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RESEARCH REPORT

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ABSTRACT

Favorable features of the D-^{3}He fuel cycle in a field-reversed configuration are described. Based on a theoretical analysis, one find that the estimated plant efficiency is more than 70% and the 14 MeV neutron power fraction is as small as 1%. To reach the D-^{3}He innition temperature of 100 keV with a reasonable external power source, one can first ignite a D-T configuration and then alter the fuel to D-^{3}He. Heating of the plasma is attributed to energetic fusion charged particles and no additional heating is neccessary. The equilibria of D-^{3}He ignited plasmas may be self-sustained due to the preferential trapping of fusion protons in a field-reversed configuration.

INTRODUCTION

In thermonuclear fusion based on deuterium and tritium fuels, most of the fusion energy is released as 14 MeV neutrons. The engineering requirements on the wall leading for a commercial fusion reactor are accordingly difficult to achieve. Advanced fuels have been studied so as to mitigate these engineering problems and possibly find a reasonable reactor system with higher plant efficiency.

The p-^{11}B fuel cycle seems attractive because no neutron appears with this fuel cycle. Nevertheless, the requisite temperature for this fusion is as high as 400 keV and associated radiation losses are large and ignition cannot be obtained. The D-^{3}He fusion fuel cycle yields relatively small amount of 14 MeV neutrons and a self-ignited state of the plasma is most attainable at temperature of 100 keV which is appreciably lower than other advanced fuel cycles. Favorable features of this fuel cycle combined with a field-reversed mirror can be seen in a conceptual design [SAFFIRE](1). A practical problem faced by this fuel cycle is the very low abundance of helium-3 in nature. To avoid the difficulty, the semi-catalized deuterium(2) or the DD-^{3}He(3) fuel cycles have also been intensively considered.

The recent discovery of large quantities of mineable helium-3 in the lunar soil(4) changes picture for D-^{3}He fusion. The possible use of helium-3 is rather determined only by the costs of mining and shipping. Assuming favorable economics for ^{3}He accumulation, we will try to describe some promisiong features of the D-^{3}He fuel cycle in a field reversed configuration.

COMPARATIVE STUDIES OF ADVANCED FUELS

Performance analyses can be carried out(5) on the basis of particles and energy balance equations for respective component of fuels. Nuclear reactivities are modified by taking account of two-component effects and nuclear elastic collisions. To simplify the analysis, quantities are averaged over the plasma volume and a simple formula of the synchrotron radiation:

$$2.5 \times 10^{-38} n_e^2 K_c \, \frac{1-\beta}{\beta} \, T_e^2 (1 + T_e/204)(1 + \Sigma_j n_j T_j / n_e T_e) \quad W/m^3 \, .$$

is employed(6). The quantity T denotes the temperature in keV and K_c is the fraction of the synchrotron radiation. Other quantities are the traditional ones.

The figures of merit of various fuel cycles are expressed in terms of the requisite confinement parameter, the obtainable radiation parameter, and the fraction of fusion power released as 14 MeV neutrons. These quantities have been calculated for various fusion fuel cycles: D-T, Cat.D, DD-^{3}He, D-^{3}He, p-^{6}Li, and p-^{11}B. Fig.1 shows fuel cycles: fusion produced tritium and helium-3 are refueled in the Cat.D, whereas tritium is stored in a tritium bank and trasmuted helium-3 is refueled in the DD-^{3}He fuel cycle. The above figures of merit are calculated for respective fuel cycles, the results of which are shown in fig.2. Symbiotic systems such as fission-fusion hybrid or semi-catalized deuterium fuel cycles are excluded from our consideration because these systems have too many variables to determine optimum operation conditions. p-^{6}Li, or p-^{11}B fuel cycles are also excluded because it is impossible for these fuel cycles to attain self-ignition.

The requisite confinement parameter of the D-T fuel cycle is as small as 2×10^{20} s m^{-3} at the temperature of 13 keV. Both confinement parametrers of the DD-^{3}He and D-^{3}He fuel cycles are larger by the factor 5 at the temperature 100 keV. The obtainable radiation parameters are as large as 84% and 70%, respectively in D-^{3}He and DD-^{3}He fuel cycles if the β-value is 90%. Since the plant efficency, η_p, defined by the ratio of the net electricity and the fusion power can be rewritten in terms of the efficiency of the direct energy convertor η_{dc}, that of the thermal convertor η_t, and the radiation parmeter Ψ_r as:

$$\eta_p = \eta_{dc}\Psi_r (1 - \eta_t) + \eta_t \quad ,$$

the higher radiation parameter gives rise to a power plant with a higher efficiency. By employing reasonable values of η_{dc} and η_t to be 0.75 and 0.35, respectively, one estimates plant efficiencies as high as 76% in D-^{3}He fusion and 69% in DD-^{3}He fusion, provided that the very high β-values are obtainable. The 14 MeV neutron fraction is as small as 1% in the D-^{3}He and 15% in the DD-^{3}He fuel cycle, which are to be compared to the values of 80% in the D-T and 33% in the Cat.D fuel cycles.

The estimated characteristics of 1 GW fusion power plants based on various fusion fuel cycles are tabulated in table 1: a typical plasma temperatures, required confinement parameters, estimated plant efficiencies, 14 MeV neutron power fractions, and additional engineering requirements. The capacity of the tritium bank is estimated at 300 kg in the DD-^{3}He fusion plant and 20 kg in the D-^{3}He fusion plant. The β-values of the plsmas have been assumed to be as high as 90%. A smaller β-value does not change the values of the D-T plant listed in this table. On the other hand, the synchrotron radiation losses are strongly effected in other fuel cycles where plasmas of higher temperature are needed, and consequently brings in unsatisfactory plant efficiencies.

It is clear that with high beta containment, a fusion system with a high plant efficiency and small 14 MeV neutron yields is possible with the D-^{3}He or DD-^{3}He fuel cycle. Further, it is indispensable for this fusion plant to install a set of large direct energy convertors, because a large franction of fusion power is released as the kinetic energy of charged particles. Required capacity of the direct energy convertor is as large as 1 GW for a 1 GW fusion power plant.

As far as we know, the characteristics of plasmas in a field-reversed configuration meets the above requirements: plasmas are surrounded by a natural divertor as illustrated in Fig.3 and very high beta values of stable plasmas have been obtained in experiments(7). Thus we henceforth consider a fusion reactor system based on deuterium and tritium fuels in a field-reversed configuration which is very attractive if plasmas with the requiste energy lifetimes can be produced.

TRANSITION OF PLASMA FROM D-T TO D-^{3}He IGNITION(8)

An operation temperature of a D-^{3}He or DD-^{3}He reactor is required to be as high as 100 keV. Although plasma heating to such high temperatures seems to be formidable, an effective use of energetic charged particles produced by nuclear fusion reactions may reduce this difficulty. One way of obtaining the desired conditions is to plan a transition of plasma operation from D-T to D-^{3}He self-ignited state. The transition is basically attributed to a thermal instability of the burning plasma and controlled by an applied magnetic field as well as the fueling.

Particle balance equations and the energy balance equation are supplemented by the model scaling of average beta:

$$<\beta> = 1 - X_s^2/2 \quad ,$$

where X_s is the separatrix radius of the field-reversed configulation normalized by the wall radius. A feedback control with magnetic compression-decompression(9) of the magnetic field B_w at the wall is expressed by the equation:

$$\tau_d \, \dot{B}_w/B_w = -G(T-T_0)/T_0$$

where τ_d and G denote respectively the time constant and the gain of the feedback loop and $T_0(t)$ is the slowly varying programed temperature.

As the fuel tritium is replaced incrementally by helium-3 simultaneously with the magnetic field control, the plasma temperature follows the preprogramed path and the density of each ion-species should approach the target values. An example of this transition is exhibited in Fig.4. The trajectory of a transition on $n\tau$-T diagram is also drawn in Fig.5.

Transition from D-T to D-^{3}He or DD-^{3}He ignition state is attainable mainly by heating due to fusion charged particles. Thus, plasma heating to the temperatures of self-ignition of a D-^{3}He or a DD-^{3}He can be possible without any additional heating once a D-T ignition is attained.

SUSTAINMENT OF A CONFIGURATION DUE TO FUSION PROTONS(10)

The steady operation of a commercial fusion reactor is the preferential model for generating electricity that optimizes the engineering costs. A burning D-^{3}He plasma in a field-reversed configuration produces large quantities of energetic protons, some of which will be lost as they are born, while others are trapped. Even with an isotropic source $S(r,z)$ of fusion protons the preferential trapping allows a directed flow of fusion protons in this configuration. If an electric shorting mechanism exists to prevernt radial electric field from rising, this flow gives rise to an electric current.

We assume that the fusion protons are lost if their guiding centers impinge on far away from the separatrix: protons with sufficiently negative $p-av$ escape directly (p, v, and a represent respectively the canonical angular momentum devided by the mass M, the speed of a particle, and the separatrix radius). Then the distribution function of fusion protons is obtained:

$$f(p,v) = \frac{1}{4\pi} \frac{1}{v^3 + v_c^3} \left| \frac{<S>}{<\nu>} \right|_{p_0, v_0} h(p_0 - \alpha a v_0) ,$$

where H is the Heviside's step function and ν is the electron drag rate. α is a scrape-off parameter defined by $1 + v_0/a\omega_{ci}$. $p_0 = p_0(p, v)$ is the birth angular momentum of a particle born with speed v_0, which reaches the point (p,v), through the solution of the equation

$$\frac{d}{dv} \frac{p(v)}{v} = - \frac{<\nu U>}{<\nu>} v^{-2} .$$

The quantity $U(r,z)$ is the flux function multiplied by e/M and symbol $< >$ represents the average over the accessible domain $rv > |p - U|$.

The current density carried by the fusion protons is given in our case by the equation

$$j_p(r,z) = \frac{e}{2r^2} \int_0^{v_0} v \, dv \int_{U-rv}^{U+rv} [p - U] f(p,v) dp .$$

The expression for the current density has been evaluated numerically when an elongated Hill's vortex equilibrium is chosen for the plasma and the plasma temperature is assumed isothermal. An example of the resultant proton current density is shown in the solid curve of fig. 6, for the case where: the ratio of separatrix radius, a, to fusion produced Larmor radius, r_L, at the separatrix $\equiv a/rL \equiv \alpha_{eff} = 15$. An approximate form for the current prefile is obtained by assuming the fusion produced proton lasts $0.6/<\nu>$ and then is lost. The dashed curve in fig. 6 gives this current profile and it is seen to correspond with the result of the analytic slowing down calculation. Similar current profiles have been obtained from the numerical evaluation of particle orbits moving in a magnetic field determined from an elongated Hill's Vortex equilibrium and slowing down due to drag. The comparisun of the Monte-Carlo and the analytic slowing down calculation is shown in Fig.7.

The simple analytical model allows for a self-consistent evalution of a magnetic field which retains fusion products. We assume a background pressure whose functional dependence on the magnetic flux is

$$P(U) = \frac{4\alpha}{\sigma}\,\frac{Mv_0^2}{a\mu q^2}\,[1 - exp(-\sigma\frac{U}{U_{max}})] \quad .$$

The equation to be solved for an elongated equilibrium is,

$$\frac{1}{x}\frac{\partial}{\partial x}\frac{1}{x}\frac{\partial U}{\partial x} = -4a^2 v_0\,[exp(\frac{-\sigma U}{U_{max}}) + \frac{8f}{x}I_M\,(U)\,\frac{U_{max}}{\delta}\,\{1 - exp(-\sigma)\}]$$

with $x = r/a$

$$I_M\,(U) = \frac{1}{4}[1 - \frac{(U-1)^2}{x^2}]\,h\,(x^2 - (U-1)^2)$$

$$f = \frac{0.6}{8}\,\frac{n_{0d}\,n_{0\,^3He}\,Mv_0^2}{n_{0e}v_0}\;n_0\,v_i\;\frac{n_{0e}T_e}{\sum_j n_{0j}T_j}$$

where n_j and T_j are the density and temperature of species j and the subscript o refers to quantities on the field null.

This equation is solved over the domain $0<x<1$, with the conditions

$$\frac{\partial U(x=1)}{\partial x} = \alpha_{eff}, \quad U(x=1) = U(x=0) = 0 \,,$$

with an iteration on α and U_{max} needed to satisfy these conditions. As the proton production f varies, these solutions lead to, changes, in the enclosed magnetic flux for a given external magnetic field (specified by α_{eff}) and a maximum plasma beta at the field null. Examples of how the maximum magnetic flux U_{max} changes with increasing f is shown in Fig.8. Curves 1,2,3, and 4 are for $f = 0$, 0.1, 0.2, and 0.4 respectively. It is estimated that $f \simeq 0.25$ for D-^{3}He mixture at T=100 keV. Note, that for small α_{eff} the effect of retaining the charged particles slightly increases the magnetic flux, while at larger magnetic fields, the retention of charged particles decreases the magnetic flux, for the same plasma radius and external magetic field. Retaining the fusion poroducts also forces the background plasma to have a reduced maximum beta, as the fusion product beta must also be supported by the external magnetic field.

The effect is shown in fig. 9 where the maximum central beta of the background plasma is plotted for $f = 0.0$, 0.1, 0.2 and 0.4 respectively for various values of α_{eff}. As the background plasma maximum beta has reduced significantly from unity (e.g. $\beta_{max} \rightarrow 0.65$, for larg α_{eff} when f=0.2) it is clear that a large fraction of the magnetic field is due to fusion product currents. A critical question is whether this magnetic field can be sustained indefinitely. In classical theory, the currents we have calculated may really be flows accompanied with an electron back-current. We note that in our model the background plasma has a $Z_{eff} > 1$ because of the existong ^{3}He, and the Ohhawa effect will allow ($1- 1/Z_{eff}$) of the flow to become electrical current. However, classical theory also predicts that large radial electoric fields arise, which should be detrimental to stability unless they are shorted out. If a shorting mechanism, such as that due to anomalous viscosity arising from Kelvin-Helmholtz instability as postulated by Riemann and Sudan (11), we would have the beneficial effect of eliminating the large destabilizing electric fields and the conversion of fusion product flows to current, with the possibility of steady state sustainment of the equilibrium profile. Clearly more investigation of this anomalous process is needed.

CONCLUSIONS AND DISCUSSIONS

It becomes clear that a very high plant efficiency of more than 70% and relatively small 14 MeV neutron fraction of 1 % for the fusion plasma are attainable by the use of D-^{3}He fuels. In order to make practical the D-^{3}He fuels, a very high beta value of the plasma with a temperature of 100 keV is needed. Further, installation of direct energy convertors of large capacity is required. Characteristics of a field-reversed configuration seem to meet these requirements.

The D-^{3}He ignition temperature of 100 keV is achieved through a transition of burning operation from a D-T burning state. Heating is due to energetic fusion charged particles and no additional heating is necessary.

A combination of D-^{3}He fuels and a reversed-field configuration may gives rise to an electric current enough to suport the configuration steadily, provided that electric field shorting mechanism exists. This current is attributed to a preferential trapping of energetic fusion protons.

Favorable features of D-^{3}He fuels in a field-reversed configuration have been so far described. The analysis is, however only a beginning and detailed studies on equilibrium, stability, and transport phenomena are needed. It should be noted that the presence of directed flows of energetic components of charged particles or an associated plasma rotation are to be included in the considerations.

Plasma heating to an ignition temperature of D-^{3}He is possible with the aid of the transition to the burning state from a D-T ignition state. Nevertheless, obtaining a D-T ignited plasma is a problem yet to be solved.

REFERENCES

(1) : J.G. Gilligan, G.H. Miley, and D.Dreiemeyer;
Proc. 4th ANS Topl. Mtg., King of Prussia, PA, October 14-17, 1980

(2) : E. Greenspan and G.H. Miley;
Nuclear Technology/Fusion, 2, 43 (1982)

(3) : H. Momota et. al;
Fusion Technology, 11, 436 (1987)

(4) : L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski;
Fusion Technology, 10, 436 (1986)

(5) : H. Momota, Y. Tomita, and Y. Nomura;
IPPJ 460 (Institute of Plasma Physics, Nagoya Univ., 1980)

(6) : G.H. Miley; *Fusion Energy Conversion*,
(ANS, Illionis, 1970)

(7) : see for example
R.E. Siemon, et.al.;
Fusion Technology, 9, 13(1986)

(8) : see details of the model
M. Ohnishi, et. al;
Fusion Technology, 12, 249(1987)

(9) : M. Okamoto and M. Ohnishi;
J. Nucl. Sci. Tech., 20, 366(1983)

(10) : H.L. Berk, H. Momota and T. Tajima;
to be published in Physics of Fluids

(11) : A. Reiman and R.N. Sudan,;
Comments on Plasma Physics and Controlled Fusion, 5, 167 (1979)

TABLE CAPTIONS

Table I : The estimated characteristics of 1 GW fusion plants based on various fusion fuel cycles: the typical plasma temperatures, the required confinement parameters, the estimated plant efficiencies, the associated 14 MeV neutron powers, and the additional engineering requirements to be developed.

FIGURE CAPTIONS

Fig. 1: Fuel flows:exhausted tritium is once stored in a tritium bank and transmuted helium-3 is refueled in DD-^{3}He of D-^{3}He fusion

Fig. 2: (a) Required confinement parameters,
(b) Obtainable radiation parameters,
and (c) Resultant 14 MeV neutron power fractions respectively as a function of the plasma temterature of various fusion fuel cycles

Fig. 3: A favorable field-reversed configuration: plasma is surrounded by a natural divertor

Fig. 4: An example of the objective time-variation (upper) and concentrations for respective species of fuels (lower)

Fig. 5: An example of the transition pass from D-T to D-^{3}He self-ignited state

Fig. 6: An example of the current density carried by fusion protons in a field-reversed configuration

Fig. 7: The comparison of the Monte-Carlo and the analytic slow down calculation

Fig. 8: Effect of trapped fusion products or the maximum contain magnetic flux $\tilde{u}_{max}$ for $\sigma = 0.1$
Curves 1,2,3, and 4 are for f = 0.0, 0.1, 0.2 and 0.4 respectively

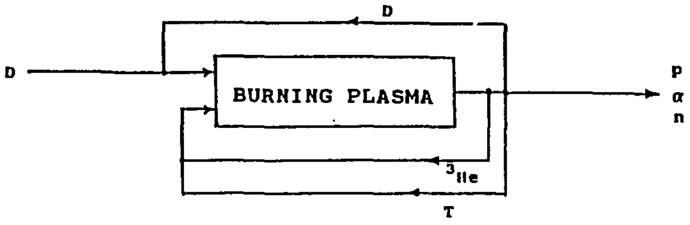
Fig. 9: Background plasma beta (plasma pressure at null/magnetic pressure at seperatrix/ as a function of α_{eff} for $\sigma = 0.1$ Curves 1-4 are for f = 0.0, 0.1, 0.2 and 0.4 respectively.

TYPICAL PARAMETERS OF 1 GW PLANT

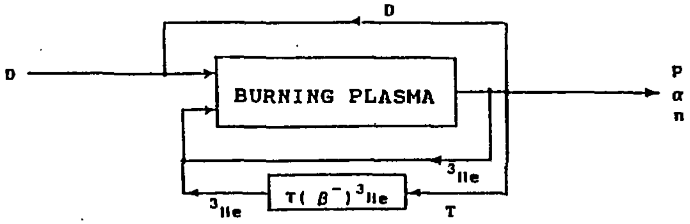
	DT	Cat.D	DD^{3}He	D^{3}He
T(keV)	13	40	100	100
$n\tau$ (s m^{-3})	2×10^{20}	2×10^{21}	1×10^{21}	1×10^{21}
Plant Efficiency (%)	45	65	70	78
14MeV Neutrons (MW)	1800	550	215	13
Engineering Requirement	T Breeding		300kg T Bank	50kg/y ^{3}He Fuel

Table 1

Cat. D



DD^{3}He



D^{3}He

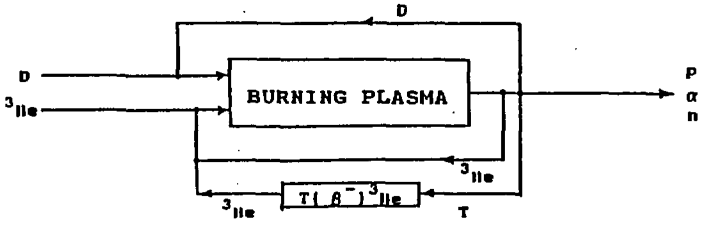


Fig. 1

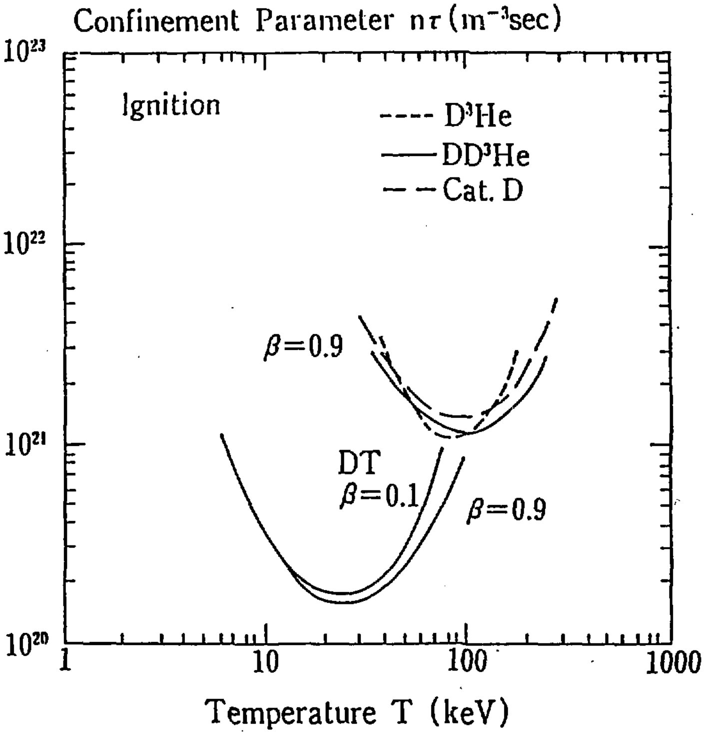

Confinement Parameter nτ (m⁻³sec)
10²³
10²²
10²¹
10²⁰
Ignition
---- D³He
—— DD³He
— — Cat. D
β=0.9
DT
β=0.1
β=0.9
1
10
100
1000
Temperature T (keV)

Fig. 2 (a)

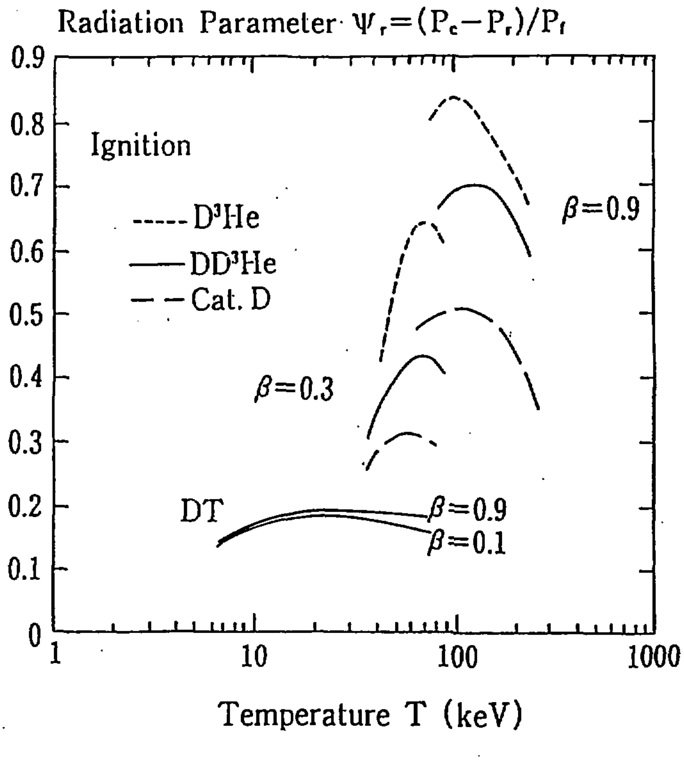
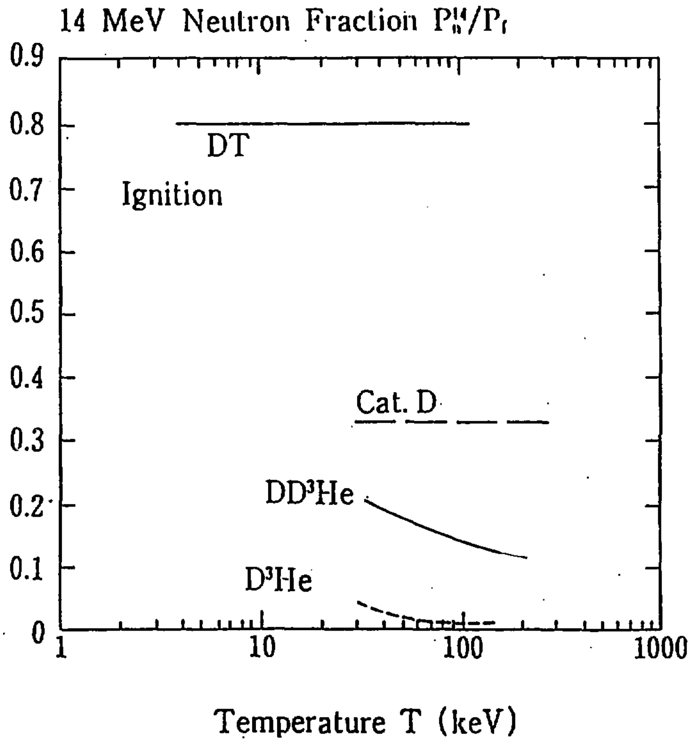

Radiation Parameter $\Psi_r=(P_c-P_r)/P_f$
Ignition
D³He
DD³He
Cat. D
β=0.9
β=0.3
DT
β=0.9
β=0.1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
Temperature T (keV)

Fig. 2 (b)



14 MeV Neutron Fraction P_n^{14}/P_f
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DT
Ignition
Cat. D
DD³He
D³He
1
10
100
1000
Temperature T (keV)

Fig 2 (c)

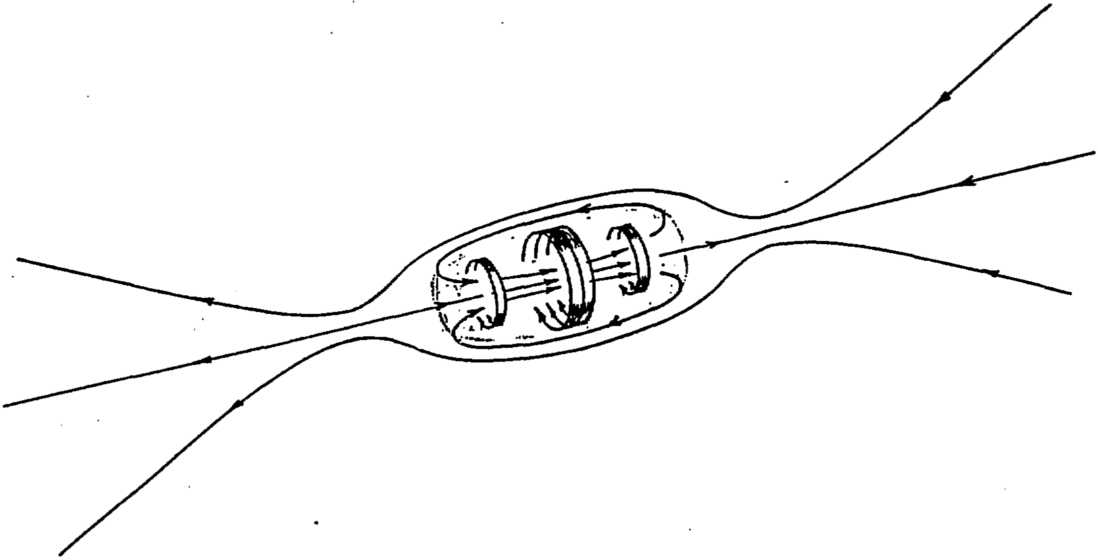


Fig 3

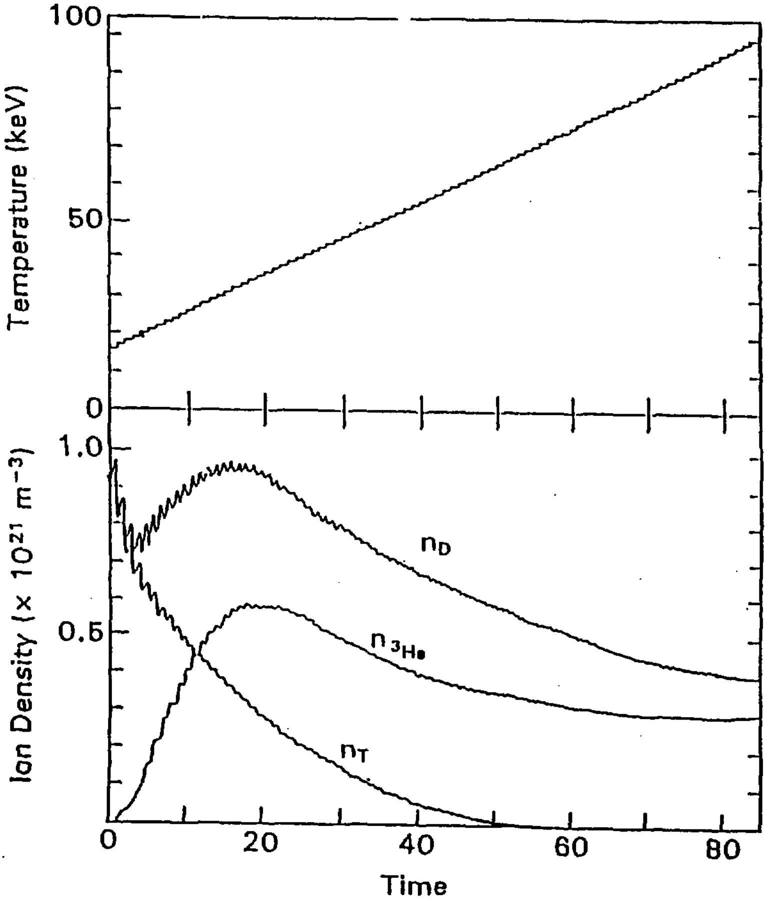

100
50
0
Temperature (keV)
1.0
0.5
Ion Density (× 10^{21} m^{-3})
n_D
$n_{^3He}$
n_T
0
20
40
60
80
Time

Fig.4

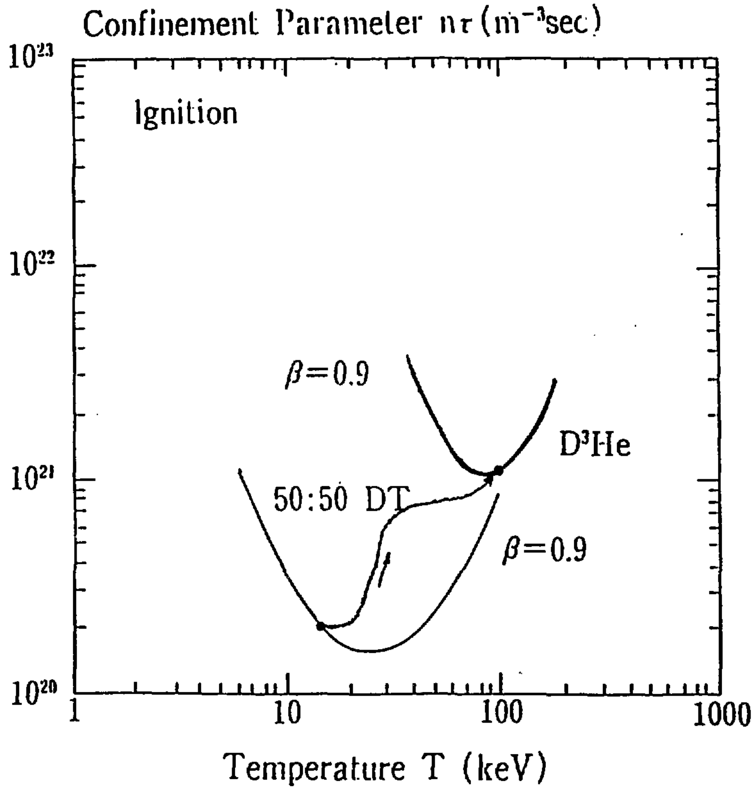

Confinement Parameter nτ (m⁻³sec)
10²³
10²²
10²¹
10²⁰
Ignition
β=0.9
D³He
50:50 DT
β=0.9
1
10
100
1000
Temperature T (keV)

Fig.5

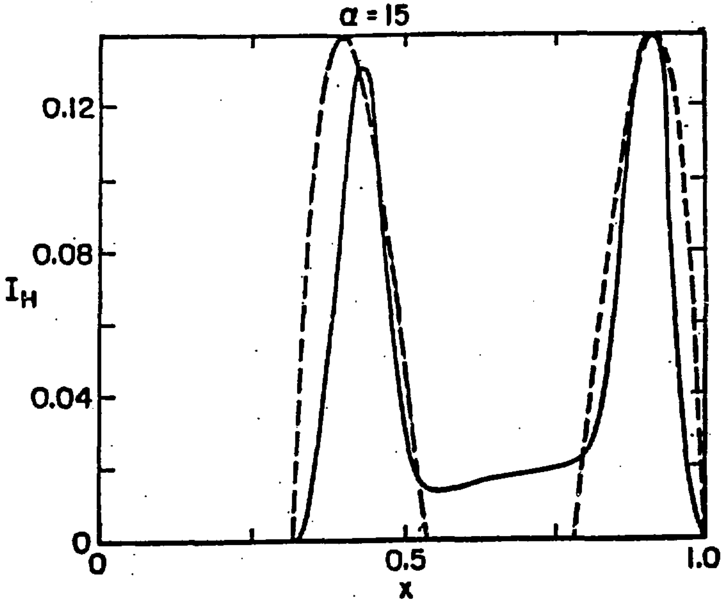


Fig.6

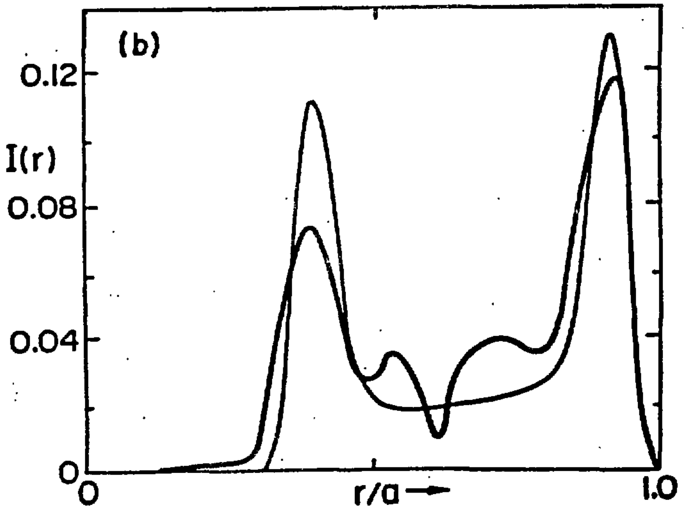


Fig.7

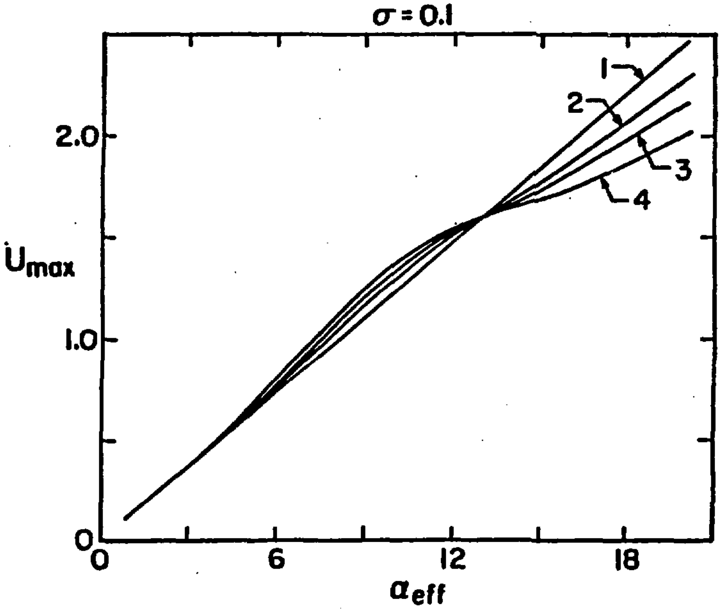


Fig.8

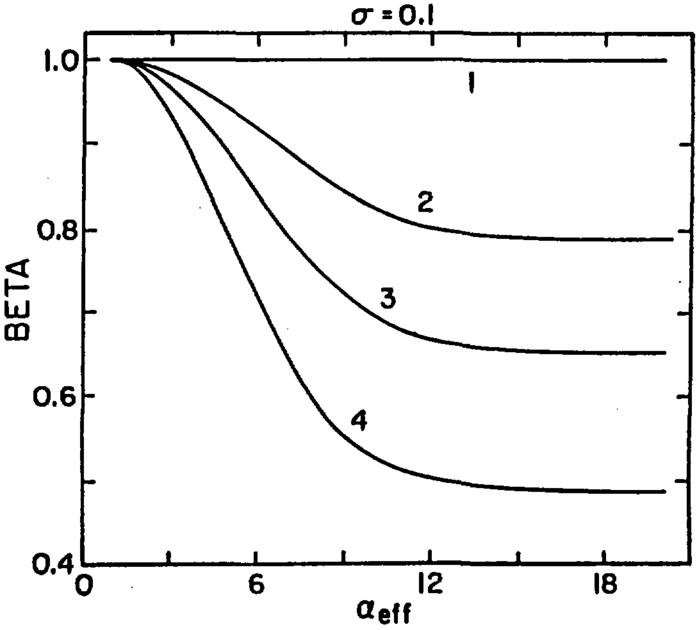


Fig.9