INJECTOR SYSTEM FOR X-RAY FEL AT SPring-8

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Abstract

The SPring-8 X-FEL based on the SASE process has been developed to generate X-rays of 0.1 nm. The design goals of the slice beam emittance and peak current at the end of the linac are 1 π mm mrad and 3 kA, respectively. The injector of the linac generates an electron beam of 1 nC, accelerates it up to 30 MeV, and compresses its bunch length down to 20 ps. We adopted the following keys to toward the goals: 1) A 500 kV thermionic gun (CeB_6) without a control grid ejecting a beam holding the low rms emittance of 0.6 π mm mrad, 2) a beam deflector downstream gating the beam to form a bunch of a 1 ns length, 3) multi-stage RF structures (238, 476 and 1428 MHz) bunching and accelerating the beam gradually to maintain the initial emittance, and 4) extra RF cavities of 1428 and 5712 MHz linearizing the energy chirp of the beam bunch to achieve the bunch compression resulting the required peak current.

INTRODUCTION

Early in 2007, the construction of the SPring-8 XFEL started [1] aiming at generation of 0.1 nm X-rays by the combination of an 8 GeV high gradient linac (400 m) and a mini-gap undulator of in-vacuum type (90 m).

The most remarkable feature of the SPring-8 XFEL is that a thermionic gun will be employed, while most of the SASE-based FELs have utilized RF guns which have been believed being the most promising. The reason of choosing thermionic gun is as follows: A carefully designed therminonic gun can generate a solid cylindrical beam pulse holding uniform charge densities without the nonlinear space charge effect, therefore the initial beam emittance can be as low as the thermal emittance [2].

The above concept has been proved being right by the success of the SCSS test accelerator [3] which achieved SASE at wavelength of about 50 nm in June 20th, 2006. The SCSS test accelerator is now tentatively providing EUV laser pulses to leading-edge researchers.

The present performance of the SCSS test accelerator is as follows [4]: The shortest wave length is 50 nm and its intensity fluctuation is about 10% rms. The normalized slice emittance of the bunch's core is estimated to be 0.7 π mm mrad and the peak current is ~350 A.

The targeted beam performance of the XFEL linac to realize lasing in the undulator section is the followings:

Beam energy: 8 GeV
Peak current: > 3 kA
Normalized emittance: < 1 π mm mrad

We have designed the SPring-8 XFEL based on the experience of the SCSS test accelerator, however, the velocity bunching ratio is designed to be about 1/5 of that of the SCSS (~100) to suppress the emittance growth as low as possible. Thus we will introduce two L-band APS structures instead of the SCSS's S-band structures. In addition, extra RF cavities of 1428 and 5712 MHz will be installed to linearize the bunch compression process to enhance the compression factor.

BEAM PARAMETER DESIGN [3,5]

Our present principle of the injector design is mainly focused on minimizing the emittance growth as follows:

- Generating a solid cylindrical beam pulse holding uniform charge densities by a CeB_6 single crystal cathode without a control grid.
- Optimizing the multi-stage velocity bunching system to minimize the emittance growth caused by the space charge effect.

Design of beam bunching

In order to realize the bunch compression ratio of 3000 (1 A to 3 kA) with the minimum emittance growth caused by the space charge effect or the coherent synchrotron radiation, we have optimized the bunch compression by distributing several bunching sections in the linac.

In the low energy region below 10 MeV, the velocity bunching by three-stage accelerating cavities are designed to compress electron bunches to 1/20 in length as presented in Fig. 1. In the upper energy region, three magnetic chicanes in the main accelerating section will compress them and enhances the peak current finally up to 3 kA as shown in Fig. 2 and 3. Optimum electric field strengths are listed in Table 1.

In order to enhance the bunching efficiency and avoid the over bunching, we will introduce two sets of harmonic RF cavities as illustrated in Fig. 1. The RF cavity of 1428 MHz will be installed downstream of the booster and linearize the velocity bunching process. The short travelling wave structure of 5712 MHz downstream of the L-band accelerating structures will compensate the nonlinearity of the bunch compression process at the three-stage magnetic bunch compressor downstream.

Table 1: Optimum electric field strengths in the RF structures and their shunt impedances.

RF Cavity	Gradient/Voltage	Shunt Impedance
238 MHz	198 kV	10.2 MΩ
476 MHz	801 kV	8.5 MΩ
L-Correction	138 kV	9.6 MΩ × 2
L-APS	13.9 MV/m	> 30 MΩ/m
C-Correction	12 MV/m	> 47 MΩ/m

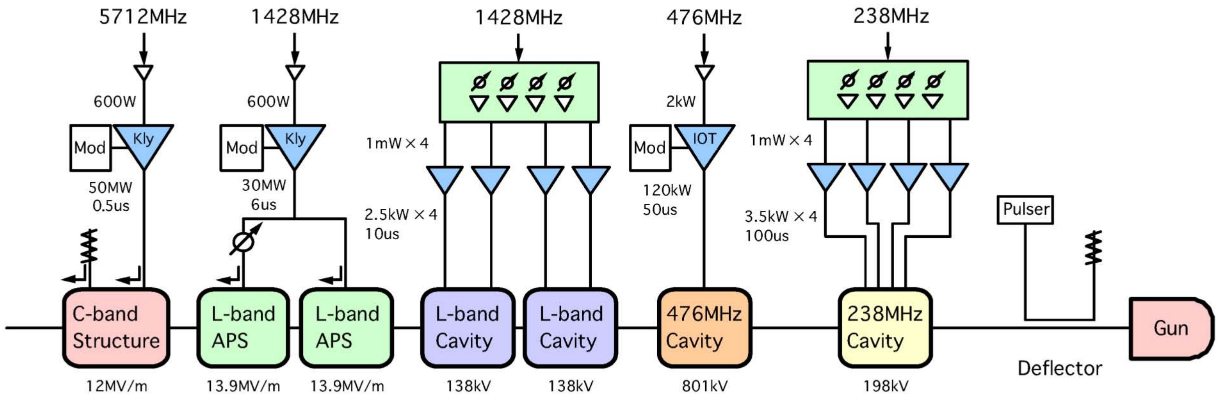

Figure 1: Block diagram of the injector's RF system.

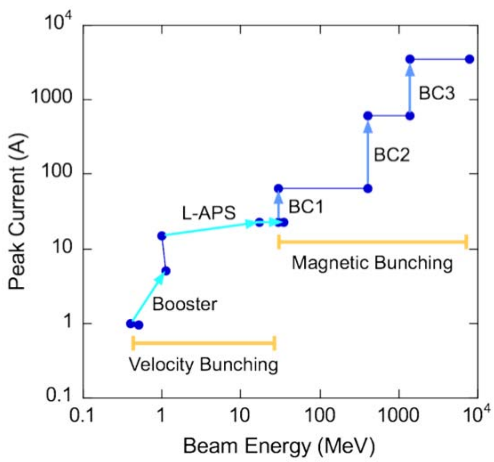

Figure 2: Scheme of bunch compression.

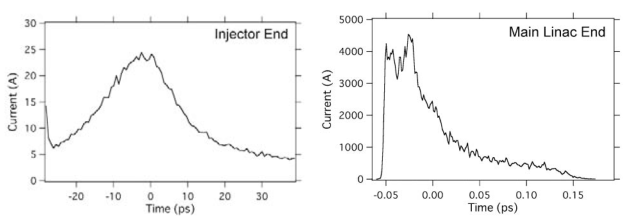

Figure 3: Simulated bunch charge distributions at the end of the injector (left) and main linac (right).

Design of Beam Optics

The injector will be equipped with pancake-shape solenoids as beam focusing magnets as well as the SCSS test accelerator (See Fig. 4). Since they will be discretely mounted in the injector to separate the two functions – acceleration and focusing, beam tuning of the linac will be greatly facilitated as we have seen in the beam tuning of the SCSS linac. The focusing system will be carefully adjusted to maintain a diameter of the beam bunch as constant as possible during bunching because the over focusing may cause the emittance growth due to the nonlinear space charge effect.

In addition, two circular collimators will be installed to shape up the beam.

Beam Stability

Because even slight beam instability in an injector part of SASE FEL results unstable laser oscillation in an undulator section, an RF system for SASE FEL has to be very carefully designed to minimize its instability in amplitude and phase. We are thus estimating acceptable instabilities of linac devises by means of a hand-made 1D beam simulation code. Table 2 shows tentative tolerance of linac devices which permit 10% variation (rms) of the peak beam current.

For example, the tolerance of the electron gun voltage variation was estimated being only 0.003% rms, intensive development of the inverter power supply for modulators consequently realized the variation of ~0.001% rms.

Table 2: tentative tolerance of linac devices

Devise	ΔV/V (% rms)	Δϕ (deg. rms)
Electron gun	0.003	
238 MHz SHB	0.01	0.01
476 MHz booster	0.01	0.02
L-band correction	0.03	0.06
L-band APS	0.01	0.06
C-band correction	0.1	0.1

ELECTRON GUN [2]

The electron gun will be the almost same as that has been used for the SCSS test accelerator. The electron gun will be mounted on the gun tank filled with insulator oil as shown in Fig. 4. The beam design parameters are summarized in Table 3.

Table 3: Gun design parameters

Beam energy	500 keV
Peak current	1 – 3 A
Pulse width	1.6 μs
Repetition rate	60 pps
Normalized emittance	0.4 π mm mrad

Cathode

The initial emittance of an electron gun is dominated by its cathode size. We employed a single-crystal CeB_6 cathode with a 3 mm diameter. The theoretical thermal emittance is 0.4 π mm mrad at ~1400°C. A high beam

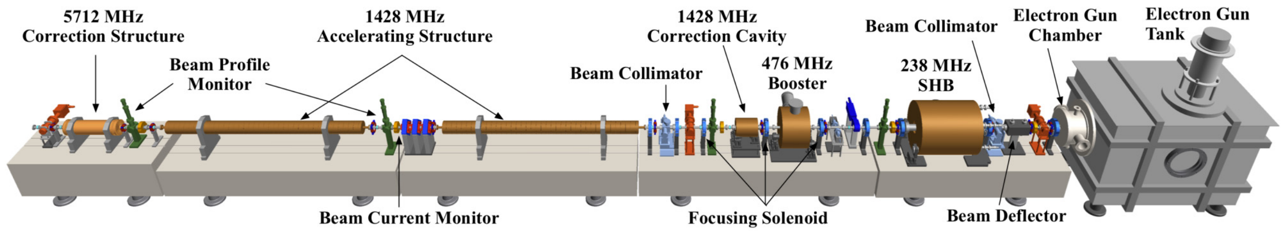

Figure 4: 3D illustration of the injector section.

current of ≥ 1 A can be produced from the CeB_6 crystal at this temperature without jeopardizing its long lifetime.

A graphite heater is used instead of a conventional metallic filament because graphite is mechanically and chemically stable even at very high temperature and does not evaporate like other metals [6].

Beam deflector [3]

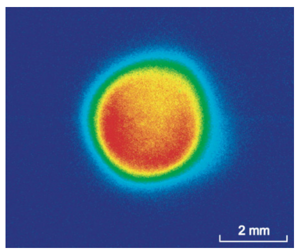

Figure 5: Beam profile at downstream of deflector.

The emittance of a traditional themionic cathode gun is degraded by the electric field distortion caused by a grid mesh, we therefore eliminate a control grid. Instead of a control grid, a beam deflector will gate the long-pulsed beam from the cathode to form a 1 ns beam.

The beam deflector is composed of a set of parallel plates and an electric dipole magnet excited always. A fast gate pulse applied to the deflector electrodes excites a pulsed electric field cancelling the DC magnetic field, resulting a gated beam pulse of a 1 ns width.

Figure 4 is a hard edge beam profile observed at a screen monitor downstream of the deflector.

MULTI-STAGE BUNCHING SYSTEM

SHB & Booster

The 238 MHz SHB gives the energy modulation to the initial beam. The beam bunch passing the 1.6 m beam transport line holds the compressed charge density distribution because of the velocity bunching as shown in Fig. 2. The cavity is equipped with four input couplers and four solid-state amplifiers feed RF powers of 3.5 kW to each coupler as illustrated in Fig. 1.

The 476 MHz booster cavity accelerates the beam up to 1.1 MeV to avoid the space charge effect. The cavity is driven by an IOT (Eimac CHK2800W) which can generate the maximum power of 120 kW.

L-band Accelerating Structure

The 1 MeV beam will be accelerated up to 35 MeV by two L-band structures of APS (Alternative Periodic Structure) type (Fig. 6). The structure will have 18 accelerating cells and a coupler cell.

An L-band (1428 MHz) klystron will generate an RF power of 20MW and the power will be divided to both structures via a directional coupler (Fig. 1). A vacuum type waveguide circuit will be installed not to use insulation gases such as SF_6, a circulator will not be available. Therefore the circuit has to be carefully designed to cancel the reflected powers from the APS's couplers not to damage the klystron.

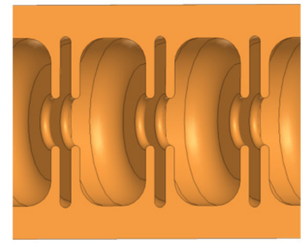

Figure 6: Model of L-band APS structure

The most important advantage of APS type comparing to a normal travelling wave structure are as follows: An APS type has an RF coupler, which results the field asymmetry, at around the center of accelerating structure, not at the entrance cell like a travelling wave type. Thus low energy beams just entering the structure do not get the emittance growth due to the field asymmetry and are accelerated up to the sufficient energy at around the coupler cell.

Correction Cavities

The L-band correction cavity is twin pill-box cavity which has nose corns to enhance the shunt impedance. This cavity will be driven by four solid-state amplifiers as presented in Fig. 1.

The C-band correction cavity is actually a short version (26 cells, $3\pi/4$ mode) of the C-band traveling wave structure, the choke mode cavity type, used in the main accelerator section. However, the structure is the constant impedance type to ease its fabrication. A 50 MW C-band klystron will drive the structure as shown in Fig. 1.

REFERENCES

[1] T. Shintake, "Status of X-ray FEL/SPring-8 Machine Construction", in these proceedings.

[2] K. Togawa et al., "CeB_6 electron gun for low-emittance injector", PR STAB, 10, 020703 (2007).

[3] H. Tanaka et al., "Low Emittance Injector at SCSS", Proc. of FEL 2006, Berlin, pp. 769-776 (2006).

[4] H. Tanaka et al., "Operation Status of the SCSS Test Accelerator: Continuous Saturation of SASE FEL at the Wavelength Range from ~50 to 60 nm", in these proceedings.

[5] T. Hara et al., "Beam Parameters of the SCSS Prototype Accelerator Designed by PARMELA and Comparison with Measured Values", Proc. of APAC 2007, Indore, pp. 169-171 (2007).

[6] K. Togawa et al., "Graphite Heater Optimized for a Low-emittance CeB_6 Cathode", Proc. of PAC 2007, Albuquerque, p1013-1015 (2007).