Relevant Advances of the Ignitor Program*

F. Bombarda[1,2], B. Coppi[2], A. Airoldi, G. Cenacchi[3],
P. Detragiache[1]
[1]ENEA, Italy
[2]Massachusetts Institute of Technology, Cambridge, MA
[3]Previously at ENEA, Italy

Paper 1C27
2007 International Sherwood Fusion Theory Conference
April 23 - 25, 2007

Abstract

The main purpose of the Ignitor experiment [1] is to establish the “plasma reactor physics” in regimes close to ignition, as required for net energy producing reactors, where the “thermonuclear instability” can set in with all its associated non-linear effects.

That reactor relevant plasma regimes require $Q > 50$ is well understood by now [[2]]. The only appropriate solution at this time to reach this objective is the adoption of normal-conducting magnets. Furthermore, experiments without a divertor chamber can sustain, for equal overall sizes and magnetic field values, higher currents and therefore achieve better confinement parameter [2].

The broader range of accessible plasma regimes, which include extended limiter and double-null configurations, will be discussed in the context of a “science first” approach to the development of a fusion energy program. In fact, since the process of attaining ignition has been investigated extensively [1], the more recent efforts have been devoted to identify the conditions where the thermonuclear instability is barely prevented over the entire length of the current pulse, to define the parameter space that can be covered in H-mode regimes, and to simulate the plasma performances at lower field and currents. While tritium is the necessary step forward of any advanced fusion facility, Ignitor can provide novel and important results even when limited to operate with H, D, and He plasmas in the early phase of its experimental life.

[1] B. Coppi, A. Airoldi, F. Bombarda, et al, *Nucl. Fusion* **41(9)**, 1253 (2001).

[2] P.H. Rebut, *Plasma Phys. Control. Fusion* **48**, B1, 2006.

Ignition conditions: $P_\alpha = P_L$

$$\varepsilon_\alpha n^2 \langle \sigma \mathrm{v} \rangle / 4 = 3nT / \tau_E$$

$$\langle \sigma \mathrm{v} \rangle \propto T^2$$

$$P_\alpha \propto n^2 T^2$$

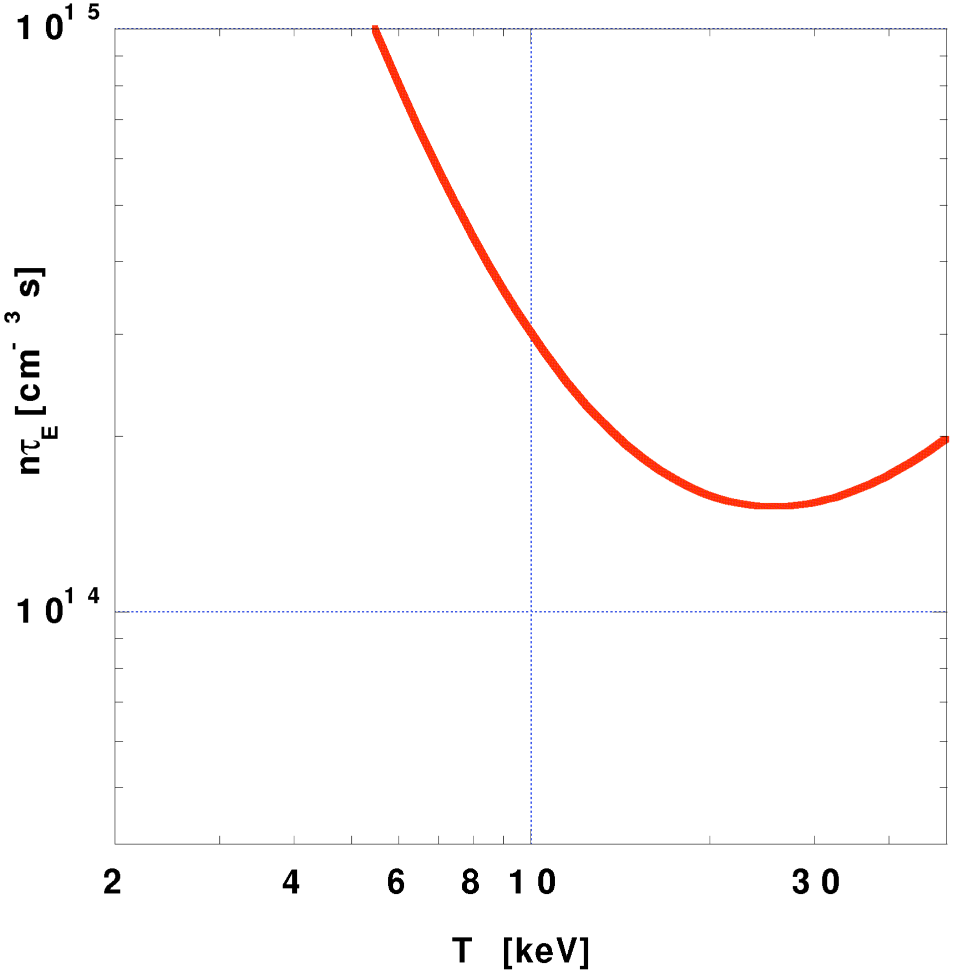
From stability considerations: $p \propto B_p^2$

$$\Rightarrow P_\alpha \propto B_p^4$$

Furthermore

$$T_e \sim T_i$$

$$Z_{eff} \sim 1$$



Reactor Relevant Plasma Regimes

$$Q = 5K_f \big/ \left(1 - K_f\right) > 50$$

$$K_f = P_f \big/ \left(5P_L\right) \lesssim 1$$

$P_F = 5P_\alpha$ =Total fusion power

$P_\alpha = n^2 < \sigma \mathrm{v} > E_\alpha / 4$

$P_L = 3VnT \big/ \tau_E$

$$Q = 10 \Rightarrow K_f = 2/3$$

Even if it could be reached, it is too low for a meaningful reactor!

Instabilities at All Scales

⇒Macroscopic Modes:

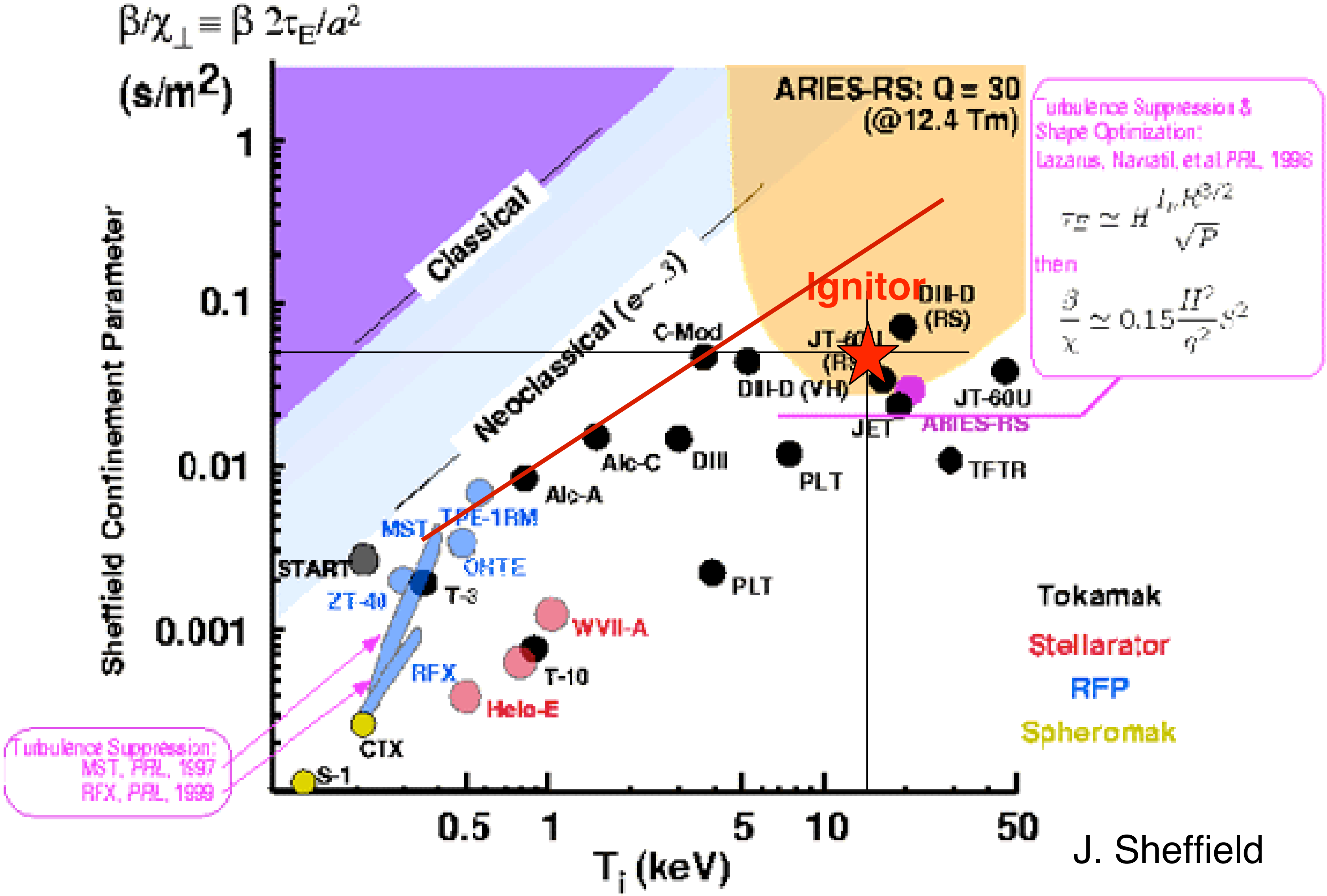
- Internal $m = 1$
- Ballooning Modes + α-particles
- ELMs

⇒Mesoscopic Reconnecting Modes involving Fishbone Modes due to α-particles

⇒Contained Magnetosonic Modes

$\tau_{\alpha}^{Sl} \sim \tau_{E}$ is not a recommended design criterion

Fusion Energy Relevant Levels of β/χ have been Achieved for Short Pulses



Turbulence Suppression & Shape Optimization:
Lazarus, Navratil, et al. PRL, 1996

$$\tau_E \simeq H \frac{I_p R^{3/2}}{\sqrt{P}}$$

then

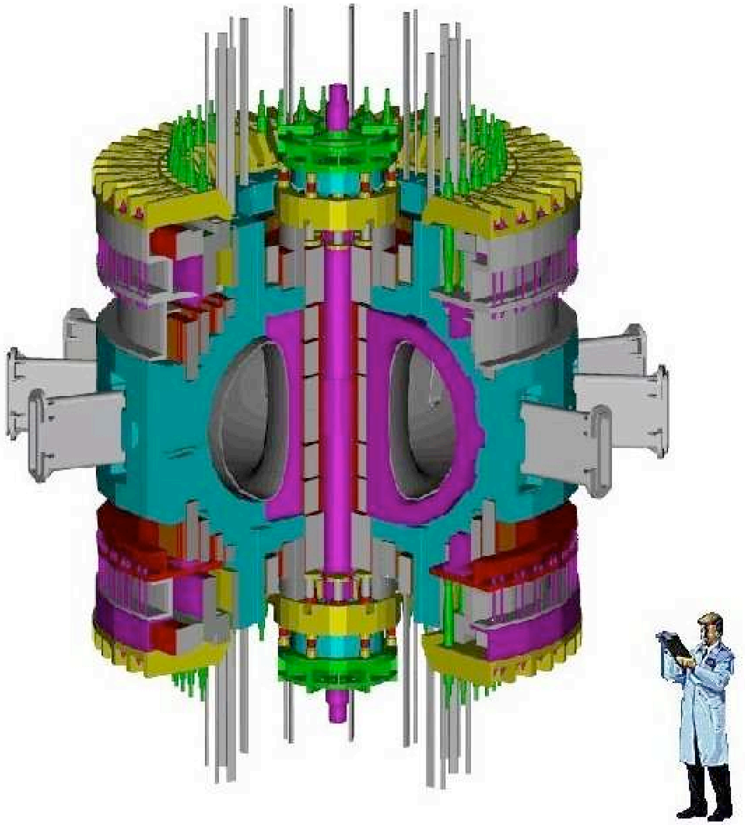
$$\frac{\beta}{\chi} \simeq 0.15 \frac{H^2}{q^2} S^2$$

Turbulence Suppression:
MST, PRL, 1997
RFX, PRL, 1999

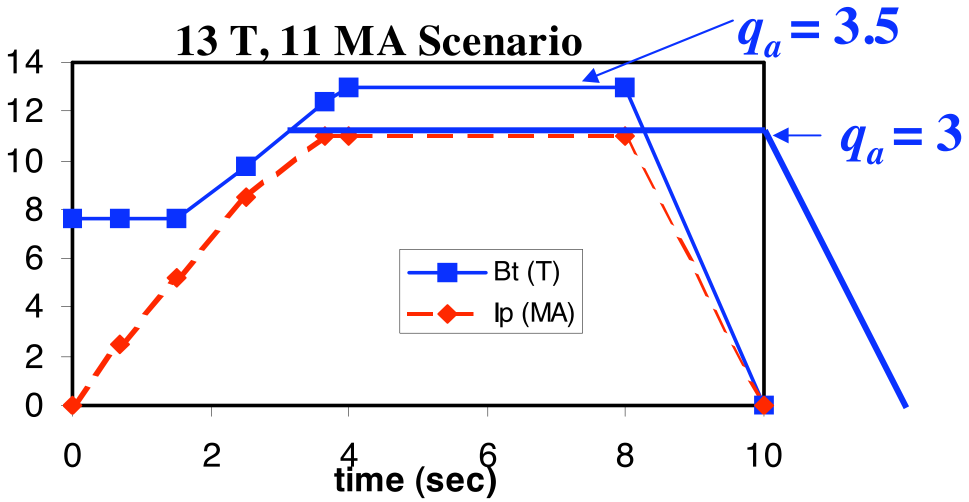
J. Sheffield

IGNITOR

Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
RF Heating P_{icrh}	<18 MW



R	1.32 m
a	0.47 m
κ	1.83
δ	0.4
V	10 m^3
S	36 m^2
Pulse length	4+4 s



The Ignitor Strategy

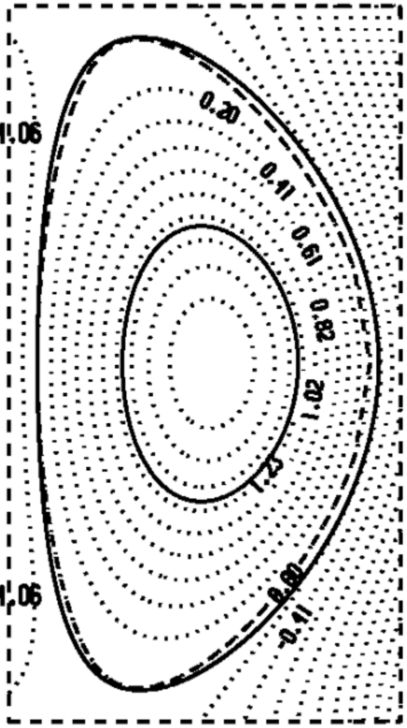
$n\tau T$: high density, moderate τ_E, low temperature

$n/n_{limit} < 0.5$, low β_p consistent with known stability limits

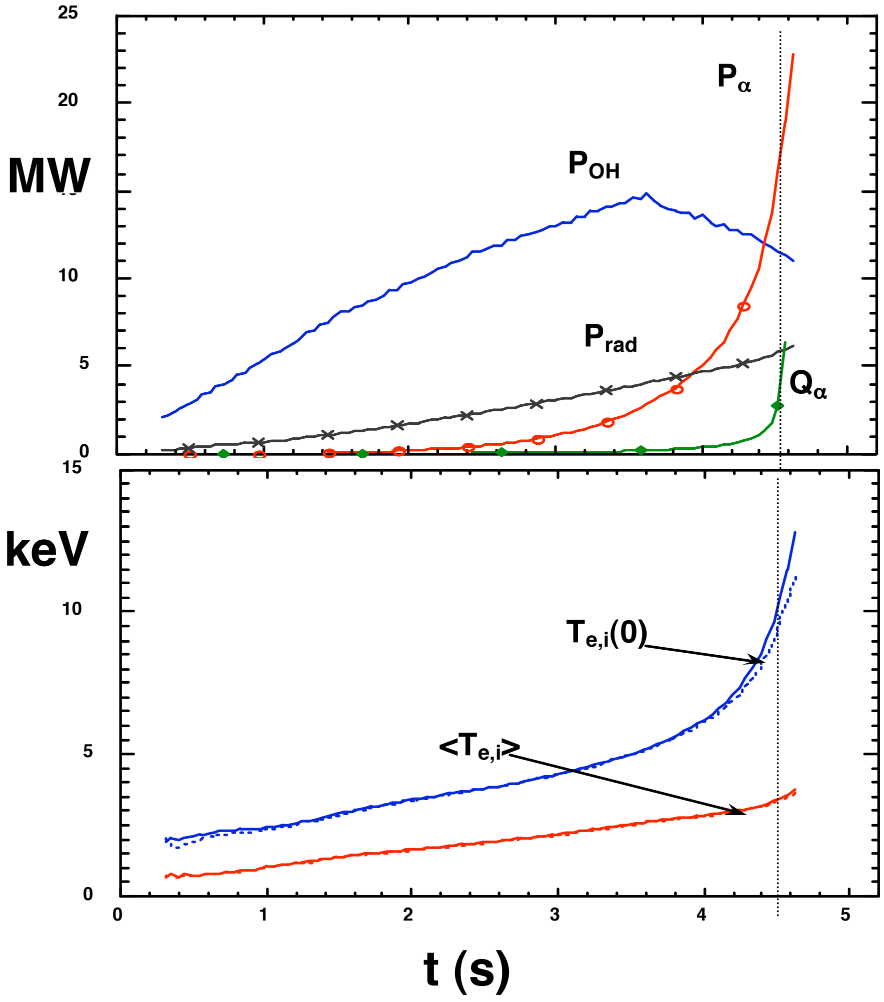
$\tau_{\alpha,sd} << \tau_E$, $\tau_{burn} >> \tau_E$

Typical Parameters at Ignition

T_{e0} , T_{i0}	11.5, 10.5 keV
n_{e0}	10^{21} m^{-3}
$n_{\alpha 0}$	1.2×10^{18} m^{-3}
P_α	19.2 MW
β_{pol}, β	0.2, 1.2%
τ_E	0.62 s
τ_{sd}	0.05 s
Z_{eff}	1.2



13 T, 11 MA

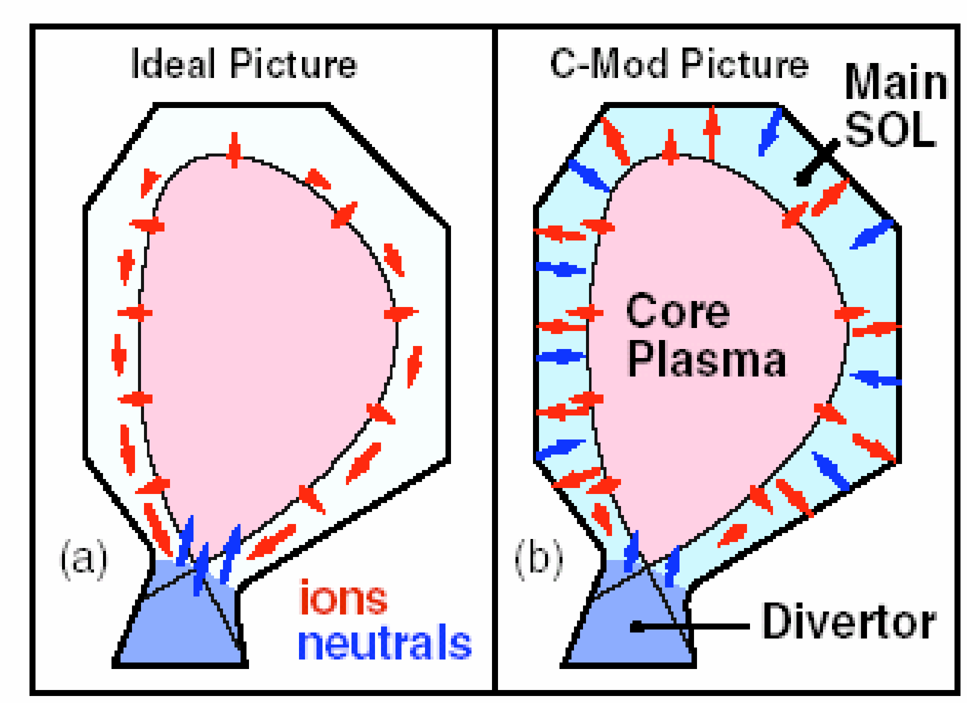


A. Airoldi and G. Cenacchi

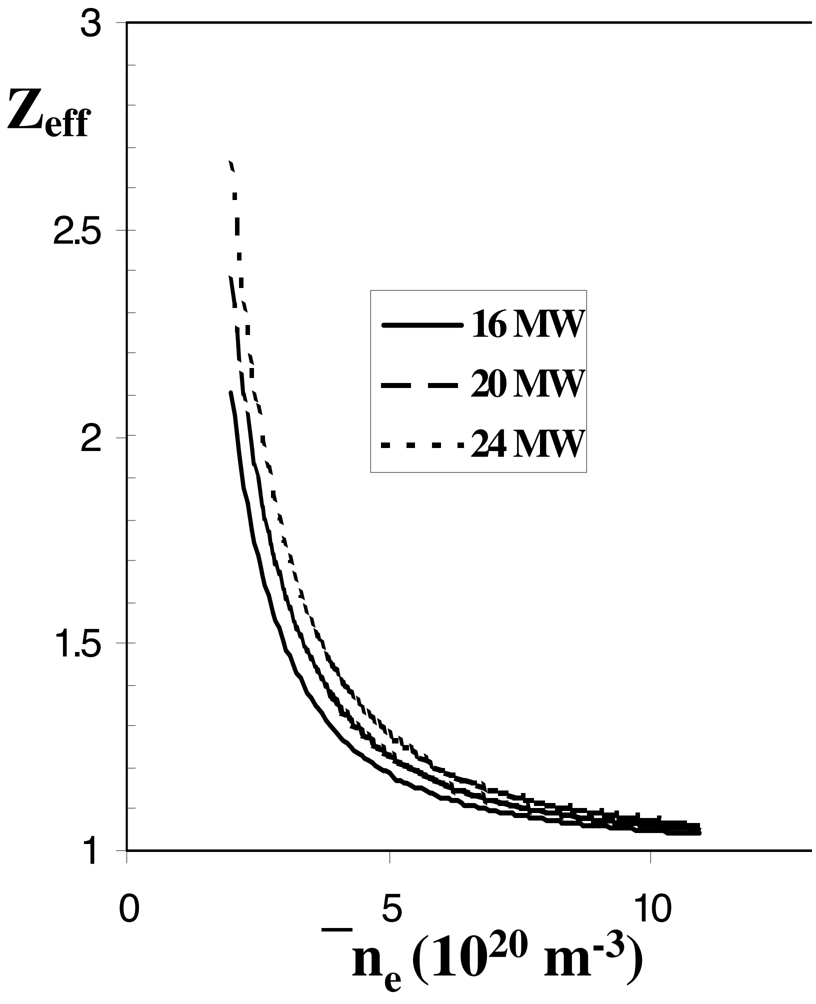
Divertor: why not?

Divertor machines do not produce “cleaner” plasmas than limiter, high density devices.

At high density, the low temperature reduces sputtering from the wall and impurities are effectively screened from the main plasma.



LABOMBARD, et al., *Nucl. Fusion* **40** (2000) 2041.



G.F. Matthews, et al.,
J. Nuclear Mat. **241-243**, 450 (1997)

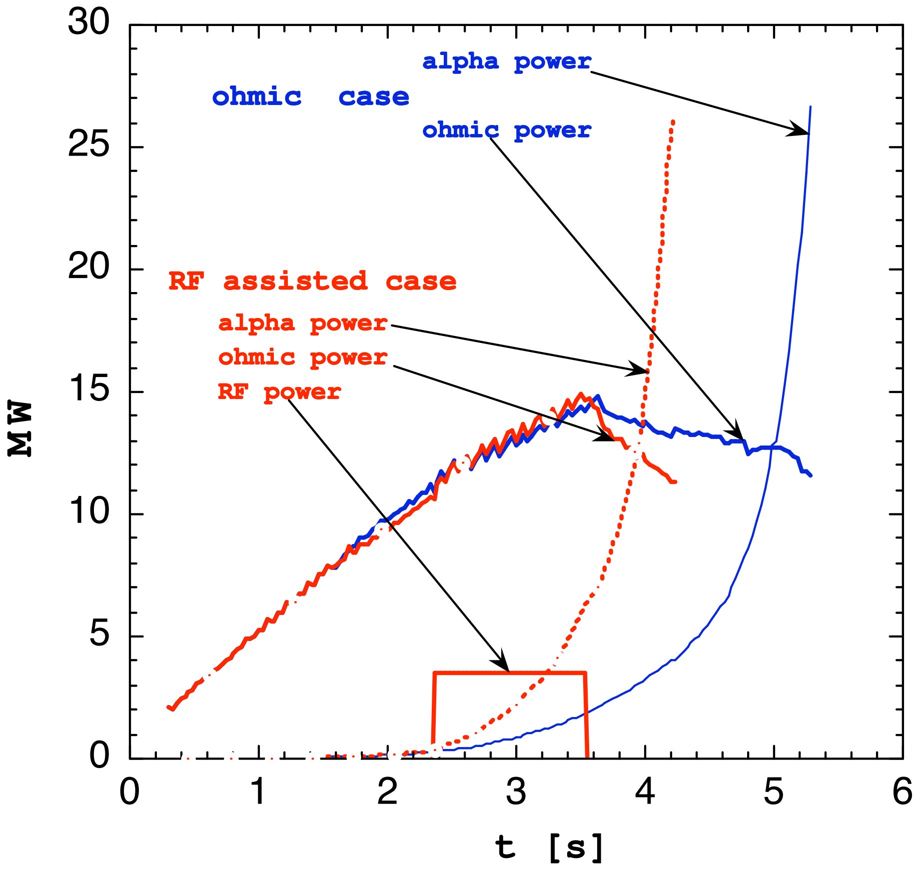
RF Accelerated Ignition

A. Airoldi and G. Cenacchi

Ignition can be accelerated by the application of modest amount of ICRH during the current rise.

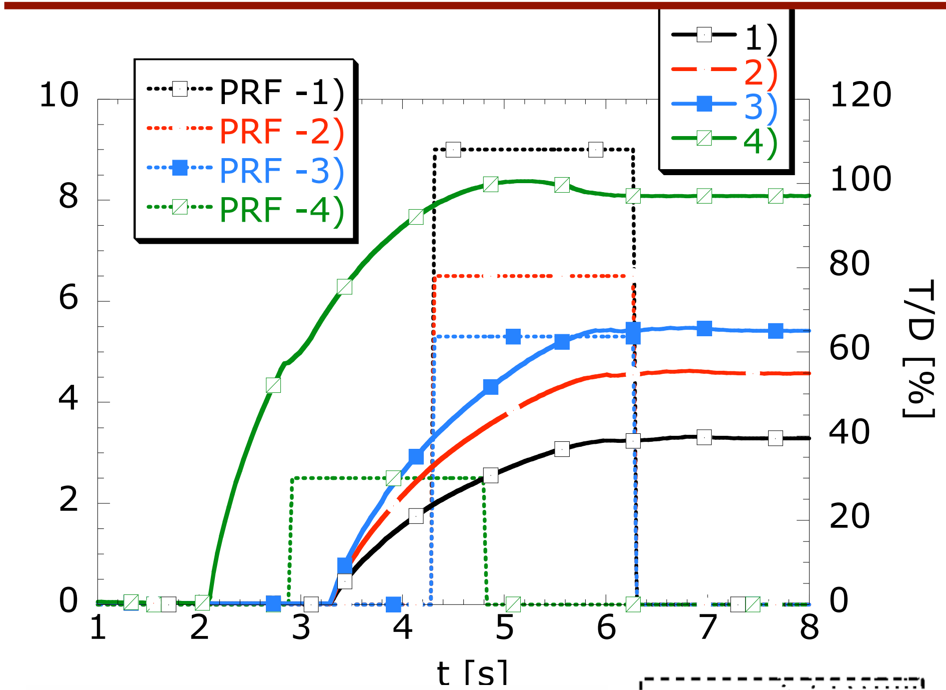
The full current flat top is available to study the plasma under ignition conditions.

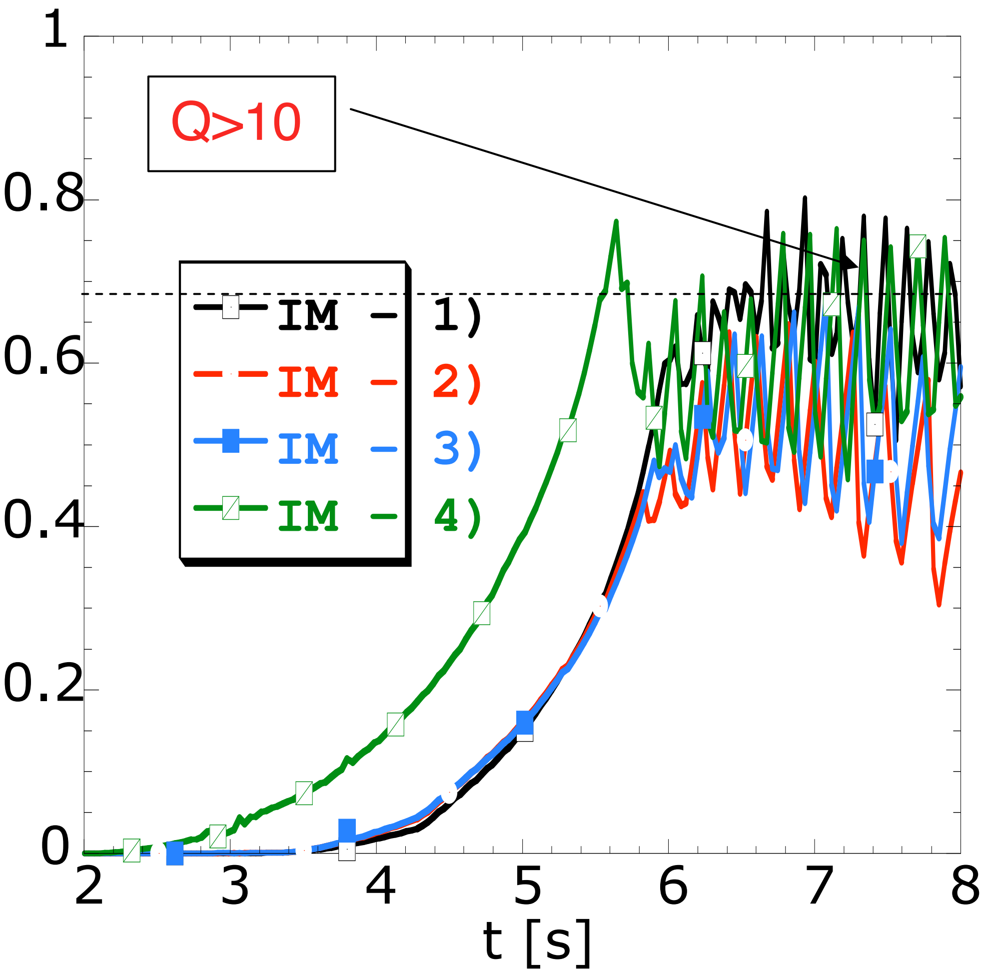
(Note that ignition occurs when only Ohmic heating is present)

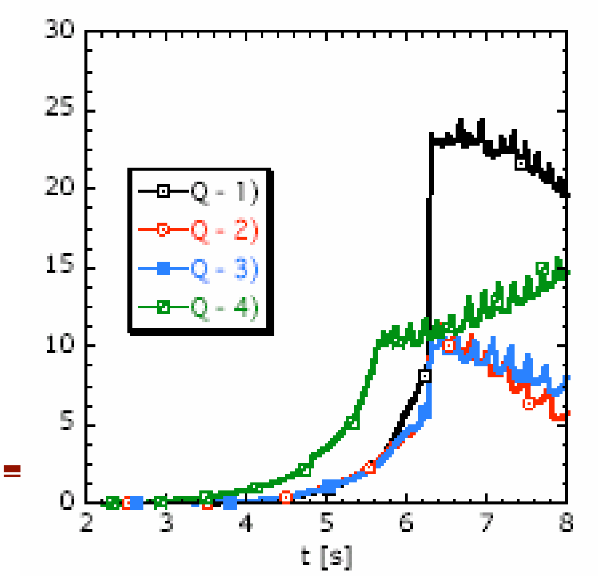


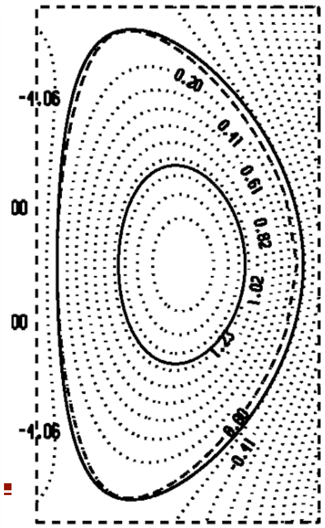
Comparison of Ohmic and RF accelerated ignition scenarios (JETTO code).

Ignition Control by means of Tritium and RF









13 T, 11 MA

With proper timing, the RF power compensates for the unbalanced fuel ratio. As a result, only small differences in the ignition margin are observed.

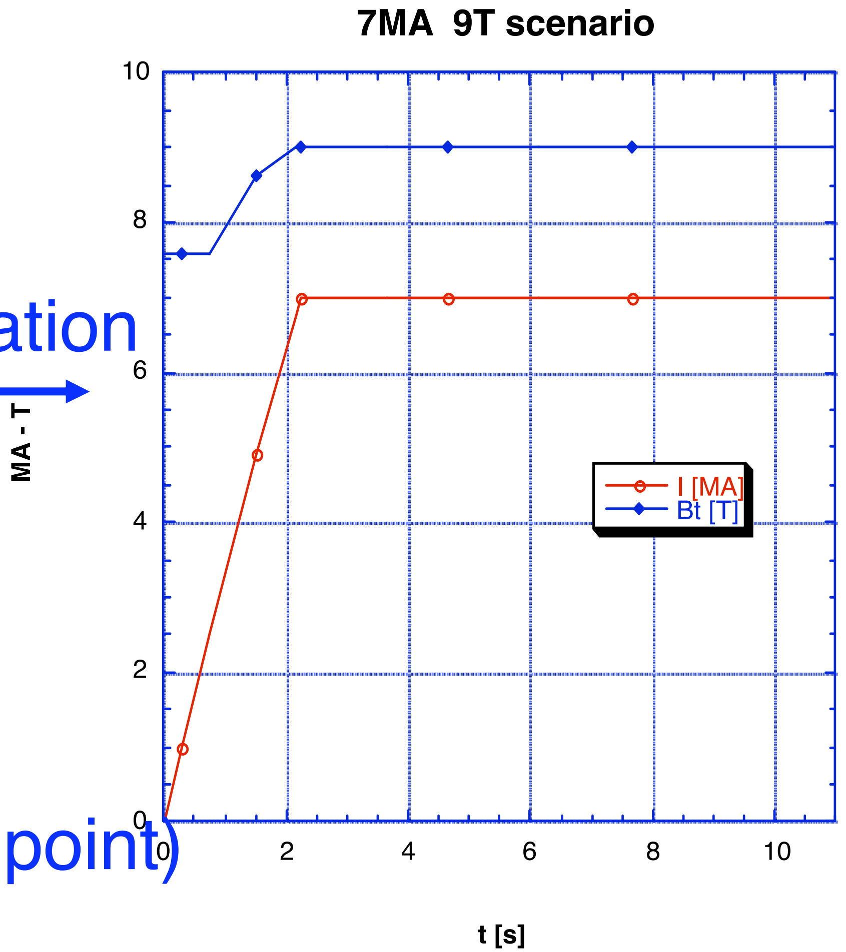
Scenarios with reduced parameters

Magnetic field up to 9T

Plasma current up to

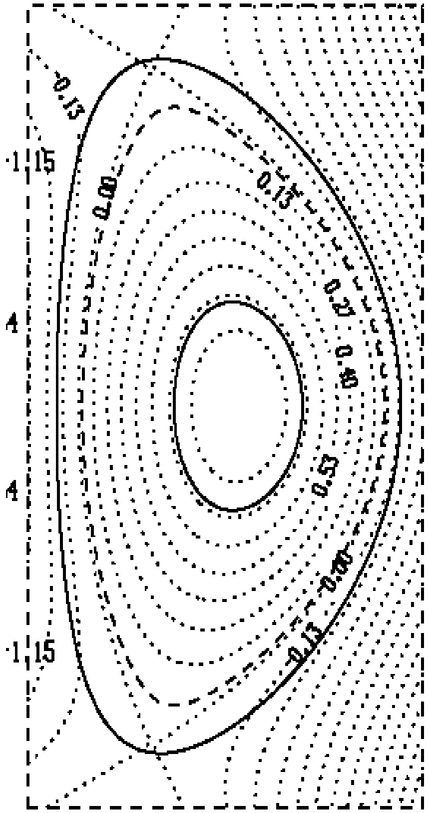
i) 7 MA, “first wall limiter” configuration

⇒ Long pulse



or

ii) 6 MA (double X-point)



The pulse length is consistent with mechanical and thermal requirements of the magnets, and available magnetic flux

7 MA, 9 T
First Wall Limiter

Bohm-GyroBohm transport model

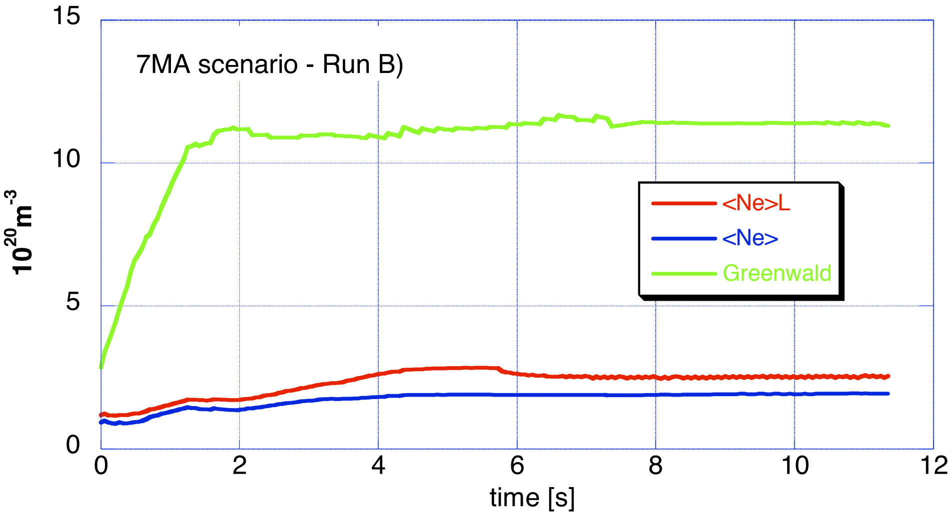
D-T plasma with T fed from 0.8 s

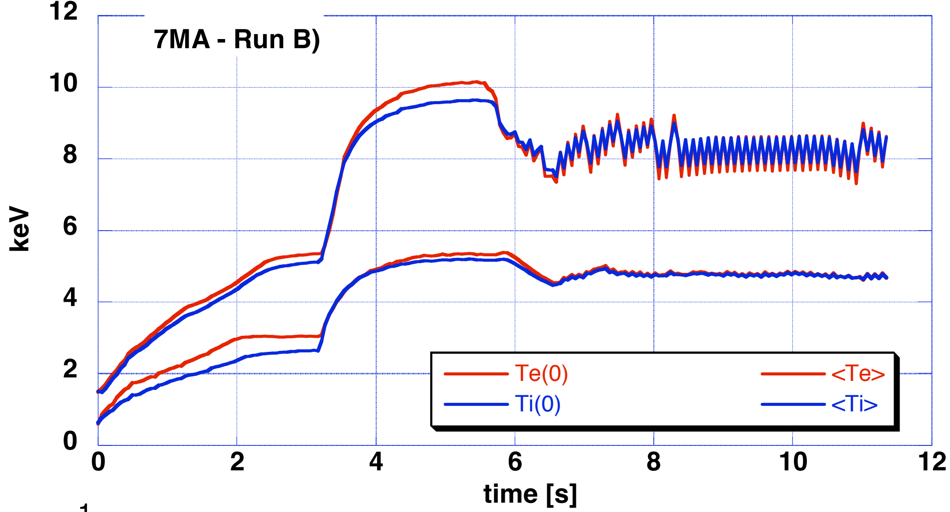
effective charge $<Z_{eff}>$~1.5

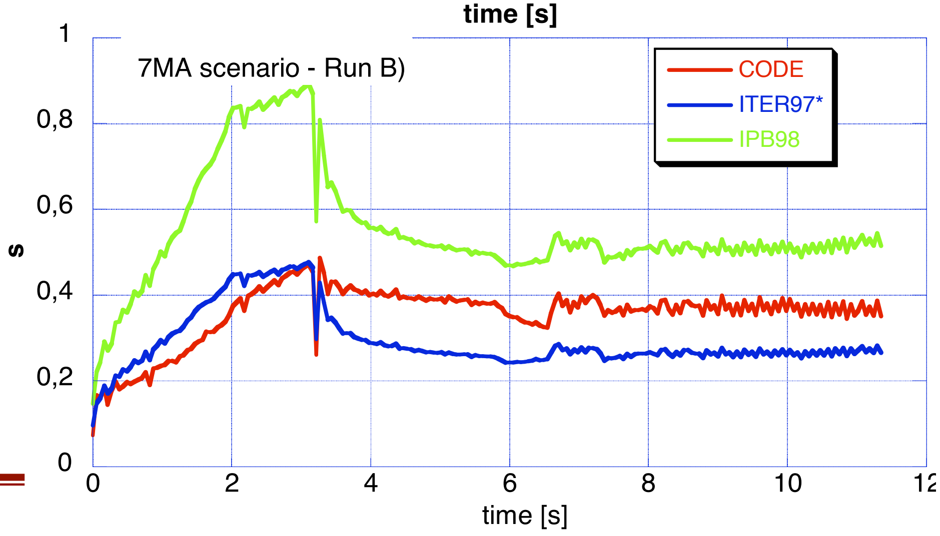
density during the current flattop : $<n_e>$~$2x10^{20}m^{-3}$

ICRH (~7.7MW) from 3.5 s until the end of flattop

⇒Peak temperatures above the ideal ignition temperature are produced: plasma density can be increased without encountering the bremsstrahulung barrier



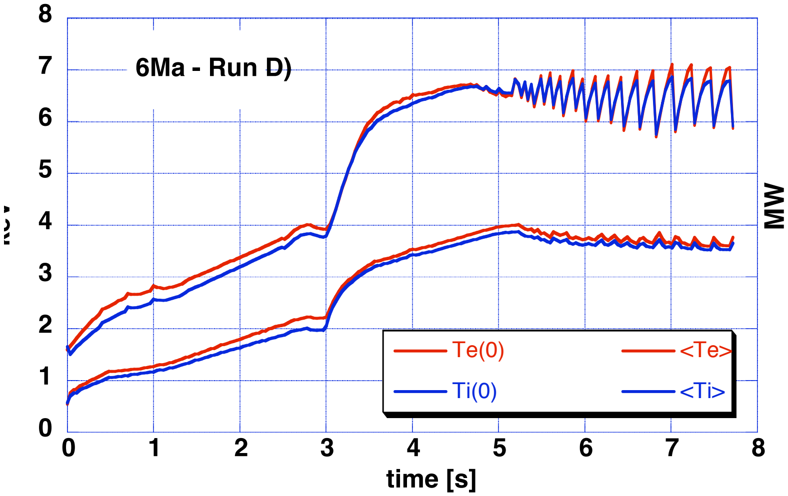


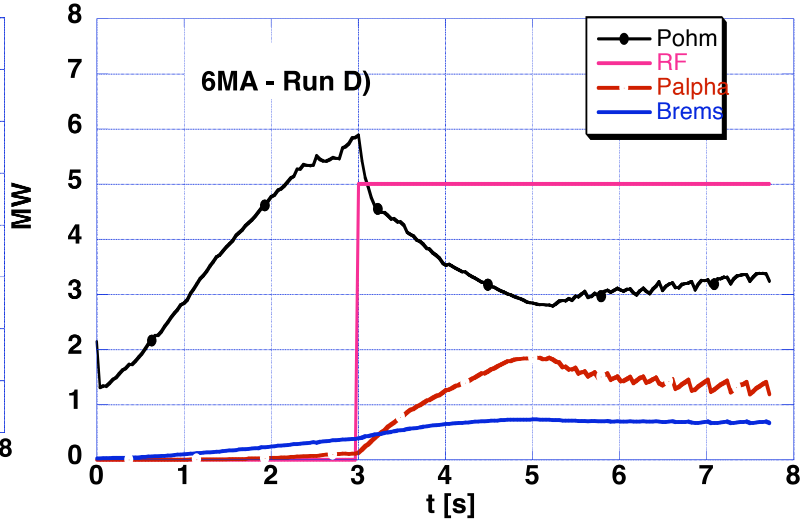


Ignitor Project

Double X-Points Scenario

(6 MA, 9 T no transport barrier)

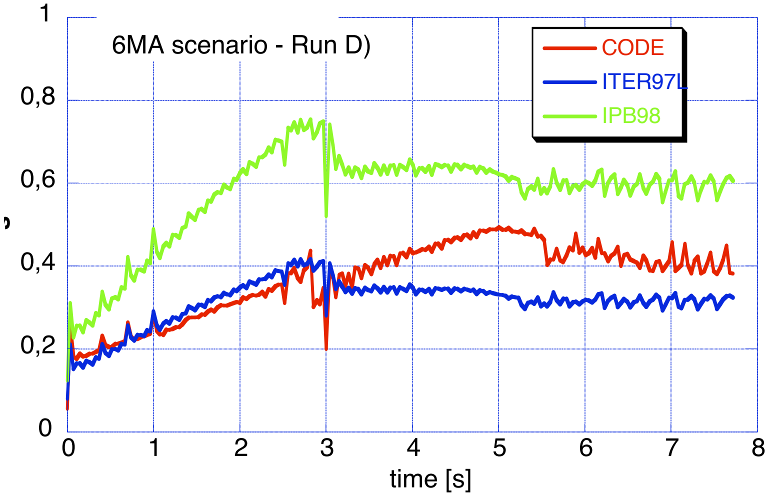


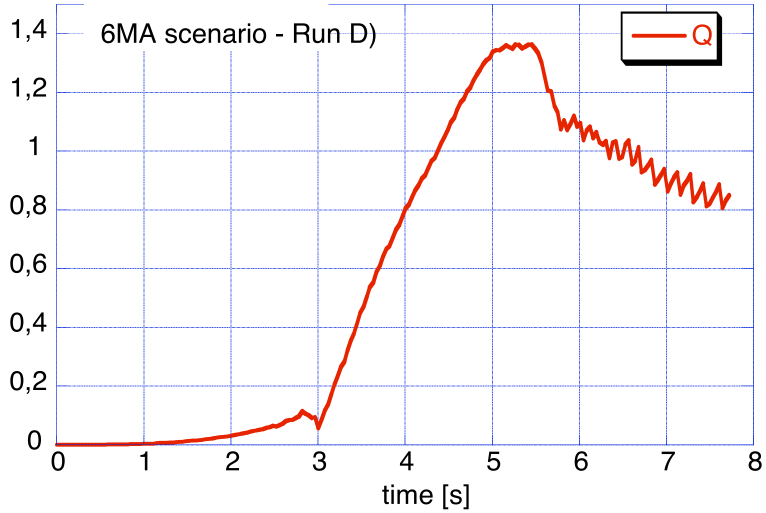


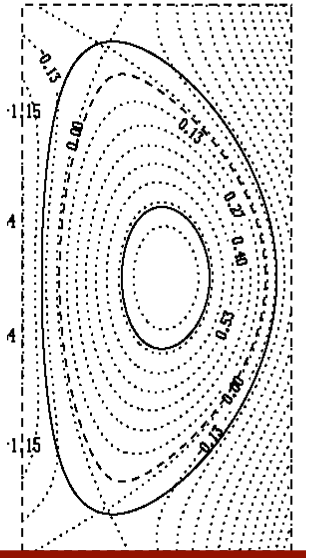
Equilibrium configuration with X-points inside the first wall

Rx=1.17m

Zx=0.84m





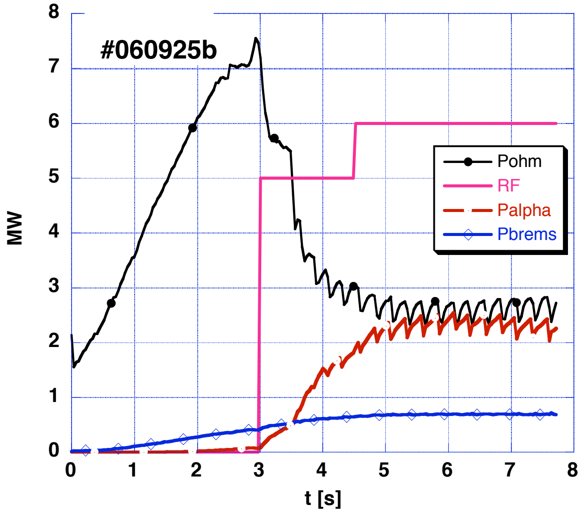


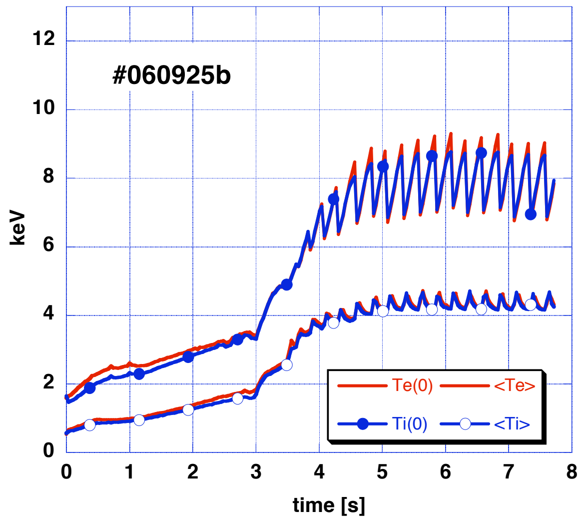
A. Airoldi, G. Cenacchi, JETTO code

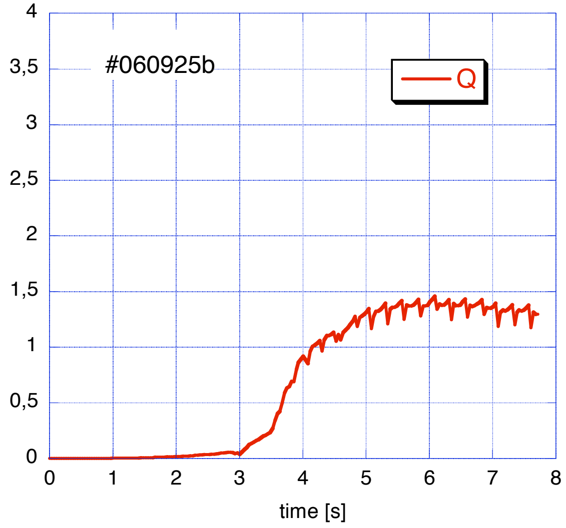
Ignitor Project

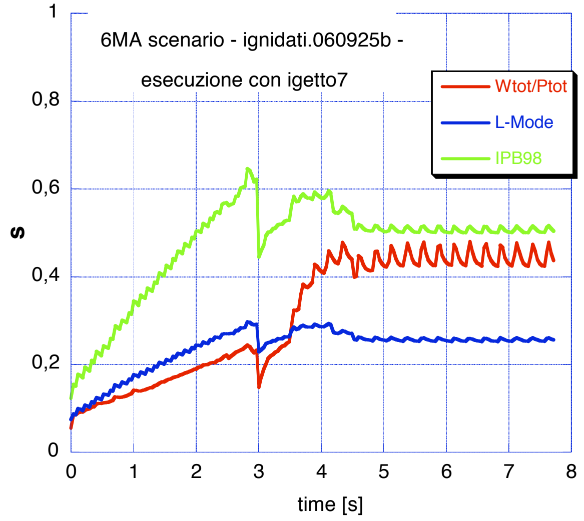
Double X-Points Scenario

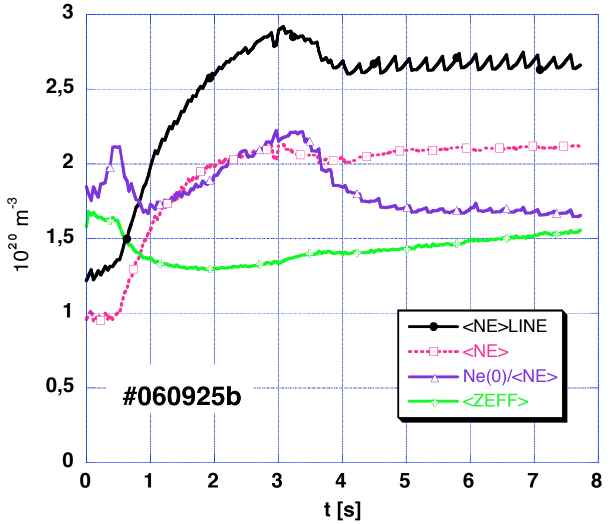
(6 MA, 9 T, H-mode)

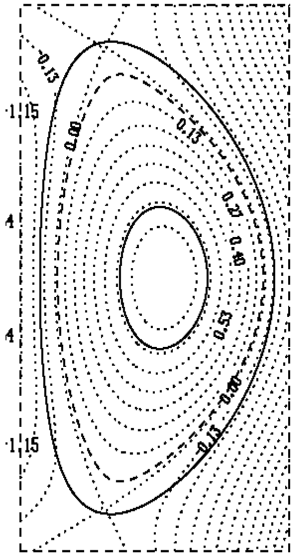












A. Airoldi, G. Cenacchi, JETTO code

ICRH Physics

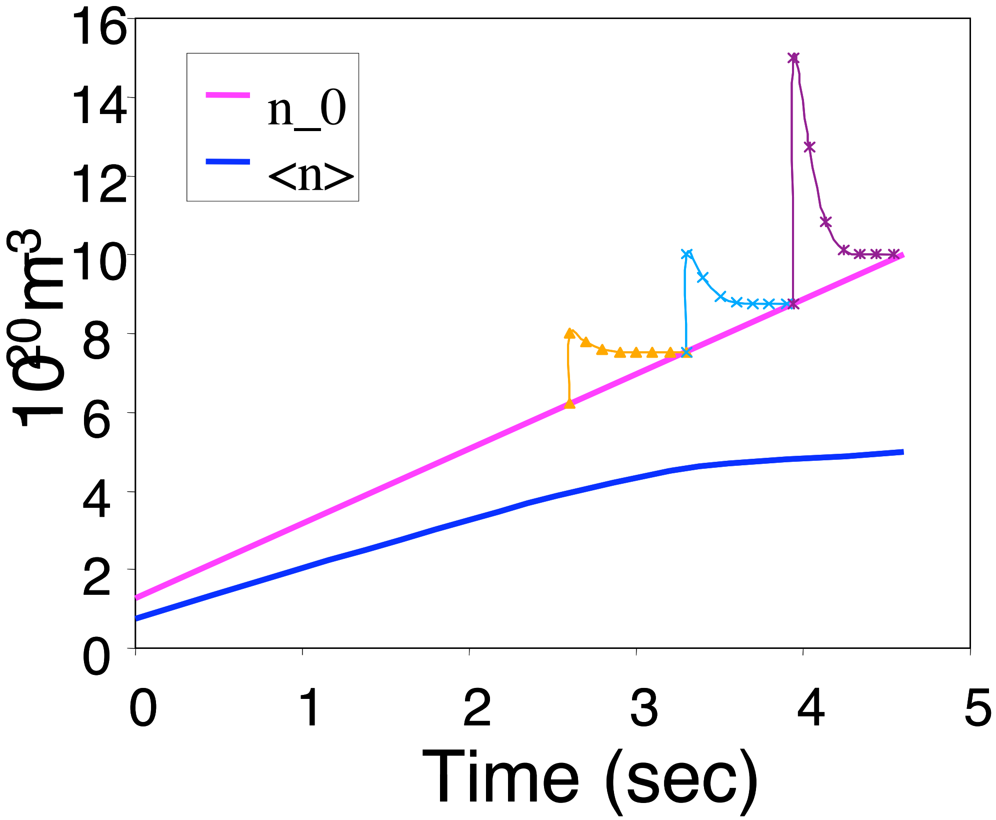
The application of modest amounts of ICRH power (3-6 MW), either during the current rise or the pulse flat-top, can be used to increase the temperature in a range of accessible plasma regimes and provide a safety margin for the attainment of ignition.

The available frequencies of the ICRH system can cover the range of operation at magnetic fields from 9 to 13 T. Different heating scenarios are considered:

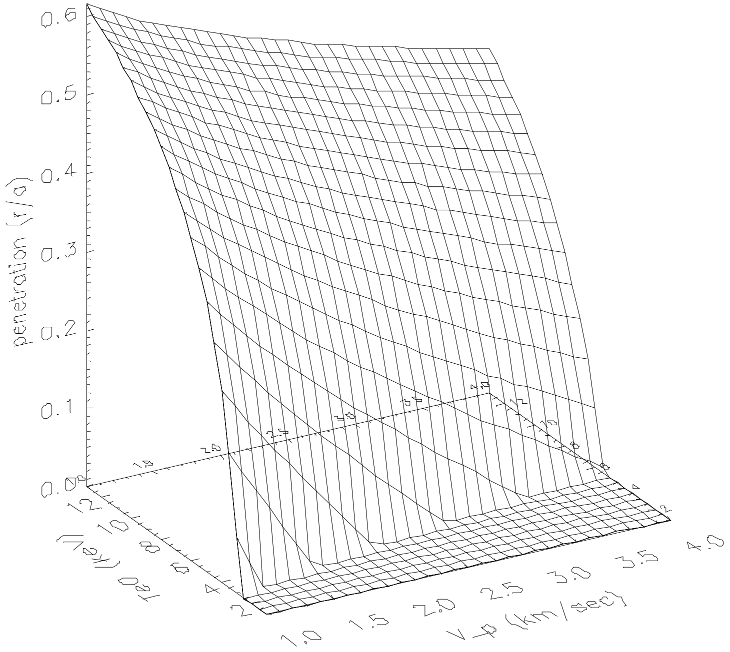
B (T)	H/D/T	T/He^3	D
9	1st,2nd,3rd at x-0.5	2nd,1st at x - -0.5	
10	1st,2nd,3rd at x-0.9	2nd,1st at x- -0.25	1st at x- -0.95
11	Out of res	2nd,1st at x--0	1st at x- -0.75
12	Out of res	2nd,1st at x-0.2	1st at x- -0.6
13	Out of res	2nd,1st at x-0.4	1st at x- -0.4

Pellet Injection Scenario

Good pellet penetration with injection from the low field side can be expected even in burning plasma condition



Penetration of 4 mm pellets in Ignitor



$T_e=(T_{e0}-T_a)(1-x^2)^2+T_a$

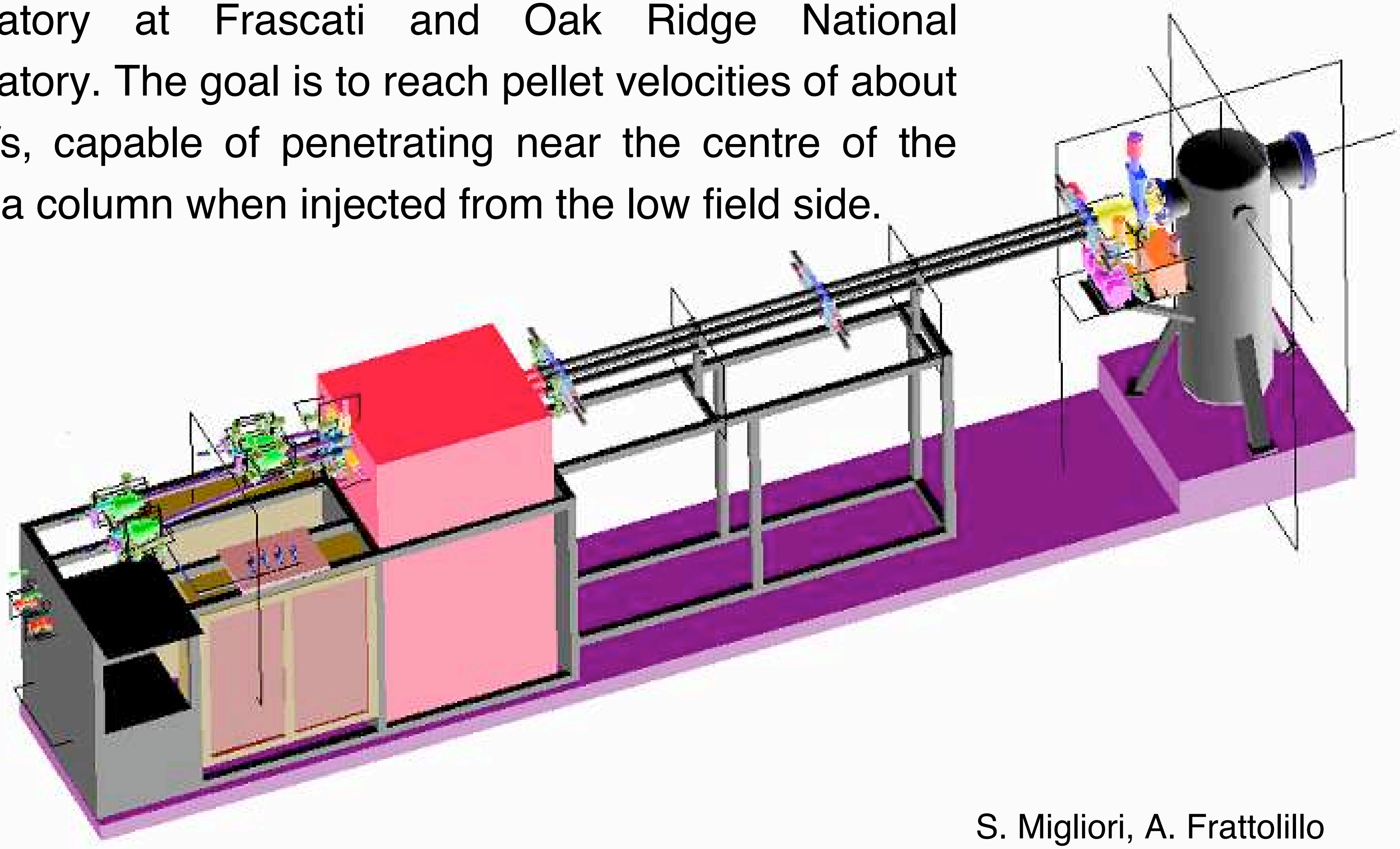
$n_e=(n_{e0}-T_a)(1-x^2)^1+n_a$

$n_0 = 0.5 \div 12.5 \times 10^{20}\ m^{-3}$

$a = 0.47\ m$

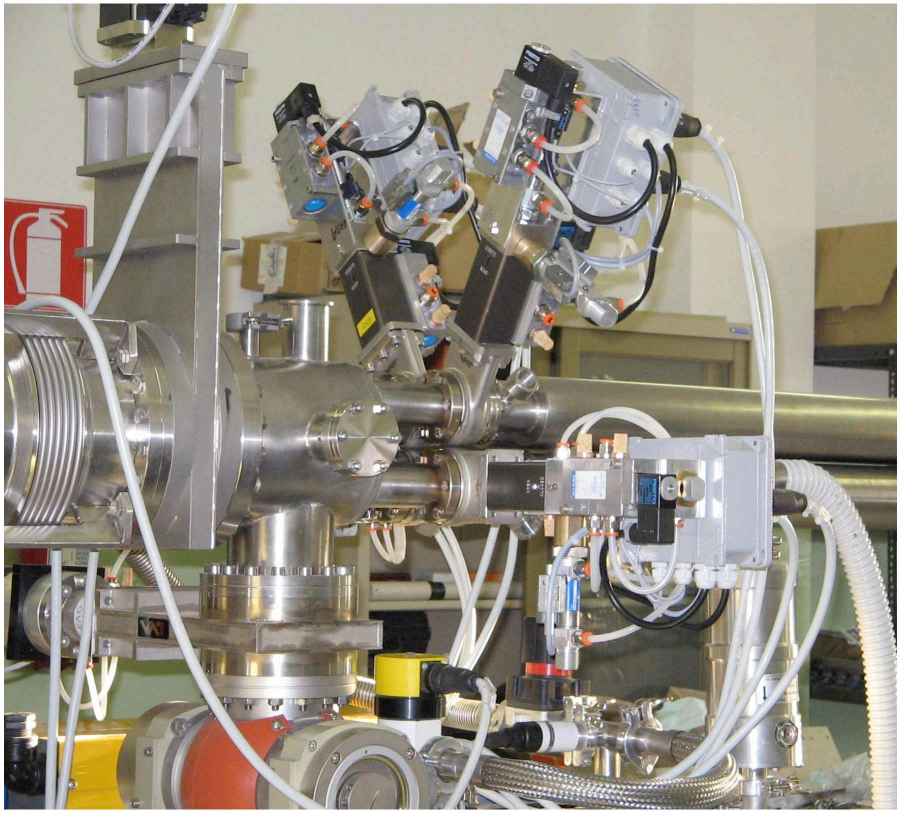
The Multiple Barrel, High Speed Ignitor Pellet Injector (IPI)

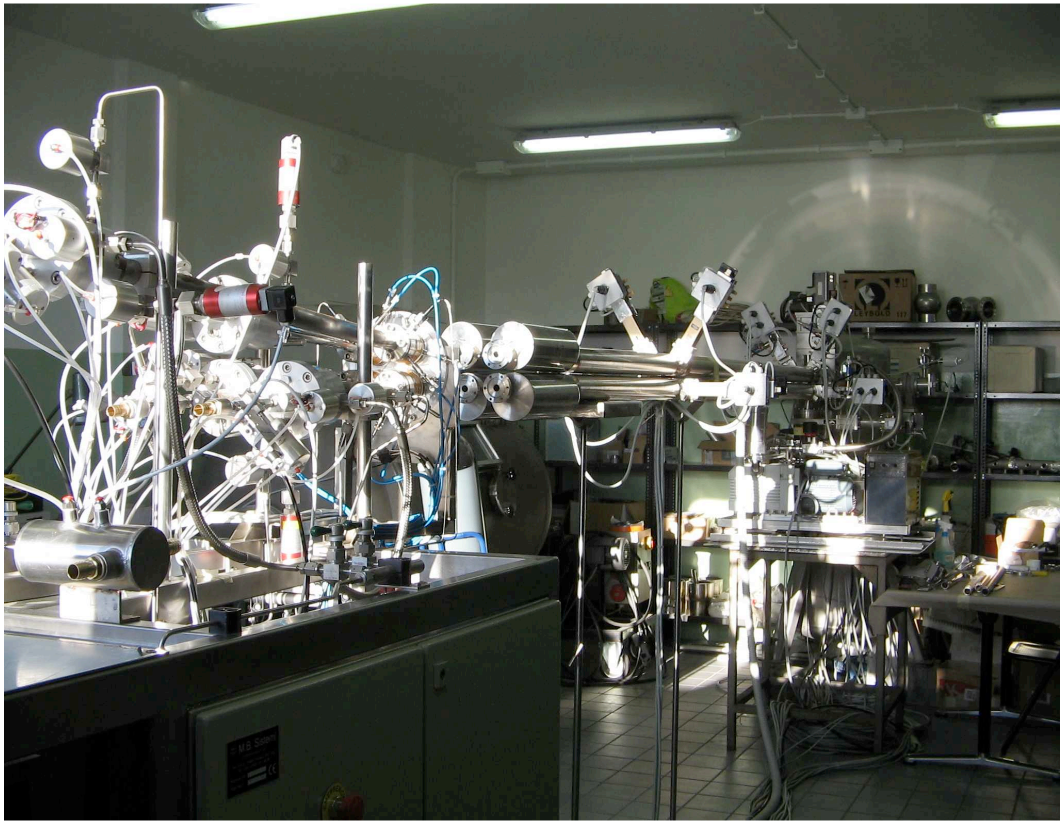
A four barrel, two-stage pneumatic pellet injector is under construction in collaboration between the ENEA Laboratory at Frascati and Oak Ridge National Laboratory. The goal is to reach pellet velocities of about 4 km/s, capable of penetrating near the centre of the plasma column when injected from the low field side.



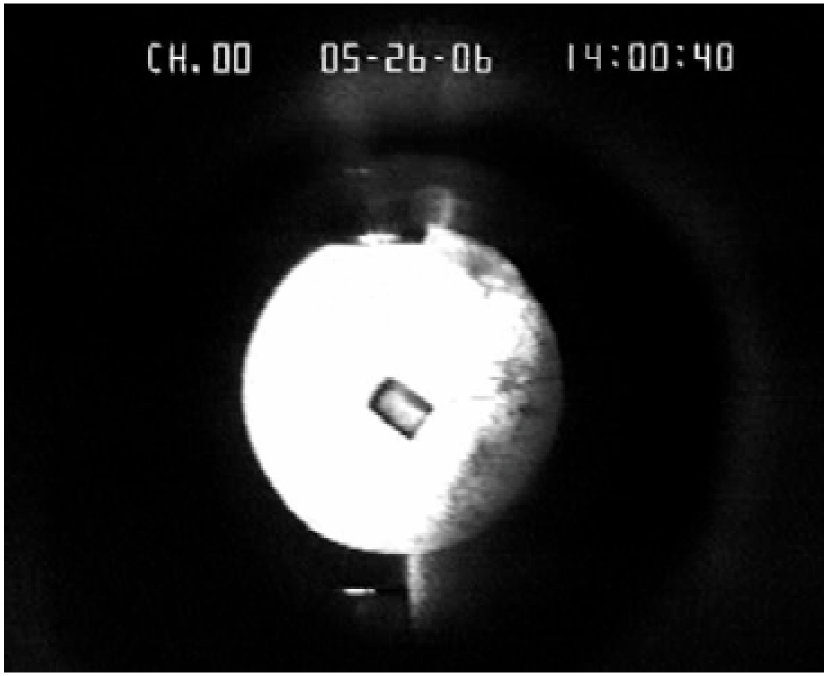
S. Migliori, A. Frattolillo

A set of 4 fast closing gate valves of the gas removal system



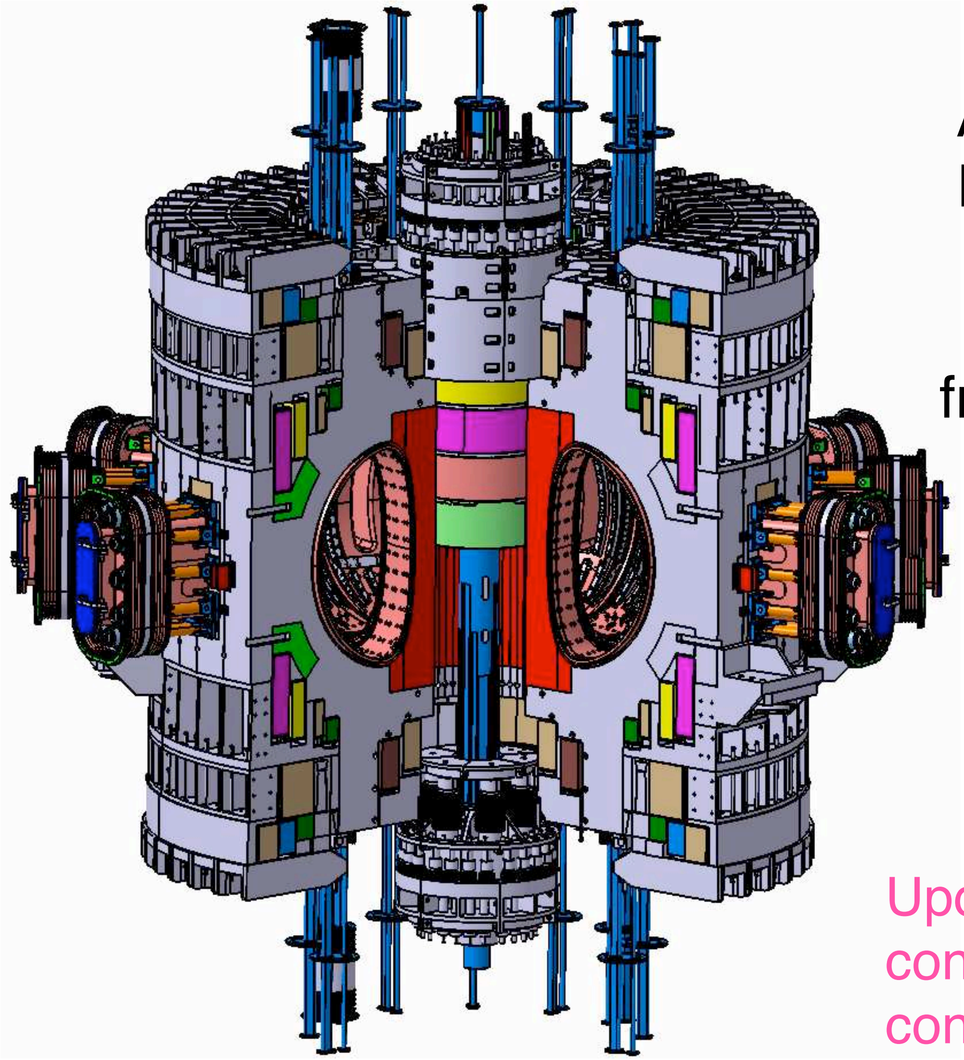


ENEA Propelling sub-system built at Criotec Impianti.

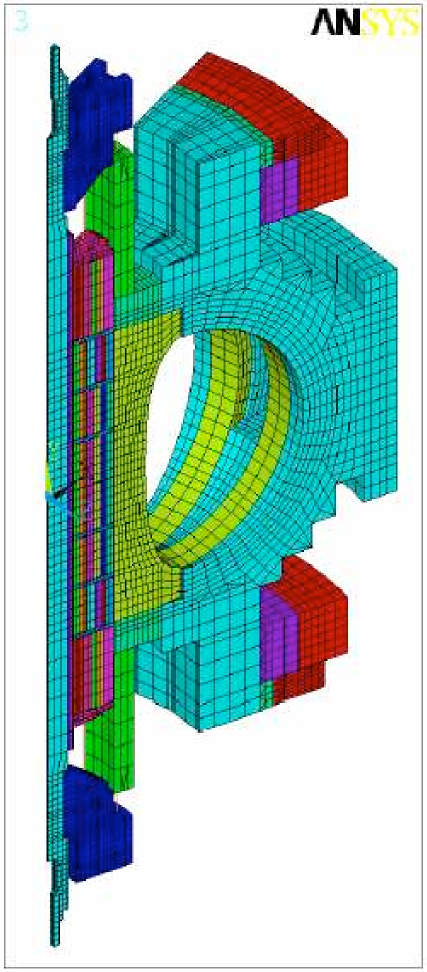


In-flight picture of a 3 mm D2 pellet, traveling at about 1.2 km/s (right)

Design Completion



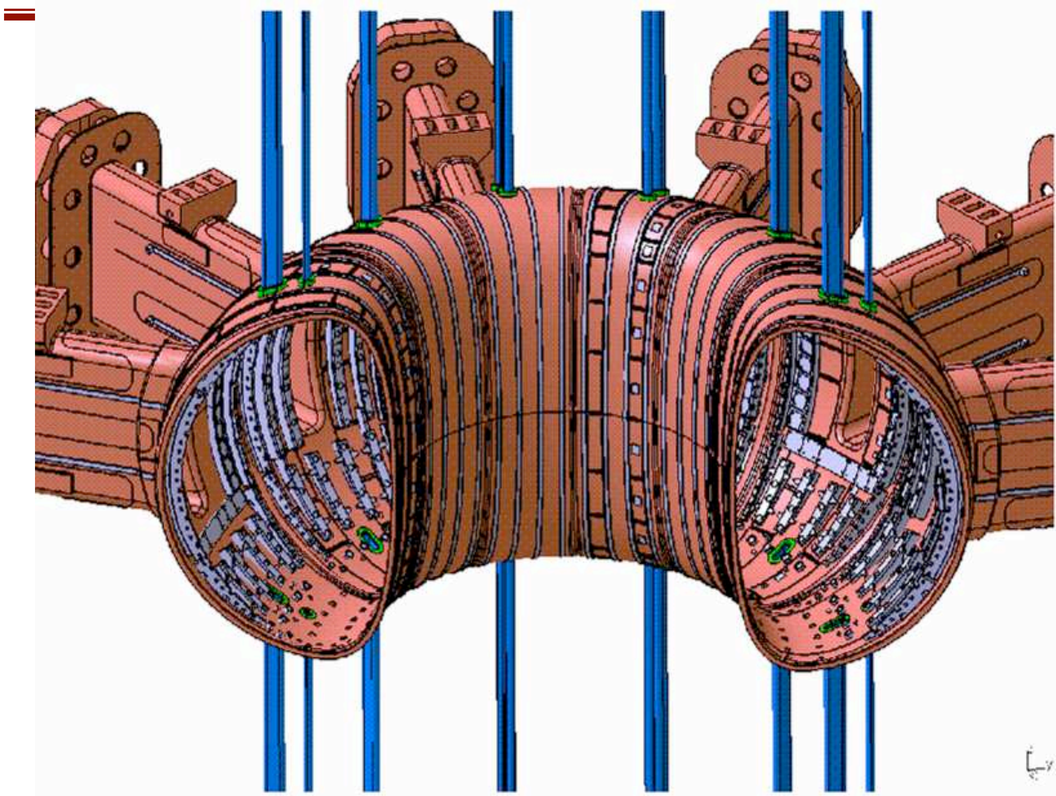
The non-linear structural analysis of the Load Assembly by means of Finite Element ANSYS model takes into account the effects of friction at the interfaces of significant components.

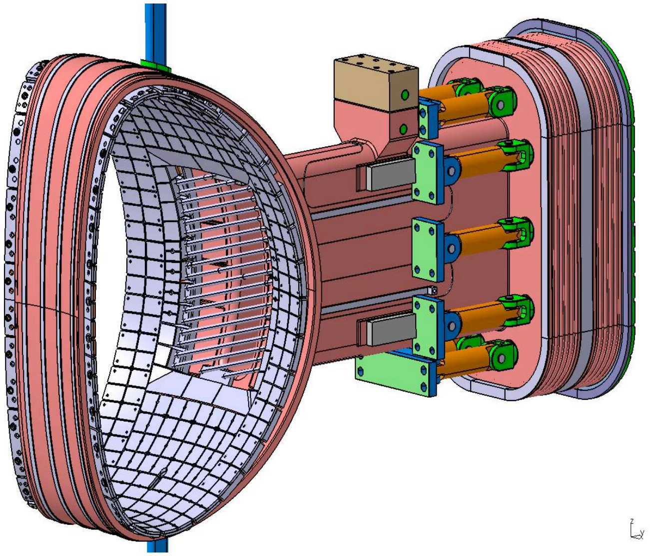


Updated plasma disruption conditions for VDE’s have been considered.

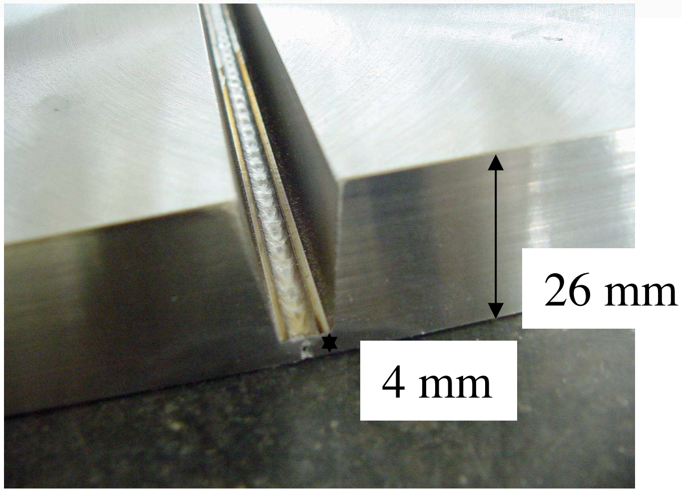
Inconel 625
12 D-shaped sectors
Variable thickness 26-52 mm

Plasma Chamber





One sector of the plasma chamber including the ICRH Faraday shield and first wall.

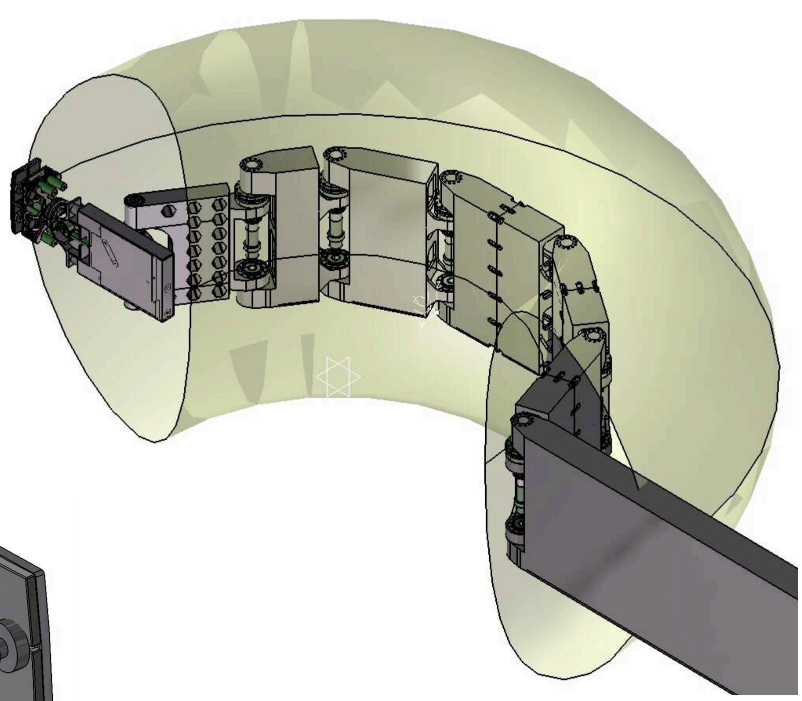


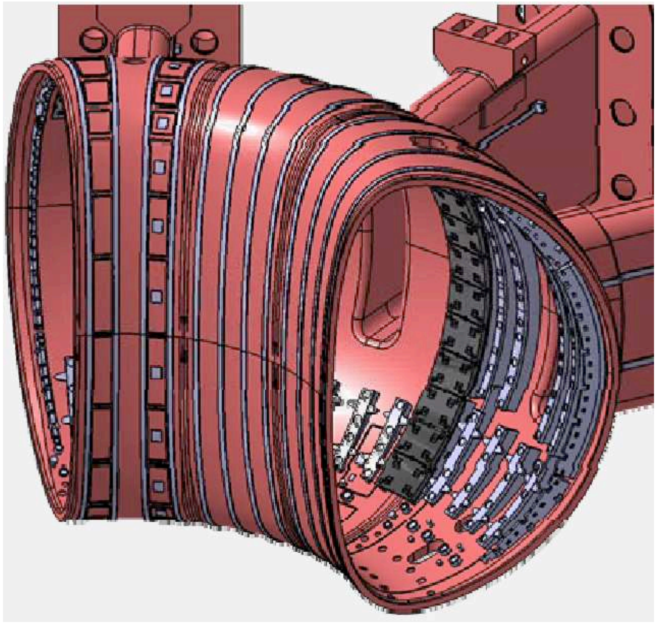
Each sector is joined to the adjacent one by a laser butt welding which ensure vacuum tightness. Once the torus is completed, the welding groove is filled by TIG-NG (Narrow Gap) to strengthen the joint.

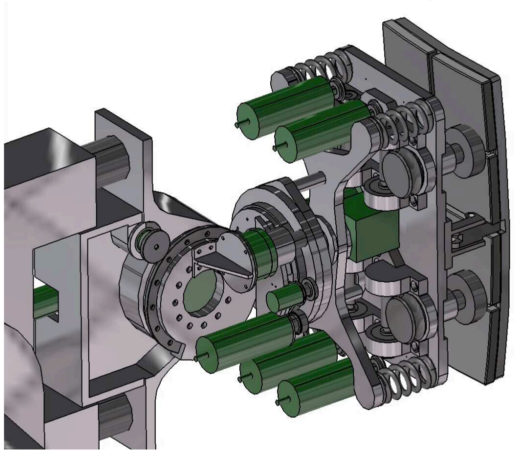
Remote Handling

Initial assembly of the machine requires remote handling

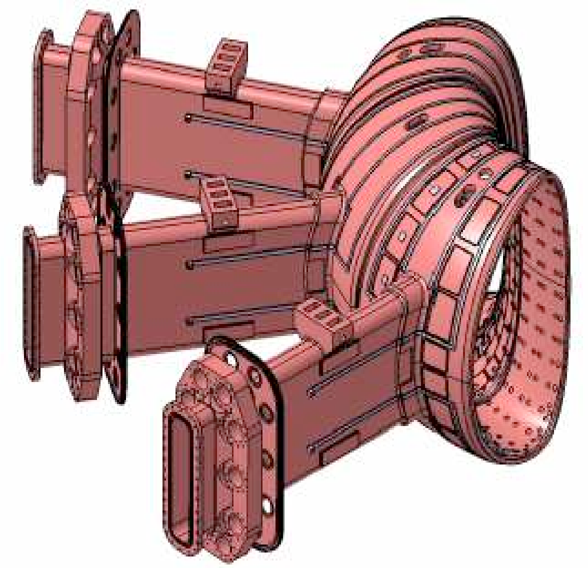
The 3D virtual mock-up analysis of the boom kinematics has verified that it is possible to reach all positions inside the Plasma Chamber





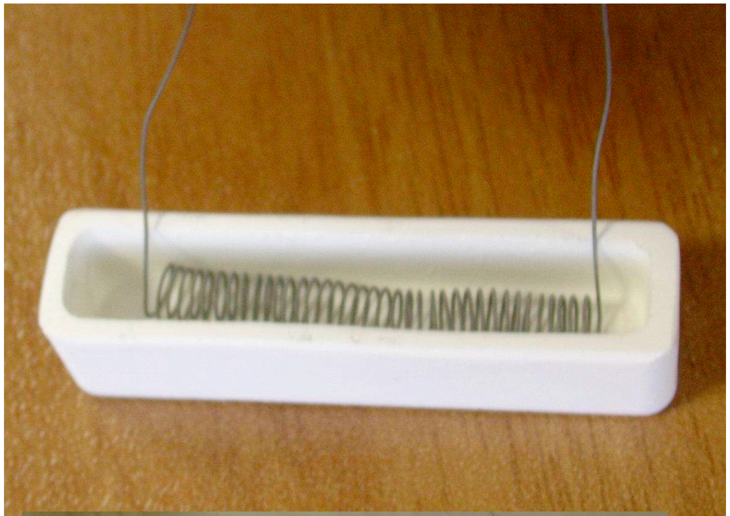


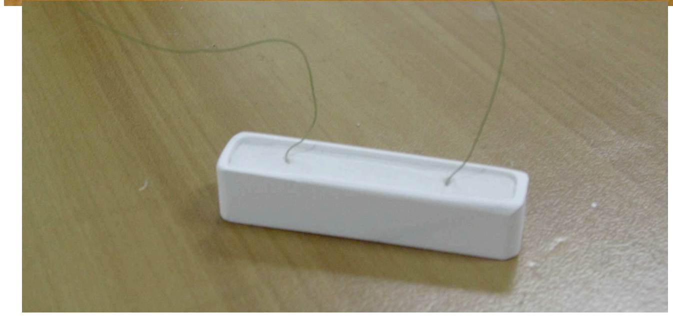
Fully extended boom inside the plasma chamber and end effector for tile carrier

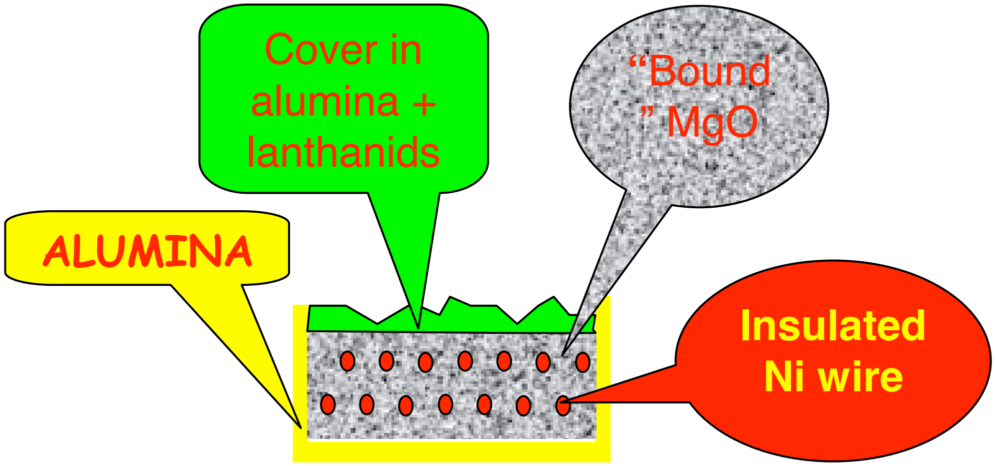


Magnetic Diagnostics

BP experiments pose demanding conditions on insulators used for magnetic diagnostics





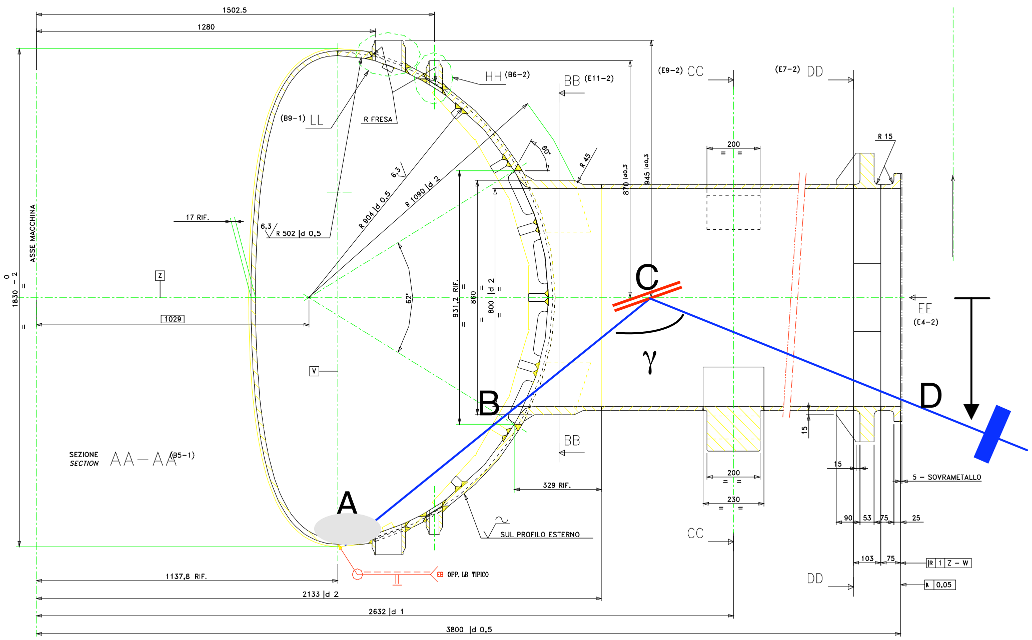


Università di Lecce

SALENTEC Advanced Technologies

Ignitor Project

X-ray Imaging for Plasma Position Control



λ = 25-40 Å

$\theta_B = 12.2°$

$\theta_s = 26.7°$

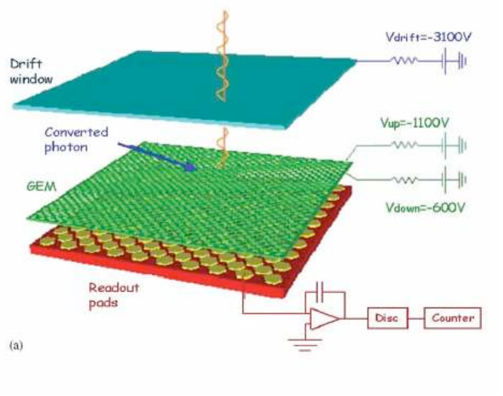
2d = 165 Å

2R = 10 m

D_{CD} = 2 m

R_i = 10%

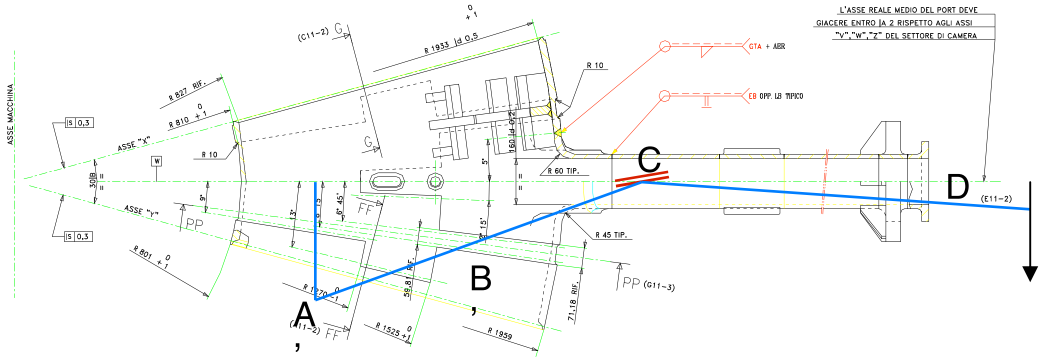
Δx(plasma) = 15 cm



GEM Detectors

- High counting rates (<1MHz/pixel)
- Good imaging capability (high contrast and low noise)
- Energy resolution
- Wide dynamic

~ ms time resolution



The ITER “Precipice”

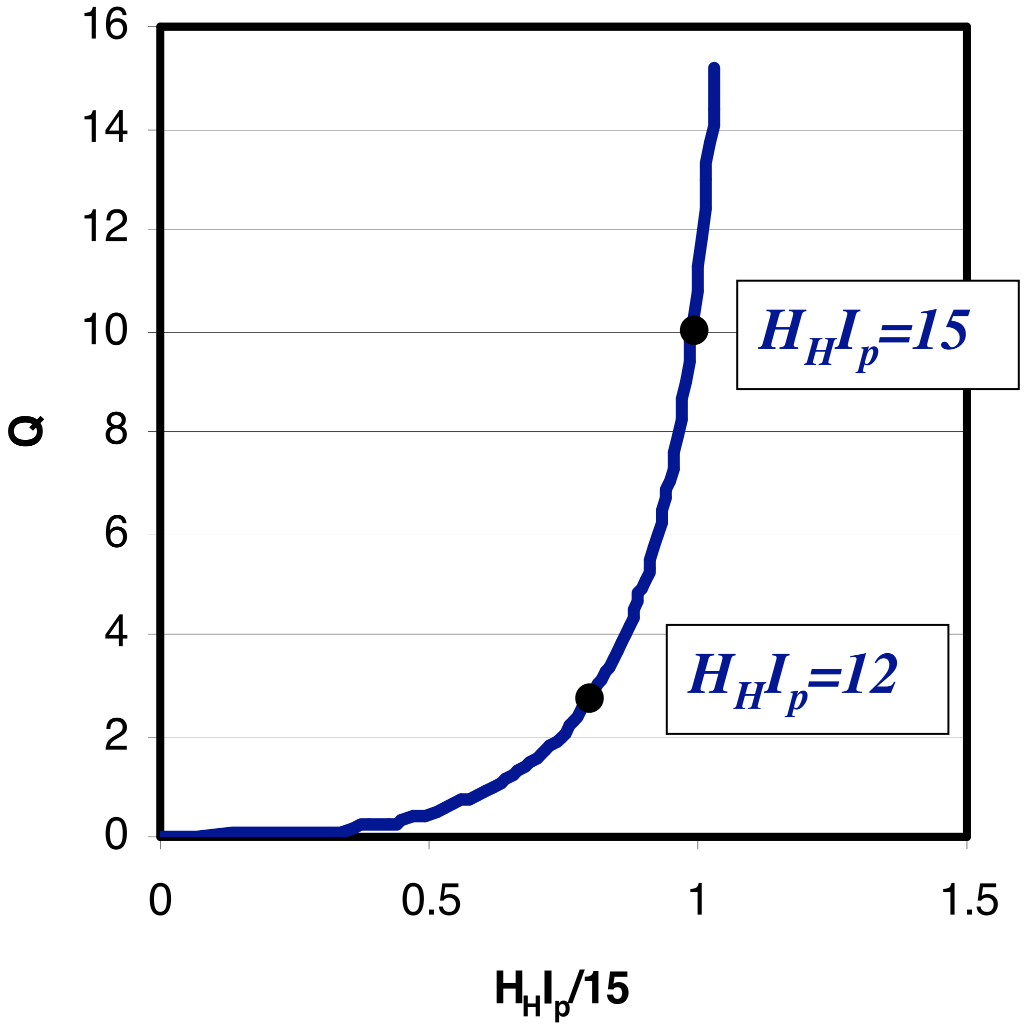
For burning plasma experiments operating in the H-mode regime, the energy confinement time scaling (IPB98(y,2)) and the L-H threshold power requirement [1] combine to make K_f a very sensitive function of the parameter $X=H_H I_p$ [2],

$$K_f \simeq \frac{2}{3}\frac{X^3}{X_0^3}$$

$$Q = \frac{5K_f}{1-K_f}$$

where, for ITER-FEAT, $X_0 = 15$ MA at $Q = 10$ and $H_H = 1$

[1] J.A. Snipes, et al., *Plasma Phys. Control. Fusion* **42**, A299 (2000).
[2] Summary of the ITER Final Design Report, Sect 3.1 (July 2001)



$$Q = \frac{5K_f}{1 - K_f}$$

$$K_f \propto X^3$$

$$K_f = \frac{Q}{Q+5}$$

Ignitor Project

Ignitor is the “Largest” among Presently Proposed Experiments

Given the high value of the average poloidal field and the relatively low temperature at ignition (e.g. $T_{i0} \cong 10.5$ KeV), it contains the largest number of orbits of thermal nuclei, for the same value of the magnetic safety factor *q*.

$$L_p = \frac{\bar{a}}{\bar{\rho}_{bi}} \propto \frac{I_p}{\sqrt{T_i}}$$

a = minor radius

$$\rho_{bi} = \frac{v_{thi} m_i c}{e\bar{\bar{B}}_p}$$

$$5\bar{a}\bar{\bar{B}}_p = I_p$$

$$\frac{L_p\big|_{Ignitor}}{L_p\big|_{ITER}} > \frac{11}{12.75}\sqrt{2} = 1.22$$

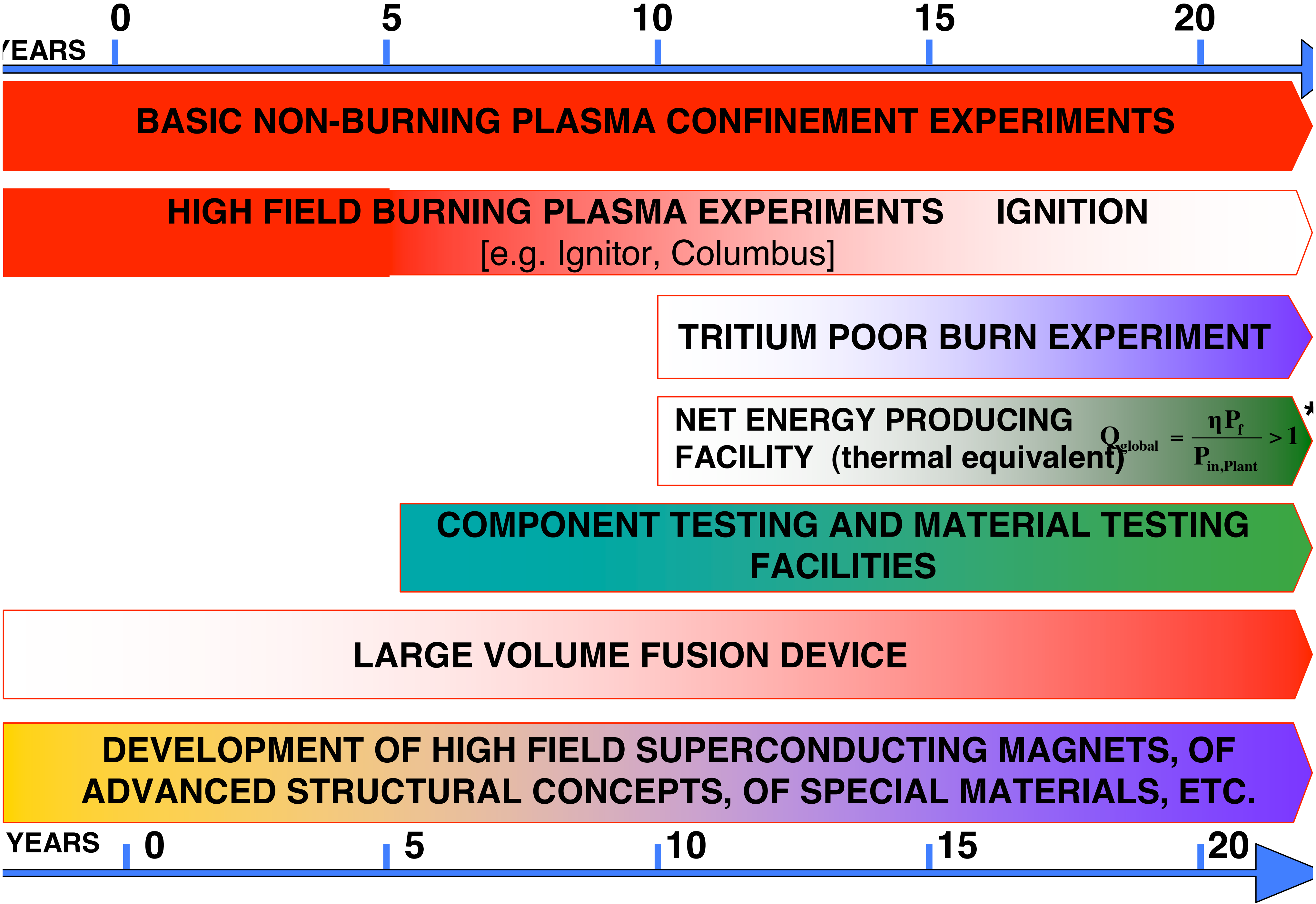
TIME SCALE RATIOS

Relevant Parameters		**ITER**	**FIRE**	**IGNITOR**	**ITER/IGNITOR**
		@ $q_a = 3$			
Pulse flat top	t_{pulse} (s)	400	20	6	66
Criticality param.	$K_f = P_{alpha} / P_{Losses}$	2/3	2/3	1 a)	
Minor radius	a (m)	2	0.595	0.47	
Peak el. temperature	T_{e0} (keV)	25	13	11.5	
Profile param.	α_T (parab)	1	1	2	
Purity param.	Z_{eff}	1.7	1.4	1.2	
Current redistribution time	$\tau_{cr}^{coll} \propto \frac{a^2 T_{e0}^{3/2}}{Z_{eff}} \frac{1}{\left(1+(3/2)\alpha_{T,parab}\right)}$ b)	118	4.7	1.8	65

a) Ignition : onset of the thermonuclear instability
b) Freidberg Report (FESAC Burning Plasma Report, September 2001)

MESSAGE: IGNITOR IS AS “STATIONARY” AS ITER (66/65 ≅ 1) EVEN WHEN THE LONGEST PHYSICS TIME (the collisional current redistribution time τ_{cr}^{coll}) IS CONSIDERED. Note that τ_{cr}^{coll} may not be physically relevant. In fact, the current redistribution could be controlled by collective processes in the considered regimes. In this case $\tau_{cr}^{eff} < \tau_{cr}^{coll}$.

Example of "SCIENCE FIRST" development path



BASIC NON-BURNING PLASMA CONFINEMENT EXPERIMENTS

HIGH FIELD BURNING PLASMA EXPERIMENTS **IGNITION**
[e.g. Ignitor, Columbus]

TRITIUM POOR BURN EXPERIMENT

NET ENERGY PRODUCING FACILITY (thermal equivalent) $Q_{global} = \frac{\eta P_f}{P_{in,Plant}} > 1$ *

COMPONENT TESTING AND MATERIAL TESTING FACILITIES

LARGE VOLUME FUSION DEVICE

DEVELOPMENT OF HIGH FIELD SUPERCONDUCTING MAGNETS, OF ADVANCED STRUCTURAL CONCEPTS, OF SPECIAL MATERIALS, ETC.

* P_f = fusion power produced $P_{in,Plant}$ = total power input into the plant η= conversion efficiency