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EFFECTIVE TURBULENT HEATING BY A DOUBLE PULSE IN TRIAM-1

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The efficient ion heating by a double turbulent heating pulse combined with positive and negative polarities is observed experimentally without the deterioration of the confinement properties of a tokamak plasma in TRIAM-1. The increment of the ion temperature by the double pulse with the opposite polarity is the sum of the increments of the ion temperature by each single pulse. These experimental results enhance the posibility of the turbulent heating by a multiple pulse.

Key words: Double turbulent heating pulse, Efficient ion heating, Double pulse with opposite polarity, Multiple pulse.

1. Introduction

It is necessary for a thermonuclear fusion reactor that the ion temperature (T_i) is greater than 10 keV and that the product ($n\tau$) of ion density (n) and energy confinement time (τ) is greater than 10^{14} cm^{-3}sec. In order to obtain such a plasma further heating methods[1] must be applied to tokamak plasma. A turbulent heating method has been explored as one of further heating methods. The turbulent heating method is based on the following principle[1]: by driving a sufficiently large current through a plasma, current-driven instabilities (the ion-cyclotron instability, the ion-acoustic instabilty and the Buneman instability) are produced and then the plasma resistivity becomes much higher than the classical one and it results in the rapid plasma heating. Many experiments on the turbulent heating have been explored not only in linear machines[2)-6)] but also in toroidal devices.[7)-11)] In these experiments, in order to produce the high pulse current for the turbulent heating a high electric field ($\gtrsim$100 V/cm) was applied to the low

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temperature plasma and then the turbulently heated plasma could not be confined successfully.

In the TRIAM-1 tokamak,[12)-19)] the turbulent heating has been studied experimentally. And a relatively low electric field ($\lesssim$10 V/cm) is applied to a well-confined high-temperature plasma and the effective ion heating has been observed without deterioration of the confinement properties. In the turbulent heating by a single pulse, however, the increase of the ion temperature is limited by the current disruption due to the reduction of the safety factor ($q(a)\simeq 2$) in the case of the positive polarity, and by the lack of MHD equilibrium due to vanishing of a total plasma current in the case of the negative one[16)]. Therefore the turbulent heating by a multiple pulse method is required in order to achieve the more efficient ion heating for a fusion plasma.

This report describes the experimental results which are obtained by the application of the double pulse on the stably confined tokamak plasma produced by the ohmic heating in TRIAM-1, in order to investigate whether or not the turbulent heating by a multiple pulse method is usefull as the further heating method.

2. Experimental Device and Diagnostic Methods

The TRIAM-1 device is a small high-field tokamak; the toroidal field $B_t \simeq 40$ kG, the major radius $R=25.4$ cm and the minor radius $a_L=4$ cm. The device can produce a high plasma current and a high electron density plasma such as Alcator[20)] on account of the large B_t/R-value ($\sim$16 T/m).

For the application of the turbulent heating pulses, the vaccum chamber is insulated in the toroidal direction by two ceramic breaks. Primary coils for the turbulent heating are inside the bore of the toroidal magnetic field colis and consist of four parallel poloidal loops located just outside the vacuum chamber as shown in Fig. 1. In our previous turbulent heating experiments, in order to minimize the error field caused by the coil current for the turbulent heating at the center of plasma, the ratio of the inner coil current to the outer coil one has been adjusted by inductors and four primary coils have been connected in parallel with a capacitor bank. In this experiment, however, the inner coils and the outer coils are connected independently with capacitor banks (3.7 μF, 40 kV, 3 kJ) as shown in Fig. 2. And it was ascertained before the double pulse experiment that the error field has no effect on the plasma confinement and on the heating of the plasma. The current rise time of these pulses is about 5 μsec, and the applied toroidal electric field is below 10 V/cm.

The ion temperature (T_i) is obtained by a neutral particle energy analyzer (NEA). The electron temperature (T_e) is measured by a ruby laser Thomson scattering method. The line-average electron density ($\bar{n}_e$) is monitored by a 2mm-microwave interferometer. A one-turn loop and a

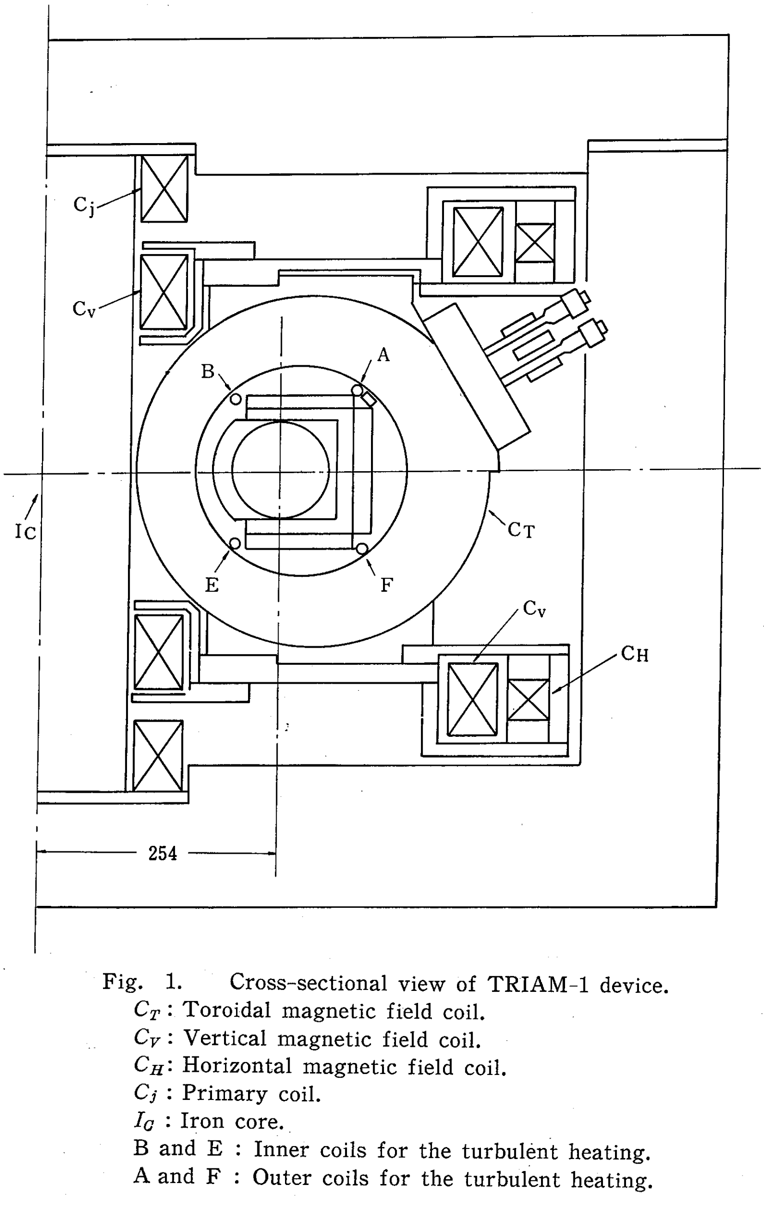

Fig. 1. Cross-sectional view of TRIAM-1 device.
C_T : Toroidal magnetic field coil.
C_V : Vertical magnetic field coil.
C_H: Horizontal magnetic field coil.
C_j : Primary coil.
I_C : Iron core.
B and E : Inner coils for the turbulent heating.
A and F : Outer coils for the turbulent heating.

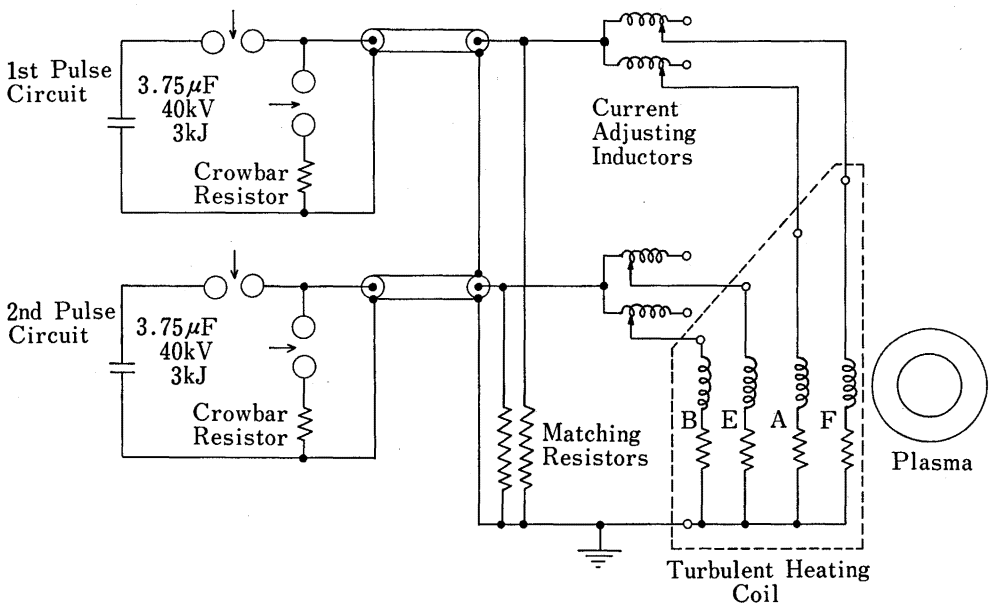

Fig. 2. Electric circuit for the turbulent heating.

Rogowskii coil are used for the measurements of the pulsed loop voltage (V^{TH}_{loop}) and the plasma current (I^{TH}_{p}) induced by the heating pulses. Density fluctuations ($\widetilde{V}_{m}$) in a skin layer are observed just after the application of the heating pulses by a 4mm-microwave scattering system, which is a conventional homodyne detection system.

3. Experimental Results

The first turbulent heating pulse is applied to a stably confined high-temperature plasma ($T_{e0}\simeq 320$ eV, $T_{i0}\simeq 120$ eV, $\bar{n}_e\simeq 2\times 10^{13}$ cm^{-3}) at 5 msec after the initiation of discharge, when the toroidal field (B_t) is 28 kG and the ohmic heating current (I_p) is 17 kA. The second turbulent heating pulse is superimposed at 30 μsec after the application of the first one as shown in Fig. 3.

The effect of plasma heating by the double pulse with the same polarity, which consists of two current pulses with the same direction as plasma current is investigated. And the heating effect by the double pulse with the opposite polarity, which consists of the first current with negative polarity and second one with positive polarity is investigated. In each case, the second current is fixed and the first current is changed. Then the increment of the ion temperature by the double pulse is compared with that by each pulse.

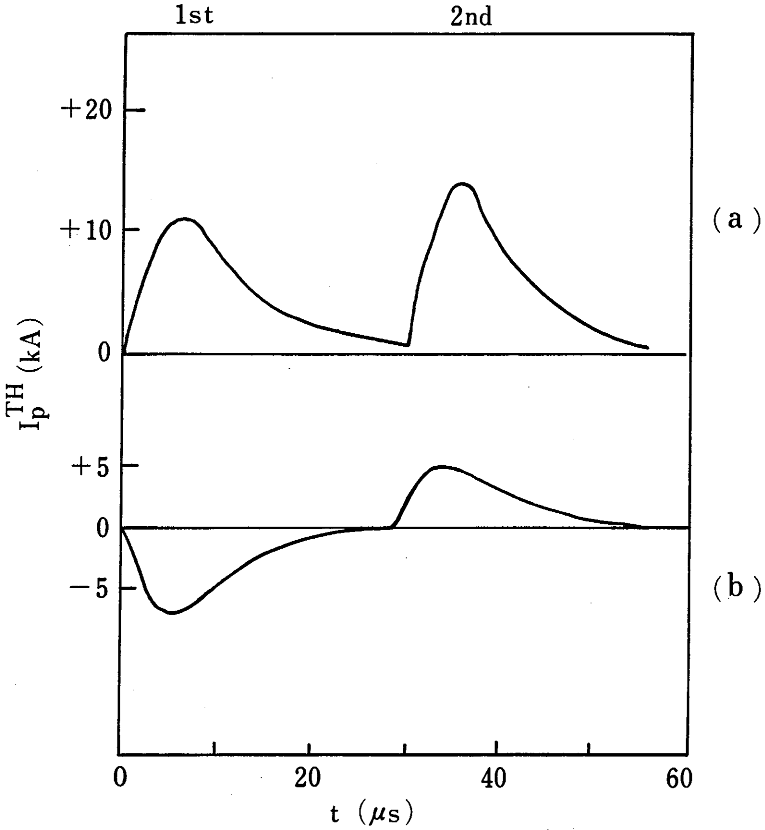

Fig. 3. Turbulent heating current by a double pulse.
(a) The double pulse with the positive first and positive second current.
(b) The double pulse with the negative first and positive second current.

Figure 4 shows the relation between the central ion temperature (T_i) by the same polarity double-pulse heating and the current ratio ($I_p^{TH}(F)/I_p^{TH}(S)$) of the first heating current ($I_p^{TH}(F)$) to the second one ($I_p^{TH}(S)$).
The ion temperature increased by only the first pulse are also shown by the black triangle (▲). In this figure, the ion temperature by only the first pulse increases with increasing the current. Therefore if the first pulse and the second pulse contribute to the ion heating independently, the ion temperature by the double pulse should change according to the broken curve in this figure. The experimental results, however, show that the ion temperature by the double pulse decreases to that by only the first pulse

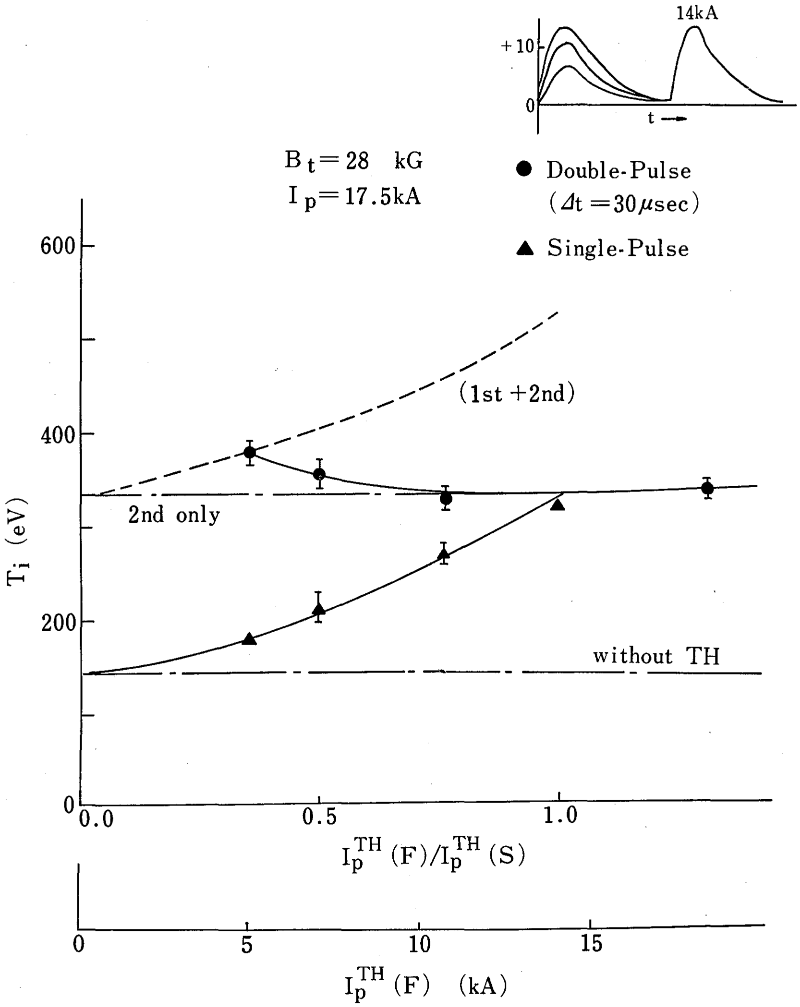

Fig. 4. The relation between the central ion temperature by the same polarity double pulse and the current ratio of them. The broken curve is the ion temperature by the double pulse which is expected when each pulse contributes to the ion heating independently.

with increasing the current ratio. Figure 5 shows the relation between the density fluctuations ($\widetilde{V}_m$) and the current ratio ($I_p^{TH}(F)/I_p^{TH}(S)$). The frequency of the density fluctuation is several MHz, and then the fluctuation is considered to be the low-frequency ion-acoustic instability[21].

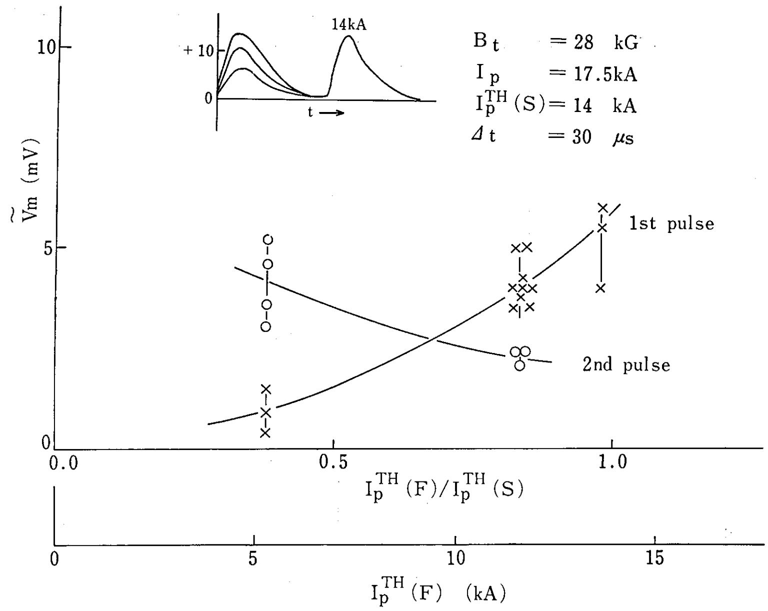

Fig. 5. The dependence of the density fluctuations on the current ratio in the case of the same polarity double pulse.

The fluctuation level due to the first pulse becomes larger with increasing the turbulent heating current as indicated by ×-symbol. When the second current is kept constant, the fluctuation level due to the second pulse becomes smaller with increasing the current of the first pulse. This implies that the plasma heating by the first pulse is disadvantageous for the excitation of the ion-acoustic wave by the second pulse.

Next, we investigate the heating effect in the case of the opposite polarity double pulse, which consists of the first current with negative polarity and the second one with positive polarity. Figure 6 shows the relation between the central ion temperature (T_i) by the double-pulse heating and the current ratio ($I_p^{TH}(F)/I_p^{TH}(S)$). In this case, the experimental results show that the ion temperature by the double pulse agrees with that estimated by each pulse heating, i. e., that the increment of the ion temperature by the double pulse ($\Delta T_i(D)$) is the sum of the increments of the ion temperature by each single pulse ($\Delta T_i(F)$ and $\Delta T_i(S)$). Moreover the level of the density fluctuation by the second pulse does not decrease with increasing the current of the first pulse as shown in Fig. 7. These results imply that the ion-acoustic instability by the second current pulse is caused as strongly as that by only the second pulse.

As described above, in the case of the double pulse with the opposite polarity, each pulse causes the ion-acoustic instability just like a single pulse and then contributes to the ion heating of plasma independently.

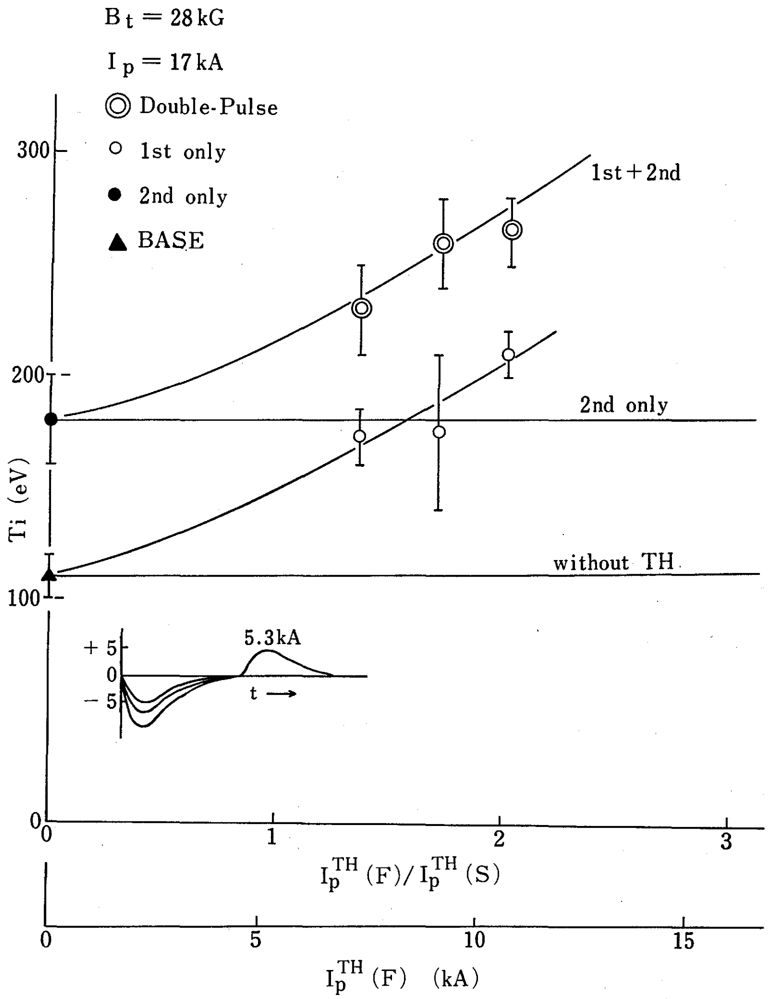

Fig. 6. The relation between the central ion temperature by the opposite polarity double pulse and the current ratio of them.

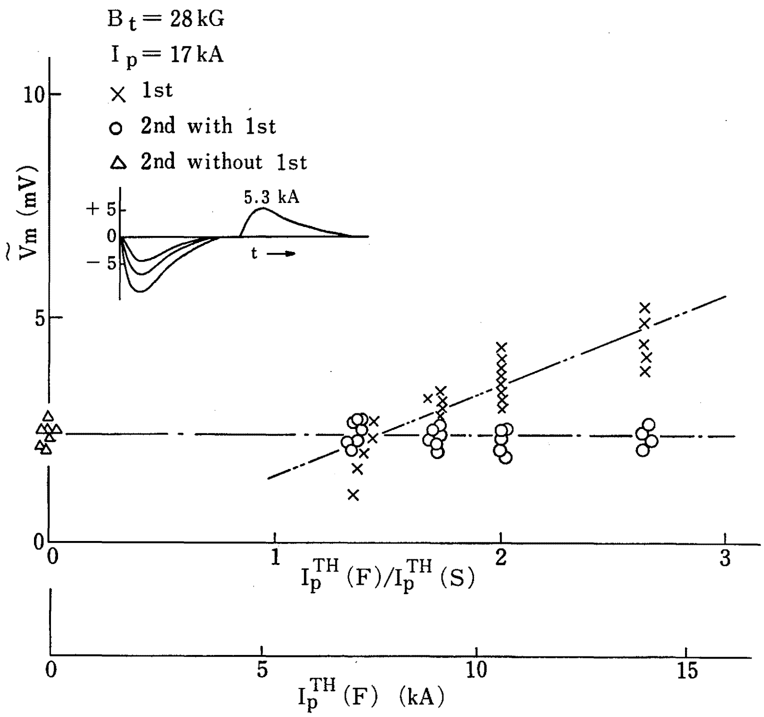

Fig. 7. The dependence of the density fluctuations on the current ratio in the case of the opposite polarity double pulse.

4. Discussion

These experimental results may be explained as follows. The ion heating by the moderate toroidal electric field observed in TRIAM-1 results from the interaction between the ion-acoustic wave and the particles which have the velocity comparable to the phase velocity of the ion-acoustic wave. And then the ion velocity distribution is flattened near the phase velocity. Just after this, if the successive pulse with the same polarity, whose current is less than the first one, is applied, it is difficult to excite the ion-acoustic wave because of the stronger Landau-damping. Therefore the second pulse with much larger current than the first one should be applied to excite the ion-acoustic wave which is responsible for the ion heating.

If the successive pulse with the opposite polarity is applied, however, the electron velocity distribution is drifted to another direction in the velocity space where the ion velocity distribution does not flatten. Then the ion Landau-damping does not interfere with the growing of the ion-acoustic wave. Therefore the ion-acoustic wave with opposite phase velocity to that by the first pulse is caused, and the wave-particle interaction occurs near the phase velocity of the ion-acoustic wave. This leads that in the case of the double pulse with the opposite polarity, two pulses contribute to the ion heating indendently.

5. Conclusion

In TRIAM-1, when a double pulse for the turbulent heating as the first step of the multiple-pulse heating method is applied in the course of the typical tokamak discharge, ions are efficiently heated up without the deterioration of the confinement properties of a tokamak plasma.

In the case of the double pulse with the same polarity, it is necessary for the effective ion heating that the second current $I_p^{TH}(S)$ for the turbulent heating must be much larger than the first one $I_p^{TH}(F)$.

In the case of the double pulse with opposite polarity, the increment of the ion temperature by the double pulse ($\Delta T_i(D)$) is the sum of the increments of the ion temperature by each single pulse ($\Delta T_i(F)$ and $\Delta T_i(S)$), that is

$$\Delta T_i(D) \simeq \Delta T_i(F) + \Delta T_i(S).$$

These experimental results enhance the posibility of the turbulent heating by a multiple pulse.

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