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GENERATION OF TUNABLE FEMTOSECOND X-RAYS FROM HIGH-PERIOD-NUMBER RESONANT TRANSITION RADIATION EMITTERS

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Abstract

Femtosecond resonant transition radiation (RTR) in x-ray region can be generated from alternatively stacked multilayer structures when they are driven by relativistic ultrashort electron beams. These structures can be fabricated by coating layer pairs of high and low density materials. By increasing the number of these layer pairs, narrow-band x-ray can be generated. In this report, we present our efforts on the development of a 12 keV femtosecond narrow-band x-ray source by driving high-period-number RTR emitters with the NSRRC photoinjector linac system. Radiation wavelength is tunable by varying the incident angle of the beam. A few tens MeV, ultrashort beam has been available from the photoinjector system via velocity bunching in the rf linac. A 100-period (200 layers) Mo/Si multi-layer emitters with thin substrate have been fabricated. For a 100 pC drive beam, the expected photon yield from such emitter is about 4×10^4.

INTRODUCTION

Time-resolved x-rays diffraction and absorption spectroscopy are powerful techniques to study fast phenomena at atomic resolution. In contrast to large scale facilities, compact x-ray sources driven by ultra-short electron beam are of interest to some user applications. Common cost effective methods like inverse Compton scattering (ICS) and resonant transition radiation (RTR) are usually employed to generate narrow-band x-rays in laboratory scale. RTR is generated when electron bunch pass through periodic boundaries of alternatively stacked dielectric materials of different densities. In comparison with ICS, RTR is more compatible with other instrument in the same beam line because the emitter is usually small. Also, adjustment of resonant photon energy is easy to achieve by rotating the emitter such that the period length along the beam trajectory.

In this study, we try to develop a 12 keV femtosecond narrow-band x-ray source by driving a high-period-number RTR emitters with the high brightness electron beam generated from the NSRRC photoinjector linac system [1]. This injector system has been in regular operation since its first operation in 2016. Sub-picosecond beam can be generated by velocity bunching of electrons in the rf linac located downstream. Radiation wavelength is tunable by varying the incident angle of the beam.

DESIGN OF RESONANT TRANSITION RADIATION EMITTERS

The existence of transition radiation (TR) was predicted by Ginzburg and Frank in 1949[2]. For a charged particle traveling across the boundary between two media of different dielectric constants, properties of transition radiation can be calculated by classical electromagnetic theory. For RTR, transition radiation from boundaries of a periodic structure interfere constructively at the point of observation as shown in Fig.1[3], Angular and spectral distributions of RTR is determined not only by the radiation from a single boundary but also the interference of radiations from the periodic boundaries.

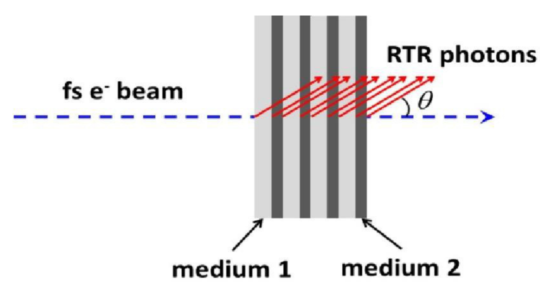

Figure 1: An illustration of the ultrafast RTR source being developed in NSRRC.

In X-ray region, dielectric constant can be described by Drude model. The angular-spectral distribution of forward transition radiation emitted from a boundary when a single electron incident normally on the interface is given as [4]:

$$\frac{d^2 W_{TR}}{d\Omega d\omega} = \frac{e^2}{16\pi^2 c^3}\omega^2 \sin^2 (Z_1 - Z_2)^2 \qquad (1)$$

where

$$Z_{1(2)} = \frac{4c}{\omega[\gamma^{-2} + \theta^2 + (\omega_{p1(2)}^2 / \omega^2)]} \qquad (2)$$

$\omega_{p1(2)}$ is the plasma frequency of material 1 (or 2).

From Eq.(1), it is obvious that more radiation can be obtained with large difference in dielectric constant between medium 1 and 2. It means that the situation that the atomic mass of one medium is high but the other is

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low would be ideal for generating more radiation energy. However, material of higher atomic mass usually means higher x-ray absorption. Therefore, there is always a trade-off between the two criteria described above and selection of materials cannot easily be determined from a single equation. In practice, the feasibility of fabricating such structures is of main concern.

The RTR emitter under study is composed of layer pairs of 365-nm Mo and 392 nm Si. It is designed for generation of narrow band x-ray which centered at 12 keV. This emitter is designed for an electron beam with 33.6 MeV beam energy generated from the NSRRC photoinjector. Bunch length of the electron beam of 60 fs is achievable when the photoinjector be operated in short bunch mode with velocity bunching according to space-charge tracking simulation. Ultrafast x-ray pulse of approximately of the same length can therefore be generated. The calculated spectral and angular distributions of RTR with above mentioned condition are shown in Fig. 2. Since the period number of the emitter is high, there shows clear resonant peaks both in spectral and angular distribution.

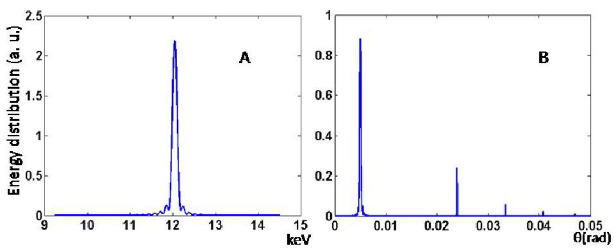

Figure 2: (A)Spectral distribution of RTR with 33.6 MeV beam energy (γ = 65.7) at 5 mrad observation angle (~1/γ). (B)Angular distribution of 12keV RTR with normal incidence (γ = 65.7).

Thanks to the high transmittance of hard x-ray in most materials, the radiation bandwidth is not limited by x-ray absorption up to dozens or even hundreds of layers. Fig. 3 shows that the photon yields of the RTR emitter under study would reach saturation at about one hundred periods of layers. Design parameters of the 12 keV RTR emitter are summarized in Table 1.

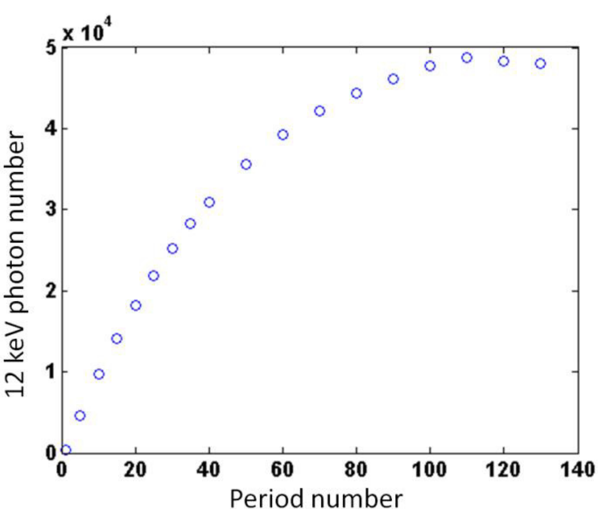

Figure 3: Relation between period number and photon yield at the resonant peak of RTR which is 12 keV in our case.

Table 1: Design Parameters of the 12 keV RTR Emitter

Average thickness of Mo layer [nm]	365
Average thickness of Si layer [nm]	392
Number of layer pairs	100
Nominal x-ray energy [keV]	12

THE NSRRC PHOTOINJECTOR

The x-ray RTR in our study is driven by the NSRRC photoinjector. The system is able to generate short electron bunch when the rf linac is operated near zero-crossing phase in velocity bunching and ultrafast x-ray pulse can be generated from the RTR emitters. Recently, limited by the available klystron power for the rf linac, a 17.7 MeV beam with bunch length at about 500 fs has been obtained. When the rf linac is operated in acceleration phase (on crest), maximum beam energy of 60 MeV has been achieved. The accelerating gradient of the system will be upgraded to 18 MV/m in near future to allow aggressive bunch compression to 100 fs at 33.6 MeV beam energy. Fig.4 is the photoinjector in the tunnel of the NSRRC Accelerator Test Area (ATA).

Figure 4: The NSRRC photoinjector in the ATA tunnel.

FABRICATION OF RTR EMITTERS

For the 100-period RTR emitter mentioned above, a total thickness of about 75 μm is considered to be very thick for most thin film production processes. Sputtering is considered as an appropriate fabrication process for this kind of structures with reliable quality in reasonable production time.

Thermal stress is the main issue of concern during the sputtering process. To fabricate structures with hundreds of periodic thick layers, time to slow down the deposition rate for relaxation of thermal stress is limited. The choice of materials is restricted to those with adhesion between media that are resistant to thermal stress. After several trails, Mo and Si is the most stable combination we have obtained, and it provides reasonable photon yields in our case of study. Fig. 5 shows two emitters with 100 periodsMo/Si layers, which have been fabricated with the sputtering system in ITRC.

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Si wafer with common specification should be a good substrate since low surface roughness. However, x-ray absorption and bremsstrahlung radiation forced us to consider thinner substrates. Emitter #1has 100 periods of Mo/Si layer pairs deposited on a kapton foil, and emitter #2 is same structure deposited on a 100-μm thin Si wafer.

Figure 5: Two RTR emitters mounted on a fixture. Emitter #1 is 100 periods Mo/Si deposited on a kapton foil and emitter #2 is the same structure deposited on a 100 μm Si substrate.

EXPERIMENTAL SETUP AND PROGRESS

Fig. 6 is a sketch of the experimental setup. RTR emitter is mounted on a rotatable feedthrough, so the period length of emitter on the trajectory of electron beam can be changed to adjust resonance photon energy. There is a dipole magnet after the emitter to bend the electron beam to beam dump. RTR is detected with a silicon drift detector (SDD) to get its spectrum and photon number. Pin hole before the detector can reduce the acceptance angle to measure spectra with different divergence angle.

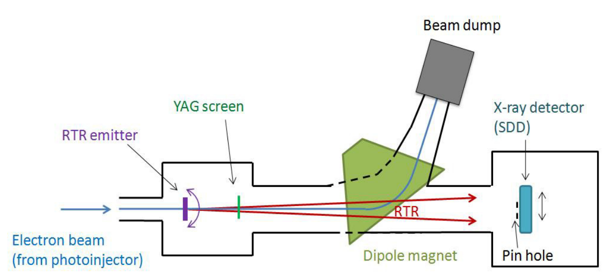

Figure 6: Setup for the femtosecond x-ray RTR experiment at NSRRC.

The photoinjector is still under characterization. Some parameters such as beam energy cannot be measured accurately with existing beam diagnostic tools. Although an accurate beam energy measurement is not immediately available, we still be able to measure the x-ray spectrum generated from the emitter driven by the electron beam in this context. Several radiation peaks have been observed in the x-ray spectrum ranging from 6 to 10 keV during initial test. Measurement of angular distribution and total flux are still in progress.

SUMMARY

RTR emitters with 100 periods Mo/Si layer pairs have been fabricated in ITRC. They are designed to generate femtosecond x-rays with a resonant peak at 12 keV when it is driven by the ultrashort electron beam generated from the NSRRC photoinjector. The setup has been installed and the photoinjector is under testing. In the first run, x-rays peaks have been found in the radiation spectrum with x-ray detector. However, the causes for the peaks have not been identified yet. We will have more machine runs in the following months for observation of spectral and angular distribution of radiation energy.

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