Improved laser pumping by intense electron beams via a backscattering reflector

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Experiments demonstrating improved laser media pumping using electron-beam concentration by means of a backscattering mirror are reported. The backscattering mirror increases the electron pumping density by as much as a factor of 3 at low gas pressures. Use of the concentrator resulted in more than a 50% increase in Ar_2^* excimer emission. The $N_2(C \rightarrow B)$ amplified spontaneous emission can be saturated on a gain length of only 10 cm.

I. INTRODUCTION

Direct electron-beam excitation is one of the most widely used techniques for pumping excimer lasers because of the high peak powers available, broad spectral applicability, scalability, and proven technology.[1–3] Efficiencies for conversion of electron-beam energy into excited states of the rare-gas buffers can be close to 50%. Pulsed *e*-beam generators usually produce electron beams with current densities on the order of 10–1000 A cm^{-2} with electron energies ranging from several hundred keV to a few MeV.

Several different geometries are commonly used for coupling the electron beam into the active medium (Fig. 1). Because of the straightforward design considerations, the one- or two-sided transverse pump geometry is most frequently employed. In this scheme, the electron beam produced by a cold cathode enters the laser medium by passing through a thin foil supported by an Hibachi-type structure. The coaxial or radial pumping scheme described in Ref. 4 lends itself to the production of very high and uniform pump power densities, but suffers from the problem of scaling to large volumes. Improved coupling of *e*-beam energy into the laser medium can be obtained by longitudinal excitation; however, this requires the use of intense, pulsed magnetic guiding fields.[5] In this work, a simple backscattering mirror has been designed to conform to transverse pumping, and at the same time, to obtain the high pumping densities usually achieved with longitudinal and coaxial pumping.

II. BACKSCATTERING OF ELECTRONS AND THE PRINCIPLE OF A BACKSCATTERING MIRROR

Backscattering of electrons in the range of several hundred keV to several MeV from thick targets has been investigated by Bothe,[6] Frank,[7] Wright and Trump,[8] and Lockwood *et al.*[9] In each work, the backscattering coefficient is introduced as the fraction of the incident electrons which are backscattered from the target, irrespective of their energy. These investigators found that the normal incidence backscattering coefficient for electrons from targets with a thickness larger than the penetration depth of the electrons is only a function of the electron energy and the atomic number Z of the material. The normal incidence backscattering coefficient reported in the literature[7–9] is $\eta_{90^\circ} \approx 0.50 \pm 0.05$ for 1-MeV electrons, and an atomic number of $Z \approx 80$, and decreases nonlinearly to $\eta_{90^\circ} \approx 0.08 \pm 0.02$ for aluminum ($Z = 13$).

The energy distribution of the backscattered electrons was also investigated. In all cases, the energy of the backscattered electrons varies from almost zero up to the energy of the incident electrons. For low Z materials (i.e., carbon), the distribution is fairly broad and peaked at about one-half of the incident electron energy. For atomic numbers greater than $Z \approx 20$, the energy distribution of the backscattered electrons is much narrower, and the peak approaches the incident energy. For a lead target as employed in our experiments, the mean energy of the backscattered electrons reached approximately 75% of the 1-MeV incident energy.

In the detailed investigations by Frank[7] and Lockwood *et al.*,[9] the backscattering coefficient and the energy distribution of the backscattered electrons were also investigated as a function of the angle of incidence of the electron beam on the target. The angular distribution of the backscattered electrons is of particular interest for the present work. Frank[7] found a broad angular distribution due to diffusion of electrons in the backscattering mirror. For all angles of incidence, it peaks at the angle one would expect if a simple reflection law were valid for the process. As the angle of incidence Θ changed from normal ($\Theta = 90^\circ$) to grazing incidence, the backscattering coefficient was found to increase and to become less dependent upon Z. For lead, the backscattering coefficient at 30° is about 70% for 1-MeV electrons, 1.3–1.5 times the backscattering coefficient at normal incidence. Furthermore, as the angle of incidence is decreased, the energy distribution of the backscattered electrons peaks closer to the energy of the incident electrons. With a 30° incident angle, the mean energy of the backscattered 1.75-MeV electrons from lead amounted to about 90% of the energy of the incident electrons.

These results may be summarized as follows: When a surface of sufficiently thick and high Z material is bombarded by electrons in the energy range of 1 MeV, the surface behaves as a lossy mirror with substantial surface scattering. Although the quality of such an electron mirror is far from that of optical mirrors, it is possible to build simple reflector devices for electrons exploiting the effects associated with backscattering.

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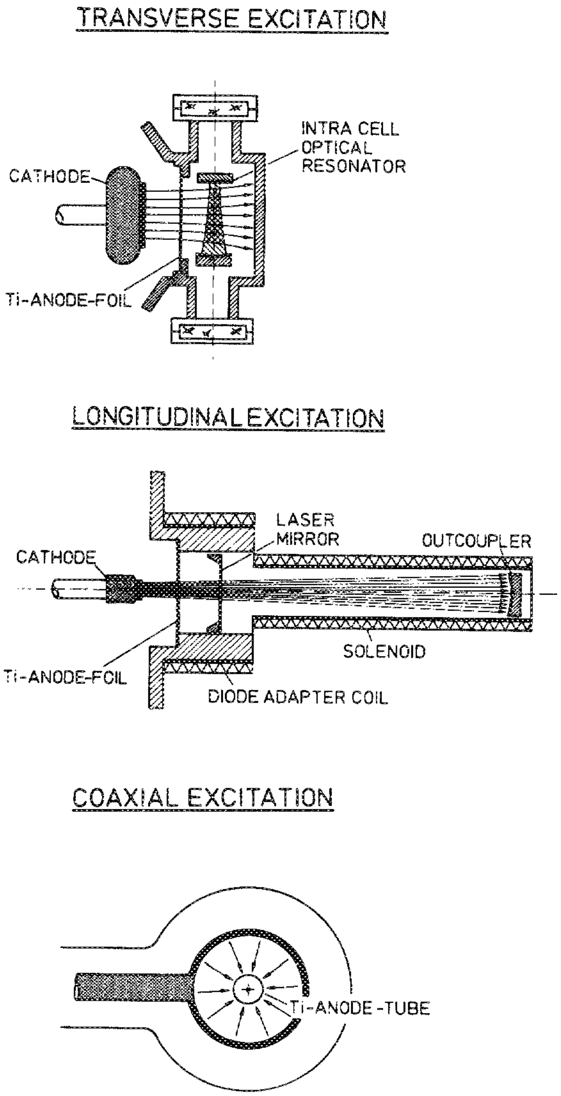

FIG. 1. Transverse, longitudinal, and coaxial excitation geometries used in e-beam pumped excimer lasers.

III. EXPERIMENTAL SETUP

In this work we report on a cylindrical, concave backscattering mirror for electrons that is used to focus a high-power electron beam in order to increase the electron current density for laser pumping. A Physics International Pulserad 110 electron-beam generator was used to transversely excite the gas mixtures. The e-beam energy was 1 MeV and the pump-pulse duration was 10 ns (FWHM). In the absence of the backscattering mirror, an energy deposition density of approximately 60 J/l in 6-atm argon was measured by a calorimeter. The principle of the concave backscattering mirror for electrons is shown in Fig. 2. A 10-cm long piece of lead ($Z = 82$) was machined into a parabola-like shape. The curved inner section is part of a circle that has a continuous transition into a wedge-shaped opening. The approximate focal point, i.e., at about half the radius of curvature of the circle, is located at the optical axis of the laser cell. The outer surface of the backscattering mirror has a circular shape constructed to fit inside the laser cell. Free gas circulation is permitted through open space between the cell and the back of the mirror.

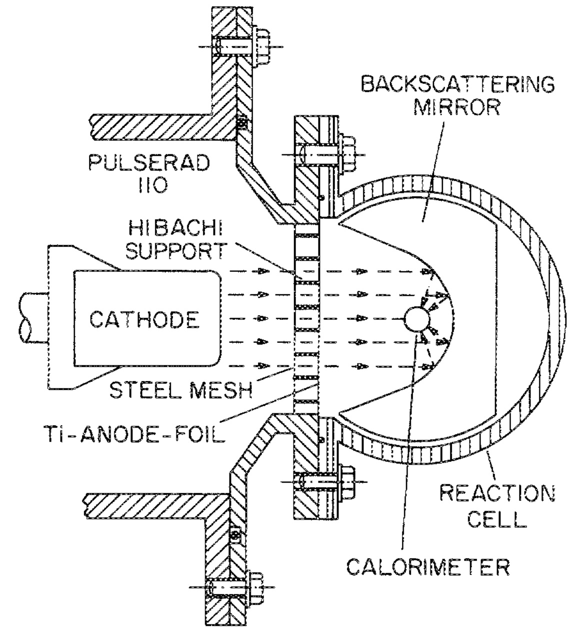

FIG. 2. Concave backscattering mirror geometry in a transverse electron-beam pumped laser device. A large fraction of the e-beam was focused toward the center of the reaction cell. The stainless-steel wire mesh improves the homogeneity of the electric field which is distorted by the Hibachi support.

During usual e-beam operation, electrons are accelerated from the carbon cold cathode of 7.5 cm length, towards a highly transparent steel mesh serving as the anode. They penetrate the Hibachi structure and pass through a 50-μm-thick titanium pressure foil in order to enter the laser cell. Since the electron beam is only slightly divergent due to space charge and scattering effects, the backscattering mirror concentrates the electrons in the vicinity of the focal line of the concave mirror. Due to electron-beam divergence, the less-than-ideal parabolic shape of the mirror and the relatively broad angular distribution of backscattering, the backscattered electrons do not converge to an ideal line focus, but rather, contribute to an enhanced energy density in a finite volume of several millimeters diameter centered around the focus line of the mirror. This concentration of the electrons leads to an enhanced pumping density of the laser medium in the focal region.

In addition to the electron concentration effect, other factors of the backscattering process also contribute to an enhanced pumping density. Below several hundred keV of electron energy E, the energy loss due to ionization of the gas, which is the dominating loss process in this energy region, varies approximately as E^{-1}. Since the backscattered electrons have lower energies than the primary electrons, this effect leads to an increased pumping density of the gas.

Probably more relevant is the production of Bremsstrahlung in the high Z material. The spectral distribution of the bremsstrahlung photons varies over a wide range from almost zero energy up to the incident electron energy, with a peak at about 20%–40% of this energy.[10] The total efficiency of x-ray production for a lead backscattering mirror may be estimated to be about 4% for 1-MeV electrons.[10] This corresponds to about 1 J of x rays for our experimental conditions.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

To test the performance of the electron backscattering mirror, calorimetric, fluorescence, and laser experiments were performed with the experimental setup shown in Fig. 2. In order to measure the total electron-beam energy close to the optical axis, a 7-cm-long, 3-mm-diam cylindrical aluminum calorimeter was constructed. Aluminum was chosen because of its high thermal conductivity and small backscattering coefficient of $\sim 10\%$ for normally incident electrons and electron energies of several hundred keV. The calorimeter was placed on the optical axis of the laser cell in the focal region of the backscattering mirror (Fig. 2). The total electron energy absorbed by the calorimeter was measured with and without the backscattering mirror.

The results are shown in Fig. 3 when helium and argon are used as buffer gases. In vacuum without the backscattering mirror, the absorbed energy in the calorimeter is quite low. This is due to the divergence of the electron beam caused by the space-charge effect. With an argon or helium pressure of several Torr to several hundred Torr, electron impact ionization of the buffer gas produces slow electrons and ions, which effectively reduces beam divergence. The secondary electrons, repelled by the space charge of the electron beam, leave the beam on a subnanosecond time scale, while the positive ions that are left behind neutralize the repulsive space-charge forces produced by the *e*-beam. Thus, the beam divergence is greatly reduced, leading to an increased current density. For increasing argon pressures above 1-atm multiple electron scattering and energy loss lead to a slow decrease in the total energy measured by the calorimeter (Fig. 3).

When the backscattering mirror is inserted in the cell, a dramatic increase of the energy absorbed in the calorimeter is observed for both buffer gases. At zero pressure, the relative energy increase amounts to about a factor of 3. For argon as a buffer gas, the relative energy increase due to the backscattering mirror is about 30% from 1 to 4 atm, and decreases at higher pressures (Fig. 3). At pressures greater than 4 atm, both scattering and energy loss effects dominate, especially for argon. Therefore, the electrons do not reach the backscattering mirror as an almost parallel beam anymore, but exhibit an angle of incidence distribution that becomes broader with increasing argon pressure, which finally leads to an isotropic backscattering distribution. Energy loss and scattering are far less important in helium due to its low Z value. Therefore, the energy which is absorbed primarily due to backscattering is practically independent of the helium pressure (Fig. 3), and the improvement due to the backscattering mirror is considerable.

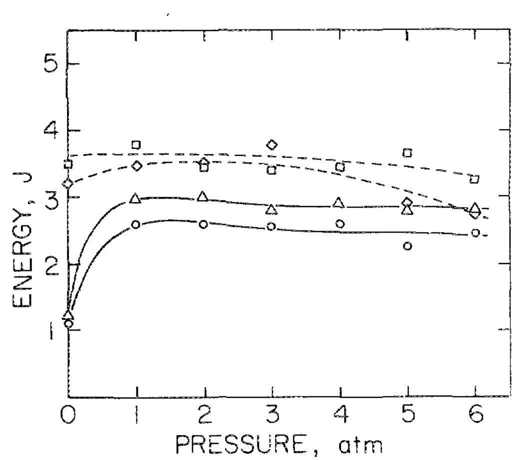

FIG. 3. Dependence of total electron energy absorbed by the calorimeter as a function of buffer gas pressure. The circle-solid line is with Ar buffer; triangle-solid line with He buffer; diamond-dashed line with Ar and backscattering mirror; and square-dashed line with He and backscattering mirror.

These calorimetric data can only provide an approximate picture of the operating principle of the backscattering mirror. Unfortunately, the energy absorbed in the calorimeter is not directly proportional to the pumping density in the gas. The backscattered electrons have lower energy than the primary electrons. For a certain electron density produced by the backscattering mirror, this leads to a reduced absorbed energy in the calorimeter. However, the pumping density in a gas is higher for lower energy electrons. Also, the calorimeter blocks part of the electron beam. Therefore, the enhanced energy absorption in the calorimeter due to the backscattering mirror is only a lower limit for the actual improvement in pumping density.

In order to evaluate the potential of the backscattering mirror, in particular, for short-wavelength laser pumping, fluorescence and laser experiments were performed. Fluorescence and superfluorescence from a 90% Ar/10% N_2 mixture on the $N_2\,(C\rightarrow B)$ transition at 358 nm and the fluorescence of the argon excimer radiation at 126 nm were investigated. Care was taken to limit the observed region in the cell to about the same volume as the calorimeter using appropriate apertures. The $N_2\,(C\rightarrow B)$ emission was measured by a photodiode with an interference filter for spectral selection. The Ar_2^* radiation was observed by means of a fast photomultiplier equipped with scintillator at the exit slit of a 0.25-m VUV spectrometer.

Experimental results obtained with and without the backscattering mirror are depicted in Figs. 4 and 5. Without the backscattering mirror, the $N_2\,(C\rightarrow B)$ emission at low argon pressure was essentially fluorescence radiation characterized by a temporal pulse width of about 20 ns (Fig. 4). The intensity increased faster than linearly with increasing argon pressure, and was accompanied by temporal pulse narrowing to about 3 ns at 6 atm. This narrowing indicates the onset of amplified spontaneous emission. When the backscattering mirror is employed, strong amplified spontaneous emission with a narrow pulse is already observed with only 1 atm of gas mixture in the cell. When the pressure is increased, no further pulse narrowing occurs and the amplified spontaneous emission starts to saturate at a gain length of only 10 cm. The radiation output observed with the backscattering mirror in the cell at 1-atm gas pressure is higher than the output obtained at 6 atm without the backscattering mirror.

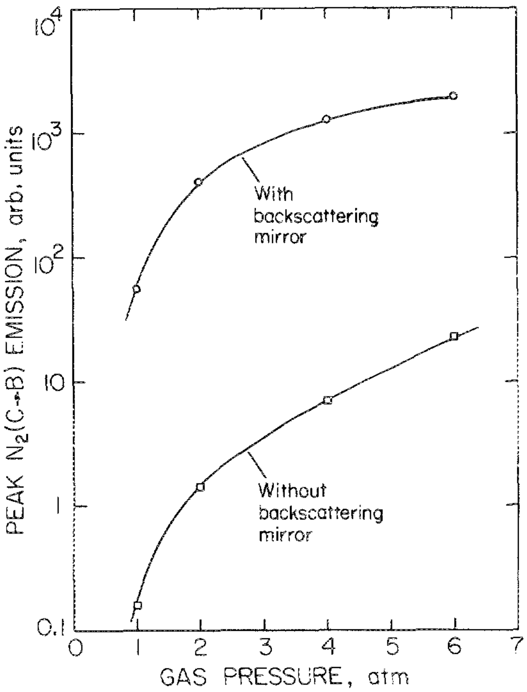

FIG. 4. N_2 ($C \to B$) emission output with and without an *e*-beam concentrator as a function of 10% N_2 and Ar mixture pressure. The nonlinear behavior of the output was due to the amplified spontaneous emission.

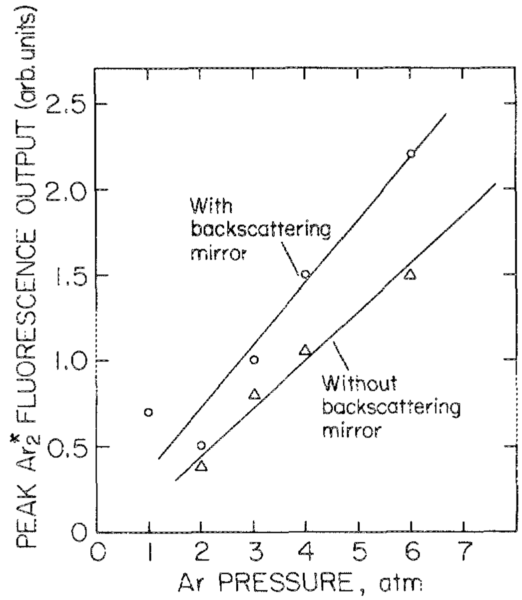

FIG. 5. Ar_2^* fluorescence output with and without *e*-beam concentrator as a function of Ar pressure.

The VUV fluorescence of Ar_2^* around 126 nm is also considerably enhanced by the backscattering mirror (Fig. 5). The relative fluorescence increase due to the backscattering mirror amounts to about 50%. However, the actual increase in pumping density is much higher because the Ar_2^* fluorescence scales less than linearly with current density due to electron quenching of the excited states.

V. SUMMARY AND CONCLUSIONS

It has been experimentally demonstrated that a high-power electron beam can be considerably concentrated when an electron backscattering mirror is used. The device leads to saturated amplified spontaneous emission on the 358-nm N_2 ($C \to B$) transition in transverse-pumped Ar/N_2 mixtures for a gain length of only 10 cm. Improved fluorescence was also observed for the 126-nm Ar_2^* excimer emission.

New proposed VUV and XUV laser systems require helium- or neon-based gas mixtures,[11] in which case both gases have a comparatively low stopping power for high-energy electrons. Higher pumping densities for electron-beam excitation are, therefore, a crucial component for the success of such lasers. In fact, backscattering reflectors cannot only be useful for electron-beam pumping of lasers, but can potentially be beneficial in other areas where high electron densities are required.

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