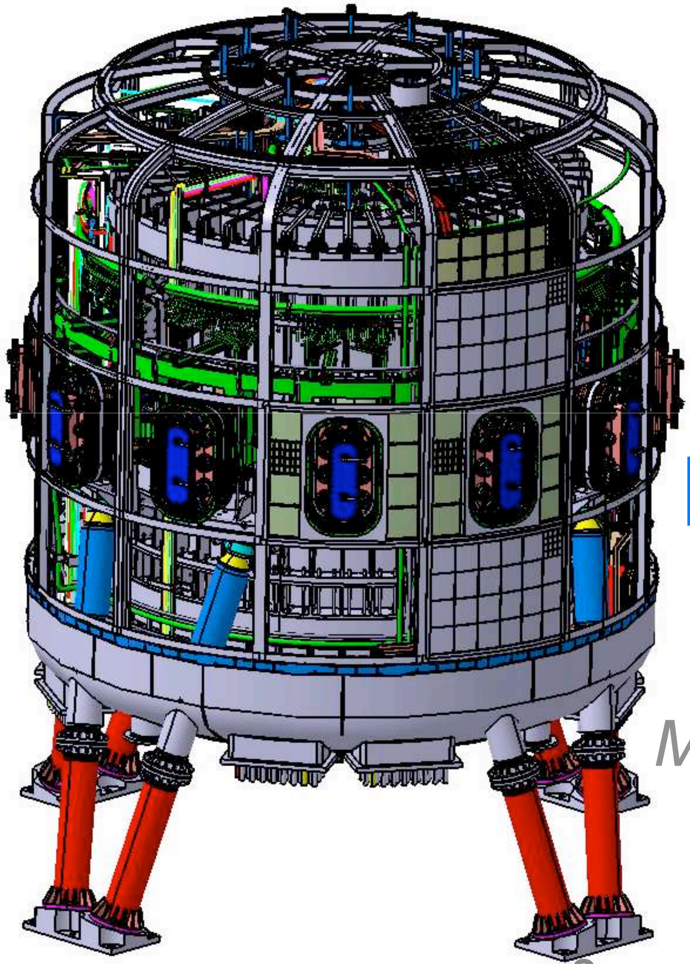
Ignitor Project

Massachusetts Institute of Technology



New Approaches to Ignition and Developments for Fusion Energy Sources*

B. Coppi

Massachusetts Institute of Technology

Cambridge, MA

Sponsored in part ENEA of Italy and by the U.S. Department of Energy.

2008 International Sherwood Fusion Theory Conference, Boulder, CO, March 30 – April 2, 2008

Ignitor Project

Unexpected discoveries

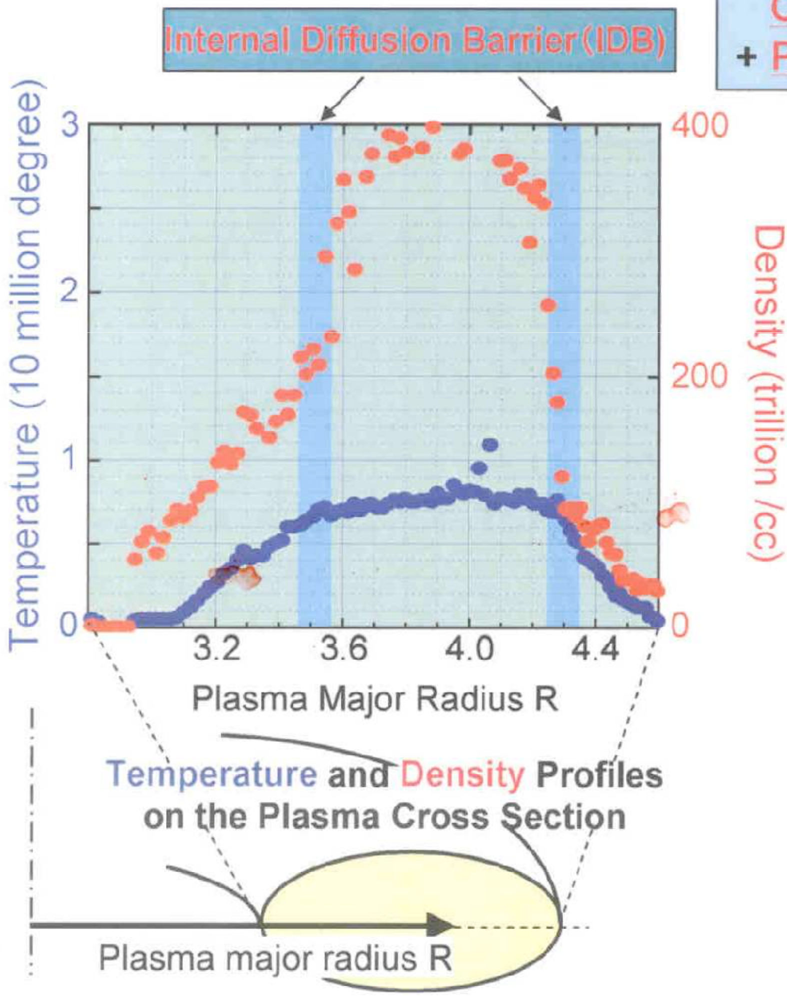
- Investigating the physics of fusion burning plasmas in depth is likely to produce unexpected discoveries that can facilitate greatly the path to a significant fusion reactor.
- The best example of this is the discovery of the delayed neutrons in the fission process that has made the control of fission reactors practically possible.
- A more recent example in plasma physics is the discovery of the spontaneous rotation phenomenon that is expected to be present in fusion burning plasmas and may have beneficial effects.
- Less recent findings are those of the increase of plasma purity with density and the “Profile Consistency”.
- A very recent breakthrough was achieved on LHD, with the discovery of the IDB (Internal Diffusion Barrier) regime of super-dense-core plasmas

Internal Diffusion Barrier (IDB) Realizes Super-Dense-Core Plasma

Scenario of Confinement Improvement

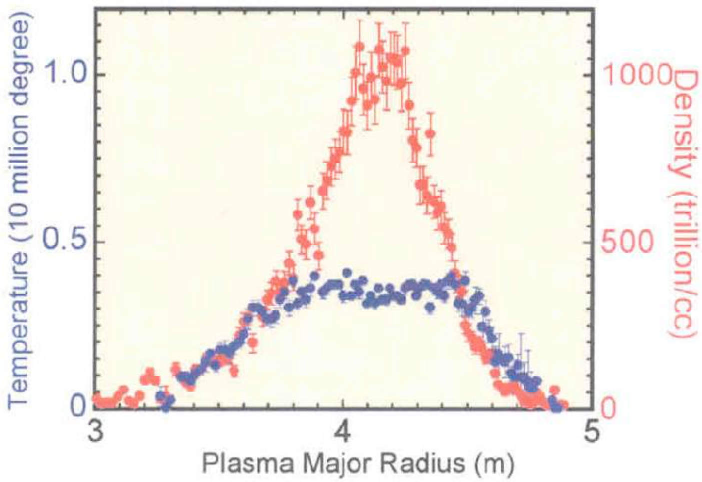
Particle Control ⟹ Formation of Diffusion Barrier ⟹ Confinement Improvement

Core Fueling by Pellet Injection
+ Particle Control at Edge by Efficient Pumping



Further improvement together with peaked density profile

- Fusion triple product 4.4×10^{19}keVs/m^3
  Central density $5\text{x}10^{20}$/m^3,
  Central temperature 10 million degree
  Central beta 4.4% (2.64T)
- High density of 1×10^{21}/m^{-3}



IDB Scenario and Super Dense Core Reactor

- Edge Control

  Core fueling by pellet injector

  Particle pumping by LID ➔ Low edge density
- Confinement Improvement (IDB)

  Present Interests : Position sensitivity of IDB foot & MHD stability
- New Ignition Scenario (SDCR)

  High Density and Lower Temperature Core

  Parameters (n, T, beta) obtained are encouraging

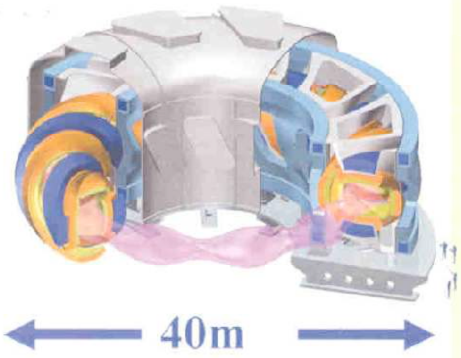
Reduced engineering demand and neoclassical ripple transport

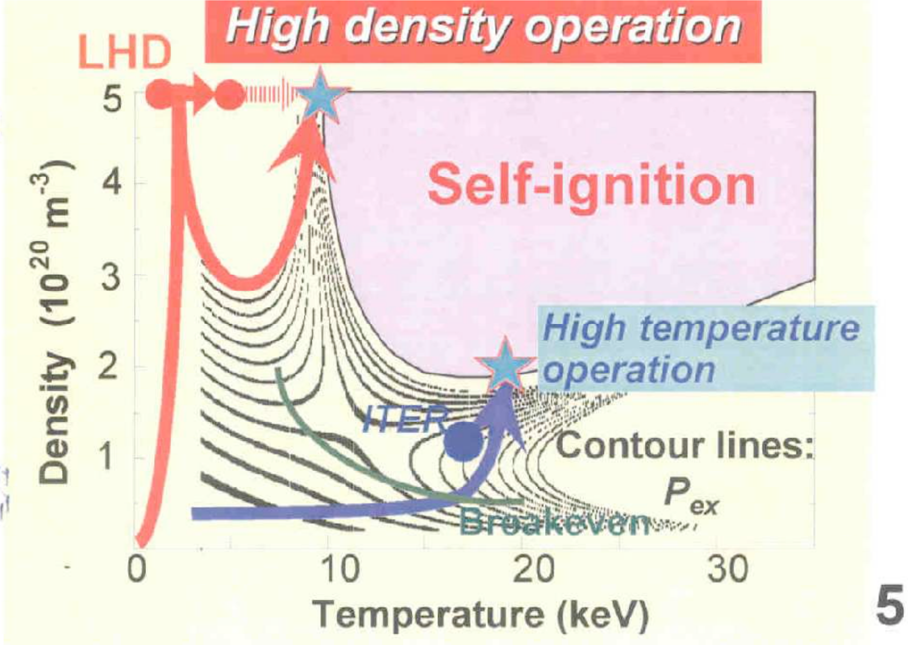
FFHR

1,000 MW

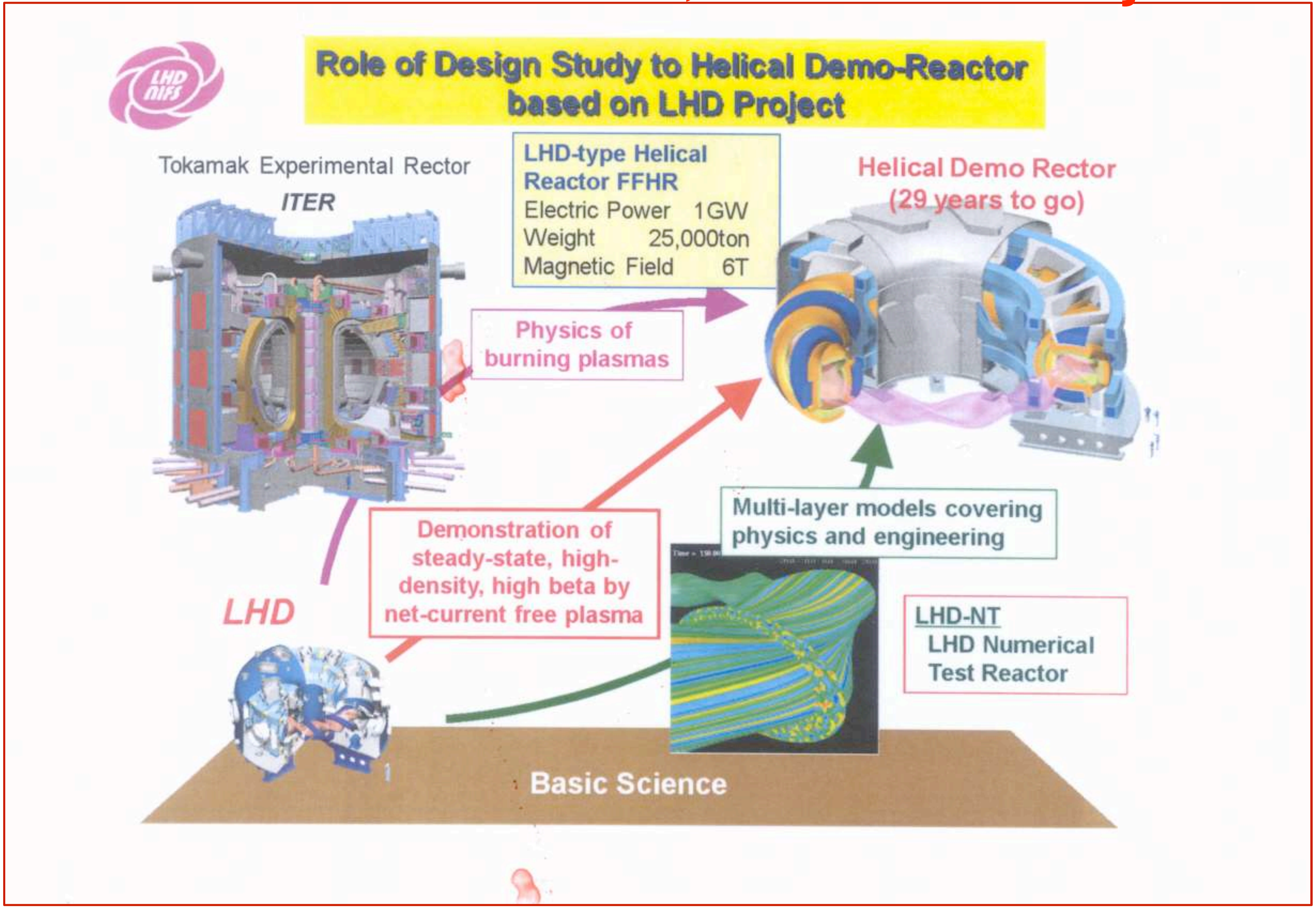
6Tesla

25,000 ton





Christmas ‘07 greetings from the Director of the LHD device, Dr. O. Motojima



Role of Design Study to Helical Demo-Reactor based on LHD Project

Tokamak Experimental Rector

ITER

LHD-type Helical Reactor FFHR

Electric Power	1GW
Weight	25,000ton
Magnetic Field	6T

Helical Demo Rector (29 years to go)

Physics of burning plasmas

Demonstration of steady-state, high-density, high beta by net-current free plasma

Multi-layer models covering physics and engineering

LHD-NT
LHD Numerical
Test Reactor

LHD

Basic Science

M. Zarnstorff, DPP07

ARIES-CS: a Competitive, Attractive Reactor

Reference parameters for baseline:

NCSX-like config.

$\langle R \rangle = 7.75$ m

$\langle a \rangle = 1.72$ m

$\langle n \rangle = 4.0 \times 10^{20}$ m^{-3}

$\langle T \rangle = 6.6$ keV T(0)=12 keV

$\langle B \rangle_{axis} = 5.7$ T

$\langle \beta \rangle = 6.4\%$

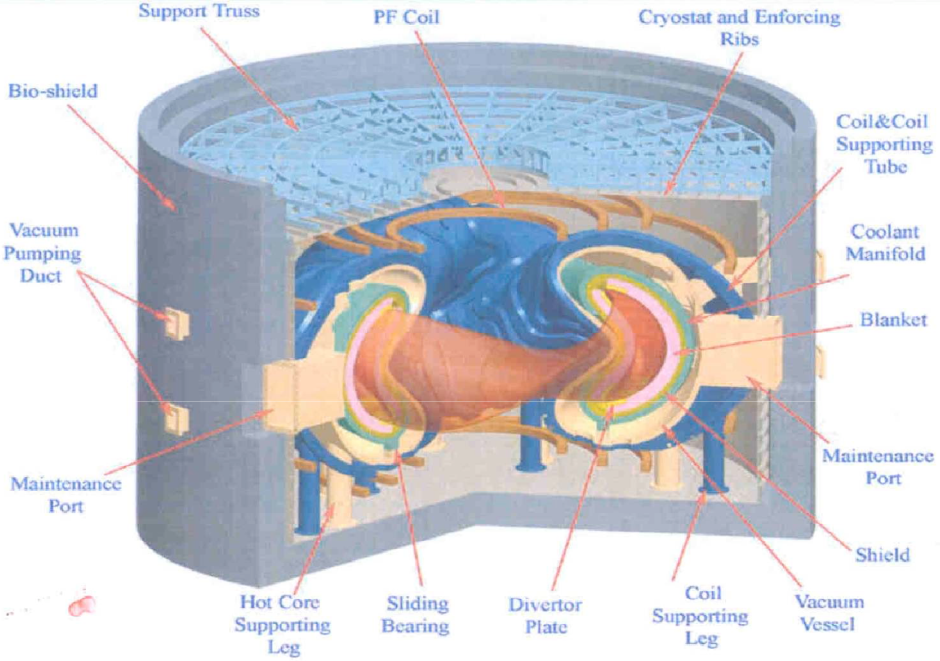
H(ISS95) = 2.0

H(ISS04) = 1.1

$I_{plasma} = 3.5$ MA (bootstrap)

P(fusion) = 2.364 GW

P(electric) = 1 GW



Aries-	-I	-RS	-CS	-AT	-CS
Blanket			LiPb/FS	LiPb/SiC	LiPb/SiC
COE(92)	99.7	75.8	61.3	47.5	48.

Based on NCSX design

Aries-CS Team

Ignition conditions: $P_\alpha = P_L$

$$\varepsilon_\alpha n^2 \langle \sigma v \rangle_{fus} / 4 \simeq nT / \tau_E$$

P=Power

$$\langle \sigma v \rangle \propto T^2$$

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

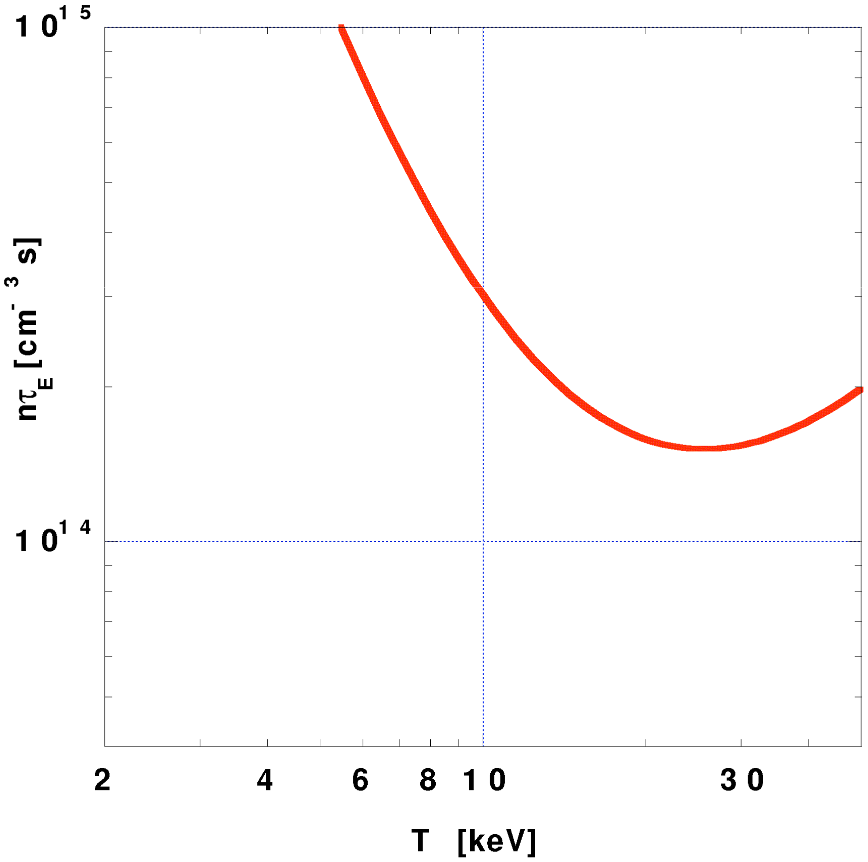
From stability considerations: $p \propto B_p^2$

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

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

$P_\alpha = \left\langle n^2 < \sigma \mathrm{v} > \right\rangle \left(E_\alpha / 4\right) V$

$P_L = 3V \left\langle nT \right\rangle \Big/ \tau_E$

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

Too low for a meaningful reactor!

Instabilities at All Scales

⇒Macroscopic Modes:

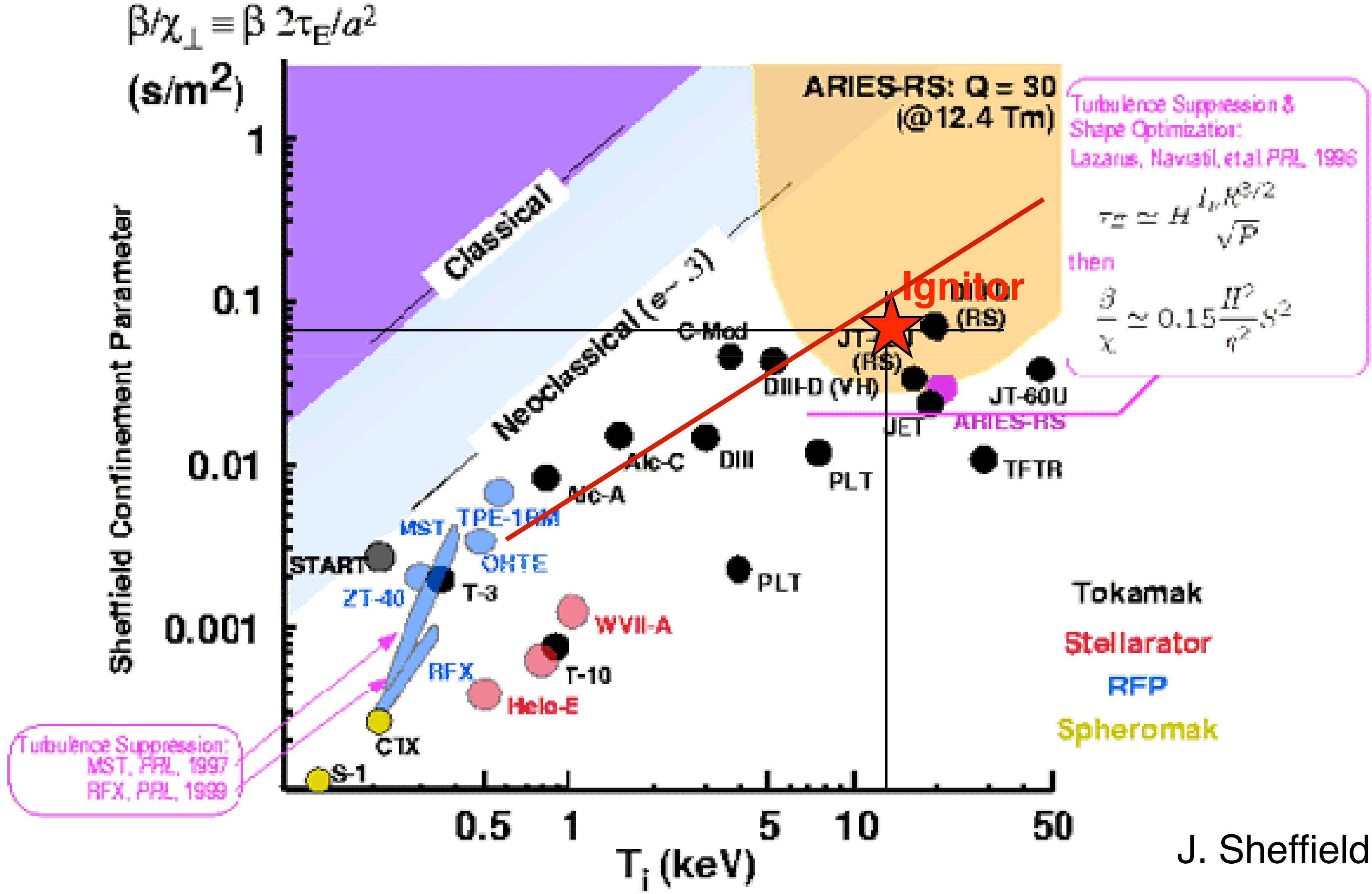
- Internal $m = 1$
- Ballooning Modes + α-particles
- ELMs

⇒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

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

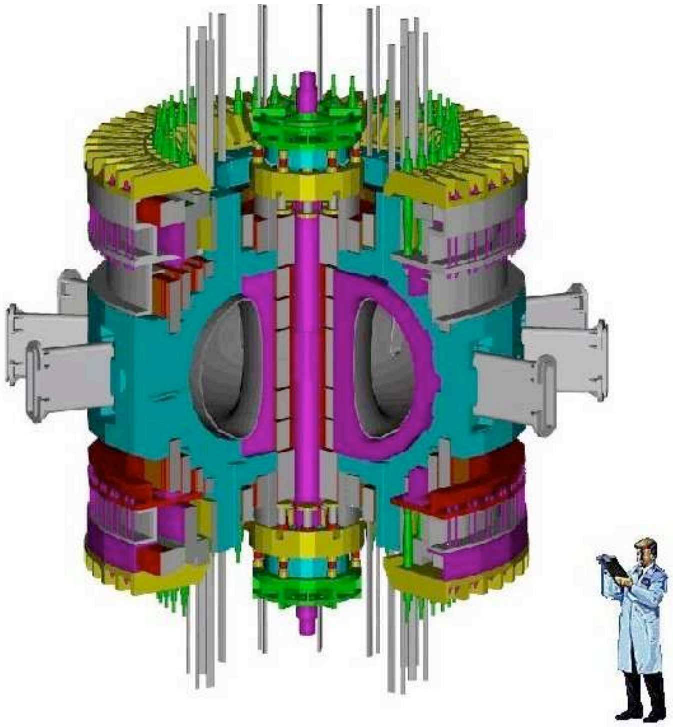
then

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

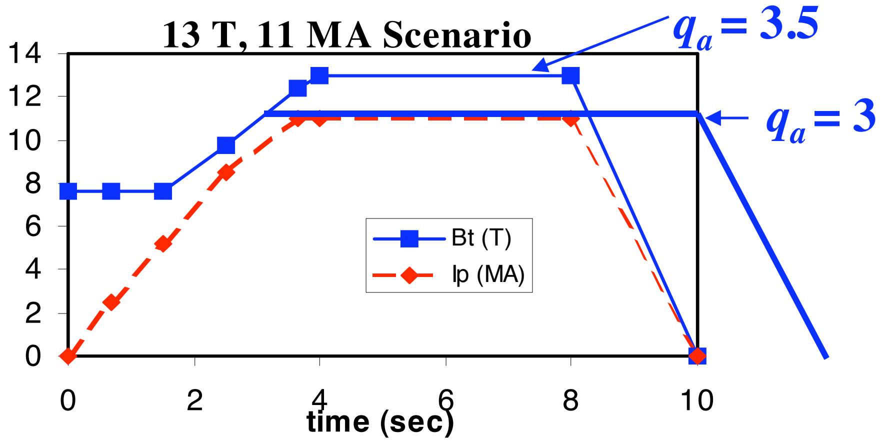
Turbulence Suppression:
MST, *PRL*, 1997
RFX, *PRL*, 1999

J. Sheffield

IGNITOR



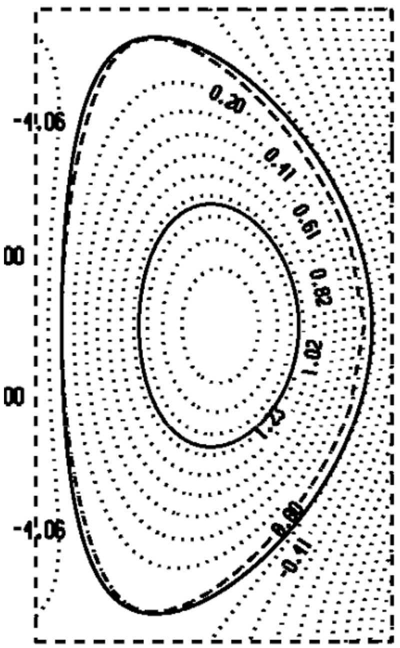
Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
Pulse length	4+4 s
RF Heating P_{icrh}	<12 MW



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

Ignitor Project

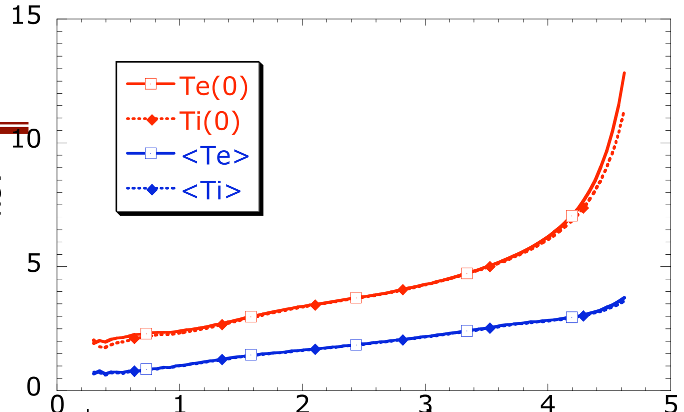
Ohmic Ignition

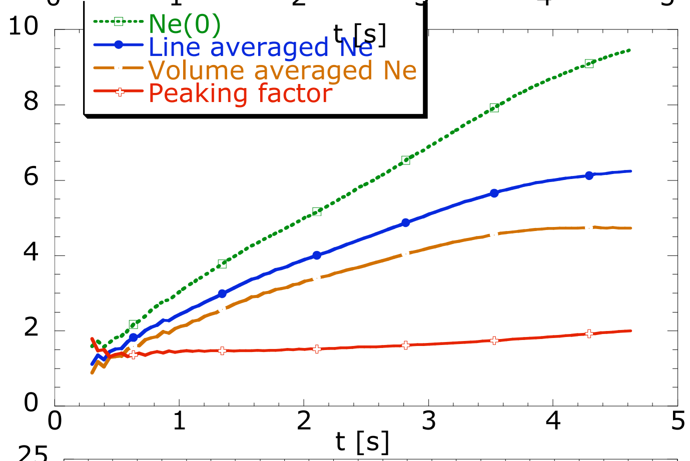


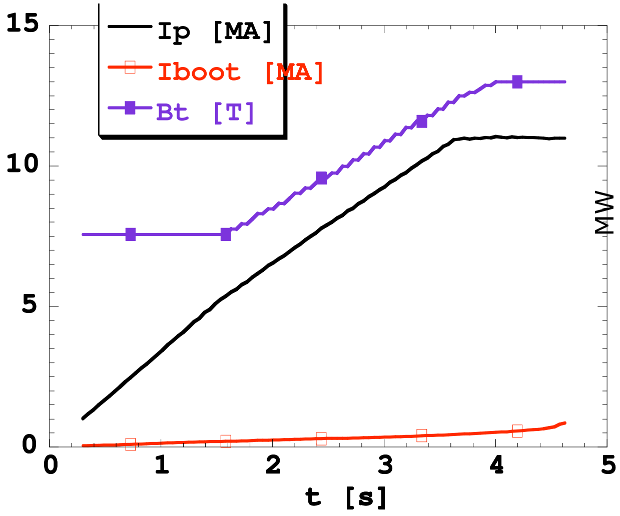
T_{e0} , T_{i0}	11.5, 10.5 keV
n_{e0}	10^{21} m^{-3}
$n_{\alpha 0}$	1.2 × 10^{18} m^{-3}
P_{α}	19.2 MW
β_{pol}, β	0.2, 1.2%
τ_E	0.62 s
τ_{sd}	0.05 s
Z_{eff}	1.2

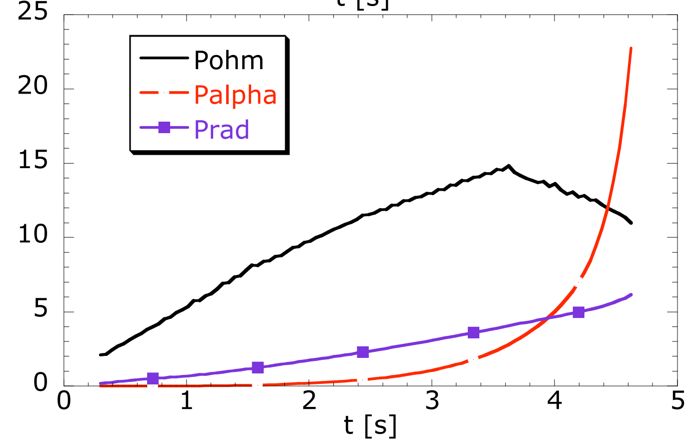
13 T, 11 MA Extended Limiter Configuration

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









The Ignitor Strategy

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

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

$\tau_{\alpha,sd} \ll \tau_E$, $\tau_{burn} \gg \tau_E$

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. Extended limiter and Double X-point Configurations
6. Up-down symmetry to minimize unbalanced stresses.

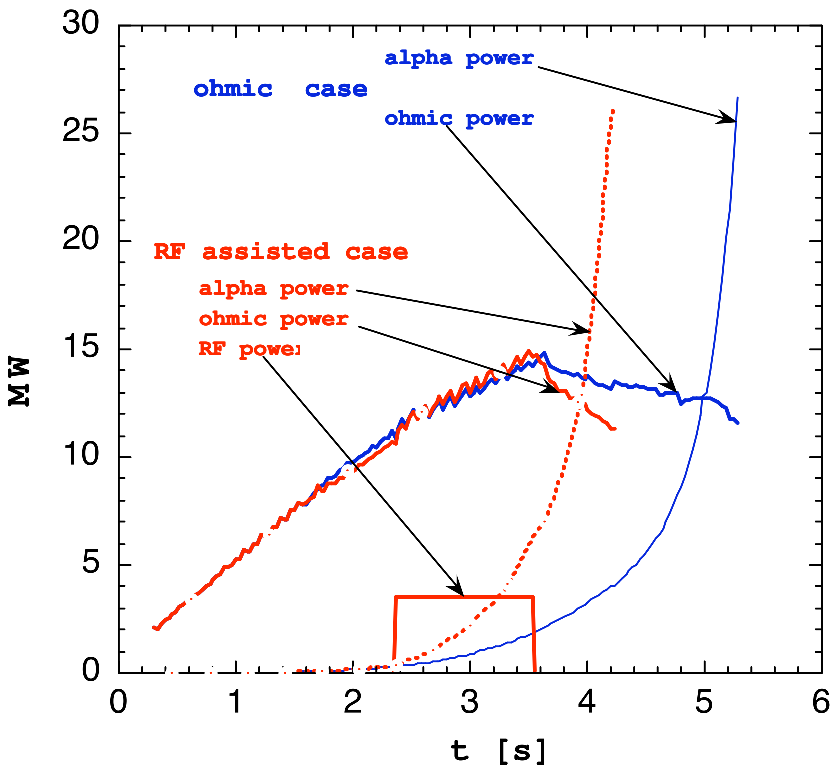
RF Accelerated Ignition

A. Airoldi and G. Cenacchi

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

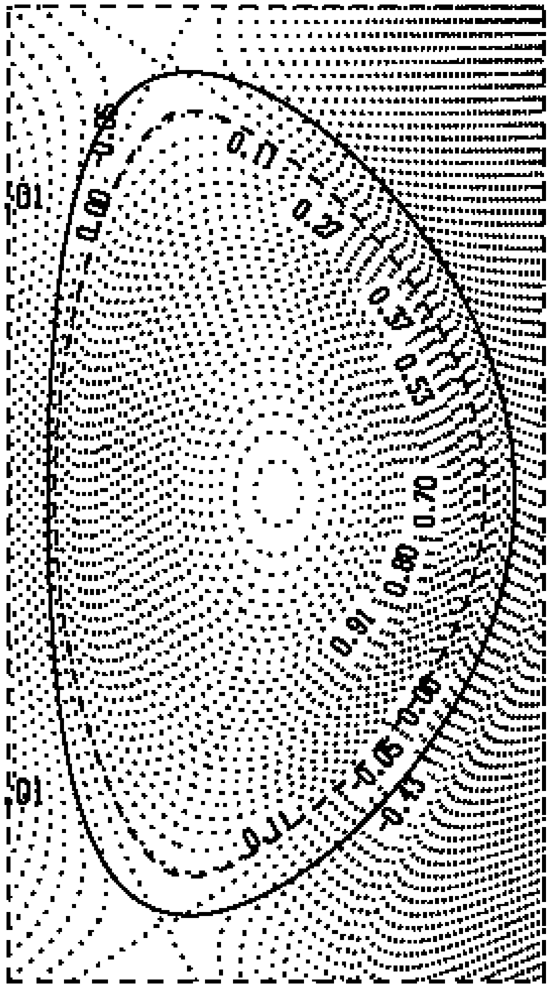
The full current flat top is available to study the plasma under ignition conditions.

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

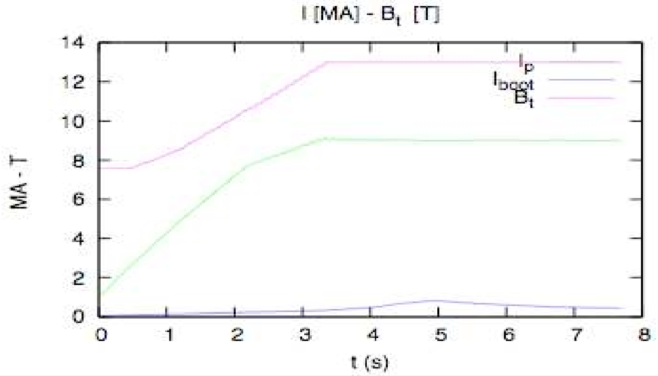


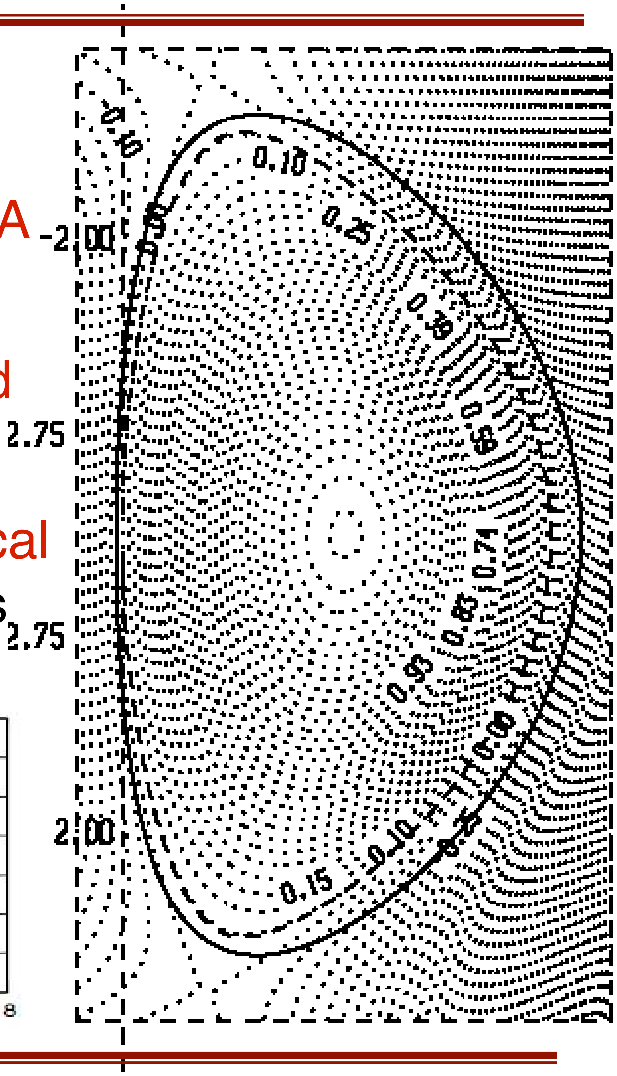
Comparison of Ohmic and RF accelerated ignition scenarios (JETTO code).

Double Null Configuration



- Magnetic field up to 13T
- Plasma current up to 9MA
- Ramp-up time 3.6s for current and magnetic field
- Pulse length (8s) consistent with mechanical and thermal requirements





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:

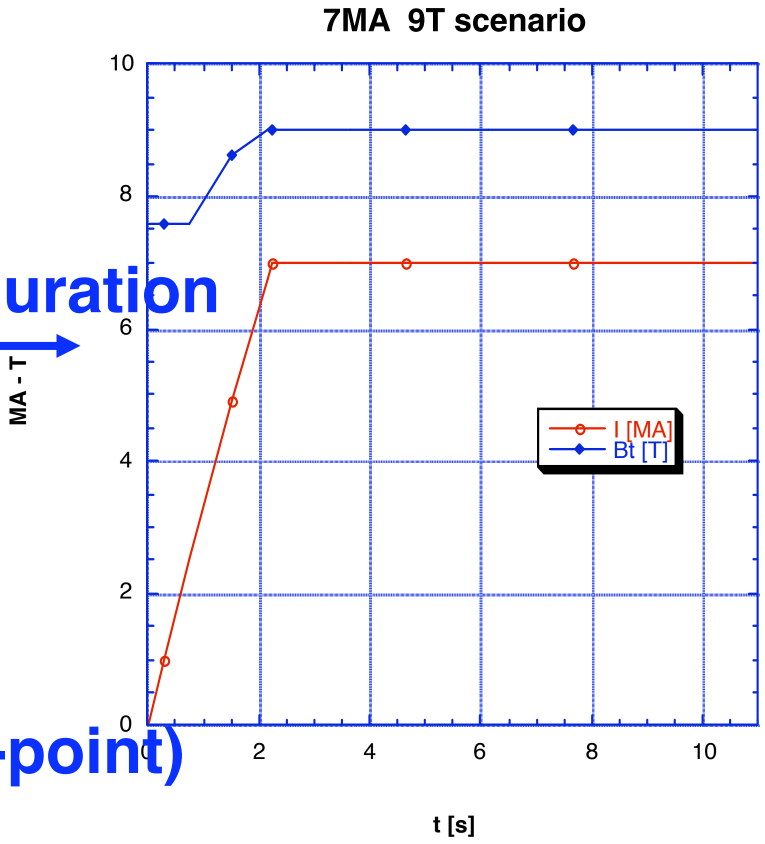
B (T)	H/D/T	T/He^3	D
9	1st,2nd,3rd at x-0.5	2nd,1st at x - -0.5	
10	1st,2nd,3rd at x-0.9	2nd,1st at x- -0.25	1st at x- -0.95
11	Out of res	2nd,1st at x--0	1st at x- -0.75
12	Out of res	2nd,1st at x-0.2	1st at x- -0.6
13	Out of res	2nd,1st at x-0.4	1st at x- -0.4

Scenarios with reduced parameters

Magnetic field up to 9T

Plasma current up to

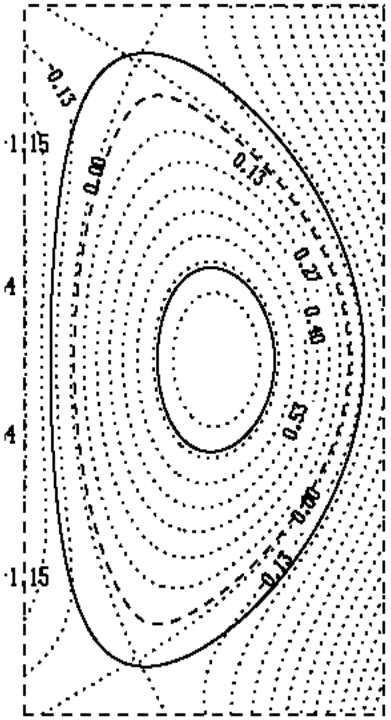
i) 7 MA, “first wall limiter” configuration



⇒ Long pulse

or

ii) 6 MA (double X-point)



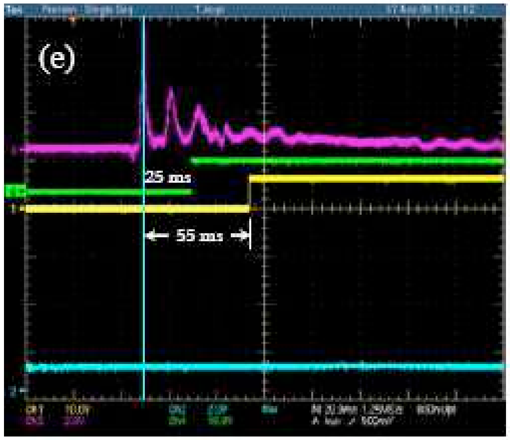
The pulse length is consistent with mechanical and thermal requirements of the magnets, and available magnetic flux

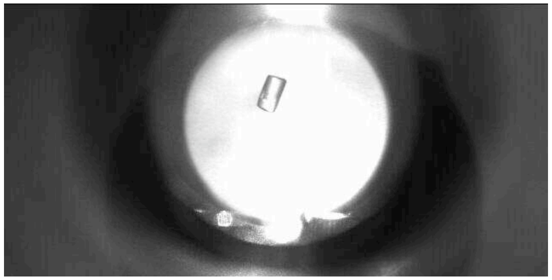
Ignitor Project

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.

The innovative concepts at the basis of the Ignitor Pellet Injector (IPI) design are the proper shaping of the propellant gas pressure front to improve pellet acceleration, and the use of fast valves to considerably reduce the expansion volumes which prevent the propulsion gas from reaching the plasma chamber.





S. Migliori, A. Frattolillo

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**		**IGNITOR**	**ITER / IGNITOR**
		@ $q_a = 3$			
Pulse flat top	t_{pulse} (s)	400		6	66
Criticality param.	$K_f = P_{alpha} / P_{Losses}$	2/3		1 a)	
Minor radius	a (m)	2		0.47	
Peak el. temperature	T_{e0} (keV)	25		11.5	
Profile param.	α_T (parab)	1		2	
Purity param.	Z_{eff}	1.7		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		1.8	65

a) Ignition : onset of the thermonuclear instability

b) Freidberg Report (FESAC Burning Plasma Report, September 2001)

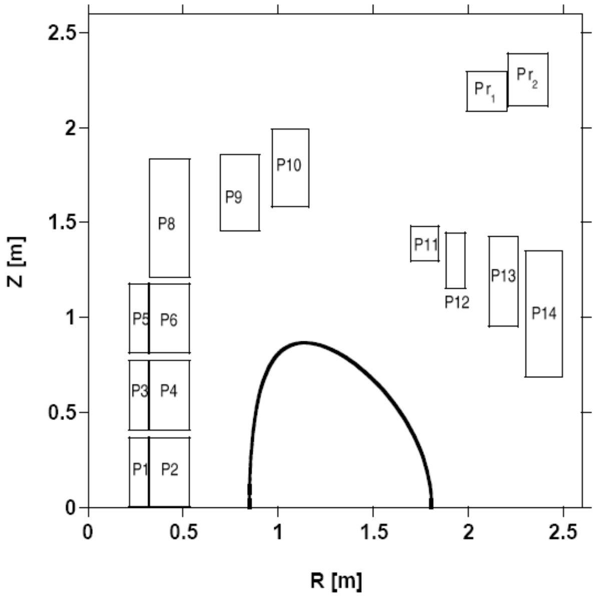
MESSAGE: IGNITOR IS AS “STATIONARY” AS ITER (66/65 ≅ 1) EVEN WHEN THE LONGEST PHYSICS TIME (the collisional current redistribution time τ_{cr}^{coll}) IS CONSIDERED. Note that τ_{cr}^{coll} may not be physically relevant. In fact, the current redistribution could be controlled by collective processes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

High Field, High Temperature Superconducting Magnets

The recent discovery of a new HT superconductor material operating in high magnetic fields opens exciting new possibilities for fusion reactors

The Ignitor design is the first to adopt this material for the two largest poloidal field coils.

MgB_2 has the advantage of a relatively high superconducting temperature, and excellent superconducting properties, without compromising its affordability and robustness, even when made into wires.



Columbus Superconductors

GRUPPO MALACALZA

Cher Collègue,
1: C'est avec beaucoup d'interet et de sympathie que j'ai lu le texte que

Cher Collègue,
1: C'est avec beaucoup d'interet et de sympathie que j'ai lu le texte que vous avez bien voulu me communiquer.J'en suis d'acccord avec vous sur tous les plans. Je m'étais consacré à l'écriture d' une demi douzaine de textes

niveau de lecteur ,a été publié par Odile Jacob.Mais les autres textes, très spécialisés sur la fusion,n'ont pas été publié par l'académie des sciences.

2: De plus, je suis ce problème depuis le début de ITER (mi 80) avec Jules Horowitz qui était responsable de ce sujet au CEA, et qui ,notamment, a
décidé du transfert de toute la fusion à Cadarache. Horo
Président du Conseil scientifique et technique de Euratom
traité de Euratom qui coiffe le JET (qui n'a pas tenu s
successifs, à chaque contrat de renouvellement,de mettre
divertor pour ITER)

From "Robert Dautray" <Robert.Dautray@laposte.net>
Subject Re: Lettre a` C.Allegre
Date Fri, July 29, 2005 9:58 am
To "Bruno Coppi" <coppi@psfc.mit.edu>

3:De plus, je connais depuis 50 ans les problèmes des réa
puissance, par la pratique journalière d'un ingénieur.La
génération qui remplacera dans le monde entier nos PWR, e
"advanced PWR ou BWR", avec une vie d'au moins 80 ans. Le
concept nouveaux qui disent tout faire, y compris de dét
déchets radioactifs et leurs actinides, ignorent les réalités techniques et
industrielles . Donc la surgénération est aussi pour dans bien plus de 80 ans .

5; Nous avons le temps de faire de la bonne physique de fusion, sans concurrence avec la fission et notamment d'atteindre et étudier en priorité l'ignition contrôlée de la fusion qui était le seul objectif du ITER de 1990, objectif prioritaire que l'on a fait disparaitre en gardant le mot ITER , pour des raisons financières et d'autres, extérieures à la science, en jouant sur les mots.

4: Nous ne sommes donc pas pressés pour les ressources d'énergie nucléaire
de f

5; N
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1990
ITER
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6: J
ther
cadr

7: J
n'ont aucun sens,la physique du centre thermonucléaire du soleil , que j'ai longuement étudié et décrite dans un de mes textes pour l'académie des sciences, étant celle d'un plasma dense et optiquement épais,. émettant essentiellement à l'extérieur de la sphère de R de la zone thermonucléaie(R thermo/ R surface extérieure solaire =0, 2,) des rayons X alors que les plasmas peu denses sont essentiellement des émétteurs de neutrons de hautes énergies.
Mais je m'arrête-
Il est triste de constater que les scientifiques ne disposent pas de moyens de traiter les grands problèmes de leurs domaine, ni dans les sociétés savantes, ni dans les journaux scientifiques concernés.-

avec mes sentiments les meilleurs
robert dautray---

Plan for collaboration with Ignitor, approved by FESAC and by the Ignitor Group

C.4.3 U.S. participation in an Italian IGNITOR

U.S. participation in an Italian IGNITOR would be much like the traditional U.S. collaboration on international facilities such as JET, JT6-0U, etc. The U.S. community would identify key areas of interest and would propose to the DOE/OFES a package that would include a balance of research participation and supporting hardware. This package would be discussed with the Italian host of the IGNITOR facility and might result in a formal proposal to the OFES for funding to participate in IGNITOR in the specified manner. These perspectives are addressed in this part of the white paper.

Performance of burning plasma research by U.S. researchers would be the primary objective of U.S. participation in IGNITOR. U.S. and IGNITOR organizational structures and processes must enable opportunities for the U.S. researchers to exploit IGNITOR as a research tool, as a participant in the research activity. Elements that must be assured in the negotiations include:

(R1) the right for U.S. researchers to propose experiments

(R2) U.S. researcher participation in experiments with access to all data related to IGNITOR experiments

(R3) proposal/development/design/fabrication/installation/operation of advanced diagnostics and enabling technology (e.g., plasma control tools) both in and beyond the baseline

(R4) the opportunity to perform theory and integrated modeling both in design and analysis of experiments

(R5) U.S. participation in fusion technology activities such as the development and testing of high-field RF systems

U.S. Contributions to IGNITOR:

U.S. contributions to IGNITOR would be focused in areas such as baseline and advanced diagnostic systems, RF heating components, the pumping system, and the fueling system. The U.S. contributions would be "in-kind contributions," in which the U.S. commits to provide specific components in exchange for access to IGNITOR for associated research. The U.S. would be obligated to provide the product irrespective of the actual cost to the U.S. To assure completion of scope within the budget, the U.S. must include sufficient contingency in the budget estimates for "in-kind contributions."

Conclusions

Achieving ignition is essential both in terms of exploring the relevant non-linear plasma dynamics and providing the basis for a net power producing D-T reactor

Ignitor is the only experiment that can reach **ignition**

The completed Ignitor design is self-consistent (physics and engineering)

The physics of burning plasmas, auxiliary heating and fuelling systems, diagnostics, control methods, RH procedures, in Ignitor will all be **reactor relevant**