THE ULTRASHORT BEAM LINAC SYSTEM AND PROPOSED COHERENT THZ RADIATION SOURCES AT NSRRC

W.K. Lau, N.Y. Huang, A.P. Lee, NSRRC, Hsinchu, Taiwan.
Z.Y. Wei, Department of Engineering and System Science, NTHU, Hsinchu, Taiwan

Abstract

The NSRRC ultrashort beam facility is a few tens MeV linac system for generation of GHz-repetition-rate femtosecond electron pulses. The electron source for this linac system is a 2998 MHz, thermionic cathode rf gun with on-axis coupled rf structure in which the longitudinal electric field profile is trimmed to optimize the electron distribution in longitudinal phase space. Bunch compression will be done in the rf linac during the early stage of beam acceleration by velocity bunching. With this femtosecond electron beam, generation of broadband coherent THz synchrotron radiations from bending magnet and narrow-band coherent radiation from undulator are being studied.

INTRODUCTION

High power THz radiations found interesting applications in studying the dynamical processes of various materials. Free electron lasers and other coherent spontaneous emission sources are good candidates to produce high power THz radiations [1]. Coherent emission of spontaneous radiations from a bunch of N_e electrons is possible as long as its bunch length is much shorter than the radiation wavelengths of interest [1-3]. Depending on the bunch form factor, the power of coherent spontaneous radiations can be $\sim N_e^2$ times higher than that from a single electron. In cooperated with proper bunch compression scheme, the thermionic rf gun injectors allow the possibility to produce femtosecond electron pulses at relatively low beam energy. They are very well suited for the production of coherent radiations in THz range. Sucessful generation of coherent transition radiations (CTR) with the SUNSHINE and SURIYA facilties are good examples [4,5]. Similar system is under construction in Tohoku University, Japan [6].

A few tens MeV ultrashort beam linac system is under construction at NSRRC to produce GHz-repetition-rate sub-100 fs electron pulses. A thermionic cathode rf gun will be used to generate electron bunches with optimal time-energy correlation for bunch compression in the rf linac via velocity bunching [7-9]. Since on-axis coupled structure (OCS) rf gun shows better performance over previous design and has the advantage that it allows precision tuning of gun cavity microwave properties [10,11], it is now under consideration at NSRRC to employ such rf gun in our system. In this report, the design of this new rf gun will be discussed. The effectiveness of velocity bunching in the rf linac with new rf gun parameters expected from this OCS rf gun are re-examined. We can expect that this high repetition-rate ultrashort electron beam will be available in the near future, we now looked into the possibilities to generate broadband coherent synchrotron radiation (CSR) from bending magnet as well as narrow-band coherent THz radiations from undulators (CUR) for material studies with THz spectroscopy.

THE 30 MEV ULTRASHORT BEAM LINAC SYSTEM

This 2998 MHz thermionic cathode rf gun linac system is designed to produce thousands of sub-100 fs electron pulses of few tens pC bunch charge in each of the 10 Hz, ~1 μsec macropulses. Bunch compression scheme employed in this system rely mainly on velocity bunching in the rf linac. Beam selection is done by an energy filter in an alpha magnet at linac upstream. Space charge dynamics in the system is being studied with PARMELA [12] and GPT [13].

The 2998MHz RF Gun with On-axis Coupled Structure

Starting from circuit analysis and 2D SUPERFISH calculations, we determined preliminarily the inner dimensions of the OCS rf gun cavity (Fig. 1). The cathode assembly is located on the side-wall of the half-cell which is on the left-hand side of Fig.1. Microwave power is fed into the full-cell of the gun cavity and coupled to the half-cell through an on-axis coupling cell (the middle-cell).

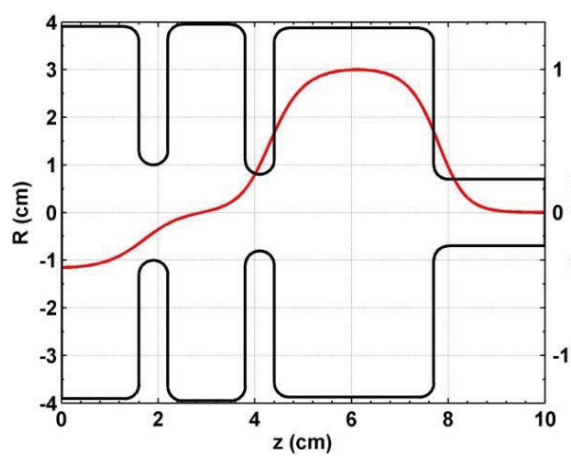

Figure 1: Geometry of the NSRRC 2998 MHz OCS rf gun. The red line is the relative amplitude of the longitudinal component of the rf electric field along the cavity axis when it is operated at π/2-mode.

Main parameters of the rf gun operating mode (π/2-mode) are listed in Table 1. It is worth noting that we decided to adjust the field ratio (i.e. full-cell to half-cell) to 2.5 for

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best beam quality and minimization of the number of back-streamed electrons onto the 0.25 inches cathode surface [10]. Waveguide to rf cavity coupling ratio at π/2-mode will be adjusted to ~4 for best impedance matching under beam loading .

Table 1: Parameters of the NSRRC OCS rf Gun Cavity

Frequency [MHz]	2998
Operating mode	π/2-mode
Field ratio (full-cell/half-cell)	2.5
Ohmic Q	~ 10,500
Input coupling coeff.	~4
Mode separations (0-/π-mode) [MHz]	12.5/10.5

The electron distribution in longitudinal phase space and the electron population in a bunch as a function of time at designed electric field profile is shown in Fig.2. As can be seen from this figure, electrons are concentrated at the head of a bunch. Only the electrons fall into the energy range of the top few percent with good beam quality are of interest. A typical bunch charge of 20-30 pC can be obtained after beam selection.

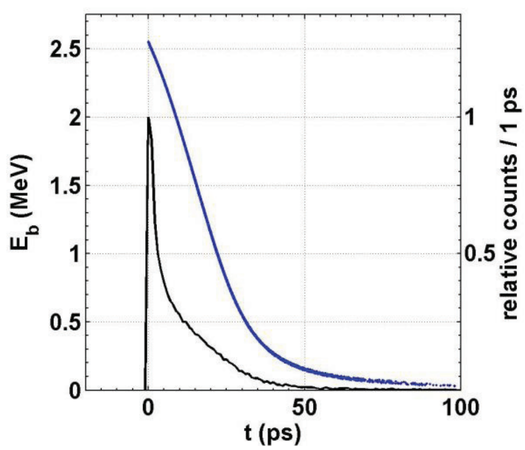

Figure 2: The Electron distribution in longitudinal phase space (blue) and the electron population in a bunch as a function of time (black) at operating field strength.

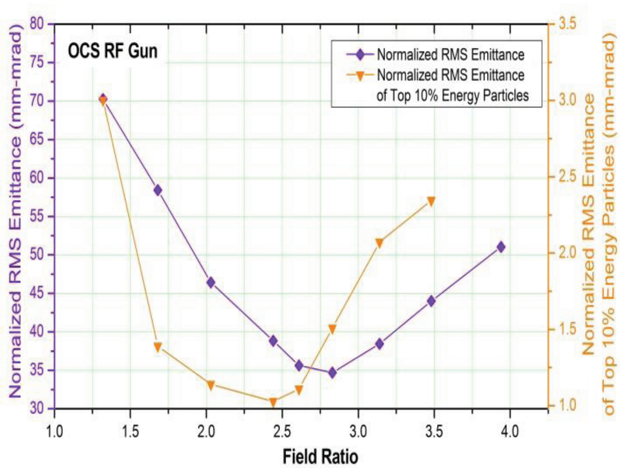

Figure 3: Dependence of the projected transverse emittance (purple) and the emittance of the electrons within the top 10% in energy (orange) on field ratio.

Fig.3 shows the dependence of projected transverse emittance on field ratios with field amplitudes adjusted to keep the maximum beam energy at about 2.5 MeV. The optimum field ratio for lowest emittance is at ~2.75. However, if we are able to select those electrons with energies fall into the top 10% range by the momentum filtering in the alpha magnet, the field ratio for lowest emittance is at 2.0~2.6 and transverse beam emittance of a few mm-mrad is achievable. Therefore, we decided to set the field ratio at ~2.5, the field amplitude of full-cell is ~90 MV/m to get 2.5 MeV. These calculation is done with PARMELA. Typical beam parameters after the alpha magnet are listed in Table 2.

Table 2: Typical Beam Parameters After the Alpha Magnet

Energy [MeV]	2.5
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

Velocity Bunching

Beam dynamics in the thermionic rf gun injector has been studied extensively by computer simulation with GPT under various operation conditions with the effects of space charge included. Typical input parameters for a 30 pC after the alpha magnet are listed in Table 2 above. A 5.2 m rf linac is under consideration and is located at ~1.75 m away from the beam exit at alpha magnet. With accelerating field gradient of the rf linac set at 15 MV/m, bunch duration after bunch compression near the linac exit can be as short as 50 fsec RMS. Bunch current of 250 A can be achieved at ~30 MeV beam energy. Beam parameters optimized for shortest bunch length at linac exit are listed in Table 3.

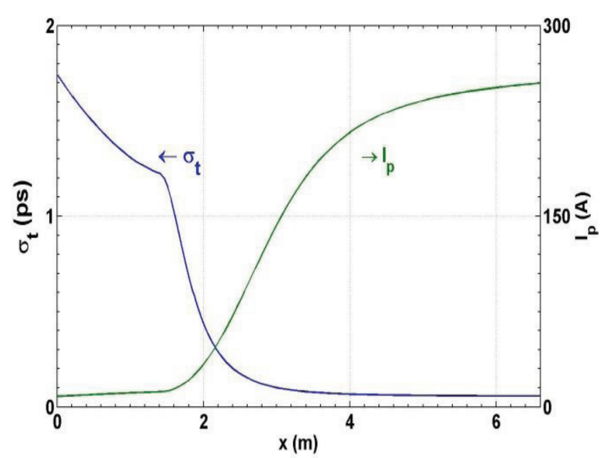

Figure 4: Evolution of the duration (blue) and peak current (green) of a 30 pC electron bunch along beam path from the alpha magnet exit to the 5.2 m linac exit. The accelerating gradient of the rf linac is set at 15 MV/m.

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Table 3: Optimized Parameters for Shortest Bunch Length at the Exit of the rf Linac

Energy [MeV]	37
Bunch charge [pC]	34
Minimum bunch length [μm]	17 RMS
Normalized emittance [mm-mrad]	4.4
Energy spread [%]	0.47%
Beam radius [mm]	2.4 RMS

COHERENT THZ RADIATIONS FROM SHORT BUNCHES

Coherent Synchrotron Radiation

Coherent synchrotron radiation can be generated by passing the 100 fsec beam with typical parameters of 30 MeV and 30 pC in energy and bunch charge respectively from the NSRRC ultrashort beam linac system through a bending magnet with field amplitude of 0.1 T. The total power spectrum of coherent and incoherent synchrotron radiation $P(\omega)$ is strongly depend on the bunch form factor of the femtosecond bunches according to Eq.1 [17].

$$P(\omega) = p(\omega)\left[N_e + N_e(N_e - 1)g^2(\sigma_z)\right] \quad (1)$$

where $p(\omega)$ is the single electron power spectrum, $g^2(\sigma_z)$ the bunch form factor and $g(\sigma_z) = \exp(-2\pi^2\sigma_z^2/\lambda^2)$ with wavelength λ. The form factor of a 100 fsec bunch is plotted as a function THz frequency in Fig. 5. Its values are very close to unity for radiation frequencies less than 10 THz.

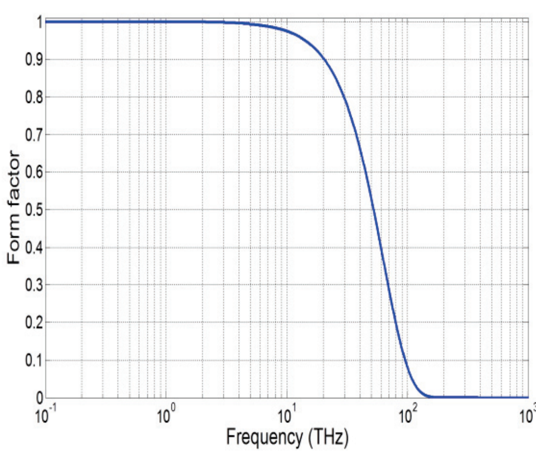

Figure 5: Bunch form factor of a 100 fsec beam as a function of THz frequency.

CSR power spectrum from the 3 GHz-rep-rate, 100 fsec beam are calculated and shown in Fig. 6 [14]. In this calcaulations, 3000 bunches in a macropulse of 10 Hz repetition-rate is assumed. For a 30 pC electron bunch, there are ~1.87×10^8 electrons. The spectrum ranges from low frequencies to ~30 THz and the intensity is about ~10^{16} times larger than the single electron power spectrum depending on the value bunch form factor as expected. Incoherent radiation spectrum is also plotted in Fig. 6 for comparison purpose. Critical frequency of the incoherent synchrotron radiation in this case is 571 THz. It corresponds to 0.059 eV in energy. Broadband coherent THz radiations is considered to be useful for broadband THz spectroscopy.

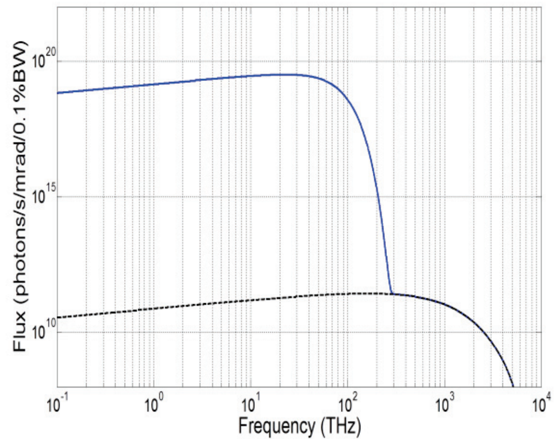

Figure 6: Spectrum of coherent synchrotron radiation in flux (blue). Incoherent synchrotron radiation (dashed line).

Coherent Undulator Radiation

Coherent undulator radiation is studied by considering a pulsed 8 cm bifilar helical undulator [15]. Without consideration of end effects, the magnetic field generated by the bifilar helical undulator is expressed as [16-18]:

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

where B_u is the amplitude of the undulator field, $\lambda_u=k_ur$, $\chi=\theta-k_uz$, $k_u=2\pi/\lambda_u$ and λ_u is the undulator period. The main parameters of this helical undulator are re-called here in Table 4.

Table 4: Parameters of the Pulsed Helical Undulator

Undulator period [cm]	8
Number of periods	10
Radius [cm]	2.8
Peak field [T]	0.1 max.
Undulator constant	0.75 max.

Expected coherent radiation frequency at maximum peak field is about 3 THz for electron beam energy adjusted to ~12.3 MeV. To calculate the spectral distribution of radiation energy from a single 12.3 MeV electron propagating through the helical undulator, we assumed the number of periods is very large and use the formula derived in Ref. 16. The result is shown in Fig. 7. Incoherent part of the undulator radiation is also plotted in Fig. 7 for comparison. Estimated peak power of the 10-cycles THz pulse emitted from one bunch is 2.59 MW. Average power is, however, only a few watts because of the low duty factor of the high power microwave and linac system.

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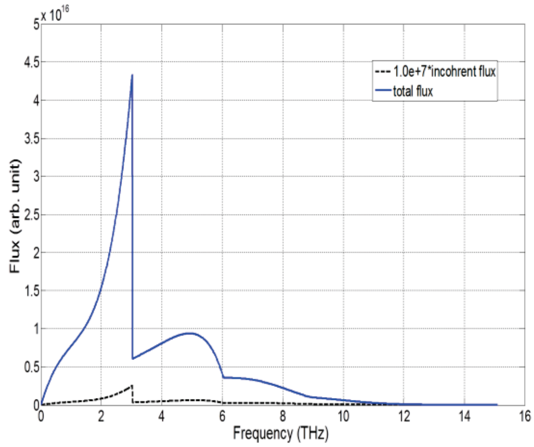

Figure 7: Spectral distribution of THz radiation energy from the 8 cm period helical undulator (blue). Incoherent undulator radiation spectrum is multiplied by a factor of 10,000,000 is also plotted for comparison purpose (dashed black).

SUMMARY AND DISCUSSIONS

A few tens MeV thermionic rf gun linac system is under construction at NSRRC for generation of GHz-repetition-rate sub-100 fs electron pulses. The thermionic cathode rf gun with optimal time-energy correlation will be used for bunch compression in the rf linac via velocity bunching to generate short bunches. Since OCS rf gun has better performance over previous design and the advantage that it allows precision tuning of gun cavity microwave properties, it is now under consideration to employ such rf gun in our system. The effectiveness of velocity bunching in the rf linac with new rf gun parameters expected from this OCS rf gun are re-examined. With accelerating field gradient of the rf linac set at 15 MV/m, bunch duration after bunch compression near the linac exit can be as short as 50 fsec RMS. Bunch current of 250 A can be achieved at ~30 MeV beam energy. With the GHz-repetition-rate ultrashort electron pulses generated from this system, the possibilties of broadband and narrow-band coherent THz radiation production by propagating this prebunched electron beam through bending magnets as well as an 8 cm period bifilar helical undulator are being studied. High power coherent THz radiations are expected.

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