THE SEED LASER SYSTEM FOR THE PROPOSED VUV FEL FACILITY AT NSRRC

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Abstract

The possibility of establishing a free electron laser (FEL) facility in Taiwan has been a continuing effort at National Synchrotron Radiation Research Center (NSRRC) in the past several years. The Baseline design of the envisioned NSRRC FEL is a high gain harmonic generation (HGHG) FEL seeded by a 266 nm laser. The seed laser is produced by adding an optical parametric amplification (OPA) system pumped by upgrading the existing IR laser system. To provide broad tunability of the FEL radiation, the seed laser will be tunable. The spectrum considered for seeding the FEL is between 266 - 800 nm with peak power of 200 MW. The spatial and temporal overlap between the sub-100 fs electron bunch and the 100 fs UV seed laser is under study.

INTRODUCTION

An FEL facility aimed for VUV and THz radiation is being studied at NSRRC in Taiwan [1]. To fulfil the user needs, this facility is designed to be operated in two modes, one for VUV applications and the other 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. 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.

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 an HGHG section. Design emphasizes versatility of operation and beam quality control and compensation of nonlinearities, with an envision that it will allow as much as possible future upgrades as well as later R&D of FEL physics. 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 researches 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.

In the beginning of 2013, the first operation of the 2998 MHz photoinjector at NSRRC has been successfully preformed after high power microwave processing of the photoinjector cavity up to 60 MV/m. A 266-nm, 300-μJ ultra-violet (UV) laser system has been installed as the drive laser for the photocathode RF gun. A stable electron beam with energy of 2.6 MeV at 250 pC bunch charge has been achieved. Beam transverse emittance of ~3 mm mrad is measured at 250 pC with Gaussian laser pulse [2]. 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 PROPOSED FEL FACILITY

The System Layout

The Baseline design of the envisioned NSRRC FEL is an HGHG FEL seeded by a 266 nm laser. 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 an 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 FELs has been discussed widely in recent 10 years [3]. 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 4 m × 5 m experimental area for users, the whole facility tightly fits into the existing 38 m × 5 m long tunnel in the TPS Linac Test Laboratory.

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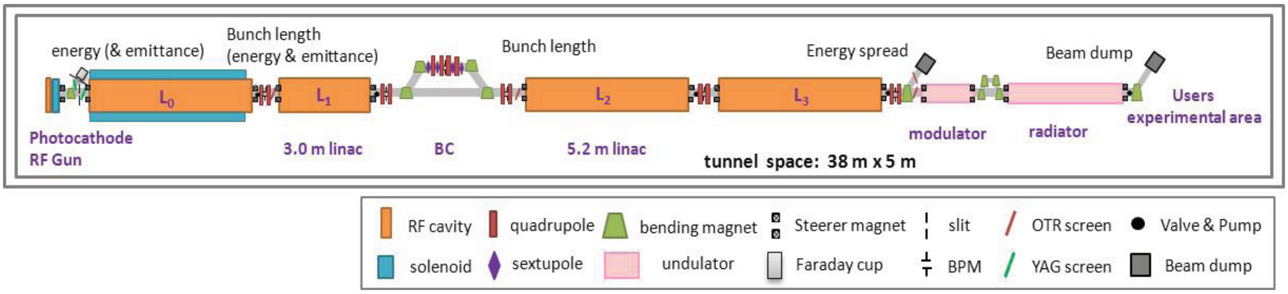

Figure 1: Layout of the proposed FEL facility at NSRRC.

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 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.

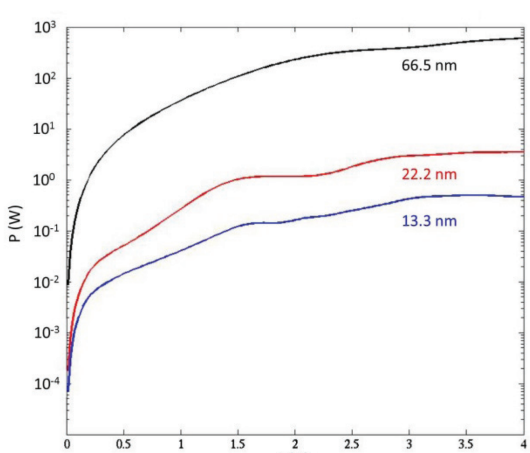

Figure 2: The growth of the radiation power in the undulator. The fundamental (66.5 nm), the 3rd harmonic (22.2 nm), and the 5th harmonic (13.3 nm) radiations are marked as black, red and blue lines respectively.

The seeding laser with wavelength between 266 – 800 nm with peak power of ~ 100 – 200 MW is adopted in this estimation.

As mentioned above, the EPU56 will serve the dual functions as an HGHG modulator and a THz coherent undulator radiation (CUR) undulator. When the 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, L_0 will be optimized to generate 100 pC, 100 fs electron bunches at 27.3 MeV through velocity bunching. 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. 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 1: Estimated Beam Performance and Radiation of the VUV/THz FEL at NSRRC

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
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
THz radiation	
Frequency [THz]	4.5
Total radiated energy [μJ]	2.7
Peak power [MW]	0.7

THE ULTRAFAST LASER SYSTEM

The Existing Laser System

The ultrafast laser system used to drive the photocathode rf gun was purchased from Coherent Corporation and it is a Ti:sapphire laser system based on the chirped-pulse amplification technique [4]. This system

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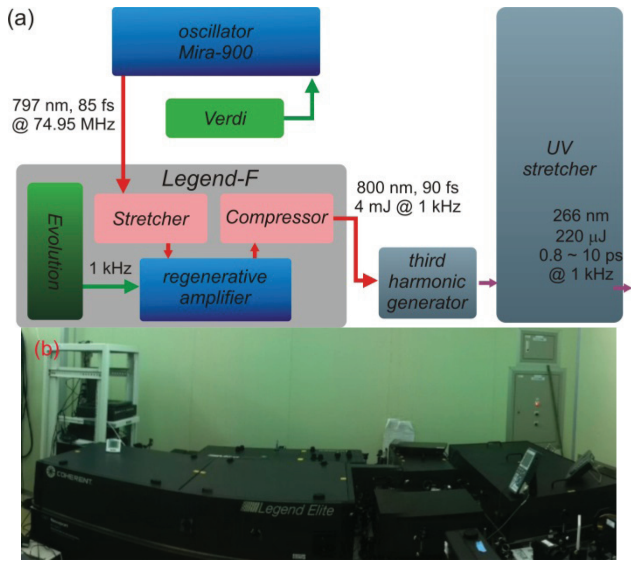

Figure 3: (a) Layout and (b) photo of the ultrafast laser system.

consists of an oscillator (Mira-900), an amplifier (Legend-F), a third harmonic generator (THG), and a UV stretcher. The layout of the laser system is shown in Fig. 3. The oscillator is an 85-fs passively mode-locked oscillator pumped by Verdi, a 5-W cw frequency-doubled $Nd:YVO_4$ laser. It delivers 16 nJ energy per pulse, 74.95 MHz repetition rate and a central wavelength of 797 nm. The seed laser from the oscillator is then conveyed into the Legend-F amplifier. It is composed of three essential elements, an optical pulse stretcher, a regenerative amplifier and an optical pulse compressor. Before entering the amplifier, the laser pulses are stretched with an Öffner-type all-reflective stretcher. After stretched, the laser pulses are amplified by a regenerative amplifier while the energy is raised from nJ to mJ level and meantime the repetition rate of the laser is modulated to 1 kHz by a frequency-doubled diode-pumped Nd:YLF laser (Evolution). The amplified laser pulse is further compressed with a grating compressor. Currently the IR laser output from the Legend is 4 mJ per pulse with energy stability <0.5% RMS, which is lower than that of factory specifications due to the degradation of optics such as the compressor grating.

In order to extract photoelectrons from the Cu photocathode RF gun efficiently, the photon energy of the laser pulse should be higher than the work function of Cu ~ 4 eV. For this reason the laser frequency from the Legend is tripled by a THG, which mainly consists of two nonlinear crystals. After the THG, a UV laser pulse with 266 nm, corresponding to photo energy of 4.5 eV, is generated. The UV laser pulse can be further stretched from 800 fs to 10 ps by a UV stretcher, which is consisted of four fused silica prisms. We set the pulse duration of the UV laser at 8 ps for initial gun test. Similarly, the UV laser energy of 220 μJ at the exit of the UV stretcher is a little lower, compared to that of factory specifications due to the degradation of the nonlinear crystals and prisms. Although the UV energy attenuates to about 100 μJ after propagating to the Cu cathode due to mirror loss and absorption of the air, it is sufficient for the photocathode RFgun.

The Upgraded Laser System for FEL Seeding

As mention above, in order to provide broad tunability of the FEL radiation, the part of the spectrum considered for seeding the FEL is between 266 – 800 nm with peak power of 100 – 200 MW. We aimed to cover wavelengths in the range 66.5 – 200 nm with the expected performance. One method to obtain such light sources with broad spectra is using an OPA system, followed by appropriate non-linear crystals and laser splitting schemes. A feasible OPA system is a TOPAS as was chosen at FERMI@Elettra [5]. The signal and idler waves of TOPAS span from 800 nm to 2.4 μm. Through a sequence of nonlinear harmonic generation and mixing, the frequency is up-converted to UV. Figure 4 shows the tuning spectra of the TOPAS. The desired FEL seed laser wavelength is 266 nm, laser pulse energy is 300 μJ, and FWHM pulse width is 1.5 ps, corresponding to the peak power of 200 MW. It means that when using the TOPAS system, the 800-nm pump energy should be larger than 40 mJ. The laser energy of the existing laser system is too low to be used as the pump source for producing such high energy of 266 nm from the OPA process. Furthermore, the seed laser should be shared with (a much smaller need of) the RF gun. Therefore we plan to add a 4-pass amplifier after the existing laser system to boost the laser energy.

Figure 5 shows the layout of the upgraded laser system. First, a beam splitter will be inserted after the regen amplifier. The stretched, expanded 800-nm laser pulse with 4 mJ (80% output of the regen amplifier) is then compressed to 100 fs and used to generate the UV laser pulse by the THG. Then the UV laser pulse is used as the drive laser of the photocathode RF gun as mentioned above. The residual laser pulse (20% output of the regen amplifier) will be used as the seed pulse for the 4-pass amplifier. This 4-pass amplifier will be pumped by a frequency-doubled Q-switched Nd:YAG laser from both ends. This amplifier is made of a 10-mm-long, 1.5-cm diameter, 0.25% doping, normal-cut Ti:sapphire crystal with anti-reflective coating, and seven folding mirrors in a bow-tie configuration. At the Ti:sapphire crystal, the pump beam diameter is 3.9 mm FWHM and the laser beam diameter is 2.6 mm FWHM. With pump energy of

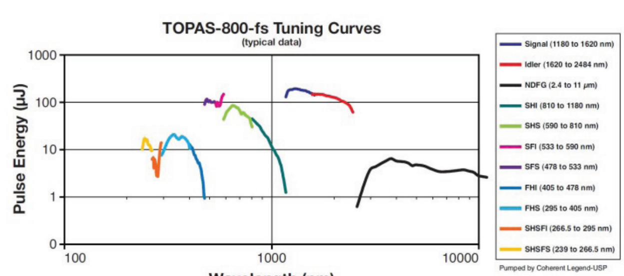

Figure 4: Spectra of the TOPAS.

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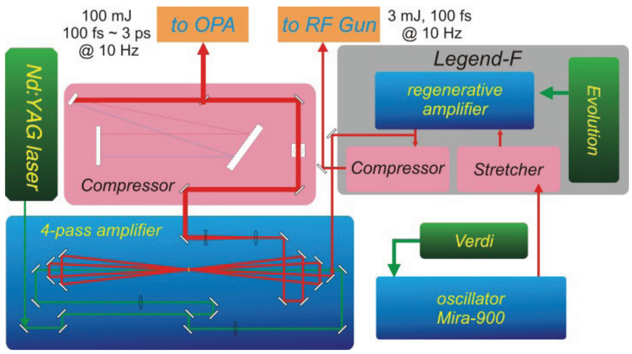

Figure 5: Layout of the upgraded laser system.

600 mJ, the laser pulses are amplified to 130 mJ. After the 4-pass amplifier the laser beam is expanded to 20-mm diameter in clear aperture. The amplified laser pulse is further compressed to 100 fs with 100-mJ energy by another grating compressor. Pulse durations of the laser pulse can be varied from 100 fs to 3 ps with either sign of chirp by adjusting the grating separations. In addition, in order to match the repetition rate of the RF system, the repetition rate of the upgraded laser system will be tuned from 1 kHz down to 10 Hz by adjusting the Pockels' cell timing inside the regen amplifier. The amplified 800-nm laser pulse with 100 mJ, 1.5 ps can be used to pump the OPA system to generate the UV laser for the FEL seeding.

In the initial stage of this FEL project our objective is to generate the ultrashort electron beam via velocity bunching in L_0 for THz CUR before next summer. Before installing the existing EPU56 undulator at the exit of L_0, it is a good opportunity to produce ultrashort x-ray sources through the Thomson scattering once the 100 MeV electron beam and the 100 mJ laser pulse are ready. Furthermore, high-order harmonic generation (HHG) will be investigated as well when the laser system is upgraded to support the HGHG FEL. We will for example try to optimize the 5th harmonic to reach the EUV regime using this facility. With HHG seed down to 66.5 nm directly, the 3 m long undulator can be used as direct amplifier. A comparison between a HHG seed amplifier and a HGHG FEL can be an interesting topic.

Synchronization

To generate and accelerate electron bunches from the photocathode RF gun, one has to make synchronization between the laser and the RF system. The fine synchronization with the RF reference can be carried out at the level of the laser oscillator. The laser oscillator can be locked with the signal generator by a Synchrolock which was also bought from Coherent [6]. Coherent specifies a time jitter is less than 250 fs RMS when the Synchrolock is used to lock two laser oscillators. Since the oscillator phase noise may have variations, we think the time jitter is < 1 ps RMS when an external RF signal is used to drive the Synchrolock. In order to make sure the good synchronization between the UV pulse and the electron beam during seeding process, we will set the pulse duration of the UV pulses at 1.5 ps since the time jitter of the current system is < 1 ps. The proposed FEL facility will provide intense, fully coherent ultrafast light sources up to the extreme VUV region. The femtosecond VUV pulses and IR laser pulses can be used to do some time-resolved pump-probe experiments. But a time jitter of < 1 ps is still too long for the VUV pulses with respect to the experimental pump lasers. An optical timing system based on stabilized fiber links has been developed for the LCLS to provide synchronization at the sub-20 fs level [7]. We will improve the time jitter of our system by referring to what has been done at LCLS. We will also plan a full series of measurements to characterize the overall timing stability of the VUV and laser pulses.

CONCLUSION

In this proceeding, we report the feasibility of building a new light source at NSRRC which delivers the VUV radiation from a 4th 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. The seed laser will be produced by adding OPA system pumped by upgrading the existing IR laser system with installing a 4-pass amplifier. We expect the energy upgrade of the laser system will start in the beginning of 2015 and the first lasing of VUV FEL will be in 2016. 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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