ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC-8/09
October 26, 2009

A TWIN-LASER SYSTEM DRIVING A POWERFUL INVERSE COMPTON X-RAY SOURCE

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Abstract

The basics of a complete twin-laser system driving both the LINAC accelerator and the interaction chamber of a powerful inverse Compton source is discussed. The pourpose is the production of trains of 100 pulses, 10 ps long, with an internal frequency of 100 MHz at a repetition rate of 10 Hz. The pulse energy of the egun-laser, the one driving the accelerator photocathode, is about 10 μJ, while the Compton-laser, the one driving the interaction chamber, is 1 J. The egun-laser is conceptually based on a powerful Nd:YAG(YLF) oscillator seeded by a saturated laser pulse. The Compton-laser is based on a commercial 1 J-15 ps-10 Hz Nd:YAG(YLF) coupled to a passive enhacing cavity which can generate the pulse trains. The energy and brilliance of the two lasers are discussed in view of producing an X-ray source capable of delivering more than 10^{10} photons per second.

PACS: 87.59.-e, 95.85.Nv, 41.75.Jv, 42.60.-v, 42.60.By

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Laboratori Nazionali di Frascati

1 Introduction

There is a pervasive demand for hard X-ray beams in modern medical [1–5] and academic research applications [6]. Many experiments have demonstrated the physics of X-ray production via inverse Compton scattering (ICS) [6–12]. The high-brightness electron beams produced by radiofrequency photoinjectors [13] coupled to lasers with excellent beam quality (M^2 less than 2) allow efficient ICS sources. These sources can generate monochromatic tunable X-ray pulses of notable power thanks to the multigigawat peak power lasers. However, the average power is relatively low because of the low repetition rate of the commercial lasers coupled to the low efficiency of the Compton scattering process. The way proposed to enhance the ICS average power is by ri-using the same laser pulse many times given the fact that the laser pulse remains almost un-altered after an interaction (only one photon over 10^{10} is scattered from the pulse) [11]. From this observation the idea of adding to the Compton laser a ring cavity aimed to recirculate the laser pulses for successive Compton interactions was proposed [11,14–16] and also tested [11,14]. We discuss a multiplexing Compton-laser system capable of providing trains of 100 pulses 1J-10ps at 10 Hz repetition rate, in conjuction with an egun-laser system providing a correspondent electron pattern with 1 nC bunches The system ought to be capable to generate an X-ray flux of $> 10^{10}$.

The Compton process is governed by the physical law [17]

$$N_x = \sigma_T \left(\frac{N_e \cdot N_\nu}{A} \right) \cdot FF \tag{1}$$

where $\sigma_T [\sim 6\,10^{-25}]$ is the total Thomson cross section, N_e is the total number of electrons in the electron bunch, N_ν is the total number of photons in the laser beam. The term FF is a form factor less than unity that depends on rms electron and photon pulse durations τ_e and τ_ν and on the spot sizes of the electron and photon beams at the interaction point.

The number of X-photons is proportional to the product $N_e \cdot N_\nu$ and inversely to the interaction region area A. Thus, high X-flux means high colliding electron and photon fluxes and high brilliance.

The LINAC accelerator, generating the electron pulses colliding with the photon pulses, must provide trains of electron pulses with exactly the same time pattern as the incident Compton photon time pattern. A pulsed laser system delivering pulse trains of 1 kW power and 100 MHz is not in production. Here we present a possible design for this egun-laser coupled to the correspondent Compton laser.

The project is to design an efficient ICS source of monochromatic X-ray beam with $> 10^{10}$ photons per second at a first stage. The goal of 10^{12} flux is pursued with possible up-grading of both the LINAC and laser systems. This X-ray source would have the peak and average power interesting for medical purposes. In the project discussion, we refer to the numbers quoted in Ref. [4] and reported in Fig. 1. The numerical simulation results reported in the paper claim a number of 10^8 photons per shot with the system parameters showed in the figure, that is 1 nC electron bunch charge, 1 J energy of 1064 nm laser pulse and 20 μm interaction spot-size.

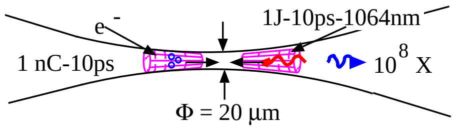

Figure 1: Sketch of the interaction point with the reference numbers relative to the ICS interaction.

2 The Compton-laser

The calculated 10^8 X-photon bunch produced (in the above assumed experimental configuration) indicates that a gain of $10^2 - 10^3$ is needed for obtaining the programmed X-ray flux of 10^{10} X-photons. Turnkey lasers operating at that 1 J pulse energy with a repetition rate equal-higher than 100 Hz are not produced even as custom machine. Due to the small cross section of the ICS interaction, the idea of multiplexing the 10 Hz drive laser pulse by trapping it inside a passive high finesse ring cavity is proposed (as in other Labs [11,14–16]).

The pulse injection into the ring cavity by insertion inside the cavity of the usual polarization plate coupled to a Pockels cell cannot be used because of the too high losses (of the order of several percent) at the 1 J pulse energy level. The insertion of a mm-thick non-linear crystal thin-slab (a BBO material) which switches the radiation from the red to the green, coupled to an input dichroic mirror, seems to be a proper solution [18,15]. The losses of the cavity elements can be quoted minor than 1%, for a finesse higher than 500. The design of the cavity will have focusing mirrors (off-axis parabolas) such to get the required $20\,\mu m$ spot size in one arm.

The free spectral range of the cavity should be 100 MHz, that is 10 ns interval among the laser pulses. Resulting the pulse decay time with that cavity finesse longer than 4 μs, we may assume the first 100 recirculations almost constant. The pulse pattern is scketched in Fig. 2. The cavity synchronization can be tuned by carefully controlling through one PZT mirror mounting the pulse round trip.

Observing that the expected up-conversion efficiency is $\sim 50\%$ and that one green

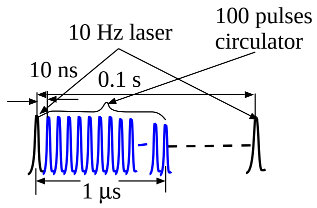

Figure 2: Temporal pattern of the Compton-laser pulses.

photon is produced by a pair of red photons, the expected X-photon flux results in

$$N_X \sim \frac{10^8}{4} \cdot 10^3 \ s^{-1} \tag{2}$$

The high average power indicates that Nd:YAG(YLF) crystal is the appropriate one. Nd:YAG can be used even if it can deliver pulses as long as 15 ps because the following up-conversion squeezes the pulse of more than 30 %. We will see in the next section that Nd:YAG cristal is an appropriate choice for the egun-laser.

A laser system complete of both Compton and egun-laser systems is sketched in Fig. 3

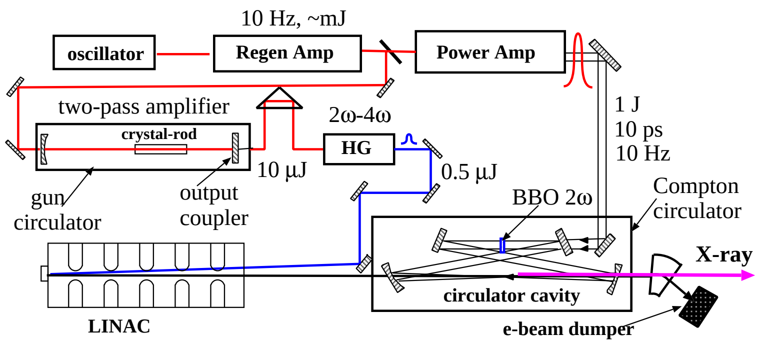

Figure 3: Schematic of the complete twin-laser system of the Compton scattering X-ray source.

3 The egun-laser

The egun-laser driving the photo-cathode must generate the same pulse-pattern as the Compton-laser system. Hence, its system architecture has to be quite similar to the Compton one.

The output pulses' energy of this laser must be stable within a couple of pecent, because the electric and magnetic fields of the accelerator are finely tuned to a set of values for the optimized operation, that is for the highest brilliance at a certain bunch charge.

This stability demand does not allow a passive circulator. In fact, the output 1064(1053) nm red laser radiation must be up-converted to 266 nm for the cathode photo-emission. This conversion is done by two steps non-linear interactions and energy instabilities are amplified in a non-linear process. The stringent condition on the energy stability of the train pulses forces for a very powerful 100 MHz oscillator delivering exactly 100 well-done pulses in time-coherence with those of the Compton-laser. We note that $10\,\mu J$ pulse energy with 100 MHz frequency means 1 kW power output, a really high power level. However, this power level is required for macro-pulses $1\,\mu s$ long. Thus, a possible scheme could be an oscillator seeded by pulses already at the saturation value (High Power Driven oscillator HPDO). The pilot laser has to the same as that of the Comption-laser, as depicted in Fig. 3. HPDO can be thought of as an active circulator with an output coupler.
The numbers relative to the egun-laser reported in Fig. 3 account for a quadrupling efficiency of 10% and a transport plus shaping losses of 50%. The considered photocathode material is Cs_2Te for its robustness and high quantum efficiency 1% [19]. Fig. 4 shows the schematic of the proposed egun-laser system. The basic idea is to launch into the

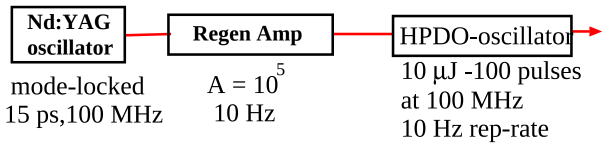

Figure 4: Schematic of the egun-laser (without harmonic conversion) with tentatively numbers to be hopely soon checked. High Power Driven Oscillator (HPDO) is proposed to be pumped by a flashlamp.

HPDO a pulse having an energy nearby $10\,\mu J/T$, being T the transmission of the output coupler and $10\,\mu J$ the programmed output laser pulse energy, and to set the gain such that active medium refills in two-passes the energy losses.
The laser system is going to be built and tested.

4 Conclusions

An auto-consistent powerful laser system aimed to drive a powerful inverse Compton source of X-rays has been discussed. The schematic of a twin laser system, one driving the accelerator photocathode and the second providing the incident photons for the Compton scattering, operating with high frequency trains of 10 μJ per pulse the first and 1 J the second is presented for the first time, to our knowledge. A driven powerful laser aimed to deliver trains of 100 pulses 10 ps long at 100 MHz frequency with 1O Hz repetiton rate is proposed for driving the photo-cathode of radiofrequency electron guns.

acknowledgments The author recognizes helpful discussions with the colleagues S. Cialdi, L. Serafini, D. Cipriani and Dr. P.D. Bimbi of Quanta System. The work is partly supported by Ministero Istruzione Universita' Ricerca, Progetti Strategici, DD 1834, Dec, 4, 2002

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