PREFACE

M. CHATELIER

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

In the late 1970s, whereas JET started construction at Culham in the frame of the EURATOM program, the perspective of early preparation for the construction of a future "after-JET" fusion machine capable of producing fusion energy with a high gain over long durations came under discussion in France. This perspective acted as a strong incentive to gather the French magnetic fusion activities and forces (at that time split between Fontenay-aux-Roses and Grenoble) at Cadarache, a nuclear research center suitable for hosting a fusion device of nuclear standard with a favorable technical and social environment. Building strong fusion expertise at such a site was seen as an additional asset for Cadarache to become a candidate for hosting a big after-JET project. Because of the long time delay expected before a decision could be made for this project (naively supposed to be in the range of 10 to 20 yr!), the necessity of an accompanying program in parallel to JET for the EURATOM/ Commissariat à l'Energie Atomique (CEA) teams in Cadarache, following the close of the tokamaks TFR in Fontenay-aux-Roses and PETULA in Grenoble, was considered.

The need for substantial progress in the technology required for future machines and particularly the need to increase the pulse duration were seen as grounds for such a project. However, the separate development of the different technological areas needed for next step devices was not considered appropriate; integration within a single tokamak device of the different required technologies was perceived as a more ambitious and motivating choice. This choice also offered the prospect of a scientific program in fusion plasma physics, centered on the yet unexplored aspects of long pulse discharges (such as fully noninductive current drive or erosion of plasma-facing components), consistent with the move of the scientific teams to Cadarache.

The proposal for a large tokamak (Tore Supra, having approximately one-fifth to one-fourth of the JET plasma volume) with a toroidal superconducting (SC) magnet based on NbTi and subcritical He bath at 1.8 K technologies was conceived based on the experience of the CEA experts in SC magnets and cryogenics at Saclay and Grenoble. The poloidal system, designed with copper coil technology, was generously sized in order to allow for a nominal 1.7-MA plasma current at the nominal toroidal field on axis of 4.5 T over 30 s. It should be noted that 30 s (called long pulse at the beginning of the Tore Supra exploitation!) was originally identified as the appropriate timescale for addressing most technological challenges of high-power, long pulse plasma discharges, such as active cooling of the plasma-facing components or the development of continuous noninductive current drive and/or heating systems. This has been extensively verified on Tore Supra, over durations much longer than 30 s, with the noticeable exception of plasma-facing-component erosion for which steady state seems to be meaningless. Finally, real-time control of long plasma discharges, as well as the development of compatible plasma diagnostics, was expected to benefit from long pulse conditions and environment.

Since the beginning of Tore Supra in 1988 until today (2009), the SC magnet has operated fully reliably, in a routine operation mode (with the exception of one single current quench due to a strong disruption at high current). However, obtaining long duration plasma discharges required developing, in addition to the permanent SC magnet, a high-performance heat exhaust capability to remove the current drive and heating power. Two generations of actively cooled plasma-facing components were successively developed. The first generation, implemented from the very beginning of Tore Supra, revealed the difficulties of carbon-metal binding, an essential feature to obtain effective heat transfer from the plasma boundary to the coolant in the 10 MW/m^2 range of power densities to be extracted. The reliability and consistency of the overall chain of actions for the realization of large areas of high heat flux components, from conception to industrial production and eventually operation, proved to be essential in the successful achievement of the record long pulse, high-power (6 min/3 MW, 1 GJ injected and extracted) discharge in 2003. These results were obtained in the frame of the CIEL project, a full set of second-generation high heat flux components, capable of removing 15 MW of convected power and 10 MW of radiated power in steady state.

Running routinely long pulses in a tokamak also requires developing powerful and reliable heating and current drive systems. On Tore Supra, fully noninductive current has been routinely obtained via lower hybrid waves [lower hybrid current-drive (LHCD)]. Despite the power and duration limitations of the original LHCD system, it was robust enough to allow the 2003 record values. The success of the CIEL project, which is still far from reaching its design limit, validates the CIMES project, currently under completion, which is an improved version of the original LHCD system with an actively cooled (ITER-like) "Passive Active Multijunction" antenna and 16 continuous-wave klystrons (3.7 GHz) upgraded at 700 kW. The CIMES project should result in doubling the power coupled to the plasma, allowing increasing the discharge duration or, more interestingly, doubling the plasma density to reach higher-performance plasmas.

Many other long pulse systems have been or are being successfully tested and contribute to the Tore Supra scientific program: plasma heating by means of ion cyclotron waves [ion cyclotron resonant heating (ICRH), three antennas, 3×4-MW generator power, 30 s]; plasma heating, current drive, and magnetohydrodynamic (MHD) activity control by means of electron cyclotron waves (electron cyclotron resonant heating, 0.8 MW with two gyrotrons at 118 GHz, 210 s; one poloidally and toroidally steerable antenna); plasma fueling by means of continuous pellet injection or supersonic gas injection. The permanent toroidal field during and between discharges, which prevents conventional conditioning methods to be used during experimental sessions, has triggered a program of conditioning tests with ICRH waves, which is important for ITER. Of course, a large number of "short" duration discharges contributed to the wealth of experimental results when the long pulse features were not the focal point of research. Among many results, one can cite original heating scenario developments; studies of synergy between various heating and noninductive current drive schemes; in-depth studies of turbulence with innovative diagnostics and its link to particle and energy transport; investigation of MHD stability of vanishing loop voltage discharges, of radiating layers, and of scrape-off-layer physics, etc. The work carried out using an ergodic divertor also deserves special attention for the considerable knowledge it has brought regarding the effect of a resonant magnetic perturbation on the plasma edge that has been seminal to the first proposal to use such perturbations for edge-localized-mode control.

Tore Supra has played and still plays a very specific role in the European and worldwide fusion program as the very first machine to have allowed power densities in the range 10 MW/m^2 with no limitation in time, except ultimately from erosion/redeposition processes after hours of plasma operation in a row [the Deuterium Inventory in Tore Supra (DITS) project]. What has been learned with Tore Supra will become the normal standard of operation with forthcoming SC mediums to large devices and with ITER particularly. It should be pointed out that technological developments and operational aspects (real-time control) of Tore Supra have required a rather long training period to cope with the various constraints associated with active cooling of every square centimeter of material facing the plasma, which makes these SC machines less flexible than the short pulse, inertially cooled machines.

The written contributions to this special issue of *Fusion Science and Technology* on Tore Supra are the fruits of the time and effort by a broad community of technologists and scientists from the beginning of construction to the present. It is certainly very difficult to acknowledge every single contribution, even more difficult to ascertain that nobody has been accidentally missed, but the length of the "Tore Supra Team Members 1988–2008" list indicates the size of the work. A large number of international collaborations, from both inside and outside Europe, have been instrumental to the achievement of the technological and scientific program. The specific involvement of the United States/U.S. Department of Energy, especially during the first 10 yr of operation, has been particularly fruitful.

Finally, Claudio De Michelis, who volunteered to put together the various contributions of this special issue on Tore Supra, deserves our great consideration for his constant efforts to stimulate overburdened authors to deliver and to enhance, wherever possible, the coherence of the individual parts.