PROSPECTS FOR PROTON ACCELERATORS DRIVEN BY THE RADIATION PRESSURE FROM A SUB-PW CO_2 LASER *

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Abstract

Laser acceleration of ion beams is normally realized via irradiating thin-foil targets with near-IR solid-state lasers with up to petawatt (PW) peak power. Despite demonstration of significant achievements, further progress towards practical application of such beam sources is hindered by the challenges inherent in constructing still more intense and higher-contrast lasers. Our recent studies of the Radiation Pressure Acceleration (RPA) indicate that the combination of a 10-μm CO_2 laser with a gas jet target offers a unique opportunity for a breakthrough in the field. Strong power scaling of this regime holds the promise of achieving the hundreds of MeV proton beams with just sub-PW CO_2 laser pulses. Generation of such pulses is a challenging task. We discuss a strategy of the CO_2 laser upgrade aimed to providing a more compact and economical hadron source for cancer therapy. This include optimization of the 10-μm short-pulse generation, higher amplification in the CO_2 gas under combined isotopic and power broadening effects, and the pulse shortening to a few laser cycles (150-200 fs) via self-chirping and the consecutive dispersive compression.

INTRODUCTION

Hadron cancer therapy employs proton- and ion- beams to destroy cancer tissues deep inside the human body. The advantage of particle beams compared with x-ray radiation therapy rests on the so-called Bragg peak of the particles' dose deposition that can be set exactly at the location of pathological cells, with minimum damage to healthy cells in the beam's path. Conventional hadron therapy relies on particle-accelerators and beam delivery systems that are bulky and expensive to build and operate. Therefore, access to this treatment presently is very limited. Laser-driven particle beams might open the way to less expensive, highly productive hadron-therapy clinics.

Mainstream efforts in these directions rely primarily on solid-state lasers based on chirped pulse amplification (CPA). We describe here an alternative approach, founded on the emerging technology of ultra-fast carbon dioxide (CO_2) gas lasers that offer distinct advantages due to their long wavelength ($\lambda \approx 10\mu$m), such as the $\sim\lambda^2$ scaling of the electrons' ponderomotive energy and critical plasma-density.

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PROTON ACCELERATION

RPA Among Other Acceleration Mechanisms

In most laser-ion acceleration studies, thin foils were irradiated by near-IR solid-state lasers with up to petawatt peak power. Here, the dominant mechanism for laser-ion acceleration was Target Normal Sheath Acceleration (TNSA). We note that in sheath acceleration the plasma's temperature that drives thermal expansion, and thus, the ion-energies, scale only $\sim(I\lambda^2)^{1/2}$ for intensity I and wavelength λ.[1] Progressing with this pace from the recently achieved 68 MeV [2] to 200 MeV required for treating most of the cancers calls for increase in laser intensity by the order of magnitude. Such lasers are not available yet. Another problem with the TNSA method is the broad energy spread of the produced ions.

Several authors proposed that at higher laser intensities radiation pressure can propel the electrons contained within an overcritical plasma surface which stops and reflects the laser beam.[3-5] Theoretical studies indicate that radiation pressure converts directly the photon momentum to charged particles with their energy $\sim(I\lambda^2)$.[3, 6] Radiation Pressure Acceleration (RPA) generally benefits from the ability to set the target's plasma density at a near-critical value that is difficult to achieve with solid-state lasers where the density of the target's material usually is far above (solids), or far below (gases) the laser/plasma resonance condition. A new class of ultra-fast mid-IR CO_2 lasers offers a different solution. The potential advantages of long-wavelength lasers as ion-beam drivers are based on the interplay of physical parameters, such as the ponderomotive energy conveyed to a charged particle by the laser field ($\sim\lambda^2$), and the critical plasma-density ($\sim\lambda^{-2}$). For CO_2 lasers, the critical electron plasma density, $n_{cr}=10^{19}$ cm^{-3}, is easily achievable in a gas jet. In addition, the gas jet affords good control over the repetition rate and purity of the produced beams. Therefore, combining an ultra-intense CO_2 laser with a gas-jet target offers a unique opportunity for a breakthrough, as is implied by the recent ATF experiment described in the following Section.

ATF RPA Experiment

We focused the CO_2 laser beam with an *f*/3 off-axis parabolic reflector onto a supersonic hydrogen-gas jet. Interestingly, the proton beam, observed on a spectrometer screen at 1.5 MeV, makes a compact spot that closely resembles the pinhole used at the entrance to the spectrometer. By de-convoluting instrument's function, we obtained a normalized emittance 8 nm-rad and energy spread 4% rms. This contrasts to broad-band spectra obtained when solid targets are irradiated with a high-intensity optical laser [7], or with a CO_2 laser [8]. Hence, we consider that a combination of a long-wavelength laser and a low-density target is the condition for generating these quasi-monoenergetic proton beams. The measured spectral brightness 7×10^{11} proton/MeV/strad is 100× greater than previous laser-generated quasi-monoenergetic ion beams.[9, 10]

A gas-jet, overdense for to the drive CO_2 laser, still is sufficiently transparent to optical radiation. This allows using frequency-doubled YAG beam for optical probing of the laser/jet interaction region. The recorded plasma density map clearly shows a steep front of the propagating shock wave above critical density and an evacuated area behind it.[11, 12].

The demonstrated hole-boring through the gas jet combined with other attributes, such as circular laser polarization and a narrow proton-energy spectrum, indicate that the ATF experiment met conditions for the RPA regime never successfully achieved even with the most powerful solid-state lasers. Though the obtained proton energy is relatively low, the excellent theoretical power-scaling of the RPA regime supports our plan for progressing towards ~200 MeV proton energies via the ATF laser power upgrade.

Planned RPA Research

We plan to upgrade the RPA ion-source to beam energies of importance to clinical applications, in concert with the laser development. Prospects for linear scaling the ion energy with the laser's intensity are not just theoretical expectations, but based on recent experimental results: Researchers at the Neptune Laboratory, UCLA, registered 20 MeV protons using a 15 TW CO_2 laser.[8] Accordingly, the planned ATF CO_2 laser upgrade to 100 TW might bring us to the verge of demonstrating the ~200 MeV ions needed for the full-scale hadron-cancer therapy.

The planned research includes optimizing the RPA process and instrumentation. Note that an optimum density-distribution with a sharp gradient at the critical electron density does not occur naturally in a gas jet, but develops upon laser impact and the subsequent formation of the shock wave. This may imply the need to precede the main accelerating laser pulse with another "conditioning" pulse to form the proper plasma distribution. Theoretical studies support improving the hole-boring process via incrementally delivering the laser energy in a series of pulses.[13] To explore this approach, we plan to generate and amplify two laser pulses with a variable delay and intensity.

Other optimization parameters include the laser's contrast, polarization, pulse duration, focal size, different nozzle profiles and gas mixtures. To improve the contrast, we might implement a plasma mirror technique, successfully used in experiments with optical lasers.[14]

ULTRA-FAST CO_2 LASER TECHNOLOGY

Present Status of the ATF CO_2 Laser

The ATF is one of the only two facilities worldwide operating picosecond, terawatt-class CO_2 lasers. Our laser system consists of a picosecond pulse-injector based on fast optical switching from the output of a conventional CO_2 laser oscillator, and a chain of high-pressure gas laser amplifiers.

A picosecond solid-state laser with $\lambda\approx1$ μm is used for generating a low-power 10-μm pulse. This process employs two methods; semiconductor optical switching [15], and the Kerr effect [16]. The produced 5-ps, 0.1 MW, 10-μm seed pulse is amplified in a chain of high pressure (~10 atm.) CO_2 laser-amplifiers. At the first stage, the pulse is seeded into an isotope-filled regenerative amplifier where it is trapped for 10-12 round trips and then released on reaching the ~1 GW level. A final high-pressure, large-aperture (10 cm) amplifier boosts the laser power to 1 TW. More details on the ATF laser system can be found in our recent publication [17].

Development of a Sub-PW Ultra-fast CO_2 Laser

Starting from the ATF's existing picosecond terawatt CO_2 laser, we will establish new regimes of laser operation with the ultimate goal of attaining a peak power in the hundreds of terawatts at 10-μm. This advance cannot be just a straightforward scaling of the laser apparatus; we must implement a host of innovative techniques. First, we are replacing the present 10-μm pulse slicer with a commercial, all-solid-state integrated unit comprising a Ti:Sapphire laser and an optical parametric oscillator (OPO). This system will provide 350 fs (FWHM), 40 µJ pulses - a considerable improvement over the parameters of the current system (5 ps, 0.1 µJ). Shortening the pulse duration from the present 5 ps leads to nearly proportional increase in the energy extracted from the amplifier due to a better match between the pulse- and gain- bandwidths. However, when an ultra-shot laser pulse acquires high intensity, undesirable nonlinear effects in optical elements and in the gas medium may cause uncontrollable stretching and distortions of the beam. We will lessen such nonlinear effects by incorporating a stretching/compression technique similar to that used in conventional Ti-Sapphire CPA laser systems. The prospect for shortening the CO_2 laser's pulse to few laser cycles still exists. We will explore this possibility via a new approach to self-chirping and compression by passing the laser beam through a xenon gas that has a high nonlinear refractive index. Preliminary theoretical analysis shows that we can convert a quasi-linear frequency chirp, induced by Kerr-effect in xenon, into pulse-compression in a dispersive element by nearly an order-of-magnitude without appreciable energy loss.[18] Overall, via pulse compression and improved energy extraction from laser amplifiers, we anticipate an increase of over two orders- of- magnitude in the laser peak power up to 100 TW, giving us an opportunity to implement the RPA regime for generating ~200 MeV ion beams.

CONCLUSIONS

In our experiments, we demonstrated the merits of long-wavelength picosecond CO_2 lasers for generating proton-beams. In particular, wavelength scaling of the electrons' ponderomotive energy and critical plasma density permitted our production of high-quality proton beams via the interaction of a CO_2 laser beam with a hydrogen gas- target. The intensity of the CO_2 laser was 100 times lower than the minimum required for producing protons of the same energy with a solid-state laser. The circular polarization of the laser beam, the occurrence of the effect close to the critical gas density, and especially, the monoenergetic proton spectrum indicate that the ATF experiment met conditions for the RPA regime never attained previously, even with the most powerful solid-state lasers. Our beams are superior in many respects to other energy-modulated ion-beams reported from laser-plasma acceleration.[9, 10] They are free from impurities (pure proton beams), have high spectral brightness (>100× previous reports), narrow energy-spread (>2× narrower than previous reports), and high contrast (>20× than previously reported). Though presently the proton beam's energy is relatively low, the excellent theoretical power-scaling predicted for the RPA regime allows us to anticipate progress towards ~200 MeV energies via the ATF laser upgrade. The resulting very high brightness will make these particle beams ideal for variety of applications, including hadrographic imaging of material structures and biological tissue, for studying matter under extreme conditions, such as in high-density target implosions, or in situations similar to those in the center of planets (warm dense matter). The high brightness of laser-produced proton- and ion-bunches also makes them potential candidates for injection into a conventional accelerator.

Our current vision of the ATF CO_2 laser's upgrade strategy to 100 TW includes four main stages: 1) Implementing the generation of a 10-μm injection pulse with an all-solid-state parametric generator; 2) using chirping/compression for improving energy extraction from the amplifier and reducing detrimental nonlinear effects; 3) adding an amplification stage to the current 2-stage amplification system; and 4) establishing a self-chirping/compression technique for shortening the pulse to hundreds of femtoseconds. Extending wavelength coverage of ultra-fast sub-PW-class laser sources up to mid-IR will enrich the laser science and technology and will greatly benefit the advanced accelerator research program.

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