THE NSRRC PHOTO-INJECTOR DIAGNOSTIC TOOS FOR INITIAL BEAM TEST

A.P. Lee , M.C. Chou, N. Y. Huang, J. Y. Hwang, W. K. Lau, C.C. Liang, M.T. Tsou,
NSRRC, Hsinchu 30076 Taiwan.
P. Wang, Department of Engineering and System Science,
National Tsing Hua University, Hsinchu 30013 Taiwan

Abstract

The High brightness injector project at NSRRC aims to develop a100 MeV photo-injector system for light source R&D at NSRRC. This photo-injector system equipped with a photocathode rf gun, a solenoid for emittance compensation, an S-band linac as well as various beamdiagnostic tools is designed for operation in two different modes. One is to generate high brightness electron beams for future free electron laser experiments. The other is to produce ultra-short electron bunches by velocity bunching. It also allows us to perform inverse Compton scattering experiment for generation of fs x-ray. In the beginning of this project, the photocathode rf gun was installed in the booster room of TLS at NSRRC. The normalized beam transverse emittance is 5.5 mm-mrad at ~250 pC with Gaussian laser pulse. Recently, a 100 MeV photo-injector system is being installed in the 38 m by 5 m tunnel of the NSRRC linac test laboratory. The rf gun, the 35 MW high power microwave system and a 5.2 m lina has been set up. The UV driver laser system will be set up in the new temperature controlled clean room in the linac test laboratory. For initial beam test, some beam diagnostic tools are considered. They are presented and discussed in this paper.

INTRODUCTION

The development of high brightness beam produced by a photo-injector has been driven mainly by self -amplified spontaneous emission free-electron laser (SASE FEL) applications. The high brightness electron beam is now an important subject of light source research for developing high gain free electron laser. For high gain FEL, the key issue is to produce an ultra-low emittance beam then compress the beam to higher peak current and to accelerate it to the high energy by the main linac system. Since the injector produces the high brightness electron beams that determine the FEL performance, development of injectors show the strong demand in producing high brightness electron beams.

Photo-injectors that deliver low emittance beams at nC bunch charge are commonly used in high gain FELs worldwide. As a result of the continuing developmentfor high brightness electron beam technology, photo-injectors have now become an essential sub system in many x-ray FEL facilities such as LCLS, European FEL, FLASH, Swiss FEL and SPARC etc. A photo-injector system mainly consists of a photocathode rf gun with a emittance compensation solenoid and a traveling wave S-band linac which accelerates the beam up to ~100 MeV. In the rf gun, electrons are emitted from the cathode surface of the cavity by illuminatingan intense UV laser. These electrons are then accelerated to relativistic energy in a few centimeters by the rf field so that the space charge effect degrading the transverse emittance and the beam energy spread is reduced. An emittance compensation solenoid as well as the three-dimensional laser beam shaping is applied for further reduction of space charge emittance growth.

A THz/VUV free electron laser facility isproposed at National Synchrotron Radiation Research Center (NSRRC) in Taiwan [1, 2]. The FEL complex comprises the following parts. A photo-injector is to generate a bright electron beam with energy ~100 MeV, then a 3 m long linac section to modulating theelectron beam with energy chirp. A double dogleg with linearization optics in the middle section of the dog-leg dipole magnets is used as a bunch compressor. Follow the compressor, two 5.2 m linear accelerators in which the beam is time-compressed and accelerated to 325 MeV, then the system to transport the beam to the undulator which is generate the VUV FEL radiation.

PHOTO-INJECTOR SYSTEM

Before constructing the VUV/THz FEL, the high brightness injector project is proposed to develop the photo-injector capable of producing low emittance sub -100 fs electron beams for the VUV/THz FEL.The 100 MeV high brightness photo-injector of the driver linac system proposed for the VUV FEL facility is under construction in the NSRRC linac test building as shown in Fig. 1. The design of the photo-injector is done by the computer simulation using the particle tracking code, General Particle Tracer (GPT) [3]. A 3.5 MeV low emittance beam with bunch charge of 100 pC is generated from the photocathode rf gun operated at the peak rf accelerating gradient 70 MV/m and optimum laser injection phase23°with respect to rf field. The 5.2 m rf linac with 18 MV/m accelerating gradient is set downstream after the photo-cathode rf gun for boosting beam energy. The optimum location of the linac for getting lowest transverse emittance is according to the Serafini's theory [4]. The linac can be put near the relative local maximum of beam emittance after the solenoid magnet with field strength adjusted correctly for emittance compensation. This optimum location is at 1.35 m from the cathode surface when the solenoid magnet is operated at 1400 Gauss. Beam parameters of the photo-injector in the GTP simulation are summarized in Table 1. Details of hardware components are presented in the following sub sections.

ISBN 978-3-95450-176-2

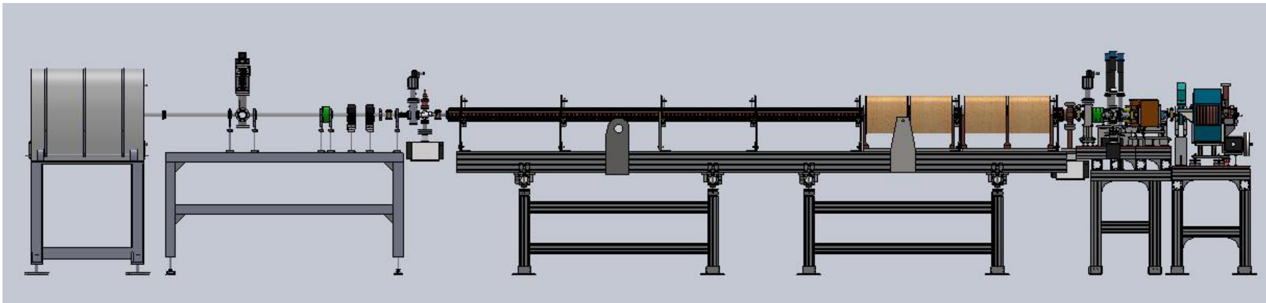

Figure 1: The layout of the photo-injector is being built at NSRRC.

Table 1: Beam parameters at the entrance of the linac.

Initial beam parameters:	
Peak E field in the rf gun	70 MV/m
Laser injection phase	23° (GPT setting)
Initial beam radius	0.6 mm
Initial bunch length	6 ps (FWHM)
Initial beam profile	Uniform cylindrical
Initial beam charge	100 pc
B field of solenoid	1400 Gauss
Beam parameters at the entrance of the rflinac:	
Beam energy	3.54 MeV
Projected energy spread	37 keV
Projected relative energy spread	1.0 %
Sliced energy spread	0.55 keV
Sliced relative spread	0.0016 %
Charge	100 pC
Bunch length	2.25 ps (rms)
Peak current Ip	~ 19 A
Normalized emittance	0.98 mm-mrad
Sliced emittance	0.59 mm-mrad

Photocathode Rf Gun

The photo-cathode rf gun is 1.6-cell BNL GUN-IV type with a polycrystalline copper photocathode except that our operating frequency is set at 2998 MHz. [5]. The dimension of the cavity is scaled to meet the resonant frequency at 2998 MHz. The cathode is illuminated by an 266 nm wavelength UV laser with pulse shaping technique to optimize the final beam quality. Because the measured value of the quantum efficiency of copper at 266 nm is ~10^{-5}, the laser must deliver ~100 μJ on the cathode in order to produce a ~100 pC bunch charge. The gun operates in the fundamental, TM010-π mode of the two-cell cavity. A solenoid magnet is integral to the RF gun operation. The solenoid focuses the beam from the gun exit to the entrance of the linac structure and compensates the emittance growth due to linear space charge.

In the beginning of developing the photo-injector system, a gun test facility (GTF) has been setup in the TLS booster room for testing photo-cathode rf guns. In the spring of 2013, the first operation of the photo-cathode rf gun has been successful accomplished which can be operated at peak field of 58 MV/m. Electron bunches with Gaussian beam shape are characterized with energy of 2.3 MeV, bunch charge of 250 pC and normalized transverse emittance of 5.5 mm-mrad [6]. Since the condition of the rf gun is not optimized, further improvements of the rf gun are in progress. A new photo-cathode rf gun with improved inner wall surface condition will be fabricated for operation at peak field higher than 70 MV/m.

Ultrafast Laser System

The NSRRC ultrafast laser system which was purchased from Coherent Corporation is a Ti:sapphire laser system based on the chirped-pulse amplification technique. This system consists of an oscillator (Mira-900), an amplifier (Legend-F), a third harmonic generator (THG), and a UV stretcher. In 2013 the laser system was successfully used for driving the NSRRC photocathode RF gun [7]. The drive laser system delivers the 3-mJ IR laser pulse with 100-fs pulse duration and the 180-mJ UV laser pulse with 800 fs to 10 ps tunable pulse width at that time. Following the high brightness injector project the whole laser system was moved to the NSRRC linac test laboratory and installed in a temperature-humidity controlled clean room in the beginning of this year.

The laser system will be served as the drive laser for the photocathode RF gun and the seed laser for the VUV FEL. Therefore the laser system will be upgraded by adding a multipass amplifier to increase the laser energy. Figure 1 shows the layout of the upgraded laser system. First, the output energy of the regen is raised from 4.5 mJ to 6 mJ. After that, a beam splitter is inserted in front of the compressor inside the Legend-F. The penetrated stretched 800-nm laser pulse with 80% output energy of the regen amplifier is then compressed to 100 fs and used to generate the UV laser pulse by the THG. The UV laser pulse with 266-nm wavelength, corresponding to photo energy of 4.5 eV, is used to extract photoelectrons from

ISBN 978-3-95450-176-2

the Cu photocathode of the rf gun. The pulse duration of the UV laser can be further stretched from 800 fs to 10 ps by a UV stretcher, which is consisted of four fused silica prisms. Currently, the output energy of the IR laser pulses is 3.8 mJ with energy stability <0.3% RMS. The UV energy is 550 mJ at the exit of the THG and attenuates to 150 mJ with energy stability <1.9% RMS after propagating to the Cu cathode due to energy loss from optical components.

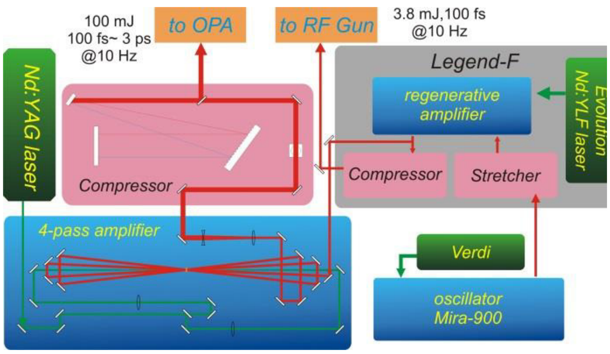

Figure 2: Layout of the upgraded laser system.

The residual laser pulse (20% output energy of the regen amplifier) will be used as the seed pulse for the 4-pass amplifier. The 4-pass amplifier is made of a 10-mm-long, 1.5-cm diameter, 0.25% doping, normal-cut Ti:sapphire crystal and seven folding mirrors in a bow-tie configuration. It will be pumped by a frequency-doubled Q-switched Nd:YAG laser from both ends. With 532-nm pump energy of 600 mJ, the IR laser pulse energy will be expected to amplify to 130 mJ. The amplified laser pulse is further compressed to 100 fs with 100-mJ energy by another grating compressor. Before the compressor the laser beam size will be expanded to 35-mm diameter in clear aperture such that the laser can be propagated in the air after compressed. After that, it can be used to pump the OPA system to generate the UV laser for the FEL seeding. The desired FEL seed laser wavelength is 266 nm, laser pulse energy is 300 mJ, and FWHM pulse width is 1.5 ps, corresponding to the peak power of 200 MW. 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.

High Power Microwave System

The high power microwave system consists of a 35 MW klystron, a klystron modulator, rf vacuum waveguide system. The high power S-band klystron, Thales model TH2100A,can produce max peak power of 35MW at pulse duration of 4.5 μs. The klystron and focusing magnets has X-ray shields that meet radiation safety requirements. A conventional line-type high voltage modulator consists of 8 sections of pulse forming network which is charged and discharged by a thyratron provide 30kV high voltage to the klystron. A driver amplifier system with the one kilowatt ThalesTH2047 klystron for the high power TH2100A pulsed klystron has been installed. The output microwave is distributed by the vacuum waveguide system, including the hybrid couplers, high power phase shifter and rf windows to the rf gun and the accelerating linac. The amplitude fed to the gun and linac can be adjusted using the high power hybrid. This microwave system is synchronized with the driver laser system, so the phase of microwave fed to gun can be changed by a phase shifter installed after the oscillator and the phase of microwave fed to the linac is controlled using high power phase shifter.

RfLinac

The linac is a 5.2 m, 2998MHz constant gradient traveling-wave structure which is operated at $2\pi/3$-mode. The structure is designed the same as the DESY LINAC-II type and is manufactured by Research Instruments GmbH. It totally has 156 cells with149 normal cells. The power is coupled to the first cell at one arm with the opposite arm shorted and the last 6 cells coated with Kanthal layer for absorbing the power. The shunt impedance, attenuation parameter, and filling time, are 52 M Ω/m, 5dB and 0.69μs, respectively. It can accelerate electron beam to about 97 MeV without beam loading with 35 MW input rf power.

BEAM DIAGNOSTICS

Based on the results of the GPT simulation study, beam diagnostics are designed for characterizing the beam from the rf gun. The instrumentation for the beam diagnostics are set in the gun-to-linac (GTL) drift section as shown in Fig. 4. Two steering magnets allow correcting beam offset and angle. An inductive current transformer is for non-destructive bunch charge measurements. A six-way cross in the beamline allows for on-axis injection of the photocathode drive laser pulse. A rectangular dipole magnet with nominal field 0.05 T is used as the spectrometer bending magnet for energy and energy spread measurements at downstream of the photo-cathode rf gun system. A faraday cup installed after the dipole is used to measure the bunch charge comparing to the ICT.

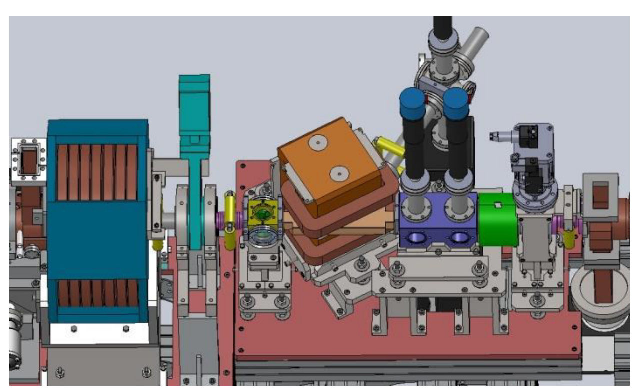

Figure 3: the layout of the beam diagnostic system after the gun.

ISBN 978-3-95450-176-2

Bunch Charge Measurement

Unlike Faraday cup which collects bunch charge by intercepting the electron beam, ICT can be used for non-destructive measurement by passing the beam through the ICT core. The ICT is a transformer which can be used to measure the bunch charge by integrating the beam signal with rise time in the order of picoseconds with no significant loss. To measure the bunch charge with an ICT, a ceramic gap is installed to break the wall current on the vacuum beam pipe and a metallic shield is attached to the vacuum chamber on both sides of the electrical break as wall current bypass as well as rf shield. In our setup, the Bergozin-air type ICT with inner diameter of 82 mm and turn ratio of 5:1 (ICT-082-070-05:1) is chosen to match the dimensions of our beam pipe.

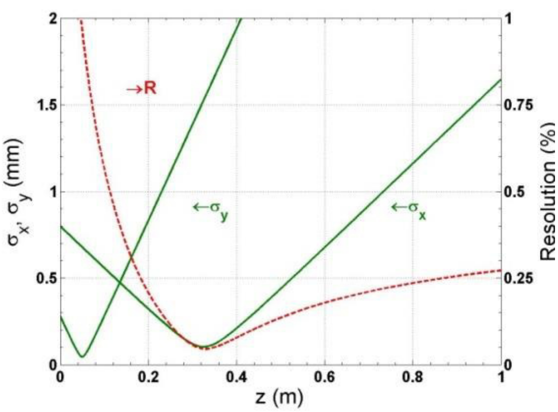

Figure 4: Calculated resolution and beam sizes after a 60° bending magnet. Note that the position at magnet exit is set at z = 0 in these plots.

Energy and Energy Spread Measurement

A 17 cm rectangular dipole magnet with a pole gap of 40 mm will be used as the spectrometer bending magnet for energy and energy spread measurements at downstream of the photo-cathode rf gun system. The physical dimensions of this dipole magnet are shown in Fig. 6. In general, large bending angle and large dispersion are beneficial to improve of beam spectrometer resolution, so we choose 60° as the bending angle. In order to know where to put the screen for best resolution, the analysis of the evolution of beam envelope after the bending magnet without the consideration of momentum spread is necessary. As shown in Fig. 4, the position of optimum resolution is at z ~ 0.33 m which is about the position of minimum horizontal beam size. The estimated resolution is ~ 10 times smaller than the expected beam energy spread of the photo-cathode rf gun. This rectangular dipole magnet with 60° bending angle provides a wider range for putting the screen that allows energy spread measurement at good resolution. A quadrupole pair can be installed before the bending magnet for further improvement of resolution if needed. The position of the screen is located at 33cm away from the exit of the magnet. A 10 x 10 mm screen should be big enough to display the profile of a dispersive beam at this position.

Emittance Measurement by the Multi-slit Method

The design rule of the multi-slit mask is specified by some criteria [8]. The original design of the multi-slit mask that has been used for testing the first prototype photo-cathode rf gun is made of 2 mm thick stainless steel with 50μm slits that are separated at 300μm apart. The slits are cut by electrical discharge machining (EDM) and the edges of the slits are irregular. It is hard to determine the average width of each slit for data analysis. Beside blurred image has been observed on the YAG screen in addition to the image formed by the transmitted beam edge. It is believed that this blurred image is related to the scattering of electrons from the slits. Therefore, an improvement of the multi-slit mask to avoid edge scattering of electrons is considered

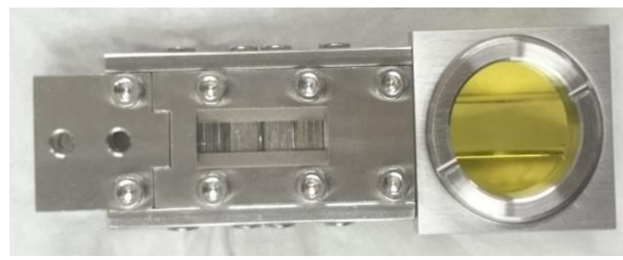

Figure 5: multi-slits stacked in a stainless steel holder.

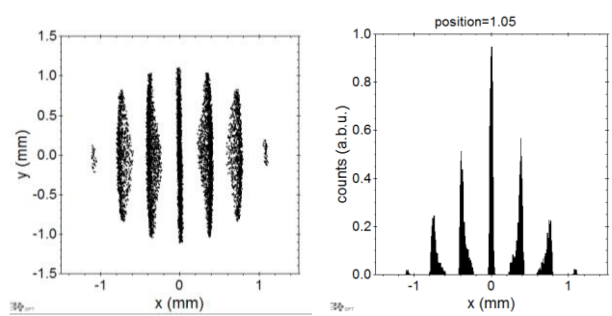

Figure 6: The distribution of the transmitted electron beam at the position of the screen when the multi-slit with the separation of 500 μm. The slit is located at the position 95 cm, and the distance from the slit to the screen is 10 cm.

A new multi-slit mask is fabricated for emittance measurement. The thickness of the stainless steel multi-slit mask should be at least 2.6 mm to stop a 3.5 MeV beam. The mask thickness is set at 5 mm. Slits of 50μm in width and separation of 500μm. Fabrication of C-shaped elements is also possible for slit separation of 300μm.The minimum width and thickness of the slits are limited by the capability of machining methods, so the EDM method is not suitable. The new multi-slit mask is made by stacking C-shaped stainless steels which are machined by precise grinding. A prototype mask has been fabricated in the Mechanical and Systems Research Laboratories of Industrial Technology Research Institute (ITRI) in Taiwan.

ISBN 978-3-95450-176-2

Figure 5 shows multi-slits stacked in a stainless steel holder integrated with a YAG screen. From the GPT simulation while the mask is set at the position 95 cm from the cathode plate, the image of beamlets on the screen will not overlap if the distance from multi-slit to screen is less than 15 cm. Since the edge scattering is not considered in the simulation, the distance is set as 10 cm. The distribution of electron beamlets at the position of the screen is shown in Fig. 6.

SUMMARY

The photo-injector system for the THz/VUV FEL is being builtat NSRRC. The installation has been started in January 2015 and will be finished at the end of 2015. In the first phase, the objective is to generate the ultrashort electron beam via velocity bunching in the 5.2 m linac for THz coherent radiation. Before installing the undulat or, the parameters of beams generated by the photocathode rf gun will be measured. The quadrupole scan is used to measure the transverse emittance and the coherent transition radiation is usedto measure the bunch length after electron beams exit the linac. Then, the RTR experiment will also being carried out [9]. Besides, producing ultrashort x-ray sources through the inverse Compton scattering is to be considered since the 100-MeV electron beam and the 100-mJ laser pulse are ready.

REFERENCE

[1]. N.Y. Huang, et al., "Linac design for the proposed NSRRC THz/VUV FEL facility", THPRO047, IPAC'14 (2014).

[2]. N.Y. Huang et al., "Study of a THz/VUV free electron laser facility in Taiwan", THPRO050, IPAC'14 (2014).

[3]. General Particle Tracer, http://www.pulsar.nl/gpt.

[4]. Luca Serafini and James B. Rosenzweig, "Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors:mA theory of emittance compensation", Phys. Rev. E 55, 7565 (1997).

[5]. A.P. Lee et al., "Operation of the NSRRC 2998 MHz photocathode rf gun",WEPWA058, IPAC'13 (2013).

[6]. A.P. Lee et al., "Emittance and bunch length measurement of electron beam from the photocathode gun at NSRRC", THPRO048, IPAC'14 (2014).

[7]. M.C. Chou et al., "Operation of the drive laser system for the 2998 MHz NSRRC photoinjector", WEPWA059, IPAC'13 (2013).

[8]. J. Rosenzweig and G. Travish, "Design Consideration for the UCLA PBPL Slit-based Phase Space Measurement", Lecture Notes (1994).

[9]. P. Wang et al., "Design of a resonant transition radiation source in the soft x-ray range", TUPJE050, IPAC'15(2015).

ISBN 978-3-95450-176-2