# A LASER PULSE TRAPPER FOR COMPTON BACKSCATTERING APPLICATIONS*

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*Abstract*

The repetition rate for high peak power, short pulse lasers used in Compton backscattering for production of x-rays, positrons and other reaction products is typically much lower than that for the electron bunches. The production rate can be increased by trapping a laser pulse [1] in a delayed line for repeated collision with a plurality of electron pulses. The temporal and spatial characteristics of a trapped laser pulse are calculated including effects of dispersion, self phase modulation and self focusing through the delay line optics. For ultra short laser pulse, the DULY Box includes a pulse stretcher and a pulse compressor in order to minimize non-linear effects. Experiments are planned to verify and optimize the box design.

## INTRODUCTION

The DULY Box [1] is a device which traps a laser pulse in an optical delay line and allows multiple collisions of the laser pulse with electron multibunches. It can be used to enhance the yield of Compton backscattering products such as x-rays, positrons and gamma rays. Enhanced production of positrons or gamma rays can increase the luminosities of future linear colliders. The DULY Box is also potentially applicable to other reactions whose yields depend on the collision frequency with a high intensity laser pulse, e.g. laser isotope separation. The optical delay line can be implemented either in a linear configuration or a ring configuration [2].

The goal of the DULY Box is to preserve the properties of a single laser pulse (temporal and frequency profiles, energy, spot size, focal point, etc.) for as many times of interaction with the target as possible. To achieve this, the design of the DULY Box must avoid linear (group velocity dispersion) and non-linear optical effects (self phase modulation, self focusing) which could otherwise destroy the beam. This is accomplished either by operating in a limited laser parameter space (low energy, long pulse) or by stretching and subsequently recompressing a high-energy, short laser pulse within the delay line. A properly designed amplifier to replenish the energy loss in each round trip is an integral part of the device.

## ANALYSIS OF A LONG PULSE VERSION

An analysis of the DULY linear and ring cavities was performed to determine the parameters under which a high peak power laser pulse may be trapped without destroying itself during the propagation in the cavity.

*Gaussian vs. Flat-Top Spatial Distribution*

Figure 1 compares the near- and far-field profiles of equal-energy Gaussian and flat-top ($10^{th}$ order super-Gaussian) near-field modes. The size of each near-field beam is set to minimize diffraction effects when passing through a 5-cm diameter aperture. As can be seen, the flat-top intensity is 4.5 times less than the Gaussian, leading to greatly reduced nonlinear effects upon propagation through material. The far-field (focal) distributions show the diffraction-limited beam size after focusing with a 10-cm focal length lens. Although a significant fraction (16%) of the energy ends up in the secondary lobes, the flat-top still produces a focal intensity 1.4 times that of the Gaussian. This, coupled with the lower near-field intensity and uniform profile for amplification, make the flat-top the spatial mode of choice for this application even though it must be relay-imaged.

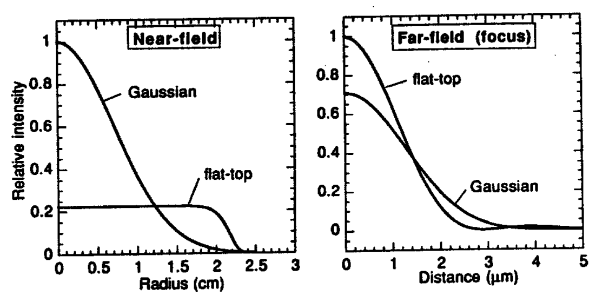


Figure 1 Near- and far-field spatial profile of equal-energy beams which pass through a 5-cm diameter aperture with minimal diffraction and the focused profile of each beam.

*Group Velocity Dispersion (GVD) and Self-Phase Modulation (SPM)*

A pulse envelope with central frequency $\omega_o$ will propagate through material with group velocity $v_g = \partial\omega/\partial\beta(\omega)$, where $\beta(\omega) = n(\omega)\omega/c$ is the propagation constant. If the pulse is composed of many frequency components (as is a short pulse), the different frequencies will propagate with different velocities. An initially transform-limited pulse will be stretched in time by GVD.

The index of refraction of a material depends on the laser intensity,

$$n(I) = n_0 + n_2|E|^2 = n_0 + \gamma I ,$$

where $n_0$ is the ordinary index of refraction, $n_2$ the nonlinear index of refraction, $E$ the pulse electric field, $\gamma$ the nonlinear index coefficient, and $I$ the laser intensity.

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This intensity-dependent index change produces a variation of phase in time across a pulse as it propagates through material. SPM leads to spectral broadening of optical pulses through the generation of additional frequency components. Since only the phase of the pulse varies in time, the pulse intensity as a function of time remains the same. However, these additional frequency components may cause temporal broadening through group-velocity dispersion. A measure of the nonlinear phase accumulation of a pulse as it propagates through a length $L$ of material is given by the $B$-integral,

$$B(I) = \frac{2\pi}{\lambda}\int_0^L \gamma I dz ,$$

where $\lambda$ is the wavelength of light and $z$ is the propagation direction. Noticeable spectral distortion begins at $B \approx 1.5 - 2.0$.

*Pulse Propagation*

The nonlinear Schrödinger equation for the complex pulse amplitude $A$ describes propagation through material [3],

$$i\frac{\partial A}{\partial z} = -\frac{i}{2}\alpha A + \frac{1}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \gamma |A|^2 A .$$

Loss and gain are included in the term with $\alpha$. The second term on the right hand side gives the group-velocity dispersion (higher order terms in $\beta$ can also be added) and the last term includes nonlinear effects with nonlinear coefficient $\gamma$. We solve the above equation with the split-step Fourier method [4], where the dispersion and absorption terms are separated from the nonlinear terms. The equation is valid for pulse durations ≥ 50 fs. For shorter pulses, higher order terms must be included.

*Analysis of Ring Cavity*

We will first calculate the effect of GVD in a relay-imaged ring cavity assuming a transform-limited 1.06-μm input pulse of a given duration, no SPM, and material pathlength of 16 cm (KD*P Pockels cell: 3 cm, fused silica lenses/windows: 3 cm, amplifier: 10 cm). Figure 2 shows the increase in pulse duration, including also the higher-order dispersion terms, as the pulse circulates in the ring cavity.

If the initial pulse is not transform-limited it will lengthen at an increased rate corresponding to its excess bandwidth. To maintain a constant intensity at the interaction point the pulse duration must be greater than approximately 5 ps. In this regime the number of interactions will be limited by the nonlinear phase accumulation or $B$-integral.

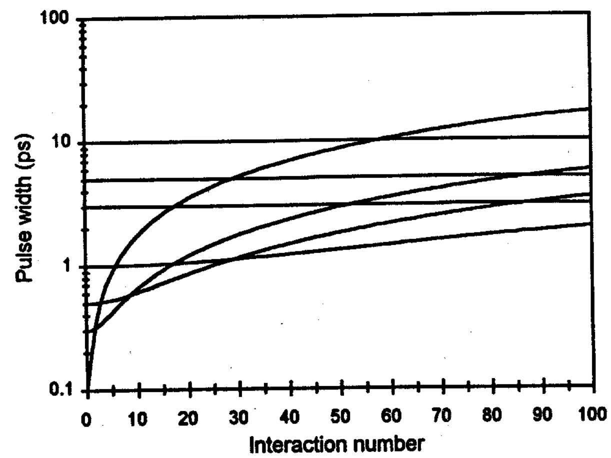
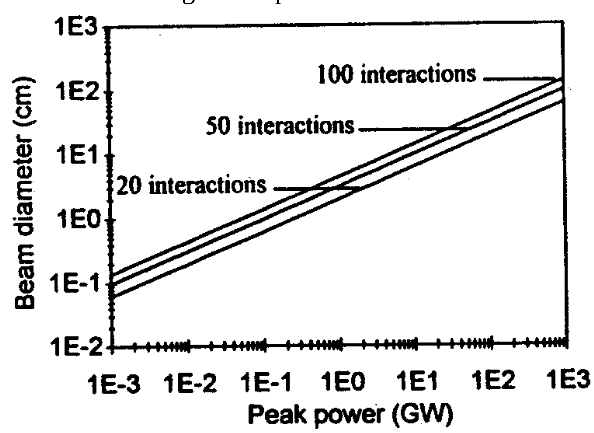



Figure 2 Plot of pulse duration vs. number of interactions for various starting values of pulse lengths.

An approximate expression for the number of interactions ($N$) possible in the above ring cavity as a function of pulse duration ($\tau_p$, in picoseconds), energy ($U$, in Joules), diameter ($D$, in cm), wavelength ($\lambda$, in μm), and desired maximum $B$-integral (in radians) is given by

$$N = 0.036\frac{B\lambda D^2\tau_p}{U(13+0.5D)} .$$

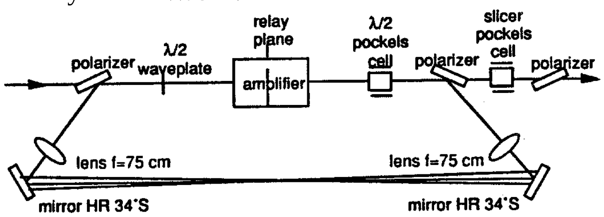
Using the above equation with a target $B$=2 to limit SPM and self-focusing, we can plot the beam diameter required to achieve a given number of interactions as a function of desired peak power. To trap 1-J, 20-ps pulses (50 GW) for 100 interactions, the beam diameter is 30 cm. The above equation is only a rough guide; as the beam becomes larger the optics need to be thicker.




## EXPERIMENTAL DESIGN

A small-scale experiment has been designed to trap 10-20 ps pulses for many (40+) passes without destroying the pulses either temporally or spatially. A flat-top spatial profile with a beam diameter of 6.5 mm was chosen in order to use standard size 9-10 mm diameter optical components (amplifier rod, Pockels cells). This allows trapping of pulses with energy on the order of 1.0 mJ, depending on the number of passes desired.

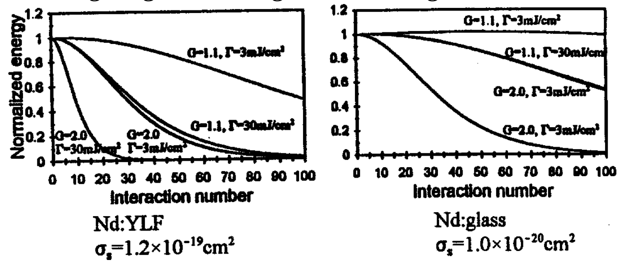
A relay-imaged ring cavity with a round-trip time of approximately 10 ns is shown below. To trap the pulse, the Pockels cell is turned on to its half-wave voltage with rise time < 5 ns. The voltage can be varied while the pulse is trapped to maintain constant intensity at the interaction point. The pulse is switched out for measurement after the desired number of round trips by turning off the Pockels cell. Since a small fraction of light will leak out on each round trip, a slicer Pockels cell is necessary to separate the desired pulse from the sum of the leakage pulses before the diagnostics. The focused spot in the cavity is approximately 300 μm giving an intensity of $10^{11}$ W/cm$^2$.




In order not to extract the stored energy from the amplifier too quickly, an amplifier medium with a high saturation fluence ($\Gamma_s = h\nu/\sigma_s$) or low stimulated emission or gain cross section ($\sigma_s$) is desired. The circulating fluence should then be maintained at a level well below the saturation fluence. In this analysis we assume the amplifier is pumped once before the circulating pulse arrives. It is also possible to laser-pump the amplifier each round trip. The parameters for some common amplifier materials are listed below.

| Gain medium | Wavelength (nm) | Gain cross section (cm$^2$) | Saturation fluence (J/cm$^2$) |
|---|---|---|---|
| Nd:YAG | 1064 | $2.8\times10^{-19}$ | 0.7 |
| Nd:YLF | 1053 | $1.2\times10^{-19}$ | 1.6 |
| Nd:glass | 1053/1064 | $1.4\times10^{-20}$ | 4.7-19 |
| Ti:sapphire | 1053 | $2.8\times10^{-20}$ | 6.7 |
| Ti:sapphire | 800 | $3\times10^{-19}$ | 0.8 |
| Yb:glass | 1000-1070 | $0.8\text{-}4.0\times10^{-21}$ | 50-230 |

The initial gain is determined by the cavity losses, typically 10% per round trip, giving a gain G=1.1. Gains per pass higher than G=2 may be necessary if a pulse stretcher and compressor is included in the ring (see below). In the figures below, we show the calculated pulse energy (normalized) as a function of number of interactions for amplification in Nd:YLF and a low-gain Nd:glass using initial gains of 1.1 and 2.0 and input fluences of 3 mJ/cm$^2$ (1 mJ, 6.5 mm diameter) and 30 mJ/cm$^2$. As can be seen, even at very low circulating fluence the energy extraction in Nd:YLF is too rapid to maintain constant energy. The smaller gain cross section of Nd:glass allows better energy balance in trapping the pulse, and a still smaller cross section (Yb:glass) would allow higher gains and higher circulating fluence.




## DULY BOX FOR ULTRA SHORT PULSE

To trap a recirculating, ultra short (< 1 ps), high power laser pulse in a delay line for repeated interaction with a high rep-rate electron beam, the DULY Box may be installed *in place of* a pulse compressor in a chirped pulse amplification (CPA) high power laser system [2]. A stretched, long pulse, high power, linearly polarized laser beam enters the box via a polarizer. The pulse is then focused and compressed spatially and temporally to interact with an electron pulse. After interacting with the electron pulse, the laser pulse is again stretched and its energy replenished by an amplifier before starting the next round trip. The stretched laser pulse avoids the nonlinear problems as it goes through a dispersive medium and maintains its energy by the loss-compensation amplifier during each round trip. The system implementation of this box uses similar pulse compression and pulse stretching methods as in the standard CPA, except the diffraction gratings should have a very high efficiency and very low loss. Work is in progress on the design and analysis of such a system for an enhanced positron and gamma source for possible linear collider applications.

## CONCLUSION

We have analyzed the effects of group velocity dispersion and nonlinear index of refraction upon a laser pulse trapped in a recirculating delay line, and have provided a simple relation between the laser beam size required to stay below a given *B*-integral limit as a function of input pulse parameters and amount of material it passes through.

## REFERENCES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