JAERI-M
87-096

OBSERVATION OF H-MODE BY ELECTRON CYCLOTRON HEATING OF JFT-2M TOKAMAK PREHEATED BY A NEUTRAL BEAM

July 1987

Katsumichi HOSHINO, Takumi YAMAMOTO, Norio SUZUKI
Hisato KAWASHIMA, Satoshi KASAI, Tomohide KAWAKAMI
Hikosuke MAEDA, Tohru MATOBA, Toshiaki MATSUDA
Hiroshi MATSUMOTO, Yukitoshi MIURA, Masahiro MORI
Kazuo ODAJIMA, Hiroaki OGAWA, Toshihide OGAWA
Kazumi OHASA, Seio SENGOKU, Teruaki SHOJI
Hiroshi TAMAI, Toshihiko YAMAUCHI, Yoshihiko UESUGI
and Akimasa FUNAHASHI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

JAERI-M レポートは、日本原子力研究所が不定期に公刊している研究報告書です。
入手の問合わせは、日本原子力研究所技術情報部情報資料課（〒319－11茨城県那珂郡東海村）あて、お申しこしください。なお、このほかに財団法人原子力弘済会資料センター（〒319-11茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.
Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　刷　日立高速印刷株式会社

Observation of H-mode by Electron Cyclotron Heating of JFT-2M Tokamak Preheated by a Neutral Beam

Katsumichi HOSHINO, Takumi YAMAMOTO, Norio SUZUKI
Hisato KAWASHIMA, Satoshi KASAI, Tomohide KAWAKAMI
Hikosuke MAEDA, Tohru MATOBA, Toshiaki MATSUDA
Hiroshi MATSUMOTO, Yukitoshi MIURA, Masahiro MORI
Kazuo ODAJIMA, Hiroaki OGAWA, Toshihide OGAWA,
Kazumi OHASA, Seio SENGOKU, Teruaki SHOJI
Hiroshi TAMAI, Toshihiko YAMAUCHI, Yoshihiko UESUGI
and Akimasa FUNAHASHI

Department of Thermonuclear Fusion Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

(Received June 11, 1987)

H-mode is observed by the electron cyclotron heating(ECH) of JFT-2M tokamak preheated by a neutral beam(NB). The effect of the ECH to the realization of the H-mode varies as the position of the electron cyclotron resonance(ECR) layer. The effect of ECH is prominent when the ECR layer locates just inside of the separatrix. This shows that the edge electron heating is effective for the attainment of the H-mode. And the effect of ECH is comparable to or better than that of the NB heating.

Keywords: H-mode, Electron Cyclotron Heating, JFT-2M Tokamak, Tokamak Confinement

中性粒子ビームにより予備加熱されたＪＦＴ－２Ｍトカマクの電子サイクロトロン加熱によるＨモードの観測

日本原子力研究所那珂研究所核融合研究部
星野　克道・山本　巧・鈴木　紀男・川島　寿人
河西　敏・河上　知秀・前田　彦祐・的場　徹
松田　俊明・松本　宏・三浦　幸俊・森　雅博
小田島和男・小川　宏明・小川　俊英・大麻　和美
仙石　盛夫・荘司　昭朗・玉井　広史・山内　俊彦
上杉　喜彦・船橋　昭昌

（１９８７年6月11日受理）

中性粒子ビーム（ＮＢ）により予備加熱されたＪＦＴ－２Ｍの電子サイクロトロン加熱（ＥＣＨ）によりＨモードが観測された。Ｈモードの実現に対するＥＣＨの効果は，電子サイクロトロン共鳴（ＥＣＲ）層の位置により変化する。

ＥＣＲ層がプラズマ周辺に存在するときに，ＥＣＨの効果が大である。このことは，Ｈモードの生成に対して周辺の電子加熱が効果的であることを示す。そして，ＥＣＨの効果は，中性粒子入射加熱と同等あるいはそれ以上である。

那珂研究所：〒311－02　茨城県那珂郡那珂町大字向山８０１－１

Contents

目　　次

1. Introduction

The H-mode state of tokamak plasmas has been found to be attained by neutral beam heating(NBH)[1-9] or by radio frequency heating of ion cyclotron range of frequency(ICRF)[8),10-12]. At the transition to the H-mode which is characterized by a sudden decrease in the intensity of the Deuterium Balmer line(D_α), the peripheral electron temperature is found to rise not only in H-mode in divertor configurations[2-4] but also in the limiter configurations[13]. Then it naturally arises a question whether H-transition occurs by heating the peripheral plasma or not. To investigate it, the ECH is suitable by its controllability of local power deposition. By this motivation, the first experiment was carried out in the JFT-2M tokamak in March 1986. And in some shots as shown in Fig. A(a), (b), H-transition was found during the ECH of NBI heated JFT-2M plasma. But the correlation was not firm. Since then, understanding of the operational region for the H-transition and experience have progressed much in the JFT-2M tokamak, and this time (June 1987), ECH has been clearly observed to bring L-mode during NBH to H-mode.

2. Experimental Setup

JFT-2M tokamak is a non-circular tokamak which has an iron core[14-15]. The major and minor radii of the full sized D-shaped plasma are R=1.31 m and a x b=0.35 m x 0.53 m. Operations with the plasma configurations of D-shaped limiter(elongation $\kappa < 1.7$), single null or double null divertor are possible. The limiter as well as the divertor plate is made of graphite (Fig.1). Taylor discharge cleaning is employed for the cleaning of the vacuum chamber.

The frequency of the ECH system is f=59.8 GHz[16], and net (radiated) power in this experiment is P_{ECH}=110 kW.

Typical hydrogen beam energy and current are 34 keV, 65A. Injection power of one beam line is up to 880 kW. The injection angle is 38° with respect to the plasma axis.

1. Introduction

The H-mode state of tokamak plasmas has been found to be attained by neutral beam heating(NBH)[1-9] or by radio frequency heating of ion cyclotron range of frequency(ICRF)[8),10-12]. At the transition to the H-mode which is characterized by a sudden decrease in the intensity of the Deuterium Balmer line(D_α), the peripheral electron temperature is found to rise not only in H-mode in divertor configurations[2-4] but also in the limiter configurations[13]. Then it naturally arises a question whether H-transition occurs by heating the peripheral plasma or not. To investigate it, the ECH is suitable by its controllability of local power deposition. By this motivation, the first experiment was carried out in the JFT-2M tokamak in March 1986. And in some shots as shown in Fig. A(a), (b), H-transition was found during the ECH of NBI heated JFT-2M plasma. But the correlation was not firm. Since then, understanding of the operational region for the H-transition and experience have progressed much in the JFT-2M tokamak, and this time (June 1987), ECH has been clearly observed to bring L-mode during NBH to H-mode.

2. Experimental Setup

JFT-2M tokamak is a non-circular tokamak which has an iron core[14-15]. The major and minor radii of the full sized D-shaped plasma are R=1.31 m and a x b=0.35 m x 0.53 m. Operations with the plasma configurations of D-shaped limiter(elongation $\kappa < 1.7$), single null or double null divertor are possible. The limiter as well as the divertor plate is made of graphite (Fig.1). Taylor discharge cleaning is employed for the cleaning of the vacuum chamber.

The frequency of the ECH system is f=59.8 GHz[16], and net (radiated) power in this experiment is P_{ECH}=110 kW.

Typical hydrogen beam energy and current are 34 keV, 65A. Injection power of one beam line is up to 880 kW. The injection angle is 38° with respect to the plasma axis.

3. Experimental Results

The plasma configuration taken in the experiment is lower single null divertor discharge as shown in Fig. 1. A conical horn antenna, which locates in the equatorial plane of the low field side, radiates the wave in the polarization of the extraordinary mode(X-mode). The smallness of the divergence of the microwave beam enables the local power deposition.

The line average plasma density is set below $\bar{n}_e < 2 \times 10^{19}\ m^{-3}$, because the cutoff density of the second harmonic ($f=2f_{ce}$, f_{ce}: electron cyclotron frequency) X-mode is $n_{eX} = 2.23 \times 10^{19}\ m^{-3}$.

The direction of the toroidal field is clockwise and the direction of the plasma current is counter clockwise in the top view. And the ion gradient-B drift ($\propto \vec{B} \times \nabla B$) is toward downward. The threshold power(P_c) for the transition to the H-mode by neutral beam heating(NBH) ranges between 220∿280 kW in the coinjection. The effect of ECH to the H-transition is found without ambiguity with restricted ECH power due to the low threshold power P_c of NBH in the JFT-2M tokamak.

The positions(r_0) of the second harmonic ECR layer are also shown in Fig. 1. Namely,

Case A: central toroidal field B_{t0} = 1.13 T, r_0/a=0.32
(a: radius of the separatrix = 28 cm)

Case B: B_{t0} = 1.23 T, r_0/a= 0.72,

Case C: B_{t0} = 1.31 T, r_0/a=1.1.

Thus the electron heating occurs in the off-center region of the plasma in case A, just inside of the separatrix in case B and just outside of the separatrix in Case C (cf. Fig.3(b)).

Fig. 2(a) shows a time evolution of the H-shot by ECH in the case B. The ECR layer locates just inside of the separatrix. The NBH power (P_{NBH} = 145 kW) applied for 0.2 sec is well below the threshold power (P_c = 250∿280 kW). By the application of ECH at time of t=0.8 sec(P_{ECH}=113kW, radiated power), the intensity I_{ECE} of the electron cyclotron emission (f=90.0 GHz) which indicates the radiation temperature around r = -30 cm(r/a=1.0), begins to rise, and the intensity of the D_α line begins to be depressed. Then clear H-transition occurs. Thus the ECH brought the L-mode state to H-state. This H-state has another typical characteristics of the H-mode: those are, the linear increase in the density and increase in the stored energy(W_s). The H-state continues till the end of the ECH pulse (70∿80msec). The large drop in loop voltage V_L shows that an efficient electron heating occurs by the peripheral ECH, taking that the displacement of the plasma column is controlled well within 1 cm into account. The total additional power injected into the vacuum chamber is P_{tot}=258 kW (ECH: 113 kW, NBI: 145 kW) in this case. Fig. 2(c) shows the same case with NBH(P_{NBH}=252 kW) only. Conditions are the same as in Fig. 2(a). The P_{NBH} is almost as large as P_{tot}(= P_{ECH}+P_{NBH}) in the previous case (Fig. 2(a)). P_{NBH} of this case is very close to the threshold power P_c. But, as seen, the clear suppression of the D_α line does not occur.

By comparing Fig. 2(a) and 2(c), it is known that edge electron heating is effective for the realization of the H-mode.

Fig. 2(b) and 2(d) shows a variation of the stored energy W_s^{FIT} obtained from a magnatic fitting with density for the cases in Fig. 2(a) and 2(c), respectively. The attained stored energy W_s^{FIT} is almost the same as W_s^{FIT} = 15 kJ (ℓ_i=1.0). A difference between the two cases is shown in density. $\bar{n}_e$ reaches $3.5 \times 10^{19} m^{-3}$ with ECH without H to L re-transition. Whereas the H to L re-transition occurs at 2.7×10^{19} m^{-3} with NBI only. The marked feature in both cases is that the stored energy W_s^{FIT} saturates at almost a constant value during the H-mode in spite of the linear increase in density during the H-mode.

In Fig. 3, an effectiveness of the ECH to the realization of the H-mode is compared among the case A, case B and case C. The abscissa is the position of the ECR layer r_0 nolmalized by the radius of the separatrix a. The ordinate of Fig. 3(b) is the NB power. The position of the limiter and the chamber wall is as shown in the figure. P_c(broken line) is the threshold power for the H-transition with NBH only.

The experimental procedure is as follows; Set the ECH power at constant power of P_{ECH}=113 kW. Inject the ECH in the preheated plasma by NBH. Vary the NBH power shot by shot, while the ECH power is fixed at the constant value. Examine whether H-transition occurs or not.

NB power at each shot in each case is plotted by a circle in Fig. 3(b). The closed circle indicates that the H-transition occured by ECH in that shot. The open circle indicates that the H-transition does not occur by ECH in that shot. A threshold NBH power P_{cE} at the L-H boundary, thus obtained, is shown by the solid line. As the effect of ECH becomes large, the region between P_c and P_{cE} (a hatched region) should extend below. P_c - P_{cE}, thus obtained, is plotted in Fig. 3(a) as a function of the position of the ECR layer. P_c-P_{cE} is considered as a kind of "saving of the NBH power" by ECH. This figure shows that this saving is the largest when the

ECR layer locates just inside of the separatrix(case B). This fact shows that the edge electron heating was more effective for the H-transition than the off-center resonance heating of case A.

In case B, the effect of ECH is larger than that of the NBH.

4. Conclusions

(1) By the application of ECH, H-transition of the L-mode plasma which is additionally heated by NBH is clearly demonstrated.

(2) The additional edge electron heating is shown to be effective for the attainment of the H-mode.

(3) ECH extends the plasma density of the H-mode to the larger value than NBH does. The H-to-L re-transition does not occur within the ECH pulse length in spite of such higher density.

(4) The stored energy during the H-mode by ECH as well as the H-mode by NBH stays almost constant in spite of the linear increase in density during the H-mode.

Acknowledgements

The authors are grateful to the members of the JFT-2M operation group for their excellent cooperation. They also acknowledge Drs. Y. Tanaka, M. Tanaka, K. Tomabechi and S. Mori of the Japan Atomic Energy Research Institute for their continuous encouragement.

ECR layer locates just inside of the separatrix(case B). This fact shows that the edge electron heating was more effective for the H-transition than the off-center resonance heating of case A.

In case B, the effect of ECH is larger than that of the NBH.

4. Conclusions

(1) By the application of ECH, H-transition of the L-mode plasma which is additionally heated by NBH is clearly demonstrated.

(2) The additional edge electron heating is shown to be effective for the attainment of the H-mode.

(3) ECH extends the plasma density of the H-mode to the larger value than NBH does. The H-to-L re-transition does not occur within the ECH pulse length in spite of such higher density.

(4) The stored energy during the H-mode by ECH as well as the H-mode by NBH stays almost constant in spite of the linear increase in density during the H-mode.

Acknowledgements

The authors are grateful to the members of the JFT-2M operation group for their excellent cooperation. They also acknowledge Drs. Y. Tanaka, M. Tanaka, K. Tomabechi and S. Mori of the Japan Atomic Energy Research Institute for their continuous encouragement.

ECR layer locates just inside of the separatrix(case B). This fact shows that the edge electron heating was more effective for the H-transition than the off-center resonance heating of case A.

In case B, the effect of ECH is larger than that of the NBH.

4. Conclusions

(1) By the application of ECH, H-transition of the L-mode plasma which is additionally heated by NBH is clearly demonstrated.
(2) The additional edge electron heating is shown to be effective for the attainment of the H-mode.
(3) ECH extends the plasma density of the H-mode to the larger value than NBH does. The H-to-L re-transition does not occur within the ECH pulse length in spite of such higher density.
(4) The stored energy during the H-mode by ECH as well as the H-mode by NBH stays almost constant in spite of the linear increase in density during the H-mode.

Acknowledgements

The authors are grateful to the members of the JFT-2M operation group for their excellent cooperation. They also acknowledge Drs. Y. Tanaka, M. Tanaka, K. Tomabechi and S. Mori of the Japan Atomic Energy Research Institute for their continuous encouragement.

References

1) Wagner F., Becher G., Behringer K., Campbell D., Eberhagen A., et al.: Phys. Rev. Lett. 49, 1408 (1982).

2) Wagner F., Fussmann G., Grave T., Keilhacker M., Kornherr M., et al.: Phys. Rev. Lett. 53, 1453 (1984).

3) Wagner F., Bartiromo R., Becker G., Bosch H., Eberhagen A., et al.: Nucl. Fusion 25, 1490 (1985).

4) Murman H. and Huang M.: Plasma Phys. and Contr. Fusion 27, 103 (1985).

5) Kaye S., Bell M., Bol K., Boyd D., Brau K., et al.: Proc. of the Eleventh European Conference on Controlled Fusion and Plasma Physics, Aachen, West Germany, 1983, part 1, p.19.

6) Nagami M., Kasai M., Kitsunezaki A., Kobayashi T., Konoshima S.: Nucl. Fusion 24, 183 (1984).

7) S. Sengoku and the JFT-2M team: J. Nucl. Mater. 145/147, 556 (1987).

8) Odajima K., Funahashi A., Hoshino K., Kasai S., Kawakami T., et al.: 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Kyoto, paper IAEA-CN-47/A-III-2 (1986).

9) Tanga A., Bartlett D., Behringer K., Bickerton R., Cheetham A., et al.: 11th Int. Conf. on Plasma Phys. and Controlled Nuclear Fusion Research, Kyoto, post deadline paper IAEA-CN-47/K-I-1 (1986).

10) Keilhacker M., Gierke G., Muller E., Murmann H., Söldner F., et al.: Controlled Fusion and Plasma Physics 28, 29 (1986).

11) Steinmetz K., Noterdaeme J., Wagner F., Wesner F., Bäumler J., et al.: Phys. Rev. Lett. 58, 124 (1987).

12) Matsumoto H., Ogawa T., Tamai H., Odajima K., Hasegawa M., et al.: Japan Atomic Energy Research Institute Report JAERI-M 86-147 (1986), to be published in Nucl. Fusion.

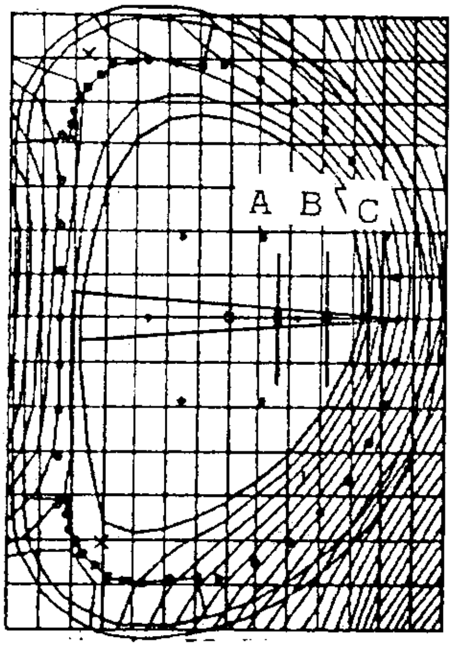
13) Hoshino K., Yamamoto T., Kawashima H., Yamauchi T., Uesugi Y., et al.: Jour. Phys. Soc. Jpn. 56, 1750 (1987).

14) Shoji T., Odajima K., Mori M., Suzuki N., Matsuzaki Y., et al.: Japan Atomic Energy Research Institute Report JAERI-M 83-194 [in Japanese] (1983).

15) Shoji T., Funahashi A., Hoshino K., Kasai S., Kawakami T.: Proc. of 11th Europ. Conf. on Controlled Fusion and Plasma Physics, Aachen, 1983, vol. 7D part 1, p.55.

16) Hoshino K., Yamamoto T., Kawashima H., Shibata T., Shibuya T.: Japan Atomic Energy Research Institute Report JAERI-M 85-169 (1985).

SHOT 38297
TIME(MSEC) 601



IP-CURRENT	(KA)	214.3
P-AVERAGE	(M)	1.296
Z-AVERAGE	(M)	-0.007
R-INNER	(M)	1.005
R-OUTER	(M)	1.586
RJ	(M)	1.292
ZJ	(M)	0.012
A-HALF	(M)	0.291
A-AVERAGE	(M)	0.337
ELLIPTICITY		1.398
TRIANGULARITY		0.517
CROSS AREA	(M**2)	0.358
VOLUME	(M**3)	2.912
Q-SURF		3.996
BT	(T)	1.227
BP+LI/2-1/2		0.336
BETAPI		0.465
QL-(1)		2.514
QL-(2)		2.762
STORED ENERGY		9.577
<BETA-T>	(%)	0.366
SEPARATRIX R	(M)	1.05
SEPARATRIX Z	(M)	-0.43

Fig. 1 Configuration in the experiment. Lower single null divertor configuration. Three positions (A, B, C) of the ECR layer are taken in the present experiment.

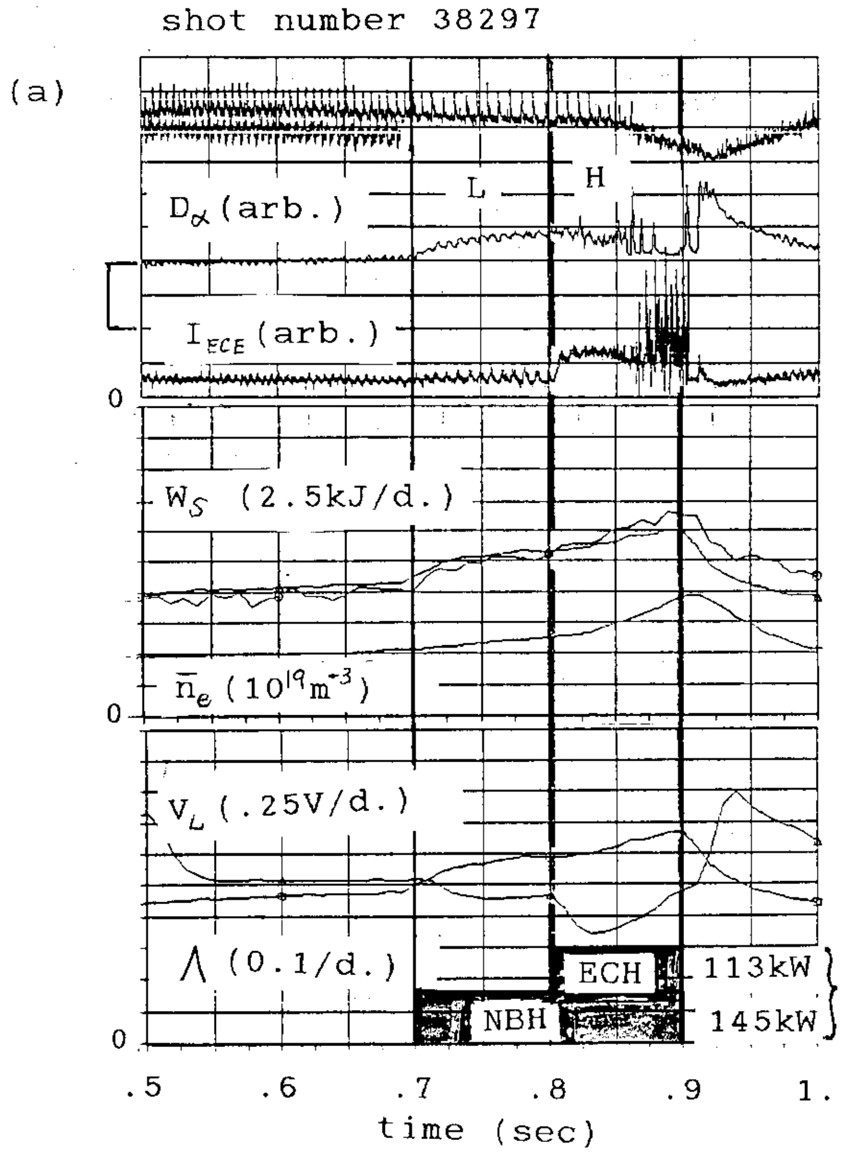


Fig. 2(a) Time evolution of the H-shot by ECH. B_{t0} = 1.23 T.

I_p= 214 kA. P_{ECH} =113 kW. P_{NBI} =145 kW. P_{tot} =258 kW.

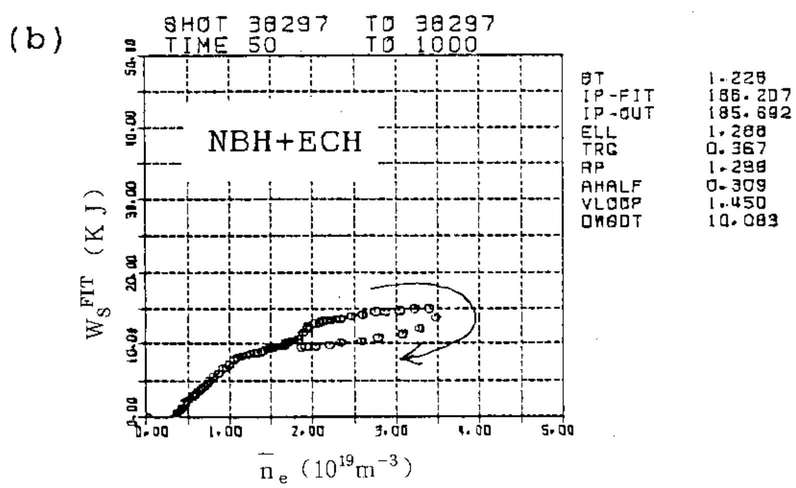


Fig. 2(b) Average density $\bar{n}_e$ vs. stored energy W_s^{FIT} for Fig. 2(a).

The conditions are the same as in Fig. 2(a).

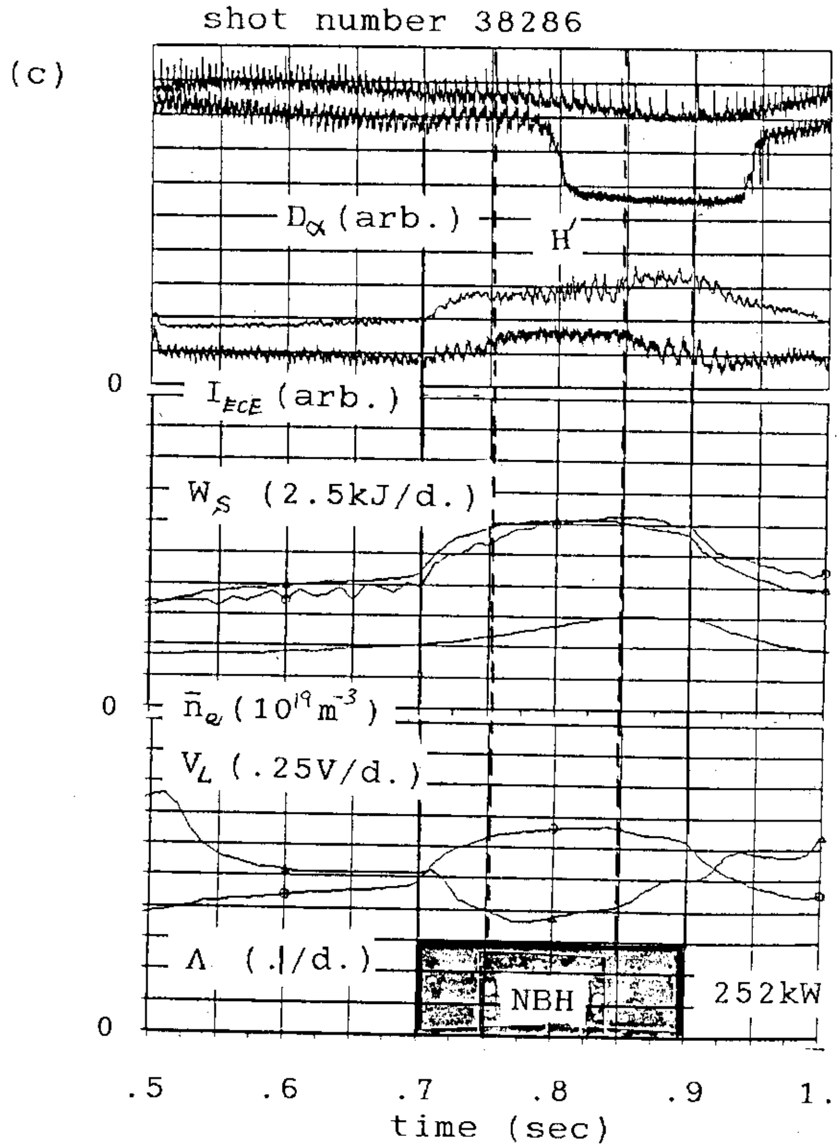


Fig. 2(c) Time evolution of H-shot by NBH. P_{NBH} =252 kW. Plasma conditions are the same as in Fig. 2(a).

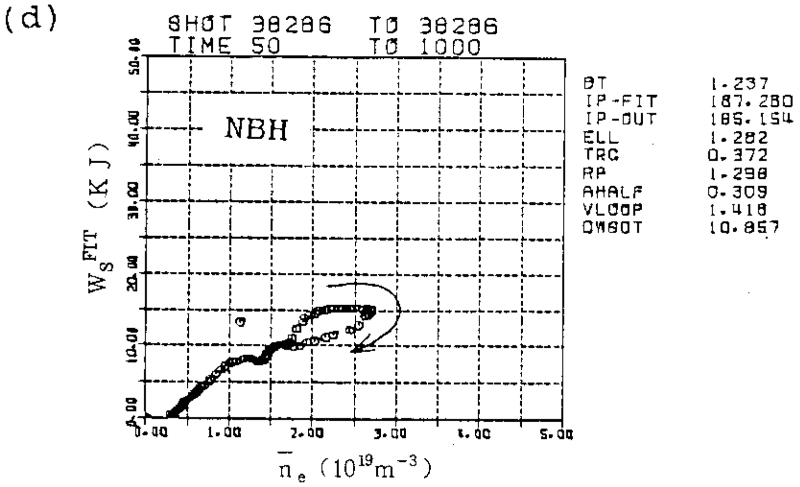


Fig. 2(d) Average density $\bar{n}_e$ vs. stored energy W_s^{FIT} for Fig. 2(c). The conditions are the same as in Fig. 2(c).

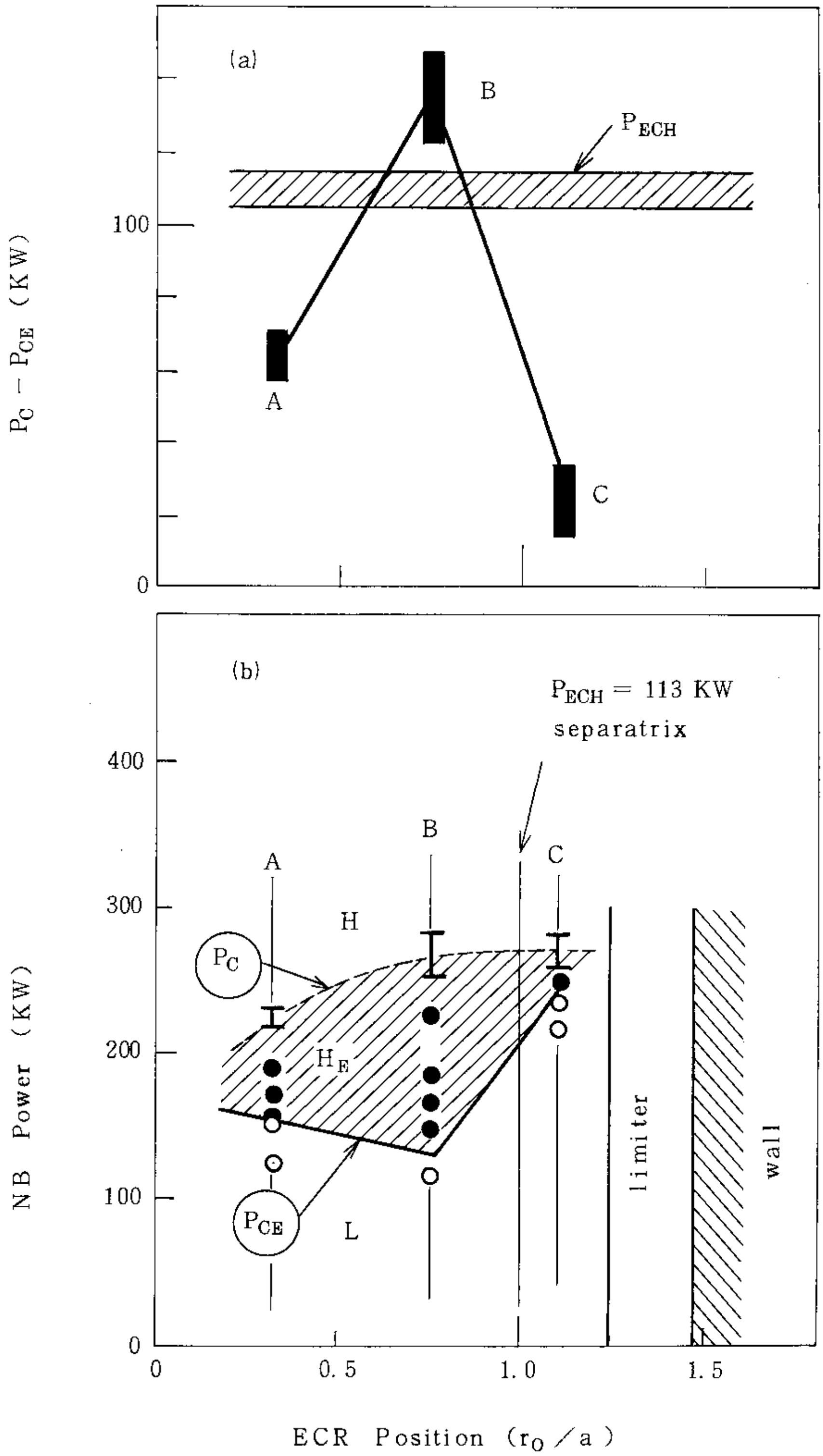


Fig. 3(a) Position of the ECR layer vs. P_c-P_{cE} . Here P_c is the threshold power for the H-transition by NBH. P_{cE} is the threshold power with ECH.

Fig. 3(b) Position of the ECR layer vs NB power. I_p= 214 kA. P_{ECH} = 113 kW. The hatched region indicates a "saving of NB power" by ECH.

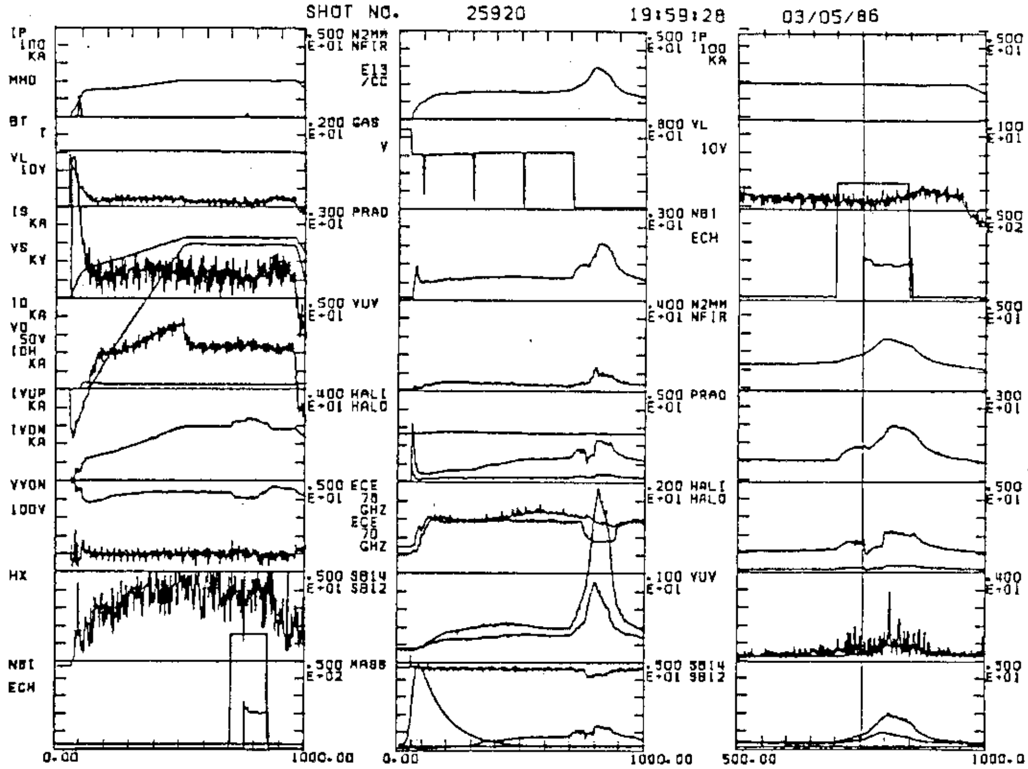


Fig. A(a) shot summary for the shot in which H-transition occurs during the ECH pulse superposed on NBH pulse.

Date: March 5/1986

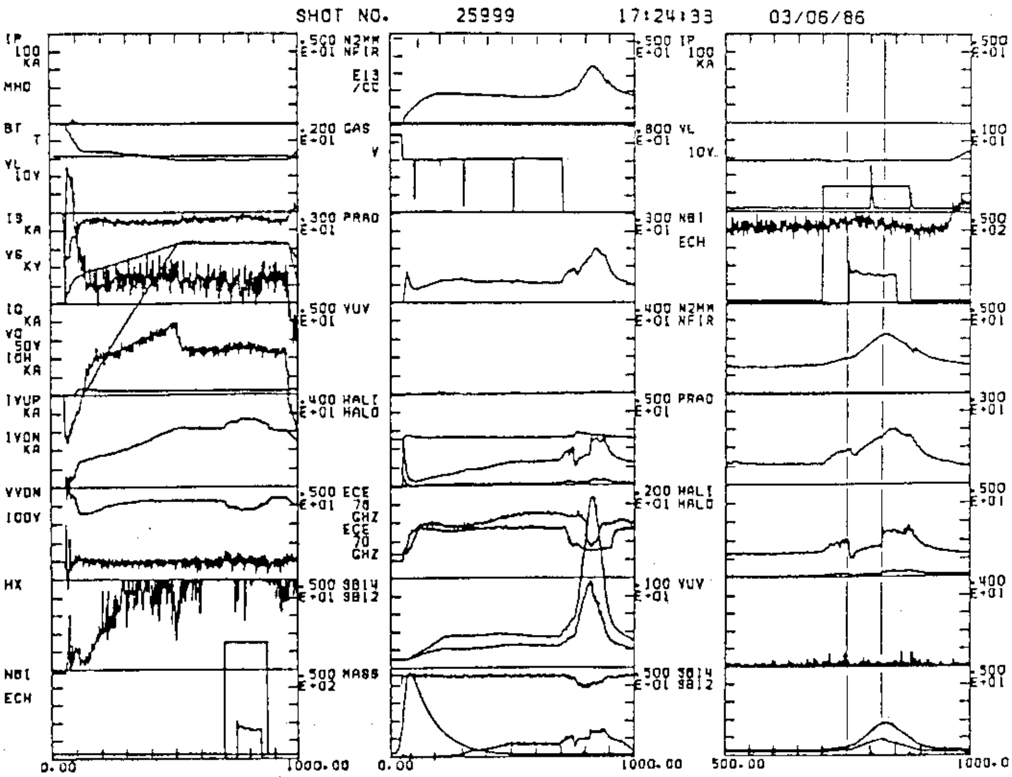


Fig. A(b) ibid. March 6/1986