CONSIGLIO NAZIONALE DELLE RICERCHE

Overview of Ignitor performance predictions

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FP 03/8 November 2003

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Overview of Ignitor performance predictions

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Abstract

Quasi-stationary subignited regimes are investigated for Ignitor using the JETTO transport code by controlling the isotopic composition of the plasma and applying appropriate pulses of additional heating to the plasma column. The analysis includes sawtooth oscillations that are expected to arise at the end of the current ramp-up. The two primary ion species (Deuterium and Tritium) evolve separately under independent inflows. The results of the simulations confirm that a careful balance between main ion inflow and RF power injection allows a large range of possibilities for producing sub-ignited discharges throughout the plasma current flattop.

1. Introduction

Among the burning plasma experiments that have been proposed so far, Ignitor [1] has been the first and remains the only one to have the capability of attaining ignition, that is the condition where the power deposited by the fusion α-particles compensates for all plasma losses. The main characteristics of the machine that allow it to reach its goal are the high values of plasma current, poloidal field, and plasma density that it can produce. 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. The combined databases of well confined plasmas with n_0 close or exceeding $10^{21} m^{-3}$, provided by Alcator A, C, C-Mod and FT, FTU machines, give a reliable foundation for extrapolations to Ignitor. A number of simulations carried out with the 1-1/2 D JETTO code [3,4] to study the attainment of ignition have pointed out that Ignitor can operate in standard L-mode regimes where no pressure pedestal is formed at the edge of the plasma column. It has also been shown that a modest injection of ICRH power, during the current rise, may accelerate the achievement of ignition thus allowing the investigation of the relevant burning plasmas over times that exceed the current redistribution time. The optimal conditions for ignition have been identified on the assumption that the primary ion species consists of a mixture of Deuterium and Tritium (D-T) in the same amount. This means that along the simulation the two components present equal spatial distributions. On the other hand, as different fuelling systems (gas inflow, pellet injection) are provided, the ratio between deuterium and tritium ions is likely to differ from unity and the profiles are surely not the same. In the latest studies, here presented and discussed, the deuterium and tritium evolution is governed by independent supplies. This feature is important to study the transition from ignited to sub-ignited discharges during the current flattop; in fact the fuel composition can partially control the thermonuclear instability. In this paper steady state subignited conditions are investigated by balancing the fuel composition and the additional heating power in the presence of sawtooth oscillations. Different trigger conditions are assumed for these instabilities.

The paper is structured as follows: in section 2 the standard Ignitor scenario and the modelling of the plasma evolution implemented in the JETTO code are described. Section 3 summarizes the former simulations and discusses the recent results obtained by assuming the separate fuel feeding. In the final section some conclusions are drawn.

2. Modelling set-up

The Ignitor experiment is conceived to exploit the beneficial effects of the simultaneous increase of the toroidal magnetic field, the plasma current and the particle density. In the reference scenario the toroidal magnetic field reaches 13T and the plasma current *11MA* in 4s; the subsequent flattop lasts 4s, as indicated in Table I.

Table I –Ignitor reference design parameters

Parameter	**Symbol**	**Value**
Major radius	R_0	1.32m
Horizontal minor radius	a	0.47 m
Vertical minor radius	b	0.86 m
Elongation	k	1.83
Triangularity	δ	0.4
Aspect ratio	A	2.8
Toroidal magnetic field	B_T	≤13 T
Plasma current	I_p	≤11 MA
Edge safety factor (@11MA)	q_ψ	3.6
Current ramp-up time	t_{ramp}	4 s
Flattop time (@11MA)	t_{flat}	4 s
Plasma volume	V_0	$\approx$10 m^3
Plasma surface	S_0	$\approx$ 34 m^2

All simulations here described have been performed with an ad hoc version [3] of the JETTO equilibrium-transport code [5]. A different and specialized version is usually applied to reproduce JET experimental results [6]. This code predicts the time evolution of plasma profiles: electron and ion temperatures, plasma fuel and impurity densities, plasma current, internal (ohmic and alpha) and additional powers, together with plasma shape and dimensions. In the most recent version of JETTO the separate evolution of primary ions is implemented. The code allows self-consistent computations of MHD equilibrium, transport fluxes, sources (such as the alpha power or other additional heating), sinks (such as radiation losses) and large scale instabilities (such as sawtooth oscillations). In addition to neoclassical and anomalous thermal diffusion, both electrons and ions undergo thermal transport due to convection. The particle pinch experimentally observed in tokamaks in recent years [7] is modelled by an inward convection since the first version of the code. Current penetration follows the neoclassical formulation.

2.1 Equilibrium configurations

The MHD equilibrium configuration is free-boundary, and is updated along the plasma current ramp-up and flattop. The currents in the poloidal windings assuring the desired plasma shapes are previously computed by a standard equilibrium solver [8] for some "key" plasma configurations, according to the foreseen plasma parameters and taking into account the engineering constraints, as elsewhere described [9]. The consistent evaluation of MHD equilibrium configurations and of current penetration process makes it possible to check the flux balance at the plasma boundary. The total poloidal flux change required along the discharge evolution to establish the nominal plasma current is estimated [3], with the internal flux consumption following the Poynting formalism. The bootstrap current contribution, allowing a spare in the required flux, is automatically taken into account.

2.2 Transport models

Different electron thermal diffusivity models have previously been used and compared [3,4]. A lot of former evaluations are based on the Coppi-Mazzucato formulation while the last ones assume a mixed Bohm-gyroBohm expression [10]:

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

where D_B is the Bohm diffusion term, $\alpha_B=4.3\times10^{-3}$ 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 [11], $f(s)=H(s)[s^2/(1+s^2)]$ is 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. The ion thermal diffusivity is taken to be neoclassical, increased by a small fraction of the electron χ_e. The particle (main ions and impurities) diffusion coefficient follows the electron thermal diffusivity in the form $D_p = \alpha_p \chi_e$. The two impurity species explicitly treated are carbon and oxygen. A heavy impurity (iron) has also been tested [12].

2.3 Sawtooth oscillations

The high current foreseen in Ignitor forces the central low shear region to extend over a significant fraction of the plasma column when the safety factors drops below unity and macroscopic instabilities will set up. The possibility of an active sawtooth stabilization by the presence of energetic particles is here not considered. Different models have been applied to study the central region: flattening of the current density profile or Kadomtsev reconnection, flattening temperature, density and current profiles, with period determined in different ways [13]. In recent evaluations some alternative choices have been made. They span from the absence of instabilities to different sawtooth trigger mechanisms. The critical shear model, applied to reproduce FTU experiments [14] in the presence of electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD), is used with the same coefficient calibrated on ohmic FTU discharges. Other triggers have been tried as a critical peaking factor of the plasma pressure and a critical value of the Bussac poloidal beta. A complete Kadomtsev reconnection is applied in any case. The region involved in the redistribution of current and pressure profiles is the one where the safety factor is less than unity.

2.4 RF heating

Ignitor has been designed to attain ignition by ohmic heating only, if optimized discharges are considered; however an ion cyclotron resonance heating system [15] is included in the project as backup and possible knob to accelerate ignition. By considering 115 MHz as working frequency, the resonant interaction is assured in a sufficiently central plasma region [16] for a toroidal field variation from 9T to 13T in the plasma centre. The

ICRH power injection has been treated by a simple model that takes into account the deposition region, the application time and the total power absorbed, so allowing to identify different heating scenarios. The local source term due to the RF power is written in the form:

$$P_{RF}=P_0\exp\{-(\square-\square_c)/(\square_2-\square_1)\}^2$$

where P_0 is defined so that the total absorbed power is an assigned value, $\square_c$ indicates the flux surface corresponding to the maximum power deposition and $\square_1$, $\square_2$ define the absorption region.

2.5 Deuterium/tritium fuel cycle

The particle evolution is governed by the diffusion equation whose boundary condition includes the recycling that assures the density conservation in the absence of external inflow. The increase in the plasma density is modelled by an inward inflow lasting from the fuelling times t_{fon} to t_{foff}. Each ion species has its specific value for these parameters. In the diffusion equations of the primary ions the boundary condition includes also the recycling that assures the density conservation in the absence of external inflow. After t_{foff}, another knob allows to maintain or not the density value reached. In the deuterium case, after t_{foff} the density is conserved, as it was usually done in the previous simulations where a single species having $A_i=2.5$ was considered. This model can satisfactory represent a gas puffing mechanism, but is not adequate to treat a pellet injection able to assure an internal fuel deposition.

3. Results

A number of previous simulations have identified the optimized conditions allowing the attainment of ignition just after the end of the plasma current ramp, at volume averaged density around $5\square 10^{20}\ m^{-3}$ [4, 17]. The time evolutions of the principal discharge parameters: toroidal magnetic field, plasma current, electron densities and peaking factor, ohmic, alpha and losses power, together with electron and ion temperatures are shown in Fig.1.

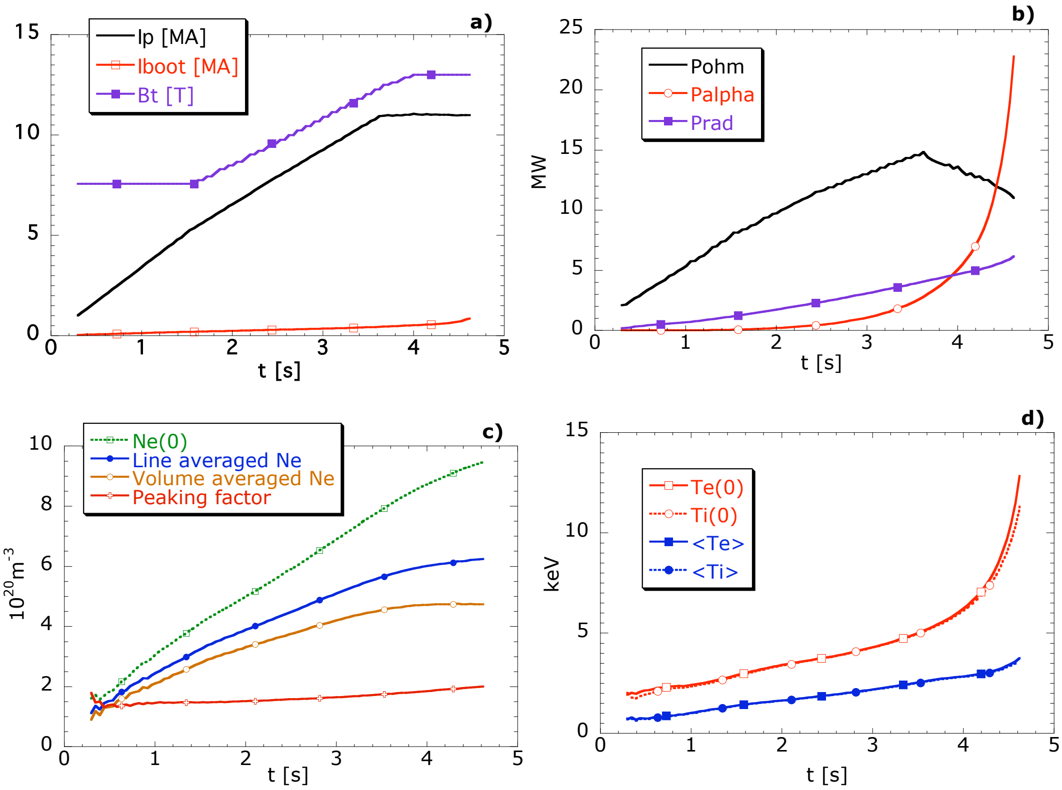


Fig.1 – Time evolution of some parameters in an optimized case using the Coppi-Mazzucato model. In the frame a) are shown magnetic field, total and bootstrap current. In b) ohmic and alpha powers and radiation losses (impurity radiation, bremsstrahlung and synchrotron). In c) electron densities and the peaking factor given by n(0)/<ne>. In d) electron and ion temperatures. The simulation is stopped when ignition is attained

In the case here shown the electron diffusivity follows the Coppi-Mazzucato model; analogous optimized performances have been obtained under different assumptions about the plasma thermal properties [4]. One of the main outcomes of our analyses is the key importance of the plasma density (averaged value and spatial profile) for the attainment of ignition. Moreover a consistent pressure profile has been identified at ignition [4]. Many other remarks are valid independently of the adopted transport model as the performance degradation due to high impurity content and to the presence of sawtooth oscillations. However it has been shown that in the degraded cases a suitable application of auxiliary heating can recover the optimal conditions [16].

The abovementioned predictions were usually stopped at ignition and the plasma fuel was treated as a single ion species of atomic mass 2.5. Notice that this assumption is "*in itself*" an optimistic hypothesis and it should be handled with care when deuterium discharges are extrapolated to D-T experiments. In fact the product $n_D n_T$ in the fusion power is maximum when the n_D and n_T profiles are equal while, in the experiments, being fed by separate systems, they will be different. Recent evaluations refer to shots where the Deuterium and Tritium ions evolve separately under different inflows [18] so as to study more realistic conditions along the current flattop. In the first discharge here presented the tritium gas is fed from *1.8s* to *6.1s*. The tritium to deuterium ratio is compared to the evolution of the electron density in the upper right plot of Fig.2, where the evolution of the main plasma parameters is presented. The volume averaged electron density maintains the optimal value around $5\times10^{20}m^{-3}$ from *4.5s* to *6s* and then decreases following the drop in the tritium component. The ion temperature is equal for each considered species: in fact there is a single evolution equation for the ion energy. No additional heating and no MHD instabilities are considered so the central safety factor drops to a value as low as 0.6. Ignition is attained at 6.7s (See Fig.3); shortly after the alpha production reaches a maximum and then decreases due to the lacking of fuel. Notice the high values achieved by the alpha power and the electron/ion peak temperatures, well over the ones usually obtained in the simulations and assumed as safe for the machine integrity.

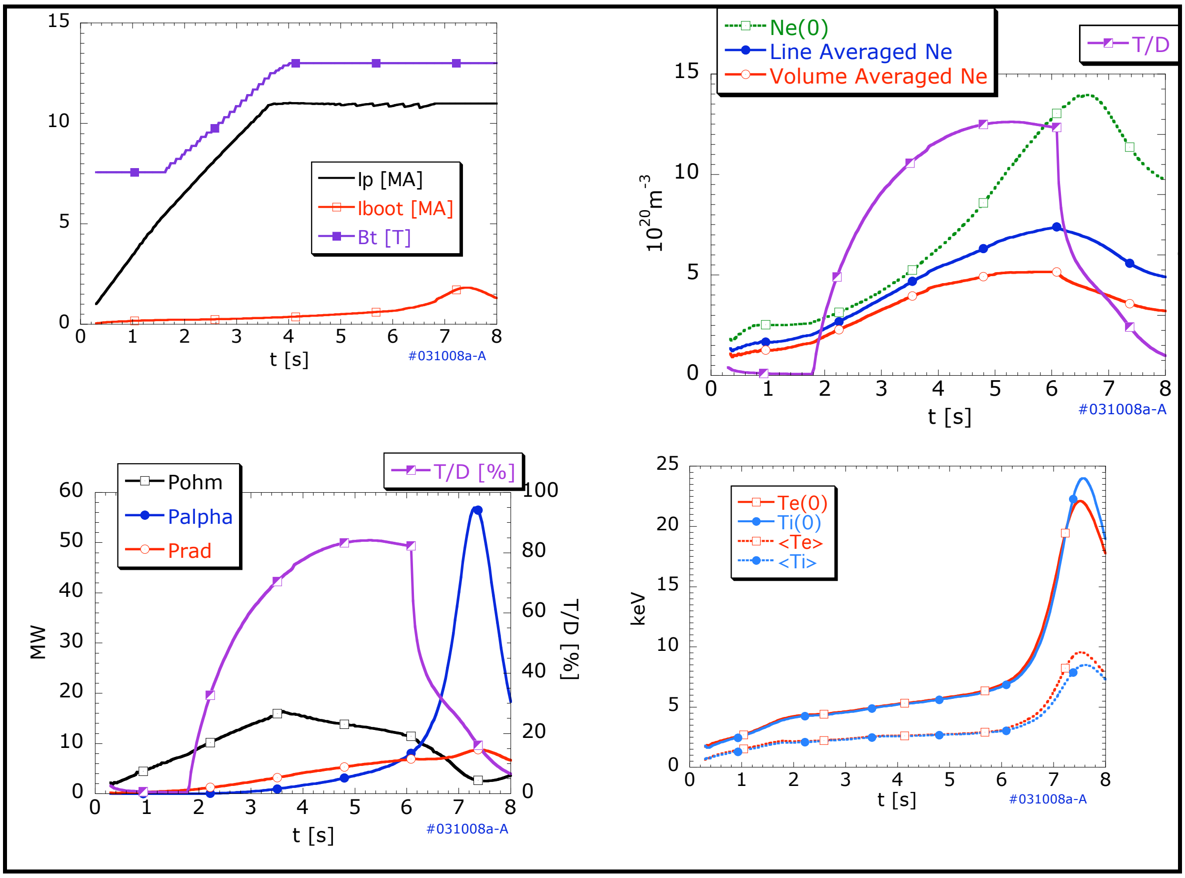
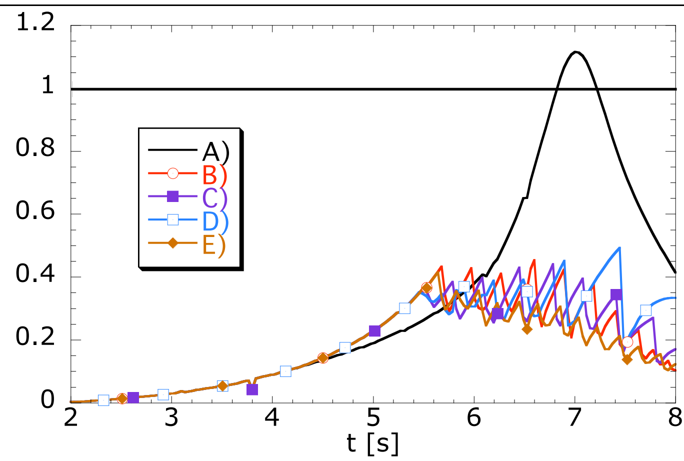


Fig.2. Time evolution of plasma parameters in an ohmic discharge with tritium injection from 1.8s to 6.1s, using the Bohm-gyroBohm model. Macroscopic instabilities are not considered.

However, in the same conditions, the activation of some instabilitiy mechanism degrades the performances. Different sawtooth trigger conditions have been considered when the safety factor in the central region is below unity and the time evolution of the relevant ignition margin defined by $I_M=P_{\square}/P_{loss}$ is plotted in Fig.3. Case A) is the same of Fig.2 and is represented for comparison. The other shots differ by the trigger condition (as listed in the right side of Fig.3) and they all include a 1.5MW pulse of additional heating from *4.3s* to *5.8s*; this fact is pointed out by the I_M increase before the first crash. Independently of the model considered for the sawtooth trigger, the performance comes out to be degraded. The basic condition for the sawtooth onset is that the safety factor fall under unity: when it happens the different trigger conditions (critical shear, pressure peaking or $\square_{p1}$ value) are anyway satisfied. This accounts for the similar results in the different simulations.



A) no sw

B) critical shear

C) p(0)/<p>=3.25

D) $\square_{p1}$=0.16

E) $\square t_{rep}$=0.2

Fig 3 – Evolution of the ignition margin I_M in the absence and in the presence of sawteeth.

The subsequent analysis is committed to the possible improvements obtainable, even in the presence of instability oscillations, by a longer tritium pulse or by an increased additional heating. Here the sawtooth trigger mechanism is given by the pressure peaking factor that is not allowed to overcome *3.25*. Case C) in Fig.3 is assumed as test shot; cases C2) and C3) have the tritium fuelling continued up to *7.1s* and moreover in case C3) the RF pulse is increased to *3MW*. The different options are listed in Table II; the ignition margin plotted in Fig.4 shows the better performance recovered. The major enhancement is due to the increase in the additional heating, as it gives a boost to the ion temperature around *5-6 keV*. These analyses open a wide operation space where sub-ignited plasmas can be maintained during the flattop time.

Table II – Timing of the T feeding and I_M characteristic features.

Shot	Time of T feeding	RF power	I_M max	$t(I_M$ max)	I_M at 1st trigger
C	1.8s – 5.8s	1.5 MW	0.44	6.8s	0.35
C2	1.8s – 7.1s	1.5 MW	0.48	7.6s	0.35
C3	1.8s – 7.1s	3.0 MW	0.61	6.9s	0.53

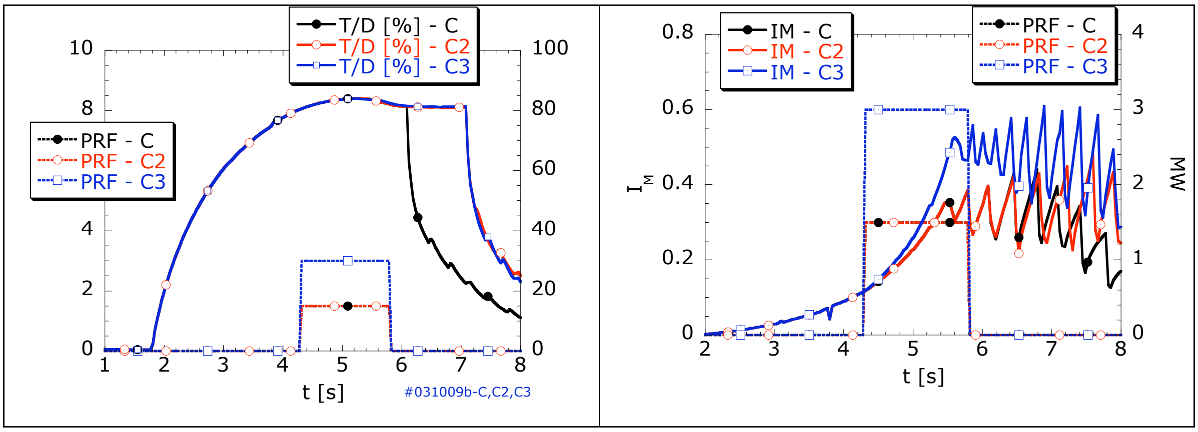


Fig.4 – Time evolution of the additional RF power pulse contrasted with the T/D percentage and the ignition margin for the shots listed in Table II.

Other combinations of tritium increase and RF pulse are plotted in Fig. 5 together with the relevant ignition margin evolution. The injected additional power is sufficient for obtaining sub-ignited conditions: the closer Tritium/Deuterium percentage is to 100%, the lower a power needed to obtain fusion performance. When the fuel composition is poorer, higher amount of additional heating produces higher temperatures that in part compensate for the reduced factor n_T□n_D in the alpha power source. Notice that the parameter $Q=P_{fus}/P_{IN}$, being P_{IN} the total input power (ohmic and additional) turns out to be near or greater than 10.

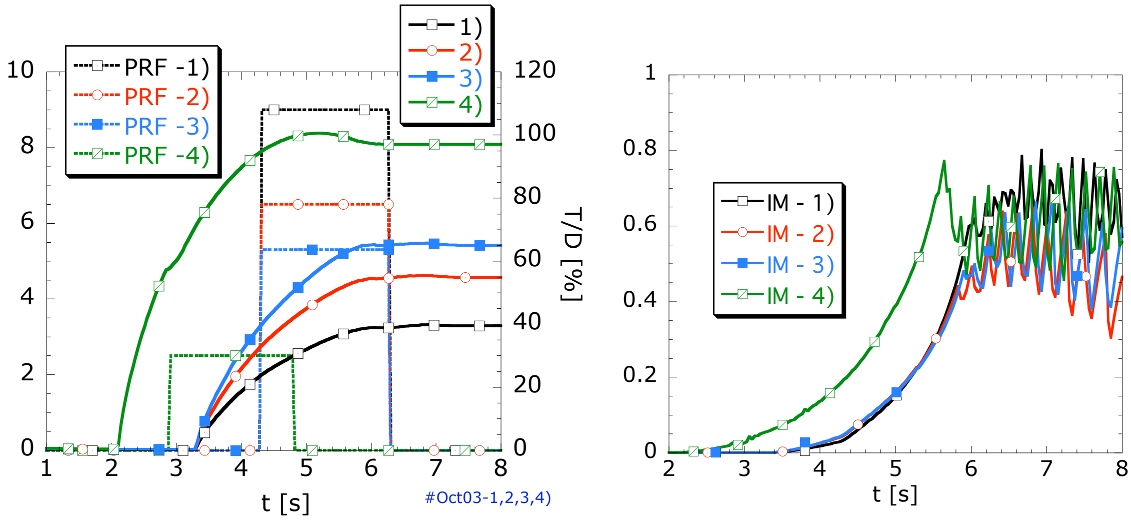


Fig.5a – RF pulse and tritium/deuterium ratio on the left. Ignition margin on the right.

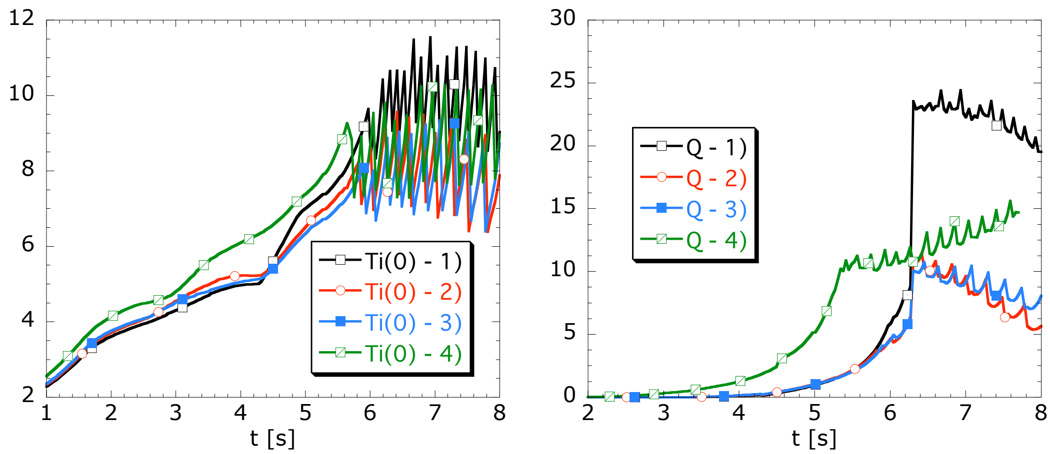


Fig.5b – Peak ion temperatures and Q evolution in the cases in Fig.5a

These evaluations assure that a careful balance between main ion inflow and RF power injection allows a large range of possibilities for producing sub-ignited discharges along the plasma current flattop. Notice that the ignition margin at the first crash is near equal to the maximum value further attained. Moreover the tritium fuel can be less than half of the deuterium component if sufficient additional heating is provided. Another feature to be pointed out is that a bit more RF power allows the ignition attainment before the sawteeth onset. In fact, in the same conditions of case 4) in Fig.5, a slight increase in the injected power (that is *3MW* instead of *2.5MW*) is enough to ignite before the first crash, so recovering previous optimized results [19]. The ohmic and alpha power evolutions relevant to the two cases are compared in Fig.6.

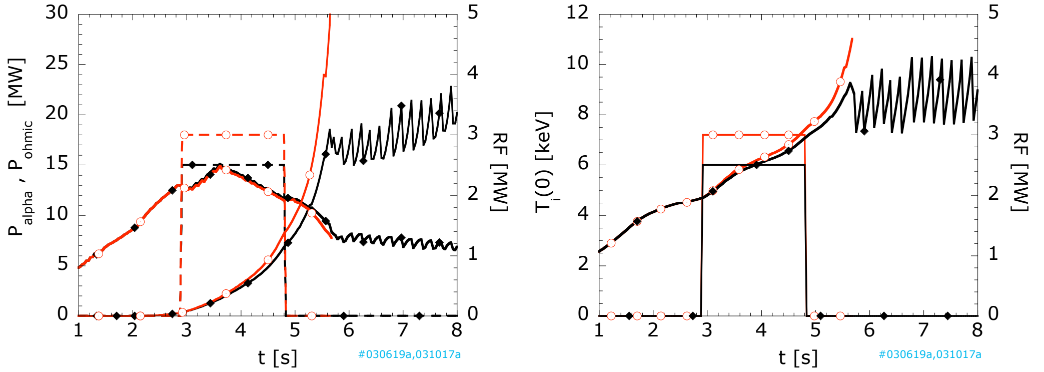


Fig.6 Time evolution of ohmic, alpha and RF powers in the left frame. Ion peak temperature in the right frame. The black lines refer to case 4) of Fig.5. In the other case the simulation is stopped when ignition is achieved.

Conclusions

This paper refines previous evaluations by tackling the problem of the control of the tritium fuel in Ignitor. In this context the ignition achievement is not considered the main and unique goal of the machine, as indeed it turns out to be obtainable. It has been verified that subignited discharges can be maintained during the flattop time by combining the tritium to deuterium ratio and the additional heating power. A higher amount of additional heating compensates for a fuel poorer in the tritium component by producing higher temperatures that increase the fusion rate production albeit the n_T/n_D factor in the alpha power source is reduced. The results here discussed confirm the Ignitor capability of exploring, with high confidence, ignited and subignited conditions.

Acknowledgments

Strong benefits to this work are due to repeated discussions with Bruno Coppi who devised Ignitor. His criticism and encouragement are warmly acknowledged.

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