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CO_2 LASERS IN HIGH ENERGY PHYSICS

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Abstract

Several proof-of-principle laser accelerator experiments turned a long-wavelength of a CO_2 laser to advantage. Ongoing advancement to multi-terawatt femtosecond CO_2 lasers opens new venues for next-generation laser acceleration research.

It is hardly possible to find a field of natural science or technology that is not moved forward by lasers. Among these areas is high energy physics (HEP) - one of the most fundamental scientific disciplines. It advances the frontiers of our understanding of matter and energy, their structure and origins.

The main tool of HEP is a particle accelerator. Lasers have found a number of applications in accelerator technology. They drive photoelectron injection guns, perform a variety of particle beam diagnostics, and demonstrate capability to beam cooling and focusing. Production of radiation via Thomson scattering between laser and relativistic electron beams promises to evolve into novel ultra-bright x-ray sources for multi-disciplinary applications. Prospective high-energy gamma-gamma colliders are also based on the same principle. However, probably the most notable and important application of lasers in HEP would be direct high-gradient particle acceleration.

In order to look deeper into the structure of matter, scientists shall bring to interaction particles accelerated to higher and higher energies. So far, accelerator technology responds to the quest by exponential energy increase 10 times per decade. However, conventional RF technology approaches its limit to the accelerating gradient at ≤ 100 MeV/m defined by vacuum breakdown. Consequently, a future RF accelerator of the TeV energy needs to be tens of kilometers long. High-energy accelerators are already the most expensive scientific instruments. At this scale they become not affordable to any nation. Demise of the Superconducting Supercollider in the middle of its construction in 1992 was a shocking illustration to this.

To make an accelerator more affordable we need to make it smaller. This means that scientists shall find a way to increase acceleration gradient by orders of magnitude. This is why they turned attention to lasers - the sources of the highest fields achieved in the laboratory environment. The transverse electric field E_L associated with laser intensity I_L is defined by

$$|E_L|^2 = 2I_L / \varepsilon_0 c \tag{1}$$

and reaches E_L=1 TV/m at ready achievable $I_L = 10^{18}$ W/cm^2. The laser accelerator research explores methods of using such enormous transverse electromagnetic fields productively for high-gradient acceleration.

CPA solid state lasers based on chirped pulse amplification dominate the field of advanced laser accelerator research. These lasers emerged in 1980-s and reached technical maturity now days. Over the same time period we observe decline in application of powerful CO_2 lasers in big scientific projects. Why do we revisit now this situation? What are the merits of CO_2 lasers for high-field physics and accelerators? There are at least two. Both of them are based on the ten times longer wavelength of CO_2 lasers to compare with solid state lasers.

The first attractive point is that a CO_2 laser with its $\lambda \approx 10$ μm presents a viable compromise between conventional RF technology and optical laser drivers (typically at $\lambda \approx 1$ μm), which allow extremely high gradients but do not demonstrate any comparable particle beam quality so far.

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

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

At a given intensity, a CO_2 laser reaches 100 times higher ponderomotive potential than does a solid state laser. This implies a possibility of the proportional increase in a throughput of such laser-induced processes as particle acceleration, x-ray production, etc.

At the first glance these arguments can be dismissed exercising tighter diffraction-limited focusing of short-wavelength beams. Let us consider, however, two practical situations:

Performing laser/electron beam interaction for a purpose of monoenergetic acceleration or x-ray generation requires the laser focus broader than the electron beam. A CO_2 laser has sufficient focusing capability to match a size of the low emittance e-beams.

Considering volumetric interactions, for example Thomson scattering in plasma or field ionization of atoms and molecules, ten times tighter focus of the 1-μm laser results in 1000 times smaller volume where you can see an equivalent effect. Indeed, this volume can be defined as $w_0^2 \times z_0$, where $z_0 = \pi w_0^2/\lambda$ is Rayleigh distance, $w_0 = \frac{2}{\pi}\lambda M^2 F\#$ is the Gaussian beam radius at the intensity level of $1/e^2$, M^2 is the beam quality factor equal to 1 for ideal Gaussian beam, and $F\# = f/2W_0$ is a ratio of the lens focal length f to the initial beam diameter $2W_0$.

These simple considerations lead to an observation that the 1 TW CO_2 laser may be equivalent in certain cases to the 100 TW solid state laser. This justifies efforts in developing such technology. Unfortunately during the last decade the efforts are still scarce and 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 MARS laser system [1] at the UCLA Neptune laboratory recently upgraded to the 40 ps pulse duration includes a master oscillator; an optical switch, and the 10-atm regenerative amplifier followed by the 3-atm booster amplifier. The system produces 1 TW dual wavelength radiation used for plasma beatwave acceleration [2].

Building a picosecond CO_2 laser system, researchers face a problem of spectrum modulation by rotational molecular structure. In principle, this bandwidth limitation can be alleviated by pressure broadening or using multi-isotope mixtures [3,4]. Both approaches are not practical for the big-volume MARS-type amplifier. However, the UCLA researchers have found a different intricate solution to this problem. Transmitting a focused laser pulse through a gas cell they observed a frequency chirp due to the gas ionization. When the pulse is returned back into the amplifier, the chirped tail is filtered out by the gain. An output pulse was chopped from 200 to 40 ps [5]. This was achieved actually due to a combination of several effects: filtering, gain saturation and power broadening. Similar to pressure broadening, power broadening allows building a "bridge" between rotational lines. As soon as vibrational lines are smeared out into a 1 THz wide quasi-continuum as short as 1 ps pulses can be amplified in a CO_2 laser [3].

The BNL ATF gives another example of a picosecond CO_2 laser with the terawatt capability. Our approach relies on direct pressure broadening of the rotational spectral lines. For this purpose we have constructed one of the kind 10-atm big-volume booster amplifier[6]. The 10 J output is extracted through a window of the 10-cm diameter. The laser action is excited by the 1-MV x-ray preionized discharge.

Shown in Fig.1 is a combination of principle elements of the ATF laser named PITER-I. A mode-locked Nd:YAG laser helps the CO_2 laser to generate megawatt picosecond pulse by turning a semiconductor optical switch on. The regenerative amplifier increases the power to the gigawatt level. Presently, the ATF is in a process of upgrading its CO_2 laser system to the terawatt power. The 10-atm big-volume amplifier is already installed and is in operation. However, initial elements still need to be upgraded to deliver a proper 1 ps pulse for final amplification to ~10 J. Meantime, even operating at the present 200 ps pulse duration and the 30 GW peak power PITER-I still enables cutting edge user's experiments as we discuss next.

The BNL ATF is by far not just a laser laboratory but an established DOE user's facility for high energy physics and basic energy science. For this mission the ATF is equipped with a high-brightness linac synchronized to high-power laser pulses. Many researches understand convenience of using a long-wavelength laser in combination with a low-emittance relativistic e-beam for proof-of-principle particle acceleration experiments. As a result nearly all non-plasma laser acceleration experimental efforts in US are concentrated now in the ATF. This unique situation is illustrated by Fig.2 that shows a variety of schemes under test or in preparation at the ATF. We review here one of these experiments that demonstrates advantages of the long-wavelength radiation for the next-generation laser accelerators.

Until now, in laser acceleration experiments electrons were sprayed over a range of energies with just a few particles observed near the maximum of the accelerating field. The next milestone 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 a form of a sinusoidal or shaped close to it relativistic wave. This may be a laser or plasma wave. In order that co-propagating electrons are being accelerated monoenergetically they shall occupy a small portion of the wave period and shall be focused to a narrow beam to compare with a radial scale of the wave. Then all particles are subject to quasi-uniform field amplitude. In the case of direct acceleration of relativistic electrons in a laser beam the 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 the only one possible way to produce such microbunch train: to use the same laser.

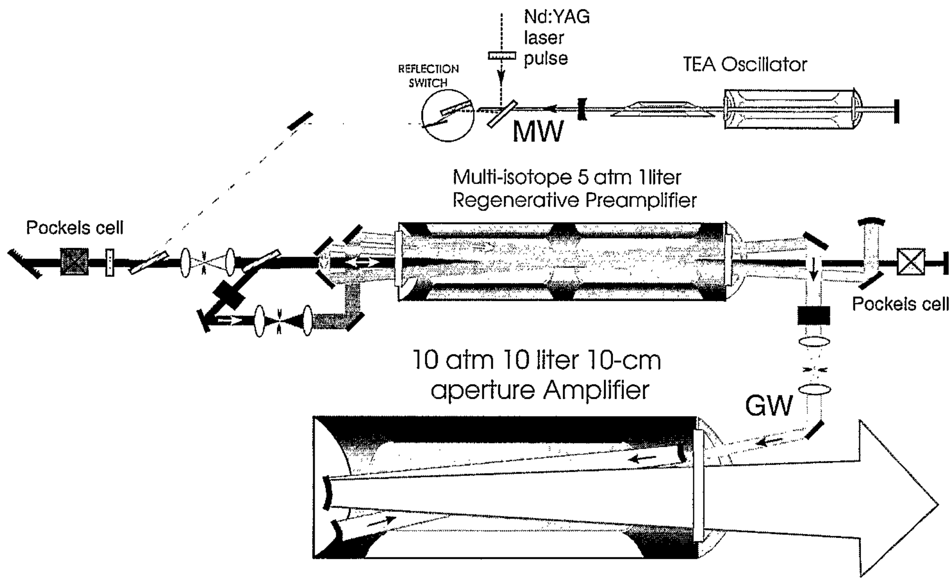

Figure 1. PITER-I optical scheme.

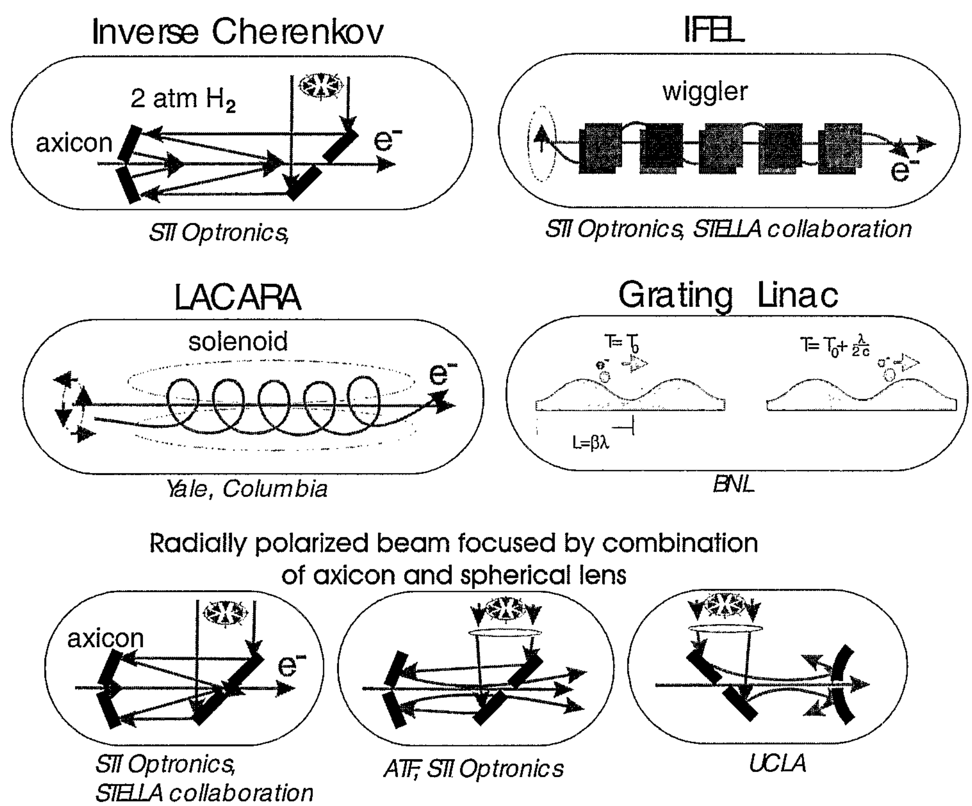

Figure 2. ATF laser acceleration experiments. Institutional users are listed under each icon.

The plan is simple. If we achieve sinusoidal energy modulation in the laser wave and allow electrons to drift or transmit them through dispersive compressor (e.g., magnetic chicane) they group together into small microbunches exactly periodical to the laser wavelength. In Fig.5 of the LASERS'97 publication [7] we show modeling of this process that assumes practically achievable electron beam parameters and a CO_2 laser. Such microbunches can be accelerated monoenergetically.

So, the idea of a monoenergetic laser accelerator evolves into a two-stage concept where the first stage serves as a buncher while the second produces monoenergetic acceleration instead of sinusoidal energy modulation. The first staged electron laser acceleration experiment abbreviated to STELLA [8] is based on the principle of inverse free-electron laser (IFEL)[9]. As is shown in Fig.3, a single laser beam is split between two wigglers. The set of electron spectra in Fig.4 shows selective acceleration of microbunches. This first demonstration of a possibility to phase laser accelerator stages became feasible due to a relatively long wavelength of the CO_2 laser in comparison with thermal drifts and other characteristic motions and vibrations in the system. This is also easier to produce bunches much shorter than the laser period when this period is long. Thus, STELLA gives us an example how a long wavelength laser facilitates a task of demonstrating the next generation laser accelerator.

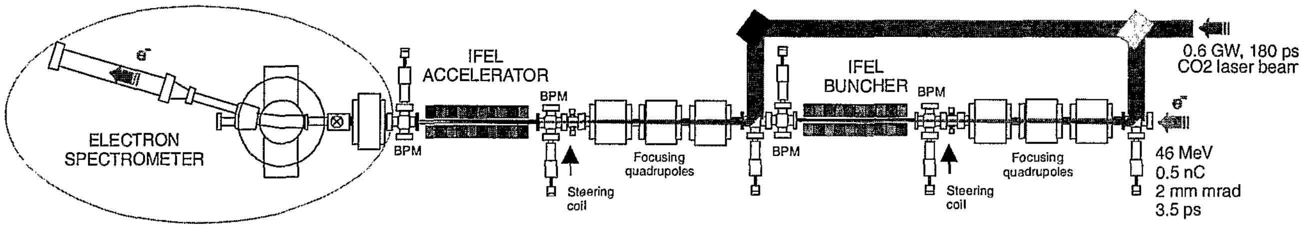

Figure 3. STELLA scheme

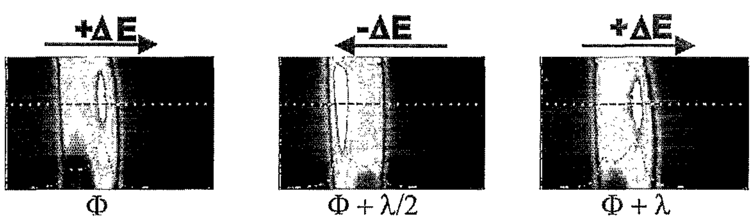

Figure 4. Phase control over electron acceleration in STELLA experiment

Laser driven plasma wake field accelerators (LWFA) look especially promising in achieving ultra-high-gradient acceleration [10,11]. Fundamental advantage of a CO_2 laser for this application is due to quadratic dependence of energy acquired by electron from electromagnetic wave during period of oscillation (see Eq.2). Ultimately this helps to attain a high acceleration gradient even at a low plasma density n_p

$$E_a^{\max}[\text{GV/m}] = 2.8\times10^4\left(\frac{\lambda}{r_L}\right)^2 P_L[\text{TW}]/\lambda_p[\mu m], \quad (3)$$

where $\lambda_p \sim n_p^{-1/2}$ is the plasma wavelength.

Why low plasma density is desirable? Because, it allows accelerating proportionally higher bunch charge and, that is more relevant to the present discussion, to achieve reasonably small energy spread.

In the LWFA, the plasma period is set approximately equal to the laser pulse length. So, if we want to achieve a decent beam quality the bunch shall be compressed not to a portion of the laser wavelength but just to a portion of the laser pulse duration, which is typically in a picosecond or femtosecond range. This is still beyond what has been achieved so far with conventional electron injectors. However, this looks doable if we utilize electron bunch compression in the laser-induced plasma wake. For example, injecting the 5 MeV 200 fs electron bunch produced by a photocathode RF gun into a plasma wake at the negative slope of the accelerating field we introduce energy modulation that compresses the bunch to 20 fs. This bunch duration is sufficiently short to ensure acceleration with the energy spread of 2% and normalized emittance 5 mm.mrad in the plasma wake induced by the 1 ps CO_2 laser[12]. Such laser is under development at the BNL ATF[6].

Switching from acceleration to the mentioned above Thomson scattering we just change from co-propagation of the electron and laser beams, as is required for acceleration, to counter-propagation. A laser beam interacting with a counter-propagating relativistic electron beam behaves like a wiggler of an extremely short period. With the 70 MeV e-beam and a CO_2 laser, as short as 1 Å x-rays may be produced at a divergence and spectral bandwidth comparable with conventional synchrotron sources. Thus, we can use more compact and economical accelerator. In the counter-propagation configuration the x-ray pulse duration is close to the electron bunch length, which can be at a femtosecond scale. The x-ray photon number is proportional to the delivered laser photon number and, at the fixed laser energy, the last parameter is proportional to λ. This is one of the factors that explains a high position of the ATF Thomson source among other attempted so far and planned experiments. For detailed description and recent results on the ATF Thomson scattering experiment see this Proceedings [13] and references wherein.

We can anticipate that in a near future a TW CO_2 laser will establish a respectful position within a family of ultra-fast lasers via demonstration of quasi-monoenergetic electron acceleration over an extended interaction distance at a gradient beyond conventional accelerators and, in the area of x-ray generation, by demonstrating ultra-bright femtosecond Thomson x-ray source and study of nonlinear Thomson scattering.

Speaking about more distant future, there are no fundamental obstacles to reach 100 TW peak power with CO_2 lasers. This can be achieved with the already existing hardware. For example, the UCLA MARS amplifier delivers more than 100 J energy in a single pulse. As we discussed, power broadening provides sufficient bandwidth for 1 ps pulse amplification. Fig.5 shows simulations for strongly saturated regime of the 3 ps pulse amplification in the 3-atm amplifier [14]. Simulations show that if we seed 1 TW pulse into this laser, 100 TW can be extracted after about 4 passes. Even up to 1 PW output does not look out of question provided that 10 TW is available at the input and the beam is gradually expanded to the full 30-cm aperture of the MARS amplifier. It is just a matter of modifying the front end of the MARS laser system to produce a proper seed pulse. The ATF PITER-I laser may serve as an example. It is designed to operate at 10 J and 1 ps – the exact input parameters necessary to reach 1 PW by saturating the MARS amplifier.

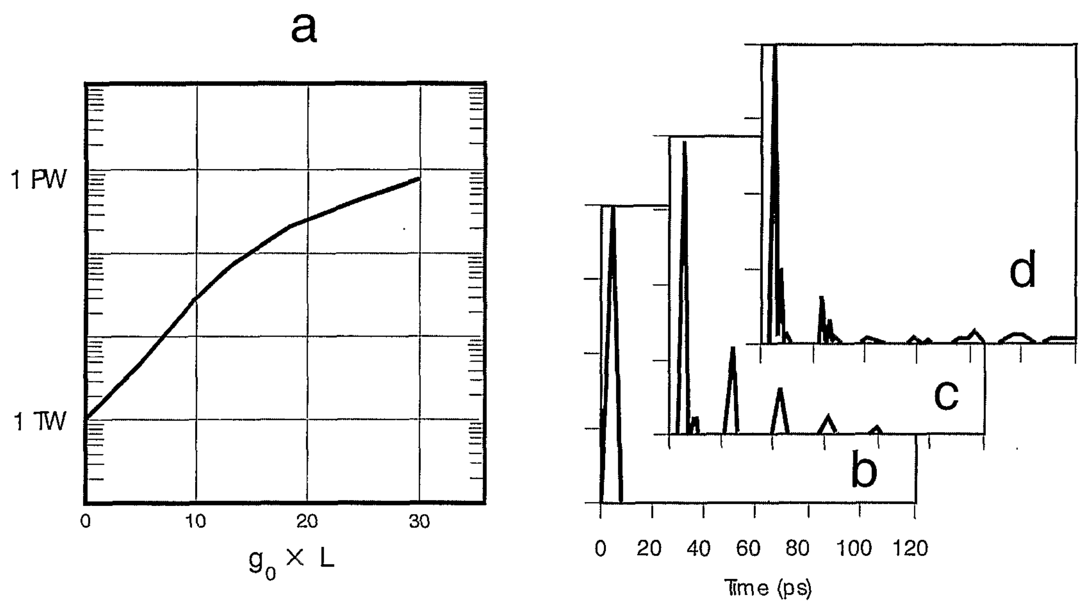

Figure 5. Simulations of the 3-ps CO_2 pulse amplification applicable to a hypothetical combination of the MARS and PITER-I laser systems; a) power gain with 30 times beam area expansion, b) 10 MW initial pulse before amplification, c) 1 TW pulse output from PITER I at the entrance to the MARS amplifier, d) 1 PW pulse after the MARS amplifier.

In addition, there are also potentials to shorten the CO_2 laser pulse down to 100 fs. There are several ways to realize such regime. The most straightforward way is to build a broad 7 THz continuum in the gain spectrum by mixing all possible isotopes of oxygen and carbon in the laser amplifier [3,15]. Such continuum can support direct amplification of the 100 fs pulse.

Another possibility to reach the 100 fs pulse duration starting with 1-2 ps pulse is due to pulse chirping via gas ionization followed by compression in the dispersive optical material [3].

The 1 PW 10-μm radiation focused to the diffraction limit with a realistic #F=2 produces field with the laser strength parameter $a = eE/mc\omega$ =100 that makes possible efficient realization of a number of highly relativistic exotic processes such as GeV ion acceleration via Coulomb explosion or direct ponderomotive acceleration of electrons in a laser focus, study of Unruh radiation, etc.

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REFERENCES

[1] S.Yu. Tochitsky, R. Narang, C. Filip, C.E. Clayton, K.A. Mash, and C. Joshi, *Optics Lett.* **24**, 1717 (1999)

[2] M. Everett, A. Lal, D. Gordon, C. Clayton, K. Marsh, and C. Joshi, *Nature* **368**, 527 (1994)

[3] P.B. Corkum, *IEEE J. Quantum Electron.* **QE-21**, 216 (1985)

[4] V.T. Platonenko and V.D. Taranukhin, *Sov. J. Quant. Electron.*, **13**, 1459 (1983)

[5] S.Yu. Tochitsky, C. Filip, R. Narang, C.E. Clayton, K.A. Mash, and C. Joshi, *Proceedings of LASERS'2000*, Albuquerque, NM, December 4-8, 2000, STS Press, McLean, 417 (2001)

[6] I.V. Pogorelsky, I. Ben-Zvi, M. Babzien, K. Kusche, J. Skaritka, I. Meshkovsky, A. Dublov, V. Lekomtsev, I. Pavlishin, Yu. Boloshin, and G. Deineko," Laser Optics '98, St. Petersburg, June 22-26 1998, "Superstrong Laser Fields and Applications", *Proc. of SPIE* **3683**, 15 (1999)

[7] I.V. Pogorelsky, *Proceedings of LASERS'97*, New Orleans, December 15-19, 1997, STS Press, 799 (1998)

[8] W.D. Kimura, A. van Steenbergen, M. Babzien, I. Ben-Zvi, L.P. Campbell, D.B. Cline, C.E. Dilley, J.C. Gallardo, S.C. Gottschalk, P. He, K.P. Kusche, Y. Liu, R.H. Pantell, I.V. Pogorelsky, D.C. Quimby, J. Skaritka, L.C. Steinhauer, and V. Yakimenko, *Phys. Rev. Lett.*, **86**, 4041 (2001)

[9] R.B. Palmer, *J. Appl. Phys.* **43**, 3014 (1972)

[10] T. Tajima and J.M. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979)

[11] A. Madena, Z. Najmudin, A.E. Dangor, C.E. Clayton, K.A. Marsh, C. Joshi, V. Malka, C.B. Darrow, C. Danson, D. Neely, and F.N. Walsh, *Nature* **377**, 606 (1995)

[12] N.E. Andreev, S.V. Kuznetsov, and I.V. Pogorelsky, *PRST-AB*, **3**, 021301 (2000)

[13] I.V. Pogorelsky, I. Ben-Zvi, K. Kusche, P. Siddons, V. Yakimenko, T. Hirose, T. Kumita. Y. Kamiya, T. Omori, J. Urakawa, K. Yokoya, S. Kashiwagi,A. Zigler, B. Greenberg, D. Kaganovich, I.V. Pavlichine, I.K. Meshkovsky, F. Zhou, D. Cline, "Relativistic Thomson Scattering Experiment at BNL, Status Report", *these Proceedings*

[14] I.V. Pogorelsky, I. Ben-Zvi, W.D. Kimura, N.A. Kurnit, and F. Kannari, *Infrared Physics and Technology*, **36**, 341, (1995)

[15] Z.A. Biglov and V.M. Gordienko, *Current Problems in Laser Technology*, **4**, 84 (1991) (in Russian)