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Onset of the thermonuclear instability and oscillatory states near ignition*

A. Airoldi[1], G. Cenacchi[2] and B. Coppi[3]

[1] *IFP "P. Caldirola", EURATOM-ENEA-CNR Association Milan, Italy*
[2] *CRE ENEA, Bologna, Italy*
[3] *Massachusetts Institute of Technology, Cambridge, MA, USA*

Introduction

The Ignitor experiment [1] is conceived to benefit from the programmed increase of the toroidal magnetic field (up to 13T), the plasma current (up to 11MA) and the particle density. In the reference scenario the plasma current reaches the maximum value in 4s and the subsequent flattop lasts 4s. The high ratio B_t/R_0 ensures peak plasma densities around 10^{21} m^{-3} and line averaged values that are far from the known density limits [2] for good plasma confinement. A number of simulations carried out with the JETTO transport code [3,4] to study the attainment of ignition have pointed out that Ignitor can reach its goals by operating in L-mode regimes, where no pressure pedestal is formed at the edge of the plasma column. Steady state sub-ignited conditions were investigated by varying the plasma composition and the ion cyclotron heating [5]. In the present study we describe representative discharges where oscillatory states are maintained near ignition.

Numerical Model

In the JETTO code the MHD equilibria are evaluated and coupled to the diffusion equations for the toroidal current density, the electron and ion thermal energies, the plasma fuel densities and two impurity ion densities. The electron thermal transport model is based on the semiempirical Bohm-gyroBohm expression [6]:

$$\chi_e=D_B(\alpha_B q^2 f(s)+\alpha_{gB}\rho^*)(a/L_{Te})$$

where D_B is the Bohm diffusion coefficient, $\alpha_B=4.3\times10^{-3}$ and $\alpha_{gB}=0.1$ are numerical coefficients calibrated so that the energy confinement time is around the value predicted by the ITER97L-mode scaling, $f(s)=H(s)[s^2/(1+s^2)]$ a step function of the magnetic shear s, a the small plasma radius, q the local safety factor and L_{Te} the characteristic temperature gradient length. This model was found to reproduce many experimental results and specifically some FTU data in the presence of electron cyclotron resonance heating at high density. The ion diffusivity is given by the neoclassical value to which a small fraction of the electron χ_e can be added.

Sawtooth oscillations are considered adopting a complete reconnection model (that is pessimistic according to modern theories and experimental indications) triggered by an assigned value of the pressure peaking factor. The ICRH power injection process is represented including the width of the deposition region, the application time and the total absorbed power [5].

The evolution of each individual density profile is governed by a diffusion equation. The density increase is modelled by an inward inflow lasting from the fuelling time t_{fon} to t_{foff}. Each ion species has its specific values for these parameters. In the diffusion equations for the primary ions the boundary condition includes the recycling that assures density conservation in the absence of external inflow. Moreover it is possible to maintain or not, after t_{foff} , the density value reached and to reduce the tritium inflow when the averaged electron temperature overcomes an assigned value.

Representative subignited conditions

The combined influence of RF power and reacting fuel influx was investigated earlier [5] with the aim of producing steady state sub-ignited plasmas and the results showed that fusion relevant conditions could be obtained even with a Tritium/Deuterium percentage as low as 40%. Here we describe some conditions where an interesting fusion burning regime can be produced. In the first case tritium is fed 2s after the discharge start-up so as to assure equal contents of deuterium and tritium (See Fig. 1, left panel) during the flattop duration. The working density during the flattop time is 5.4×10^{20} m^{-3} and the impurity content produces an effective charge $\langle Z_{eff} \rangle \sim 1.3$. An RF pulse (3MW), whose wide spatial distribution is centered at half plasma column, is provided from 3s to 5s (See Fig.1, right panel). The boost given to the temperature increase by the RF pulse around the value of 5-6 keV, when the alpha power overcomes the bremsstrahlung loss at ~4s, is evident. Sawteeth are triggered when the pressure peaking factor ($p_{kf}=p(0)/\langle p \rangle$) outreaches a selected value assumed to be 3.0. The first crash occurs when p_{kf} is quite above 3.0, since the q=1 surface enters the plasma column only at 5.5s, as clearly displayed in the left panel of Fig.2, where p_{kf} is represented together with the value of the central safety factor q_0. In the central panel of the same figure, the ratio between the volume of the plasma column enclosed by the q=1 surface and the total plasma volume is shown together with the local value of the magnetic shear parameter. The region corresponding to the q=1 layer, due to the high plasma current, extends up to 30% of the plasma volume.

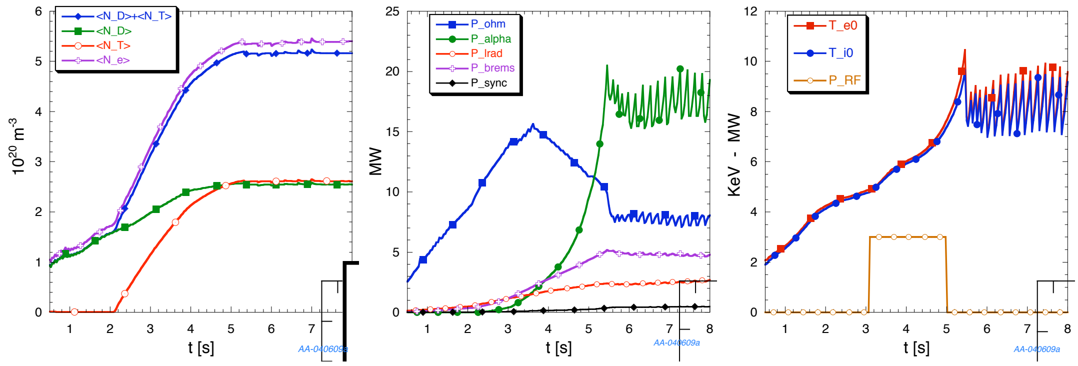

Fig 1. Time evolution of some plasma parameters: left panel presents electron and ion densities; central panel shows ohmic and alpha powers together with radiative losses; right panel shows the peak temperatures of electrons and ions combined with the RF power pulse.

The fusion gain $Q=P_{fus}/P_{input}$ (See right panel in Fig.2) remains over 10 and the ignition margin, $I_M=P_\alpha/P_{input}$, after reaching ~ 0.9 before the first crash, oscillates around 0.6. This performance, actually considerable and comparable with those foreseen for ITER, can be improved by a bit more RF power as it will be shown in the next shots.

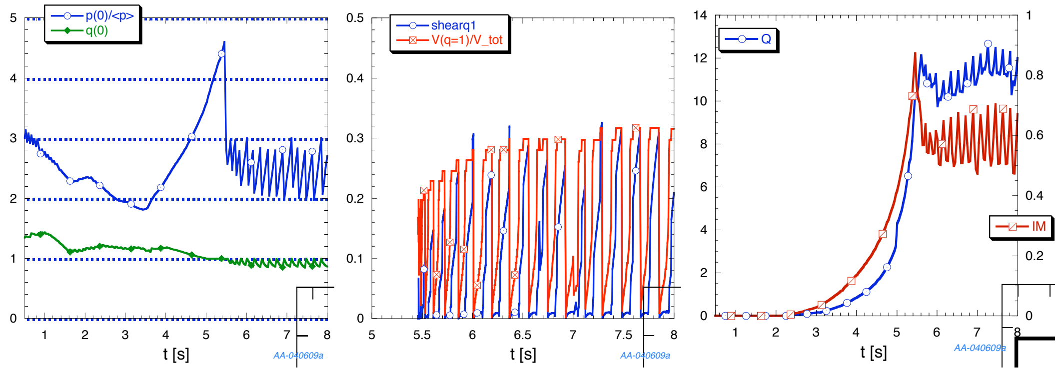

Fig.2 – Evolution of pressure peaking factor and central safety factor (left panel). Central panel shows the magnetic shear on the q=1 surface and the ratio between the q=1 volume and the total plasma volume. Fusion gain Q and ignition margin on the right panel.

In fact, by injecting 3.2MW, with all other conditions unchanged, ignition is attained before the first sawtooth crash and afterwards alpha power could grow steadily reaching values unsustainable. A possible way to control the thermonuclear instability is the reduction of the fuel feeding when the averaged electron temperature overcomes a fixed value. Two shots whose difference is the tritium feeding reduction when <Te> reaches 4.5 keV (Shot 2) or 4.8 keV (Shot 3) are now analyzed. The temperature evolution and the tritium density are plotted in the left panel of Fig.3. The lower tritium content causes an immediate increase in the temperature, but afterwards produces a reduction in the alpha power (See the central panel of Fig.3). However it must be observed that even in this condition the alpha power produced, although not explosive, could be excessive, particularly for shot 3). In both cases ignition is achieved at 5.5s and, after the first crash, the ignition margin oscillates around a value higher than the one of the first shot (~0.7 instead of 0.6).

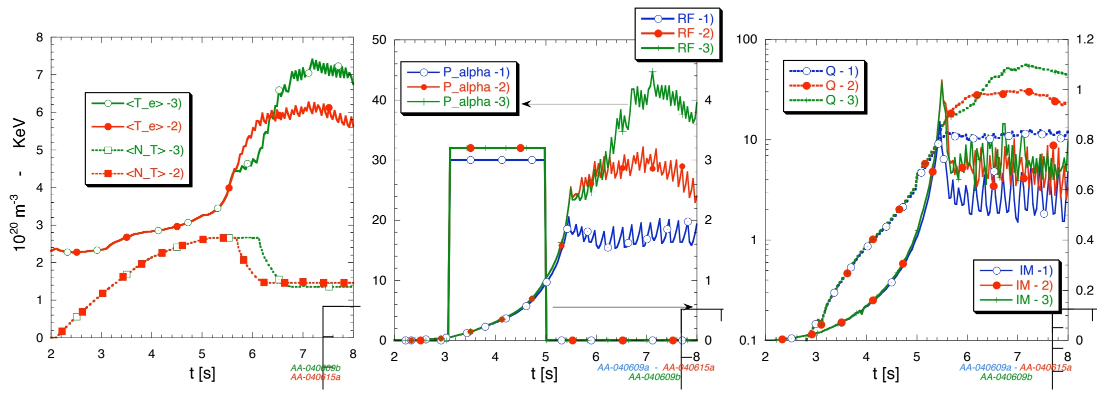

Fig.3 – Time evolution of averaged electron temperature and tritium density in the left panel. Alpha and RF power for the three shots in the central panel. Fusion gain, Q, and ignition margin for the same shots in the right panel.

The right panel in Fig.3 gives the ignition margin and the fusion gain for all described discharges. Note that the attainment of ignition triggers the thermonuclear instability which can lead to a high production of fusion power that could be unacceptable. Note that an ignition margin near 0.6 corresponds to the fusion gain Q about 10.

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