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An improvement of plasma confinement by pellet injection was investigated in ion cyclotron range of frequency (ICRF) wave heated plasmas with a single null divertor configuration on JFT-2M. Pellets were injected into the L- and H-modes of the ICRF heated plasmas. Global energy confinement time (τ_E) was drastically improved in both modes. Such an improvement by the pellet fueling in the H-mode could not be achieved in the neutral beam (NB) heated plasmas. Line averaged electron density of 6×10^{19} m^{-3} ($\Delta\bar{n}_e = 3 \times 10^{19}$ m^{-3}) obtained by the pellet fueling was maintained for about 100 ms, so it is considered that particle confinement is improved. Radiation loss was not large in the pellet fueled discharges.

Keywords: Solid Pellet, Confinement, H-Mode, Ion Cyclotron Range of Frequency, Single Null Divertor, Plasma, Tokamak

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固体ペレット入射による第２段加熱（ICRF）ダイバータプラズマの閉込めの改善

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（1987 年９月７日受理）

ＪＦＴ－２Ｍ装置において，イオンサイクロトロン周波数帯（ICRF）波によって加熱しているシングル・ヌル・ダイバータ配位のプラズマへ重水素ペレット（714－833 m／s）を入射して，プラズマの特性改善に関する研究を行った。ICRF 加熱中のＬモードとＨモードプラズマにペレットを入射した。エネルギー閉込め時間が両モードにおいて，従来のガスパフ補給法でのＨモードにおける閉込め時間よりも 1.4 － 1.7 倍改善された。特に，Ｈモードへのペレット入射による閉込めの改善は，連続入射している中性粒子入射（NBI）加熱プラズマでは得られず，ICRF 加熱プラズマにおいて初めて得られた結果である。ペレット入射により得られた平均電子密度の値（$6\times10^{19}\ \mathrm{m}^{-5}$（増加分＝$3\times10^{19}\ \mathrm{m}^{-3}$））は，約 100 ms に渡り持続しており，粒子閉込め時間の改善がうかがえる。また，放射損失の大きな増大は見られない。

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1. Introduction

In tokamak fusion research experiments, global energy confinement is drastically deteriorated with increase of auxiliary heating (ion cyclotron range of frequency (ICRF) wave and neutral beam (NB) injection) powers to achieve high temperature and high-beta plasmas [1]. Thus, one of the important objects in recent heating experiments is to improve plasma confinement during ICRF and NB heatings. In ASDEX[2], DIII[3], DIII-D[4], PDX[5], JET[6] and JFT-2M[7], the high confinement mode (so-called the H-mode) has been discovered in neutral beam heated divertor discharges. Especially, in JFT-2M, the H-mode can be obtained in nearly circular plasmas with limiter configuration in addition to single or double null divertor configuration in both NB and ICRF heated discharges. Another high confinement mode during NB heating has also found in ISX-B (Z-mode by Ne injection)[8] and DIII(P-mode by multi-pellet injection)[9].

In TFTR, an enhanced confinement regime has been developed in NB heated discharges, which is characterized by high ion temperature of 20 keV, high value of β_p and low collisionality. This discharge is so-called supershot [10].

In many tokamaks e.g. ISX[11], Alcator-C[12], TFR[13], PDX[14], PLT[15], ASDEX[16], DIII[9], TFTR[10,17] and JET[18], pellet fueling experiments have been performed to study possibility of improvement of plasma characteristics. Especially, in Alcator-C[12], a plasma with high electron density ($\bar{n}_e$) and high $n_e(0)\tau_E$ has been produced by pellet fueling. Achieved $n_e(0)\tau_E$ ($0.6-0.8 \times 10^{20}$ sec.m^{-3}) reached the Lawson criterion. In JET Ohmic heated discharges[18], the operational regime, e.g. density limit exceeded by a factor of 2, is extended by large pellet injection, and increment of electron and ion temperatures is observed in pellet fueled ICRF heating[18]. Results of pellet injection on TFTR have indicated increased density limit and improved energy confinement in Ohmic discharges [10,17]. Also, in NB-heated divertor discharges with single null X-point on JFT-2M, very high confinement, which is superior to the confinement in the H-mode although it is transient, has been found on a large pellet injection (increment of electron density $\Delta\bar{n}_e = 4.5 \times 10^{19}$ m^{-3}) just before H-transition (in L-mode)[19]. However, a pellet injection during the H-mode has deteriorated plasma confinement.

Recently, in ICRF-heated divertor discharges with L-H transition in single null X-point operation, very high confinement discharges were discovered, which were achieved by injecting a large pellet ($\Delta\bar{n}_e$ =

3-4 × 10^{19} m^{-3}) in the L-mode as well as in NB-heated divertor discharges. Furthermore, more improvement of confinement in the H-mode were achieved by injecting a large pellet in divertor discharges with ICRF heating. Such an improvement could not found in NB-heated discharges.

In this paper, an improvement of global energy confinement with the pellet in ICRF heating are described. The experimental arrangements are presented in the next section. The characteristics of discharges with very high confinement are described in section 3. In the last section, results are discussed and summarized.

2. Experimental Arrangement

2.1 pellet injector[20]

The pellet injector is a pneumatic type with a single gun barrel, which is similar to an injector developted in Oak Ridge National Laboratory (ORNL)[21]. A frozen pellet size in the carrier is 1.65 mm in diameter and 1.65 mm in length. A gun barrel length is 18 cm. A propellant gas is hydrogen or helium with room temperature. Maximum pressure is up to 30 kg/cm^2. Most of the propellant gas is evacuated from an injection line with a mechanical booster pump (500 m^3/h) with a rotary pump and a turbo-molecular pump (100 ℓ/s) plus rotary pump. Also, two guide tubes (4 mm and 10 mm in inner diameter) and two fast magnetic valves are used to reduce inflow rate of propellant gas into a plasma.

A pellet velocity in the injection line is monitored by a time of flight method (using a pair of photo-interruptors) as shown in Fig. 1. The maximum velocity is about 970 m/s propelled by H_2-gas. In usual injection experiments, the pellet velocity is 714 -- 833 m/s. Reproducibility of the velocity is 80 to 90 %. During injection experiments, a pellet mass is monitored by a microwave cavity method from shot to shot[22], and is periodically checked from a pressure rise in the vacuum chamber (so-called drift chamber) in which the pellet evaporates, closing a gate valve in front of the vacuum vessel of JFT-2M.

Information of ablation is obtained by using a photo-diode with an interference filter in a horizontal direction and a 8-ch filtered photo-diode array in a vertical direction[23]. By using this array, a pellet velocity in a plasma can be estimated from a measurement of local ablation.

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2.2 JFT-2M tokamak

The JFT-2M tokamak has a stainless-steel vacuum vessel of a D-shaped cross-section with major and minor radii of 1.31 m and 0.415 m × 0.595 m, respectively. A circular or non-circular plasma can be produced by controlling magnetic configuration. An open divertor has a single or double null X-point. The material of divertor plates and fixed and movable limiters is graphite. The fixed limiter is localized at two positions separated by 180° in the toroidal direction as shown in Fig. 2. Titanium is gettered on the vessel wall and/or limiters before the beginning of a day's experiment.

2.3 auxiliary heating system

Three loop antennae for ICRF heating are located at intervals of 0.37 m on the high field side of the torus. They are fed from 16.8 MHz RF generators in present experiments. Maximum generator power is about 4 MW. The phase relation of the antennae is variable. The experiments were performed on out-of-phase operation with an inverse phase of the central antenna.

Hydrogen neutral beam (NB) heating is also possible. Typical accelerating voltage and beam current are 34 keV and 60 A. Injection power is up to 900 kW in co-injection and is up to 500 kW in counter-injection. The injection angle is about 38° with respect to the major axis of a torus.

3. Pellet Injection into Auxiliary-Heated Plasmas

In ion cyclotron range of frequency (ICRF) wave heated single null divertor discharges, a plasma is transfered to high confinement mode (H-mode) after about 30-40 ms from start of RF as well as in NB heated discharges. During the H-mode, stored energy of the plasmas(Ws), line averaged electron density ($\bar{n}_e$) and radiation loss power (P_R) including charge exchanged particle loss continuously increase until the H-mode is terminated by large radiation cooling[24]. The H-transition accompanies sudden drop of Balmer line (H_α/D_α) emission. Global energy confinement time (τ_E) is improved in H-mode, and its value is close to that for $\bar{n}_e$ = 3-6 × 10^{19} m^{-3} in Ohmic heating (30-40 ms). These characteristics are very similar to that in NB heating.

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B_t is 1.21 T and the plasma current I_p is about 272 kA. The amount of hydrogen gas in the working gas (H_2+D_2) is about 30 %. In the plasmas with this ratio, the electrons are dominantly heated by ICRF wave (electron heating mode)[25]. A deuterium pellet is injected into the L-mode or H-mode during ICRF heating in single null divertor discharges in order to study whether confinement is improved or not in both modes. A single null X-point is selected to be located in lower region of the vacuum chamber (Fig. 3).

In this paper, $\beta_p + \ell_i/2 \equiv \Lambda + 1$ is calculated by the magnetic fitting code [26] from magnetic probe signals assuming six filament currents in the plasma. The stored energy is estimated from both this calculation and the diamagnetic measurement. Two results generally agrees well each other within about ±5 %. The fitting code results are mainly used in the confinement analysis.

3.1 injection in L-mode

The plasma was heated from 600 to 900 ms by ICRF wave (launched power P_{rf} = 600-800 kW). A deuterium pellet was injected at 660 ms during the L-mode, before H-transition. Figure 4 shows time histories of line averaged electron density ($\bar{n}_e$), plasma stored energy (Ws), Mirnov oscillation ($\dot{\tilde{B}}_\theta$) signal, time differential of Ws ($\dot{W}s$), emission of the Balmer D_α line (I^{D_α}) in the divertor region (solid line) and in the main plasma region (dotted line) and radiation loss power (P_R) including a charge exchanged neutral particle loss. A density raise by a pellet is about 3.2×10^{19} m^{-3}, which was measured along a vertical chord at major radius R of 1.24 m using the HCN laser interferometer. Emission of the D_α line rapidly increases by a pellet ablation and after about 10 ms, drops by terminating ablation of the pellet and keeps lower level for about 20 ms (t = 680-700 ms) as shown in Fig. 4(e). These phenomena indicate that the particle recycling is reduced. During keep of lower I^{D_α} level, amplitude of MHD oscillation is very small and plasma stored energy (Ws) continuously increases (Fig. 4(b)). And radiation loss power P_R is still low level. So, global energy confinement time ($\tau_E = Ws/(P_{total}-dW_s/dt)$, P_{total}: total input power) rose up to 55-60 ms for about 20 ms after pellet injection (Fig. 4(d)). This improvement is transient, so the very high confinement level keeps only for about 20 ms. When MHD oscillation with large amplitude grow at t = 700 ms following sudden jump of D_α line emission, the increase of Ws is stopped and after that time small amplitude MHD oscillations continuously appear and stored energy degrades (τ_E deteriorates to Ohmic heating level or lower level). During this degradation, electron density still gradualy rises. It is found from P_R signal that this is due to an impurity accumulation into a central region of the plasmas. Spectroscopic measuerments of iron line emissions (FeX and FeXVIII) indicate this tendency.

Sometimes, plasmas were disrupted after 40 ms from pellet injection by rapid and large growth of MHD oscillation and rapid increase of D_α line emission and radiation loss power (Fig. 5). Then, maximum Ws is about 32 kJ, and volume averaged toroidal beta value $<\beta_t>$ is about 1.3 %, corresponding to Toroyon factor g = 1.6 according to $<\beta_t> = gIp/aB_t$ (I_p: plasma current(MA), B_t: toroidal magnetic field strength at giometrical axis (minor axis) of a torus (T), a: half-width of the plasma along the midplane)[27]. Radiation loss power in ICRF heating with pellet fueling was larger than that in NB heating with pellet fueling as shown in Fig. 6. Thus the plasma disruption attributes to a large amount of radiation cooling and is not due to beta limit (in NB heating, the disruption in pellet injection is due to beta limit [19]).

Figure 7 shows the ablation profile obtained from the horizontal measurement of D_α line emission. The horizontal axis is Rout-R, Rout is a major radius crossed an outside separatrix surface in the midplane and R is the local position of the plasma from the major axis of the torus. The pellet penetrated deeply in a core plasma, exceeded a minor axis of a torus (R = 1.31 m) as drawn by a solid line. The horizontal position of a plasma is controlled as the magnetic axis is located near the minor axis of the torus. Maximum ablation is around Rout-R = 0.12 m, e.g. about one half of the plasma minor radius. The dotted line indicates a profile for the injection in L-mode during NB heating[19].

3.2 injection in H-mode

The pellet fueling could not improve energy confinement in H-mode in NB heated discharges with the single null X-point, in which the gas puffing was stopped at NB start. Radiation cooling is very enhanced by pellet injection and the stored energy strongly degrades as shown in Fig. 8.

In ICRF heated discharges with the single null X-point, a deuterium pellet was injected after about 30 ms from the beginning of H-transition. Electron density raise ($\Delta\bar{n}_e$) is about 3×10^{19} m^{-3}. Radiation loss after the pellet fueling is slightly large compared with that in discharges fueled the pellet in the L-mode. During subsequent decreasing of radiation, Ws continuously increases until the radiation again begins to increase. Ws is up to about 35 kJ. These characteristics are significantly different from that for injection in the H-mode during NB heating. Energy confinement time is improved up to about 50 ms around $\bar{n}_e = 6 \times 10^{19}$ m^{-3} as shown in Fig. 9. This value exceeds τ_E (30-40 ms) in the H-mode in the gas fueled discharges [24] and also is larger than that in ICRF heated discharges with gas fueling. Electron temperature T_e^{sx}, which is obtained from analysis of soft X-ray spectrum measured in the tangential direction, decreases from approximately 1.35 keV to less than 1.1 keV, immediately following the injection and is recoverd up to the value before pellet injection or higher value for 20-30 ms after pellet injection as shown in Fig. 10.

The pellet ablation profile is shown in Fig. 7 by a broken line. The pellet is ablated slightly more outside than in the L-mode cases in ICRF and NB heatings. Most of the pellet is ablated around Rout-R = 0.15 m. Ablation in a scrape-off layer is very little as in other cases. In NB heating cases with pellet injection into the H-mode, the pellet is strongly ablated inside separatrix layer compared with above-mentioned cases.

Once the confinement was improved by pellet injection in present series experiments (L- and H-modes injection), after that sometimes the L-mode and the H-mode periodically repeated. These characteristics are similar to those of the H-mode in gas fueled limiter-discharges with ICRF heating[24]. These plasma behaviors are very strange. The reason is still open question.

Global energy confinement time (τ_E) is linearly improved with $\bar{n}_e$ in the range of 4-6.2 × 10^{19} m^{-3} on $\bar{n}_e$-τ_E diagram in Fig. 9. Maximum confinement time in both H- and L-modes is about 1.4-1.7 times as large as that in Ohmic heating around $\bar{n}_e = 6 \times 10^{19}$ m^{-3}. On the other hand, confinement time for the H-mode without pellet in ICRF heated single null divertor discharges is 30-40 ms for 4-6 × 10^{19} m^{-3} and total input power P_{total} = 0.8-1.1 MW [24], which is in comparison with τ_E in Ohmic heating. Present experimental results reveal that energy confinement time can be improved by the pellet fueling in both L- and H-modes during ICRF heating on the single null X-point operation, although the phenomena are transient.

4. Discussion and Summary

On pellet injection into the H-mode in ICRF heated discharges, global energy confinement was remarkably improved, but in NB heated discharges with pellet injection into the H-mode plasma, properties were deteriorated. This defference in two type heatings seemes to be due to the effect of fast ions with high energy and/or thermal electrons with higher temperature in the peripheral region than that in the L-mode discharges on the pellet ablation. Usually, in the H-mode the very steep gradient of electron temperature (pedestal of temperature) appeares just inside the separatrix. In JFT-2M, the pedestal in the H-mode is observed in both NB and ICRF heatings [7,28]. The temperature is 300-500 eV in two cases. Therfore, it is considered that the contribution of thermal electrons in the peripheral region of the plasmas to the pellet ablation is nearly the same. On the other hand, the fast ions with high energy are much produced in NB heating compared with ICRF heating, because the ICRF heating mode in the present experiments is limited to electron heating mode even if the pellet is injected, so that the RF power is dominantly absorbed by electrons (the number ratio of hydrogen to deuterium n_{H2}/n_{D2} is about 14 % after pellet injection (~43 % before pellet injection)). From these facts, the pellet in the H-mode discharges with NB heating is much ablated in the more outside region as shown in Fig. 7 (dash - dotted line), so the plasma in the peripheral region is strongly cooled following the degradation of the stored energy. In L-mode injection, in which the pellet was injected after 10 ms from start of NB injection, the fast ions are not sufficiently produced, so the pellet can penetrate deeply exceeding the separatrix layer.

Sometimes, the plasmas were disrupted by pellet injection. In these cases, the amplitude of the MHD oscillation signal during Ws increasing after pellet injection kept a certain level following large amplitude oscillations. There is no phase with very small amplitude oscillation as it can be seen in no-disrupted cases. Also, the MHD oscillation with relatively large amplitude can be seen during the deterioration phase of Ws. It seems to be key point that the MHD oscillation is controlled to maintain improved confinement in the ICRF heated discharges with pellet injection. The ICRF heated plasmas in present series experiments are slightly contaminated by impurities compared with discharges obtained the good H-mode.

The present results are summarized as follows,

(1) Plasma stored energy increases linearly by pellet injection and resultantly global energy confinement time were drastically improved in both L- and H modes in ICRF heated discharges with the single null divertor configuration.

(2) Line averaged electron density of 6×10^{19} m^{-3} ($\Delta\bar{n}_e = 3 \times 10^{19}$ m^{-3}) was maintained for about 100 ms. Particle confinement may be improved.

(3) Radiation loss power including charge exchanged particle loss was not large during maintaining improved confinement.

(4) Pellet can penetrate across a plasma center. Maximum particle deposition is near one-half of a plasma radius.

Acknowledgements

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References

[1] KAYE, S.M., Phys. Fluids 28 (1985) 2327.

[2] WAGNER, F., BECKER, G., BEHRIUGER, K., CAMPBELL, D., EBERHAGEN, A., et al. Phys. Rev. Letters 49 (1982) 1408.

[3] DeBOO, J.C., BURRELL, K.H., EJIMA, S., KELLMAN, A.G., OHYABU. N., et al., Nucl. Fusion 26 (1986) 211.

[4] LUXON, J., ANDERSON, P., BAITY, F., BAXI, C., BRAMSON, G., et al., 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-47/A-III-3 (1-86) Kyoto (1986).

[5] FONCK, R.J., BECRSDORFER, P., BELL, M., BOL, K., BOYD, D., et al., in Proc. of the 4th Int Sym. in Heating in Toroidal Plasmas, Rome, 1984 (ENEA, Frascati, 1984), Vol. I, p37.

[6] TANGA, A., KEILHACKER, M., BARTLETT, D., BEHRINGER, K., BICKERTON, R.J., et al., 11th Int. Conf. on Plasma Physics and Contralled Nuclear Fusion Research, Postdead Line Paper, Kyoto (1986)

[7] SENGOKU, S., and JFT-2M team, 7th Int. Conf. on Plasma Surface Interaction, Princeton, 1986.
ODAJIMA, K., FUNAHASHI, A., HOSHINO, K., KASAI, S., KAWAKAMI, T., 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-47/A-III-2, Kyoto (1986).

[8] MURAKAMI, M., EDMONDS, P.H., HALLOCK, G.A., ISLER, R.C., LAZARUS, E.A., in Proc. of the 10th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, London, 1984 (IAEA, Vinna, 1985) Vol. 1, 87.

[9] SENGOKU, S., ABE, M., HOSHINO, K., ITOH, K., KAMEARI, A., et al., in Proc. of the 10th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, London, 1984 (IAEA, Vinna, 1985) Vol. 1, 405.

[10] HAWRYLUK, R.J., ARUNASALAM, V., BELL, M.G., BITTER, M., BLANCHARD, W.R., et al., 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, IAEA-CN-47/A-I-3, Kyoto (1986).

[11] MILORA, S.L., J. Fusion Energy 1 (1981) 15, MILORA, S.L., FOSTER, C.A., THOMAS, C.E., BUSH, C.E.WILGEN, J.B., et al., Nucl. Fusion 20 (1980) 1491.

[12] GREENWALD, M., PARKER, J., BESEN, M., FIORE, C.L., FOOD, M., et al., in Proc. 11th Europ. Conf. on Controlled Fusion and Plasma Physics, Aachen, 1983 (European Physical Society, 1983) Vol. 7D, Part I, 7.

[13] EQUIPE TFR, in Proc. 10th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, London, 1984 (IAEA, Vinna 1985) Vol. 1, 103.

[14] MILORA, S.L., SCHMIT, G.L., HOULBERG, W.A., ARUNASALAM, V., ATTENBERGER, S.E., et al., Nucl. Fusion, 22 (1982) 1263.

[15] HOSEA, J., BELL, R., BITTER, M., CAVALLO, A., COHEN, S., et al., in Proc. 12th Europ. Conf. on Controlled Fusion and Plasma Physics, Budapest, 1985 (European Physical Society, 1985) Vol. 9F, Part II, 120.

[16] VLASES, G., BUCHL, K., CAMPBELL, D., in Proc. 11th Europ. Conf. on Controlled Fusion and Plasma Physics, Aachen, 1983 European Physical Society, 1983) Vol. 7D, Part I, 127.

[17] SCHMIT, G.L., MILORA, S.L., BELL, M.G., BITTER, M., BUSH, C.E., et al., in Proc. 12th Europ. Conf. on Controlled Fusion and Plasma Physics, Budapest, 1985 (European Physical Society 1985) Vol. 9F, Part II, 674.

[18] GONDHALEKER, A., CHEETHAM, A., BURES, M., CAMPBELL, D., COHEN, S.A., et al., 11th Int. Conf. on Plasma Physics and Contralled Nuclear Fusion Research, IAEA-I-1-6 (poster session), Kyoto (1986).

[19] MIURA, Y., KASAI, S., SENGOKU, S., HASEGAWA, K., SUZUKI, N., et al Japan Atomic Energy Research Institute Report JAERI-M 86-148 (1986), "Characteristics of Pellet and Neutral Beam Injected Single Null Divertor Discharges of the JFT-2M Tokamak".

[20] KASAI, S., MIURA, Y., HASEGAWA, K., SENGOKU, S., OGAWA, H., et al., Japan Atomic Energy Research Institute Report, JAERI-M 86-109 (1986), "First Results of Pellet Injection Experiments in JFT-2M Additionally Heated Plasmas".

KASAI, S., HASEGAWA, K., MIURA, Y., ISHIBORI, I., Japan Atomic Energy Research Institute Report, JAERI-M 86-035 (1986), "Production and Ejection of Solid Hydrogen-Isotope Pellet (Single Pellet)" in Japanese.

[21] MILORA, S.L., FOSTER, C.A., Rev. Sci. Instrum., 50 (1979) 482.

[22] JENSEN, P.B., ANDERSEN, V., J. Phys. D: Appl. Phys. 15 (1982) 785.

[23] MIURA, Y., KASAI, S., TAMAI, H., HASEGAWA, K., Japan Atomic Energy Research Institute Report, JAERI-M 85-192 (1985), "The Device for Poloidal Profile Measurement of H_α-line Emission by Photodiode and its Calibration" in Japanese.

[24] MATSUMOTO, H., OGAWA, T., TAMAI, H., ODAJIMA, K., HASEGAWA, M., et al. to be publish in Nucl. Fusion, "H-mode Phenomena during ICRF Heating on JFT-2M".

[25] TAMAI, H. ODAJIMA, K., MATUMOTO, H., OGAWA, T., KIMURA, H., et al, Nucl. Fusion 26 (1986) 365.

[26] SWAIN, D.W., and NEILSON, G.H., Nucl. Fusion 22 (1982) 1015.

[27] TOROYON, F., GRUBER, R., SAURENMANN, H., SEMENZATO, S., SUCCI, S., Plasma Physics and Controlled Fusion 26 (1984) 209.

[28] YAMAUCHI, T., MATOBA, T., HASEGAWA, M., Read at the Autumn Meeting of the Phys. Soc. of Jpn., Kobe, September, 1986, 27P-M-6 (Advance abstracts Vol. 4, P.174).

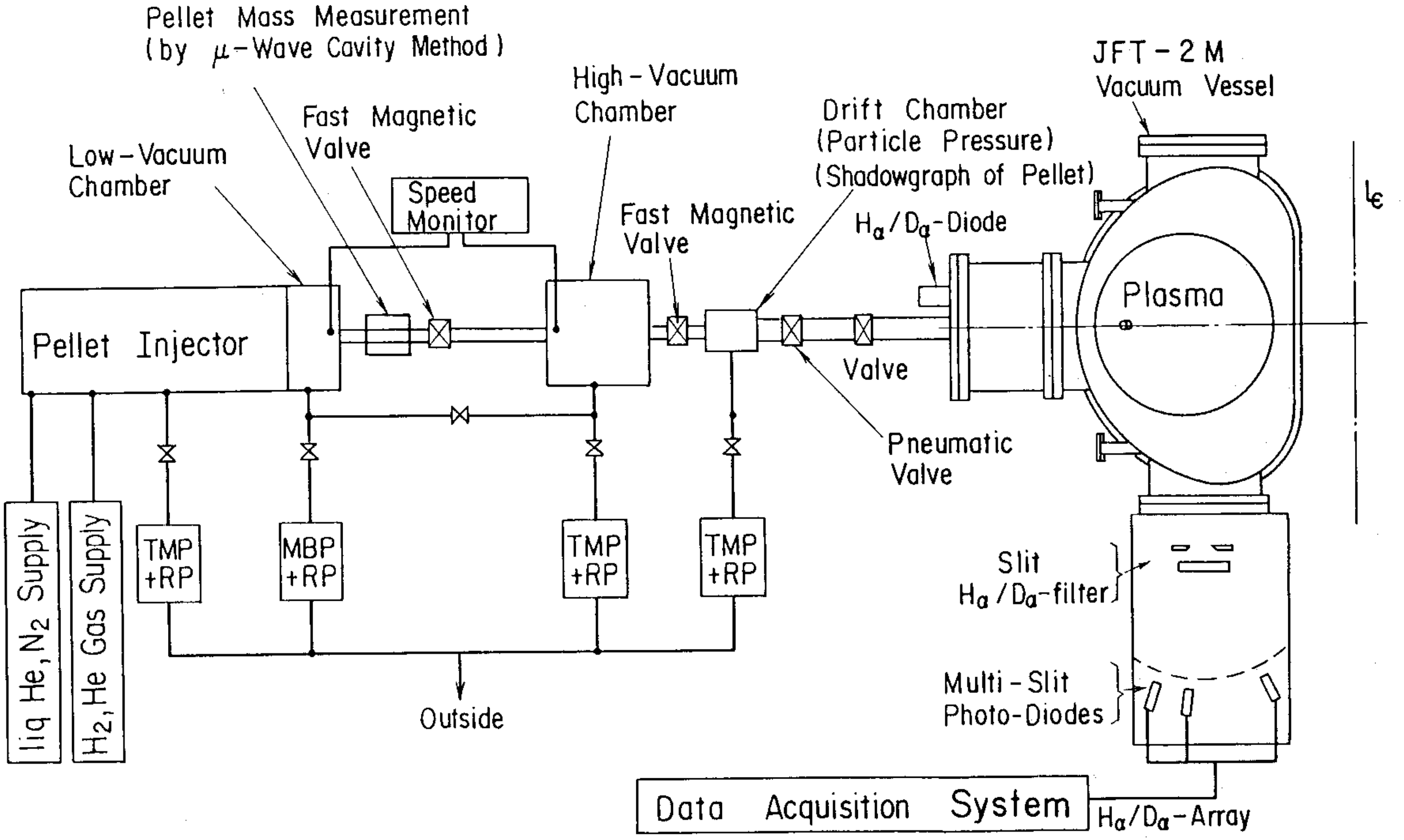

Fig. 1 Schematic diagram of the single pneumatic pellet injector. TMP: turbo molecular pump, MBP: mechanical booster pump, RP: rotary pump.

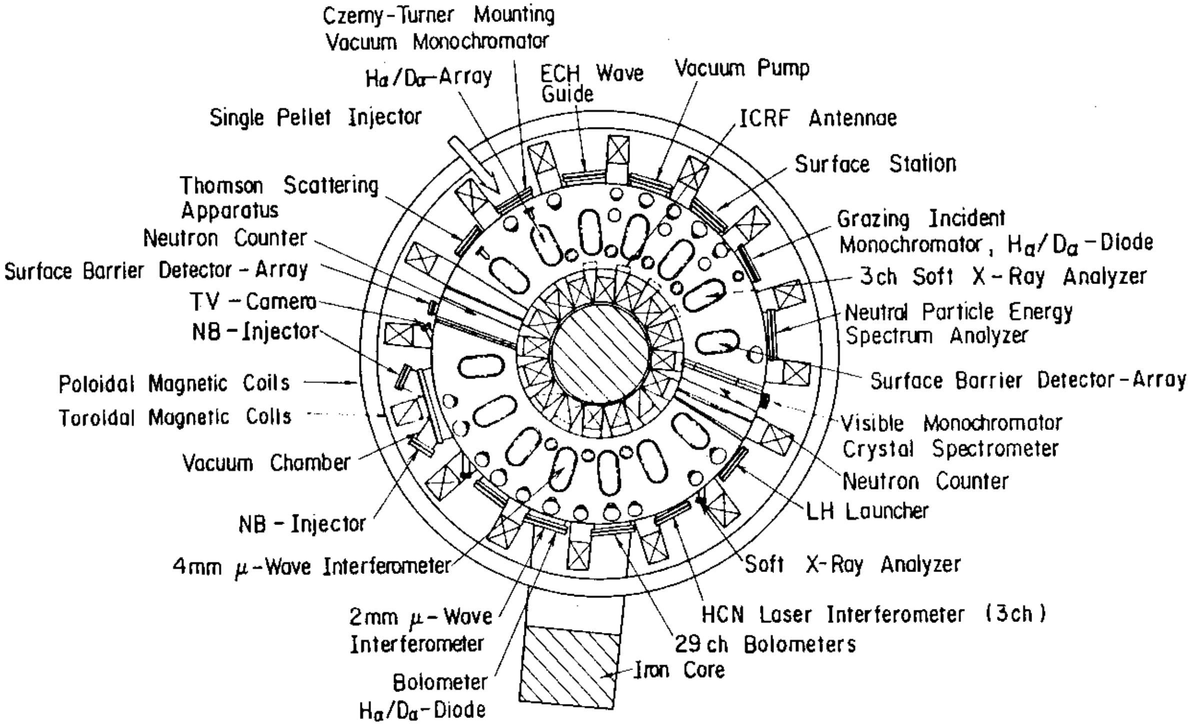

Fig. 2 Plane view of JFT-2M tokamak and arrengement of the single pellet injector, the auxiliary heating systems and diagnostic apparatuses.

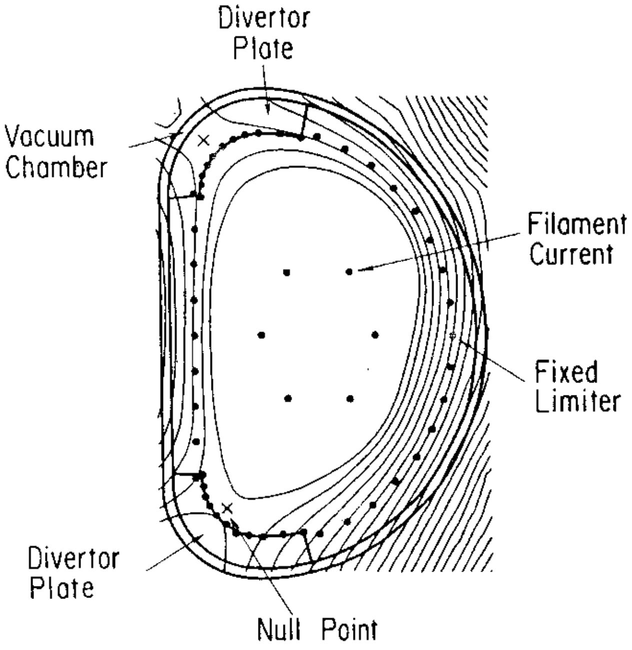

Fig. 3 Typical magnetic configuration in lower single null divertor discharges.

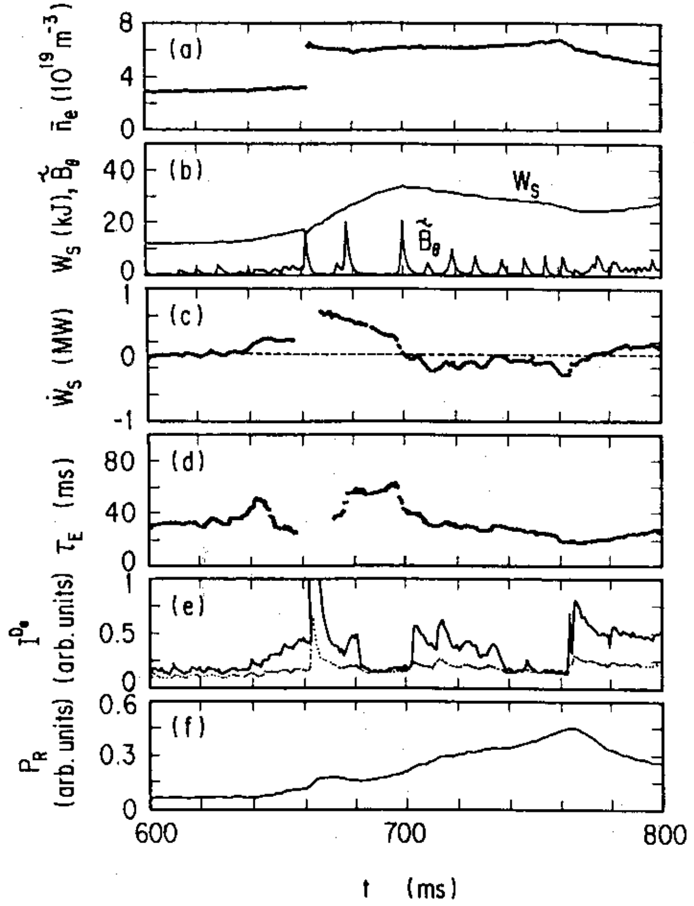

Fig. 4 Time histories of (a) line averaged electron density ($\bar{n}_e$), (b) plasma stored energy (Ws), Mirnov oscillstion signal ($\dot{\tilde{B}}_\theta$), (c) time differential of Ws ($\dot{W}s$), (d) global energy confinement time (τ_E), (e) intensities of Balmer D_α line emission in the divertor and main plasma regions ($I^{D\alpha}$), and (f) radiation loss power (P_R) including charge exchanged neutral particle loss. The pellet is injected into L-mode at 660 ms and ICRF heating is from 600 to 900 ms.

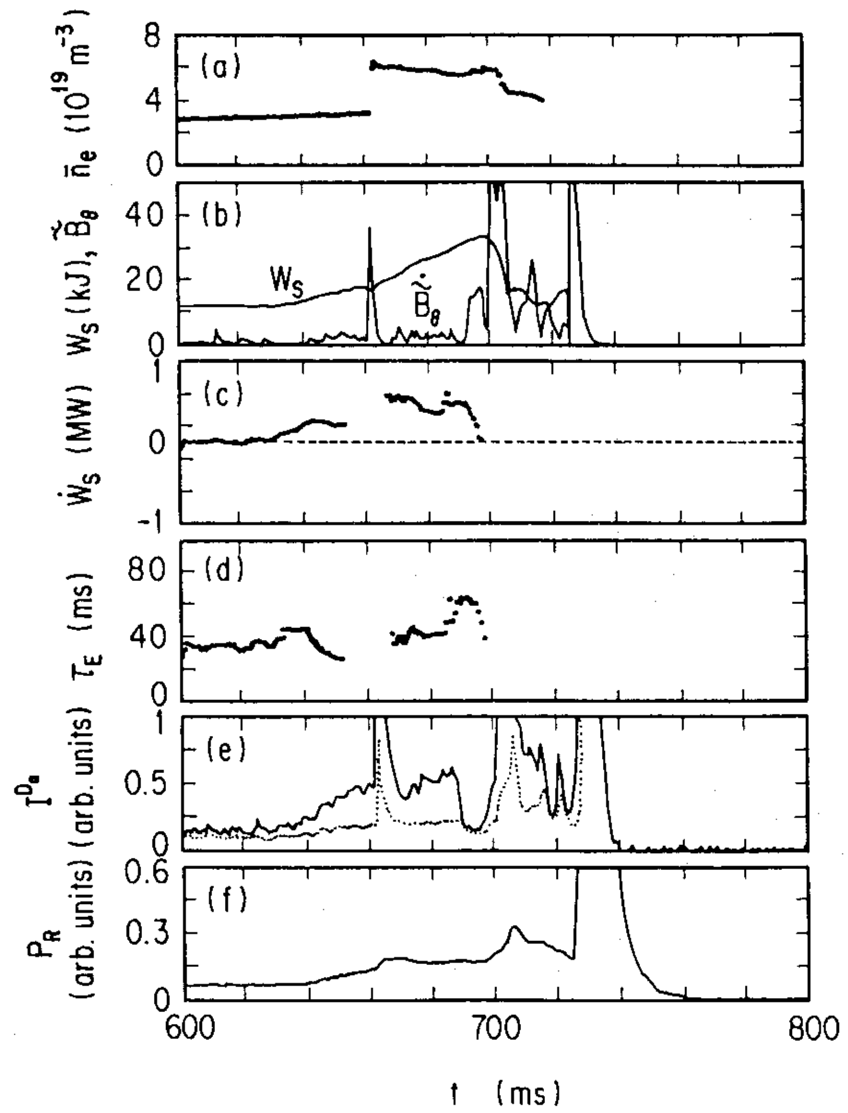

Fig. 5 Time histories of $\bar{n}_e$ (a), Ws and $\dot{\tilde{B}}_\theta$ (b), Ws (c), τ_E (d), $I^{D\alpha}$ (e) and P_R (f). The pellet is injected into L-mode at 660 ms.

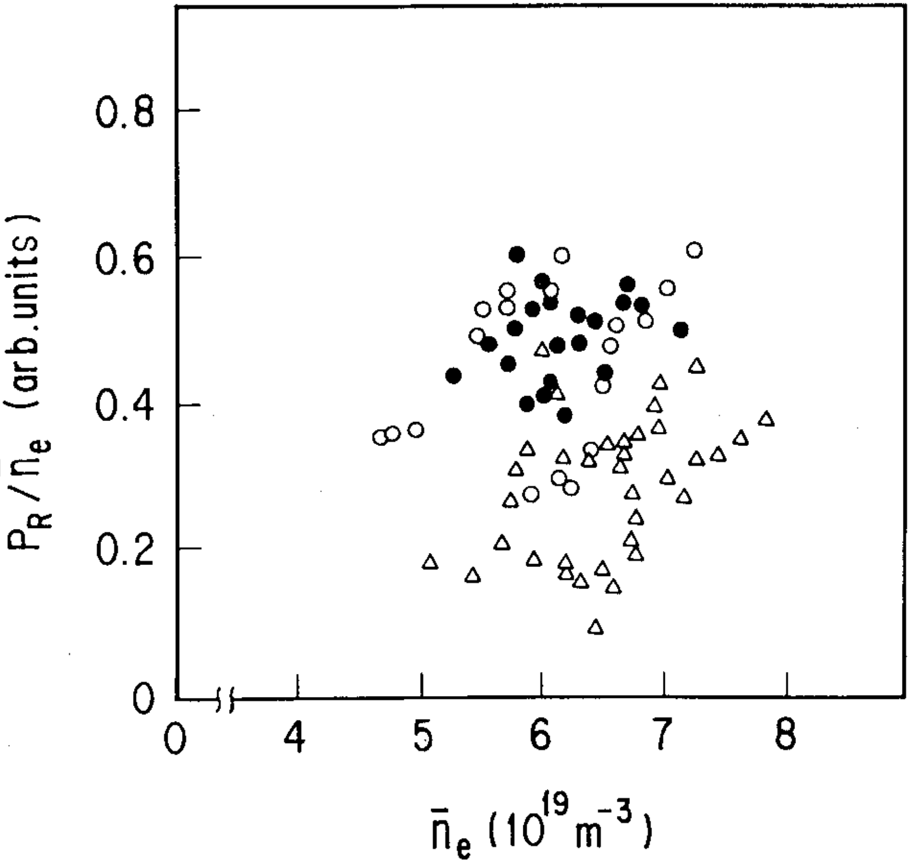

Fig. 6 Normalized radiation loss power ($P_R/\bar{n}_e$) versus line averaged electron density ($\bar{n}_e$). Open circles and closed circles are pellet injection into L-mode and H-mode in ICRF heated discharges, respectively. Triangles are pellet injection into L-mode in NB heated discharges.

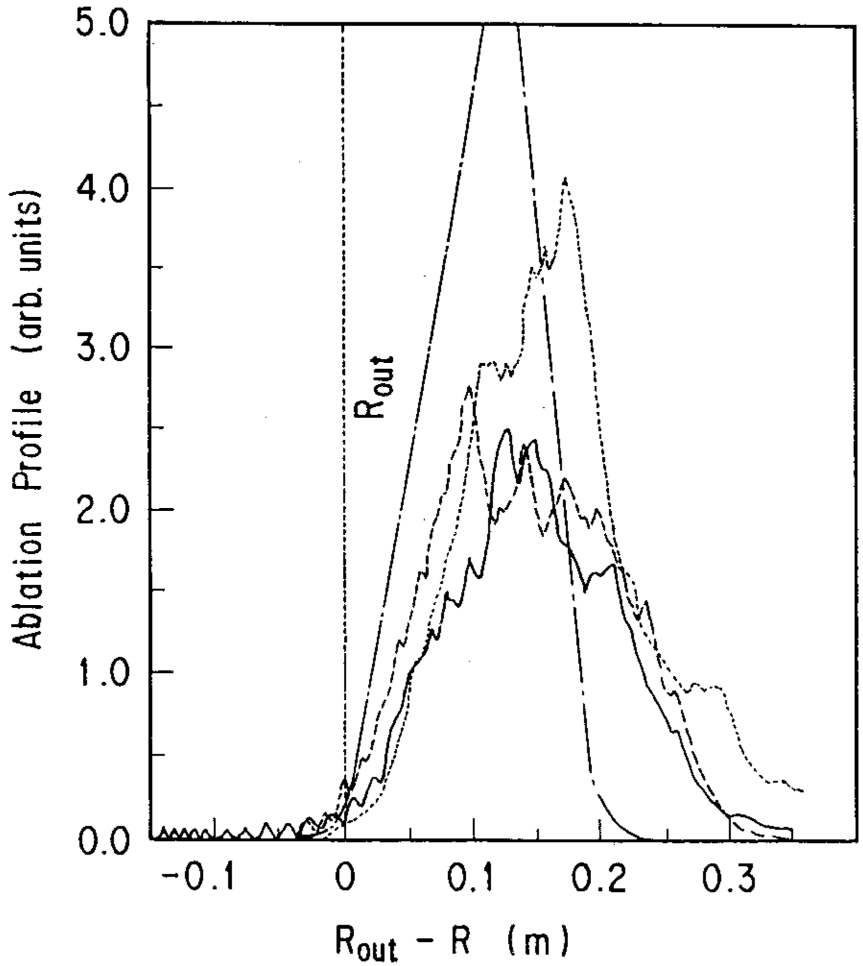

Fig. 7 Ablation profiles of D_2 pellet. Solid and broken lines are profiles in pellet injection into L-mode and H-mode of ICRF heated discharges, respectively. Doted and dash-dotted lines are profiles in pellet injection into L-mode and H-mode of NB heated discharges with single null divertor configuration.

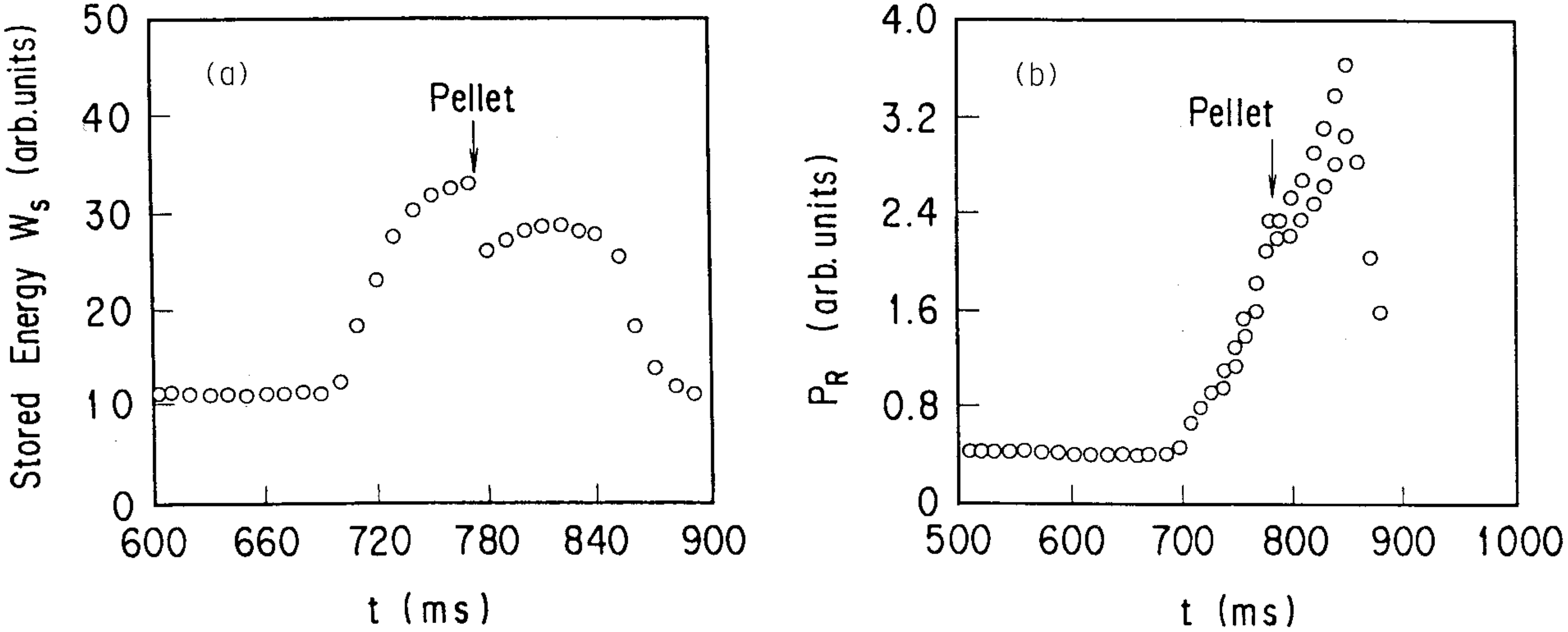

Fig. 8 (a) time history of plasma stored energy (Ws) and (b) P_R in pellet injection into H-mode of NB heated discharges with single null divertor configuration.

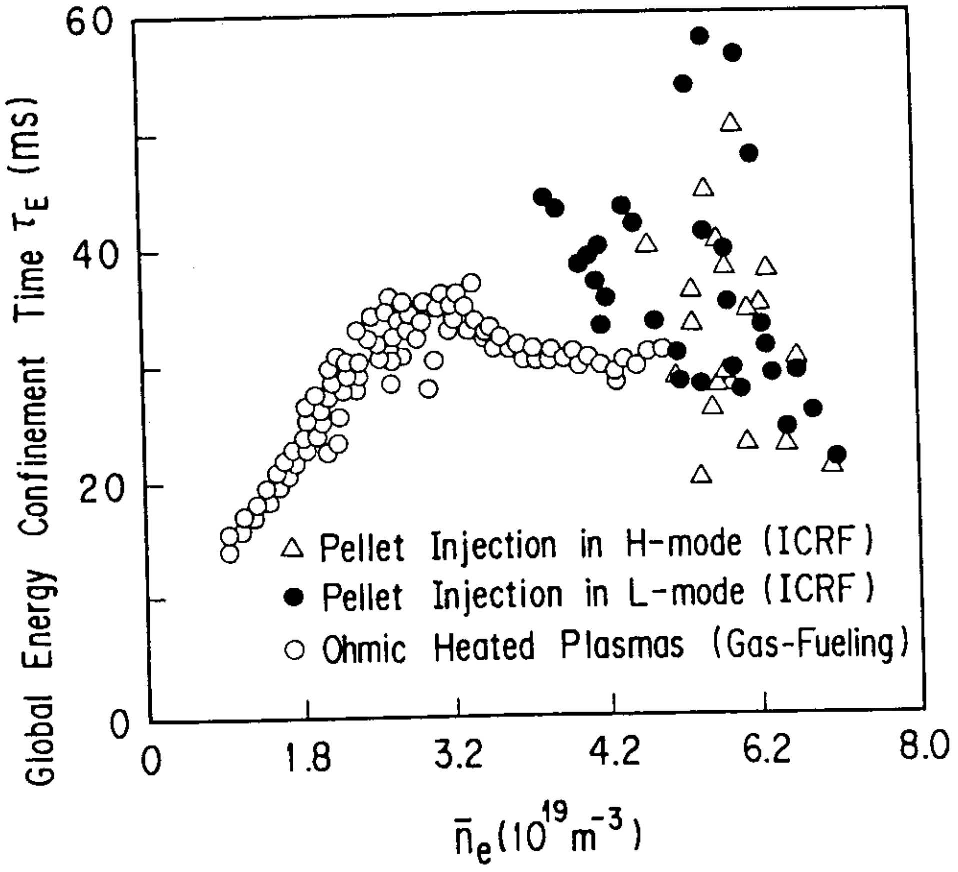

Fig. 9 Global energy confinement time (τ_E) versus line averaged electron density ($\bar{n}_e$). Closed circles and triangles are pellet injections into L-mode and H-mode in ICRF heated discharges with single null divertor configuration. Open circles are in ohmic heated discharges with the same configuration.

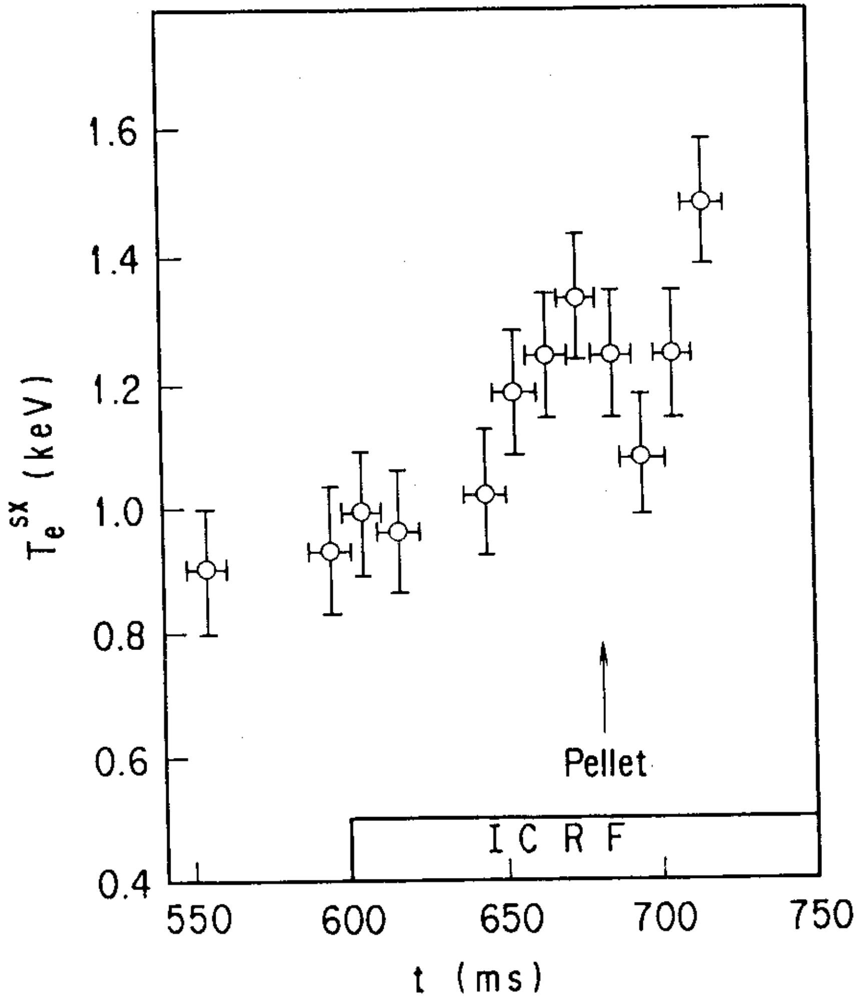

Fig. 10 Time evolution of electron temperature T_e^{SX} estimated from soft X-ray measurement in pellet injection into H-mode of ICRF heated discharges.