Excimer Laser Pumped by an Intense, High-Energy Heavy-Ion Beam

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(Received 25 July 2006; published 11 October 2006)

High-energy heavy ions are an ideal tool to generate homogeneously excited, extended volumes of nonthermal plasmas. Here, the high-energy loss (dE/dx) and absolute power deposition of heavy ions interacting with matter has been used to pump an ultraviolet laser. A pulsed 70 MeV/u ^{238}U beam with up to 2.5×10^9 particles in $\sim$100 ns beam bunches was stopped in a 1.2 m long laser cell filled with a 1.6 bar Ar-Kr-F_2 mixture (typically 50%:49.9%:0.1%). Laser effect on the 248 nm KrF^* excimer transition is clearly demonstrated.

DOI: 10.1103/PhysRevLett.97.153901 PACS numbers: 42.60.By, 41.75.Ak, 42.55.Lt

Short wavelength lasers generally require a high power, nonthermal method of excitation. In this Letter we demonstrate particle beam pumping of a 248 nm KrF excimer gas laser, using projectiles of extremely high mass, energy, and charge, in the form of a pulsed, focused beam of relativistic ^{238}U ions. The beam was provided by the heavy-ion synchrotron SIS 18 at the Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany.

Heavy-ion beam pumping of lasers is based on the following considerations: Heavy ions have a very high energy loss (dE/dx) in matter which scales quadratically with the charge of the projectile as described by the Bethe formula. The combined effects of ion-beam focusing, the dependence of power deposition from the projectile energy, and the angular scattering of the projectiles, lead to an almost cylindrical and homogeneously excited volume on the beam axis [1], which can be well matched with the mode volume of a laser resonator. Additionally, experiments at GSI have shown that the stopping power also depends strongly on the properties of matter, and particularly in ionized matter extremely high stopping power was observed [2]. Recently, the SIS 18 synchrotron at GSI became capable of providing intense, low-emittance, and short pulses of heavy-ion beams, and therefore an experiment was performed to study the possibility of using such beams for pumping short wavelength lasers.

Heavy-ion beam pumping [3] of gas lasers had first been demonstrated in 1983 stimulated by so-called nuclear pumped laser experiments in which the flux of nuclear fission fragments is used to pump gas lasers [4]. Various laser schemes have been studied [5–8], but due to the limited pumping power levels provided by ion accelerators, the wavelength range of ion-beam pumped lasers had been limited to the infrared and visible spectral region [3,9,10]. This situation has now changed due to the strongly improved beam intensity of the GSI accelerators. Short wavelength ion-beam pumped lasers may have some applications as special light sources, e.g., in the form of tunable excimer lasers of the pure rare gases in the vacuum ultraviolet (Ne to Xe, 80 to 170 nm). These broadband gain media may also be used for short-pulse production. Another important aspect is that observation of laser effect in ion-beam induced plasmas can be used as a sensitive tool for studying such plasmas. Besides laser experiments the general aspects of the formation of heavy-ion beam induced plasmas have been extensively studied [1,2,11,12]. Because population inversion and laser effect only occurs under specific conditions with respect to plasma density and temperature, electron density and temperature, as well as opacity of the target material at the laser wavelength, a comparison of the laser parameters with model calculations can provide a deep insight into the excitation and deexcitation processes in ion-beam induced plasmas.

In this Letter we describe a heavy-ion beam pumped laser in the ultraviolet spectral range which has become possible by the considerable improvement in the beam intensity and quality of the SIS 18 synchrotron, as well as in beam transport and handling at the HHT experimental area. A KrF excimer laser scheme has been used for this pioneering experiment, because of the strong ionic channel for forming the KrF^* excimer molecules [13] and the large cross section of heavy ions to produce these ionic precursors. Furthermore, the KrF laser light at a wavelength of 248 nm can still propagate to the detection systems through ambient air, thus simplifying this first experimental setup.

A 1.2 m long stainless steel laser cell of 38 mm inner diameter was aligned with the ion-beam axis at the high intensity target station (HHT) of the SIS 18 facility. The ion beam exited the beam line through a thin (150 μm) aluminum foil and traversed about 2 m of air before entering the laser cell through a scintillator plate and a steel entrance foil. A flat laser mirror consisting of a 3.2 mm thick, Al-MgF_2 coated, quartz substrate was also traversed by the ions. The ions were then stopped in the laser gas before reaching the second laser mirror. This mirror was dielectrically coated and highly reflective for 248 nm light (>99.8%) and its quartz substrate had a radius of curvature of 3 m. The laser medium consisted of about 50% Ar and 50% Kr. The fluorine was added as a 0.25% F_2 admixture to the Kr gas. The gas mixture was filled into the laser tube in a continuous flow mode to avoid depletion of F_2 due to chemical reactions. The pressure was adjusted to 1.6 bar, a pressure for which the projectiles were stopped near the end of the laser tube. This was controlled by observing the fluorescent light through a view port near the end of the cell with a CCD camera.

Beam pulses provided by GSI's UNILAC linear accelerator were accumulated in the SIS ring using the multi-multi-turn injection and electron-cooling scheme and then accelerated to a particle energy of 250 MeV/u. The four beam bunches existing in the SIS ring during the acceleration phase were merged into one pulse of about 100 ns duration using adiabatic rebunching and fast bunch rotation techniques, extracted, guided in the beam transport line and focused onto the target. The energy loss of the projectiles before entering the laser medium was very high in this particular test setup, which had to be placed behind the routinely used target station. Only the final 70 MeV/u of the particle energy were actually deposited in the laser gas mixture. Up to about 2.5×10^9 ions per pulse were available which corresponds to 6.7 J pulse energy and up to 67 MW pumping power, respectively. The pulses could be applied as single pulses or with a repetition rate of up to about 0.1 Hz. Pulse intensity could be varied by changing the number of particles accumulated in the synchrotron. The beam diameter in the target gas could not be measured reliably. An estimated value is 2 mm corresponding to a spatially averaged pumping power density of $\sim$20 MW/cm^3.

Two fast, UV-enhanced photodiodes (IRD AXUV 20HS/BNC 05-1) with transmission filters for 248 nm light and two compact spectrometers with fiber optics coupling were used for light detection. Light emitted on the laser axis was reflected off a diffuse Al reflector and light emitted perpendicular to the laser axis was observed through view ports near the entrance of the ion beam into the laser cavity and near the end of the laser cell. Electronic cameras were used for aligning the ion beam with the laser axis by observing the scintillator plate at the entrance to the laser cell and the fluorescent light emitted from the laser gas near the end of the range of the ions.

Laser effect was clearly observed as soon as the number of projectiles per beam pulse exceeded 1.3×10^9. This is demonstrated by Fig. 1 which shows spectra of the light emitted on the laser axis just below and above threshold.

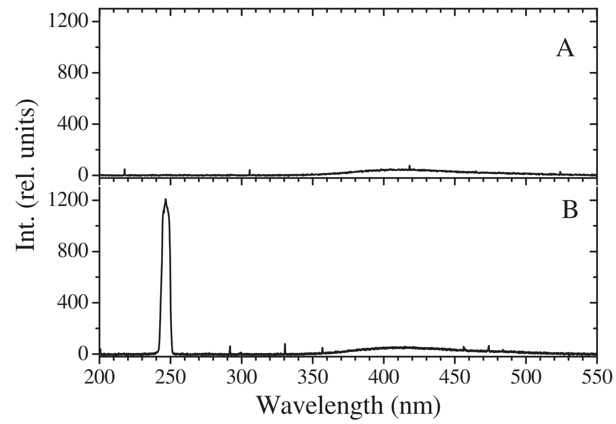

FIG. 1. Demonstration of laser effect. The laser line at 248 nm appears in the emission along the laser axis as soon as the laser threshold is reached [lower spectrum (b), pumped with 1.3×10^9 particles/pulse], whereas this line is completely absent below threshold [top spectrum (a), pumped with 0.98×10^9 particles/pulse]. The broadband feature around 400 nm is due to Kr_2F emission [13]. The narrow spikes are artefacts in the CCD detector of the spectrograph due to the background of hard radiation at the experimental area.

Systematic variation of the pumping pulse intensity resulted in a threshold at $(1.25 \pm 0.1) \times 10^9$ particles per pulse ($\sim$30 MW) and a steep increase in laser intensity which doubled approximately with every increase of $\sim 2 \times 10^8$ particles in the pumping pulse up to a maximum pumping power of $\sim$60 MW available in this experiment (Fig. 2). The Al-MgF_2 laser mirror had a maximum reflectivity of 90% which corresponds to an average value of optical gain of 5×10^{-4} cm^{-1} at laser threshold. Line narrowing of the laser light with respect to the spontaneous 248 nm emission was observed but without a quantitative result due to the limited resolution of $\sim$2 nm of the spectrometers used. The time structure of the laser pulses is shown in Fig. 3. The emission of spontaneous light on the 248 nm KrF excimer transition followed essentially the

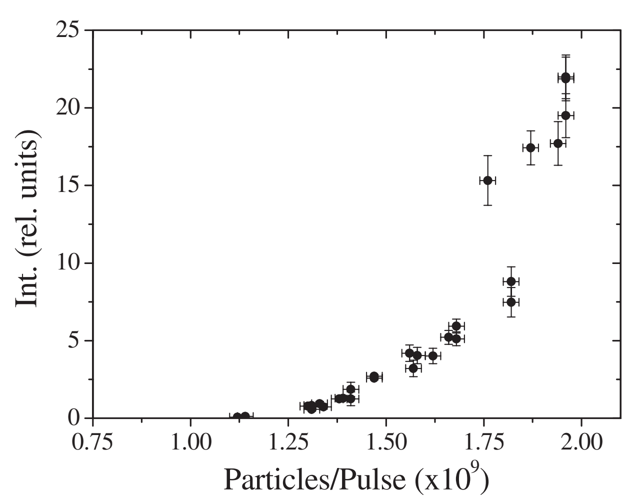

FIG. 2. Demonstration of the threshold behavior of the laser.

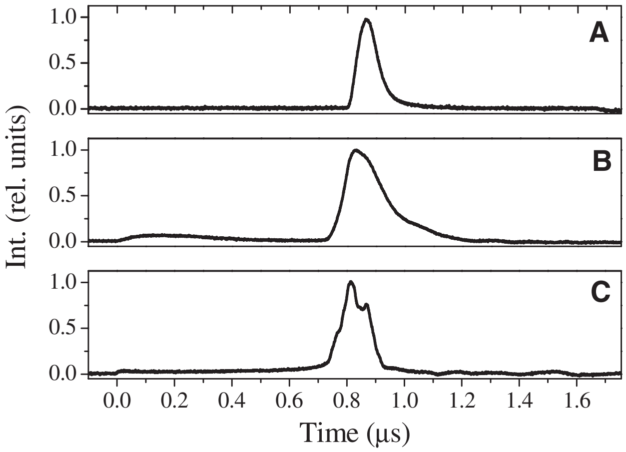

FIG. 3. Time structure of laser emission (a), spontaneous emission (b) and ion-beam pulse (c). The time structure of the ion-beam intensity was measured with an inductive current probe.

pumping pulse convoluted with the temperature dependent gas kinetics. Laser pulse duration (FWHM) ranged from 60 ns near laser threshold to 84 ns for pumping pulses with 2.46×10^9 particles.

In summary, a heavy-ion beam pumped ultraviolet excimer laser was demonstrated, enabled by the beam parameters now available at the accelerators at GSI. Next experiments will be performed using the excimer laser transitions of the pure rare gases to study ion-beam induced plasmas. The concept described here will also be of interest to be considered for the higher power levels, target densities, and consequently shorter wavelengths regions at the projected FAIR facility at GSI. This facility will provide intense bunched beams of heavy ions that exceed the current parameters up to 2 orders of magnitude [14]. The use of heavy-ion beams as a pumping source may lead to new pumping schemes which rely on the high cross sections for multiple ionization of the target species.

The work has been supported by BMBF Project No. 06F130 and in part by the GSI-INTAS Project No. 03-54-4254. The authors acknowledge the help of H. Wahl (GSI) and the accelerator staff at GSI in preparing and performing the experiment.

[1] N. A. Tahir *et al.*, Phys. Rev. Lett. **95**, 035001 (2005).
[2] J. Jacoby *et al.*, Phys. Rev. Lett. **74**, 1550 (1995).
[3] A. Ulrich, H. Bohn, P. Kienle, and G. J. Perlow, Appl. Phys. Lett. **42**, 782 (1983).
[4] A. V. Karelin, A. A. Sinyanskii, and S. I. Yakovlenko, Quantum Electron. **27**, 377 (1997) and references therein.
[5] M. Salvermoser, A. Ulrich, and J. Wieser, Phys. Rev. E **58**, 6531 (1998).
[6] A. Ulrich, R. Gernhäuser, W. Krötz, J. Wieser, and D. E. Murnick, Phys. Rev. A **50**, 1931 (1994).
[7] B. Busch, A. Ulrich, W. Krötz, G. Ribitzki, J. Wieser, and M. Winkler, J. Appl. Phys. **74**, 5960 (1993).
[8] A. Ulrich *et al.*, Z. Phys. A **341**, 111 (1991).
[9] H. Tomizawa, M. Salvermoser, J. Wieser, and A. Ulrich, Atmospheric and Oceanic Optics **13**, 236 (2000).
[10] A. Ulrich, J. Wieser, A. Brunnhuber, and W. Krötz, Appl. Phys. Lett. **64**, 1902 (1994).
[11] A. Ulrich *et al.*, J. Appl. Phys. **62**, 357 (1987).
[12] J. Jacoby *et al.*, Phys. Rev. Lett. **65**, 2007 (1990).
[13] Ch. A. Brau, in *Excimer Lasers*, edited by Ch. K. Rhodes, Topics in Applied Physics Vol. 30 (Springer-Verlag, Berlin, Heidelberg, New York, Tokyo, 1984), 2nd ed.
[14] D. H. H. Hoffmann *et al.*, Laser Part. Beams **23**, 47 (2005).