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ELECTRON-TEMPERATURE REQUIREMENTS FOR NEUTRALIZED INERTIAL-CONFINEMENT-FUSION LIGHT-ION BEAMS

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ABSTRACT

Because of their large self-space-charge fields, light ion beam drivers of energy and power sufficient to achieve inertial confinement fusion (ICF) cannot be focused on a small fuel pellet unless neutralized. Even if initially neutralized with comoving electrons, these beams will not stay neutralized and focus during propagation through a vacuum chamber unless the initial thermal energy of the neutralizing electrons is sufficiently small. In this paper we discuss the effects which contribute to the effective initial temperature of the neutralizing electrons, including compressional shock heating. We also employ a simple heuristic model to construct envelope equations which govern axial as well as radial beam compression and use them to predict the largest initial electron temperature consistent with the required beam compression. This temperature for typical light ion beam systems is about ten eV--a temperature which may be possible to achieve.

INITIAL ELECTRON TEMPERATURE

The electron, rather than the ion temperature or emittance, limits the final beam size of focused neutralized light ion beams. This is because the electrons are highly mobile compared to the ions. Therefore, any electrostatic field energy seen by the electrons during the neutralization process will be transferred to the electrons. These hot electrons will become hotter as the beam focuses and eventually arrest beam focusing by spending progressively more time outside the ion beam. In other words, even in "neutralized" light ion beams, ion space charge repulsion is dominant.

The worst possible neutralization occurs when all the electrostatic field energy in a bare ion beam is transferred to the electrons. This could happen during side injection of neutralizing electrons and result in keV electron temperatures.(1)

Lower initial electron temperatures can be achieved by passing the ion beam through a plasma or other electron source and allowing space charge fields to accelerate the electrons to the ion speed. One-dimensional particle simulations of this process indicate that charge and

current neutralization results in an initial three-dimensional electron temperature of approximately 1/20 the energy of an electron comoving with the beam.(2) For a 5 MeV He_4^{+1} beam this temperature is 34 eV. Somewhat lower initial temperatures may be possible if the accelerated electrons are accelerated smoothly up to the ion speed with externally applied fields.(3)

ELECTRON SHOCK HEATING

It is not commonly known that there is a lower bound on the initial electron temperature below which the focusing ions will produce shocks in the neutralizing electrons. Such shocks will heat the electrons and possibly the ions during the beam compression more rapidly than the usual adiabatic heating law describes. Therefore, neutralizing the beam with electrons cooler than this shock heating limit does not result in a proportionate decrease in the final beam size.

The shock heating limit can be understood in terms of a simple model. The model is that of a cold gas inside a container, one wall of which is a piston compressing the gas. The container and piston represent the shrinking potential well of the focusing ion beam while the cold gas represents the initial state of the neutralizing electrons. Light ion beams will in general be focused axially as well as radially; here we confine the model to a one-dimensional compression.

As the piston begins to compress the gas, the gas particles adjacent to it are struck and rebound with a speed which is twice the speed of the moving piston. These race ahead of the piston, reflect from the opposite wall, return to the piston, rebound again and so on. If the gas is collisionless, it becomes a collection of interpenetrating streams. Eventually the gas becomes so energetic the average particle speed is large compared to the piston speed and further compression is in accordance with the adiabatic gas law.

A qualitative description of such shock heating is contained in Ref. (4) from which we reproduce Fig. 1. There the P-V relation or equivalently the P-L relation, where L is the piston-wall separation and P is the pressure exerted by the gas on the piston for a shock compression, is shown (solid line). In contrast to what happens during a quasistatic compression, P jumps discontinuously each time the leading gas stream begins a new collision with the piston. In the limit of large compressions, the P-L relation approaches an adiabat (dashed line), which according to Fig. 1 is also a rough approximation to the complete P-L

relation. For our purpose, the important parameter is the initial gas temperature, T, which corresponds to this adiabat, explicitly

$$T = \frac{P}{\rho_o} = \frac{mu_o^2}{3} \tag{1}$$

where ρ_o is the initial gas density, m is the gas particle mass, and u_o is the piston compression speed.

We take T from Eq. (1) as the approximate shock heating limited electron temperature for a focused neutralized ion beam. For a radially focusing beam, $u_o = \dot{R}$ where $\dot{R}$ is the time rate of charge of the radial beam envelope so that

$$T = \frac{2}{3} \left(\frac{m_e}{m_i}\right) \frac{m_i V_b^2}{2} \tag{2}$$

where $m_e (m_i)$ is the electron (ion) mass. For a neutralized beam of 5 MeV He_4^{+1} ions focused at a half angle θ where $\tan \theta = 0.1$, T = 4.5 eV. It is unlikely that neutralizing the beam with cooler electrons will result in better radial focusing.

ENVELOPE EQUATIONS

In the previous sections we discussed the initial neutralizing electron temperature likely to result from an actual neutralization process and the electron temperature below which there will be electron shock heating. In this section we derive dynamic equations for the axial as well as radial beam envelopes. From their energy integrals, we can extract the maximum allowed initial electron temperatures consistent with the required beam focusing.

Envelope equations for neutralized beams can, under certain conditions, be derived by taking RMS averages of single particle trajectories.(5) Here we prefer to motivate the envelope equations by appeal to a simple heuristic model. The model is valid under the following conditions:

(1)   the radial and axial ion and electron local density remain self-similar as the beam is focused,

(2)   the average random electron energy is interpreted as a temperature,

(3)   the ions are cold,

(4) the electron Debye length is small compared to beam dimensions,

(5) R << (R/L)V_b where R and L are the radial and axial beam envelope dimensions.

Condition (1) is generally required of all envelope equations. Under conditions (2-4) the ion beam envelope dynamics may be modeled as if all the ion mass were concentrated at the radial and axial envelope and the electrons are a warm gas filling the volume contained in the ion beam envelope. Condition (5) allows the envelope shape to be approximately a cylinder. This last condition may, in fact, be violated during the initial compression, that is, the beam may look more like a cone than a cylinder.

In this model the ion beam envelope from the beam center of mass point of view defines a shrinking cylinder during beam compression, illustrated in Fig. 2. The warm electron gas exerts a pressure on the envelope which opposes the inertia associated with beam compression or focusing. In general, the electron pressure need not be isotropic, and the beam envelope need not compress self-similarly in the sense that the beam envelope radius, R, and length, L, maintain a constant ratio.

The equations of motion for R and L are, therefore,

$$m_i \ddot{R} = (2\pi RL)P_\perp \qquad (3)$$

and

$$m_i \ddot{L} = (\pi R^2)P_{||} \qquad (4)$$

where the electron pressures $P_\perp$ and $P_{||}$ are defined with the ideal gas equations of state

$$P_\perp = \frac{T_\perp}{\pi R^2 L} \qquad (5)$$

and

$$P_{||} = \frac{T_{||}}{\pi R^2 L} \qquad (6)$$

in terms of the temperatures $T_\perp$ and $T_{||}$. Combining Eqs. (3) and (5) and Eqs. (4) and (6) and Eqs. (5) and (7) gives

$$m_i \ddot{R} = \frac{2T_\perp}{R} \tag{7}$$

and

$$m_i \ddot{L} = \frac{T_{||}}{L} \quad . \tag{8}$$

In Eqs. (3-8) the subscripts "$\perp$" and "$||$" denote, respectively, transverse or radial and axial quantities (see Fig. 2). In addition to Eqs. (7-8) there is an independent energy integral

$$\frac{m_i \dot{R}^2}{2} + \frac{m_i \dot{L}^2}{2} + T_\perp + \frac{T_{||}}{2} = \text{constant} \tag{9}$$

which comes directly from the first law of thermodynamics applied to this system.

The three Eqs. (7-9) contain four unknowns. Therefore, a fourth condition is required to solve. Here we consider several possibilities:

1. **Self-Similar Compression.** If the beam axial and radial envelopes compress at the same rate, an initially isotropic electron temperature will remain isotropic. Therefore, it has been suggested that self-similar beam compression is desirable in order to avoid temperature anisotropy driven plasma instabilities.(6) In fact, the self-similar compression description, $R = fL$ where f is a constant, and temperature isotropy, $T_\perp = T_{||}$, are inconsistent requirements except for $f = \sqrt{2}$, as substitution of these conditions into Eqs. (7-8) will show. In actual light ion ICF beams $f \cong 0.1$.

2. **No Coupling Between $||$ and Motion.** In this approximation the axial and radial compressions occur independently and the electrons heat, assuming their initial temperatures are above the shock heating limit, according to two independent adiabatic heating laws

$$T_\perp R^2 = T_{\perp o} R_o^2 \tag{10}$$

and

$$T_{||} L^2 = T_{||o} L_o^2 \quad . \tag{11}$$

Here the subscript "o" denotes an initial condition. There is one redundant equation among the set of Eqs. (7-11).

Assume there is just enough ion inertia to achieve the desired compression. Then at the focal time, denoted by the subscript "f", $\dot{R}_f = 0$

and $\dot{L}_f = 0$. Therefore, from Eqs. (7-8) and (10-11) the required initial temperatures $T_{\perp o}$ and $T_{||o}$ may be found in terms of the compression ratios R_o/R_f and L_o/L_f

$$T_{\perp o} = \frac{m\dot{R}_o^2/2}{(R_o/R_f)^2 - 1} \tag{12}$$

and

$$T_{||o} = \frac{m\dot{L}_o^2}{(L_o/L_f)^2 - 1} \quad . \tag{13}$$

Equation (12) has been obtained previously (5,7) and more strictly limits the initial electron temperature than Eq. (13). For example, consider the parameters from a recent proposal:(8) $m_i\dot{R}_o^2/2 = \tan^2\theta$, $m_i v_b^2/2 = (.1)^2$ 5 MeV = 50 keV, $R_o/R_f = 100$, $m_i\dot{L}_o^2/2 = 2$ MeV, and $L_o/L_f = 10$. In this case $T_{\perp o} = 5$ eV and $T_{||o} = 40$ keV.

The requirement that the maximum allowed transverse temperature as determined by Eq. (14) exceed the transverse compression shock heating temperature given by Eq. (2) leads to the following requirement

$$\frac{R_o}{R_f} < \left(\frac{3m_i}{2m_e} + 1\right)^{1/2} \quad . \tag{16}$$

A graph of the allowed parameter regime in terms of the radial compression ratio, R_o/R_f, and atomic number, z where $m_i = z(1836)m_e$ is shown in Fig. 3.

3. Complete Coupling Between || and ⊥ Motion.

According to the foregoing analysis, the assumption of no transverse-axial coupling will lead to the development of a temperature anisotropy in an initially isotropic electron gas. This anisotropy could in turn drive the temperature anisotropy Weibel instability.(9) While the deleterious effect of this instability has not been investigated, it could actually aid beam focusing by keeping the electron temperature near isotropy and relieving the transverse electron pressure. Fringing fields will also contribute to the same end.

Here we consider the isotropic limit with $T_{\perp} = T_{||}$ in which case the energy equation can be replaced with a single adiabatic law

$$T^{3/2} R^2 L = T_o^{3/2} R_o^2 L_o \quad .$$

(17)

Humphries has solved Eqs. (7) and (17) with $T_\perp = T_{||} = T$ and $\dot{L} =$ constant.(10) It is, however, just as convenient to solve Eqs. (7-8) and (17) with $T_\perp = T_{||} = T$ exactly. We show only one solution to illustrate that the required initial electron temperature, T_o, is reduced below those given by Eq. (14).

Normalized beam envelopes during about the last tenth of their trajectories before reaching the point of radial focus is shown in Fig. 4. Initial conditions in this example are shown in the figure caption. Note that a radial compression, R_o/R_f, of about 100 is reached with an initial temperature of 20 eV. Without coupling of the transverse and axial motion, Eq. (12) indicates an initial temperature of no more than 5 eV is required.

CONCLUSION

The temperature of the neutralizing electrons required to obtain a 100 to 1 radial compression of a typical 5 MeV He_4^{+1} light ion ICF beam is between about 5 to 20 eV depending on the coupling between transverse and axial electron motion. This is slightly below what has been demonstrated possible with passive neutralization schemes and slightly above the shock heating limit. This suggests that effective neutralization of such beams is possible but difficult.

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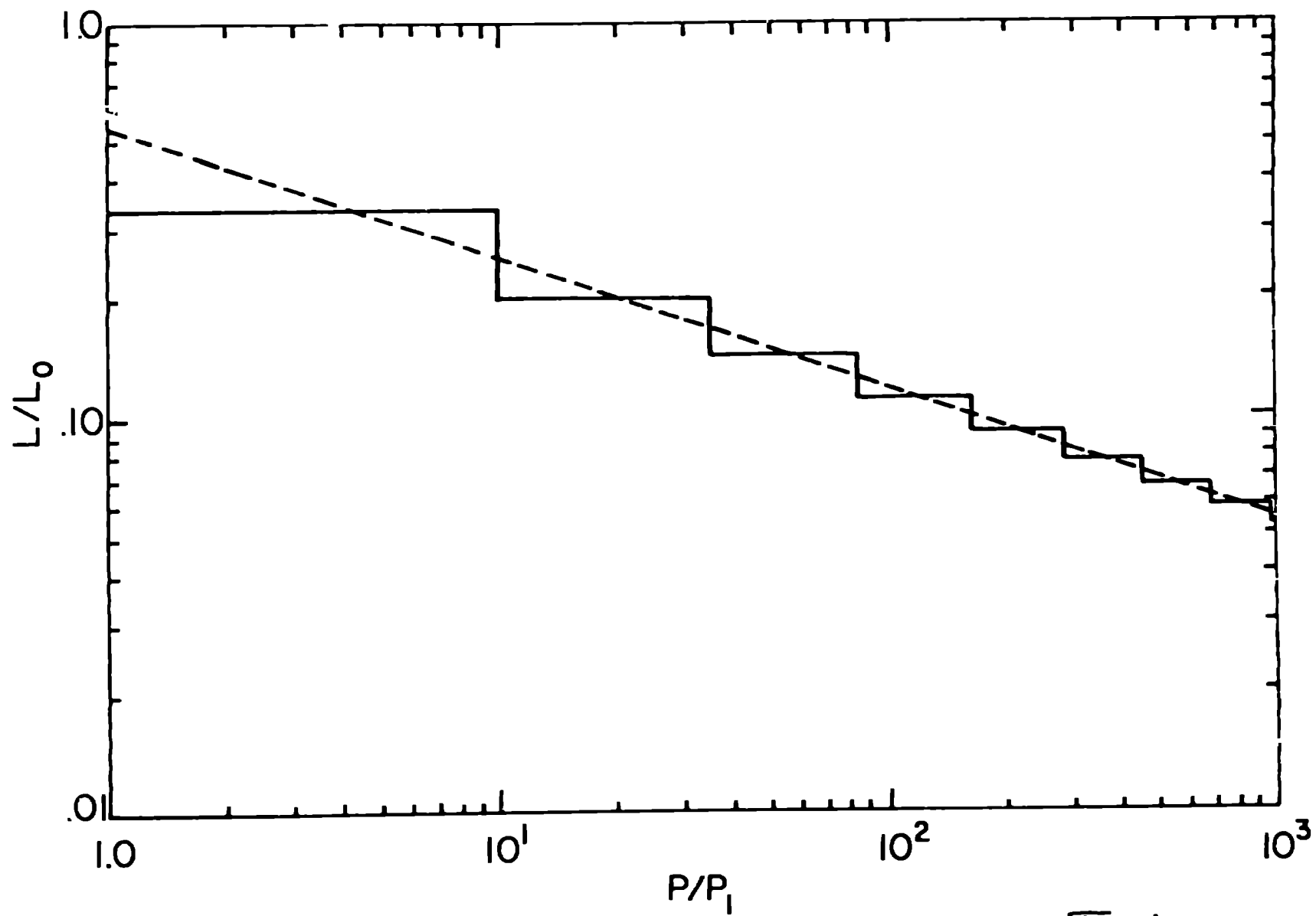
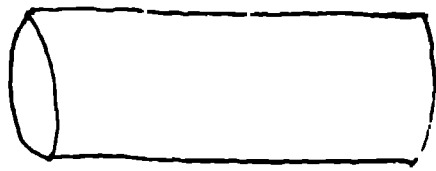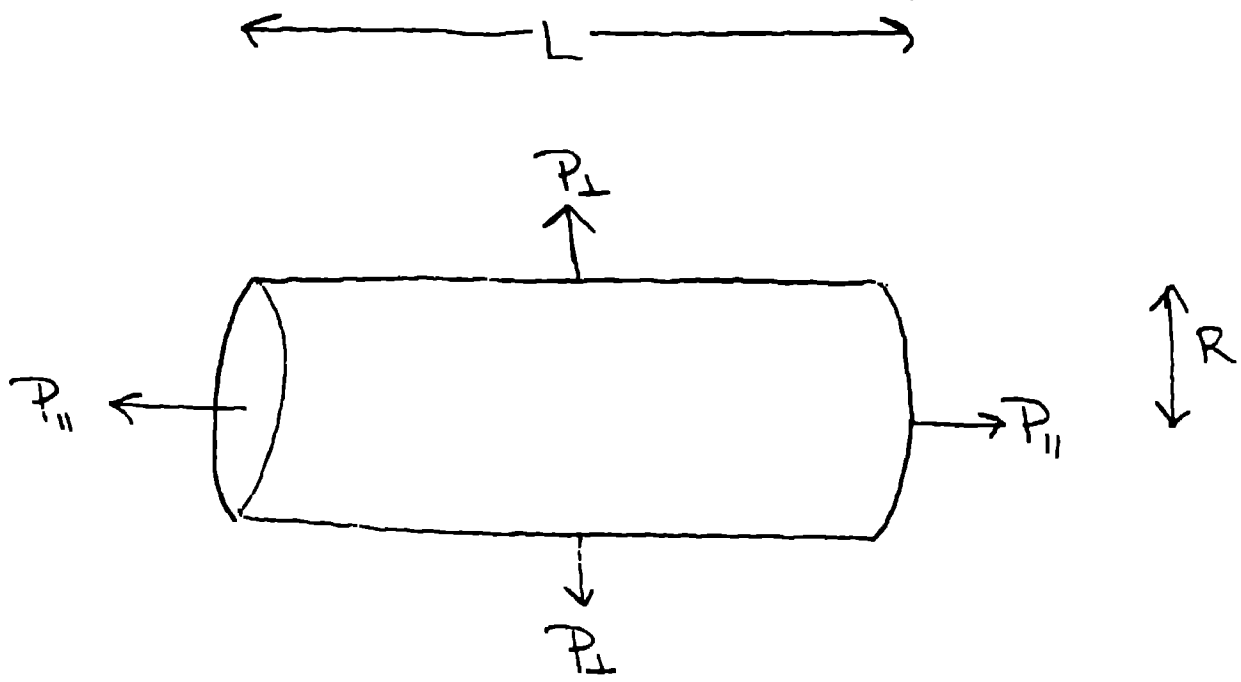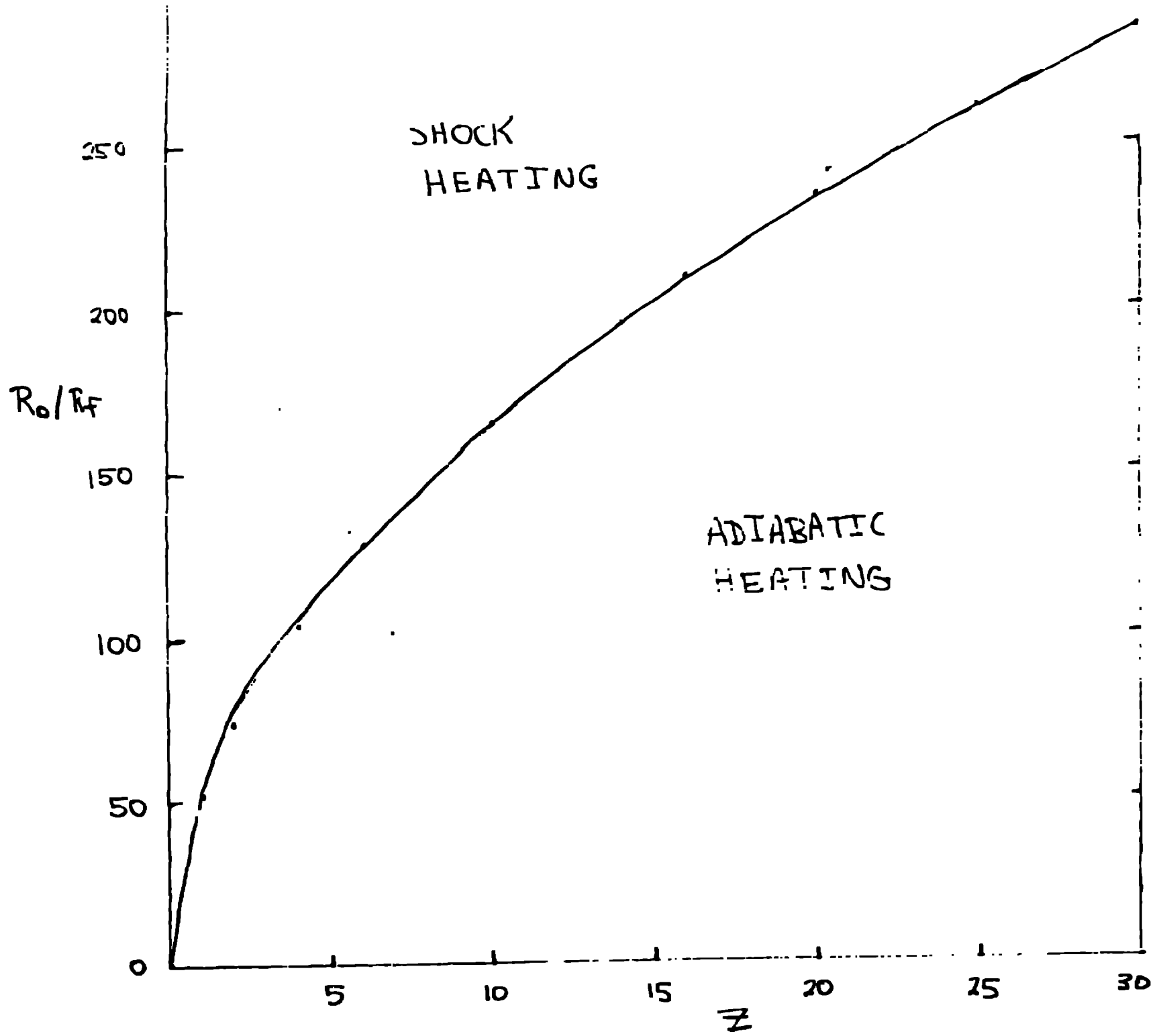7. Weibel, E. S., Phys. Rev. Lett. 2, 83 (1959).

Fig 1

Fig. 2

Fig 3

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