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TRANSIENT TEMPERATURE VARIATIONS DURING THE SELF-HEATING OF A PLASMA BY THERMONUCLEAR REACTIONS

Howard D. Greyber

March 21, 1955

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ABSTRACT

The possibility of transient temperature variations during the self-heating of a plasma by thermonuclear reactions was investigated. Calculations were performed on an IBM Card Program Calculator. Estimates of the time scale for self-heating were obtained. It was concluded that it would be unsafe to assume that the nuclear temperature is always equal to or greater than the electron temperature in a discussion of plasma instabilities for a plasma with 10 percent or greater tritium concentration.

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To discuss the energy balance in a fully ionized gas with very low Z nuclei and a temperature in the region of 10-1000 kev, it is necessary to consider the temperatures of the ion and electron gases separately. This is because the energy transfer mechanism between ions and electrons becomes, in this region, smaller than the characteristic energy sources and sinks for the two gases.

If, in addition, the radiation produced escapes more or less freely from our system,* the radiation present is not in equilibrium with the matter (and, in fact, the concept of radiation temperature is not applicable). If we state that the energy source for our fully ionized gas is the thermonuclear reactions among its constituents, then the combination of the aforesaid conditions,

$$(1) T_n \neq T_e$$

$$(2) T_n, T_e \gg \text{"radiation temperature,"}$$

where T_n = nuclear or ion temperature, T_e = electron temperature, is usually described as "nonequilibrium thermonuclear burning."

Such a process is probably at least a rough approximation to the thermonuclear burning contemplated in some form of CTR.** Due to the extremely low density of the plasma, the system is essentially "open" to radiation. Also, if a 50% D-50% T plasma is contemplated, for temperatures above 10 kev, T_n will be appreciably different than T_e .

* Dimensions "reasonable," i.e., 0.1 to 100 meters; density is low.

** Controlled Thermonuclear Reactor - any geometry.

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The motivation for this work arose from an observation by M. Rosenbluth¹ that in a different but related physical situation, T_e could exceed T_n during transient heating. We have undertaken to trace the transient temperatures to be expected in an idealized physical situation that still bears some resemblance to what one envisions for the CTR.

If we assume a system completely open to neutrons and radiation and closed as far as loss of charged particles or any other form of energy drain other than neutrons and radiation is concerned, we may write for a constant volume system (magnetic field increasing in such a way as to keep constant volume):

$$(1.6 \times 10^{-9}) \frac{3}{2} n \dot{T}_n = a P_{DD} + b P_{DT} - P_{i-e} \quad (1a)$$

$$(1.6 \times 10^{-9}) \frac{3}{2} n \dot{T}_e = (1 - a) P_{DD} + (1 - b) P_{DT} + P_{i-e} - P_B \quad (1b)$$

where

T = temperature in kev

n = number of particles per cm^3

P_{DD} = energy production rate from DD reaction

$$= (n_D^2 / 2) \overline{\sigma_{DD} v} [2.4 + (1/2)(3.5)] [1.6 \times 10^{-6}] \text{ ergs sec}^{-1} \text{ cm}^{-3}. \quad (2)$$

Only deposition of charged particle energy is counted. One-half of a DT reaction is added for each DD reaction. We assume no depletion and instantaneous deposition.

P_{DT} = energy production rate from DT reaction

$$= n_D n_T \overline{\sigma_{DT} v} (3.5)(1.6 \times 10^{-6}) \text{ ergs sec}^{-1} \text{ cm}^{-3} \quad (3)$$

n_D = number of deuterons per cm^3

n_T = number of tritons per cm^3 .

The coefficients a and b indicate the fraction of nuclear energy deposited to the nuclear and electron gases and are approximations to the graphs in LA-401.² The expression for a is identical with that used by Fermi and Ulam³:

$$a = 0.3 + 0.005 T_e$$

$$1 - a = 0.7 - 0.005 T_e$$

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$$b = 0.01 T_e$$

$$1 - b = 1 - 0.01 T_e; a, b \text{ are always kept } \leq 1$$

P_{i-e} = energy transfer rate from nuclear gas to electron gas

$$P_{i-e} = 1.244 \times 10^{-21} n^2 \frac{T_1 - T_2}{T_2^{3/2}} \text{ ergs sec}^{-1} \text{ cm}^{-3}$$

P_B = energy production rate in bremsstrahlung radiation

$$P_B = 5.38 \times 10^{-24} n^2 T_e^{1/2} \text{ ergs sec}^{-1} \text{ cm}^{-3}.$$

We have done the calculations for $n = 10^{14}$ but it is clear that one may scale the results simply for number density. The time scale will vary inversely with density; hence for $n = 10^{15}$, divide times on accompanying graphs by 10, etc.

The integrations were carried out on the IBM Card Program Calculator, and the results are shown in Figs. 1, 2 and 3. Three cases were run: (I) 50 percent T and 50 percent D; (II) 10 percent T, 90 percent D, and (III) 1 percent T, 99 percent D. Some cases were run for two different starting temperatures.

A check calculation was run with $\Delta t = 0.01, 0.1$ and 1.0 second and the comparison showed that the interval of $\Delta t = 0.1$ used gives graphs quite close to those for $\Delta t = 0.01$, and hence, fairly accurate.

However, a much larger source of error is our assumption of instantaneous deposition of energy by the fast charged reaction products. A rough estimate of the time for a 3.5-Mev He^4 nucleus (or a 1-Mev t) to slow down to zero energy in a deuterium-tritium mixture at $n = 10^{14}$ is given by

$$\tau = 0.4 (T_e^{1/2})$$

where

T_e is in kev

τ is in seconds.

Thus for $T_e = 25$ kev, $\tau = 2.0$ seconds. One can infer how the curves would look were this factor correctly introduced into the calculation. First we note that qualitatively, since a fast charged particle spends most of its time losing energy to the electron gas, and only near the end of its range, rapidly loses the remainder to the nuclear gas, (1) the T_e curve will exceed

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the T_n curve by a larger amount in the range below 70 kev than calculated. (2) the cross-over points where $T_e = T_n$ will be at higher values than calculated. Also the time scales for the rise of temperature with time will be increased, i.e., the time to reach $T_n = 100$ kev may be greater than calculated by perhaps as much as a factor of 2.

The results of the calculation, although rough, give us an idea of the time scales involved in the self-heating process. Of course, other losses than those considered here, such as energy lost in particles diffusing to the walls, energy lost in particles leaking through magnetic mirrors, or useful output such as work against moving mirrors, or particles exiting to a diverter, etc., would all tend to lengthen the time for a given temperature rise. It is clear that our Equations (1a) and (1b) could easily be generalized to include extra terms such as above-mentioned or energy input terms such as compression or magnetic pumping while burning, if simple expressions are available. The time-dependent energy deposition feature, although complicated, could also be added.

We derived the equations for the case of a plasma at constant pressure while burning (constant magnetic field - experimentally obtained by "crow-barring" the magnet coils) and integrated them also on the CPC. Unfortunately, there appears to have been a numerical error in these calculations and no graphs are given for these cases.

One qualitative result of this work is that it would be unsafe to assume nuclear temperature always equal to or greater than electron temperature in a discussion of plasma instabilities for a plasma with tritium concentration equal to or greater than 10 percent.

Acknowledgment

It is a pleasure to thank Dr. Marshall Rosenbluth and Dr. George Bing for several stimulating discussions.

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Fig. 2

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Fig. 3

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