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I.V. Pogorelsky
Accelerator Test Facility
BNL

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Strong-Field Physics with Mid-Infrared Lasers

I.V. Pogorelsky

Accelerator Test Facility, BNL, Upton, NY 11973, USA

Abstract. Mid-infrared gas laser technology promises to become a unique tool for research in strong-field relativistic physics. The degree to which physics is relativistic is determined by a ponderomotive potential. At a given intensity, a 10 μm wavelength CO_2 laser reaches a 100 times higher ponderomotive potential than the 1 μm wavelength solid state lasers. Thus, we can expect a proportional increase in the throughput of such processes as laser acceleration, x-ray production, etc. These arguments have been confirmed in proof-of-principle Thomson scattering and laser acceleration experiments conducted at BNL and UCLA where the first terawatt-class CO_2 lasers are in operation. Further more, proposals for the 100 TW, 100 fs CO_2 lasers based on frequency-chirped pulse amplification have been conceived. Such lasers can produce physical effects equivalent to a hypothetical multi-petawatt solid state laser. Ultra-fast mid-infrared lasers will open new routes to the next generation electron and ion accelerators, ultra-bright monochromatic femtosecond x-ray and gamma sources, allow to attempt the study of Hawking-Unruh radiation, and explore relativistic aspects of laser-matter interactions. We review the present status and experiments with terawatt-class CO_2 lasers, sub-petawatt projects, and prospective applications in strong-field science.

INTRODUCTION

Four years ago at the the first meeting of this series we talked about emerging terawatt (TW) CO_2 laser technology and what 10 μm beams promise for strong physics applications [1]. Since then, CO_2 laser interacting with relativistic electron beams produced acceleration and x-ray radiation effects to unmatched quality and intensity [2,3]. Two CO_2 lasers that already attained or approach TW level are in operation on the US East and West coasts [4,5], and advanced ideas about petawatt-class CO_2 lasers are conceived. This paper provides a "status report" on this still low profile but promising laser technology.

Why are we interested in CO_2 lasers? There are at least two reasons. Both of them are based on the ten times longer wavelength of the CO_2 lasers to compare with the solid state lasers.

The first attractive point is that CO_2 lasers allow a viable compromise between conventional RF linear accelerators that reached perfection in the beam quality and optical laser drivers that far prevail in acceleration gradients but do not demonstrate decent beam quality so far.

The degree to which physics is relativistic is determined by a ponderomotive potential

$$W_{osc} = e^2 E_L^2 / 2m\omega^2 , \tag{1}$$

where e and m are correspondingly the electron charge and mass and ω is the laser frequency $\omega = 2\pi c/\lambda$. At a given intensity, the 10-μm CO_2 laser reaches 100 times higher ponderomotive potential than the 1-μm solid-state lasers. This implies a possibility of the proportional increase in throughput of such processes as laser acceleration [6], x-ray production via Thomson scattering [7], etc.

At first glance, these arguments can be dismissed by exercising tighter focusing of the short-wavelength beams:

$$w_0 = \frac{2}{\pi} \lambda M^2 F\#, \tag{2}$$

where w_0 is the Gaussial beam radius at the level of $1/e^2$, M^2 is the beam quality factor equal to 1 for ideal Gaussian beam, and $F\#$ is a ratio of the lens focal length to the initial beam diameter, $f/2W_0$. However, such statement has very limited relevance.

Let us look first into conditions for laser acceleration. Until now, electrons in laser acceleration experiments have been spread over a range of energies with just a few particles observed near the maximum of the accelerating field. Next goal in laser accelerator development is to demonstrate practically meaningful monoenergetic acceleration that resembles qualities of conventional accelerators. What is actually needed to achieve this goal? Accelerating field normally exists in form of a sinusoidal (or shaped close to it) relativistic wave. This may be laser or plasma wave. In order that co-propagating electrons are accelerated monoenergetically they shall occupy a small portion of the wave period and shall be focused to a spot small to compare with radial scale of the wave. Low emittance e-beams are typically focused to 10-100 μm size that is accessible with a CO_2 laser.

Considering volumetric interactions such as Thomson scattering in stationary plasma or field ionization, ten times tighter focus of the 1-μm laser results in the 1000 times smaller interaction volume proportional to $w_0^2 \times z_0$, where z_0 is Rayleigh distance $z_0 = \pi w_0^2 / \lambda$. This leads to the observation that 1 TW CO_2 laser may produce a process yield equivalent to the 100 TW solid state laser.

STATUS OF TWps-CO_2 LASER TECHNOLOGY

Above considerations justify efforts in development of mid-IR laser technology. Unfortunately these efforts are still scarce and are not consistent with a promise that this technology provides. There are just two research facilities in the US, UCLA and BNL ATF, that promote this technology.

The UCLA Neptune terawatt CO_2 laser system (see Fig.1) includes master oscillator; optical switch controlled by YAG laser to produce a picosecond CO_2 pulse; regenerative amplifier followed by booster amplifier shown in Fig.1 that is recycled Los-Alamos Antares laser built in 1980's. The system produces dual wavelength radiation used for next-generation laser beatwave acceleration experiment that is presently in preparation.

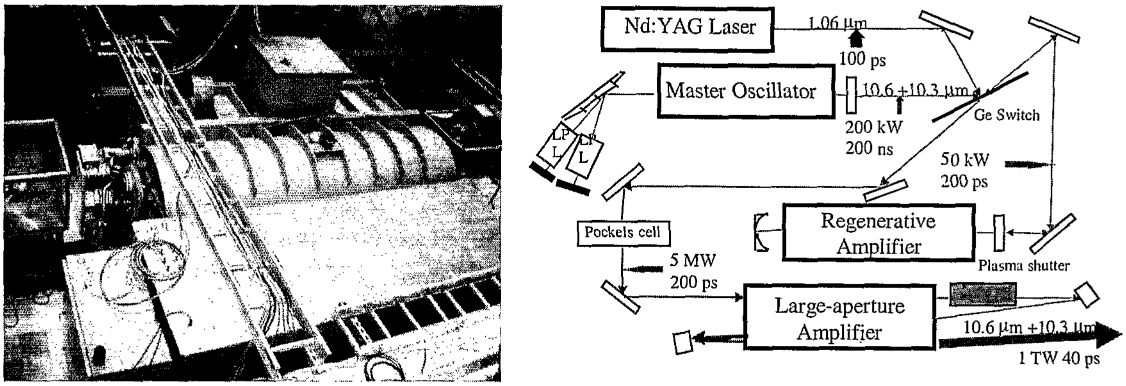


FIGURE 1. Optical diagram of the UCLA Neptune laser and picture of the large-aperture amplifier.

The main complication in building ultra-fast CO_2 lasers is deep modulation of their gain spectrum by rotational structure. This bandwidth limitation can be alleviated by pressure broadening or using multi-isotope mixtures [5]. Both these approaches are not practical for the big-volume Neptune amplifier designed for 3-atm pressure. However, UCLA researchers found an intricate solution to this problem. Focusing laser pulse in a gas cell they observed frequency chirp due to gas ionization [4]. When the pulse is returned back into the amplifier, the chirped tail is filtered out by a relatively narrow individual rotational line. In combination with gain saturation and power broadening, spectral filtering allows to compress the laser pulse from 200 ps to 40 ps. Similar to pressure broadening, power broadening allows to build a bridge between rotational lines. In principle, as soon as the vibrational band is smeared out into a quasi-continuum as short as 1 ps pulses can be amplified directly.

BNL ATF offers another example of a picosecond CO_2 laser with the TW capability named PITER I, where we capitalize on the pressure broadening effect. To this end, one of a kind 10-atm, big-volume booster amplifier has been constructed. The laser action is excited by the 1 MV x-ray preionized discharge. Voltage is applied to electrodes shown in Fig. 2 where the amplifier is opened for maintenance. The 10 J output is extracted through a 10 cm diameter window.

Shown in Fig. 2 the combination of the principle elements of PITER I looks similar to the Neptune laser. Mode-locked solid state laser helps to generate 10 µm picosecond pulse by turning on a semiconductor optical switch. Regenerative preamplifier, combined with 4 additional passes through the same active medium, increases the power to 1 GW. Presently, ATF is still in the process of upgrading its CO_2 laser system to the TW level. 10 atm booster amplifier is already installed and is in operation. However, initial elements still need to be upgraded to deliver a proper 1 ps pulse to the booster amplifier. Meantime, even operating at the present 200 ps pulse duration and 30 GW peak power the ATF laser still enables cutting edge experiments as we discuss in the next Section.

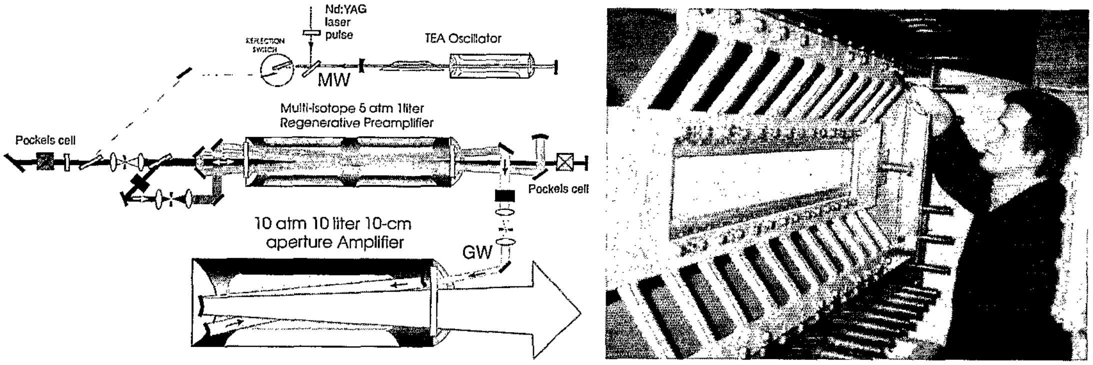


FIGURE 2. Optical diagram of the BNL PITER I CO_2 laser and picture of the booster amplifier.

CURRENT AND PROSPECTIVE PROOF-OF-PRINCIPLE EXPERIMENTS

Many researchers understand the convenience of using long-wavelength lasers in combination with low-emittance relativistic beams for proof-of-principle particle acceleration experiments. As a result, nearly all non-plasma laser acceleration experimental efforts in the US are concentrated now at the ATF - a user's facility operating on a regular basis for high energy physics studies. For this mission ATF is equipped with a high-brightness 70-MeV linac synchronized to high power laser pulses.

A variety of laser acceleration schemes are presently under test or in preparation at the ATF. After testing the inverse Cherenkov scheme based on direct electron acceleration by radially polarized laser field in unionized gas [8] the ATF proceeded to processes based on second order interaction where laser accelerates electrons affected by external electric or magnetic field. In inverse free electron laser (IFEL) linearly polarized laser beam is phased with a planar wiggling of electrons in magnetic undulator producing additional accelerating force in the direction of the local propagation [9]. Similar to this, in LACARA (laser driven electron cyclotron autoresonance accelerator) circularly polarized laser field enhances spiral motion of electrons propagating in a superconducting solenoid [10].

Several schemes based on the first order direct interaction of the Gaussian or Bessel laser focus with e-beam are under consideration. They are based on combinations of axicon or spherical focusing of annular-shaped beams.

Concluding the list, ATF approaches technical capabilities to conduct grating linac experiment proposed at early days of ATF more than a decade ago [11].

Staged Electron Laser Accelerator (STELLA)

Each of the listed above accelerators could be a subject of a separate paper. We review here just one that illustrates advantages of long-wavelength radiation for non-plasma laser accelerators. This experiment has produced the results that advanced accelerator community characterizes as a step towards laser accelerators of the next-generation [12].

In the case of the direct acceleration of relativistic electrons in the laser beam a condition for monoenergetic acceleration requires that electron beam shall be focused much tighter than the laser and grouped into microbunches exactly to the laser period. We can add to it that such bunch train shall be much shorter than the laser pulse envelope. There is probably only one possible way to produce such microbunch train: to use the same laser.

The idea is simple. If we achieve sinusoidal energy modulation in the laser wave and allow electrons to drift or transmit them through dispersive compressor, a good portion of them group together into a small microbunch and this is exactly periodical to the laser wavelength. Modeling of this process that assumes practically achievable electron beam parameters and CO_2 laser shows sub-micron microbunches (see Fig. 3). Such short microbunches can be accelerated monoenergetically in the 10-μm laser beam.

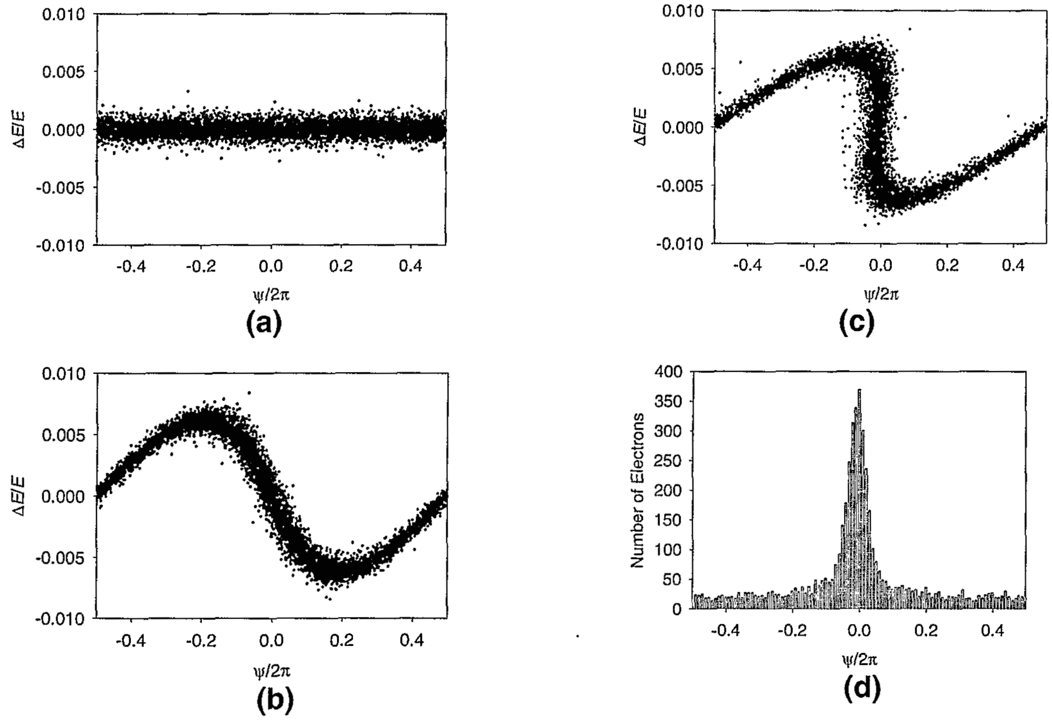


FIGURE 3. Simulations of electron beam bunching at $\Delta E/E$=1.2% energy modulation in IFEL wiggler: a) initial uniform energy distribution; b) energy modulation at the wiggler exit; c) energy distribution at the entrance to the ICA cell; d) longitudinal density distribution in which 50% of the electrons are bunched into FWHM=0.63 μm.

A concept of monoenergetic laser accelerator evolves into two-stage scheme where the first stage serves as a buncher while the second produces monoenergetic acceleration. This is an idea of the first staged electron laser acceleration experiment abbreviated to STELLA. As is shown in Fig. 4, a single laser beam is split between two 30 cm long, 10-period IFEL wigglers.

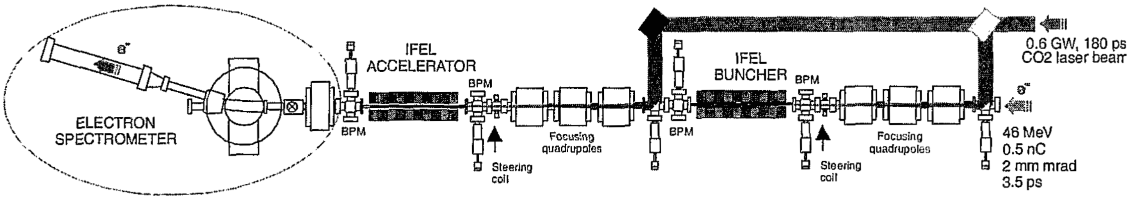
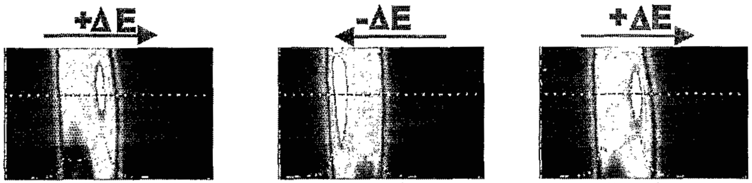


FIGURE 4. Principle diagram of STELLA experiment

Extent of phase control over the two-stage acceleration process is illustrated by the set of spectra shown in Fig. 5. This sequence of spectra is obtained when the optical delay of the accelerating laser beam changes half wavelength from the maximum acceleration to ultimate deceleration of electrons.



Φ $\Phi + \lambda/2$ $\Phi + \lambda$

FIGURE 5. Phase control over microbunch acceleration in STELLA experiment

Note that no active phase stabilization has been applied. The demonstrated phase control is possible due to a relatively long wavelength of the CO_2 laser to compare with naturally occurring thermal drifts and vibrations in the optics and accelerator components. The longer wavelength also relaxes requirements to the microbunch duration. Thus, STELLA gives an example how a mid-IR laser facilitates the task of demonstrating the next generation laser accelerator.

Prospective Next-Generation LWFA

There are good prospects for setting at the ATF the next-generation LWFA experiment. The CO_2 laser is a meaningful candidate for this application due to the quadratic wavelength scaling of the ponderomotive potential (see Eq.1) that drives a plasma wake. This ultimately allows the attainment of a high acceleration gradient even at a low plasma density

$$E_{acc}^{\max}[GV/m] = 2.8\times10^{4}(\lambda/w_0)^2\, P_L[TW]/\lambda_p[\mu m]. \tag{3}$$

Reasonably low plasma density ($\sim 10^{16}$ cm^{-3}) is desirable because it allows to accelerate proportionally higher bunch charge,

$$N_e < n_e(c/\omega_p)^3 = 4\times10^{6}\lambda_p[\mu\mathrm{m}] \tag{4}$$

at a small electron energy spread and emittance. To validate this claim, the optimum parameter space for the next-generation LWFA has been verified by simulations [13] made for 1 ps CO_2 laser that is under development at the ATF. Simulations demonstrate that, in order to achieve beam quality comparable to conventional accelerators, the injected electron bunch shall be much shorter than has been achieved so far using conventional RF techniques. For example, 200 fs minimum bunch duration demonstrated so far in FR linacs, being just 10% of the resonance plasma wavelength (λ_p=800 μm) at the axis of the parabolic plasma channel, is still not sufficient to ensure an adequate beam quality control.

A possible solution could be using a plasma wake as a bunch compressor. Simulations show that injecting the 5 MeV electron bunch at the negative slope of the accelerating field we introduce the energy modulation that compresses the bunch 10 times. This approach to monoenergetic LWFA is illustrated by the scheme in Fig. 6.

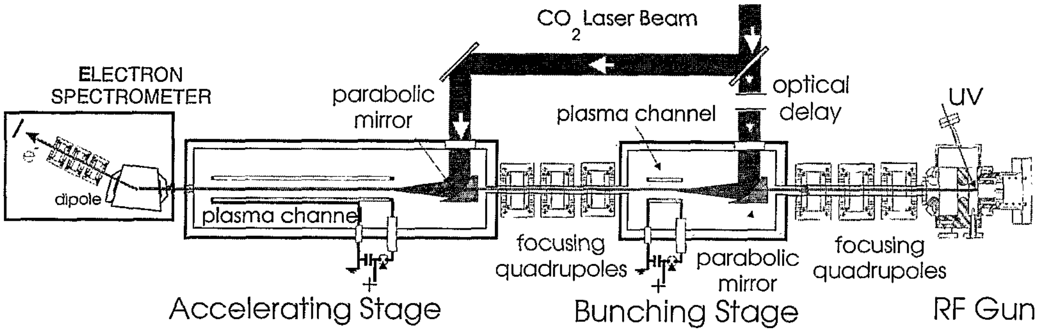


FIGURE 6. Diagram of prospective two-stage monoenergetic LWFA.

The 200 fs 5 MeV electron bunch produced by a photocathode RF gun is focused into the bunching LWFA stage where it is compressed to 20 fs (see Fig. 7).

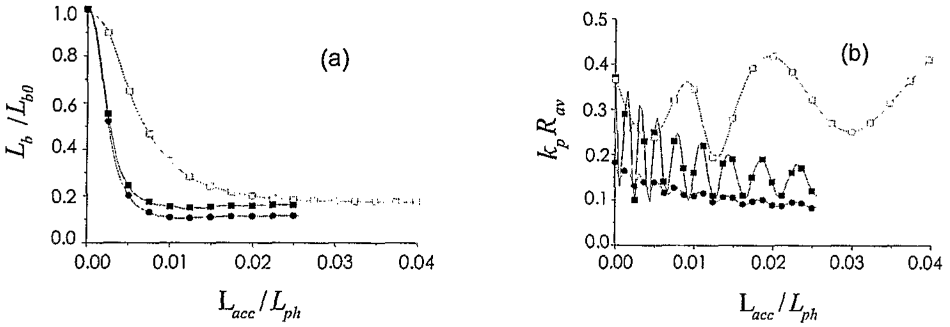


FIGURE 7. Bunch compression in channel guided LWFA;
(a) longitudinal bunch compression, (b) transverse bunch dynamics;
open squares –ϕ_{max}=0.04, R^0_{av} =50 μm, solid squares - ϕ_{max}=0.19, R^0_{av} =50 μm, circles - ϕ_{max}=0.19, R^0_{av} =25 μm.

Simulations shown in Fig.7 assume the following initial e-beam parameters: energy 5 MeV , energy spread 1.5%, geometric emittance 0.6 mm.mrad, bunch length

200 fs, and the rms radius R_{av}^{0}=25–50 μm. We see that a good control over the bunch compression process is possible at a small initial e-beam radius R_{av}^{0}=25 μm and relatively strong wakefield potential ϕ_{max}=0.19. Injecting the compressed bunch into the accelerating stage we observe also reduction in the relative energy spread from 5 to 1-2% and preservation of the normalized emittance.

It is important to see if these properties could be maintained when a similar configuration is used in a multi-stage scheme. Simulations [14] demonstrate a steady increase of the electron energy and a good control over the e-beam quality. Such performance requires a precise control of the optimum phases for injection and extraction of bunches from the accelerating stages.

We conclude this paragraph with a statement that analytical and computer calculations prove a possibility of the multi-GeV monoenergetic electron accelerator driven by a picosecond CO_2 laser and utilizing a conventional electron injector.

High-Brightness Relativistic Thomson X-Ray Source

Another application of a high-power CO_2 laser that we analyze here is x-ray generation via Thomson scattering.

A laser beam interacting with a counter-propagating relativistic electron beam behaves like a wiggler of an extremely short period. Relevant expressions for the wavelength, angular divergence, intensity, and brightness of the produced x-rays follow:

$$\lambda_X = \lambda/4\gamma^2, \tag{5}$$

$$\theta_0 = 1/\gamma, \tag{6}$$

$$N_X[photon/\,pulse] = 6.7\times10^{11}\,\mathrm{E}_{\mathrm{L}}^{\mathrm{eff}}[J]Q[nC]\lambda[\mu\, m]\big/ r_L^2[\mu\, m], \tag{7}$$

$$B\left|photon/\,mm^2 mrad^2\,\mathrm{sec}\right| = N_x\gamma^2\big/2(\pi r_b)^2\tau_b\,. \tag{8}$$

With a 70 MeV e-beam and a CO_2 laser, as short as 1 Å x-rays can be produced at the divergence and spectral bandwidth comparable with conventional synchrotron sources. Thus, much more compact and economical accelerator can be used. X-ray pulse duration is close to the electron bunch length, which can be on the femtosecond scale.

Let us consider what is the optimum choice for a laser and an accelerator when designing a high-brightness laser synchrotron source for a particular x-ray wavelength. As long as λ_X is considered as an invariant then choosing the CO_2 laser, with its wavelength 10 times longer than a solid state laser, requires a 3 times more energetic e-beam. This immediately improves angular divergence of the produced x-rays. X-ray yield will rise 10 times proportional to λ. This stems from the facts that number of x-ray photons is proportional to the number of delivered laser photons, which is proportional to λ at the fixed laser energy. When combining these factors together, we come to the conclusion that using a CO_2 laser as a driver for the relativistic Thomson source opens the prospect for up to 100 times increase in the brightness of the produced x-rays to compare with the 1-μm laser.

Using these considerations as design criteria, we assembled Thomson source in the ATF electron beamline as is shown in Fig. 8. Electron beam and CO_2 laser pulses are focused at the interaction point in a head-on collision. Laser beam is backscattered into x-rays. Dipole magnet separates electron beam from x-rays that pass a foil window to a Si detector.

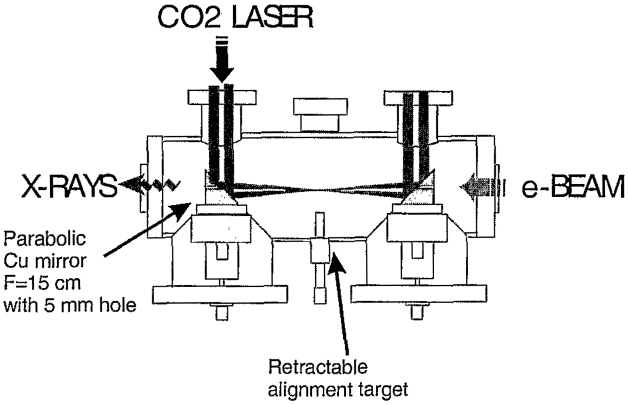


FIGURE 8. Interaction cell of the ATF Thomson x-ray source

Using 15 GW laser we obtained the highest photon yield ever demonstrated via laser Thomson scattering on relativistic electron beams [15]. On the diagram in Fig.9 you see earlier results obtained in LBNL and NRL. Lambda-proportional x-ray yield and counter-propagation configuration are the factors that explain a high position of the ATF source in this competition. We move now to the next stage where 1 TW CO_2 laser will be used in the same configuration and actually in the same interaction cell. We expect to observe strong harmonics and a noticeable shift in the fundamental peak energy (see Fig.10) due to relativistic mass shift of electron [15]. This is an illustration of one of our introductory statements that CO_2 laser allows attaining relativistic physics at rather moderate power.

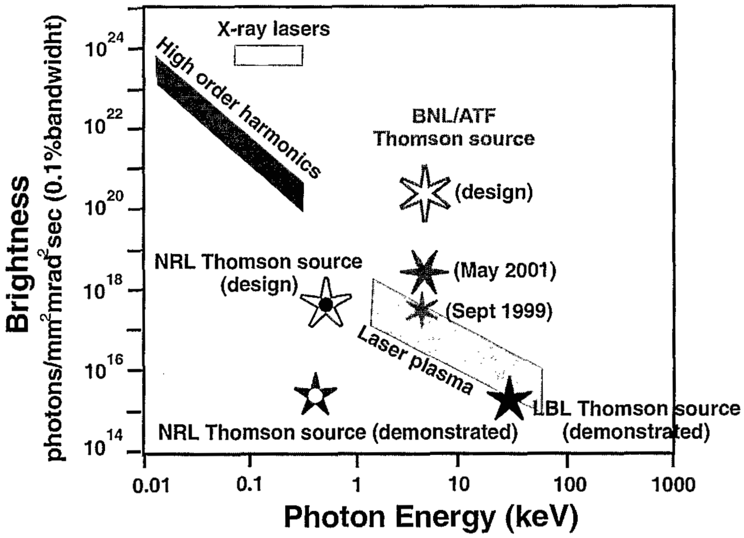


FIGURE 9. ATF Thomson scattering source. Demonstrated and design parameters

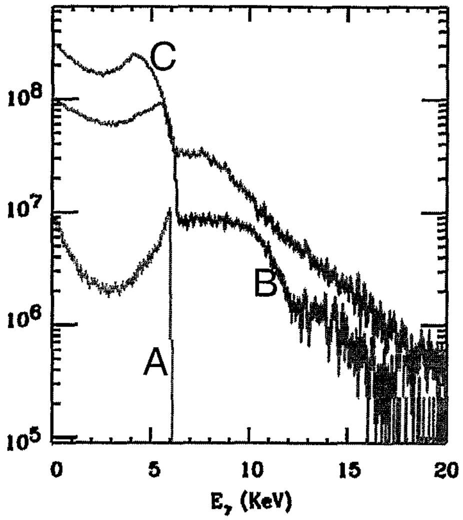


FIGURE 10. Thomson scattering spectra simulated for conditions of the recent ATF test done with the 30 GW CO_2 laser (A) and projects for 0.3 TW (B) and 1 TW laser power (C).

CONCLUSIONS

The BNL ATF is engaged in a string of the next-generation laser acceleration experiments including STELLA II, LACARA, and LWFA in a plasma channel. Simultaneously, UCLA will attempt next-generation beatwave experiment. All these experiments use terawatt CO_2 laser and strive to demonstrate quasi-monoenergetic electron acceleration at a gradient above conventional accelerators and over extended interaction distance. Another application of the terawatt CO_2 lasers - demonstration of nonlinear Thomson scattering and realization of ultra-bright femtosecond Thomson x-ray source may provide the first time opportunity to initiate studies in a parameter space approaching LCLS regime. Success in these experiments will establish a respectful position of CO_2 lasers within a family of ultra-fast lasers.

A reasonably confidential forecast towards 100 TW CO_2 lasers and beyond can be based on the already existing laser modules. For example, energy up to 1 kJ can be potentially extracted from the 30-cm aperture Neptune amplifier [16]. As we discussed, power broadening at 10^{11}-10^{12} W/cm^2 provides sufficient bandwidth for the 1-ps pulse amplification. Thus, it is just a matter of modifying the front end of the Neptune laser system to produce a proper seed pulse. The ATF laser designed to operate at 10 J, 1 ps is an example of a system that may serve for this purpose. Such input would be sufficient to reach 1 PW peak power from the Neptune amplifier after 4 passes with gradual beam expansion to the full aperture of the amplifier in a saturated regime.

There are also potentials to shorten CO_2 laser pulse down to 100 fs. The most straightforward way is to build 7 THz broad continuum in the gain spectrum by mixing all possible isotopes of oxygen and carbon. Such continuum can support direct amplification of the 100 fs pulse. Another possibility to reach 100 fs pulse duration starting with 1-2 ps pulse is due to pulse chirping via gas ionization followed by compression in the material with a negative dispersion (e.g., conventional ZnSe IR window) [17].

Combination of the energy boost above 100 J with prospective pulse compression to 100 fs may allow CO_2 laser to approach the multi-petawatt level. The 1 PW 10 μm radiation focused to diffraction limit with F#=2 optics produces field with a=120 that makes possible efficient realization of a number of exotic highly relativistic processes such as GeV ion and electron acceleration via Coulomb explosion or direct ponderomotive expulsion from the laser focus, study of Unruch radiation, etc.

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