1 ms MULTI-BUNCH ELECTRON BEAM ACCELERATION BY A NORMAL CONDUCTING RF GUN AND SUPERCONDUCTING ACCELERATOR*

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Abstract

KEK-STF (Superconducting Test Facility) has been constructed to establish super-conducting accelerator technology for ILC (International Linear Collider). This facility is also used to demonstrate a high-brightness quasi-monochromatic X-ray generation by inverse laser Compton scattering. For the both purposes, high intensity electron beam in multi-bunch and long macro-pulse formats is important. The beam commissioning has been started since February 2012. 1 ms macro pulse train is successfully generated and 40 MeV acceleration was confirmed. We report the progress of the beam commissioning including the basic beam properties.

INTRODUCTION

Aim of KEK-STF(Superconducting Test Facility)is establish the super-conducting accelerator technology for ILC(International Linear Collider) which is a future project of high-energy physics. In STF, a beam acceleration test will be performed with parameters almost equivalent to those in the real ILC, 8.7 mA average current in 0.9 ms length macro-pulse. In super-conducting accelerator, the input RF power and phase should be well controlled by monitoring RF field of the cavity for stable beam acceleration which can be examined only with a real beam. In ILC beam format, the 3.2 nC bunch is repeated with 369 ns spacing up to 0.9 ms. Total number of bunch is 2625 in a macro pulse. We call this operation mode as ILC mode.

Another purpose of STF is MEXT Quantum Beam project, generating high brightness and quasi-monochromatic X-ray by inverse Compton Scattering[1]. In this case, 62 pC bunch is repeated each 6.15 ns up to 1 ms macro pulse. We call this mode as Q-beam mode.

These high-average and long macro pulse beam formats are generated by a normal conducting 1.3 GHz photo-cathode RF gun. It was originally developed by DESY for FLASH/XFEL[2]. The Gun cavity fabricated by FNAL was installed at KEK-STF. The design peak field of the gun is 50 MV/m at 4.5 MW RF power. Cs_2Te photo-cathode is employed for beam generation. It is prepared as thin-film by evaporation on Mo cathode block in a vacuum chamber (preparation chamber)[3].

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By switching laser systems, the macro pulse in ILC mode and Q-beam mode are produced with this RF gun system. A laser system for ILC mode was developed as a collaborative work between KEK, Hiroshima Univ., IAP, and JINR in Russia in 2010[4][5]. This system is based on 3 MHz Yb fiber oscillator. The pulse train is amplified by Nd:YLF laser pumped by flash lump. 266 nm UV pulse train up to 0.9 ms was obtained as 4th harmonics of the fundamental mode. Another laser system based on 162.5 MHz mode-lock oscillator with MOPA system was developed for Q-beam mode[6]. UV laser pulse train was obtained as FHG by LBO and BBO. Typical UV laser energy per bunch is 500nJ or less.

The STF beam line setup for Q-Beam mode is schematically shown in Fig. 1. 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), etc. SC accelerator boost up the beam energy up to 40 MeV. The beam size at IP (Interaction Point) for laser-Compton scattering after acceleration is designed to be 10μm[7].

In this article, we report successful generation and acceleration of 1 ms macro pulse by this photo-cathode RF gun and super-conducting accelerator.

STF INJECTOR

The injector is based on 1.3 GHz L-band normal conducting RF gun originally developed by DESY for FLASH/XFEL[2]. The design peak field is 47 MV/m with 4.0 MW input RF power. To generate 1 ms long macro pulse with RF gun, suppressing dark-current, i.e. field-emission from the cavity wall, is an important issue. The dark-current should be well below the average beam current in the macro pulse for a stable operation and clear X-ray signal detection from the laser-Compton scattering. The gun cavity conditioning was performed with nominal high power RF processing and ethanol rinse. The detail of the conditioning was explained elsewhere[8][9][3].

The cavity processing was performed in three stages. Between the first and second stages, ethanol rinse for the cavity was performed. The summary of the cavity conditioning was given in Fig.2; The dark current is shown as a function of accelerating field. The dark current was decreased roughly more than an order of magnitude by the

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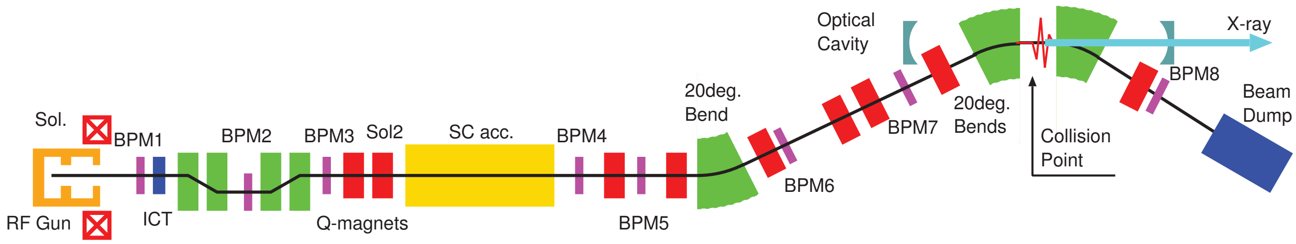

Figure 1: Schematic view of STF beam line. Beam current and position are measured by ICT(Integrated current Transformer) and BPM (Beam Position Monitor). After acceleration by a couple of SC cavities, the beam is focused on IP (Interaction Point) down to 10μm for efficient laser Compton scattering.

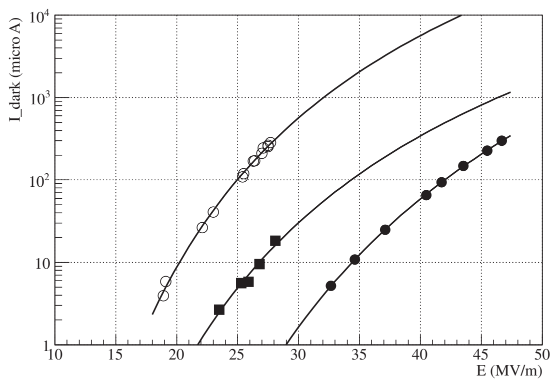

Figure 2: Dark current as a function of field, after first processing(open circle), second processing (filled square) and third processing (filled circle). Lines are expected dark current based on Fowler-Nordheim theorem.

ethanol treatment. Further reduction was observed by high power RF processing. Lines in Fig. 2 show the expectations according to Fowler-Nordheim theorem[10] assuming 4.7 eV work-function of Cu as cavity material. The expectation at 40.2 MV/m was 5.9 mA for first processing, 0.36 mA for second processing, and 0.062 mA for third processing which corresponds to 0.6% of the beam current. The dark current was suppressed by two orders of magnitude by the cavity conditioning.

The laser system for Q-beam mode was developed by Waseda Univ. and KEK for the Quantum Beam mode[6]. IR pulse train is generated by $\mathrm{Nd} : \mathrm{YVO_4}$ mode lock oscillator in 162.5 MHz. The pulse train is amplified by a couple of two path Nd:YLF amplifiers. The CW IR pulse train is then clipped by Pockels cell to form the macro pulse structure, i.e. 1 ms pulse train in 5 Hz. The IR laser energy 17μJ / bunch is achieved. UV pulse train is generated by conversion from IR to UV with non-linear crystals, LBO for SHG and BBO for FHG, respectively. Finally, more than 500nJ/bunch UV laser is obtained.

Cs_2Te cathode was made on Mo plug by evaporation in another vacuum chamber (preparation chamber) connected to the RF gun cavity. After the evaporation, the cathode plug is transferred and inserted to the gun cavity from backside without breaking vacuum. 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 real operation is enhanced by the strong surface field in RF Gun giving more than 2 % QE[11].

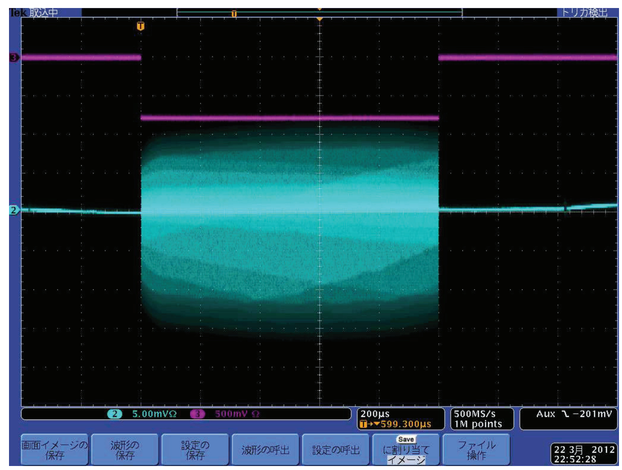

Figure 3: Beam temporal profile taken by BPM2 sum signal.

1 ms BEAM GENERATION

1 ms beam generation test has been started since February 2012. Up to this period, 4.0 MW RF was successfully fed into the RF gun cavity, but the commissioning was performed with 2.0 MW RF for lower trip rate. Starting from 40μs, 1 ms pulse generation from the RF gun was examined. During the experiment, the field in the cavity was typically 33 MV/m. Detail of the tuning was given in Ref.[11]. After the basic beam tuning, number of bunches was gradually increased. After several iterations of the tuning and the bunch number increments, 1 ms macro pulse generation was achieved. Figure 3 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. Square pulse shown above it is the gate signal for laser pulse and has 1 ms duration. The bunch intensity was slightly less than 60 pC measured by ICT output. According to these measurements, it was confirmed that the multi-bunch electron beam with 1 ms pulse duration and very close to 10 mA average current was successfully generated by the photo-cathode RF gun.

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1 ms BEAM ACCELERATION

The beam is accelerated by the SC accelerator. It consists from a couple of 1.3 GHz 9 cells cavities made from Nb with its length 1 m. These cavities are installed in a super-fluid He cooled cryomodule operated in 2 K. The acceleration field is 14.5 and 24.0 MV/m for each cavities[7], respectively. After the injector tuning, the acceleration test was performed with a shorter pulse length. The horizontal beam orbit after the first bending magnet was observed at BPM6 by scanning RF phase of the SC accelerator. The result is shown in Fig. 4. A clear dependence of the horizontal beam position on the RF phase was observed. According to a beam optics design, the crest beam position corresponds to 40.2 MeV/c[12]. The beam acceleration more than 40 MeV was confirmed.

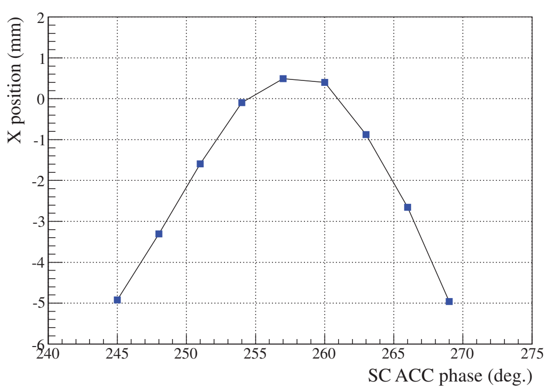

Figure 4: The horizontal beam position by BPM6 is plotted as a function of RF phase of SC accelerator. The maximum position corresponds to 40.2 MeV/c[12].

The final goal of Quantum Beam experiment at STF is demonstrating a high flux quasi-monochromatic X-ray generation by laser-Compton scattering with a compact system. The target value is more than $1.0 \times 10^{10} Photon/sec/1\%BW$. To realize this number, not only amount, but also quality like low-emittance and small spot size at IP are important. The design beam emittance at IP is $0.5\pi\mathrm{mm.mrad}$ and the beam size is $10\mu\mathrm{m}$ in rms for efficient X-ray generation. The bunch length is 12 ps and the bunch charge is 60 pC. The laser pulse stored in the optical cavity has the same 12 ps bunch length with 50 mJ energy per bunch.

The beam size and beam emittance was measured with tungsten wire scanner $10\mu\mathrm{m}$ in radius. This scanner is set at IP on a retractable mount. The emittance was qualified with Q-scan method in horizontal and vertical directions, respectively. The results were 0.82 and 1.34 $\pi\mathrm{mm.mrad}$ for horizontal and vertical directions, respectively. The bunch charge was 35 pC which is almost one half of the designed value. The RF power for RF gun was 3.5 MW giving 40 MV/m peak field . The field gradient of SC accelerator was 14.5 and 24.0 MV/m giving 40.2 MeV beam energy. The measured beam emittance is still twice bigger than the designed value. The beam size was measured directly with the same wire scanner. The results were 36.2 and 36.1 $\mu\mathrm{m}$ in horizontal and vertical directions, respectively. These numbers are still more than three times larger than the designed value, 10 $\mu\mathrm{m}$.

The both beam emittance and beam size are way from the designed numbers. It means that the emittance tuning and the beam optics tuning have to be carefully done. For example, the beam size at cathode should be optimized to minimize the emittance growth by the space charge effect. Solenoid strength should be adjusted for the emittance compensation at the given bunch charge and size. The beta matching should be made at the exit of SC accelerator including the focusing effect.

Although we have demonstrated the quantitative design parameters of the beam, e.g. bunch charge, average current, macro pulse length, and energy, these numbers were achieved not at once. Up to now, the maximum intensity of 1 ms pulse accelerated up to 40 MeV was 6.5 mA corresponding to 40 pC bunch charge. Demonstrating the beam satisfying the all requirements at once is another important mile-stone.

SUMMARY AND FUTURE PROSPECT

At KEK-STF, the beam test to generate 1 ms and 10 mA pulse was successfully carried out. The basic beam parameters such as beam current, macro pulse length meet the requirements. The beam was accelerated by SC accelerator and more than 40 MeV energy was confirmed, but the intensity was 60% of the designed value. The beam emittance was measured as 0.8 and 1.3 $\pi\mathrm{mm.mrad}$ for horizontal and vertical axes, respectively. The beam size at IP was 36 $\mu\mathrm{m}$ which is more than three times larger than the designed value. For efficient X-ray generation, these properties should be improved by progress of the beam and optics tuning.

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