CP1-035

DYNAMICS OF IGNITING PLASMAS

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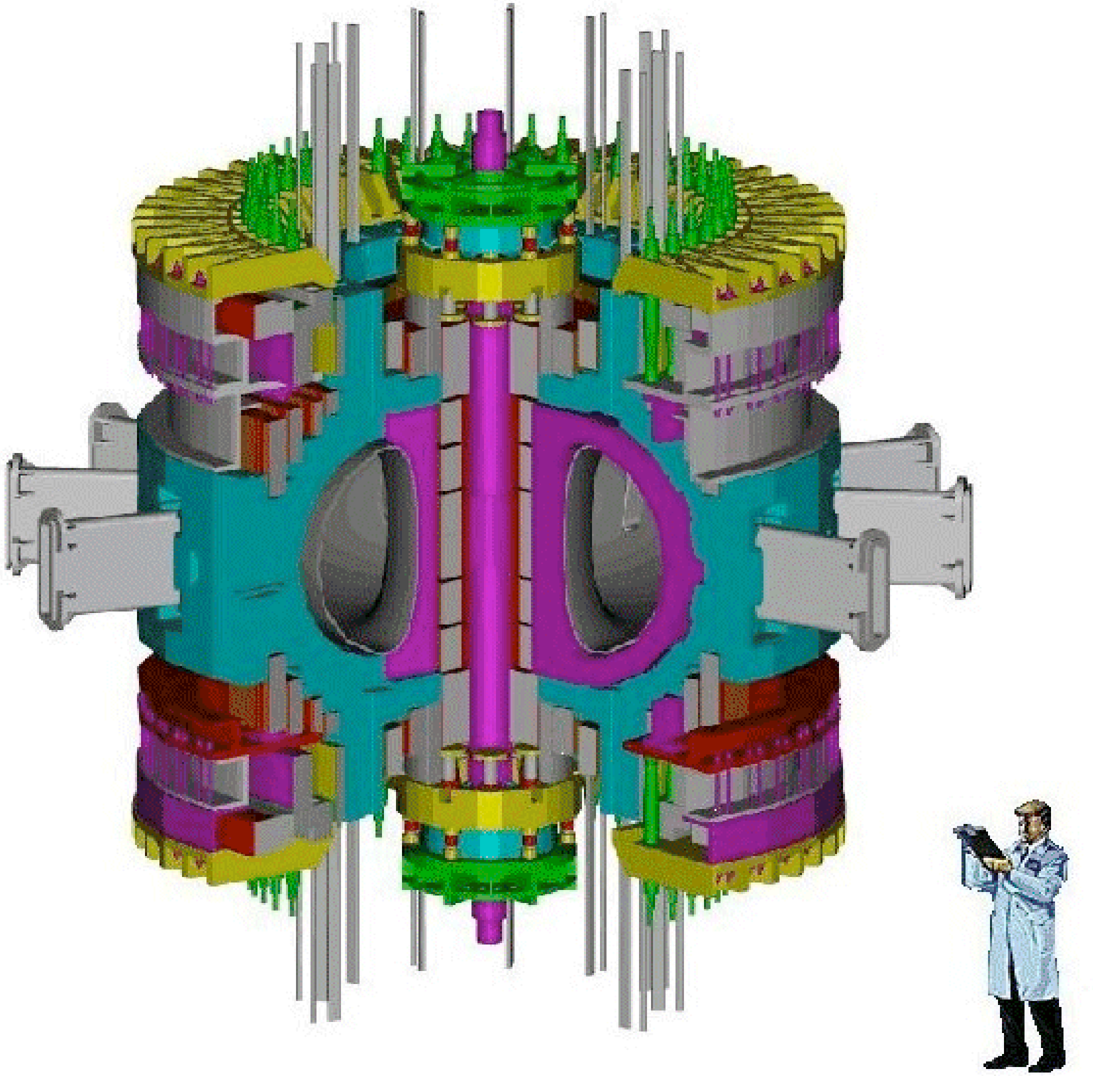
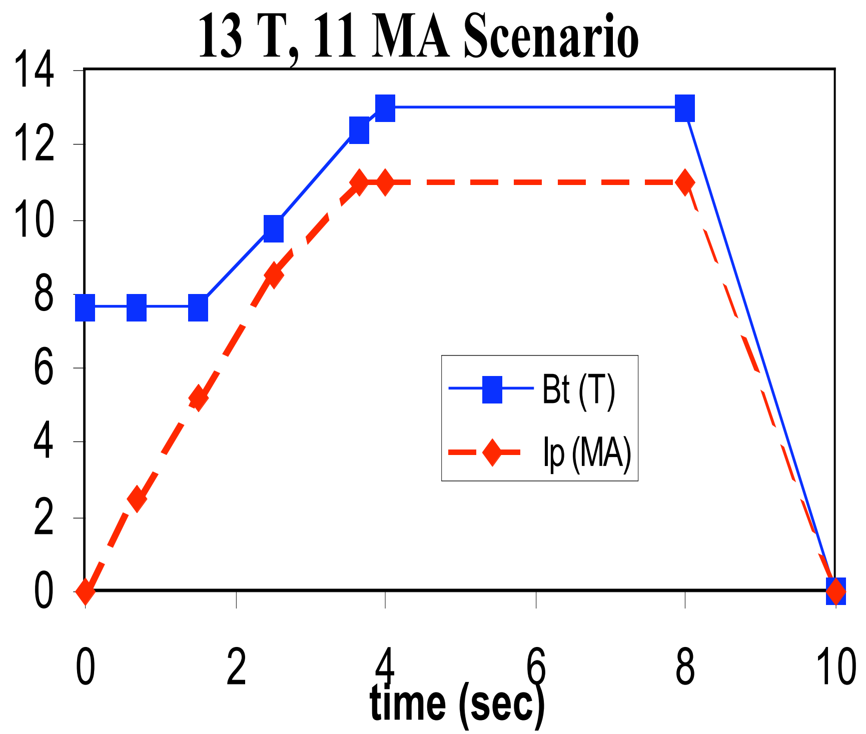
Abstract

A unique feature of the Ignitor experiment [1,2] is that is designed to reach for the first time the conditions where the thermonuclear instability due to α-particle heating can develop. We have investigated the means by which the instability can be controlled, including the injected plasma heating power, the deuterium/tritium concentrations, and the effects of the expected sawtooth oscillations driven by the plasma pressure gradient. An ad hoc version of the JETTO transport code [3] has been used with the deuterium and tritium densities evolving separately under independent inflows. The boundary conditions for the main ion diffusion equations include recycling that assures density conservation in the absence of external inflows. Different combinations of the inflows of the main ions and of the duration and values of the injected RF power are shown lead to a large range of possibilities, from the onset of ignition and of the thermonuclear instability to quasi-stationary burning plasmas with a fusion gain, $Q=P_{fus}/P_{input}$, exceeding 10.

IGNITOR MACHINE



Standard Ignitor scenario



Major radius	R_0	1.32m
Minor radii	a×b	0.47m × 0.86m
Aspect ratio		2.8
Elongation	k	1.8
Triangularity	δ	0.4
Toroidal field	$B_T(R_0)$	13T
Toroidal current	I_p	11MA
Poloidal current	I_ϑ	8 MA
Plasma Volume	V	10 m^3
Plasma Surface	S_a	36 m^2
Safety factor	q_Ψ	3.6
Discharge time	t	(4 + 4)s

Thermal transport 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 [4]:

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

being D_B the Bohm diffusion, $\alpha_B=4.3\times10^{-3}$ and $\alpha_{gB}=0.1$ 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.

Modelling set-up

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 characterized by 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 a further knob allows to reduce the tritium inflow when the averaged electron temperature overcomes an assigned value.

Subignited representative conditions

In the illustrative 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 is such to produce an effective charge $\langle Z_{eff} \rangle \sim 1.3$.

An RF pulse (3.4MW), whose wide spatial distribution is centered at half plasma column, is provided from 3.2s to 4.8s (See Fig. 2, right panel).

Notice the boost given to the temperature increase by the RF pulse so that the alpha power overcomes the bremsstrahlung loss at ~4s.

Sawteeth are triggered when the pressure peaking factor ($p_{kf}=p(0)/\langle p \rangle$) outreaches a selected value assumed to be 3.0.

Plasma density evolution

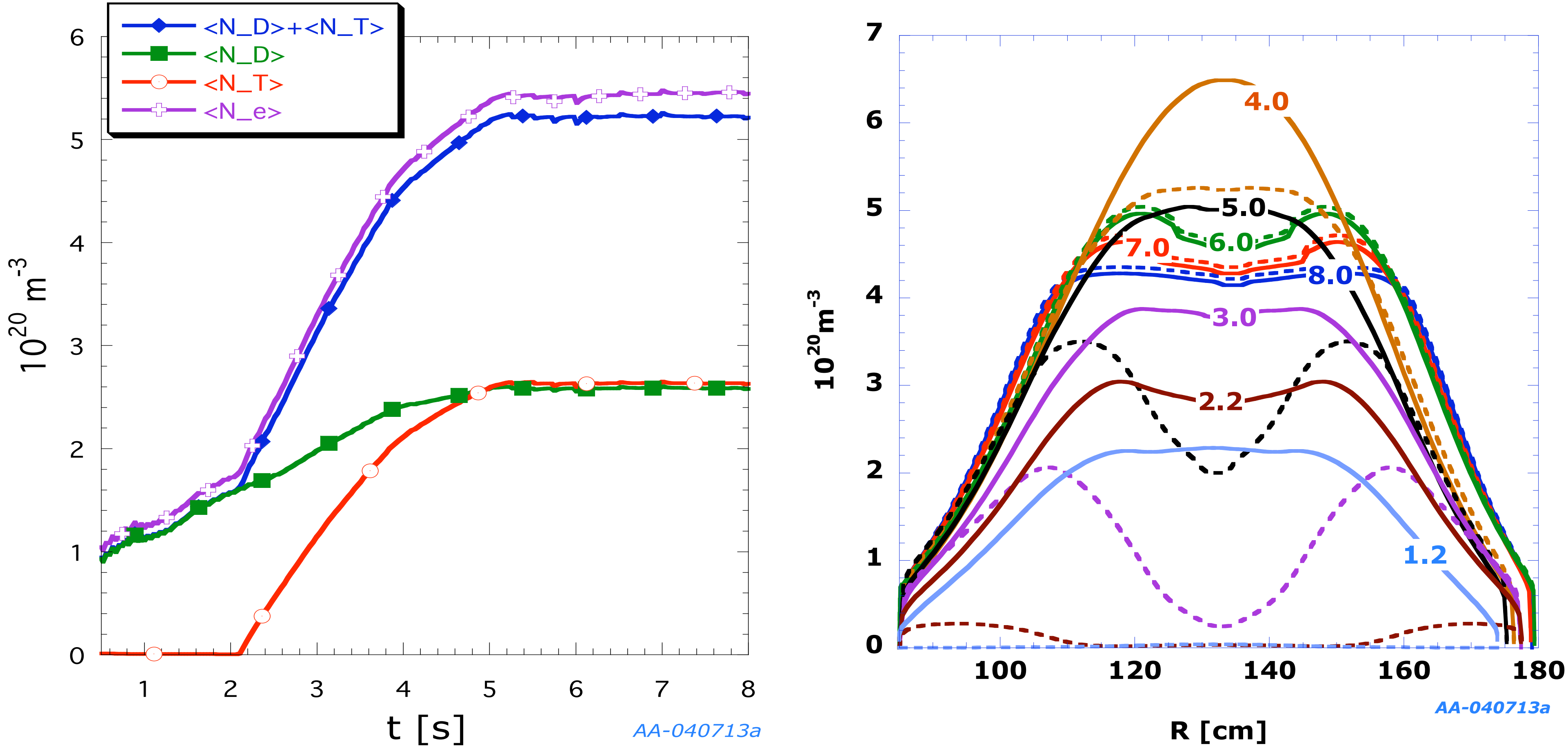


***Fig. 1 -** Electron and ion densities in the left panel; deuterium (full lines) and tritium (dotted lines) profiles at selected times (labels on the curves) in the right panel.*

Powers and ion temperature evolution

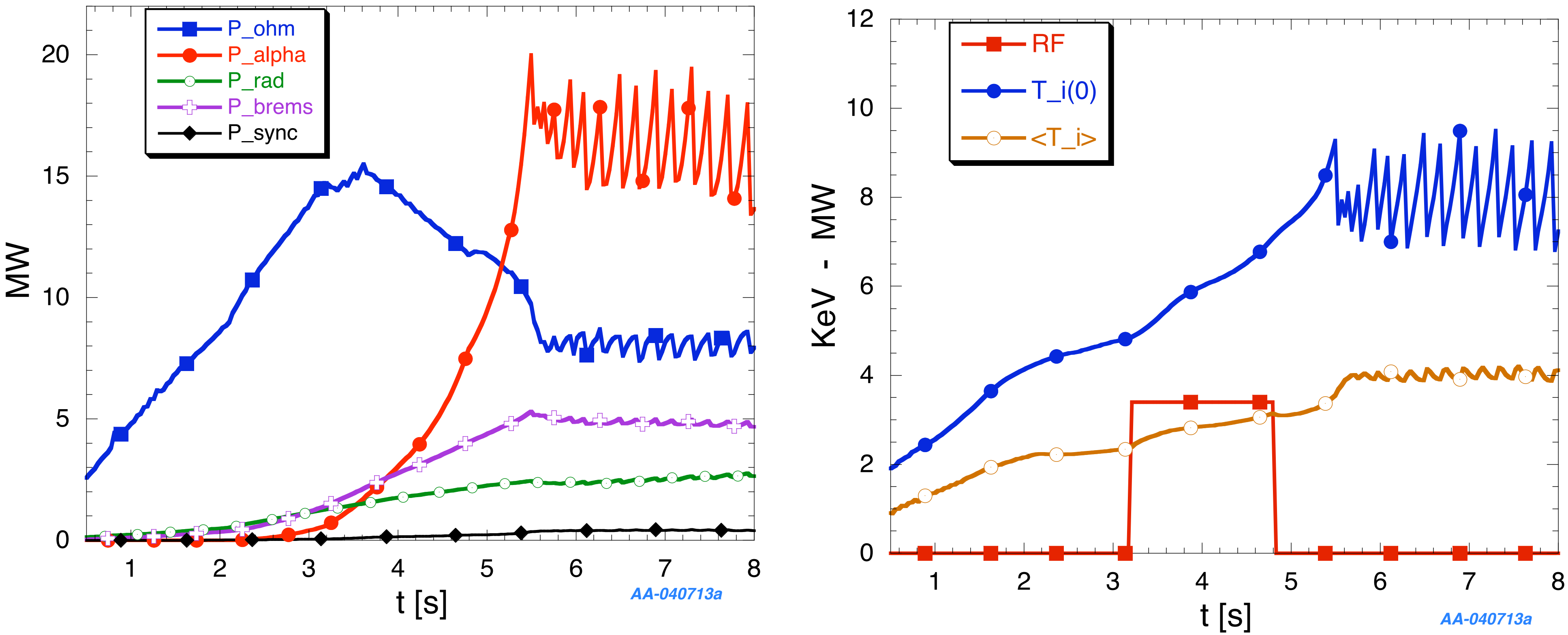


Fig. 2 - *Left frame: ohmic, alpha and loss powers; right frame: peak and volume averaged ion temperature and RF pulse. The RF pulse facilitates the alpha power overtaking of the bremsstrahlung losses.*

Safety factor profiles

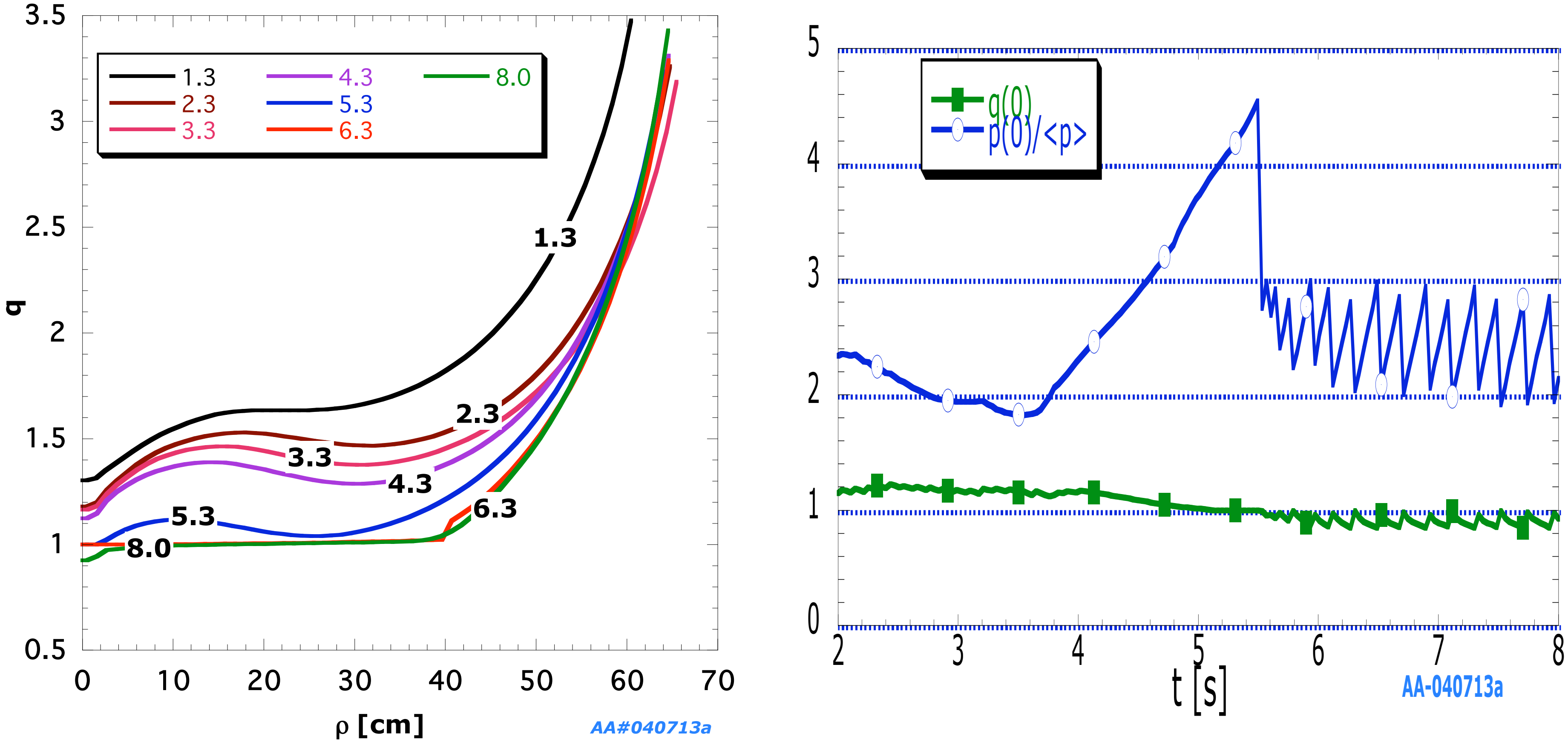
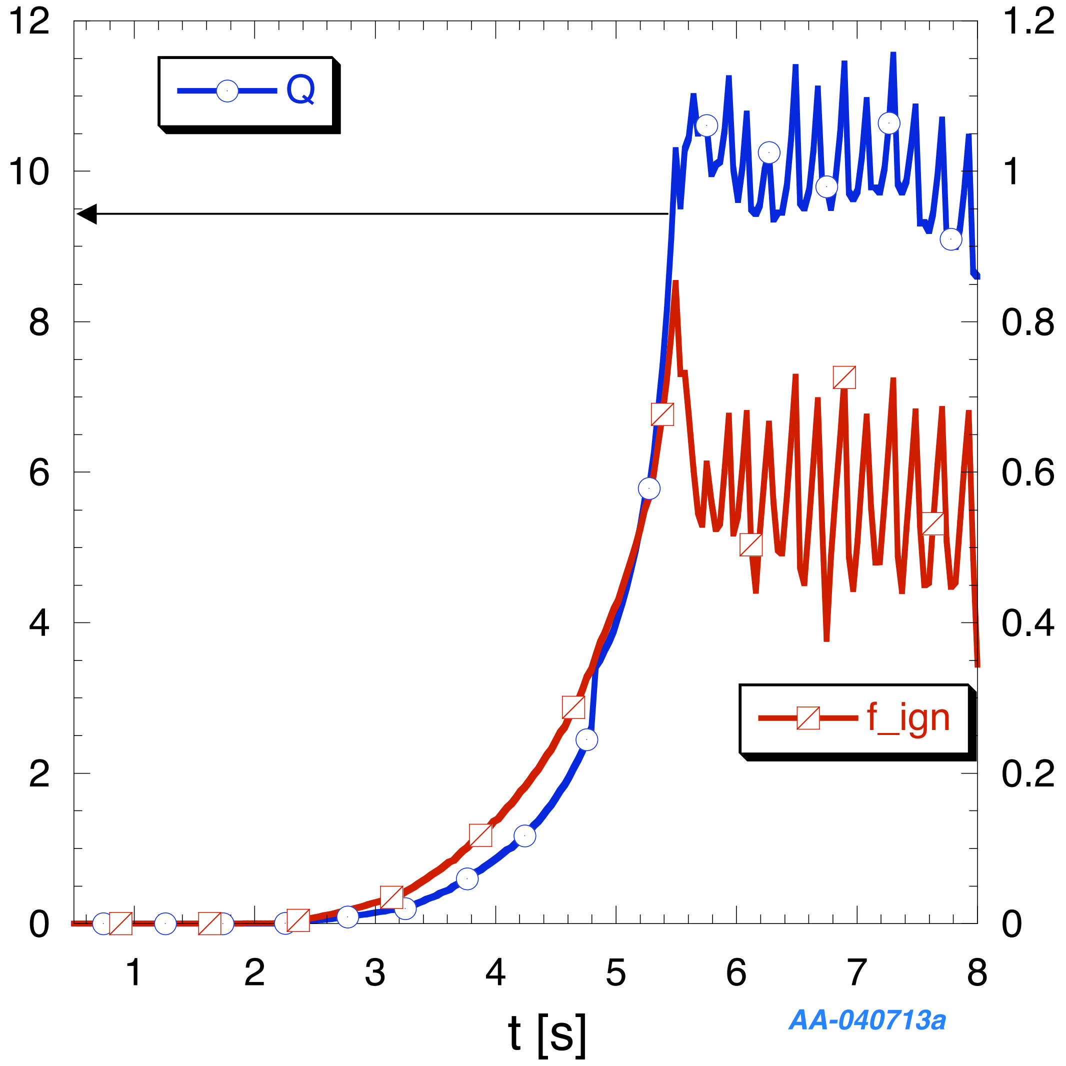


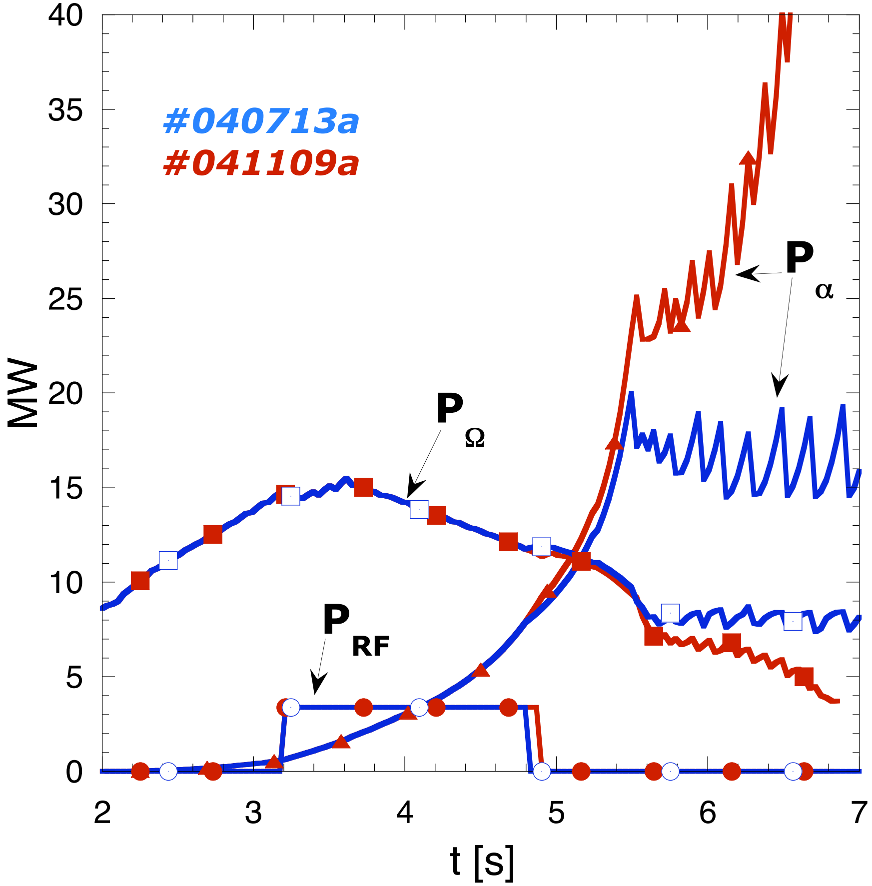
Fig. 3 - *Safety factor profiles at selected times (labels on the curves) in the left panel. Pressure peaking factor and central q in the right panel*

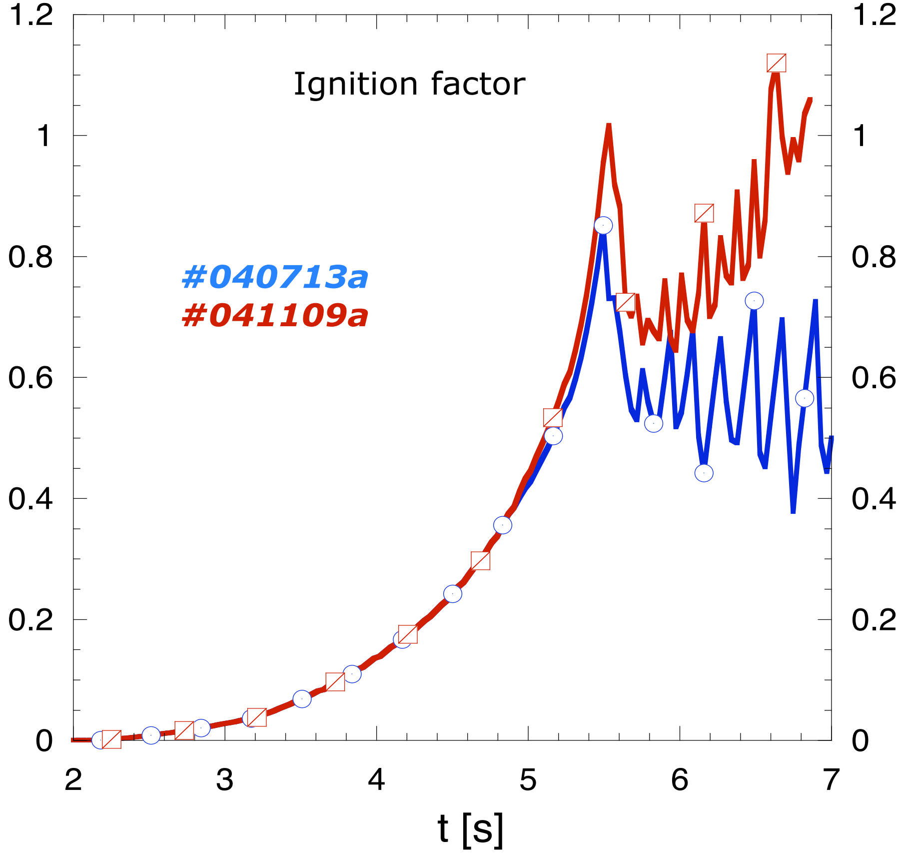
Fusion gain Q and ignition factor



The fusion gain $Q=P_{fus}/P_{input}$ remains ≈10 and the ignition factor, $f_{ign}=P_{\alpha}/P_{input}$, after reaching ~ 0.9 before the first crash, oscillates around 0.6. This result can be dramatically improved by a bit higher or longer RF pulse as it will be shown in the next shot.

Effects of a longer RF pulse





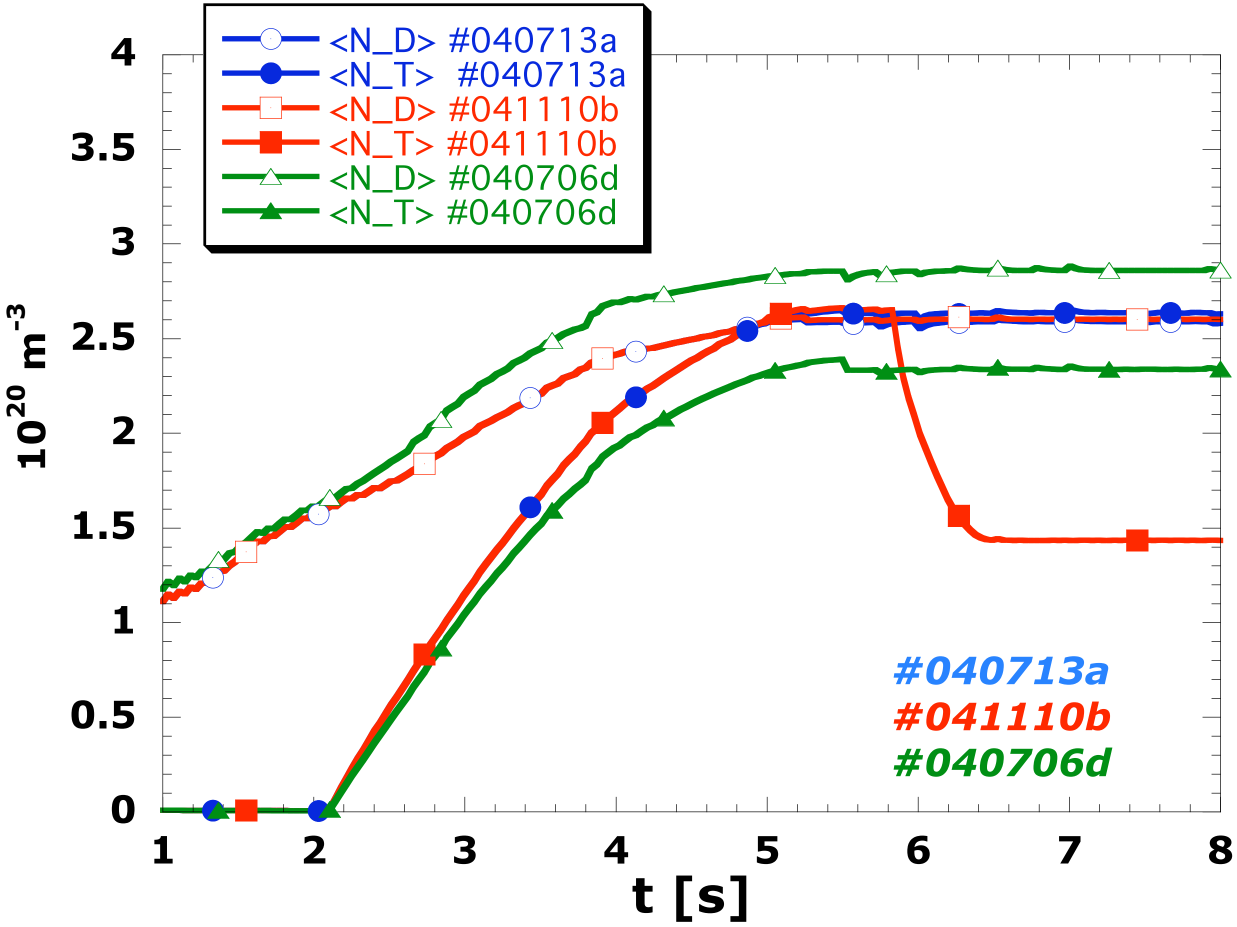
A bit longer RF pulse produces ignition before the first sawtooth crash and alpha power growth up to values that could be unsustainable by the machine structure.

Control of thermonuclear instability

In order to avoid a dangerous fusion power production it is possible to operate with a D/T mixture more diluted than the 50/50 nominal one. This unbalanced mixture can be produced by a lower tritium inflow or by a reduction in the tritium recycle triggered when the electron temperature overcomes a selected value.

The previous illustrative shot **(#040713a)** is now contrasted with a pulse **(#040706d)** having a lower tritium content, i.e D/T = 55/45, and a pulse **(#041110b)** with a tritium reduction up to D/T = 64/36, triggered when the averaged electron temperature overcomes 4.5 keV.

Different tritium feeding - 1)



In the pulse #041110b the tritium feeding is reduced when $\langle T_e \rangle$ overcomes 4.5 keV

Fig. 4 - *Time evolution of volume averaged deuterium and tritium densities. Open markers refer to D density, full ones to T density.*

Different tritium feeding - 2)

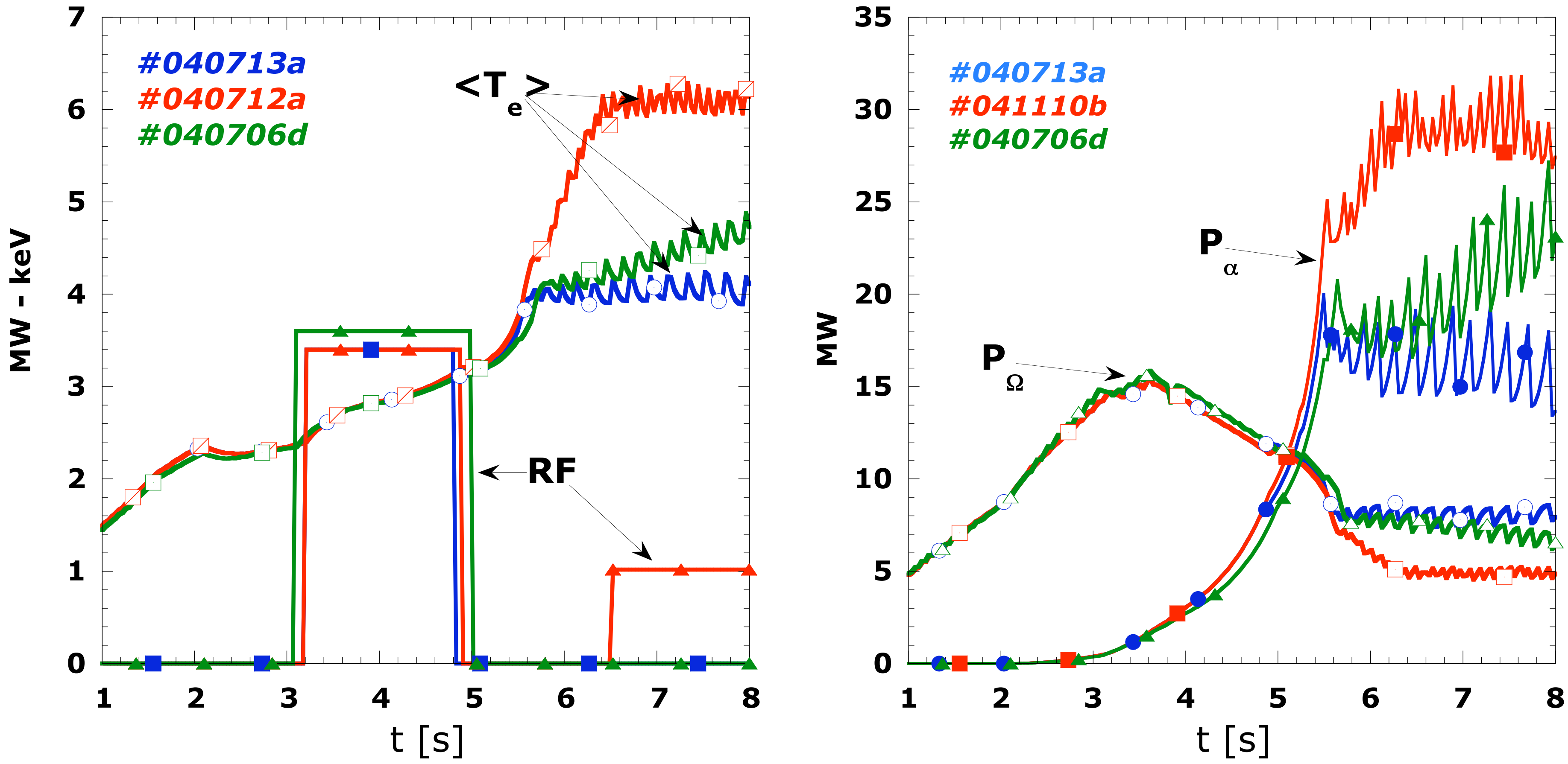


Fig. 5 - *Left panel: RF power and volume averaged electron temperatures. Right panel: ohmic and alpha powers.*

Different tritium feeding - 3)

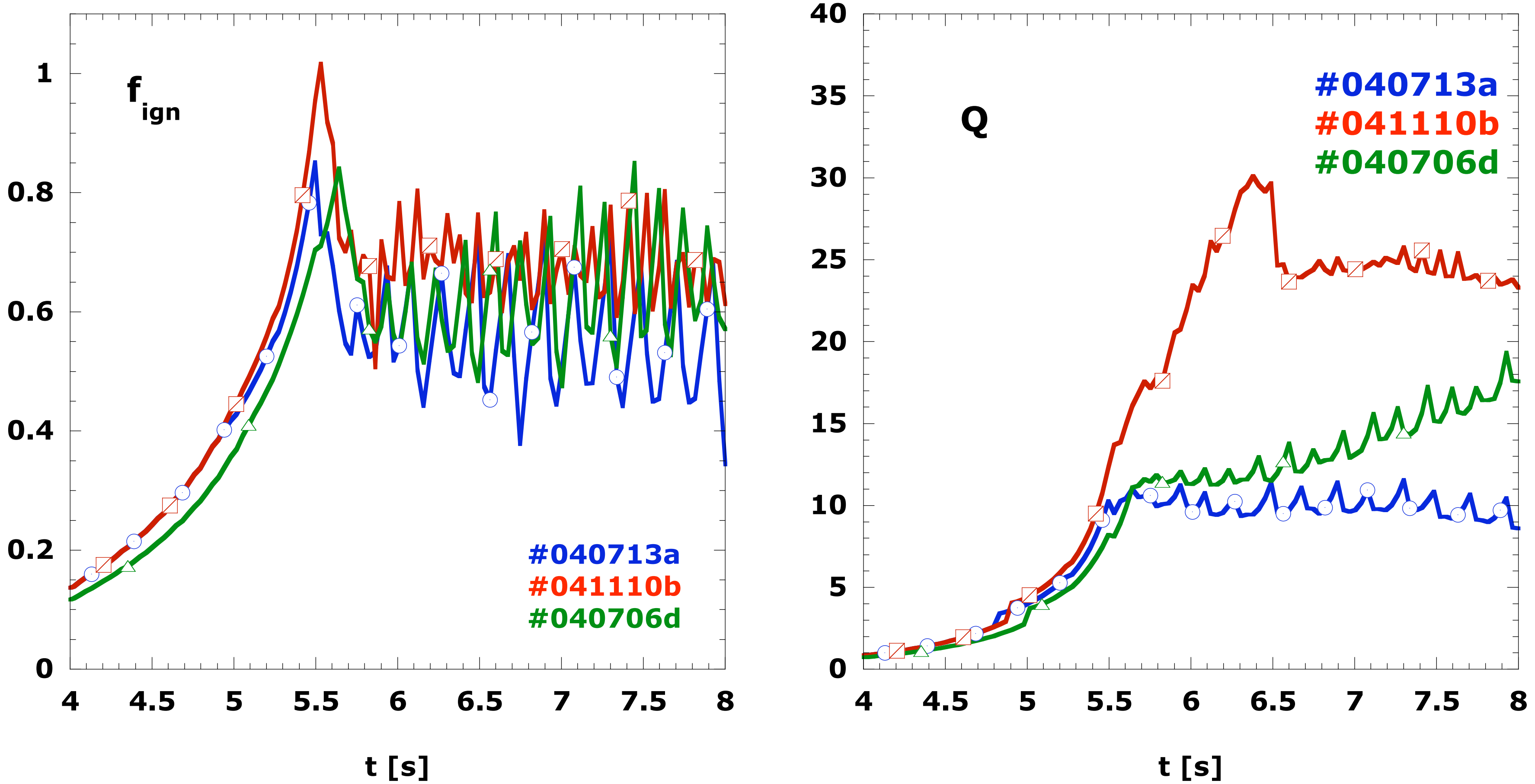


Fig. 6 - *Time evolution of ignition factor (left panel) and fusion gain (right panel).*

Comments

- **The ignition attainment triggers the thermonuclear instability with a production of alpha power which could be excessive.**
- **It is safer to consider operative scenarios in subignited conditions: in fact an ignition margin near 0.6 is sufficient to assure a fusion gain, *Q*, overcoming 10.**
- **Subignited discharges can be maintained during the flattop time by properly combining the tritium to deuterium ratio and the additional heating power**

References

[1] B. Coppi, al., Report PTP99/06, MIT, Cambridge, MA (1999)

[2] B.Coppi, et al., *Nucl. Fusion* **41**, 1253 (2001)

[3] A.Airoldi, G.Cenacchi, *Nucl. Fusion* **37**, 1117 (1997)

[4] G. Vlad, et al., *Nucl. Fusion* **41**, 687 (2001)

[5] A.Airoldi and G. Cenacchi, IFP Report FP 03/8 (2003)