EMISSION OF COHERENT T-RAYS FROM TRAINS OF ULTRASHORT ELECTRON PULSES IN A PULSED HELICAL UNDULATOR

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Abstract

GHz-repetition-rate relativistic electron pulses with duration shorter than 100 fs can be produced from the thermionic rf gun injector system which is now under construction at NSRRC. Experiments for production of coherent sub-THz or THz radiations by passing this prebunched electron beam through an 8 cm period bifilar helical undulator are suggested. The undulator will be powered by a 200 μs current pulser at 10 Hz repetition frequency. Conditions for obtaining coherent emission and expected properties of the radiations are discussed.

INTRODUCTION

Relativistic ultrashort electron pulses at GHz-repetition-rate can be generated from a thermionic cathode rf gun injector system. In such system, A linearly energy chirped electron is produced from the gun with an optimum accelerating field profile. An alpha magnet is installed to provide the dispersion required for bunch compression [1, 2]. Alternatively, one can performs bunch compression by velocity bunching in the rf linac structure during the early stage of beam acceleration [3-5].

It is well known that the emission of coherent radiations from a bunch with N electrons is possible as long as its bunch length is much shorter than the radiation wavelengths [6-8]. The power of the coherent radiation will be $\sim N^2$ times higher than that of the spontaneous radiation from a single electron depending on the bunch form factor. Furthermore, as pointed out by Gover and Dyunin [7], the bandwidth of the coherent radiation from an undulator by a periodic train of electron bunches is inversely proportional to the number of bunches in the train. Since the thermionic rf gun injectors has the capability to produce long trains of periodic ultrashort bunches, they are very well suited for the generation of narrow-band coherent radiations. Generation of coherent transition radiations (CTR) in the THz range with the thermionic rf gun injectors of SUNSHINE and SURIYA facilities by hitting beams on metallic foils are good examples of pre-bunched electron beam coherent radiations [1, 9].

In this report, we describe the activities in NSRRC to construct a few tens MeV thermionic rf gun injector system for generation of high brightness ultrashort electron pulses. We plan to use a bifilar undulator to demonstrate the capability of this injector system for the production of coherent THz radiations. This undulator will be powered by a current pulser. Conditions for obtaining coherent emission and expected properties of the radiations are discussed.

GENERATION OF GHZ-REP-RATE ULTRASHORT ELECTRON PULSES

A 30 MeV, 2998 MHz thermionic rf gun injector is designed for light source R&D at NSRRC. This injector is able to deliver thousands of sub-100 fs electron pulses of few tens pC bunch charge in each macropulse. Each macropulse has pulse duration of ~1 μs at 10 Hz repetition frequency. Bunch compression scheme employed in this system rely mainly on velocity bunching. Experimental studies of inverse Compton scattering ultrafast x-ray and intense coherent THz radiation sources are planned.

The thermionic rf gun is designed to operate at accelerating field gradient of 25 MV/m and 50 MV/m in its half-cell and full-cell respectively. Since the electron at head of a bunch from the rf gun has higher kinetic energy than those at its tail, the bunch tends to decompress in drift sections. The alpha magnet helps to rotate the particle distribution in longitudinal phase space clockwise and the collimator installed in the vacuum chamber of the magnet can be used to select electrons in the desired range of momentum. In ideal situations that space charge effects are negligible, it may be feasible to compress the bunch to extremely short duration. However, as space charge effects become significant, bunch compression with alpha magnet at low beam energy becomes very ineffective. In this case, further bunch compression in the rf linac during beam acceleration by velocity bunching is indispensable. For velocity bunching, rf phase at beam injection has to be optimized for efficient compression. A high power phase shift will be installed for linac phase adjustment.

Expected Performances

Beam dynamics in the NSRRC thermionic rf gun injector has been studied extensively by computer simulation under various operation conditions with the effects of space charge included. Typical beam parameters near the entrance are listed in Table 1.

Table 1: Typical Beam Parameters at the Entrance of the rf Linac

Energy [MeV]	3.0
Bunch charge [pC]	30
Minimum bunch length [μm]	300 RMS
Peak current [A]	30
Normalized emittance [mm-mrad]	3.3
Energy spread [%]	0.28
Alpha magnet gradient [gauss/cm]	400

ISBN 978-3-95450-123-6

Beam parameters optimized for shortest bunch length at linac exit are listed in Table 2. The accelerating field gradient in the rf linac has been set at 15 MV/m.

Table 2: Optimized Parameters for Shortest Bunch Length at the Exit of the rf Linac

Energy [MeV]	28
Bunch charge [pC]	30
Minimum bunch length [μm]	21 RMS
Normalized emittance [mm-mrad]	3.8
Energy spread [%]	0.3%
Beam radius [mm]	3.8 RMS

System Construction

The linac section used in this system is a 5.2 m, 2998 MHz constant gradient traveling-wave structures operating at 2π/3-mode. This structure is similar to the DESY LINAC-II design and is manufactured by Research Instruments GmbH. It has 156 cells that provide shunt impedance of ~50 MΩ/m but with the last 6 cells coated with Kanthal layer as collinear microwave absorber. High power microwave is coupled to the first cell at one arm with the opposite arm shorted. This linac is now on its supporting stands and aligned. High power test will be performed in the near future.

Figure 1: The rf linac for the NSRRC thermionic rf gun injector.

An alpha magnet has been fabricated and tested at full available current from the DC power supply with adequate cooling. The vacuum chamber for the alpha magnet has been built and tested up to ~ 420 guass/cm gradient at an excitation current of 110 A. It is limited by the available current of the power supply. A motorized collimator has been installed in the vacuum chamber for beam selection before acceleration by rf linac.

The thermionic cathode rf gun is a 2998 MHz, 1.5-cell standing wave structure with a tunable side-coupled cell for the two cells (the full-cell and half-cell) of the rf gun and allows fine adjustment of the full-cell to half-cell field ratio. Therefore, the cavity is operating at π/2-mode such that the two electric fields in the cells are 180° out of phase. A cathode assembly without nosecone for beam focussing will be used. The cathode is a dispenser type with flat surface of 6 mm in diameter. The dimensions of the cavity near the beam axis have been optimized for ultrashort bunch generation at linac exit. The field ratio is adjusted to 2.5:1 to produce a linear energy chirp near the head of the bunch. Parts for the rf gun cavity has been machined and assembled. Cell frequencies are tuned to the decided values and the waveguide-to-cavity coupling coefficient β is adjusted to about 5 during cold test before vacuum brazing for compensation of beam loading.

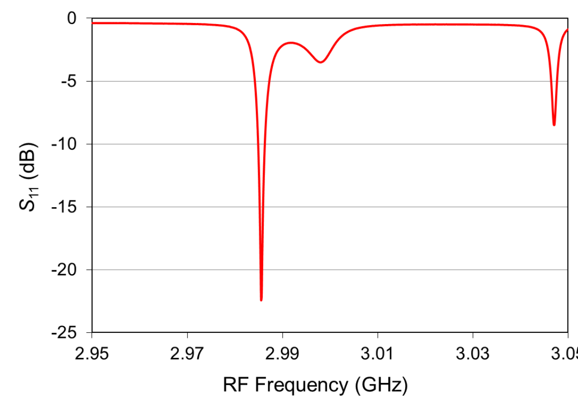

Figure 2: Frequency response of the 2998 MHz rf gun cavity. The second dip is the operating mode (π/2-mode).

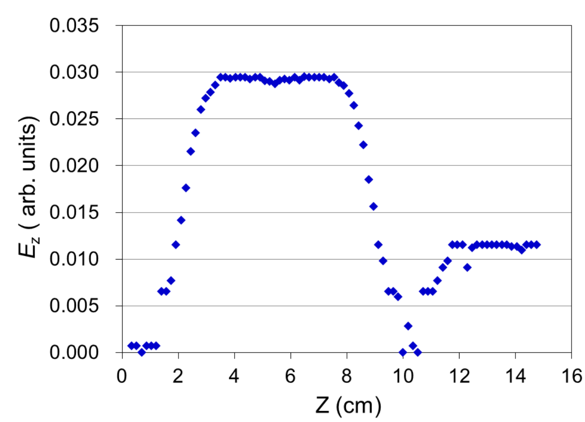

Figure 3: The results of bead-pull measurement for the NSRRC 2998 MHz thermionic cathode rf gun. Full-cell to half-cell field ratio is adjusted to 2.5:1 in this case.

THE PULSED BIFILAR HELICAL UNDULATOR

It is a pulsed 8 cm bifilar helical undulator driven by a 10 Hz, 200 μs half-sine current pulser. Since the duration of the beam macropulse is about 1 μs, it occupies only ~2% of the 200 μs pulse near its peak. Field variation across the macropulse should be within 0.04%. The current pulser is originally designed for the Taiwan Photon Source (TPS) storage ring injection septum

ISBN 978-3-95450-123-6

magnet with pulse-to-pulse stability of +/- 0.1% [10]. The stability of the pulser should be good enough for initial experiments. However, modification is needed for operation at peak current higher than 10 kA. Without consideration of end effects, the magnetic field generated by the bifilar helical undulator is expressed as [11-13]:

$$\vec{B}_u(x) = 2B_u\left[I_1'(\lambda)\hat{e}_r \cos(\chi) - \frac{1}{\lambda} I_1(\lambda)\hat{e}_\theta \sin\chi + I_1(\lambda)\hat{e}_z \sin\chi \right] \quad (1)$$

where B_u is the amplitude of the undulator field, $\lambda=k_u r$, $\chi=\theta\text{-}k_u z$, $k_u=2\pi/\lambda_u$ and λ_u is the undulator period. A summary of preliminary parameters of this helical undulator are listed in Table 3. Inductance of the undulator has been calculated with the simplified formula derived by Fajans [14] and is kept at about 2µH.

Table 3: Parameters of the Pulsed Helical Undulator

Undulator period [cm]	8
Number of periods	10
Radius [cm]	2.8
Inductance [µH]	2.0
Peak current [kA]	14.6 max.
Peak field [T]	0.1 max.
Undulator constant	0.75 max.
Pulse shape	half-sine
Pulse duration [µs]	200
Pulse rep-rate [Hz]	1-10

Radiation Power and Spectral Distribution

Expected coherent radiation frequency at maximum peak field is about 3 THz for electron beam energy at ~12.3 MeV. To calculate the spectral distribution of radiation energy from a single 12.3 MeV electron propagating through a helical undulator with parameters as listed in Table 3, we assumed the number of periods is very large and use the formula derived in Ref. 11. The result is shown in Fig. 4.

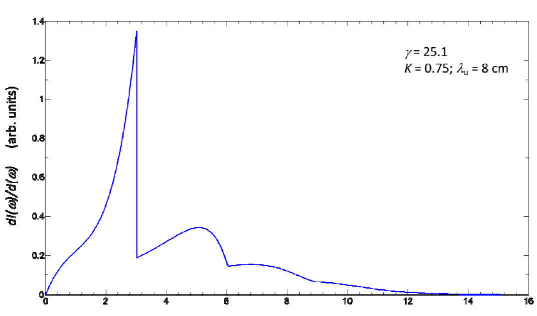

Figure 4: Spectral distribution of radiation energy.

Since total radiated energy in the helical undulator per electron is given by the following equation [16, 17]:

$$\Delta E = 1450 \frac{E_0^2[GeV]K^2}{\lambda_u^2[cm]} L_u[m] \cdot \quad (2)$$

where L_u is the total length of the undulator which is 0.8 m in our case. ΔE in this case is 1.54x10^{-3} eV per electron. For a 30 pC bunch, the number of electrons per bunch is ~1.87x10^{8}. Total radiated energy per bunch is then 8.61x10^{-6} J. Peak power of the 10-cycles THz pulse emitted from one bunch is 2.59 MW. Average THz radiation power per 1 µs macropulse is 25.87 kW. It is a hundred times lower than the peak power because the THz pulses has an empty gap of 330 ps in between. The THz signal from the undulator can therefore be considered as a 1 µs pulse train with amplitude modulation at 3 GHz. Since the undulator has 10 periods and there are 3,000 bunches in a macropulse. The radiation bandwidth (Δλ/λ) at the centre frequency should be of the order of 10^{-5}. Table 4 summarized our calculations.

Table 4: Calculation of the Radiation Power at 3 THz

Beam energy [GeV]	0.0123
Undulator period [cm]	8
Undulator constant	0.75
Undulator length [m]	0.8
Energy loss per electron [eV]	1.54x10^{-3}
Number of electron per bunch	1.87x10^{8}
Peak THz power [MW]	2.59
Average THz power in macropulse [kW]	25.87

Stability of Trajectories of Low Energy Electrons

It is of interested to fill the empty gap between THz pulses with longer undulators and radiation wavelengths. We now look into the possibility to generate continuous sub-THz coherent radiation across the macropulse. It can be done with the NSRRC thermionic rf gun injector system without the linac section (Table 1).

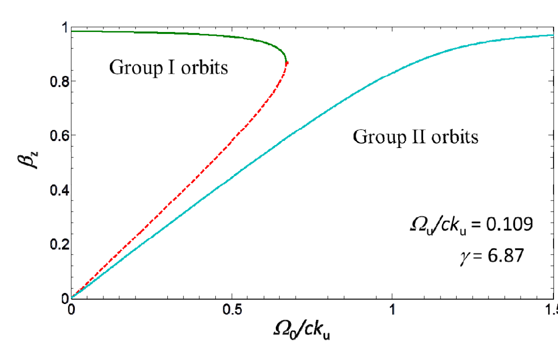

Figure 5: Axial velocity of the stable orbits (solid lines) and unstable orbits (dashed line) as functions of solenoid field.

ISBN 978-3-95450-123-6

At ~3 MeV beam energy ($\gamma = 6.87$), emission of coherent radiation at ~ 0.2 THz is possible. However, as space charge force becomes significant for relatively low energy beam, axial guide field is needed. A coarse estimation indicated that a solenoidal field of a few hundred gauss will be enough to guide the beam. Stability of electron trajectories is shown in Fig. 5 for an idealized helical undulator field [13, 15]. Electron trajectories in the undulator are stable as long as the guide field is within some critical value of Ω_0/ck_u (green solid line in Fig. 5). As shown in Fig. 5, this critical value is ~ 0.65. It corresponds to the guide field amplitude of ~ 5 Tesla.

SUMMARY AND DISCUSSIONS

With the GHz-repetition-rate ultrashort electron pulses generated from the thermionic rf gun injector system which is under construction at NSRRC, the feasibility of coherent sub-THz or THz radiation production by propagating this prebunched electron beam through an 8 cm period bifilar helical undulator are being evaluated. Coherent THz radiations of MW-level peak power are possible. Further studies on the effects of beam quality and current termination of undulator on the properties of the radiation are in progress.

ACKNOWLEDGMENT

The authors would like to thank our colleagues, Mr. Fann, Chyi-Shyan, Dr. Lin, Ke-Kang and Dr. Tsai, Kuang-Lung, for helpful discussion on the specifications of the current pulser for the helical undulator.

REFERENCES

[1] P. Kung et al., Phys. Rev. Lett., Vol. 73, p. 967 (1994).
[2] S. Rimjaem, et al., Nucl. Instr. and Meth., A533, p. 258 (2004).
[3] L. Serafini, A. Bacci, M. Ferrario, in Proceedings of the 2001 Particle Accelerator Conference, p. 2242 (2001).
[4] N.Y. Huang et al., Nucl. Instr. and Meth., A637, S76 (2011).
[5] F. Miyahara et al., in Proceedings of IPAC'10, Kyoto, THPD094 (2010).
[6] A. Gover and E. Dyunin, in Proceedings of FEL'06, Berlin, MOAAU01, p.1, (2006).
[7] A. Gover, PRST-AB, 8, 030701 (2005).
[8] F. Hinode et al., Nucl. Instr. Meth., A637, S72 (2011).
[9] C. Thongbai et al., Nucl. Instr. Meth., A587, p. 130 (2008).
[10] K.L. Tsai et al., NSRRC-Linac-2010-02 (2010; in Chinese).
[11] B. Kincaid, J. of App. Phys., Vol. 48, p. 2684 (1977).
[12] J.P. Blewett and R. Chaseman, J. of App. Phys., Vol. 48, p. 2692 (1977).
[13] H.P. Freund and T.M. Antonsen Jr., "Principles of Free-Electron Lasers", Chapman & Hall, London (1992).
[14] J. Fajans, Rev. Sci. Instrum. 60, p. 3073 (1989).
[15] L. Friedland, Phys. Fluids 23, p. 2376 (1980).
[16] H. Wiedemann, "Particle Accelerator Physics II – Nonlinear and High-order Beam Dynamics", Springer-Verlag, Berlin (1995).
[17] J.C. Sheppard, LCC Tech. Notes LCC-0095 (2002).