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CONSIDERATIONS OF DEVICE AND OPERATIONAL FLEXIBILITY IN FER

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Considerations of Device and Operational Flexibility in FER

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Expected physics uncertainties in DT burning plasma of FER, which may not be removed completely at the start of construction or DT operation, are reviewed. Several possible device and operational flexibility scenarios to cope with these uncertainties are considered. They are (1) Plasma size enlargement scenario, (2) Plasma shape flexibility scenario, (3) Heating/Current drive/Control system flexibility scenario, (4) Impurity control system flexibility scenario and (5) Advanced operation scenario. Feasibility of these flexibility scenarios are examined and shown to be practicable. However, careful assessment of the physics data base is necessary at the start of construction and DT operation to proceed to actually implement these flexibilities in FER.

Keywords: Tokamaks, FER, Design, Flexibility, Operation

核融合次期装置の装置および運転フレキシビリティ

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核融合次期装置の建設開始時点またはＤＴ燃焼実験開始時点においても確定され得ない可能性のある物理データベースについて概観した。これに基づき装置および運転シナリオに確保しておくことが望ましいフレキシビリティを設定した。それらは(1)プラズマサイズ増大(2)プラズマ形状フレキシビリティ(3)加熱／電流駆動／制御システムフレキシビリティ(4)不純物制御システムフレキシビリティ(5)先進運転フレキシビリティである。これらのシナリオの成立可能性が調べられ，いずれも工学的に適用可能であることが確認された。しかしながら実際の適用にあたっては，建設および実験の各段階でデータベースの慎重な評価と判断を必要とする。

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1. Introduction

Fusion Experimental Reactor(FER) is planned in JAERI as the next large device to JT-60, according to the conclusions by three subcommittees under Nuclear Fusion Council on the next stage device. Its primary physics missions are self-ignition and controlled long burning. In designing the device, which can achieve these missions, with consideration of cost-effectiveness, we must take into account of the uncertainties of the physics assumptions. In principle, these uncertainties should be minimized at the start of construction of FER with the extensive research studies on JT-60, JFT-2M and other devices of the world, at least for the behaviour of hydrogen plasmas. However, there might possibly still exist some uncertainties due mainly to the programatic schedule of FER. In addition, we must consider the possible large uncertainties of the DT burning plasma, which cannot be removed in the existing or planned devices before FER. In this context, the device will become fairly attractive if it has large flexibilities in various ways to ensure the achievement of the missions.

In this report, we will first examine the possible expected uncertainties of the physics assumptions, and then study the feasibility to provide the device with the flexibility to cope with these uncertainties. We will also examine the flexibility for the future possible advanced operation scenario to make the device more attractive.

2. Requirements for device flexibility and typical scenarios

There are two categories of requirement for the device flexibility. One is for achieving the primary missions (mainly referred to ignition) of the device, and another one is for the advanced purposes after having achieved the primary missions. The major reason for the first requirement is that the uncertainty of physics data base will still remain, especially concerning the DT burning, even when construction and machine operation starts, since the full DT burning will be done at the first time in FER. Expected possible uncertainties are summarized in Table 1. In this table, major items of physics assumptions for the design are listed on the left column. In other words, they are research items of FER. Possible uncertainties are listed on the medium column. Double circle and star denote the uncertainty with

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2. Requirements for device flexibility and typical scenarios

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Let us examine each uncertainty briefly. Energy confinement will be most uncertain at present. FER relies on the so-called H-mode class of confinement. However, confinement scaling law has not been established yet even for hydrogen and deuterium plasma. Although the scaling law for hydrogen plasma will be clarified with the extensive research studies in JT-60, JFT-2M, JET, TFTR and other devices, there still remain many unknown factor, which may probably deteriorate the energy confinement in FER. For example, fast α-particles produced by DT reaction, impurity accumulation, sawtooth and other MHD activities and so on. Beta scaling has relatively well established in hydrogen plasma, while that in DT burning plasma may have some uncertainty. Also impurity contamination in DT burning plasma is uncertain, and it has a large impact on the available beta value for fuel ions. Required flexibility to cope with these uncertainties for confinement capability is to increase the plasma size, plasma current and so on with additional expense. As for heating and current drive systems, optimum methods are expected to be clarified by the time of construction start. However, heating and current drive systems are fairly important driving and controlling methods of the plasma. In addition, each heating and current drive system (RF and NBI) has its favorable feature. Thus, it is very desirable to have the capability for the installation and replacement of all of the heating methods even after DT operation. Non-inductive current ramp-up is a prerequisite capability for FER to attain a full plasma current. Thus it is desirable to have a capability for adding extra non-inductive current drive system, though JT-60 achieved a fairly encouraging experiments on lower hybrid current sustain and ramp-up in the large device. Steady state operation is not a primary mission for FER. However the device will become fairly attractive, if it has a capability to install non-inductive current drive system for the burning plasma, when some driving method are developed. In addition, profile (especially plasma current) control is expected to be quite favorable for improving confinement, enhancing beta, so that flexibility for installing every possible current drive system, if favorable from this context too. Plasma shape and magnetic field configuration are related to plasma performance, while the definite conclusion for the optimum shape and configuration has not been obtained. Considering unknown feature in DT burning plasma, it is desirable to have an operation capability with a variety of plasma shaping and magnetic configurations. As for the burning temperature control, decisive control method has not been identified yet, mainly because the definite transport scaling law is not known. Since the burning control is a key issue for the ignition physics, this control is a major research item for FER. Thus the device should have a capability to install or replace possible major control schemes, including heating and current drive systems. Stability control is essential for the sound operation of FER to achieve the mission. Although the control methods for various instabilities are not clearly known, similar scale of device flexibility as the shaping and burn control should be installed or replaced. Impurity control is also one of the key issues to achieve self-ignited long burning. However optimum divertor configuration, and also optimum divertor and wall material, which are suitable for the burning plasma, are not well understood yet. As for divertor materials, low Z material, e.g. graphite, is found favorable in the present day experiments, by suppressing the contamination of heavy metal impurities. However, graphite will not withstand long plasma burning due to its large erosion rate. In addition, it is expected that the plasma density control is rather difficult or very careful conditioning will be required due to the large adsorption of hydrogen in graphite. It is not clear that this feature can be compatible with H-mode plasma characteristics, since the suppression of density rise will be one of the key issues to maintain the H-mode plasma stably long. Thus, at present, it is difficult to specify the candidate material for divertor plate confidently. In this context, it is desirable to have a capability of replacing the divertor and first wall material, when it is necessary.

Major reason for the second requirement is that the device will become more attractive, if it has the potential to achieve more advanced purposes by altering the device with the additional investment, after having achieved the primary missions. Examples of these advanced purposes include high beta and steady state operations in physics area, and high fluence operation in engineering area.

Based on the summary in Table 1, we have prepared the following flexibility scenarios to cope with the expected possible uncertainties.

(1) Plasma size enlargement scenario to maximize the plasma size by decreasing or improving the shield and altering the divertor structure.

(2) Plasma shape flexibility scenario for the operations with a variety of plasma shape, e.g., high triangular shape double null configuration,

limiter operation.

(3) Heating/Current drive/Control system flexibility scenario to provide flexible machine structure, which enables replacement and/or addition of various heating/current drive/control system, even after DT operation.

(4) Impurity control system flexibility scenario for the modification of divertor structure (e.g., long divertor throat, closed divertor structure), and replacement of wall and divertor plate materials.

(5) Advanced operation scenario to provide the flexibility for future possible advanced operation scenario, such as high beta, high neutron wall loading, high heat flux operation, steady state operation, and high fluence operation.

3. Sensitivity studies

Before proceeding to the detailed studies of each scenario, we have made sensitivity studies to examine the effect of size enlargement on ignition margin. The effects of the reduction of inboard (Δa_{in}), outboard (Δa_{out}), upper and lower (Δb) shield are shown in Fig.1. In this study, standard FER scaling law (Mirnov type)1) is assumed and other geometrical parameters are fixed to FER reference reactor (option ACS) parameters2). Safety factor q_φ is fixed, so the plasma current is changed according to the alteration of the device geometry. It is seen from this figure that the effect of Δa_{in} and Δb are remarkable, while no increase of ignition margin is obtained with Δa_{out}. In Fig.2, the effect of the increase of ellipticity (κ), triangularity (δ), magnetic field on axis (B_T) and Troyon coefficient (C_β) on the ignition margin I_g are shown. In Figs.3-6, the effects are examined for a variety of confinement scaling laws. The expressions of these scaling laws are tabulated in Table 2. General tendency of the increase in ignition margin is fairly similar for all of the scaling laws considered, while the degree of increase is slightly different.

4. Plasma size enlargement scenario

According to the sensitivity studies in the previous section, enlargement of plasma size by reducing the shield thickness of inboard and

limiter operation.

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4. Plasma size enlargement scenario

According to the sensitivity studies in the previous section, enlargement of plasma size by reducing the shield thickness of inboard and

lower/upper shield and by altering the divertor into thin flat structure is fairly effective to increase the ignition margin. To reduce the shield thickness, stainless steel shield must be replaced by some other material, which has an equivalent shielding capability with thinner thickness, to satisfy the design criteria for toroidal coils. Here, as an example, the inboard shield is reduced by 10 cm and upper shield by 20 cm, by replacing each movable shield with tungsten shield. The divertor plate is also assumed to be replaced with thin flat type plate, which results in lowering the null point by 40 cm. The outboard shield is retracted by 25 cm only to keep the elongation to 1.7. The resultant plasma parameters and ignition margin for typical scaling laws are listed in Tables 3 and 4, respectively. Ignition margin is increased up to 1.5 based on the reference scaling law (Mirnov type). Figures 7 and 8 show the operation space of plasma current I_p and supplied volt-second to the plasma Ψ for the reference plasma and size enlarged plasma, respectively. Solid and dotted lines denote the limiting lines due to the maximum field (10 T for solenoid coils and 12 T for divertor coils) of each coil for high beta and low beta plasma, respectively. Coil numbers are labeled by square and their locations are shown in Fig.9. Note that the limiting lines of enlarged plasma move from those of reference plasma, particularly, line of No.15 coil (divertor coil) moves upward, since the null point approaches to the coil in this case. In addition, line of No.10 coil (solenoid coil) moves downward due to the cancelling effect by equilibrium field component. Mainly these two effects widen the operation space and compensate the increase of plasma current to some extent, and 200~300 seconds of burn time is still available in this enlarged plasma, if the plasma current can be ramped-up to 11.5 MA. Configuration of the enlarged plasma is shown in Fig.10.

Several contrivances must be considered for this alteration of the reactor core component. One possible method is that the inner and upper shield are combined into L-type structure, which can be removed and replaced with tungsten shield. As for divertor plate, it must be replaced with thinner flat type structure as shown in Fig.10. In addition, the outboard shield is retracted with use of the extra shield and spacer. For the inboard shield, tungsten shield must be partially installed in the permanent shield from the initial construction phase, to prevent the neutron streaming through the stainless steel vessel of tungsten pebble shield as shown in Fig.11. Heat flux on divertor plate becomes considerably high, since the fusion power increases and the inclination of the divertor plate becomes small due to the flat structure of the divertor. Graphite tile or tungsten armor with BeCu heat sink will be a possible candidate for divertor plate, while this simplified divertor structure may not withstand the long plasma burning or specified fluence, so that the simultaneous achievement of the physics missions (ignition and long burning) may not be attained in this contingency case. Retraction of outboard shield will cause the modification of outboard shield and also the toroidal field ripple becomes large. Possible method to avoid these potential problem is higher elongation plasma $\kappa \sim 1.87$ without retraction of the outboard shield. In this case, controllability of vertical position instability must be strengthened.

Application of this size enlargement scenario needs careful examination. Alteration of the reactor core structure, which is highly activated, is quite cumbersome task, and require considerable extra cost for tungsten shield. Thus, careful assessment for the ambiguity of physics data base should be made in, at least, two steps. The first step is at the start of construction. If the confinement scaling law and other physics data base have been sufficiently established in the existing devices by then, the construction will be started based on these data bases to realize the required device size. Even in this case, the capability for the flexibility of size enlargement scenario should be included, since the uncertainty under full DT burning condition should still remain. The second step is at the start of DT burning. During the initial hydrogen discharge phase, confinement scaling laws and other physics assumptions should be examined carefully, and the decision should be made on the plasma size in DT burning phase. If the experiments in hydrogen discharge phase are confirmed to be well described by the physics assumptions used in designing the device and the ambiguity of DT burning plasma is not expected to be so large, then DT operation will be started with the reference plasma size and the size enlargement scenario may be used for the contingency of the possible ambiguity with DT burning. When the expected plasma performance is not attained in hydrogen discharge, though such a situation should not be encountered, in principle, with a careful assessment of the physics data base at the construction start, size enlargement will be provided from the beginning of DT operation. With these procedure or phased operation and construction, difficulty in replacing and handling the highly activated component should be minimized and the cost could be saved if the physics assumptions hold as expected.

5. Plasma shape flexibility scenario

In this flexibility scenario, the degree of plasma shaping, such as elongation, triangularity, is increased and different configuration, such as double null divertor and limiter configuration, will be employed to increase the ignition margin or to operate with a different shaping plasma. Here, as an example, we will examine the effect of triangularity on the plasma operation. As shown in Fig.2, the ignition margin is increased with increasing the triangularity through the increase of the plasma current for the same q_φ value. However, the available burn time will be decreased due to the operating limit of the divertor coils or shoulder part of the solenoid coils. This feature is shown in Fig.12. Available volt-second in this figure is obtained from Fig.13, in which solid and dashed lines are the maximum field limiting curves of No.13 and 14 coils for high and low beta plasma with constant q_φ value as a function of triangularity. The start of burn is usually determined from the low beta line for No.13 and 14 coils (dashed line), so that the solid-dashed line shows the start of burn and end of burn. However, if the plasma beta is increased in low triangularity plasma and then the triangularity is increased to the specified value, the start of burn could be on the solid line (high beta line for No.13 or 14 coils), resultantly the available flux for burning could be increased. Shaded region in Fig.12 shows this possible increase of the available flux for burning. When the triangularity exceeds 0.3, the available flux decreases drastically. Thus, the plasma current and/or minor radius must be decreased to obtain a higher triangularity and finite burn time.

6. Heating, Current drive, Control systems flexibility scenario

Major items of this flexibility scenario include the flexible structure for using a variety of heating/current drive/control systems, and the back-up scenario for non-inductive current ramp-up. As for the first item, critical point is to use and replace tangential neutral beam injector and RF systems at any phase of the machine operation. As a matter of course, the decision of the methods for heating and current drive system needs a careful assessment of the data base at the start of construction and DT operation in the same context of the size enlargement scenario. Example of simultaneous

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As for the second item, two back-up scenarios are considered. One is reinforcement of LH power by increasing the number of LH port. This scenario is included in the category of the first item. Another is the modification of operation scenario. Figure 15 shows this example. In this figure, path (A) shows the reference operation scenario, where plasma current is ramped-up to 8.7 MA non-inductively and subsequently inductive burning starts. Path (B) shows an example of back-up scenario for non-inductive current ramp-up, where plasma current is ramped up to about 4 MA non-inductively, and subsequently ramped-up to 8.7 MA inductively. With this scenario, 100~150 seconds of burn time is still available, where we have assumed Spitzer resistivity and Neo-Alcator confinement scaling during the inductive current ramp-up phase. Path (C) is the full inductive operation, where 16 seconds flat top with 4 MA can be available. Plasma current could be ramped-up to 6 MA inductively, while no flat top is available in this case. This full inductive operation scenario will be useful for the initial cleaning up and aging of the plasma facing component and RF launcher, and so on.

7. Advanced operation scenario

Major purposes of this scenario are to provide the test bed for the demonstration of advanced physics, such as high beta, steady state operation and to provide the higher potential for engineering testing by, for example, high fluence operation, though they are not included in the primary missions for FER. Here, we will examine higher fluence operation ($\sim 1 MW \cdot Y/m^2$) as an example.

It is expected that the tritium procurement will be primary obstacle for this higher fluence operation. Then, it will be required to install tritium breeding blanket as much as possible. We assume that breeding blanket of 30 cm thickness with tungsten shield in the inboard region of the improved ACS reference reactor. Resultant device parameters are installation of tangential NBI and RF systems into the reference ACS reactor is shown in Fig.14. Several contrivances in design phase are necessary for this purpose. They include the removal of triangular post (this is also necessary for the size enlargement scenario), measure for the suppression of neutron streaming into water tank type shield due to the removal of the triangular post, and shape of outer shield modules.

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$a = 1.2\,m$, $R = 4.6\,m$, $B = 5\,T$, $I_p = 7.7\,MA$. Operation of this small plasma must inevitably be driven mode of operation. Figure 16 shows the feature of this mode of operation. Solid line shows Q value as a function of temperature, in which upper curve is evaluated with reference FER scaling (Mirnov type) and the lower curve with degraded scaling by a factor of 1.5. Dashed lines denote the required heating power for these operations. If the plasma current is fully driven non-inductively, required current drive power is shown by solid-dashed line, where current drive efficiency $\eta = n_{20}RI/P = 0.3$ was assumed. This value of the efficiency is the best data so far obtained in JT-60. Power balance is achieved at the temperature, where the line crosses with the dashed lines P_{in}. At this temperature, attained Q value is evaluated to be 3~4 both for reference and degraded confinement cases. In the case of full inductive operation, increasing the plasma temperature will be beneficial to a higher fluence with smaller shot number. As shown in Fig.17, neutron wall loading P_w decreases with temperature, while the burn time increases more rapidly, and consequently available fluence Φ during one shot of the burn increases.

8. Conclusions

Physics uncertainties and correspondingly required device and operational flexibilities in DT burning phase are reviewed. Based on the review, several typical flexibility scenarios have been chosen and studied in detail. They are (1) Plasma size enlargement scenario, (2) Plasma shape flexibility scenario, (3) Heating/Current drive/Control system flexibility scenario, (4) Impurity control system flexibility scenario and (5) Advanced operation scenario. All of the scenarios have been shown to be practicable and to enhance the device performance considerably. As for the size enlargement scenario, alteration of the reactor core component may require considerable cost, so total cost may exceed that of the larger device, which is designed to have larger ignition margin from the beginning. However, if the reference ACS reactor could ignite, no such alteration is necessary and total cost could surely be saved. Trade-off study for risk and cost-saving is necessary to establish the final flexibility scenarios. Also careful assessment of the physics data base is necessary at the start of construction and DT operation to decide which flexibility scenarios we should include into the device.

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(2) M. Sugihara, T. Mizoguchi, A. Hatayama, K. Shinya, S. Yamamoto et al.,Plasma Physics Design and Major Specifications of Candidate Reactors for FER Design Studies - Conceptual Design Study of FY86 FER -, Japan Atomic Energy Research Institute Report, JAERI-M 87-108 (1987) (in Japanese).

(3) Y. Shimomura, N. Suzuki, M. Sugihara, T. Tuda, K. Odajima et al., Empirical Scaling of Energy Confinement Time of L-mode and Optimized Mode and Some Consideration of Reactor Core Plasma in Tokamaks, Japan Atomic Energy Research Institute Report, JAERI-M 87-080 (1987).

(4) Y. Shimomura and K. Odajima, Comments on Plasma Physics and Controlled Fusion 10 (1987) 207.

Table 1 Major uncertainties on physics assumptions and corresponding required flexibilities

Physics assumptions (Research items for FER)	Uncertainties	Required flexibilities
(1) Confinement (•energy confinement •beta scaling)	◎ Confinement scaling in DT burning plasma ◎ Beta scaling in DT burning plasma	• Increasing plasma size, current, magnetic field by additional expense or innovations
(2) Heating and Current Drive	◎ Optimum heating methods to DT burning state ◎ Non-inductive current ramp-up to large plasma current ☆ Optimum non-inductive current drive scheme in burning plasma	• Replacement/addition of heating and current drive systems
(3) Plasma Control		
① Plasma shape, magnetic field configuration	◎ Optimum shape and field configuration to obtain optimum plasma performance in burning plasma	• Operation capability with a variety of plasma shapes and field configurations
② Burn Control	◎ Optimum burn control scheme	• Replacement/addition of all sorts of control system, especially heating/current drive system
③ Stability Control (disruption, MHD activity, profile control)	◎ Optimum control schemes for each instability in burning plasma	• same as above
④ Impurity Control and Ash Exhaust	◎ Optimum divertor configuration and divertor/wall materials in burning phase	• Alteration of divertor structure and replacement of divertor/wall materials

Table 2　Expressions for energy confinement scaling laws considered in sensitivity study

Scaling	Expression
FER Reference (Mirnov type)	$\tau_E = 0.155\ a\ I_p\ \sqrt{\kappa}$
ASDEX-H	$\tau_E = 0.1\ R\ I_p$
JAERI Optimized[3)]	$\tau_E = 0.045\ a\ R\ B\ \sqrt{\kappa}\ \sqrt{M}$
KG-H	$\tau_E = (\tau_{NA}^{-2} + (2\tau_{KG})^{-2})^{-0.5}$
KG-L	$\tau_E = (\tau_{NA}^{-2} + \tau_{KG}^{-2})^{-0.5}$
JAERI L-mode[4)]	$\tau_E = 0.085\ a^2\sqrt{M} + 0.095\ M^{0.2} Z_{eff}^{0.2} n_e^{0.6} I_p^{0.8} B^{0.2} a^{0.8} R^{1.4} \kappa^{0.4} P^{-1}$

Table 3 Major device and plasma parameters of enlarged plasma

Major radius	R (m)	4.5
Minor radius	a (m)	1.43
Field on axis	B (T)	4.53
Plasma current	I_p (MA)	11.5
Elongation	κ	1.7
Fusion power	P_f (MW)	635

Table 4 Ignition margin I_g, confinement time τ_E and Q value for various scaling laws of enlarged plasma

Scaling	τ_E	I_g	Q
FER Reference (Mirnov type)	3.30	1.51	∞
ASDEX-H	5.30	2.13	∞
JAERI-Optimized	2.21	1.29	∞
KG-H	2.25	1.11	∞
KG-L	0.64	0.35	2.75
JAERI L-mode	0.30	0.17	1.04

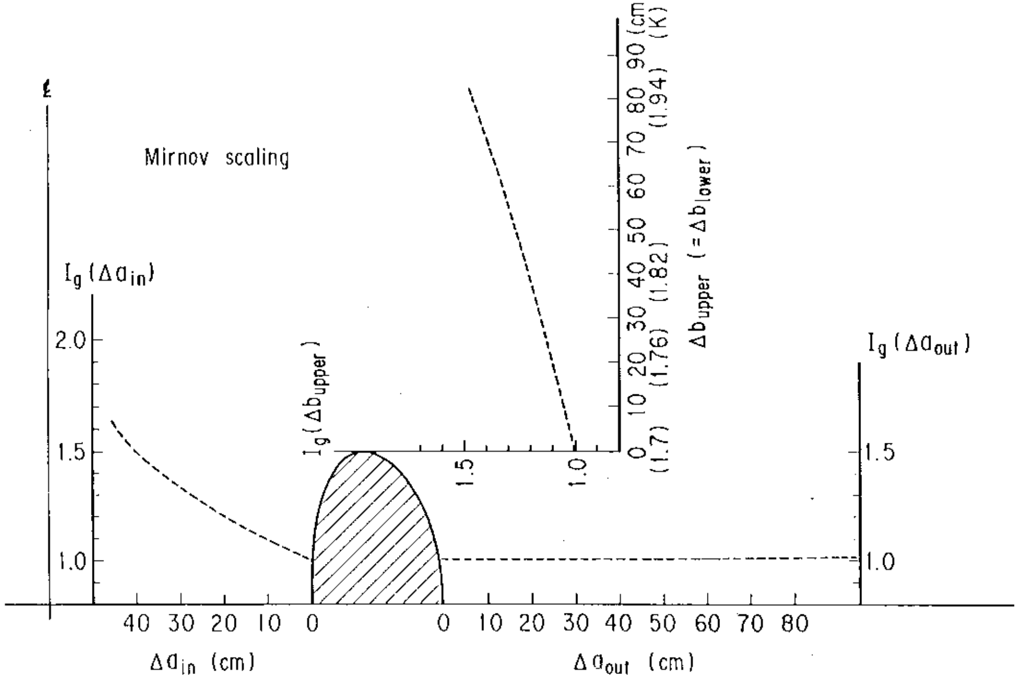

Fig. 1 Sensitivity for increase of ignition margin with respect to the reduction or retraction of the inboard (Δa_{in}), outboard (Δa_{out}) and lower/upper (Δb) shield.

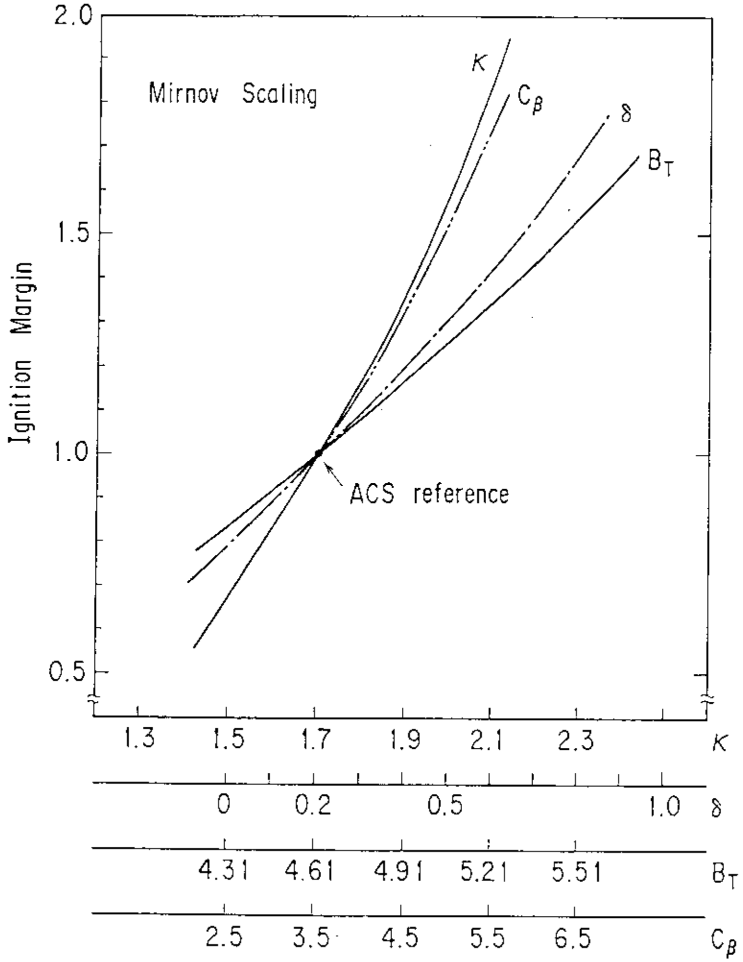

Fig. 2 Sensitivity for increase of ignition margin with respect to the increase of elongation (δ), triangularity (κ), field on axis (B_T), Troyon coefficient (C_β).

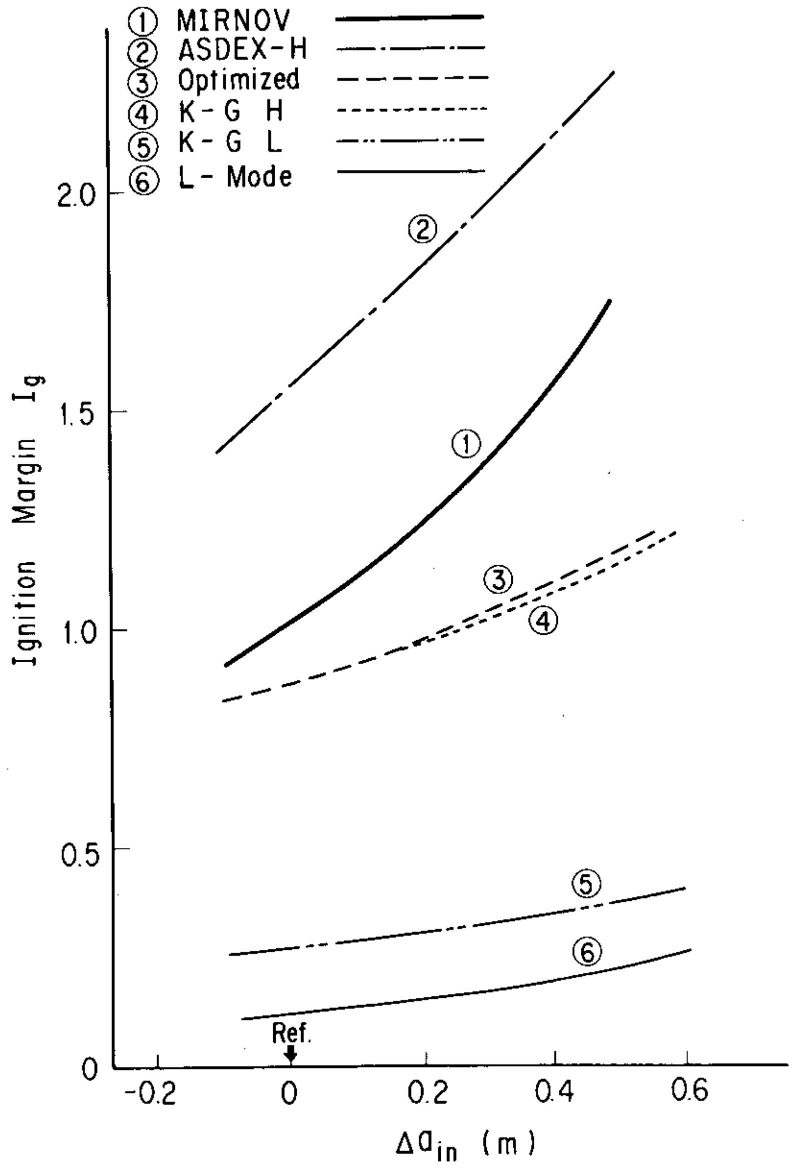

Fig. 3 Sensitivity for increase of ignition margin with respect to Δa_{in} for various scaling laws.

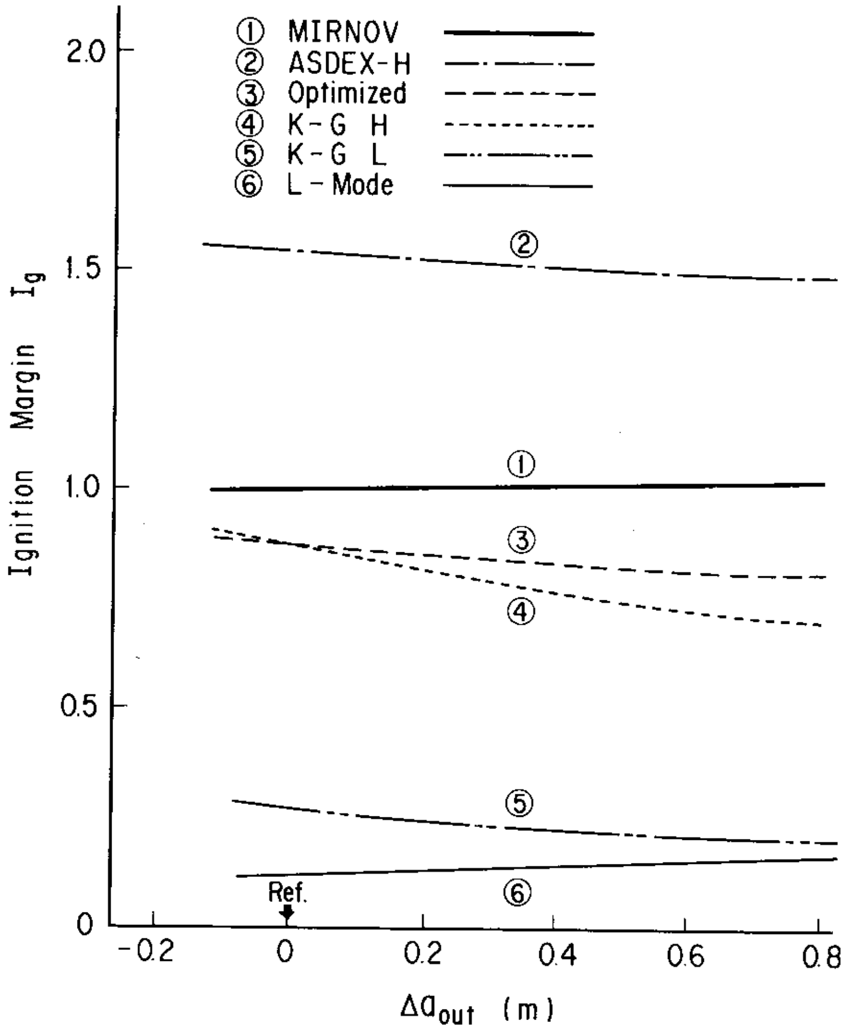

Fig. 4 Sensitivity for increase of ignition margin with respect to Δa_{out} for various scaling laws.

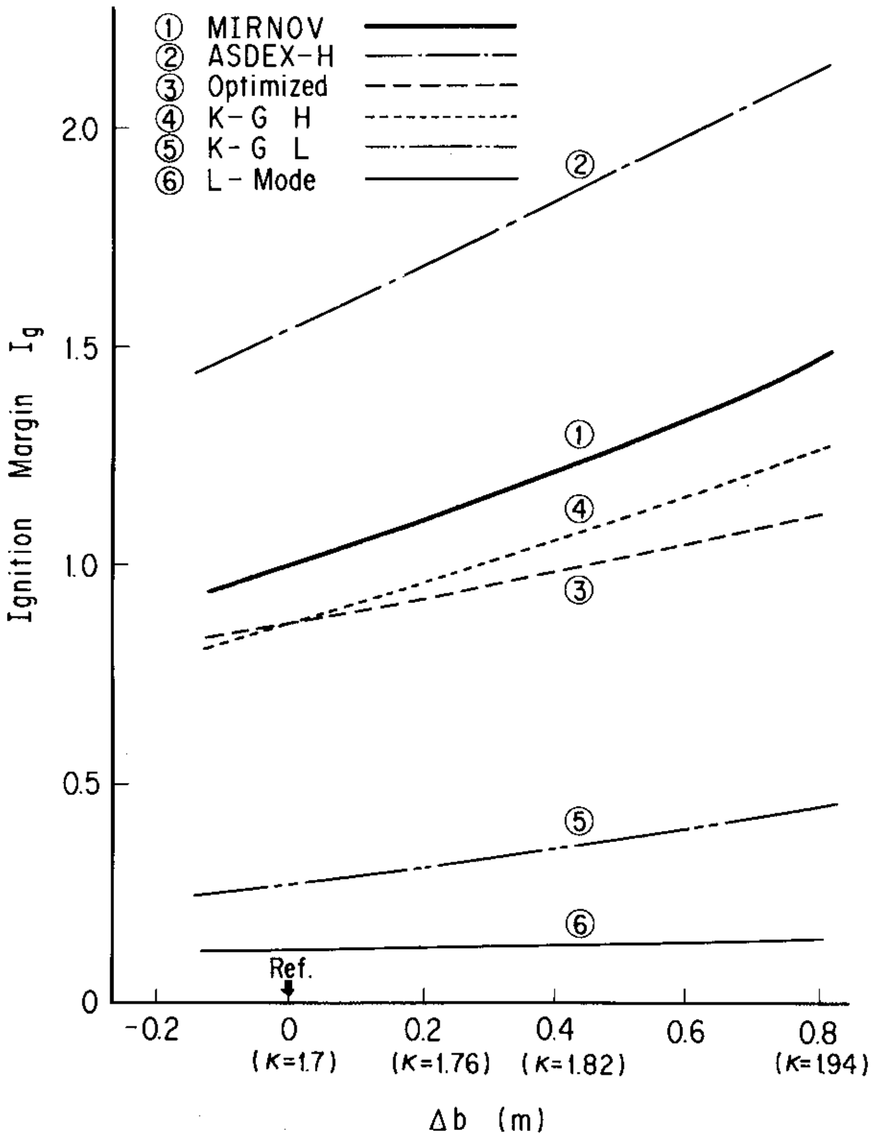

Fig. 5 Sensitivity for increase of ignition margin with respect to Δb for various scaling laws.

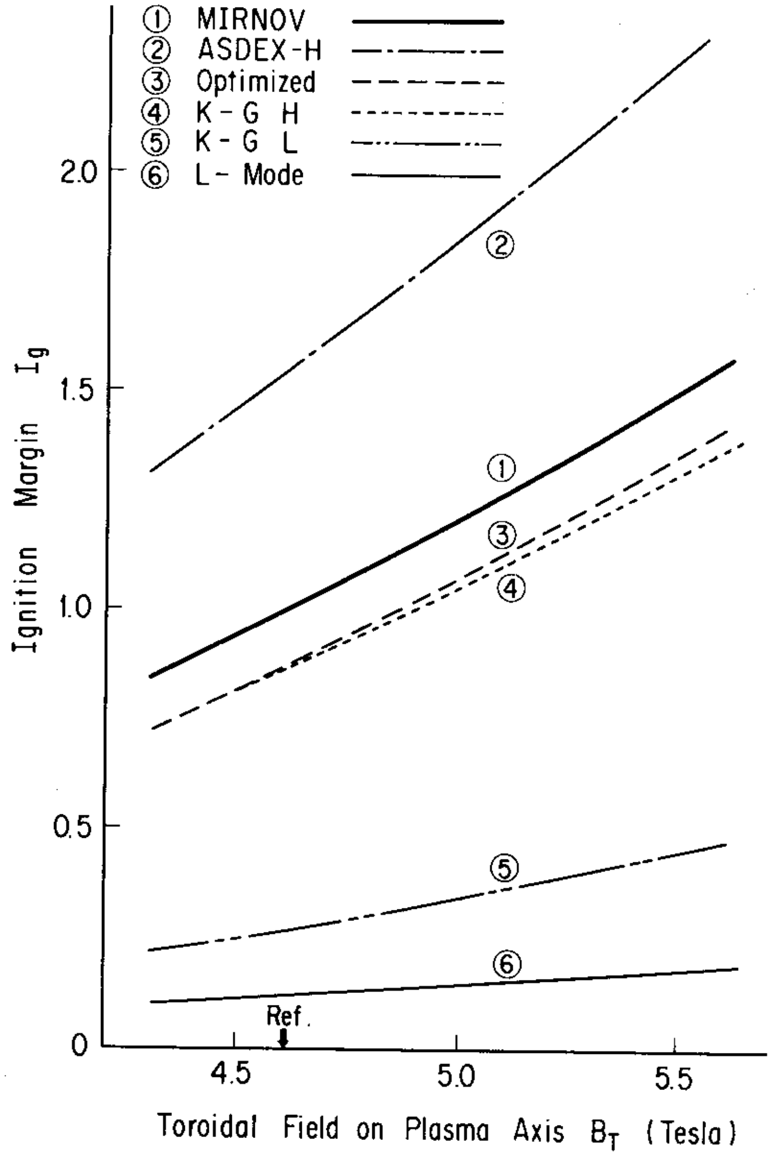

Fig. 6 Sensitivity for increase of ignition margin with respect to B_T for various scaling laws.

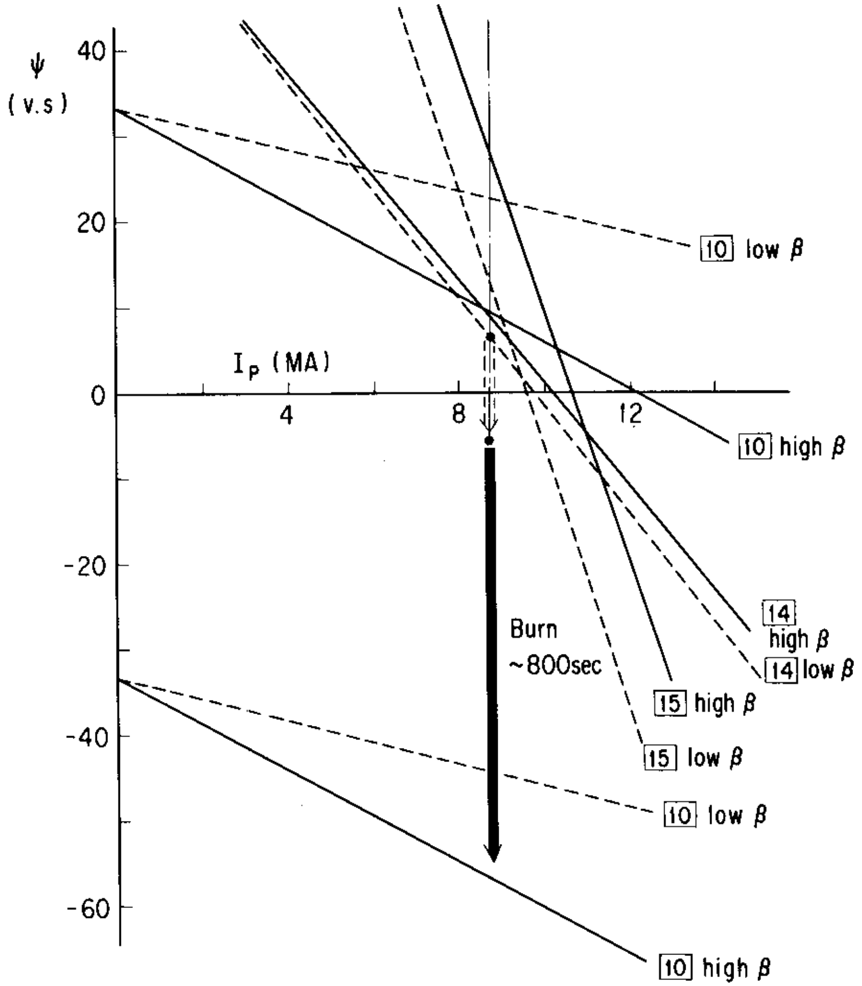

Fig. 7 Operation region in plasma current I_p and supplied volt-second ψ space for reference ACS plasma. Solid lines denote the limiting lines by maximum field in high beta plasma and dashed lines in low beta plasma, respectively.

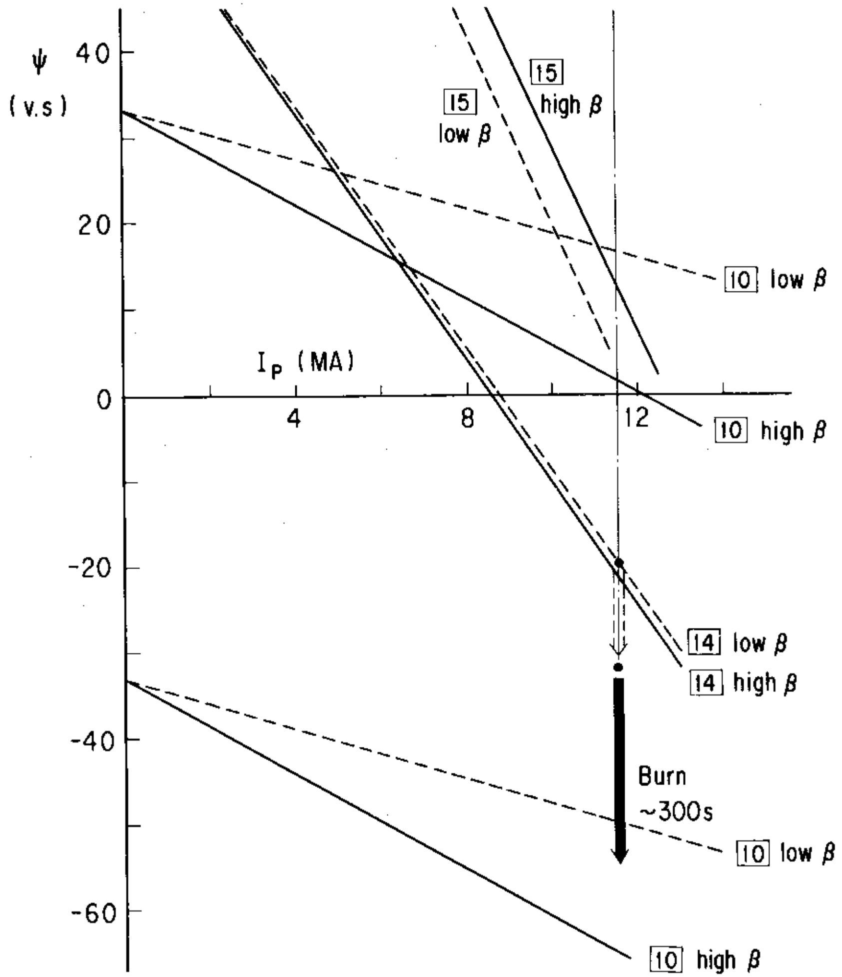

Fig. 8 Operation region in plasma current I_p and supplied volt-second ψ space for enlarged plasma. Solid lines denote the limiting lines by maximum field in high beta plasma and dashed lines in low beta plasma, respectively. Lines of #15 coil move upward, since the null point approaches the coil due to the enlargement of plasma size.

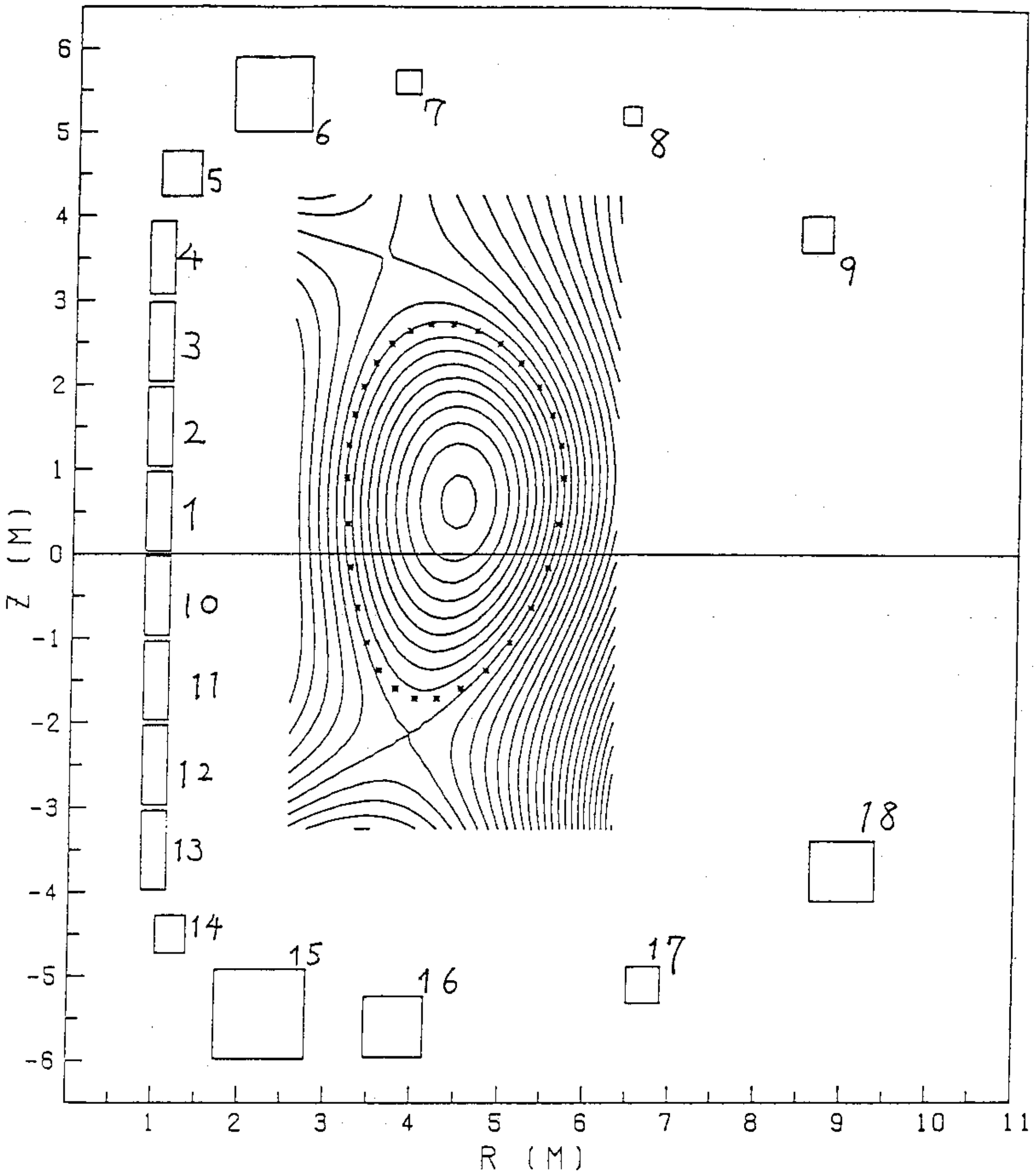

Fig. 9 Plasma equilibrium and coil location of ACS reference reactor.

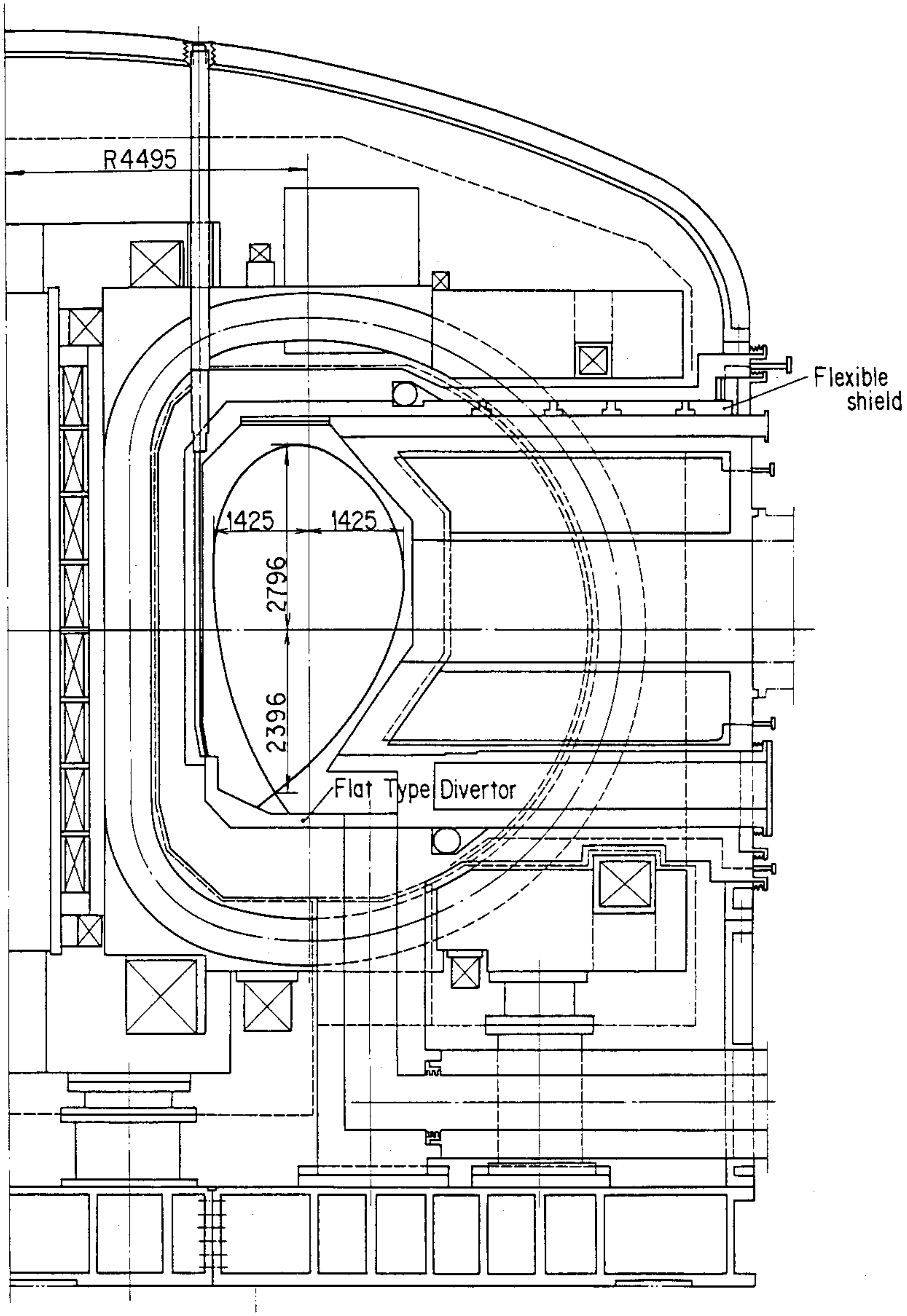

Fig. 10 Cross sectional view of enlarged plasma.

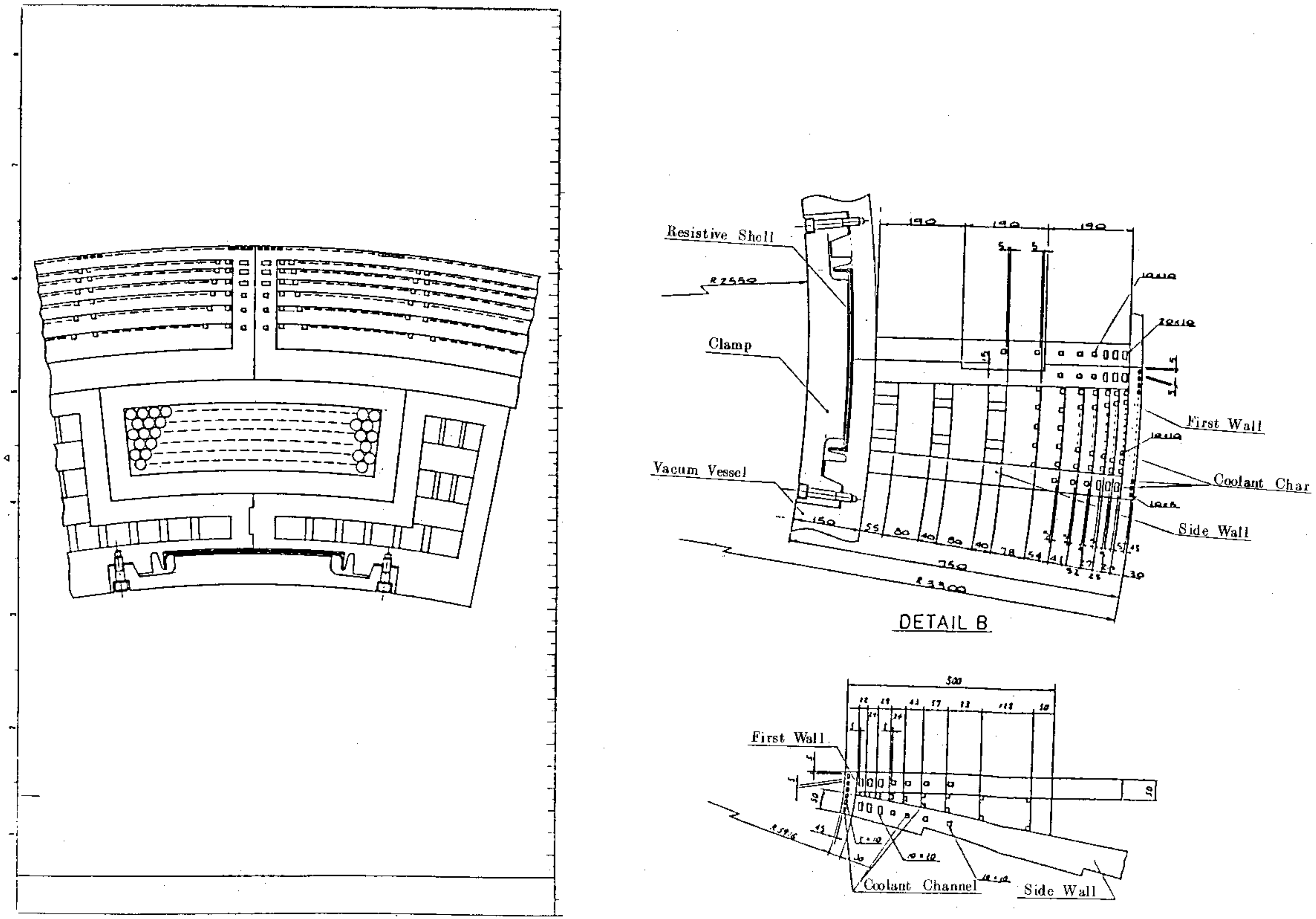

Fig. 11 Inboard shield altered into tungsten shield.

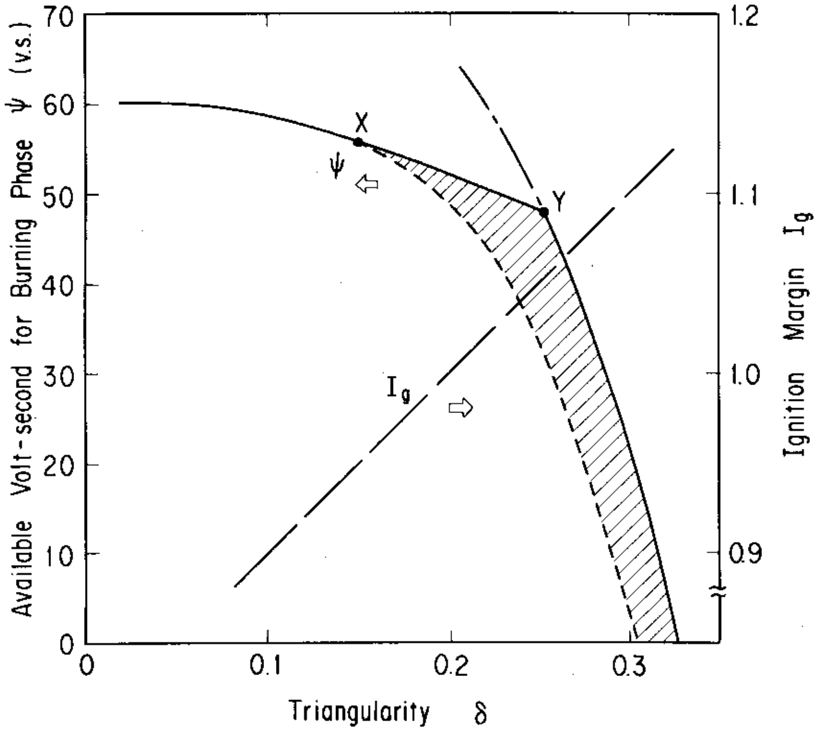

Fig. 12 Available volt-second ψ for burning phase and ignition margin I_g as a function of triangularity δ.

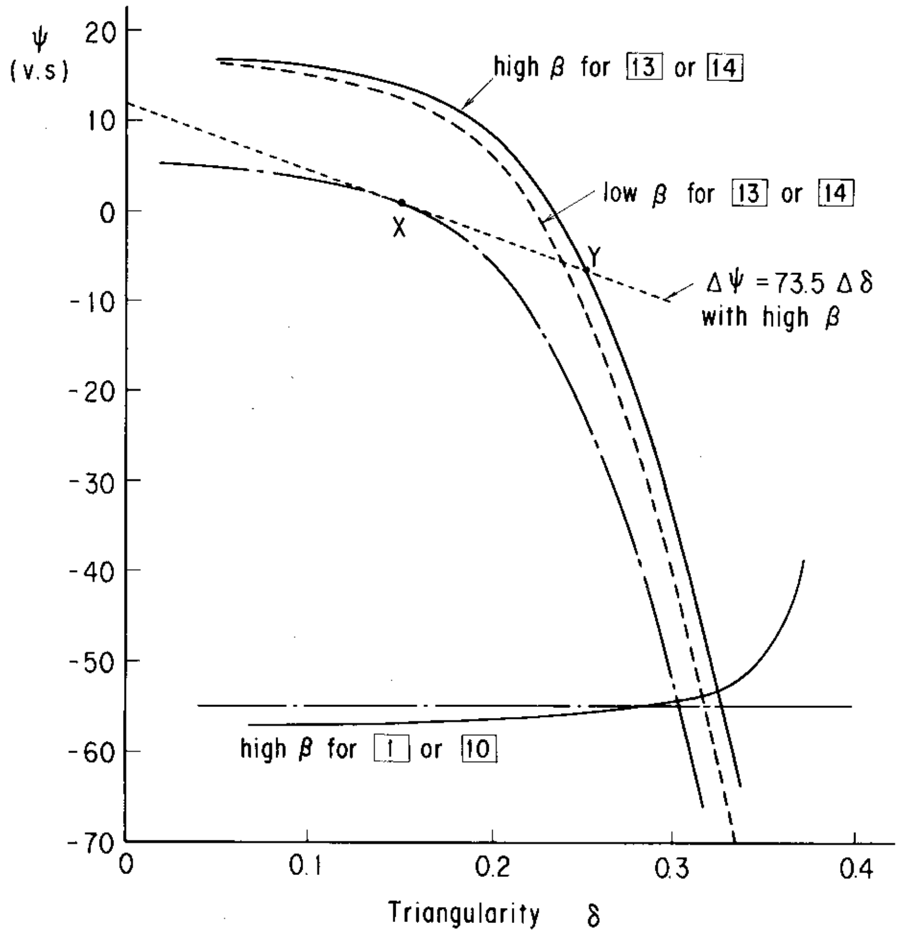

Fig. 13 Limiting curves by maximum field for #13 or 14 coils with respect to δ.

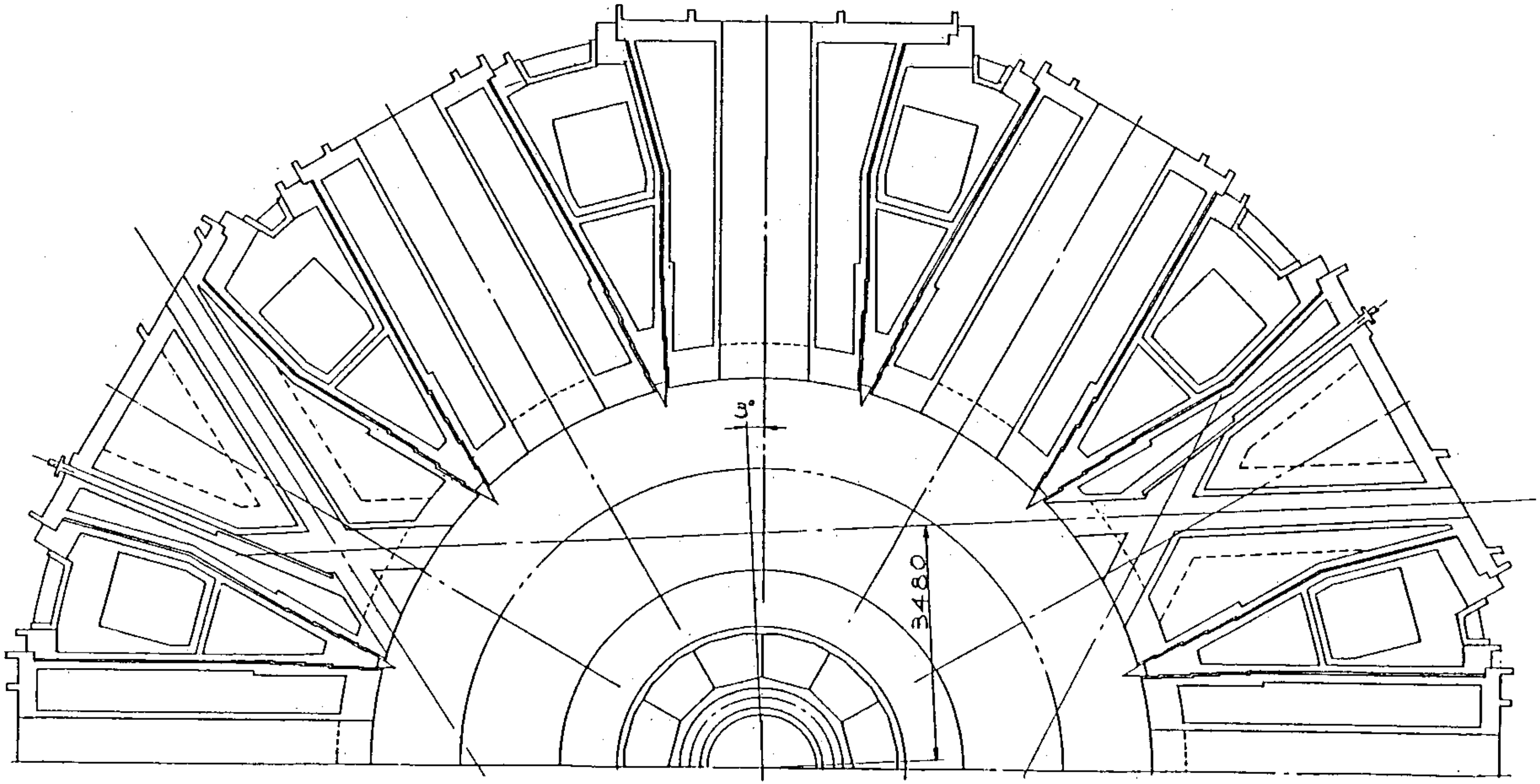

Fig. 14 Plane view of ACS reference reactor, where tangential injection NBI and RF systems are installed simultaneously.

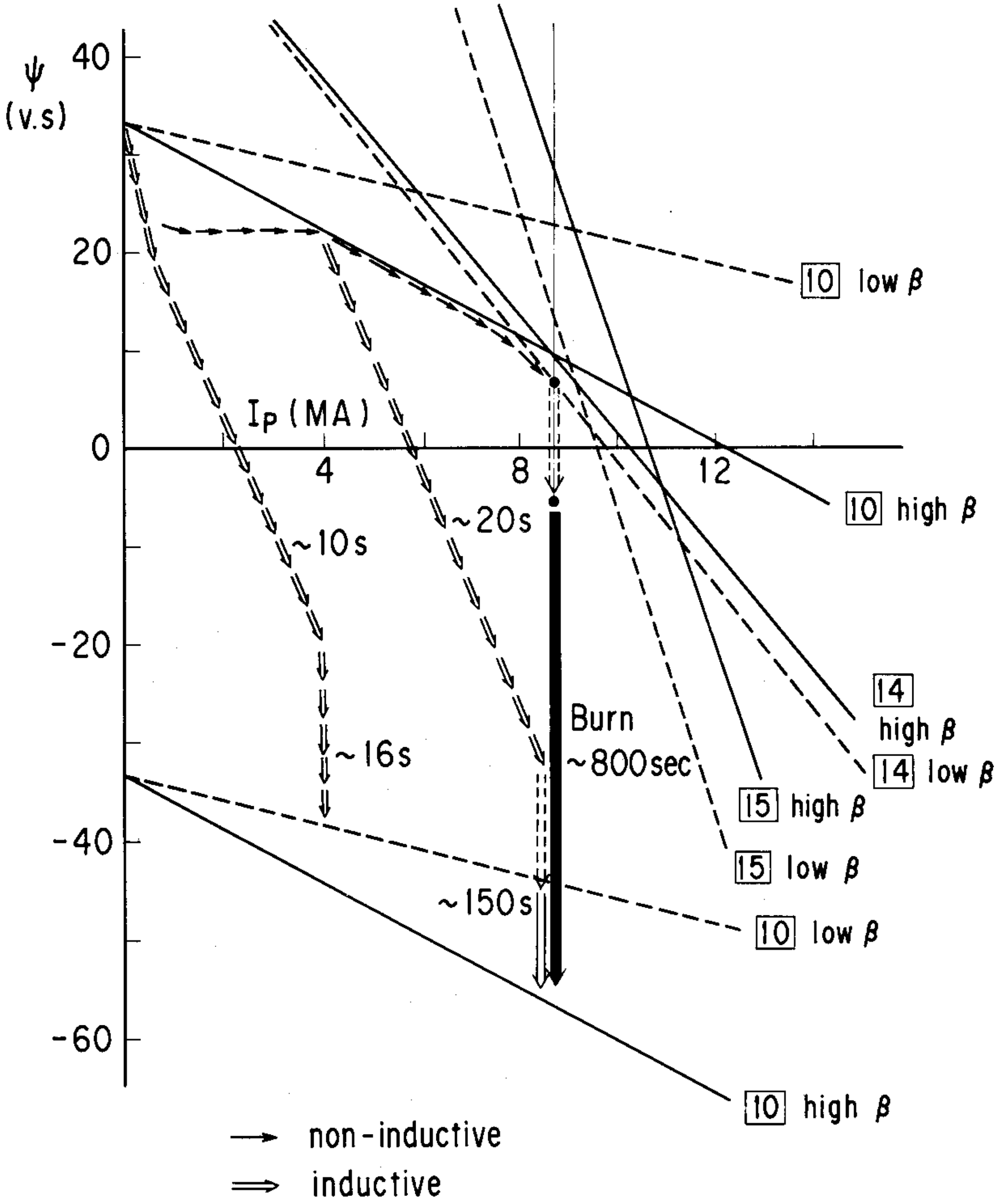

Fig. 15 Operation region in plasma current I_p and supplied volt-second ψ space for reference ACS plasma. Solid lines denote the limiting lines by maximum field in high beta plasma and dashed lines in low beta plasma, respectively. Path (A) denotes non-inductive current ramp-up scenario. Path (B) denotes the scenario, where plasma current is ramped-up to 4 MA non-inductively, and subsequently ramped-up inductively. Path (C) denotes the full inductive operation.

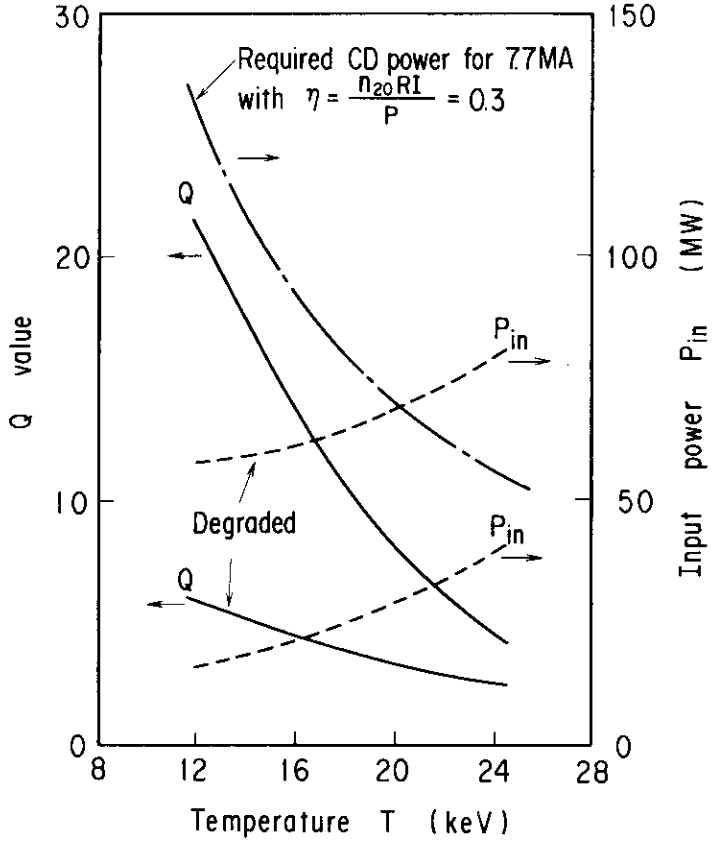

Fig. 16 Advanced operation scenario with small plasma size due to installation of breeding blanket. Solid lines denote available Q values for reference Mirnov type scaling (upper line) and degraded confinement by a factor of 1.5 (lower line). Dashed lines are required heating power for the respective Q values. Solid-dashed line shows the required current drive power for current drive efficiency $\eta = n_{20}RI/P = 0.3$.

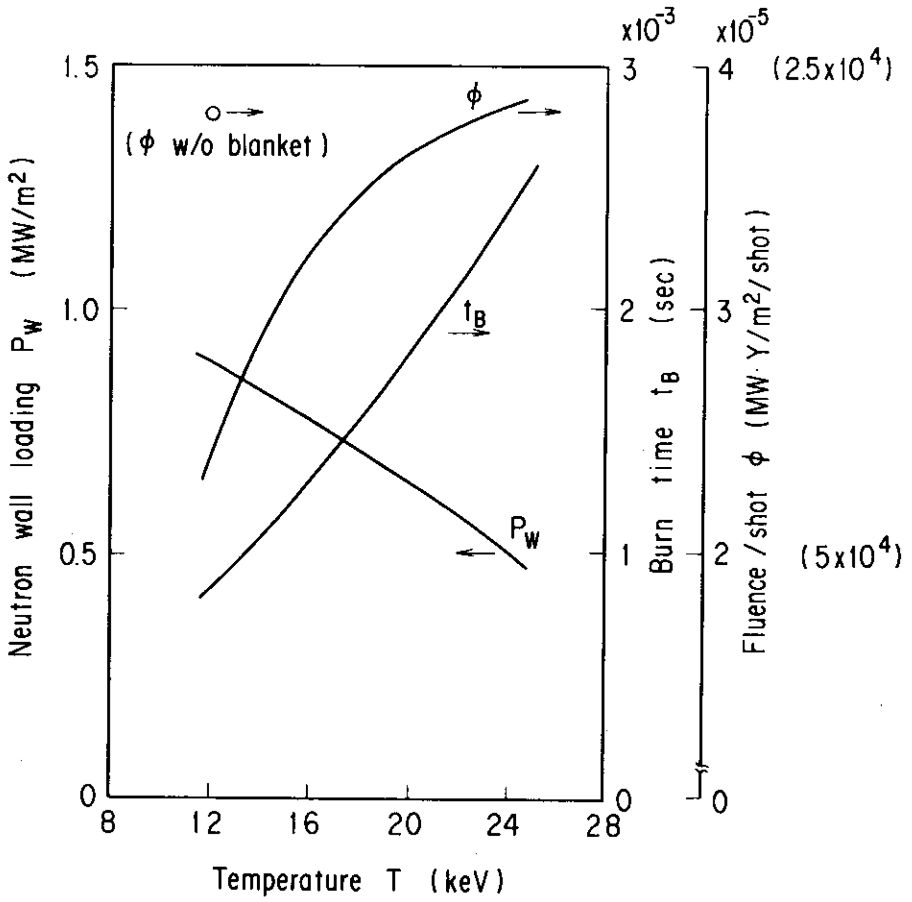

Fig. 17 Neutron wall loading P_w, burn time t_B, available fluence during one shot burning ϕ with respect to plasma temperature T in advanced operation scenario.