TITLE: APPLICATION OF CONVENTIONAL LASER TECHNOLOGY TO
GAMMA-GAMMA COLLIDERS

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Application of Conventional Laser Technology to Gamma-Gamma Colliders*

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ABSTRACT

A future e^-e^+ (electron-positron) linear collider can be configured with perhaps minimal modification to serve as an $\gamma\gamma$ (gamma-gamma) or a $e^-\gamma$ collider. This is accomplished by Compton-backscattering low energy photons (from a laser source) off of the high-energy electron beams prior to the crossing of the electron beams. However, to be competitive with the e^-e^+ configuration, the luminosity cannot be compromised in the process. This requires that the laser source deliver a sufficient number of photons per pulse with a pulse format and rate matching that of the electron beams. As it turns out, this requires an average optical power of 5 to 15 kW from the laser which is beyond the current state of the art. In this paper, we address how to generate the required pulse format and how the high average power requirement can be met with conventional laser technology. We also address concerns about the survivability of mirrors located near the interaction point. Finally, we list a program of research and development which addresses some of the unknowns in such a system.

*Summary of the Conventional Lasers working group.

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INTRODUCTION

Our goal in this paper is to describe several possible laser systems which are suitable for the efficient production of gammas for the linear collider designs proposed at the Linac 93 conference. Most of these designs, namely NLC, JLC, CLIC, DLC and VLEPP are similar enough such that a solution which fits the needs of, say, NLC can be extended to any of the others quite simply. The TESLA design is somewhat different in that the time between microbunches is very long (1 μ sec) which is made up for by having a very large number of bunches (800) per macropulse. In this paper, we will concentrate on the NLC design but we mention what must be altered to handle a design like TESLA.

LASER REQUIREMENTS

The laser requirements have been spelled out in great detail by Telnov [1] but for completeness, we will briefly review them here.

Laser wavelength

The frequency of the laser light should be as high as possible, but below the threshold for rescattering the gammas into pairs through the reaction $\gamma + \omega_0 \rightarrow e^+ e^-$. This occurs when the laser frequency ω_0 times the maximum gamma frequency ω_γ is greater than $m^2 c^4$, i.e. when $\omega_0 \omega_\gamma > m^2 c^4$. The maximum gamma frequency (which occurs for direct Compton backscatter) is related to the electron beam E_0 energy by $\omega_\gamma = \frac{x}{1+x} E_0$, where $x = \frac{4E_0 \omega_0}{m^2 c^4}$. Substituting for ω_γ in terms of x gives the above threshold condition as $x > 2(1 + \sqrt{2}) \approx 4.8$. Thus the optimum laser wavelength is $\lambda = 4.2 E_0 [\text{TeV}] \mu\text{m}$. For example, a 0.25 TeV design requires a 1.05 μm laser. Because most of the collider designs considered in this workshop are around 0.25 TeV, we will consider mainly solid-state lasers operating around 1 μm . Any demonstration experiments at lower beam energy would benefit from shorter wavelength lasers and here the gaseous excimer lasers, with their potential for high repetition rate and high energy per pulse in the ultraviolet, could be used. But the 1 μm solid state lasers can also be efficiently frequency converted

with efficiencies roughly 75% into $0.5\text{ }\mu\text{m}$, 60% into $0.33\text{ }\mu\text{m}$, and perhaps 40-50% into $0.25\text{ }\mu\text{m}$ light in the 1 psec pulse regime.

For collider energies above 0.25 TeV, longer wavelength sources are needed. Fortunately, these sources are being developed for other applications and some of these will be mentioned later in this paper.

Pulse format

The laser pulse format naturally must match that of the electrons at the interaction point (IP). The electron pulse format is determined by rf and wakefield considerations. The rf pulses powering the x-band high-gradient accelerating structures are expected to be around 120 nsec for the NLC design. This is therefore the macropulse length. Each macropulse will contain a number of bunches separated by enough time for the wakefields of the previous bunch to decay away. This bunch separation time is as low as 1.4 nsec for NLC or as high as 9 nsec for DLC. TESLA, with a 1000 nsec bunch separation, is a special case which we will discuss later. These pulse formats are repetitively pulsed from 50 to 300 Hz, typically, with the NLC design calling for 180 Hz.

In the gamma-gamma configuration, as pointed out by Palmer in this workshop [2], the luminosity may be increased by propagating more charge per bunch with a larger inter-bunch spacing, among other things. For numerical simplicity, we will assume that we need about 60 bunches per macropulse with a 2 nsec spacing at a repetition rate of 180 Hz.

Pulse energy

To minimize the required average laser power, we would like to arrange the laser time- and space-scales such that all the electrons in the microbunch see the laser pulse while it is at it's highest intensity. For a laser pulse length l_γ and an electron pulse length l_e , laser energy will be wasted for $l_\gamma > l_e$ and peak power requirements go up needlessly for $l_\gamma < l_e$. It is therefore desirable to have $l_\gamma \approx l_e$ which we will assume for the remainder of this discussion. The interaction length is limited by the Rayleigh range $2\beta_\gamma$ of the focused laser beam as long as $2\beta_\gamma < l_\gamma$. Given the Compton scattering cross section σ_c ,

the probability of an electron Compton scattering a laser photon is $2n_\gamma\beta_\gamma\sigma_c$, where n_γ is the photon density of the focused laser beam at the conversion point. For a gaussian laser beam, the quantity $n_\gamma\beta_\gamma$ is a function only of the power in the beam and not on the focal length or f/number of the focusing optics. If we focus the laser tighter, the intensity and therefore n_γ will be increase but the depth of focus ($2\beta_\gamma$) will be reduced and the product will not change. However, to avoid nonlinear effects which scale with the laser field strength, we choose the longest useful value for the depth of focus which is $2\beta_\gamma \approx l_\gamma$. We have thus constrained the laser parameters to $2\beta_\gamma \approx l_\gamma \approx l_e$. Finally, to obtain a scattering probability near unity, we must have $2n_\gamma\beta_\gamma\sigma_c \approx 1$. With the other constraints, this is a condition on the laser energy A_γ . Solving this equation for the laser energy gives $A_\gamma \approx \frac{\pi c l_e \hbar}{2\sigma_c}$. [1] Taking $\sigma_c = 0.75 \pi r_e^2$, where r_e is the classical electron radius, we find that $A_\gamma \approx 2.6 l_e(\text{mm}) \text{ J}$. Thus for the NLC design with $l_e = 2\sigma_z = 0.2\text{--}0.5 \text{ mm}$, $A_\gamma \approx 0.5\text{--}1.3 \text{ J}$. For the remainder of this paper, we will assume that the required laser pulse is nominally 1 J in $l_\gamma = 0.3 \text{ mm}$ which is a pulse width of 1 psec. This Joule in a psec is routinely achieved in the so-called "table-top terawatt" lasers which are operating around the world but at low repetition rates.

REVIEW OF CURRENT TECHNOLOGY

Technology-driving applications

There are a number of laser applications which are driving the laser technology in the right direction for the gamma-gamma collider needs. One of these is x-ray lithography where an inexpensive source of soft x-rays are needed for the manufacturing of future generations of integrated circuits. [3] As the dimensions of the smallest features on the chip shrink, so must the wavelength of the light source which exposes the photoresist. To obtain the desired watts of soft x-rays, the laser illuminates a metal target where a plasma is formed. A short pulse is desirable so that the laser interacts with a high-density plasma rather than a low density blow-off plasma. Conversion efficiencies are low so that the laser needs to be kW or multi-kW to achieve the watts of narrowband

x-rays from the target. The beam quality needs to be high to obtain small spots (small source size) and therefore high brightness for the x-rays. All these requirements overlap with the gamma-gamma beam requirements.

Another driving application is high average power lasers for cutting, welding, annealing, and other material processing needs. These manufacturing applications still require a good beam quality but the pulse length need not be ultrashort.

A third application is atmospheric sensing. These applications include general global winds measurements to feed into weather models and diagnostics for various atmospheric conditions such as the vorticity prior to tornado formation or wind shear situations near airports. Another remote sensing application is laser ranging and targeting. For these outdoor uses,[4] many of the materials under development are the so-called eye-safe laser materials. These are typically solid state lasers like Nd:YAG which, however, operate at longer wavelengths where they are not transmitted by the cornea of animals. These applications do not need particularly high power. But the implication for gamma-gamma colliders is that materials are being developed and characterized today in the 1–3 μm regime which is important for linac energies from 0.25–0.7 TeV. While solid state lasers are extending to longer wavelengths, technology is being developed to convert gaseous CO_2 lasers at 9.6–10.6 μm down to 4.8–5.3 μm using frequency doublers. The motivation is to have a source of high power laser light in the atmospheric propagation window at 4.8 μm . Good nonlinear optical materials for this mid-infrared band have not generally been available but a recent measurement on a crystal of AgGaSe_2 showed up to 78% doubling efficiency for 1 nsec 9.55 μm CO_2 laser pulses. [5] Also, novel synthetic nonlinear crystal composed of diffusion-bonded stacks of alternately-rotated plates of GaAs has been built which provides quasi-phase matching for second harmonic generation while maintaining the mechanical and thermal properties of the bulk GaAs material.[6] Therefore, a high power source of photons may even be available at the unusual wavelength of 4 or 5 μm as would be required for a 1 TeV collider.

Diode laser arrays

High average power lasers must be pumped to their upper lasing level very efficiently in order to minimize wasted pump energy which will accumulate in the laser material in the form of heat. For optically pumped lasers, this essentially requires that the pump radiation be narrow-band and be resonantly absorbed in a transition with a high branching ratio to the upper lasing level of interest. This is indeed the case with diode lasers pumping Nd:YAG. The diode lasers are produced in bars which can currently deliver peak powers over 120 W/cm of bar length. [7] These bars can be stacked to form a 2-D array of emitters with microchannels carrying a liquid cooler built right into the silicon substrate. [8] With this cooling, peak power densities of about 1 kW/cm² and average power densities of over 100 W/cm² have been achieved. [7] 1-D and 2-D arrays at various power levels are available commercially although the highest power arrays are still under development.

Any limitations in the power density from diode arrays can be overcome today by coupling the light into a fiber bundle. The packing density of the fibers is enough to deliver easily 5 kW/cm² for two-sided pumping of the gain medium. [9] Thus any limitation on the laser output will definitely not be the pumping lasers but rather the thermal loading of the gain medium.

Laser systems under development

Perhaps the most significant advances in high average power solid state lasers are being made at TRW and LLNL. The TRW group has described [10] a diode pumped Nd:YAG laser with a $1.1 \times$ diffraction-limited beam with 1 J per pulse operating at 100 Hz with a "wall plug" efficiency of 9.4%. The pulse length was 7 nsec rather than the 1 nsec or so that would be required in a chirped pulse amplification (CPA) scheme for the gamma-gamma application but the technology should be applicable at the shorter pulse length. In the most recent CLEO meeting (Conference on Lasers and Electro-optics), the TRW group presented a paper entitled "Diode-array-pumped kilowatt laser development"

so they are clearly setting their sights on achieving a multiple kW class laser technology.[11]

The group at LLNL has described[3] a 1 J per pulse diode-pumped Nd:YAG operating at 400 Hz. Here the pulse length was 2-5 nsec, more in line with what we would like for the CPA lasers. An upgrade to 1 kW was described[12] at the SPIE's conference on "Diode pumping of average-power solid state lasers" held in January 1993.

All the high power glass lasers use a zig-zag slab arrangement and diode pumping. An example is shown in Fig. 1. The limitations are not due to limited pump power but to thermal distortion of the laser material. This affects the beam quality, especially in a multipass amplifier scheme as all of these systems use. The zig-zag path itself compensates to zero order the thermal gradients normal to the face of the slab but more compensation is needed in high power situations. Two approaches are taken here. The mechanically simple approach is to allow some distortion of the beam on the first pass of the amplifier but then use a phase conjugate mirror to reflect the beam back along the input path.[13] These mirrors have the property of reflecting the "time-reversal" of the incident waveform which results in any aberration accumulated on the first pass of the amplifier to be exactly "undone" on the second pass. The double-passed beam therefore acquires no net distortion from the amplifier. This is the approach used at LLNL and TRW and is taking them up the kW level.

Another thermal compensation technique is the moving-slab-laser scheme.[14] Here, the width of the slab is much wider than the width of the beam. One can imagine the slab coming out of the page in Fig. 1. The diode array, however, is narrow and pumps a volume just wide enough to cover the beam. Now, if the slab is set into motion, moving back and forth transverse to the beam, then the heat load will be spread out over a much larger volume than the volume of the beam. This buys a big factor in cooling power which pushes the maximum output power up dramatically.

Future outlook

Kilowatt-class laser systems are not only feasible but are operational today. Ten or twenty kW lasers can be built today by combining the high power pumping sources with a moving slab laser configuration. However, these lasers are not yet suitable for the collider application where diffraction-limited, short (1 psec) pulses are needed. A key technology in the systems which have demonstrated diffraction-limited pulses is the phase conjugate mirror which allows a single laser beam to be amplified to high power despite the thermal distortion in the media. It is not yet resolved how well these mirrors will work with the broad bandwidths needed to produce psec pulses. Since the thermal distortion will be roughly stationary in time, it is possible that adaptive optics[15] can be used (instead of phase conjugate mirrors) to adjust the phase fronts to correct for the distortion. This technology is used to correct earth-bound telescope mirrors for aberrations in the atmosphere due to air turbulence.

Although the very-high-power (> 10 kW) lasers are on the drawing board, it has not been demonstrated that the beam quality there will be sufficiently good since even the moving-slab lasers are pushing the thermal limits at these power levels. The good news is that Nd:glass, due to its high saturation fluence, is a good material for the high power lasers. This happens to be one of the materials of choice for tabletop terawatt lasers as well due to its broad gain bandwidth. So the potential is there for 10's of kW beams composed of psec pulses.

A laser architecture related to the moving slab is the moving disk amplifier which Basu and Byer claim has potential for MW average powers.[9] This works by essentially adding a second dimension to the motion of the gain material allowing for even greater ratios of pumping volume to total disk volume. Perhaps this technology will run "cool enough" for good beam quality at 10 or 20 kW without requiring the phase conjugate mirror technology.

A final option is to use coherent beam combining technologies to spread the power load over several amplifiers. The optical industry is in a boom period right now and

rapidly approaching the day when they can design and manufacture exotic optics that were not imagined possible a few years ago. These include binary phase optics and holographic optical elements, both of which can be used to combine beams that have been multiplexed in some way, either by frequency, polarization, angle, etc. For example, there was recently a theoretical paper by a group in China on coherent laser beam summation using phase gratings [16]. Also, a group at Hughes Research Labs reported experimental results on combining the outputs of multiple parallel laser amplifiers into a single beam using a phase-conjugate mirror. [17].

OBTAINING THE MICRO-BUNCH PULSE FORMAT IN THE OPTICAL BEAM

As discussed earlier, the required pulse format varies from machine to machine but, for the sake of simplicity, we'll take a nominal 60 or so micropulses with a 2 nsec separation (500 MHz) at a macropulse repetition rate of 180 Hz. In this section we discuss various ways to obtain this optical pulse format.

Passive approach

The simplest technique to obtain a long train of laser pulses with short spacing between pulses is to use a cascading string of beam splitters and optical delay line combinations, each of which adds a replica of the input pulse or pulses to the back end of the pulse train so that the length of the train increases arbitrarily. The length of each delay line must double from one to the next. This is shown schematically in Fig. 2. A related kind of optical multiplexing has been used in high-energy KrF lasers where effective pulse lengths must be long to efficiently extract the energy from the laser pump source.[18] By inspection of Fig. 2, one can see that to obtain a 2 nsec pulse separation, the length of each side of the first delay line must be 1 nsec which is about 30 cm. If one follows the pulse through m delay lines, one sees that the number of pulses coming out is 2^m all uniformly spaced at twice the unit length of the first line, i.e. a 2 nsec for our example. Moreover, if all the beam splitters have 50% transmission and 50% reflection, then all the pulses are of equal amplitude. Finally, since two identical pulse trains are

needed anyway (one for the electrons and one for the positrons), the final beam splitter does not represent a loss of optical power.

For our example of 60 or so pulses, we would use $m = 6$ delay lines requiring a total of $3m+1 = 19$ optical elements. A minor difficulty with this approach is in that all these optical elements must be precisely aligned to ensure not only that the beams overlap axially but also that the output beam is perfectly periodic in time. In principle this could be accomplished to arbitrary precision by an adaptive-optics approach where a computer positions each optical element until the output is just right.

The output energy per pulse is limited by the damage threshold of the first element. For our example, the output energy would be $(64 \times 2)^{-1}$ of the damage threshold (in J/cm^2) times the beam area. For our 1 J/pulse needs at the conversion point, and accounting for losses in the compressor and other downstream optics, the incident energy would need to be around 200 J. One normally thinks of a damage threshold of $>5 \text{ J}/\text{cm}^2$ for dielectric mirrors and beamsplitters for single or low-repetition-rate pulses suggesting that this optical arrangement could work at high power (after the amplifiers) if the mirror area is $> 20 \text{ cm}^2$. However, it is not clear what the true damage threshold is for beams with a 500 MHz internal structure and high average powers. Thermal distortion of the flatness of optics (due to small but finite absorption) may force one to minimize the number of optics after the amplifiers. This, as well as energy extraction considerations, would favor putting the multiplier on the front end of the system.

Active approach

A second approach is to accumulate pulses from a lower repetition source into an accumulator cavity thus effectively multiplying the pulse frequency. This is illustrated in Fig. 3. The master oscillator of the laser source naturally produces a train of pulses but with a typically frequency of $f_{\text{osc}} \approx 50\text{--}100 \text{ MHz}$. Suppose the oscillator produced pulses at the k^{th} subharmonic of the desired frequency f_{out} ($f_{\text{out}} = 500 \text{ MHz}$ in our example of 2 nsec bunch spacing) so that $f_{\text{osc}} = f_{\text{out}}/k$. For a 50 MHz oscillator, k would be 10. If this pulse train is injected into an accumulator cavity with round-trip frequency f_{accum} equal

to the $(mk \pm 1)^{\text{th}}$ subharmonic of f_{out} , where m is an integer greater or equal to 1, then the bunches in the accumulator cavity will stack up at f_{out} . In other words, we want $f_{\text{accum}} = f_{\text{out}} / (mk \pm 1)$ so that $f_{\text{osc}} / f_{\text{accum}} = m \pm 1/k$. The number of pulses N in the accumulator cavity, once it is filled, is $N = f_{\text{out}} / f_{\text{accum}} = mk \pm 1$. Going back to our example and taking the positive sign, we could accumulate 11, 21, ..., or 61 pulses in the cavity. We initially wanted 60 or so pulses to match to the 120 nsec rf pulse length. A difficulty with this approach is the need to actively (and rapidly) switch in the pulses to avoid losses to the previously injected pulses. Alternatively, one could open the "gate" (the Pockels cell) into the cavity partially so that pulses can leak in and then compensate for the inevitable leaking out with a section of gain as shown in Fig. 3.

A third alternative for obtaining the long train of pulses is to keep m small, i.e. keep the length of the accumulator cavity short and produce a short train of pulses at f_{out} . This train can be regeneratively amplified and multiplied later in that same cavity or in another separate regenerative amplifier cavity. The idea is illustrated in Fig. 4. If the input and output gates are closed—trapping the pulse train inside the cavity—then the pulse can be efficiently amplified through many round trips of the cavity by turning on a high-gain section within the cavity. Once the stored energy in the gain medium is nearly exhausted, the output gate can be partially opened and the pulse train allowed to leak out over several round trips. In principle, by modulating the transmittance of the output gate and the temporal gain profile, an arbitrary pulse envelope can be generated. This could be an important advantage of this scheme over the passive scheme which generates a temporally uniform envelope. This advantage comes from the fact that upon later amplification the pulse train envelope will necessarily distort in time. This active pulse generator can pre-compensate for this gain-saturation effect resulting in a more uniform output train of pulses at the 1 J per pulse level. However, one could also pre-compensate the passive scheme also by sending the outputs through a variable-transmittance device.

We have described a few ways to generate the desired pulse train which are probably most suitable for low power stages of the system. These would be followed by one of the amplification schemes described in the next section.

The TESLA design is difficult because the length of the macropulse ($\approx 800 \mu\text{sec}$) is longer than the fluorescent lifetime of a typical laser glass ($\approx 330 \mu\text{sec}$) so that some re-pumping during the macropulse is necessary. This is non-trivial since the pump source must deliver on the order of 1 J for each micropulse which, at 1 μsec per pulse, is a peak power of 1 MW albeit with a low duty cycle. Another difficulty is that the use of many micropulses per macropulse and the huge spacing between micropulses probably eliminates the possibility of using the passive multiplier. This beam may have to be split up into 10 or more beams resulting in 10 or more μsec between micropulses. This will allow more time to re-pump the gain medium between micropulses, dropping the peak power requirements an order of magnitude. The beams can then be interleaved back to 1 μsec spacing after amplification using some beam combining technology and this whole process would repeat at the desired 10 Hz. We will not explicitly discuss TESLA further in this paper.

SOME POSSIBLE LASER CONFIGURATIONS

The total optical power needed in the NLC design ranges from 5 to 15 kW depending on what set of parameters one takes. In this section we will address three approaches to tackle the problem of high average power. The first approach is the brute force approach where you assume an amplifier is available at this power. In the second approach, one uses several lower power amplifiers and recombines the separate beams in some lossless way. The third approach is to recycle the beam in some way so that the average power requirements from the laser actually drop. This brings up the issue of the configuration of the mirrors at the IP. Several ideas for this geometry will also be described.

In all the following scenarios, we assume that we have an oscillator which is phase-locked to the rf of the accelerating structure to within a psec (this is the state-of-the-art). This oscillator, perhaps a cw mode-locked Ti:sapphire oscillator which can produce ≈ 50 fsec pulses at wavelengths between $0.7\text{--}1.1\text{ }\mu\text{m}$, [19] is followed by a grating stretcher which selects a certain bandwidth and stretches it out in time to somewhere between 300 and 1000 psec. [20] This stretched pulse is injected into a Ti:sapphire regenerative amplifier [21] providing a 50 MHz train of about 10 pulses, each at the mJ level. The regenerative amplifier reps at 180 Hz matching the rep rate of the rf linac. For the passive pulse train arrangement discussed above, only one of the 10 pulses would be switched out of the regenerative amplifier and injected into the optics to be multiplied by 64. For the active pulse multiplier approach, all 10 pulses would be sent into the accumulator cavity.

Single laser-amplifier configuration

The most straight forward approach is to take the entire macropulse (≈ 64 pulses separated by 2 nsec) generated by either the passive beamsplitter arrangement or by the leaky regenerative cavity arrangement described earlier and amplify the entire 130 nsec envelope until each micropulse has about 1 J of energy. Due to gain saturation, the initial envelope may need to be tailored in order for the amplified envelope to be more or less flat in time. All this will occur at 180 Hz.

The peak intensity of the 1 J, 1 nsec pulse is not very high by laser standards (prior to compression) and it can therefore be propagated at a small beam diameter, say, 1.0 cm^2 , limited by non-linear effects in the gain medium [22]. The moving slab laser should be quite effective in dissipating the thermal gradients leading to beam distortion since the ratio of pumped volume to total volume can be made very small. The required gain is quite modest. For the passive arrangement, a 10 mJ input pulse gets divided by 64 and then re-amplified to a few Joules requiring a net gain of around a few times 10^4 . A typical gain per pass value of 10–15 requires only 4 passes of the amplifier or single passing of 4 amplifiers. Multiple amplifiers in series does not necessarily reduce the total

thermal distortion compared to multipassing a single amplifier since each amplifier must be pumped just as hard to obtain the gain of 10. The multipass system does, however, have a much higher efficiency and lower complexity. After being amplified, this train of stretched pulses is compressed to a train of psec pulses by reflecting off a pair of diffraction gratings.[23]

If phase conjugate mirrors or adaptive optics can be used to compensate for the thermal distortion in the moving slab scheme, or if the proposed moving disk scheme[9] is further developed, then these schemes should be capable of providing the ≈ 10 kW of near diffraction limited, 1 J per 1 psec pulses needed for the gamma-gamma collider.

Recombining several lasers

An alternative to the brute force approach is to divide the task of providing the high power among several amplifiers. The oscillator pulse can be split up somehow and recombined in a lossless way after amplification. The price to pay is in additional optical complexity. One such design is shown in Fig. 5. The 50 fsec Ti:sapphire laser we have been considering has a 250 Å bandwidth which is about 20 times the bandwidth of our desired transform-limited 1 psec pulse. One could in principle subdivide this oscillator pulse into 20 beamlets, each with a slightly different center frequency, and amplify them separately and recompress them separately into 20 pulses of 1 psec duration while maintaining perfect synchronism between the pulses. This would drop the average power requirement for each amplifier by a factor of 20. In practice, even if there were only 5 or 10 beamlets, the amplifier requirements would drop into the kW class rather than the 10 kW class taking a great burden off the thermal distortion compensation techniques. Note that since the center frequency of each beamlet is different, one must use either a very broadband amplifier material or use a variety of more narrowband materials but with their gain profiles spread out over a range of frequencies. A Nd:glass system at 1 μm would fall into this latter category requiring a mixture of different glasses to provide gain to all the beamlets. A laser system operating near 0.8 μm could possibly get by with just

Cr:LiSAF which has a very wide gain profile. However, the Cr:LiSAF technology is in its infancy whereas the Nd:glass technology is quite mature.

In the implementation sketched out in Fig. 5, a conventional pulse stretcher[20] is used to both stretch the 50 fsec pulse in time and to subdivide it into several beamlets. Each beamlet has a pulse length proportional to its bandwidth which can be typically 10 psec per Å. For a beamlet bandwidth of, say, 30 Å, the pulse width in the amplifiers would be 300 psec. Each beamlet is independently multiplied and amplified as in the single laser-amplifier scheme discussed above. The optical delay between beamlets is adjusted so that, in time, the beamlets become either interleaved or stacked end-to-end as they leave the compressor. Therefore, each beamlet need only contain a fraction of the total number of micropulses. In our example of 64 micropulses per macropulse, one could use 8 beamlets each with 8 pulses. In this case, a 10 kW beam needs only 1.3 kW amplifiers.

Mirror configuration at the IP and recycling

In the section on laser requirements earlier, we arrived at the 1 J in 1 psec by, among other things, taking $2\beta_\gamma \approx l_\gamma \approx l_e$. For a 1 psec pulse, $l_\gamma = 300 \mu\text{m}$ so that the Rayleigh length $\beta_\gamma \approx 150 \mu\text{m}$. For a gaussian beam, the associated spot size is about $w_0 \approx 7 \mu\text{m}$ requiring a focusing f/number of f/6 or a half-angle of about 80 mrad. The available angle within the detector is limited. In his talk at this workshop, F. Richard showed a JLC proposed detector design with the mask positioned at a 10° angle with a clear half-angle behind the mask of about 150 mrad. Therefore, the laser needs something like half of the linear angle in the beam pipe so that positioning of the mirrors is a non-trivial task. This should be kept in mind in the following discussion on possible mirror configurations.

A gamma-gamma collider requires two conversion points (where the laser beams Compton scatter off the electron or positron beams) and therefore two independently-pointable laser beams. The laser beam is insignificantly perturbed in traversing the conversion point since there are about 10^8 incident photons per incident electron. The

second laser beam could therefore be the transmitted laser beam from the first conversion point. This would eliminate the need for a second laser beam line. An example of this recycling is shown in Fig. 6(a). The reflected beam can exit through the same vacuum window it enters, simplifying the laser beam transport somewhat. The first one or two optical pulses would be wasted since the returning beam will not make gammas for an IP-to-mirror round trip time.

In the case of an $e^- \gamma$ collider where there would be only one conversion point, a high-Q optical "storage box" could be used to repetitively collide a single laser pulse with the train of electrons.[24] This cavity need be filled only once per macropulse, dropping the average power requirements for the laser source dramatically.

One of the key issues is the survivability of the mirrors in the detector environment. The mirror must remain highly reflective in order to handle the multi-kW loading from the optical beam. By using mirrors at grazing incidence as illustrated in Fig. 6(b), both the input beam and the halo of post-collision debris are spread out over a much larger area on the mirrors. However, the reflectivity of the s- and p-polarized light is substantially different from metal surfaces at grazing angles of incidence[25] (p-polarized light has a lower reflectivity over all angles of incidence). Thus, without some correction, circularly polarized light will come out elliptically polarized. Perhaps the beam can be pre-conditioned to take this into account or the mirror can be coated to enhance the p-polarization reflectivity.

If the halo around the spent particle beams is the limiting factor in the mirror survivability, one could move the mirrors off axis as shown in Fig. 6(c). In this case, the crossing angle will limit the effective length of photons that each electron sees. However, this loss could be partially compensated by applying a front-to-back tilt of the light pulse (as illustrated in Fig. 6(c)) and therefore having a "crab crossing" at the conversion point.

AREAS IN NEED OF R&D

In summary, there are no obvious show-stoppers in the application of conventional laser technology to the needs of a gamma-gamma collider. However, there are many questions that still need to be addressed and technologies which need to evolve beyond today's state-of-the-art. Below is a brief list of some of these areas of research and development that were identified during the meeting of the working group.

Average power laser technology

Improved thermal properties of lasing materials.

Develop moving-slab and moving-disk amplifier technologies.

Demonstrate psec and diffraction limited pulses @ multi-kW levels.

Extend psec, diode-pumped lasers out to 3 μm .

Investigate frequency-doubled CO_2 technology.

Beam quality improvements achievable by phase-conjugation technology with 1 nsec, broadband pulses.

Optics

Damage threshold of optics for these unusual long multibunch pulses.

Radiation from particle beam: effects on optical damage threshold and absorption.

Polarization control in a grazing-incidence optical arrangement.

Details of crab-crossing optical arrangement.

Halo around spent e^+/e^- beams

Calculate composition and angular distribution.

Determine likely impact to surface and bulk of optics.

Strategies for protecting optics from radiation and debris.

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FIGURE CAPTIONS

Fig. 1. A schematic of a zig-zag slab MOPA (master oscillator power amplifier) laser system. The double-passed laser is diode pumped with a typical "wall-plug" efficiency of 10%.

Fig. 2. A passive pulse multiplier composed of optical delay lines which increase in length by a factor of two each time. The pulse trains in the figure are not drawn to scale. The pulse-to-pulse separation is actually twice the unit length of the first delay line.

Fig. 3. An accumulator cavity acts like a pulse multiplier since it can stack up a large number of pulses at any desired interpulse spacing from a lower repetition-frequency source.

Figure 4: A regenerative pre-amplifier for amplifying and shaping the long output train of pulses prior to the final stages of amplification. Once the cavity is filled from the upstream source (multiplexer or accumulator cavity), the input gate is closed and the trapped light is repetitively amplified in the high gain material. As the gain begins to saturate, the output gate is partially opened to leak out the desired envelope of micropulses.

Figure 5: Schematic of a frequency-multiplexing scheme to distribute the high average power requirements among a number of amplifiers running in parallel. The resulting pulse trains out of each amplifier are appropriately delayed so that they will add up in series, i.e., one pulse train following another.

Figure 6: Three possible arrangements of the laser focusing optics within the vertex detector. (a) An optical arrangement to re-use the laser beam from the first conversion point at the second conversion point. (b) Grazing incidence optics to reduce the fluence of the laser and the collision debris on the mirrors. (c) Mirrors are moved out of the electron-positron beamlines and the angular mismatch is compensated by a "crab crossing" of the optical beam with the particle beam.

Figure 1

Figure 2

Accumulator cavity

Figure 3

Regenerative amplifier

Figure 4

Figure 5

Figure 6