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LINAC DESIGN FOR THE PROPOSED NSRRC THZ/VUV FEL FACILITY

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Abstract

A driver linac based on a photocathode RF gun injector system for a proposed free electron laser facility at National Synchrotron Radiation Research Center (NSRRC) in Taiwan is under study. This facility is designed to be operated in two modes, one for the VUV application and one for the THz application to fulfil the user needs. Generally the VUV radiation prefers a low emittance, high peak current beam free from collective instability during acceleration and magnetic pulse compression, whereas the THz radiation needs a moderate charge in hundred femtosecond bunch length free from space charge degradation in a transport line. In this paper, the schemes of bunch compression as well as the strategy to optimize and control of the beam quality will be presented

INTRODUCTION

To develop the base of FEL research study in Taiwan, a feasibility study of a THz/VUV FEL facility at NSRRC has been carried out [1]. It has been suggested that this machine should allow dual-mode operation for tunable coherent radiations in the VUV range with high gain harmonic generation (HGHG) FEL and in the THz range with coherent undulator radiation (CUR). Hence, a high brightness injector has been proposed to meet these goals. Figure 1 is the layout of the driver linac system.

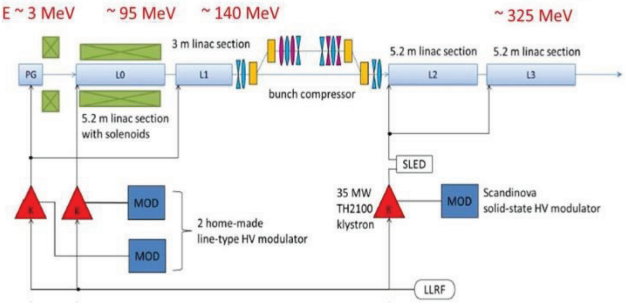

Figure 1: Schematics of the driver linac system for the NSRRC THz/VUV FEL facility.

One unique feature of this linac injector is to employ a magnet compressor with linearization optics to avoid the use of expensive X-band high power microwave system which is not quite available commercially. On the other hand, hundred femtosecond beam at few tens of MeV can be generated via velocity bunching in this linac. The beam is then transferred to the downstream modulator of the VUV HGHG FEL. THz CUR is therefore generated in this undulator without switching on the magnetic compressor. Details of the linac design are discussed as follows.

BUNCH COMPRESSOR WITH LINEARIZATION OPTICS

Velocity bunching and magnetic bunching are two kinds of useful compression scheme for the injector design. Although velocity bunching scheme is more compact in size, magnetic bunching scheme with a chicane compressor is chosen for the VUV Baseline instead because it uses the available accelerations more efficiently. Most importantly, an adjustable optics can be inserted into the magnetic bunch compressor for the compensation of nonlinear terms in the longitudinal phase space. These nonlinear terms come from the high order terms of the rf wave and the high order dispersion of the bunch compressor [2, 3]. It offers a wider flexibility which will be important for envisioned later operations.

Assuming that the centroid energy of the injected electron is E_i and there is no energy chirp for simplicity ($\delta_i = 0$), the energy of the accelerated beam whose centroid is operated at an injection rf phase φ can be expressed as

$$E_f(z) = E_i + eV_0 \cos(\varphi + 2\pi z/\lambda), \qquad (1)$$

where V_0 is the peak accelerating voltage of the rf field, λ is the rf wavelength. The correlated energy spread can then be expressed as

$$\delta(z) = \frac{eV_0 \cos(\varphi + 2\pi z/\lambda)}{E_f} = h_1^b z + h_2^b z^2 + h_3^b z^3 + \ldots, \qquad (2)$$

where

$$\begin{cases} h_1^b = -\dfrac{E_f - E_i}{E_f} k \tan\varphi, \\ h_2^b = -\dfrac{E_f - E_i}{2E_f} k^2, \\ h_3^b = \dfrac{E_f - E_i}{6E_f} k^3 \tan\varphi. \end{cases} \qquad (3)$$

For a general dispersive section, the longitudinal position of an electron is

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$$z_f = z_i + R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \ldots, \qquad (4)$$

where R_{56}, T_{566} and U_{5666} are the 1st, 2nd, and 3rd order of the longitudinal dispersion function respectively. By combining Eq. (2) and Eq. (4), the longitudinal position of an electron can then be expressed as

$$z_f = z_i / C + A_2 z_i^2 + A_3 z_i^3 + \ldots, \qquad (5)$$

where

$$C = 1/\left(1 + h_1^b R_{56}\right) \qquad (6)$$

is the linear compression ratio,

$$A_2 = h_2^b R_{56} + \left(h_1^b\right)^2 T_{566}, \qquad (7)$$

and

$$A_3 = h_3^b R_{56} + 2h_1^b h_2^b T_{566} + \left(h_1^b\right)^3 U_{5666}. \qquad (8)$$

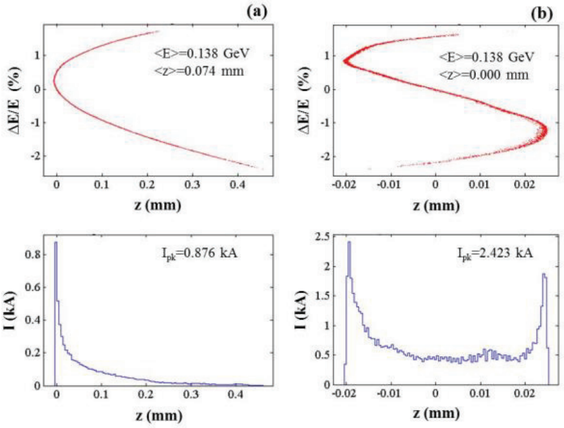

Figure 2: (a) The longitudinal phase space and its current profile after a conventional chicane. (b) The longitudinal phase space and its current profile after a chicane with optics linearization.

For a typical chicane compressor, the first order longitudinal dispersion R_{56} is negative and the second order longitudinal dispersion T_{566} has an opposite sign to R_{56}, hence A_2 is a positive value normally. As shown in Eq. (5), a non-zero A_2 leads to a high order nonlinear term in the longitudinal phase space. This phenomenon limits the compression in bunch length and causes a current spike in the compressed bunch for the typical chicane compressor as shown in Fig. 2 (a). It is well known that the longitudinal dispersion function is the integration of horizontal dispersion function in the bending magnet. As a result, an adjustable longitudinal dispersion function can be made possible by the introduction of quadrupole and sextupole magnets in the compressor. Hence the second order term in the longitudinal phase space can be compensated ($A_2 = 0$) by a chicane compressor if we can set

$$T_{566} = -\frac{h_2^b R_{56}}{\left(h_1^b\right)^2}. \qquad (9)$$

For this case as shown in Fig. 2(b), the compressed bunch can have higher compression ratio and the current distribution is smoother as compared to the conventional one.

BEAM DYNAMICS IN THE INJECTOR

Baseline for VUV HGHG FEL

The injector system is operated at 2998 MHz in S-band and is composed of three sections of 5.2 m linac and one section of 3 m linac. There are three klystrons, three modulators, and one SLED cavity. 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. The whole facility including an experimental area for users tightly fits into the existing 38 m × 5 m long tunnel in the TPS Linac Test Laboratory. The accelerating field is operated at 18 MV/m for the 5.2 m section and 20 MV/m for the 3 m section. For the Baseline operation, this injector operates at 100 pC. The slice emittance of the accelerated beam after L_0 is ~ 0.56 mm-mrad when the gun field is operated at 70 MV/m.

In this injector, a single-stage compressor is adopted to minimize the CSR induced microbunching instability which is generally more severe in the multi-stage compression scheme. However with a single compressor, the shot to shot variation of the electron beam due to the initial jitter lacks the possible compensation scheme which is provided by the second compressor. On the other hand, one should also be careful about the stronger wake field induced by the short electron bunch along the transport line. In this design, the generated beam from the cathode is tracked under the consideration of 3D space charge effects to L_0 exit by GPT [4]. The accelerated beam is then transferred to ELEGANT for particle tracking with the consideration of the CSR induced emittance growth in the compressor, the longitudinal space charge effect and the wake field in the linac [5]. Figure 3 is the optics of the designed bunch compressor in this injector. The evolution of beam energy, sliced beam current, sliced energy spread and sliced emittance are summarized in Table 1.

According to the simulation with the consideration of the space charge effects and wake field, a 325 MeV beam with sliced emittance of 0.8 mm-mrad, sliced energy spread of 1.7 keV and peak current of 500 A is achievable at the linac exit as shown in Fig. 4. In the HGHG operation, expected VUV radiation with brightness of ~ 10^{28} photons/μm^2/0.1% and peak power of 200 MW at 66.5 nm is achieved after ~ 2 m in the radiator. This fully coherent, ultrafast radiation at the extreme VUV region is very useful for the application such as the direct VUV photoionization.

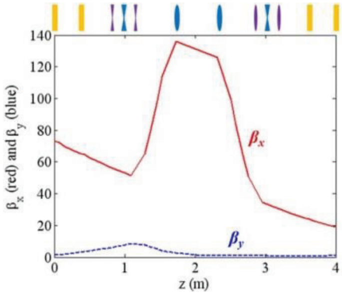

Figure 3: Optics of the bunch compressor with quadrupole (blue) and sextupole (purple) as the optics linearization.

Table 1: Summary of sliced beam characteristics for the VUV Baseline

	$L_{0,\text{entrance}}$	$L_{0,\text{exit}}$	$L_{1,\text{exit}}$	$L_{2,\text{exit}}$	$L_{3,\text{exit}}$
I_p [A]	12.0	11.7	14	500	500
E [MeV]	3.54	93.08	138	231	325
$\Delta E/E$[%]	0.016	0.002	0.001	0.003	0.005
ε_{nx} [μm]	0.59	0.56	0.56	0.74	0.74
ε_{ny} [μm]	0.59	0.56	0.56	0.80	0.80

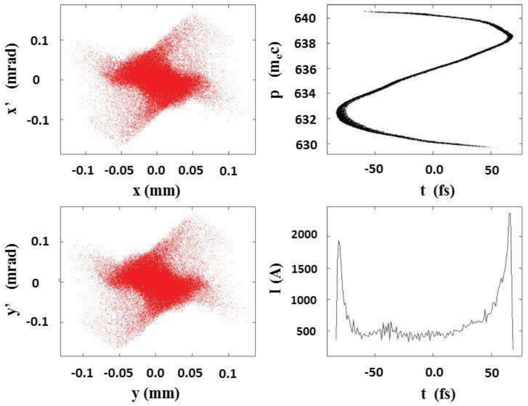

Figure 4: Electron phase space distribution at the exit of the L_3 linac.

Baseline for THz CUR

The linac system can be operated at an alternative mechanism for the generation of CUR at THz region. By turning off the chicane compressor, the first section of 5.2 m linac provides velocity bunching to control the electron distribution in the longitudinal phase space and is considered as the accelerator and compressor. The identical undulator which is served as the energy modulator for the VUV HGHG FEL is used as the THz radiator in this scheme.

An ultrashort electron bunch with beam energy of several tens of MeV is required for the coherent radiation at THz region. The bunch length is preferred to be as short as possible to enhance the form factor. Meanwhile, higher electron charge will be beneficial as the coherent radiation intensity is proportional to the square of electron numbers. Above all, the space charge beam dynamics is severe in this beamline. The effects of wake fields along the beamline had been studied and were considered to be negligible. Under careful control of space charge beam dynamics from the start to the end, a compressed electron bunch with charge of 100 pC, bunch length of ~ 100 fs at energy of ~ 27 MeV can be achieved. Synchrotron radiation radiated by this quasi-relativistic ultrashort electron bunch as shown in Fig. 5 can be coherently enhanced at THz frequency region by a sufficient form factor. The expected peak power of THz radiation from this Baseline is 0.7 MW at 4.5 THz. Furthermore, adjustable polarization of the THz radiation is possible by changing the polarization of the undulator. This property offers the user with more potential for additional interesting applications.

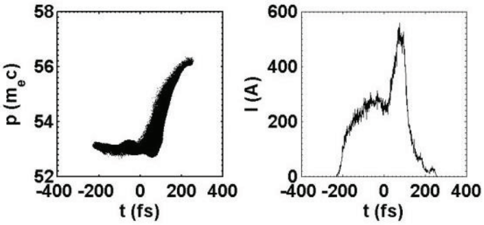

Figure 5: Longitudinal phase space and current profile of electron distribution at the exit of the L_3 linac.

CONCLUSION

An injector design for the high brightness electron beam has been studied by the electron tracking simulation from the start to the end. In order to compensate the nonlinear term of electron distribution in the longitudinal phase space, a set of linearization optics by introducing quadrupole and sextupole magnets has been adopted in this chicane compressor. On the other hand, the compressed beam at several tens of MeV can also be achieved by the velocity bunching in this injector. This high brightness electron beam will serve for the dual function of VUV HGHG FEL and THz CUR. The installation of this injector system is in progress. This Baseline offers the flexibility for future R&D extensions and will make the foundation of FEL researchers in Taiwan.

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