

# PULSE-BURST CO<sub>2</sub> LASER FOR HIGH-BRILLIANCE COMPTON LIGHT SOURCES\*

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## Abstract

We propose a novel architecture for a mid-IR, high-repetition, kilowatt-class, CO<sub>2</sub> laser system operating in a pulse-burst regime and its implementation in Inverse Compton Scattering (ICS) sources of x-ray and gamma-ray radiation. Different types of particle accelerators are considered for conversion to such ICS sources, including an energy recovery linacs and a synchrotron storage rings. The expected ICS performance parameters are compared with earlier proposals where CBETA and DAΦNE accelerators have been paired with near-IR, mode-locked solid-state lasers operating at a multi-megahertz repetition rate. A considerable increase in acting laser energy attainable in our CO<sub>2</sub> laser based scheme, combined with an order of magnitude higher number of laser photons per Joule of energy allows maintaining a similarly high average flux of produced hard x-rays while the peak flux and brilliance will be raised by three to four orders of magnitude compared to aforementioned schemes based on near-IR lasers.

## INTRODUCTION

X-ray and gamma sources based on inverse Compton scattering (ICS) from relativistic electron beams colliding with laser pulses promise to become a relatively compact and affordable complement to conventional synchrotron light sources (SLSs). Simultaneously, ICS sources offer new capabilities, including the opportunity to move further into hard x-ray and gamma spectral ranges not covered by SLSs.

Starting with proof-of-principle demonstrations [1], the ICS concept is being materialized in a working commercial LYNCEAN Compact Light Source [2] operating at soft x-rays and in gamma sources under construction, such as KEK [3] and ELI-NP [4]. Several proposals have been put forward to convert existing or newly constructed electron accelerators to high-power ICS sources [5, 6]. Most of those ICS projects are based on combining electron beams with pulses from mode-locked, near-infrared (NIR),  $\lambda_L \approx 0.8\text{-}1\ \mu\text{m}$  solid-state lasers. Such lasers can operate at a multi-MHz repetition rate matched to RF e-beam sources, such as a synchrotron and a superconducting energy recovery linac (S-ERL).

Although mode-locked quasi-CW lasers have a relatively low average power on the order of 100 W, their ability to drive an intense ICS can be enhanced by orders of magnitude via stocking laser pulses inside a high-finesse

Fabry-Pérot cavity. Tuned in resonance with the laser repetition rate, such a field-enhancement cavity (FEC) accumulates multi-kilowatts of average laser power spread between short picosecond pulses. Synchronized with counter-propagating electron bunches produced by contemporary high-current accelerators, such laser beams might allow  $\sim 10^{12}$  ph/s average x-ray fluxes. This makes ICS sources potent for many applications covered by SLSs, such as providing penetrating radiation for structural studies of materials and biological objects, typically in a spectral range shifted towards harder x-rays.

However, currently limited by the 0.1-1 mJ energy per laser pulse circulating inside an FEC, single-shot x-ray yields from such ICS sources don't exceed thousands of photons per pulse, which is usually below the requirements for pump-probe studies. Enhancing the number of radiated x-rays per pulse at a given accelerator current would require a much higher number of laser photons per pulse compared with present NIR FEC technical capabilities. To this end, we propose here an approach based on state-of-the-art short-pulse CO<sub>2</sub> lasers.

The joule-class pulsed CO<sub>2</sub> lasers can deliver high concentrations of laser photons producing instantaneous picosecond x-ray fluxes that exceed those attained with NIR-FEC based ICS sources by several orders of magnitude. This positions CO<sub>2</sub> laser-based ICS sources for studying dynamic processes at the temporal and energy scales of phase transitions, chemical reactions, and molecular interactions.

## CO<sub>2</sub> LASER DRIVER FOR ICS SOURCE

Commercially available high-pressure pulsed CO<sub>2</sub> lasers can operate at a repetition rate of up to 300 Hz [7, 8]. Combined with the novel approach of multiplying the repetition rate in the pulse-burst mode, which we propose here, this can bring us up to an effective repetition rate of  $>10$  kHz. This is still by orders of magnitude below the multi-MHz repetition rate of RF accelerators and mode-locked solid-state lasers paired to them. However, a much higher pulsed energy attainable with high-pressure CO<sub>2</sub> lasers, coupled with a higher photon number per unit of the laser energy, allows us to reach the same average x-ray photon intensity as an NIR FEC approach despite the difference in the repetition rate.

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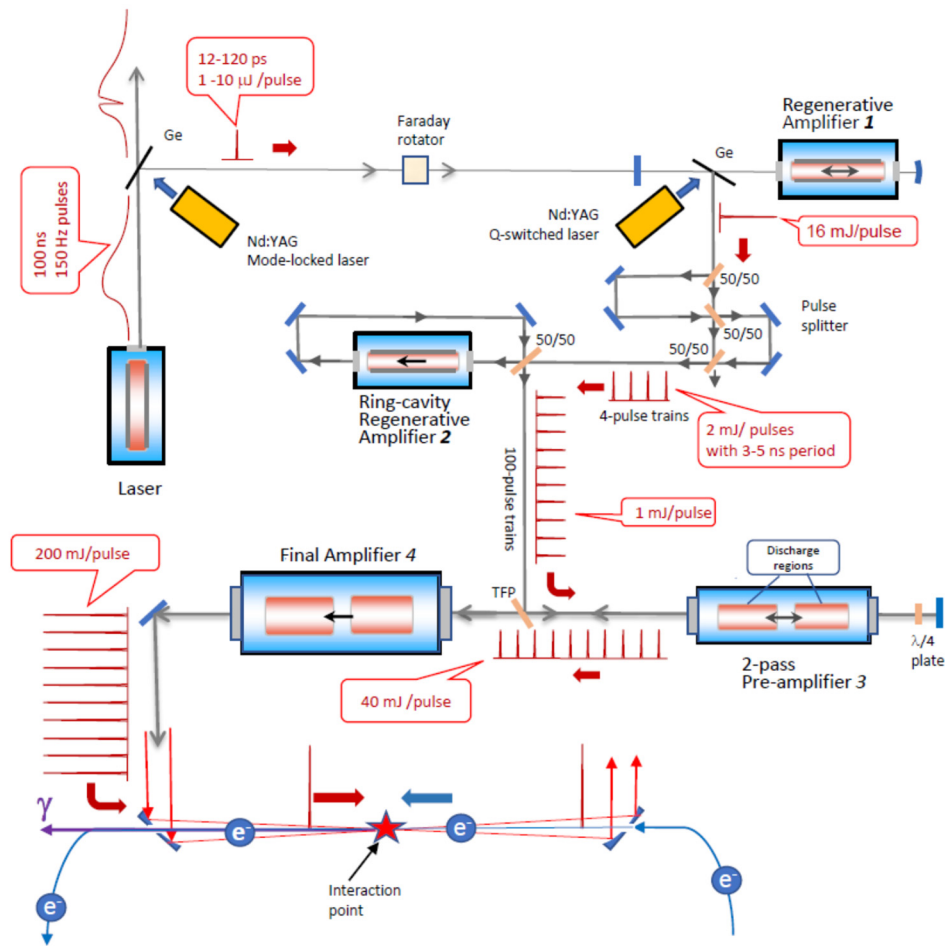


Figure 1: Principle optical diagram of the proposed LWIR laser system and an ICS interaction region (note that pulse duration is measured at FWHM; TFP stands for thin-film polarizer).

Figure 1 illustrates our proposed conceptual design of a high-repetition CO<sub>2</sub> laser system configured to deliver laser beams that allow us to maximize both *peak* and *average* ICS x-ray yields while also not degrading the bandwidth projected for ICS based on NIR lasers in [5, 6]. A 9.2- $\mu\text{m}$ , bandwidth-limited, linear polarized seed laser pulse chosen according to the particular accelerator bunch format between 12-120 ps FWHM and with the initial energy 1-10  $\mu\text{J}$  can be sliced from a  $\sim 100$  ns,  $\sim 100$  mJ output of a 150-Hz TEA CO<sub>2</sub> laser oscillator using a semiconductor optical switching method based on a Ge Brewster wafer with the reflection control by an Nd-YAG mode-locked laser [9].

This picosecond seed pulse is sent into a regenerative amplifier based on a UV-pre-ionized transverse electric discharge that brings its energy to 16 mJ. To avoid the pulse's spectral envelope modulation and narrowing upon amplification resulting in the pulse splitting and stretching in time, the laser amplifier operates with an isotopic C<sup>16,18</sup>O<sub>2</sub> mixture at the 10-atm pressure that ensures a sufficiently broad and smooth gain spectrum [10]. An amplified pulse is extracted from the regenerative cavity using another semiconductor optical switch. With an optical splitter/recombiner we produce a short train of four pulses

with the time interval between pulses matching the electron bunch train period,  $T_b$ , which varies between 3 to 5 ns for electron accelerators considered here. With the 50% optical losses on this splitter/recombiner, we will obtain four 2-mJ pulses.

Then, we seed these pulses into a second regenerative amplifier, which has a ring cavity length at the exact multiple of the bunch period ( $4cT_b$  in our example), that generates trains of  $\sim 100$  pulses at the  $T_b$  period at an average energy of  $\sim 1$  mJ/pulse, which are extracted through a 50% coupling mirror. A typical gain envelope with the FWHM  $\approx 1$   $\mu\text{s}$  in such an amplifier allows us to obtain quasi-uniform pulse trains with the  $\sim 500$  ns time envelope.

These trains are further amplified via a double pass through the third CO<sub>2</sub> laser pre-amplifier and a single pass through the final laser amplifier. To further flatten the pulse train envelope, we assume two independently triggered discharge sections per each of the last two amplifier stages. Optimizing the time delay between discharges in two discharge sections allows us to prolongate a quasi-stationary gain and extract 100 pulse trains with 200-250 mJ/pulse. Simulated pulses from this train are shown in Fig. 2.

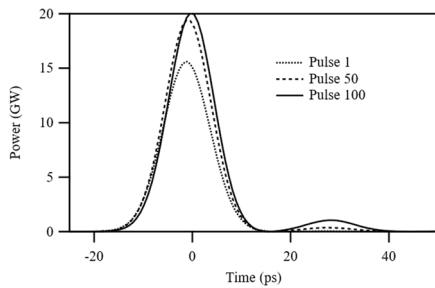


Figure 2: Simulated temporal envelopes for the 1<sup>st</sup>, 50<sup>th</sup> and 100<sup>th</sup> pulses in a train.

A water-cooled, metallic, off-axis parabolic (OAP) mirror with an optical aperture of the diameter  $D = 50$  mm compatible with this power load will be used for focusing the laser beam at the IP. A few-millimetre-diameter central hole in the focusing mirror for the e-beam and ICS beam transmission allows us to put the OAP mirror at the exact counter-propagation geometry to maximize the efficiency of the laser/e-bunch interaction.

## PERSPECTIVE ICS SOURCES BASED ON DAFNE AND CBETA ACCELERATORS

We considered different examples of perspective ICS sources based on a synchrotron accelerator DAΦNE and an S-ERL CBETA, each paired either with a near-IR solid-state laser or with a long-wave-IR (LWIR) CO<sub>2</sub> gas laser. For each of them, we show that a LWIR laser with its 15 kHz cumulative pulse repetition rate can produce average spectral fluxes and brightness competitive with the proposed earlier approach based on a multi-MHz solid-state laser. Simultaneously, this laser driver will provide about four orders of magnitude higher x-ray peak characteristics, making such ICS sources interesting for ultra-fast applications as well.

### CBETA

A 200-mJ LWIR laser pulse focused to  $\sigma_L = 40$  μm carries  $1.3 \times 10^{36}$  ph/(s cm<sup>2</sup>), which is  $10^4$  higher compared to the  $\lambda = 1.06$  μm FEC example [5]. This results in the peak brightness  $\mathcal{B}_p \approx 4 \times 10^{20}$  ph/(s mm<sup>2</sup> mrad<sup>2</sup> 0.1% BW). At the same time, a still substantial 15 kHz cumulative repetition rate of  $\lambda = 9.2$  μm laser pulses allows us to reach high average x-ray yield parameters identical to a multi-MHz FEC-based ICS source. This makes the LWIR-based source equally useful for studies intended for the 1.06-μm-based source but surely in a different spectral range closer to conventional SLSs. Its x-ray coverage, corresponding to 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> passes in the ERL beam arches, will span from 4 keV up to 49 keV. Such a hard X-ray source 100 times smaller in footprint compared to existing or under-construction 3<sup>rd</sup> generation SLSs, can be considered their viable complement, especially at the high-energy end.

### DAΦNE

In addition to having the advantage of a compact footprint, a characteristic it shares with CBETA, the projected DAΦNE ICS source will offer extended spectral

coverage into the gamma range, up to 900 keV, where it can be compared in the peak brightness and repetition rate only to the Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility (see Fig. 3). With its extremely high peak brightness,  $\mathcal{B}_p \approx 2 \times 10^{21}$  ph/(s mm<sup>2</sup> mrad<sup>2</sup> 0.1% BW), the proposed source will be indispensable for dynamic studies in the gamma range that are not covered by conventional SLSs.

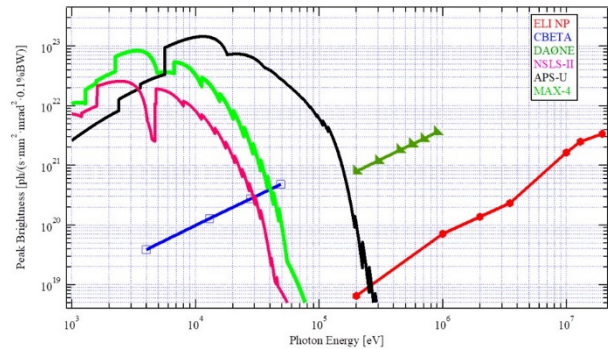


Figure 3: Positioning ICS sources CBETA and DAΦNE based on the LWIR laser driver in terms of their peak brightness in comparison with 3<sup>rd</sup> generation SLSs and ELI-NP.

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