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STUDY OF A THZ/VUV FREE ELECTRON LASER FACILITY IN TAIWAN

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Abstract

A free electron laser (FEL) facility aimed for VUV and THz radiation is being studied at National Synchrotron Radiation Research Center (NSRRC) in Taiwan. Strong consideration has been given to minimize the cost by making maximum use of existing hardware at NSRRC. One unique consideration is to use an existing undulator for the dual functions of the THz radiator and the modulator of a HGHG section. Design emphasizes versatility of operation and beam quality control and compensation of nonlinearities, with a vision that it will allow as much as possible future upgrades as well as later R&D of FEL physics. The polarization control of the THz radiation provides novel application for the users. The facility is to be housed in the existing 38-m by 5-m tunnel of the TPS Linac Test Laboratory.

INTRODUCTION

In spring 2013, operation of the 2998 MHz photoinjector at the NSRRC has been successful after high power microwave processing of the photoinjector cavity up to 58 MV/m. A stable electron beam with energy of 2.3 MeV at 250 pC bunch charge has been achieved. Beam transverse emittance of ~ 5.5 mm-mrad is measured with Gaussian laser pulse [1]. A new photo-cathode rf gun cavity is in fabrication for higher field gradient operation. Laser shaping technique can be employed to further reduce the beam emittance. The possibility of establishing a free electron laser facility in Taiwan has been a continuing effort at NSRRC in the past several years. With the installation of a new 3-GeV storage ring, the Taiwan Photon Source (TPS), it is a good time to renew this effort on the feasibility of an FEL facility. We consider it to serve two purposes:

1. To develop a technology platform for FEL research in Taiwan. This FEL platform will provide a technology base to pursue a wide range of future possibilities beyond TPS, including industrial applications such as high brightness electron gun technology, and lithography manufacturing.
2. To initiate an FEL science research, and to provide a training ground for FEL researchers in Taiwan. This facility will allow the researchers to gain experience and accumulate credentials, and prepare to compete in the FEL world stage.

To fulfil the user needs, this facility is designed to be operated in two modes, one for VUV applications and one for THz applications. Recently, there are growing interests in applications like spectroscopy, elementary excitations, and NMR spectroscopy, etc., requiring high power THz radiation from the accelerator-based devices. The non-invasive and non-ionizing nature of THz spectroscopy is vital for medicine and biology applications from the safety point of view. Polarization dependent THz spectroscopy also offers wide potential in the study of condensed matter physics. FEL in principle can provide the tunable radiation at several THz with much higher average power when superconducting linac is used. Although a superconducting linac is not considered as part of the present Baseline, the proposed facility is a necessary first step towards the next milestone. On the other hand, this proposed facility will provide intense, fully coherent ultrafast light sources up to the extreme VUV region. Direct VUV photoionization is a key approach to probe properties of valence electrons of molecules and materials, which mostly lie at about 6 - 20 eV below the ionization limit. The Baseline FEL lies in this exact energy region and is therefore most suitable to study the transformation of molecules and materials that are important in many research fields. This proposed VUV FEL light source will provide scientists a promising tool to develop more sensitive experimental methods to prove important chemical and physical processes in energy, biological and environmental sciences.

THE PROPOSED FEL FACILITY

Hardware Availability and the System Layout

The hardware availability for the Baseline accelerator facility is summarized as Table 1. Two undulators are proposed in this facility. With consideration to save time and budget, one is to reuse the existing 1-m long elliptically polarized permanent undulator EPU56 with period length of 56 mm, and the other is a cryogenic undulator CU18 with period of 18 mm already budgeted for the TPS. The undulator EPU56 is the exiting device for the operation of TLS. It can be revised to use in this setup without high extra budget. The CU18 is a planned insertion device for the TPS installation. We plan to operate it at room temperature to avoid the cost of installing a cryogenic system. On the other hand, although the advantage of using CU18 prototype is its being cost neutral to the Baseline, the fabrication schedule of CU18 is ~ 2.5 years, and that will dictate the schedule of the FEL progress. In case some additional funding becomes available, it is much more flexible if a dedicated undulator can be considered.

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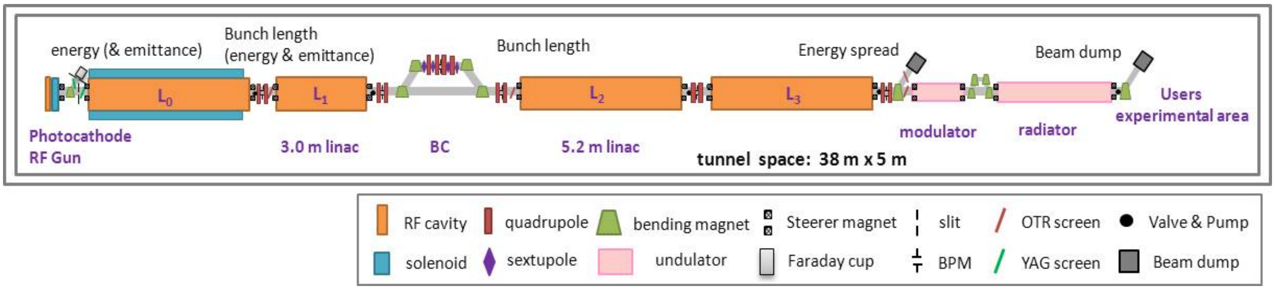

Figure 1: The layout of the proposed FEL facility at NSRRC.

Table 1: The Examination of Hardware of this System

	existing	Required
e-source	Photo rf gun, gun solenoid, high power klystron system	
Laser	Gun drive laser ($\lambda = 266$nm, $\varepsilon \sim 300\mu$J)	Upgrade laser: laser amplifier and tunable laser system
linac	5.2-m section $\times$ 3 , 3-m section $\times$ 1, high power klystron system $\times$ 2	Linac solenoid SLED cavity
undulator	EPU56 ($\lambda_u = 56$mm, N=16)	CU18 ($\lambda_u = 18$mm, N = 166)

With the existing linac sections and the high power klystron systems, an accelerated beam with beam energy of ~ 325 MeV at the linac end can be expected. With the existing hardware and the possible upgrades in the limited space, we consider the Baseline design of the envisioned NSRRC FEL as a high gain harmonic generation (HGHG) FEL seeded by a 266 nm laser to generate the VUV radiation at 66.5 nm which is 4th harmonic of laser wavelength. The resonant condition is satisfied when the radiator strength is tuned as $K = 1.98$. The performance of HGHG FEL has been discussed widely in recent 10 years [2]. In addition to being much stable and tunable with narrow bandwidth, the HGHG source also offers fully temporally coherent radiation pulse. A schematic of the overall layout is shown in Fig. 1. The length of the accelerator system from the gun to L_3 exit is 27 m. The length of the diagnostics and FEL stations is 6 m. Including a 4m$\times$5m experimental area for users, the whole facility tightly fits into the existing 38m$\times$5m long tunnel in the TPS Linac Test Laboratory.

Driver Linac with Self-linearizing Magnetic Bunch Compressor

Assuming the gun accelerating field operated at 70 MV/m, the injected beam with charge of 100 pC is considered as the Baseline operation mode. For the VUV Baseline injector, the linac system consists of a single-stage chicane compressor. Lacking an RF harmonic linearizer, a novel way of using quadrupoles and sextupoles in the chicane compressor to linearize the electron bunch phase space for compression is introduced. With the accelerating fields operated at 18 MV/m for the 5.2-m sections and 20 MV/m for the 3-m section, the compressed bunch with peak current of ~ 500 A and beam energy of 325 MeV can be achieved at the exit of the linac.

On the other hand, the chicane compressor can be switched off in the operation mode for the THz radiation. The same injector system by employing the mechanism of velocity bunching in the first section of linac and the downstream transport line can be adopted to generate an ultrashort bunch at moderate energy. With the operation of 10 MV/m accelerating gradient at an appropriate rf phase in the first section of linac L_0, a compressed bunch with peak current above kA and beam energy of ~ 27 MeV can be achieved at the downstream radiator. The strategy to control the beam quality and the beam dynamics in this injector are discussed extensively in [3].

FEL Performance

In the HGHG operation, the seed laser interacts with the electron bunch in the 1-m EPU56 modulator to imprint energy modulation on the electron bunch. The seed laser is shared with the RF gun (λ = 266nm). The peak power of the upgrade laser is 200 MW, the laser pulse energy is 300 μJ and FWHM pulse width is 1.5 ps. Through a small chicane (total length 40 cm, R_{56} = 30 μm), the energy modulation is converted into density modulation. This pre-bunched electron beam will readily radiate coherently in the radiator undulator leading to an exponential growth and reach saturation in its 3-m length as shown in Fig. 2. The FEL resonant wavelength in the radiator is $\lambda = 66.5$ nm, which is the 4th harmonic of the 266 nm seed laser. The saturated peak power near the 2-m position is 200 MW for the fundamental mode and 2 MW and 200 kW respectively for the 3rd and the 5th harmonics.

To provide broad tunability of the FEL radiation, the seed laser will be tunable. Linac energy and undulator strength K are then adjusted accordingly to maintain FEL resonance. The existing seed laser will be upgraded by adding an optical parametric amplification (OPA) system, followed by an appropriate nonlinear crystal and laser splitting schemes. Radiation with wavelength range between 66.5 - 200 nm and the brightness of 3.3 - 5.7 × 10^{28} photons/μm^2/0.1% is expected when an appropriate laser system is included. The seeding laser with

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wavelength between 266 - 800 nm with peak power of ~ 100 - 200 MW is adopted in this estimation.

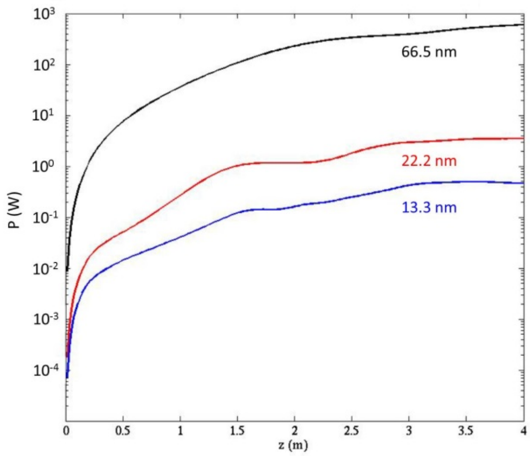

Figure 2: The growth of the radiation power in the undulator. The fundamental (66.5 nm), the 3rd harmonic (22.2 nm), and the 5th harmonic (13.3 nm) radiations are marked as black, red and blue lines respectively.

Table 2: Estimated Beam Performance and Radiation of NSRRC VUV FEL

Electron beam	
Energy [MeV]	325
Repetition rate [Hz]	10
Slice emittance [mm-mrad]	0.8
Bunch length [fs]	51.3
Peak current [A]	500
Slice energy spread [keV]	1.7
VUV radiation	
Wavelength [nm]	66.5 (1st harmonic)
Peak power [MW]	200
Gain length [m]	0.17
Photons/pulse [10^{13}]	1.1
Brightness [photons/μm^2/0.1%]	3.34×10^{28}
Temporal coherence modes	~ 1
Spatial coherence M^2	~ 2

As mentioned above, the undulator will serve the dual functions as an HGHG modulator and a THz CUR undulator. When THz radiation is desired from the undulator, the accelerated beam exiting L_0 will traverse through the beam line and reach the undulator to generate THz CUR. In such operation, the space charge effects are controlled in this long drift space. By appropriate operation of linac rf phase, the longitudinal phase space of an energy chirped beam is rotated in this long drift space. The compressed beam with bunch length of 100 fs is expected at the downstream undulator by simulation including space charge effects. The radiation frequency is 4.5 THz when the undulator strength K is 3.4. The total radiated energy is 2.74 μJ, and the corresponding peak power is 0.7 MW. Wakefields are not included in these simulations, as they are not expected to be important for the THz mode. This undulator can provide variable polarization, allowing adjustable polarization in its THz CUR. This unique property can support additional novel applications for the users.

Table 3: Estimated Beam Performance and THz Radiation by CUR

Electron beam	
Charge [pC]	100
Energy [MeV]	27.3
Bunch length [fs]	100
emittance [mm-mrad]	5.4
Energy spread [%]	1.35
THz radiation	
frequency [THz]	4.5
Total radiated energy [μJ]	2.7
Peak power [MW]	0.7

CONCLUSION

We studied the feasibility of building a new light source at NSRRC which allow dual operation modes that delivers coherent THz undulator radiation with adjustable polarization as well as VUV radiation from a fourth harmonic HGHG FEL which will be seeded externally by a tunable laser. Installation of the photoinjector system including the beam diagnostics tools and the first linac section is in progress. In the initial stage of the project, we will install the existing EPU56 undulator at the exit of L_0. Our objective is to generate ultrashort electron beam via velocity bunching in L_0 for THz CUR before next summer. In the meantime, design and fabrication of the radiator undulator CU18, laser system upgrade and construction of the linac system together with the magnetic bunch compressor will be implemented. We expect the first lasing of VUV FEL will be in 2016. The dual operation of CUR THz radiation at the end of this linac system will also be realized around this schedule. This FEL facility allows us to pursue a wide range of future possibilities beyond TPS, the newly constructed 3rd generation light source, and it will serve as the foundation for FEL researchers in Taiwan.

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