The “Science First” Approach to Fusion Research

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National Research Council, Washington, D.C.

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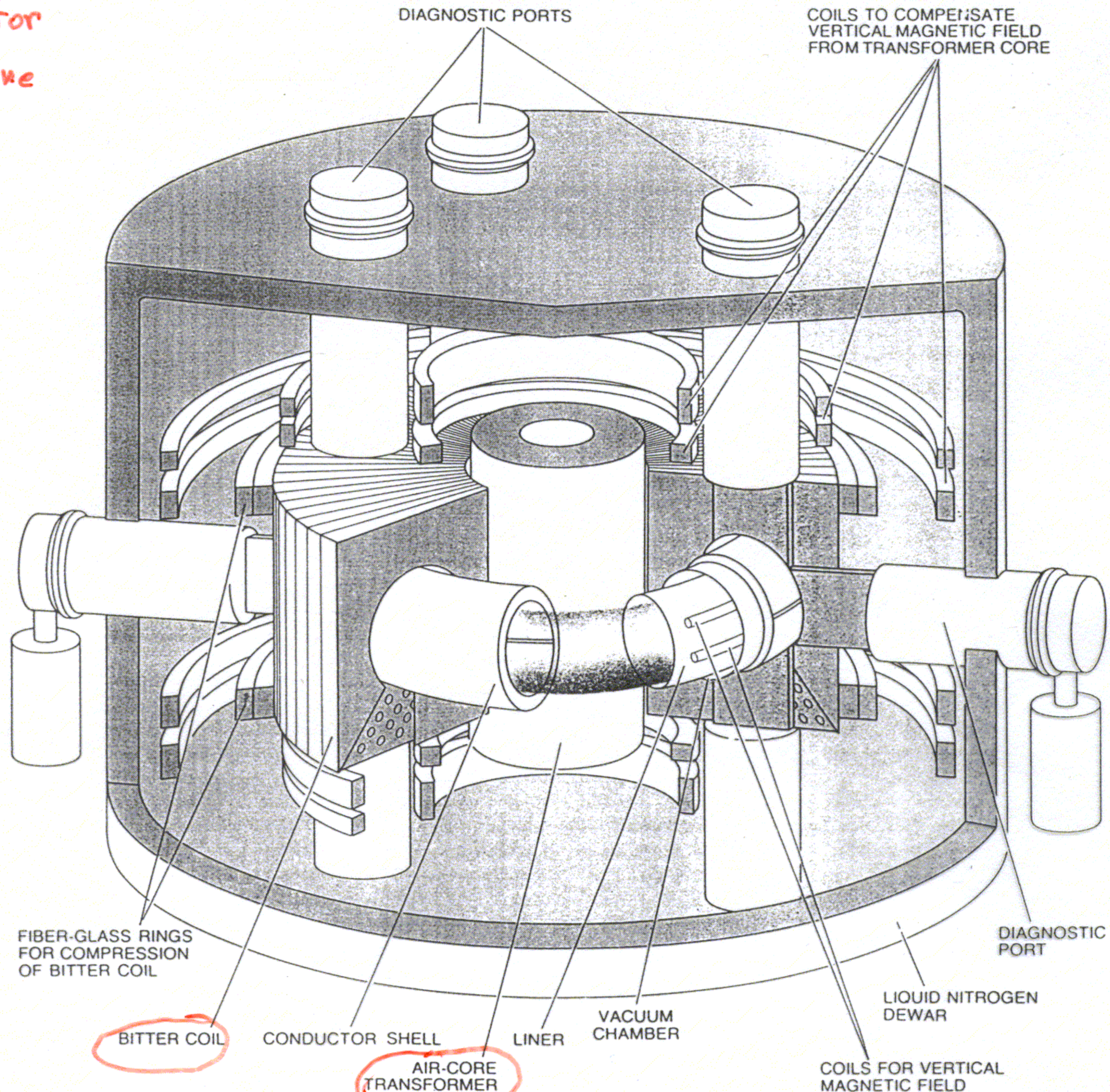
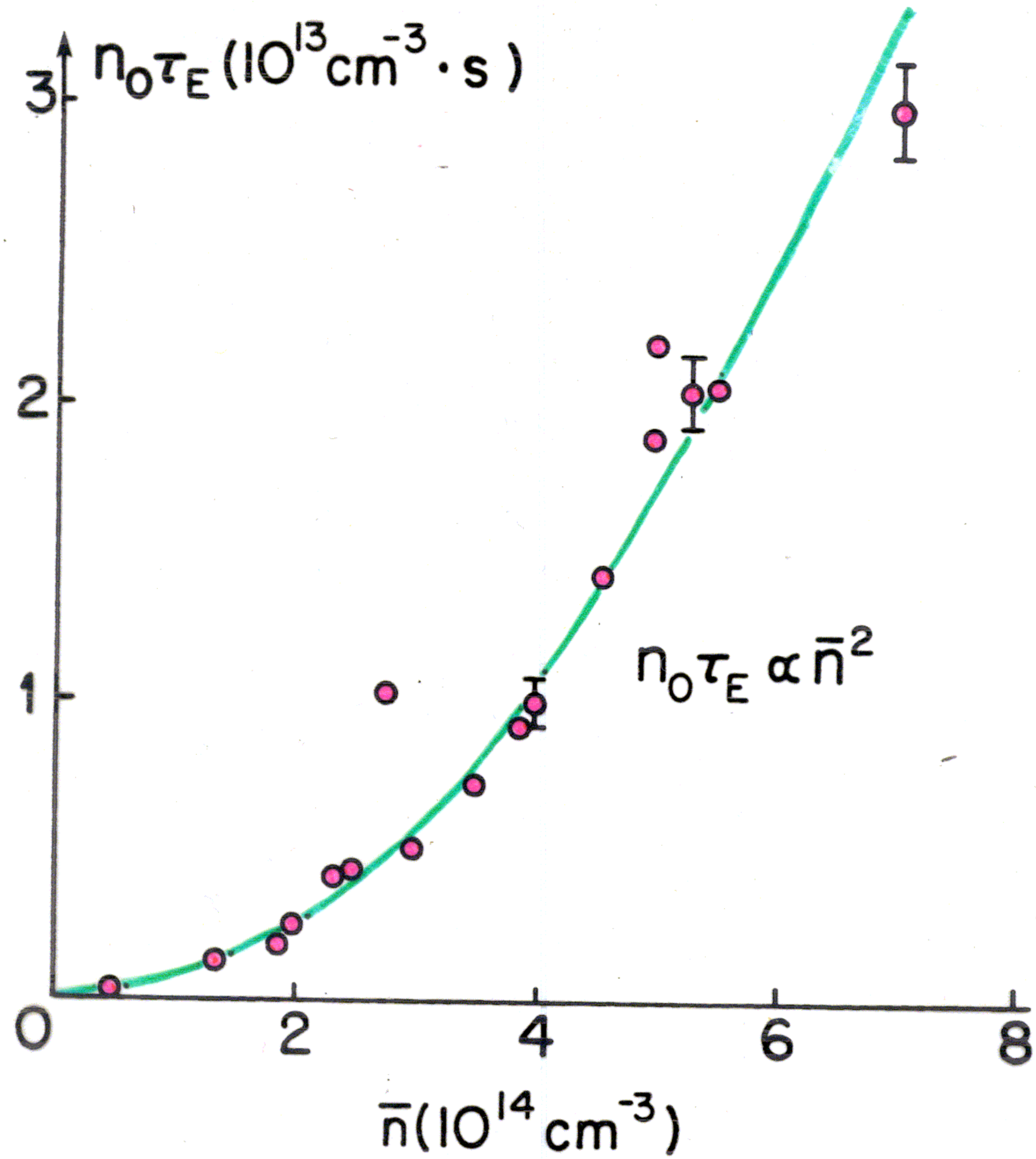
Alcator
Machine

Alto
Campo
Torus

First
machine
without
iron
dominated
magnets





parity
isotopic effect

Teller
Peierls

Basov

I) *Preaching Immorality*

Good Practical Sense
(by Trilussa)*

When, at night, they spread the rumor
That a Ghost was roaming around on the castle,
All the crowd ran and, staring at it,
Fell on their knees with their arms crossed.
But an old man stayed standing, and frankly
Wanted to say that nothing was there.

Then he reconsidered: “It would be a folly to speak out.
I, without doubt, see that it is a bed sheet:
But, rather than saying the truth by myself,
I prefer to err in the company of everyone else
Therefore, it is a Ghost, without argument.”
And he too went down sheep-like with the rest.

*Trilussa was a popular poet in the vernacular language of Rome in the 1800’s.

II) *Preaching Morality*

As Dag Hammarskjold wrote in his
Posthumously published book “Markings:”
“<u>You cannot play with</u> the animal in you
without becoming wholly animal, play with
<u>falsehood without forfeiting your right to</u>
<u>truth</u>, play with cruelty without losing your
sensitivity of mind. <u>He who wants to keep</u>
<u>his garden tidy does not reserve a plot for weeds.</u>

The "Science First" Approach to Fusion Research

The "Science First" approach recognizes the fact that (meaningful) fusion burning plasmas are intrinsically self organized physical entities for which we have limited means to make reliable theoretical predictions. The first priority is, in fact, that of closing the gap of knowledge necessary to identify the defining characteristics of a working fusion reactor.

Therefore, a set of near term experiments, based on existing knowledge of the physics of magnetically confined plasmas and on technologies that do not require major new developments, is needed, which should be designed to achieve values of the "criticality parameter" K_f in the range $2/3 < K_f \leq 1$. Like in the case of particle accelerators, it is essential to devote substantial resources to technology, but this should be oriented mostly toward the actual construction of these experiments. (Here , $K_f = P_\alpha / P_{loss}$, P_α is the power emitted as α–particles by DT fusion reactions and P_{Loss} is the rate of energy loss from the plasma.)

The problem of demonstrating and understanding controlled fusion has been recognized as one of the fundamental problems of physics. The route to a reactor through scientific understanding can not be substituted by risky "one shot" approaches suggested by the mirage of imagined power station concepts. There are other areas of science that may be considered for comparison such as that of cancer research for which the idea that short cuts could be taken, away from well proven scientific practice, cannot find credibility.

Without denying the goal to construct actual fusion power stations, I think that we should pay more attention to the near term products of fusion research. This includes, for instance, the technology of high field magnets, the development of basic plasma physics concepts and phenomena that are relevant to space physics and to astrophysics.

Looking ahead, beyond the needs of present day experiments, it is prudent to say that high field superconducting magnets will be important for future steps, as well as the development of new materials, the formulation of new structural concepts, etc. Therefore an increase of funding for fusion research should include investments in these areas taking into account that the results emerging from these efforts have a high probability of being useful for other fields of science and technology.

As next steps in fusion research beyond proving ignition, it is possible to envision an experiment aimed at studying the burn conditions of tritium poor plasmas and a demonstration high field experiment that produces more energy than it consumes. In fact, high field toroidal plasma experiments have shown that they can confine plasmas with such high densities that their reactivity can be significant even when the fraction of tritium is considerably less than the canonical 50% in a deuterium-tritium mixture.

With these perspectives in mind, my opinion is that the US should have a near term meaningful experiment on fusion burning plasmas. If this is Ignitor-like, based on the same criteria of simplicity and stability and making use of the experience gained with the Ignitor program, and if a site with good credits is chosen, the US can certainly afford such an experiment.

In the nearer term, the US could collaborate with the ongoing Ignitor program by selecting a small group of active scientists and engineers with hands on experience to participate in the full range of Ignitor activities that are ongoing.

Rather than entering immediately into negotiations on ITER-FEAT and setting deadlines, I propose that the best experts in the US, on the physics and the technologies relevant to meaningful burning plasma devices, work at a fast pace on an “ITER-Physics” experiment suitable to be constructed by an international consortium. The relevant design would not include tritium-producing blankets, be of more compact dimensions than ITER-FEAT, have higher poloidal fields, higher safety factors against the main instabilities and involve drastically smaller costs and shorter construction times. Cost-benefit considerations, made on the basis of the physics parameters to be achieved with reasonably good probability, should guide the choice of the main machine components and of the types of magnets to be adopted.

Once the main characteristics of the ITER-Physics device are identified, this could be the subject of realistic and meaningful negotiations with our colleagues from overseas.

Ignitor-like Device (Example)

The machine would have

- The same toroidal and poloidal fields as Ignitor
- The same aspect ratio as Ignitor
- A 47% larger volume
- The same plasma current that the present ITER design would have for equal safety factors ($q_a \cong 3.6$)
- The same flexible poloidal field system as that of Ignitor, based on the DIII-D design.
- The same kind of conducting material, copper at 30 K

$$R_0 \simeq 1.5\,\mathrm{m}$$
$$a \simeq 53.5\ \mathrm{m}$$
$$b/a \simeq 1.8$$
$$B_T \simeq 13\ \mathrm{T}$$
$$I_p \leq 12.5\ \mathrm{MA}$$
$$\overline{\overline{B}}_p = \frac{I_p}{5a\sqrt{\kappa}} \simeq 3.5\ \mathrm{T}$$

If the dimensions are increased further, the magnet technology to be adopted has to be different from that of Ignitor, because of current skin effects, and be of the type proposed for the *Candor* concept. This is an experiment studied to approach D-He^3 ignition conditions on the basis of present technologies and advanced (but reasonable) plasma physics notions.

SUPERCONDUCTING MAGNETS ABOVE 20 TESLA

Superconductors are key components of magnets that generate homogeneous, low-noise, and extremely stable high fields. Further increasing the strength of these fields will require meeting a number of technological challenges.

Steven W. Van Sciver and
Kenneth R. Marken

The primary motivation for developing high-field superconducting magnets is to support scientific research in a variety of disciplines. Because the magnetic field is a thermodynamic variable, it can be used to manipulate phase diagrams of magnetic materials in which the spins of the electrons order ferromagnetically or antiferromagnetically. The quantized orbital motion of electrons in the presence of magnetic fields allows scientists to probe Fermi surfaces, and the quantized electron energy levels associated with fields of order 20 tesla (T) or greater permit access to the quantum and fractional quantum Hall regime. Nuclear magnetic resonance (NMR) techniques, applicable to physical, chemical, and biological systems, have led to a remarkable technology for nondestructive imaging of living systems.

Many investigations require, or at least can benefit from, the homogeneous, low-noise, and temporally stable magnetic fields that can only be achieved with superconducting magnets. Cost and material properties, though, limit the fields that can be produced with superconducting coils. A number of manufacturers now sell 20-T superconducting magnets with bore sizes in the range of 50 mm: Many of those magnets are incorporated into research instruments such as NMR spectrometers or magnetometers. (For comparison, the highest magnetic fields are generated at facilities such as the National High Magnetic Field Laboratory. The NHMFL operates a 45-T "hybrid" superconducting magnet with a resistive insert and also operates 60-T pulsed magnets.) New superconducting materials, including high-temperature (HT) superconductors are enabling the design and construction of solenoidal magnets that have fields approaching 25 T. But achieving 20-T magnets has required many years of work, and as we magnet builders develop magnets that produce stronger fields, we find the cost and difficulty of production growing rapidly. Going beyond 20 T in a superconducting magnet demands long development schedules, large R&D groups, and the application of complex engineering principles. Still, superconducting magnets with ever higher fields are in demand, and efforts to meet that demand continue.

[redacted]

Historical highlights

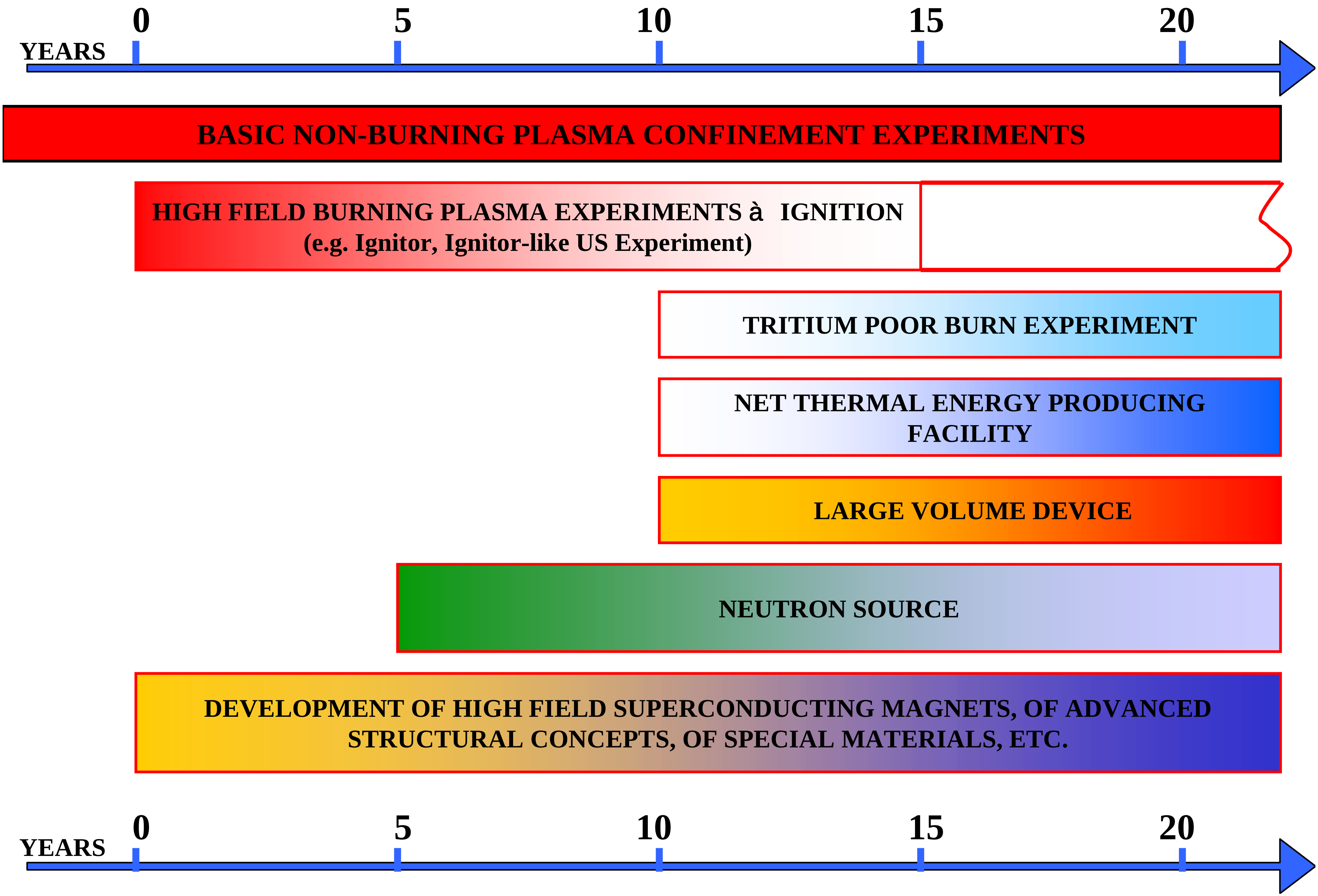
Soon after Heike Kamerlingh Onnes discovered superconductivity in 1911, he speculated that one could produce a magnetic field of 10 T by means of a modest-sized superconducting coil wound from lead wire. But Onnes never built a 10-T magnet: The inherently low critical fields of the elemental type I superconductors he was using would not allow the impressive fields he imagined. The fundamental limit imposed by those low critical fields prevented the development of superconducting magnet systems until the discovery of type II superconductivity many years later. (For a summary of the evolution of superconducting magnets, see the plot and photographs in figure 1. For a brief tutorial on superconductivity, consult the box on page 39.)

The first successful magnet that used a type II superconductor was built in 1954 by George Yntema of the University of Illinois. The magnet, which used iron pole pieces with niobium (Nb) wire windings, produced a field of 0.7 T. In the course of developing his magnet, Yntema made the important observation that the transport current of his wire depended on the amount of metallurgical cold work introduced into the wire during the drawing process. Thus, unlike the critical temperature and fields—thermodynamic variables that describe the superconducting state—the critical current in a type II superconductor is, to a large extent, a metallurgical variable that depends on processing methods.

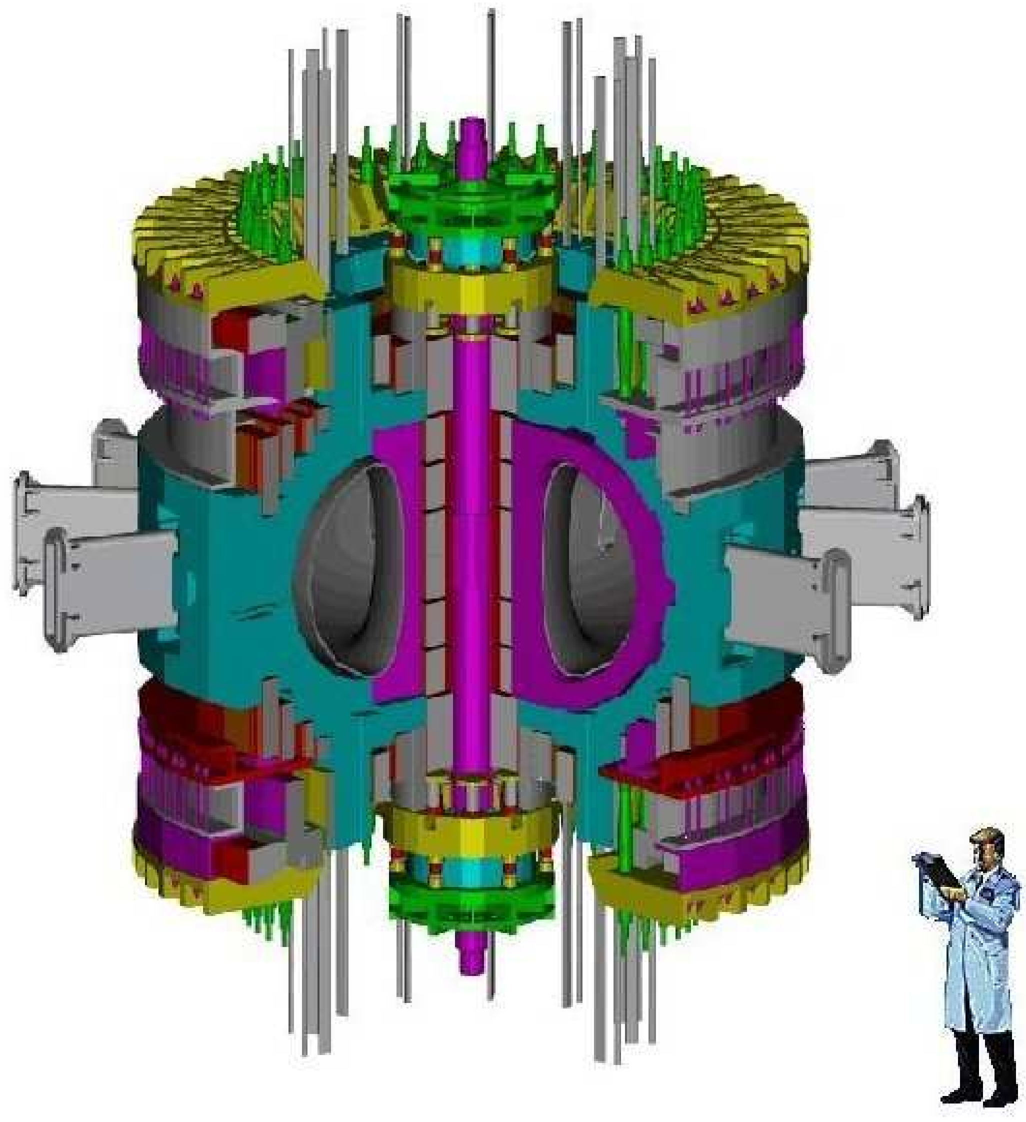
In the early 1960s, the discovery by John Kunzler (Bell Telephone Laboratories) of the high superconducting current density in niobium tin (Nb_3Sn) and the almost simultaneous invention by John Hulm (Westinghouse Electric Corp) of a method to produce niobium zirconium (NbZr) wire in long lengths led to a flurry of coil construction activities. By 1963, General Electric Co had produced a Nb_3Sn tape superconducting magnet with a field of greater than 10 T. About a decade later, multifilament Nb_3Sn wire was developed. The multifilament configuration allows for improved magnet stability and increased current densities: Almost all high-field research magnets used today are based on multifilament Nb_3Sn technology.

The discovery of HT superconductivity in 1986 brought about a resurgence in magnet technology. HT superconductors allow for magnets operating well above liquid helium temperature, 4.2 K. But those materials also have very high critical fields, which suggests that they can

EXAMPLE OF "SCIENCE FIRST" STRATEGY FOR FUSION



IGNITOR MACHINE

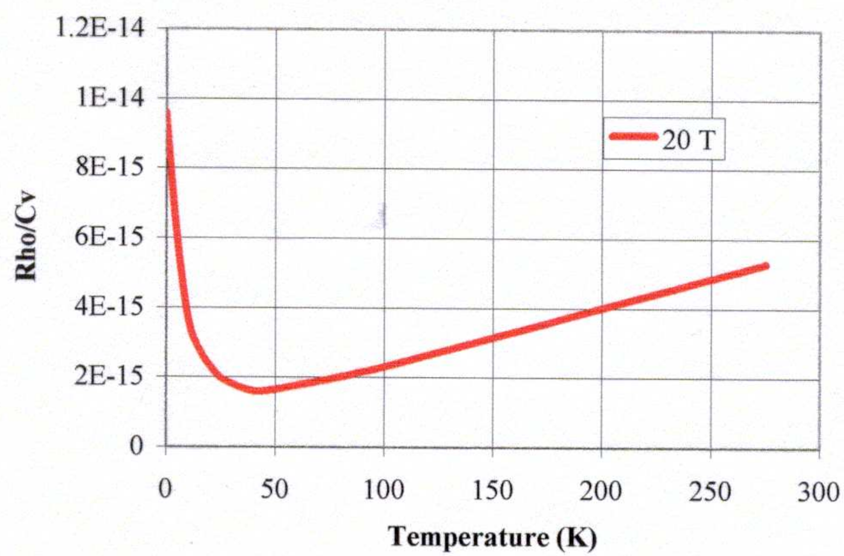


Ignitor Reference Design Parameters

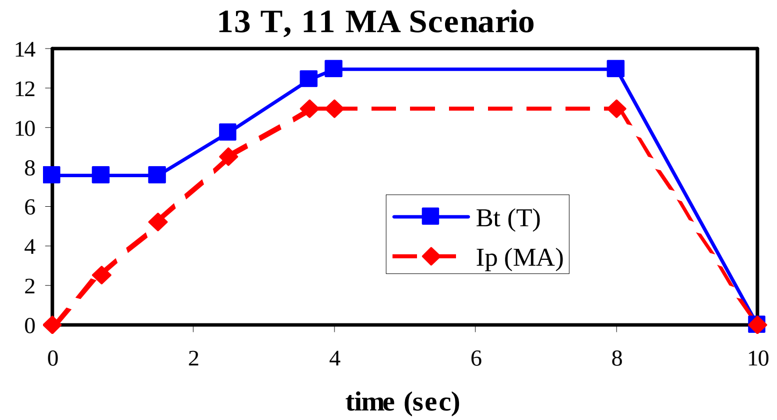
major radius	R_0	1.32 m
minor radius	$a \times b$	0.47×0.86 m
aspect ratio	A	2.8
elongation	κ	1.83
triangularity	δ	0.4
toroidal field	B_T	$\lesssim$13 T
toroidal current	I_p	$\lesssim$11 MA
maximum poloidal field	$B_{p,max}$	$\lesssim$ 6.5 T
mean poloidal field	$\overline{\overline{B}}_p \equiv I_p / 5\sqrt{ab}$	$\lesssim$ 3.5 T <<
poloidal current	I_θ	$\lesssim$9 MA
edge safety factor @ 11 MA	q_ψ	3.6
plasma volume	V	$\simeq$ 10 m^3
plasma surface	S	$\simeq$ 34 m^2
ICRF heating (70-140 MHz)	P_{RF}	18 – 24 MW
Optimal ICRH (115 MHz)	$P_{RF}{}^{OP}$	3–5 MW

IGNITOR PROJECT

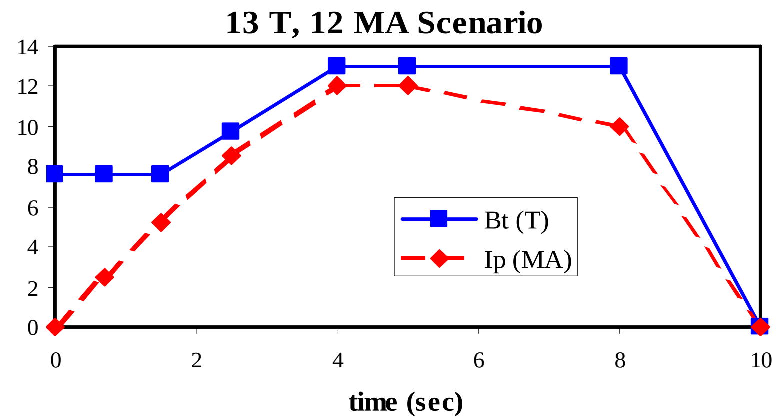
Ratio of resistivity to specific heat for the copper material adopted for the toroidal magnet



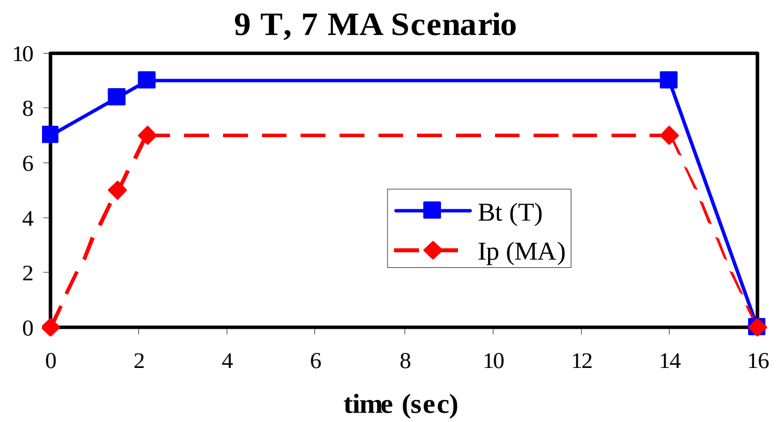
Examples of operating scenarios



a)



b
)



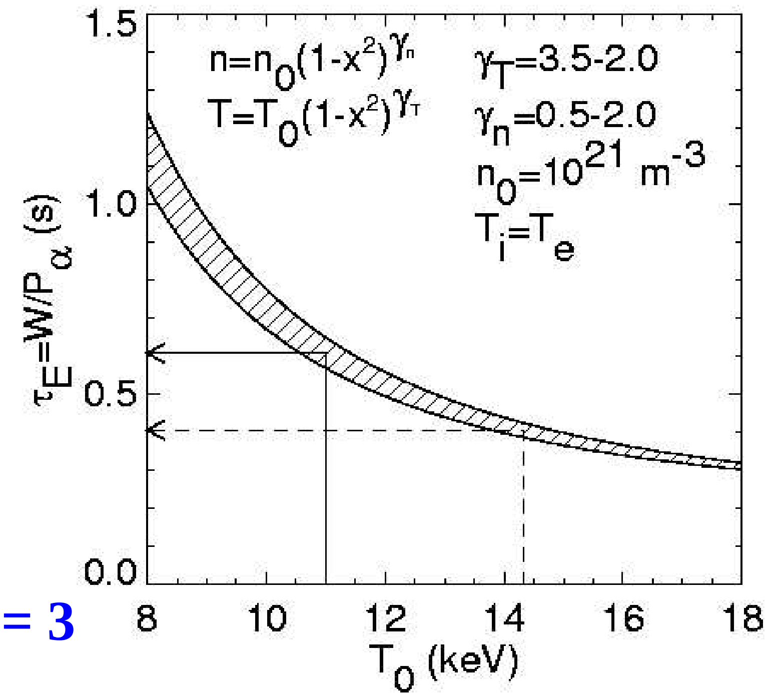
c)

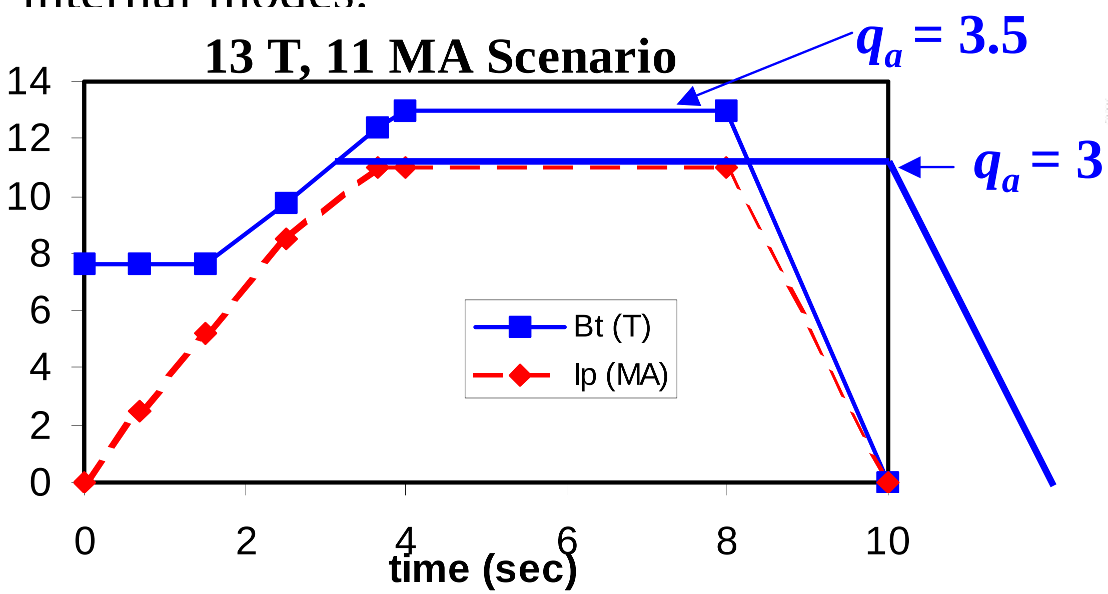
$$K_f = \frac{P_\alpha}{P_L}$$

The Ignitor strategy

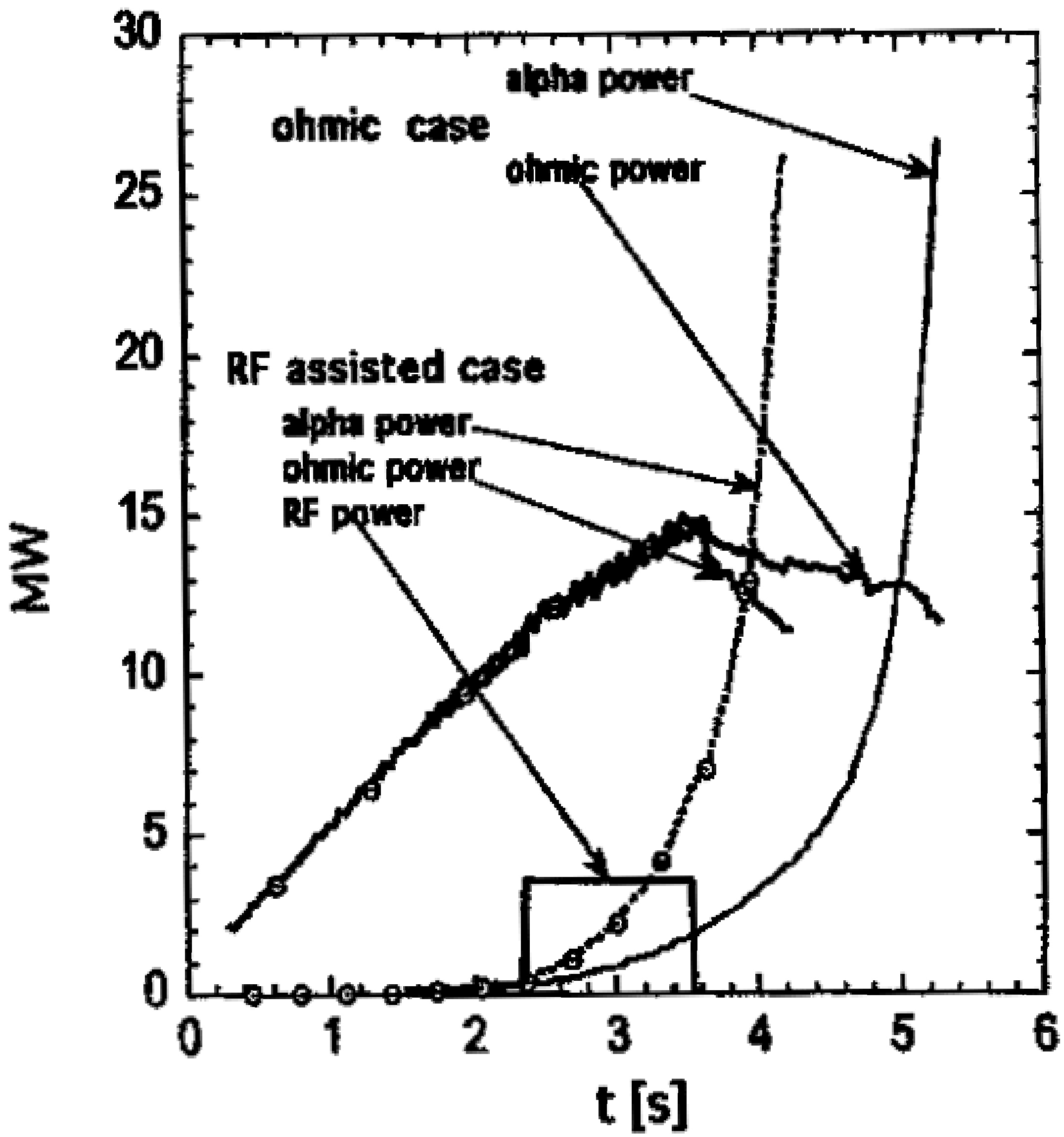
Use compact, high field limiter configurations to reach ignition at low temperature, high density, and trigger the thermonuclear instability.

Low β_{pol} and a small q = 1 region provides a defense to ideal MHD and resistive m = 1 internal modes.





$\frac{\rho_{bi}}{a}$

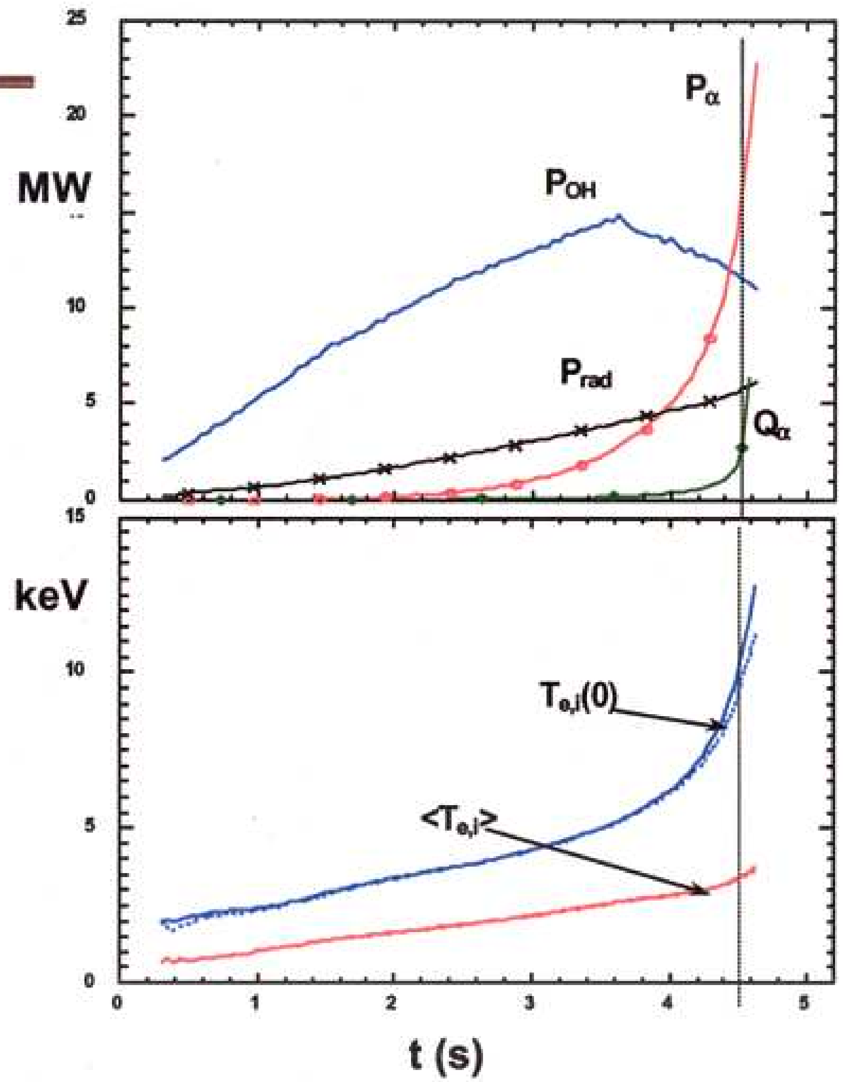


Comparison between the evolution of the powers in a purely ohmic case and a RF assisted case. The RF case shows the ignition attainment just at the end of the current ramp. (i.e. the plasma ignites before the start of the pulse flat top)

Ohmic Ignition (No RF applied)

JETTO Simulations

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	0.2, 1.2%
q_ψ, q_0	3.5, ~ 1.1
τ_E, τ_{sd}	0.62, 0.05 s
Z_{eff}	1.2



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

IMPORTANCE OF TIME SCALE RATIOS

Relevant Parameters		ITER	FIRE	IGNITOR	$\frac{\text{ITER}}{\text{IGNITOR}}$
		@ $q_a = 3$			
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	$\tau_{cr}^{coll} \propto \frac{a^2 T_{e0}^{3/2}}{Z_{eff}} \frac{1}{(1+(3/2)\alpha_{T,parab})}$ [b)]	118	4.7	1.8	65

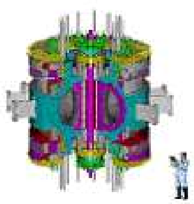
a) Ignition : onset of the thermonuclear instability
b) Freidberg Report

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 $\tau_{cr}^{eff} < \tau_{cr}^{coll}$.

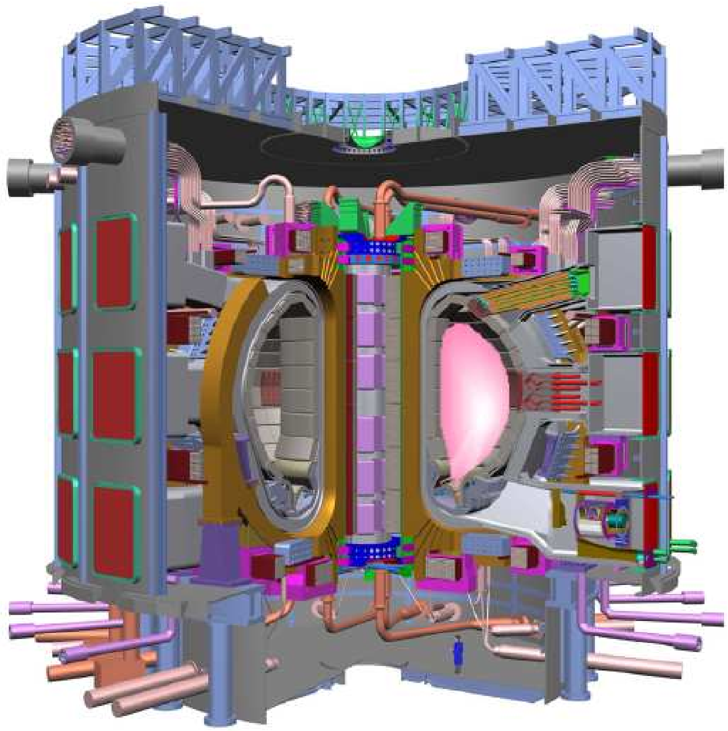
The poloidal magnetic field pressure is the driving parameter of the Ignitor design

q

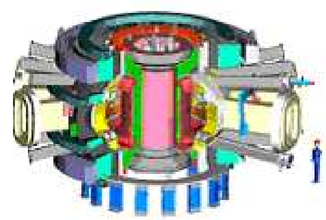
$$\beta_p = \frac{8\pi p}{B_p^2} < 0.3$$



IGNITOR



ITER-FEAT



FIRE

	IGNITOR	ITER-FEAT	FIRE
$q_\psi \simeq 3.5$	$\boxed{\bar{\bar{B}}_p \simeq 3.5\,\mathrm{T}}$ $\boxed{I_p \simeq 11\,\mathrm{MA}}$	$\bar{\bar{B}}_p \simeq 1\,\mathrm{T}$ $I_p \simeq 12.8\,\mathrm{MA}$	$\bar{\bar{B}}_p \simeq 1.7\,\mathrm{T}$ $I_p \simeq 6.2\,\mathrm{MA}$
$q_\psi \simeq 3$ lower safety actor)		$\bar{\bar{B}}_p \simeq 1.15\,\mathrm{T}$ $I_p \simeq 15\,\mathrm{MA}$	$\bar{\bar{B}}_p \simeq 1.9\,\mathrm{T}$ $I_p \simeq 7.7\,\mathrm{MA}$

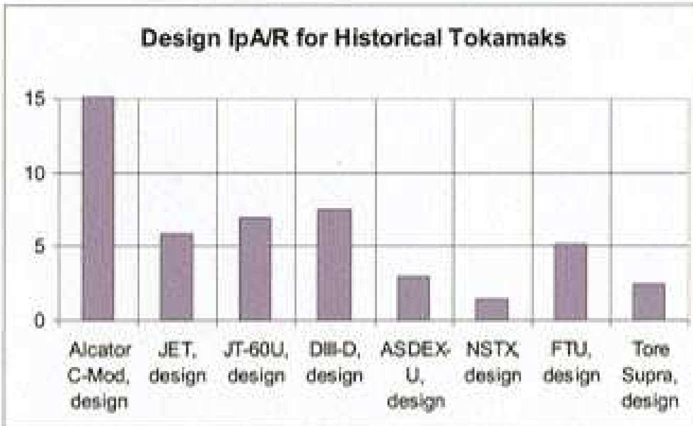
q_ψ = safety factor for plasma stability $\quad I_p$ = plasma current $\quad \bar{\bar{B}}_p$ = confining (poloidal) magnetic field

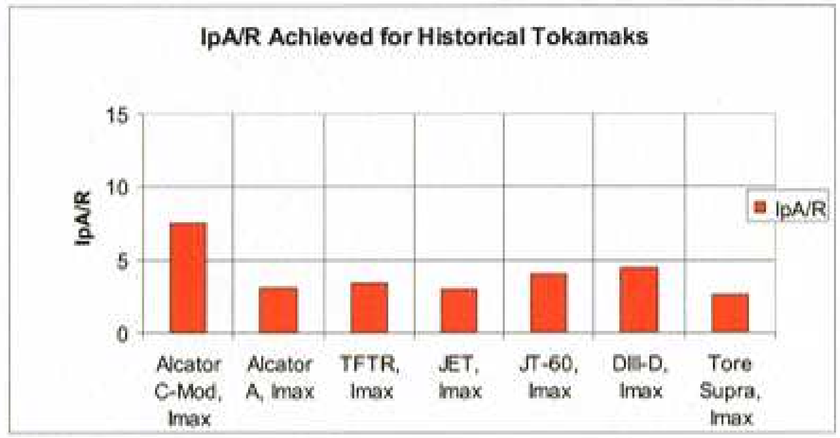
MIT Plasma Science and Fusion Center

Fusion Technology & Engineering Division

IpA/R Historical Survey

$\propto \bar{\bar{B}}_p$

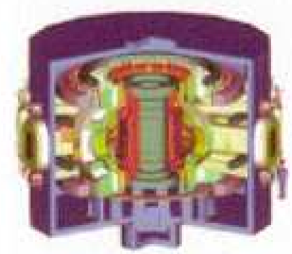




FIRE IpA/Ro 2x as high as world record

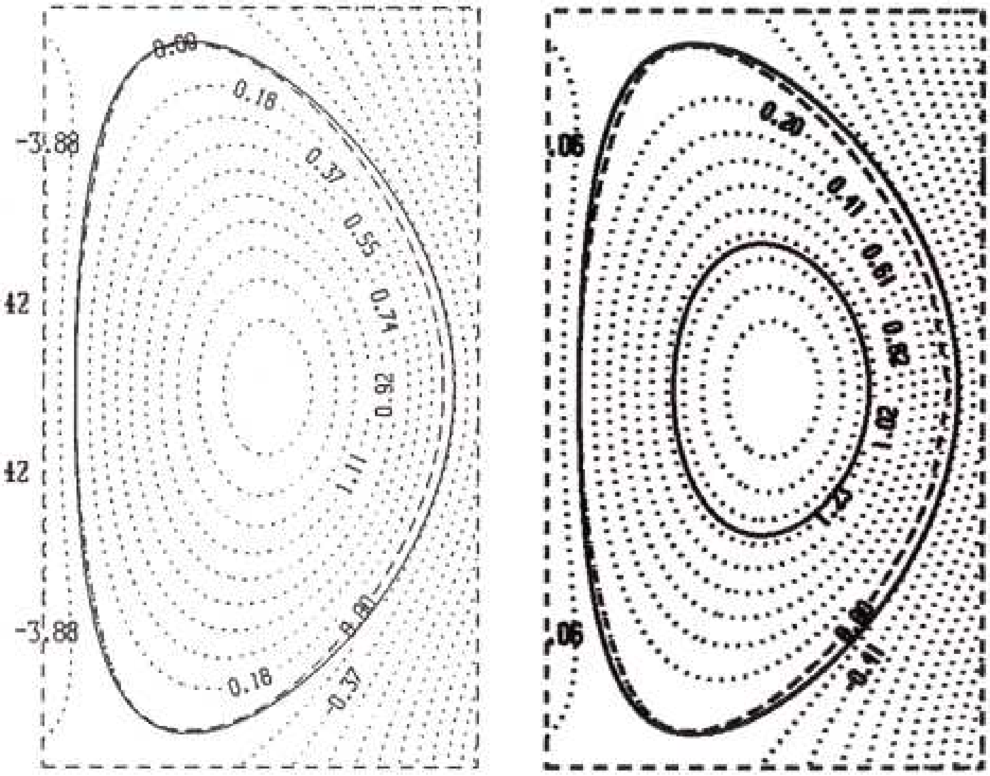
IGNITOR IpA/Ro 70% higher than other designs

FIRE IpA/Ro 2x as high as ITER

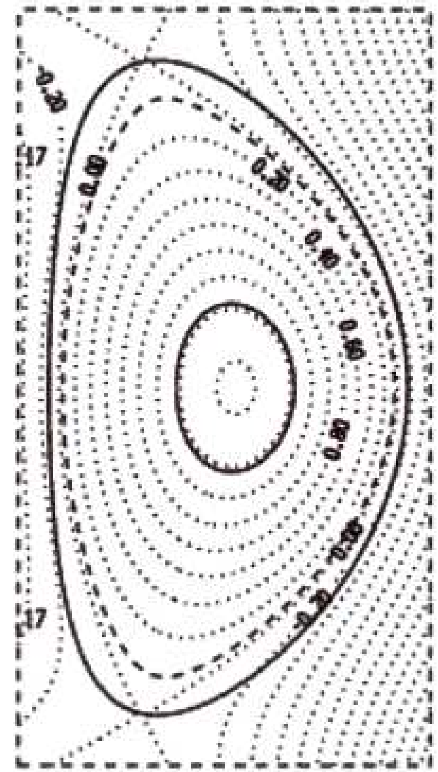


J. Schultz

Magnetic Configurations @ 13 T



11 MA, LIMITER

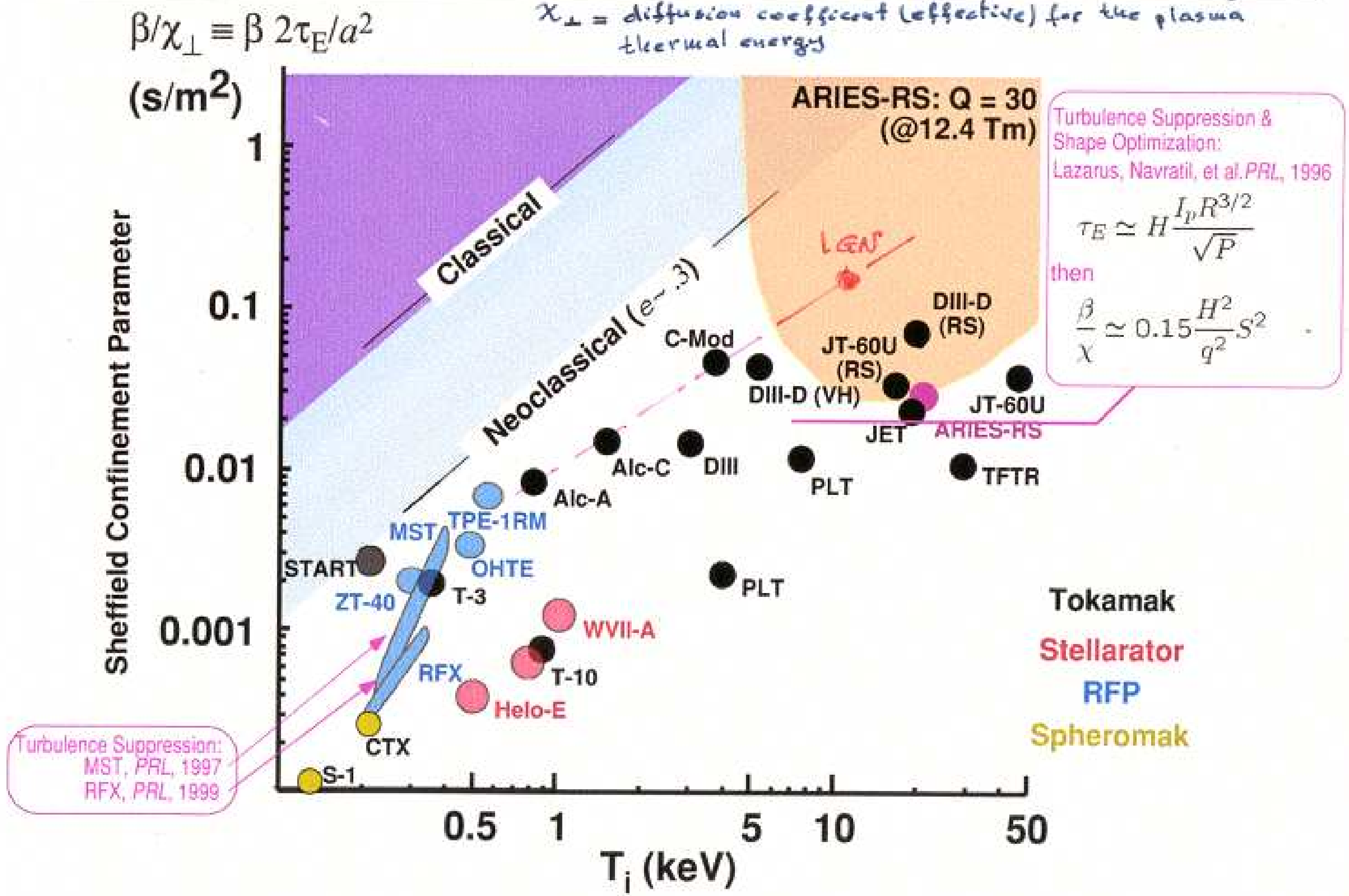


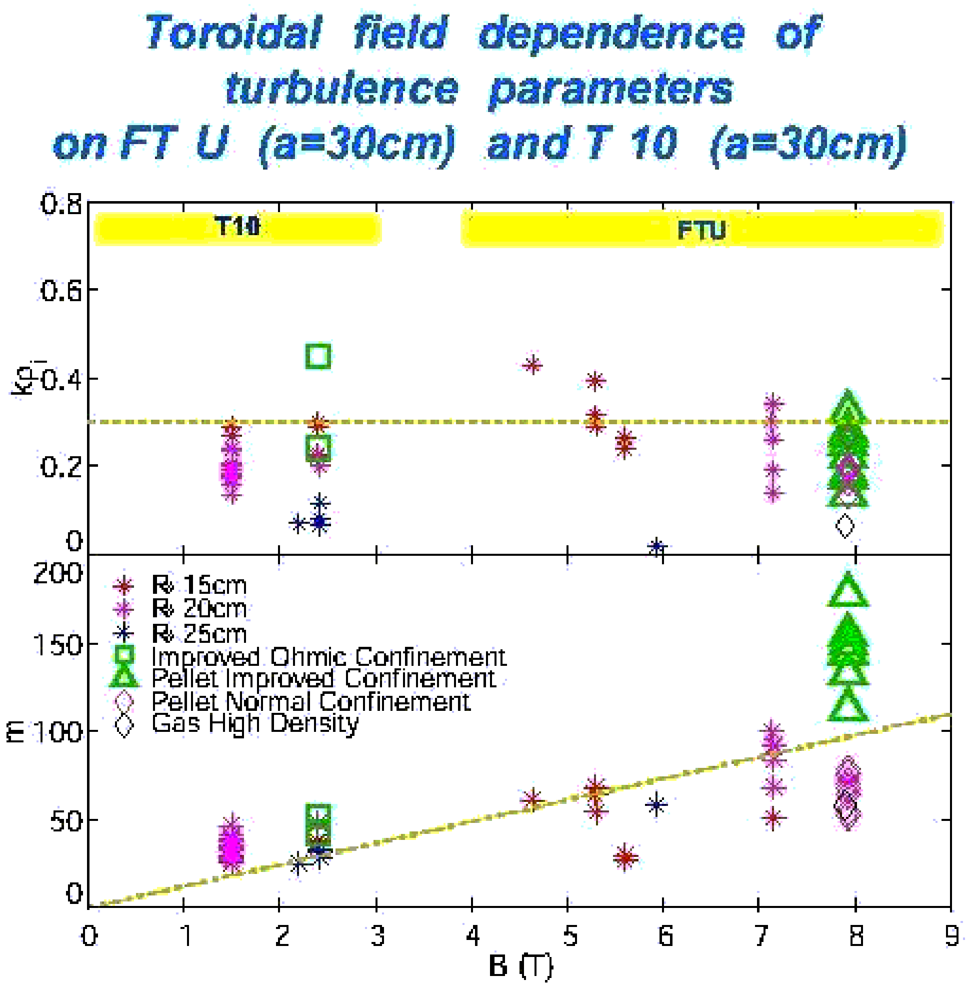
9 MA, DN

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

$\beta = 8\pi \frac{\langle n(T_e+T_i)\rangle}{B^2}$

$\chi_\perp$ = diffusion coefficient (effective) for the plasma thermal energy





Le misure dello spettro di turbolenza negli esperimenti con pellet mostrano la differenza tra confinamento migliorato (triangoli verdi) e non (triangoli viola)

I dati si riferiscono a due scariche con pellet e mostrano l'evoluzione nel tempo del numero m e del parametro k rho che permane al di sotto della soglia per i modi ITG in entrambi i casi

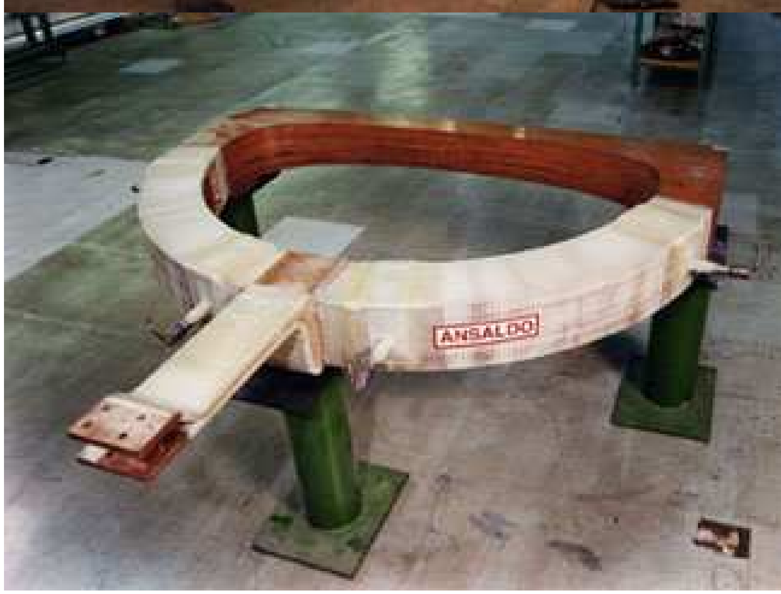
Il miglioramento del confinamento si manifesta con la presenza di celle convettive più piccole (m grandi)

I dati indicano un aumento degli m delle fluttuazioni all'aumentare di B

Ignitor : Thermo-Mechanical analysis of the ICRH antenna system

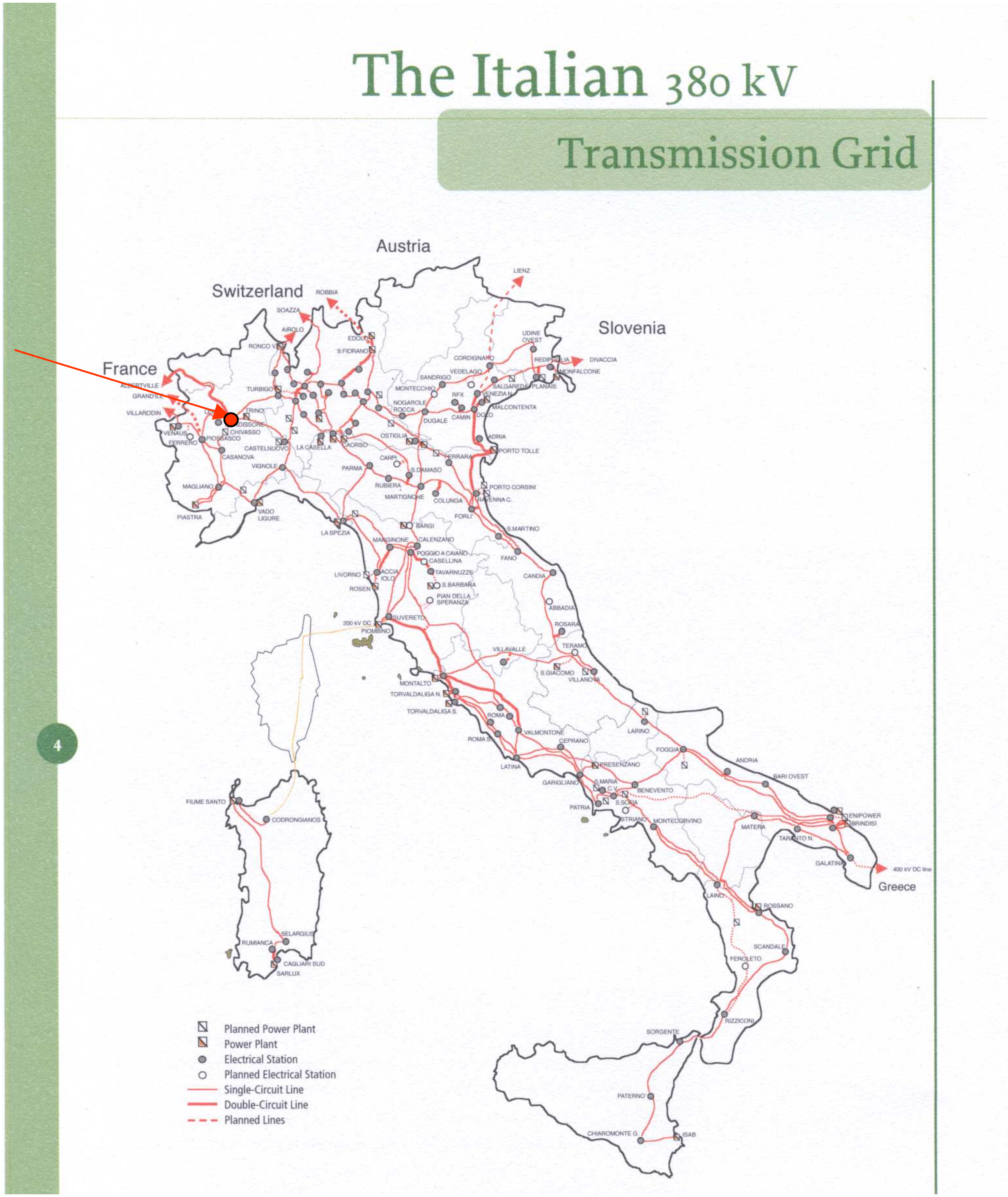
The Ignitor *R&D* program has included the construction of full size prototypes of key machine components

(Illustrations of other components can be supplied, if requested)



Selected site for Ignitor

Rondissone



C.E.S.I

ENEL Center of Rondissone (courtesy of ENEL)

C.4.3 US participation in an Italian IGNITOR

US participation in an Italian IGNITOR would be much like the traditional US collaboration on international facilities such as JET, JT6-0U, etc. The US 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 US researchers would be the primary objective of US participation in IGNITOR. US and IGNITOR organizational structures and processes must enable opportunities for the US 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 US researchers to propose experiments
- (R2) US 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) US participation in fusion technology activities such as the development and testing of high-field RF systems

<u>US Contributions to IGNITOR:</u>

US 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 US contributions would be "in-kind contributions", in which the US commits to provide specific components in exchange for access to IGNITOR for associated research. The US would be obligated to provide the product irrespective of the actual cost to the US. To assure completion of scope within the budget, the US must include sufficient contingency in the budget estimates for "in-kind contributions."

Endorsement of the Ignitor Consortium Corporation by the Regional Government of Piedmont

REGIONE
PIEMONTE

Il Presidente

Prot. 646 AQA

Torino, 3 LUG. 2002

Spett.le
IGNITOR s.c.r.l.
Via Bruno Buozzi n.28
10024 MONCALIERI

Egregio ing.Boggio Sella,

ho appreso, dalla documentazione che avete inviato, della creazione della società consortile IGNITOR s.c.r.l. , che, come da Statuto, è senza finalità di lucro ed è destinata alla realizzazione dell'esperimento Ignitor nella stazione ENEL di Rondissone (ferme restando le procedure autorizzative).

Come a suo tempo discusso nell'incontro con lo scrivente, la formula della società consortile risulta essere la più adatta a realizzare questo importante progetto. La Vs. iniziativa, supportata con generosità da capitali privati, è pertanto molto apprezzata.

Come è noto, a dicembre 2001, ho inviato ai Ministeri competenti ed al Presidente del Consiglio una lettera per esprimere il grande interesse che questa Regione ha per l'insediamento di IGNITOR in Piemonte.

Con la presente, oltre all'apprezzamento della Giunta, ritengo opportuno confermare che:

- la Regione Piemonte intende procedere alla approvazione della disegno di legge 115, non appena si riceva risposta di approvazione da Roma,
- è particolarmente apprezzato l'obbiettivo di creare un Centro Studi per la scienza dei Plasmi presso il Politecnico di Torino,
- siamo certo d'accordo a promuovere sia la partecipazione di Enti ed Istituzioni finanziarie regionali a IGNITOR s.c.r.l., sia di appoggiare l'erogazione di prestiti a fronte di programmi di ricerca scientifica realizzati nella ns. Regione,
- la disponibilità ad esaminare adeguate azioni di sollecito nei confronti dei Ministeri competenti e degli Enti interessati.

Distinti saluti.

on. Enzo Ghigo

Piazza Castello, 165
10122 Torino
Tel. 011.432111

Excerpts from

FROM YEARNING TO BURNING

Possible broad-brush guidelines for "burning plasma" thinking

By M.Rosenbluth (December 6th, 2000)

… we ultimately judge ourselves and are judged by others in terms of progress towards the fusion goal, both in understanding and in performance.

… the point at which science and the fusion energy goal converge is in a burning plasma experiment. It is there that we confront the unresolved issues of transport scaling, self-heating, burn control, and alpha physics, and also demonstrate that fusion energy is more than a fantasy.

The Fermi paradigm that a good scientific experiment is one with a 50% chance of success may apply here, although for such a major venture the bar should no doubt be somewhat higher, at least for meaningful partial success.

In view of past history and present …. it seems prudent to look for the least costly experiment which has a high probability of success, both in answering the most critical science issues and in serving to convince the world that fusion is a scientific possibility.

There seems to be general agreement that a Q of 10 for a few energy confinement times is needed to qualify as a convincing burning plasma experiment.

Ignitor approach

Flexibility to explore different confinement scenarios, and adequate power (including Ohmic) for extensive experiments with H or D are highly desirable. At this time it would appear that only the Tokamak is mature enough to qualify for a burning Next Step,…

There is evidently a huge cost saving in going to an inertial Cu high field machine with limited pulse length. …. such limited evidence as exists suggests that once a discharge has been established, its disruptivity in late flat top stages decreases radically so that very long pulse physics issues may be secondary. … Confinement steady state, alpha slowdown, limited information on He buildup and diffusion, and some understanding of current evolution are issues determining pulse length desirability.

Ignitor approach

How does transport scale with size (rho*) as we approach reactor scale? We can expect much progress in theory and simulation over the next years but the problem is so complex that a benchmark at relevant size is surely required.

What effect will a high alpha population and self- heating have?… We are very short on experiments and nonlinear theory is still rudimentary. Here is the core of “burning plasma physics”.

A decision on whether a divertor is necessary could have a big impact on cost. This seems indicated by cost comparisons between Ignitor and Fire designs. A higher current (and thus plausibly better confinement) can be obtained if the chamber is fully utilized, and difficult disruption engineering problems with shaping coils are avoided with limiter discharges.

We need to study in the next few years other enhanced confinement modes such as those observed with peaked profiles in high field machines. This suggests CMod experiments to supplement those underway on FTU in support of Ignitor. In accordance with the minimal cost-limited objectives philosophy I am suggesting, the non-diverted option with its modified boundary physics must be seriously considered. It may be a large cost reducer.

With the philosophy of minimal cost and risk in pursuit of the 2 key objectives, low beta appears to be a plus…. On the other hand any precise current profile control will be very doubtful although perhaps not needed at low beta.

….a strong case can only be made with regard to the toroidal , strong external field concepts, but these seem now the most promising ones.

Let’s move expeditiously from Yearning to Learning!

We should have a flame before worrying about the boiler (J. Dawson)