# MULTI-BUNCH BEAM GENERATION BY PHOTO-CATHODE RF GUN FOR KEK-STF*

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*Abstract*

The purpose of KEK-STF (Superconducting Test Facility) is to establish super-conducting accelerator technology for ILC (International Linear Collider). Another aim is MEXT Quantum Beam project which is a high brightness X-ray generation by inverse laser Compton scattering. In both projects, high intensity electron beam in multi-bunch and long macro-pulse is essential. An L-band normal conducting RF gun was fabricated by DESY-FNAL-KEK collaboration and the cavity conditioning was performed since 2010. The cavity conditioning dramatically reduced the unwanted dark-current by two orders of magnitude and it is 100$\mu$A at 40 MV/m gradient typically. In the beam generation test from February 2012, 1.0 ms macro pulse was successfully generated in designed beam intensity.

## 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, 8.7mA average current in 0.9ms length macro-pulse. In super-conducting accelerator, the input RF power is 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 was installed 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, $Cs_2Te$ photocathode is employed. $Cs_2Te$ is prepared as thin-film by evaporation on Mo cathode block in a vacuum chamber (prepation chamber) designed by Sugiyama[2]. After Mo heat cleaning, Te is evaporated. Amount of Te is controlled by monitoring thickness and usually it is between 10-40nm. Cs is then evaporated on the surface. UV light is simultaneously illuminated on the cathode plug to observe emission current by photo-electron effect. Cs evaporation is optimized for higher quantum efficiency. Up to now, 7% in quantum efficiency is obtained.

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[3, 4]. 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. 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[5]. The beam format in this project is different from the ILC format; 62pC bunch is repeated each 6.15ns up to 1.0 ms macro pulse duration with 162450 bunches. The same gun system commonly used without any modification except the laser system. The laser system based on 162.5 MHz mode-lock oscillator with MOPA system was developed for Quantum Beam project[6]. UV laser pulse train was obtained as FHG by LBO and BBO. Typical UV laser energy per bunch is 1$\mu$J or less.

The STF injector setup is common for ILC and Q-Beam mode as given in Fig. 1. $Cs_2Te$ cathode is set to the gun cavity from backside of the cavity by the load-lock system. The beam properties are observed by various beam monitors set in the beam line, FC (Faraday Cup), ICT (Integrated Current Transformer), BPM (Beam Position Monitor). The chicane magnets are set to avoid any conflict between the laser injection and electron extraction. The laser is then injected to the cathode in right angle. Solenoid magnets, Quadru-pole magnet are placed for beam focusing. The beam is sent to super-conducting accelerator for further acceleration.

In this article, we report successful generation of 1ms macro pulse by this photo-cathode RF gun. The beam intensity was close to 10 mA which is the designed value.

## RF GUN CAVITY CONDITIONING

The gun cavity conditioning was performed with nominal high power RF processing and ethanol rinse. The high

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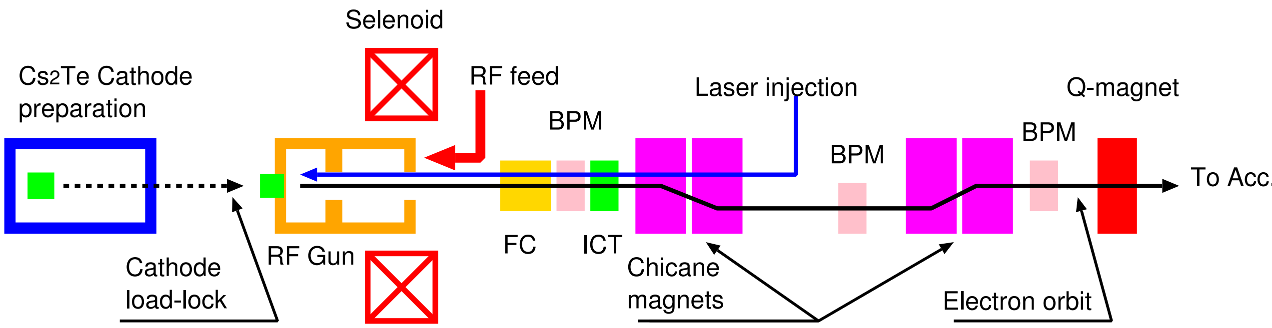


Figure 1: Injector setup for STF beam line. Chicane orbit is designed for laser injection in right angle to cathode surface. Beam current and position are measured by FC (Faraday Cup), ICT (Integrated current Transformer), BPM (Beam Position Monitor). Solenoid and Q-magnet are set for beam focusing and transporting.

power RF processing was done in three stages. The peak power of RF was 1.7MW in the first and second stages, and 5.0 MW in the third stage. Between the first and second stages, ethanol rinse for the cavity was performed.

In the RF processing, RF power generated by 1.3 GHz klystron up to 1.0 ms was fed to RF gun cavity through a door-knob type coupler. Detail explanation of the system setup is given in Ref.[7] and [2]. In RF processing, Mo cathode plug was inserted, but $\mathrm{Cs_2Te}$ cathode was not evaporated on the plug as long as not mentioned. Cavity temperature is controlled by a chiller providing 110 l/min cooling water during the process.

In all stages, RF processing was started from $20\mu s$ pulse duration. Vacuum interlock was set to $2.0\mathrm{E}-4\mathrm{Pa}$. Then, the peak power and pulse duration was gradually increased. In the first stage, it took more than 82 hours to reach 1.0 ms duration with 1.7 MW peak power. In the second stage, it took only 15 hours to reach 1 ms duration with 1.7 MW RF power. In the third stage, it took 60 hours to reach 1ms with 4.0 MW RF corresponding to 46 MV/m.

Between the first and second stages, ethanol rinse for the cavity was performed. The cavity wall was only treated and inner coupler cylinder was not treated. The cavity was removed from the experimental setup and was placed the exit side (downstream) up. PVC sponge was cut to fit to the cavity inner wall. The sponge was fixed at the end of a rotating rod. The rod with the sponge was inserted to the cavity filled by pure ethanol and the rod was rotated by 10 minutes. After removing the rod, the cavity was rinsed by fresh ethanol three times to remove any dusts. The cavity was dried by rough-pumping and filled by dry nitrogen gas.

In each stages, dark current from the gun cavity was observed by Faraday cup set at downstream of the cavity exit. The dark current is due to field emission process from the cavity wall where high electric field is induced. The dark current becomes experimental background and unwanted beam loss. The dark-current from the cavity became significant for more than 1.4 MW input RF power[7].

The dark current can be analyzed based on Fowler-Nordheim theorem[8]. In the calculation, all cavity is made by copper represented by work function of 4.7 eV. During the cavity processing, the dark-current was measured several times to make sure progress of the conditioning. The measured data were consistent to Fower-Nordheim theorem[9].

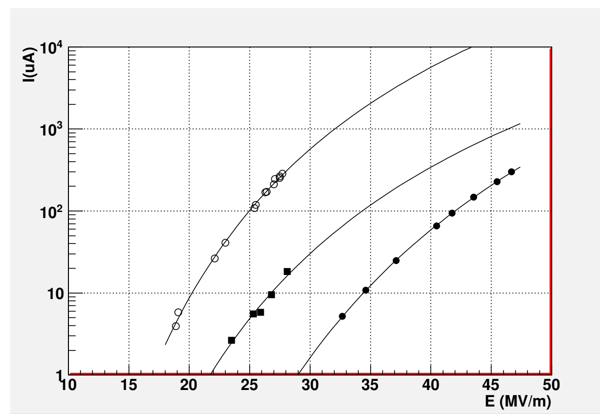


Figure 2: Dark current as a function of field, after first processing(open circle), second processing (filled square) and third processing (filled circle). Lines are expected dark current based on Fowler-Nordheim theorem.

The dark current is plotted in Fig.2 as a function of accelerating field in MV/m. The dark current was decreased roughly more than an order of magnitude before and after the ethanol treatment by comparing first processing (open circle) and second processing (filled square) data. Further reduction was observed by high power RF processing by comparing second and third processing (filled circle) data. Lines in Fig. 2 show the expectations according to Fowler-Nordheim theorem. The expectation at 40.2 MV/m was 5.9mA for first processing, 0.36mA for second processing, and 0.062mA for third processing which corresponds to 0.6% of the beam current. The dark current was almost suppressed by two orders of magnitude by the cavity conditioning. The field enhancement factor $\beta$ was extracted as 350 for first stage, 324 for second stage, and 193 for third stage.

The result of the same type RF Gun by DESY-PITZ shows less darkcurrent by more than factor of 5[10]. They processed the cavity up to 7.0 MW and performed dry-ice cleaning. The difference might be due to total conditioning time, peak power, and cleaning technique. According to the DESY experience, there is some possibility for further reduction of the dark current with more conditioning process.

## 1MS BEAM GENERATION

1ms beam generation test has been started since February 2012. The cathode QE (Quantum Efficiency) of $Cs_2Te$ was measured in preparation chamber by UV light from Xe lump and was typically more than 5% at the evaporation, but it was rapidly decreased down to less than 1%. QE in operation was qualified by observing bunch charge with ICT as a function of laser bunch energy as shown in Fig.3 which shows that QE in real operation depends on the laser energy. QE at zero laser energy limit is more than 2% in this case. This number is several times larger than that measured in the preparation chamber. These properties can be explained by surface field and space charge, but they should be studied more quantitatively.

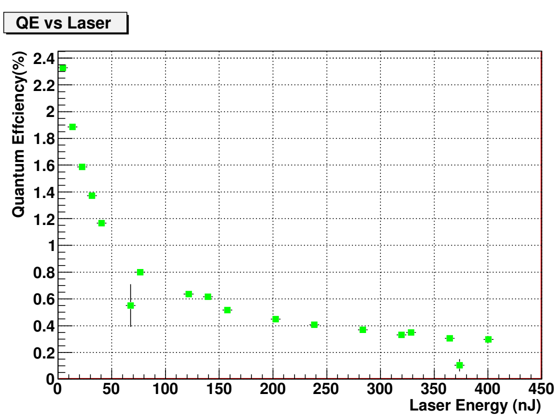


Figure 3: Quantum efficiency as a function of laser energy per bunch.

Starting from short pulse less than $1\mu s$, the long bunch generation from the RF gun was examined. During the experiment, the field in the cavity wass typically 33 MV/m. The beam tuning was started from the laser centering that the laser position were adjusted to electrical center of the RF gun cavity. Assuming that the cavity electrical center and solenoid field center are aligned, the laser position adjustment was made by minimizing the beam position shift with solenoid field perturbation. The second procedure was phase scanning where the beam current was measured as a function of RF phase of the gun cavity. The RF phase was set to 30° (zero ○ corresponds to zero field) for good beam property. After these basic beam tuning, number of bunches was increased. After several iterations of the tuning and the bunch number increments, 1 ms macro pulse generation was achieved. Fig.4 shows the temporal profile of the 1 ms macro pulse. The shaded area shows sum of BPM signals which consist in 162450 bunches, but it is a shaded area due to limited resolution. The signal is sum of BPM electrodes and is independent from the beam

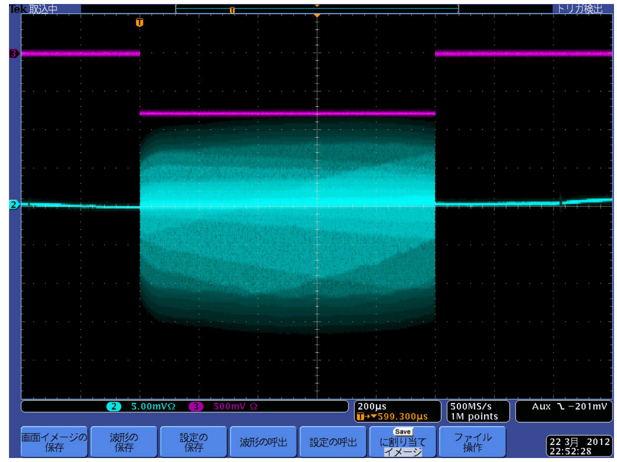

Figure 4: Beam temporal profile taken by BPM sum signal.

position. Square pulse shown above it is the gate signal for laser pulse and has 1 ms duration. The bunch intensity was slightly less than 60pC measured by ICT ouput. According to these measurements, it was confirmed that the multi-bunch electron beam with 1ms pulse duration and very close to 10mA average current was successfully generated by the photo-cathode RF gun.

## SUMMARY AND FUTURE PROSPECT

In KEK-STF, the L-band normal-conducting photocathode RF gun was successfully conditioned to operate up to 4.0 MW RF input with 1.0 ms pulse duration. The beam test to generate 1.0 ms and 10mA pulse was carried out at KEK-STF and the pulse satisfying the designed value was confirmed. The detail beam property such as emittance, intensity flatness in a macro pulse, orbit fluctuation, etc. should be studied. After boosting up to 40 MeV by the 2K super-fluid He cooled super-conducting accelerator, the beam will be delivered to X-ray generation experiment by Laser Compton scattering.

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