IGNITOR

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Energy Development Fusion Summer Study

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Introduction

- **The Ignitor Project: description and status**
- **Fusion issues**
- **Technical issues**
- **International Collaboration**

Perspectives

- Demonstration of fusion ignition is a major scientific and technical goal for the controlled fusion program.
- The design for a fusion reactor is unknown at this stage.

  A major driver for a reactor design will be the method for extracting the fusion energy to generate electricity — need better schemes.
- Two major components of a magnetically confined plasma reactor can be addressed in a near term ignition experiment:

  The ignition process will be similar for any magnetically confined, predominantly thermal plasma.

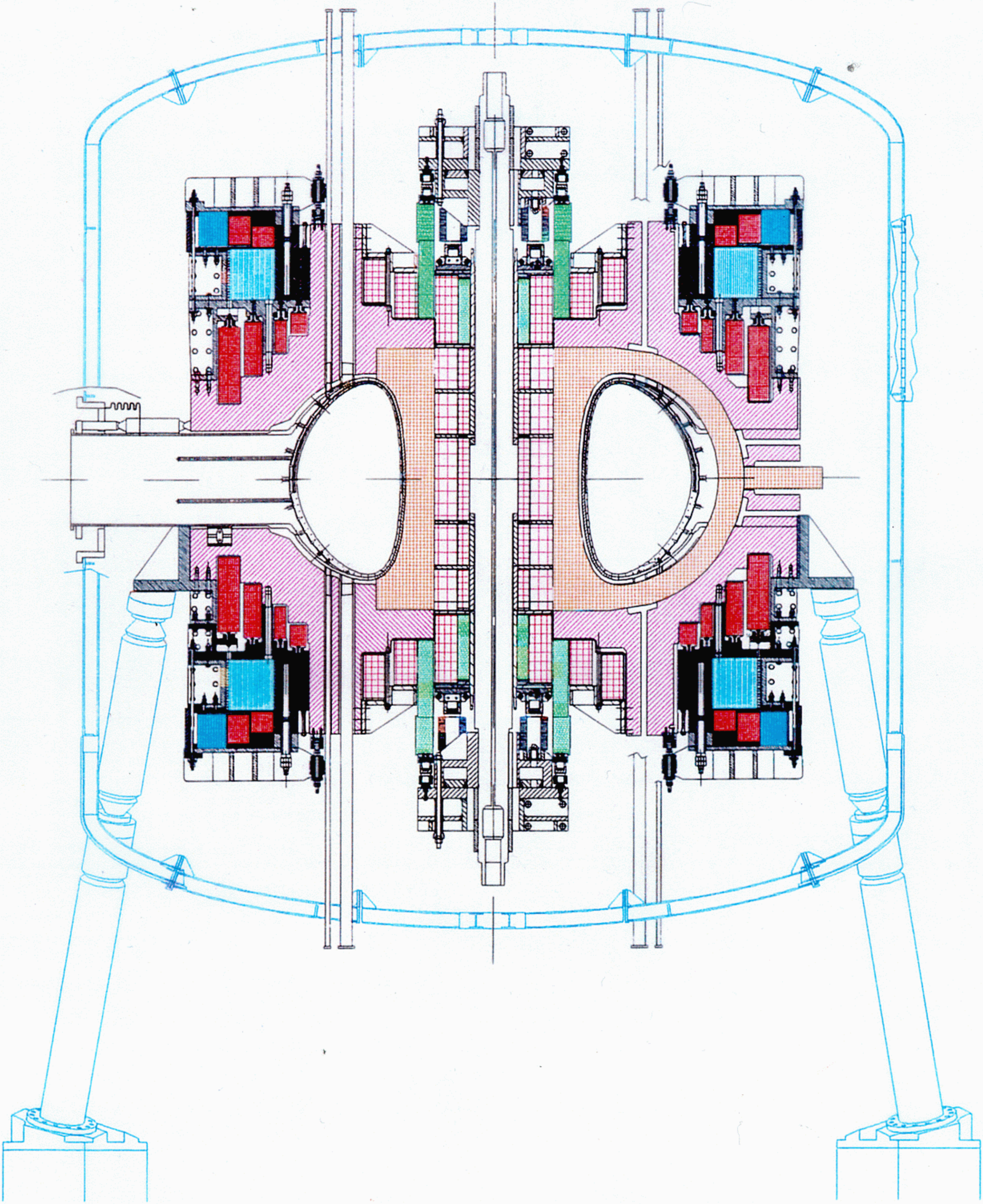
  A reactor would most likely be operated at driven, subignited power levels for safe, rapid control. It is unlikely that the economically desirable burning point would naturally fall on the boundaries of plasma energy confinement,

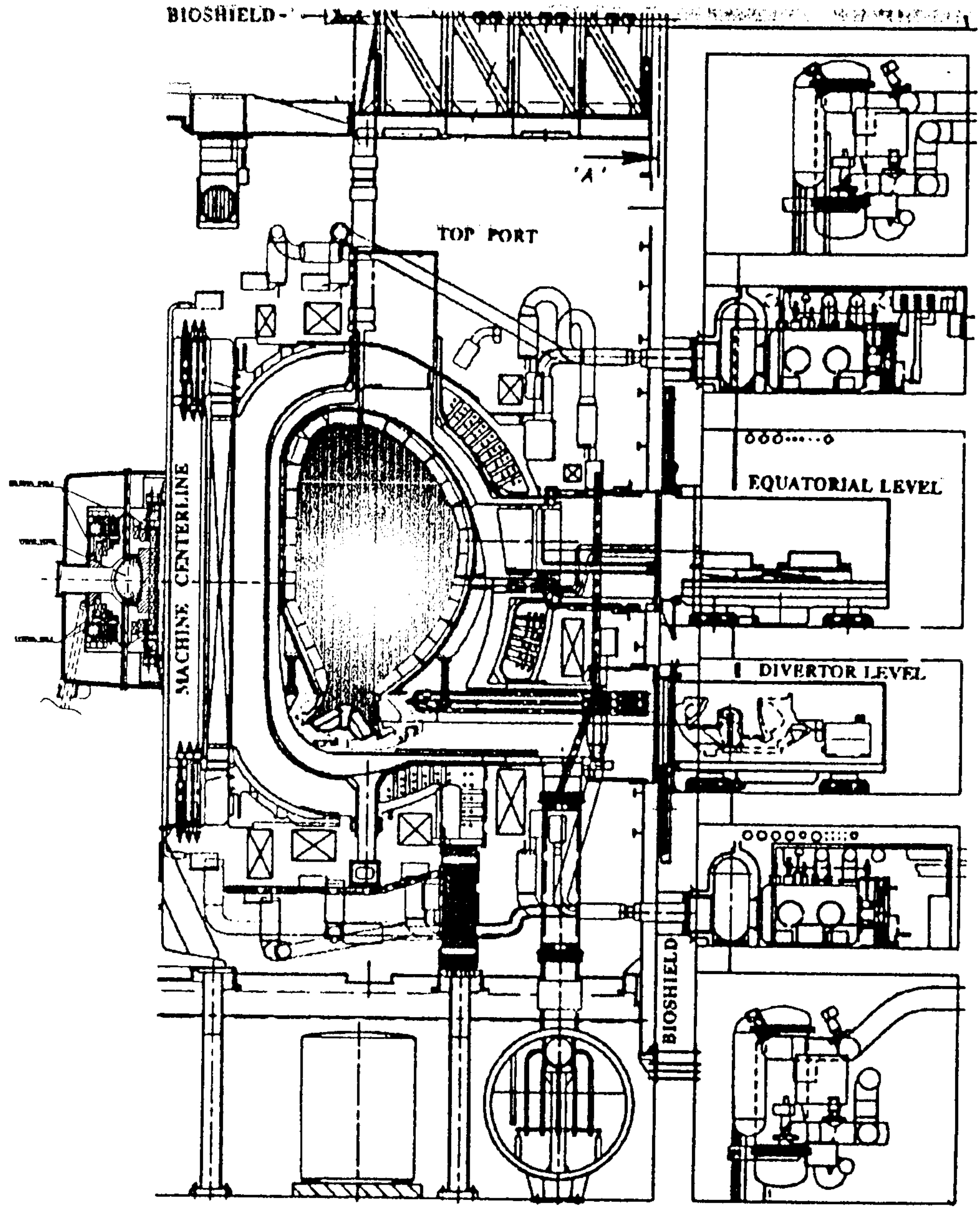
etc. in such a way that the burning is self-controlled to the desired level. (Required for advanced fuels such as D-^{3}He, D-D)

The Ignitor Project

Ignitor is a high magnetic field, tight aspect ratio tokamak. It has been designed to use presently available technologies and understanding of physics to demonstrate and investigate fusion burning plasma condition in a relatively inexpensive, near term experiment.

- **Attain burning plasma conditions in high density ($n_o \approx 10^{21}\mathrm{m}^{-3}$), low temperature ($T_o \sim 12$–15 keV) conditions.**
- **Investigate the transport and stability of ignited plasmas.**
- **Investigate the use of auxiliary heating in reaching burning conditions.**
- **Methods for control and fuelling of burning plasmas**
- **Test diagnostics for burning plasmas.**
- **Evaluate D-^{3}He and other advanced-fuel fusion reactions.**





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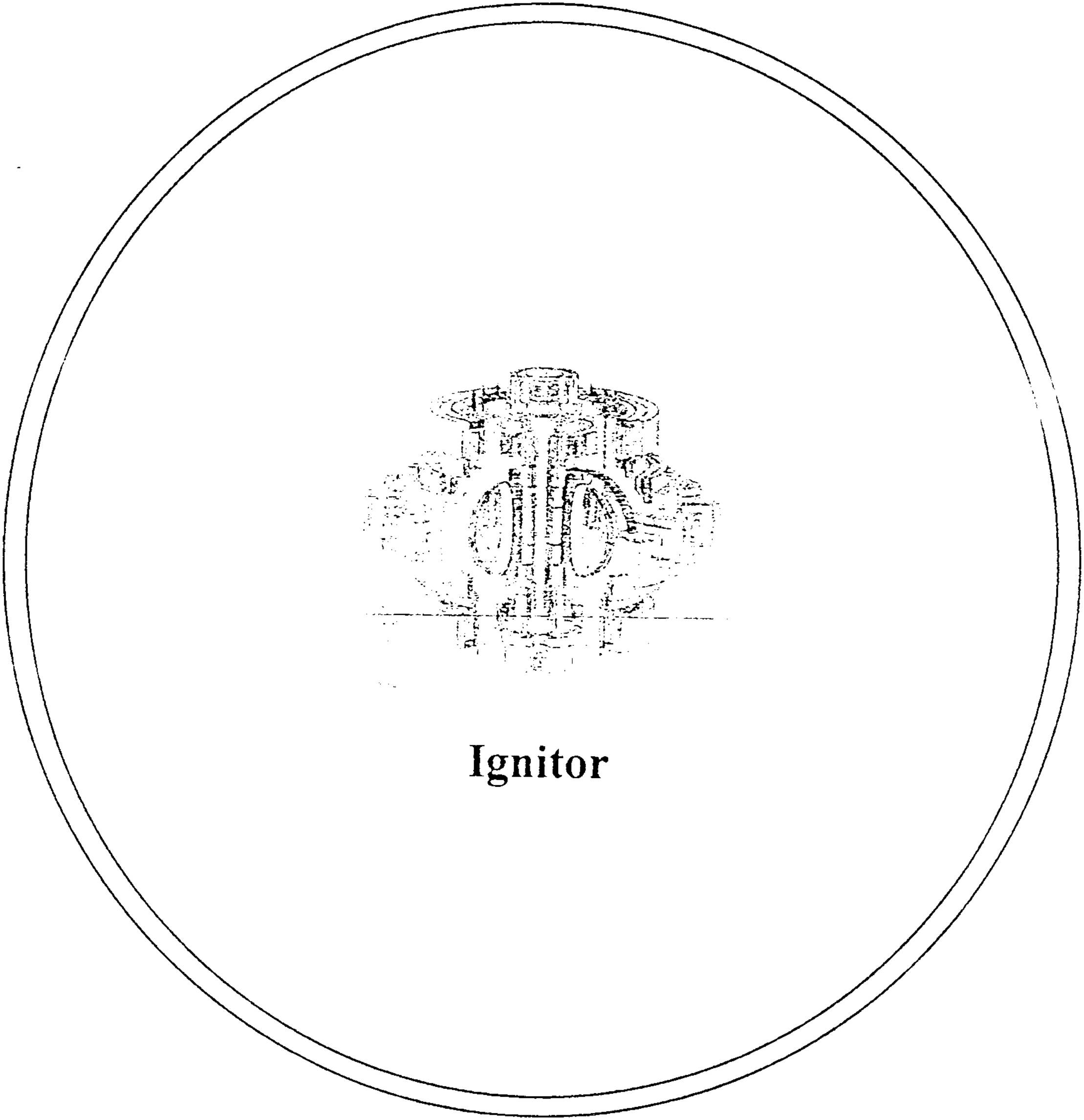
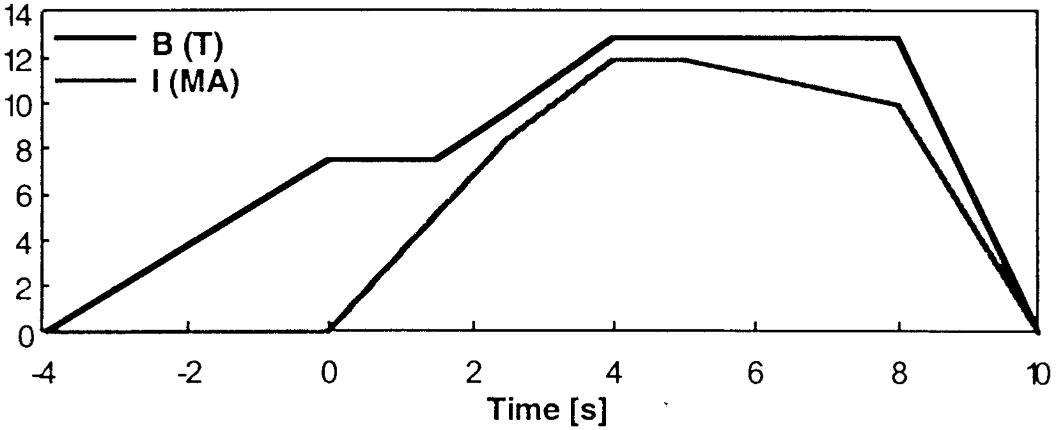
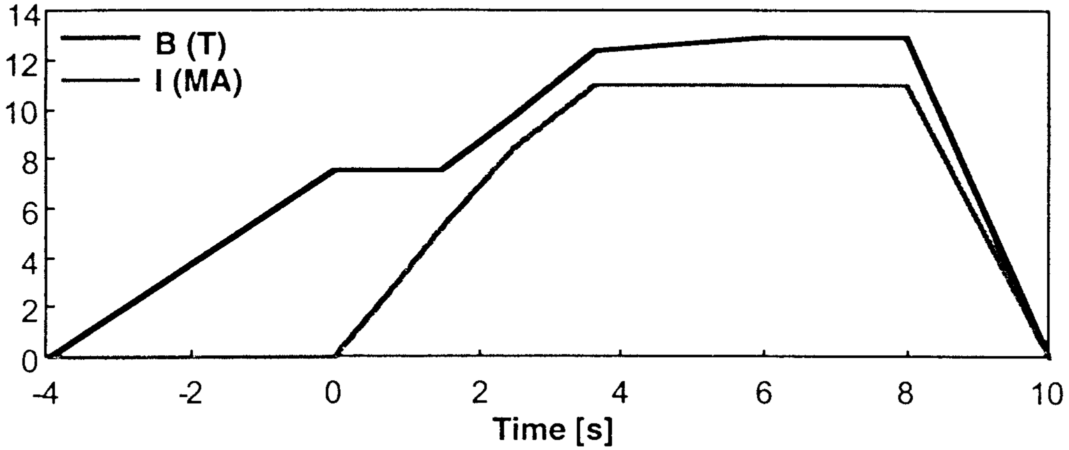
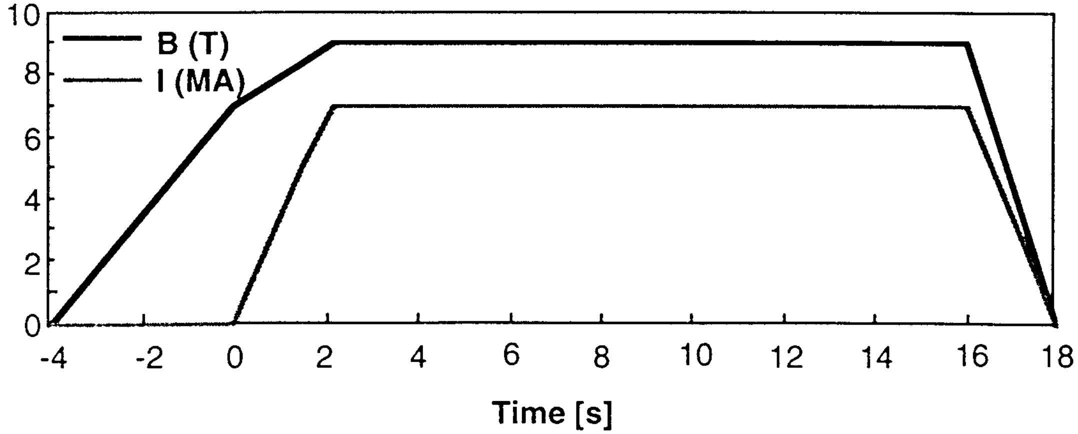


NIF

Possible pulse scenarios


13 T - 12 MA Scenario

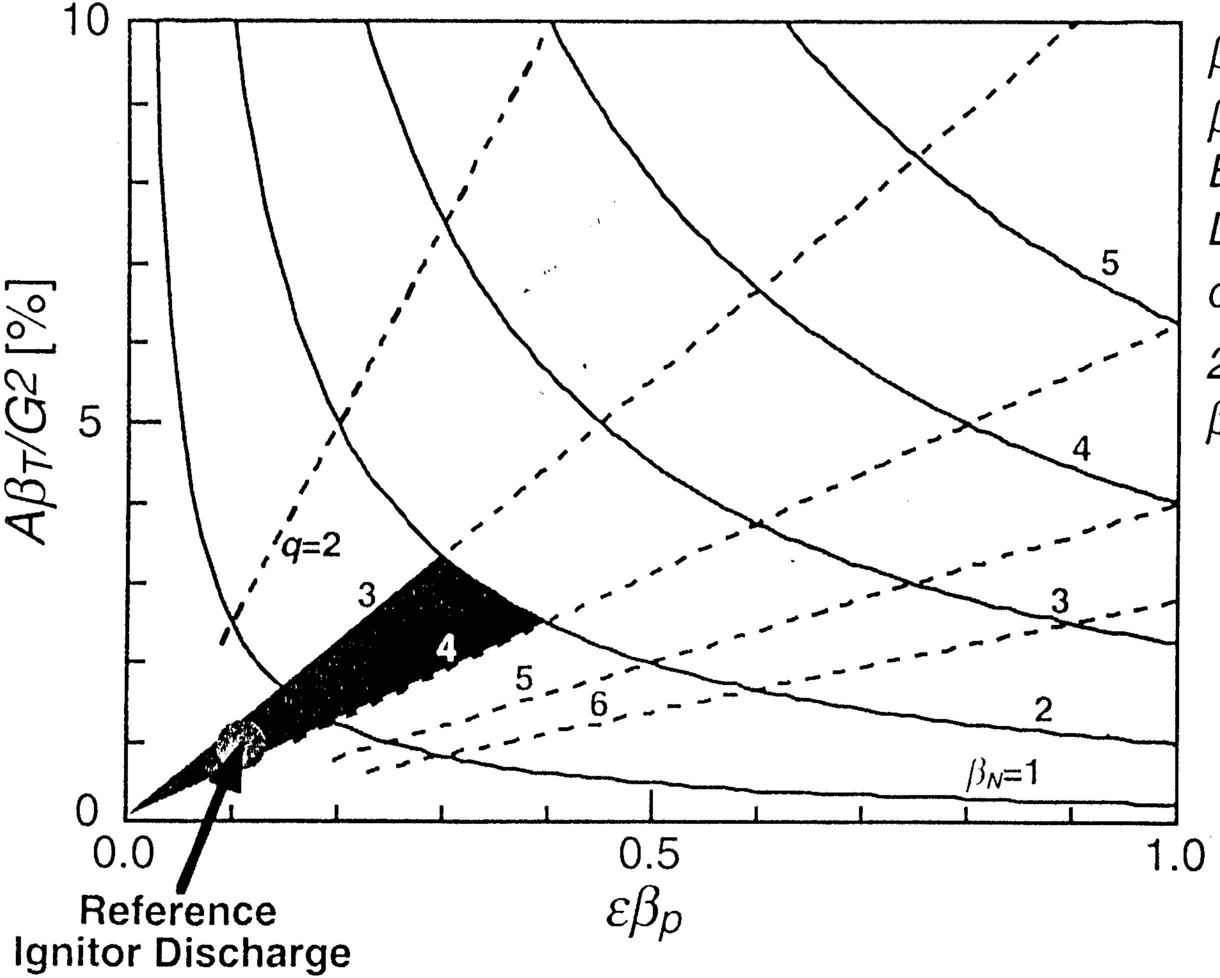

13 T - 11 MA Scenario


9 T - 7 MA Scenario

Reference Design Parameters

major radius	R_o	1.32 m
minor radius	$a \times b$	0.47×0.86 m
aspect ratio	A	2.8
elongation	κ	1.83
triangularity	δ	0.43
toroidal field	B_T	≤ 13 T
toroidal current	I_p	≤ 12 MA
mean poloidal field	$\overline{B}_p \equiv I_p/5\sqrt{ab}$	≤ 3.75 T
edge safety factor	q_ψ	3.6
magnetic flux swing	$\Delta\phi$	36 Vs
plasma volume	V_o	$\approx 10\ \mathrm{m}^3$
plasma surface	S_o	$\approx 36\ \mathrm{m}^2$
auxiliary heating	P_{RF}	18–24 MW

Operational Limits



$\beta_T = 2\mu_o\langle p\rangle/B_T{}^2$

$\beta_p = 2\mu_o\langle p\rangle/B_p{}^2$

$B_p = \mu_o I/L_p$

$L_p = 2\pi a G$

$q_\psi = L_p B_T/2\pi R B_p$

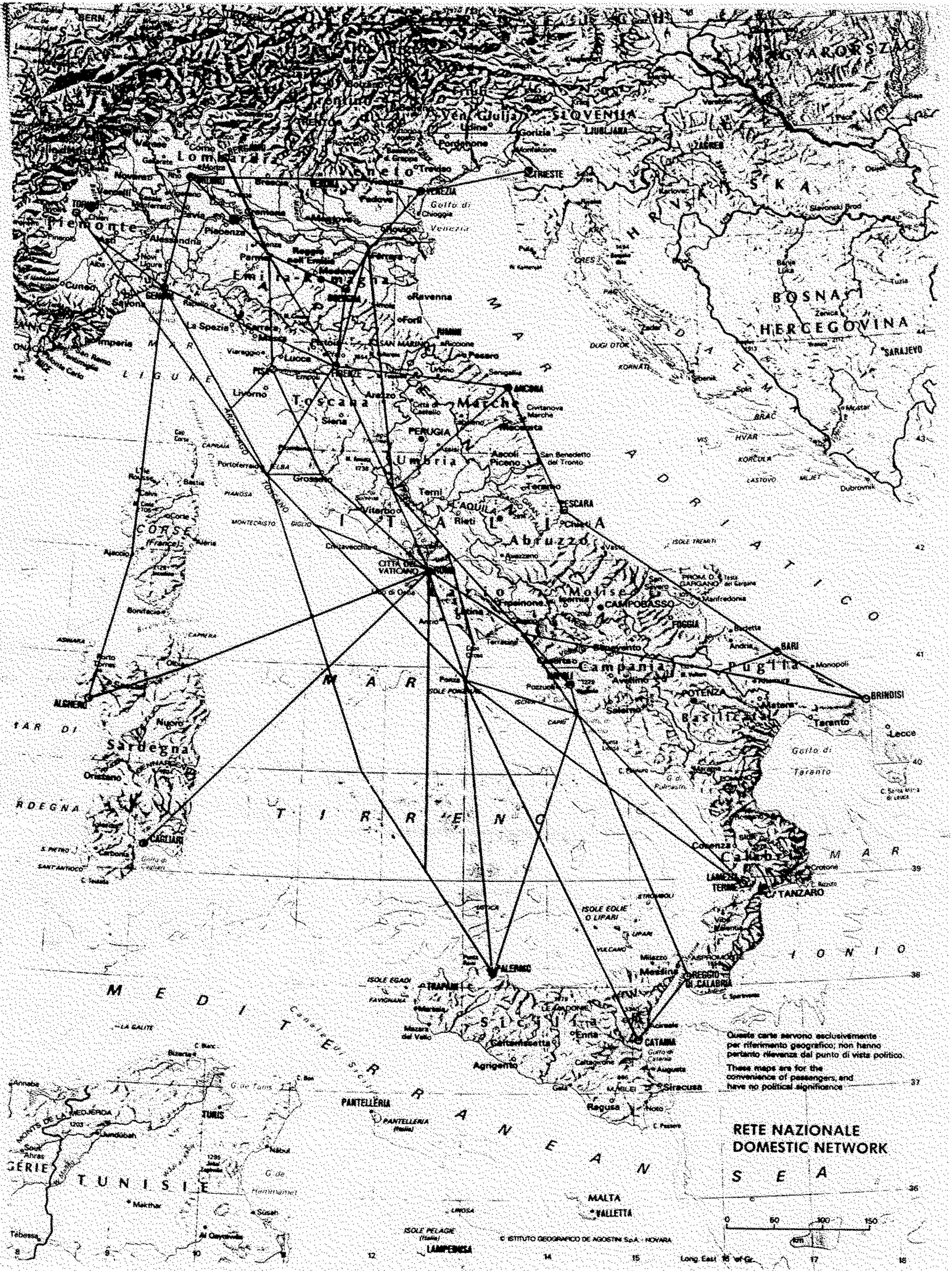
$2G^2 = (1+\kappa^2) f(\kappa,\delta..)$

$\beta_T = 1\mathrm{x}10^{-8}\beta_N I/aB_T$

from: E. Mazzucato '99

Ignitor design: summary

- Parameters
- Configuration: 12 toroidal sectors (2 TF coils, 4 C-clamps per sector)
- Toroidal field magnets: 24 TF coils (TF ripple $\leq 1.5\%$)
  (Normal conducting magnets, copper, Bitter-type plates)
- Access: 12 horizontal ports, 80 x 17 cm^2
  4 small vertical ports per sector
- Limiter, no divertor
  inner wall
  pumped outer limiter
  single lower X-point
  double X-point
- First wall material: Molybdenum
- Support Structure (see picture)
- Initial cooling to 30 K (liquid N to 77 K, then gaseous He)



RETE NAZIONALE
DOMESTIC NETWORK

Queste carte servono esclusivamente per riferimento geografico; non hanno pertanto rilevanza dal punto di vista politico.

These maps are for the convenience of passengers, and have no political significance

Conclusions

- **High field, compact experiments are the only ones that, in terms of known ignition physics, will allow investigation of meaningful fusion burning regimes. This approach lends itself to interesting developments, including advanced fuel fusion, e.g., D-^{3}He.**

- **Ignitor can study all the fundamental physics issues for plasma ignition and fusion burning, which affect all burning experiments and foreseeable reactor designs (magnetically confined). These issues cannot be studied in a non-burning experiment.**

  It will afford a short-time-scale testbed for heating methods (RF) and diagnostics for future experiments.

- **It must handle the basic same problems of nuclear radioactivity as a typical experimental reactor (licensing, tritium containment and inventory, cool down, etc.).**

- **Debates on "reactor-relevance" are not justified until more is known about the actual behavior of burning plasmas.**

- **Reference pulses at 13 T**

  4 sec I_p-ramp to 12 MA for 1/2 sec, slow ramp-down

  4 sec ramp to 11 MA for ~ 4 sec

- **Planned duty cycles:**

  ~ 3000 Full power D-T shots

Technical and Physics Issues Addressed

- Demonstration of controlled fusion ignition / high levels of fusion burning
- Demonstration/confirmation/(discovery?) of fusion physics understanding necessary for future experiments/reactors
  α-particle behavior: Confinement, slowing down
  Instabilities due to fast fusion charged particles
  Ash removal via instabilities, . . .

- Tests of plasma confinement and behavior in the presence of dominant fusion heating and high levels of heating beyond that reached by present experiments
  Energy confinement
  Particle density confinement and edge physics
  Tritium retention in machine and control of D:T concentration

- Auxiliary (RF) heating
  Pellet injection at high density

"Killer" pellets to suppress heating and control disruptions
Gas puffing
Use of current ramp phase for heating and stability control
Real-time prediction and control of ignition and burning (transport simulation, transport models)
Demonstration of sub-ignited, controlled burning

- Basic diagnostics for fusion burning plasma
  Testbed for innovative diagnostics
- Remote handling and maintenance of machine
- Further development of high field tokamak concept
- More realistic tests of advanced fuels such as D-^{3}He than in present machines

International Collaboration

- Ignitor was developed from the outset on the assumption that international collaboration and U.S. participation would play an important role.

    Diagnostics
    ICRF heating system
    (Other RF heating systems)
    Pellet injector
    First wall design
    Pumped limiter
    Remote handling

- Recent meetings:

    2nd International Workshop on the Ignitor, May 5-7, 1999, Washington DC

    1st International Workshop on the Ignitor, Nov 1998, MIT, Cambridge MA

    APS-DPP November meetings, 1994–1999
      Ignitor subsession with participation from the Italian Ignitor Project

    IAEA Conference on Fusion Energy (Plasma Physics and Controlled Nuclear Fusion Research) — report from the Ignitor Project

The Ignitor Project

- Principal Investigator: Bruno Coppi, M.I.T.
- Funding (appropriated):

  150 B It. lira through FY1999 → $80 M U.S.

  10 B It. lira for FY2000 (so far)
- Participation:

  ENEA, Italian Ministry of Industry, Ministry of Research and Universities, CNR, Politecnico di Torino, Universita' di Pisa, others
- Site: Caorso, Italy

  Close to Turin, Milan, Venice

  Site of decommissioned fission power plant
  - Nuclear containment / operating licenses
  - Access to the electrical grid
  - Buildings exist
  - Large electrical alternator available

Reference Ignitor Discharge

	endramp	ignition	
t	3.0	4.3	time(s)
$l_i/2$	0.32	0.4	internal inductance
β_p	0.08	0.13	poloidal beta
β_T	0.8	1.26	toroidal beta (%)
n_{eo}	11.0	11.0	peak electron density ($10^{20}\mathrm{m}^{-3}$)
$n_{\alpha o}$	1.5	12.0	peak α-density ($10^{18}\mathrm{m}^{-3}$)
q_o	0.83	0.71	central safety factor
q_ψ	3.3	3.6	edge safety factor
$V_{q=1}$	1.4	5.8	volume of $q = 1$ surface (%)
I_p	12.0	12.0	plasma current (MA)
W	7.5	11.7	internal energy (MJ)
T_{eo}	4.0	11.0	peak electron temperature (keV)
τ_E	0.71	0.66	energy confinement time (s)
Z_{eff}	1.2	1.2	Z-effective
P_{OH}	13.0	9.5	ohmic power (MW)
P_α	2.0	17.8	α-power (MW)
P_B	3.2	4.1	bremsstrahlung power (MW)
P_{IC}	0.4	0.5	cyclotron and impurity power (MW)
$\Delta\phi$	29.2	31.4	magnetic flux variation (Vs)
I_{BS}	0.6	1.0	bootstrap current (MA)

Reversed Shear Scenario

	endramp	ignition	
t	2.0	3.0	time(s)
I_p	7.0	7.0	plasma current (MA)
B_T	12.0	12.0	toroidal magnetic field (T)
β_p	0.37	0.58	poloidal beta
β_T	0.89	1.33	toroidal beta (%)
n_{eo}	6.39	6.75	peak electron density ($10^{20}\mathrm{m}^{-3}$)
$n_{\alpha o}$	1.5	12.0	peak α-density ($10^{18}\mathrm{m}^{-3}$)
q_o	4.3	3.2	central safety factor
q_{min}	1.7	1.5	minimum safety factor
r_{min}	0.18	0.19	radius of minimum-q (m)
q_ψ	4.8	4.9	edge safety factor
T_{eo}	11.2	15.1	peak electron temperature (keV)
T_{io}	11.7	17.2	peak ion temperature (keV)
τ_E	1.08	0.75	energy confinement time (s)
τ_E/τ_L	2.8	2.7	ratio to ITER89-P L-mode
Z_{eff}	1.2	1.2	Z-effective
P_{OH}	2.9	2.3	ohmic power (MW)
P_α	5.5	14.6	α-power (MW)
P_{Aux}	8.0	2.0	auxiliary heating power (MW)
P_B	1.2	2.0	bremsstrahlung power (MW)
P_{IC}	1.0	1.2	cyclotron and impurity power (MW)