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RESEARCH REPORT

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On the Fast Ion Heating of Plasma

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ABSTRACT

A critical survey is given about experimental results on anomalously fast ion heating, including the linear turbulent heating experiment and others, which often be said to have close correlation with the plasma turbulences. Results may not be explained consistently in terms of only the plasma turbulence, usually considered so far. We intend to give a comment suggesting another mechanism of fast ion heating, named the turbulent macroscopic process. It is associated with a macroscopic motion of plasma, or an instability of long wavelength fluctuations, which was set in as a result of the change of plasma parameters of discharge column, the parameter change being originated from the usual high-frequency short-wavelength plasma instabilities.

1. INTRODUCTION

There are two trends in the present day research of plasma heating for the thermonuclear fusion. One is to heat a Tokamak plasma of about 2 KeV ion temperature up to over 20 KeV. To this end, one needs a heating method which furnishes the heating rate faster than the classical Ohmic heating. The turbulent heating is considered a good candidate for this purpose. The other trend is to first produce a high temperature (about 20 KeV) plasma and then confine it as an afterglow state in an appropriate magnetic field configuration. We know, at present, several experimental results1) which show ion heating up to 4 - 5 KeV in the open magnetic field configuration without careful examination of the longitudinal energy loss. Laser heating and compression of a solid pellet is also a good example of this latter approach.

In order to raise the heating efficiency, it is important to have a proper understanding of the physical mechanism underlying the fast ion heating. Since in the fast ion heating experiment the final temperature has to be much higher than the initial temperature, the process normally contains highly nonlinear phenomena. Simple classical considerations2) will then be insufficient to understand the process.

Theoretical studies, including nonlinear process, have been steadily advanced, a representative of which is the weak turbulence theory3). Within its framework, the directed energy of the electrons is dissipated at the rate, $i^2 \cdot R_{anomalous}$, and is shared only partly by the ion thermal energy. The nonlinear Landau damping is considered a possible mechanism of ion heating 4). The calculated heating rate is, however, too small to explain the experimental result. Effect of ion trapping is then considered more important, and a computer simulation 5), carried out by the particle-in-cell method, shows an efficient ion heating by ion-acoustic turbulence up to approximately the same temperature as the electrons.

At present, experimental results of the turbulent heating, in particular those of the basic linear turbulent heating experiments, are not given a consistent explanation, especially regarding the ion-heating data; some look consistent with the expectation of the weak turbulence theory, but others are not. In addition to the turbulent heating experiments, there are several others which are known to show fast ion heating 6), some of them being considered closely related to the turbulent heating.

The present comment intends to give a critical survey of the experimental results of fast ion heating and to suggest a possible physical mechanism which is different from those usually considered in the analyses of the turbulent heating experiments. The mechanism we suggest is associated with a macroscopic motion of plasma, or an instability of long wavelength fluctuations which was set in as a result of the change of plasma parameters of the discharge column, the parameter change being originated from the usual high-frequency, short-wavelength plasma instabilities$^{7)}$. Such a process will hereafter be refered to as the turbulent macroscopic process and be distinguished from the usual turbulent heating process in which only the microscopic fluctuations are taken into consideration.

In the following, we first discuss the results of the linear turbulent heating experiments and present the possibility of explaining the results in terms of the turbulent macroscopic process. The analyses are then extended to the fast ion heating experiments other than the turbulent heating. A brief conclusion is given at the end.

2. ION HEATING IN THE TURBULENT HEATING EXPERIMENTS

It is now established that in the linear turbulent heating experiments the ions can be heated substantially along with the electron heating. Thus the linear turbulent heating is considered a good candidate for the further heating of torus plasmas.

Historically, the ion heating was observed$^{8)}$ when the applied electric field exceeded a critical value which was theretofore unavailable. The observed ion heating was then tentatively explained as an effect of the turbulence produced by the Buneman instability. The dependence of the anomalous resistivity as well as the heated ion energy, nT_i, on the applied electric field and on the drift velocity of the directed electron current were experimentally examined, and the results appeared to indicate that the onset of the ion heating coincides with the occurrence of the anomalous resistivity data characteristic to the Buneman instability. However, when the experimental results were more carefully examined by refined measurements, several new features which are unexplained by the Buneman instability have come out.

Before discussing these features, let us briefly describe some basic experimental results which seem to be explained by the standard theory of plasma turbulence. First, the observed energy loss of the directed electron current is expressed as $i^2 \cdot R_{observed}$, and the heated total energy of plasma associated with the motion perpendicular to the basic magnetic field, $n(T_e + T_i)_\perp$, is proportional to $V^2_{electrodes}$ 9). The experimental resistivity, $R_{observed}$, is not very far from the theoretical prediction based on the weak turbulence theory 10). Secondly, the observed energy spectrum of the ion component indicates a two-temperature Maxwellian distribution, and is consistent with the results of the computer simulation 11) which also shows the evolution of a two-temperature ion distribution as a result of the ion acoustic turbulence.

We now discuss those features which are not explained by simple arguments of heating by plasma turbulence. The first feature is observed in the turbulent heating of arc plasma, having been heated up to about 2 KeV[12]. When the heating pulse (of about 5 μsec duration) is applied, the onset of the ion heating always delayed by 0.5 μsec or more from the start of the heating pulse, although the anomalous resistivity sets in immediately after the start of the heating pulse (the delay time is less than 0.1 μsec). In the process of this ion heating, the fraction of the high-temperature ion component is increased, but its temperature remains almost constant as a function of time. High frequency oscillations around the ion plasma frequency were also observed. The second feature is on the TN-5 machine[13]. When the experiment was conditioned such that the heating current flows only on the surface of the plasma column (20 cm in diameter) during the entire discharge, the central part of the column, as well as the boundary, was observed to be heated. As far as one can see from the magnetic-probe results presented in Ref.12, the inner part of the plasma column appears to be undisturbed, although the current behavior outside the plasma is extremely complicated during the discharge. The third feature is observed in the BSG-II machine when it is operated under the condition just above threshold for ion heating[14]. Under such condition, the turbulence evolved can be treated as weak, so that if the ion heating is due to a plasma turbulence, it should follow the prediction of the weak turbulence theory. Namely, if the ion heating is due to Landau damping (linear or nonlinear) of ion-acoustic waves excited by the electron current, the heating rate should depend on the ion mass. Experiment was carried out by adding a small amount of argon ions as probing impurities to the host helium ions, and the result shows a simultaneous heating of both species of ions with approximately the same heating rate, in contradiction to the prediction of the weak turbulence theory.

Now, a suggestive experimental result was obtained on the BSG II machine when the D.C. magnetic field, along which the plasma column is located and the heating current flows, is as low as 2 kilo gauss and the heating is conditioned just above threshold. Namely, along with the ion heating a resistive hump of the voltage drop between the discharge electrodes is always observed, which is shown in Fig.1. Simultaneously the plasma is found to expand radially across the magnetic field. As a result a discharge trace of damage is formed on the glass tube surrounding the plasma column. Close examination of this trace indicates the presence of screw type plasma current when it radially expanded. The resistive hump is observed to be delayed by about one μsec from the initiation of the heating current, and this delay time is controllable by changing the operating conditions. In particular, it decreases when either the magnetic field or the current is increased. This dependence remind us of the screw instability in a collision-dominated positive column, investigated by Hoh and Lehnert[15). The similarity of these two results, the screw instability in a collision-dominated positive column and the expanding screw current in a collisionless turbulent plasma, suggests a possibility that the initially dissipationless plasma is transformed to a dissipative plasma as a result of the anomalous resistivity due to turbulent, high-frequency fluctuations. If the ion heating is due to the acceleration associated with a macroscopic plasma motion, rather than the resonant acceleration by Landau damping, the observed simultaneous heating of the heavy and light ion components can naturally be understood.

So far, similar experimental characteristics have not been examined systematically for a stronger magnetic field configuration. However, it is worth pointing out the possibility of explainging the results for the arc plasma and the TN-5 machine in terms of the turbulent-dissipative drift instability. First, explanation of the results of the TN-5 machine from our viewpoint will be the following. The surface current first excites high-frequency oscillations on the surface which initiate a macroscopic drift-dissipative instability. The excited macroscopic plasma motion will then extend to the entire plasma column and heat the whole plasma. The magnetic-probe measurements can detect only the temporal current distribution, but not the macroscopic plasma behavior. The latter may be detected by measuring the electric field distribution. We next attempt a similar explanation for the results of the arc plasma. The anomalous resistivity observed immediately after the start of the heating pulse will excite a drift-dissipative instability on the surface, and a high-energy ion component is produced. The energy distribution of this high-energy component will determine the ion temperature as measured by a statistical summing-up of many discharge shots. The delay in the appearance of the high-energy particle flux will correspond to the time needed for the macroscopic plasma motion to extend over the entire plasma column. As an indication of the extension of plasma motion, the heating current shows a resistive hump at about the same instant as the onset of the high-energy particle flux, as in the case of the BSG II machine.

In the above arguments, the mechanism by which ions are heated via macroscopic process is left open to question. We, however, point out that in the presence of a magnetic field ion motion due to unidirectional acceleration can be made isotropic inside the plane perpendicular to the magnetic field. Such an isotropic ion motion can likely be observed as a high-energy tail in the ion energy distribution.

3. FAST ION HEATING OTHER THAN TURBULENT HEATING

Having pointed out the possible importance of the turbulent-macroscopic process in the linear turbulent heating experiments, we now turn our attention to the other fast ion-heating experiments and discuss the possibility of similar heating mechanisms. To this end, we first summarize various ion heating experiments in the T_i- $n\tau$ diagram in Fig.2. Our specific attention is on the group of experiments located in the low $n\tau$ and high T_i region. Generally speaking, a better plasma heating is available by suppressing the energy loss from the plasma. On the other hand, the results in this group are obtained in open magnetic field configurations. Namely, ion temperature of several KeV is obtained in a straight or mirror magnetic field without any particular management to prevent energy loss along the magnetic field. Thus the heating rate for this group must be very high.

We now discuss on some of the experiments in this group. First, for the plasma focus experiment we estimated the ion temperature by the total neutron yield with the assumption that the neutrons were produced by thermonuclear reactions. The neutron yield depends on the bias magnetic field and the maximum yield obtains with zero bias field. In addition, the neutron flux show some anisotropy. Recent measurement showed16) that as a function of time the neutron yield becomes maximum, not at the instant of the maximum pinch of the plasma column, but a few tenths μsec after the maximum pinch; at this instant the plasma has a diffuse radius, about ten times larger than that of the most strongly pinched column. This suggests a relation of the neutron yield, and hence the ion heating, to a macroscopic process. Indeed, other photographic data indicate the existence of a macroscopic instability.

Moreover a strong electron current is observed which may produce a microscopic plasma turbulence and a resulting anomalous dissipation$^{17)}$. We next consider the so-called collisionless shock experiment$^{18)}$. Ion heating of this case is also maximized when the bias magnetic field is zero. Again a macroscopic process appears to be important in the fast ion heating. Namely, its mechanism is considered$^{19)}$ that a concentric potential barrier is formed by turbulently dispersive current layer perpendicular to the magnetic field, and the potential barrier hits and accelerates the ions progressively as it contracts radially toward the axis. In this way, high ion-temperature plasma is produced on the axis of the column before arrival of the potential barrier. In this experiment the ion heating is strongly reduced when the bias magnetic field increases to about 300 gauss. Finally we discuss the plasma collision and compression experiment$^{20)}$. The initial plasma is produced by collision of two counter-streaming plasmas injected along the magnetic field. The heating method is similar to the thetapinch compression. The plasma itself is uncompressed as measured by the density profile, but the ion temperature and the electron temperature are concurrently increased up to 4 KeV within the period of 0.6 μsec. Neutron yield at the initial stage looks anisotropic. The experiment is similar to the collisionless shock experiment, but the ion heating is observed in the magnetic field of 1.5 kilo gauss. During the heating process low frequency oscillations of 20 ~ 30 MHz are observed. These oscillations are presumably due to a macroscopic instability and are supposed to be responsible for ion heating. The heating efficiency depends on the initial plasma which is produced by an anomalously efficient collision, the anomaly being possibly due to ion counter-streaming instabilities.

4. CONCLUDING REMARK

One can think of three type of heating methods faster than the Ohmic heating. They are

i) S-type: Heating by absorption of a coherent wave energy which is excited, for instance, by Stix coil.

ii) T-type: Heating by absorption of the energy of turbulent fluctuations excited by the input of a directed energy; the heating process may be described by the weak turbulence theory.

iii) M_t-type: Heating associated with a turbulent-macroscopic process described above.

Efficiency of the S-type heating is relatively low, so that it will be applicable only to a well-confined plasma. A larger heating efficiency is expected by the T-type heating, but is not sufficient to account for many of the observed fast ion heating. In most experimental results falling in the low $n\tau$ and high T_i region of the $n\tau$-T_i diagram, the observed fast ion heating appears to be associated with a macroscopic plasma motion together with a microscopic turbulence generated by the input of a directed energy. Our conclusion may then be stated that the M_t-type ion heating is worth investigating as a possible mechanism common to many of the observed fast ion heating experiments.

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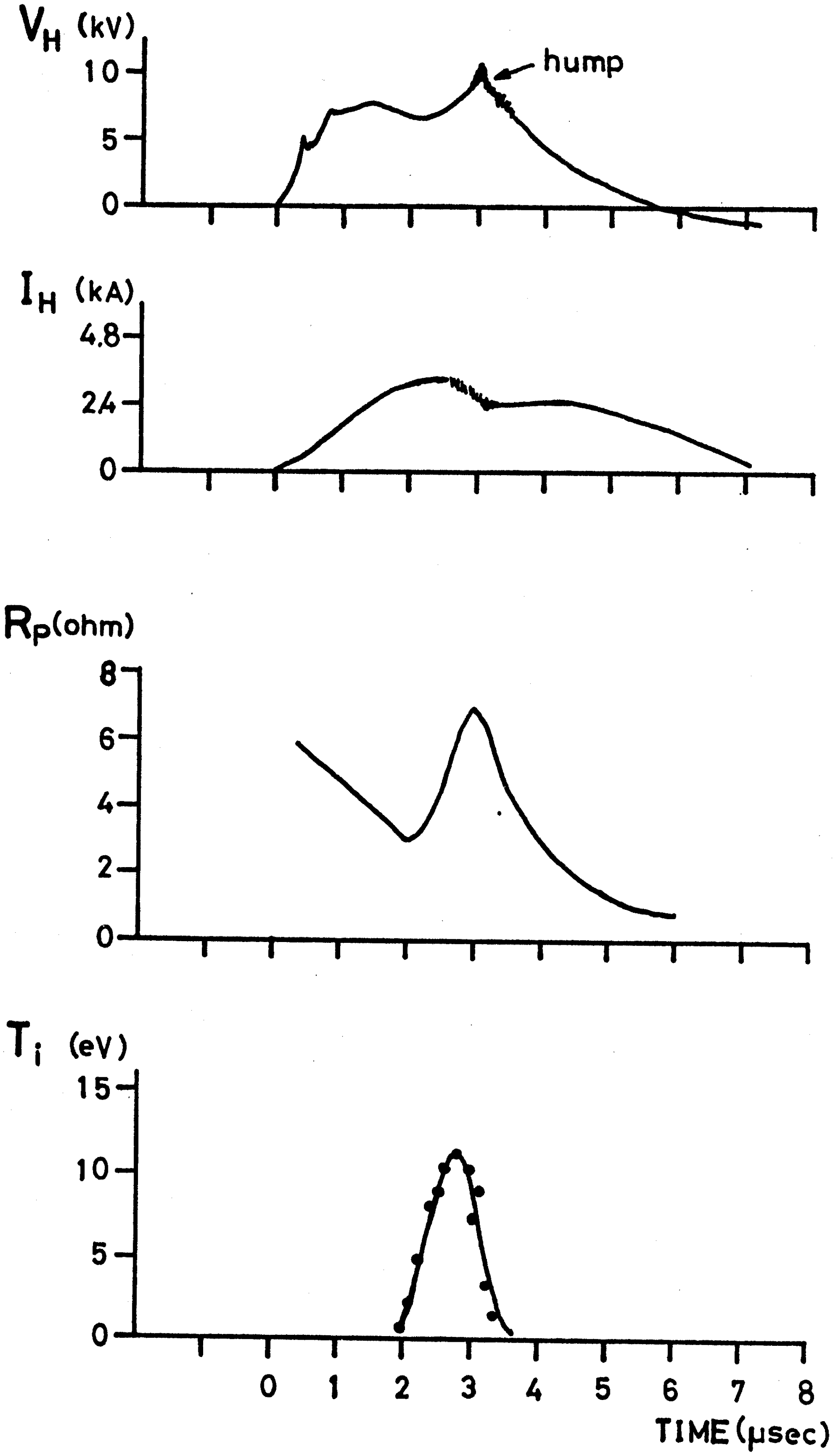
FIGURE CAPTION

Fig.1 Current-Voltage characteristics of linear turbulent heating experiment, indicating a resistive hump. R_p is the observed resistivity of plasma.

Fig.2 $n\tau$ - T_i Diagram, mainly including heating experiments. Abbreviation is as follows: F plasma focus, TH turbulent heating, B burnout V, C-C plasma collision and compression, SCY scyllac, L giant Laser, C(RF) stellarator C, U(RF) Uragan stellarator, T-4 Tokamak.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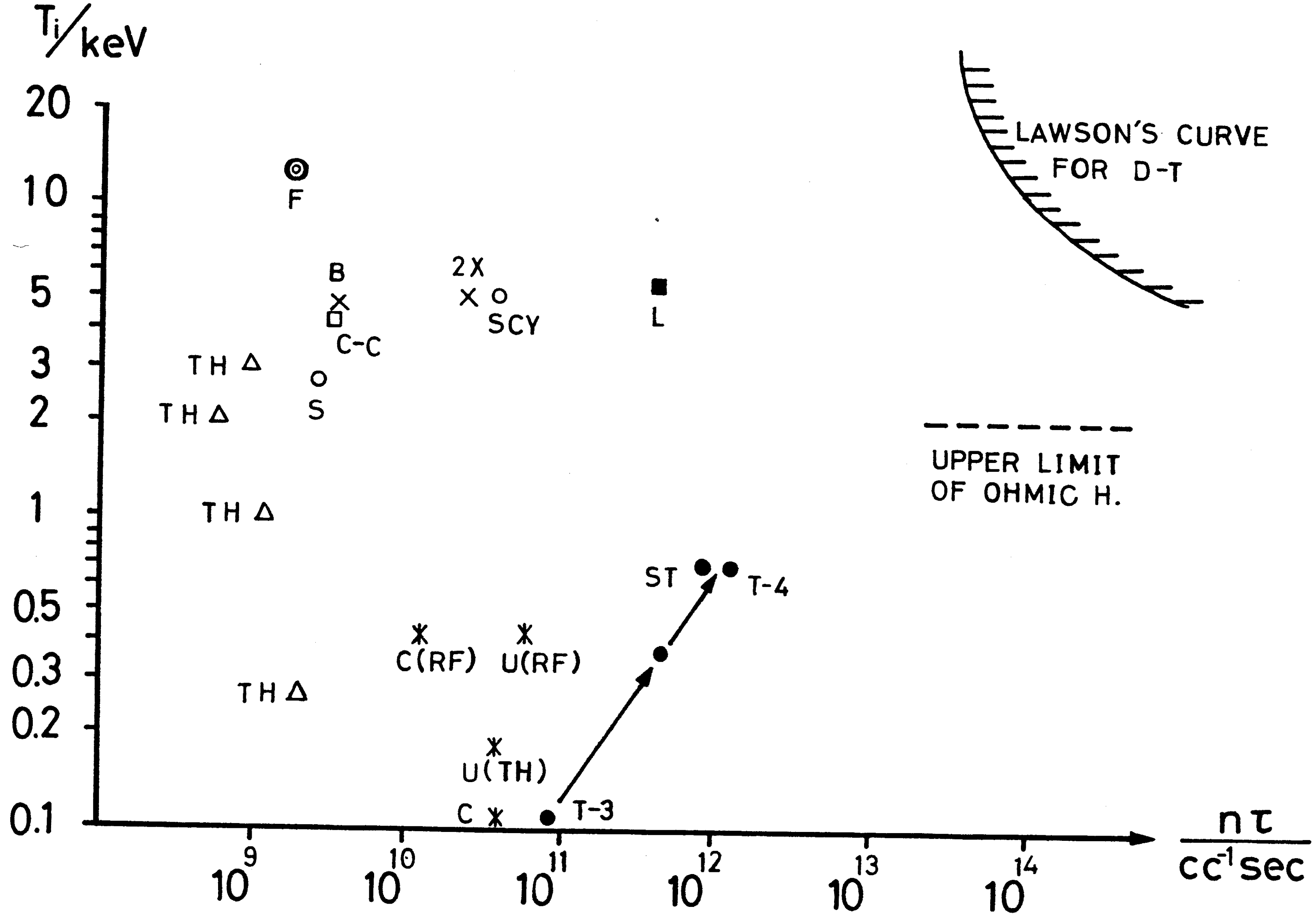
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LAWSON'S CURVE FOR D-T
UPPER LIMIT OF OHMIC H.
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
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