DESIGN STUDY OF LOW-EMITTANCE INJECTOR FOR SASE XFEL AT POHANG ACCELERATOR LABORATORY*

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Abstract

We report on the design study of the low-emittance injector for the SASE-XFEL that is being considered as the possible choice for the next-generation light sources at the Pohang Accelerator Laboratory (PAL), POSTECH. The PAL XFEL will utilize existing 2.5-GeV linac combined with a new 700-MeV linac, and aims to achieve the SASE saturation at 3 Å with 3-GeV beam energy and mini-gap in-vacuum undulators. Requirements imposed on the beam quality are tight, e.g., the normalized rms emittance at the entrance of the undulator should be less than 1.5 μm rad. Since the basic beam quality of the linac is determined by its injector system, the injector system should be developed as soon as possible, well before the start of the machine construction, which would greatly help to find and solve potential obstacles in achieving the required beam qualities. In this article, we report on our preliminary design work on the injector system and scheme for the development of the system.

INTRODUCTION

The PLS (Pohang Light Source) in the PAL/POSTECH is the 2.5-GeV light source with the full-energy injection linac. The PLS linac uses 44 SLAC-style accelerating structures powered by 80-MW klystrons and 200-MW modulators. While it is the world 3rd in its beam energy, it has been under-utilized with beam injections into the storage ring only two times a day. Utilization of the PLS linac as the 4th generation light source (PAL XFEL) has been one of the hot issues in the PAL since last year, and relevant design work has been performed. [1] As shown in Ref. 1, the PAL XFEL aims to achieve 3-Å lasing with 3-GeV beam energy. This implies it requires very high-quality beams at the entrance of the undulator. For the 4th generation light source, we are going to add a new 700-MeV linac, with a low-emittance electron gun and two bunch compressors, to the head of the main linac. In this way, we could lessen the modification and shutdown period for the main linac. The successful construction of the new linac and the conversion of the main linac into the 4th generation light source would require its electron source be prepared as soon as possible with required beam qualities. Due to these reasons, we have already started to construct the RF photo-injector system and will test its performance in a dedicated test-stand.

DESIGN CONSIDERATION

In Table 1, we summarize requirements imposed to the injector for the PAL XFEL.

Table 1: Injector requirements for PAL XFEL

Charge	1 nC
Beam Energy	150 MeV
Repetition Rate	30 Hz
Emittance (normalized, rms)	< 1.2 μm rad
Energy Spread (rms)	< 0.1 %

There are two representative schemes for XFEL injectors. One is the LCLS-style injector based on the RF photo-cathode gun and the emittance compensation by the generalized Brillouin flow (Invariant Envelope). Many laboratories are demonstrating the practicability of this scheme. [2][3][4] There is another unique approach at the SCSS (SPring-8 Compact SASE Source) in the SPring-8. The SCSS adopts thermionic DC gun with a single-crystal cathode. The DC Gun is followed by a fast chopper and a standing-wave-type pre-buncher. The DC gun has already demonstrated 1-μm emittance [5] at sufficiently high charge. The success of this scheme seems largely depend on the transverse and longitudinal optics design in the low-energy part from the gun exit to the beginning part of the first accelerating structure.

As the injector for the PAL XFEL, we are going to adopt the RF photo-cathode gun with the IE emittance compensation scheme. The SCSS-style injector will be chosen as a backup option. This is because it does not rely on the laser for generating electrons, and this would make the system inherently stable and reliable.

In order to deduce the basic requirements for the realization of the reliable RF photo-injector system, we briefly mention on the IE emittance compensation.[6] The transverse dynamics of charged-particle beams, with the perveance, κ_s, propagating through the linear focusing channel, K_r, and accelerated at the rate of γ' is described by the following equation,

$$\sigma'' + \sigma'\left(\frac{\gamma'}{\beta^2\gamma}\right) + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\varepsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0 \qquad (1)$$

The rms beam size, σ and derived qualities (e.g., emittance) are damped as the beam is accelerated because of the non-vanishing σ′. This implies that the so-called emittance oscillation is damped and the emittance can be made frozen to a very low value under a certain condition.

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This is achieved by providing proper matching conditions at the accelerator entrance, in both the transverse and the longitudinal planes, given by two equations below,

$$\sigma' = 0 \tag{2}$$

$$\gamma' = \frac{2}{\sigma}\sqrt{\frac{\hat{I}}{2I_0\gamma}} \tag{3}$$

(2) is to require the beam waist be formed at the accelerator entrance, which is commonly done in linear electron beam devices, e.g., klystrons. (3) is a new requirement determining the accelerating gradient of the structure with given beam size, σ and peak current, $\hat{I}$. The constant I_0 in (3) is called the Alfvén current with the numerical value of 17 kA.

Fig. 1 shows normalized emittance evolutions after the RF gun and the emittance-compensating solenoid with and without the downstream acceleration. It is clearly seen that the emittance and the beam size are frozen to a certain value with acceleration (thick lines), which otherwise diverge (thin lines) due to the space-charge repulsion force.

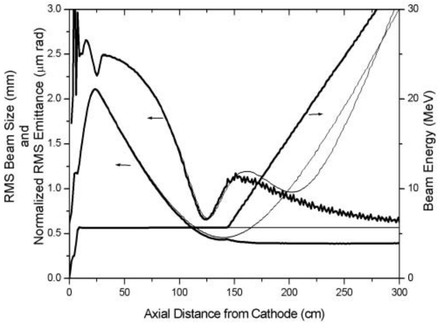

Figure 1: Comparison of beam rms sizes and normalized emittance evolutions with (thick lines) and without (thin lines) acceleration. Accelerator entrance is located at z = 1.5 m. Also shown are beam energy profiles (right scale).

Based on the principle of the IE emittance compensation, we list up practical requirements for the realization of reliable XFEL injectors,

- Low-emittance electron gun (such as the RF gun + high-power laser with profile control capabilities)
- High gradient booster accelerator with good alignment
- Solenoids with low field errors and good alignments
- Low-jitter RF system

Without describing the above requirements in detail, the author presents in Fig. 2 - 5 some results from the PARMELA simulations that have been done for evaluating impacts of operation parameters on the performance of the LCLS-type injector.

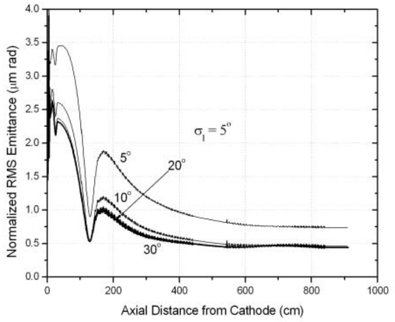

Figure 2: Variation of normalized emittance profiles (along z) with different rms bunch lengths. Bunch shape is Gaussian with cut at +/- 5°. Shown are emittance profiles for different rms bunch lengths. Notice better performance with larger rms length, i.e., more flat bunch shape.

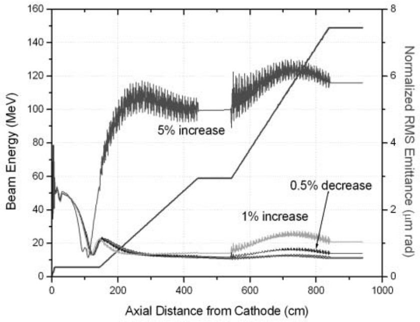

Figure 3: Variation of normalized emittance profiles and beam energies (along z) with different percent deviations of gun solenoid current from the optimum value.

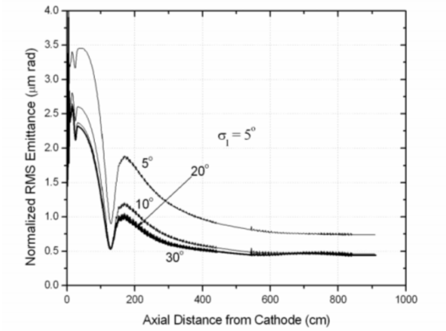

Figure 4: Variation of normalized emittance profiles and beam energies (along z) with different initial phases (w.r.t. rf zero phase)

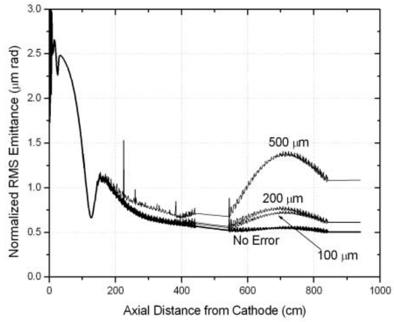

Figure 5: Variation of normalized emittance profiles with different alignment errors in the 1st accelerating column. Errors are input in a cell-by-cell manner and are assumed to be random with peak values as indicated.

FABRICATION OF RF GUN

We are fabricating the 1.6-cell RF photocathode gun (BNL Gun-IV type) for use in the injector test-stand that will be described in the next section. Another gun with similar design will be also fabricated for the femto-second electron diffraction facility [7] that is being established with the collaboration with the Chemistry department in the KAIST (Korea Advanced Institute of Scientist and Technology, Korea) and Dr. Xijie Wang at the BNL. At the PAL, there has been active work on developing high-power klystrons for use in the PLS linac. Recently, we have succeeded to fabricate an 80-MW pulsed klystron and all relevant facilities have been in-house established. [8] This capability would play a vital role in developing high-performance RF photo-injector at the PAL.

Before embarking in the fabrication of the RF gun, we have prepared a cold model to check the tuning property of the gun cavities. See Fig. 6 for its appearance.

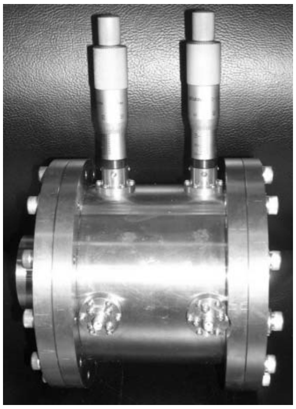

Figure 6: Appearance of cold model of RF gun cavity.

It has two tuners and loop couplers installed at each cell, which allow easy checks of cavity tuning properties. Tuning of each cell for resonating the gun cavity at the π mode with the required frequency (e.g., 2856 MHz) can be done referring to the following equations [9],

$$f_1 = f_\pi\left(1 - \frac{k\sqrt{r}}{2}\right), \quad f_2 = f_\pi\left(1 - \frac{k}{2\sqrt{r}}\right) \tag{2}$$

where, f_1 & f_2 are resonant frequencies of half and full cells,
f_π is the (required) π-mode frequency,
k is the coupling factor between the two cells = mode separation / f_π,
and r is the volume ratio between the two cells (= 1/0.6 = 1.67).

Using $k = 1.16 \times 10^{-3}$, r = 1.67, and f_π=2856 MHz, f_1 = 2853.861 MHz, f_2 = 2854.717 MHz. Dimensions of each cell can be determined from numerical calculation using computer codes such as the SUPERFISH. Specific parameters of each cell are obtained by completely detuning the other cells. Fig. 7 illustrates these procedures. The upper two figures are SUPERFISH calculation for the half (left) and the full (right) cells. After determining independent cell dimensions, those two cells are combined to yield the π-mode resonance at the required frequency, f_π as shown in the lower figure in Fig. 7.

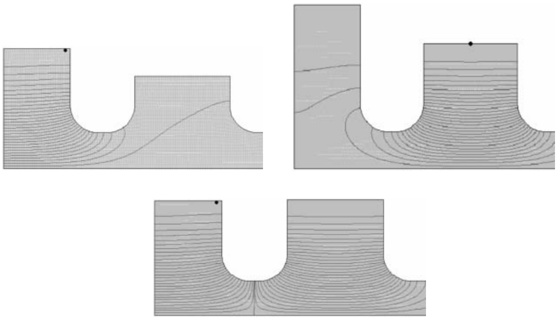

Figure 7: Scheme of determining cell dimensions. Dimensions of each cell are determined by completely detuning the other cells. (Upper figures) When both cells are combined, π-mode resonance occurs at the required frequency, f_π = 2856 MHz. (Lower figure)

Network-analyzer measurement of the two resonant modes in the gun cavity is shown in Fig. 8. With π-mode resonance at the 2856 MHz, the mode separation between the 0- and π-mode was 3.4 MHz. The suppression of the 0-mode is not done because the loop coupler used in this cold model is wide-band.

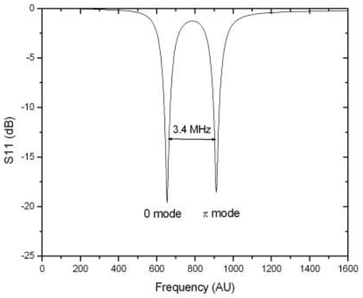

Figure 8: Network-analyzer measurement of the gun cavity cold-model.

Transient response of the gun cavity to pulsed rf power is important because of the mode beating phenomenon. By applying pulsed rf to the full-cell coupler, time-evolution of cavity field was observed at the other coupler in the half cell. In Fig. 9 we show the time-profile of the cavity field together with the input rf waveform. The rippling in the rising part of the cavity-field waveform is believed to be caused by the mode beating. Note the period of the rippling corresponds to the inverse of the mode separation. Since the characteristic time of the standing-wave cavity is proportional to the Q-factor of the cavity, measured transient period shown in Fig. 9 will be different from the real gun that is made of brazed copper. Also notice that the falling part of the cavity-field waveform is a simple exponential decay, which would be the indication of the enough decay of the 0-mode during the rf pulse. The relevance of these observations to the practical aspect of gun operation is that the pulse duration of the rf power input should be long enough to allow the 0-mode to decay sufficiently. Otherwise, the condition of the cell balance will not be met and the beam quality is deteriorated.

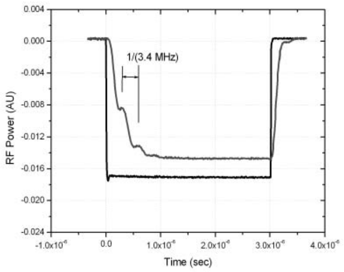

Figure 9: Transient response (upper trace) of gun cavity to pulsed rf input (lower trace).

We will proceed to machine the gun cavity by the use of ultra-precision turning lathe. After brazing, the assembly will be baked with procedures similar to the klystron fabrication. Whole fabrication will be controlled by well-arranged quality-control procedures in order to achieve high performance and reliability.

INJECTOR TEST-STAND

For the early development of the injector for the PAL XFEL, we are going to setup a test-stand that is equipped with a photo-cathode RF gun, an accelerating structure, diagnostic devices, and a rf source system. See Fig. 10 for the layout of the test-stand.

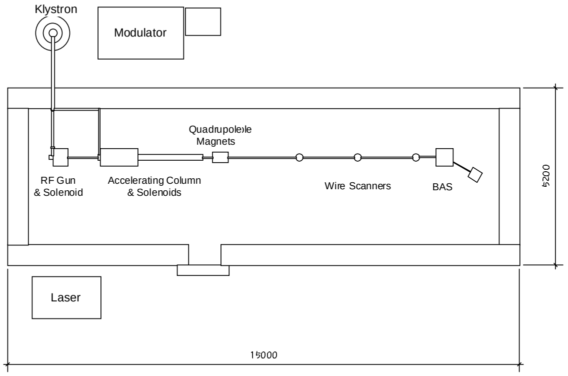

Figure 10: Layout of planned injector test-stand for the PAL XFEL.

We will employ standard diagnostics for measuring the emittance and the energy spread. Devices for measuring slice parameters will be also installed. Compact and movable emittance analyzer would be very useful for optimizing the delicate IE (Invariant-Envelope) emittance compensation.

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