PHYSICS AND ENGINEERING ISSUES OF PPI (POHANG PHOTO-INJECTOR) FOR PAL XFEL*

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Abstract

The PAL XFEL, an X-ray Free Electron Laser (XFEL) project based on the Self-Amplified Spontaneous Emission (SASE), is under progress at the PAL (Pohang Accelerator Laboratory). Successful completion of the project is expected to impose stringent requirements on the beam qualities such as the normalized emittance (< 1.0 mm-mrad) and the un-correlated energy spread (~10-5). This requires careful and systematic planning for ensuring the generation and the preservation of high-brightness beams in the whole machine. The PPI (Pohang Photo-Injector) is to achieve these requirements with high reliability and stability. In this article, we discuss various physics and engineering issues involved in the design and construction of the PPI. We also report on the R&D status of photo-cathode RF gun at the PAL.

INTRODUCTION

The PAL XFEL, an X-ray Free Electron Laser project, aims to achieve lasing at hard X-rays with relatively low beam energy (3.7 GeV) [1]. This is mainly due to the site constraint within which the machine should be constructed. This fact inevitably requires very low emittance beams at the entrance of the undulator. If we assume the slice emittance requirement of < 1 mm mrad (normalized, rms) at the undulator entrance, the injector of the PAL XFEL should provide the slice emittance better than 0.8 mm mrad, with 25-% emittance increase during the transport through the driver linac. In terms of the usual projected emittance, this requirement would be translated into 1.0 mm mrad (normalized, rms).

The transverse emittance of the XFEL injector is not the whole story. It is generally known that the energy spread of the electron beam should be low for the efficient FEL interaction between the electron beam and the radiation, but not too much low in order to avoid the micro-bunching instability. Therefore some means for controlling the energy spread of the electron beam should be provided, e.g., the laser heater as in the LCLS.

Fulfilling the above requirements is quite challenging and necessitates careful design and construction of the injector for the PAL XFEL, the PPI (Pohang Photo-Injector). In this article, the authors describe various issues relevant to the PPI development. We also report on the progresses made in the GTS (Gun Test Stand) facility that has been constructed at the PAL for the high-brightness R&Ds toward the PPI development.

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PPI ISSUES

In Table 1, we summarize the requirements imposed on the PPI for the PAL XFEL.

Table 1: PPI requirements.

Charge	1 nC, nominal
Beam Energy	> 130 MeV
Repetition Rate	60 Hz, max.
Projected Emittance (normalized, rms)	< 1.0 mm mrad
Un-correlated Energy Spread	~10^{-5}, rms

The function of the injector for a XFEL machine is to provide high-brightness beams with optimum 6D phase-space properties. The ideal injector would generate high-brightness beams, and accelerate them up to the energy above which the space-charge forces are reduced to such a level that downstream beam transport and acceleration are done without the loss of the beam brightness.

Presently we neither have the definite scheme of achieving the PPI requirements nor find prior demonstration of such performance level with high stability and reliability. The best record on the transverse emittance is 1.2 mm mrad (normalized, rms) at 1 nC that was reported by J. Yang et al. [2]. The emittance was measured by the quad scan method at the beam energy of 14 MeV. Since it is known that the quad scan method at low beam energy overestimate the emittance, the actual value is believed to be lower than that. This conjecture could be further justified with the consideration of the emittance compensation process [3] from which we see enough emittance damping is expected at considerably higher energy than that of the J. Yang's experiment. The electron source for the PPI will be an improved version of the BNL/SLAC/UCLA 1.6-cell RF gun which would be a natural choice for the PAL XFEL which is based on existing S-band (2856 MHz) linac. The PPI layout is not finalized yet but its basic scheme would much resemble that of the LCLS injector [4].

The operating principle of the PPI is the generalized Brillouin flow (Invariant Envelope matching) [3]. Therefore much of the PPI physics issues are related to the realization of the principle with final beam performances conforming to the PPI requirements. The engineering issues are to achieving the performances with high stability and reliability.

Physics Issues

The realization of the generalized Brillouin flow with the Ferrario's second working point requires the following conditions,

$$\sigma' = 0 \tag{1}$$

$$\gamma' = \frac{2}{\sigma}\sqrt{\frac{\hat{I}}{2I_0\gamma}} \tag{2}$$

at the entrance of the first accelerating structure. (1) is to require the beam waist be formed at the accelerator entrance, and (2) is the requirement determining the accelerating gradient of the structure with given beam size, σ and peak current, $\hat{I}$. The constant I_0 in (2) is called the Alfvén current with the numerical value of 17 kA. Meeting the conditions will require measurements of the emittance oscillation profiles with various operation conditions of the photocathode RF gun. *In-situ* diagnostic of the profile would be very convenient but, if this is not feasible, enough prior measurements are needed for the practical machine design which various tolerance budgets. For this purpose we have developed special diagnostic device called the emittance meter. It is to measure the emittance evolution profiles and its design was inspired by the work of the INFN-LNL, Italy [5]. Details are reported in Ref. [6]. Fig. 1 is its outer appearance shown with the gun system.

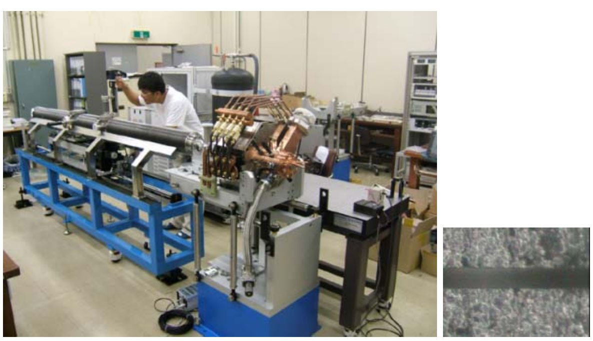

Figure 1: Appearance of emittance meter (left). Right figure is magnified view of 40-μm width slit mode on 0.5-mm thick tungsten plate.

The PARMELA simulation of the expected emittance profiles for the LCLS-style injector with and without acceleration is shown in Fig. 2.

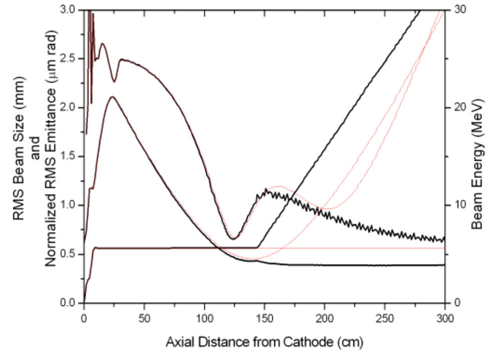

Figure 2: PARMELA simulation of emittance and beam size profiles for LCLS-style injector. Thin (red) lines are for those without acceleration. Thick (black) ones are for those with acceleration.

The intrinsic emittance of electron beams on their birth on the cathode surface becomes important when the total emittance of a photocathode RF gun is reduced down to 1 m level. We have studied the details of the cathode intrinsic emittance (usually called the thermal emittance) considering the photo-emission process. It was found that, when the photons are p-polarized (electric vector normal to the cathode surface), the intrinsic emittance and the quantum efficiency of the photocathode strongly depend on the incidence angle of the photons onto the cathode surface. This is due to the different angular distributions for electrons from the cathode surface and bulk, and the surface to bulk photoemission ratios depend on the photon incidence angle. This occurs only when the photons are p-polarized. Fig. 3 is the angular distributions for photoelectrons by the p-polarized photons with different incident angles.

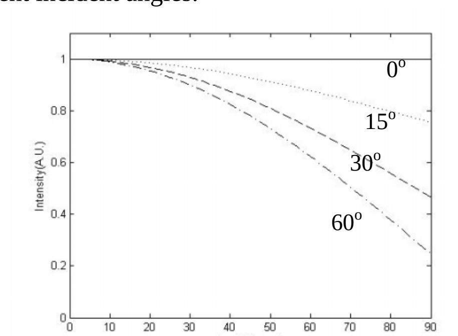

Figure 3: Angular distributions of photoelectrons for different incidence angle of p-polarized photons.

Fig. 4 is the rms normalized emittance vs. the incidence angle of p-polarized photons. Fig. 5 shows the quantum efficiency, the ratio R, and the reflectivity variations for the incidence angle of the p-polarized photons. All of these quantities were normalized to the values of normal incidence case.

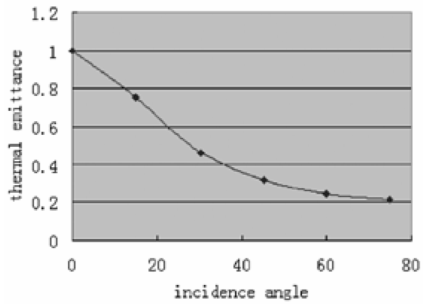

Figure 4: Cathode intrinsic emittance of photoelectrons by p-polarized photons at oblique incidence.

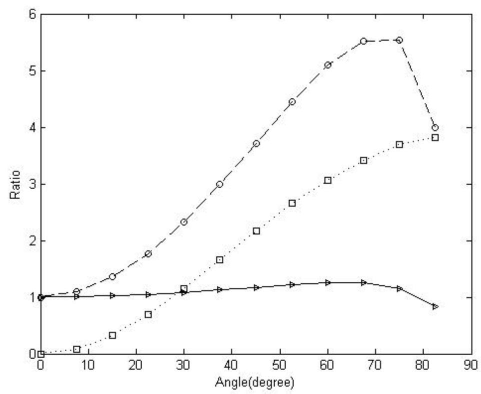

Figure 5: Quantum efficiency (top), R, and reflectivity changes vs. incidence angle of p-polarized photons.

From these theoretical investigations it could be expected that the cathode intrinsic emittance can be reduced by the use of the p-polarized photons at oblique incidence. Additional benefit is the increased quantum efficiency.

Another issue of the PPI as the very low emittance injector is measuring the divergence of such low-emittance beam. We are going to investigate the possibility of this using the electron diffraction. The electron diffraction patterns by a sample with well-known properties, measured and compared with theoretical prediction can provide valuable information on the beam divergence. This is useful for measuring beams with very low divergence since the diffraction pattern is very sensitive to the beam divergence. See Fig. 6 where the expected diffraction patterns for different beam divergences are shown. Note that in order to obtain clear ring pattern after the diffraction, very low beam divergence is required. This suggests a great scientific application of the ultra low divergence beam. If we can make the beam bunches very short (< 1 ps) as is usually obtained with the photocathode RF guns, they can be used for studying ultra-fast dynamics of the nature. This has been really proposed by several scientists [7] and its feasibility will be tested at the PAL.

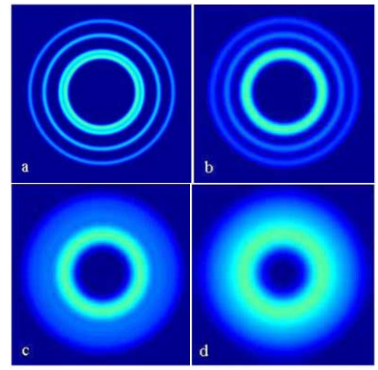

Figure 6: Expected diffraction patterns of electrons with different divergences of 0.05 (a), 0.1 (b), 0.2 (c), and 0.3 (d) mrad.

Engineering Issues

Along with physics issues, there are numerous engineering issues to be solved in developing the PPI. They are largely related to the stability and the reliability of the machine for securing high-quality electron and photon beam qualities for user services.

The first issue the authors would like to address is the cathode lifetime. The lifetime of the cathodes of photo-injectors strongly depend on the vacuum conditions at which they operate. For both of the Copper and the Cs2Te which would be the representative types of metal and semiconductor cathodes for modern photo-injectors, vacuums as good as 10-10 Torr or lower seem to be the must. In order to achieve such vacuum, the load lock system for in-situ fabricating and loading the cathodes to the gun cavity can be used. The concept is not new since the load lock system has been already used in the TTF guns at the DESY or will be used in the LCLS injector. The good vacuum condition also needs strict quality control during the fabrication. High temperature firing of gun components in an UHV furnace (followed by air exposure for assembling) and low-temperature bake-outs (after assembling) should be scheduled. Vents to dry N2 gases should be always observed wherever possible.

The performance of laser system directly determines electron beam quality. Pulse shapings in both transverse and longitudinal planes are required. When one adopts ultra-fast and high-bandwidth lasers (e.g., Ti:Sapphire), pulse stretching schemes for obtaining ps pulses should be seriously considered. Pulse stretching with gratings is traditional and generally yields good results but necessitate tight environmental control on order to obtain high stability. Stretching by simple dispersive medium (e.g., fused silica rod) would be convenient but suffers from large losses and nonlinear characteristics. We are examining using prism pair which is expected to be compact and generate transform-limited photons. The stability issue of the laser is connected to the cathode quantum efficiency. Present-day commercial Ti:Sapphire RGAs (ReGenerative Amplifiers) can provide pulse energy up to 2.5 mJ @ IR with high stability. With 10 % UV conversion efficiency and 50 % losses during photon beam delivery to the cathode, UV pulse energy as high as 125 J is available at the cathode. With this UV energy, quantum efficiency of mid-10-5 is required for 1-nC charge. Higher laser energy can obtained with multi-pass amplifiers but these are not stable enough. In other words, the quantum efficiency of the cathode should be at least 5×10^{-5} in order to achieve stable electron beams with the use of stable lasers (e.g., RGAs).

Wakes induced in the accelerating structure would deteriorate the emittance. Short-range wake is important and since this is not easily damped, straightness of the accelerating structure becomes important.

For a small timing jitter of electron beams, good synchronization between the RF and the laser is essential. The RF phase stability is directly determined by the gun voltage stability of the klystron. For a pulsed RF system powered by the pulsed modulator, the pulse voltage stability becomes very important especially for short (s) RF pulses. For the PAL XFEL (RF frequency = 2856 MHz), 0.1-% modulator stability translates into 0.1-degree RF phase stability.

Beam diagnostics should be accurate. Tomographic measurements of 6D phase-space characteristics would be useful especially for high-brightness injectors for XFELs. Tomography for injectors would be challenging because of the space-chage forces at low energy.

STATUS OF GTS (GUN TEST-STAND)

A test facility for the RF photoinjector is being built at the PAL. At this facility called the GTS (Gun Test-Stand), important high-brightness R&Ds for developing the PPI will be performed. Advanced beam diagnostics utilizing the electron diffraction is also scheduled. The opportunity of electron diffraction with femto-second electron bunches, called the FED (Femto-second Electron Diffraction) will be available to users. Fig. 7 is the layout of the GTS.

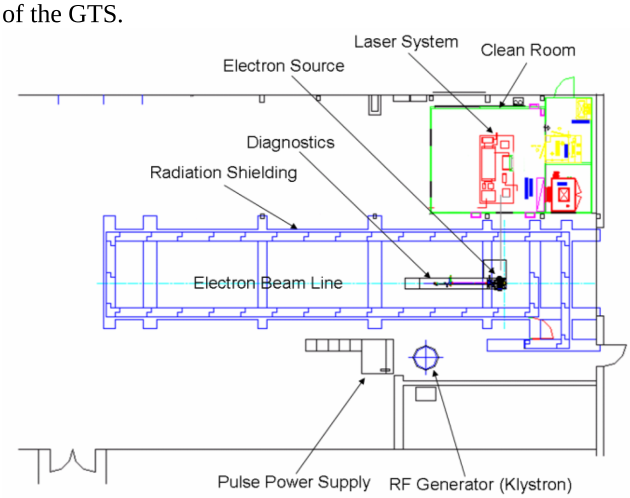

Figure 7: Layout of GTS (Gun Test-Stand) at the PAL.

The laser system consists of the Spectra-Physics "Tsunami" oscillator, the Spitfire-Pro-HPR Ti:Sapphire amplifier, an UV converson unit, and a pulse stretcher. It is running stably in a dedicated clean room with the temperature stability better than +/- 1 ^{o}C. A photocathode RF gun has been successfully fabricated by the collaboration with Dr. X. Wang at the BNL. The gun cavity has been tuned at 2856.25 MHz at 25 ^{o}C and with vacuum condition inside the cavity. The mode separation was set to 3.4 MHz. Coupling coefficient between the waveguide and the cavity was set to 1.25. See Fig. 8.

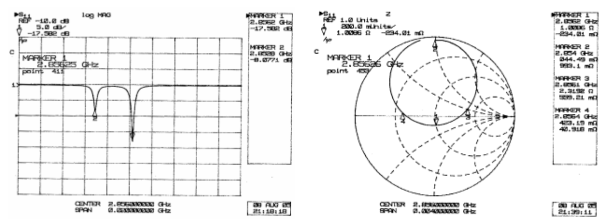

Figure 8: Tuning of gun cavity. S_{11} measurement (left), smith-chart representation of the cavity impedance (right).

Field measurement for the solenoid magnet has been done. The uniformity of the axial magnetic field at the center of the solenoid was ~10^{-4}. Fig. 9 is the measured on-axis B_z profile.

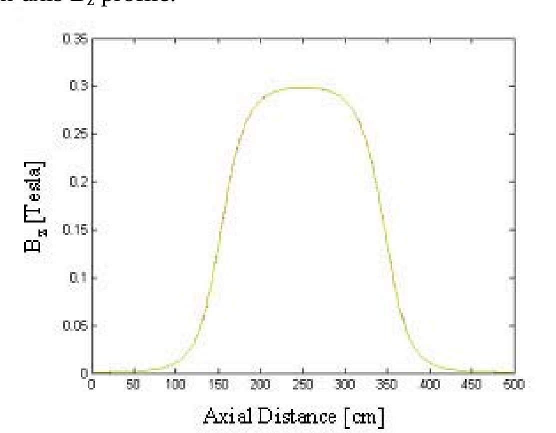

Figure 9: Measured on-axis Bz profile. Excitation current was 200 A. Field uniformity at magnet center is ~10^{-4}. Offset between mechanical and field centers are approximately 0.1 mm.

The construction of the GTS is near completion and the first beam in expected in the September in this year.

REFERENCES

[1] J. S. Oh et al., NIM-A528, pp. 582-585.
[2] J. Yang et al., Proc. of the EPAC2002, pp. 1828-1830, J. Yang et al., JAP92, No. 3, pp. 1608 – 1612.
[3] R. Serafini et al., PRE-55, pp. 7565-7590.
[4] LCLS Conceptual Design Report, SLAC-R-593.
[5] A. Cianchi et al., Proc. of the EPAC2004, pp. 2622 – 2624.
[6] J. Park et al., To be appear at the PAC05 Proceedings.
[7] X. J. Wang et al., Proc. of the PAC03, pp. 420 – 422.