# FOCUSING OF ULTRASHORT ELECTRON BUNCH FOR FEMTOSECOND INVERSE COMPTON SCATTERING X-RAY SOURCE

N.Y. Huang, S.S. Yang, National Tsing Hua University, Hsinchu, Taiwan
W.K. Lau, National Synchrotron Radiation Research Center, Hsinchu, Taiwan
H. Hama, Laboratory of Nuclear Science, Tohoku University, Sendai, Japan

*Abstract*

Design of an intense but tightly focused ultrashort electron beam for production of sub-hundred femtosecond X-ray pulses that based on head-on inverse Compton scattering (ICS) has been studied. The three dimensional (3D) space charge dynamics has been tracked and optimized throughout the whole beamline. It is found that the focusing ultrashort electron pulses as short as 67 fs can be produced by compressing the energy-chirped beam from a thermionic cathode rf gun with an alpha magnet and linac operating at injection phase near zero crossing. This multi-bunch electron beam has an intensity of 30 pC per bunch and is accelerated to 27 MeV with an S-band linac structure. The compressed electron beam is focused to 64 μm for scattering with an 800 nm, 3.75 mJ laser in the laser-beam interaction chamber. With this method, total peak flux of back-scattered X-ray photons exceeds $10^{18}$ photons/sec is achievable with the shortest wavelength of 0.7 Å.

## INTRODUCTION

Ultrafast X-ray can be used as a strobe to uncover the rapidly changing microscopic world at atomic resolution. With head-on inverse Compton scattering (ICS) of infrared laser by MeV electron beam, compact linac-based machines can be designed for production of high peak brilliance ultrafast hard X-rays. It has been demonstrated that picosecond X-ray pulses with peak photon flux as high as ~ $10^{19}$ photons/sec can be obtained via head-on ICS [1]. In such configuration, wavelengths of the backscattered photons are upshifted according to the following relation:

$$\lambda_X = \lambda_L (1 + a_0{}^2 / 2)/4\gamma^2 \qquad (1)$$

where $\lambda_L$ is the laser wavelength, $\gamma$ is the Lorentz factor, and $a_0$ is the laser strength parameter which is related to the laser intensity by $a_0 = 0.85\times10^{-9}[\lambda_L(\mu m)][I_0(W/cm^2)]^{1/2}$. Angular distribution of backscattered photon flux density is given as [2]

$$\frac{dF}{d\Omega} = \alpha N_0 \dot{N}_b a_0{}^2 / \theta_\Sigma^2 \qquad (2)$$

where $\alpha$ = 1/137, $\theta_\Sigma$ is the half-angle of radiation cone, $N_0$ is the number of laser periods, $\dot{N}_b = fI_b/e$ is the electron flux which is a product of filling factor, $I_b$ is the peak current of electron bunch, $f = min[1, \sigma_0{}^2/\sigma_b{}^2]$ is the filling factor and the cross sections of laser and electron beams are denoted as $\sigma_0$ and $\sigma_b$ respectively. The back-scattered photon flux can be calculated by integrating the angular flux density $dF/d\Omega$ over all solid angle. Unlike orthogonal ICS, the X-ray pulse duration from head-on ICS is limited by the electron bunch length. Obviously, high peak current and small beam size of electron beam that matches the laser spot size at the interaction point helps to improve X-ray photon flux. However, the space charge force within an intense ultrashort electron bunch has significant effect on particle dynamics in such low energy machine and therefore it needs to be studied carefully in the design of bunch compression.

In this study, space charge tracking has been done by General Particle Tracer (GPT) [3] starting from cathode to the interaction point through the whole beamline and it has been optimized for shortest bunch length at highest possible peak current. It is found that the final beam focusing for head-on ICS has significant degradation effect on electron bunch length due to path length differences. This problem can be resolved by adding solenoid magnetic field on the linac to help beam focusing. Based on this set of beam parameters, an ultrashort head-on ICS X-ray source at Å wavelength with high peak flux up to $10^{18}$ photons/sec can be expected for an infrared laser at mJ pulse energy.

## LOW ENERGY BEAMLINE FOR ULTRASHORT ELECTRON PULSES

An S-band linac system that employs a thermionic cathode rf gun as an electron source as well as an alpha magnet and a linac as the bunch compressor for 20-30 MeV femtosecond electron beam is being constructed at NSRRC for generation of ultrafast X-ray by head-on ICS in the near future [4]. Fig. 1 depicts the layout of the NSRRC S-band ultrashort electron beamline for head-on ICS experiment. The 1.5-cell side-coupled thermionic electron rf gun is modified from the original SSRL design with nose cone around the 0.25" thermionic dispenser cathode removed to avoid excessive beam focusing near cathode. A collimator will be installed in the alpha magnet for beam selection before injecting into the existing 2998 MHz linac. A quadrupole triplet is placed at the linac upstream for beam adjustment inside the linac structure to avoid beam loss. A waveguide phase shifter will be installed into the high power microwave system which allows the adjustment of linac phase. By adjusting the linac phase, bunch compression can be done not only by the alpha magnet but also by velocity bunching in the linac [5]. After acceleration in the linac, the compressed electron beam will be focused into the interaction chamber at the interaction point and collide with the focused laser beam from the opposite direction. In our first ICS experiment, an 800 nm infrared Ti:Sapphire laser with pulse energy at 3.5 mJ will be used.

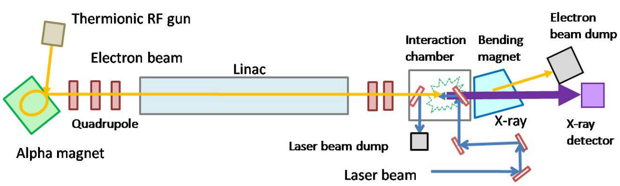


Figure 1: The layout of the NSRRC ultrashort electron beamline for ICS experiment.

## SPACE CHARGE DYNAMICS DURING BUNCH COMPRESSION

When accelerating gradients of 25 and 50 MV/m are applied to the half cell and full cell of the gun cavity respectively, a electron beam with maximum energy at 2.56 MeV and 182 pC bunch charge can be generated. Bunch length is about 39 ps at the gun exit. Electron distributions in the longitudinal and transverse phase spaces at the gun exit are shown in Fig. 2. In one rf cycle, electrons that are accelerated by higher $E_z$ field will leave the gun first and suffer less defocusing force due to $E_r$ field. Therefore, the head of a bunch will have higher energy and less divergence than the rest of the bunch. For this reason, the electron distribution in the transverse phase space has a "butterfly" shape. In the longitudinal phase space, a nearly linear distribution is beneficial to the bunch compression with a proper beam selection.

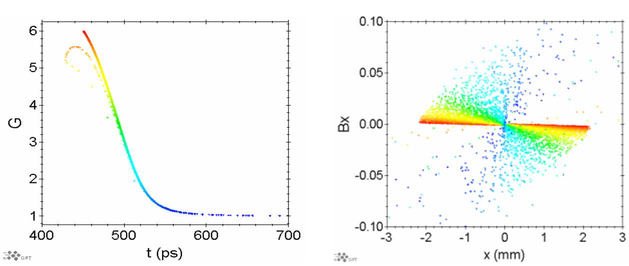


Figure 2: The longitudinal and transverse phase spaces of electron beam at the gun exit.

To cooperate well with the alpha magnet operation, the electron beam from the gun will traverse a 43.5 cm drift section before entering the alpha magnet for rotation of bunch distribution in the longitudinal phase space. The desired energy range of the bunch can be selected by the collimator in the vacuum chamber of the alpha magnet. The left Fig.3 depicts the electron distribution in longitudinal phase space at the entrance of the alpha magnet (only $\gamma > 5.87$ is shown). It is clear that the head of a bunch has more electrons and will suffer stronger space charge force. As the bunch traverses the drift section, a fraction of electrons is pushed ahead by the longitudinal space charge force. As a result, these electrons are accelerated by the longitudinal space charge force and the distribution of the bunch in the longitudinal phase space gets distorted. Meanwhile, the electron distribution at the end of the drift section is no longer suitable for bunch compression at downstream. To avoid this problem, we set the collimator such that only the electrons with $\gamma$ in the range between 5.87 and 6.0 are selected (right of Fig. 3).

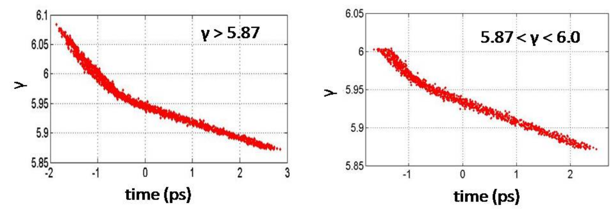


Figure 3: Longitudinal phase space of the bunch head at position 43.5 cm away from the gun exit.

The bunch has to be over-compressed by the alpha magnet to compensate bunch lengthening due to longitudinal phase space rotation in a second drift section that connects the alpha magnet vacuum chamber and the rf linac. With alpha magnet gradient at 394 Gauss/cm, beam with about 30 pC bunch charge and bunch length ~ 1.22 psec after the alpha magnet can be obtained (the collimator width is set at ~ 1 mm). However, the normalized horizontal emittance of the filtered beam is increased from 1.7 mm-mrad to 3.4 mm-mrad under the action of the alpha magnet [6]. The horizontal motion disordered by the space charge force is strongly coupled with the longitudinal emittance, so the emittance growth in the horizontal phase space results from a complicate process [7]. Therefore, the beam has different distributions in horizontal and vertical phase space at the exit of alpha magnet. On the other hand, the bunch has a counterclockwise rotation in the longitudinal phase space in the alpha magnet and so the bunch length will decrease and then increase again in the drift section after the magnet. The linac is put at the position where the bunch tends to lengthen again.

Further bunch compression can be done by the rf linac through velocity bunching when the electron bunch enters the linac near the rf zero crossing phase [8]. However, in this case, the transverse motion of the beam is more difficult to control. With rf feeding power at 9 MW and rf phase operated at the near zero crossing point, the beam evolution after the alpha magnet to the interaction point is shown as Fig. 4. The bunch is accelerated to ~ 27 MeV and is compressed to 55 fs at the linac exit.

## FOCUSING OF ULTRASHORT BUNCH

The beam after the linac has to be focussed to a tiny spot of about few tens $\mu$ m at the interaction point for effective X-ray photon production. Since the speed of the electrons after acceleration is close to that of light, evolution of electron distribution in the drift section located downstream is just a mere rotation in longitudinal phase space. However, after final focusing, the bunch length is found to be increased to more than a hundred fsec. The bunch lengthening is due to the path length differences of electrons during final focusing by the quadrupoles. Therefore, it is important to keep beam size in the linac as small as possible and a focusing lens with longer focal length can help to relieve this problem.

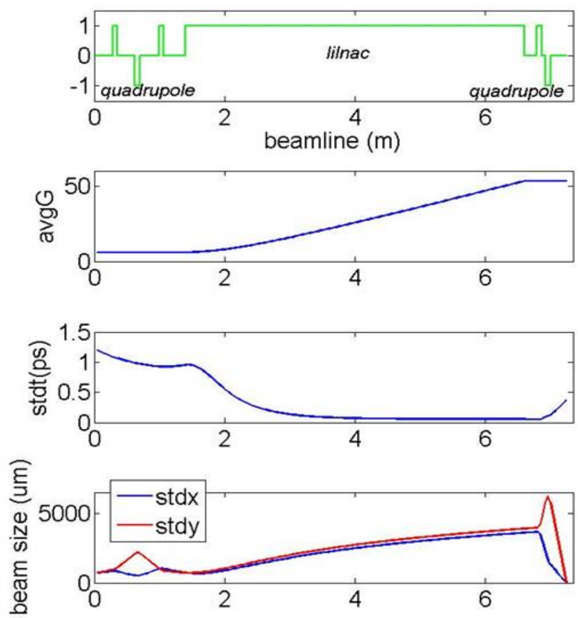


Figure 4: The evolution of beam characteristics from the exit of alpha magnet to the interaction point.

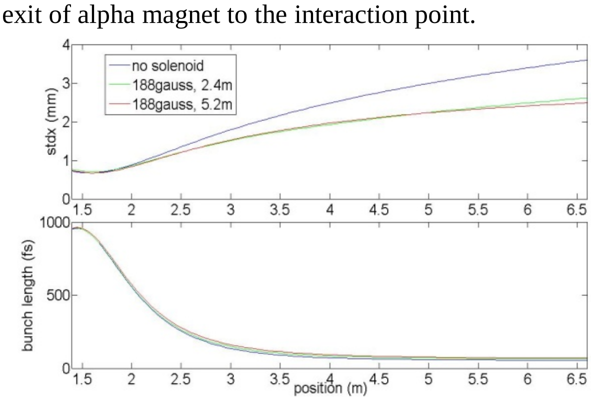


Figure 5: The different evolution through linac by applying the solenoid.

For a better beam size control in the linac, a section of solenoid with length gradient at 188 Gauss is applied in the linac section. And quadrupoles with a longer effective length (10 cm) is used after the linac for final focusing. With the assistance of solenoid field, as can be seen in Fig. 5, the beam divergence is weaker and the beam size at the linac exit is compensated to about 2.6 mm. Since the solenoid magnetic field is effective only in the earlier stage of beam acceleration, a shorter solenoid (2.4 m is used in the beamline) at the low energy end of the linac will be enough. Secondly, with longer quadrupoles for final focusing, the weaker gradient can be used to provide similar focusing strength and the longer focal length helps to relieve the path length difference problem. Two different quadrupole settings are found such that the goal of sub-100 fsec bunches can be met. That is, a tightly focused 96.6 fsec beam of 30 μm beam size can be achieved at the interaction point. For a shorter bunch length at 67 fsec as shown in Fig. 6, a 27 MeV electron beam with 30 pC bunch charge is focused to 64 μm at the interaction point.

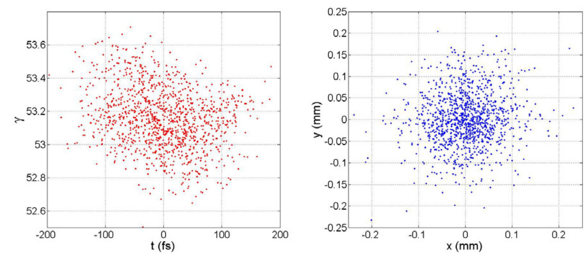


Figure 6: The focused sub-hundred femtosecond electron beam at the interaction point.

## CONCLUSION

The driver linac system that employs a thermionic rf gun and an alpha magnet for generation of a tightly focused ultrashort electron beam are studied. It can be used to produce sub-hundred femtosecond hard X-ray source with high peak flux via head-on ICS. The transverse and longitudinal beam dynamics under the action of 3D space charge force are discussed. This compressed electron beam with energy ~27 MeV, normalized emittance 3.7 mm-mrad is able to generate sub-hundred femtosecond hard X-ray with total peak flux at ~ $1.3\times10^{18}$ photons/s within a ~18.8 mrad radiation cone by using the 3.5 mJ infrared laser focused to the same focal size at the interaction point in our first head-on ICS experiment. It corresponds to a brightness of ~ $3.16\times10^{15}$ photons/(s-mm$^2$-mrad$^2$). Since we are using a moderate energy laser at hand, one can improve the X-ray photon number per pulse by using TW laser with higher pulse energy. Furthermore, since this compact linac system delivers thousands of GHz-repetition-rate electron pulses in one macropulse, an optical cavity can be used to circulate the laser pulses for interaction to improve the average photon flux.

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