

CONSTRUCTION OF INJECTOR SYSTEM FOR SPring-8 X-FEL

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Abstract

The installation of the XFEL injector system has been almost completed except for a few components. The completed thermionic electron gun has achieved generation of 500 keV beams of a 1 A peak current. The completed RF cavities satisfy the required performance. All the devices of the injector except for the gun tank are mounted on six precise stone tables and the RF cavities were aligned with the position errors less than 50 μm . The short-term RF variations observed in the completed RF sources almost satisfy the requirement. The long term phase variations larger than the tolerances will be reduced by feedback control. The L-band accelerating structures are APS type and have been manufactured very precisely not to cause the emittance growth. The L-band waveguide system employs a vacuum type without a circulator and thus it was carefully designed and fabricated to minimize RF reflections to a klystron for its stable operation. This design and the accuracy of the waveguide components were verified to satisfy the requirement of VSWR<1.2.

INTRODUCTION

Early in 2007, the construction of the SPring-8 XFEL started aiming at generation of 0.1 nm X-rays, and will be completed by the end of this year [1]. The installation of the injector started from the middle of May and was almost completed at the end of July except for a few components.

The most remarkable feature of the SPring-8 XFEL is employment of a thermionic gun. This carefully designed thermionic 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]. A thermionic gun injector, however, requires stepwise bunching of an electron beam by means of complex multistage RF cavities not to degrade an initial emittance.

The injector design is 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 introduced 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.

The acceptable instabilities of the RF voltages in the gun and the cavities, which permit 10% rms variation of the peak beam current, are only about 0.01% rms in

amplitude and 120 fs rms in phase according to beam simulation. The long-term RF variations can be compensated by feedback control of the RF amplitude and phase, the short-term or pulse-to-pulse variations, however, have to be reduced as much as possible by improving RF equipment such as amplifiers. Thus we have carefully designed and manufactured the RF cavities, amplifiers and control systems, giving the highest priority to the stabilization of the short-term variations.

ASSEMBLY OF INJECTOR [3]

Electron Gun System

We employed a single-crystal CeB6 cathode with a 3 mm diameter. The theoretical thermal emittance is 0.4 π mm mrad at $\sim 1400^\circ\text{C}$. A graphite heater is used instead of a conventional metallic filament. The cathode is not equipped with a control grid not to degrade the initial emittance.

The electron gun is mounted on a gun tank filled with insulator oil (see Fig. 1). The gun tank is equipped with a pulse transformer and a 500 kV diode tube working as a high-power dummy load for the transformer.

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 canceling the DC magnetic field, resulting a gated beam pulse of a 1 ns width.

The completed electron gun was examined for its high voltage performance at a test bench before the installation in the tunnel. We have achieved generation of 500 keV electron beams of a 1 A peak current. The beam emittance could not be directly known at the test bench, but it will

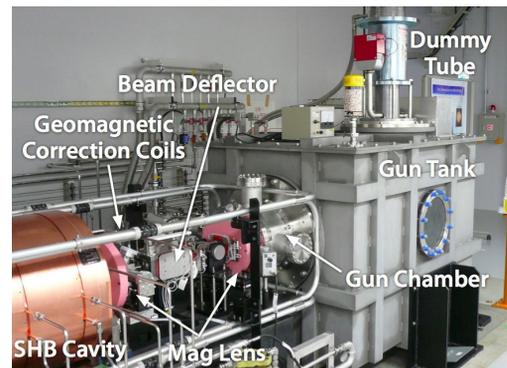


Figure 1: Electron gun system installed in the tunnel.

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Table 1: Achieved Parameters of the RF Cavities and their RF Sources

| | SHB | Booster | L-correction | L-APS | C-correction |
|---------------------------------|---------------------|---------------------|---------------------|-------------------|----------------------------|
| Cavity type | reentrant single | reentrant single | reentrant tandem | APS (19 cells) | traveling wave $3\pi/4$ |
| Frequency [MHz] | 238.000* | 476.000* | 1428.000* | 1428.00 | 5712.02 |
| Unloaded Q | 15,326 | 26,082 | 20,156/20,388 | 24,300 | 10582 |
| β | 1.56 | 1.66 | 3.02/3.03 | 1.45 | – |
| Shunt impedance [$M\Omega/m$] | 11.6 | 26 | 58.0/56.1 | 32.8 | 52.4 |
| Effective length [m] | 0.51 | 0.3 | 0.115/cavity | 2.08 | 0.416 |
| $\Delta f/\text{temp}$ [kHz/K] | -4 | -8 | -24 | -24 | -97 |
| RF source type | solid-state | IOT | solid-state | klystron | klystron |
| RF power | 3.5 kW \times 4 | 120 kW | 2.5 kW \times 4 | 30 MW | 50 MW |

* tunable

be verified during the beam commissioning period in comparison with the emittance values measured at the SCSS test accelerator's injector.

RF Cavities & RF Sources

The 238 MHz SHB provides the energy modulation to the initial beam so as to compress the charge density due to the velocity bunching. The 476 MHz booster cavity accelerates the beam up to 1.1 MeV to avoid the space charge effect. The L-band APS accelerating structures accelerates the beam up to 35 MeV. A few cells of the primary APS contribute the velocity bunching.

In order to enhance the bunching efficiency and avoid the over bunching, we have introduced two sets of harmonic RF cavities: The L-band tandem pill-box cavity and the short C-band traveling wave structure were installed downstream of the booster and downstream of the L-band accelerating structures, respectively.

Almost all the RF cavities were installed in the tunnel, however, the second APS cavity will be installed in December 2010.

Achieved parameters of all the RF cavities and RF sources are presented in Table 1.

Installation and Alignment

All the devices of the injector except for the gun tank are mounted on six precise stone tables made of gabbro. The upper surfaces of the tables were perfected to result the flatness of $< 13 \mu\text{m}$. Every table has two T-slot tracks to precisely position devices. The tables are also equipped with air pads which levitate the body to ease its positioning.

Every table was positioned referring to an alignment laser target on a monument in the tunnel so as to precisely align with the horizontal, vertical and longitudinal position errors less than $50 \mu\text{m}$.

Every RF cavity was also aligned referring to the laser target with the position errors less than $50 \mu\text{m}$. All the electric magnets and profile monitors were horizontally positioned by the T-slot tracks.

The gun tank was directly settled on the tunnel floor with the position errors less than $100 \mu\text{m}$.

Geomagnetic Field Correction

We introduced geomagnetic correction coils (see Fig.1) to cancel the geomagnetic field by a uniform magnetic field to ease fine beam tuning at the low energy section less than 1MeV. Four geomagnetic correction coils were installed to cancel the horizontal and vertical components of the geomagnetic fields. Every coil comprises six components to ease installation of the coils.

Before the beginning of the installation of the injector's components, we surveyed the geomagnetic field at around the injector area in the accelerator tunnel. The measured data showed that the magnetic field strongly depended on positions and it suggested the geomagnetic correction would not function well.

The source of the inhomogeneous magnetic field was magnetism of the reinforcing steels in the RC floor. We demagnetized the floor by means of a flat square coil generating a alternating and decaying field. The vertical components of the residual field with subtraction of the genuine geomagnetic field distribute in a range of 0 - 0.05 after the demagnetization, while -0.1 - 0.5 before it.

STABILIZATION OF ACCELERATING VOLTAGE [4]

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.

Table 2 shows the tolerance for linac devices which permit 10% variation (rms) in the peak beam current and achieved stability of devices.

The RF phase stability of RF cavities strongly depend on their body temperature because of their high quality factors. Though we have introduced fine coolant temperature control systems ($\Delta T < 10 \text{ mK}$ std.) for RF cavities, the RF phase variations will be still much larger than the tolerances as shown in Table 2. These variations will appear as long-term variations.

Table 2: Tolerances and Achievements of Accelerating Voltage Variations

| | Tolerance (σ) | | Achieved stability (std.) | | |
|--------------|------------------------|--------------|------------------------------|---------------------------|---------------------------|
| | $\Delta V/V$ | $\Delta\phi$ | Power source $\Delta V/V$ | RF cavity $\Delta\phi$ | RF cavity $\Delta\phi$ |
| Gun | 0.003% | – | 0.001% | – | – |
| SHB | 0.01% | 0.01° | – | 0.02° | 0.12° |
| Booster | 0.01% | 0.02° | 0.013% | 0.014° | 0.19° |
| L-Correction | 0.03% | 0.06° | 0.026% | 0.062° | 0.09° |
| L-APS | 0.01% | 0.06° | 0.002% | 0.004° | 0.20° |
| C-Correction | 0.1% | 0.1° | 0.002% | 0.004° | – |

On the contrary, the short-term RF variations observed in the completed RF sources almost satisfy the requirement as presented in Table 2 [5].

All the solid-state amplifiers and its control circuits including their enclosures were very carefully designed to minimize RF instabilities.

The voltage stability of the gun and the klystrons are almost determined by the stability of the high voltage inverter power supplies. The power supply shows very low instability of 10 ppm std., which is sufficiently smaller than the most severe tolerance for the gun accelerating voltage.

As we have described above, the coolant temperature variations may cause unacceptable long-term phase fluctuations. These fluctuations will be compensated by feedback phase control as we have already succeeded in stabilization of the SCSS test accelerator [6].

L-BAND SYSTEM [3]

Accelerating Structure

We employed an APS type, because it has an RF coupler, which results the field asymmetry, at around the center of accelerating structure, not at the entrance cell like a traveling 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.

The structure is composed of two 1-m long accelerating structures and a central coupler cell brazed with the two structures. They have been very carefully machined, brazed and tuned to satisfy its specification. The first structure was perfectly fabricated as shown in Table 1, the second one, however, encountered a problem during its brazing process. Thus the second one will be completed in November 2010.

Waveguide System

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. A vacuum type waveguide circuit was installed not to use insulation gases such as SF₆, that is, a circulator was not be available. Therefore the circuit had to be carefully designed to

cancel the reflected powers going to the klystron from the APS's so that the reflection to the klystron will not cause RF instability in the klystron output cavity.

The design and the accuracy of the waveguide components were verified as follows: We first measured the S21 parameters of the whole waveguide system. We fed RF signals to the input port for a klystron and measured the S parameters at each output ports for the APS's. When an S21 at one output port was measured, the other output port was terminated by a dummy load. The phase difference of the S21's was just 90.0° when the phase shifter installed in the waveguide for APS-2 was at the middle point. That is, the backward waves reflected at the input ports of each APS will be almost perfectly combined to be absorbed in the RF load and the minimum reflection to the klystron will be observed.

We also measured the VSWR at the input port when the both output ports were short-circuited. The result was VSWR=1.1 and it is smaller than the specified value of 1.2. Note that this value is the worst case that RF powers from the klystron are completely reflected at the input ports of both APS's. The residual reflection may be caused by the dividing ratio error of the directional coupler, the reflections from the directional coupler and the phase shifter. In the actual operation of the L-band system, the voltage reflections from the APS will be less than 1/5 during the later half of the RF pulse. Thus the actual VSWR will be smaller than 1.1 in the later half of the RF pulse.

In order to allow RF phase tuning for the APS-2 in the range of $\pm 7.5^\circ$ without resulting VSWR > 1.2, the difference of the resonant frequencies of each APS structure has to be smaller than 2.7 kHz according to our estimation [3].

The newly designed high power RF load employs an SiC duct as an absorber [7]. Now the completed RF load is in RF conditioning process at a test bench to verify its performance.

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