1.5% at 0.145 Torr to 4% at 0.03 Torr. These values of $c_{\rm H}$ multiplied by the plasma density are found to be proportional to the observed H emission as a function of pressure which indicates experimentally that $c_{\rm H}$ varies in the assumed manner. The arrows in Fig. 3 at the value of v_D/v_e of 0.094 mark the onset of the instability as predicted by the theory for a value of $c_{\rm H}$ of 1.5%. This prediction agrees well with the experimentally observed threshold. The predicted values of W/nT_e and $\Delta\theta$ near threshold are very sensitive to all parameters so that no reliable predictions are available for $v_D/v_e < 0.12$. The theory[3] does not predict the spectral shape of the turbulent spectrum. We have detailed data on this aspect of the saturation which requires further theoretical consideration.

In conclusion, we have studied in detail the saturated state of the current-driven ion-acoustic instability in a positive-column plasma and find that the saturation of the turbulent state is due to a 1 to 4% H^+-ion concentration present in this experiment and probably in all previous experiments which also used nonbakable vacuum systems. Ion-resonance-broadening theory applied to the H^+ impurity ions appears to be the most plausible mechanism to describe the measured properties of the saturated state of the instability. We are presently building a high-vacuum system with which to study the instability without a background concentration of H^+ ions.

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Energy Deposition in Laser-Heated Plasmas

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The number and energy distribution of suprathermal electrons produced in a laser-heated plasma can be quantitatively obtained directly from the experimental x-ray spectrum with only the assumption that the fast electrons lose energy by bremsstrahlung and electron-electron collisions. The result is independent of the spatial and temporal distribution of electron density and temperature.

The x-ray spectra from laser-irradiated plasmas typically shows an athermal component which cannot be attributed to the radiation from a plasma with a well-defined temperature and hence Maxwellian electron distribution. The hard radiation is believed to be due to energetic electrons produced by resonant absorption, or by laser-plasma instabilities. The correlation between the observed x-ray spectrum and the athermal electron population is usually made by the use of computer models which incorporate various models of the absorption process. In this note I show that a simple direct correlation exists which allows essentially model-independent determination of the fast electron distribution and also direct determination of the energy deposited in fast electrons. I base my analysis on the simple and reasonable assumption that electrons produced in the absorption process, with initial energies well above the temperature of the bulk population, lose energy by radiation and by collisional exchange with the much colder thermal electrons, that collisions among the suprathermal electrons can be ignored, and that the fast-electron density is much less than the thermal-electron density.

The radiation emitted into all solid angles by a single electron of energy ϵ per unit path length per unit radiated energy[1] is

$$\frac{d^2\epsilon_{\rm rad}}{dx\,d(h\nu)}=\frac{8}{3}\frac{e^2}{\hbar c}\frac{e^4}{mc^2}\frac{\langle Z^2\rangle N_i \ln\Lambda_{\rm rad}}{\epsilon} \tag{1}$$

with $\langle Z^2\rangle$ the average value of Z^2 and

$$\ln\Lambda_{\rm rad}=\ln\frac{\epsilon^{1/2}+(\epsilon-h\nu)^{1/2}}{\epsilon^{1/2}-(\epsilon-h\nu)^{1/2}},\quad h\nu\leqslant\epsilon; \qquad =0,\quad h\nu\geqslant\epsilon. \tag{2}$$

The rate of energy loss by electron-electron collisions[2] is

$$\frac{d\epsilon}{dx}=-\frac{4\pi\langle Z\rangle N_i e^4}{\epsilon}\ln\Lambda_{\rm coll} \tag{3}$$

with

$$\Lambda_{\rm coll}\cong 3/2e^3(\theta^3/\pi n_e)^{1/2}. \tag{4}$$

The total energy radiated by the electron of initial energy ϵ_0 in stopping may be obtained by combining Eqs. (1) and (3), with the result

$$\frac{d\epsilon_{\rm rad}}{d(h\nu)}=\frac{2}{3\pi}\frac{e^2}{\hbar c}\frac{\langle Z^2\rangle}{mc^2\langle Z\rangle}\int_{h\nu}^{\epsilon_0}\frac{\ln\Lambda_{\rm rad}\,d\epsilon}{\ln\Lambda_{\rm coll}}. \tag{5}$$

The ratio of the two Coulomb logarithms is slowly varying with ϵ and $h\nu$; we approximate the ratio by taking the average value for $\ln\Lambda_{\rm rad}$ of 2 and by evaluating the collision logarithm at 10 keV and $n_e=10^{21}/\mathrm{cm}^3$, where $\ln\Lambda_{\rm coll}=7.85$. The result is

$$d\epsilon_{\rm rad}/d(h\nu)=\lambda_Z(\epsilon_0-h\nu)/mc^2, \qquad \lambda_Z=3.95\times10^{-4}\langle Z^2\rangle/\langle Z\rangle. \tag{6}$$

The energy radiated by a distribution of electrons produced with initial energy ϵ_0 is

$$\frac{dE_{\rm rad}}{d(h\nu)}=\int_{h\nu}^{\infty}n(\epsilon_0)\frac{d\epsilon_{\rm rad}}{d(h\nu)}d\epsilon_0 \tag{7}$$

$$=\frac{\lambda_Z}{mc^2}\int_{h\nu}^{\infty}n(\epsilon_0)(\epsilon_0-h\nu)d\epsilon_0. \tag{8}$$

From this result we find

$$\frac{d^2}{d(h\nu)^2}\frac{dE_{\rm rad}}{d(h\nu)}=\frac{\lambda_Z}{mc^2}n(h\nu) \tag{9}$$

and

$$N_{\rm fast}=\int_0^\infty n(\epsilon_0)\,d\epsilon_0=\frac{mc^2}{\lambda_Z}\left(\frac{d}{d(h\nu)}\frac{dE_{\rm rad}}{d(h\nu)}\right)_{h\nu=0}, \tag{10}$$

$$E_{\rm fast}=\int_0^\infty n(\epsilon_0)\epsilon_0\,d\epsilon_0=\frac{mc^2}{\lambda_Z}\left(\frac{dE_{\rm rad}}{d(h\nu)}\right)_{h\nu=0} =2.28\times10^{-10}\frac{\langle Z\rangle}{\langle Z^2\rangle}\left(\frac{dE_{\rm rad}}{d(h\nu)}\right)_{h\nu=0}\ \mathrm{J}. \tag{11}$$

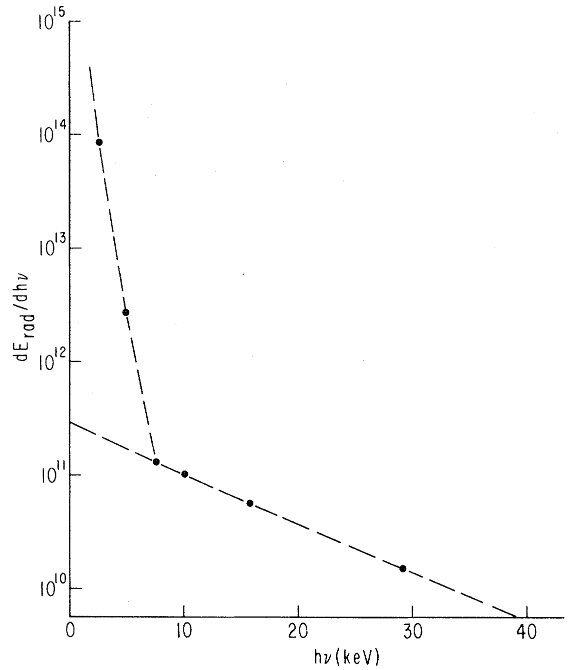

FIG. 1. X-ray spectrum for a 80-μm-diam glass microballoon target with 30 J incident in a 70-psec pulse. For uniform illumination the power is 2×10^{15} W/cm^2. The dashed curves are best fits to the data and have been used in the estimates given in the text.

The distribution of radiation emitted by the fast electrons at $h\nu\to0$ may be readily estimated by extrapolation of the energetic spectrum (see Figs. 1 and 2).

The preceding calculation is valid only if the fast electrons slow down in a time considerably less than the time for the hydrodynamic expansion of the corona. If the slow-down time is too long, the electrons can lose energy in work done in accelerating the plasma. The slow-down time depends on the density which is determined by the motion of the electron resulting from scattering. At the critical density for 1-μm radiation, the slowing-down time as determined from Eq. (2) is $\tau=(1.26\times10^{-13}\ \mathrm{sec\ keV}^{-3/2})\epsilon_0^{3/2}$ or, for an energy of 20 keV, 12 psec. The actual time is considerably less since the electron scattering causes diffusion into the dense plasma. This conclusion also holds in the presence of magnetic fields since scattering, drift resulting from the inhomogeneity of the fields, and motion along the fields will bring the electron into regions of high density where rapid energy loss occurs.

As examples let us consider two measurements reported by the Lawrence Livermore Laboratory[3,4] shown in Figs. 1 and 2. For the glass

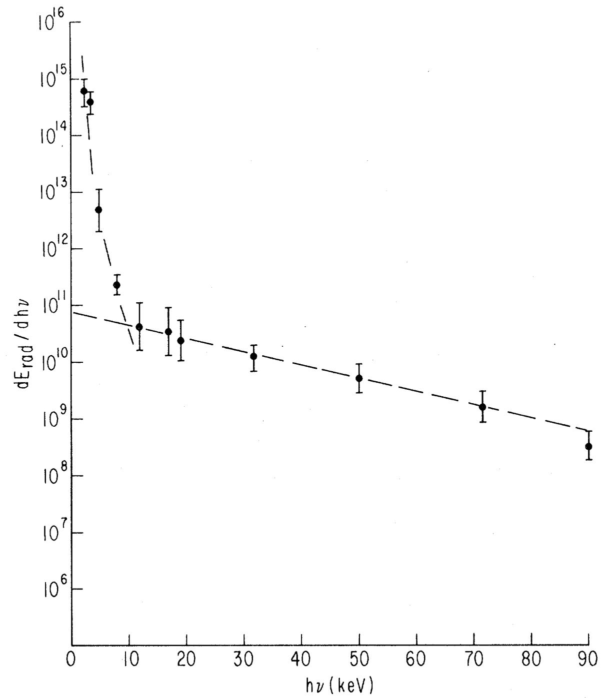

FIG. 2. X-ray spectrum from a parylene disk with 9.0 J incident and a focal spot of 30-μm-diam. The pulse length is approximately 130 psec giving a power of 10^{16} W/cm^2.

microballoon experiment, we find (for $\langle Z\rangle = 10$, $\langle Z^2\rangle = 108$) $E_{\text{fast}} = 6.3$ J and $\langle\epsilon\rangle = 10$ keV. The measured absorbed energy is about 20% of 30 J incident or 6.0 J. For the parylene (C_2H_5) disk experiment we find (for $\langle Z\rangle = 2.43$, $\langle Z^2\rangle = 11$) $E_{\text{fast}} = 4.0$ J and $\langle\epsilon\rangle = 30$ keV. The measured absorption is 30–40% of 9.0 J incident or 2.7–3.6 J, again in reasonable agreement with the spectral estimate. These results strongly imply that nearly all of the absorbed energy is in fast electrons, consistent with the previous interpretation.[3,4] If the electrons are produced by resonant absorption, the average energy is[5]

$$\langle\epsilon\rangle = (m_e\omega_0\varphi_{\text{abs}}L/n_c)^{1/2}, \qquad (12)$$

with φ_{abs} the absorbed laser flux per unit area and L the electron density scale height evaluated at the critical density surface. For the glass microballoon, the absorbed flux is about 4×10^{14} W/cm^2, giving $\langle\epsilon\rangle = (18\text{ keV }\mu\text{m}^{-1/2})L^{1/2}$. For the parylene disk, the absorbed flux is about 3×10^{15} W/cm^2, giving $\langle\epsilon\rangle = (49\text{ keV }\mu\text{m}^{-1/2})L^{1/2}$. These estimates are in approximate agreement with the x-ray spectrum only if the scale height is of the order of 1 μm, a surprising and somewhat implausible result. The average energy may, however, be reduced from Eq. (12) by the varying angles of incidence and polarization of the laser beam.

This analysis shows that the number of fast electrons produced in laser-plasma interaction can be directly determined from the x-ray spectrum. The production rate is approximately determined by the laser pulse length. The spatial origin is given by the illuminated area and may be reasonably assumed to be at the critical density surface. This provides a highly useful, nearly model-independent input to computer codes and hence a semi-empirical procedure for determining other effects of the fast electron production such as shell and fuel preheat.

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