INJECTOR LINAC UPGRADE AND NEW RF GUN DEVELOPMENT FOR SuperKEKB

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Abstract

The SuperKEKB commissioning has finally started. The final goal of luminosity is 40 times higher than KEKB. The injector upgrade is required to obtain the low emittance and high charge beam corresponding to the short beam life and small injection acceptance of the SuperKEKB ring. In the injector linac, several new instruments have been installed. Flux Concentrator (FC) was developed for high charge positron beam capture. The target of positron bunch charge is 4 nC. The new damping ring will be used for positron beam to reduce beam emittance to 10 mm-mrad. However, electron beam must be reached to 20 mm-mrad normalized emittance at 5 nC beam charge without damping ring. Thermionic gun was used for KEKB injector and it was able to generate enough beam charge. However, its emittance is too large. Therefor we developed photo cathode S-band RF gun. This new RF gun has unique accelerating cavity which called quasi-traveling wave side coupled cavity. Laser system for this photo cathode has been also developed. The laser system is constructed with Yb:YAG thin disk for high power and pulse shaping.

INTRODUCTION

The upgrade of KEKB to SuperKEKB is going on. Since high luminosity is required in SuperKEKB, improvement of beam emittance and high charge is necessary. The injector linac has many challenging issues. Table.1 is upgrade parameter of electron and positron beam.

Table 1: Electron and Positron Beam Parameter

	KEKB (e+/e-)	SuperKEKB (e+/e-)
charge [nC]	1 / 1	4 / 5
Emittance [mm-mrad]	2100 / 300	20 / 20

In the positron beam, SuperKEKB beam charge is 4 times higher than KEKB beam charge. Primary electron beam for positron beam generation is 10 nC. It is same charge as KEKB. Therefore new Flux Concentrator (FC) and capture section was developed for efficient positron generation [1]. Since generated positron beam has large emittance, new damping ring has been constructed to reduce beam emittance.

In the other hand, the RF gun is developed to realize both of high charge and low emittance electron beam. Since we have no damping ring for electron beam, high charge beam generation with low emittance is essential in the gun. We are developing a photo cathode S-band RF gun for high charge (5 nC) low emittance (20 mm-mrad) beam generation. A thermionic cathode DC gun was used in KEKB for both of electron injection beam and positron primary electron beam. However this conventional gun does not have potential of low emittance generation. The new RF gun development is very important issue for electron beam.

Emittance preservation is one of the big issues. Total length of our linac is 600 m. In SuperKEKB, the beam charges are not small enough to ignore wakefield effect. Precise alignment of beam line is required to avoid transverse wakefield effect. However, small misalignment is remained. This small misalignment may be cancelled to using offset injection. The misalignment should be less than 0.1 mm in locally and 0.3 mm in globally. Target value of emittance will be able to be achieved with performing precise alignment and offset injection.

Optimum optics and magnet adjustment is required for both of electron and positron beam offset injection. The KEK injector is required simultaneous injection for HER, LER, PF and PF-AR ring at 50 Hz. The pulse quadrupole magnet and pulse steering magnet has been developed for pulse-to-pulse modulation [2].

Several new devices such as RF gun, FC and pulse magnets have been developed for achieve low emittance high charge electron and positron beam. The SuperKEKB Phase 1 commissioning had been carried out from February to June 2016. We had been able to confirm the performance of the new devices in KEK injector linac.

NEW RF GUN DEVELOPMENT

We are developing a photo cathode S-band RF gun for high charge (5 nC) low emittance (20 mm-mrad) beam generation. A thermionic cathode DC gun was used in KEKB. Since it is difficult to make a low emittance beam with the thermionic gun, the new RF gun must be installed to realize required electron beam parameter. However the standard on-axis coupled 1.5 cell RF gun is not suitable for this high charge beam, because standard gun is used up to about 1 nC by ordinary. If we obtain 5 nC in the gun, beam size will be too large. We have to consider both beam focus and emittance preservation. Thus it is necessary to make a focusing field against the space charge in the cavities. In this on-axis coupling cavity, however, it is difficult to arrange the field freely on the axis. Since beam hole is also the coupling hole. Thus annular coupling is required.

We are developing a new advanced RF gun. It has new acceleration scheme, we call it as a quasi-traveling wave. In this method, higher accelerating field and stronger focusing field are expected. It is very efficient accelera-

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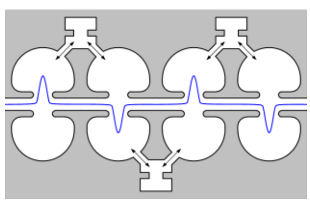
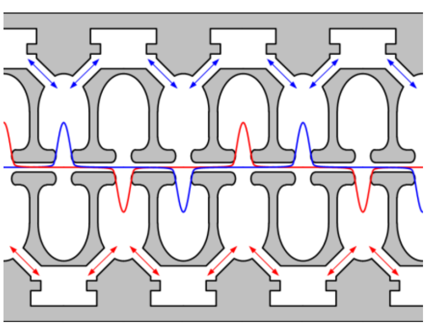
tion method. This quasi-traveling wave cavity is realized by using a two side couple cavities.

Annular coupled cavities as Disk and Washer (DAW) [3] or side coupled cavities are possible to make narrow acceleration gap. The narrow gap makes the focus field. Our DAW RF gun is using this focus field. Side coupled cavity also can be made the narrow gap. However, these cavities have a long drift space as Fig.1 (a) that shown normal side couple cavities. Due to the long drift space, those RF gun generates beam with a divergence angle.

One solution is to use two standing wave cavities. If two side coupled cavities are arranged staggered, we obtain a double standing wave field as Fig.1 (b). These two standing wave side coupled cavities are independent electromagnetically. If we feed RF power with π/2 phase difference, acceleration field is similar to traveling wave to accelerated beam. Since two side coupled cavities are possible to place on the same axis, a quasi-traveling wave can be realized. Quasi-traveling wave can realize very efficient beam acceleration and focusing.



(a) Normal side coupled cavities



(b) Quasi traveling wave side coupled cavities

Figure 1: Structure of the quasi traveling wave cavity.

2D Cavity Design

The first cavity of RF gun is most important for beam quality. Since beam energy of cathode cell is still low, space charge affects beam size and emittance. First cavity should be designed to have strong focus field. However nonlinear component of the strong focus field causes emittance growth. In addition, we must avoid the electric field concentration at the cavity surface.

SUPREFISH and GPT (General Particle Tracer) calculation code were used for 2D cavity design. Figure 2 is whole cavities structure design and electric field (SUPERFISH result). This cavity shape is obtained by using automatic downhill simplex method calculation. This RF gun has total of seven acceleration cavities. These are divided into two standing wave structure of 3 and 4 side coupled cavities respectively. There are no couplings to next cavity on the axis.

Figure 3 shows the beam tracking simulation for 5 nC beam charge result; emittance is 5.5 mm-mrad: beam size is 0.4 mm (standard deviation) at exit of RF gun (z = 250 mm). In the Fig.3, we can find that the beam size becomes gradually smaller in the RF gun. This is caused by not additional magnetic field but the focusing electric field of RF gun. Beam energy will be 11.5 MeV with 20 MW RF input. The energy spread is 0.6 %. These results satisfy the requirement in our application.

In addition, we confirm that this gun can generate 10 nC beam generation by calculation; emittance is 10 mm-mrad; beam size is 1.2 mm; energy spread is 1 %. It is enough margins.

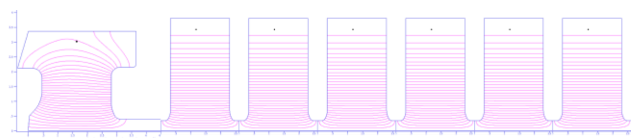


Figure 2: Designed RF gun cavities (SUPERFISH calculation result).

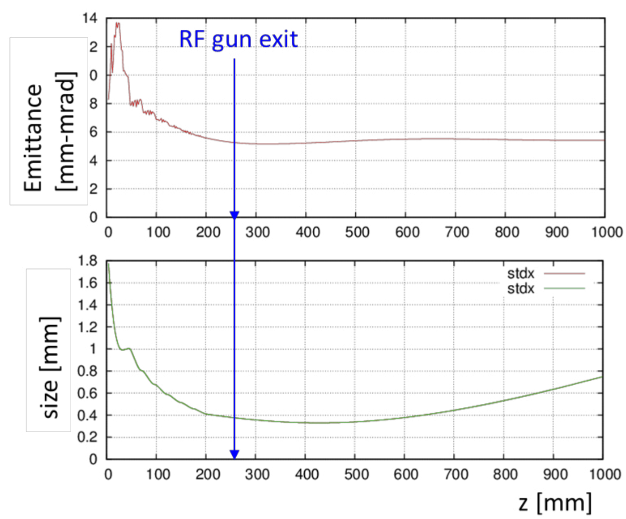


Figure 3: Beam tracking simulation result.

3D Cavity Design

CST MICROWAVE STUDIO was used for 3D cavity design. Figure 4 is the calculation result of the regular cell of a side coupled cavity. The acceleration mode and coupling mode are adjusted to be same frequency. Coupling value k is 3 %. This gun has two standing wave cavities; we designed two types coupler as shown Fig.5.

Figure 6 shows the whole cavity shape. The side couple cavities of the two standing wave cavities are mounted as 90 degrees in the azimuthal angle. It has two ports for RF feed. We use 90 degree hybrid for RF feed. We manufactured a compact 90 degrees hybrid. It will be mounted RF gun directly. We already finished mechanical design as shown in Fig.7.

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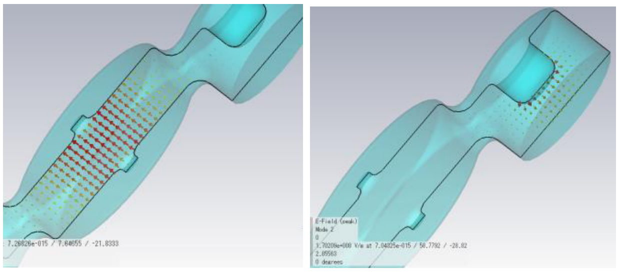

(a) Accelerating made (b) Coupling mode

Figure 4: regular cell cavity calculation result.

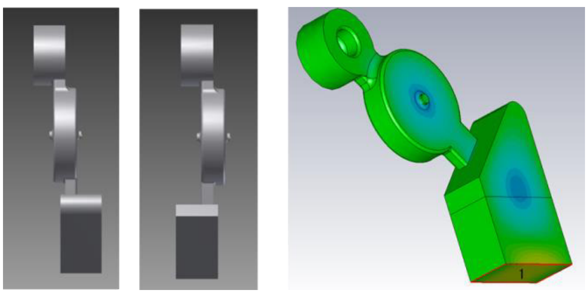

Figure 5: Two type couplers and calculation result.

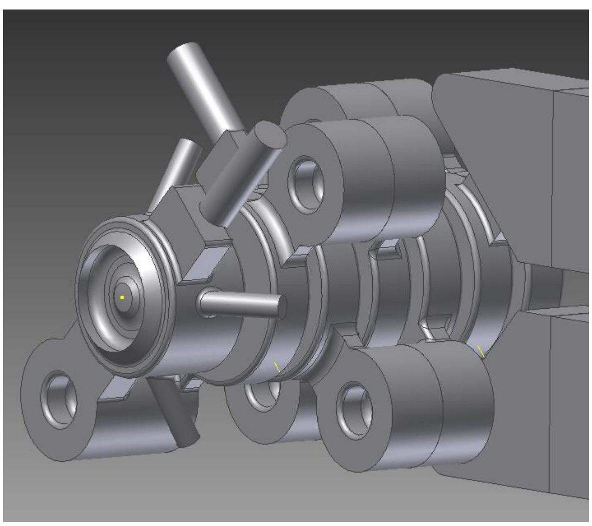

Figure 6: Whole cavity shape.

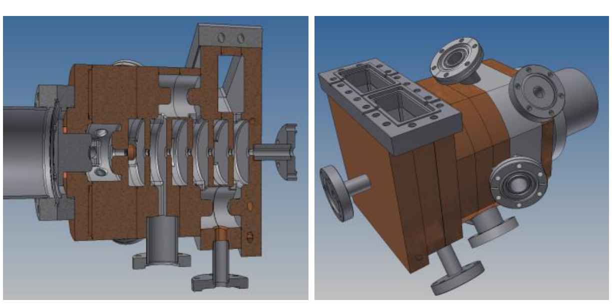

Figure 7: mechanical design.

Laser System and Cathode

The new laser system has been also developed for the RF gun. A schematic diagram of the laser setup is shown in Fig.8. The seed pulse with the pulse energy of 0.2 ns and spectrum of 1025-1070 nm was generated by an Ytterbium (Yb) doped fiber ring oscillator. The pulse repetition is 51.9 MHz, synchronized with 51.9 MHz and 2856 MHz RF from master oscillator which is used in linac. After an Yb fiber pre amplifier, the pulse was chirped to ~20 ps by a transmission grating stretcher with a spectral mask. An Yb-doped large-mode-area polarizing double-clad photonic crystal fiber was employed to the first amplification stage. Then, the pulse repetition rate of 25 Hz, double bunch was separated with two Electro Optic (EO) modulators. To increase the pulse energy, another Yb-doped LMA PCF was used. So the pulse was amplified to µJ-level, which was strong enough to be amplified by Yb:YAG thin-disk stage. To obtain the mJ class pulse energy, several multi-pass amplifier stages were employed. Deep UV pulses for the photocathode are generated by using two frequency-doubling stages. High pulse energy and good stability were obtained. Finally, the pulses were injected into RF gun [4].

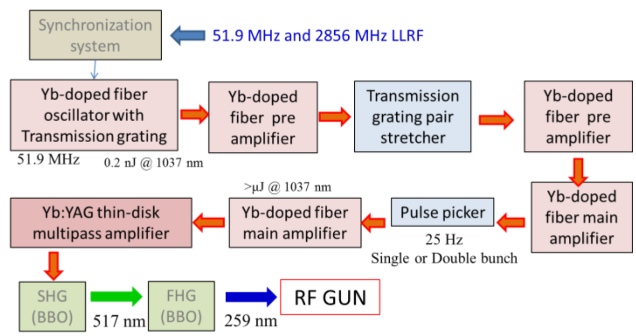

Figure 8: Layout of Laser system.

We succeeded in developing an iridium cerium (Ir_5Ce) photocathode which has a reasonably high QE (~ 9.1×10-4 at 219 nm at room temperature) and long lifetime (>LaB_6) [5].

RF Gun Install in Injector Linac Beam Line

The new RF gun was installed at A1 sector injector in September 2013. RF power is fed two cavities by using 90 degree hybrid for π/2 phase advance. Laser power is injected from angled laser port. Figure 9 shows installed the RF gun.

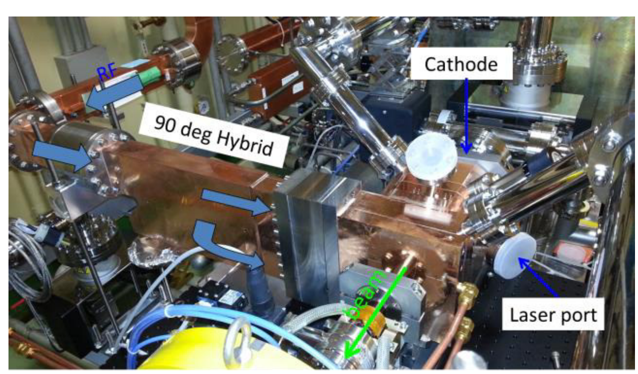

Figure 9: Installed RF gun.

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The laser hut was constructed near the RF gun. Injected laser is fourth harmonics. First, laser pulse was converted to second harmonics at laser hat. The second harmonics was used for transportation from laser hut to RF gun. Transported second harmonics was converted to fourth harmonics at near the RF gun. BBO crystal was used for conversion. Optics for injection is shown Fig.10. Injection angle is 60 degree.

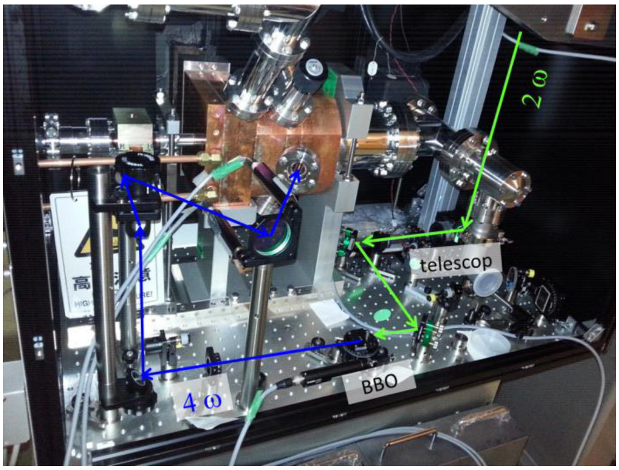

Figure 10: Laser injection component near the RF gun.

In Phase 1 beam operation, conventional thermionic DC gun system was also used. Two electron guns are installed in A1 sector. The conventional thermionic DC gun was being used in KEKB operation. This line was shifted to higher position. Normal beam line is used for study of the new RF gun. This thermionic gun was used for positron primary beam and normal electron beam operation in Phase 1. This short beam line which is used for thermionic gun is merged to normal line by using two bending magnet. RF gun beam line was used for study in Phase1. Figure 11 shows two beam lines of RF gun and thermionic gun.

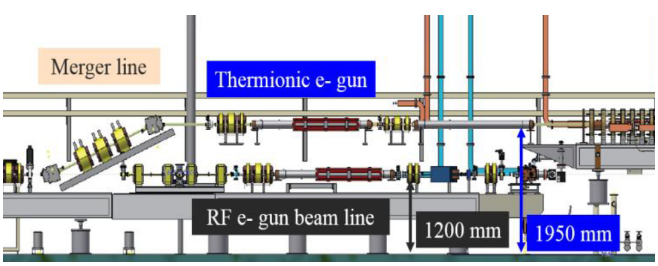

Figure 11: Thermionic gun and RF gun beam line.

RF GUN COMMISSIONING AND PHASE1

Phase 1 commissioning started at Feb. 2016 and finished at Jun. 2016. Injector linac supplies electron and positron beam with thermionic gun, charge is 1 nC to both of HER and LER. The RF gun study had been carried out on parallel.

RF Gun Study

The RF gun was also operated at 1 nC beam charge. Stability of beam charge is laser power stability. Charge stability of gun exit was less than 5 % at 1.7 nC in 7 hours measurement as shown Fig.12. It is capable for normal operation.

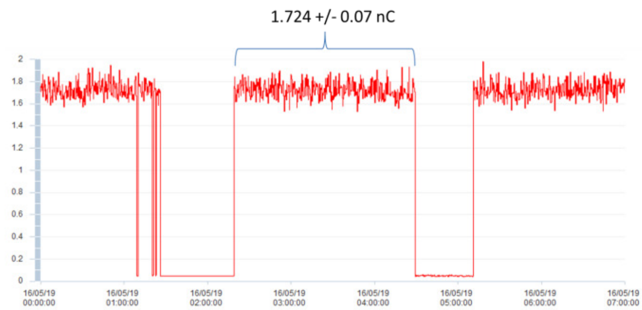

Figure 12: Beam charge stability of RF gun.

Laser spot position on cathode stability is one of the big issues. Beam position is varied by laser position at cathode. Beam position exit of gun is measured with beam position monitor (BPM). As a result, stability is 0.5 mm in horizontal, 0.2 mm in vertical (in sigma). Distance of RF gun is very far (~10 m) from laser hut. Transportation optical line needs precise treatment. It should be improved for Phase 2.

Laser spot profile decides beam quality. We could not realize good Gaussian beam in 4th harmonics. We have to improve laser spot profile till Phase 2.

Normalized emittance at 1 nC beam charge was measured at AB sector in linac. The emittance was about 20 mm-mrad in horizontal and vertical. Measurement emittance is larger than simulated emittance. It might be due to laser pulse quality. We must improve laser spot profile, position jitter and pulse length.

HER Injection with RF Gun

Beam emittance value of RF gun was larger than calculated value. However we attempted to do beam injection to HER with the RF gun. Stability of the RF gun beam was same as the thermionic gun. Certainly, emittance of the RF gun is smaller than emittance of thermionic gun. As a result, we achieved HER injection with RF gun. It was continuous 10 days injection. Injection efficiency and stability were almost same as thermionic gun. Figure 13 is an example of injection history graph with the RF gun injection.

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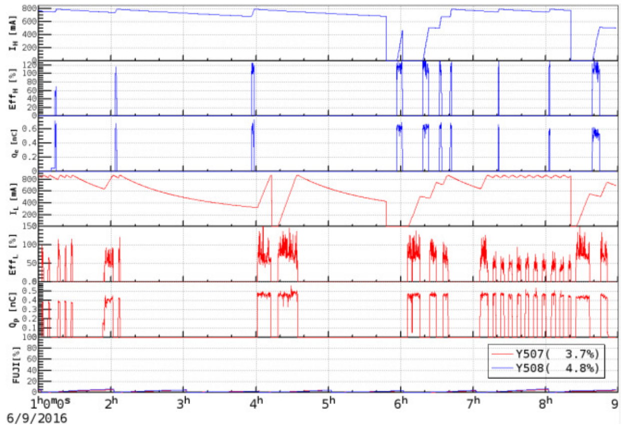
Figure 13: RF gun beam injection history graph.

SUMMARY

KEK injector linac has a lot of mission for SuperKEKB upgrade, such as RF gun development, flux concentrator development, low emittance reservation and others. SuperKEKB Phase1 commissioning was carried out from Feb. to Jun. 2016. Basically, injection beam was generated from conventional thermionic gun. New FC was used for generation of positron. Electron and positron beam injection was achieved. Beam charge was 1 nC in electron and positron for HER and LER. We continued the RF gun beam study during phase1. Beam charge stability was achieved 5 % at 1 nC with the RF gun. We attempted to test injection to HER with the RF gun. As a result, we succeeded in continuous 10 days electron injection to HER with the RF gun. However beam charge and emittance had been not achieved final target with the RF gun. It is required to improve the laser system problems which are less pulse energy, profile and position jitter for SuperKEKB operation.

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