CHAPTER 1: THE FTU PROGRAM

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The Frascati Tokamak Upgrade (FTU) has been operating for more than 12 yr since its first plasma in 1990 and has played an important role in several aspects of the tokamak research. As the first paper of this special issue containing papers on all aspects of FTU, this paper briefly summarizes the main dates, the general description of the facility, the objectives, and the major achievements in FTU.

KEYWORDS: *high-field tokamaks, Frascati Tokamak Upgrade, tokamak fusion research*

I. INTRODUCTION

The Frascati Tokamak (FT) Upgrade (FTU) facility is a high-magnetic-field compact tokamak, the construction of which was completed in 1990 (Ref. 1). Such tokamaks[2] have the advantage of producing thermonuclear-grade plasmas at high plasma density, low impurity concentration, and relatively low beta. A clear advantage is to operate with high magnetohydrodynamic (MHD) limits as well as high Greenwald density limits. Operating in a regime with high values for the electron-ion collision rate results in a short slowing-down time for the alpha particles. Consequently, they can eventually distribute their energy to the bulk plasma in a short timescale, comparable to the energy confinement time. This line of facilities includes the Alcator series of experiments developed at the Massachusetts Institute of Technology and the FT built at Frascati. The main focus of the research program in FTU is to develop scenarios relevant for burning physics experiments (BPXs) and the underlying physics understanding. In this paper, a brief introduction to the content of this special issue is given. The reader is then referred to specific chapters to find more precise and detailed information on the various areas of the FTU scientific and technical program.

II. THE FTU FACILITY

The main parameters of the FTU facility are indicated in Table I. The magnetic field is produced from

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TABLE I

Main Parameters of FTU

Magnetic field	8 T
Major radius	0.935 m
Minor radius	0.305 m
Plasma current	1.6 MA
Flattop duration	1.5 s
Temperature of first wall	-100°C
Repetition rate	20 min
Maximum linear density	4×10^{20} m^{-3}
Maximum electron temperature	15 keV
Maximum energy confinement	0.12 s
Maximum neutron yield	1.3×10^{13} neutrons/s

circular nitrogen-cooled magnetic coils. The magnetic flux is generated from an air-core transformer. The plasma shape is circular and is defined by poloidal or toroidal limiters. Details on the design and the construction of the facility are extensively described in Chapter 9. The first FTU plasma was produced in April 1990 using a stainless steel poloidal limiter. Following installation of several poloidal limiters with various materials, a toroidal limiter in molybdenum was successfully installed in 1995, allowing reliable and cleaner operation to be achieved. The interior of FTU with its toroidal limiter can be seen in Fig. 1. The FTU was operated in 2000 up to its maximum designed parameters: 1.6 MA at 8 T in deuterium plasmas lasting for 1.5 s. It is to be noted that the operation of the machine has been very reliable. Specific techniques for plasma conditioning have been developed since the temperature of the first wall is much lower than in other tokamaks (about -100°C). Boronization is the technique used at present (in 2002), which has proven to be very effective, in particular for plasma densities below 1×10^{20} m^{-3} with high additional power, allowing relatively low Z_{eff} and low fraction of radiated power (30%) to be achieved for the present maximum injected power of ~3 MW (Ref. 3). The special role of the metal wall and the subsequent changes after boronization as well as the effect of the cooling capability of the wall to -100°C are discussed in Chapter 10.

Some of the heating and ancillary systems of FTU can be seen in Fig. 2. Heating and current drive in the FTU is essentially performed with radio-frequency (rf) techniques chosen to optimize electron heating at high density in order to study regimes relevant to a fusion reactor where alpha particles will mainly heat electrons. As described in Chapter 11, the machine was designed with a lower hybrid (LH) system for plasma heating and current drive [lower hybrid current drive (LHCD)] at a frequency of 8 GHz to avoid damping on the ions and to privilege damping on electrons, a subsequent ion heating taking place from electron-ion collisions owing to the high-density operation. The first LHCD module was installed in 1992, showing high-power handling capability (10 kW/cm^2) (Ref. 4), and the system was operated at almost its full capability in 2001, delivering up to 2.2 MW to the plasma with two launchers for a duration of ~1 s. Progressively, other heating systems have been installed: an electron cyclotron (EC) resonance heating (ECRH) system at 140 GHz and an ion Bernstein wave (IBW) system at 433 MHz. The list of the main parameters of the heating systems is shown in Table II. A high-velocity pellet injector was installed in order to increase the operating plasma density. A first high-speed

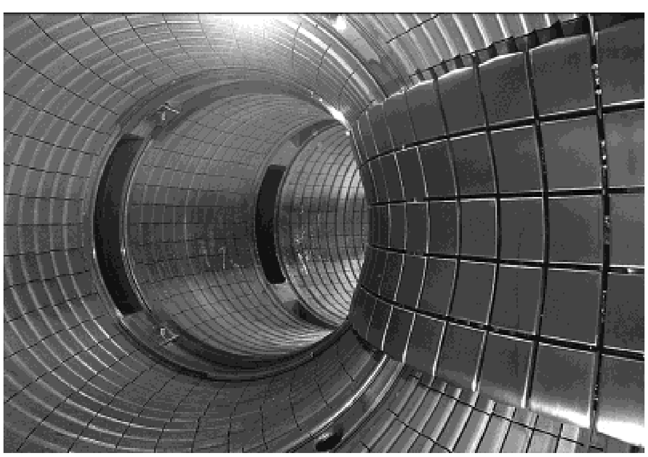

Fig. 1. Inner view of the FTU equipped with a molybdenum toroidal limiter.

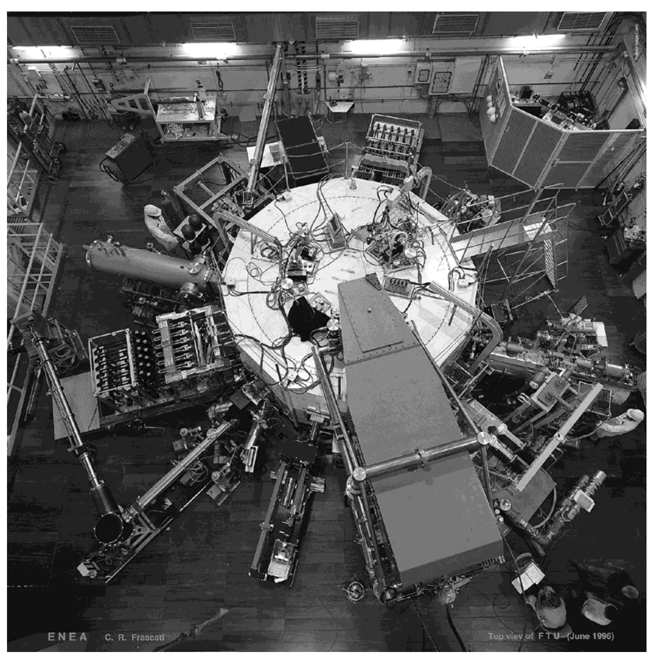

Fig. 2. Top view of the FTU. Some additional heating systems and diagnostics can be seen.

TABLE II

Main Parameters of the FTU Heating Systems

	LHCD System	ECRH System	IBW System
Frequency	8 GHz	140 GHz	433 MHz
Nominal unit power per tube (on load)	1 MW	0.5 MW	0.5 MW
Pulse length	1 s	0.5 s	1 s
Number of tubes	6 gyrotrons	Up to 4 gyrotrons	2 klystrons
Length of transmission line	20 m	20 m	20 m
Number of ports	2	4	2
Launcher type	Phased array of waveguides (48 per structure)	Mirror system	2 waveguide system
Window position	20 cm from mouth	Outside the cryostat	Outside the cryostat
Maximum launched power on plasma	2.2 MW (10 kW/cm^2)	1.2 MW with three gyrotrons	0.4 MW

single-barrel pellet injector (2 to 2.5 km/s) was tested in 1992. The present pellet launcher (from Risø National Laboratory) was successfully operated in 1996. It is a multibarrel pneumatic launcher (up to eight pellets in one plasma shot) launching pellets at velocities up to 1.5 km/s from the equatorial plane. The corresponding achieved results are discussed in Chapter 4. A vertical pellet launcher has been installed and is under commissioning tests at present.

FTU is equipped with diagnostics that are standard diagnostics for tokamak studies. They are presented in Chapter 8: interferometers, Thomson scattering, electron cyclotron emission, reflectrometry, spectroscopy, X rays, and neutrons. Special attention has been given to the diagnosis of fast electrons generated by LHCD. Improvements have been steady through the years, and a substantial upgrade is in progress, including increased accuracy for profile measurements (density and temperature) and the installation of a motional stark effect (MSE) system for the measurement of the plasma current profile.

III. OBJECTIVES AND MAJOR ACHIEVEMENTS

Operation of a cryogenic machine is of general interest since several future machines are planned to be operated with cryogenic cooling of the magnets (IGNITOR, FIRE, etc.). It is also to be noted that operation with metallic walls is of increased interest since the problem of tritium retention in carbon tiles has been identified in the Joint European Torus (JET), leading to the consideration of a full metal first wall in ITER, a feature that can be studied in FTU.

From its conception, FTU was designed to have the capability of operating in regimes relevant to the next generation of BPX, namely, at high magnetic field and high densities that are hardly achieved in other devices, with the exception of Alcator C-MOD. Although several dimensionless parameters are clearly different from those anticipated in ITER, such as β_P, β_N, and ρ^*, some others such as collisionality are similar. One of the interests is to operate with parameters similar to ITER, allowing, for instance, testing of additional heating and current drive systems in a similar range of parameters such as magnetic field and density. The FTU program has been focused on the basic understanding and the exploration of new regimes of relevance to BPX. Their highlights are discussed in Chapter 2 and are summarized later in this section.

One of the main physics objectives in FTU has been the production of steady internal transport barriers (ITBs) with electron heating only; this is the subject of Chapter 3. These scenarios are highly relevant for advanced scenarios in ITER where the main heating source is from collisions with alpha particles. Electron ITBs have been produced in several experiments with high central electron temperature, but at low electron density ($\sim 1 \times 10^{19}$ m^{-3}), so that the electron and ion populations remain decoupled. More recently, ITBs have been produced with electron and ion temperatures in the same range, but with both populations heated separately, therefore remaining in effect decoupled. An important issue for BPX, namely, that the turbulence stabilization mechanisms invoked to produce ITBs (magnetic shear, shear flow, etc.) are not hampered or even suppressed when the electron and ion population are coupled through collisions, has not yet been investigated. Experiments on advanced scenarios in FTU have tried to address this open issue. First, electron transport barriers, i.e., plasmas with reduced heat diffusivity in the core, were achieved in 1998 with ECRH in the plasma current ramp phase leading to record (at the time) central electron temperatures[5]; results extended in 2000 to higher densities[6]: T_{e0} of 14 keV at a line average density of 0.4×10^{20} m^{-3}, with the radial zone of improved confinement remaining rather narrow. First indications of the production of wide electron ITBs (about half plasma radius) were reported in 2000 (Ref. 7), subsequently extended to higher densities for time duration much longer than the energy confinement time, comparable to the current diffusion time.[8] Plasmas with electron temperature of 11 keV at a central density of 0.9×10^{20} m^{-3} were achieved with the simultaneous use of ECRH and LHCD. Energy confinement is up to a factor of 1.6 as compared to the ITER97 L-mode scaling law. The neutron yield was substantially increased, with ion heating occurring through ion-electron collisions.[9] These discharges are a first answer to the issue of the effect of collisions on the ITER ITBs.

Great attention has also been devoted to the production of high-density plasmas with central densities typically above 5×10^{20} m^{-3}, as discussed in Chapter 4. There is a new regime: The repetitive pellet enhanced plasma (PEP) modes, allowing good confinement at high density to be achieved, have been developed. Two successive PEP modes were obtained in 1997 with plasma current up to 0.8 MA. Multiple PEPs were achieved in 2000 (Ref. 7) at plasma current of 1.2 MA, with the number of pellets limited only by the time duration of the current plateau. In this way quasi-steady high-density, high-confinement plasma with low impurity concentration was achieved, resulting in a fusion product $n_i T_i \tau_E$ up to 0.8×10^{20} m^{-3} keV/s (Ref. 10). In these discharges, the neutron yield reaches values of 1.5×10^{13} neutrons/s, which is quite a large value for relatively low volume plasmas with ohmic heating only. Radiation-improved modes have also been achieved but are still in an early stage of development.

A summary of the parameters achieved in some of the best FTU pulses is shown in Table III. Some of the achieved FTU parameters are shown in perspective with other machines in Fig. 3 (Ref. 11). The physics associated with these regimes has also been a clear focus of the efforts in FTU—including MHD stability (see discussions in Chapter 5), plasma transport properties (both global and local as discussed in Chapter 6), and plasma-wave physics—which is essential for the development of these scenarios (see Chapter 7). These studies are still in progress and have been essential for the optimization

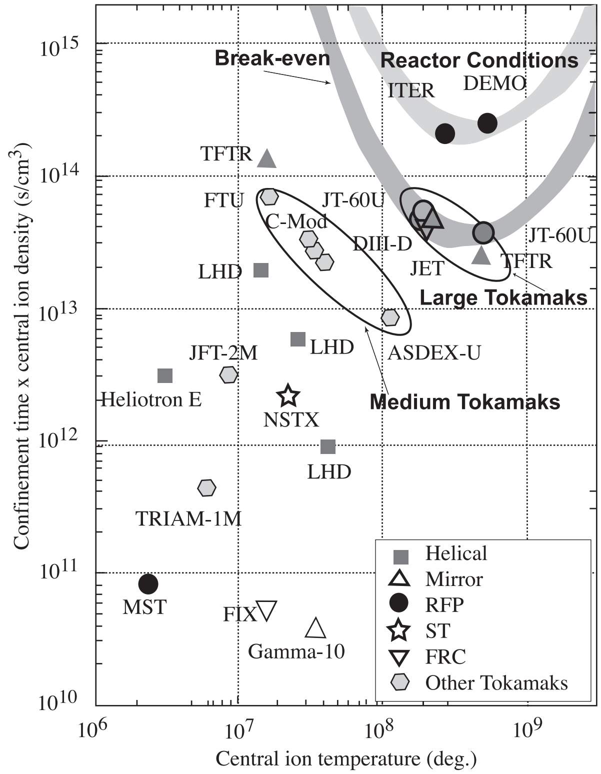

Fig. 3. Fusion plasma performances achieved in FTU and in some other machines on the Lawson diagram (from Kamada et al.[11]). FTU data correspond to the repetitive PEP modes.

TABLE III

Main Parameters of Some of the Best Discharges in FTU

	Pellet Fueling #12747	Pellet Fueling #20169	Electron ITB #20859	Electron ITB #21548	LHCD #22424
B_t (T)/I_p (MA)	7.0/0.8	7.0/1.1	5.4/0.5	5.3/0.35	7.1/0.5
Additional power (MW)	—	—	1.70(LH) 0.35(EC)	1.5(LH) 0.70(EC)	1.6(LH)
n_{eo} (10^{20} m^{-3})	6.0	4.5	0.76	1.2	1.3
T_{eo} (keV)	1.5	1.4	11.3	7.2	5.6
T_{io} (keV)	1.2	1.4	1.2	1.0	1.4
τ_E (ms)	118	83	21	16	29
H_{97}	1.46	1.14	1.39	1.62	1.51
Z_{eff}	1	1	4.0	1.5	1.2
I_{CD}/I_P	—	—	0.55	1.0	0.74
Neutron yield 10^{12} n/s	5	13	0.07	0.09	0.6

of the advanced regimes. Their main achievements are summarized in the following:

1. Full current drive has been achieved for the first time at high densities,[12] up to 0.8×10^{20} m^{-3} at $I_p = 0.5$ MA, with LHCD, therefore allowing the LHCD database to be extended up to values of direct interest for ITER. At the same plasma current, up to 75% current drive has been achieved at $n_e = 1.2 \times 10^{20}$ m^{-3}. A substantial increase of the neutron yield, by a factor up to 6, was observed at these densities, which is indicative of direct ion heating from collisions with the electron population, thus confirming the initial design of LHCD in FTU.

2. ECRH has been extensively used to stabilize MHD tearing modes, in particular giving information on mode coupling[13] and on the requirements of such a system to stabilize classical and neoclassical tearing modes on a reactor. ECRH has also allowed a large variety of transport studies to be performed.[14] In particular, modulated ECRH has been used in a very innovative and pioneering way, leading to interesting insights on electron transport physics.

3. Synergy between ECRH and LHCD based on the damping of the EC wave on the fast electron population generated by the LH wave, thanks to Doppler-shifted resonance, has been extensively studied.[15] Damping has been achieved either at a much higher field than the cold resonance, thus extending the operating range of ECRH, or at a lower field than the cold resonance, the domain of direct interest for ITER.

4. The IBW system has produced plasmas with clear indications of improved confinement in the plasma core, possibly associated with ITBs. Experiments in 2002 with two launchers have confirmed the 1999 initial experiments[16] showing a substantial increase of the pressure profile.

5. MHD studies have aimed at the basic understanding of some of the phenomena limiting the plasma performances (internal kink modes, triggering of sawteeth,[17] mode reconnection, fishbones). They have also been instrumental in the optimization of high-performance modes in FTU. MHD spectroscopy is becoming an important tool for exploring new domains such as the high-frequency MHD modes.

IV. FUTURE PLANS

The main lines of research in FTU for the coming years include the following:

1. *The continuation of development of ITBs at high density, including measurement of turbulence:* In order to have plasmas where collisions are playing a dominant role, operation at higher power and/or higher confinement is needed. Synergistic effects between all rf waves might be needed.

2. *Study of edge effects linked to the FTU metal wall:* Conditioning metallic walls remains an important issue for FTU. A lithium poloidal limiter, using a capillary porous structure, is being prepared (in collaboration with the Troisk Institute for Innovation and Fusion Research) and will be installed in the near future.

An upgrade of the ECRH system aiming at replacing the present 140-GHz gyrotrons with gyrotrons equipped with a depressed collector, thus improving the gyrotron efficiency, is being considered but is not yet approved. It could allow the present power to be almost doubled. The power supplies were initially foreseen for such an upgrade.

The study of energetic particles is also under consideration. This requires the development of an rf system capable of producing such particles, for instance an ion cyclotron resonance heating (ICRH) system. A feasibility study is under way in collaboration with the Politecnico di Torino. A two-strap antenna system capable of launching up to 1 MW of power at a frequency of ~80 MHz corresponding either to the minority hydrogen resonance at 5 T or to the helium minority resonance at 8 T sounds possible. Such a system will not only permit the production of energetic particles but also probe the ion transport in electron ITBs and heat ions at the plasma core of FTU, thus significantly improving the performance of FTU.

Diagnostics are being improved, including the Thomson scattering system, the measurement of radial density profiles with a significantly improved accuracy, the radial measurement of ion temperature, and the measurement of the current profile with an MSE system.

A new experiment called FT3, still at a conceptual stage, is being contemplated in view of the preparation for ITER operation. The aim of the FT3, in line with conceptual designs of steady-state tokamak reactors with magnetic field in the range of 8 to 9 T, is to compare the relative merits of some advanced scenarios including improved L-modes (repetitive PEP modes, for instance), H-modes with ITBs, etc., by demonstrating their performances in subignited conditions (equivalent $Q_{DT} > 1$). A main feature is the significant fast particle component generated by ICRH in order to simulate the effect of alpha particles in the plasma center. Physics aims as well as some technical features of FT3 are described in Chapter 12, with the main parameters summarized in Table IV. It is an upgrade of the FTU machine recovering most of the existing facilities: torus hall, power supplies, etc. It is conceived with low-temperature cryogenic cooling, allowing operation at a current plateau time duration (4 to 10 s) comparable to the current diffusion time (about a few seconds) and with an open divertor. The use of ICRH in the minority scheme can provide both central heating and fast particles. It is anticipated that up to a

TABLE IV

Main Parameters of FT3

Magnetic field	8 T
Plasma current	6 MA
Major radius	1.3 m
Minor radius	0.48 m
Elongation	1.8
Triangularity	0.45
Additional power	25 MW
Density (Greenwald limit $\sim 8 \times 10^{20}$ m^{-3})	4×10^{20} m^{-3}
$Q_{equivalent DT}$ (conventional H-mode)	1.3
$Q_{equivalent DT}$ (with ITBs)	5
$Q_{equivalent DT}$ (with enhanced L-mode)	1.5

few mega-electron-volt deuterons can be contained in the machine. Present or upgraded LHCD and ECRH systems will also be used. Vertical fast pellet injectors can provide deep fueling. A set of sophisticated diagnostics, similar to the one foreseen for ITER, would have to be installed, in particular, to study collective modes effects.

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