CONFINEMENT OF OHMICALLY HEATED PLASMAS AND TURBULENT HEATING IN HIGH-MAGNETICFIELD TOKAMAK TRIAM-1

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https://doi.org/10.5109/6617929

出版情報：Reports of Research Institute for Applied Mechanics. 27 (85), pp.85-98, 1979-12. 九州大学応用力学研究所

Reports of Researh Institute for Applied Mechanics
Vol. XXVII, No. 85, 1979

CONFINEMENT OF OHMICALLY HEATED PLASMAS AND TURBULENT HEATING IN HIGH-MAGNETIC-FIELD TOKAMAK TRIAM-1

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TRIAM-1, the tokamak device with high toroidal magnetic field, has been constructed to establish the scaling laws of advanced tokamak devices such as Alcator, and to study the possibility of the turbulent heating as a further economical heating method of the fusion oriented plasmas.

The plasma parameters obtained by ohmic heating alone are as follows; central electron temperature $T_{e0}=640$ eV, central ion temperature $T_{i0}=280$ eV and line-average electron density $\overline{n_e}=2.2\times10^{14}$ cm^{-3}. The empirical scaling laws are investigated concerning T_{e0}, T_{i0} and $\overline{n_e}$.

The turbulent heating has been carried out by applying the high electric field in the toroidal direction to the typical tokamak discharge with $T_{i0}\simeq 200$ eV. The efficient ion heating is observed and T_{i0} attains to about 600 eV.

Key words: Tokamak device, confinement, high density discharge, high current density, turbulent heating

1. Introduction

The tokamak device is one of the most promising devices for the magnetically confined thermonuclear fusion reactor, and many confinement and heating experiments are carried out. The upgraded devices for attaining the ignition condition, for example TFTR, JET, T-20 and JT-60, are under construction or projected. On the other hand, according to the recent Murakami scaling law[1)], high density plasmas may be

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stably attainable in the tokamak devices with high toroidal magnetic field. From this point of view, it may be possible to attain the ignition plasmas in a comparatively small-sized device. Many further heating methods such as neutral beam injection and RF heating are proposed and the experiments are carried on. But the problems concerning their low heating efficiency and high cost are unsolved so far. The turbulent heating method is now one of the attractive methods with theoretically indicated high heating efficiency and low economical cost. A few turbulent heating experiments[2)-5)] are carried out in the tokamak plasmas. No turbulent heating, however, is attempted in the well-confined high temperature tokamak plasma.

The TRIAM-project was started in April, 1977 for the purpose of minimization of the tokamak-type fusion reactor. The purpose of this project is to clarify the role of the turbulence in the process of loss and heating of the high-temperature and high-density plasma. The scaling laws of advanced tokamak devices such as Alcator will be studied. The turbulent heating experiment in such a high temperature and high density plasma is also attempted. The study of the role of the turbulence in so-called anomalous phenomena is one of the important topics not only in systemizing the fundamental plasma physics but also in achieving the controlled thermonuclear reactions. For the first step of this project, TRIAM-1 device (the 1st Tokamak of Research Institute for Applied Mechanics) was constructed and the experiments were started in the end of 1978. The confinement experiments of high temperature and high density plasmas are carried out and the empirical scaling laws in the high field tokamak are studied. The preliminary experiment of the turbulent heating shows the effective ion heating.

2. Experimental Apparatus

The vacuum chamber is made of stainless steel of thickness of 5 mm and acts the resistive shell with the skin time of $\tau_s \simeq 200\,\mu$sec. The maximum B_t/R value is 15.6 T/m, where B_t is toroidal magnetic field and R is major radius of plasma. Therefore the mean plasma current density more than 1000 A/cm^2 is expected at the $B_t=40$ kG discharge. The pumping system consists of two seriesly connected turbo-molecular pumps with a mechanical-booster and a rotary pump. The equivalent pumping speed at the evacuation port of vacuum chamber is about 100 l/s, and the ultimate pressure is 5×10^{-10} Torr. The device parameters of TRIAM-1 are summarized in Table 1.

Figure 1 shows the cross sectional view of TRIAM-1 device. As shown in Fig. 1 the turbulent heating coil consists of four parallel poloidal windings which are located just outside the vacuum chamber and inside the toroidal coils. In Fig. 2 the configuration of the vacuum

Table 1 Parameters of TRIAM-1.

Major Radius	25.4 cm
Limiter Radius	4 cm
Maximum Toroidal Field	40 kG
Maximum Vertical Field (Pre-Programmed)	1000 G
Maximum Horizontal Field (Pre-Programmed)	50 G
Iron Core (Without Pre-Magnetization)	0.037 Vsec
Maximum Electric Field for Turbulent Heating	6 kV
Maximum Plasma Current	47 kA
Duration Time	12 msec
Electron Density	2.2×10^{14} cm^{-3}
Electron Temperature	640 eV
Ion Temperature	280 eV

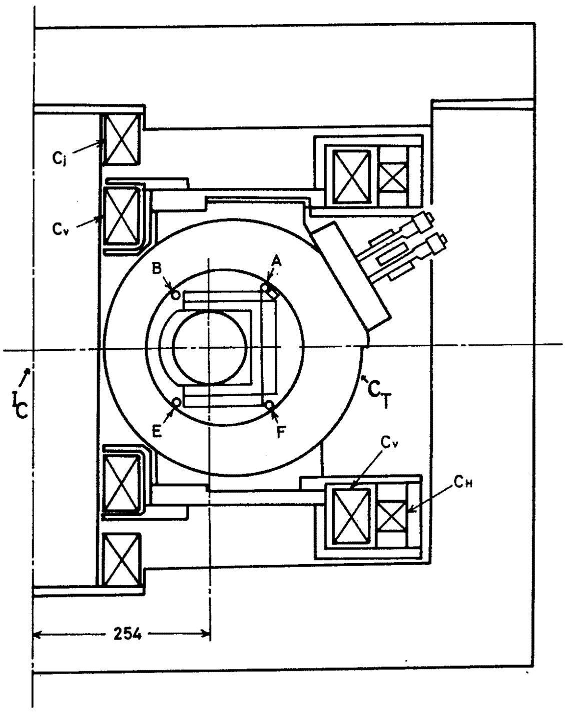

Fig. 1 Cross-sectional view of TRIAM-1 device.
C_T : Toroidal field coil.
C_V : Vertical field coil.
C_H : Horizontal field coil.
C_J : Primary coil.
A, B, E and F: Turbulent heating windings.
I_C : Iron core.

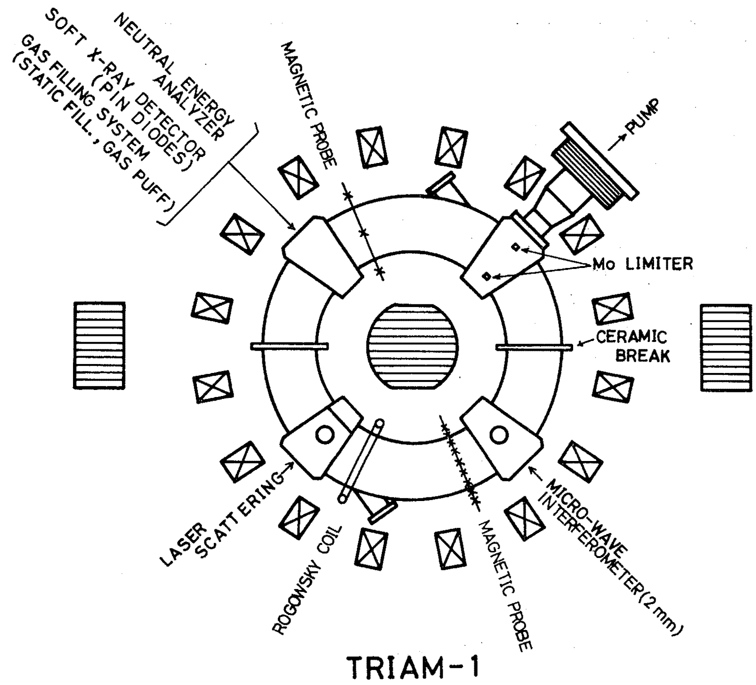

Fig. 2 Plan view of TRIAM-1 with diagnostic instruments and pumping system.

system and the diagnostic instruments are shown. Two ceramic breaks in the toroidal direction, for the purpose of turbulent heating experiment, are equipped.

3. Confinement of Ohmically Heated Plasma

3. 1. Current Density of Plasma

In Fig. 3 mean current density $\langle j \rangle$ obtained in TRIAM-1 is shown as a function of B_t/R, where $\langle j \rangle = I_p/\pi a_p^2$ (I_p is plasma current and a_p is minor radius of plasma which is assumed to be limiter radius a_L). Mean current density of the other tokamaks is also shown in case of $q(a)=3$. In TRIAM-1 the current density has attained to 950 A/cm² at $B_t=35$ kG and $\langle j \rangle = 1000$ A/cm² is expected to be obtainable at $B_t=40$ kG.

3. 2. Representative Discharge without Gas Puffing

The temporal variations of plasma parameters in the discharge without gas puffing are shown in Fig. 4. The central electron temprature T_{e0} measured by laser scattering is 640 eV and the line-average

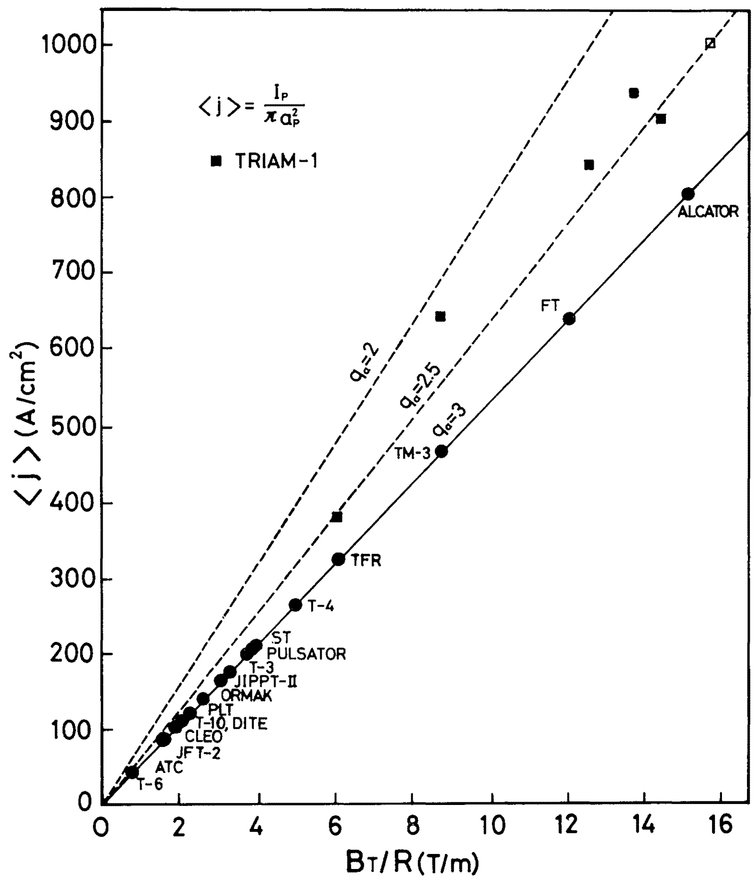

Fig. 3 Mean current density versus B_t/R-value.
B_t : Toroidal magnetic field.
R : Major radius of plasma.
■: Obtained in TRIAM-1.
□: Expected value in TRIAM-1.

electron density is $5\times10^{13}\,\mathrm{cm}^{-3}$. The discharge duration time t_d is longer than 40 times of the skin time τ_s. This shows that the vertical and horizontal magnetic fields are well pre-programmed. In this discharge $q(a)$ value decreases to 2.5.

The discharge in Fig. 5 has been obtained on the similar condition to the one in Fig. 4. In this discharge, the central ion temperature T_{i0} is also measured by the neutral particle energy analyzer. The electron temperature T_{e0}, however, is considerably lower than that in Fig. 4 and is very close to T_{i0}. Two different explanations are considered. The first is as follows. The current density of this discharge is about

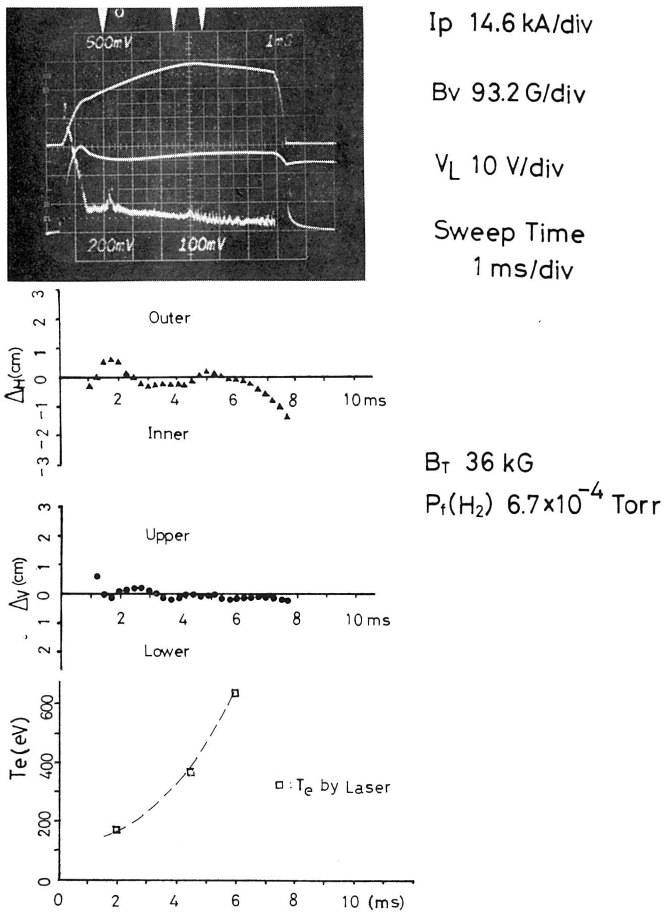

Fig. 4 Discharge characteristics without gas puffing. The arrows of the upper oscillogram indicate the timings when the electron temperature is measured by Thomson scattering.

Δ_H : Horizontal displacement of plasma column.
Δ_V : Vertical displacement of plasma column.
The electron temperature T_{e0} attains to 640 eV.

740 A/cm^2 and the streaming parameter $\xi = \langle u_d \rangle / \langle v_{the} \rangle \simeq 0.2 - 0.3$, where $\langle u_d \rangle$ and $\langle v_{the} \rangle$ are the drift and electron thermal velocities averaged over plasma cross section, respectively. So this discharge may be in the slide-away region studied in Alcator[6], and this may lead to $T_{e0} \cong T_{i0}$. The second is as follows; if ion confinement time $\langle \tau_{Ei} \rangle$ is longer enough than energy equipartition time $\langle \tau_{eq} \rangle$, then the ratio T_{e0}/T_{i0} can approach to unity[7].

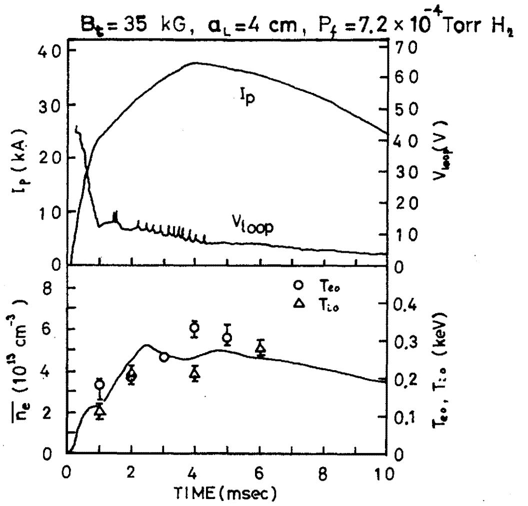

Fig. 5 Discharge with $T_{e0} \simeq T_{i0}$ obtained on the similar condition in Fig. 4. The central ion temperature T_{i0} and line-average electron density are measured by neutral particle energy analyzer and 2 mm microwave interferometer, respectively.

3.3. Representative Discharge with Gas Puffing

The temporal variation of I_p, V_{loop}, $\overline{n_e}$ and T_{e0} in case of high density discharge with gas puffing are shown in Fig. 6(a). Although disruptions occur several times during the discharge and the loop voltage changes considerably, $\overline{n_e}$ has reached $2.2 \times 10^{14}\,\mathrm{cm}^{-3}$. As the plasma radius a_p is small (≤ 4 cm), the slight shrinkage of the plasma minor radius by the cooling of plasma periphery will affect MHD stability very severely. The disruptive behaviour of this discharge is due to the strong cooling of plasma periphery by strong gas puffing, and the plasma becomes unstable magneto-hydrodynamically. This disruptive behaviour due to gas puffing can be suppressed by such a way as in the JIPP T-II tokamak[8], where the plasma current is supplementarily increased by the secondary power supplying banks. The heating of the plasma periphery by turbulent heating also may be effective. Fine control of gas puffing with this supplementary heating of the plasma periphery will lead the discharge stable and more higher value of $\overline{n_e}$ is expected.

The increasing rate of $\overline{n_e}$ is about $3.6 \times 10^{13}\,\mathrm{cm}^{-3}$/msec and is about 10 to 20 times as large as that of the other tokamaks. The high increasing rate of $\overline{n_e}$ seems to be due to the high current density of the discharge. By these reasons, extremely high-density plasma is expected in TRIAM-1, in spite of the smallness of the device and the comparatively short duration time of discharge.

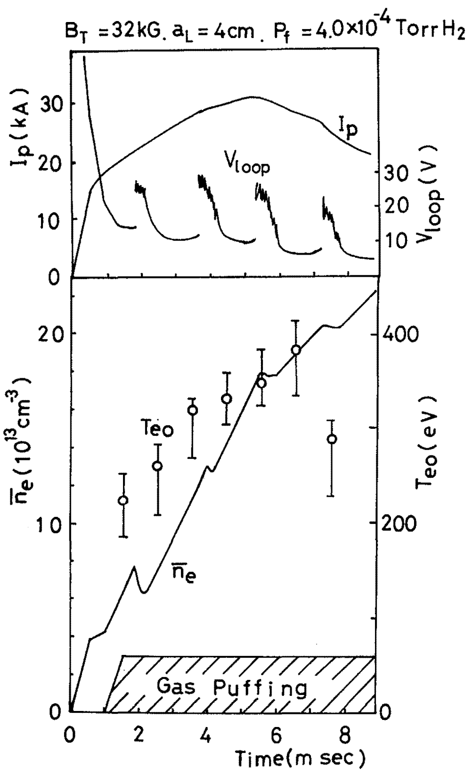

Fig. 6(a) Temporal variation of I_p, V_{loop}, $\overline{n_e}$ and T_{e0} in high density discharge with strong gas puffing.

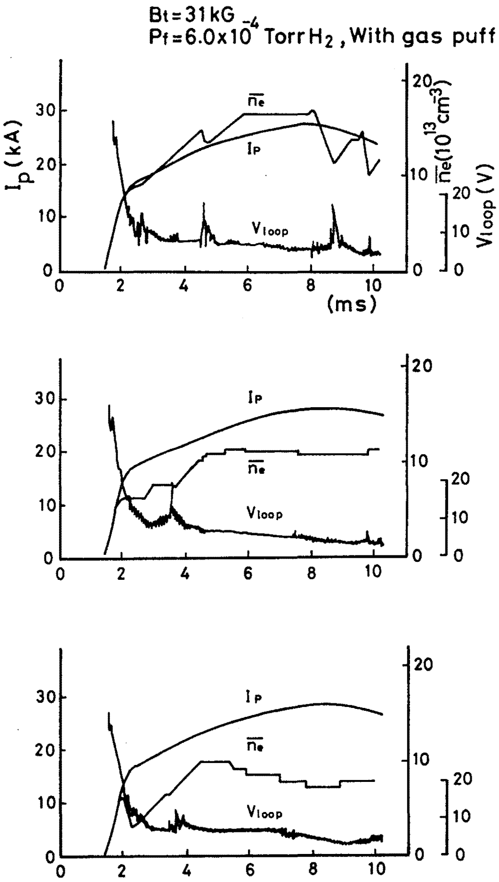

Fig. 6(b) Temporal variation of I_p, V_{loop} and $\overline{n_e}$ with moderate gas puffing.

We have obtained the stable high density discharge with moderate gas puffing and carefully adjusted pre-programmed vertical and horizontal magnetic field. Representative discharges are shown in Fig. 6(b).

3.4. Scaling Laws of Line-Average Electron Density, Central Ion Temperature and Central Electron Temperature

Maximum electron density $\overline{n_e}$ in TRIAM-1 is shown in Fig. 7 as a function of B_t/R together with those of the other tokamaks. The high density plasma of $\overline{n_e}=1\times10^{14}\,\mathrm{cm}^{-3}$ is obtained even without gas puffing. The higher density plasma ($\overline{n_e}=2.2\times10^{14}\,\mathrm{cm}^{-3}$) has been obtained by the strong gas puffing and the value of $\overline{n_e}$ is about 2 times as large as

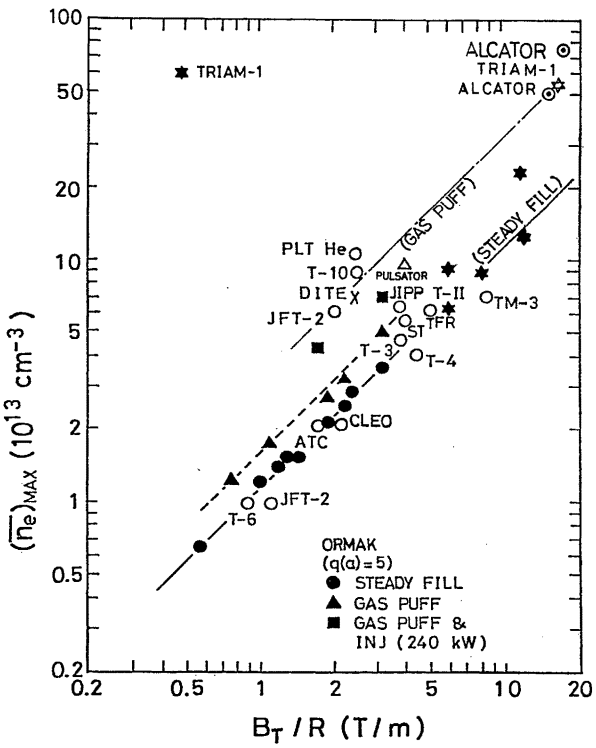

Fig. 7 Scaling of $\overline{n_e}$ as a function of B_t/R.
★: Obtained in TRIAM-1.
☆: Expected value in TRIAM-1.

Murakami scaling. As stated in subsection 3-4, the higher $\overline{n_e}$ value is expected in TRIAM-1, and this is shown in Fig. 7 with white star.

The scalings of T_{i0} and T_{e0} are shown in Fig. 8. The results of TRIAM-1 have a good agreement with the well-known Artsimovich scaling law of T_{i0}. The central electron temperature T_{e0} increases in proportion to the plasma current.

4. Results of Turbulent Heating Experiments

To study the possibility of turbulent heating as the further heating method of the fusion oriented plasmas, the turbulent heating experiment has been attempted in TRIAM-1.

To excite the current-driven turbulence in plasma the very high electric field (E^{TH}) is applied by means of four poloidal windings equipped just outside the vacuum chamber. In order to induce the pulsive

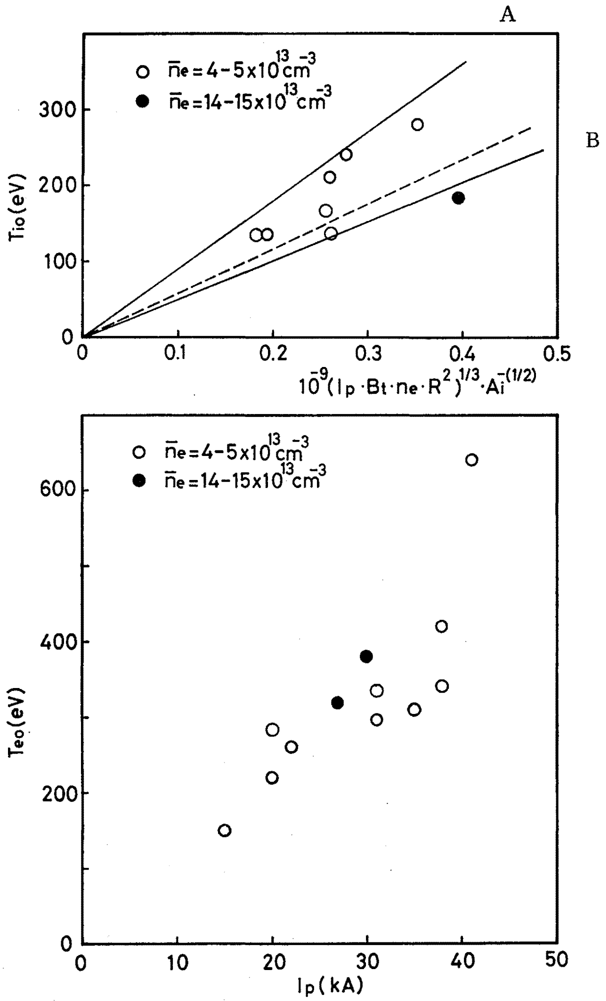

Fig. 8 Scaling laws of central ion and electron temperatures. The electron and current density distributions are both assumed to be parabolic in A and flat in B.

high electric field in plasma two ceramic breaks in the toroidal direction of the vacuum chamber are equipped. Maximum toroidal electric field applied on the surface of the vacuum chamber is about 6 kV. The rise time of the pulsive current (I_P^{TH}) is about 5 μsec.

The temporal variations of I_p, V_{loop}, $\overline{n_e}$, T_{e0}, T_{i0}, I_P^{TH} and E^{TH} are shown in Fig. 9. The pulsive electric field is applied to the typical tokamak plasma with $I_p \simeq 20$ kA and $\overline{n_e} \simeq 4\times10^{13}$ cm^{-3} in the same direction of I_p at 2.3 msec after the initiation of the discharge, where $B_t=$

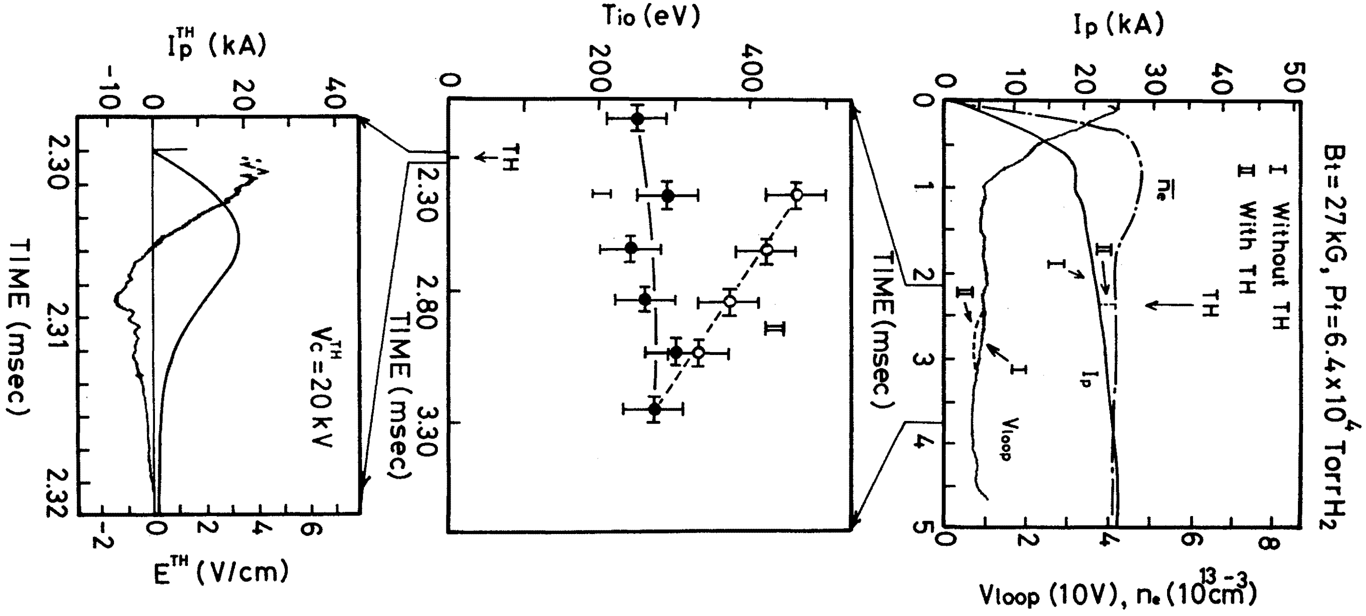

Fig. 9 Representative discharge with turbulent heating at B_t=27 kG.

E^{TH} and I_p^{TH}: Toroidal electric field and plasma current induced by the pulsive heating current.
V_c^{TH}: Charging voltage of the capacitor for the turbulent heating.
The "*TH*" in the figure means the timing of the application of pulsive electric field.

27 kG. At 0.5 msec after the application of the pulsive high electric field, the loop voltage of the plasma decreases to be about 80 %. The central ion temperature $T_{i0}=240$ eV increases to 460 eV at about 150 μsec after the pulsive field application and decreases to the value without turbulent heating with the decay time of 1 msec (The detail measurement of the decay time may give the knowledge of the ion energy confinement time).

Figure 10 shows the increment of the central ion temperature ΔT_{i0} by the turbulent heating as a function of the applied pulsive electric field E^{TH}. In this figure, the results of the discharges at $B_t=27$ kG (Fig. 9) and 31 kG are shown. In the case of $B_t=31$ kG and $E^{TH}=9$ V/cm the central ion temperature increases from 170 eV to 580 eV. The energy spectra in the case are shown in Fig. 11.

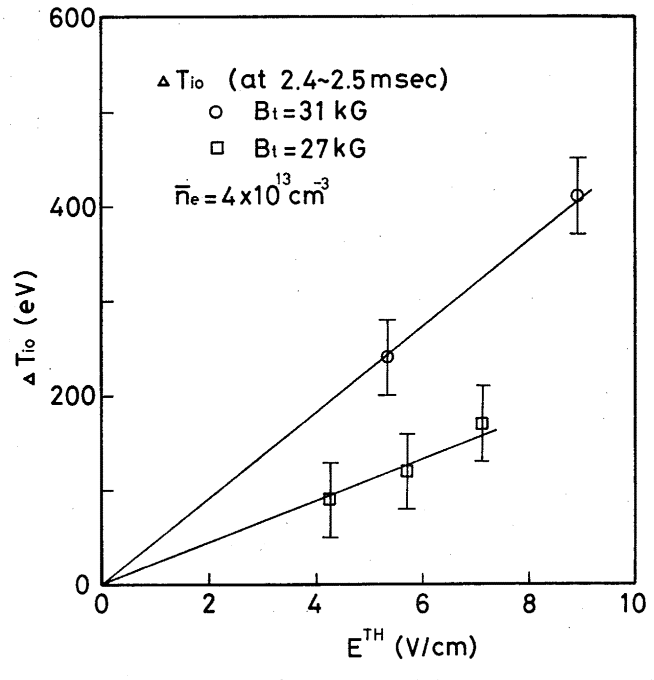

Fig. 10 The increment of the central ion temperature ΔT_{i0} shown as a function of the pulsive toroidal electric field E^{TH}, where $B_t=27$ kG (Fig. 9) and 31 kG. The value of ΔT_{i0} is estimated in 100 μsec to 200 μsec after the application of the pulsive electric field and E^{TH} is the applied maximum value.

5. Conclusion

In the high toroidal magnetic field tokamak, TRIAM-1, the typical

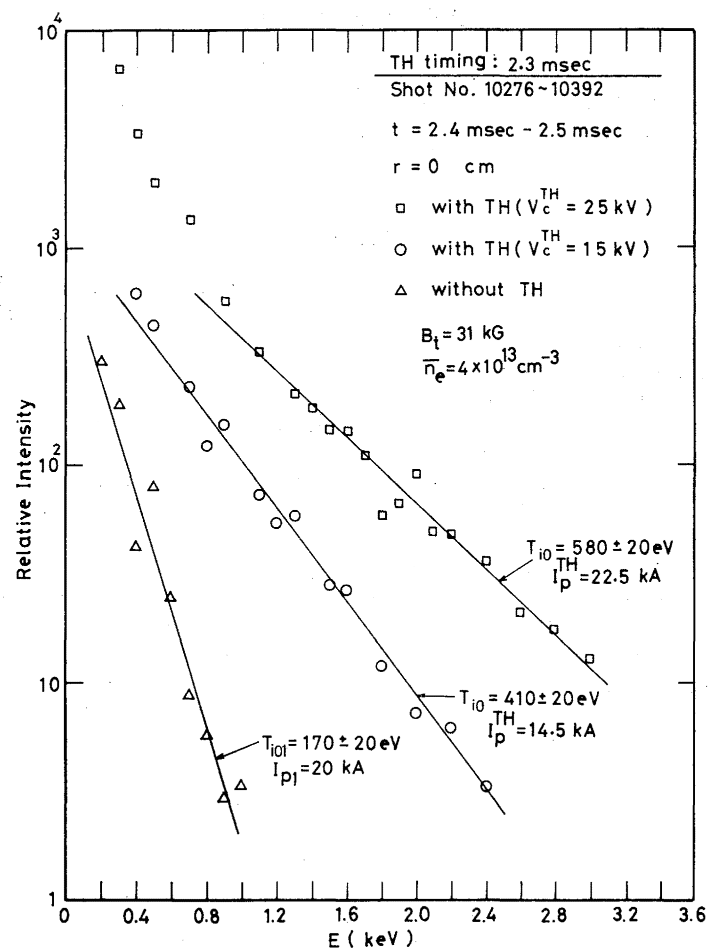

Fig. 11 Energy spectra of charge-exchanged neutrals in case of B_t=31 kG shown in Fig. 10.

tokamak plasma has been obtained by ohmic heating as $T_{e0}=640$ eV, $T_{i0}=280$ eV and $\overline{n_e}=2.2\times10^{14}$ cm^{-3}. The empirical scaling laws of T_{e0}, T_{i0} and $\overline{n_e}$ are studied. The experimental results show that the high magnetic field tokamak is advantageous to obtain the high temperature and high density plasma.

The turbulent heating is applied to the well-confined high temperature tokamk plasma. The ion component is very effectively heated up and the central ion temperature increases from 170 eV to 580 eV. It is concluded that the turbulent heating method is very effective for heating the tokamak plasma.

Acknowledgement

The authors express their sincere thanks to Professor K. Kitajima and Professor N. Yajima for their continuous encouragements, and also to Mr. S. Kawasaki and Mr. H. Nakashima for their helps in the experiments.

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(Received October 8, 1979)