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The First Terawatt Picosecond CO_2 Laser for Advanced Accelerator Studies at the Brookhaven ATF

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DISCLAIMER

THE FIRST TERAWATT PICOSECOND CO_2 LASER FOR ADVANCED ACCELERATOR STUDIES AT THE BROOKHAVEN ATF

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Abstract

The first terawatt picosecond CO_2 laser system is under development at the Brookhaven Accelerator Test Facility. Presently operational 1-Joule 100-ps ATF laser will be upgraded with a 10 atm amplifier capable of delivery ~15 Joules of laser energy in a 3-ps pulse. We describe the design of the x-ray preionized 10-atm amplifier of a 10-liter active volume energized by a 1-MV, 200 kA transverse electric discharge. The amplifier, equipped with internal optics, permits the accommodation of a regenerative stage and a multi-pass booster in a relatively compact single discharge volume. The ATF terawatt CO_2 laser shall become operational in 1997 to serve for laser acceleration, x-ray generation and other strong-field physics experiments.

I. INTRODUCTION

Lasers are the sources of the most intense electromagnetic radiation and strongest electric and magnetic fields available for laboratory research. For example, focusing of a terawatt laser beam into a 30-μm spot results in an intensity of 10^{17} W/cm^2 and, associated with it, an electric field of 10 GV/cm that exceeds by four orders of magnitude fields attainable in conventional particle accelerators. Such capability stimulates a new high-energy physics discipline to emerge: laser-driven high-gradient particle accelerators. Experimental activity in this field has been vitalized by recent development of, so-called, T^3 (table-top terawatt) solid state lasers operating at wavelengths of $\lambda \approx 1$ μm.

Another novel driver source for advanced particle accelerators may be provided by the emerging picosecond terawatt CO_2 (psTW-CO_2) laser technology. There are a number of considerations that favor such an application of long-wavelength ($\lambda \approx 10$ μm) psTW-CO_2 lasers.

In general, particle acceleration by a fast-oscillating electromagnetic field becomes possible when a relativistic particle moves in synchronism with the phase of the driving field. The long wavelength of a CO_2 laser helps to meet this requirement. This feature is of particular importance for far-field acceleration schemes, examples of which are the inverse Cherenkov and inverse FEL accelerators.

Proposed near-field accelerator schemes are based on the accelerating action of evanescent fields developed near the periodically shaped surfaces under laser irradiation. Since the spatial scale of such structures is comparable with the laser wavelength, these schemes look practical when a CO_2 or longer-wavelength laser is used as the accelerator driver.

The advantage of slow-oscillating fields for particle acceleration in plasma stems from the fact that the energy of oscillatory motion acquired by the electron from an electromagnetic wave is quadratically proportional to the wavelength. Hence, any process where the field-induced electron oscillation is paramount is dramatically enhanced. The examples of such processes are: relativistic self-focusing, avalanche and tunneling ionization, and plasma wave excitation, which are especially relevant for electron acceleration in a plasma.

Conventional subnanosecond, multigigawatt CO_2 lasers, intensity-modulated with the period of a plasma wave, have been used successfully in laser beatwave accelerator (LBWA) experiments[1,2] with up to 30 MeV electron acceleration over a 1 cm interaction distance demonstrated. The efficiency of plasma acceleration schemes that, in addition to LBWA, include laser wakefield accelerator [3] would be greatly enhanced by laser power increase and pulse shortening

provided by the psTW-CO_2 laser. The detailed analysis of advantages of the psTW-CO_2 lasers for particle acceleration studies is done in [4].

The laser synchrotron x-ray source described in [5] serves as another example of how the psTW-CO_2 laser may benefit strong-physics applications. Here, we gain from a λ-proportional photon flux and λ-proportional laser strength parameter that defines the efficiency of high harmonics generation via nonlinear Compton scattering.

The approach to a picosecond, high peak power CO_2 laser is being pursued at the ATF, where a 10-GW, 100-ps table-top CO_2 laser system is in operation to test several laser acceleration schemes and the upgraded psTW version of this laser is under construction.

The problems that hindered thus far the development of psTW-CO_2 lasers are related to the relatively narrow rotational structure typical for molecular gas spectra (~10^{10} Hz at atmospheric pressure). That is why picosecond pulse formation via a mode-locking technique and subsequent amplification have not been as successfully obtained with CO_2 lasers as with solid state lasers, which have wide crystal-host broadening of ion spectral lines (10^{12}-10^{13} Hz). However, at high gas pressure, the individual rotational CO_2 lines can be collisionally broadened to a quasi-continuum of a 10^{12} Hz width. Also, alternative ways to produce CO_2 pulses with picosecond time scales have been developed including: optical parametric oscillation and semiconductor switching. The last method is based on modulating the reflective and transmissive properties of a semiconductor by optically controlling the free-carrier charge density. Subpicosecond IR pulses have been demonstrated by this method[6].

These principles constitute the approach of the ATF CO_2 laser upgrade to the terawatt level which has been presented previously[7]. The key technical issue that needs to be resolved to make a psTW-CO_2 laser possible is construction of a high-pressure, big-aperture CO_2 laser amplifier. We provide an update on the progress in design and construction of a 10-atm, 10-*l* amplifier discharge module that shall boost the output power of the ATF CO_2 laser to the several terawatt level.

II. EMERGING PICOSECOND TERAWATT CO_2 LASER TECHNOLOGY

In solid state lasers, radiation transitions within the outer electron shells of active ions exhibit broadening to 5-50 THz due to the perturbation action of a host matrix. Such a broad gain spectrum makes possible the generation and amplification of picosecond and even femtosecond laser pulses. On the contrary, it has been realized that to build a picosecond CO_2 laser is a problem because the spectral gain in the gas discharge is periodically modulated by a molecular rotational structure. Due to the discrete spectrum, and for other technical reasons, mode-locking techniques do not work for CO_2 lasers as well as for solid state lasers. Such a modulated spectrum also impedes amplification of picosecond pulses.

Two alternative methods have been proposed to produce picosecond and sub-ps CO_2 laser pulses. Both of them require a short-wavelength, short-pulse laser. By frequency mixing in a nonlinear crystal, the difference frequency at 10 μm may be generated in a parametric oscillator. At the ATF we use another method, semiconductor switching, to generate picosecond CO_2 laser pulses of a variable duration.

The semiconductor optical switching method is based on the modulation of the reflective and transmissive properties of a semiconductor slab, placed into the CO_2 laser beam, by optically controlling the free-carrier charge density. A short-wavelength picosecond laser pulse with a photon energy above the band gap of the semiconductor creates a highly reflective electron-hole plasma in the surface layer of a semiconductor, such as germanium, which is normally transparent to 10-μm radiation. To define the trailing edge of the pulse, shortening it to a few picoseconds, the complement to reflection switching, transmission switching, may be used for a second stage. An optically delayed control pulse cuts off the trailing edge of the transient pulse by initiating reflection and absorption. The resulting "sliced" transmitted pulse has a variable length defined by optical delay adjustment of the control radiation before the transmission switch.

Instead of the transmission switch in a double semiconductor slicer configuration, the transient response of a thin etalon can be exploited[8]. The etalon, tuned to minimum reflectivity, serves as a differentiator transmitting radiation with a constant or slow-varying intensity while reflecting at intensity gradients shorter than the double optical thickness of the etalon. For instance, a 100-μm thick Ge etalon placed after the reflection switch may serve for efficient differentiating of the transient pulse with a steep leading front, producing ~ 3-ps high-contrast IR pulses.

Another way to eliminate the tail in the reflected pulse is to use a semiconductor material with previously introduced radiation damage to the lattice structure. For such materials, subpicosecond electron-hole recombination times have been measured[9].

Let us address now the problem of amplification of short picosecond laser pulses in the active medium of the CO_2 laser. If the input laser pulse is shorter than 18 ps, its spectrum covers several discrete rotational transition lines. The electric field of such an input pulse excites a polarization in CO_2 molecules, which are in various rotational states. Since molecules in different states are characterized by different frequencies, these polarization components eventually become dephased. As a result, the spectral and time structure of the induced radiation will not remain equal to those of the initial pulse. At a low, ~1 atm, gas pressure the discrete gain spectrum transforms the spectrum of the input pulse from continuous to discrete, and its inverse Fourier transform corresponds to a pulse train with an 18 ps period. At higher pressure, the broadening effect smoothes the discrete gain spectrum. As a result, the pulse splitting is reduced and ultimately disappears at an amplifier pressure of 15 atm.

An alternative to achieving gain smoothing is by reduction of the spectrum modulation period using a multi-isotope gas mixture. Replacement of one of the oxygen nuclei by that of a different isotope destroys the symmetry of the CO_2 molecule. This means that twice as many radiation transitions are allowed and the gain spectrum becomes twice as dense as with a regular CO_2 molecule. If we consider a mixture of $^{12}C^{16}O_2$:$^{12}C^{16}O^{18}O$:$^{12}C^{18}O_2$ = 1:2:1, then, due to isotopic shifts, the combined spectrum will have in overlap regions an approximately 4-times denser rotational line structure than with a regular CO_2 molecule. Computer modeling[10] shows that the reduction in spectral line interval, together with pressure broadening, results in considerably less short-pulse distortion during amplification. The technical advantage of this approach is related to the greater ease of establishing a large-aperture stable discharge at 4-5 atm in comparison to 10-15 atm.

At the total bandwidth of the 10P CO_2 branch, $\Delta\nu \approx 1$ THz, the fundamental limit for the laser pulse duration, as defined by the ratio $\Delta\nu \times \tau \approx 0.5$, is $\tau \approx 0.5$ ps. As short as 0.6 ps CO_2 laser pulses have been demonstrated from a high-pressure regenerative amplifier[11].

When estimating laser amplifier efficiency, the following two physical parameters play the major role: small signal gain $g_o=\sigma N^*$, where σ is the gain cross-section, and N^* - population inversion at the laser levels; and saturation fluence $E_s=h\nu/2\sigma$.

Parameters g_o and E_s regulate the energy amplification process described by the Franz-Nodvik equation

$$E_{out} = E_s \ln\{1 + \exp(g_o l)[\exp(E_{in}/E_s) - 1]\}. \quad (1)$$

The product of these parameters gives also an estimate of the energy potentially extractable from the amplifier in a single pass in a strongly saturated regime:

$$E_{max} = g_o E_s l S, \quad (2)$$

where l and S are, correspondingly, the length and aperture of the amplifier.

The ratio E_{max}/τ characterizes the peak laser power from the amplifier. We know already that the pressure increase helps to reduce the pulse duration, τ. Now, we need to understand how E_{max} depends upon the pressure.

Due to pressure broadening of the gain spectrum, there is a linear proportionality of E_s to the pressure via the parameter σ. The small signal gain, g_o, is inversely proportional to σ. However, g_o depends also upon N^* which is subject to the electric discharge conditions. The electron-molecule collision frequency and, hence, the pump rate both rise proportionally to the pressure. If the discharge is faster than collisional quenching of the inversion, then we may consider $N^* \sim P$ and g_o invariant with pressure. Ultimately, we come to the conclusion that $E_{max} \sim P$.

Computer simulation[10] for a τ_0=3 ps pulse propagating in a 10-atm amplifier gives $E_s \approx 500$ mJ/cm^2 and, at the typical g_o=4%/cm, the extractable specific energy is $E_{max}/lS \approx 20$ mJ/cm^3. Taking into account that the total discharge volume may exceed 10 l, extraction of as high as 100 J of energy in a few-picosecond pulse from a single, reasonably compact CO_2 laser amplifier looks possible. However, the limiting factor to the high energy extraction will be the damage threshold of the output window, $E_{th} \approx 500$ mJ/cm^2.[10] For an optical window of a 10×10 cm^2 size, the extractable energy is 30-50 J which corresponds to 10-15 TW peak power at a 3-ps laser pulse duration. These estimates make psTW-CO_2 lasers quite competitive with the T^3 solid state lasers.

The main physical parameters of solid state and CO_2 lasers are compiled in Table 1. It is interesting that the gain cross-section per ion or molecule is comparable for both. However, about ten times higher concentration of active ions in solid state than CO_2 molecules in a gas makes gain in solid state lasers about ten times higher. About ten times higher

photon energy makes the specific stored energy in solid state about hundred times higher than in gas. However, much bigger volume of gas amplifiers makes the total stored energy per CO_2 amplifier stage similar or higher than for a big-size slab solid state amplifier. Because of the ease of the heat removal by fast gas exchange in the CO_2 amplifier, it is potentially capable of high repetition rates that are difficult to attain with solid optical elements. This may be important for future advanced particle accelerators.

Table 1. Typical Parameters of Solid State and CO_2 Lasers

PARAMETER	Solid State	10-atm CO_2
Bandwidth (THz)	5-50	1
Cross section ($\times 10^{-20}$ cm^2)	1-30	5
Gain (%/cm)	~50	3-4
Saturation energy (J/cm^2)	1-20	0.5
Breakdown threshold (J/cm^2)	1	3
Stored energy (J/cm^3)	1	0.01
Active volume (cm^3)	10-100	10,000
Gain relaxation time (μs)	>1	0.2
Average power short-term limit (W)	1-10	100-1000

III. TERAWATT CO_2 LASER PROJECT AT THE ATF

The psTW-CO_2 laser system is the upgrade version of the presently operational 10-GW ATF CO_2 laser[10]. As long as a number of basic principles and elements of the present ATF laser will be preserved after the upgrade, it would be relevant to give its brief overview.

The ATF CO_2 laser system includes: a hybrid TEA oscillator, picosecond semiconductor switch, and a UV-preionized multipass TE amplifier.

In the laser oscillator, a diffraction grating tunes the laser wavelength stepwise between the individual rotational lines in the gain spectrum of the CO_2 molecules, which are vibrationally excited in the electric discharge. In addition to the 1-atm discharge-cell, the oscillator also includes an auxiliary low-pressure discharge cell. The narrow spectral line of the low-pressure discharge selects the particular longitudinal eigenmode to build-up inside the laser cavity. Piezo-tuning of the cavity length matches a mode spectral position to the gain peak. The output single-mode laser pulse has a smooth envelope, free from the stochastic mode-beat spikes otherwise typical for free-running TEA CO_2 lasers.

The semiconductor double-stage switching method is used to slice a 100-ns oscillator pulse to the desired picosecond width. A 10-ps Nd:YAG laser, that serves as a photocathode driver for the ATF linac, also supplies a pulse for slicing. Using the same initiator for the linac and for the CO_2 pulse slicing ensures the desired picosecond synchronization of the electron bunch and laser pulse at their interaction region (see Fig.1).

To reach a power level needed for laser accelerator studies, the switched picosecond pulse is transmitted through the 8-pass CO_2 amplifier that features a 120-cm long, 3-atm, UV-preionized, transverse electrical discharge energized by a 150-kV pulse. The limited spectral bandwidth of the amplifier defines ~100 ps minimum duration of the output laser pulse. Thus, at the amplifier output energy of 1 J, the available peak power is ~10 GW.

The design concept for the CO_2 laser upgrade presumes slicing and then amplification of a short (~3 ps) laser pulse. We also expand the amplifier cross-section, thus allowing a high energy extraction through the large-aperture output window. Both pulse shortening and energy increase should permit an increase of the peak power from several GW to the several TW level. Fig.2 presents a principal optical diagram for the modified CO_2 laser system. The presently operational oscillator and semiconductor switch will supply a picosecond seed pulse into a regenerative preamplifier which will share a portion of the active discharge region in a large-aperture multi-isotope amplifier. After the regenerative amplifier, four or five additional passes, with the laser beam expanded to ~80 cm^2, will boost the output power to the 5 TW level in a ~3-ps pulse.

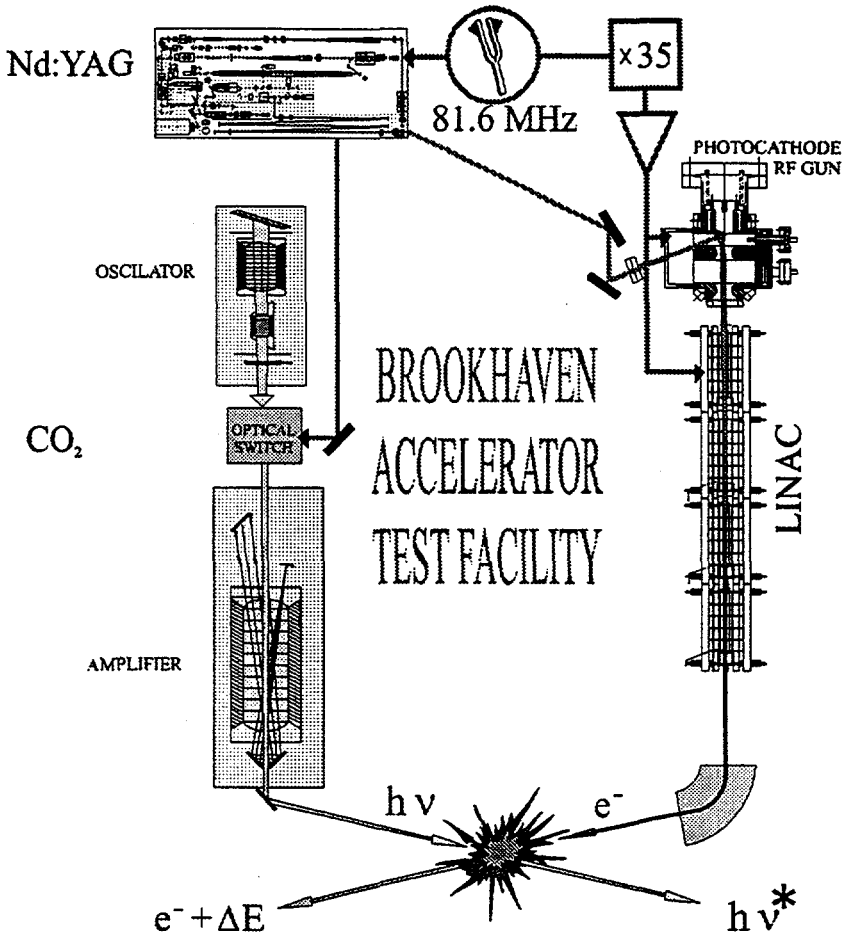

Fig.1 Principal diagram of the ATF laser system and linac synchronized to 1 ps for e^--hν interaction experiments

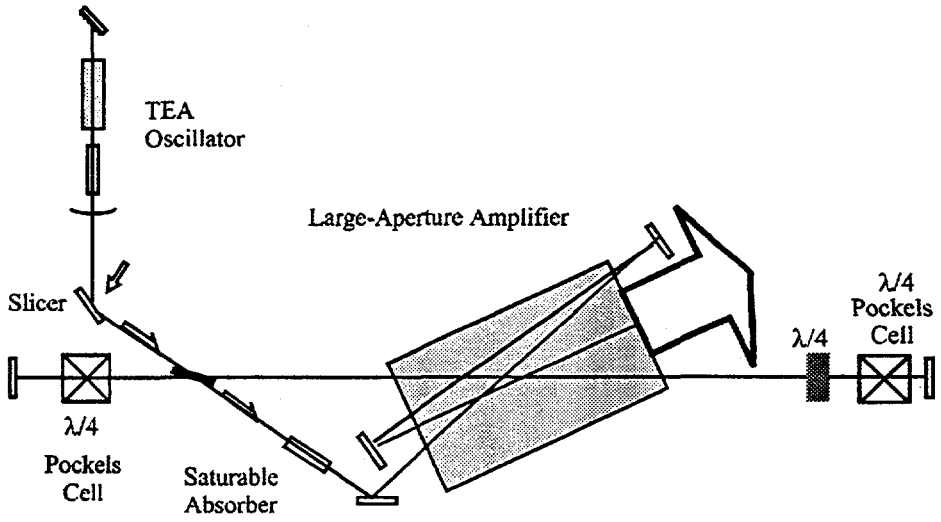

Fig.2. Principal optical diagram of the psTW-CO_2 laser system

Essential for the amplifier design is the discharge mechanism to create uniform gas excitation in a ~10 *l* volume under high pressure. A self-sustained glow discharge can exist only at $dP \leq 0.1$ cm.atm, where *d* is the interelectrode distance

and P - the gas pressure. Above this point, an external ionization source should be applied to prevent discharge from arcing. The simplest corona and UV-preionization methods work well up to $dP \approx 15$-20 cm.atm. Above that level, more intense and volume-penetrating x-ray and e-beam preionizers are used. High ionization efficiency of e-beams makes it possible even to reduce the discharge voltage two times below the self-glow level (so-called "e-beam sustained" discharge). It helps to maintain the discharge at the optimum normalized field strength, V/dP, resulting in high efficiency of the upper laser level excitation. However, a high probability of e-beam window failure (usually thin metal foils), especially at a high pressure, makes e-guns inconvenient for this application.

X-ray preionization, while somewhat more complex than the UV-preionization which is used in the present 3-atm ATF CO_2 amplifier, has advantages for large-aperture high-pressure discharge applications. Because of strong absorption of UV radiation by CO_2 molecules, it is difficult to implement even for $dP>25$ cm.atm (e.g., $P=5$ atm and $d=5$ cm). The penetration range for >30keV x-rays is much larger. Another important advantage of x-ray preionization is the elimination of spark discharges associated with the UV preionization method which contribute significantly to the dissociation of CO_2, thus shortening gas lifetime.

With relatively simple corona-cathode e-guns, collimated "sheets" of x-rays with the cross-section of 0.1 m^2 or more can be readily produced. At applied ~100 kV cathode voltage, the e-beam with the current density of ~1 A/cm^2 maintained during ~1 μs is adequate to generate in the interelectrode space the initial photoelectron concentration necessary for starting a uniform volumetric discharge at $dP \approx 50$-100 cm.atm.

After the choice of the preionization mechanism is done, the next key decision would be regarding the discharge parameters.

An electrical energy deposition into the discharge of ~120 J/l.atm is needed to attain a typical gain of ~2.5%/cm. For the 10-atm, 10-l discharge, that results in $E_{dep} \approx 10$ kJ.

The high-voltage pulsed power supply for the discharge shall comply with requirements of the breakdown and sustain potentials set by parameters d, P, and ξ, where ξ is the proportion of the molecular components in the CO_2:N_2:He mixture. Based on available data, we can draw a semi-empirical law for the reduced sustain voltage:

$$V_s/dP[\text{kV/cm.atm}]=2.5(1+0.1\xi[\%]). \quad (3)$$

As follows from Eq.(3), a technically feasible pulse generator with the output voltage of 1 MV is capable of sustaining a discharge in $\xi=15\%$ mixture at $dP=80$ cm.atm. The discharge voltage and energy define the capacitance of the high-voltage generator bank that should be ~20 nF. Together with inductance and active resistance of the discharge circuit, the storage capacitance defines the discharge duration that can be 300-500 ns in our case.

There is at least one extra requirement that may further restrict our choice of the discharge duration. Glow discharge is a transient phenomenon at $P \geq 0.1$ atm, and contracts into streamer channels during the time interval that decreases inversely proportional to the gas pressure. For a 10 atm pressure, that condition requires the discharge duration of <300 ns that is difficult to provide using a Marx-type generator with the specified above parameters. That is why the discharge circuit of the ATF psTW-CO_2 laser includes also a pulse forming line built as a tunable water capacitor connected to the Marx generator. This design permits variation of the pump pulse duration between 100-300 ns at a peak current of up to 200 kA.

A cross-sectional diagram of the high-pressure x-ray preionized amplifier designed for the ATF terawatt CO_2 laser system by Optoel Co. (St. Petersburg, Russia) is shown in Fig.3. X-rays penetrate into the active volume of $100\times10\times10$ cm^3 through the mesh ground electrode and Be window that separates the vacuum x-ray tube from the high-pressure discharge volume. The big, 10×10 cm^2, optical aperture of the amplifier helps to accommodate the regenerative amplifier and subsequent multipass amplification in one discharge cell. This, together with the multipass mirror set-up inside the discharge volume, permits a reasonably compact design of the terawatt laser system.

The layout of the main components of the high-power CO_2 laser amplifier is shown in Fig.4. It includes: a high-pressure discharge vessel, x-ray preionizer with a pulsed power supply, Marx generator, and a water capacitor. The drawing in Fig.4 does not show a gas circulation and recovery system, external optics and other auxiliary components that will be assembled around the amplifier.

The psTW-CO_2 laser system, with parameters summarized in Table 2, will become operational in 1997. The collimated laser beam will be transported to the experimental hall and interact with picosecond 50-MeV, 1-nC electron bunches to test several laser acceleration schemes, nonlinear Compton scattering and other prospective applications.

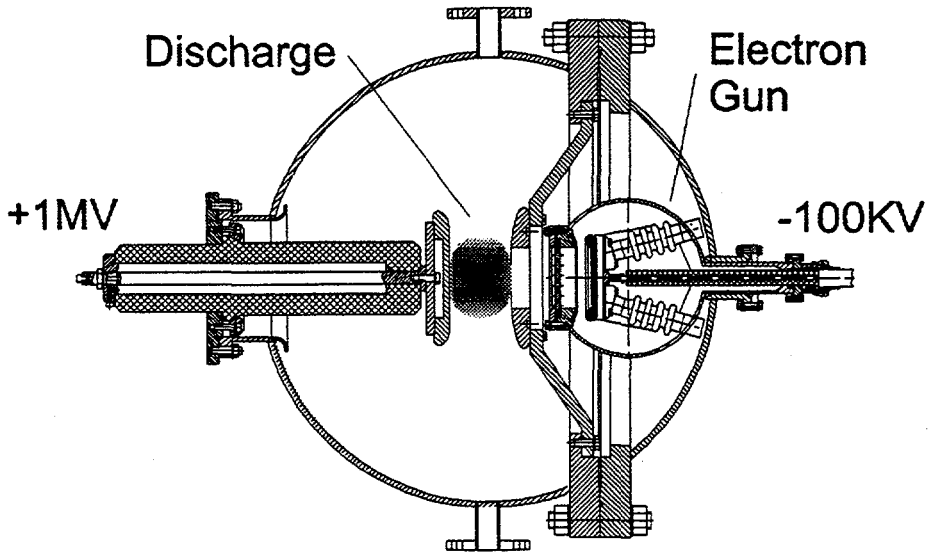

Fig.3 Cross-sectional diagram of the x-ray preionized CO_2 laser amplifier

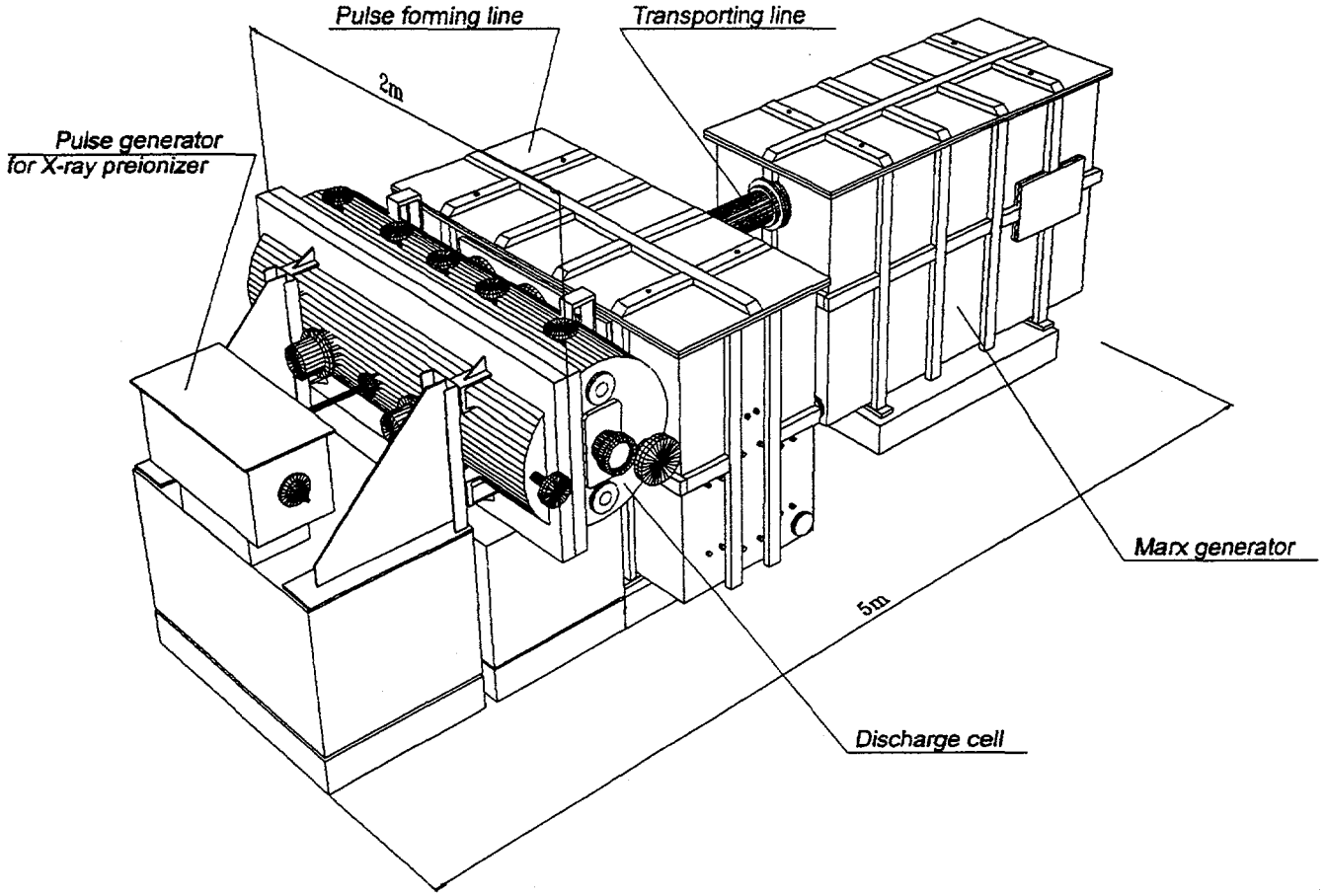

Fig.4 Layout of the main components of the high-power CO_2 laser amplifier

Table 2. Design Parameters of the ATF psTW-CO_2 Laser System

Oscillator	
Type	Hybrid, TEA
Pulse Duration [ns]	100
Output Energy [mJ]	100
Output Peak Power [MW]	1
Max Repetition Rate [Hz]	0.3
Picosecond Slicer	
Type	Semiconductor switching
Control Laser	Nd:YAG
Control Laser Energy [mJ]	10
Control Pulse Duration [ps]	10
Sliced Pulse Duration [ps]	3
Sliced Energy [μJ]	1-2
Output Peak Power [MW]	~0.5
Max Repetition Rate [Hz]	3
Amplifier (electro-physical)	
Type	High-pressure, x-ray preionized
Pressure [atm]	10
Active Volume [*l*]	10
Discharge Voltage [MV]	1
Discharge Pulse Duration [ns]	100-300
Discharge Peak Current [kA]	150-200
Stored Electric Energy [kJ]	10
Repetition Rate [Hz]	0.1
Amplifier (optical)	
Regenerative Stage Output [mJ]	30
Final Output Aperture [cm^2]	80
Final Output Energy [J]	~15
Pulse Duration [ps]	3
Output Peak Power [TW]	~5

IV. CONCLUSIONS

The first terawatt picosecond CO_2 laser is under construction at the ATF. It is an upgrade version of the 10-GW, 100-ps laser that is presently used at the ATF for laser acceleration studies. The power boost to several terawatt will be attained via laser pulse shortening to 3 ps and energy increase from 1 J to ~15 J. This is possible due to installation of a new x-ray preionized amplifier of 10 atm pressure and 10 *l* volume. The high pressure and the possibility of using a multi-isotope gas mixture expand the amplifier bandwidth to 1 THz, thus permitting amplification of short picosecond pulses. The overall dimensions of the ATF laser will not exceed the foot-print size of a typical T^3 solid state laser.

The new ATF laser may become a valuable instrument for strong-field physics study. For example, there are several reasons why a CO_2 laser, with its wavelength ten times longer than that of conventional solid state lasers, may be attractive for advanced laser acceleration study. That includes:

- slow phase slippage of accelerated particles from a relatively shallow electromagnetic wave crest;
- macroscopically-sized accelerator structures and e-beams for near-field accelerators;
- strong plasma wave formation and relativistic self-focusing at a low plasma density useful for plasma accelerators.

All these features are discussed in more detail in [4]. Similarly, the psTW-CO_2 laser opens new prospects for development of high-intensity laser synchrotron x-ray and gamma sources as discussed in [5].

Expected for commissioning in 1997, the first psTW-CO_2 laser laser will become available to the ATF users to explore the proposed above and other strong-field physics phenomena in mid-IR region.

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