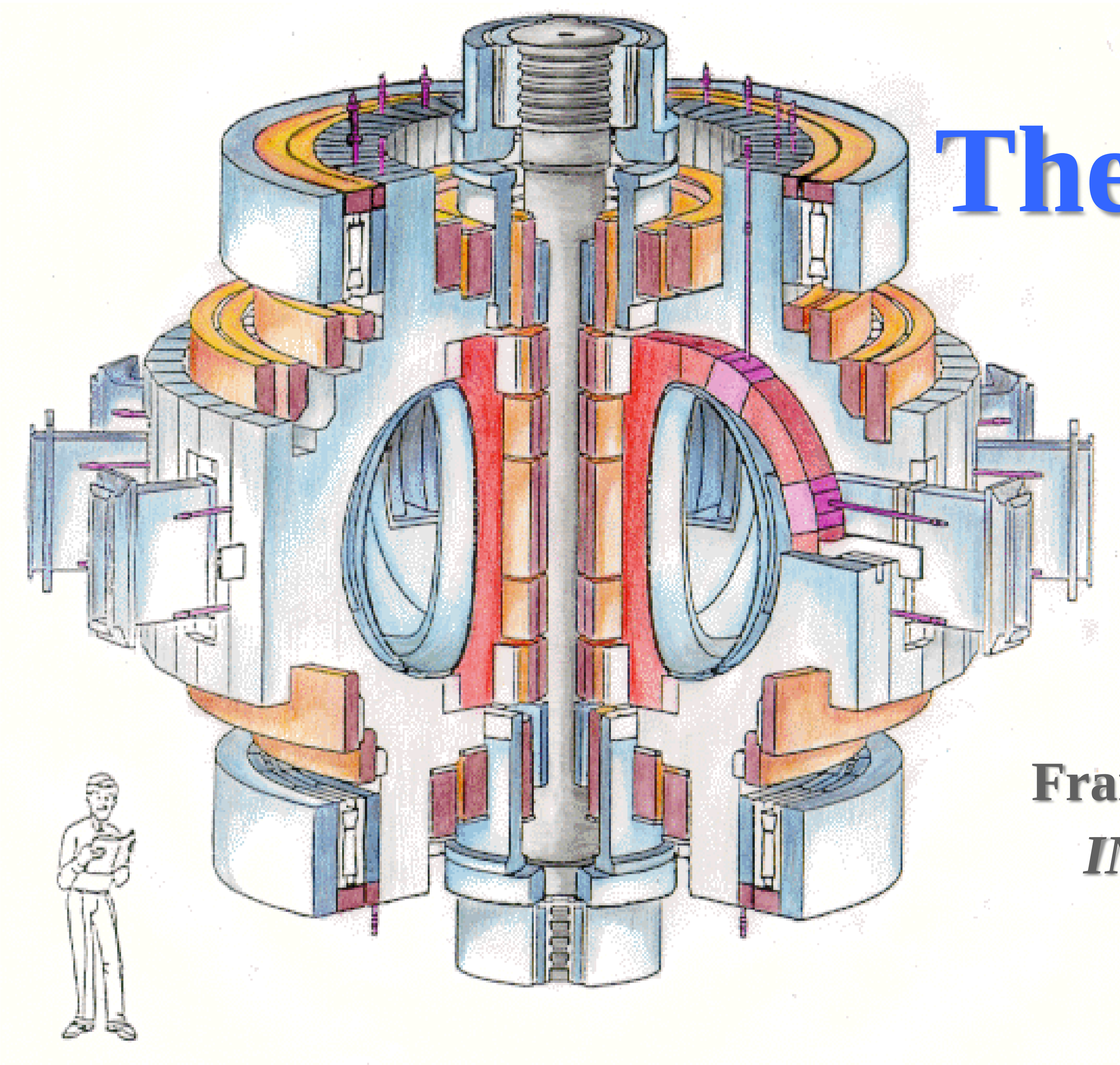
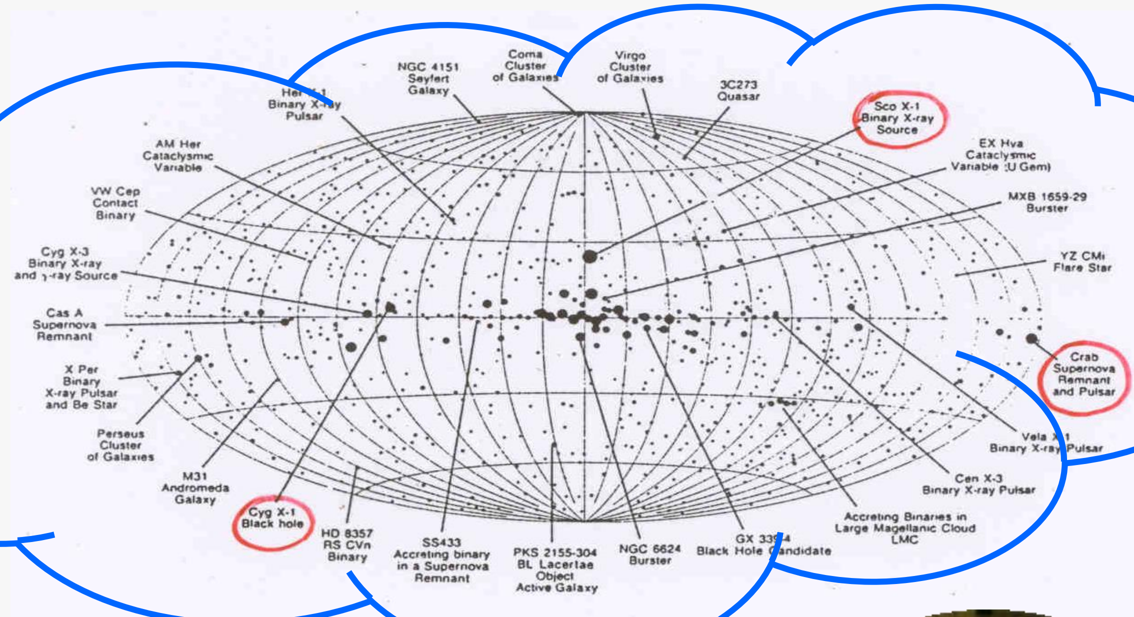


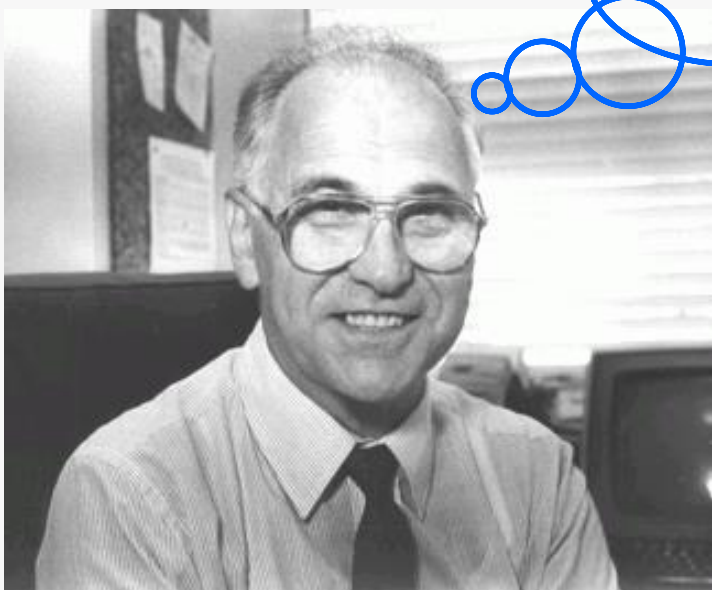
The Ignitor Project

Francesca Bombarda
INFN (Rome, Italy)

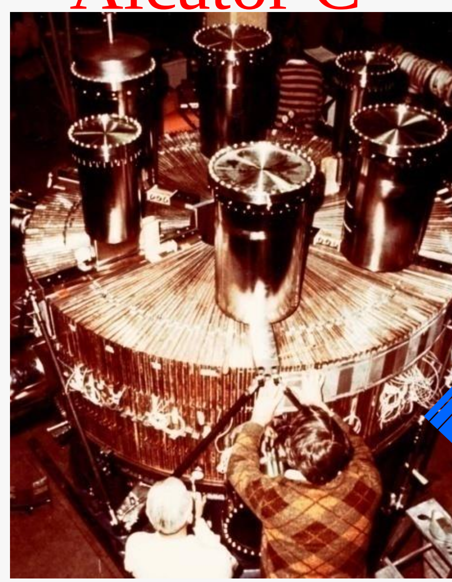
X-ray sources known in 1969 when the Alcator program was proposed



Bruno Coppi

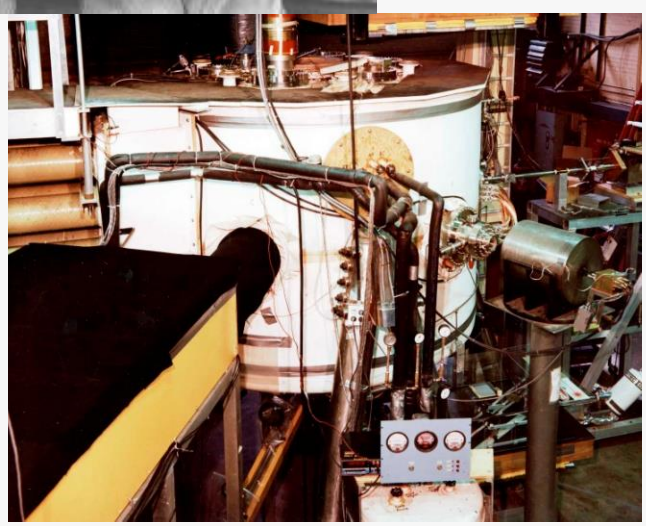


Alcator C



FT

Alcator A

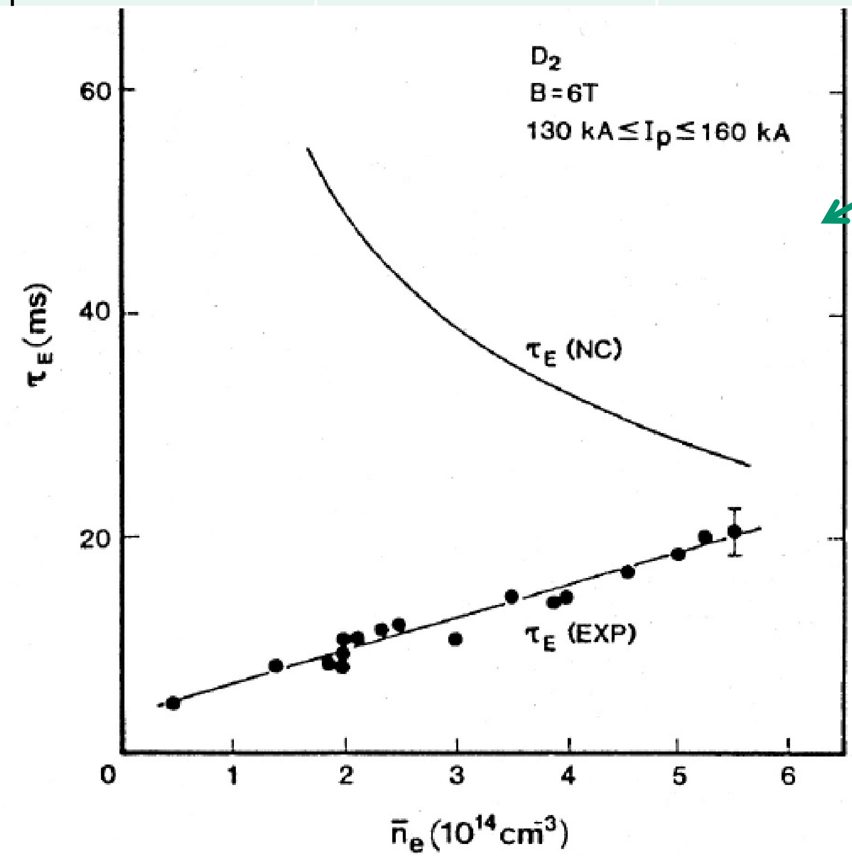


IGNITOR

Ignitor Project

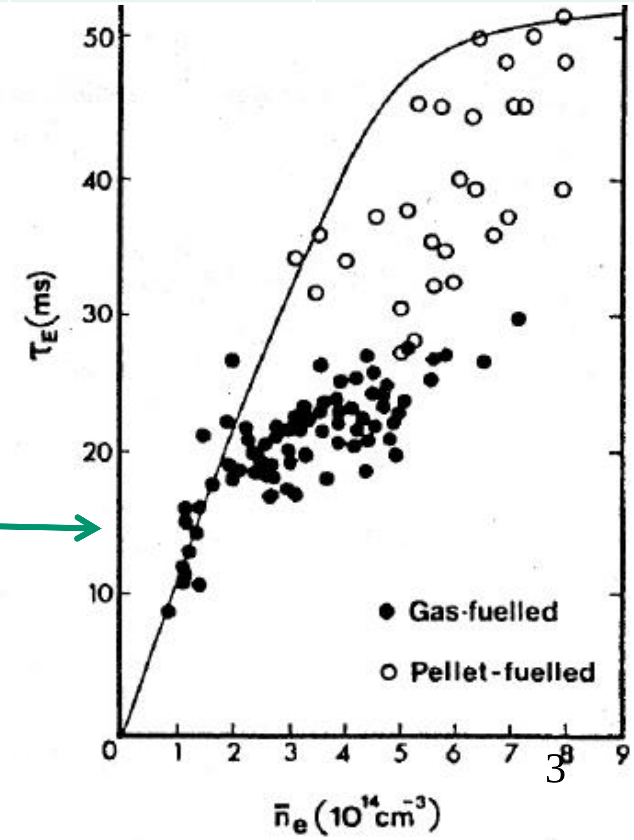
High field tokamaks:
($j(0) \propto B_T/R \sim 10$)

	Alcator A	Alcator C	FT	FTU	Alcator C-Mod
Years	1972-1979	1978-1987	1977-1987	1989-	1993-2016
R/a (m)	0.54/0.10	0.64/0.17	0.83/0.20	0.935/0.33	0.67/0.22, 1.9
B_T (T)	9	10	10	8	8
I_p (MA)	0.3	0.8	1	1.6	1.4 (2)



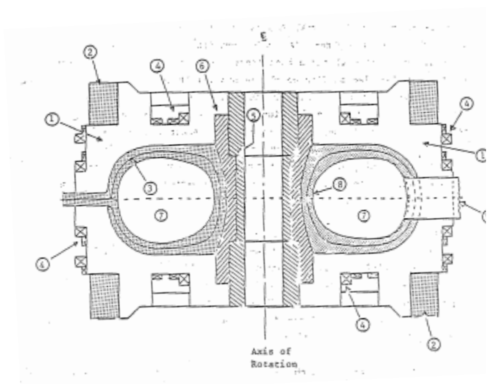
Alcator scaling

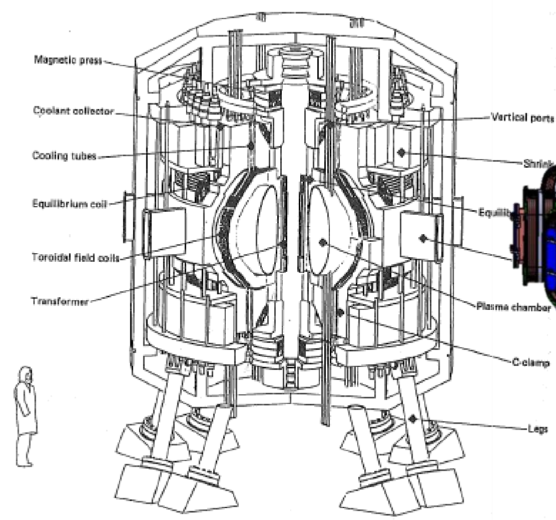
Neo-Alcator scaling

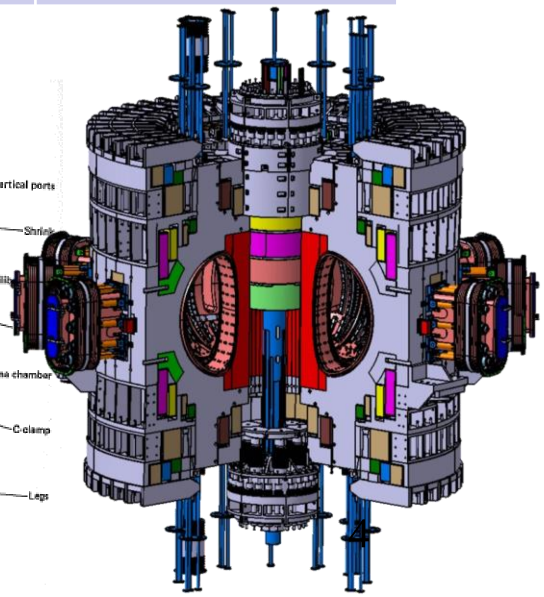


Ignitor Growth Chart

	1975	1983	1988	Present
Ref.	CPPCF 3, 47 (1977)	Report Panel Adams	PPCFR Nice 1988, V.3, 357	
R_0 (m)	0.5	1.09 $\rightarrow$	1.17	1.32
a (m), κ	0.2	0.34	0.435, 1.79	0.46, 1.83
B_T (T)	15	10	13.1	13
I_p (MA)	<3	2.7	12	11
T_0 (keV)	10	3$\rightarrow$5.3	15	11
n_0 (m^{-3})	10^{21}	$\rightarrow$1.9x10^{21}	10^{21}	10^{21}







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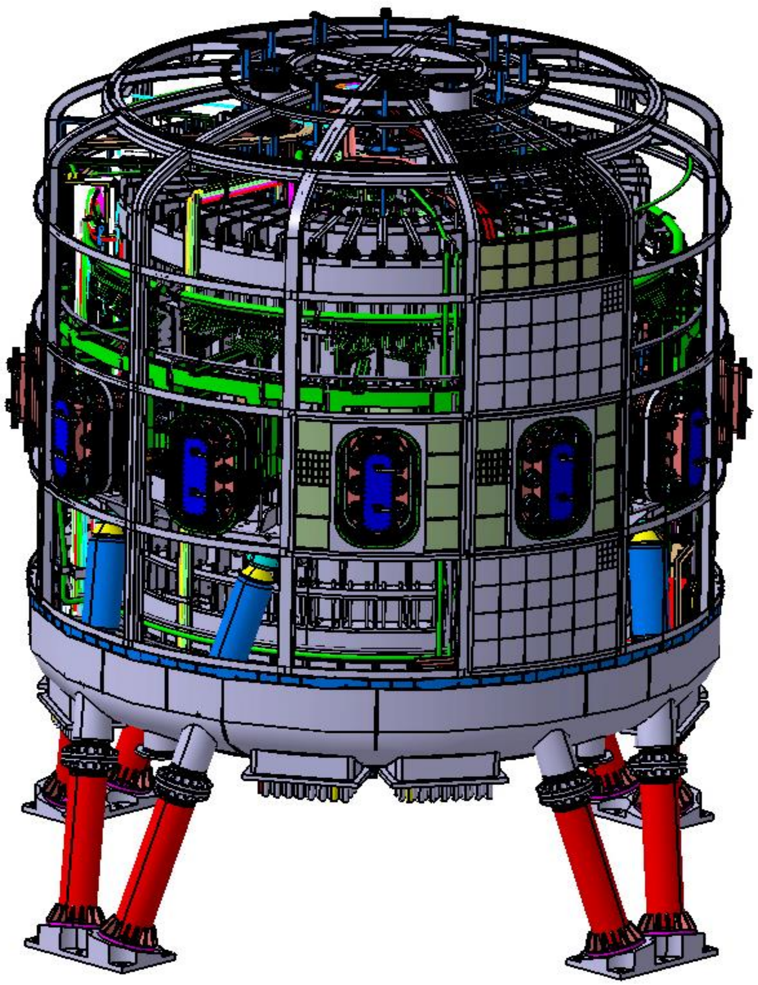
T_0 (keV)	10	3$\rightarrow$5.3	15	11
n_0 (m^{-3})	10^{21}	$\rightarrow 1.9\mathrm{x}10^{21}$	10^{21}	10^{21}

Certain features have not changed:

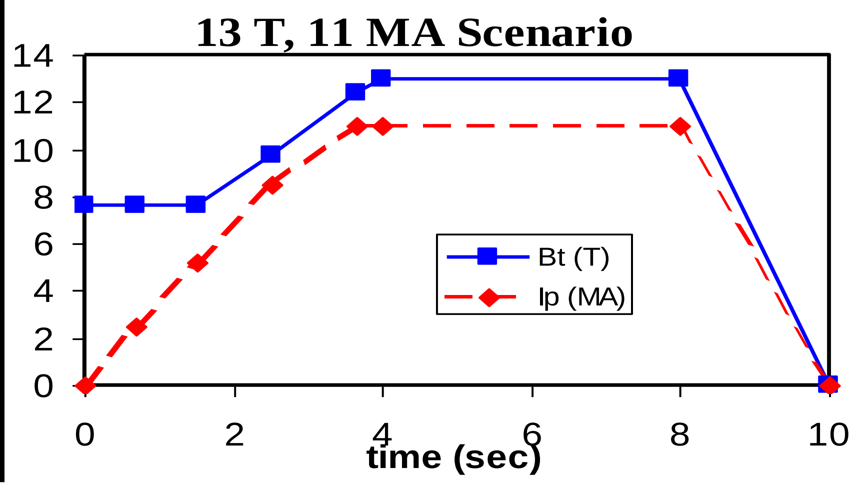
- The IGNITOR name
- The “Ignition” goal, at high density, high field
- The marginal role of auxiliary heating
- Limiter configuration (no divertor)

Ignitor: an Ignition Experiment in the Context of a "Science First" Fusion Program

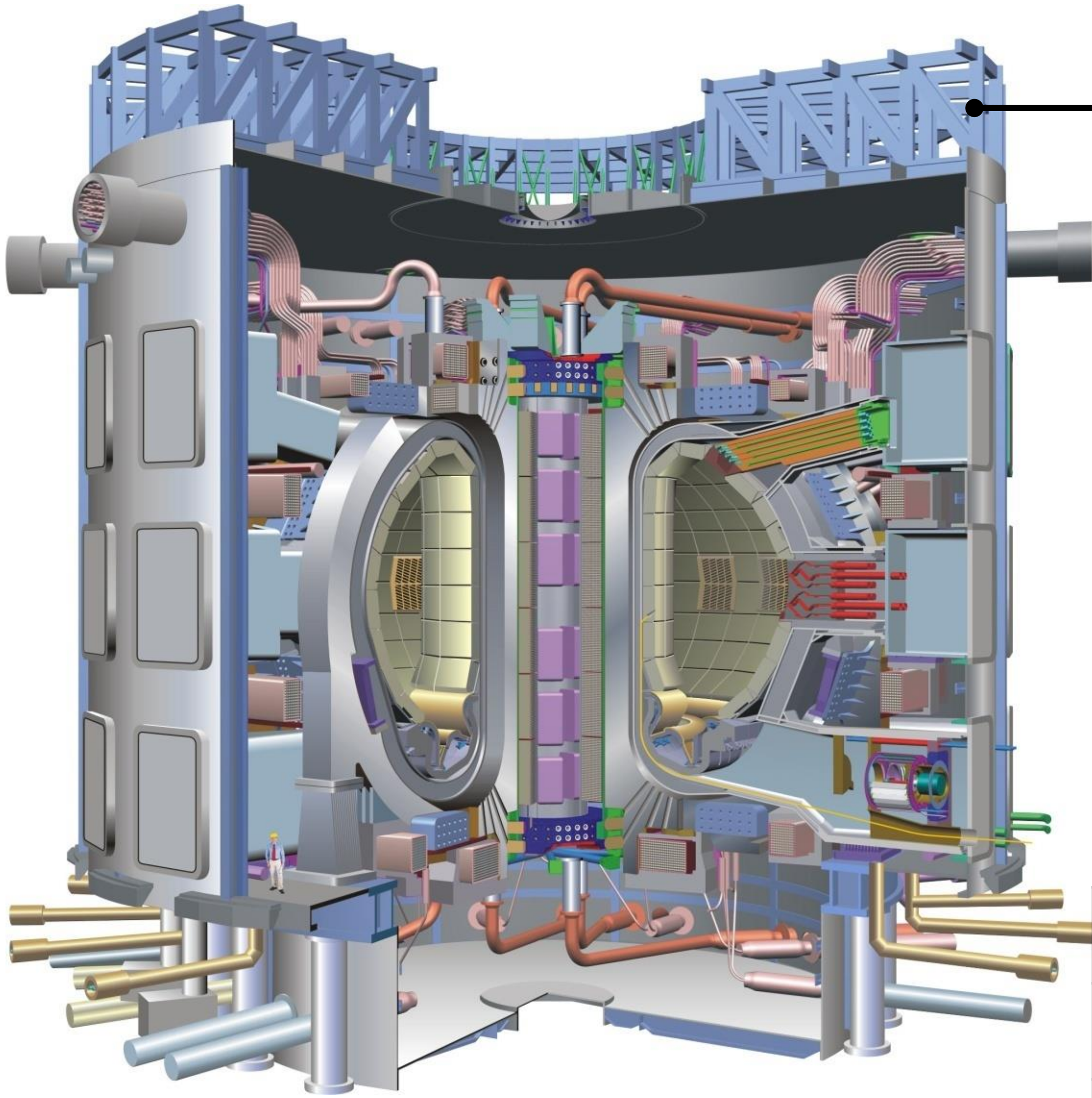


Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
Pulse length	4+4 s
RF Heating P_{icrh}	<12 MW

R	1.32 m
a	0.47 m
κ	1.83
δ	0.4
V	10 m^3
S	36 m^2



The “big” and the “small” path towards fusion



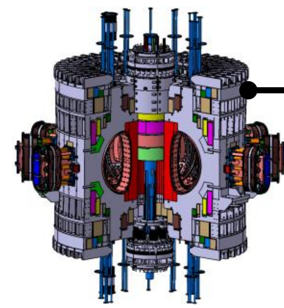
ITER

Diameter: 29 m

Height: 26 m

Pl. Volume: 800 m^3

Weight: 23,000 ton



IGNITOR

Diameter: 7 m

Height : 8 m

Pl. Volume: 10 m^3

Weight : 700 ton

	Ignitor	ITER
R_0, a (m)	1.32, 0.46	6.2, 2.
B_T (T), I_p (MA)	13, 11	5.3, 15
Q	∞	10

Ignitor Project

Outline

- Scientific goals and operational program
- The ignition strategy, stability issues
- Other Confinement Regimes and X-point configurations
- Machine Design principles
- Plasma Wall Interaction issues
- Auxiliary Heating and Pellet Injection
- Diagnostics
- “Reactor Relevance” and the High Field path to fusion
- Conclusions

Ignitor Project

The Ignitor scientific goals

The main goals of the Ignitor experiment are:

- Demonstration of ignition in magnetically confined plasmas;
- The physics of burning plasma processes;
- Heating and control of burning plasmas.

❖ Fusion ignition is a major scientific and technical goal for contemporary physics. The ignition process will be similar for any magnetically confined, predominantly thermal plasma.

❖ Ignitor is the first, and presently the only machine designed to reach ignition ($P_\alpha = P_{Loss}$).

❖ Heating methods and control strategies for ignition, burning and shutdown can all be established in meaningful fusion burn regimes, on time scales sufficiently long relative to the plasma intrinsic characteristic times ($\tau_{\alpha,sd} << \tau_E$, $\tau_j \cong \tau_{burn} >> \tau_{E,}$).

❖ Ignitor will provide a crucial test regarding PSI in limiter configuration

Plasma regimes

- None of the plasma regimes obtained in present experiments are really suitable for the reactor
- A single burning plasma experiment will NOT be sufficient to fully understand the "reactor physics"
- Until the fundamental physics issues of fusion burning have been identified and confirmed by experiments, the defining concepts for a fusion reactor will remain uncertain

$$K_f = P_f / (5P_L) \lesssim 1 \qquad Q = 5K_f / (1 - K_f) > 50$$

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

Ignition conditions: $P_\alpha = P_L$

$$P_\alpha \propto n^2 T^2 \quad \text{for D-T}$$

$$\langle p \rangle \approx 1-4\,\text{MPa}$$

$$p \propto B_p^2$$

$$(\beta_{pol} \sim \text{cost})$$

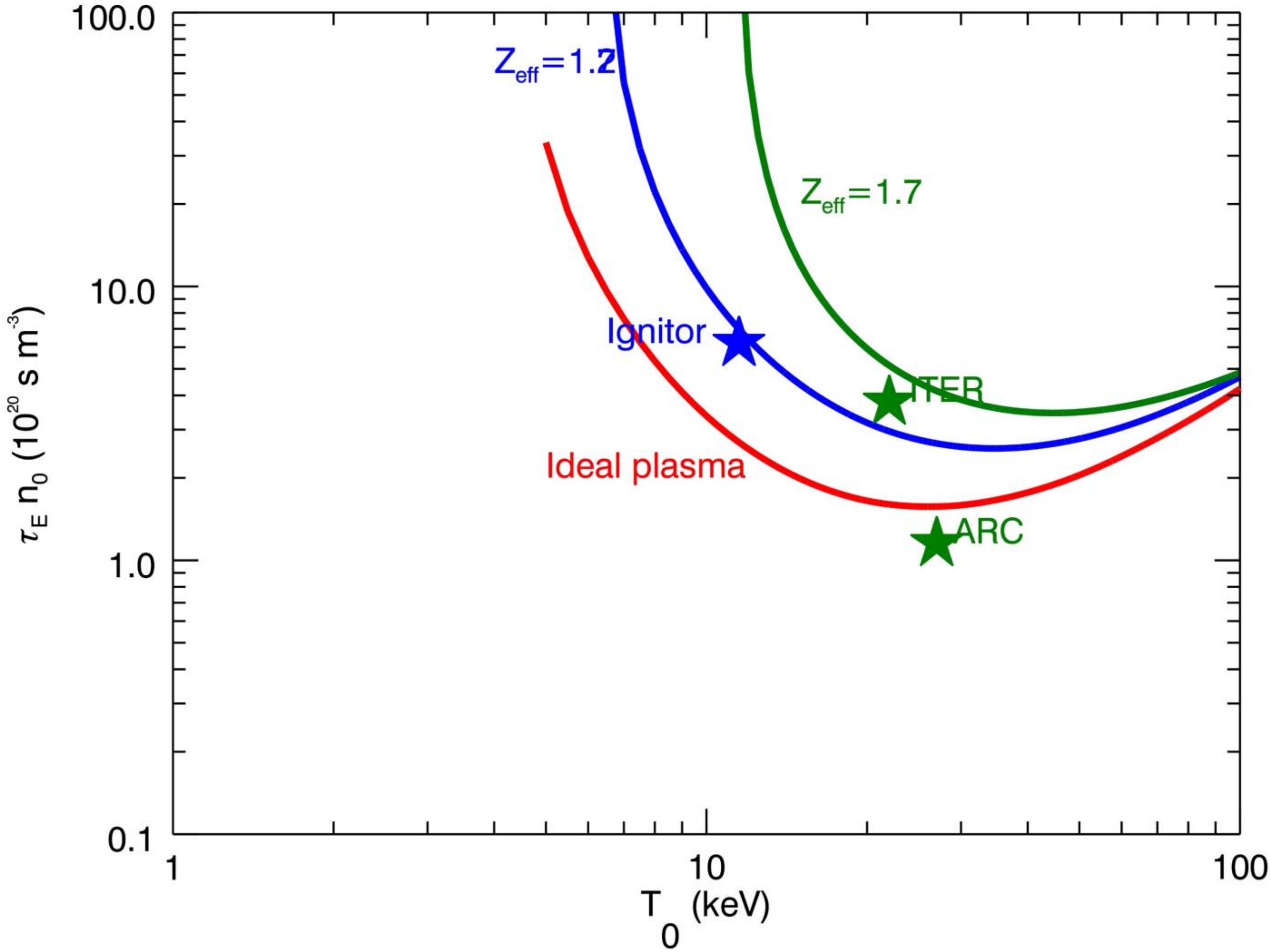
$$\Rightarrow P_\alpha \propto B_p^4$$

Furthermore

$$T_e \sim T_i$$

$$Z_{eff} \sim 1$$

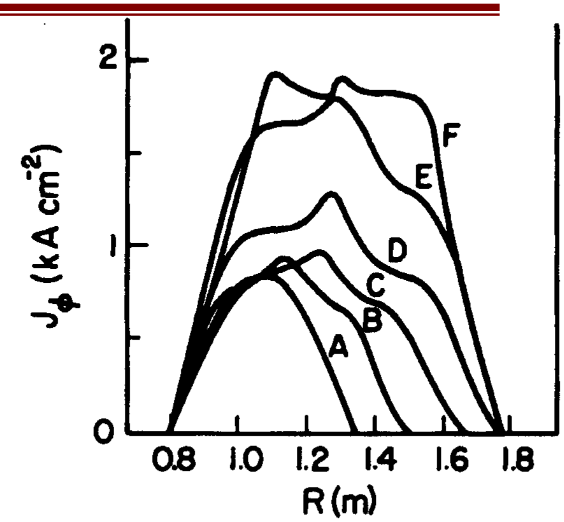
$$\varepsilon_\alpha n^2 \langle \sigma \mathrm{v} \rangle / 4 = 3nT / \tau_E$$



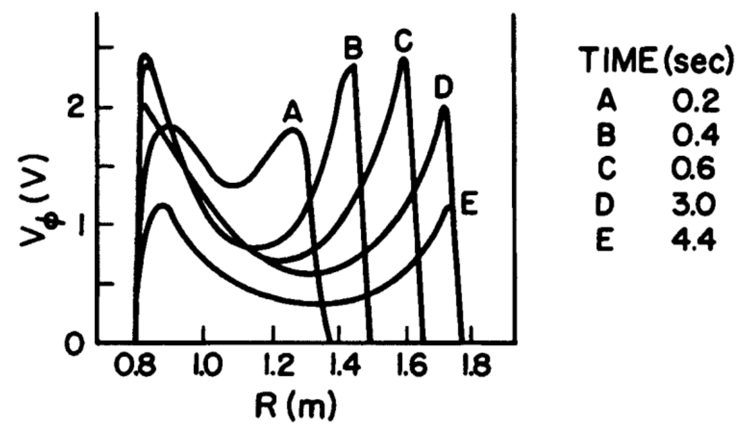
$$P_{\alpha H} + P_\Omega + P_{aux} - \partial W / \partial t - P_L = 0$$

The Ignitor path to ignition

- $n\tau_T$: high density, moderate τ_E, low temperature to approach the thermonuclear instability
- $n/n_{limit} < 0.5$, low β 's consistent with known stability limits
- $\tau_{\alpha,sd} << \tau_E$, $\tau_{burn} >> \tau_E$



1. High current for B_p, mostly Ohmic heating + fusion α's
2. Minimal reliance on additional heating
3. No transport barrier ⇒ less impurity trapping in the main plasma
4. High edge density, low edge temperature ⇒ naturally radiative edge, less sputtering
5. Relatively peaked density profiles
6. Up-down symmetry to minimize OoP stresses.



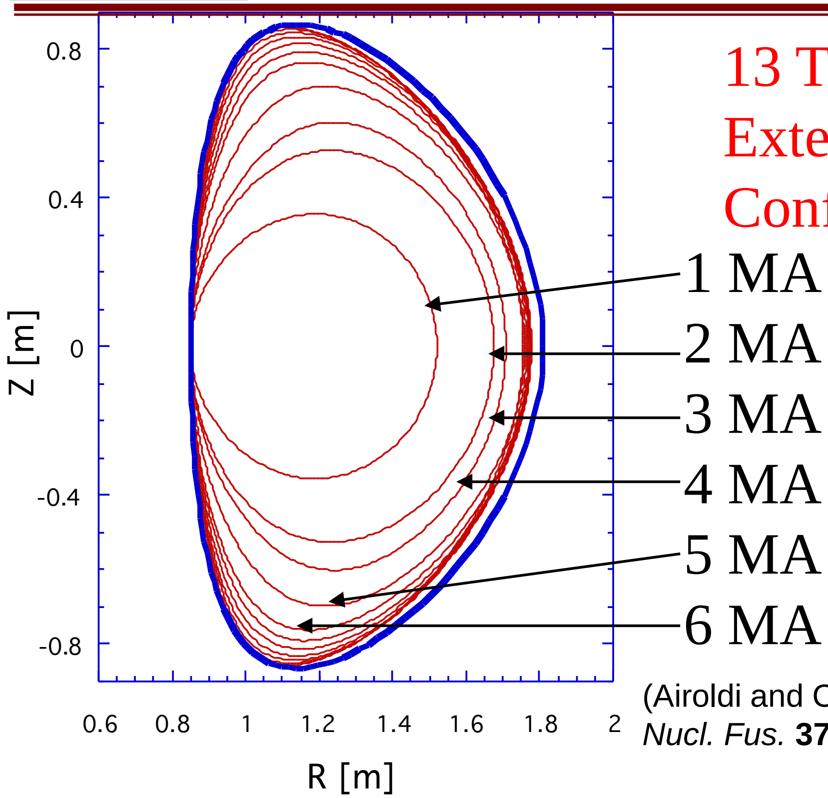
M. Nassi, L.E. Sugiyama, 1992

Density is the key

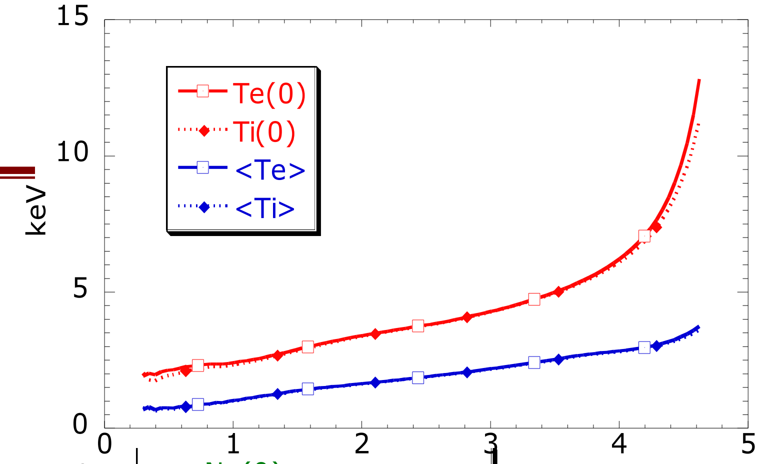
Ohmic Ignition

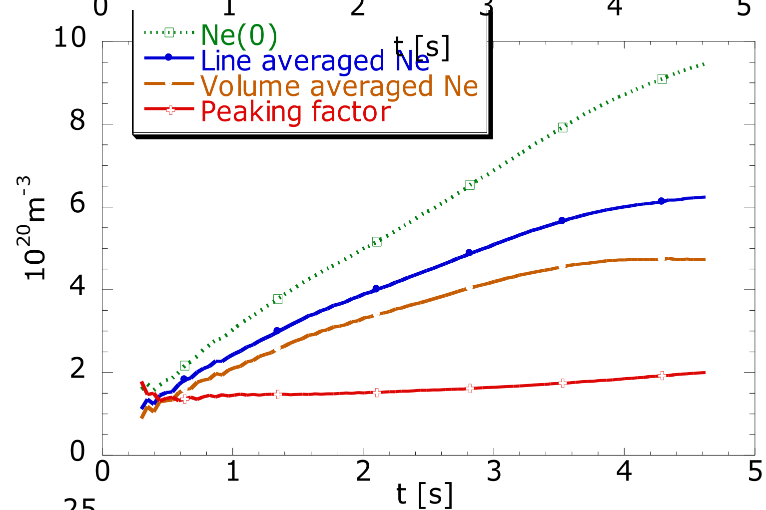
Ignitor Project

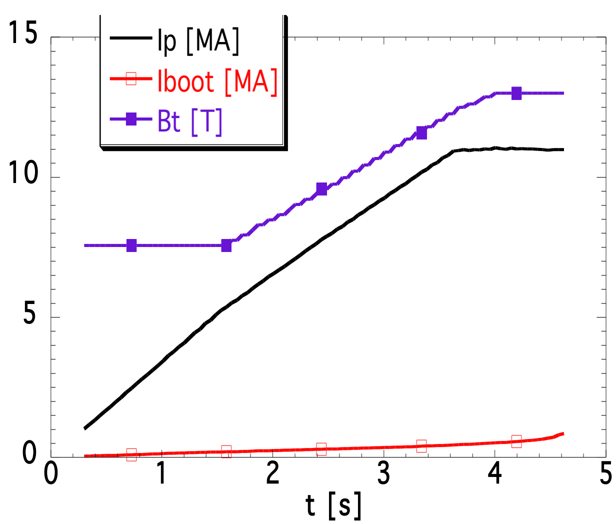
13 T, 11 MA
Extended Limiter
Configuration



(Airoldi and Cenacchi, *Nucl. Fus.* **37**,1117(1997)



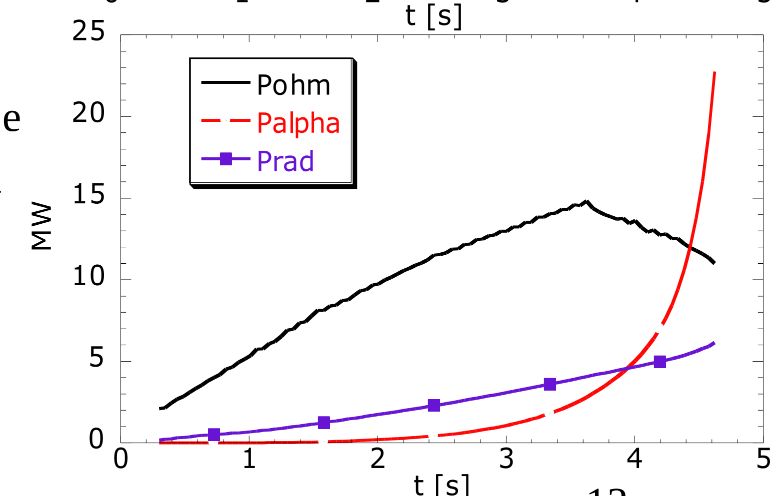




CMG model for χ_e

χ_{ei} =Neo-classical

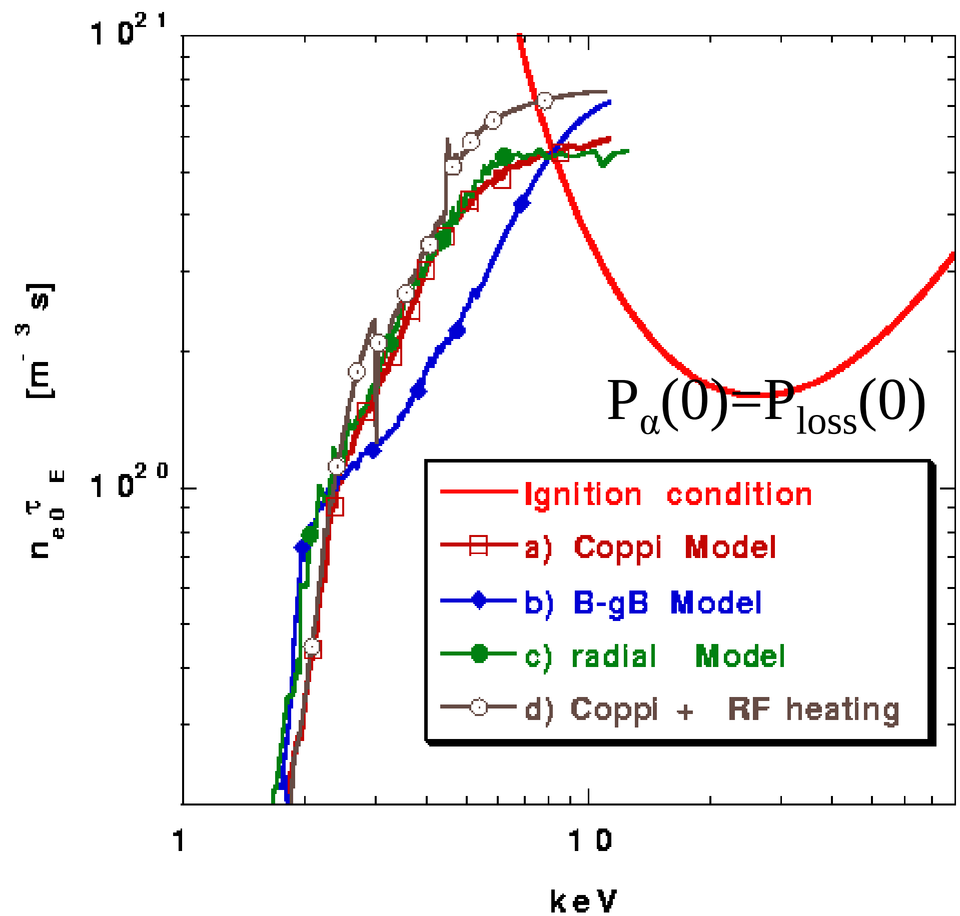
+ 5% χ_e



A. Airoldi and G. Cenacchi *Nucl. Fusion* 41, 687 (2001)

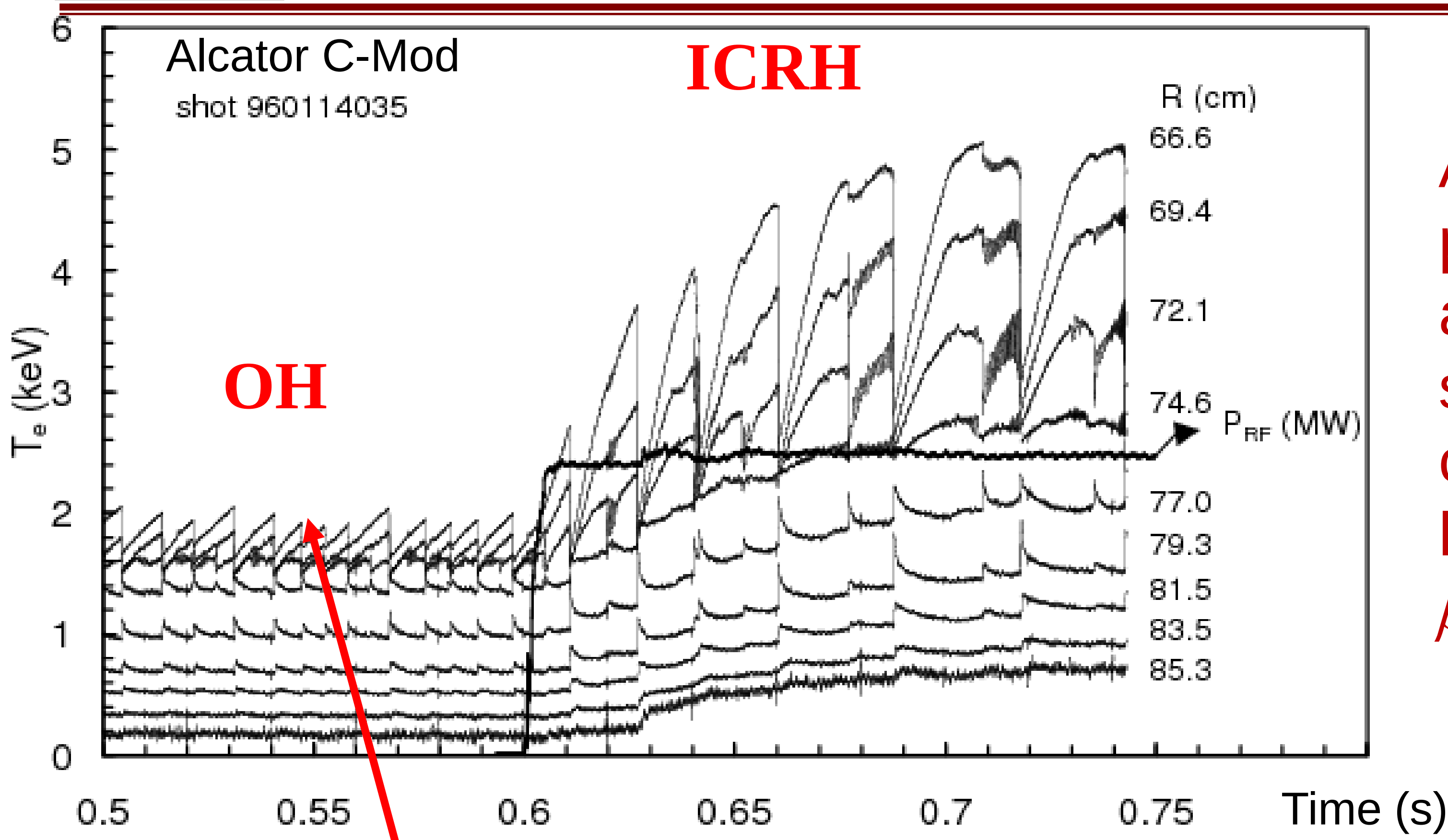
Reference Plasma parameters @ Ignition

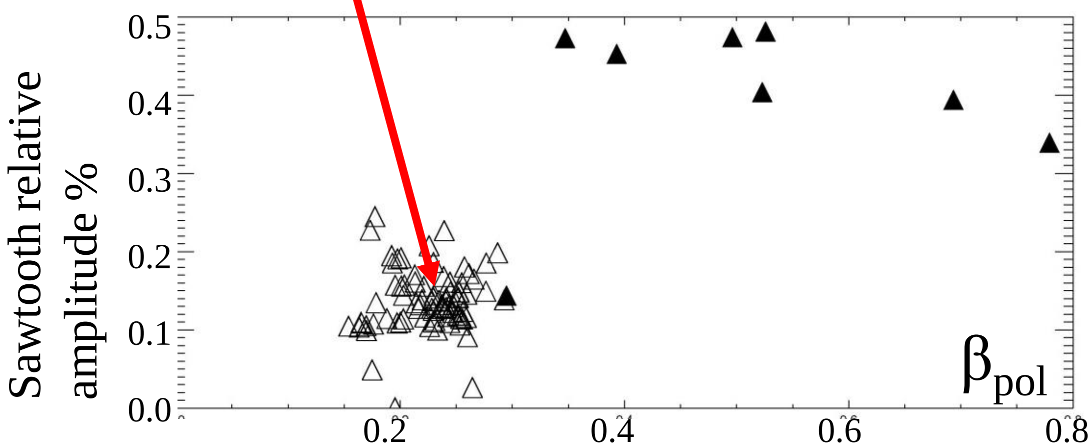
R, a	1.32, 0.47 m
κ, δ	1.83, 0.4
I_P	11 MA
B_T	13 T
T_{e0} , T_{i0}	11.5, 10.5 keV
n_{e0}	10^{21} m^{-3}
$n_{\alpha 0}$	1.2×10^{18} m^{-3}
P_{α}	19.2 MW
W_{pl}	11.9 MJ
$P_{OH} = dW/dt$	10.5 MW
P_{rad}	6 MW
β_{pol}, β, β_N	0.2, 1.2%, 0.7
q_{ψ}, q_0	3.5, ~ 1.1
τ_E, τ_{sd}	0.62, 0.05 s
Z_{eff}	1.2



The most accessible conditions to reach ignition regimes involve relatively peaked density profiles: $n/\langle n\rangle>2$

Stability Issues





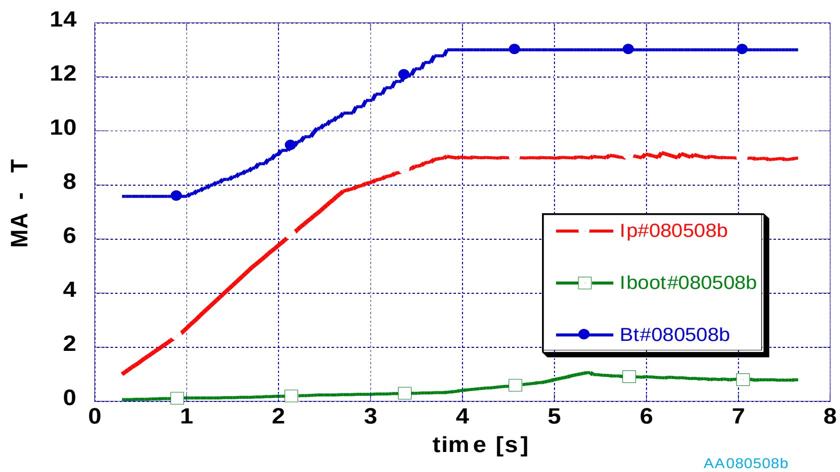
An important protection against large sawteeth is connected to the **low value**s of $\beta_{pol} = 8\pi p/B_p^2$

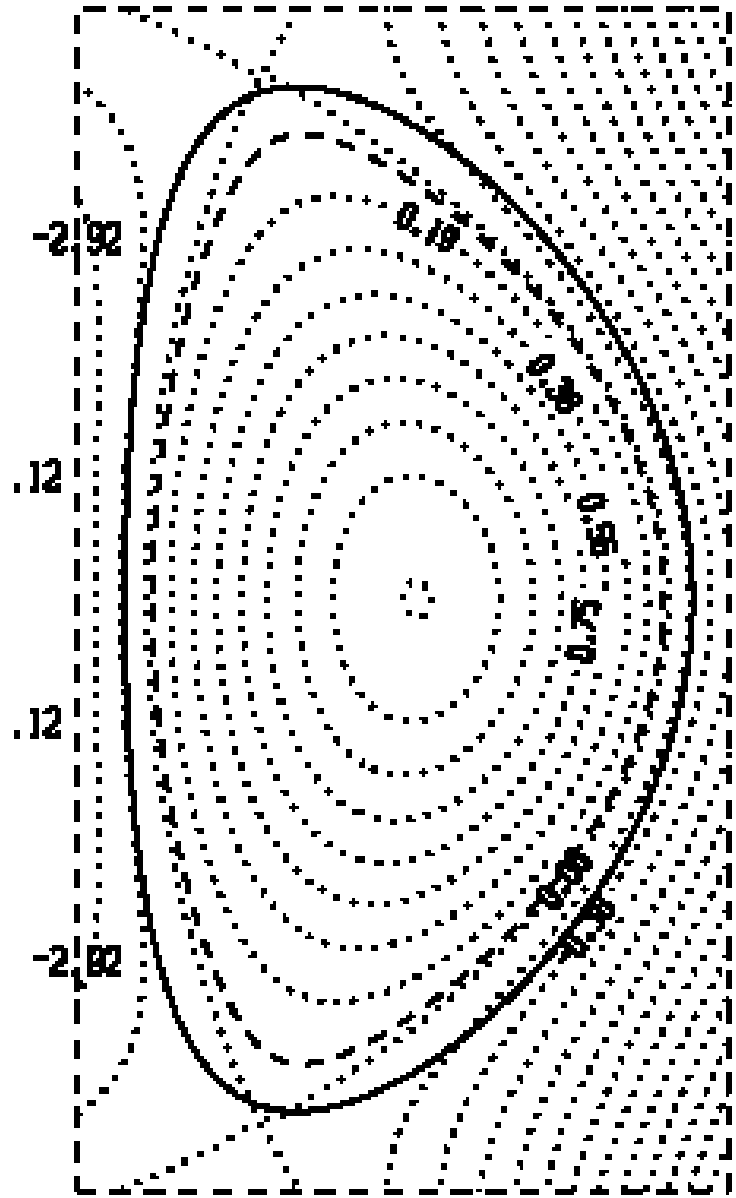
(See the analysis of plasmas produced by Alcator C-Mod reported in BOMBARDA, F., BONOLI, P., COPPI, B., et al., *Nucl. Fus.* **38** (1998) 1861.

Ignitor Project

Double Null Configuration

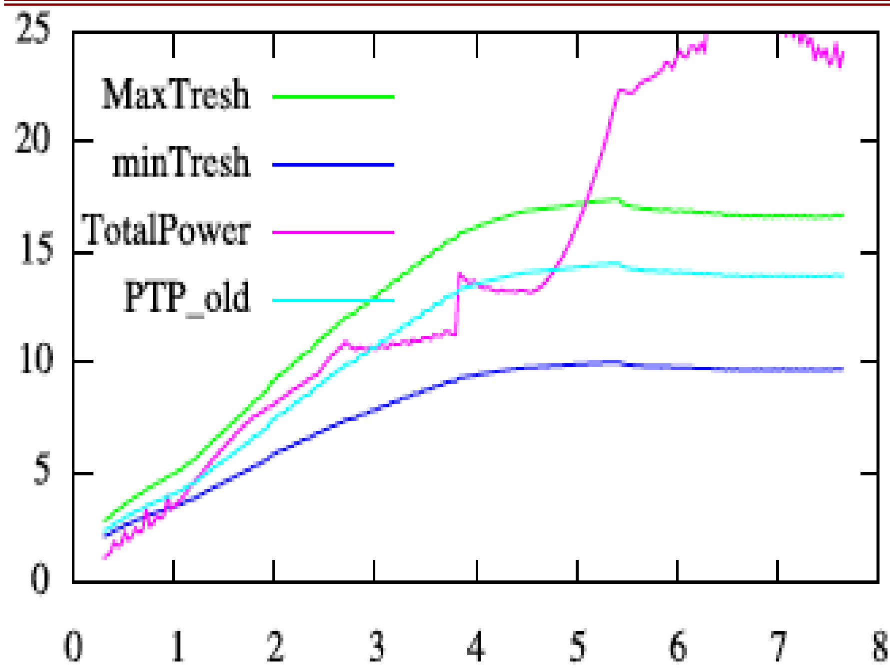
- Magnetic field up to 13T
- Plasma current up to 9 MA
- Ramp-up time 3.8 s for current and magnetic field
- Pulse length (7.65 s) consistent with mechanical and thermal requirements



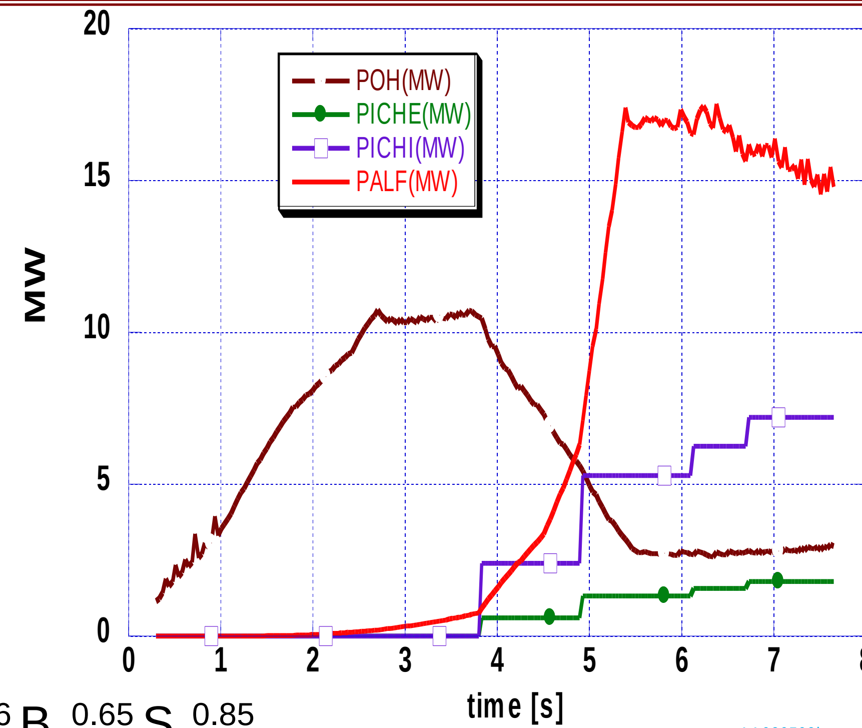


Ignitor Project

Transition to H-mode



t [s]



$P_{tresh,Max}=0.077 n_{e20}^{0.56} B_T^{0.65} S_p^{0.85}$

$P_{tresh,min}=0.075 n_{e20}^{0.44} B_T^{0.58} S_p^{0.80}$

$P_{PTP,old}=0.108 n_{e20}^{0.49} B_T^{0.85} S_p^{0.84} / \langle A_i \rangle$

A. Airoldi, G. Cenacchi,
APS-DPP 2008
GP6.000622

Ignitor is likely to produce an EDA-type of H-mode, similar to C-Mod. In this regime ELMs are not present, due to the high recycling associated with high edge densities. Also the I-mode should be possible.

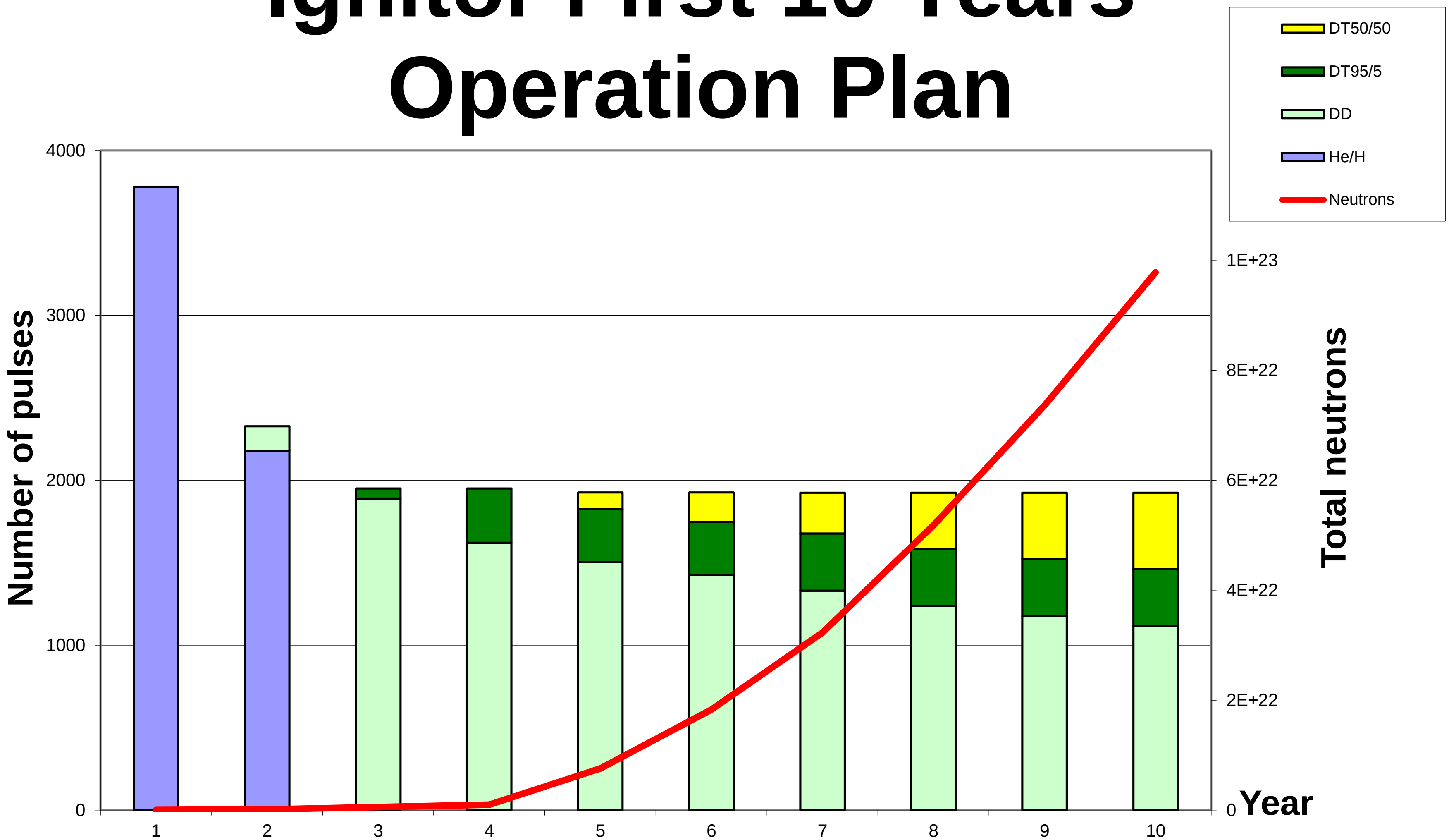
[1]D.C. McDonald, A.J. Meakins, et al., *PPCF* **48**, A439 (2006)

[2]B.Coppi, et al., MIT R.L.E. Report PTP **99/06** (1999)

Ignitor Operational Program

- Phase I: H and ^{4}He - Commission to full power all systems and subsystems, with the exception of the tritium handling and diagnostic systems relying on fusion reactions
- Phase II: D - Radiation screening requirements brought almost at final levels, but the tritium handling and recovery systems do not need to be in place yet. In this very "physics intensive" phase, the main ignition scenarios will be tested, and alternative paths explored. The full range of currents and toroidal fields will be utilized, and at this point, an assessment of the adequacy of the available ICRH power will be done, following the verification of the effectiveness of the proposed heating schemes.
- Phase III: D-T - Finally, the use of T will allow the most ambitious part of the program. None of the experiments carried out so far with D-T fuel were actually close to the conditions necessary for truly burning plasmas (i.e., $T_e \cong T_i$, $Z_{eff} \cong 1$, good α-particle confinement). Tritium can be injected in trace quantities or up to the ideal concentration 50-50 with deuterium.

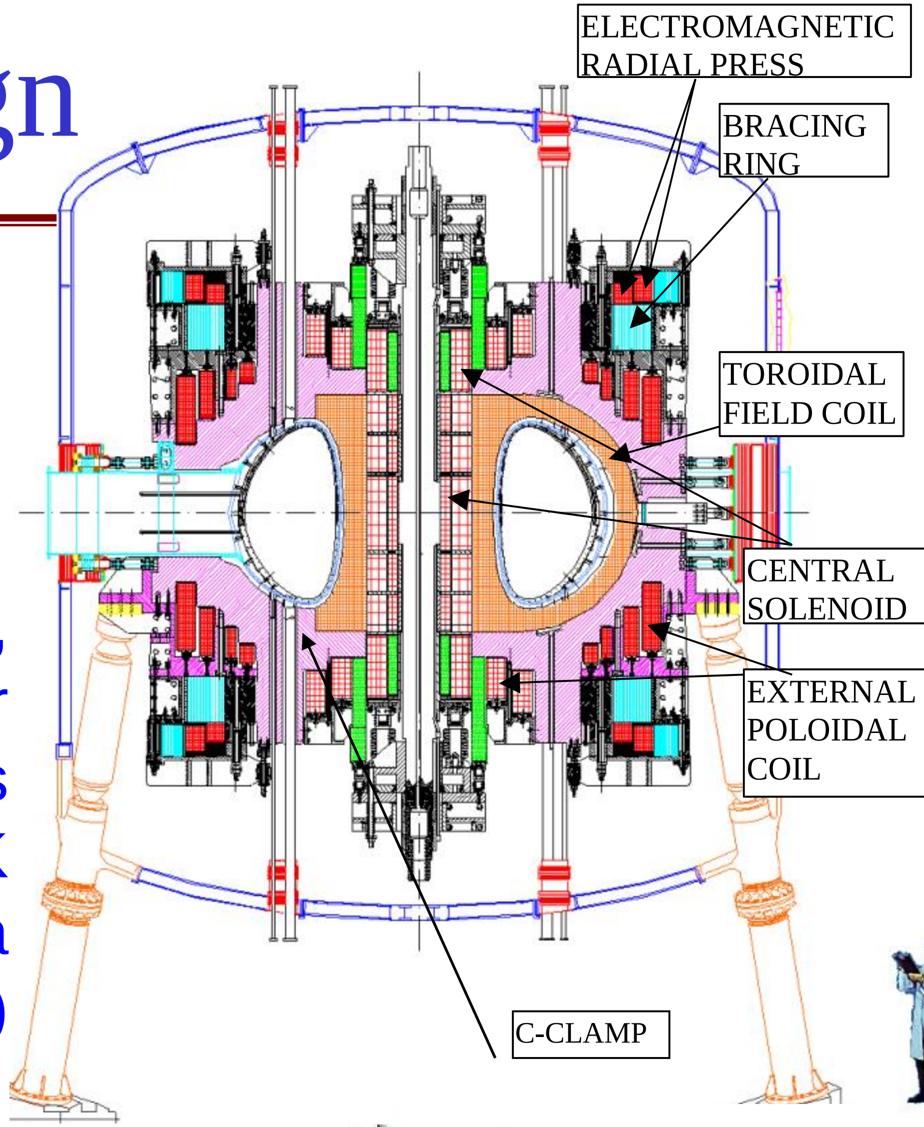
Ignitor First 10 Years Operation Plan



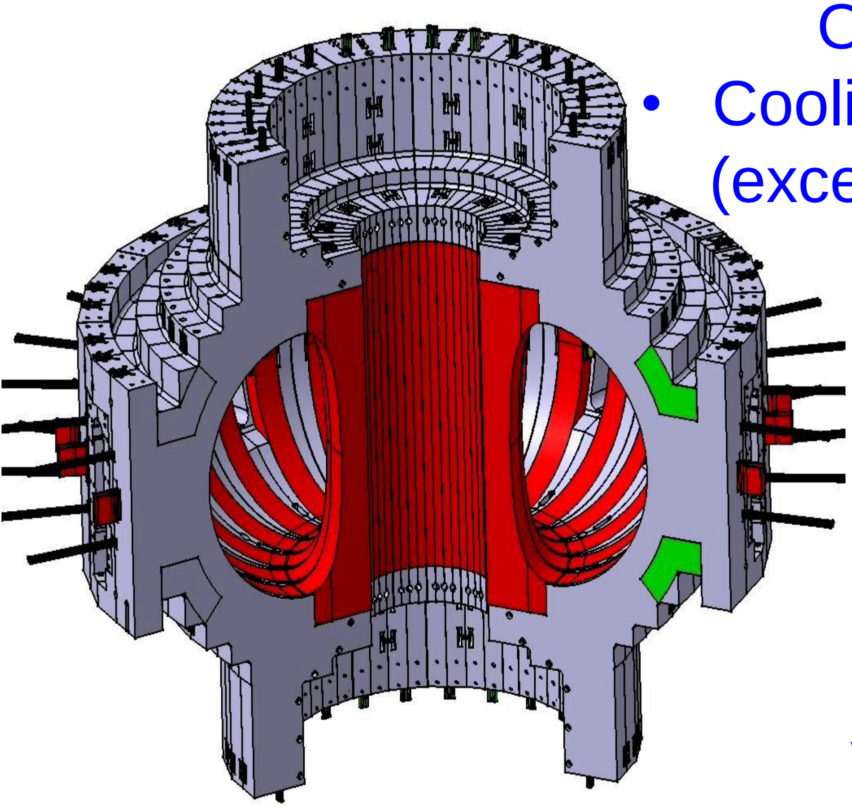
Machine Design

The machine is characterized by a complete structural integration among major components.

- Bucking and Wedging
- Passive and Active Compression
- No Divertor, optimized for OOP forces
- Cooling to 30 K (except Plasma Chamber)



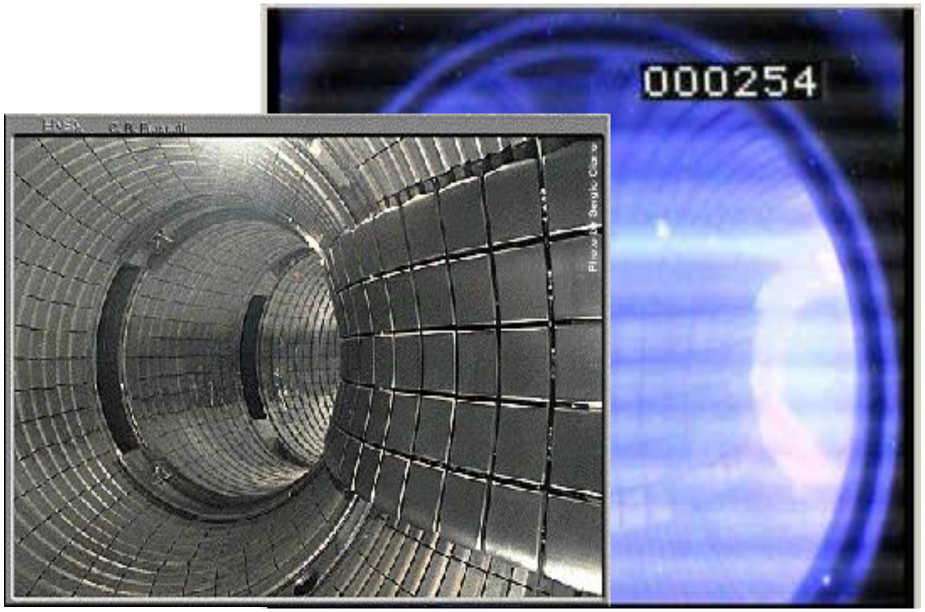
AnsaldoNucleare



2D/3D design and integration of core machine components produced with Dassault CATIA-V software.

First Wall Limiter vs. Divertor

“FWL” (e.g., FTU)

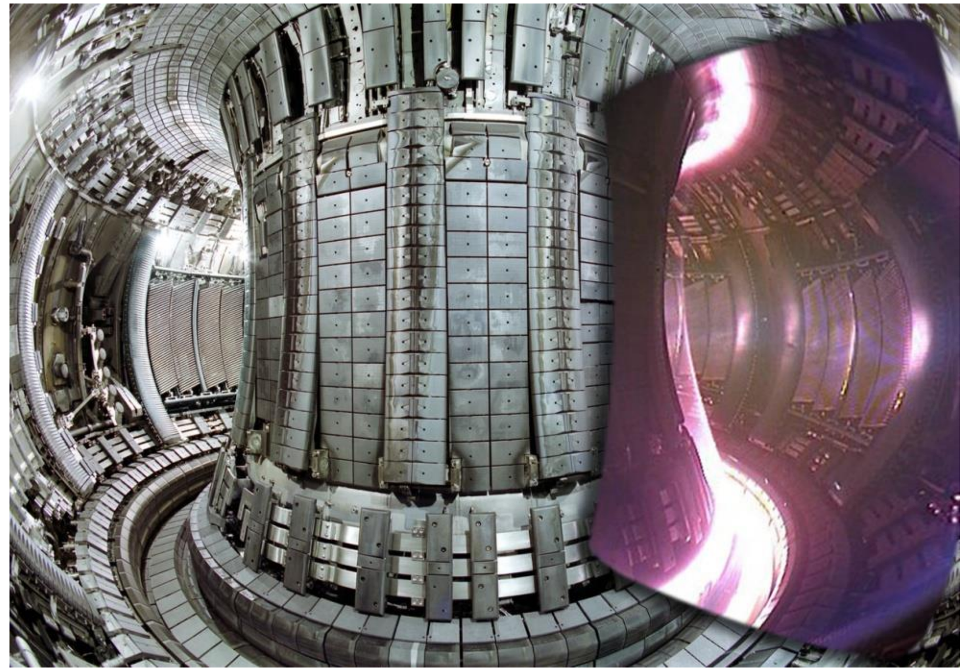


PWI (ideally) spread over the wall

Sometimes adopted in compact, high field /density machines

Grazing incidence of B to (part of the) wall

Divertor (e.g., JET)



PWI (ideally) concentrated to divertor

Most often adopted in large, medium-to-low field /density machines

Finite B incidence to wall

Thermal Wall Loading

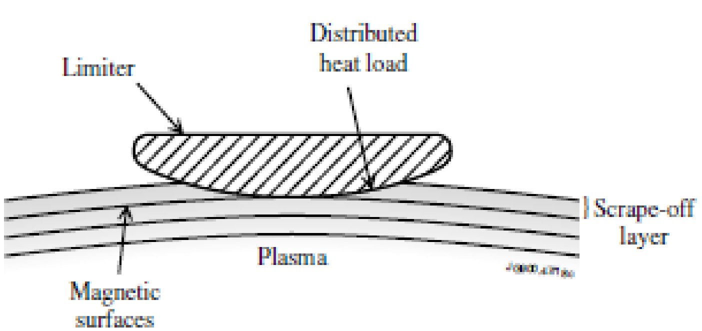
Three components (neglecting nuclear loads):

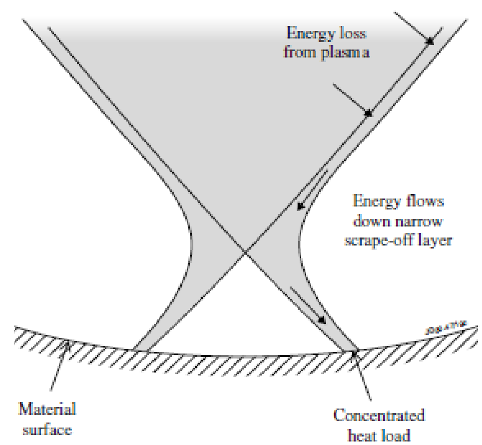
1. Parallel convection $q_{//}(\mathrm{r})=q_0\exp(-r/\lambda_E)$, $\lambda_E < 10$ mm
2. Cross-field diffusion $q_\perp = \mathrm{F}\, q_{//}$
3. Radiation $q_{rad} = f\, P_{rad}/S_{pl}$,

$$P_{rad} \propto Z^3 \langle n_e \rangle^2 \frac{Z_{eff} - 1}{\langle Z \rangle (\langle Z \rangle - 1)} + c Z_{eff}^2 \langle n_e^2 T_e^{1/2} \rangle$$

$$q_w = q_{||} \sin(\alpha) + (q_\perp + q_{rad}) \cos(\alpha)$$

In configurations with the plasma perfectly parallel to the first wall, and with negligible diffusivity, the thermal wall loading would be vanishing….





Characteristics of the Ignitor SOL

Ignitor Project

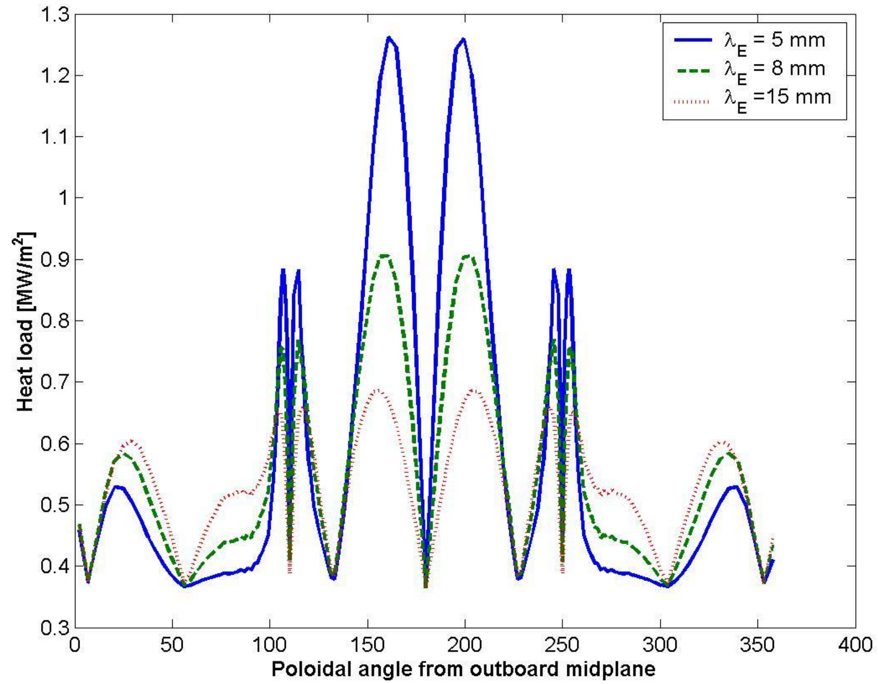
$n_e(a) \cong 2\text{-}3.5 \times 10^{20}\ m^{-3}$

$T_e(a) \cong 35\text{-}60\ eV$

⇒ "complex SOL regime" [1]: radiation, ionization and charge exchange are all important in reducing particle energy and spreading out the power transported across the LCFS by energetic particles

⇒ "High Recycling Regime" (ions)

⇒ "Edge Radiative Regime" (electrons)

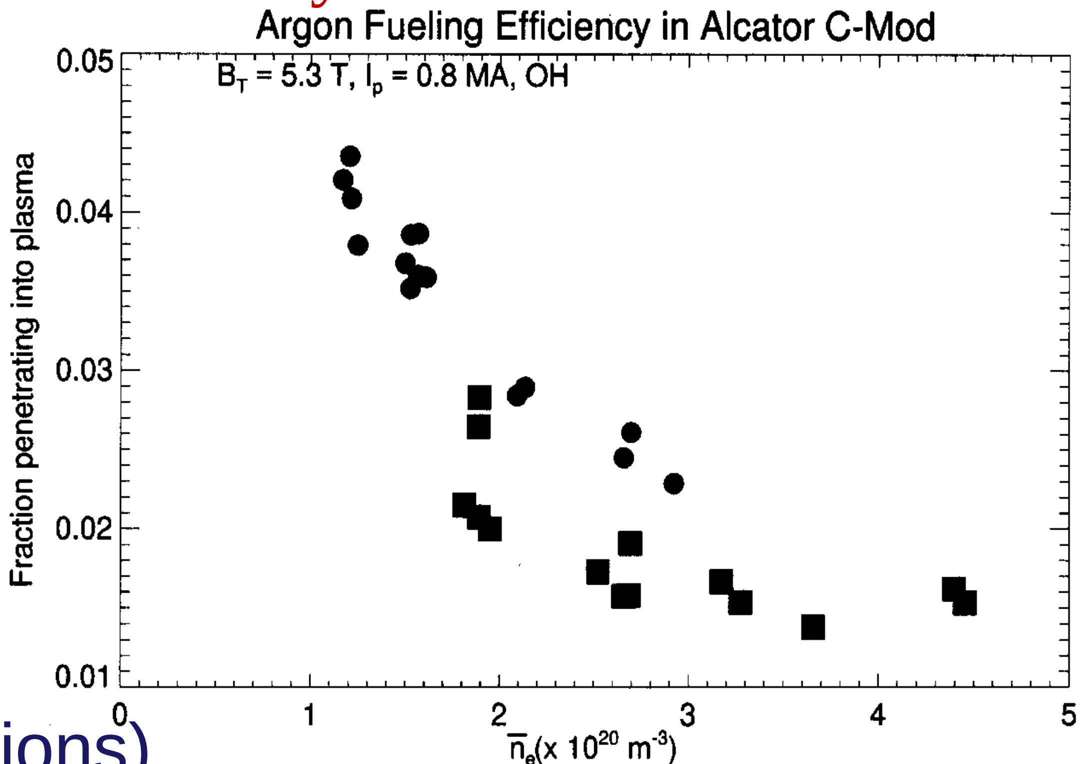


Heat Load for P_{in} = 18 MW, P_{rad}= 70% P_{in} and a range of three possible values for λ_E. In the worst case considered, the expected maximum heat load onto the wall is < 1.3 MW/m^2.

[1] P.C. Stangeby, G.M. MCCracken , *Nuclear Fusion* **30**, 1225 (1990).

Impurity Screening

- At high density, lower temperatures reduce sputtering from the wall; medium/high Z impurities are effectively screened from the main plasma.
- All-metal limiter machines could turn out the best solution for the requirements of plasma-wall interaction control in high density, reactor relevant plasmas.



⇒ "High Recycling Regime" (ions)

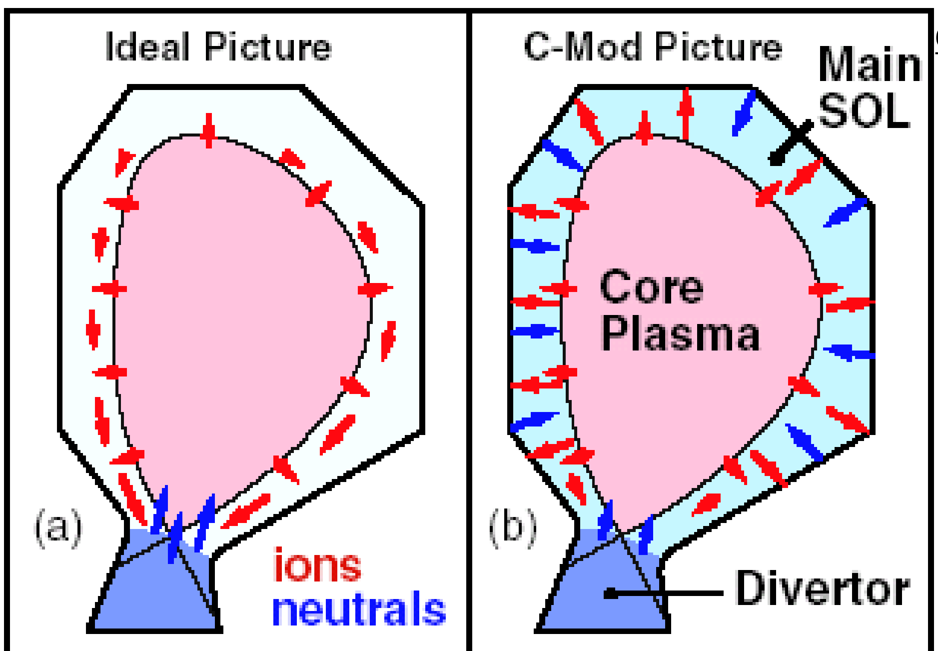
⇒ "Edge Radiative Regime" (electrons)

The high density approach avoids the need for divertors to manage impurities!

Ignitor Project

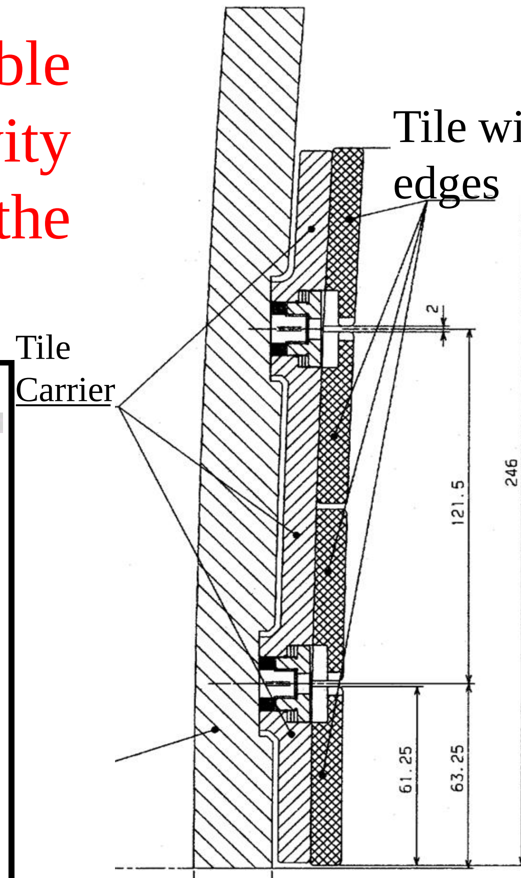
Why not a divertor

- Machines with divertors do not produce “cleaner” plasmas than limiter, high density devices.
- Divertors reduce the usable volume inside the magnet cavity thus limiting, on a given device, the achievable plasma performances.



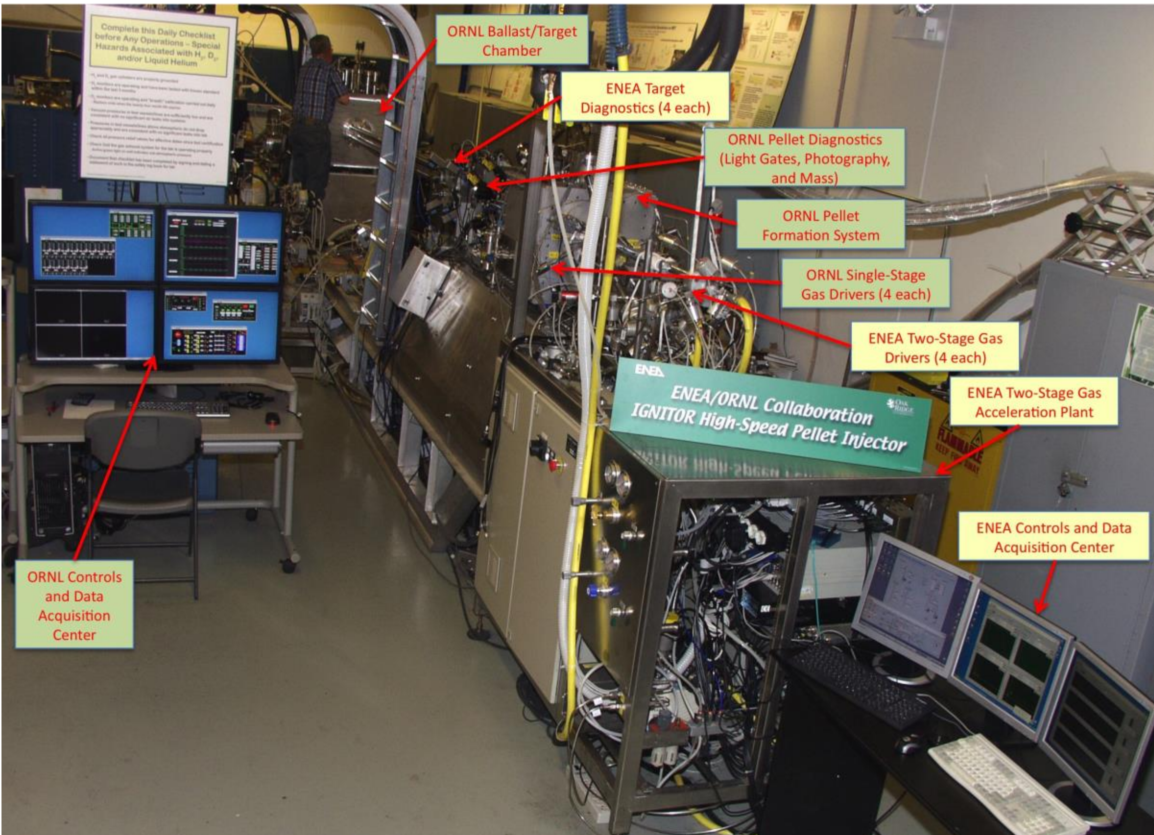
LABOMBARD, et al., *Nucl. Fusion* 40 (2000) 2041.

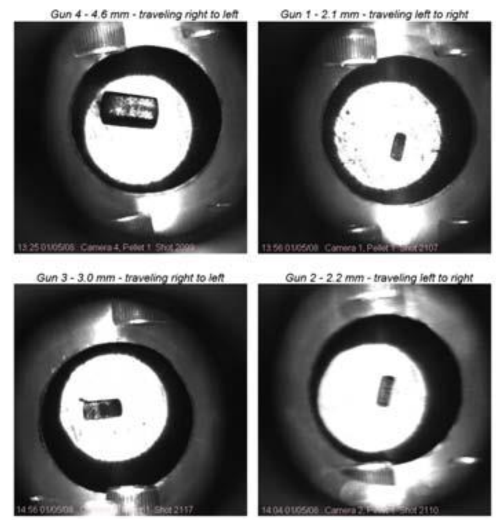
The Ignitor FW is covered with Mo tiles, supported by Inconel plates attached to the vessel, to be installed and replaced by RH. The FW profile is nearly conformal to the plasma shape



The second most important contribution that Ignitor can make to the fusion program is the demonstration that, at high density, limiter configurations can operate in reactor relevant regimes.

The Multiple Barrel, TSG Ignitor Pellet Injector (IPI)



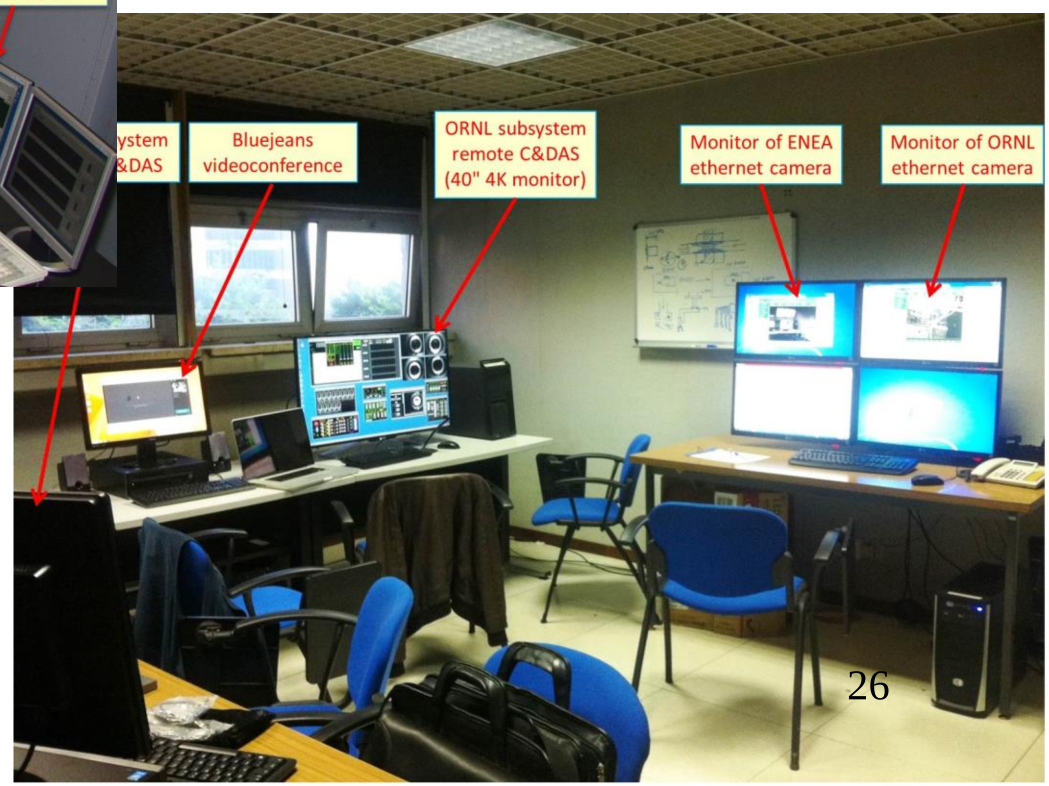


Target:
4 km/s
Achieved:
2.2 km/s

S. Migliori, A. Frattolillo

New experimental campaign programmed for the fall, after modification of cryostat insulation

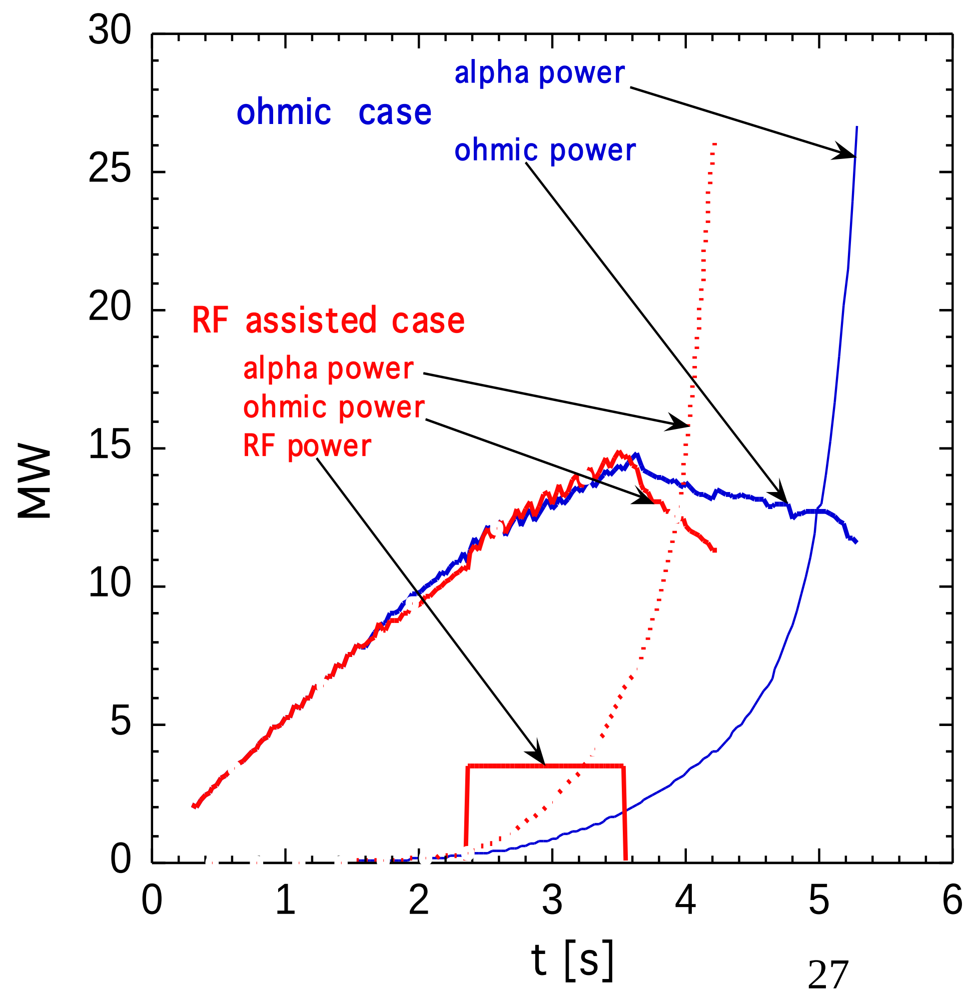
The IPI remote control room at ENEA - Frascati



ICRH Assisted Ignition

- Ignition can be accelerated by the application of ICRH during the current rise.
- Modest amounts of ICRH power (3-6 MW), either during the current rise or the pulse flat-top, can be used for plasma heating in a variety of plasma regimes, and to provide a safety margin for the attainment of ignition.
- The full current flat top is available to study the plasma in burning conditions. (Note that ignition occurs when ohmic heating only is present)

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



A. Airoldi and G. Cenacchi

Mitigation of Thermonuclear Instabilities

Ignitor Project

- When self-heating of the plasma by the fusion α-particles leads to a significant rise of the plasma temperature, internal plasma modes may be excited and saturate the thermonuclear instability at acceptable levels without external intervention.
- ***In case the internal process is not effective, a scenario is considered whereby Ignitor is led to operate in a slightly sub critical regime, i.e. the plasma parameters are chosen so that the thermonuclear heating power is slightly less than the power lost, and a small fraction of ^{3}He is added to the optimal Deuterium-Tritium mixture.***
- **The difference between power lost and α-heating is compensated by additional ICRH heating directly of the minority species (minority heating).**
- The energy balance equation becomes

$$\frac{\partial}{\partial t}\left[\frac{3p_e}{2}+\sum_{\alpha=D,T}\left(\frac{3p_\alpha}{2}\right)\right]+\nabla\cdot\vec{q}_e+\nabla\cdot\sum_\alpha \vec{q}_\alpha = S_{\text{sources+sink}}$$

$$p = 2n_e kT$$

$$\vec{q} = -\chi\nabla\left(\kappa T\right)$$

$$S_{\text{sources+sink}} = P_\alpha + P_{OH} + P_{ICRH} - P_{brem}$$

$$\nabla\cdot\vec{q}_e \approx -\frac{3}{2}\frac{p}{\tau_{Energy}}$$

A. Cardinali, G. Sonnino, *Eur. Phys. J.* **D 69**,194 (2015)

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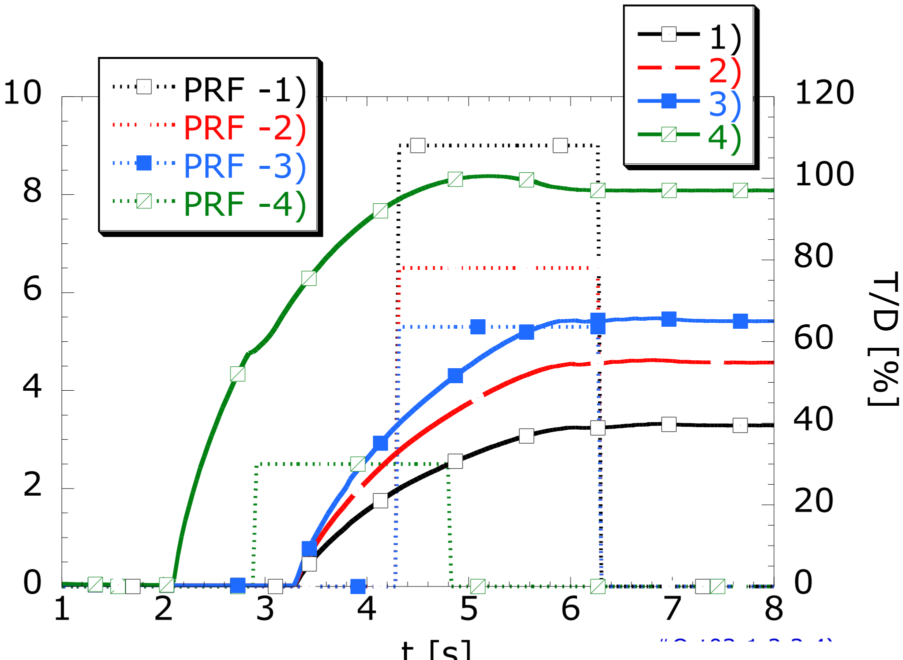
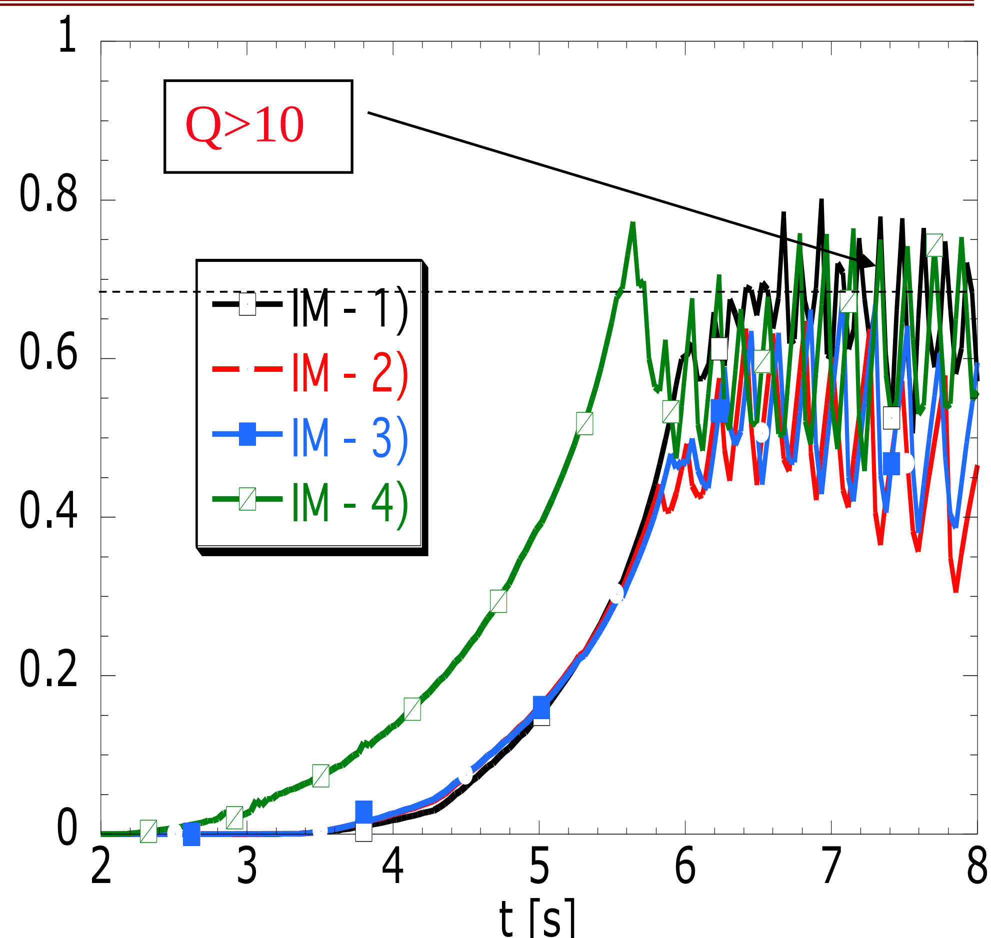
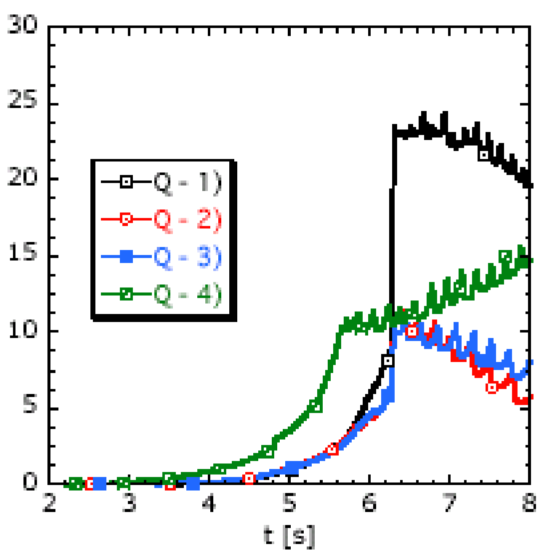
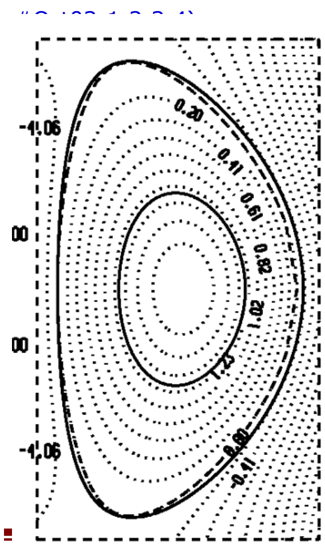
Ignition control by means of Tritium and RF









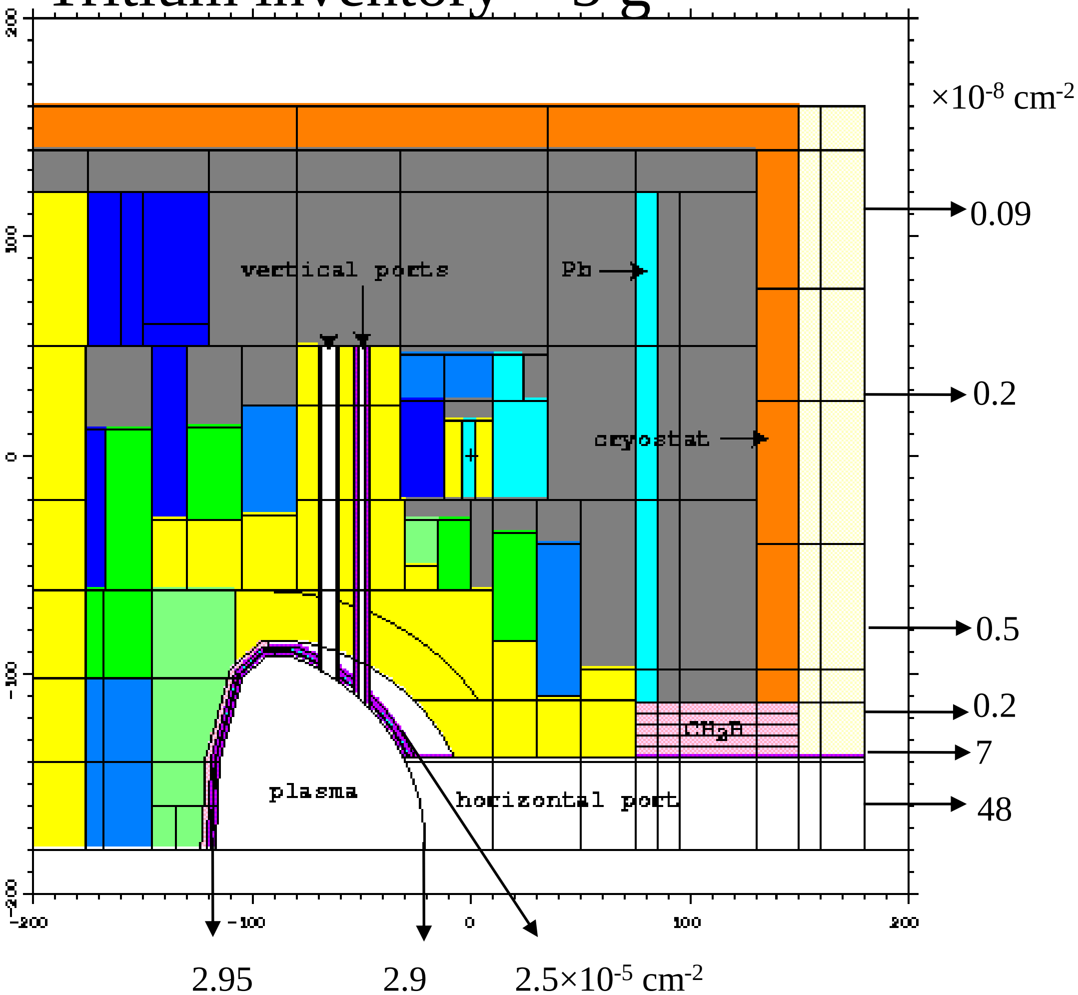
13 T, 11 MA

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

A. Airoldi and G. Cenacchi

Radiation and Activation

Tritium inventory < 5 g



High neutron flux, low fluence

@ FW: 10^{15} cm^{-2} s^{-1}, 3×10^{18} cm^{-2}

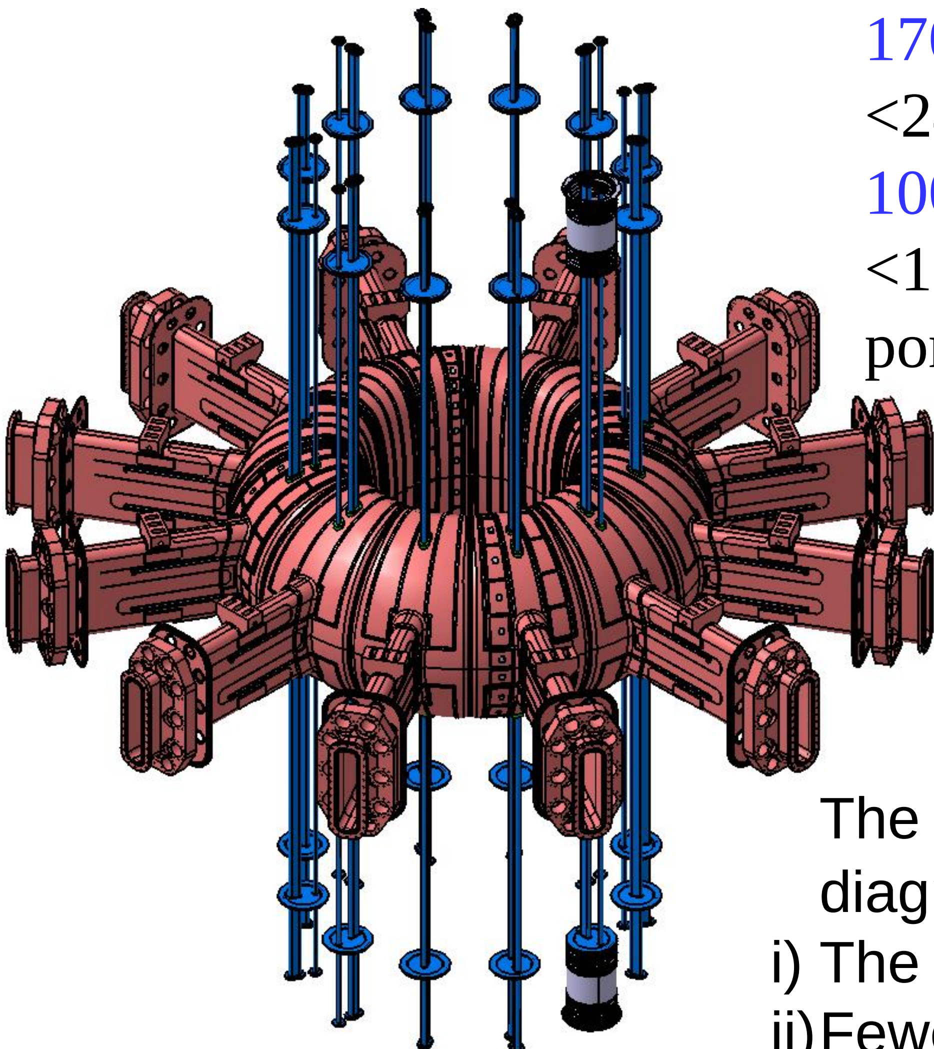
@ port flange: 10^{13} cm^{-2} s^{-1}, 4×10^{16} cm^{-2} (no plug)

The optimization of shielding around the machine allows hand-on access to the cryostat after reasonably short cooling times.

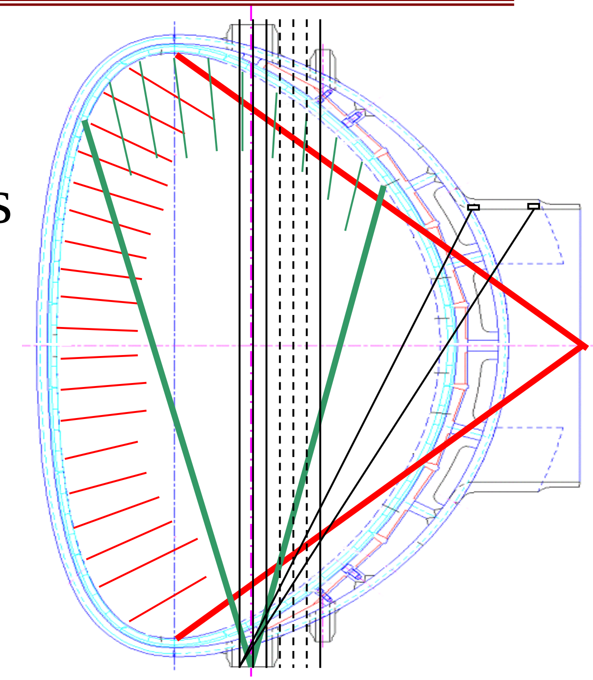
Fluences are not an issue, but prompt radiation effects could be problematic on magnetic coils and optical fibers.

S. Rollet at al., *Fus Eng & Des* **51**, 599 (2000)

Diagnostics Opportunities



6-8 Horizontal ports
170×800 mm
<24 Oval vertical ports
100×35 mm
<16 Circular vertical ports Ø 35 mm

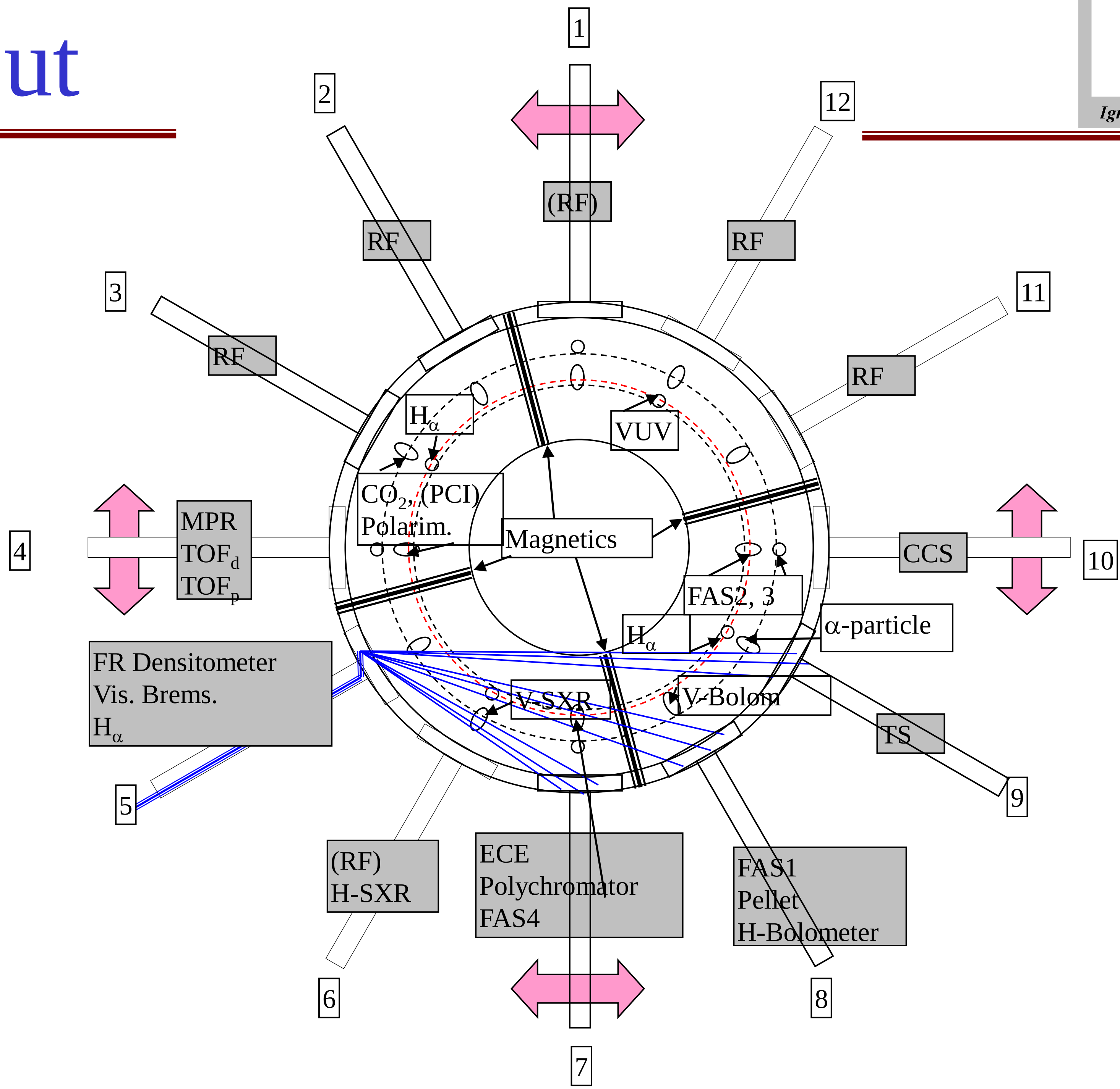


No manned access
⇒ Similar to FTU (80×400mm)

The limiter configuration greatly simplifies the diagnostic requirements, in two ways:

i) The vertical line-of-sights are “clean”
ii) Fewer diagnostics are needed for the edge.

Layout



1
2
12
3
11
4
10
5
9
6
8
7
(RF)
RF
RF
RF
RF
MPR
TOF$_d$
TOF$_p$
CCS
H_α
VUV
CO_2, (PCI)
Polarim.
Magnetics
FAS2, 3
H_α
α-particle
FR Densitometer
Vis. Brems.
H_α
V-SXR
V-Bolom
TS
(RF)
H-SXR
ECE
Polychromator
FAS4
FAS1
Pellet
H-Bolometer
Ignitor Project

Ignitor Project

"Reactor Relevance"

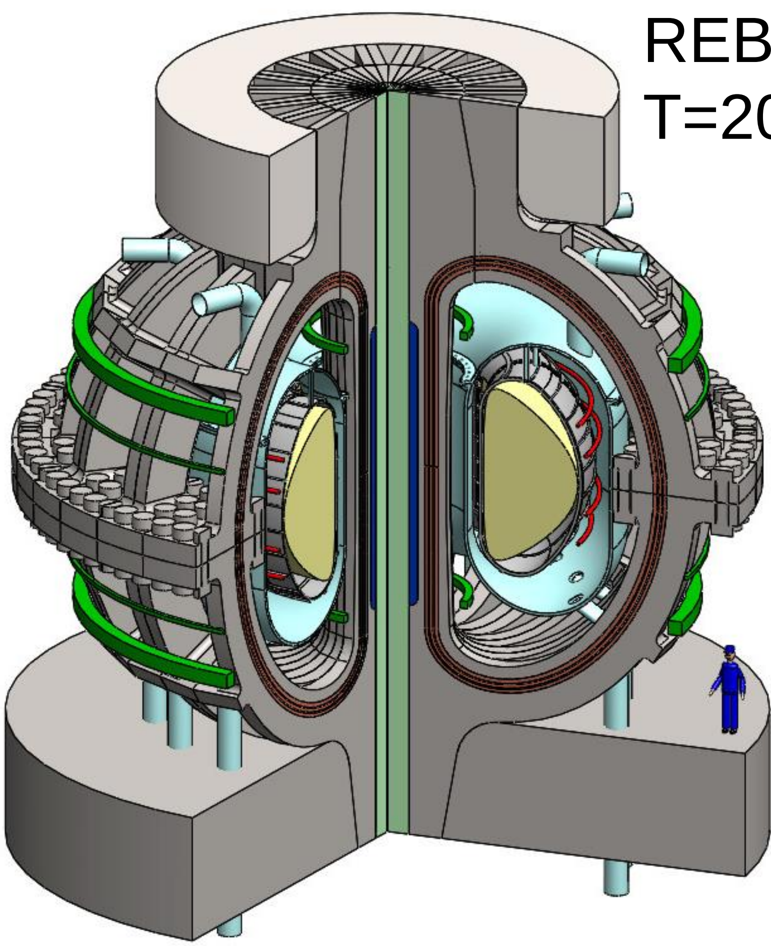
- Alpha-particle heating and transport
- Burn control
- Access to multiple transport regimes
- Relevant parameters (time scales, pressure, orbit confinement, collisionality…)
- Extended Limiter for distributed thermal loads
- Possible test of alternative ash pumping techniques
- First experiments with D - ^{3}He
- Compact diagnostics

ARC (Affordable, Robust, Compact)

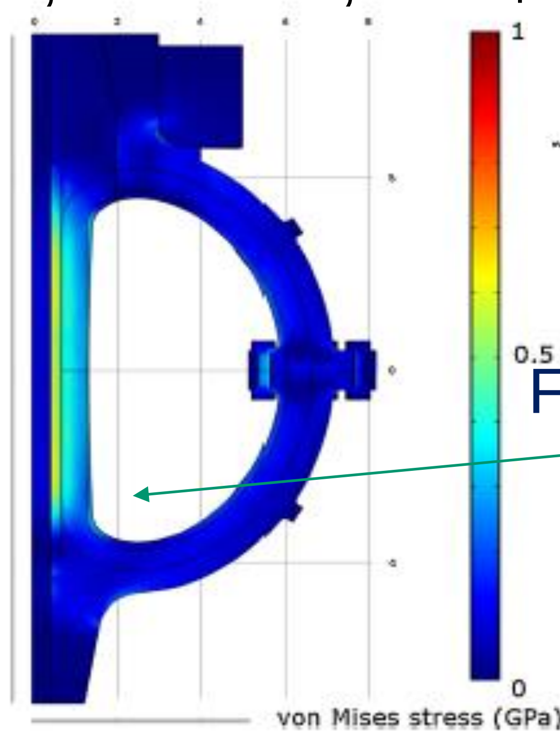
“A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets”

B.N. Sorbom, et al., *Fusion Engineering & Design*, in press
http://dx.doi.org/10.1016/j.fusengdes.2015.07.008

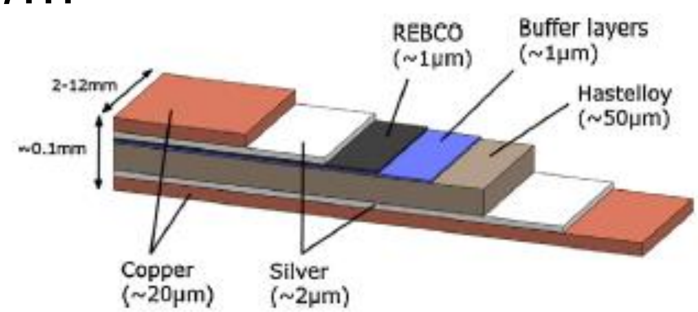
B_T = 9.2 T
I_p =7.8 MA
R=3.3 m



REBCO: Rare Earth Barium Copper Oxide
T=20 K, 5730 km, <36 $/m



.24. Results of stress simulations in the TF coils. The maximum stress in the stain-
s steel 316LN structure is 660 MPa, which gives safety margin of approximately
.



Field at magnet interface:
23 T
Max stress: 660 MPa

P_{fusion}=525 MW
$P_{elect,\ net}$ =190 MW
Cost: < 5.6 B$

Examples of topics for joint scientific accompanying programs

- Fast pellet injectors
- ECH scenarios with 300 GHz sources
- Helicon Waves and other FW scenarios
- Liquid Metal Limiters
- Evolution of high field machines : the tilted coil concept and Neutron Source Facility
- Polarized Fusion (this afternoon)

Ignitor Project

Conclusions

- The fusion program needs Ignitor but it doesn't know it: the high field approach is considered non-viable for a reactor – FALSE!
- We need to promote changes in mentality: fusion is not "just" a technological issue, it is still very much of a physics problem.
- We need to reach out to a broader audience and offer useful areas for collaboration

…and thank you for the attention!