Pulse-Burst CO_2 Laser for High-Brilliance Compton Light Sources

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OUTLINE

Based on available mid-IR CO_2 laser technology, we propose a novel architecture for a kilowatt-class laser system operating in a pulse-burst regime and its implementation in the Inverse Compton Scattering (ICS) x-ray source. Different types of particle accelerators are considered for conversion to such ICS sources, including DAFNE synchrotron storage ring and CBETA energy recovery linac. The expected ICS performance parameters are compared with earlier proposals where the same accelerators have been paired with near-IR solid state lasers operating at a multi-MHz repetition rate [1,2]. A considerable increase in acting laser energy attainable in our 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-four orders of magnitude compared to schemes based on near-IR lasers**. Operating at 50-500 keV photon energy not attainable with contemporary synchrotron light sources, the proposed ICS sources will become indispensable for pump-probe and other ultra-fast material studies that require building up meaningful data sets from a single x-ray pulse.

LASER ARCHITECTURE

A concept for an LWIR laser system for driving a high-brightness ICS source is illustrated in Fig.1. Physical principles of this system are similar to a terawatt-class LWIR laser operated at the BNL Accelerator Test Facility. The main difference is that the laser system proposed here delivers 100 pulses per shot and is designed for a much higher, 150 Hz rep. rate.

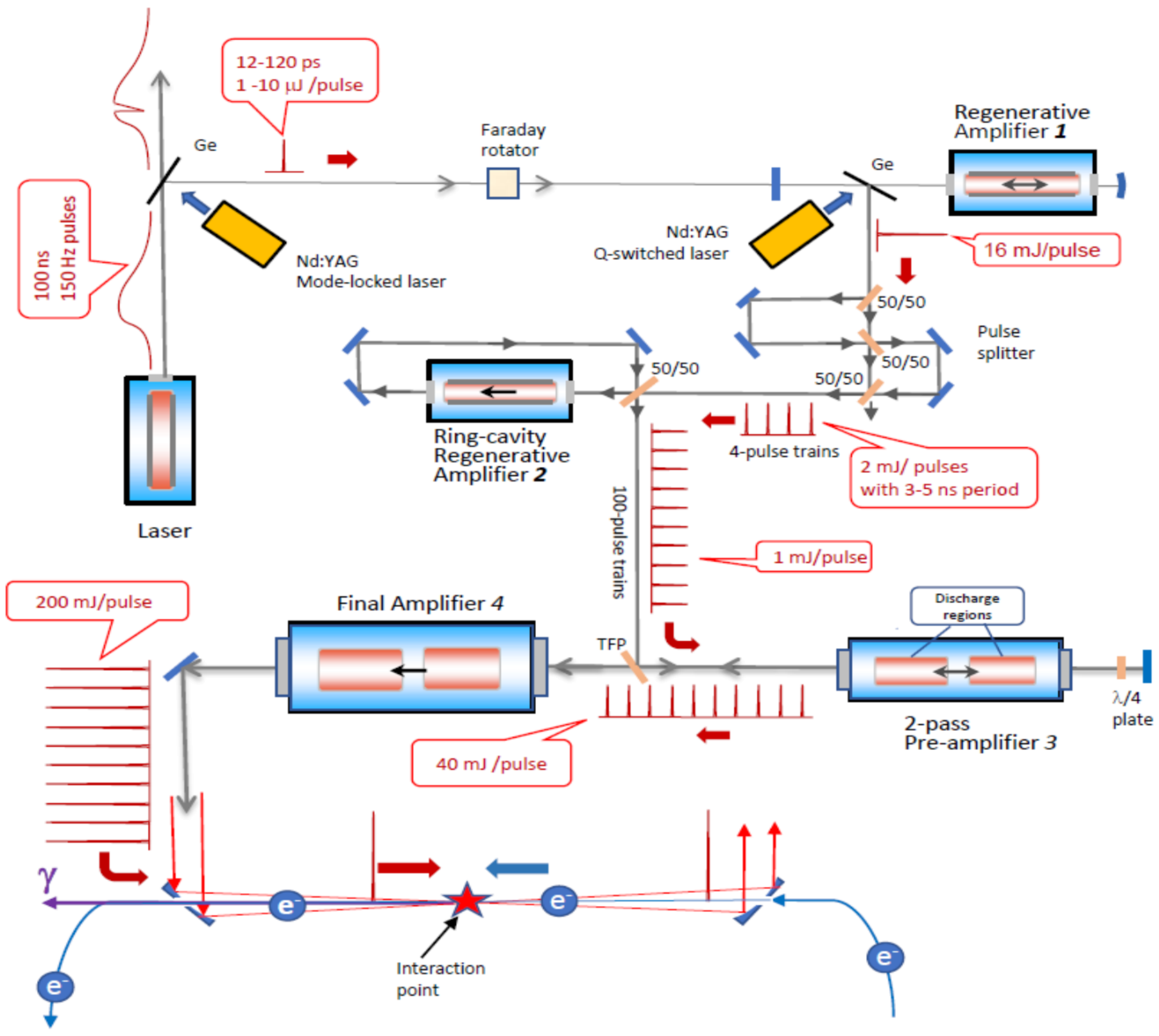

Figure 1. Principle optical diagram of an LWIR laser system and an ICS interaction region (note that pulse duration is measured at FWHM; TFP stands for thin-film polarizer)

Laser model / Parameter	**Preamplifier 1** PAR HP	**Preamplifier 2** PAR HP	**Preamplifier 3** PAR LAHP (2 sections)	**Final Amplifier** PAR HPHE (2 sections)
Active volume (mm^3)	10×20×800	10×20×800	22×22×800 × 2	45×45×1000 × 2
CO_2: N_2: He (bar)	0.3:0.1:9.6	0.2:0.2:9.6	0.5:0.5:9.0	0.5:0.25:7.25
^{18}O content (%)	43	43	43	47
Discharge voltage (kV)	55	70	160	300
Discharge current (kA)	1.7	3.5	4 × 2	10 × 2
Input energy/pulse (mJ)	0.001	2	1	40
Out. energy/pulse (mJ)	16	1	40	200
Train length (pulses)	1	100	100	100
Out. energy/train (J)	NA	0.1	4	20
Average power (W)	2.4	15	600	3000
Wall-plug power (kW)	5	13	30 × 2	160 × 2

- A seed picosecond pulse is sliced from a multi-ns CO_2 laser oscillator output by a semiconductor optical switching technique.
- This pulse is split into a train of 100 pulses that get amplified in a series of high-pressure gas-discharge CO_2 laser amplifiers with some of them having two sequential discharge sections in order to extend the gain envelope.
- The 100-pulse output trains with 200-mJ/pulse produced at the 150 Hz repetition rate are focused onto the counter-propagating synchronized electron beam.
- A few-millimeter-diameter central hole in the focusing mirror for the e-beam transmission, which proved not to affect the focus quality and has been routinely used in the ATF's ICS experiments, allows us to put the OAP mirror at the exact counter-propagation geometry to maximize the efficiency of the laser/e-bunch interaction.

SIMULATED PULSE-BURST LASER TRAINS

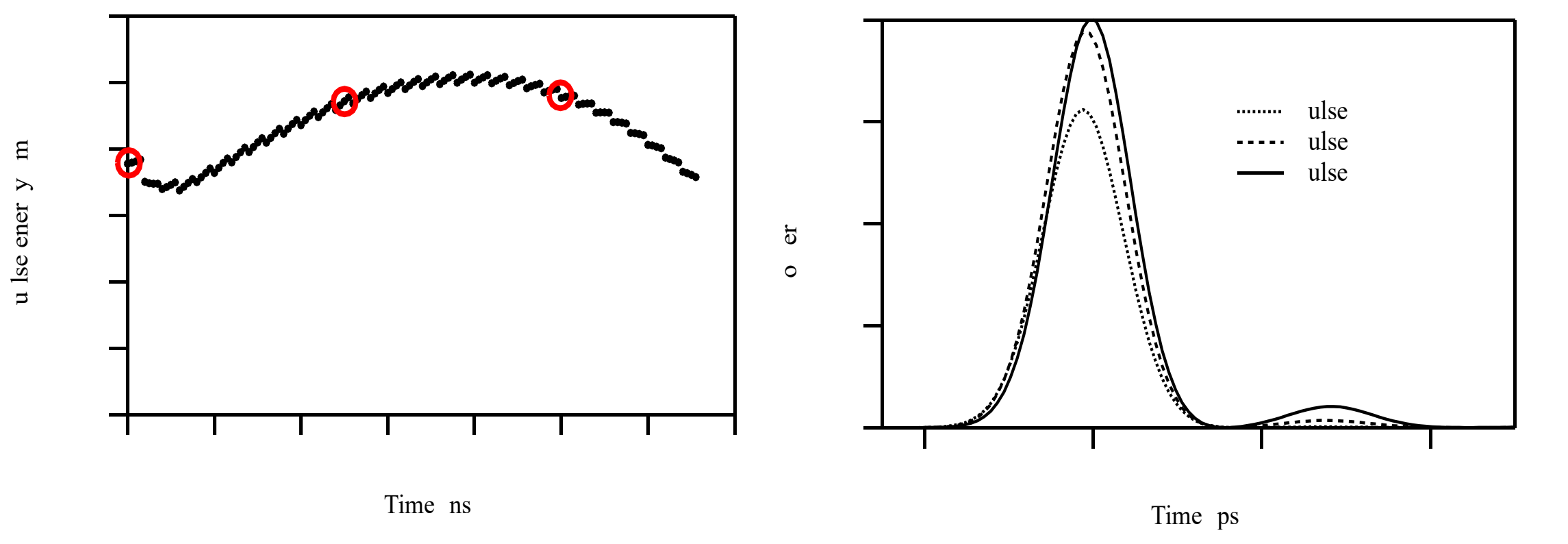

Figure 2. 100-pulse laser trains with T_b=5 ns and individual pulse duration τ_L=5 ps (12 ps FWHM). Left: the output train envelope with marked positions for the 1st, 50th and 100th pulses in a train. Right: temporal envelopes for the 1st, 50th and 100th pulses in a train.

PERSPECTIVE ICS SOURCES BASED ON DAΦNE AND CBETA ACCELERATORS

We characterize here the performance of different kinds of potential ICS sources based on concrete examples of circular accelerators, including DAΦNE (synchrotron) and CBETA (S-ERL) paired to either an NIR solid-state laser or an LWIR CO_2 gas laser.

Symbol	**Parameter**	**CBETA**		**DAΦNE**	
λ	Laser wavelength (µm)	**1.06**	**9.2**	**1.06**	**9.2**
$\mathcal{E}_e$	Beam energy (MeV)	150		510	
$\Delta\mathcal{E}_e/\mathcal{E}_e$	Beam energy spread (RMS)	0.05%		0.06%	
T_b	Bunch periodicity (ns)	0.77	3.1	5.4	
τ_e	Bunch rms length (ps)	4		50	
C	Bunch charge (pC)	32	123	8152	
ϵ_n	Beam emittance (mm mrad)	0.3		0.1	
σ_e	Beam radius at IP (µm)	3.2		40×600	
τ_L	Laser pulse rms length (ps)	5.7	5.3	20	42
E_L	Laser pulse energy at IP (mJ)	0.06	200	0.2	200
N_L	Laser photons per pulse	3×10^{14}	9×10^{18}	10^{15}	9×10^{18}
f_L	Laser pulses per sec	1.3×10^{9}	15×10^{3}	184×10^{6}	15×10^{3}
P_{av}	Laser average power at IP (kW)	81	3	36.8	3
σ_L	Laser rms radius at IP (µm)	25	40	40	133
ϕ	Collision angle	18°	0°	8°	0°
$\mathcal{E}_\gamma$	Gamma energy (MeV)	0.427	0.049	4.94	0.566
τ_γ	Gamma pulse rms length (ps)	4		50	
f_γ	Gamma repetition rate	1.3 GHz	15 kHz	184 MHz	15 kHz
N_γ/N_e	Conversion efficiency	2.2×10^{-6}	6×10^{-2}	10^{-7}	5×10^{-4}
N_γ	Gamma per pulse (ph)	450	4.7×10^{7}	4.8×10^{3}	2.9×10^{7}
$\mathcal{F}_{av}$	Average flux (ph/s)	5.8×10^{11}	7.5×10^{11}	9.1×10^{11}	4.3×10^{11}
$\mathcal{F}_p$	Peak flux (ph/s)	4.5×10^{13}	5.3×10^{18}	4.2×10^{13}	2.3×10^{17}
$\mathcal{B}_{av}$	Average brightness*	4.9×10^{13}	6.1×10^{13}	7.4×10^{15}	3.8×10^{15}
$\mathcal{B}_p$	Peak brightness*	4.2×10^{15}	4.4×10^{20}	3.4×10^{17}	2.2×10^{21}
$\Delta\mathcal{E}_\gamma/\mathcal{E}_\gamma$	Gamma energy spread (BW)	1.4%		0.85%	
$\mathcal{F}_{av,BW}$	Average flux in BW (ph/s)	9.3×10^{9}	7.8×10^{9}	5.5×10^{9}	1.6×10^{10}
$\mathcal{F}_{p,BW}$	Peak flux in BW (ph/s)	7.6×10^{11}	5.5×10^{16}	2.5×10^{11}	9.0×10^{15}

* $ph/(s\cdot mm^2\cdot mrad^2\cdot 0.1\% BW)$

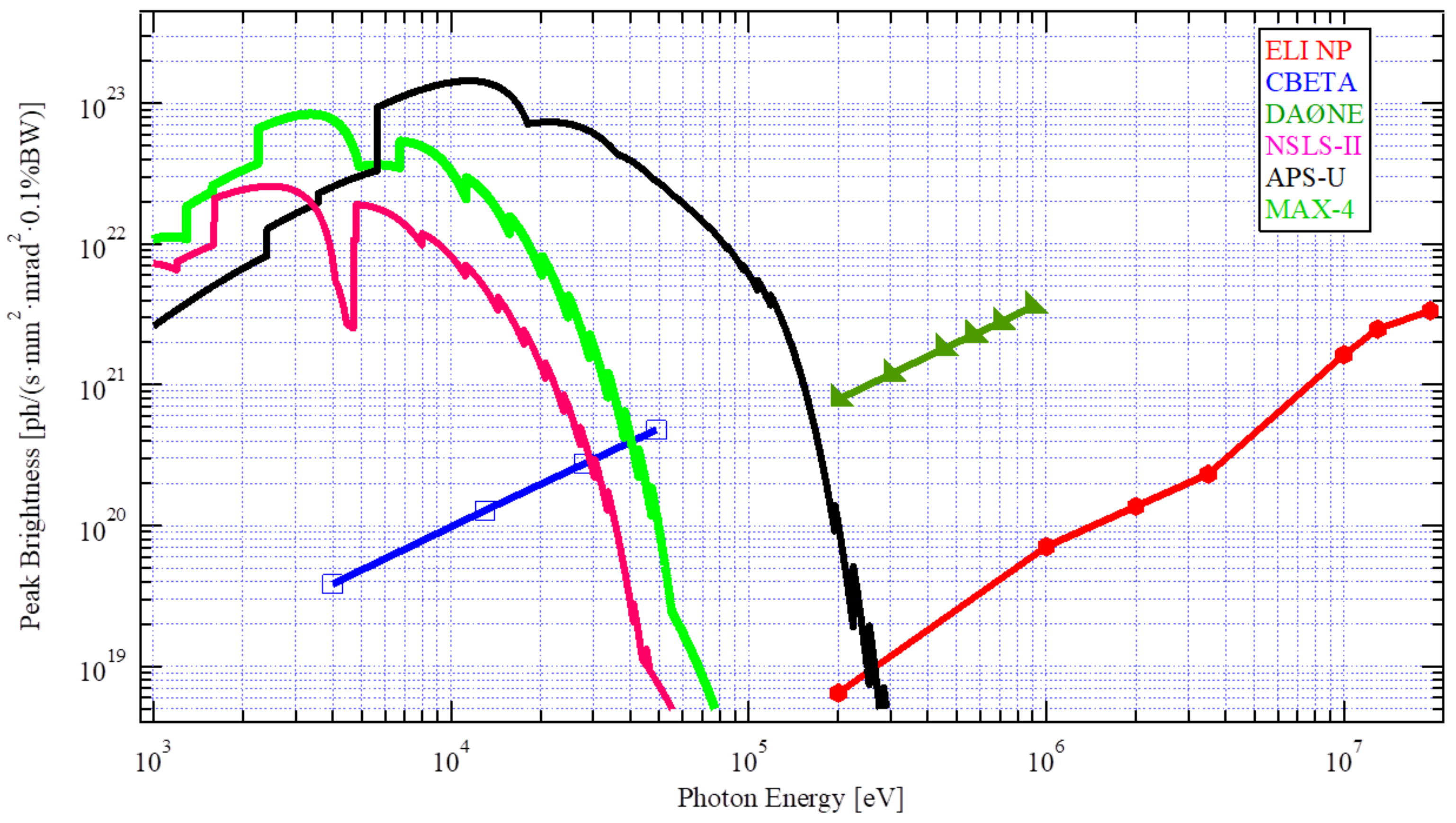

Figure 3. Positioning ICS sources CBETA-9µm and DAΦNE-9µm in terms of their peak brightness in comparison with 3rd generation Synchrotron Light Sources and ELI-NP facility.

REFERENCES

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CONCLUSIONS

The proposed laser system, combined with DAΦNE and CBETA accelerator facilities, will enable ICS sources where 10^{20}-10^{21} $ph/(s\cdot mm^2\cdot mrad^2\cdot 0.1\% BW)$ *peak* brilliances at 50-1000 keV photon energy range can be achieved that is comparable or exceeds the capabilities of contemporary synchrotron light sources (SLSs) at hard x-rays (see Fig.3).

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