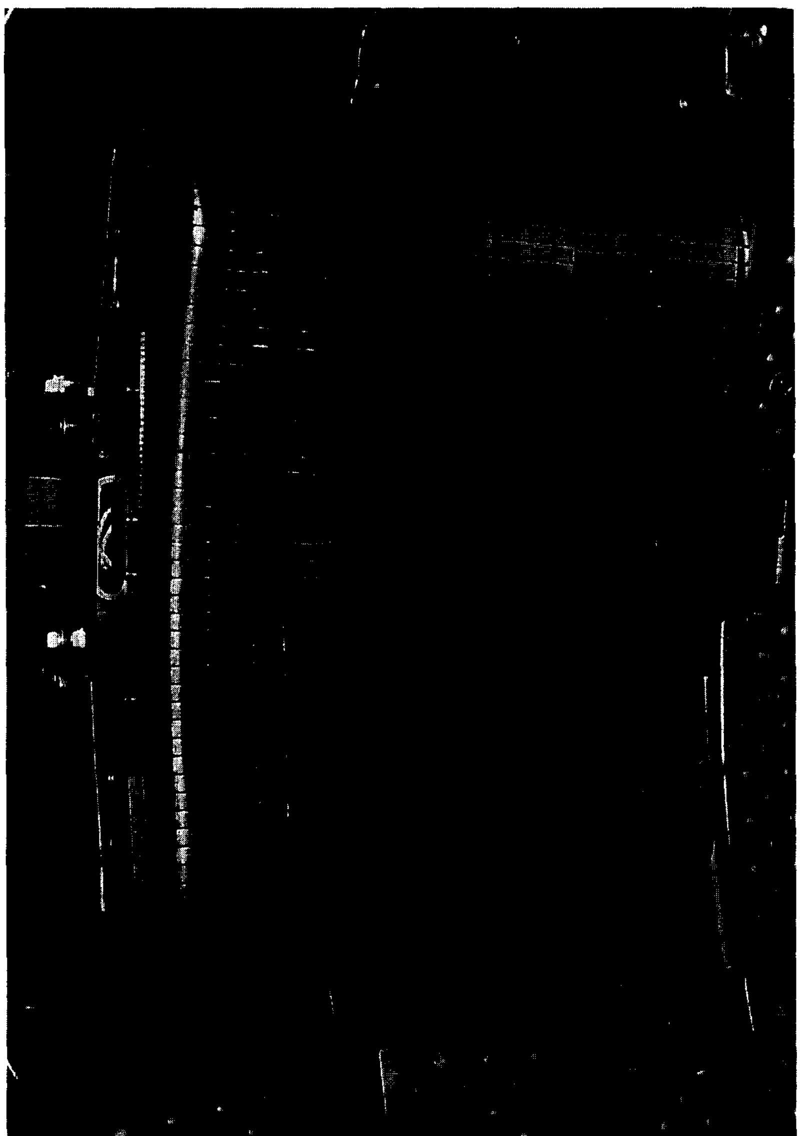

Fig. 6. Outboard limiter.

6). In contrast to the bottom limiters, the contour of the front face was accurately machined to spread the heat load uniformly across it, and the design accounted for local ripple in the toroidal magnetic field. The design goal for steady state was 1.5 MW for the overall limiter (6 MW/m^2 on average). Local power flux as high as 30 MW/m^2 on the leading edge and about 10 MW/m^2 on the front face were expected, with geometry optimised for particle extraction and $\lambda_q = 2$ cm. There were separate cooling circuits for the leading edge (< 50°C, > 8.5 m/s) and the front face (< 120°C, > 7 m/s). A maximum temperature difference of 80°C is tolerated between the inlet and outlet temperatures at the leading edge to avoid critical heat flux. Ten flowmeters and 34 thermocouples provide extensive calorimetry. Some residual local braze flaws or cracks within the pyrolitic graphite were identified prior to the installation of the limiter on Tore-Supra in spite of efforts. They were accepted on the basis of extensive analysis of the impact on performance of various braze defects.

8. Experimental results on the bottom limiters

A maximum power of 0.7 MW has been removed by a single bottom limiter during 6 s (this duration was not a limit). Steady state surface temperature was reached after 2 s due to the small thickness of the carbon coverage. The average power density was 4 MW/m^2 and a peak power density of 8 MW/m^2 was reached.

Using three of these limiters simultaneously, 1.2 MW were removed during 25 s (again not a limit for these limiters); this corresponded to an average power density of 2.5 MW/m^2 As indicated earlier, each of the 6 bottom limiters suffered from generic braze flaws and/or cracks within graphite tiles. On the basis of hot water–IR tests, the best individual Y tubes within the whole set of limiters were selected, and reassembled as a 'high standard' limiter. All local hot spots previously observed were suppressed by this procedure and the limiter worked well within the range of its design parameters. This underlines the importance of a rigorous quality control during the manufacturing process to reject unacceptable braze defects. Unfortunately hot spots appeared on some tiles enhancing the fragility of the thin graphite tiles.

9. Outboard limiter experimental results

The maximum power presently extracted with the actively cooled outboard limiter is 0.8 MW (design value 1.5 MW) during 9 s, with an averaged temperature of 850°C on the leading edges (maximum 1500°C), corresponding to a peak power density of 17 MW/m^2 [10] (critical heat flux 40 MW/m^2) and to an average power density of 3 MW/m^2. Infrared images have been made, similar to those of the bottom limiters, showing that the time constant to reach steady state is five seconds and also that some localised hot spots are present on the leading edge, corresponding to the pre-existing braze flaws or cracks in the tile material. These defects are smaller than single tiles area to allow the heat to be removed through the remaining bond and steady state to be reached. The maximum temperature on the front face is 550°C.

Three values of plasma current 0.8, 1 and 1.5 MA were used to test the limiter in ohmic conditions, for which the extracted power at steady state was 220, 270 and 720 kW, i.e., 34, 35 and 52% of the input ohmic power respectively. The observed dependence is consistent with earlier experiments with bottom limiters where the e-folding length for heat on the SOL was found to scale as $\lambda_q \approx I_p^{-1/2}$ [11], meaning that when the plasma current increases, not only the input power increases but also the heat load concentrates on the front face of the limiter. A toroidal asymmetry (by 12–18%) of the power deposition onto the limiter is found, with the electron drift side being colder. Preliminary experiments with ICRF and LH power were started when the outboard limiter was pierced by runaway electrons.

10. Ergodic divertor

An ergodisation of the magnetic field lines is created at the edge by a multipolar magnetic perturbation, over a region 0.1–0.2 m wide, resulting in a low temperature, high density, highly radiating plasma. This region, ten times broader than the conventional scrape-off depth, has favourable properties, such as neutral particle (impurity) screening, high radiating rate, low sputtering and peripheral MHD mode stabilisation. The plasma core remains unaffected by the perturbation. This scheme is expected to lower the fraction of the input power convected between the divertor bars where neutraliser plates are located. Until now, the ergodic divertor scheme has been considered as a tentative experiment and has not been designed for long pulse steady state operation.

Fig. 7 is a general view of one of the six divertor modules [12]. Each module consists of 8 current bars distributed poloidally on the outboard side of the tokamak and directed along the magnetic field direction ($q_\psi = 3$). These current bars are located in a stainless steel casing, covered with bolted flat graphite tiles 1 cm thick. Between each pair of current bars a neutraliser plate collects the particles and heat flux along the magnetic field lines which are strongly deflected due to the ergodic divertor local perturbation. The neutralisers are OFHC copper boxes covered with semicylindrical or flat brazed graphite tiles (5890 PT), 4 mm thick, to handle the concentrated heat flux at these locations (expected capability 10 MW/m^2 peak). They were tested and withstood an incident flux density of 9 MW/m^2 for a surface temperature of 1200°C.

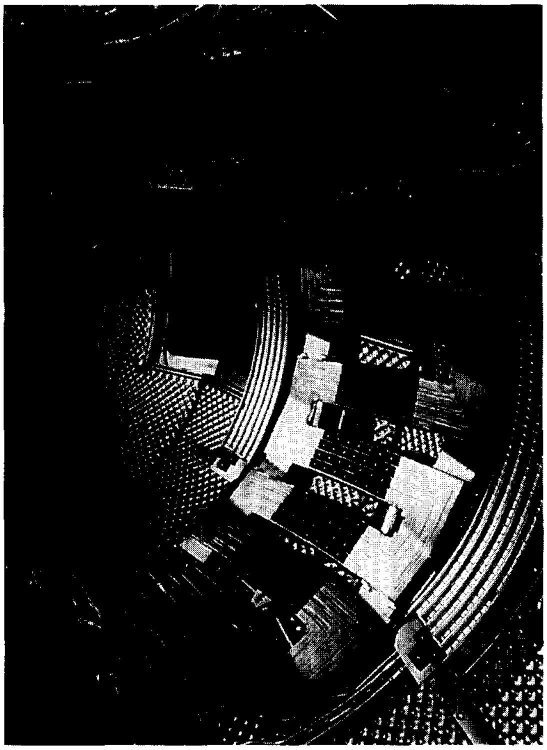

Fig. 7. Ergodic divertor module.

Particle control is provided by titanium getters located behind the neutraliser plates in a closed area.

After several years of operation at low (ohmic, 1 MW) or moderate (ohmic + ICRH and LHCD, 4 MW) power, considerable progress has been achieved in the understanding of the physics involved in the ergodic divertor concept. A review of the physics results obtained with the ergodic divertor may be found in [13,14]. However, the shape of these neutralisers was originally chosen to create a throat channelling ions and neutrals towards the titanium getters located behind the ergodic divertor casings. As a consequence, the total area was small and the angle of incidence with the field lines was large, particularly at the neutraliser tips. Therefore, only moderate power exhaust experiments, limited by the maximum power load of 10 MW/m^2 on the neutraliser plates, could be undertaken with this configuration.

11. Ergodic divertor upgrading

Very encouraging results have been obtained with the ergodic divertor and the achievement of stationary highly radiating edge conditions with the injection of a seeding impurity gives the hope that a scheme for heat control can be achieved with this device.

However, the experience gained to date is not yet sufficient to support the implementation of an actively cooled, ergodic divertor considered capable of coping with a broad variety of experimental conditions during long pulses. Indeed, the ergodic divertor has been used primarily in moderate input power conditions. Therefore, an intermediate step is to prove that steady state highly radiating conditions can also be achieved at high input power in Tore-Supra. The neutraliser geometry, with the prominent leading edge and small surface, has been the

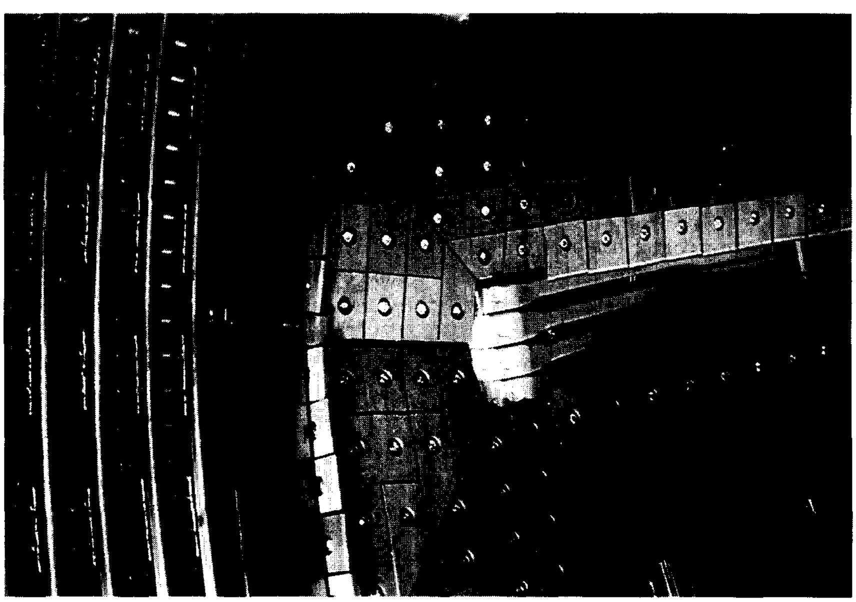

Fig. 8. Prototype of the improved neutraliser.

primary limitation to performance. The features of the upgraded ergodic divertor rely on a conservative technology to give a better chance of performing reliable physics experiments. The current bars are unmodified, since the multipolar magnetic perturbation was found to be adequate from the origin. The front face of the modules are covered with bolted CFC tiles, 2 cm thick, semi-inertially cooled, to remove 1 MW/m^2 during 30 s (6 m^2 total) with a surface temperature below 1000°C. The most sensitive parts are the neutraliser plates, which have an optimised shape with respect to heat deposition and fill all the gap area between the current bars (Fig. 8). These actively cooled neutraliser plates, made of CrZr copper covered with a BC coating, are designed to provide steady state heat removal at an average power density of 5 MW/m^2 over 0.6 m^2 (42 neutralisers). Critical flux density limits are above this value by at least 50%. The neutralisers have a vented structure to allow particle exhaust based on neutral particle collection (see Ref. [15]) in contrast to the early version of the ergodic divertor which relied on ion collection. Titanium getters, located behind the divertor modules on each side, are unmodified.

12. Outer wall

The outer first wall is located further away from the plasma boundary than the inner wall, and is made of stainless steel wafer plates, actively cooled by pressurised water [16]. The surface of the outer first wall is 62 m^2 out of the 80 m^2 of the total surface. it receives the radiated and charge exchange fluxes emitted by the plasma. If the overall maximum input power (25 MW) were radiated, the average power density on these elements would be 0.3 MW/m^2. There is presently no particular technological problem associated with this kind of actively cooled elements. Carbonisation or boronisation have been used to avoid bare metal surfaces in front of the plasma.

13. Toroidal bottom pump limiter

An alternative to the ergodic divertor has been considered for Tore-Supra that does not rely necessarily on highly radiating regimes which are still quite uncertain. This alternative consists of a toroidal belt pump limiter having the capability of removing 15 MW of convected power permanently (25 MW total, 40% radiated). Located at the bottom of the device, it has a surface of 7 m^2 and a single throat located on the inboard side (see Fig. 9). Using a 'cosine model,' the calculated peak heat flux on the front face is 5-6 MW/m^2, twice the average value of 2 MW/m^2. The heat flux at the leading edge can be feedback controlled by changing the plasma major radius, R. Since the limiter is flat and horizontal, this can be achieved at constant plasma minor radius (an important feature for antenna coupling). Particle collection and exhaust can also be maximised by adjusting the heat load on the leading edge at the maximum acceptable value. The position and width of the limiter has been calculated to avoid any contact of the plasma boundary with other plasma facing components, in order to maximise particle collection [17] ($R_i = 2.22$ m, $R_e = 2.71$ m, $R_0 = 2.4$ m, $a = 0.72$ m).

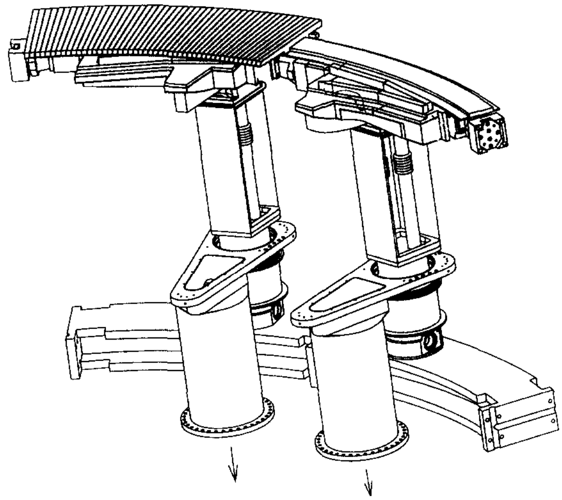

Fig. 9. Toroidal bottom pump limiter.

The limiter is composed of 576 elements assembled on a rigid structure. The whole limiter is isolated from the vessel by ceramic rings, allowing biasing up to 2.5 kV.

Each element is trapezoidally shaped as shown on Fig. 10 (495 mm long, 28 mm thick and with a mean width of 25.7 mm) and is designed to sustain a heat flux of 10 MW/m^2. CFC flat tiles are joined on a hardened copper heat sink with two internal cooling channels. Water flows out to the free end in one channel and back in the other. A 2 mm OFHC copper compliant layer is used between CFC and copper. Thermohydraulic conditions are 3.5 MPa, 170°C, 10 m/s. Industrial contracts have been placed to develop the joining process of the Nil CFC (from SEP) on the CuCrZr substrates.

The limiter front face and the neutralisers are bolted and hydraulically connected to a stainless steel support that is used as a mechanical reference plane and as a manifold, and is designed to sustain disruption forces. The position of the overall assembly can be adjusted by three hydraulic jacks allowing for a fine tuning of the vertical axis position and horizontal flatness to fit with the plasma position independently of the machine vessel. The temperature distribution in an element of the limiter under the most severe conditions (15 MW/m^2, $\lambda_q = 1.1$ cm, $R_0 = 2.4$ m, $a = 0.72$ m) and with subcooled boiling water has been modeled with a finite element code. The limits of the system in terms of local power density are imposed by the critical heat flux and the braze temperature (< 600°C) at

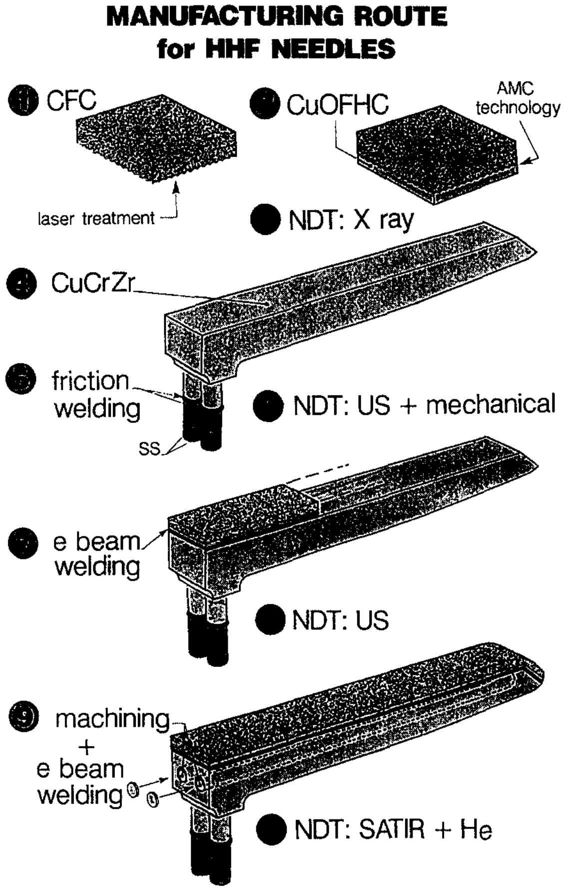

Fig. 10. High heat flux element for the toroidal bottom pump limiter.

the leading edge: 10 MW/m^2 and 9 MW/m^2, respectively, corresponding to an overall power handling capability of 23 or 21 MW. Neither the surface temperature of the CFC at the leading edge nor the rest of the limiter are limitations. A minimum safety margin of 50% is associated with the leading edge critical heat flux limit.

Prototypes of such elements have been manufactured and tested on the FE 200 e-beam test facility. Satisfactory results were obtained with heat fluxes and powers close to twice the design values (Fig. 11).

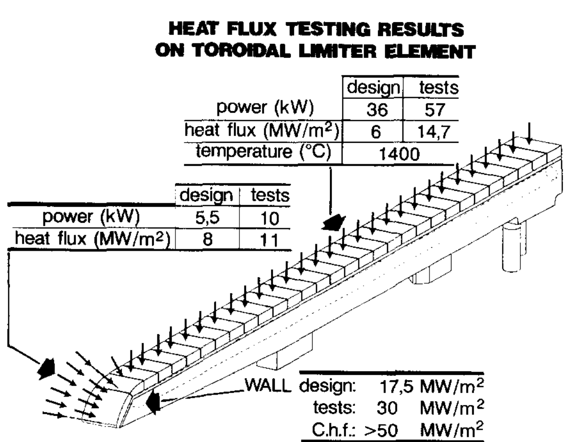

Fig. 11. Test results on a toroidal bottom pump limiter element.

14. Conclusions

Tore-Supra is presently the only fusion device in the world that has incorporated in its design active control of heat and particles in a realistic environment for high power long pulse steady state operation. A first generation of plasma facing components, installed in the early experimental phase of the machine, has been tested and has provided much information on physics and technology, as well as the operational difficulties of its 'early childhood.'

The 10 m^2 inner wall was used to run a 120 s discharge, although at relatively low input power (3 MW). The weakness of the brazing process adopted at the origin was revealed by these experiments. A 400 toroidal sector of the inner wall rebuilt using a new brazing technology developed in 1994 and stringent quality control has been tested successfully up to now.

Modular pump limiters were used successfully over 30 s, also at moderate power (3 MW). Very efficient particle control was achieved. Mean power densities of roughly 3 MW/m^2 were handled but produced large peak/average ratios and thermal excursions of the limiter's ridge. A viable concept requires a toroidally symmetric limiter of large area to handle larger input power levels. A design for such a limiter, that is flat and horizontal with a single throat on the inboard side, has been proposed. Development of elements with CFC brazed over strengthened copper for the front face has been done and testing is satisfactory.

Experiments with the ergodic divertor provided encouraging results; specifically, a high density, low temperature edge plasma, appropriate for high radiating conditions was formed. These results were obtained at relatively moderate input power and it was considered important to confirm them at a larger value of the input power and still large radiated fractions. This is the aim of the upgrading of the neutraliser plates whose shape has been optimised and of the improvement of the front face coverage of the divertor modules. Operation with the rebuilt neutralisers will start in 1996.

It has become more and more obvious that any good performance obtained on mock ups is insignificant unless stringent quality control is applied to the entire series production. This is why a dedicated effort has been made to improve all quality control measures for plasma facing components, i.e., brazed joint integrity (hot water/IR imaging, e-beam, radiography), systematic high temperature, high pressure tests etc., during the fabrication and assembly.

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