DESIGN STUDY OF INJECTOR SYSTEM USING RF ELECTRON GUN WITH GRIDDED THERMIONIC CATHODE TOWARDS SOFT X-RAY FREE-ELECTRON LASER*

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Abstract

The high-brightness synchrotron radiation facility NanoTerasu provides users with extremely stable synchrotron radiation by employing top-up injection of an electron beam from a 3-GeV linear accelerator into a diffraction-limited storage ring. NanoTerasu plans to develop a soft X-ray free-electron laser (SX-FEL) using this linear accelerator. To achieve an SX-FEL with a practical gain length, the linear accelerator must generate an electron beam with a peak current of 2.5 kA and a normalized emittance of 2 mm mrad or less. We have already developed a low-emittance electron gun system based on a gridded thermionic cathode and have begun designing a low-emittance pre-injector using this system. The linear accelerator based on the electron gun system is planned to serve both as the injector for the storage ring and as the driver for the SX-FEL. This presentation describes the configuration of a compact SX-FEL linear accelerator that can be installed within existing facilities. It also presents a bunch compression scheme that preserves slice emittance, together with particle tracking simulation results for the newly designed pre-injector.

INTRODUCTION

The high-brightness synchrotron radiation facility NanoTerasu employs a 3 GeV low-emittance storage ring based on a multi-bend achromat (MBA) lattice [1]. Synchrotron radiation generated by undulators achieves a brilliance exceeding 10^{21} photons/s/mm²/mrad²/0.1% b.w. in the soft X-ray to tender X-ray region, with a coherence ratio of approximately 10% [2]. A 3 GeV electron beam with an emittance of 2 nm rad and a bunch charge of 0.36 nC, generated by a 3 GeV linear accelerator, is injected into the storage ring through an 80 m-long beam transport line. The linear accelerator has a total length of 110 m and consists of a 40-MeV pre-injector equipped with a low-emittance electron gun system and a high-gradient C-band accelerator [3].

One of NanoTerasu's future plans is to repurpose the linear accelerator currently used as the injector for the 3 GeV storage ring as the drive system for a soft X-ray free-electron laser (SX-FEL). The required beam performance for the SX-FEL includes a beam energy of 2.5 GeV, an energy spread of 0.01% or less, a peak beam current of 2.5 kA or higher, and a normalized emittance of 1.5 mm mrad or less. To generate such a high-density electron beam, a low-emittance pre-injector and two magnetic bunch compression systems are essential.

CONFIGURATION OF LINEAR ACCELERATOR FOR SX-FEL

Table 1 summarizes the radiation and beam parameters for the SX-FEL, and Fig. 1 shows the layout of the NanoTerasu accelerator complex**.** The SX-FEL undulator section and the experimental hall are planned to be located downstream of the 3-GeV linear accelerator. A magnetic chicane for beam energy filter is installed between the exit of the linear accelerator and the undulator section. Downstream of the undulator section, a beam diagnostic system capable of measuring the bunch length and beam charge is installed to evaluate the peak beam current. The 2.5 GeV electron beam is then guided to a bending magnet and finally to the beam dump.

Table 1: Radiation and Beam Parameters for SX-FEL

Parameter	**Value**
Wavelength	1.2 nm
Beam energy	2.5 GeV
Energy spread	0.01 %
Normalized emittance	< 2 mm mrad
Beam charge	0.3 nC
Peak beam current	2.5 kA
Bunch length	< 80 fs
Repetition rate	> 10 pps
Saturation length	25 m
Peak power	2 GW

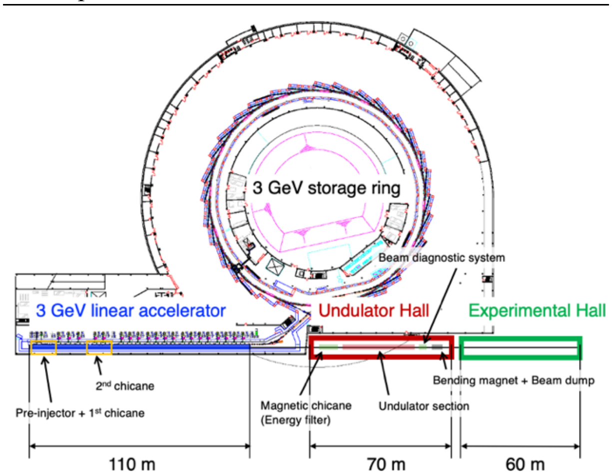

Figure 1: Layout of NanoTerasu accelerator complex, which consist of 3 GeV linear accelerator, 80 m long beam transport line and 3-GeV storage ring. Experimental hall and undulator hall of SX-FEL site is placed after the 3-GeV linear accelerator building.

SCHEMATIC OF BUNCH COMPRESSION

The three-stage bunch compression scheme for achieving a beam peak current of 2.5 kA or higher is as follows. In the first stage, bunch compression is applied to the electron beam emitted from the electron gun system. An electron beam with a pulse width of 300 ps and an energy of 500 keV is longitudinally compressed by applying velocity modulation. After the beam energy is increased to 25 MeV while applying an energy chirp, magnetic bunch compression is performed using a magnetic chicane. The bunched beam is then further accelerated to a central energy of 400 MeV, and an additional energy chirp is applied. Final bunch compression is achieved as the beam passes through the second magnetic chicane section.

Throughout these three stages of the bunch compression process, excessive bunch compression must be avoided in order to suppress emittance degradation caused by space-charge effects, which depend on the increase in charge density within the bunch. In each bunch compression stage, emittance growth can be suppressed by selecting an appropriate bunch length that takes the relativistic γ factor (beam energy) into account.

In general, assuming a cylindrical beam, the transverse force within the beam due to space-charge effects is inversely proportional to γ^2, as shown in Eq. (1). Therefore, when bunch compression is performed at sufficiently high beam energy, emittance growth caused by space-charge effects can be avoided. Table 2 summarizes the target bunch length, peak beam current, $1/\gamma^2$, as functions of the beam energy.

$$\gamma m_0 \frac{d^2r}{dt^2} = 2\pi e \frac{\rho_0}{\gamma^2}\, r \tag{1}$$

where m_0 is the electron rest mass, r is the beam radius and ρ_0 is charge density. Table 2 summarizes the beam parameters determined by considering the above requirements in the bunch compression process.

Table 2: Target Peak Beam Current, Target Bunch Length and $1/\gamma^2$, as Function of Beam Energy

	Energy	**Bunch length**	**Peak current**	**$1/\gamma^2$**
E-gun	50 keV	300 ps	2 A	8.3e-1
Pre-inj.	1 MeV	50 ps	20 A	3.9e-1
BC 1	25 MeV	500 fs	500 A	2.8e-4
BC 2	400 MeV	80 fs	2500 A	1.6e-6

25-MEV PRE-INJECTOR

Table 3 summarizes the beam performance required for the SX-FEL at the 25-MeV pre-injector. Figure 2 shows the 25-MeV pre-injector and first magnetic chicane. Low-emittance electron gun system with the gridded thermionic cathode has already been developed and are used currently in existing pre-injector [4]. The 500 keV beam emitted from the electron gun system can produce a normalized emittance of 1.7 mm mrad / 0.6 nC. The electron gun system is also used in the 25-MeV pre-injector.

Table 3: Beam Parameter of 25-MeV Pre-Injector

Parameter	**Value**
Beam energy / Energy spread	25 MeV / 11 %
Normalized emittance	< 2 mm mrad (slice)
Beam charge / Peak current	0.4 nC / 20 A
Bunch length	50 ps

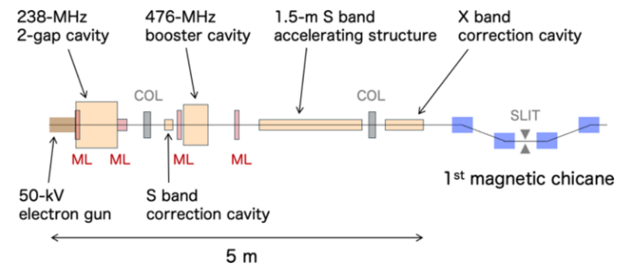

Figure 2: Layout of 25-MeV pre-injector and 1st magnetic chicane. The symbols ML and COL represent a magnetic lens and a beam collimator.

In the first bunching process after the electron gun system, the bunch compression ratio achieved by velocity modulation using a 238-MHz sub-harmonic buncher is reduced to avoid emittance growth. In addition, an S-band single-cell correction cavity, functioning as a nonlinear correction cavity, is installed to maintain the uniformity of the longitudinal charge distribution during the bunching process. The correction cavity is located downstream of the 238 MHz sub-harmonic buncher. To ensure proper completion of the velocity-modulated bunching, the beam energy is increased to approximately 0.9 MeV using a 476-MHz booster accelerating cavity.

The next stage of bunch compression employs magnetic chicanes installed at two locations: downstream of the 25-MeV pre-injector and in the 400 MeV section. In this magnetic bunch compression process, nonlinearity correction is also essential. An energy chirp is formed along the longitudinal direction of the electron bunch by applying off-crest RF phase in each accelerating section, and the bunch subsequently passes through the magnetic chicane. The energy chirp within the bunch is introduced by the off-crest RF acceleration in the accelerating sections, which inevitably imparts energy nonlinearity caused by RF curvature to the bunch. In addition, ideal bunch compression cannot be achieved solely with a magnetic chicane because of geometric aberrations inherent in the chicane optics. To compensate for these nonlinear effects, an X band correction cavity is installed downstream of the S-band accelerating structure in the 25-MeV pre-injector. This correction cavity compensates for the longitudinal energy nonlinearity of the electron bunch, thereby enabling an approximately linear bunch compression process in the magnetic chicane.

Beam transport from the electron gun system to the entrance of the S-band accelerating structure employs four magnetic lenses to suppress transverse beam divergence. Each magnetic lens generates a localized converging magnetic field, thereby avoiding interference from the electromagnetic fields of adjacent RF cavities.

PARTICLE TRACKING SIMULATION

In the design of the 25-MeV pre-injector, the beam performance was evaluated using the particle-tracking simulation code PARMELA. Figure 3 shows the simulation results, including the normalized slice emittance and beam current profiles at various positions from the 50 kV electron gun to the exit of the 1st magnetic chicane. As the initial particle distribution, we used the results of a CST simulation.

The particle distribution of the beam emitted from the electron gun has a beam current of 2 A and a normalized slice emittance of 1 mm mrad with a 300 ps pulse width. The beam emitted from the electron gun passes through a 238-MHz cavity with two gaps. In the first gap, the low-emittance beam from the electron gun is accelerated up to 430 keV. Increasing the beam energy suppress emittance growth caused by space-charge effects, as shown in Fig. 3(a) and (b). In the second gap, the 430 keV beam undergoes velocity modulation, resulting in the formation of an energy chirp with a central energy of 320 keV. The core part of beam with energy chirp is linearized in the S-band correction cavity, as shown in Fig. (c) and (d). To achieve the target bunch length while avoiding over-bunching, the beam energy is increased to 0.9 MeV using a 476-MHz booster cavity, which slows the progression of velocity-modulated bunching.

The beam energy is then further increased using the S-band accelerating structure. At the same time, to introduce an energy chirp in which the head of the bunch has lower energy, the RF phase of the S-band accelerating structure is set to 30 degrees off crest. A spatial collimator, located downstream of the S-band accelerating structure, is used to remove the beam halo by extracting the beam core. The extracted beam has a central energy of 25 MeV and a bunch length of 20 ps (FWHM).

A magnetic chicane with an R_{56} of 23.8 mm is installed downstream of the 25-MeV pre-injector. To achieve linear bunch length compression in the magnetic chicane, an X band correction cavity is installed between the S-band accelerating structure and the magnetic chicane. Figure 3 (e), (f) show the particle distribution of the bunch at exit of X band correction cavity.

After passing through the magnetic chicane, the energy-chirped beam is compressed to a bunch length of 300 fs (FWHM). As a result, a beam current of 550 A or more is achieved while maintaining a normalized slice emittance of 1 mm mrad, as shown in Fig. 3 (g) and (h).

In addition, since the energy slit is located at the dispersive point of the magnetic chicane, the core part of the beam can be selectively extracted.

SUMMARY

In the SX-FEL planned at NanoTerasu, an undulator section with an effective length of 25 m will be located downstream of the 3 GeV linear accelerator. The SX-FEL requires a peak beam current of 2.5 kA or higher, a normalized emittance of 1.5 mm mrad or less, and an energy spread of 0.01%. To achieve these beam parameters, we are investigating a velocity-modulated bunching scheme combined with magnetic-chicane-based bunch compression. During this bunching process, it is crucial to maintain a uniform longitudinal electron distribution by employing a nonlinearity correction cavity, to prevent emittance growth. Particle-tracking simulations using PARMELA for the 25-MeV pre-injector and first magnetic compressor confirm that a high-density bunched beam can be generated. The total length of the 25-MeV pre-injector assumed in the simulations is within 5 m, indicating that it can be accommodated within the same space as the existing injector.

We plan to perform particle tracking simulations for the 2nd magnetic bunch compression stage, as well as beam optics optimization for the accelerating section and undulator section, and subsequently use the resulting high density particle distribution to simulate SX-FEL lasing.

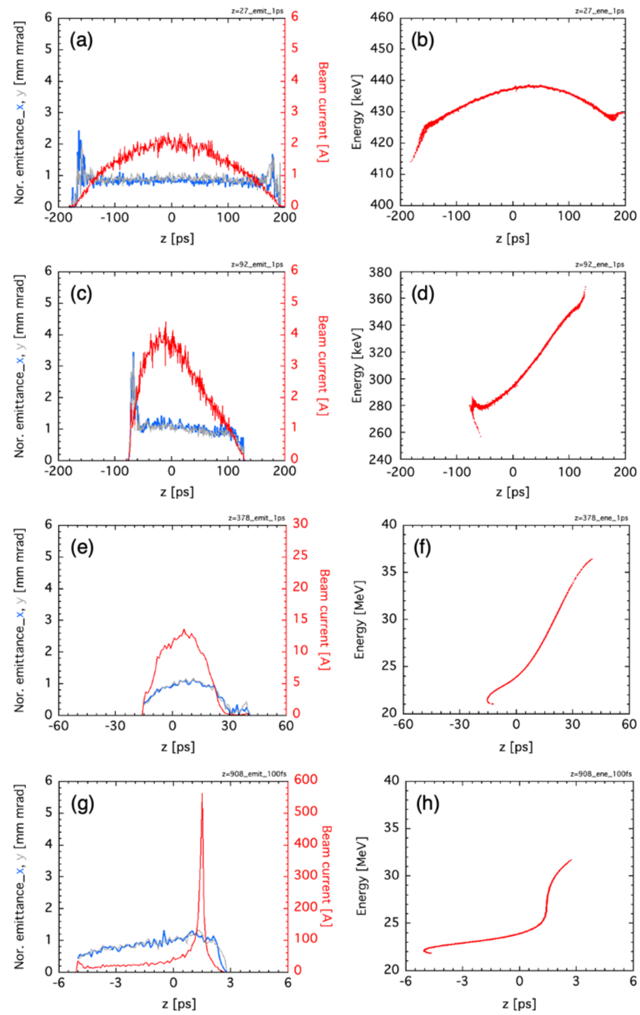

Figure 3: Normalized slice emittance, peak beam current and energy profile as a function of the longitudinal bunch position (time) at (a, b) the exit of 1st gap in 238-MHz cavity, (c, d) the exit of S-band correction cavity, and before (e, f) and after (g, h) the magnetic chicane with energy slit. The left side corresponds to the bunch head.

REFERENCES

[1] S. Obara *et al.*, “Commissioning of a compact multibend achromat lattice NanoTerasu: A new 3 GeV synchrotron radiation facility,” *Phys. Rev. Accel. Beams*, vol. 28, no. 2, Feb. 2025.
doi:10.1103/physrevaccelbeams.28.020701

[2] N. Nishimori, T. Asaka, K. Ueshima, Y. Hosaka, S. Obara, and K. Kan, “Commissioning and user operation of NanoTerasu accelerator system,” Journal of Physics: Conference Series, vol. 3010, no. 1, p. 012011, May 2025. doi:10.1088/1742-6596/3010/1/012011

[3] T. Asaka *et al*., “Basic design of 3-GeV linear accelerator for a next-generation SR source”, in Proc. of the 16th Annual Meeting of Particle Accelerator Society of Japan, Kyoto, July 31 - Aug. 3, 2019, pp.771-775.

[4] T. Asaka *et al.*, “Low-emittance radio-frequency electron gun using a gridded thermionic cathode,” *Phys. Rev. Accel. Beams*, vol. 23, no. 6, Jun. 2020.
doi:10.1103/physrevaccelbeams.23.063401