INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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A Proposal of JIPP Toroidal Experiment for Confinement and Heating of Hot Plasma

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Contents

§1. Introduction

Increase of ion temperature is as important as increase of confinement time to realize a fusion grade plasma. In order to increase the ion temperature, it is important that the heating is effective as well as the pumped energy is confined well.

The maximum heating power is limited by technical as well as physical reasons, so that it is tried to optimize the parameters of device to make the temperature maximum with possible heating power. The magnitude of the toroidal field is stronger and the plasma volume is smaller than the case in which the parameters of device is optimized to make the confinement time (or $n\tau$) maximum.

In this proposal, it is aimed to study the transport of hot plasma with several keV in a hybrid system of stellarator and tokamak. The heating mechanism and the loss mechanism of the energy during the heating processes are subjected to be investigated. It is possible to make the plasma parameter into the region of dissipative trapped electron instability. However the study of dissipative trapped ion instability is difficult unless the plasma is heated effectively.

The study of MHD instability is important problem and the control of the current distribution will be important for the stability of the confined plasma. The poloidal field of the stellarator field can be easily charged, so that the radial distribution of the rotational transform angle can be variable and it is equivalent to control the current distribution in some sense.

The stellarator configuration has equilibrium state even without the plasma current so that the stellarator has equilibrium state at the build up phase of the plasma current and it is expected that the interaction of the plasma and wall can be reduced at the build up phase of the plasma current. The parameter range of the produced plasma may be extended. It can be also expected that the necessary magnetic flux of the ohmic heating coil is reduced. The effect of the magnetic limiter on the interaction of the plasma and wall can be examined.

The injection of high energy neutral and RF heating (lower hybrid resonant heating or ion cyclotron resonant heating) are used as the methods of further heatings. Output powers of neutral injectors and RF oscillators and transmission system must be more than several megawatts. We intend to produce plasmas with $T_e \gtrsim 2 \sim 3$ keV, $T_i = 1 \sim 1.5$ keV by ohmic heating and to increase the electron and ion temperatures to several keV by further heatings.

This proposal is a natural extension of JIPP-T-II project[1], which has already started.

§2. Optimization for Increase of Plasma Temperature

When a plasma with the density n, the temperatures T_e, T_i and the volume V is confined with the energy confinement time τ and when the plasma is heated with the power of P_h, there is a following relation in steady state

$$P_h = \frac{n(T_e + T_i)V}{\tau} \tag{1}$$

$$\tau = \frac{a^2}{5.8D}$$

where a is the minor radius of plasma and D is the diffusion coefficient. When the major radius of plasma is denoted by R, then the plasma volume is $V = \pi a^2 2\pi R$ and we find

$$T_e + T_i = \frac{1}{2\pi^2 n} \frac{P_h}{RD} \ . \qquad (2)$$

It can be considered that the heating power is proportional to the plasma surface and P_h is expressed by $P_h = 2\pi a 2\pi R p_h$ where p_h is the power density at the plasma surface. Consequently Eq.(2) is reduced to

$$T_e + T_i = \frac{2p_h}{n} \frac{a}{D} \ . \qquad (3)$$

The poloidal beta ratio has upper limits β_p^{cr} and

$$\frac{n(T_e + T_i)}{B_p^2/2\mu_o} \equiv \beta_p < \beta_p^{cr} \ , \qquad (4)$$

where B_p is the poloidal magnetic field. The upper limit of β_p due to the bootstrap current is $\beta_p < 0.5(R/a)^{1/2}$ and the upper limit of β_p due to the equilibrium condition is $\beta_p < 0.5(R/a)$. When $n = 3 \times 10^{13}$ cm^{-3} and $T_e + T_i = 8$ keV, the poloidal field for $\beta_p = 1$ is $B_p = 0.31$ W/m^2.

When the heating power per unit area of the plasma surface is limited, an optimizing condition to make $T_e + T_i$ maximum is to make aD^{-1} maximum. An optimizing condition for the maximum confinement time is to make a^2D^{-1} maximum. Consequently a toroidal device which is optimized to have the maximum temperature has stronger toroidal magnetic field B_t tends to have larger aspect ratio R/a_p compared with a device which is optimized for the confinement time. When the parameters of the geometry of devices are given, the total energy necessary to excite the toroidal magnetic field and to excite the ohmic heating coil of the air core type can be estimated. We choose the following parameters of devices tentatively to obtain the maximum temperature taking account of the necessary total energy and the technical boundary conditions:

Major radius:	$R = 1.5$ m
Minor radius:	$a_p = 0.35$ m
Aspect ratio:	$R/a_p = 4.3$
Toroidal field:	$B_t = 5$ W/m^2
Poloidal field:	$B_p = 0.39$ W/m^2 (for $B_t = 5$ W/m^2, $q = 3$)
Plasma current:	$I_p = 0.68$ MA (for $q = 3$),
	$I_p = 0.82$ MA (for $q = 2.5$)
Flux of current transformer:	$\Phi = 7$ V-s .

A schematic diagram of device is shown in Fig.1 and Fig.2. More details of the device will be described in Sec.5.

§3. Scaling Laws of Plasma Parameters

The boundaries of MHD, plateau and banana region in n, T diagram are shown in Fig.3 with $Z_{eff} = 3$. The region in which the diffusion coefficient due to dissipative trapped electron instability becomes large is around

$$\nu_{ei} = \frac{T_e}{eBa^2} \approx \omega^* .$$

The diffusion coefficient due to dissipative trapped ion instability becomes dominant near

$$\nu_{ei} = \varepsilon^{3/2} \frac{T_e}{eBa^2} \approx \varepsilon^{3/2} \omega^* .$$

These regions are also shown in Fig.3.

The scaling of parameters of plasmas produced by ohmic heating is

$$\eta j^2 = \frac{nT_e}{\tau} , \qquad \tau = \frac{a^2}{5.8D} .$$

When the diffusion coefficients D of pseudoclassical one, empirical one $0.04B_p^{-1}$ (MKS unit) and $1/\gamma$ time of Bohm one are used, we find that

$$\tau_{pc} \approx \frac{0.47}{2} a^2 B_p^2 \left(\frac{T_e}{e}\right)^{1/2} \left(\frac{10^{20}}{n}\right)$$

$$\tau_{EX} \approx 4a^2 B_p$$

$$\tau_{B\gamma} \approx 2.8\gamma_B a^2 B_t \left(\frac{T_e}{e}\right)^{-1} .$$

Consequently, scaling of plasma parameters can be shown in Fig.3. Here we choose B_t = 5 W, R = 1.5 m, a = 0.35 m, q = 3, Z_{eff} = 3. The dependence of the confinement times on the electron temperature is shown in Fig.4 in the cases of pseudoclassical one, empirical one, 100 τ_B, 20 τ_B and dissipative trapped electron and ion instabilities.

From these results it is possible to reach the region of plasma parameters where dissipative trapped electron instabilities is important, however it is difficult to reach the region of dissipative trapped ion instability unless the plasma is heated very effectively.

§4. Plasma Heating

The temperature of plasma heated by ohmic heating is limited by $T_e \gtrsim 2 \sim 3$ keV due to the reduction of the resistivity at higher temperature. Consequently further heating is necessary to increase the temperature furthermore.

The total number N of electrons is

$$N = n\pi a^2 2\pi R = 10^{20}$$

when the density is 3×10^{19} m^{-3}. In order to increase the temperature by $\Delta(T_e + T_i) \gtrsim 5$ keV in the case of $\tau_E = 25$ ms the necessary amount of the input power P_h is

$$P_h = \frac{N \times (T_e + T_i)}{\eta \tau_E} \sim \frac{3.2}{\eta} \times 10^6 \text{ watts}$$

provided that η is heating efficiency. The duration of heating must be longer than say $3\tau_E$, that is, about 0.1 sec.

4.1 Injection of High Energy Neutral Beam

Let us consider the injection of neutral beam with the energy of 60 keV. When the ion density is $n_i = 3 \times 10^{19}$ m^{-3}, the mean free path is about 1.1 m. If the tangential injection is carried out, the path of the neutral beam is about 2.5 m length. Consequently, the neutral beam can be absorbed effectively. When the electron temperature is $T_e \sim 2$ keV, 60 % of the injected energy contributes to heat ions. If a power source with 1 Megawatt is developed, 4 neutral injectors can heat the plasma by $\Delta(T_e + T_i) \approx 6\eta$ keV.

4.2 RF Heating

When the efficiency of RF heating is assumed to be 0.5, the necessary output power of RF oscillator and the transmission system is about 8 Megawatts. The frequency of the lower hybrid resonant heating is about 0.78 GHz ($\lambda \sim 38.4$ cm) when $B_t = 5$ W/m^2 and $n = 3 \times 10^{19}$ m^3. The four parts may accept the necessary input power, although there are technical problems to be solved.

It is observed that the current peaking due to the overheating of the central region induces internal kink modes and disruptive instabilities. The electron heating of boundary region of plasma by LHRL or ECRH may be effective to suppress the current peaking and to control the current distribution.

§5. Device

As the toroidal field is strong, we adopt D shape toroidal field coils to reduce the maximum stress. An air core type is chosen for the ohmic heating coil and the air core coil are arranged outside the toroidal coils for the convenience of assembling and disassembling and for getting better accessibility.

5.1 Coils of Toroidal Field

When the toroidal field is 5 Wb/m^2, the internal stress of the coils becomes critical amount of the structural material. Consequently D shape coil is adopted. The stress distribution of D shape coil is much more uniform than that of circular coil. The computational results of the internal stress of coils by a finite element method is about 10 kg/mm^2 at maximum.[2] The necessary amount of the power and the energy to produce the toroidal field becomes larger than those of circular coil but there are merits that the stress distribution becomes much more uniform and the supporting method becomes easier.

The necessary amounts of the power and the energy to excite the toroidal field of 5 W/m^2 is about 190 MW at the stationary period. The time constant L/R of the toroidal coil system is about 3 sec. When the forcing voltage at the current rising period is 1.5 time that of the stationary state and the flat top of the current is 1.0 sec, the total energy is about 720 MJ.

The necessary amount of the vertical field for the equilibrium of the current carrying plasma is about 0.25 W/m^2 at maximum. The total torque acting on the toroidal coil is about 2.8×10^7 Newton-m.

5.2 Ohmic Heating Coil

An air core type is adopted. The swing of the magnetic field can be larger than that of an iron core type. The strength of the leakage magnetic field at the plasma region can be much smaller. Although the necessary amount of the energy becomes much larger than that of an iron core type, the development of inductive storage and the circuit braker enable the air core type practical.[3,4] We choose the positions of the ohmic heating coils outside the toroidal coil as the assembly and disassembly of the device become much easier. Although the necessary energy for the ohmic heating coils is larger in this case, the necessary energy for the toroidal field coils becomes smaller.

The self-inductance L_p of the plasma is about $L_p \sim 3.8 \times 10^{-6}$ H and the necessary magnetic flux $\Delta\Phi$ is $\Delta\Phi = L_pI_p + \int R_pI_p dt = L_pI_p(1 + \beta) \sim 7$ V-sec, where the plasma current I_p is $I_p \simeq (0.8 \sim 1) \times 10^6$ A and β is the ratio of $\int R_pI_p dt$ to L_pI_p and is assumed to be $1 \sim 0.8$. The self inductance L_{OH} (equivalent inductance for one turn) is $L_{OH} \sim 0.35 \times 10^{-6}$ H and the coupling constant is $\kappa^2 \gtrsim L_{OH}/L_p \gtrsim 0.09$. Consequently the swing of the current of ohmic heating coil is $I_{OH} = \pm 10$ MAT. The necessary amount of energy for the ohmic heating coil is roughly estimated to be

$$4 \frac{L_{OH} I_{OH}^2}{2} \gtrsim 70 \text{ MJ}$$

The power of DC source to store the inductive energy into the ohmic heating coil is about 40 MW provided the resistivity (equivalent resistivity for one turn) is 0.4 μΩ. The requirement of the circuit braker of ohmic heating circuit system is about $(200 \times n)V \times (10^7\ A/n) \approx 2 \times 10^9$ VA (n is the number of turns of ohmic heating coils).

5.3 Equilibrium Field Coil

The necessary amount of the vertical field $B_\perp$ for the equilibrium of the current carrying plasma with $I_p \approx 0.8$ MA is about $B_\perp \approx 0.25\ W/m^2$. The decay index is within $0 < n < 1.5$. The coils of horizontal field are also arranged. The position of the coils is outside of the toroidal field coil by the same reason to that of the ohmic heating coil. The energy of the magnetic field is order of 7 MJ and the power of DC source at steady state is about 20 MW. At the rising period of the plasma current, the vertical field must be built up with the same time constant of the plasma current. For this purpose, we use an inductive storage. The necessary amount of the inductive storage is about 27 MJ and the requirement of the circuit braker in the circuit system of the equilibrium field coils and the inductive storage is about 0.45×10^9 VA.

5.4 Helical Coil

The pole number ℓ and the number of field period m of the stellarator field are $\ell = 2$ and $m = 4$. When the current of helical coil is $I_h \approx 10^6$ Ampere-Turn, the rotational transform angle is $\iota/2\pi \sim 1/3$ in the case of $B_t = 3Wb/m^2$ and $\iota/2\pi \sim 1/8$ for $B_t = 5\ Wb/m^2$. The power for helical coil current is about 100 MW. As the direction of helical coil current is not parallel to that of the toroidal coil, the strong force acts on the helical coil. The force is $f = B_t I_h \sin\alpha = 2.9 \times 10^6$ N/m at R = 1.5 m and $f = 4.6 \times 10^6$ N/m at inside the torus. The supporting tube of strong stainless steel is used. The detail analysis of the internal stress is under the way. This tube also supports the vacuum vessel and it plays a resistive shell surrounding the plasma.

5.5 Feedback Control Coil of Vertical Field

As the plasma current flows longer than the skin time of the resistive shell, the feedback control of the vertical field is necessary. The feedback control coils are located inside the toroidal coils, as the time constant must be shorter than several milliseconds. The power for the coils is about 12 MW and the vertical field is about 0.04 W/m^2 which is controlled by computer.

5.6 Vacuum Vessel and Others

The vacuum vessel consists of the section of ports and the section of bellows. The resistivity of the one turn loop is larger than 2 mΩ. The baking of 400° ∿ 500°C is possible. The vacuum is sealed by metal gaskets. When the outgas rate is 3×10^{-11} Torr-ℓ/sec·cm^2 and the pumping speed is 4000 ℓ/sec, the basic pressure is $p_o = 6 \times 10^{-9}$ torr. There are several kinds of forces acting on the linear. The forces F_R and F_r acting with the directions of the major and minor radius due to the atmospheric pressure are $F_R = -2\pi a^2 p \sim -30$

ton and $F_r = -2\pi^2 Rap \sim -240$ ton. The current flowing in the linear is about 0.1 MA at the rising period of the plasma current. When the plasma current is interrupted with the skin time of the liner, the induced maximum current in the liner becomes -0.5 MA. The interaction of the current I_ℓ = -0.5 MA with the vertical field is $F_R \sim 120$ tons. The hoop force is $F_R \sim 24$ tons. The interaction with the poloidal field due to the plasma current is $F_r \sim 190$ tons and the pinching force is $F_r \sim -60$ tons. The interaction of the current I_ℓ with the helical field must also be taken into account.

If the energy of plasma $n(T_e + T_i)2\pi R\pi a^2 \sim 2 \times 10^5$ J is lost with the energy confinement time $\tau_E \sim 25$ ms, the input power to the limiter may be $P_L \sim 50 \sim 100$ MW. When the limiters are exposed to the plasma during $\Delta t = 0.5$ sec, the temperature rise ΔT may be[5]

$$\Delta T = \frac{P_L}{A}\sqrt{\frac{\Delta t}{\rho C \kappa}}$$

where A is the surface area of the limiter and ρ, C and κ are the mass density, specific heat and the heat conductivity respectively. When Mo is used as a material of the limiter, ΔT must be less than 1000°C and the surface area A must be larger than 2×10^4 cm^2. The poloidal limiter must be used to have the necessary amount of the contact surface area with the plasma.

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5. Private communication with M. Ohta.

FIGURE CAPTIONS

Fig.1. Schematic diagram of device. □ coils are ohmic heating coils and ⊠ coils outside the toroidal coils are coils of vertical field.

Fig.2. Arrangement of toroidal field coils.

Fig.3. The relation between T_e and n_e of the plasma produced by ohmic heating in the cases of pseudoclassical diffusion, empirical diffusion and $1/\gamma$ time of Bohm diffusion. Artsimovich scaling of T_i is also plotted.

Fig.4. Dependence of confinement time on the electron temperature in the several cases. The electron density is assumed to be $3 \times 10^{19} m^{-3}$.

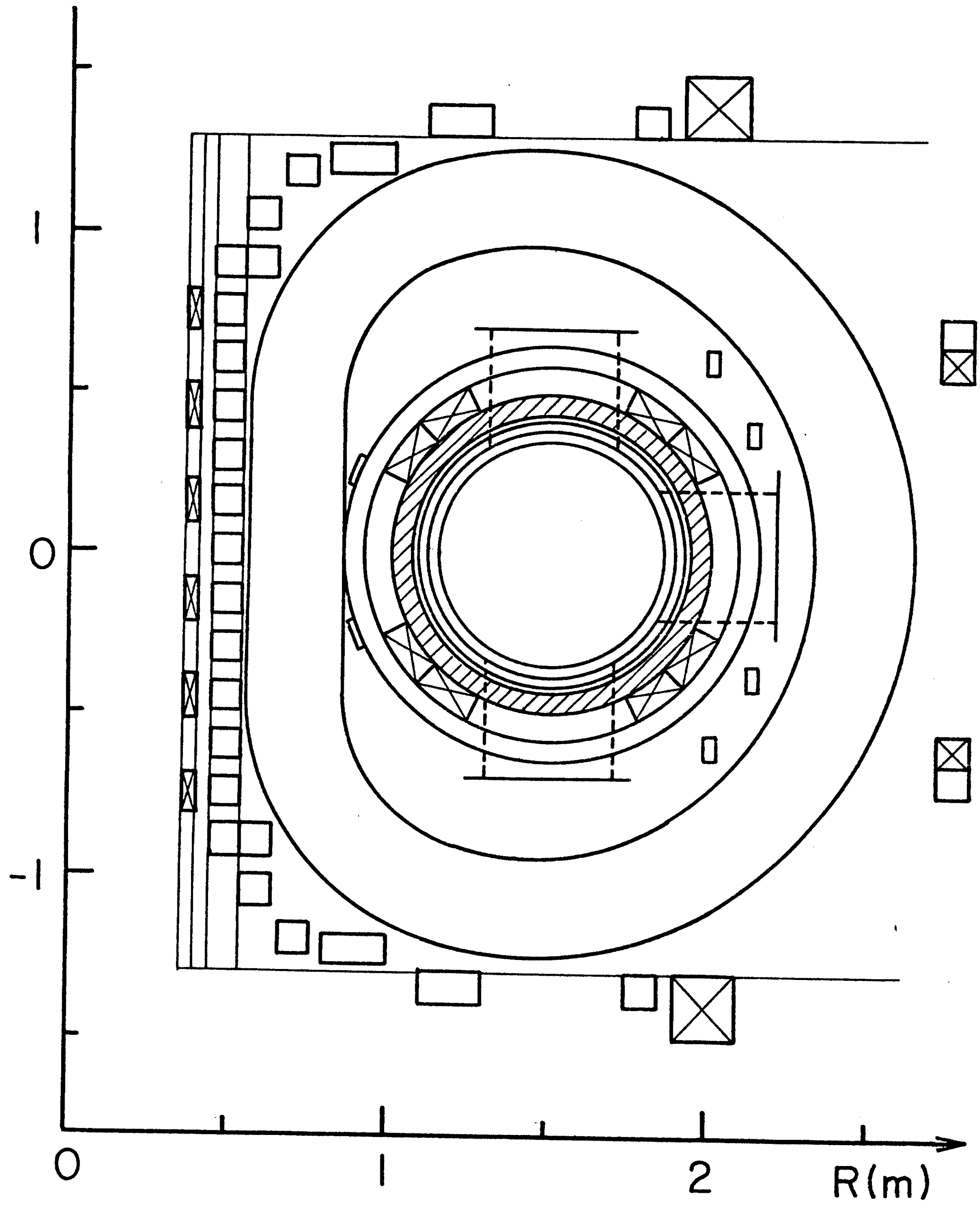


Fig.1

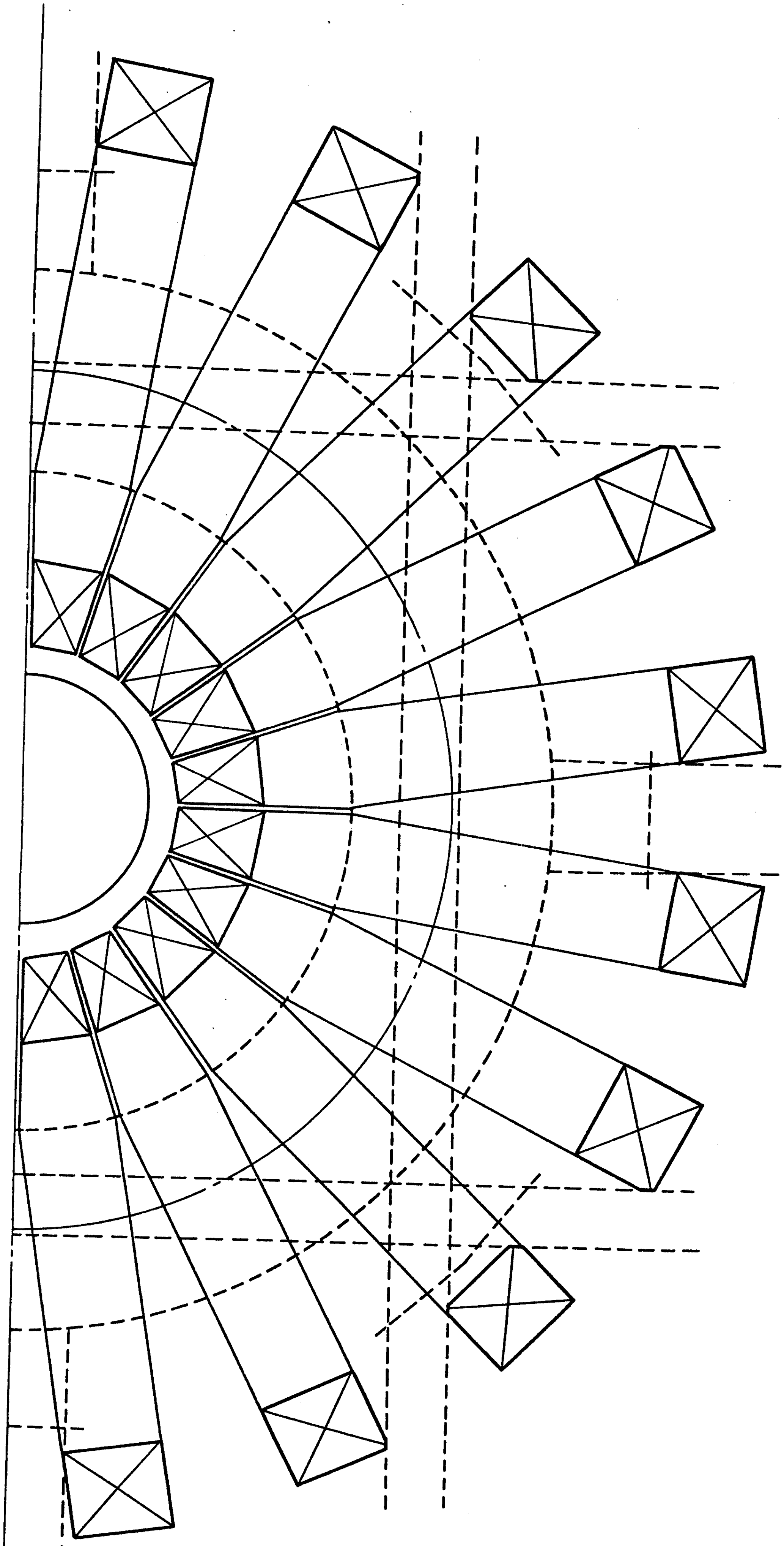
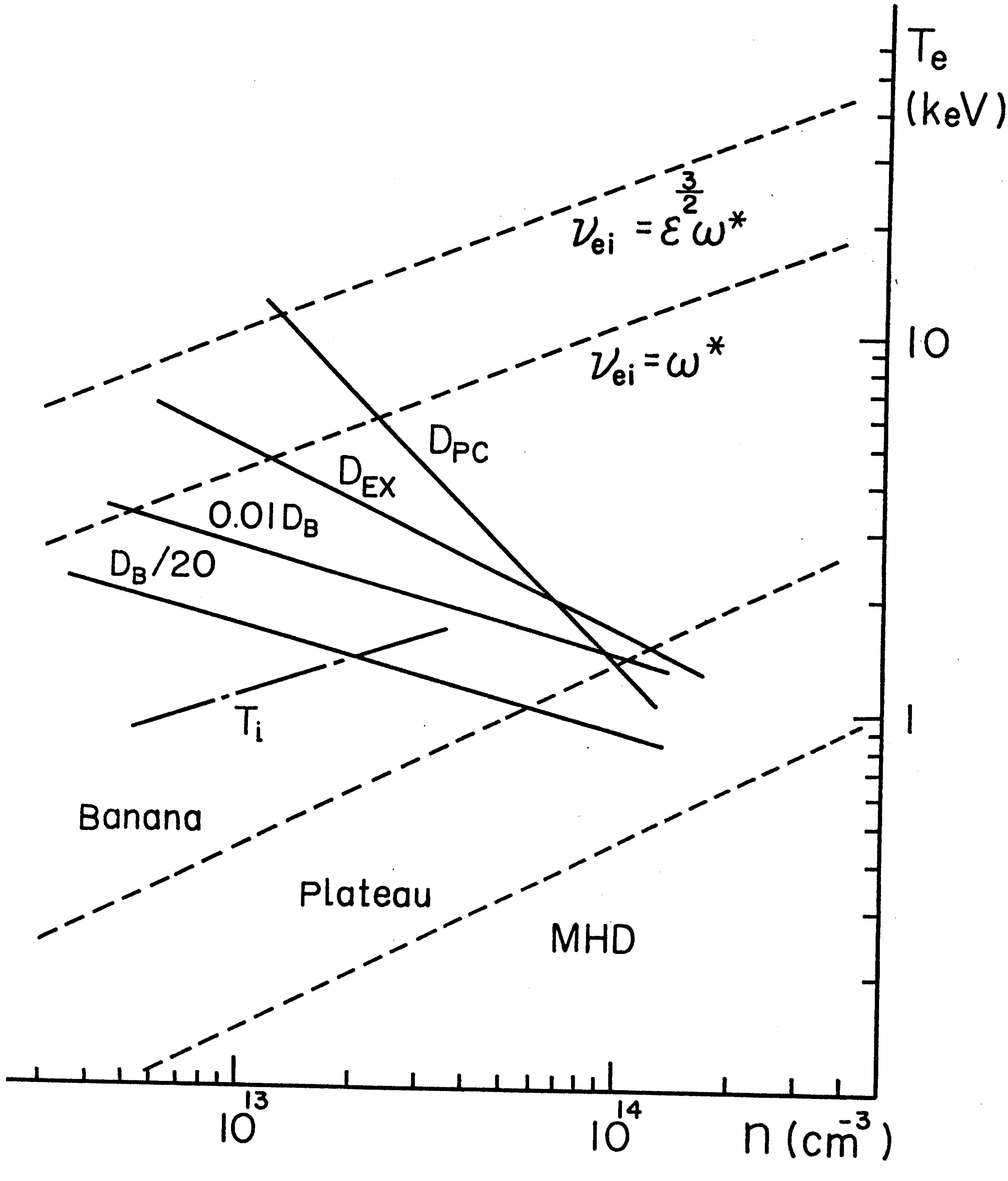
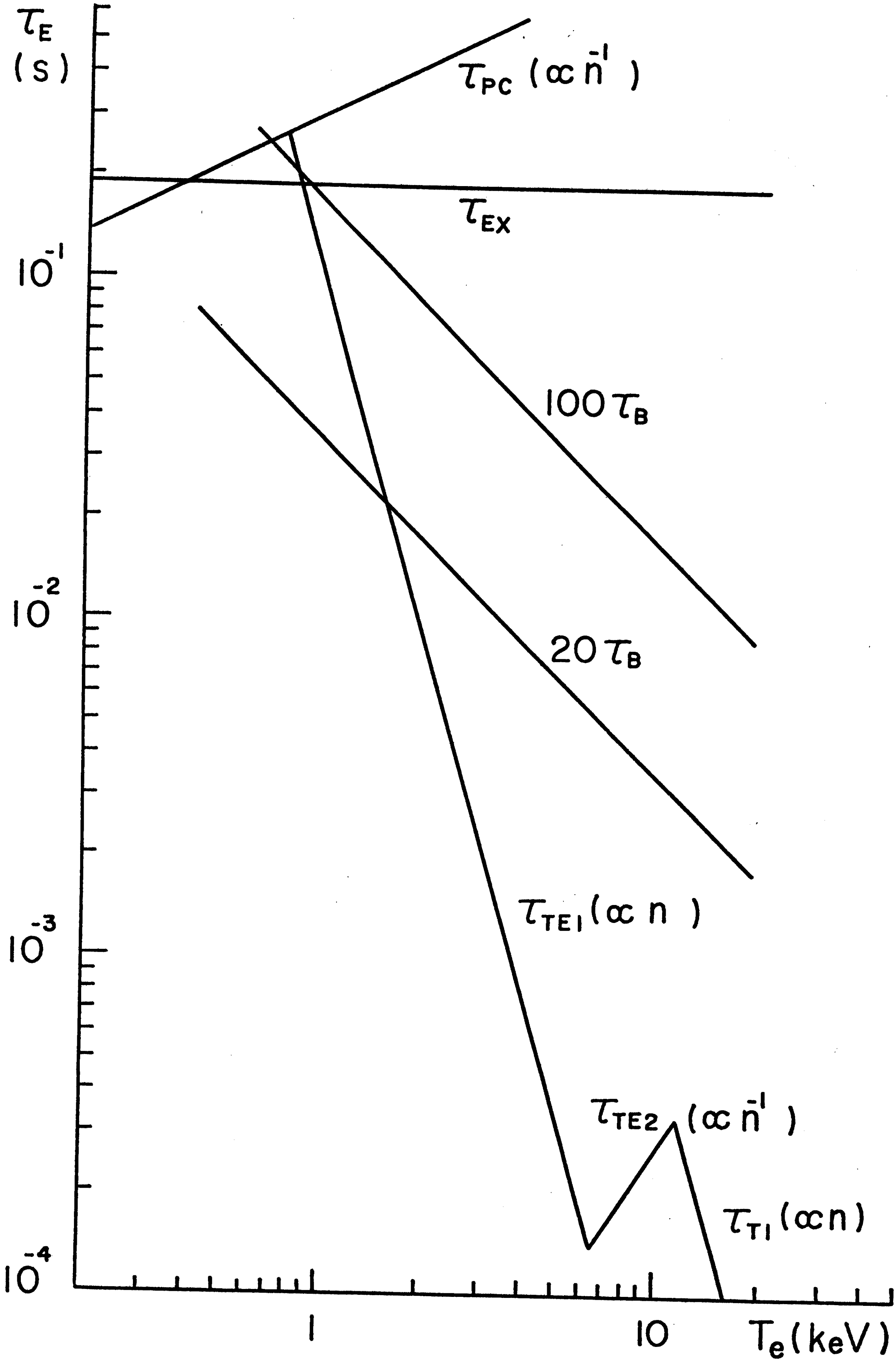


Fig.2



T_e (keV)
10
1
$\nu_{ei} = \varepsilon^{\frac{3}{2}} \omega^*$
$\nu_{ei} = \omega^*$
D_{PC}
D_{EX}
$0.01 D_B$
$D_B/20$
T_i
Banana
Plateau
MHD
10^{13}
10^{14}
n (cm^{-3})

Fig.3



τ_E (s)
τ_{PC} ($\propto n^{-1}$)
τ_{EX}
10^{-1}
$100\tau_B$
10^{-2}
$20\tau_B$
τ_{TE1} ($\propto n$)
10^{-3}
τ_{TE2} ($\propto n^{-1}$)
τ_{T1} ($\propto n$)
10^{-4}
1
10
T_e(keV)

Fig.4