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ABSTRACT

A novel concept for a fusion ignition experiment, IGNITEX, originally proposed by M.N. Rosenbluth, W.F. Weldon, and H.H. Woodson along the lines of B. Coppi's ideas for a compact thermonuclear device is analyzed. A single-turn-coil tokamak supplied by homopolar generators can ohmically heat a DT plasma to ignition conditions and maintain a thermally stable ignited phase for about ten energy confinement times. The IGNITEX experiment can provide a simple and relatively inexpensive way to produce and control ignited plasmas for scientific study.

INTRODUCTION

The realization of an experiment in which a steady fusion reaction can be self-sustained has a high scientific interest because it will prove the scientific feasibility of controlled thermonuclear fusion systems and it will allow the study of a new regime of plasma physics--that of ignited plasmas. From the technological point of view, a fusion ignition experiment can provide the ingredients needed for the design of future fusion systems and for the understanding of how better to produce and control fusion.

The tokamak magnetic confinement system seems to have the most immediate prospects for the production of a self-sustained deuterium-tritium (DT) fusion reaction. The required level of fusion reactivity can be obtained with plasma temperatures $T \sim 10$ keV. Thus, plasma stability limits and engineering constraints imply density levels for ignition $n \sim 10^{14} \text{ cm}^{-3}$. Furthermore, in order to maintain a self-sustained fusion reaction, a minimum level of plasma thermal insulation or plasma energy confinement has to be provided, $\tau_E \sim 1$ sec. Finally, because the relevant plasma heating mechanism at ignition is alpha heating, the magnetic confinement system has to ensure a high level of alpha particle containment during slowing down.

A plasma discharge will reach ignition conditions when the ignition factor, ρ = rate of alpha heating to the plasma/rate of plasma energy losses, is greater than unity, i.e., all the ignition requirements mentioned above will be satisfied when $\rho \geq 1$. Because

$$\rho \sim n_o \tau_E T_o f_\alpha$$

(n_o , T_o = density and temperature on plasma center, τ_E = global energy confinement time, and f_α = alpha particle containment factor), ignition can be achieved when

$$n_o \tau_E T_o \geq 5 \times 10^{15} \text{ keV s/cm}^3 \text{ and } f_\alpha \sim 1.$$

In this paper, a simple and relatively inexpensive experiment to produce and control ignited plasmas for scientific study is described.

IGNITEX CONCEPT

The fusion ignition experiment IGNITEX was proposed by M.N. Rosenbluth, W.F. Weldon, and H.H. Woodson¹ along the lines of B. Coppi's² ideas for a compact thermonuclear experiment. The scientific bases for the experiment are the theoretical predictions for the plasma behavior³ on the proposed confinement system and the series of high field tokamak experiments⁴ realized over the last decade of fusion research. The technological basis is provided by the recent advances in high current pulsed power systems engineering.⁵

The IGNITEX concept is to use a compact single-turn-coil tokamak⁶ to heat ohmically a DT plasma to ignition conditions and to sustain an ignited phase for several energy confinement times. The idea emphasizes simplicity and low cost.

The probability for ignition in a tokamak confinement device is much larger when strong currents are induced in the plasma. High plasma currents increase ohmic heating and alpha

heating, and decrease energy losses⁷. In addition, operation conditions are improved because the Troyon and the Murakami disruptive limits are relaxed. In IGNITEX, the major radius is

$R = 1.5$ m, the minor radius is $a = 0.5$ m, the magnetic field on axis is $B = 20$ T, the plasma current is $I = 12$ MA, and the plasma cross section has an elongation $\kappa = 1.6$.

In order to increase the load-carrying capability of conventional high field tokamaks (typically $B \sim 10$ T), the conductor filling ratio on the inner leg of the toroidal field (TF) system is significantly enhanced by using a single-turn coil TF magnet.⁸ Because of the very low impedance of this type of TF magnet system, a set of homopolar generators (HPGs) is proposed to provide the very high currents ($I = 150$ MA) required in the experiment.⁹ A toroidal field of 20 T allows ohmic ignition at low beta value so that approach to ignition conditions far from marginal stability is feasible. In addition, passive control of the thermal runaway associated with fusion ignition is possible.

An internal (to the TF coil) inductor is proposed for IGNITEX. The proximity of the poloidal field (PF) system to the plasma column increases coupling and then reduces power supply requirements. Furthermore, the traditional ohmic transformer is substituted by a structural compression bar. High ignition margin is possible with the current and field intensities in the IGNITEX device (Figure 1). The TF magnet system will be made of Al_2O_3 dispersion strengthened copper (see Table 1 for properties of the Glid Cop Al-15 material) plates and the PF magnet system will use toroidal single-turn coils made of the same material. The entire magnet system will be pre-cooled to liquid nitrogen temperature (77°K).

Figure 1. IGNITEX magnet system conceptual layout.

Table 1. Physical properties of Al_2O_3 dispersion-strengthened copper.

Property	Value	Units	% IACS
Density	8,810	kg/m ³	--
Thermal expansion	1.09×10^{-5}	in/in.*F	--
Resistivity at 20°C	3.2	$\mu\Omega \cdot \text{cm}$	54
Resistivity at -196°C	0.7	$\mu\Omega \cdot \text{cm}$	246
Thermal conductivity	365	W/m.*K	--
Heat capacity	385	J/kg.*K	--
Yield strength	580 (84)	MPa (ksi)	--
Young's modulus	117 (17)	GPa (Msi)	--
Poisson ratio	2.28 (0.33)	MPa (psi)	--
Fatigue limit	207 (30)	MPa (ksi)	--

The IGNITEX experiment will be fueled with a DT mixture and it will produce significant levels of fusion power. The activated device will be located inside a close shielding house with generators and diagnostic hardware besides the concrete shielding (Figure 2). Simple tritium and maintenance systems are envisioned for the experiment.

Figure 2. IGNITEX magnet, power supply, and shielding systems conceptual layout.

PRODUCTION AND CONTROL OF IGNITED PLASMAS

In a fusion ignition system, the thermal energy production is the relevant quantity determining the plasma state. In IGNITEX, ohmic heating accounts for most of the initial heating of the plasma column during current and field ramping (3 seconds). Before the ohmic heating efficiency is curtailed at high plasma temperatures, enough alpha heating is produced to proceed with the approach to ignition conditions (Figure 3). A measure for the quality of the path of ignition, for example in a (n,T) diagram as sketched in Figure 4, is provided by the product $B a \kappa^2$, which in

IGNITEX is high ~ 500). The width of the ignition region (Figure 4) can be evaluated by the ignition margin, $\Delta\rho$, defined as the ignition factor at marginal stability (Murakami limit, n_M). In the case of ignited plasmas constrained by density disruptions,

$$\Delta\rho \sim n_M \tau_E \text{ and then } \Delta\rho \sim I^x \text{ with } x > 2.$$

Figure 3. Electron power balance in the simulation of an IGNITEX plasma discharge.

Figure 4. Conceptual representation of the locus of the roots of the plasma power balance equation.

The steep temperature dependence of the fusion cross-section makes the minimum ignition temperature rather high (~ 4 keV) and induces a plasma thermal runaway once ignition conditions are reached. If uncontrolled, this thermal excursion will push the plasma towards the MHD Troyon beta limit in a fast time scale (~ 1 sec.) and the plasma will disrupt. In the IGNITEX device, the plasmas that can be produced are thermally stable and then the ignited phase can proceed to the end of the flat top of the discharge (8 seconds) far from marginal stability (see Figure 5 and 6). Cyclotron radiation emission is the basic mechanism for thermal runaway control.

The existence of plasma equilibrium solutions in elongated, high-current discharges with a limited number of PF coils is facilitated using an internal PF system. Equilibrium solutions throughout the IGNITEX discharge

Figure 5. Ion and electron temperature evolution throughout and IGNITEX plasma discharge.

Figure 6. Evolution of the volume-averaged toroidal and poloidal beta values throughout an IGNITEX plasma discharge.

(including null field region at breakdown) subject to engineering constraints, are easily found. Furthermore, 2-X point equilibrium configurations are readily obtained with minor variations in the pulse shape of the elongation coils. Good stability characteristics are possible by operating at low beta values with moderate elongation and close conducting shell.

The IGNITEX experiment will be operated in the L-mode. H-mode discharges with 2-X point equilibrium driven by alpha heating should be possible. High-density operation and low Z coating of the first wall system are expected to maintain low impurity levels in the ignited plasmas. High values of the mean ionic charges can prevent ignition because of fuel dilution (which lowers plasma reactivity) and increased radiation losses (mainly bremsstrahlung). Plasma-wall interaction effects are discussed in a paper by Ordonez et al. in these proceedings.

In the IGNITEX experiment, alpha particle containment should be rather high because the small alpha gyro-radius ($\rho/a \sim 3\%$) and high plasma current. A quantity that measures the degree of alpha containment is the alpha containment factor = plasma current/minimum

current for alpha containment according to neoclassical orbit theory. In IGNITEX, the alpha containment factor is 3.2. A brief description of the IGNITEX plasma at the time of ignition (~4 seconds) is given in Table 2.

Table 2. IGNITEX experiment description at the time of ignition.

Minor radius	47 cm
Major radius	150 cm
Plasma elongation	1.6
Toroidal field on axis	20.2 T
Safety factor at the plasma edge	2.72
Plasma current	12 MA
Average plasma density	$3.6 \times 10^{14} \text{ cm}^{-3}$
Average plasma temperature	6.5 keV
Average toroidal beta	0.6%
Average energy confinement time	0.54 sec
Confinement product	$3.9 \times 10^{14} \text{ sec-cm}^{-3}$
Ignition margin	3.4
Fusion power	149 Mw
Neutron wall load	3 Mw/m^2
Neutron production rate	$5.3 \times 10^{19} \text{ n/sec}$
Alpha containment factor	3.2
$T_0 n_0 \tau_E$ product	$4.7 \times 10^{15} \text{ keV/cm}^3/\text{sec}$

SINGLE-TURN-COIL MAGNET SYSTEM

The design solution for the IGNITEX TF magnet system maximizes simplicity and load-carrying capability.⁸ A single-turn coil made of dispersion-strengthened copper plates is proposed. In the case of the PF magnet system, emphasis on plasma coupling and assembly considerations suggest the use of five pairs of toroidal single-turn coils located inside of the TF coil, each coil made of dispersion-strengthened copper in two pieces with compressed bolted joints. Table 3 gives a summary of the magnet system description in IGNITEX. Stress and temperature values after the current pulse have been obtained by detailed finite element analysis of the nonlinear thermomechanical and electromagnetic problem.⁸

A single-turn coil structure is well suited to stand the large loads imposed by the IGNITEX experiment. However, maximum field generation is accomplished by employing active axial preloading (following A. Sestero's ideas for stress isotropization)¹⁰ through a 65,000 ton hydraulic press with four steel posts (Figure 7).

Manufacture of the single-turn TF coil assembly will be accomplished by systematically stacking dispersion-strengthened copper plates of appropriate cross-section (nuclear stack). A way to assemble the magnet system is as follows: one-half of the vacuum vessel and first wall assembly will serve as a mandrel for mounting the 10 semi-circular arcs of the PF coils as

shown in Figure 8. This structure will then be inserted into 6 of the single-turn TF coil sectors, and the PF coil terminals will be bolted in place. The opposite half of the magnet system can be assembled in a similar way.

Table 3. IGNITEX magnet system description.

TOROIDAL FIELD COIL		
A. <u>Dimensions</u>		
Core radius		$c = 0.4 \text{ m}$
Inner-leg width		$d_i = 0.6 \text{ m}$
Bore radius		$a = 0.5 \text{ m}$
Height		$h = 3.1 \text{ m}$
Major radius		$R = 1.5 \text{ m}$
Mass		$M = 400 \text{ tons}$
B. <u>Electromagnetics</u>		
Magnetic field on axis		$B_t = 20 \text{ T}$
Maximum magnetic field		$B_m = 30 \text{ T}$
Peak current		$I_m = 150 \text{ MA}$
Average current density (inner leg)		$J_m = 5.7 \text{ kA/cm}^2$
Magnetic energy stored		$E_m = 3.7 \text{ GJ}$
Resistive losses per pulse		$E_R = 5.8 \text{ GJ}$
Coil inductance		$L_T = 0.3 \text{ }\mu\text{H}$
Coil resistance		$R_T = 0.03 \text{ }\mu\Omega$
Time for field ramping		$t = 3 \text{ sec}$
C. <u>Mechanical</u>		
Material	Al_2O_3 dispersion copper (96% cold work)	
Compression bar	Alloy steel	
Maximum von Mises stress		
Coil	78 ksi	
Bar	115 ksi	
Maximum coil temperature	$T_m = 145^\circ\text{C}$	
D. <u>Miscellaneous</u>		
Toroidal slits	192	
Sectors	12	
Width of slits	0.076 cm	

POLOIDAL FIELD COIL SYSTEM		
A. Dimensions		
Coil width (all coils)	8.5 cm	
Total mass	22,000 kg	
Total cross-section	0.26 m^2	
Number of coils	10	
B. Electromagnetics		
Poiodal field at plasma edge	$B_p(a) = 3.8 \text{ T}$	
Peak current	$I_{OH} = 22 \text{ MA}$	
Peak current density	$J_p = 9.45 \text{ kA/cm}^2$	
Magnetic flux	$\Phi = 27.6 \text{ volt-sec}$	
Plasma current	$I_p > 12 \text{ MA}$	
Plasma self-inductance	$L_p = 1.9 \text{ }\mu\text{H}$	
Mutual inductance	$M_{POH} = 0.6 \text{ }\mu\text{H}$	
Magnetic energy stored	$E_m = 0.3 \text{ GJ}$	
Resistive losses	$E_R = 1.32 \text{ GJ}$	
Coils inductance	$L = 1.24 \text{ }\mu\text{H}$	
Coils resistance	$R = 0.27 \text{ }\mu\Omega$	
C. Mechanical		
Material	Al_2O_3 dispersion copper (96% cold work)	
Maximum von Mises stress (unsupported)	69.8 ksi	
Maximum temperature	$T_{max} = 87.0^\circ\text{C}$	
Radial distance to TF coil	2 cm	

An ignition technology demonstration (ITD) has been proposed⁸ and it is analyzed in a paper by M. Driga et al. in these proceedings. The idea is to build and operate a scale prototype to the TF magnet system in IGNITEX. The primary objective of the ITD is to simulate IGNITEX operation from the electromechanical point of view so that the risk of proceeding with the larger IGNITEX experiment is substantially reduced. The prototype should produce 20. T in a toroidal single-turn-coil arrangement fed by HPGs working in parallel in a similar fashion to the IGNITEX experiment.

Figure 7. IGNITEX device conceptual layout.

Although, in principle, alpha particle containment should be high in IGNITEX, nonaxisymmetric poloidal field perturbations could decrease the quality of alpha containment. A potential source of such asymmetries is the unbalanced discharge of the HPGs around the torus; therefore, the toroidal distribution of the on-axis field intensity around the toroidal single-turn-coil will be studied. The degree of current matching achieved in other relevant demonstrations indicates that this aspect of the operation should pose no problem for the operation of IGNITEX.

Figure 8. Assembly of the poloidal field coils over the vacuum vessel.

If successful, the ITD will substantially simplify the high-field magnet design as compared to conventional magnet systems. This simplification is precisely what allows the generation of magnetic fields higher than those conventionally obtained.

HOMOPOLAR POWER SUPPLIES

Homopolar generators can meet the demands imposed on the power supplies by the operation of the magnet system in a single-turn-coil tokamak as needed for the IGNITEX experiment. These are rather simple and compact, voltage driven dc generators. Voltage generation is achieved by the interaction of the flux created by a pair of coils with opposite currents on a steel rotor (see Figure 9). Current collection is carried out through two sets of sintered-copper-graphite brushes. For the TF generators, the rotor surface will be spun to 200 m/s and the brushes will carry 12.5 MA/m² at the flat top of the discharge. Previous experience with discharge current densities at the brushes more than five times as large indicate that over 500 pulses will be possible without brush replacement.

Figure 9. Conceptual homopolar generator design for the toroidal field power supply operation.

Operation of the TF power supply will proceed as indicated in Figure 10, with the rate of the current discharge being controlled by variation of the field excitation. Thermomechanical stresses and heating in the PF magnet system can be lowered by ringing of the

PF power supplies. Moreover, current swinging in the PF system allows for more flux to be generated and then for a larger plasma current. Current oscillations (see Figure 11) are induced by conversion of kinetic energy from the PF flywheels into magnetic and resistive energy in the PF coils and from magnetic energy back into kinetic energy in a PF magnet and power supply system which is designed undercritical. The proposed set of brushes for current collection is capable of working with rotor gyrating in both directions.

Figure 10. Toroidal field power supply operation.

Figure 11. Poloidal field power supply operation.

A set of 12 HPGs will work in parallel around the single-turn coil TF magnet system each one rated to 1 GJ, 12.5 MA and 30 volts (maximum). A set of 5 HPGs will work in series with the five pairs of PF coils with a total rating of 2.6 GJ, 22 MA and 60 volts. The arrangement of the generators can be seen in

Figure 2. A critical component of the generators is the flywheel for energy storage. Fiberglass-reinforced-epoxy-composite technology makes the design of the TF flywheel rather compact (3.75 m outer diameter, 2.25 m inner diameter, and 1 m length) with a stored energy of 800 MJ. The estimated hoop stress of 67 ksi is quite lower than the strength of 250 ksi for that material. These flywheels will be spun at 500 m/sec. with 64 kJ/kg which is about a factor of three below presently proven limits.

NUCLEAR TECHNOLOGY CONSIDERATIONS AND COST EVALUATION

The IGNITEX experiment at the time of ignition will produce 5.1×10^{19} neutrons of 14.1 MeV per second. Assuming uniform deposition in the vessel surface (40 m^2), the neutron wall load will be 3 Mw/m^2 (a level relevant to future fusion systems) at ignition and it will reach 8 Mw/m^2 during the thermal excursion (see Figure 12). Peak power density during the ignited phase (45 Mw/m^3) is comparable to the level of thermal fission reactors. An activation analysis of the IGNITEX device and its surroundings during operation is presented in a paper by T. Parish et al. in these proceedings.

Figure 12. Power losses to the first wall throughout an IGNITEX plasma discharge.

The low-voltage operation of IGNITEX minimizes insulation requirements, eliminating problems of degradation of insulation and increasing the strength of the coil. The device will be positioned within a shielded test cell located in a large experimental hall. Diagnostic equipment will be located in the

experimental hall with unlimited access for repair and adjustment during the initial H phase of the experimental program and limited access during the DD and DT phases. Remote maintenance and repair of in-vessel components, will be done by a robotic arm during the DT phase.

The IGNITEX magnet system design acts as a self-shield to post-pulse radiation so that out-vessel robotic maintenance can be eliminated. The IGNITEX device after DT operation can qualify for low level waste disposal. In addition, the self-shielding effect minimizes activation of cryostat-nitrogen and test cell air.

Typical yearly consumption of tritium in the DT phase will be 20-40 gr. (200-400 kCi). Tritium will be stored in uranium beds (as UT_3), and it will be released by controlled heating. A simple T scheme in which the necessary amount of T is bought from a supplier and the whole T exhaust is returned back is envisioned.

Table 4. Estimated basic construction costs of the IGNITEX experiment.

Title	Cost (\$ million)
Project	20
Single-turn TF coil	20
PF coil system	2.8
TF power supply	22.5
PF power supply	5
TF coil support structure	7.5
Facility	8
Vacuum vessel	2.5
First wall	1.5
Shielding	1.0
Diagnostics	2.0
Instrumentation and control	3.0
Cryogenics	2.5
Fueling	0.5
Vacuum pumping	3.5
Disposal	4.3
Remote maintenance	3.0
ESTIMATED COST	\$109.6 million

A cost breakdown for the basic construction of the IGNITEX experiment is given in Table 4. The unconventional fusion technologies to be used in IGNITEX are less expensive than their counterparts in conventional tokamaks. This makes the cost of the core of the device relatively low, \$50M. The simplicity of approach (no auxiliary heating system, no divertor system, no high voltages, no rectifiers, no windings, minimum tritium and robotic systems and so on) decreases cost as well. Finally, the IGNITEX experiment reduces costs by pursuing a sole objective, that of

production and control of ignited plasmas for scientific study.

CONCLUSIONS

Here, we briefly outline some of the characteristics that distinguish the IGNITEX design from conventional designs that have been proposed following Coppi's ideas of compact thermonuclear experiments. These differences are as follows:

--In IGNITEX, ignition is predicted to be possible with ohmic heating alone and without auxiliary heating. This arrangement is considered to be an advantage because recent experimental tokamak results show that energy confinement deteriorates gradually as the level of auxiliary heating is increased and also because of the additional complexity involved in auxiliary heating schemes.

--Ignition is predicted with the presently projected energy confinement scalings even in the standard L-mode of operation. Therefore, the problems associated with divertor designs and with the uncertainty of the H-mode of operation are nonexistent in the IGNITEX design.

--Ignition can be approached at low beta (and thus far from marginal stability) with the IGNITEX experiment. In addition, the plasma is closely surrounded by a conducting wall. These two characteristics anticipate rather stable plasmas; they give the IGNITEX design a high probability of performing as predicted and make ignition production and control possible.

--Ignition triggers a thermal excursion of the thermonuclear plasma. In conventional experiments that are designed at marginal stability, reaching ignition means crossing the stability limits for the plasma, and then the discharge disrupts. In the IGNITEX design, the plasma reaches the ignited state far from the stability limits, and the thermal excursion is stabilized by the plasma itself. During the full period of plasma ignition, the disruptive limits are not exceeded.

--The IGNITEX design has lower average current density in the inner leg of the toroidal field coil than conventional approaches (because of the high-filling factors). The stress in the coil is thus tolerable. Moreover, because of the central compression bar, the wedging stresses in the toroidal field magnet are lower than usual.

--The IGNITEX design includes an internal poloidal field system configuration with

single-turn-coil magnets that minimizes the power and energy requirements for plasma current induction, equilibrium, and shaping.

--The IGNITEX power supply operates at low voltage. Therefore, the magnet system has no severe insulation requirements. The problems associated with radiation damage, low strength, and nonavailability of appropriate insulators are minimized in IGNITEX. Furthermore, the IGNITEX magnet system design is substantially simplified with respect to conventional approaches as it has no windings, turn-to-turn transitions, and so forth.

--The IGNITEX design minimizes post-pulse radiation doses inside the primary shielding and nitrogen and air activation. It produces low level waste for decommissioning.

--The IGNITEX experiment should be less expensive to build than comparable conventional experiments because of its simplicity and unconventional technology.

In summary, the nonconventional IGNITEX experiment design emphasizes simplicity in order to maximize reliability and minimize costs.

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