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PRESENT STATUS AND FUTURE PLANS FOR TORE SUPRA

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ABSTRACT

Tore Supra is a limiter tokamak with circular plasma cross-section. The superconducting toroidal magnet is a unique feature which allows very long pulse discharges. Tore Supra has ion cyclotron resonance heating and an electron cyclotron system is being installed. Non-inductive currents are driven by lower hybrid and by the bootstrap effect. Highlights of previous results include long pulses lasting up to 2 minutes with 280 MJ coupled into the plasma and fully non-inductive discharges lasting up to 75 seconds.

Tore Supra is presently in the middle of a major shutdown for the installation of a new toroidal pumped limiter. This will be actively cooled with capability for steady state operation at total power levels around 20 MW. Future plans include upgrades to the ion cyclotron heating and lower hybrid current drive systems and a new pellet injector.

INTRODUCTION

Tore Supra (Figure 1) has been operated successfully for 12 years since first plasmas were produced in 1988. A unique feature is the superconducting toroidal magnet, which permits plasma discharges of long duration. The plasma has circular cross-section with major radius 2.4 m and minor radius 0.70 m. The role defined for Tore Supra within the European Fusion Programme is the integration of all the various physics and technology aspects that are required to achieve and investigate high–power, long-duration plasma discharges.

The initial objective of Tore Supra, set in the 1980s, was the production of discharges with current of 1.7 MA and 30 s duration at a level of plasma heating of the order of 15 MW. Since then there has been considerable progress both in fusion technology and in plasma physics. Moreover the requirements of the next-step experiments have been identified clearly by the ITER project - in particular a next-step machine will have discharges of the order of a thousand seconds. Tore Supra's power and particle exhaust and heating and refuelling systems are being upgraded for 1000 s pulse duration to meet the requirements of steady state operation.

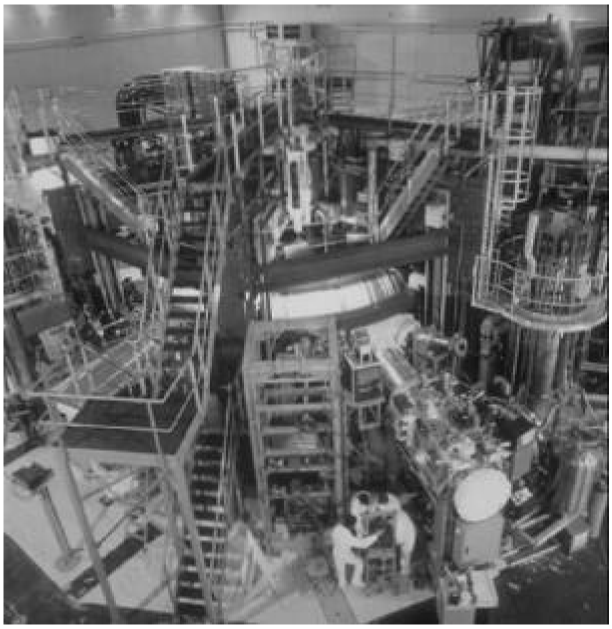

Figure 1 - overview of Tore Supra.

Experiments carried out in present-day machines have led to the discovery of new modes of operation (the so-called advanced tokamak modes) based on controlling the radial profiles of current density and plasma pressure. They result in a significant enhancement of the energy confinement time (by up to a factor 3). A substantial fraction of the plasma current is self-generated by the steep pressure gradients. These regimes hold the prospect of important improvements for a future reactor – in particular the possibility of maintaining a tokamak in steady state by a combination of enhanced confinement and a high fraction of bootstrap current.

SUMMARY OF PLASMA PERFORMANCE

Tore Supra's experimental programme has been focussed on the study of long duration plasmas with non-inductive currents. Long pulse discharges lasting up to 2 minutes were produced by coupling about 2.5 MW of lower hybrid power into plasmas with relatively low current, $I_p \sim 0.8$ MA, and low density $<n> \sim 1.5\text{x}10^{19}$ m^{-3}. An example is shown in Figure 2. The total energy coupled

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into one of these discharges – more than 280 MJ – is a world record.

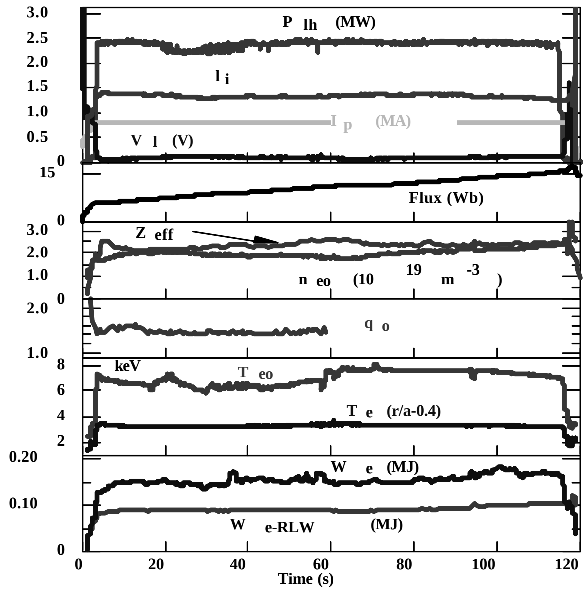

Figure 2 - time traces of the 2 minute plasma.

P_{lh} - LH power, l_i - internal inductance, I_p - plasma current, V_l - loop voltage, Z_{eff} - plasma effective charge, n_{e0} - central electron density, q_0 - central q value, T_{e0} - central electron temperature, $T_{e(r/a = 0.4)}$ - electron temperature at radius r/a = 0.4, W_e - electron stored energy, W_{eRLW} - Rebut Lallia Watkins prediction.

Lower hybrid current drive has been used also to produce discharges with zero loop voltage lasting up to 75 s. This type of plasma exhibits a stationary, globally-enhanced electron confinement – the so-called lower hybrid enhanced performance (LHEP) as well as a stationary transport barrier on the electron temperature. Similar enhancement was observed during the final 60 s of the 2 minute discharge.

Higher coupled powers have been maintained for shorter periods. A maximum of 5.3 MW has been coupled for 6 s with two lower hybrid launchers and 10 MW for 2 s has been coupled with three ion cyclotron antennas.

POWER & PARTICLE EXHAUST

One of the crucial problems for tokamak operation with long-duration, high performance plasmas is the exhaust of power and particles. At start-up in 1988, Tore Supra was equipped with a first generation of actively cooled plasma facing components. It was found that the power handling capacity was limited to about 3 MW for long pulse operation. This is too low to study the steady-state plasma regimes relevant to the problems posed by next step machines. This limitation is being addressed as the first stage of a series of upgrades. This is known as CIEL - a French acronym for *Composants Internes et Limiteur*. The main items (see Figure 3) are a toroidal pumped limiter, improved wall protection and upgraded cooling for in-vessel components. Tore Supra is presently closed for the installation. Operation with part of the new limiter will start in 2001 and with the full limiter in 2002.

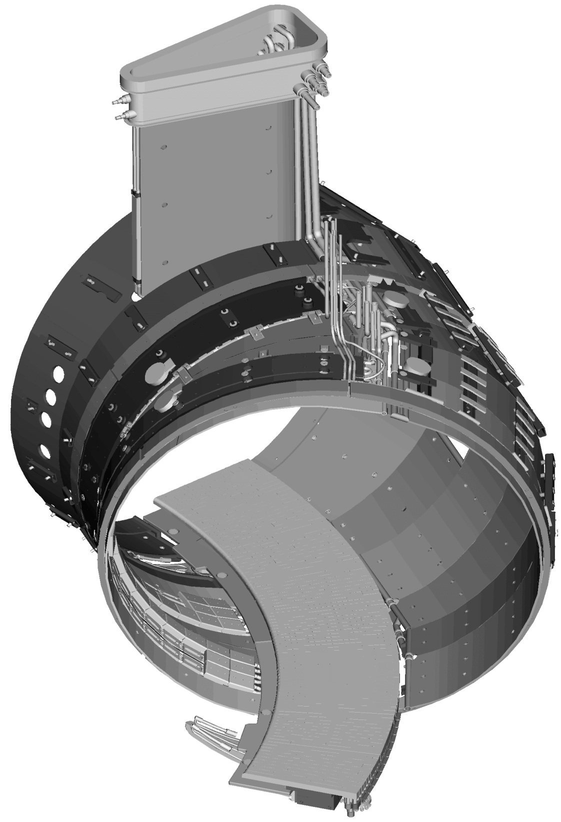

Figure 3 – schematic of the CIEL upgrade showing the toroidal pumped limiter and wall protection panels.

The toroidal pumped limiter is designed to remove about 15 MW under steady state conditions. The flat limiter with a total area of 7.5 m^2 is located at the bottom of the torus. The limiter is assembled out of many separate radial elements called “fingers”. The plasma-facing surface of each finger (Figure 4) is covered with carbon fibre composite (CFC) tiles. The CFC tiles are attached to a water-cooled hard copper (CuCrZr) heat sink via an intermediate layer of ductile high purity copper. This technology allows the pumped limiter to handle local power fluxes up to 10 MW m^2. The fingers are mounted on a carefully aligned support structure that is isolated mechanically from the vacuum vessel.

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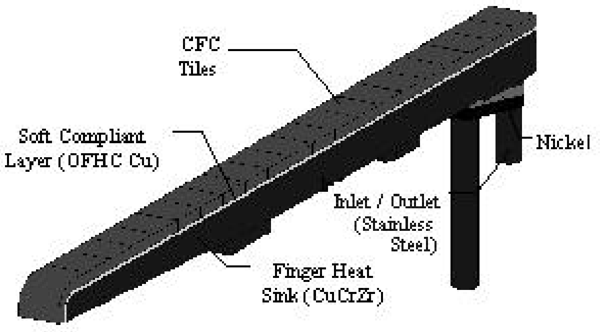

Figure 4 - schematic of a limiter finger.

The CIEL upgrade includes the installation of poloidal bumpers to protect the walls and heating antennas against runaway electrons and disruptions. Actively cooled protection panels are being installed on the walls to handle radiated power loads of about 1MW m^{-2}. Thus equipped, Tore Supra will be able to handle steady state powers in excess of 20 MW, with about 15 MW removed via the limiter and the remainder radiated to the walls.

Measuring their surface temperature using a set of infrared endoscopes will protect the toroidal pumped limiter and other internal components. These instruments will be located in six vertical ports equally spaced around the torus.

Particle control in CIEL will be achieved by means of particle exhaust regions (neutralisers) situated under the limiter and linked to a pumping system outside the torus. Cryo-mechanical pumps with the capacity to exhaust the entire plasma particle content in one second have been developed to match the required fluxes.

HEATING AND REFUELING

Tore Supra presently has lower hybrid and ion cyclotron systems that were designed for 30 s pulse operation. An electron cyclotron heating and current drive system is being installed already and will be fully operational in 2003. This will operate at 118 GHz with six gyrotrons coupled into the plasma through a 6-channel antenna and steerable mirrors. The coupled power will be in the range of 2 to 3 MW with a nominal pulse length of 210 s.

The next step in the enhancement programme will be the upgrade of systems for plasma heating and refuelling in order to make them compatible with operation at about 20 MW for discharges lasting for about 1000 s.

Due to budgetary limitations, the *CIMES* (an acronym for *Composants pour l'Injection de Matière et d'Energie en Stationnaire*) project is being planned in three phases. The first phase is presently at the approval stage and is planned for completion in 2005. This will upgrade the lower hybrid system to 8MW of steady state coupled power. A new pellet injector is also part of the first phase. The second phase, if approved, will start in 2002 and be completed in 2008. This will upgrade the ion cyclotron system to 9 MW steady state coupled power. The third phase will not be decided until 2005 and a choice will be made between a number of options. These include a further 4 MW of lower hybrid, a further 3 MW of ion cyclotron, more electron cyclotron heating or a new ergodic divertor.

Lower Hybrid System

The lower hybrid system operates at 3.7 GHz with two launchers. One launcher is of the original design and is not suitable for steady state operation at high power. A new launcher was installed and tested in 1999. It is of a new design, shown in Figure 5, with the capacity to couple 4 MW steady state. The antenna surface and number of waveguides of the new design is roughly twice that of the older version and can couple twice as much power when operated at the same power density. A second launcher of the new design will be installed to bring the total coupled power capability to 8 MW.

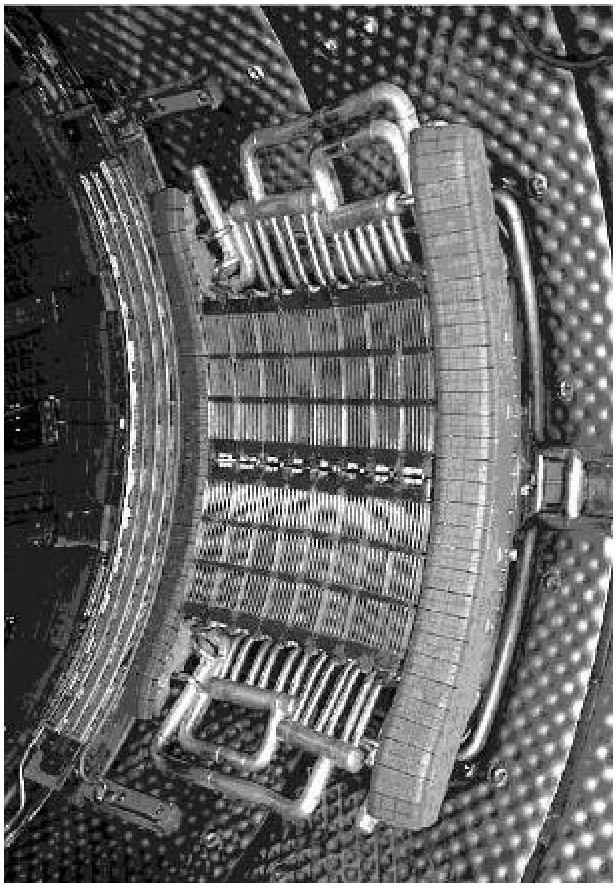

Figure 5 - second generation lower hybrid launcher showing poloidal bumper protection.

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Extra generator power is required to routinely couple 4 MW per launcher. About 5.6 MW per launcher is required at the generator to allow for transmission loses, reflected power and to give a margin for operational flexibility. The existing 500 kW klystrons (two banks each of eight tubes) will be upgraded with new klystrons rated at 700 kW steady state.

Ion Cyclotron System

The upgrade of the Ion Cyclotron system will form the second phase of the CIMES upgrade. The steady-state capability of the existing ion cyclotron system is limited both by the antennas (Figure 6) and the generators.

It is proposed to build three new antennas which will be completely actively cooled, allowing 4 MW to be coupled into the plasma routinely in steady state from each antenna – a potential total of 12 MW. However, as discussed below, this will be limited initially to 9 MW by the generator capacity. The antennas will be based on the same principles as the antennas foreseen for ITER-FEAT. Some component development, in particular of the matching capacitors, is required.

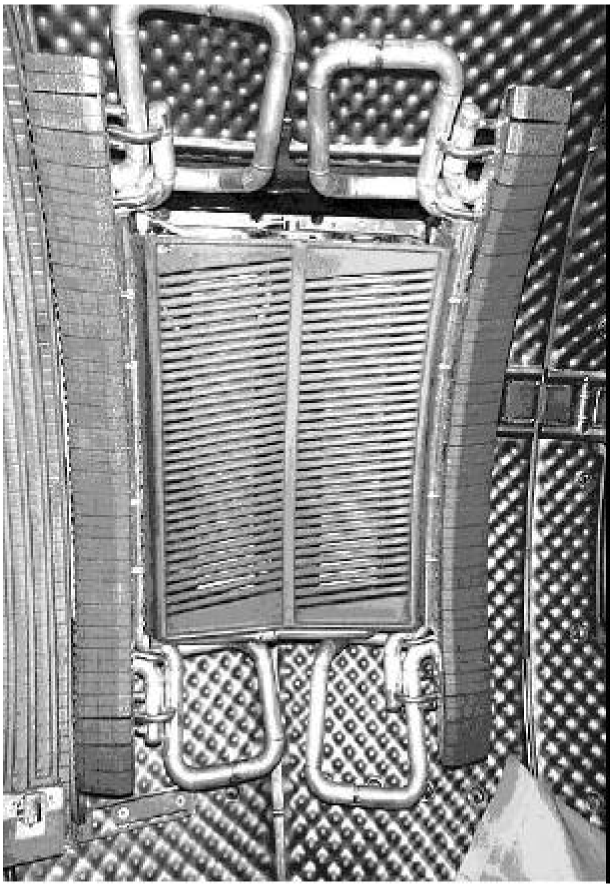

Figure 6 - ion cyclotron antenna.

The generators will be upgraded for steady state operation by replacing the tetrodes in the final amplification stage with diacrodes. The first two stages of amplification also will be improved in order to make them compatible with steady-state operation. The diacrodes presently available are rated at 2 MW. Each antenna is driven by two diacrodes. Allowing for coupling losses and an operating margin, this will be sufficient to couple 3 MW per antenna – a total of 9 MW with three antennas. However the generators will be compatible with using a 3 MW diacrode and, if this becomes available, the coupled power could be increased to 12 MW.

Fuel injection system

It is planned to buy a single-stage pneumatic injector, equipped with a screw extruder, from the PELIN company (associated with the Technical State University of Saint Petersburg). This has the necessary reliability and performance to refuel Tore Supra for 1000 s pulses. It will be installed with provision for high-field-side injection.

FUTURE PROGRAMME

Tore Supra’s future programme will exploit these new enhancements to the power and particle exhaust and heating and refuelling systems. The programme is directed at steady state discharges with total coupled energy of 20 GJ. Intermediate steps include targets of 1 GJ in 2003, 2 GJ in 2004 and 10 GJ in 2005. The key factor that sets the time-scale is the progressive increase in the available heating power. Figure 7 shows the steady state heating power planned for phases I and II as well as the interim capability for shorter (30 s) pulses.

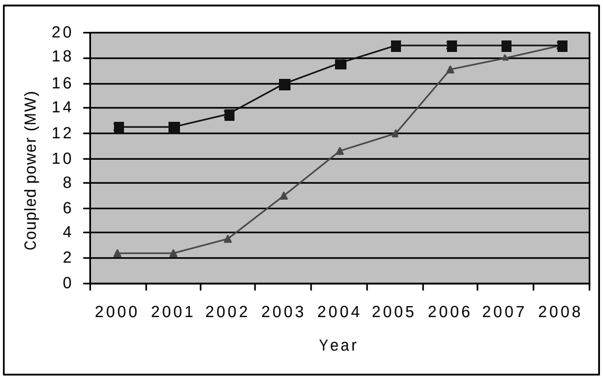

Figure 7 - Planned coupled power capability in phases I & II; steady state (triangles) and 30 s pulse (squares).

The first phase of the heating upgrade, when completed in 2005, will make available 8 MW of steady state coupled lower hybrid power. Combined with the existing ion and electron cyclotron heating, this will give a total of 12 MW steady state or 19 MW for a 30 s pulse. When phase II is completed in 2008, a total of 19 MW will be available

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steady state. The operating range in current and density for a fully non-inductive current corresponding to these coupled powers is shown in Figure 8.

Adding a further 4 MW of lower hybrid (one option for phase III) would extend the operating space to higher density. Increasing the ion cyclotron or electron cyclotron heating would improve profile control. A decision on these options can be taken in the light of experience with phase I.

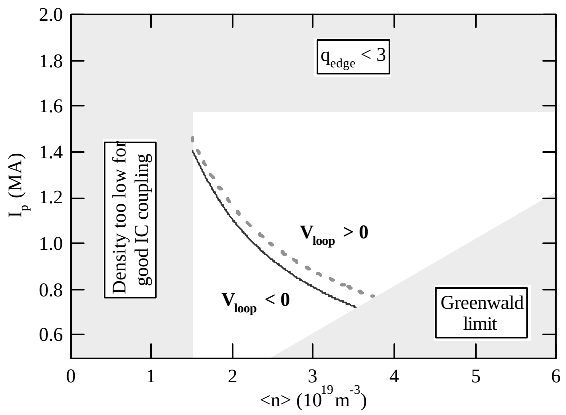

Figure 8 - Limits of current and density for fully non-inductive currents. The solid line indicates 12 MW total coupled power (8 MW LH + 2 MW IC + 2 MW EC) coresponding to the steady state capability in 2005. The broken line indicates 19 MW total coupled power (8 MW LH + 9 MW IC + 2 MW EC) corresponding to the 30 s pulse capability in 2005 and steady state in 2008.

Two broad categories of experimental regime are foreseen, roughly corresponding to the limits of the permitted operating range in current and density. Typical parameters are indicated in Table 1.

At the low density, high current limit (typically ~ $1.5x10^{19}$ m^{-3} and 1.4 MA), the steady state capability will be exploited primarily for testing technology components. It is important for next step experiments to show that systems for plasma heating, refuelling, power and particle exhaust can be operated reliably under steady state conditions. In phase I this will be at 12 MW total power; with phase II it will increase to 19 MW.

A higher density, lower current regime (typically about $3.8x10^{19}$ m^{-3} and 0.8 MA) with lower hybrid current drive and both ion and electron cyclotron heating is better suited to the exploration of advanced confinement modes. With phase I, this regime will be accessible for 30 s pulses; with phase II, it can be sustained for 1000 s. An important objective is to show that the advanced confinement modes can be extrapolated to and maintained under steady-state conditions. The programmes on JET and Tore Supra complement each other in this respect. JET can study these modes in deuterium-tritium plasmas and Tore Supra will have the capacity to maintain them for time scales longer than the characteristic times for the evolution of the current profiles.

Table 1 - typical operating regimes.

Objective	Technology	Adv. Tokamak
Phase I 2005	12 MW 1000 s	19 MW 30 s
Phase II 2008	19 MW 1000 s	19 MW 1000 s
Density	~ $1.5x10^{19}$ m^{-3}	~ $3.8x10^{19}$ m^{-3}
Current at 4 T	1.4 MA	0.8 MA
Edge q	~ 3	~ 5.5
Bootstrap fraction	~ 20%	~ 50%
Profile control	Not required	Essential
H factor	H ~ 1	H ~ 2

SUMMARY

An overview of Tore Supra's present status and future plans has been given. New toroidal pumped limiter and wall protections are presently being installed. Major upgrades are planned for the heating and refuelling systems to give tore Supra the capability to operate at high power levels under steady state conditions. This will have important applications for the physics and technology of next-step tokamaks.

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