periments of Kerns and Johnson[8] in which observations were made of a 2.5-MV, 25-kA stream formed from a Bennett cathode and incident on a $(CD_2)_n$ target. It was found that ~21 kA of stream current was focused to a diameter $\lesssim 75$ $\mu$m in a time ~25 nsec following filamentation at ~15 nsec. Filamentation and pinching initiated in the high-density plasma plume in front of the target. Typical values were $\gamma \simeq 6$, $i \simeq 0.2$, $Z \simeq \frac{8}{3}$, $\sigma_0 \simeq 0.1$ cm, and $\sigma \lesssim 3.75 \times 10^{-3}$ cm. Then, by calculation $f \simeq 35$, $\psi \simeq 0.58$ (i.e., ~300 keV), $\lambda \simeq 0.224$ cm, $\sigma_f \simeq 0.54 \times 10^{22} n^{-1}$ cm, $L \simeq 2.4 \times 10^{22} n^{-1}$ cm, $t_d \simeq 18.8$ nsec, with the requirement that $n > 3.6 \times 10^{16}$ cm$^{-3}$. The time equivalent to $t_i$ (i.e., the time taken for formation of a dense plasma within the stream) is determined, in this case, by closure of the 0.6-cm cathode-anode gap by plasma plumes from the cathode and anode surfaces.[9] The observed times[8] were consistent with established plasma-diode dynamics.[9] For all expected ranges of $n$ in the diode, $\sigma_f$ and $L$ greatly exceeded experimental dimensions. Thus, $\sigma_0 \ll \sigma_f$ and uniform-diameter conditions should exist after the 0.224-cm focusing distance. Then from Eq. (9), $\psi_0 \simeq \gamma i (\beta \sigma / \sigma_0)^2 / 2 \lesssim 0.84 \times 10^{-3}$ (corresponding to $\lesssim 430$ eV) is necessary in order to achieve the observed pinch radius. Such values, attainable with the Bennett cathode, are thought to occur due to channeling of cathode-emission electrons to the diameter of the dielectric rod before these particles have gained appreciable energy from the applied field. Such behavior would not occur, for example, in large-aspect-ratio diodes where stream electrons acquire appreciable energies before focusing occurs.

Of interest here is the behavior of the stream as it penetrates the solid target. Taking as initial conditions the values $\sigma_0 \lesssim 3.75 \times 10^{-3}$ cm and $\psi_0 \simeq 0.58$ attained within the diode, the solid-density parameters $n \simeq 10^{23}$ cm$^{-3}$ and $Z \simeq \frac{8}{3}$ give $\sigma_f \simeq 0.054$ cm $\gg \sigma_0$, $\sigma \simeq \sigma_0 \lesssim 3.75 \times 10^{-3}$ cm, $\psi \simeq \psi_0 \simeq 0.58$, $\lambda \simeq 8.4 \times 10^{-3}$ cm, $L \simeq 0.242$ cm, $t_i(+1) \simeq 0.32$ nsec, and $t_d \simeq 0.7$ nsec. Thereby, it appears that very rapidly the stream penetrates the solid over distances of several millimeters at a uniform diameter $\lesssim 75$ $\mu$m. Under such conditions, power flux densities within the target may have exceeded $1.6 \times 10^{15}$ W/cm$^2$ in these experiments.

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# Plasma Resonance in the X-Ray Emission from Gaseous Laser Targets

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I report the first observation of $CO_2$-laser-induced x-ray emission from *gaseous* targets. By varying the gas pressure, the plasma density of the target was tuned through resonance at the critical density. The x-ray emission rose quickly from zero at the critical pressure, and reached a peak when the plasma was slightly overdense. Because of the resonant enhancement, a $CO_2$-laser pulse of only 0.1 J was sufficient for this experiment.

In the interaction between a laser pulse and a solid target, the plasma density varies from ~$10^{23}$ electrons/cm$^3$ in the target to 0 in the surrounding vacuum. It is generally agreed[1] that the energy absorption takes place in the narrow critical layer where the plasma frequency equals the

laser frequency $\omega$. Nevertheless, there is no
consensus on the absorption mechanism itself.
Some theorists favor a type of nonlinear paramet-
ric interaction,[2] while others invoke a linear res-
onance model.[3]

In order to elucidate the physics of the reso-
nant interaction process itself, it is desirable to
control the plasma density to be at or near the
critical density. In studying the physics, there-
fore, a gaseous target may be more appropriate
than a solid target. For example, when hydrogen
gas at 150 Torr becomes fully ionized, the plas-
ma density is $10^{19}/cm^3$, the critical density for
the $CO_2$-laser frequency. Thus by varying the
gas pressure in the neighborhood of 150 Torr we
can study the underdense regime, the resonant
regime, and the overdense regime. Similarly
for any other gas, there will be a critical pres-
sure which depends on the charge state of the
positive ions which are formed.

In this paper I report x-ray emission from
plasmas produced in hydrogen, helium, mixtures
of hydrogen and helium, nitrogen, argon, and
helium doped with 1% xenon.

The laser source was a $CO_2$ oscillator, followed
by an optical free-induction-decay pulse shaper,[4]
with a Lumonics 103 used as a final-stage ampli-
fier. This system is more fully described by
Kwok and Yablonovitch.[5] The output is a diffrac-
tion-limited pulse of 0.1-J energy and 500-psec
duration. It was focused into the gas cell with a
spherically corrected, $f/1$, germanium, doublet
lens. The gas was filtered and cold trapped to
remove impurities which might cause premature
breakdown.[6] There was a steady flow through
the chamber to ensure a fresh charge of gas for
each laser shot.

The plasma was generated through avalanche
ionization, driven by inverse-bremsstrahlung
heating of the electrons. The focal-spot intensi-
ty was high enough to initiate[7] the avalanche by
tunneling.[8] Below a certain pressure threshold,
the gas would not break down, because of the re-
duction in collisional heating rate and the in-
crease in diffusive loss rate of electrons.[9] This
varied from ~25 Torr in argon to about ~100
Torr in helium. Observations were made over a
wide pressure range from the breakdown thresh-
old up to 1 atm.

The resonant nature of the x-ray production is
evident in Fig. 1 which plots it as a function of
gas pressure. Hydrogen has the sharpest reso-
nance. At the critical pressure of 150 Torr the
emission rises from zero, quickly reaching a
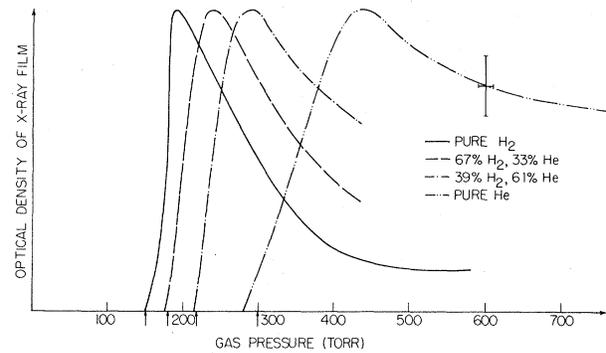


FIG. 1. X-ray emission from plasmas produced in
hydrogen-helium mixtures. The four small arrows
along the abscissa indicate the calculated gas pressure
which would give rise to a critical density of electrons
$(10^{19}/cm^3)$ for each of the four mixtures, in order of
decreasing hydrogen fraction. This shows that the on-
set of x-ray production occurs at the critical pressure.
The emission is normalized to unity at the peak value.

maximum when the plasma is ~25% overdense.
The x-ray production just below the critical pres-
sure is under the limit of our detection capabili-
ty, less than 2% of the peak emission. Helium
has the same behavior except that the onset of x-
ray emission is at 300 Torr, exactly twice the
critical pressure of $H_2$. This indicates that the
helium plasma is produced in the singly ionized
charge state, a result which will be explained
later in the paper.

Particularly fascinating are the results on $H_2$-
He mixtures which show the shift of the reso-
nance as a function of the concentration ratio.
The small arrows along the abscissa give the cal-
culated critical pressure, $p_c$, for each of the four
mixtures in order of decreasing hydrogen frac-
tion $x$:

$$p_c = kTm\omega^2/4\pi e^2(1+x),$$

where $e$ and $m$ are the charge and mass of the
electron, $T$ is room temperature, $k$ is Boltz-
mann's constant, and $\omega$ is the laser frequency.

Helium gas doped with 1% xenon showed the
same pressure dependence as pure He, but the
emission was much stronger because of the high
atomic number of xenon.

In Fig. 2 we see that argon and nitrogen also
exhibit a form of resonant behavior. Because of
the higher ionization state of which these gases
are capable, the plasma resonance is shifted to
lower pressures. We can infer a charge state of
perhaps 4 or 5 for these atoms. The ambiguity

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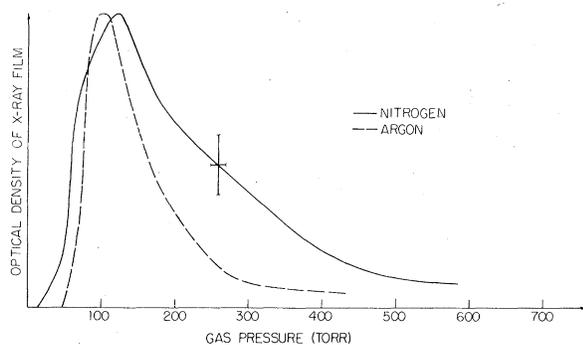
FIG. 2. X-ray emission from plasmas produced in nitrogen and argon. The emission is normalized to unity at the peak value.



FIG. 3. The solid lines show the focal spot and the cone-shaped region of laser light leading to it. The dashed lines represent the ionization front at successive instants in time. Notice that the laser-plasma interaction occurs mainly in the low-intensity region in front of the focal spot.

in the precise degree of ionization is probably responsible for the smearing out of the resonance when compared to the sharp steplike behavior of a gas like hydrogen.

The radiation was detected by two means: (a) a silicon surface-barrier detector filtered by 6.9 mg/cm$^2$ of Al foil and placed about 1 cm from the focal region; (b) small film packets of Kodak no-screen medical x-ray film filtered by 10 mg/cm$^2$ of black polyethylene and placed about 0.8 cm from the focal region. Most of the quantitative measurements were made with the film, calibrations of which have recently been published.[10]

The experimental procedure was to expose the film for 20 min at a given gas pressure, with the laser pulsing at 0.3 pulses per second. The exposures had to be reduced for argon and for He:Xe, which, because of their higher atomic number, had much more powerful x-ray emission. Typically, the film was exposed to a net optical density of about 1.

The 10-mg/cm$^2$ polyethylene filter is essentially opaque to x-ray wavelengths longer than ~ 8 Å. Therefore only bremsstrahlung and free-bound continuum radiation could be observed from the low-$Z$ gases ($N_2$, He, $H_2$), whose line emission is beyond the long wavelength cutoff of the filter. Employing the two-foil-absorber ratio technique, with foils of 10 and 20 mg/cm$^2$ of polyethylene, an effective electron temperature of 1 keV was inferred[11] for the nitrogen plasma.

There was an additional complication in the x-ray emission from $H_2$ and He. Because of their low atomic number, their bremsstrahlung and free-bound continuum radiation were very weak. Similarly, the stopping power of the gas for fast electrons was relatively small. Electrons were

emitted from the focal region with enough energy to strike a copper surface of the gas cell 8 mm away. Because of the relatively high $Z$ of the metal, this roundabout mechanism produced x-rays comparable in intensity to the continuum emission coming directly from the focal region itself. In He the two contributions were about equal, while in $H_2$ the emission from the metal surface was the stronger of the two. From the range-energy relations[12] for the fast electrons, we can infer that at least 10 keV are required to penetrate 8 mm of gas and have enough energy left over to produce x rays. A study of the fast-electron emission will be published in a forthcoming paper.[13]

To interpret these experiments more fully, it is important to know the geometry of both the plasma and the light beam which is generating it. The optical electric field $E$ is so high that the electron quiver energy $e^2E^2/2m\omega^2$ greatly exceeds the ionization potential of the gas, not only in the focal spot, but also in the cone-shaped region of laser light leading to it, as shown in Fig. 3. Under these conditions, impact ionization occurs with every collision and is roughly independent of the light intensity. Since the diffusive loss rate of electrons from the tiny focal volume is quite high, the plasma will actually avalanche more quickly in the lower-intensity region in front of the focal spot where the beam width is larger. From there the ionization front will spread as a breakdown wave,[14] further upstream toward the lens. In this relatively low-intensity region, the critical layer appears as a moving front, and this is where the resonant laser-plasma interaction actually occurs.

In the context of this picture, we can under-

stand why helium does not experience plasma
resonance in the pressure range between 150 and
300 Torr, where a doubly ionized plasma would
be resonant. Because of the factor 10 difference
in ionization cross section[15] and the factor 2 dif-
ference in ionization potential between He and
He$^+$, the avalanche ionization rate for the two
species will be vastly different. Therefore a
large cone-shaped region of singly ionized,
slightly underdense, plasma will first form in
front of the focal spot. This will defocus the
light and prevent it from reaching a high intensi-
ty for a long enough time to produce the doubly
ionized plasma. This reasoning does not apply
to nitrogen and argon, because the difference in
ionization cross section[16] between successive
stages of ionization is much less.

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# Propagation of Ion-Acoustic Waves in a Two-Electron-Temperature Plasma*

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The propagation of ion-acoustic waves (IAW) in a double-electron-temperature plasma
is investigated both experimentally and theoretically. It is found that the presence of even
a small fraction of the lower-electron-temperature component can dominate the behavior
of the waves. The results have important implications both for the use of IAW as a diag-
nostic tool for measuring electron temperature and for the interpretation of turbulent IAW
spectra.

In this paper, we examine the propagation of
linear ion-acoustic waves (IAW) in a plasma
whose electron velocity distribution may be rep-
resented by the superposition of two Maxwellians.[1]
Such electron distributions are rather frequently
encountered. For example, hot turbulent plas-
mas of thermonuclear interest often have high-
energy tails; strong electron-beam–plasma in-
teractions can result in such electron distribu-
tions; and very often, simple hot-cathode dis-
charge plasmas also have double-electron-tem-

perature distributions.[1,2] The latter type of plas-
ma is used in the present study because it is
steady state, quiescent, and the plasma param-
eters are easily varied over a fairly wide range.

When two groups of electrons at different tem-
peratures are present, the Langmuir-probe cur-
rent characteristic shows a distinct break in the
electron-retardation region. An example is giv-
en in Fig. 1. The procedure for determining both
the temperatures and the densities of the two elec-
tron distributions is well known.[1]