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Transport in High Density Igniting Plasmas*

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Introduction

Ignitor [1] is the first experiment that has been proposed and designed to achieve fusion ignition conditions in well confined deuterium-tritium plasmas. Demonstration of ignition, the study of the physics of the ignition process, and the heating and control methods for a burning, magnetically confined plasma are the most pressing issues in present day research on nuclear fusion and they are specifically addressed by the Ignitor experiment. The adopted strategy involves the use of compact, limiter configurations with high magnetic fields to reach ignition at relatively low temperatures, high densities, and induce the “thermonuclear instability” [2]. This possibility is the fundamental feature that differentiates Ignitor from all other presently proposed burning plasma experiments. Furthermore, heating methods and control strategies for ignition, burning and shutdown can all be established with this device in meaningful fusion burn regimes, on time scales sufficiently long relative to the plasma intrinsic characteristic times. The machine parameters, listed in Table I, have been chosen in order to operate at a large toroidal plasma current, with a correspondingly low poloidal beta ($\beta_p = 2\ \mu_0 \langle p \rangle / \overline{B}_p^2 \cong 0.2$ at ignition, where $\langle p \rangle$ is the volume averaged plasma pressure), and at about half the density limit, to keep far from the main density and beta operational limits. In this paper we discuss some confinement and transport experimental results obtained in the high field, high density experiment FTU (Frascati Tokamak Upgrade), and their implications for the plasma regimes expected in the Ignitor ignition scenario.

R	1.32 m	Plasma Current I_p	11 MA
a	0.47 m	Toroidal Field B_T	13 T
κ	1.83	Av. Pol. Field $\langle B_p \rangle$	3.4 T
δ	0.4	Edge q_ψ	3.5
T_{pulse}	4+4 s	RF Heating P_{icrh}	6-18 MW
Peak temperature T_{e0} , T_{i0}		11.5, 10.5 keV	
Peak density n_{e0}		10^{21} m^{-3}	
Peak α density $n_{\alpha 0}$		1.2×10^{18} m^{-3}	
Total α power P_α		19.2 MW	
Plasma stored energy W_{pl}		11.9 MJ	
Ohmic power $P_{OH} = dW/dt$		10.5 MW	
Core radiated power P_{rad}		6 MW	
Pol. and tor. beta β_{pol}, β		0.2, 1.2%	
Energy confinement time τ_E		0.62 s	
α’s slowing down time τ_{sd}		0.05 s	
Effective charge Z_{eff}		1.2	

Table I. Machine parameters and representative plasma parameters for Ohmic ignition [7].

FTU Ohmic Confinement

Confinement and transport issues for Ignitor can be investigated in existing high field, high density experiments such as FTU, which can operate in a region of parameters complementary to that of most other existing devices. In particular, the scaling of confinement with density at high fields has been addressed in the FTU experiments for B_T = 7 - 8 T. As was already observed in other high field machines, the energy confinement time τ_E increases with density up to a saturation value. This saturation occurs at about half the value of the “density limit” (Fig 1). When Ip = 0.8 MA the density profile is fairly peaked at relatively low densities and it flattens out at higher densities, when the confinement also saturates (Fig. 2). At the lowest q_ψ (q_ψ<3), however, the density profile is flatter and does not change with density, in spite of the linear increase of τ_E in the explored density range. Following the injection of pellets the positive trend of the neo-Alcator scaling with density is extended and τ_E reaches values in excess of 100 ms [3] at 0.8 MA, with a significant overall improvement above the saturation level, for n_{e0} as high as 8×10^{20} m^{-3}, close to the Ignitor reference central density. The product $n_0\tau_E$ reaches about 10^{20} sec/m^3. The corresponding effective thermal diffusivity $\chi^E \cong a^2/4\tau_E \cong 0.2$ m^2/s is within the range of the values estimated for Ignitor in order to reach ignition. The density peaking factor in these cases is above 3, sawteeth are suppressed, and there is a clear indication of the onset of an internal transport barrier. As a consequence, impurity occumulation is usually observed and the plasma returns to a lower confinement level within 50 ms. On the other hand, at 1.1 MA, the penetration of multiple pellets (up to 5) is less deep and the increase of both confinement time and density peaking is modest, but considerably more stable. Impurity accumulation is avoided

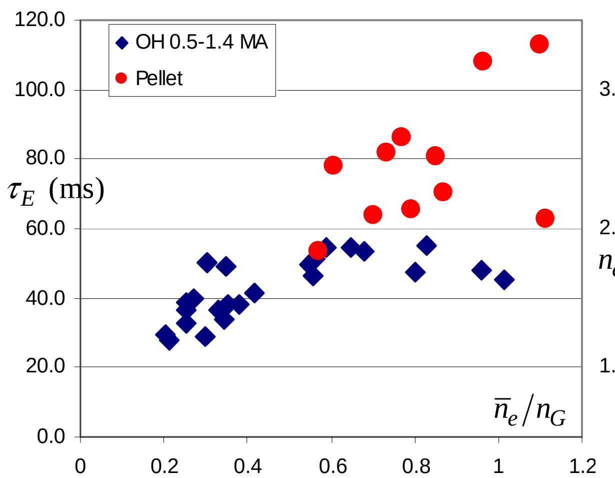

Fig. 1. FTU energy confinement time in Ohmic discharges with and without pellets, for currents ranging from 0.5 to 1.4 MA n_{e0} up to 7.3×10^{20} m^{-3} as a function of the ratio of the line average density to the density limit $n_G = I_p/\pi a^2$.

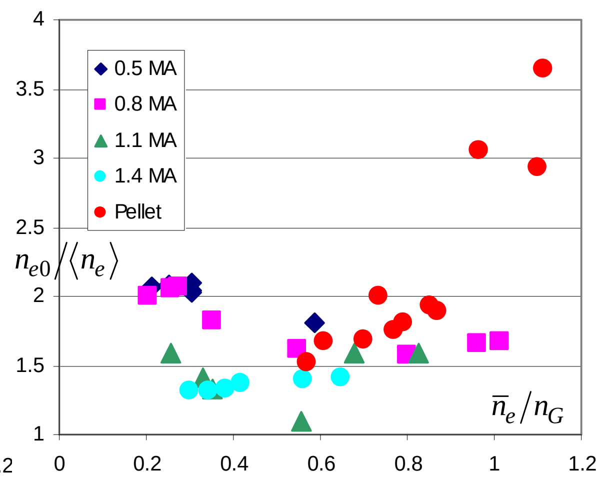

Fig. 2. Density profile peaking factors for the same discharges of Fig. 1.

thanks to the persistence of a slower (relative to the pre-pellet phase) sawtooth activity [4].

A microstability analysis of the pellet injected discharges has been carried out [5] to identify the stabilizing processes that bring about the improved confinement. In [5] it is shown that the high collisionality of FTU plasmas allows for density peaking stabilizations, which is identifyed as the main stabilizing mechanism for the electrostatic turbulence. Electromagnetic effects on ITG modes are generally negligible in FTU standard ohmic plasmas, (magnetic shear = 0.5, parameter α= 0.02, where $\alpha=-R_0q^2\beta'$) while they become important in pellet discharges (α = 0.1, $\alpha_{critical}$= 0.3) bringing about further stabilization of the ITG branch through coupling with the Alfvèn ITG [6].

Ohmic Confinement Regime in Ignitor

The approach to ignition in Ignitor was extensively simulated [2,7] by means of 1 ½ D transport codes, using different transport models. The results reported in Table I are obtained by applying the Coppi-Mazzucato-Gruber model for the Ohmic heating phase (as detailed in [7]), and a degraded transport model when α-particle heating prevails, in the JETTO code [8]. The optimal conditions under which confined plasmas can reach ignition, according to four different transport models, were identified [9,10]. In all cases, no transport barriers are invoked. The most accessible conditions for ignition involve relatively peaked density profiles (e.g., $n_0/\langle n\rangle \cong 2$). Peaked profiles are beneficial for fusion burning plasmas from several perspectives. In particular, they can provide a stability edge against the so-called η_i modes that enhance the ion thermal transport. In fact, the injection of pellets to prevent the confinement saturation was suggested originally for the Alcator C experiments to stabilize the Ion Temperature Gradient (ITG) driven modes by means of an adequate density gradient.

Extrapolations of the FTU ohmic regimes to the case of Ignitor need to take into account that the plasma current is higher (the average poloidal magnetic pressure in Ignitor is about 25 times the FTU value at 1 MA) and the plasma temperature is also10 times higher than in FTU. The line average density at ignition is less than half the density limit, and therefore the confinement time can be expected to be as high as it can be before reaching saturation. The collisionality parameter ν^* at ignition is lower than in the FTU pellet discharges. The level of desired density peakedeness, on the other hand, is similar to that observed on FTU at the lowest densities and currents. During the initial current rise the value of q_ψ at the edge is below 4, therefore density profiles that are not sufficiently peaked are to be expected. For this reason a high speed, multiple pellet injector [11] is planned as an integral part of the Ignitor facility. The injector will allow variable speeds and pellet sizes to provide sufficient penetration throughout the current rise, when density profile control is more critical and the temperature is lower. At ignition, the parameter α defined in Ref. [6] is estimated at about 0.18, therefore it can be expected that stabilizing mechanisms such as those acting in FTU pellet fuelled discharge will also take place, although the role of trapped particles in this phase remains to be assessed.

H-mode regimes

The possibility of achieving H-mode confinement in Ignitor has been also investigated for a double null configuration with the X-points laying on the first wall, and with $I_p \cong 9$ MA and $a \cong 0.44$ m. A zero-dimensional analysis of the operating space with H-mode confinement has thus been performed, solving the global power balance equation for a given value of the gain parameter $Q=P_{fus}/(P_{OH} + P_{aux})$. Confinement is assumed to scale as ITER98(y,2) when a power threshold as given in Ref. [12] is exceeded by a factor 1.3. An impurity level of 1.2% B and 10^{-5} Mo was chosen, so that Z_{eff} = 1.31. Assuming a modest profile peaking for both density ($n_0/\langle n\rangle = 1.25$) and temperature ($T_0/\langle T\rangle = 2.5$), access to high-$Q$ operation appears possible. The operating space for Q=30 is shown in Fig. 3. An interesting operating point is the one with $n_{e0} = 6.3 \times 10^{20}$ m^{-3} and T_{e0} = 16.3 keV, corresponding to P_α = 26 MW and values of normalized density $\bar{n}/n_G$ = 0.37 and normalized beta (β_N = 1.1) well below those corresponding to tokamak operating limits. Assuming flatter pressure profiles ($n_0/\langle n\rangle$=1.1 and $T_0/\langle T\rangle$=2.0), access becomes limited to values of Q up to 10.

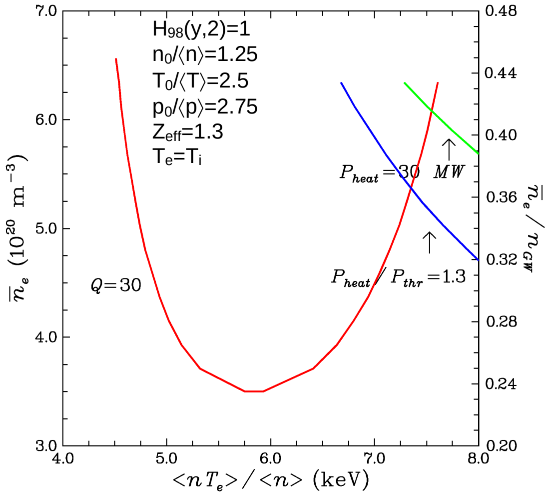

Fig. 3. Operating space for H-mode regimes in Ignitor at Q=30.

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