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REQUIREMENTS IN THE EDGE FOR H-MODE TRANSITIONS

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

日本原子力研究所
Japan Atomic Energy Research Institute

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

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In JFT-2M, conditions for H-mode transitions in the periphery of the plasma were studied. It was found that edge electron temperature does not always determines the H-mode transition. In usual sawtooth triggered H-mode cases, the minimum edge electron temperature needed for H-mode transition decreased with the increase of the electron density. And this edge electron temperature and the density seems to control the transition phenomena in this case. However, there are cases when these parameters are not determining the transition. It was found that the threshold beam heating power for H-mode was found to decrease by lowering the beam acceleration voltage. In this case, the transition took place in lower edge temperature and lower electron density compared with higher beam voltage case. Power deposition calculation shows that the lower energy beam did not preferentially heat edge electrons, instead, it delivered more power to ions in the periphery.

Keywords: H-mode, Edge Plasma, JFT-2M

Hモード遷移のためのプラズマ周辺部における条件

日本原子力研究所那珂研究所核融合研究部
松本　宏・船橋　昭昌・星野　克道・川島　寿人
河上　知秀・前田　彦祐・的場　徹・松田　俊明
三浦　幸俊・森　雅博・中沢　一郎・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・鈴木　紀男・玉井　広史・上杉　喜彦
山内　俊彦・山本　巧

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ＪＦＴ－２Ｍ装置において，周辺プラズマにおけるＨモード遷移のための条件が研究され，周辺部における電子温度が必ずしもＨモード遷移の条件とはなっていないことが明らかにされた。まず，通常の，鋸歯状振動で，Ｈモードが引起こされる場合では，周辺電子温度と，電子密度がＨモード遷移の条件となっており，密度の高いところでは，遷移に必要な周辺電子温度は低くなっている。しかし，これらのプラズマパラメーターが，Ｈモード遷移現象の条件となっていない場合も見出された。ＪＦＴ－２Ｍでは，中性粒子入射加熱のビーム加速電圧を低くすると，Ｈモード遷移の加熱入力における閾値が低くなることが観測されているが，この場合，ビーム加速電圧が低い場合，より低い周辺電子温度，電子密度においてＨモード遷移が観測されている。加熱入力分布の計算によると，加速電圧が低い場合の方が，周辺部におけるイオン加熱が強くなり，電子加熱に関しては，あまり明確な差が見られないことが明らかとなった。このことから，Ｈモード遷移の条件として，イオン加熱が重要である可能性が示唆される。

那珂研究所：〒311-02　茨城県那珂郡那珂町大字向山801－1

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1. Introduction

Since the first discovery of the enhanced confinement mode,H-mode in ASDEX [1], extensive experimental efforts have been devoted to the study of the peripheral phenomena to understand the physical mechanism of H-mode. Because, many of the strong signatures of the H-mode transition are edge phenomena. Also, the fastest time scale phenomena associated with the H-mode transitions are edge phenomena too. For examples, sudden depression of the H_α/D_α in the periphery or the sudden broadening of the density profile near the edge. Usually, the central parameters change with much slower time scales after the transition compared to those peripheral phenomena.
One of the typical H-mode observations in the periphery is the sudden formation of edge electron temperature pedestal.This observation lead a type of theoretical modeling of H-mode which tries to explain the transition by the change of plasma current profile in the edge [2].
On JFT-2M, H-mode phenomena has been observed in the wide range of operational regimes, single null divertor, double null divertor, or limiter configurations. This versatile features of H-mode in JFT-2M could offer an unique opportunity to check already proposed theoretical modelings or the universality of the edge phenomena upon which these modelings were based.
In JFT-2M, characteristics of edge electron temperature during the H-mode transition period were investigated,and it was revealed that edge electron temperature is not always a required condition for H-mode.

2.Experiments

2.1 experimental arrangement

2.1.1 ECE edge electron temperature measurement

Edge electron temperature was measured by the ECE emission at 90 GHz which is the second harmonic electron cyclotron frequency at the toroidal magnetic field of 1.61 T [3]. In this series of the experiments, the toroidal magnetic field at the center of the machine, R=1.31 m, was fixed at BT=1.25 T, and the center of the plasma was positioned around R=1.30 m. The second harmonic electron cyclotron emission

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2.1.2 FIR interferometer measurement

Line averaged electron densities at three vertical chords are measured by a hydrogen cyanide laser interferometer system [4]) whose wavelength is in FIR region. Vertical chords run at R=1.52m, 1.24m, 1.1m, whereas the center of the machine is at R=1.31m.

2.1.3 JFT-2M tokamak

JFT-2M is a tokamak with non-circular cross section with the major radius of 1.31 m. The maximum horizontal minor radius decided by the fixed carbon limiter is 0.35 m, and the distance from the center of the machine to the top carbon limiter is 0.55 m. The Maximum toroidal magnetic field is 1.4 T, and the maximum plasma current is 500 kA with the limiter configuration.

2.1.4 NBI system

JFT-2M has co-and counter- tangential beam lines. Each line injects maximum of 850 kW of the beam power in hydrogen species into the torus.

2.2 Edge Parameters of H-transition

2.2.1 Types of transition phenomena on JFT-2M

On JFT-2M, many of H-mode transitions are triggered by a sawtooth oscillation. In Fig.1,an example of this typical transition case in limiter discharge is shown. Plasma parameters were, I_p=270 kA, B_T=1.25 T, κ=1.35, and 1.3 MW of hydrogen neutral beam was injected into deuterium plasma. From the top, time evolution of ECE emission from r=0.9a, line average electron density measured by FIR interferometer at R=1.22m, R=1.10m , a ratio of these two line averaged electron density $\bar{n}_e(R=1.11m)/\bar{n}_e(R=1.22m)$, magnetic fluctuation measured by $\dot{B}_\theta$ probe, and H_α/D_α emissivity are shown. ECE and FIR densities were measured with 0.2 ms of time resolution and $\dot{B}_\theta$probe signal was with 20ms. H_α/D_α were taken by 1ms of sampling time. From the traces of FIR densities, we see that the central code density takes a dip at each sawtooth crash, and the peripheral code density increases shortly after the crash. This indicates sawtooth also modifies the density profile. In this shot, a H-mode triggering sawtooth crash takes place at 793 ms indicated by the vertical line A. With about 2 ms of a delay,at the timing shown by the line B, sudden changes of several plasma parameters appear. Peripheral cord density starts rising, H_{α}/D_{α} emission starts decreasing strongly, and high frequency magnetic fluctuation dies down. In this case, H-mode transition phenomena was triggered by the perturbation in the periphery caused by the arrival of heat or particle pulse traveled from the center by the sawtooth. Also, the transition took place near the first peak of the edge electron temperature.

On JFT-2M, some of H-mode transitions are not triggered by sawtooth. In Fig.2, this second example is shown. This is a single null divertor discharge with I_p=250 kA, and B_T=1.24 T. 615 kW of hydrogen beam was injected into deuterium plasma. In this case, H-mode transition took place by two steps. The first transition took place around 720 ms At this timing, a sawtooth crash could be happening at the center, but it's heat pulse had not arrived at the periphery,and the edge electron temperature is still at the bottom and low. Although the decease of H_{α}/D_{α} started,and the peripheral cord density started increasing. High frequency magnetic fluctuation seems to decrease at this first transition time. Around 727 ms,the second transition took place, and magnetic fluctuation clearly changes suddenly this time. This second transition should be clearly independent of the sawtooth activity and it is also clear that edge electron temperature is irrelevant for the transition in this case.

2.2.2 Edge electron temperature and electron density

There is the minimum electron density above which we observe H-mode transition in JFT-2M in all kinds of H-mode operational modes. We clearly found the dependence of this threshold density on the heating power.particularly in limiter case. In Fig.3 circles show the minimum line averaged electron density needed at instances of the transition in each neutral beam heating power. Around the threshold heating power, we see that higher density is required for the transition with smaller heating power. Well above the threshold power, we still see the same dependence although it is weak. In this series of the experiment, edge electron temperature at the instance of the H-mode transition in 85 percent of the minor radius position were measured by ECE at the same time. And, this edge electron temperatures were plotted against the line averaged electron densities of the same instance in Fig.4. Then, it clearly shows that, electron temperature necessary for the transition decrease with the increase of the density, although the range of the temperature change is not so large. In this series of the experiment or in most of the typical sawtooth triggered H-mode shots, we can generally find this required conditions in the edge in terms of edge electron temperature and the density.

2.3 comparison between SOH and A2 configuration

In JFT-2M, there are two standard poloidal coil configurations to produce limiter plasmas. One configuration is called SOH configuration, and the other is called A-2 configuration. A-2 gives more triangularity, δ, to the plasma than SOH does with the same elongation factor, κ. In limiter H-mode experiment, we generally find dependence of the threshold heating power on κ. With higher κ we find smaller heating power needed for the transition [5]. In JFT-2M, non-circularity and the triangularity increase together. So, this dependence could be also a dependence on δ. With the same κ, we can compare the effect of δ only by changing the coil configuration. However we clearly see the difference of the threshold heating power between SOH and A-2 configurations with the same κ, plasma current, toroidal magnetic field.

Dependence of the threshold density on the heating power was compared between SOH and A2 configurations. Plasma current and toroidal magnetic field were almost the same, and ellipticity κ were close to 1.2. Triangularity δ was 0.15 for SOH and 0.38 for A-2. Figure 5 shows the comparison, and not only the threshold heating power for H-mode was higher with SOH, but also, the threshold density was higher with the same heating power compared with A-2 configuration.

Edge electron temperature were also compared between the A-2 and SOH configurations. In these cases,the line averaged electron density measured vertically at R=1.1 m , whereas the center of the plasma is at R=1.30 m, by FIR laser interferometer was used. In Fig.6, ordinate is the intensity of ECE emission which is proportional to the electron temperature at r=29 cm,and abscissa is the line averaged electron density. Circles show the transition point in the figure, and the line shows the trajectory of one shot just before and after the transition as an example. This trajectory starts from the left lower point, and it goes up and down by sawtooth activity. Density is slowly rising, and at the top of the second sawtooth, H-mode transition takes place, and the density suddenly starts rising strongly. Neutral beam power were around 700 kW in this series of the experiment. Similar plot with SOH configuration is shown in Fig. 7. In This figure, only trajectories of three shots are shown. The left hand side one is the no transition case with 1.2 MW of the injection. It reaches high enough temperature for the transition by the sawtooth excursions, but the density is not high enough. The right lower case, B, is also the L-mode case with the injection power of 600 kW. In this case, the density is enough, but the temperature is not high enough. and the last case, C, is the case where H-mode transition took place at the point marked by the circle. In this transition case, 1.2 MW was injected. If we compare this transition point with the previous figure, the transition point in SOH configuration was almost on the same transition boundary of A-2 configuration shown by the circles in Fig.6. Comparing the both, it is clear that heating efficiency of the edge is much better with A-2. In A-2, with only 700 kW of the injection, edge temperature were brought to the transition boundary, whereas 1.2 MW was necessary in SOH.

This H-mode boundary condition in edge electron temperature and edge electron density variable plane is not always the same in different experimental conditions. It seems to move with plasma current or safety factor.

2.4 Beam Energy dependence

In JFT-2M, dependence of the threshold power of the H-mode on the beam acceleration energy was also found. When a bucket type ion source which had a very good proton ratio, 80 % in H^+, 10% H^{++}, 10% H^{+++} was employed we saw a clear dependence.

We found a decrease of threshold power when the acceleration voltage was reduced as is shown in Fig. 8. The minimum injection power needed for H-mode transition in each beam acceleration voltage is shown in the figure. This clear dependence was not well observed with a Duo-Pigatron type ion source whose proton ratio was poor. Although, this duo-Pigatron type ion source gives lower threshold power compared with the bucket type ion source with the same acceleration voltage.

From this acceleration voltage dependence, one may naturally think about the possibility of more preferential heating of the edge by lowering the beam energy. Beam power deposition profile was calculated by the Fokker-Planck beam slowing down code assuming a circular plasma with the Thmoson scattering electron temperature and density profile. Deposition profiles with the beam voltage of 26 kV are shown in Fig.9 and the profiles of 37 kV are shown in Fig.10. Surprisingly, deposition to electrons are almost the same, whereas the slight difference in ion deposition between the two cases is found. More power is coupled to ions in the periphery in low beam energy case.

Edge electron temperature were measured by the ECE emission and compared between the two cases. Edge electron temperature is plotted against the peripheral cord line averaged electron density in Fig.11.The Trajectory A in the figure show the case of 750 kW injection heating at the beam energy of 36 kV. Another trajectory B, show the case of 600 kW injection at the energy of 26 kV. Edge electron temperature and the electron density near the edge are higher than those of lower beam energy case, although we did not see H-mode transition in this case. However, with the lower beam energy case, we did see the transition at lower edge temperature and the lower density.

3. Discussions

In JFT-2M H-mode experiment, it is important to heat edge to get H-mode. Easiness of attaining H-mode can be expressed by the threshold heating power for H-mode transition. This threshold power sometimes does not directly reflect the physics underlying the H-mode transition phenomena. A good example is the difference of the accessibility of H-mode between A-2 and SOH configuration in JFT-2M. The difference turned out to be due to the difference of L-mode heating efficiency of the plasma, rather than a difference of triangularity in these two configurations. On the other hand, the difference of the threshold power between the different beam acceleration voltage is not simply due to the efficiency of the edge electron heating. The experimental results suggest the difference of the ion heating instead. This has not been experimentally confirmed yet. The experimental observation that threshold electron temperature decreases with the the increase of the density also suggest the importance of ion heating through electron ion collisions. This importance of ion heating at the edge is still a speculation, and the results of power deposition profile calculation is quite sensitive to the boundary conditions and the experimental information put into that calculation was not very accurate. Although it is very clear that electron heating at the edge is not the essential required condition for H-mode transition. And, heating experiment of edge ions by ICRF or by IBW could give an important information to understand H-mode transition phenomena.

Another possible important condition for H-mode would be a temperature gradient or a pressure gradient. However we could not systematically measure the temperature or the pressure gradient in these series of the experiment, and cannot conclude anything about this possibility.

4. Conclusions

In most of the typical sawtooth triggered H-mode shots, we can generally find the condition in the edge necessary for the H-mode transition in terms of edge electron temperature and the density. Sometimes, difference of threshold heating power, or the difference

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of easiness in attaining H-mode in different experimental conditions could be attributed to the difference of edge heating efficiency in pre-transition L-mode phase to bring the edge electron temperature and density to the transition boundary.
However, in certain experimental conditions, especially when the transition is not triggered by sawtooth, this edge electron temperature is not the decisive parameter. Also, from the results of low beam acceleration voltage experiment, it is speculated that ion heating in the edge instead of electron heating could be important for the H-mode transition.

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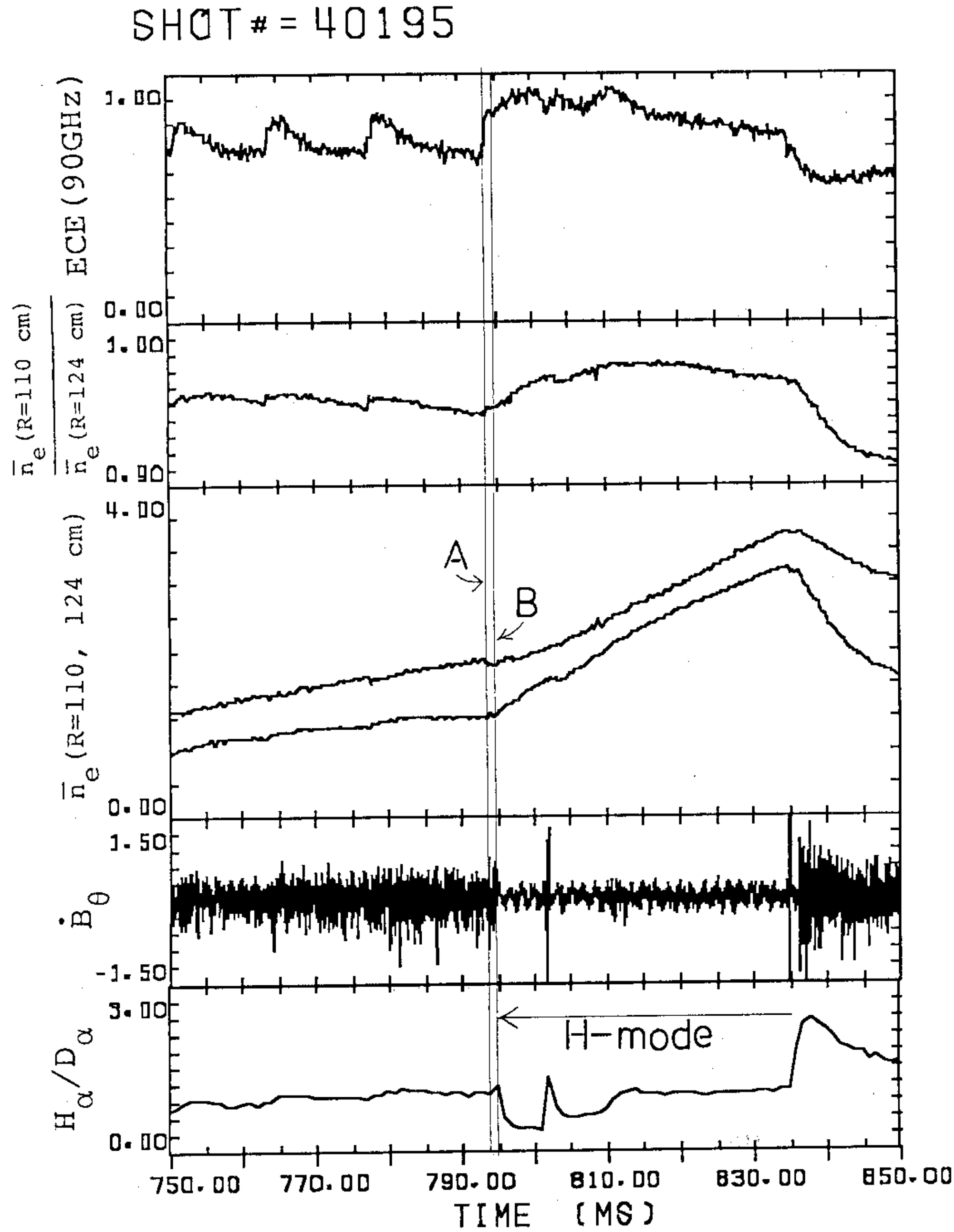

Fig. 1 Limiter H-mode case with 1.2 MW of NB injection with I_p=270 kA. From the top, time evolution of ECE emission from r=0.9a, line average electron density measured by FIR interferometer at R=1.22m, r=1.10m, a ratio of these two line averaged electron density $\bar{n}_e$(R=1.11m)/$\bar{n}_e$(R=1.22m), magnetic fluctuation measured by B_θ probe, and H_α/D_α emissivity.

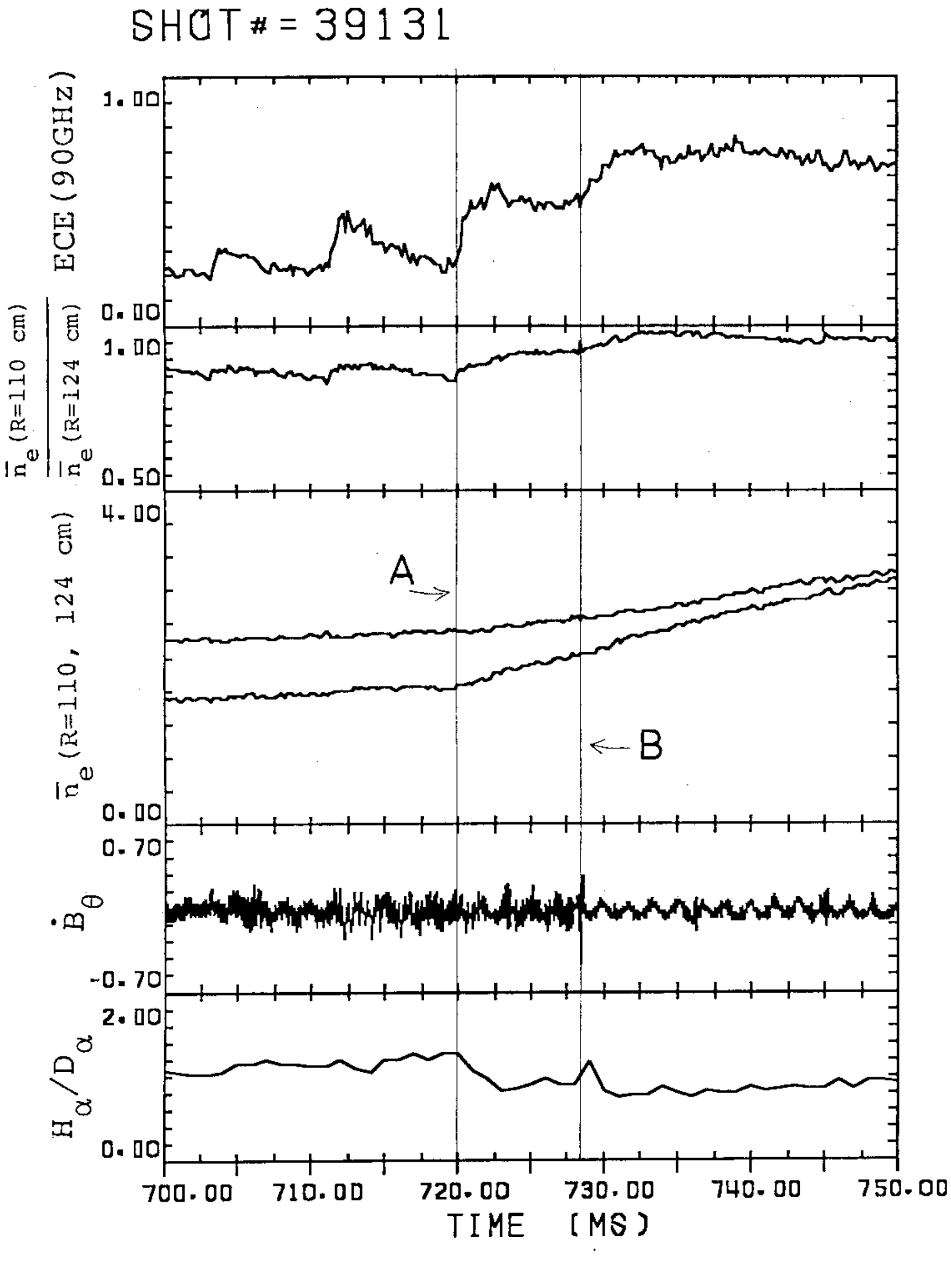

Fig. 2 A single null divertor discharge case with I_p=250 kA, and B_T=1.24 T. From the top, each traces show a time evolution of ECE emission from r=0.9a, line average electron density measure-ed by FIR interferometer at R=1.22m, r=1.10m, a ratio of these two line averaged electron density $\bar{n}_e$(R=1.11m)/$\bar{n}_e$(R=1.22m), magnetic fluctuation measured by B_θ probe, and H_α/D_α emissivity.

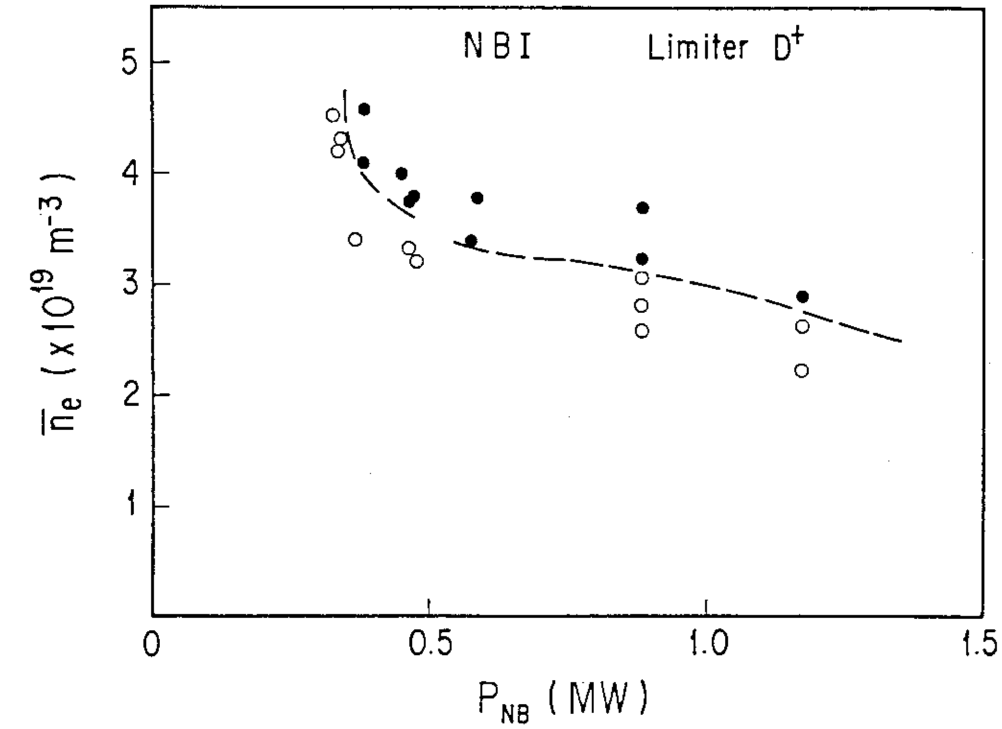

Fig. 3 Line averaged electron density near the center and neutral beam injection power at the instance of H-mode transitions are shown by closed circles. Open circles show the point which are closest to the boundary in each L-mode, non-transition shots.

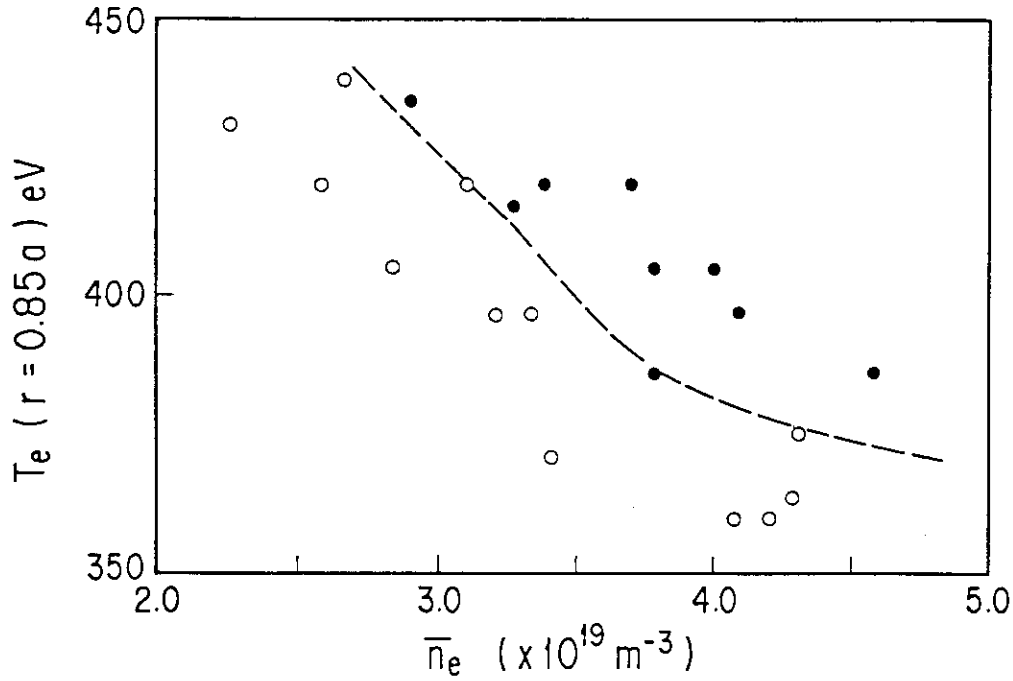

Fig. 4 Edge electron temperature in the edge (r=0.85 a) determined by the ECE measurement and the line averaged electron density at the instances of H-mode transition in the same shots of Fig. 3 are shown by closed circles. Similar data points of L-mode, non-transition cases are shown by open circles.

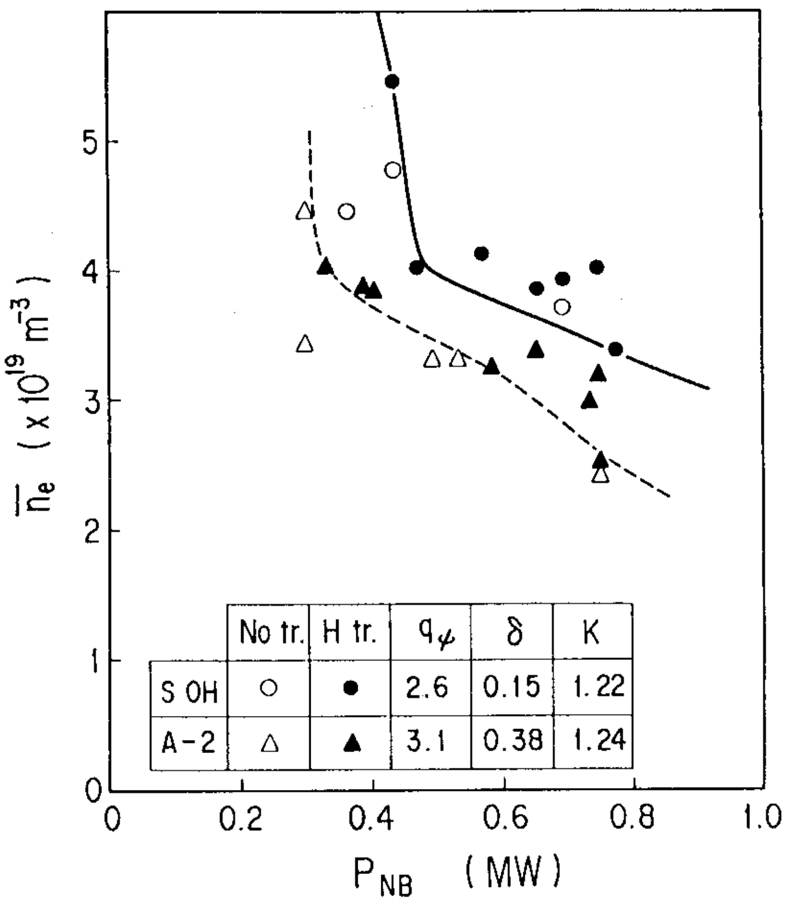

Fig. 5 Comparison of the H-mode transition boundaries between SOH and A2 configurations. Plasma current and toroidal magnetic field were almost the same, and ellipticity κ were close to 1.2 in both cases. Triangularity δ was 0.15 for SOH and 0.38 for A-2.

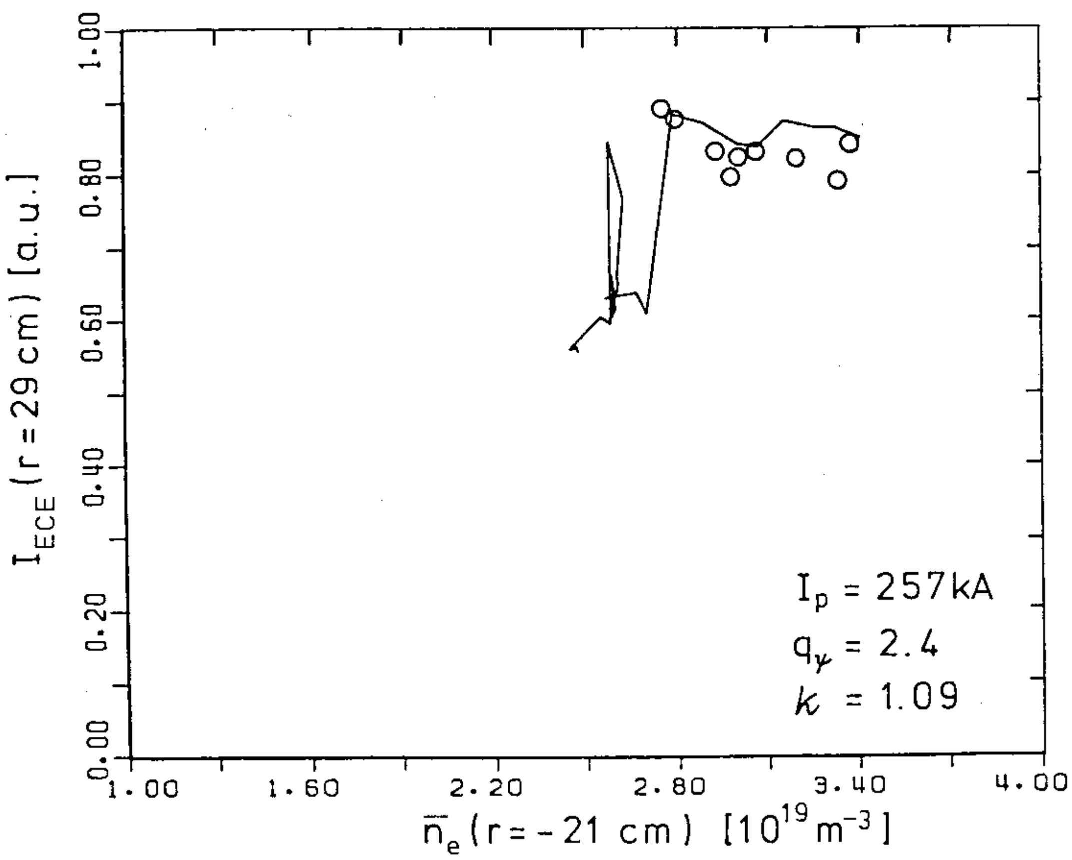

Fig. 6 An ordinate is the intensity of ECE emission which is proportional to the electron temperature at r=29 cm in high field side, and an abscissa is the line averaged electron density measured at the peripheral cord which goes through r=20 cm in the midplane. Circles show the transition point, and the line shows the trajectory of one shot just before and after the transition.

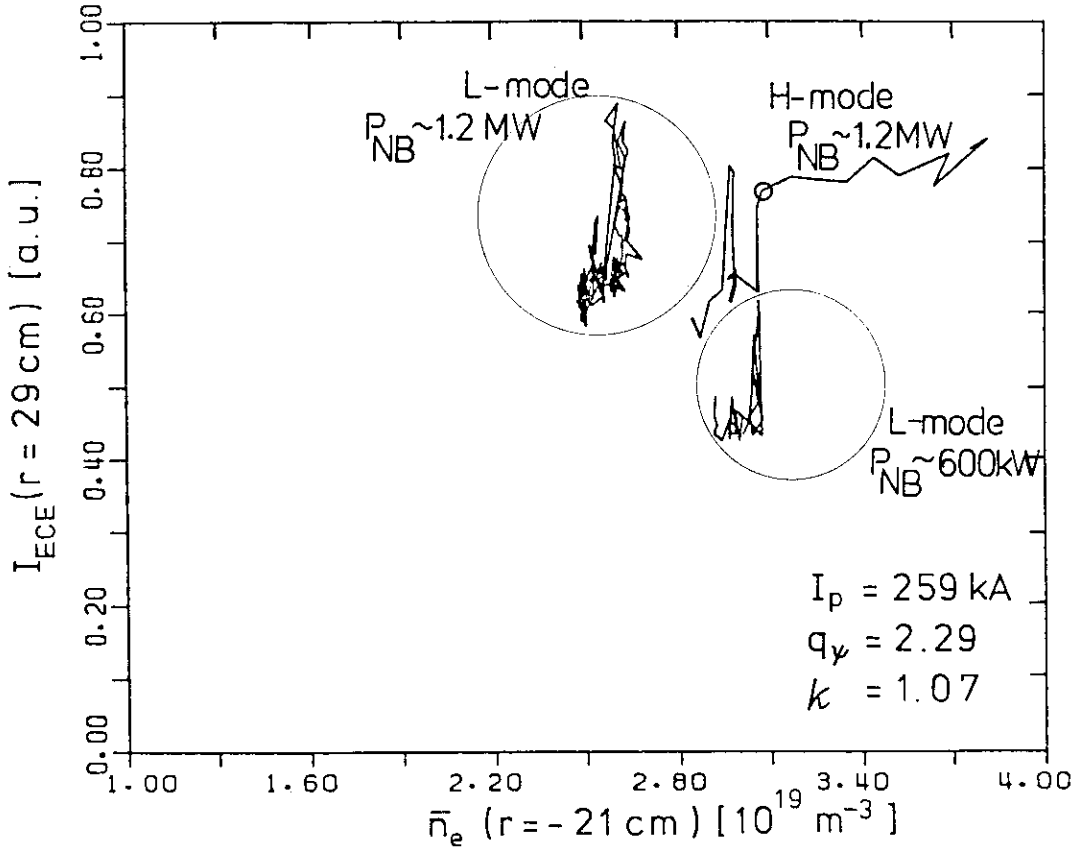

Fig. 7 Trajectories of three shots in the plane of ECE emission from the periphery and the peripheral cord line averaged electron density as Fig. 6. Edge electron temperature is also in arbitrary units as Fig. 6, but both are in the same unit. The left hand side one is the no transition case with 1.2 MW of the injection. The right lower trajectory, B, is also the L-mode case with the injection power of 600 kW. C, is the case where H-mode transition took place at the point marked by the circle. In this transition case, 1.2 MW was injected.

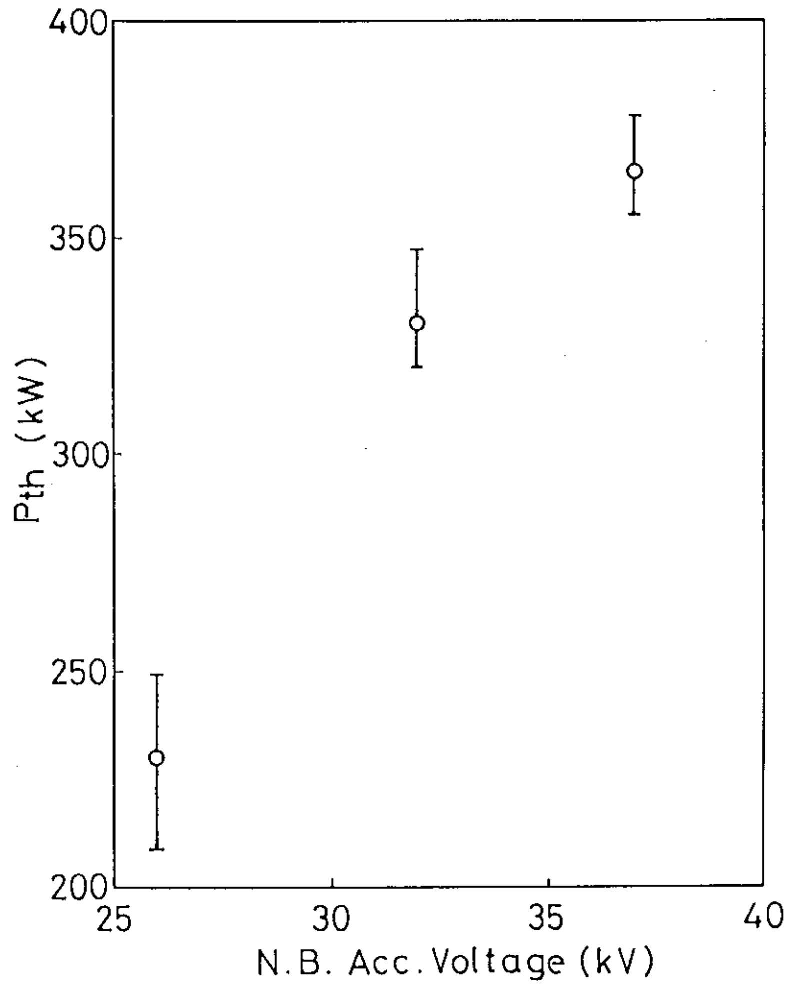

Fig. 8 Dependence of the threshold NBI heating power for H-mode transition on the beam acceleration voltage.

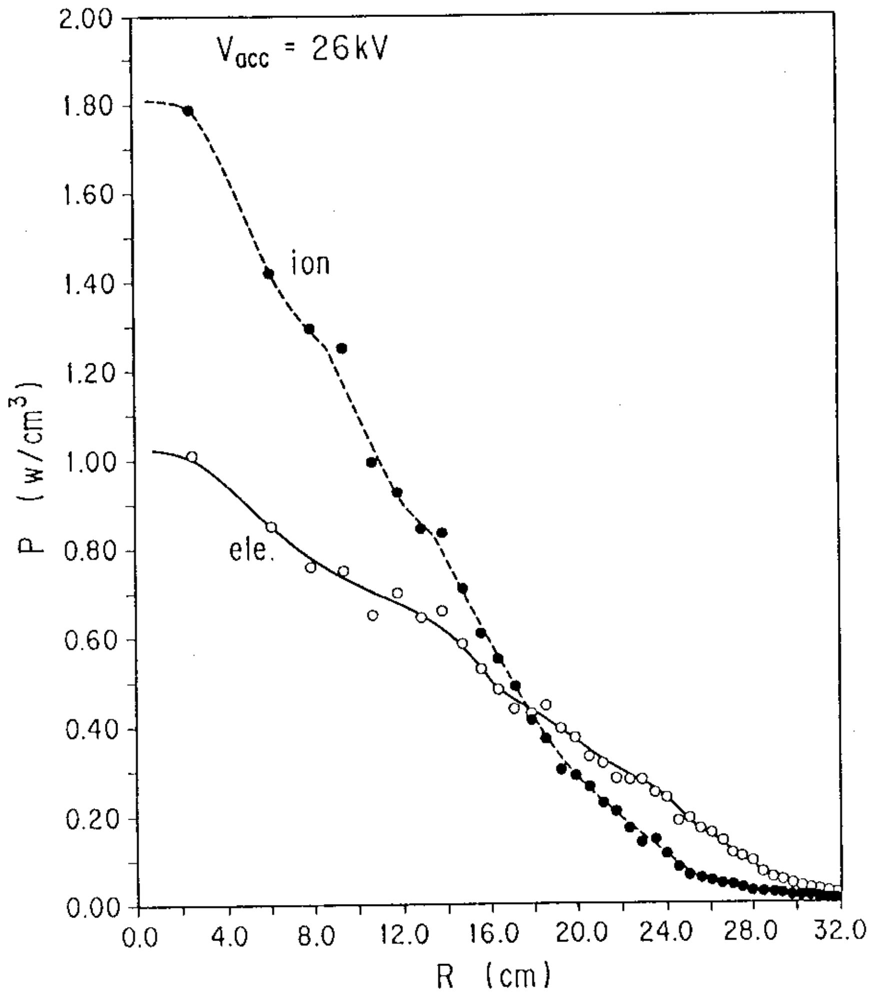

Fig. 9 NBI power deposition profiles of 26 kV beam calculated by Fokker-Planck beam slowing down code. A profile of power deposition to electrons is shown by circles. Deposition to ions is shown by closed circles.

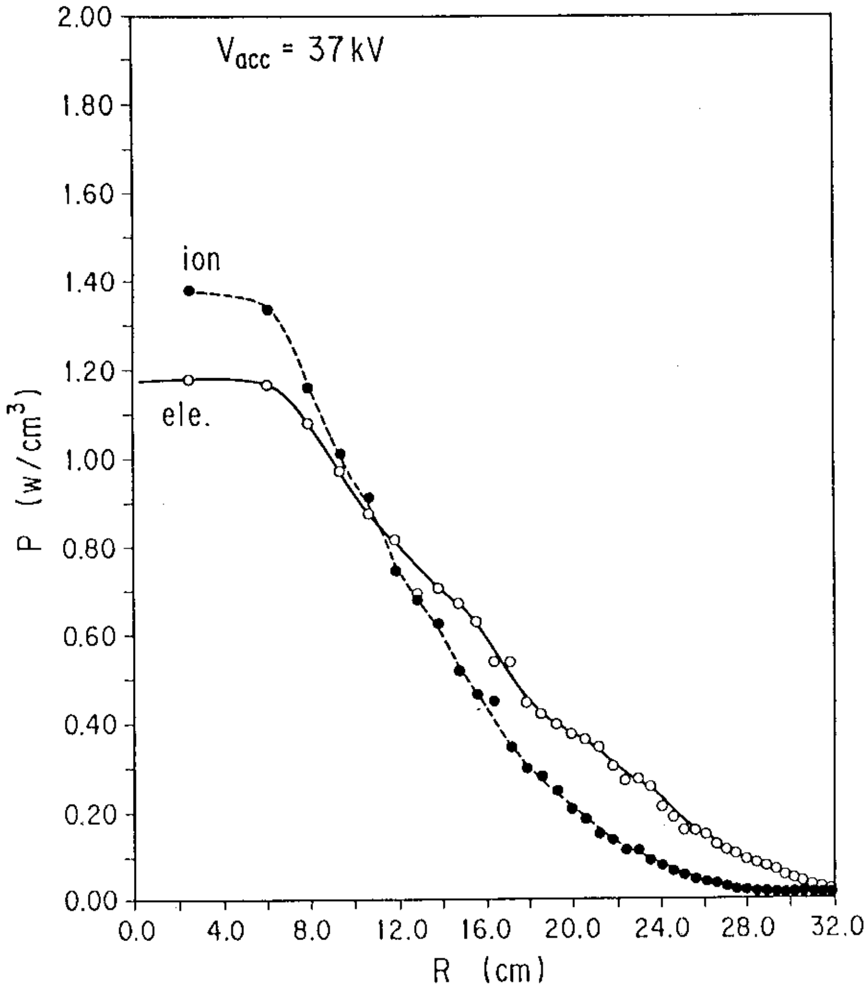

Fig. 10 NBI power deposition profiles of 37 kV beam. A profile of power deposition to electrons is shown by circles. Deposition to ions is shown by closed circles.

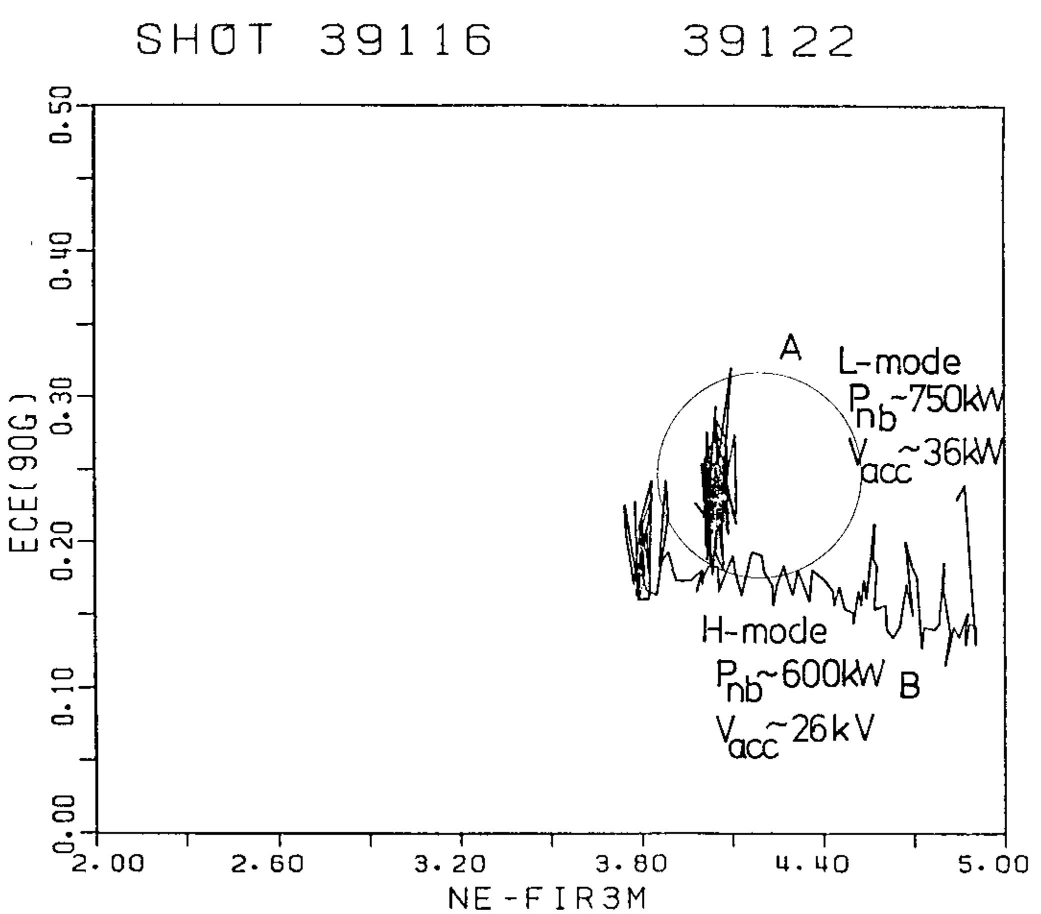

Fig. 11 Edge electron temperature is plotted against the peripheral code line averaged electron density. The Trajectory A in the figure show the no transition case with 750 kW injection heating at the beam energy of 36 kV. Another trajectory B, show the H-mode transition case with 600 kW injection at the energy of 26 kV.