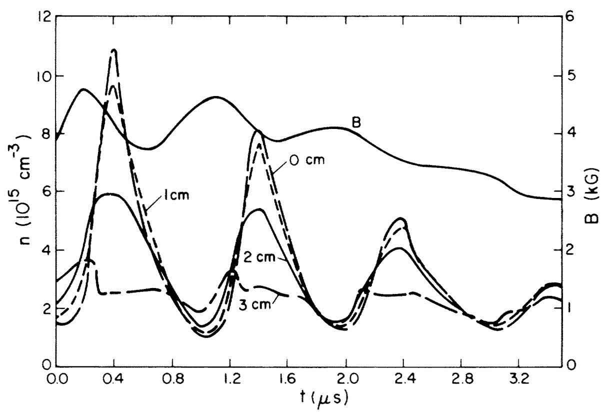

FIG. 3. External magnetic field and density at four radii as functions of time during resonant modulation. The zero of time scale is taken as the onset of resonant modulation, i.e., 2.1 μs into the main discharge.

at all radii appear to oscillate in phase with each other, and because the column radius is a half wavelength, the plasma column seems to support a large-amplitude standing wave. Because the density oscillation is roughly 90° out of phase with the external field modulation, a resonant behavior is indicated. Taking the average electron density during the peak modulation to be 6×10^{15} cm^{-3} on axis, the pressure-balance total temperature is $T_e + T_i \simeq 100$ eV. Assuming that $T_i = T_e$ (the electron temperature was not explicitly measured), we find that the Spitzer[6] ion-ion collision frequency is $\nu_{ii} \simeq 6\times 10^6$ s^{-1}. This is comparable to the radian frequency (6.9×10^6 s^{-1}) of the driven oscillation, and so the plasma regime is not highly collisional. Ohmic heating due to the field modulation is at least an order of magnitude too small to explain the experimental results.

A check was made of nonresonant excitation of the plasma column. A different auxiliary capacitor bank was discharged into the θ-pinch coil with a ringing frequency of 0.7 MHz, well below the column's natural frequency. For the same modulation field amplitude as in the resonant case (1.1 MHz), this off-resonant excitation yielded less than half as much heating.

An externally driven radial magnetoacoustic plasma oscillation has been shown to be an effective method of providing auxiliary heating for a θ-pinch plasma. Energy stored in the auxiliary capacitor bank was converted to plasma thermal energy with an efficiency of ~ 9% for the resonant condition. The increase in temperature would have been more dramatic if the plasma column had not adiabatically expanded between the application of the resonant modulation and the measurement of the quiescent profile.

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Laser Compression Studies with Neon-Filled Glass Microballoons

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We have measured the strong x-ray emission of compressed neon gas fill in glass microballoons, irradiated by a four-beam laser system. X-ray pinhold imaging and spatially resolved x-ray spectroscopy lead to estimates of the compressed-gas temperature and the compression of the glass shell. We find that the product of glass shell thickness and density at maximum compression is less than 2.5×10^{-3} g/cm^2. This is consistent with a degraded compression of the so-called "explosive-pusher mode."

Deuterium-tritium-filled glass spherical shells have yielded[1] the first direct evidence of target compression by laser irradiation. If such targets are filled with a heavier gas they can give very useful additional information even though the neutron emission is lost. We report here on x-ray measurements of neon-filled glass microballoons which yield estimates of the neon electron temperature at maximum compression as well as the maximum compression of the glass shell (through which the observed x rays are transmitted). α-particle spectral measurements[2] can also give information on the fuel (ion) temperature and the glass shell compression. Determination of the glass shell compression in microballoon experiments is crucial to the understanding of the pellet dynamics history. In particular we need to know whether the inner part of the shell moves in as a cold and dense layer ("pusher mode") or as a hot expanding plasma ("explosive mode"). X rays transmitted through the glass shell have an advantage over nuclear reaction products as a probe for measuring the shell compression. Charged particles are slowed down through a large number of excitations and ionizations of the outer electrons in the atoms of the medium. This slowing down then depends on the ionization state and degree of degeneracy of the glass shell. On the other hand, x rays are attenuated through photoionization of the innermost-shell electrons which is relatively insensitive to these parameters. The shell compression in the present study was deduced from (spectrally integrated) pinhole images through various filters. The spectrum of the central spike (Fig. 3) was too weak to employ quantitatively. If made to yield a higher signal it will enable a comparison of resolved spectra rather than just the ratio of integrated values.

The targets used in this study were glass microballoons of diameter 90 μm and wall thickness 1 μm filled with neon at 2 atm pressure. The planar four-beam laser system[3] delivered pulses of total power 0.3–0.8 TW and half-width 0.2–0.4 nsec. Absorbed energy ranged from 5 to 15 J. An x-ray pinhole camera of resolution 12 μm took simultaneous exposures through various filters. The spectrum in the range 5–18 Å was detected by a flat crystal thallium acid phthalate spectrometer. Spatial resolution (of 16 μm) in a direction perpendicular to that of the spectral resolution was achieved by placing a slit of width 14 μm between the target and the spectrometer. The spectrometer window was a 1.5-μm-thick aluminum foil, absorbing strongly below about 0.5 keV.

Lines of Ne^{+8} and Ne^{+9} ions have been observed only when two pulses of comparable energy were excited by the oscillator. Figure 1 compares part of the spectrum for the single-pulse and the double-pulse cases; sodium and silicon lines from the glass shell appear, of course, in both. Apparently, the second of the two pulses irradiated a glass shell which had expanded enough to become completely or mostly underdense, thereby

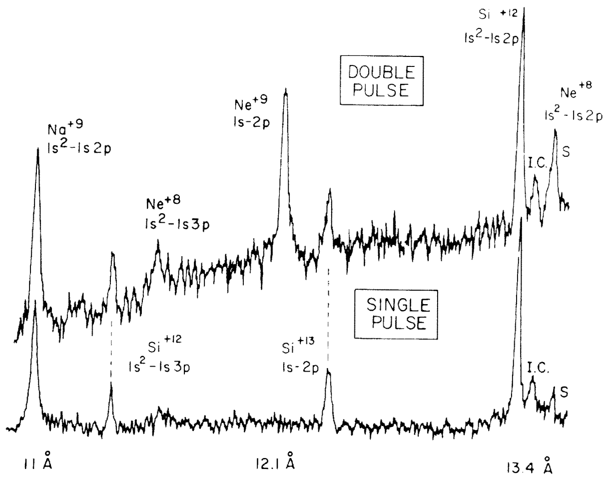

FIG. 1. Comparison of part of the x-ray spectrum for the cases where one or two pulses were excited by the oscillator. The two pulses in the latter case had comparable energies and separation of 2 nsec. Silicon lines (in second order) and sodium lines come from the glass shell. I.C. means intercombination line ($1s^2 - 1s2p\,^3P$) and S denotes dielectronic satellite lines.

directly heating the neon fill. This is supported by the x-ray image of the target showing uniform emission over its volume. Two important conclusions follow from Fig. 1. First, the converging glass shell in single-pulse experiments retains its integrity and does not mix with the fill gas. Otherwise the neon fill would be exposed to the laser and neon lines would appear in the spectrum. Second, the amount of neon in these experiments is sufficient to produce copious line radiation. In order to understand why neon fill when heated by a single pulse does not produce line radiation, we proceed to examine Figs. 2 and 3.

Figure 2 shows scans through the center of a pinhole image of the target, using two filter combinations. The image consists of a ring and a central spike. Figure 3 is an example of spatially resolved emission of a sodium line (from the glass) and a narrow band of the continuum. These two figures (and similar results[4]) show that spectral lines of the glass species are emitted in the ring but not in the central spike. On the other hand, most of the continuum is emitted at the center. The following considerations show this continuum to be predominantly emitted by the neon gas (which is completely ionized) rather than by the imploded glass. Empty microballoons have produced no central spike. Deuterium-filled microballoons at 14 atm fill pressure have produced a central spike, roughly 10 times weaker than in the case of neon. If the central spike came from

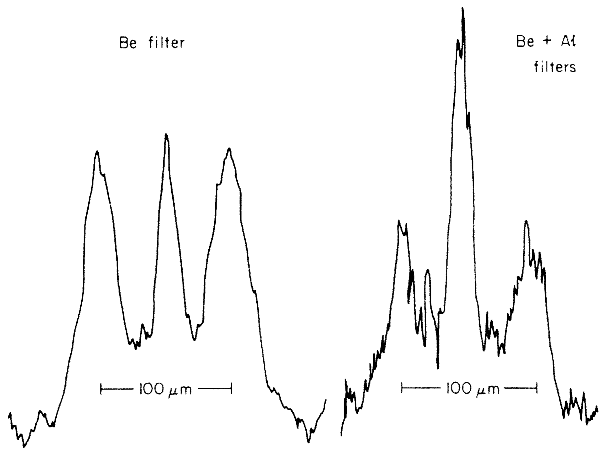

FIG. 2. X-ray pinhole images of the target through a 1-mil beryllium filter and (in addition) a 0.3-mil aluminum filter. The optical-density scales for the two images are different. The initial target position is marked. Traces are through the center of a circularly symmetric image.

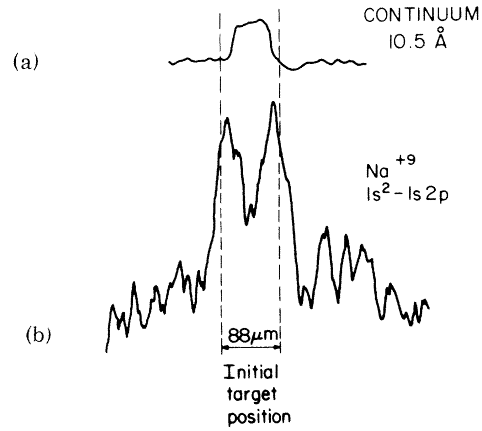

FIG. 3. Spatially resolved emission of (a) a narrow band of the continuum around 10.5 Å and (b) the resonance line of Na^{+9}.

the glass, we would expect strong central emission in all three cases. The higher central emission in the case of neon is then primarily due to the higher ion charge. The absence of strong central radiation from the imploding glass is not surprising: Independent measurements[5] have shown the implosion energy in these experiments to be less than 0.5 J and the fraction of mass imploded more than 0.5. This energy can at best heat the imploding glass to a small fraction of a keV but can raise the neon gas temperature well above 1 keV.

We now employ order-of-magnitude estimates to show why a neon fill heated through compression is expected to emit mostly continuum (bremsstrahlung) radiation. The total intensity of bremsstrahlung emission from the neon is $P_{BR} = (5\times10^{-31}$ J cm^3 keV$^{-1/2}$ sec$)n_eN_eZT^{1/2}\Delta t$, where n_e and N_e are the density and the total number of electrons and Δt the duration of emission. For the double-pulse case, assuming $T=1$ keV, a totally ionized and uncompressed gas, and Δt equal to the laser full width at half-maximum, we get $P_{BR}\sim 0.2$ mJ. The volume compression indicated by the size of the central spike in Fig. 2 is $C\sim 300$. For this case, assuming again $T=1$ keV and $\Delta t \sim 100$ psec (the time spent around maximum compression), we obtain $P_{BR}\sim 20$ mJ. We next estimate the intensity of the $1s$-$2p$ transition of Ne^{+9}. Assuming a Doppler profile we can show the optical depth[6] at the line center to be $\tau \sim (5\times10^{-18}\text{ cm}^2)n_e r$ in terms of the pellet radius r. For the uncompressed case (Fig. 1, upper spectrum) we obtain $\tau\sim 10$. However, the probability for collisionally quenching the $2p$ state is only $\alpha = 0.04$ which means that the radiation is re-emitted and the effect of self-absorption is small.[7] This probability can be calculated from[6] $\alpha = (R+1)^{-1}$, where $R = (7\times10^{17}Z^7/2^{8.5}n_e)(kT/E_i)^{1/2}$, E_i being the ionization energy. The total line intensity can then be estimated from $P_L = n_eN_e\langle\sigma v\rangle h\nu\Delta t/Z$. The excitation coefficient $\langle\sigma v\rangle$ can be estimated[6] to be 7.5×10^{-12} cm^3 sec^{-1} and so we find $P_L\sim 1.5$ mJ. For the case of compression by a factor 300 we find $\tau\sim 600$ and $\alpha\sim 0.9$. The emitted radiation will be reduced from a value estimated assuming an optically thin case by about a factor $1/\epsilon = 120$. ϵ is the escape factor of Holstein[8] for Doppler-broadened lines except that here it was calculated for a medium which absorbs its own rather than an incident radiation. Neon lines are weak in this case mainly because the lifetime against ionization is only about 2 psec so that here $\Delta t = 2$ psec. The ionization time was calculated from the relation[9] $\Delta t\sim(10^8\text{ sec cm}^{-3})Z^3/n_e$ which assumes $kT/E_i = 0.3$, the approximate condition for maximum line emission.[4] We finally obtain $P_L = \epsilon\eta_eN_e\langle\sigma v\rangle \times h\nu\Delta t/Z \sim 0.07$ mJ.

Summarizing, the case of a double pulse gives a line-to-continuum ratio of 7.5 and the case of a single pulse gives 3×10^{-3}. These rough estimates clearly explain the striking difference between the two spectra in Fig. 1: One is produced by a laser-heated fill gas, the other by a hydrodynamically heated fill gas. Also, neon lines in the single-pulse case would also suffer some absorption through the glass shell.

Having thus shown that the central spike in

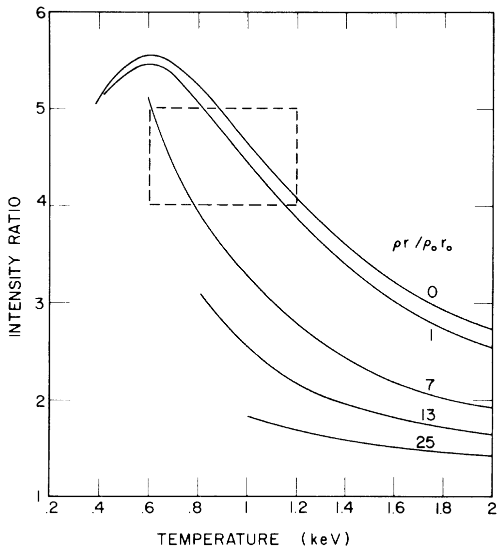

FIG. 4. X-ray intensity ratio before and after a 0.3-mil Al filter. Bremsstrahlung radiation of neon at a given temperature traverses a glass shell of density-thickness product ρr (related to the initial values) and then a 1-mil Be filter. The rectangle is determined by the error bar on the observed intensity ratio.

Fig. 2 is mostly bremsstrahlung radiation from compressed neon, we can estimate from Fig. 4 both the electron temperature in the gas and the glass shell compression at the time of maximum neon compression. We calculate here the bremsstrahlung emission from neon, transport it through a layer of glass of a density-thickness product ρr, and finally calculate the ratio of total x-ray intensity behind two filter combinations: (a) 1-mil Be and (b) 1-mil Be plus 0.3-mil Al. The absorption in the glass is mostly K-shell photoionization so that only glass of temperature smaller than a few hundred eV is effective in absorption. Indeed, imploding shells are shown by computer simulation[1] to be relatively cold up to maximum compression and then to heat up and expand. The curves of Fig. 4 were terminated on the left at a point beyond which energies higher than 1 J of neon x-ray emission would be implied (before attenuation by the glass). This is a conservative upper limit since of about 10 J absorbed energy far less than 1 J is converted to compression energy,[5] of which only a fraction is converted to x rays. These higher emission energies were thus excluded from Fig. 4. The central spike attenuates through the aluminum filter (Fig. 2) by a factor 4.5 ± 0.5 where the uncertainty is mainly due to film calibration. We conclude from Fig. 4 that the electron temperature of the compressed neon gas is 0.9 ± 0.3 keV and $\rho r/\rho_0 r_0$ for the glass shell is much smaller than 10 or ρr is much smaller than 2.5×10^{-3} g/cm^2. Within the rectangle of Fig. 4 the attenuation factor through the glass ranges between 4 and 60; the emission of 20 mJ calculated above and the observed intensity 1–3 mJ give an attenuation factor 7–20. By comparison, energy shifts of α particles in Ref. 2 indicate values of $\rho r/\rho_0 r_0$ in the range 1–2. Computer simulation[10] (for conditions different from ours) have shown that only by assuming a substantial fraction of the energy to be deposited in superthermal electrons can one get such low ρr values for the glass. This conclusion is consistent with our measurements[11] of fast ions and $K\alpha$ radiation excited by fast electrons, as well as with Brueckner's interpretation[12] of the continuous x-ray spectrum. Although the degradation of compression could be the result of a number of different causes, the present method of measuring x-ray spectra from a high-Z fill gives direct evidence of the degree of compression of both the fill and shell. This method can be the basis of a more detailed study to determine the dominant cause of compression degradation.

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