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Development of RF Heating and Current Drive Systems for Long Pulse Operation on Tore Supra

Equipe Tore Supra [#], presented by B.Beaumont.

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Abstract: Significant results on steady state control of the plasma parameters have been obtained with RF systems on Tore Supra. A sustained effort is under way to improve power transmission reliability. Developments of sources and antennas are in progress for future operation on Tore Supra with pulse length in the range of several hundreds of seconds.

SIGNIFICANT RESULTS WITH RF SYSTEMS FOR STEADY STATE PLASMA CONTROL

A large experience on long pulse (up to 2 mn) operation has been gathered on Tore Supra (1). These experiments are used to qualify scenarios and equipment for future operation during several hundreds of seconds. The goal is to be able to sustain the plasma for as long as 1000s.

The longest shot to date performed on Tore Supra is the shot #19980. It lasted 120 s, as 2.4 MW of LHCD were injected in the plasma to sustain the major part, 90%, of the 0.8 MA plasma current (Fig. 1). The total injected energy reached 280 MJ. A LHEP mode with H=1.4 compared to the ITER-96 L-mode (2) scaling was achieved throughout the discharge. The conditions for the plasma itself are not steady state : a slight density increase is observed after 1 minute, suggesting outgassing from a not yet cooled surface receiving a thermal flux. On the contrary, for the parameters shown concerning the LHCD system, such as the reflected fraction of the injected power, the pressure in the waveguide array, or the surface temperatures of the front face of the grill, stationary conditions are observed at this power level.

A plasma of 0.8 MA at full current drive has also been obtained for 75s with LH alone. An average LH power density of 24 MW/m^2 was achieved on one of the launchers located 85 mm from the plasma LCFS.

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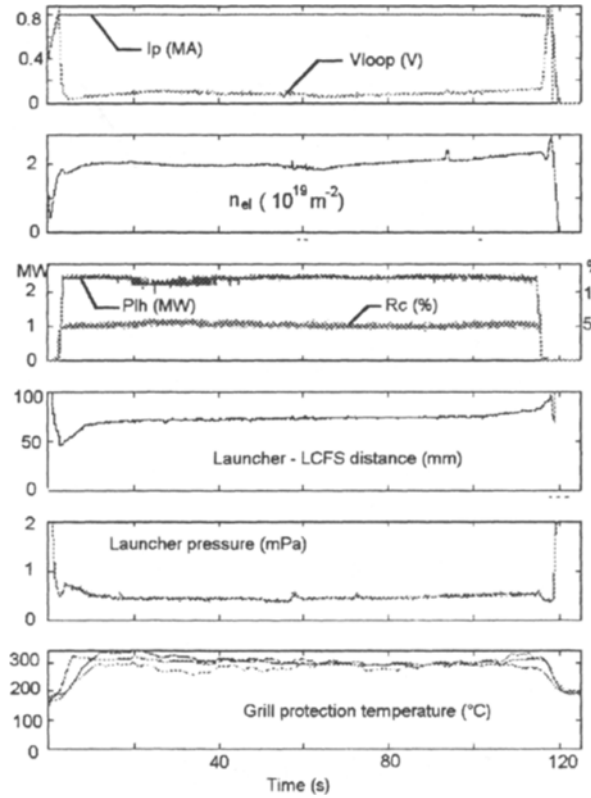

FIGURE 1. 120 s pulse with 280 MJ injected energy.

The deduced electric field inside the multijunctions is around 5.4 kV/cm. No impurity influx was observed and steady state regime at the grill was established. This discharge is used to validate the choice of 25 MW/m^2 for the nominal power density of the future LHCD launcher for Tore Supra described later in part 3.

Long discharges operation requires several feedback controls on plasma parameters (3). The LHCD system has demonstrated its ability to sustain 100% of the plasma current for long discharges by a double control of the LH power by the current and the loop voltage by the primary transformer. Further experiments (4) have also proved the possibility to control the internal inductance with the phasing of the LH array while the plasma current is driven by the LH power itself (Fig. 2).

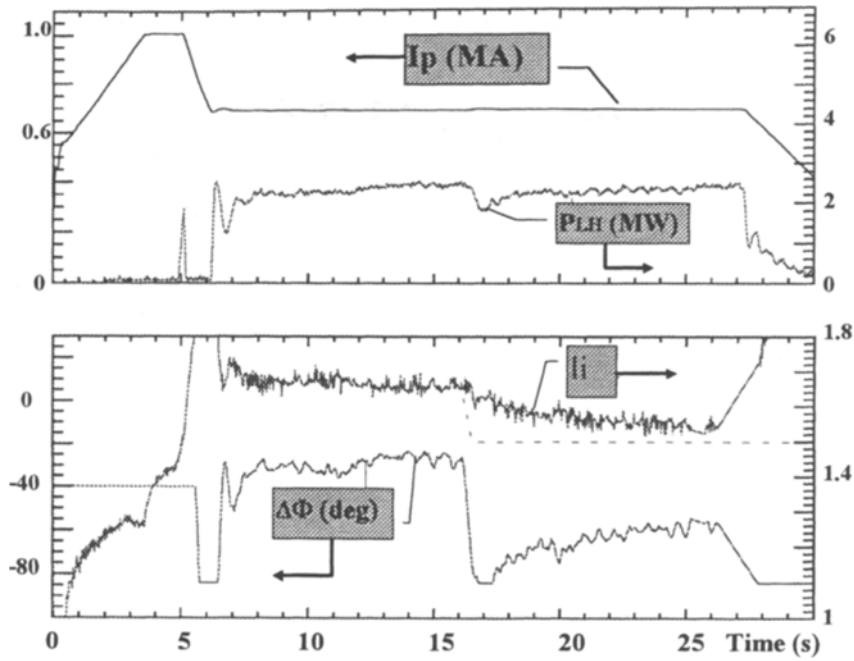

FIGURE 2. feedback control of LH power on Ip and ΔΦ on li

Proposed advanced scenarios will use the bootstrap current as a significant part of the total current. An approach to such a scenario has been studied for a duration of 5 s (Fig. 3), during which 6 MW of FWEH triggered a bootstrap fraction of nearly 45 %. Steady state conditions were observed on the energy confinement, central electron temperature, density, and impurity content (5).

FUTURE SCENARIOS FOR LONG PULSE OPERATION

A project to upgrade the internal components and limiters of Tore Supra for discharges up to 1000 s is in progress. A detailed design of a new toroidal pumped limiter, associated with a new wall protection is being studied and the fabrication will lead to an installation in TS in 1999. The goal of this new set of internal components is to be able to extract 25 MW of input power with a typical partition of 10 MW as radiated power, and 15 MW convected to the limiter (6). This limiter will provide active density control for plasmas with $\langle n_e \rangle$ in the range of $5.10^{19} m^{-3}$. High density operation will tend to increase the radiated power and equipartition. Coupling of both LH and FW power will be increased, but the net RF driven current is decreased, so that steady state operation at Ip=1.7 MA is possible only

around $\langle n_e \rangle \approx 2.10^{19} m^{-3}$. For high density operation, the scenario will use a high bootstrap fraction. Current profile will be controlled to obtain an improved confinement, which will balance in term of energy content the effect of the necessary reduction of the plasma current. The performances of the TS RF systems need to be upgraded for compatibility with the long pulse requirements. RF sources and coupling structures, initially designed for shorter pulses, are being transformed to meet this new requirement.

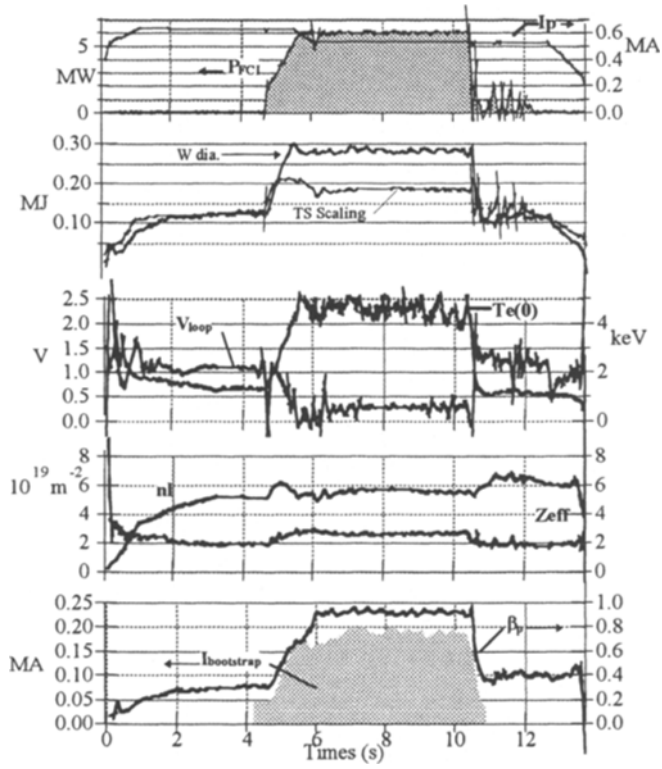

FIGURE 3. #18805 : high bootstrap fraction driven by FWEH

TECHNICAL DEVELOPMENTS OF RF SYSTEMS

ICRH and LHCD systems have been widely used on TS. The level of coupled power with the ICRH is ranging from 9.3MW during 2s to 2 MW during 27 s, and for LHCD from 6MW during 2s to 2.4 MW during 120 s.

ICRH System

The ICRF studies on TS is a field of collaboration with the US-DOE, with a special involvement of ORNL, and with ASIPP (China). The ICRH system on TS is using 3 Resonant Double Loop antennas fed by 6 high power tetrode generators. Recent developments have dealt with generator upgrades and antenna matching systems. The high power tetrodes have been enhanced by modifying the anode internal cooling circuit : the water is forced through holes in the thick anode wall. Special care in the design of the channels has allowed to keep the pressure drop through the tetrode at an acceptable level : 1.7 10^5 Pa for 800 l/mn, and a corresponding anode dissipation of 2 MW @ 60 MHz.

Long pulse testing of these tetrodes at Thomson Tubes Electroniques (TTE) have established the power limit for very long pulses (45 mn) on a VSWR≈1.1 load. The thermal equilibrium is reached after 1000 s, and the limit is at the 1.5 MW level. This limit is due to the thermal equilibrium of the grids inside the tube. As the size and geometry is fixed by the frequency range, there is no way to improve this limit in a noticeable way on conventional tetrodes. The present tubes are using pyrolitic graphite grids which are already giving the best results in term of losses (outgassing rate, overheating and thermoemission level). For higher output power, TTE is developing a new kind of tetrode, the Diacrode®, which will allow to double the output power level. Combined with an efficient cooling circuit on the anode, these tubes should allow to reach 2 MW CW on a VSWR≈2 load, any phase. This goal is at the same level as the present day ITER requirements. The preliminary test of the first prototype is scheduled for the end of 1997.

The TS antennas are now equipped with an automatic matching system. A closed loop control of the position of the matching capacitors allows to keep the VSWR below 1.2 during the pulse. Response time is today around 200 ms, and the stability studies of the loop should permit to lower this value around 50 ms. For faster response, an electrical circuit with no mechanical adjustment will need to be studied : matching optimisation could be performed either by frequency tracking or by recirculation of the reflected power to a dummy load.

Hot spots have been observed on antennas lateral protections, and lead to damages on the protective tiles. In parallel with studies of this specific RF/edge interaction (7), a new design is being developed. This design will use the same technology as the future toroidal pumped limiter for the plasma facing elements : CFC tiles bonded on copper alloy water cooled fingers. Both the toroidal and poloidal extension will be increased and improvement of performances is foreseen from the tougher design and larger surface (Fig. 4).

Qualification of RF contacts for use in vacuum has been undertaken. The use of sliding contacts in vacuum has until now been avoided by lack of confidence in the technical solution. Different contact surfaces and materials are being tested : a commercial RF contact has been successfully tested up to 1000 A r.m.s. for a 60 mm diameter coaxial conductor with pulse length of 60s (8). These contacts could

be used in a new type of vacuum matching or in vacuum stub tuners which could be incorporated in the ITER antenna electrical circuit (9).

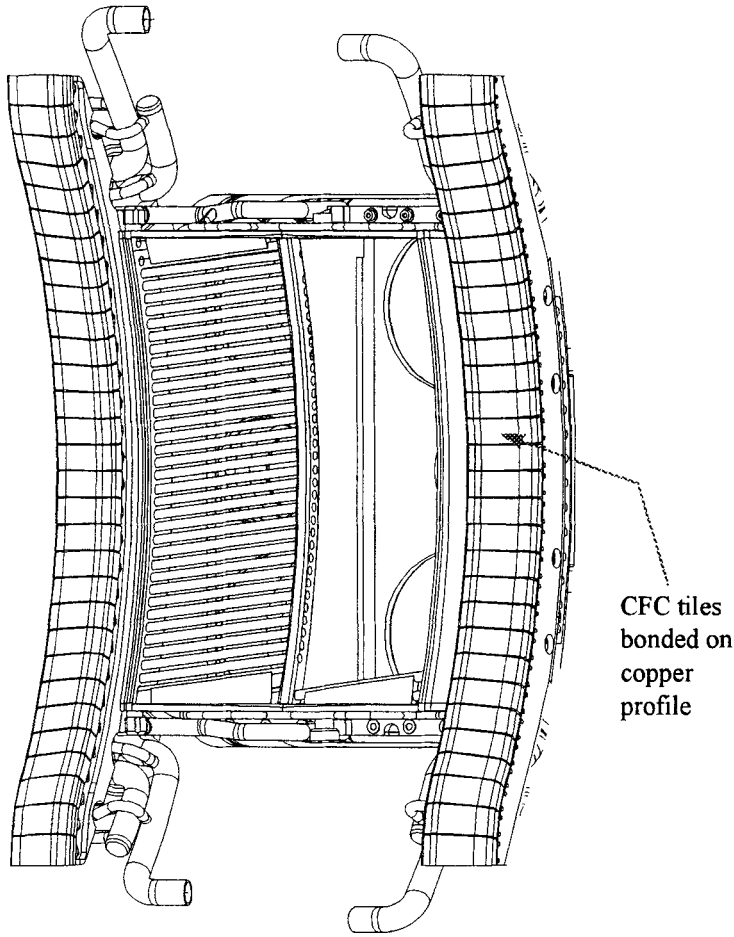

FIGURE 4. Artist view of the new lateral protection for ICRH and LHCD antennas, shown here surrounding an ICRH Antenna (Faraday shield partially omitted)

LHCD System

The TS LHCD system is using 2 multijunction launchers fed by 16 klystrons. Available source power amounts to a total of 8 MW. The present klystrons, designed for 500 kW and 210 s pulse length, have been tested up to 450 kW during 1000 s. Developments at TTE are aiming at klystrons able to deliver 750 kW during 1000 s with VSWR $\leq$ 1.4.any phase (10).

For reliable long pulse operation on TS, a new launcher is being constructed. It will use a larger frontal area in the port which will permit to launch 4 MW through a single port at an average power density of 24 MW/m^2. The fabrication of this new launcher is under way and it should be installed in 1999. This launcher will benefit of the developments for the ICRH lateral protections and will be equipped with the same elements. The multijunction array is fed through a mode converter from the rectangular waveguides. The design will allow to change the front part to an alternative configuration : the active passive waveguide array. This type of multijunction array features improved cooling capabilities at the expense of higher electrical fields for a comparable power level. This approach is a development for future long pulse operation (11).

ECRH System

The ECRH project for TS is aiming a power level of 3 MW delivered by 6 gyrotrons to the plasma through an antenna located in a horizontal port. The mirrors can be adjusted to aim at different poloidal and toroidal locations. Nominal pulse length is 210 s (12).

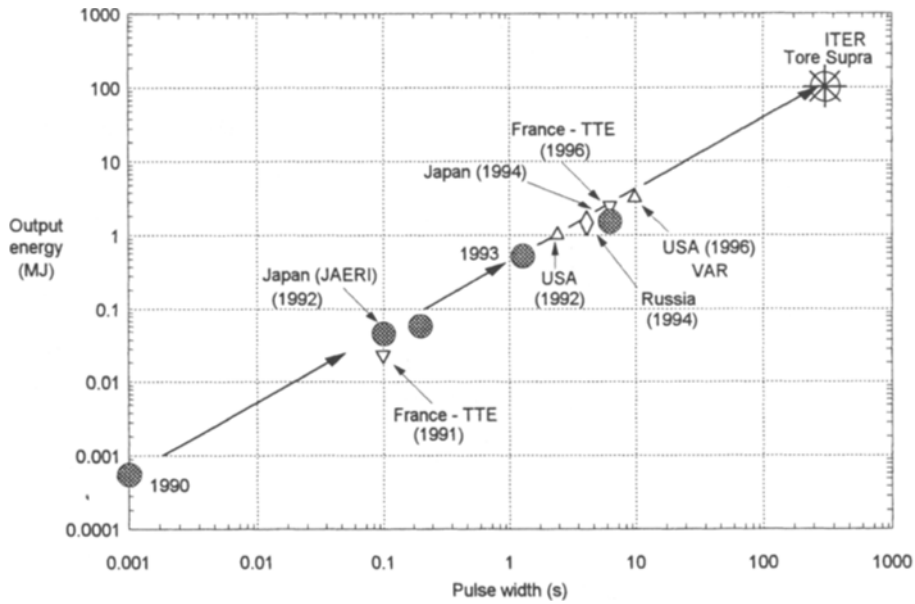

FIGURE 5. Gyrotron progress towards high energy pulses

The joint development undertaken by the CEA, the CRPP and TTE with technical support from FZK is now in its final phase, with the test of a full scale prototype.

Latest results for this gyrotron at TTE have passed a 5 s test at 500 kW output power. Pulse length is limited at the factory by the test load capability. Longer tests will be performed when the first tube will be delivered and installed at Cadarache in the end of 1997 (13). Delivery of the series of tubes is expected during 1998. First partial power operation on the plasma is foreseen in mid 1998, and the full system should be operational after the end of 1998. In terms of energy delivered and pulse length, these sources are close to what is planned for ITER (Fig. 5).

CONCLUSION

Upgrades of ICRH systems are needed to meet the future long pulse operation requirements. These developments will tend to obtain reliable power injection from the various RF systems of Tore Supra, among which some have already proven to be very efficient tools for the control of plasma parameters.

The R&D program on Tore Supra is aimed at developing a coherent solution for long pulse operation by mean of improvements of the power exhaust and particle control, as well as for power injection and plasma control systems. The technical solutions that will be tested on Tore Supra are of direct relevance for future machines.

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