HIGH POWER RF TEST OF L-BAND RF GUN AT KEK-STF*

M. Kuriki†, H. Iijima, Y. Masumoto, ADSM/Hiroshima U., 1-3-1 Kagamiyama, Higashihiroshima,Hiroshima, 739-8530
G. Isoyama, R. Kato, ISIR/Osaka U., 8-1 Mihogaoka, Osaka, Osaka, 567-0047
K.Watanabe, H.Hayano, H. Sugiyama, J. Urakawa, KEK, 1-1 Oho, Tsukuba, Ibaraki, 305-0801
Y. Takahashi, Graduate School for Advanced Studies, Hayama, Miura-gun, Kanagawa, 240-0193
S. Kashiwagi, Tohoku U., 1-2-1 Mikamine, Taihaku,Sendai, Miyagi, 982-0826

Abstract

Status of high power RF test of L-band RF gun is presented. 1.3 GHz normal conducting RF photo-injector has been prepared for KEK-STF(Super conducting Test Facility), where Super-conducting technology is being developed for ILC (International Linear Collider). MEXT Quantum Beam project, high brightness X-ray generation by inverse laser Compton scattering, also will be carried out at STF. In both cases, the high intensity electron beam in multi-bunch and long macro-pulse up to 0.9ms has important roles. The L-band RF gun cavity has been fabricated by DESY-FNAL-KEK collaboration and the first high power RF test has been carried out in 2009, but a large amount of dark-current (280μA at 28 MV/m) was observed. In order to cure the problem, the cavity surface was treated by ethanol rinsing to suppress the dark current. The second high power RF test was performed in January 2011. The dark-current was decreased by an order of magnitude, down to 18μA at the same condition. For each test, RF power was up to 1.7 MW, which was limited by the power source. The real operation will be made at 3.5 MW input power with a new power source. The third high power RF test was scheduled with this new power source from May 2011, but it was not started due to a damage on the infrastructure of STF experimental hall by the east-japan earth quake. We plan to start the RF test from September 2011.

INTRODUCTION

Aim of KEK-STF(Superconducting Test Facility)is demonstrating super-conducting accelerator technology for ILC(International Linear Collider), which is a future project of high-energy physics. In STF, a beam acceleration test is planned with parameters almost equivalent to those in the real ILC, 10mA average current in 0.9ms length macro-pulse. In super-conducting accelerator, the input RF power has to be balanced to RF power consumed by the beam acceleration. The input RF power and phase should be well controlled by monitoring RF field of the cavity. Establishing the LLRF (Low Level RF) control technique is one of the most important purpose of the STF. LLRF can be examined only with a real beam loading and the beam acceleration test is therefore very important.

In ILC beam format, the 3.2 nC bunch is repeated with 369 ns spacing up to 0.9ms. Total number of bunch is 2625 in a macro pulse. This high-average and long macro pulse beam is provided by 1.3GHz photo-cathode RF gun. It is a normal-conducting gun, which is originally developed by DESY for FLASH/XFEL[1]. The Gun cavity fabricated by FNAL has been placed at KEK-STF. The design peak field of the gun is 50MV/m at 4.5 MW RF power.

To generate the long multi-bunch beam, Cs_2Te photo-cathode is employed. Cs_2Te is prepared as thin-film by evaporation on Mo cathode block in vacuum. A special preparation chamber is designed by Sugiyama[3], so that the cathode plug is transferred to the gun cavity through vacuum transfer pipe in situ. In preparation chamber, Mo plug is initialized by heat cleaning followed by Te evaporation. Amount of Te is controlled by monitoring thickness and usually it is between 10-40nm. Cs is then evaporated on the surface, but UV light is simultaneously illuminated on the cathode plug. Emission current by photo-electron effect is observed to optimize amount of Cs evaporation. Up to now, 7% in quantum efficiency is obtained and it is even feasible for operation.

Drive laser for the cathode is another important component. A laser system was developed as a collaborative work between KEK, Hiroshima Univ., IAP, and JINR in Russia in 2010[4],[5]. 3MHz pulse train as seed laser is generated by Yb fiber oscillator. The pulse train is amplified by Nd:YLF laser pumped by flash lump. To obtain a flat gain during one macro pulse, two laser amplifiers are driven with a time delay. As a result, a flat pulse train up to 0.9 ms was obtained as 4th harmonics (266nm) of the fundamental mode. The flatness was 2.5% in rms.

The L-band RF gun system will also be used as the electron source for MEXT Quantum Beam project, generating high brightness X-ray by inverse Compton Scattering[2]. For this project, the beam format is as follows; 62pC bunch is repeated each 6.2ns. The bunch repetition is much different from that for ILC, but the same gun system commonly used except the laser system.

In this article, we report the status of high power RF test of the L-band RF gun. Stable operation with high power RF up to 3.5 MW is our purpose. Dark current by the field emission from the cavity surface, has to be an important issue and it should be even lower than the beam current, 10mA at the operation gradient, 40 MV/m.

* Work supported by Quantum Beam Project of MEXT, Japan.
† mkuriki@hiroshima-u.ac.jp

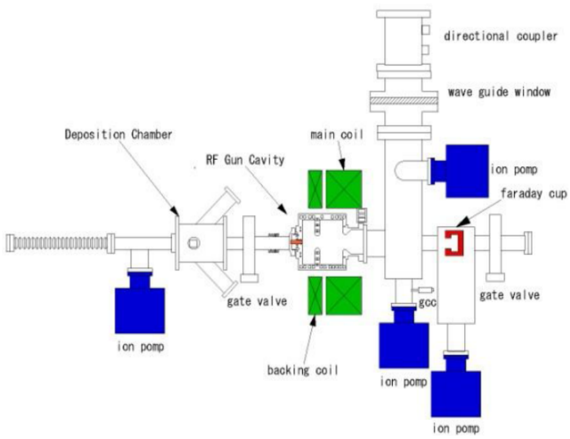

Figure 1: Schematic view of the experimental setup of RF gun high power test.

FIRST TEST

The first high power RF test was performed in April 2009. The experimental setup is schematically shown in Fig. 1. RF power generated by 1.3 GHz klystron up to 1.7 MW is fed by wave guide through door-knob type coupler. The maximum pulse duration is 1.5 ms and the maximum repetition is 5 Hz. RF circulator is connected between klystron and the RF gun cavity, so that the reflected RF pulse does not go back to klystron to prevent any damages. To monitor RF input and reflection power, 60 dB directional couplers are placed at upstream of the isolation window. Arc sensor observes discharge on the isolation window, which is one of the interlock system.

In the high power test, Mo cathode plug is inserted. $\mathrm{Cs_2Te}$ film cathode is not evaporated on the plug.

RF Gun cavity is surrounded by water jacket for cooling. 110 l/min cooling water is provided from a chiller and the temperature is controlled.

Solenoid field is provided by a couple of solenoid magnets for emittance compensation. One of them is a main solenoid magnet generating required magnetic field with 380 A current. Another magnet is for bucking to vanish any magnetic field on the cathode surface. Magnetic field on the cathode is a source of beam emittance growth.

High power RF processing of the gun cavity was started from 20μs pulse duration. Vacuum interlock was set to $2.0\mathrm{E}-4\mathrm{Pa}$. It takes 16 hours to reach the maximum power, 1.7 MW. Next, the pulse duration is increased to 40μs and it takes 2 hours to reach the maximum power. The processing was continued as 19 hours for 100μs, 14 hours for 200μs, 9.5 hours for 500μs, and finally we reached the maximum power, 1.7 MW with 1000 μs pulse duration by 21 hours 40 minutes. Up to this point, the solenoid magnets are not powered.

After the solenoid magnets are turned on, we started the processing again from 20μs pulse duration. Finally, 1.7 MW RF power was fed to the cavity with 1000μs duration and the total processing time was 111 hours. 1.7 MW input power corresponds to 29.2 MV/m field on the cathode.

In progress of the RF processing, reflected RF power became significant by increasing input RF power. It can be explained that the cavity was detuned by heat dissipation of input RF. Input cooling water temperature is controlled at a fixed point, but the equilibrium temperature of the cavity depends on the input RF power. The reflection power was minimized by changing the input cooling water temperature T as

$$T[^\circ C] = 52 - 2.5P[MW], \tag{1}$$

where P is input RF power in MW[6].

Dark current was observed by Faraday cup set at downstream of the RF gun cavity. The dark-current from the cavity became significant for more than 1.4 MW input RF power[6]. It was 284 μA at 27.7MV/m. It is even lower the beam current 9mA, but it could be up to more than 5 mA at 40 MV/m as explained later.

SURFACE TREATMENT AND SECOND TEST

Because the dark current could be significant comparing to the beam current at the operation gradient, 40MV/m, we have considered a surface treatment to suppress the field emission.

Before the treatment, several dark points, which could be burned out during the RF processing, were observed. Fig2 shows a picture of the inner surface, a dark area was found the corner of the cavity wall. A strange dark area, which looked like a finger print, was found too. These dark points and area were not found before the RF processing. There are two kinds of the colored area. One is blue colored, which looks like oxidized metal. Another color is dark purple, which looks like burned metal.

Among various surface cleaning treatment, we have decided ethanol rinsing with sponge wipe. The method was determined by a test experiment, where Cu sample pierces were washed in aluminum dummy cavity. The cavity was removed from the experimental setup and the cavity part was only treated. Inner coupler cylinder was not treated at this time. The cavity was placed the exit side (downstream) up. PVC sponge was cut to the cavity shape, so that the sponge was fit to the inner wall. The sponge was fixed at the end of a rod, which was rotated by a handy motor. The rod with the sponge was inserted to the cavity, which was filled by pure ethanol. The motor was then rotated by 10 minutes followed by ethanol rinse three times without the sponge rotation. The ethanol rinse was performed to remove any tiny pierce of PVC sponge.

After the treatment, the cavity was rinsed by hot pure water (75 deg. C). The water was drained and the cavity

Figure 2: Picture of inner surface of the RF gun cavity after the first RF processing.

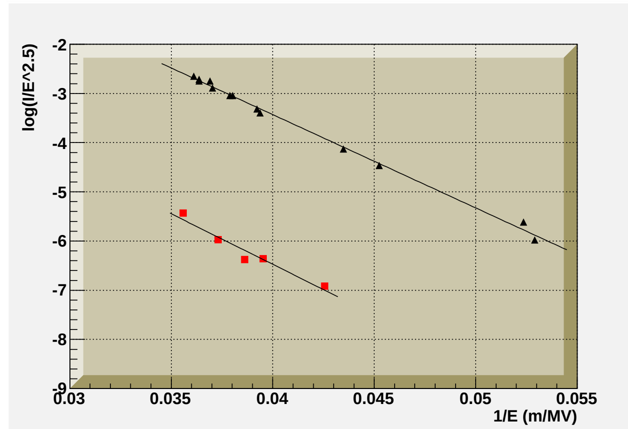

Figure 3: Fowler-Nordheim Plot of the RF processing. Field enhancement factor is extracted as 350 for the fist test (triangle) and 324 for the second test (square).

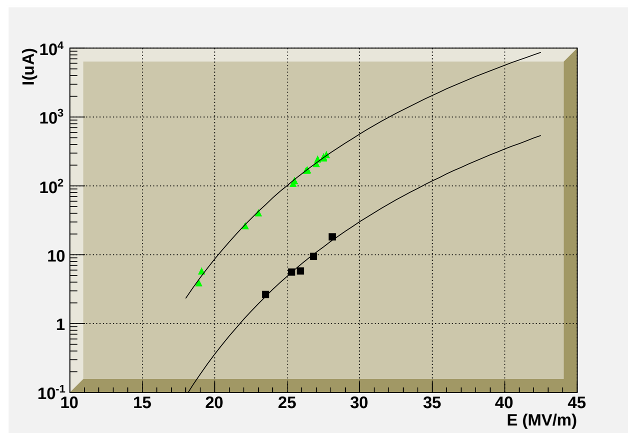

Figure 4: Dark current as a function of field, before(triangle) and after (square) treatment. The line is expected dark current based on Fowler-Nodheim theorem.

was dried by rough-pumping once. To observe the inner surface, the cavity was open to air once. The dark colored areas, which were recognized before the treatment, were not removed (changed) by this treatment. The cavity was then pumped again, and filled by nitrogen gas. The cavity was then back to the experimental setup.

RF conditioning was restarted after the cavity treatment. RF pulse duration was started from 20μs and input RF power reached to the maximum 1.7 MW soon, only several hours. The RF processing was very smooth and quick after the treatment and it took only 15 hours to reach 1000 μs duration at 1.7 MW RF power.

ANALYSIS

The dark current before and after the treatment, is analyzed based on Fowler-Nordheim theorem. It assumes the dark current is generated by the field emission process. The dark current is proportional as

$$I \propto (\beta E)^{2.5} exp\left[-\frac{6.53 \times 10^9 \phi^{1.5}}{\beta E}\right], \qquad (2)$$

where β is field enhancement factor determined by the emission current evolution as a function of the surface field, E is the surface field in V/m, and ϕ is the work function of the material. In this calculation, all cavity is made by copper represented by work function of 4.7 eV. Fig.3 shows the Fowler-Nordheim plot. The vertical axis shows

$$y = ln\left(\frac{I}{E^{2.5}}\right), \qquad (3)$$

and the horizontal axis is the inverse of the field. According Fowler-Nordheim theorem Eq. (2), data points should be on a straight line. Inverse of the line gradient is proportional to the field enhancement factor. From this calculation, the field enhancement factor is extracted to be $\beta = 350 \pm 6.7$ for the fist test, 324 ± 44 for the second test.

Fig.4 shows the dark current observed by Faraday cup before and after the treatment as a function of accelerating field in MV/m. The dark current was decreased roughly more than an order of magnitude and it was found to be 18.3 μA after the treatment at 28.1 MV/m. This number should be compared to 284 μA at 27.7 MV/m before the treatment. Expected dark current at 40 MV/m accelerating field was estimated by assuming Fowler-Nordheim theorem. Lines in Fig. 4 show the expectations. It was 5.7mA at the fist test, and 0.34mA at the second test.

The effect of the treatment was excellent. The dark current was suppressed by more than one order of magnitude. However, the dark current at the operation field could be up to 0.34 mA at 40 MV/m, by extrapolation. It is significantly lower than the beam current, 9mA, but is still several percents. Our target is even and reasonably low, close to 1% or less.

SUMMARY AND FUTURE PROSPECT

RF processing was performed up to 1.7 MW power with 1ms pulse length [3] for L-band normal conducting RF Gun. The peak field is estimated to be 28 MV/m with this power. The dark current was measured by Faraday cup at downstream of the gun cavity and was found to be 280 μA at 28 MV/m before the treatment. The dark current was decreased down to 18 μm by the treatment at the second RF test. The dark current was decreased by more than one order of magnitude by the ethanol rinsing with sponge wipe. This number is still expected to be increased up to 0.34mA at 40 MV/m, which is not still "even" lower than the beam current, 9 mA.

We plan third RF processing with an improved RF power source up to 3.5MW. By surface processing with the higher RF field, we hope that the dark current is further suppressed down to enough level. The next RF processing will be started on September 2011. If the dark-current was still significant comparing to the beam current, a further surface treatment was necessary.

REFERENCES

[1] B. Dwersteg, et al., NIM A 393(1997)p93-95

[2] http://kocbeam.kek.jp/project/index.html

[3] H. Sugiyama et al.,Proc. of PESP2010 (2010)

[4] M. Kuriki et al., Proc. of IPAC2010(2010) THPEC024.

[5] A. Potemkin et al., Quantum Electronics 40(2010)1123-1130.

[6] Y. Takahashi, et al., Proc. of 7th annual meeting of PASJ(2010)471-474