GENERATION OF SUB-HUNDRED FEMTOSECOND X-RAY VIA HEAD-ON INVERSE COMPTON SCATTERING

N.Y. Huang, S.S. Yang, Institute of Photonics Technologies, National Tsing Hua University,Taiwan
C.C. Liang, A.P. Lee, C.S. Chou, J.H. Chen, J.Y. Hwang, W.K. Lau, NSRRC, Taiwan

Abstract

The feasibility of generating sub-hundred femtosecond X-ray pulses based on head-on inverse Compton scattering (ICS) of relativistic electron pulses with laser has been studied. Relativistic electron pulses of 13.55 fsec can be produced by compressing the energy-chirped beam from a thermionic cathode rf gun with an alpha magnet [1]. This beam has an intensity of ~ 3.31×10^8 e- per bunch and is accelerated to 20.5 MeV with an S-band linac structure and is focused to 30 μm for scattering with an 800 nm, 3.75 mJ infrared Ti:Sapphire laser in the laser-beam interaction chamber. With this method, peak flux of back-scattered X-ray photons as high as 2.17×10^{18} photons/sec is achievable at ~ 1.24 Å wavelength. This femtosecond X-ray source is planned to be used as a tool for studying ultrafast phenomena in nanostructure in the near future.

INTRODUCTION

Generation of ultrafast electron and light pulses for observation of the fast changing physical world in femtosecond time scale has been a vivid research topic in the past few decades [2]. Commercial femtosecond lasers with wavelengths ranging from infrared to ultraviolet have been available nowadays. However, generation of femtosecond pulses in the X-ray regime is not yet a mature technology. Recently, thanks to the development of femtosecond electron beam technology, production of ultrafast X-ray from such femtosecond electron beam by head-on ICS is now feasible and become a useful tool complementary to X-ray free electron laser and the laser beam slicing technique in third generation storage ring synchrotron light source for studying ultrafast structural dynamics of materials at atomic resolution.

ICS is the interaction between the relativistic electron bunch and the laser pulse that the motion of relativistic electrons is modulated by the laser field and the energy of back-scattered photon will be up shifted by a factor of γ^2 [3]. The back-scattered photon wavelength λ_x is related to electron beam energy and laser wavelength λ_L through Eq. (1), where γ is the Lorentz factor, and a is the laser strength parameter which is related to the laser intensity by $a = 0.85\times10^{-9}[\lambda_L(\mu m)][I_0(W/cm^2)]^{1/2}$.

$$\lambda_X = \frac{\lambda_L}{4\gamma^2}\left(1+\frac{a^2}{2}\right) \qquad (1)$$

Head-on and orthogonal ICS are two possible setups for femtosecond X-ray generation. Since all the electrons take part in the interaction, the head-on scheme is able to generate more photons per pulse than the orthogonal scheme [4]. Neglecting nonlinear effects, the number of back-scattered X-ray photons per pulse for a head-on ICS with laser and electron beam having identical beam diameters at interaction point can be calculated from the formula expressed in Eq. (2) [5],

$$N_X = \sigma_{TH}\frac{N_b N_L}{4\pi\sigma_b^2} \qquad (2)$$

where σ_{TH} is the Thomson scattering cross section of electron which is equal to 6.65×10^{-25} cm^2, N_b is the number of electrons per bunch, N_L is the laser photon number, and σ_b is the effective beam size. It is worth noting that an electron beam with tiny beam size and X-ray with short pulse length helps to improve the peak X-ray photon flux. However, the back-scattered X-ray pulse length is limited by the electron bunch length for head-on ICS [4].

In this study, we try to design femtosecond electron beam as short as possible for a head-on ICS experiment to produce ultrafast X-ray at about 1 Å wavelength. We will briefly describe our experimental setup in the following section. The femtosecond beam dynamics in the electron beam line will be discussed afterward and the last section will be our conclusion.

THE ULTRAFAST X-RAY EXPERIMENT

In our setup as shown in Fig. 1, a 2998 MHz thermionic rf gun with flat cathode (no nosecone) will be used as the electron source to produce a linearly energy chirped beam for the alpha magnet located downstream for bunch compression. An S-band constant gradient travelling-wave linac will be used for acceleration of electron bunch to 20.5 MeV and for further enhancement of bunch compression.

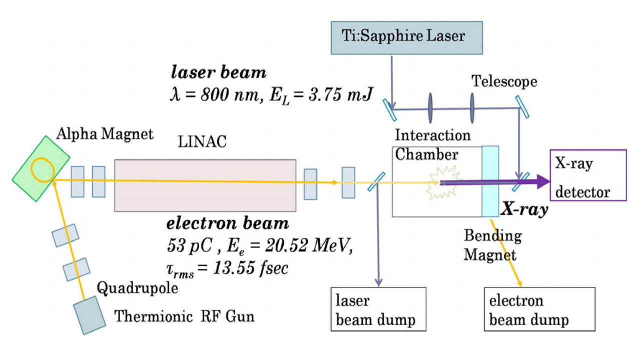

Figure 1: Experimental setup.

For economic reason, an 800 nm Ti:Sapphire laser with peak power of 37.5 GW will be used as the laser source. It is the same laser that drives a third harmonic generator to produce UV light for a photo-cathode rf gun system in different experiments. This IR laser and the ultrafast electron bunches will be focused for collision in the interaction chamber. Table 1 is a summary of designed parameters of our head-on ICS experiment.

Table 1: Designed parameters of the NSRRC inverse Compton scattering experiment

Laser beam		Electron beam	
Wavelength	800 nm	Energy	20.52 MeV
Pulse energy	3.75 mJ	Charge	53 pC
Peak power	37.5 GW	Bunch length	13.55 fsec
Focal beam size	30 μm	Focal beam size	30 μm
X-ray pulse			
Photon energy	10.0 keV ($\lambda_x = 1.24$ Å)		
Pulse duration	13.55 fsec		
Photon number	2.95×10^4 photons		
Peak photon flux	2.17×10^{18} photons/sec		

FEMTO-SECOND BEAM DYNAMICS

Multi-particle dynamics in the thermionic RF gun has been studied with PARMELA [6]. Particle distribution at gun exit as calculated by PARMELA is then transferred to ELEGANT [7] for optimization of particle dynamics for shortest bunch length at interaction point. Nonlinear effect in the alpha magnet up to third order is included. Finite aperture effects in electron beam line and wake fields in linac have been considered. Space charge effect is neglected throughout ELEGANT calculation and will be studied with other space charge tracking code in the near future.

Bunch Compression

The rf gun [8] has an average field gradient of 25 MV/m in its half cell and 50 MV/m in the full cell. It can generate 235 pC electron bunches with maximum normalized momentum at 6.02 (Fig. 2) and bunch length at 24.5 psec. With the alpha magnet gradient set at 260 Gauss/cm, the collimator set at a value that only the particles within ± 0.65% of selected normalized momentum (6.0 in our case) can pass through and the rf linac operates at 5.2 MV/m accelerating gradient (zero injection phase), electron bunches of 53 pC can be transmitted to the collision point and compressed to 13.55 fsec (Fig. 3).

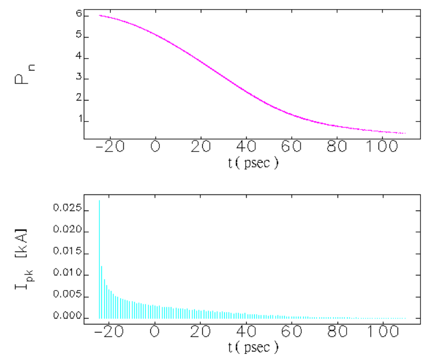

Figure 2: Energy and particle distributions of electron beam at rf gun exit (bin size = 1 psec).

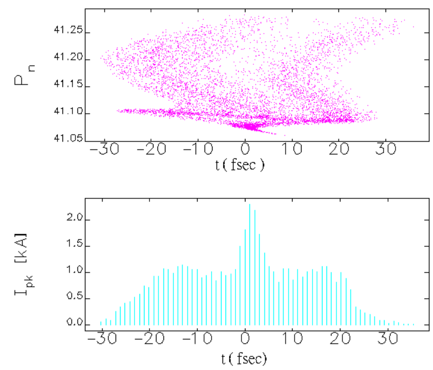

Figure 3: Energy and particle distributions of the compressed electron bunch at the interaction point (bin size = 1 fsec).

Since the head of a bunch from the rf gun has higher energy than its tail, the bunch tends to de-compress in drift sections. Therefore, the 24.5 psec electron pulses from the gun are lengthened to 72.3 psec in the drift section between the thermionic rf gun and the alpha magnet. At the alpha magnet exit, bunches are compressed to 93.58 fsec in rms bunch length. In other words, the alpha magnet helps to rotate the particle distribution in phase space clockwise and therefore the bunches are compressed by a factor of ~1000. However, as shown in Fig. 4, we have to over-compress the bunches a little bit in order to compensate bunch lengthening effect in downstream drift sections. The beam is accelerated to desired energy by rf linac so that all electrons in the bunches move more or less at the same speed, namely, particle distribution in phase space is "freezed" in the later stage of linac acceleration. Fig. 5 depicts the evolution of particle distribution in phase space along the rf linac at zero injection phase. As shown in Fig. 5, the velocity bunching mechanism also plays an important role in further compression of electron bunches in the linac. Since the tail of the bunch gains more energy while the head of the bunch gains less energy from the linac at zero rf phase, particle distribution has a counter-clockwise rotation in phase space in the first meter of linac. With this bunching mechanism, a bunch from the alpha magnet being accelerated and compressed by the rf linac can be as short as 13.62 fsec. Finally, we took advantage of the drift section between the linac exit and the collision point for further compression to 13.55 fsec.

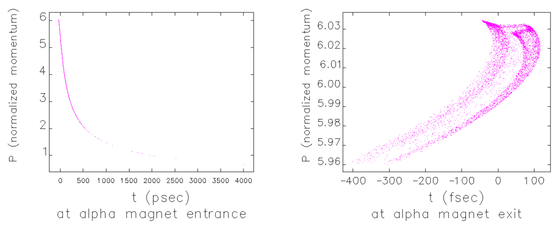

Figure 4: The temporal phase space at the entrance and the exit of alpha magnet.

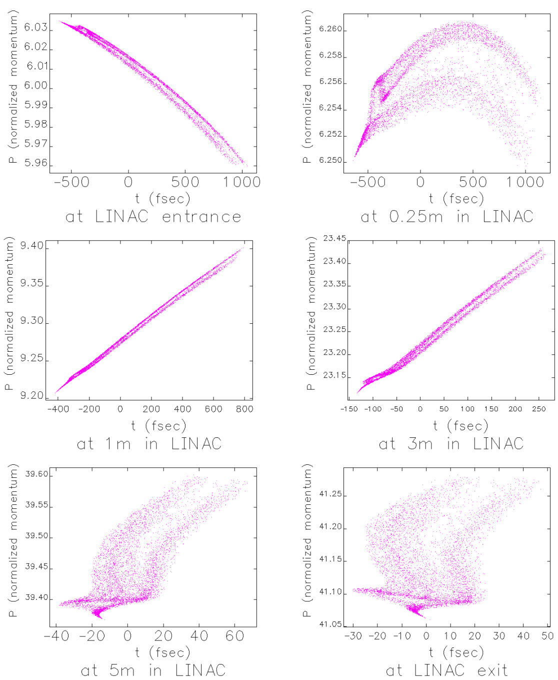

Figure 5: Bunch evolution in temporal phase space as the beam traverses the linac.

Transverse Beam Focusing

Besides temporal compression of electron bunch, we also need to focus the beam into a tiny spot in the interaction chamber to obtain high peak photon flux X-ray. Fig. 6 is the beam size evolution from the exit of rf gun to the collision point. Transverse size of the electron bunches at gun exit is about 93.2 μ m and normalized emittance is about 111.56 mm-mrad. The combined effect of alpha magnet dispersion and the collimator is responsible for the sudden blow up and drop off of horizontal beam size near alpha magnet in the beam line. As shown in Fig. 7, the beam at the interaction point can be focused to 30 μ m with proper tuning of quadruple pairs. At collision point, the normalized vertical emittance of the electron can reach 0.66 mm-mrad while the horizontal emittance can be as low as 0.61 mm-mrad. We believe the collimator in the alpha magnet is the cause of the low emittance. These tightly focussed and fully compressed bunches are critical in generating high peak flux femtosecond X-ray.

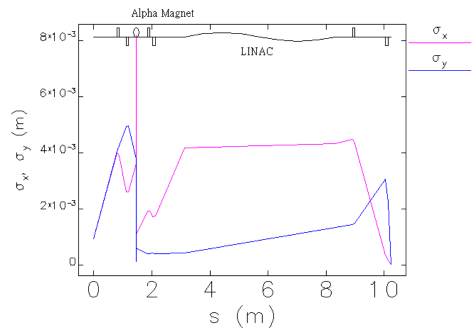

Figure 6: The beam size evolution in the beam line.

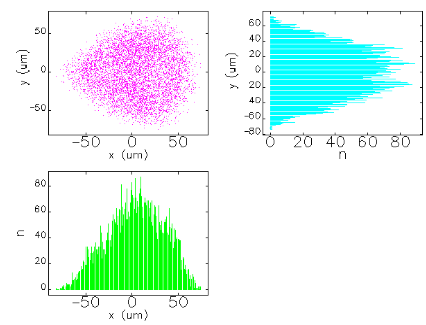

Figure 7: The spatial distribution and histogram of the electron bunch at the interaction point. (bin size = 1 μ m)

CONCLUSION

Based on our simulation study, it is very likely that sub-hundred femtosecond X-ray pulses with peak photon flux as high as 2.17×10^{18} photons/sec can be realized. Since both transverse as well as longitudinal space charge can be the limiting factors that inhibit bunch compression in our setup, further simulation study including these effects will be considered. Fabrication of the alpha magnet and thermionic cathode rf gun for a preliminary experiment is in progress.

ACKNOWLEDGEMENT

The authors would like to thank Professor Helmut Wiedemann for his continuous encouragement to study this interesting subject. We thank also Dr. Max Cornacchia and Dr. Michael Borland for their professional comments on our beam dynamic calculations and suggestions about the usage of the ELEGANT code.

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