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# Progress in High Average Power, Short Pulse Solid State Laser Technology for Compton X-Ray Sources

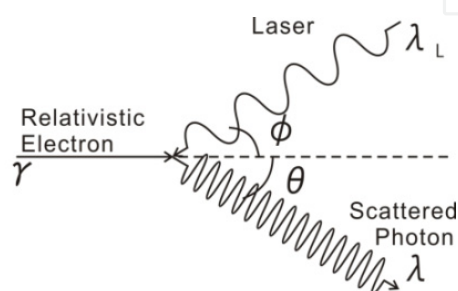
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## 1. Introduction

Laser Compton X-ray source has been developing in more than decade as an accelerator-laser hybrid technology to realize a compact, high brightness short wavelength source. The basic principle is similar to an undulator emission, in which a high intensity laser field plays as the modulating electromagnetic field. Basic principle of the laser Compton X-ray source is explained in this chapter with recent examples of phase contrast imaging of bio samples. Single shot imaging is critical for many practical applications, and the required specification is explained as the laser pulse must exceeds some threshold parameters. It is already well studied on the optimization of the laser-Compton hard X-ray source by single shot base (John, 1998, Endo, 2001). Experimental results agreed well with theoretical predictions. Highest peak brightness is obtained in the case of counter propagation of laser pulse and electron beam bunch with minimum focusing area before nonlinear threshold (Babzien et.al, 2006: Kumita, et.al, 2008). The new short wavelength light source is well matured to demonstrate a single-shot phase contrast bio imaging in hard X-ray region (Oliva, et.al, 2010). The employed laser is a ps CO<sub>2</sub> laser of 3J pulse energy (Pogorelsky, et.al, 2006), but the laser system is not an easy and compact one for further broad applications in various laboratories and hospitals.



**Figure 1.** Schematic of laser-Compton scattering process

The major challenge of the laser Compton source for single shot imaging is the generation of threshold X-ray brightness, which in turn results in a clear sample imaging. Figure 1 describes the schematic of the laser-Compton interaction between electron beam and laser.

Laser-Compton scattering photon spectrum has a peak in the forward direction at a wavelength;

$$\lambda_p = \frac{\lambda_L(1 + \frac{K^2}{2})}{2\gamma^2(1 + \beta\cos\phi)} \quad (1)$$

where  $\gamma$  and  $\beta$  are Lorentz factors,  $\lambda_L$  is the laser undulation period (laser wavelength),  $K$  is the K parameter of the undulator, which is equivalent to the laser intensity parameter, and  $\Phi$  is the angle between electrons and laser propagation direction. The spectrum depends on the angular distribution; the wavelength  $\lambda$  is emitted at

$$\theta = \frac{1}{\gamma} \sqrt{\frac{\lambda - \lambda_p}{\lambda_p}} \quad (2)$$

It is seen that higher  $\gamma$  electron beam produces higher brightness of generated X-ray beams. The general formula of obtainable X-ray photon flux  $N_0$  is calculated in the normal collision by the following expression,

$$N_0 \propto \frac{\sigma_c N_e N_p}{4\pi r^2} \quad (3)$$

where  $\sigma_c$  is the Compton cross section ( $6.7 \times 10^{-25} \text{ cm}^2$ ),  $N_e$  is the total electron number,  $N_p$  is the total laser photon number, and  $r$  is the interaction area radius. Longer wavelength laser like ps CO<sub>2</sub> laser is advantageous to generate higher brightness X-rays at a fixed wavelength due to higher  $\gamma$  factor of employed electron beam, namely higher energy accelerator. Same energy laser pulse contains 10 times photons compared to solid state laser ones. Disadvantage is that the total system size becomes larger compared to the case of solid state laser based Compton source.

The approach to increase the photon flux is equivalent to increase  $N_e$ ,  $N_p$  and decrease  $r$ , but there are instrumental limitations to realize these simultaneously. The practical limitation is the maximum electron number  $N_e$  and minimum interaction area diameter  $r$ . These are determined by emittance of the accelerated electron bunch and Coulomb repulsion. We would like to suppose it as 1nC, 3ps and focusable down to 10 $\mu$ m diameter at 38MeV acceleration energy. Another limitation is the onset of the nonlinear threshold of the higher harmonics generation, which is evident over  $10^{17} \text{ W/cm}^2$  CO<sub>2</sub> laser irradiation intensity (Kumita, et.al. 2008). Laser pulses with 1ps pulse width focused down to 10 $\mu$ m, reaches at this threshold with 100mJ pulse energy. The nonlinear Compton threshold is characterized by the laser field strength

$$a_0 = eE / m\omega_L c \quad (4)$$

where  $E$  is the amplitude of laser electric field,  $\omega_L$  is the laser frequency and  $c$  is the speed of light. The laser field strength is linearly depending on the laser wavelength. The laser energy for the nonlinear threshold of  $a_0 \sim 0.6$  corresponds to 1J with 1ps at 10 $\mu$ m focusing in case of solid state laser. Single shot imaging was already realized by a 3J, 5ps CO<sub>2</sub> laser pulse focused onto 0.5nC, 32 $\mu$ m electron bunch (Oliva, et.al 2010). The focused laser intensity is over the nonlinear threshold as  $a_0 > 1$ . The X-ray spectrum was evidently overlapped with higher harmonics of X-rays. We can then estimate as it is also possible to expect a single shot imaging with equivalent solid state laser pulse, once it is possible to focus down to 10 $\mu$ m diameter to overcome the magnitude lower laser photon number. Table 1 summarizes the design laser parameters optimized for single shot imaging. It is clear from the table that a one pulse configuration is not possible to realize a single shot imaging because of the nonlinear threshold.

Nonlinear threshold	1J
Single shot imaging	4J
Pulse width	1ps
Focus diameter	10 $\mu$ m

**Table 1.** Solid state laser parameters for single shot imaging by Compton X-ray source

Usual approach is to increase the repetition rate of the event, and the obtainable X-ray photon average flux is expressed as;

$$N = f \times N_0 \quad (5)$$

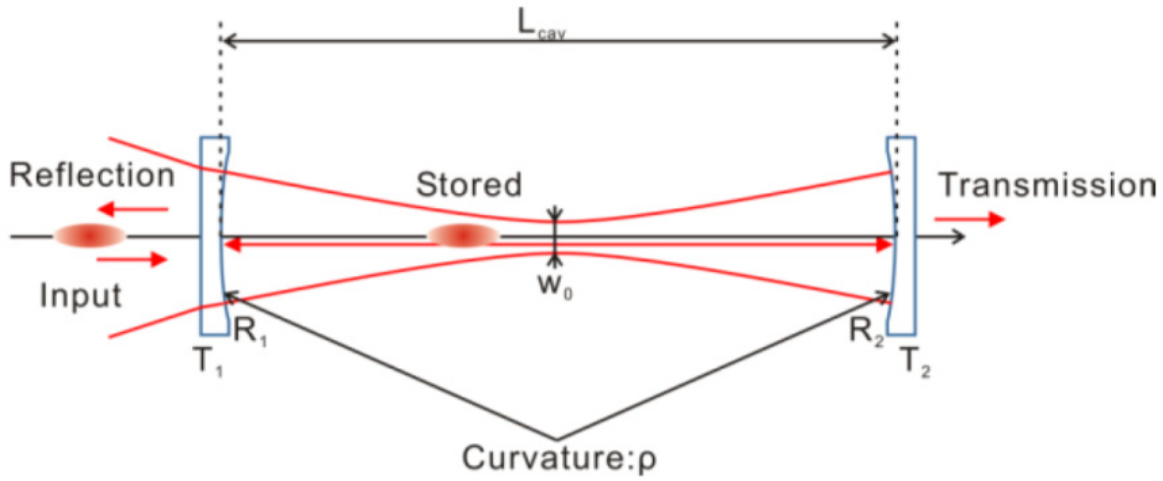
where  $f$  is the repetition frequency. Fundamental characterization of the laser-Compton X-ray source has been undertaken with  $f$  typically as 1-10 Hz. High flux mode requires  $f$  in 100MHz range in burst mode for an equivalent single shot imaging.

The first approach is the pulsed laser storage in an optical enhancement cavity for laser-Compton X-ray sources (Sakaue, et.al. 2010, 2011). The enhancement factor  $P$  inside the optical cavity was 600 (circulating laser power was 42kW), in which the Finesse was more than 2000, and the laser beam waist of 30 $\mu$ m ( $2\sigma$ ) was stably achieved using a 1 $\mu$ m wavelength Nd:Vanadium mode-locked laser with repetition rate 357MHz, pulse width 7ps, and average power 7W. The schematic of the employed super-cavity is shown in Figure 2.

Short laser pulse *input* is injected through mirror 1 with transmittance  $T_1$  and reflectance  $R_1$ . The mirror curvature is given as  $\rho$ . The beam waist is given as  $W_0$  and the cavity length is given as  $L_{cav}$ . The injected pulses overlap with the following pulses inside the cavity indicated as *Stored*. The loss is caused due to transmissions  $T_1$  and  $T_2$  of both mirrors.

An enhancement cavity requires high reflectivity and low transmittance mirror i.e. ultra-low loss mirror as an input and high reflectivity mirror as an output for high enhancement. The enhancement  $P$  is expressed by using cavity finesse  $F$  as (Hodgson, et.al, 2005);

$$P = \frac{F}{\pi} \quad (6)$$



**Figure 2.** Schematic of laser storage enhancement cavity of Sakaue

It is noted that the assumed cavity length is perfectly matched with the repetition rate of input laser pulses. Finesse  $F$  is given by;

$$F = \frac{\pi\sqrt{R_{eff}}}{1 - R_{eff}} \quad (7)$$

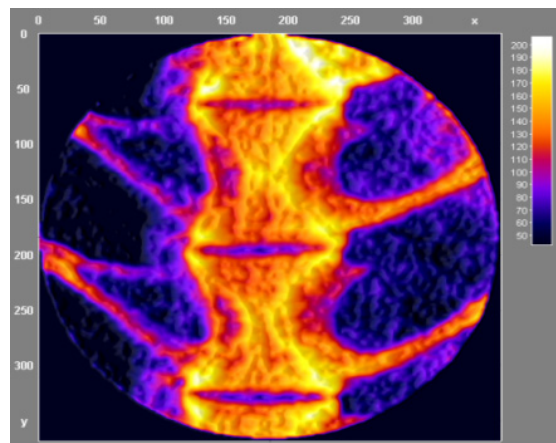
where  $R_{eff}$  is  $\sqrt{R_1 R_2}$ . As is described above, higher reflectivity provides a higher enhancement cavity. Particularly the loss, which includes both absorption and scattering on the reflection coating, is the critical issue for storing high power laser beam. The beam waist of an enhancement cavity is described as;

$$w_0^2 = \frac{\lambda}{\pi} \frac{\sqrt{L_{cav}(2\rho - L_{cav})}}{2} \quad (8)$$

where  $\lambda$  is the wavelength of the laser,  $L_{cav}$  is the cavity length,  $\rho$  is the curvature of the cavity mirror. While high enhancement is relatively easier, smaller waist cavity down to  $10\mu\text{m}$  is difficult as described in Eq. (8). Another work reported an enhancement of  $P \sim 1400$  with a  $22\mu\text{m}$  beam waist and  $72\text{kW}$  storage power (Pupeza, et.al. 2010). The scaling limit is given by optics damage, which is around  $100\text{kW}$  with ps pulse in this research stage. It was reported by Sakaue on an imaging demonstration by using the enhancement cavity approach of Fig.2, in which the stored pulse energy was  $200\mu\text{J}$  level in a burst mode of 100 pulses. The equivalent macro pulse energy was  $20\text{mJ}$ . The larger focusing spot decreased available X-ray photons in each collision event, and the required time for imaging was much longer than equivalent single shot imaging (Sakaue, et.al, 2012). The repetition rate was  $3\text{Hz}$ , and imaging of a fish bone was taken in 30 min with total laser energy of  $108\text{J}$ . Figure 3 shows an imaging example in this experiment. Once the laser is focused to  $10\mu\text{m}$  diameter, and electron beam is focused to  $30\mu\text{m}$  diameter, then the required total laser energy decreases to  $3\text{J}$ , which indicates the design parameter of Table 1 as a good measure.

Grating based X-ray phase contrast imaging is now developing as a more sensitive imaging technology (Momose, et al. 2012), and a high repetition rate X-ray source, based on an enhancement cavity combined with a compact synchrotron, was recently introduced in preclinical demonstration of biological samples (M.Bech, et.al 2009). The X-ray peak energy was 13.5keV with 3% band width. The source size was relatively large as 165 $\mu\text{m}$  due to the focusing limit of circulating electron bunch in the compact ring. The repetition rate was typically in continuous 100MHz region, but the unit imaging time period was around 100 seconds (~2 minutes) due to lower X-ray photon flux per each event.

Classical low repetition rate laser Compton X-ray source demonstrated earlier a successful in-line phase contrast imaging of biological samples (Ikekura-Sekiguchi,et.al 2008). The repetition rate was at 10Hz with 40 $\mu\text{m}$  diameter source size. The imaging was undertaken by 3ps pulse width X-ray beam of 30keV energy. The required shot number for imaging was 18000 (30 minutes). It was indicated by this experiment that a solid state laser must have higher pulse energy more than 1J, and a better beam quality for 10 $\mu\text{m}$  focusing, for single shot imaging. We evaluate a possible solid state laser technology in the following sections on this subject, by reviewing practical instrumental limitations and propose the most promising approach for a compact single shot laser-Compton X-ray imaging.



**Figure 3.** Refraction contrast imaging of bio sample (fish bone) by a laser-Compton X-ray source (Sakaue, et.al. 2012)

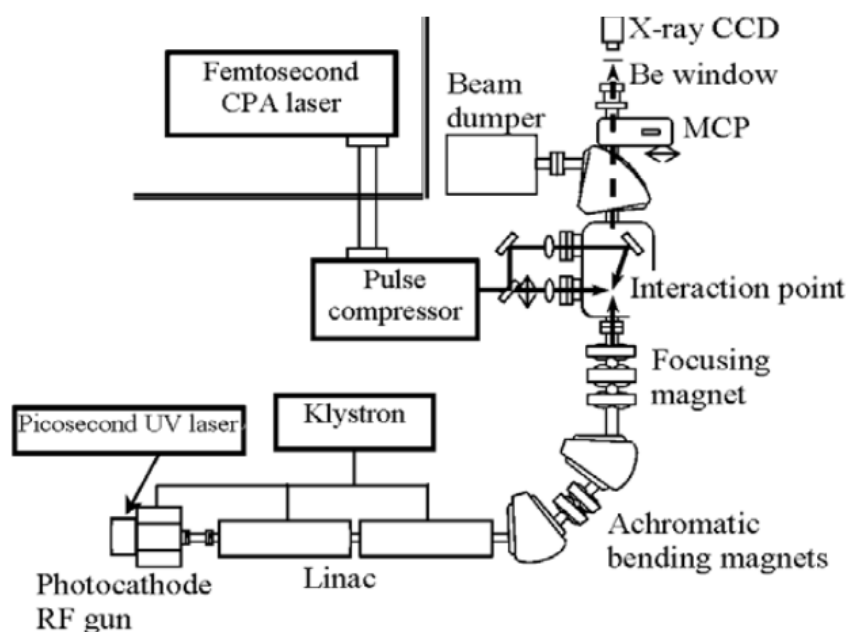
## 2. Temporal and spatial synchronization between electron beam and laser pulses

The essential technology for the laser-Compton X-ray source has been well studied in the Femtosecond Technology Project in Japan, and the achieved performance of the X-ray beam was also well characterized. Mathematical formula was obtained on its fluctuation depending on the temporal and spatial jitters (Yorozu, et.al 2002). Synchronization and stabilization technology was developed to the stage that the resulting pulse-pulse X-ray fluctuation almost reflects the laser pulse energy fluctuation (Yanagida, et.al 2003). The achieved overall performance was reported by T.Yanagida in a SPIE conference (Yanagida, et.al 2005). Figure 4 and table 2 show the system configuration and the summary of the



specification of the laser-Compton X-ray source, studied and developed in the FESTA program. A phase contract imaging was also demonstrated by this light source of bubbles in solidified adhesives.

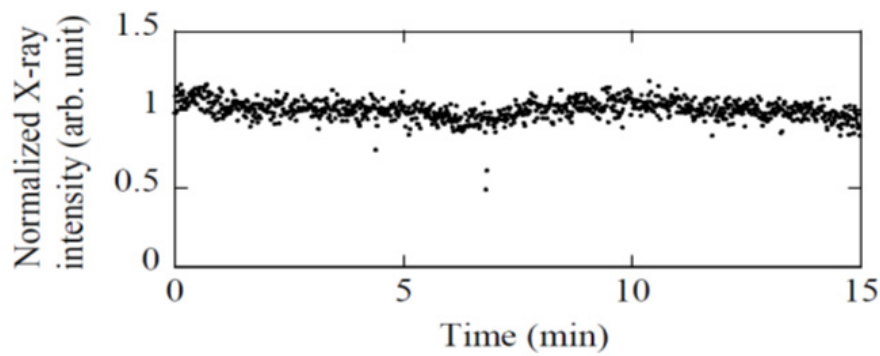
The electron beam is generated from a photo cathode RF gun driven by a synchronized picosecond UV laser, and accelerated to 38MeV energy by a S-band Linac. The achieved normalized emittance was  $3 \pi \text{mm-mrad}$ , and resulted in the focused beam size as  $30 \mu\text{m}$ . It was demonstrated as further reduction of emittance was possible by spatial and temporal shaping of irradiation laser pulse for electron beam from photo cathode (Yang, et.al.2002). The employed laser for X-ray generation was a 4TW Ti:Sapphire laser with 800nm wavelength. The laser pulse was focused down to  $10 \mu\text{m}$  diameter and the peak intensity was around  $10^{18} \text{w/cm}^2$ . The number of generated X-rays was measured with Micro Channel Plate located 2.6m downstream from the interaction point (source point). The MCP gain was calibrated using a standard  $^{55}\text{Fe}$  X-ray source with known strength. The pulse width was estimated from measured electron beam and laser pulse width. The X-ray pulse width is almost determined by longer electron beam pulse width in case of normal incidence ( $165^\circ$  interaction angle) and the cross section of the focused electron beam in case of  $90^\circ$  interaction angle. The long term fluctuation of the generated X-ray pulses is shown in Figure 5 in case of normal incidence arrangement. The repetition rate was 10Hz and the X-ray fluctuation was 6%, which is almost equivalent to the fluctuation of incident laser pulse energy. The laser focused intensity is around the nonlinear laser-Compton threshold as  $a_0 \sim 0.6$ . This was confirmed by a calculation by CAIN code in Figure 6. It is observed in the calculation of a nonlinear effect in the higher component of the generated X-ray energy distribution by blue dots (calculation by K.Sakaue).



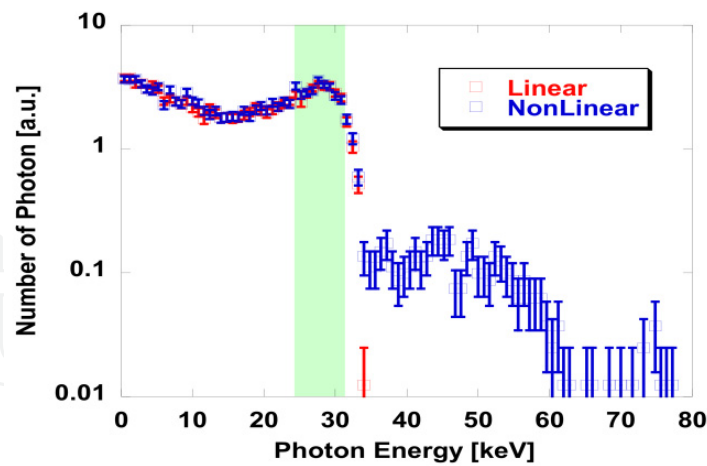
**Figure 4.** System configuration of laser-Compton X-ray source

Electron parameters		X-ray parameters	
Electron energy	38 MeV	Interaction angle	165°      90°
Bunch charge	0.8 nC	Maximum energy	33.7 keV      17.1 keV
Bunch width	3 ps (rms)	Total number of photons	2×10 <sup>6</sup> 5×10 <sup>5</sup>
Beam size	30 μm (rms)	(photons/pulse)	
Normalized emittance	3 π mm-mrad	Pulse width	3 ps (rms)      150 fs (rms)
Laser parameters		Intensity fluctuation	6%      11%
Pulse energy	200 mJ	Repetition rate	10 Hz      10 Hz
Pulse width	50 fs (FWHM)		
Wavelength	800 nm		
Beam size	10 μm (rms)		

**Table 2.** Summary of the electron beam and laser parameters and obtained X-ray parameters



**Figure 5.** Fluctuation of X-ray intensity in the normal incidence laser-Compton X-ray generation

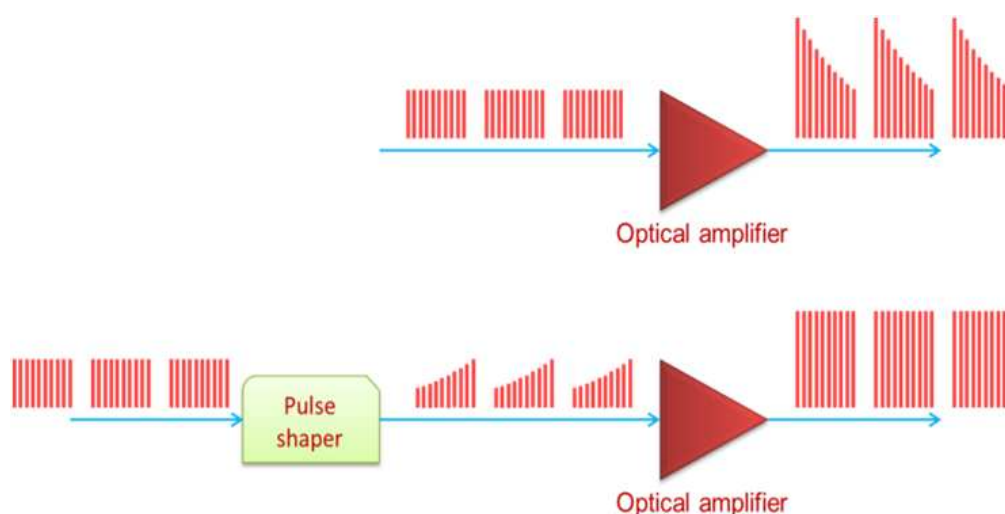


**Figure 6.** Calculated results of the X-ray energy distribution by CAIN code in log plot for linear (red) and nonlinear (blue) laser Compton scattering. Higher energy components are accompanying the linear ones. Light green region indicates the x-ray spectrum employed for imaging.

It is noticed that the component technologies for a single shot imaging by laser-Compton X-ray is well matured. There are but still several concerns necessary to design an optimized multi pulse method to realize the threshold (effective) laser energy of 4J in 10μm focus spot overlapped with electron bunch. The spatial stability of the laser-Compton X-ray source is



essentially guaranteed in the order of the focus spot, because laser and electron beam must synchronize spatially (also temporally) each other to generate X-ray beam. Stable multi pulse electron beam generation is needed for efficient and stable laser-Compton X-ray source, to avoid higher harmonics noise of X-rays by limiting laser pulse intensity in each interaction. The RF photocathode gun is irradiated by synchronized ps laser pulses to generate flat top electron beam pulse train. An earlier experiment was reported by T.Nakajyo in 2003 of 60 micro pulses generation with a flat-top shape (Nakajyo, et.al 2003). The essential technology is temporal modulation of the seed laser pulse trains by Pockels Cell, to compensate the amplification saturation of the seeded pulse trains in the power amplifiers. Figure 7 shows the example of the pulse train amplification without and with intensity modulation. The obtained flatness of the 60 bunch electron beam was equal to that of the incident laser train (<7%) during 0.5 $\mu$ sec duration. The time duration is regarded for bio imaging enough short for effective single shot imaging.

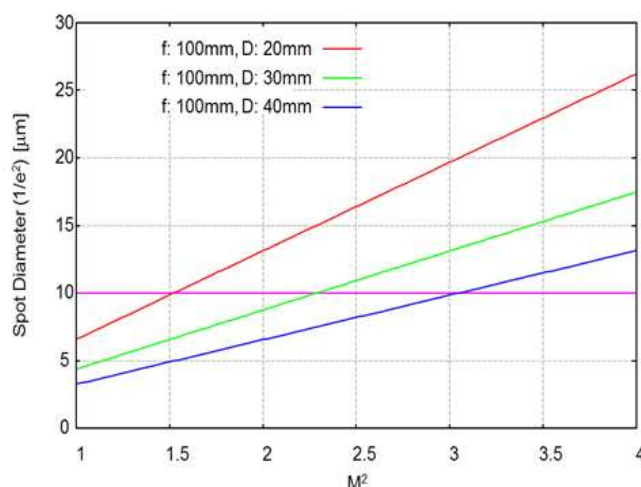


**Figure 7.** Pulse train amplification without (upper) and with (lower) intensity modulation

The other consideration is the selection of the amplifier module. It is required to focus 1J, 1ps laser pulses onto 10 $\mu$ m spot in spatial multiplexing in a near normal incidence arrangement. The requirement for the beam quality is expressed by  $M^2$  parameter of the laser beam. Figure 8 shows the relationship between  $M^2$  and focused beam spot size with the beam diameter as the working parameter. It is clear that  $M^2$  is required to be less than 2 to realize a 10 $\mu$ m focal spot diameter with 20mm original beam diameter.

### 3. Thermal distortion in solid state amplifier

The basic requirement for a laser driver in a single shot laser-Compton X-ray imaging is summarized as Table 3. The  $M^2$  of the laser beam is less than 2 from the discussions in the section 2. Detailed design work is required on the spatial configuration of 8 focusing optics to satisfy the 10  $\mu$ m focus spot by avoiding radiation damage to the optics from scattered X-ray and electrons. The main consideration is an evaluation of the innovative solid state laser technology in the last decade like fiber, thin slab and thin disc lasers.



**Figure 8.**  $M^2$  and focused beam size with beam diameter as parameters

Module pulse energy	>500mJ/ps
Module number	8 units
Multiplexed energy	4 J
Micro pulse time interval	8.4ns (119MHz)
Macro pulse width	~60ns

**Table 3.** Laser parameters for a laser driver in a single shot laser-Compton X-ray imaging around 30keV

Laser diode pumped rod type laser was regarded as the most suitable laser to meet the simultaneous requirement of high pulse energy, high average power together with high beam quality, before the fundamental solid state laser innovation. It was well known that flash lamp pumped solid state laser suffered from high thermal distortion of the laser medium due to low optical-optical conversion efficiency. Laser diode pumping was expected to solve the thermal distortion problem by improved energy conversion efficiency in the same configuration. Figure 9 is an example of a LD pumped rod Nd:YAG amplifier of 9mm diameter. Maximum LD pump power was 2.1kW, and optical-optical conversion efficiency was 41% (Endo et.al, 2004).

The fundamental difficulty of the LD pumped large rod amplifier comes from slow cooling speed of the laser material from the water jacketed located around the rod. The resulting temperature gradient causes thermal lensing, which is expressed analytically by the following expression (Koechner, 1999).

$$f = \frac{KA}{P_a} \left( \frac{1}{2} \frac{dn}{dT} + aC_{r,\phi} n_0^3 + \frac{ar_0(n_0 - 1)}{L} \right)^{-1} \quad (9)$$

Temperature profile becomes radially parabolic. The first term corresponds to the temperature depending refraction index change of 70% contribution to  $f$ , the second term is stress induced refraction index change of 20% contribution to  $f$ , and the last term is temperature depending surface effect of 10% contribution. The cumulative effect of beam

amplification and propagation of spatially non uniform beam results, combined with slight non uniform initial gain distribution, in a chaotic wave front with higher  $M^2$ . Figure 10 shows an example of beam cross section after booster amplifier of Fig.9 with 1.1kW average power at 10 kHz repetitive amplification of 6ns pulses. The beam was focused by  $f=10\text{cm}$  lens to 350  $\mu\text{m}$  diameter with 10mm initial beam diameter. The resulting  $M^2$  was nearly 35. The fundamental problem of rod amplifiers comes from temperature gradient. This was the main motivation of the enthusiastic search for a new architecture of low  $dn/dT$  solid state laser technology in the last two decades (Injeyan. et.al, 2011).

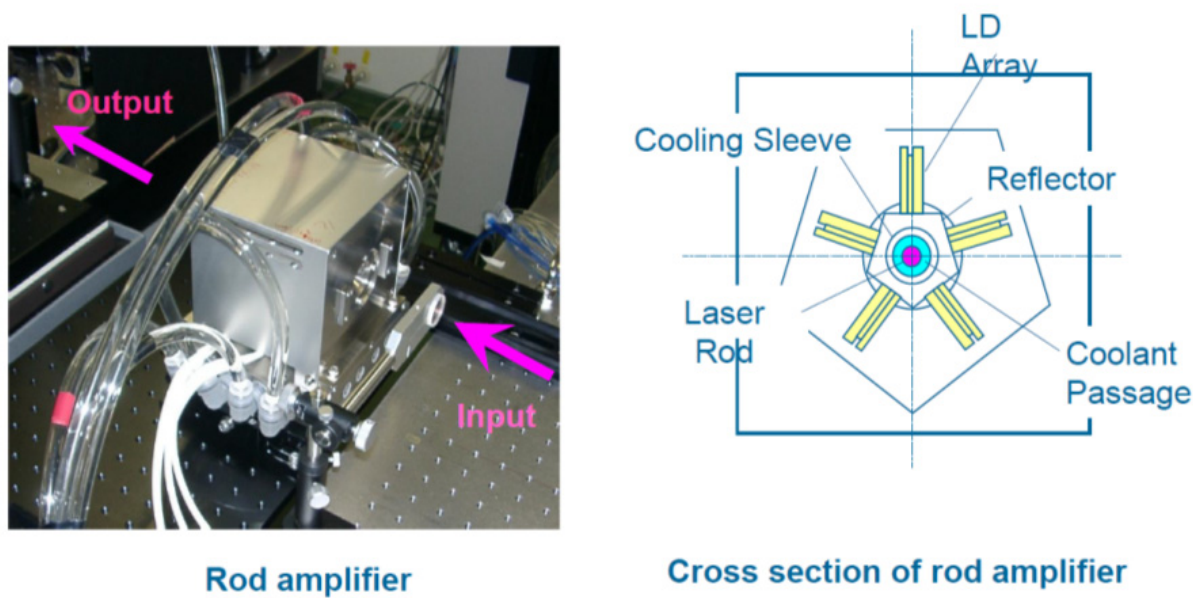


Figure 9. Outlook and cross section configuration of 9mm diameter Nd:YAG rod amplifier

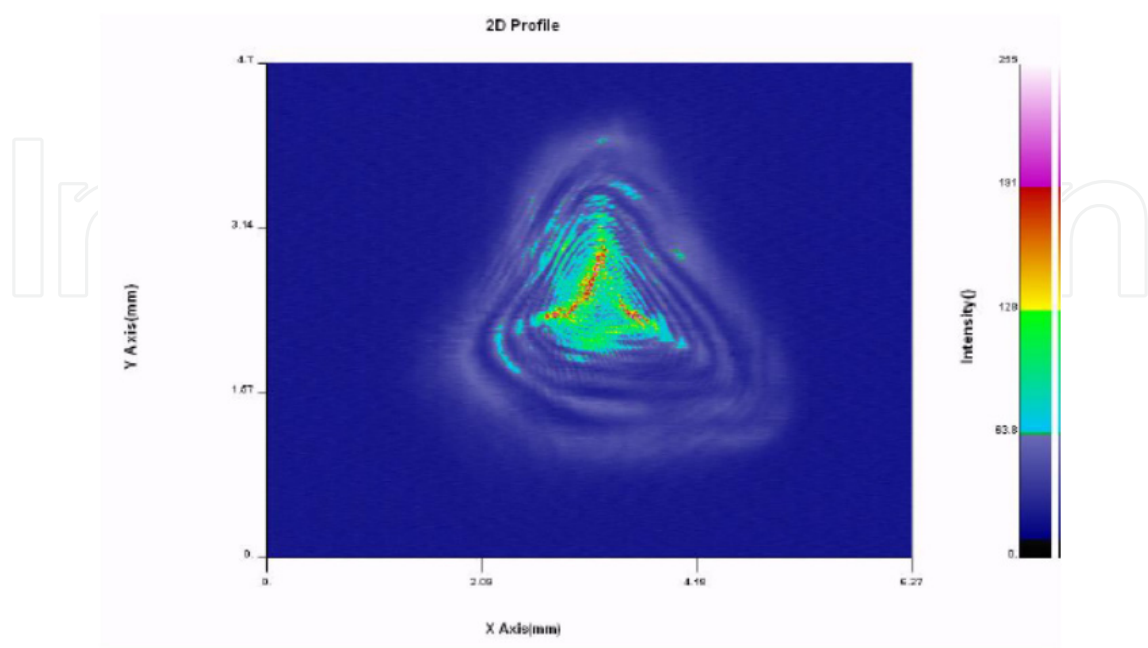
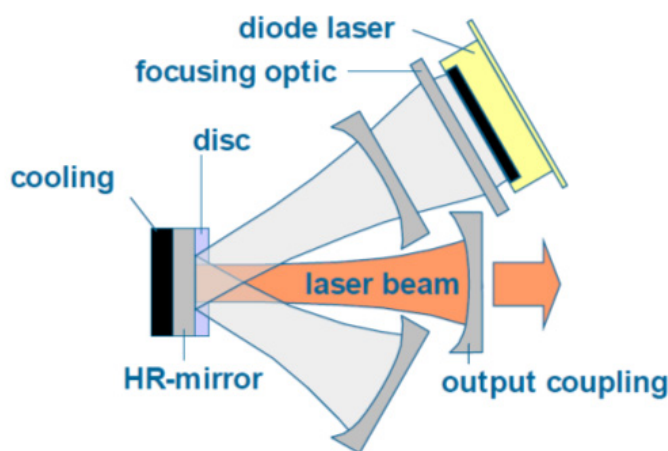


Figure 10. Beam shape after rod amplifier of 9mm diameter at 1.1kW average power

#### 4. Thin disc laser as a high beam quality, short pulse solid state amplifier

Cryogenic cooling was considered to solve the temperature gradient problem in rod type LD pumped laser. MIT laser scientists are working following on this concept with recent unprecedented results of  $M^2 < 1.05$  from cryogenically cooled (77K) bulk Yb:YAG laser in Q-switched mode of 20mJ/16ns at 5kHz. The average power was modest 100W in this experiment. The pointing stability was reported as 20  $\mu$  radian as mean deviation (Manni, et.al, 2010). One disadvantage of the cryogenic cooled Yb:YAG is the gain bandwidth narrowing, and compression to 1ps pulse width is not appropriate due to this effect (Hong, et.al. 2008). Fiber laser technology is progressing significantly with various laser specifications in CW and pulsed mode due to its efficient cooling characteristics owing to larger surface area/volume ratio. One drawback of fiber laser is its limited short pulse energy due to smaller medium diameter. There are still significant progresses in this field from its early work by a cladding-pumped, Yb doped large core fiber amplifier with specifications of 50W average power by 80MHz repetition rate of 10ps pulses with  $M^2 < 1.3$  (Limpert, et.al, 2001). Recent experiments achieved high pulse energy of 26mJ with 60ns pulse width at 5kHz repetition rate in Q-switched mode by a large-pitch fiber with a core diameter of 135  $\mu$  m (Stutzki, et.al. 2012). The average power is approaching to kW level with femtosecond pulse at high repetition rate. The reported performance was  $M^2 = 1.3$  with 0.9ps pulse width with average power 830W at 80MHz repetition rate (Limpert, et.al. 2011). Sandwiched thin slab geometry is also promising to realize low temperature gradient inside laser medium by efficient cooling from both sides of thin slab. Multi-pass amplification is successfully employed inside the medium with expanding beam shape to keep the laser intensity constant during amplification. 1.1kW average power was reported with Yb:YAG as laser medium. The repetition rate was 80MHz of 615fs pulses, with  $M_x = 1.43$  and  $M_y = 1.35$  (Russbueltdt, et.al. 2010). All these approaches are remarkable, especially regarding the beam quality  $M^2$ , but the achievable pulse width, and energy is limited due to cryogenic temperature or limited beam diameter in each technology. It is to be noticed that kW level, 80MHz femtosecond source could improve the average stored laser power in an enhancement cavity, once present limitation of optics damage is eliminated.

Thin disc laser is characterized with its larger diameter, and fundamentally suited for high pulse energy amplification. The schematic of a thin disc laser is shown in Fig.11. Thin disc of laser active medium like Yb:YAG of typical diameter 25mm is molded on a high reflectivity mirror (both wavelength of multi-pass LD; 940nm and laser wavelength; 1030nm). Water cooling from the backside of thin disc keeps the medium temperature around 15 degree. Mechanical distortion of the surface and ASE gain depletion is the main subject to be considered for high beam quality, short pulse high energy amplification. There are several activities to realize one J pulse energies with  $M^2 < 1.3$  in ps pulse length at high repetition rate by thin disc laser technology. Conceptual design of a spatially multiplexed laser driver for single shot laser Compton imaging is presented in the next section, by showing several research examples.



**Figure 11.** Schematic of thin disc laser configuration

## 5. Laser driver for single shot laser-Compton imaging

Candidate materials are considered for this particular application as Yb:S-FAP (Yb:Sr<sub>5</sub>(PO<sub>4</sub>)<sub>3</sub>F) or Yb:YAG. Comparison of both material characteristics are shown in table 4 (Payne, et.al, 1994). Both are characterized with higher quantum efficiency (Stokes factor), which is advantageous to less thermal stress after pulse energy depletion. Crystal growth to a larger diameter is important to avoid laser induced damage on the laser medium surface for 1J, ps pulse amplification at high repetition rate. It was tried to select Yb:S-FAP as the laser material by an end pumped square bar configuration, for the development as the future laser driver for high brightness laser Compton X-ray source (Ito et.al, 2006). The oscillator was a Yb:glass mode locked laser with 200fs, 170mW average power at 79.33MHz repetition rate, tuned at 1043nm wavelength. The oscillator pulse was stretched by a grating pair, and seeded into a cavity of a regenerative Yb:S-FAP laser by a Pockels Cell. Stacked laser diode array irradiated the Yb:S-FAP square rod (3.5 × 3.5 × 21 mm<sup>3</sup>) with 900 nm wavelength, for 1.3ms duration of 1J pulse energy, through a lens duct and aspheric lens. The regenerative amplifier delivered 24mJ and the pulse was compressed down to 2ps in an initial experiment. Pre-amplifiers and main amplifiers were designed on the same architecture. Main amplifier employed square rods of geometrical size as 8 × 8 × 24 mm<sup>3</sup>. Heat removal at higher repetition rate was not efficient from these amplifiers and the amplification was not perfect due to thermally induced birefringence. It was recently reported that “Mercury Laser Program” has achieved 100J in ns pulse length at 10Hz repetition rate from a side pumped thin slab Yb:S-FAP module of 3cm × 5cm aperture with a powerful cooling by He gas flow (Ebberts, et.al 2009). It is essentially proved from these experiments that Yb:S-FAP is usable as a laser material for specific ps application with higher pulse energy, once a large gas flow system is allowed in the whole system.

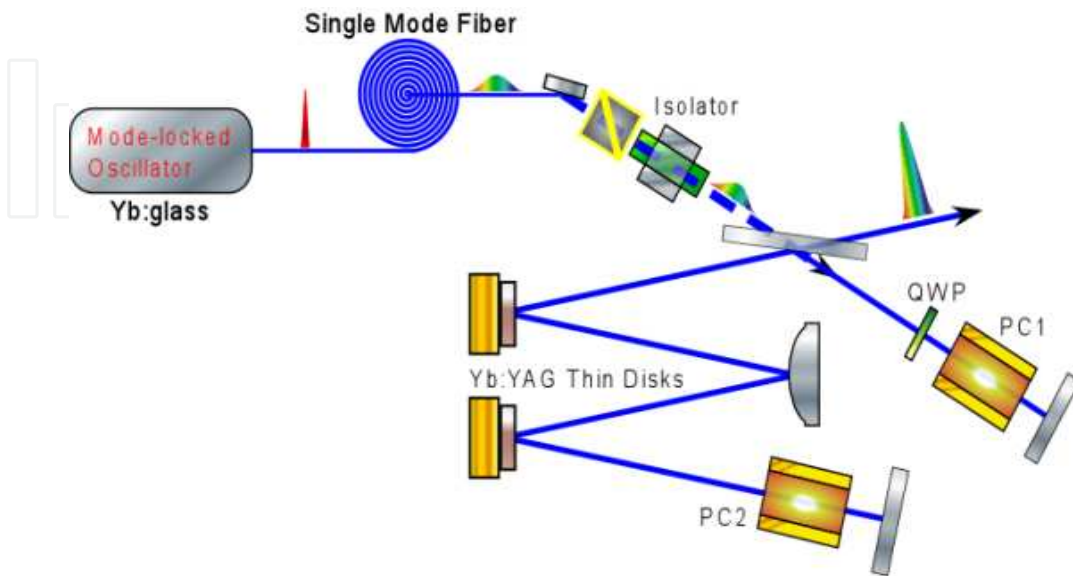
Another candidate is Yb:YAG for short pulse, high repetition rate operation for various applications. It is discussed that there is an obstacle to obtain large pulse energy in J level, from a bulk structure Yb:YAG material like a rod due to thermal population of the lower laser level (Ostermeyer, et.al. 2007). Solution might be found in a new configuration



	Yb:S-FAP	Yb:YAG
Pump wavelength (nm)	900	940
Laser wavelength (nm)	1047	1030
Fluorescence lifetime (ms)	1.26	1.0
Emission cross section ( $10^{-20}\text{cm}^2$ )	7.3	2.3
Saturation fluence ( $\text{J}/\text{cm}^2$ )	3.2	9.6
Pump saturation intensity ( $\text{kW}/\text{cm}^2$ )	2.3	32
Spectral bandwidth (nm)	3.5	9.5
Thermal conductivity ( $\text{W}/\text{mK}$ )	2	10

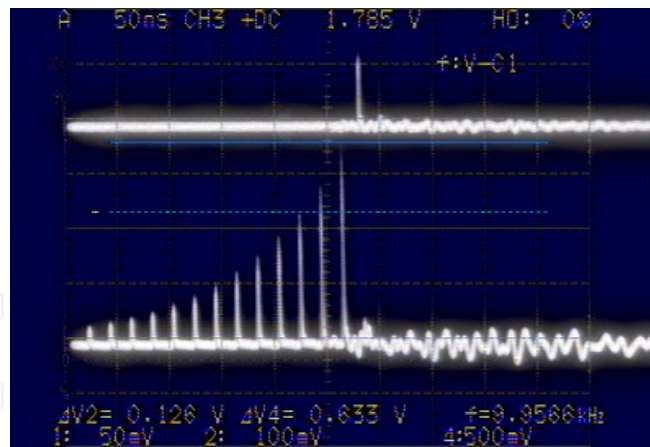
**Table 4.** Specific characteristics of Yb:S-FAP and Yb:YAG materilas

optimized for efficient cooling. Thin disc configuration is advantageous for the sake of efficient heat removal from gain media. It was tried to develop a pulsed thin disc laser with 1kW average power at 10 kHz repetition rate (Miura, et.al. 2005). Cavity optimization was performed for a regenerative amplifier, composed of two Yb:YAG thin disc modules, by compensating the deformation of optical components inside the cavity, with high beam quality at 500W CW operation. The extinction rate of linear polarization was more than 1:140. The developed regenerative amplifier module was connected with a seeder, which was a Yb:glass mode locked oscillator with 325fs pulse width and a fiber pulse stretcher. The extended pulse was injected into the regenerative amplifier cavity at 10 kHz repetition rate. The experimental configuration is shown in Fig12. Figure 13 is the pulse build up inside the regenerative amplifier cavity. Output average power was 33W in single mode, and 73W in multi mode with 50-100 ps pulse length (Miura,et.al. 2006). It was reported that an average power of 75W was achieved at 3kHz repetition rate with pulse energies exceeding 25mJ, a pulse-pulse stability of  $<0.7\%$  (rms), a pulse duration of 1.6ps from an improved single thin disc module configured in a regenerative amplifier with high beam quality as  $M^2<1.1$  (Metzger, et.al 2009).



**Figure 12.** Schematic of a dual module thin-disc regenerative amplifier





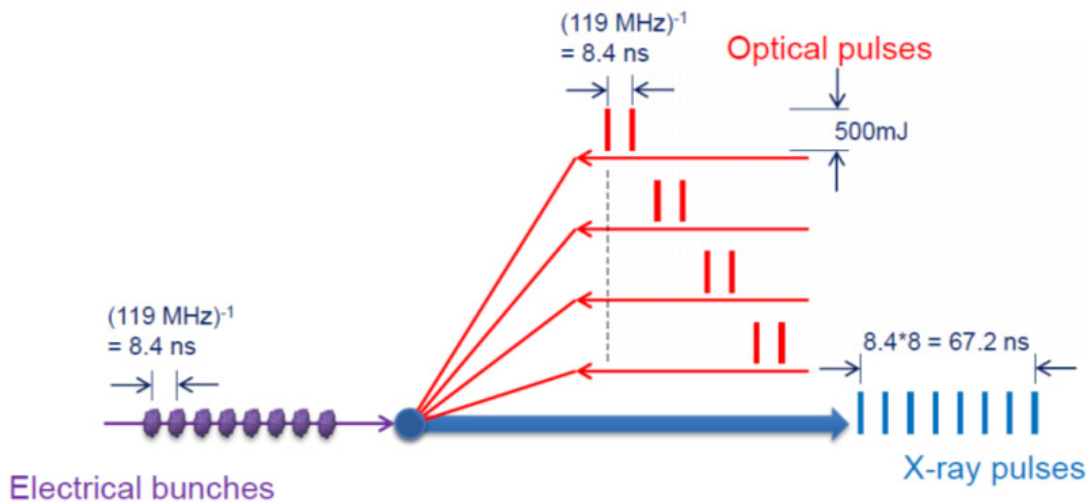
**Figure 13.** Operation of thin disc regenerative amplifier. Upper trace shows sliced out pulse, and lower trace shows building up inside cavity

Pulse energy increase to J level needs a multi pass amplifier without intra cavity Pockels Cell. The thickness of a thin disc medium is less than mm length for efficient water cooling from back side, and the single pass gain is lower than that of a rod medium in general. Multi pass optical cavity is required for this purpose, without any beam distortion during the amplification. A study was tried to design an optimized multi pass mechanical structure (Neuhaus, et.al.2008). A progress was recently reported from a group of Max Born Institute, Berlin, Germany on a development of a diode pumped chirped pulse amplification (CPA) laser system based on Yb:YAG thin disk technology, with a repetition rate of 100 Hz and output pulse energy aiming in the joule range (Tuemmler, et.al, 2009). Regenerative amplifier pulse energy was more than 165 mJ at a repetition rate of 100 Hz with a stability of 0.8% over a period of more than 45 min. The optical to optical conversion efficiency was 14%. The following main amplifier increased pulse energy to more than 300 mJ by a multi pass configuration. A nearly bandwidth limited recompression to less than 2 ps was also demonstrated. Further scaling of this technology is possible by enlargement of the thin disc diameter by careful optimization of the mitigation of surface deformation and ASE gain depletion. The latter phenomenon is well known in a small aspect ratio laser medium (Lowental, 1986). Numerical modeling of ASE gain depletion is useful to optimize working parameters, and HiLASE project is engaged in this effort to achieve 1J level picosecond pulses with high beam quality from thin disc amplifiers (Smrz, et.al.2012).

It is possible to design a spatial-temporal multiplexing of 0.5J, 1ps pulses onto the interaction point with low emittance electron bunch as is shown in Fig.14. Multiplexing of 8 pulses in polarisation combined 4 beams is the natural configuration. Timing jitter is possible in fs range which causes no actual X-ray output fluctuation. Spatial overlapping on 10 $\mu$ m diameter spot is challenging with pointing stability in the 10 $\mu$ rad range. Figure 14 indicates the multiplexing scheme to realize the laser specification of Table 2, based on 0.5J, ps thin disc laser modules of 8 units.

The generated forward directed X-ray beam has an effective pulse width <70ns, which is enough short for single shot imaging of bio samples. It is noted that the relative interaction angle between electron bunch and laser beams are fixed as 165 degree each other, in axial

symmetry. It is proposed in a white book published by ELI Nuclear Physics working group, as the first stage of gamma ray program based on laser-Compton scheme, assumes 20 micro pulses with 0.15J, ps laser pulses, which is 3J effectively (Barty,C. et.al. 2011). The macro pulse repetition rate is expected as 120Hz. The average laser power is 360W. This is a manageable specification by usable laser technology described in this article.



**Figure 14.** Spatial-temporal multiplexing of 0.5J,ps laser pulses

## 6. Conclusion

This chapter described the laser-Compton X-ray generator. The compact, high brightness X-ray source has been designed, fabricated and tested. This technology provides successful single-shot imaging of bio samples with multi J solid state laser pulses of ps pulsewidth. Advanced laser technologies were evaluated to realize a high beam quality, 1J level pulses. Thin disc laser was shown to be the best candidate for this application with Yb:YAG as the active medium. Spatial-temporal laser multiplexing was proposed to avoid nonlinear Compton effect. Some further research effort may bring us the realization of this technology.

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