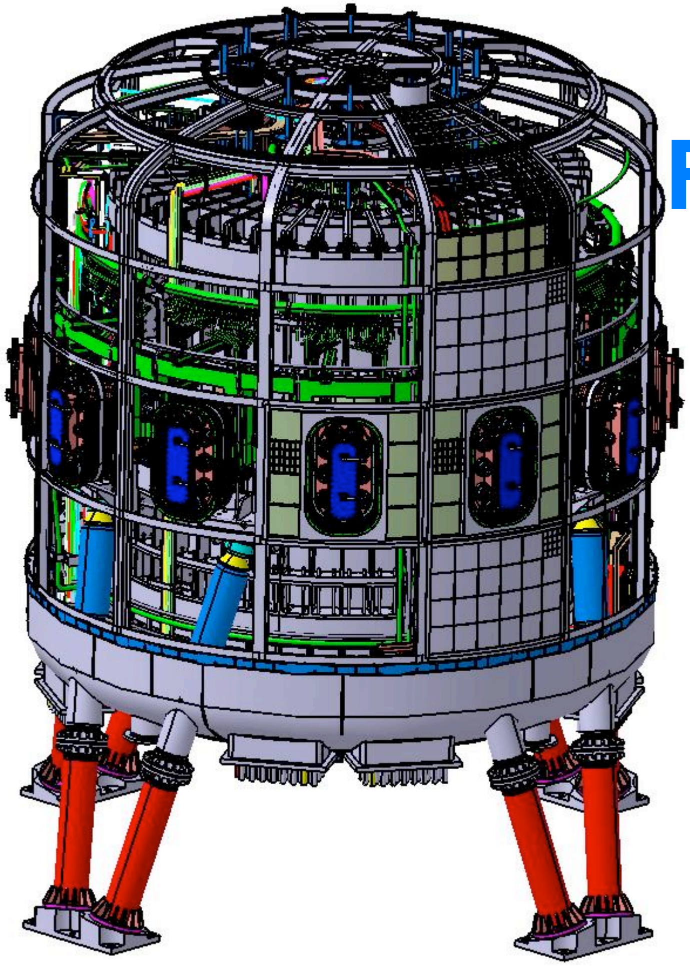

Novel Developments for Fusion Research and the Ignitor Approach

B. Coppi[1], F. Bombarda[1,2], P.Detragiache[2], A. Airoldi[3], G. Cenacchi[2]

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EPS – 9-13 June 2008

Ignitor Project

Context of Fusion Research and its Relevance

- Basic Physics Issues
- Value of Unexpected Discoveries and Relevance to Science
- New Developments (LHD experiments in Japan, Novel Superconducting Coils, Cambridge,UK, Initiative)
- Significance of Ignition: Ignitor et al.
- Envisioned developments of fission reactors (e.g. letter by R. Dautray, DOE Hqs. thinking) and Fusion Research in this Context

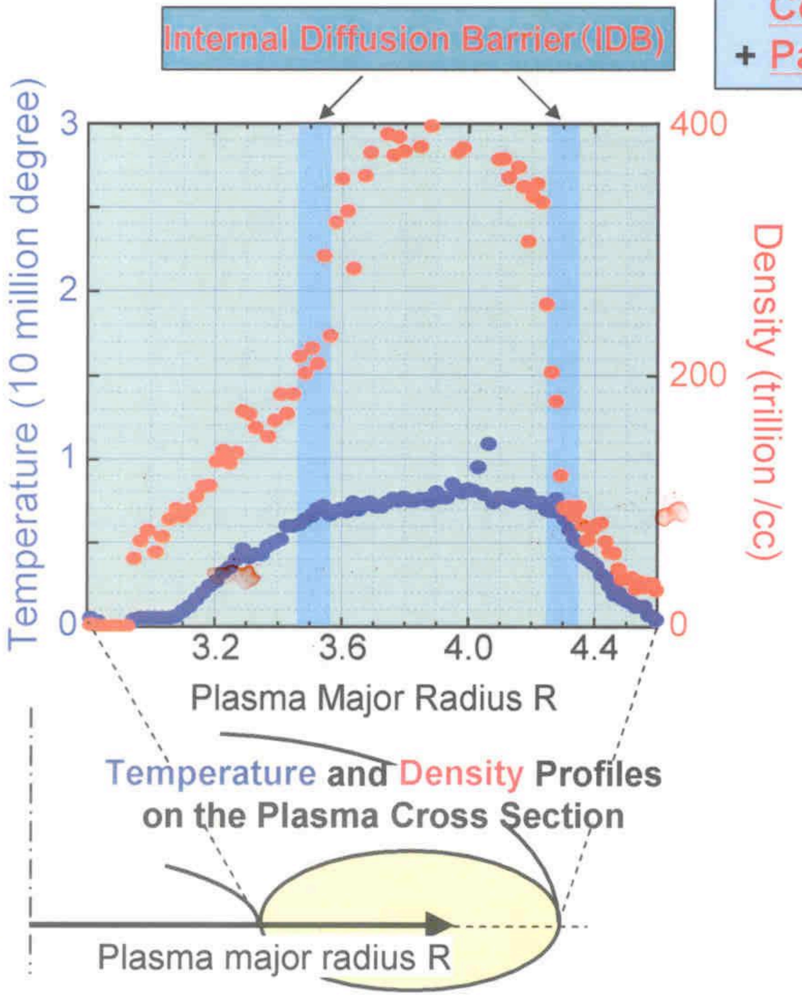
Unexpected discoveries

- 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

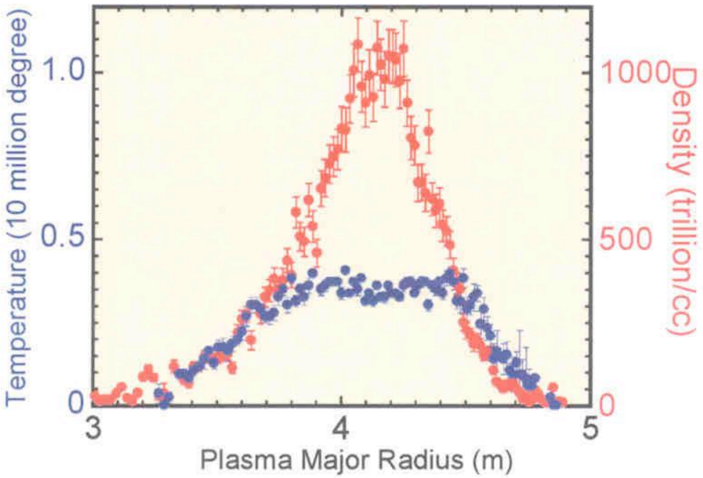


Temperature and Density Profiles on the Plasma Cross Section

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 5x10^{20}/m^3,
  Central temperature 10 million degree
  Central beta 4.4% (2.64T)
- High density of 1×10^{21}/m^{-3}

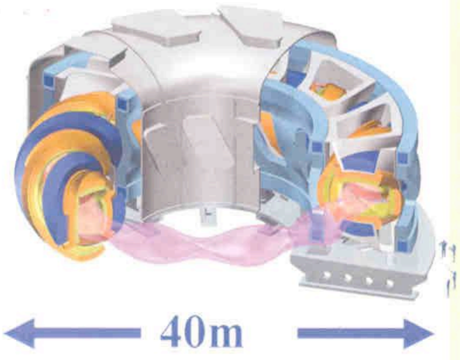


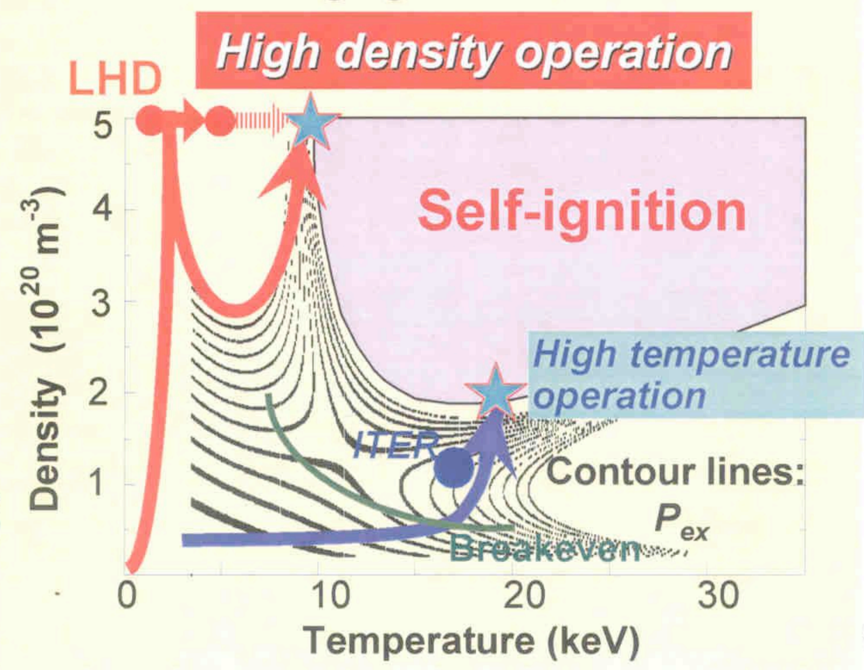
IDB Scenario and Super Dense Core Reactor

- 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

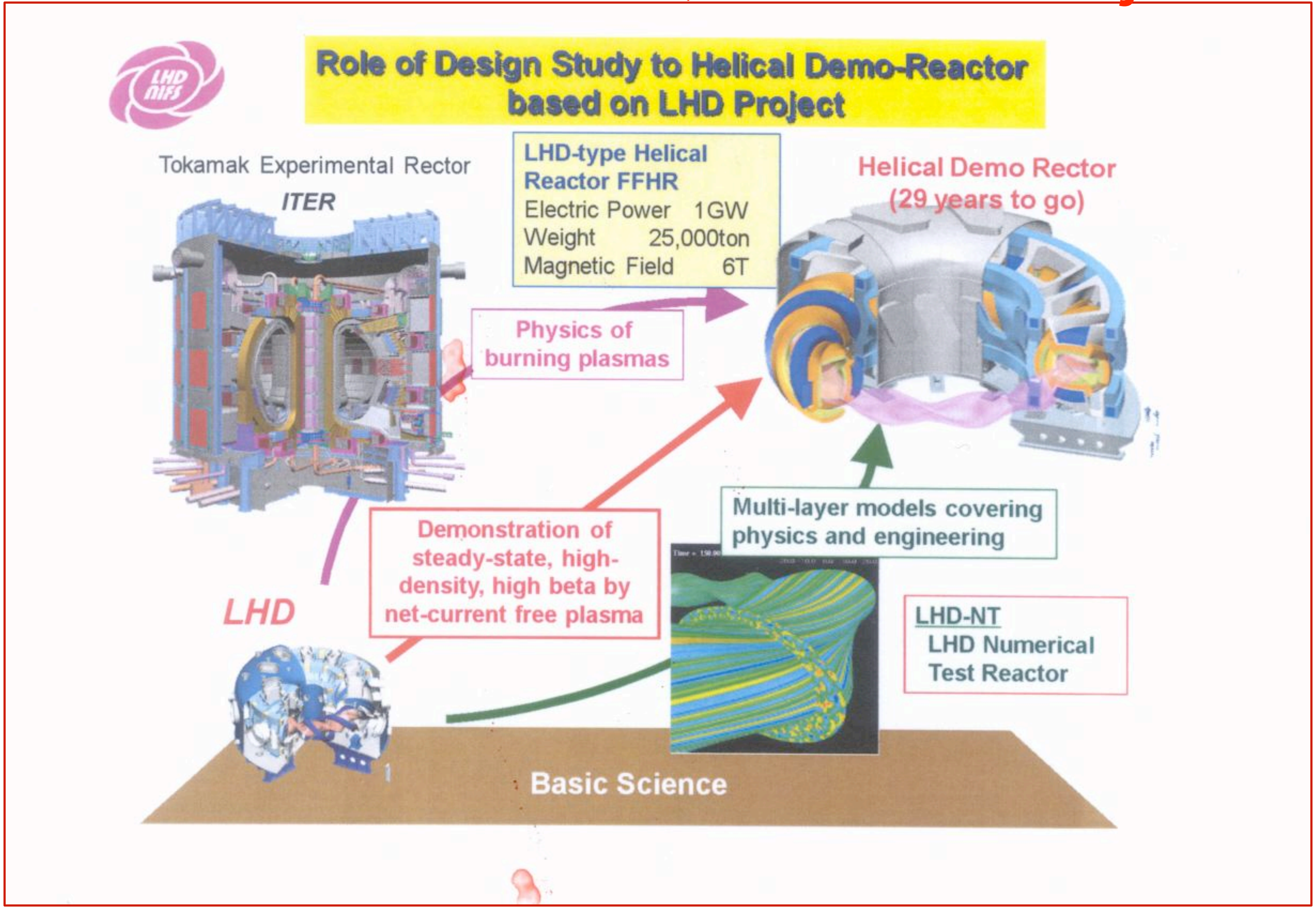
Reduced engineering demand and neoclassical ripple transport

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

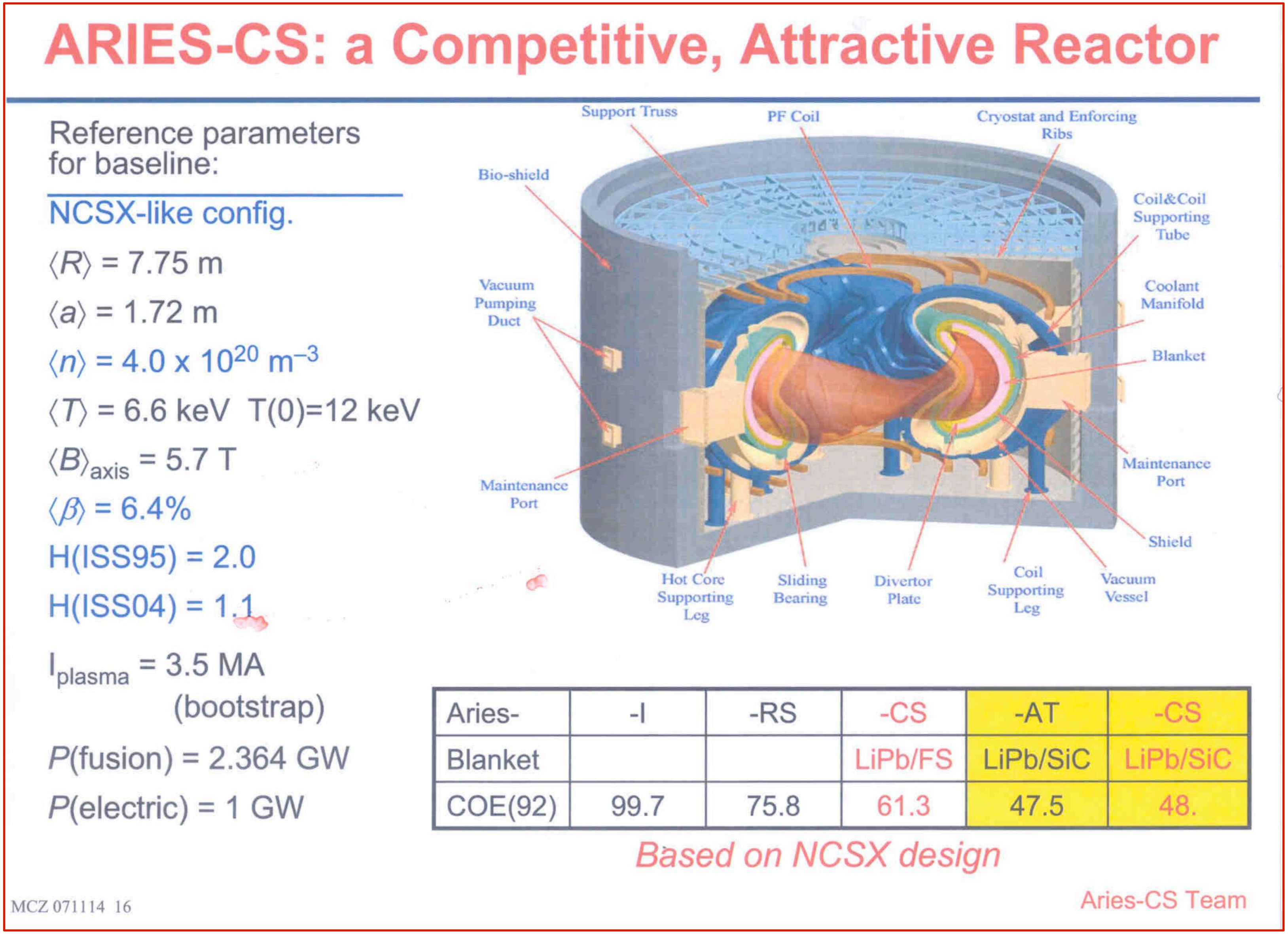
Multi-layer models covering physics and engineering

LHD

LHD-NT
LHD Numerical Test Reactor

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

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

$\langle T\rangle = 6.6$ 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

MCZ 071114 16

Aries-CS Team

Ignition conditions: $P_\alpha = P_L$

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

P=Power

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

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

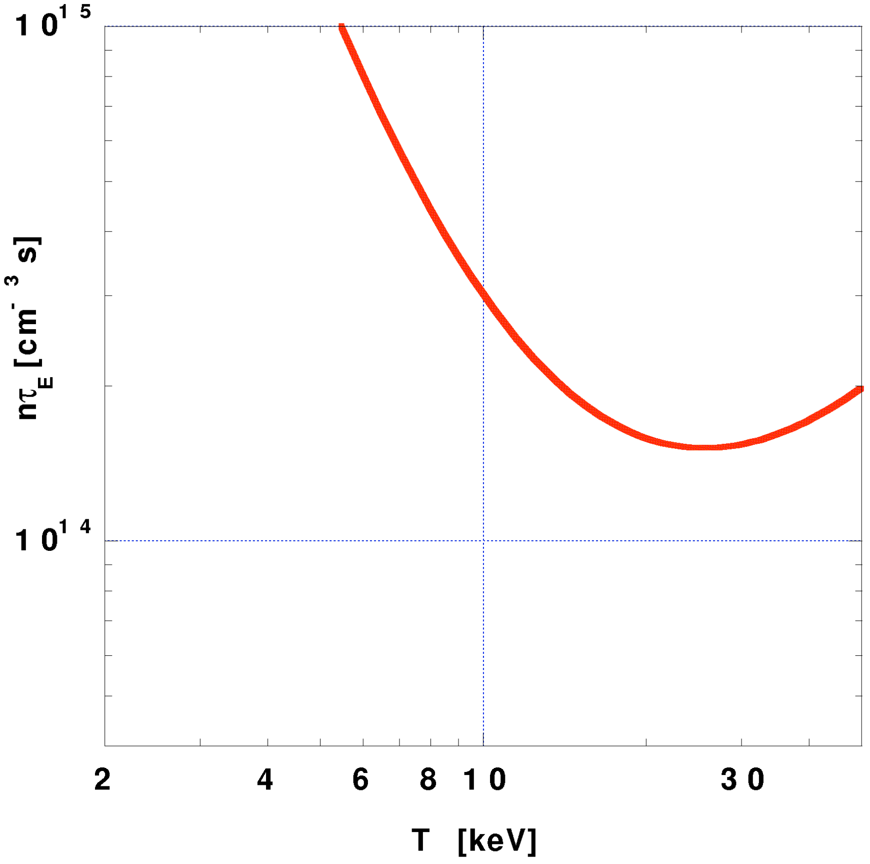
From stability considerations: $p \propto B_p^2$

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

Furthermore

$$T_e \sim T_i$$

$$Z_{eff} \sim 1$$



Reactor Relevant Plasma Regimes

$$Q = 5K_f / (1 - K_f) > 50$$

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

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

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

$P_L = 3V \langle nT \rangle / \tau_E$

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

Too low for a meaningful reactor!

Instabilities at All Scales

⇒Macroscopic Modes:

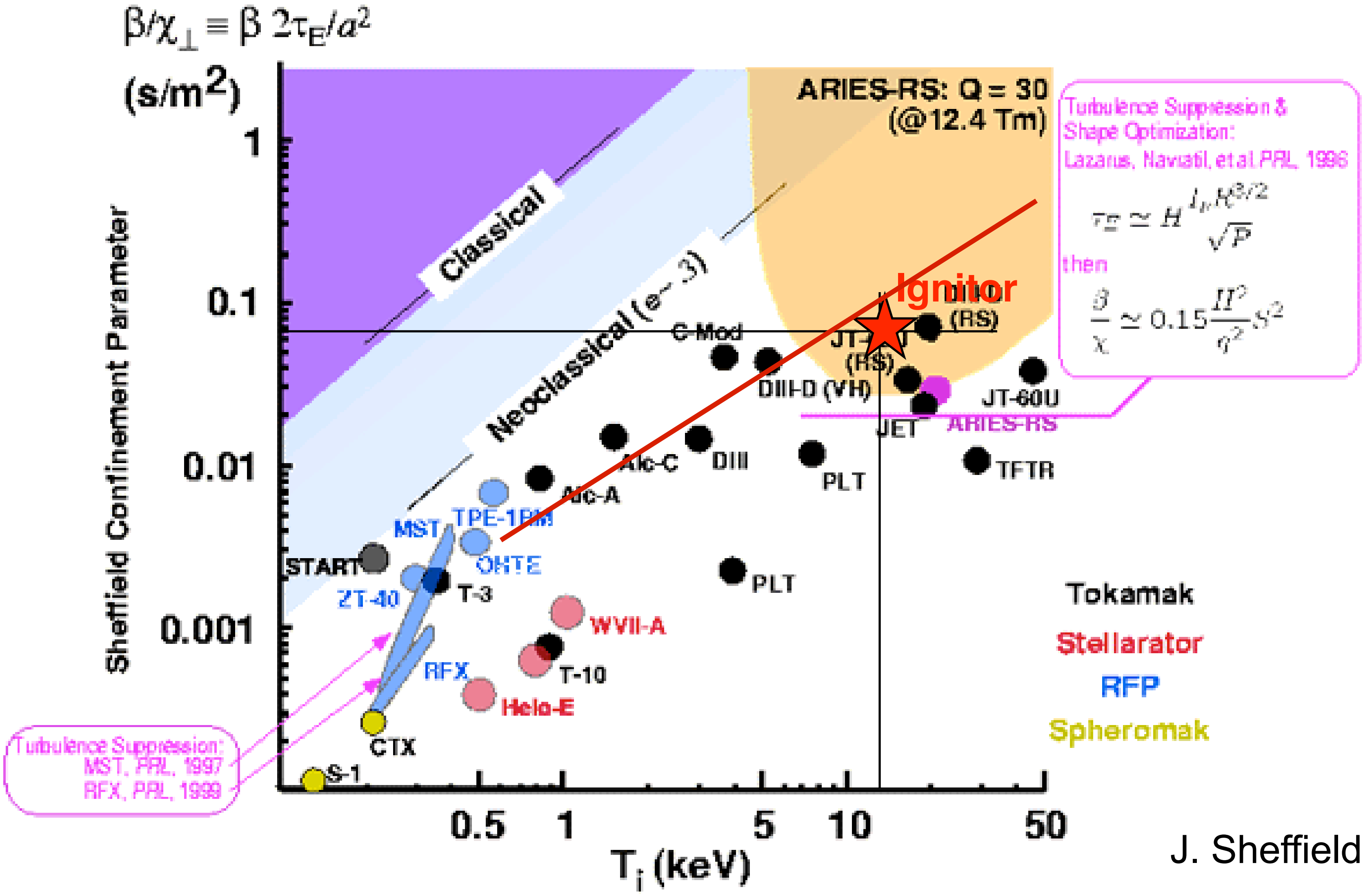
- Internal *m* = 1
- Ballooning Modes + α-particles
- ELMs

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

⇒Contained Magnetosonic Modes

$\tau_{\alpha}^{SI} \sim \tau_E$ is not a recommended design criterion

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



$\beta/\chi_{\perp} = \beta\, 2\tau_E/a^2$

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

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

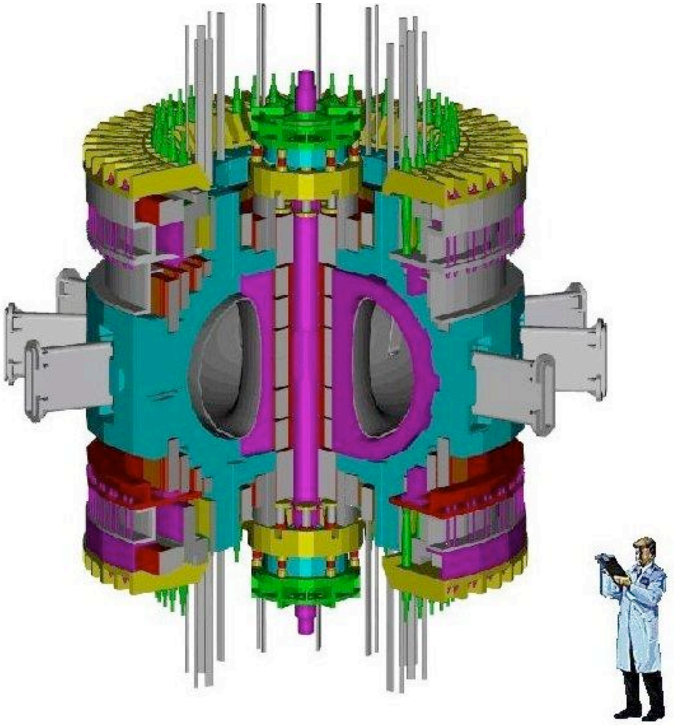
then

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

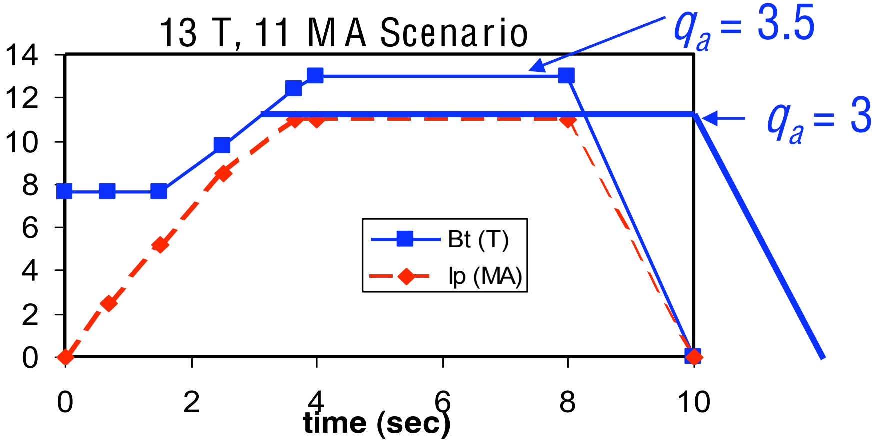
Turbulence Suppression:
MST, PRL, 1997
RFX, PRL, 1999

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



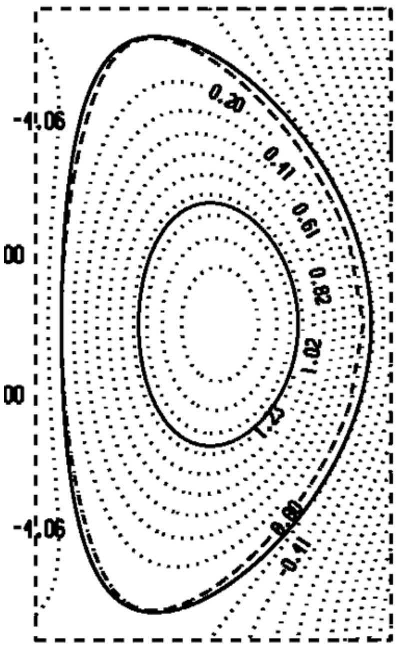
$q_a = 3.5$

$q_a = 3$

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

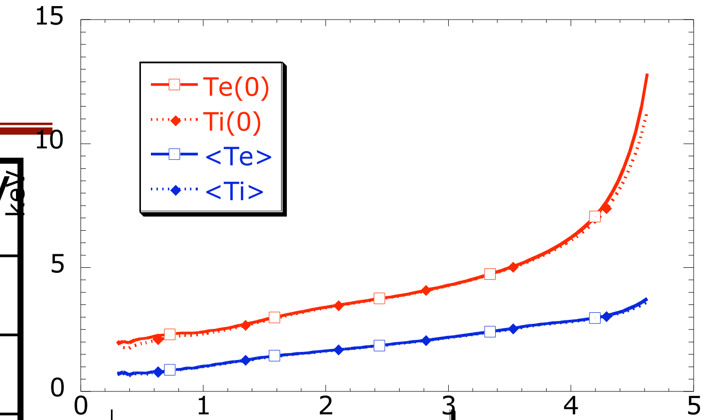
Ohmic Ignition

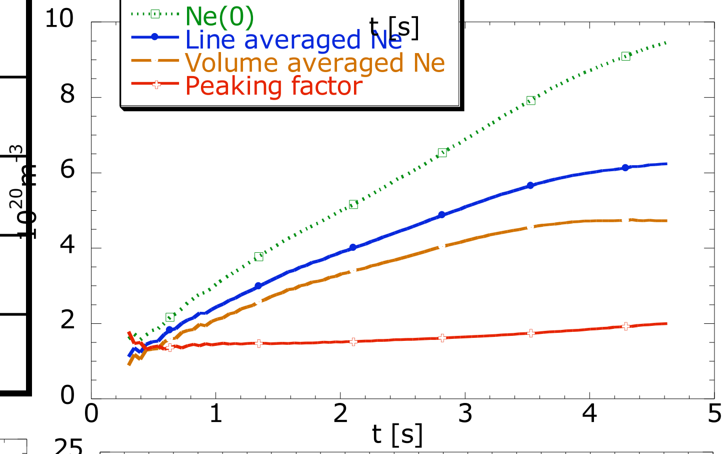
T_{e0} , T_{i0}	11.5, 10.5 keV
n_{e0}	10^{21} m^{-3}
$n_{\alpha 0}$	1.2×10^{18} m^{-3}
P_{α}	19.2 MW
β_{pol}, β	0.2, 1.2%
τ_E	0.62 s
τ_{sd}	0.05 s
Z_{eff}	1.2

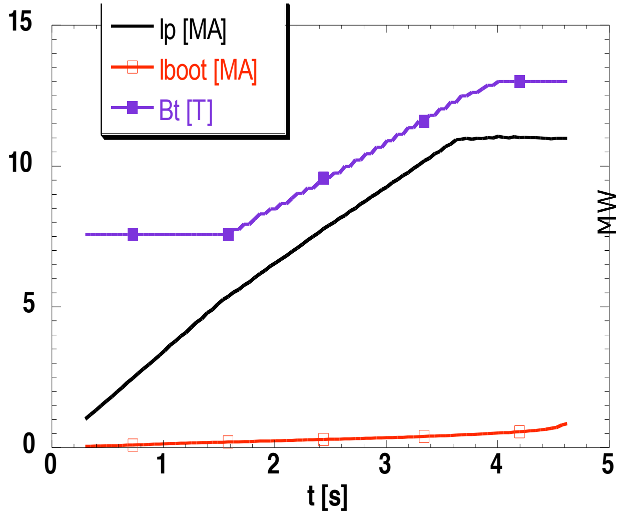


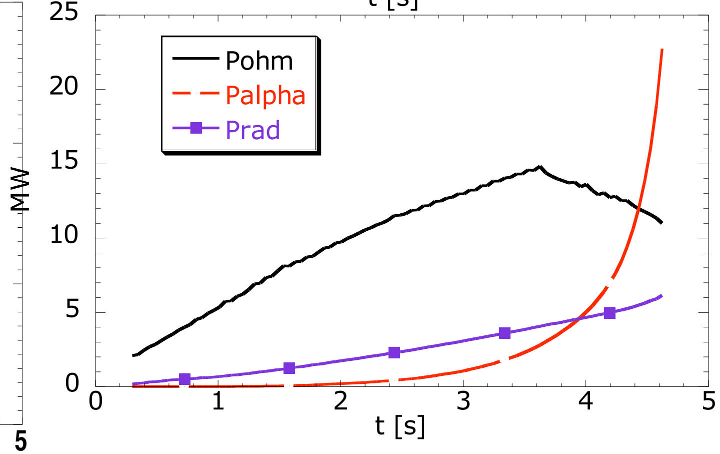
13 T, 11 MA
Extended Limiter Configuration

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

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

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

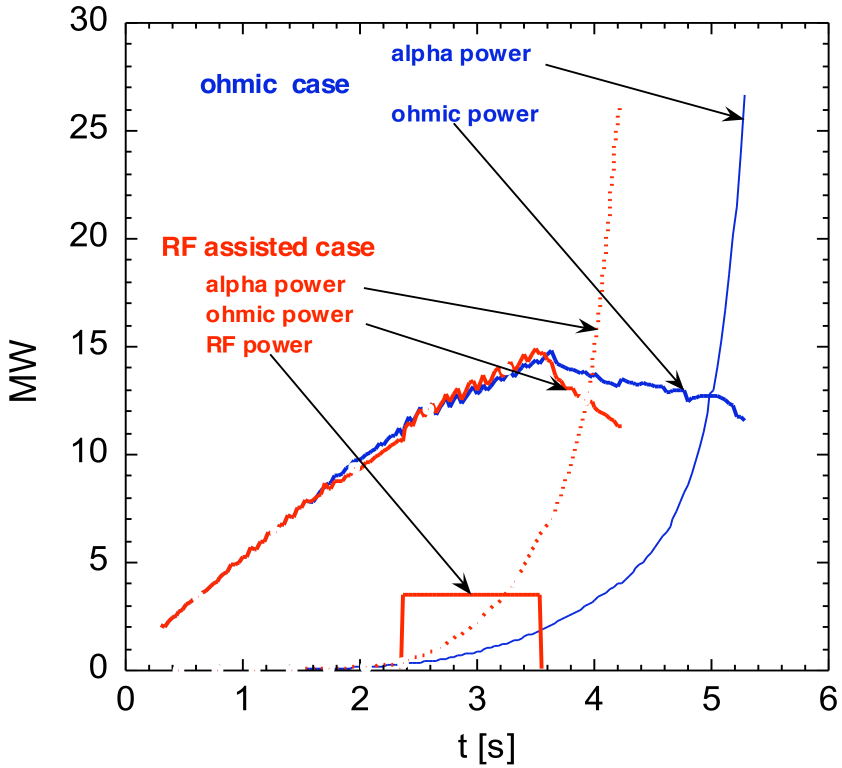
RF Accelerated Ignition

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)



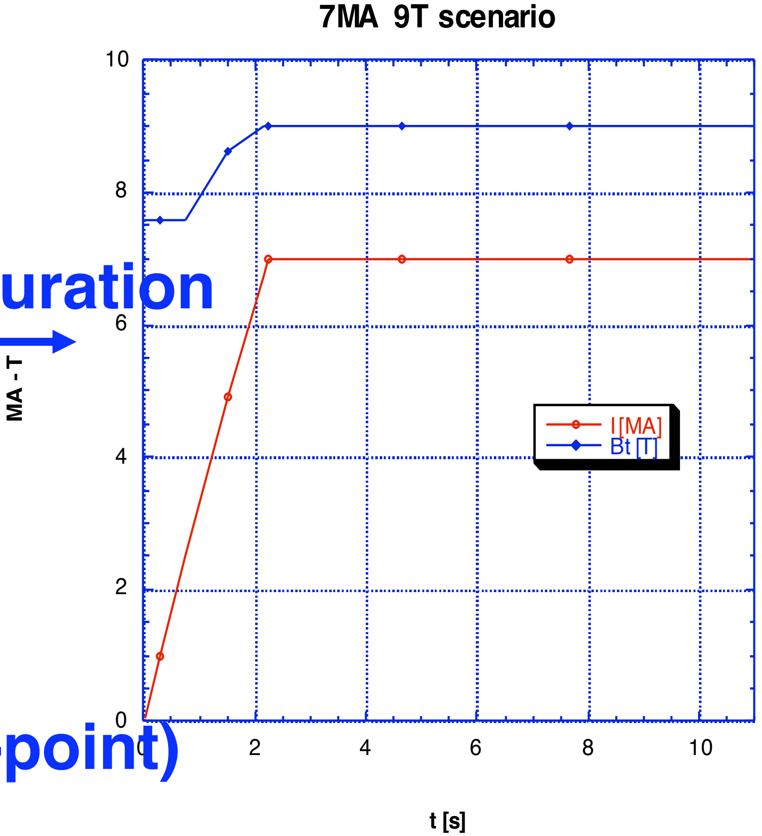
Comparison of Ohmic and RF accelerated ignition scenarios (JETTO code).

Scenarios with reduced parameters

Magnetic field up to 9T

Plasma current up to

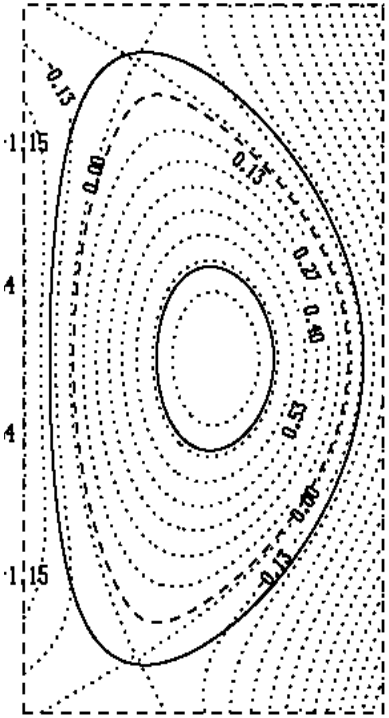
i) 7 MA, “first wall limiter” configuration



⇒ Long pulse

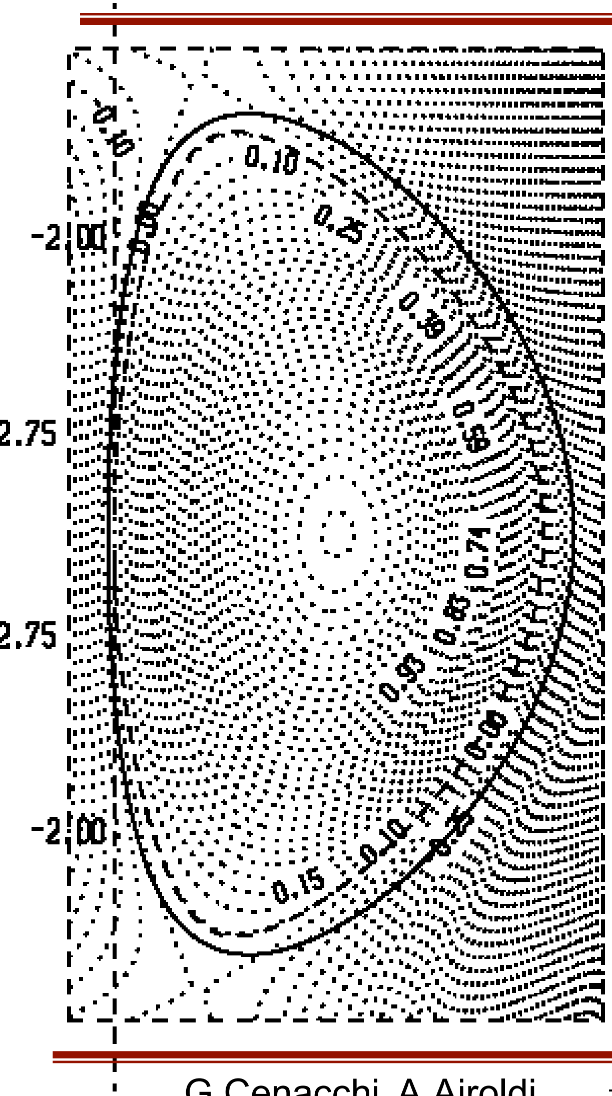
or

ii) 6 MA (double X-point)

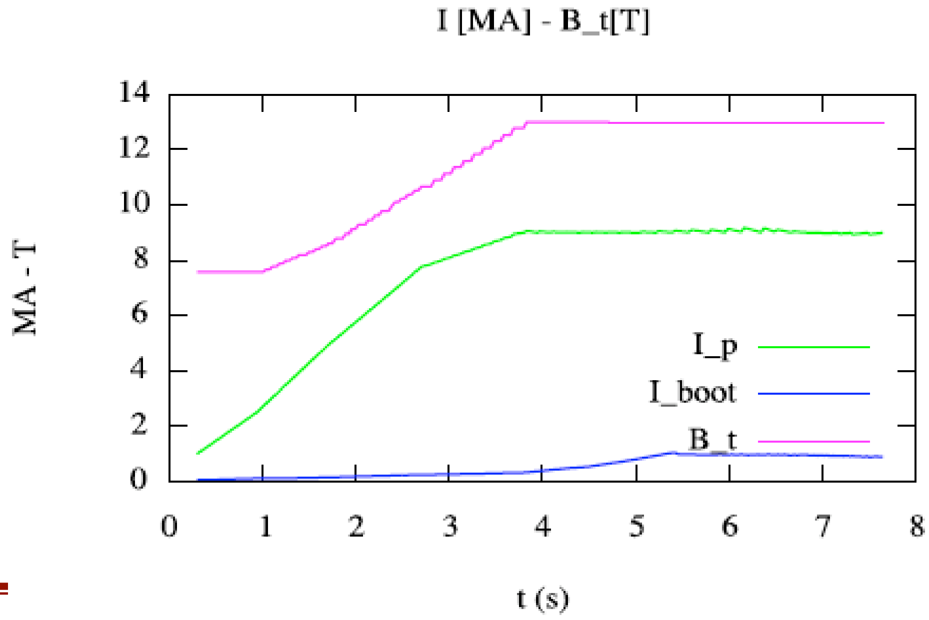


The pulse length is consistent with mechanical and thermal requirements of the magnets, and available magnetic flux

Double Null Configuration

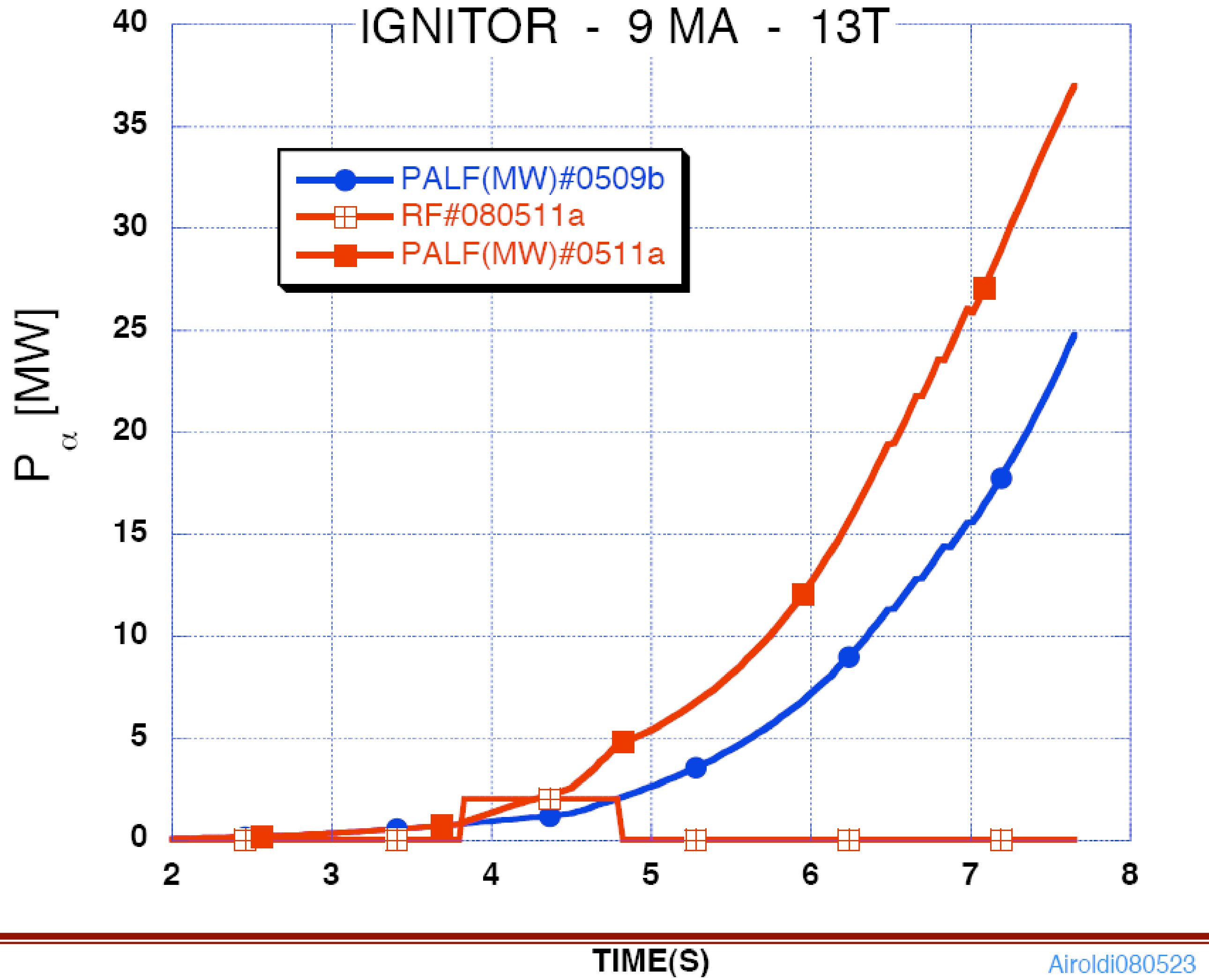


- Magnetic field up to 13 T
- Plasma current up to 9 MA
- Ramp-up time 3.6s for current and magnetic field
- Pulse length (8s) consistent with mechanical and thermal requirements



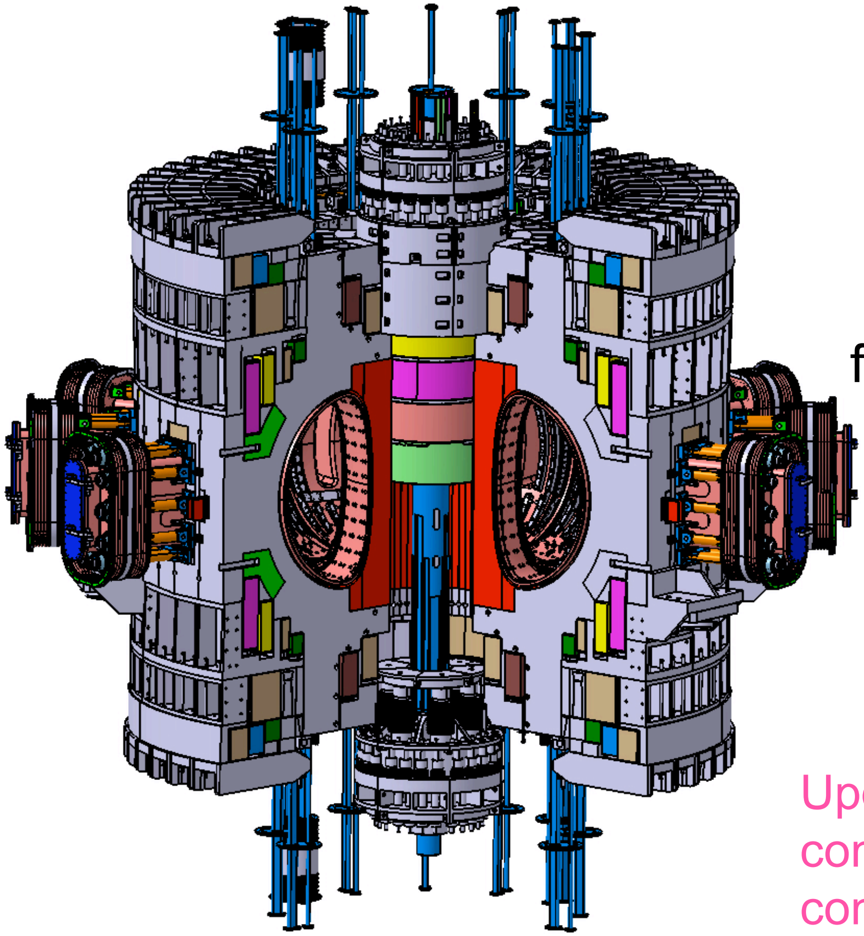
G.Cenacchi, A.Airoldi

No Sawteeth, OH and RF

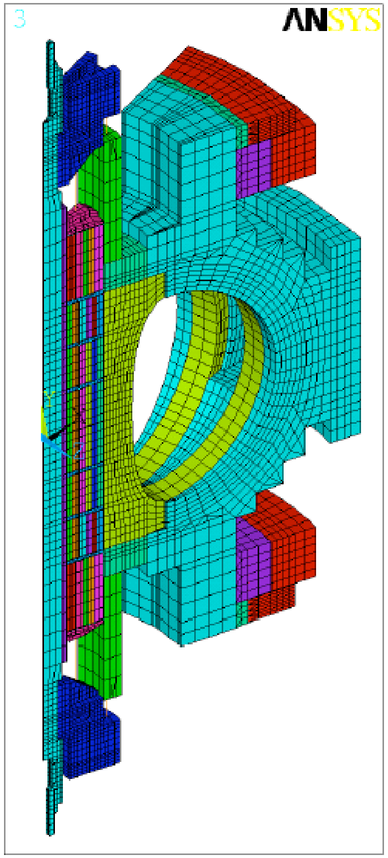


Airoldi080523

Detailed 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.



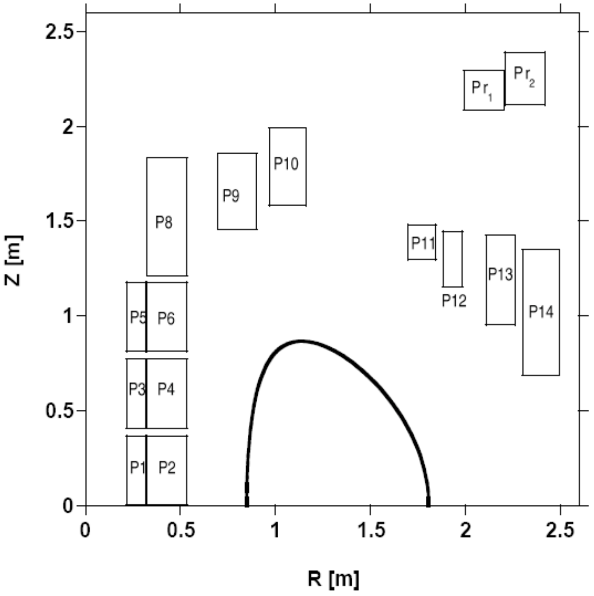
Updated plasma disruption conditions for VDE's have been considered.

High Field, Intermediate 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.

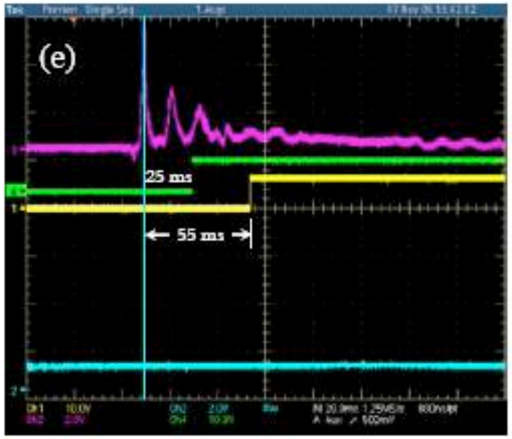
MgB_2 has the advantage of a relatively high superconducting temperature, and excellent superconducting properties, without compromising its affordability and robustness, even when made into wires.

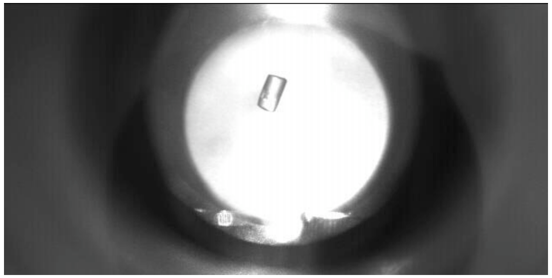


Columbus Superconductors
GRUPPO MALACALZA

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.





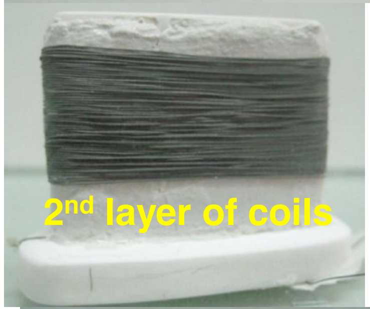
Manufacturing of Radiation-hard(er) Magnetic Pick-up Coils

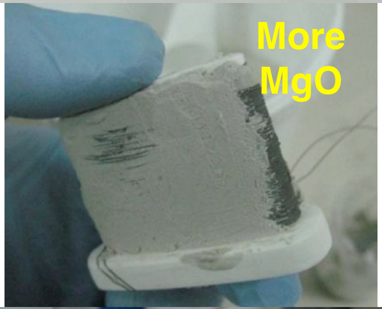

99% pure Alumina core and external casing

CAD CAM machined


Ceramawire Ni wire
1st layer


MgO insulation


2nd layer of coils


More MgO

SALENTEC Advanced Technologies


Lanthanide oxide based glass sealant

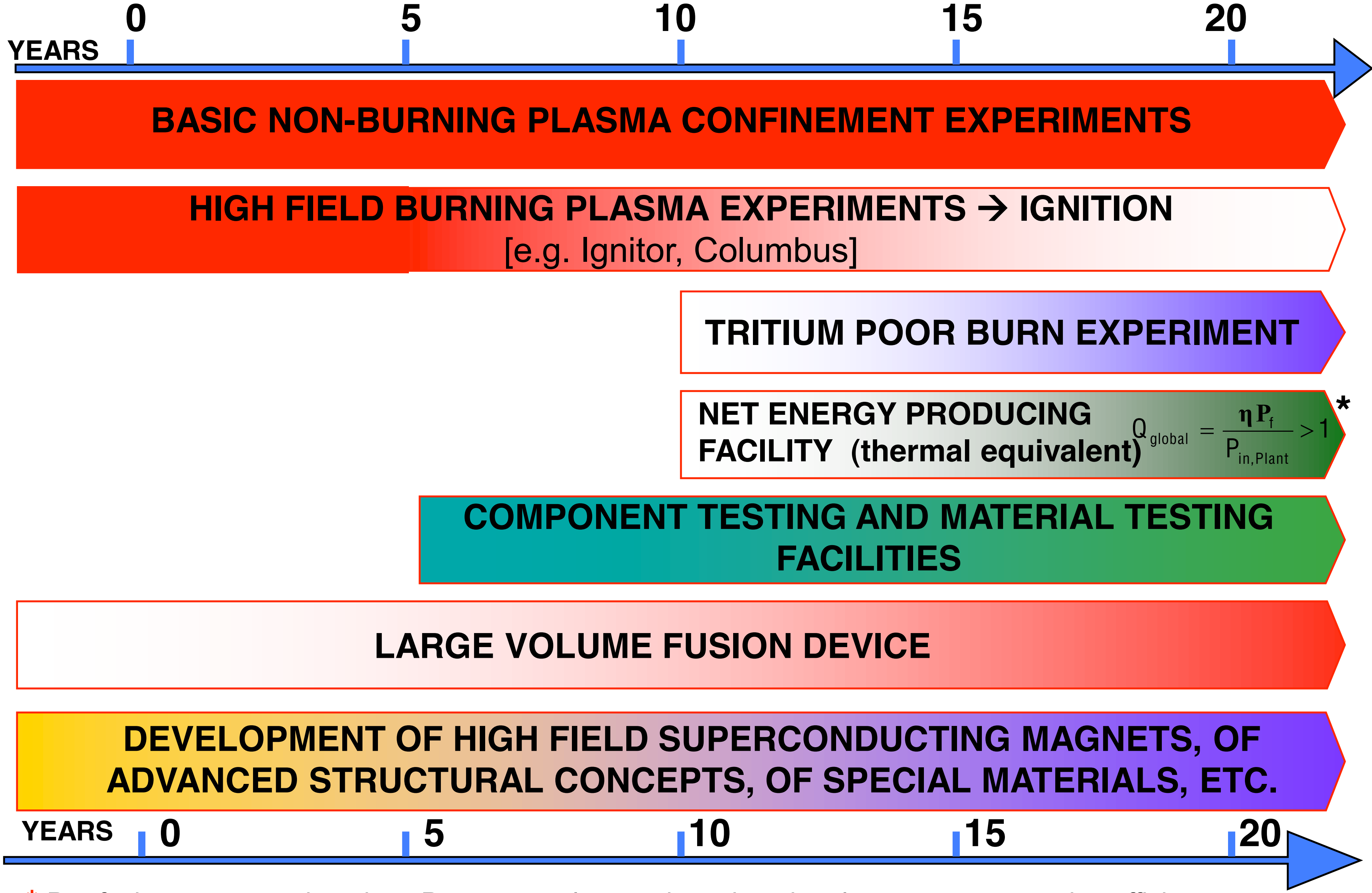

Synthering at 1100°C

Site

The Ignitor experiment can be connected to the national power grid at one of major nodes (Rondissone) or at the former nuclear power plant of Caorso . Thus, the need for flywheel generators is avoided and connection costs are minimized. Other possible sites are **Turbigo, Planais, Ostiglia…**

380 kV Italian Transmission Network

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

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

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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.

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>**

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)

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 .

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

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1990
ITER
en j

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.

6: J
ther
cadr

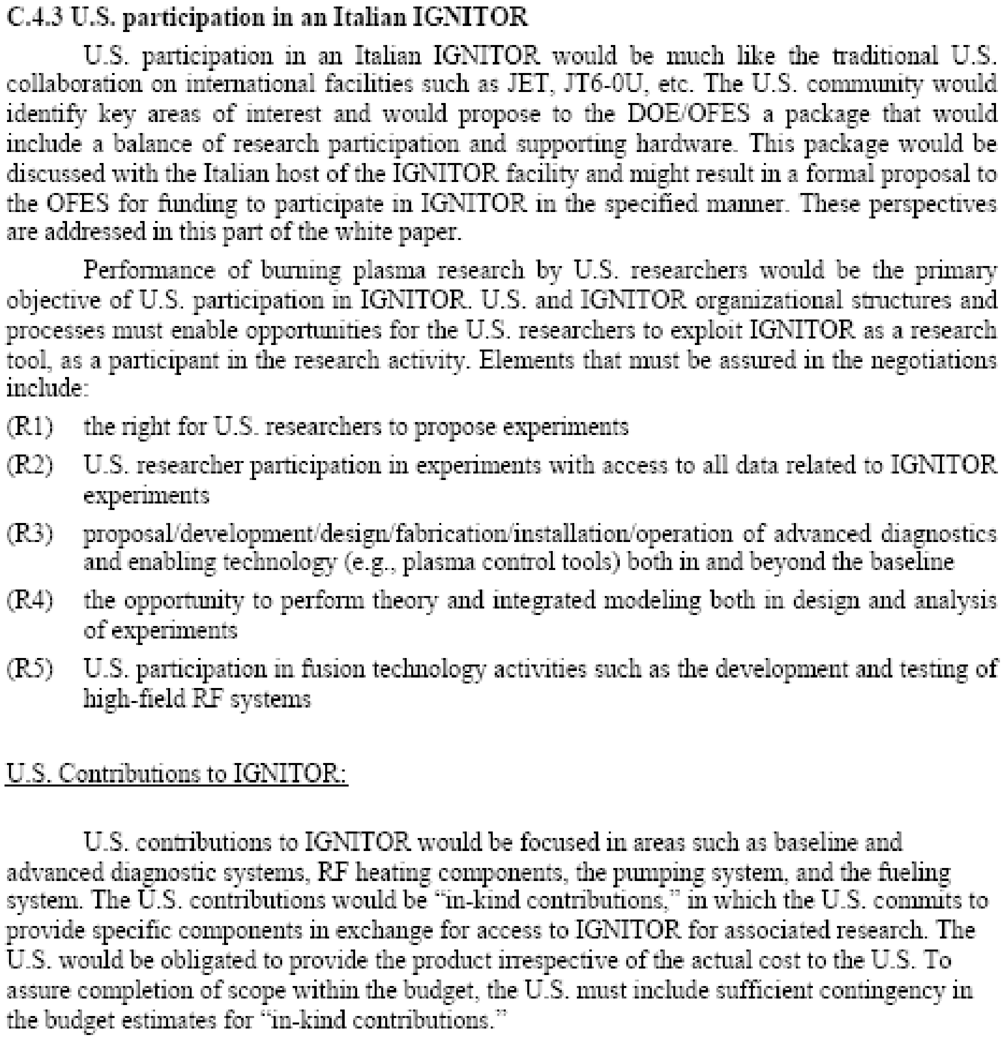
7: J
n'ont aucun sens,la physique du centre thermonucléaire du soleil , que j'ai longuement étudié et décrite dans un de mes textes pour l'académie des sciences, étant celle d'un plasma dense et optiquement épais,. émettant essentiellement à l'extérieur de la sphère de R de la zone thermonucléaie(R **thermo/ 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**