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# Laser-electron generator for X-ray applications in science and technology

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**Abstract**

The possibility of the creation and the application prospects of the laser-electron X-ray generator based on Thomson scattering of laser radiation on a bunch of relativistic electrons are considered. Such a generator fills the existing gap between X-ray tubes and synchrotron radiation sources, which is several orders of magnitude in terms of the brightness, average intensity, size, and also in the construction and running costs.

**Keywords:** Compact X-ray sources; Thomson scattering; Laser-electron X-ray generator; optical circulator; Picosecond laser

## 1. INTRODUCTION

The progress in the technologies of target production (Khalenkov *et al.*, 2006; Kilkenny *et al.*, 2005; Koresheva *et al.*, 2005; Nobile *et al.*, 2006; Schollmeier *et al.*, 2007) requires the development of adequate methods for materials and micro-objects probing. Among these methods is radiographic inspection in soft and hard X-rays with conventional tubes and laser-produced plasma sources (Abdallah *et al.*, 2007; Orlov *et al.*, 2007; Schollmeier *et al.*, 2006; Wong, Woo & Yap, 2007). However, both sources provide limited possibility for spectrum tuning and thus can not be widely applied in material science. We propose to use for target inspection, as well as for microanalysis related to target fabrication technology, a compact and tunable source based on relativistic Thomson scattering, referred to as laser-electron X-ray generator (LEXG). The project of the LEXG is developed jointly by Moscow State University and the Institute of Quantum Radiophysics of the P.N. Lebedev Physical Institute, and is aimed at the system of a linac (or a pulsed synchrotron) and a repetitive picosecond laser (Gorbunkov *et al.*, 2005; Artyukov *et al.*, 2007).

The number of X-ray photons $N$ generated in one collision of short enough relativistic electron and photon bunches equals:

$$N = N_e N_L \frac{\sigma_T}{s_e + s_L} \tag{1}$$

where $N_e$ and $N_L$ are the total numbers of electrons and photons, $\sigma_T = 6.6 \times 10^{-25}\ \mathrm{cm}^2$, $s_e = 2\pi\sigma_e^2$, $s_L = 2\pi\sigma_L^2$, $\sigma_e$ and $\sigma_L$ are transverse sizes of electron and laser beams, $\sigma_e = \sqrt{\varepsilon\beta}$, where $\varepsilon$ is emittance and $\beta$ is beta function of electron bunch in the interaction point. Because of the extremely small value of $\sigma_T$ one has to choose optimal laser and electron bunch time structure for enhancement of the X-ray flux up to $10^{10}$–$10^{12}$ photons per second. Aiming at these values, we consider several LEXG schemes; all of them include optical circulators. Optical circulator facilitates multiple interaction of each laser picosecond pulse with electron bunches in the interaction chamber providing at least 100-fold increase in X-ray photon output per one laser photon. The important advantage of the circulator is the possibility to operate with phase non-coherent laser pulses.

Accelerators and laser units of LEXG in more details are considered in Sections 3, 4, and 5. One of the first projects aimed at routine X-ray applications of LEXG has been published (Blumberg & Blum, 1993). Currently, several groups are engaged in conceptual design and prototype construction of LEXG for material science and medical applications (Gorbunkov *et al.*, 2005; Carroll, 2002; Dobashi *et al.*, 2005;

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Agafonov *et al.*, 2005; Loewen, 2003; Brown *et al.*, 2004; Vlieks *et al.*, 2002; Sakaue *et al.*, 2006; Kaertner *et al.*, 2006).

## 2. TIME STRUCTURES OF ELECTRON AND LASER BEAMS

(a) As a "building brick" to optimally arrange the time structure of electron and laser beams consider a collision of $\lambda_L = 1.06\ \mu$m, $E_L = 20$ mJ laser pulse with a single 1 nC electron bunch having equal cross section areas $s_{e,L} = 2.5 \times 10^{-5}$ cm$^2$ that is usually obtained in linacs with laser photo-cathodes. According to Eq. (2) this gives $N_0 = 10^7$ photons. For comparison, Carroll (2002) produced $10^{10}$ photons per shot for medical imaging with the 20 J laser pulse. However his installation had 0.01 Hz operation rate that is not enough for some important applications.

(b) With an operation rate of a linac $\nu_e = 10$ Hz the elementary collision (a) gives only $\Phi = 10^8$ pps. To increase the flux by four orders of magnitude (see Eq. (1)) one needs to boost the number of collisions per second.

(c) An evident solution is a multi-bunch linac operation mode. For a few microseconds operation time, the total charge can reach up to 200–500 nC (Dobashi *et al.*, 2005; Vlieks *et al.*, 2002; Sakaue *et al.*, 2006; JINR, 2001). Power consumption increases with the total charge, which is acceptable for many applications. The laser produces single pulse but the system has to be equipped with an optical circulator (Fig. 1), which is a pulse storing system with the enhancement factor of $n_c$ not less than the number of bunches $n_e$ in one linac pulse. For $n_c = n_e$ the X-ray photon flux then equals to:

$$\Phi = N_0 n_e \nu_e, \tag{2}$$

where $\nu_e$ is the operating linac frequency.

Taking $n_e \approx 100$ and $\nu_e = 10$ Hz as in (b), one obtains from Eq. (3) that $\Phi = 10^{10}$ pps, which is still less than the desired value. The same X-ray photon flux can be obtained in the 1 nC single bunch linac mode if the operation frequency 1 kHz is provided instead of 10 Hz. Corresponding high power electron guns are currently being developed (Vlieks *et al.*, 2002; Marhauser, 2006). There are three ways to gain the remaining factor of 100 in the X-ray flux.

(d) The first way is to use trains of 100 bunches, 1 nC each at 1 kHz frequency of linac (see Table 1).

(e) The second way is to increase the product of three factors contributing to $N_0$ and $\Phi$ in Eq. (3): bunch charge—5 nC (Sakaue *et al.*, 2006; Hirano *et al.*, 2006) instead of 1 nC, LINAC operation rate—100 Hz instead of 10 Hz and laser pulse energy 40 mJ instead of 20 mJ. The design becomes more aggressive but still possible (see Table 1).

(f) The third possibility is to considerably increase the number of bunches as it is developed in the CARE Project and switch to possibly lower repetition rate down to 50 Hz (Losito *et al.*, 2006; see the last column of Table 1). The required time structure of laser radiation is pulse trains of $n_L = n_e/n_c = 23$ ps pulses with 50 Hz repetition rate.

(g) Alternatively to (d)–(f), a storage ring with repetitive injection can be added into the LEXG scheme in order to reduce the photo-cathode loading. In this case, one returns to single 1 nC bunch operation of the linac but every

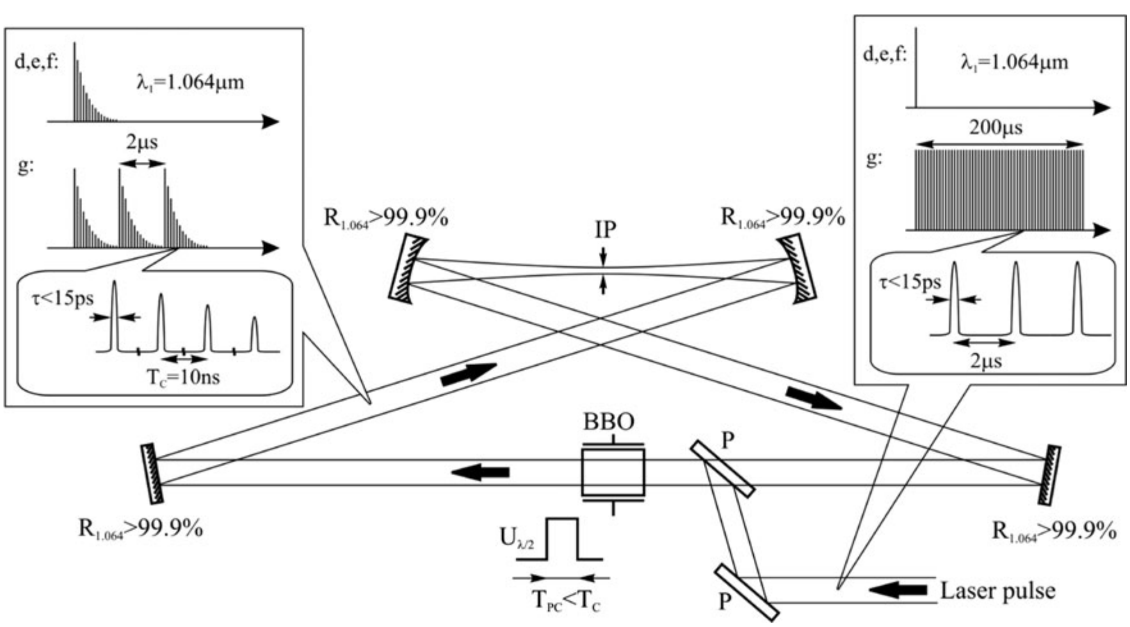


**Fig. 1.** Optical circulator based on BBO crystal Pockels cell for LEXG application. P – polarizer, $T_{PC}$ – duration of high voltage pulse applied to BBO crystal, $T_C$ – circulator round trip time, IP – interaction point. Insets show: laser radiation time structure at the circulator entrance (**right**) and inside circulator (**left**); d, e, f, g—denote the LEXG versions according to Section 2.

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**Table 1.** *Linac based LEXG (see versions discussed in (d), (e), (f)). In the last four rows the reliability of suggested systems in respect of radiation damage of the photocathode is indicated: realistic, probably realistic, hardly realistic denoted as R, P, and H correspondingly*

| LEXG version | | (d) | (e) | (f) |
|---|---|---|---|---|
| X-ray quantum energy, $\hbar\omega$ | | 33 keV | 33 keV | 33 keV |
| Laser quantum energy, $\hbar\omega_L$ | | 1.16 eV | 1.16 eV | 1.16 eV |
| Electron energy, $E_e$ | | 43 MeV | 43 MeV | 43 MeV |
| Bunch size, $\sigma_e = \sigma_L$ | | 20 μm | 20 μm | 50 μm[1] |
| Electrons in the bunch, $N_e$ | | $6 \times 10^9$ (1 nC) | $3 \times 10^{10}$ (5 nC) | $1.4 \times 10^{10}$ (2.3 nC) |
| Number of bunches, $n_e$ | | 100 | 100 | 2300 |
| Operation rate, $\nu_e$ | | 1 kHz | 100 Hz | 50 Hz |
| Pumping laser pulse energy | | 20 mJ ($N_L = 1.1 \times 10^{17}$) | 40 mJ ($N_L = 2.2 \times 10^{17}$) | 50 mJ ($N_L = 1.1 \times 10^{17}$) |
| Number of laser pulses in a train, $n_L$ | | 1 | 1 | 23 |
| Circulator enhancement factor, $n_c$ | | 100 | 100 | 100 |
| X-ray photon flux, $\Phi$ | | $10^{12}$ phot/s | $10^{12}$ phot/s | $10^{12}$ phot/s |
| e-beam average power, $P_e$ | | 4.3 kW | 2.2 kW | 10 kW |
| Laser average power at the entrance and inside the circulator | | 20 W<br>2 kW | 4 W<br>400 W | 60 W<br>6 kW |
| Photocathode 266 nm laser parameters: pulse energy, mJ; train energy, mJ; average power, W | Cu | 0.084; 8.4; $8.4^{\mathbf{P,R}}$ | 0.42; 42; $4.2^{\mathbf{H}}$ | 0.19; 440; $22^{\mathbf{H}}$ |
| | Cu, crystal | 0.022; 2.2; $2.2^{\mathbf{R}}$ | 0.11; 11; $1.1^{\mathbf{P,H}}$ | 0.05; 120; $5.8^{\mathbf{H}}$ |
| | Mg | 0.002; 0.22; $0.22^{\mathbf{R}}$ | 0.01; 1.1; $0.11^{\mathbf{R}}$ | 0.005; 12; $0.58^{\mathbf{P,H}}$ |
| | $Cs_2Te$ | $10^{-4}$; 0.01; $0.01^{\mathbf{R}}$ | $5 \cdot 10^{-4}$; 0.05; $0.005^{\mathbf{R}}$ | $2.5 \times 10^{-4}$; 0.6; $0.029^{\mathbf{R}}$ |

[1]To calculate $\sigma$ in this case we used $\beta = 1$ cm and the value of $\varepsilon$ published in [Losito *et al.*, 2006].

bunch is stored in a compact storage ring (Agafonov *et al.*, 2005; Loewen, 2003). To provide efficient electron-photon coupling in this case, the laser has to emit pulse trains of $n_L = n_s/n_c$ micro pulses (Gorbunkov *et al.*, 2005), where $n_s$ is the number of bunch revolutions in the ring without emittance degradation. The X-ray photon flux equals to

$$\Phi = N_0 n_s \nu_e. \tag{3}$$

Taking $n_s = 10^4$ and keeping $n_c = 10^2$ and $\nu_e = 10$ Hz, we obtain the required X-ray photon flux (1) and the number of micro pulses in a laser train $n_L = 10^2$. The average laser power in this case increases up to $P_L = E_L n_e \nu_e = 20$ W. Other parameters are summarized in Table 2.

To conclude, we have introduced four LEXG schemes providing $10^{12}$ pps X-ray output. Three of them are linac based (Table 1) and in the fourth one (Table 2) the storage ring is added. They exhibit different operation modes of accelerator system and photo-cathode and pumping lasers. Among the foreseen problems to be solved are ultravilot (UV) laser radiations loading on the cathode surface and large laser power trapped in the optical circulator. They will be addressed in Sections 3 and 5.

## 3. E-BEAM UNITS IN LEXG VERSIONS (D)–(G)

Tables 1 and 2 display principal parameters of four versions of LEXG providing $10^{12}$ pps. Let us consider their critical points.

Multi-bunch linac operation (see Table 1) leads to a rather high average power of the UV (~266 nm) photo-injector laser used in a photo radio frequency (RF) gun. Table 3 shows quantum efficiencies (QE) of various photo-cathode materials. Knowing QE and taking into account the 1–2 mm$^2$ area of the UV laser spot at the surface of a cathode, it is easy to estimate the main parameters of photo-injector laser and to choose acceptable cathode materials that are listed in the last four rows of Table 1.

**Table 2.** *LEXG based on a compact storage ring (see version discussed in (g))*

| LEXG version | (g) |
|---|---|
| X-ray quantum energy, $\hbar\omega$ | 33 keV |
| Laser quant energy, $\hbar\omega_L$ | 1.16 eV |
| Electron energy, $E_e$ | 43 MeV |
| Bunch size, $\sigma_e = \sigma_L$ | 20 μm |
| Electrons in the bunch, $N_e$ | $6 \times 10^9$ (1 nC) |
| Number of bunches | 1 |
| Operation rate, $\nu_e$ | 10 Hz |
| Storage ring perimeter | 6 m |
| Number of bunch revolutions | $10^4$ |
| Laser micropulse energy | 20 mJ ($N_L$=$1.1 \times 10^{17}$) |
| Laser pulses in a train | $10^2$ |
| Circulator enhancement factor, $n_c$ | 100 |
| X-ray photon flux, $\Phi$ | $10^{12}$ phot/s |
| e-beam average power, $P_e$ | 0.44 kW |
| Laser average power at the entrance and inside circulator | 20 W<br>2 kW |

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**Table 3.** *Quantum efficiency of photocathode materials commonly used in RF guns*

| Material | QE | At cathode electric field, MeV/m | Reference |
|---|---|---|---|
| Cu | $5.3 \times 10^{-5}$ | 200 | Vlieks *et al.*, 2002 |
| Cu, crystal | $2 \times 10^{-4}$ | 120 | Vicario *et al.*, 2006 |
| Mg | $2 \times 10^{-3}$ | 100–120 | Wang *et al.*, 2002 |
| $Cs_2Te$ | $>10^{-2}$ | 42 | Sertore *et al.*, 2006<br>Hirano *et al.*, 2006 |

One can see that version (d) is more acceptable from the point of view of photo-cathode radiation loading. It presents a good compromise between the bunch charge and the rate of injection. As a result, three of four cathode materials can surely be used. Copper probably is to be excluded as the loading is close to radiation damage threshold.

Version (e) requires lower power of the both pumping and photo-cathode lasers. However 5 nC injection resulting in $\sigma_e \approx 20$ μm bunch focusing has not been achieved experimentally yet. But the photo-injector with the parameters close to these values $s_e = 2\pi\sigma_x\sigma_y = 4.5 \times 10^{-5}$ cm$^2$ (see Eq. (2)) have been simulated (Kuroda *et al.*, 2006). The area $s_e$ can be reduced by a factor of ~10 for specially formed electron bunches (Limborg-Deprey, 2005).

In version (f), the loading on the photo-cathode is the largest. As a result, only $Cs_2Te$ can be used that implies special technology of high purity and vacuum, aging problems, reproducibility, and stability of QE. Note that the photo-injector similar to the one in version (f) has already been realized in the frames of CARE Project (Losito *et al.*, 2006).

In order to avoid difficulties emerging in linac based LEXG, the storage ring with finite (~$10^5$–$10^6$ revolutions (Gorbunkov *et al.*, 2005; Loewen, 2003), or ~$10^4$ revolutions as in version (g), see Table 2) bunch lifetime can be added to the source scheme. The emittance evolution in such storage rings was studied (Loewen, 2003). The requirement to cathode material radiation resistance becomes easier than in (d). The average power of the photo-cathode laser is $10^4$ times lower. The power of the pumping laser is the same. However the introduction of the ring apparently means the increase in the system cost and size.

Thus version (d) looks the most attractive among the linac based LEXG schemes from the viewpoint of photo-cathode radiation loading. The introduction of the storage ring (see (g) in Section 2) makes injection and accelerator requirements much easier but the sizes of the system larger. All the four schemes contain optical circulator to concentrate laser power in the interaction point that is necessary to achieve the required X-ray flux $10^{12}$ pps with realistic pumping laser. In more details circulator will be discussed in Section 5.

## 4. PHOTON ENERGY TUNING AND POWER SUPPLY

Relativistic Thomson scattering has a specific structure of X-ray photon beam in space and energy domains. For monochromatic electron beam the X-ray photon energy strictly corresponds to definite emission (scattering) angle θ. In other words the LEXG radiation is originally decomposed in spectrum. Narrow spectral intervals can be selected out by small apertures. The energy and angular spread of the e-beam and the angular spread of the laser beam result in the finite spectral width of the X-ray beam at all angles. In this case standard crystal monochromators can be used.

For the application in elemental analysis, the variation of X-ray spectrum in a wide range is necessary. In LEXG, this can be achieved by changing the energy of the electron beam $E_e$, which follows from the angular dependence of X-ray photon energy:

$$\hbar\omega = \frac{4\gamma^2}{1 + (\gamma\theta)^2}\hbar\omega_L, \quad \gamma = \frac{E_e}{mc^2}. \tag{4}$$

To provide possibility for fast changing of output e-beam energy $E_e$ the linac must have several accelerating structure sections each fed by separate klystron. For maximum beam energy ~50 MeV linac will consist of the RF gun with output beam energy ~5 MeV and two standing wave sections with maximum energy gain ~25 MeV each. The klystrons are excited by RF signal from the common master oscillator. At the klystron input a fast electronic phase shifter and attenuator followed by RF amplifier are installed. By changing the phase and/or amplitude of the field in the second accelerating section it is possible to change the output beam energy from pulse to pulse in the range from ~10–15 MeV up to ~50 MeV.

Let us estimate the required power supply that actually is the main part of the LEXG power consumption. For S-band (2.856 GHz), the pulsed RF power dissipated in the walls of RF gun and each section of the accelerating structure can be estimated as ~7 MW, or ~21 MW in total. Average RF power depends on the duty factor. For instance for 1 μs duration RF pulses following with 1 kHz repetition rate the total average RF power losses in the walls of accelerating structure are 21 kW.

The beam current for 500 nC charge accelerated per pulse during 1 μs is 500 mA, thus the total pulsed RF power transferred to the beam at 50 MeV is 25 MW and average beam power for 1 kHz repetition rate will be 25 kW. The total pulsed RF power provided by three klystrons is ~46 MW and average RF power is 46 kW. Taking into account klystron and modulator efficiency, electric power from the

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plug necessary to feed linac is $\sim$120 kW. Besides changing the electron energy $E_e$, LEXG offers other possibilities to manipulate with the parameters of the output X-ray beam: adjusting of electron-photon collision angle, electron bunch length, the wavelength, time structure and focusing of laser radiation, etc. For example as is shown in (Kuroda *et al.*, 2006) at 1 nC charge the bunch length can be shortened down to 150 μm. This provides the possibility to reduce the size of the X-rays emitting volume by tight focusing of femtosecond laser beam into $\sigma_L = 5$ μm spot. In order to keep the output X-ray flux the duration of laser pulse must be decreased proportionally to the bunch length. The result is the increase of LEXG brightness by a factor of $\sim$20.

## 5. OPTICAL CIRCULATOR

Optical circulator facilitates multiple interaction of each laser picosecond pulse with electron bunches in the interaction chamber providing at least 100 fold increase in X-ray photon output per one laser photon. Most of the projects consider for this purpose optical cavities with high enhancement factor (see for example, Loewen, 2003; Sakaue *et al.*, 2006, Kaertner *et al.*, 2006). In fact, by some reasons the enhancement factor for optical cavity is expected to be higher than that of circulator. However, the important advantage of the latter is the possibility to operate with phase non coherent laser pulses.

The circulator differs from the cavity by optical switch providing trapping of laser pulses in the interaction chamber. In view of losses in optical switch, the ring configuration circulator is preferable. Circulators enable single (Dobashi *et al.*, 2005) or multiple (version (f) in this paper) pulse injection and the regeneration of laser pulses inside of it (Gorbunkov *et al.*, 2005). To produce stable sharp focusing in the interaction point at least a four mirror circulator is necessary.

Figure 1 shows a circulator with intracavity Pockels cell which in the position "on" directs laser pulses in the circulator cavity and in position "off" (in the absence of an electric field) saves it in the trapped stage. Besides losses induced by discrete optical elements Pockels cell in the "off" position has additional ones. They are caused by a depolarization in electro-optic (E-O) crystal because of two factors. The first is a thermal birefringence induced by light absorbed in E-O crystal. The second is a so-called piezoelectric ringing due to acoustical waves generated in a E-O crystal when fast high voltage pulses are applied to it. Therefore the problem in the Pockels cell based circulator design is to choose a suitable electro-optic material.

Beta-Barium Borate (b-$BaB_2O_4$), known as BBO, is one of the best candidates for both nonlinear optics applications and E-O applications due to the combination of nonlinear and electro-optical properties. BBO Pockels cells are transverse-field devices because of crystal symmetry and the necessity to avoid the birefringence of the light beam in the absence of an electric field. BBO has significant advantages over other E-O materials in terms of laser power handling abilities, temperature stability, substantial freedom from piezoelectric ringing and resonance free operation. Its optical homogeneity is good ($\delta n < 10^{-6}$/cm). At 1064 nm BBO has a high damage threshold 10 GW/cm$^2$ (1.3 ns) and a low insertion loss (absorption coefficient $<$0.1%/cm) and withstands average powers in excess of 20 kW/cm$^2$ (CW).

Besides the external voltage controlled circulator, there is a possibility to utilize a completely passive one based on intracavity second harmonics generation (SHG), see Figure 2. It does not require any high voltage unit synchronized with the laser pulses. Moreover the passive circulator contains

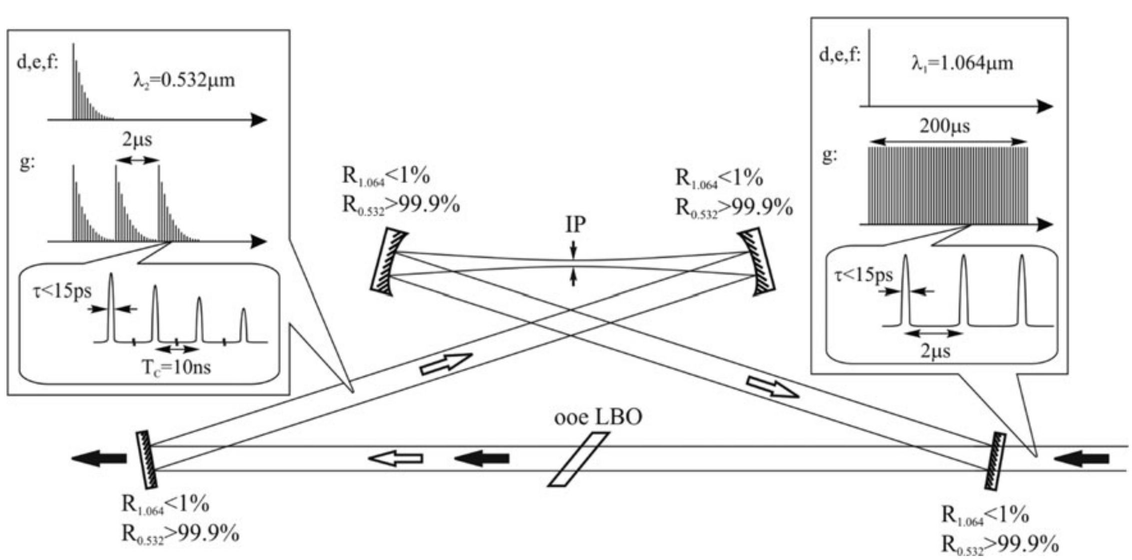


**Fig. 2.** Passive optical circulator based on intracavity second harmonic generation. LBO—Brewster nonlinear LBO crystal for Type I second harmonic generation. Black and white arrows mean 1.06 μm and 0.53 μm radiation correspondingly. Insets show the same as in Figure 1.

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in the cavity only a nonlinear crystal providing small insertion losses. In the case of normal incidence the thermal birefringence induced by light absorption does not lead to additional intracavity losses.

Lithium Triborate ($LiB_3O_5$) or LBO is a nonlinear crystal with excellent physical and optical properties. Its high optical homogeneity ($\delta n < 10^{-6}$/cm), good chemical and mechanical properties, non hygroscopicity, low walk-off angle and very high damage threshold (the highest bulk damage threshold among all known nonlinear optical crystals) make this crystal perfectly suitable for high power harmonic generation especially when high stability and long time operation are required. LBO has extremely low absorption coefficient both at 1.06 and 0.53 μm (<0.01%/cm). For this reason, aiming at lossless operation the circulator design based on Brewster angle positioned to **ooe** second harmonic generation (Type I SHG) LBO has a great potential. LBO allows temperature-controllable non-critical phase-matching (NCPM) for 1.0–1.3 μm Type I SHG. It possesses a relatively large angular acceptance bandwidth, reducing the beam quality requirements for source lasers. Temperature-tuned NCPM Type I SHG for 1.064 μm is achieved at the temperature 148°C with the temperature acceptance bandwidth of 3.9°C. LBO also provides room temperature NCPM for **oee** (Type II) SHG at 0.8–1.1 μm. Due to high laser power needed for X-ray generation (see Tables 1, 2) and taking into account relatively large LBO effective SHG coefficient (about three times that of KDP) one can see that a thin crystal (<1 cm) is suitable for efficient (>50%) both Type I and Type II SHG.

To summarize the section, we conclude that new O-E crystals (such as BBO) offer the possibility to increase the enhancement factor of optical circulators based on intracavity Pockels that is now equal to several tens (Dobashi *et al.*, 2005; Mohamed *et al.*, 2002). But the chance to overcome two orders of magnitude enhancement by O-E devices is still questionable. More promising is the completely passive circulator based on intracavity second harmonics generation in a possibly thin LBO crystal.

## 6. SUMMARY

Laser electron X-ray generator based on relativistic Thomson scattering is a prospective source to close the gap between conventional X-ray tubes and SR beamlines. The foreseen applications of LEXG are: microanalysis related to target fabrication technology, analytical methods like EXAFS and others in material sciences and chemistry; protein crystallography and development of new drugs; inspection of fast moving parts in industry; public security etc. The LEXG promises implementation of K-edge subtraction imaging in medical centers and clinics; improved diagnostics in mammography; noninvasive procedures and reduction of radiation dozes in coronary angiography; deep tumors diagnostics and therapy in oncology.

The LEXG is very flexible to meet the requirements of various application fields which follows from the great possibility to choose the parameters of laser and electron beams. Aiming at the generated X-ray flux $10^{12}$ pps several LEXG schemes have been considered. All of them use optical circulators that multiply the number of interactions of laser pulses with electron bunches. The trades off factors taken into account are: compactness of accelerator and laser units, electrical power consumption, resistance of the cathode to UV radiation of the photo-injector laser, charge and area of the electron bunch defining output X-ray flux, the IR radiation loading on the mirrors of the optical circulator multiplying the number of laser pulses in the interaction chamber. The resulting designs comprising these factors are presented in Tables 1, 2. The estimated accelerator and laser parameters show the feasibility of LEXG with the X-ray yield of $\sim 10^{12}$ pps.

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