Linac upgrade plan using a C-band system for SuperKEKB

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We are developing a linac upgrade to increase the positron energy from the current 3.5 GeV to 8 GeV for SuperKEKB. For this project, we are considering replacement of the current S-band system for the last three sectors (24 subunits) by a C-band system with six sectors (48 subunits) utilizing the current infrastructure effectively. One unit of a high-power RF source and an accelerator system were newly introduced and processing of the C-band accelerator guide up to 43 MV/m was achieved. Thereafter, an accelerator was installed in the beamline of the KEKB linac to conduct a beam acceleration test. Beam acceleration was successfully performed and the 43 MV/m acceleration gradient was confirmed. The C-band accelerator guide is now in operation in the KEKB linac. A brief description of this project and the current status of R&D are presented in this paper.

1. INTRODUCTION

The KEK B-factory (KEKB) has successfully achieved its targeted luminosity of 1×10^{34} cm^{-2} s^{-1} and has been accumulating valuable data on B-meson physics. Recently, consideration of the SuperKEKB project, which aims to achieve a one order higher luminosity, has been progressing. There are several possible schemes for the injector linac in this project, as described in section 2, and the most likely plan requires a major switch in the beam energies, i.e., a change in the positron energy from 3.5 to 8.0 GeV and in the electron energy from 8 to 3.5 GeV, in order to suppress positron beam blow-up caused by the electron cloud in the ring. At the same time, the positron and electron currents are required to be increased to 1.2 nC and 5 nC, respectively. We are now preparing to upgrade the linac under the assumption of this energy-exchange scheme. In this scheme, it is presently being considered to replace the last three sectors (24 S-band klystron units) with the six sectors using the C-band system (48 C-band klystron units)[1]. Positrons after the conversion target are to be accelerated to 8 GeV using 48 SLEDs and klystrons with 50-MW output.

In this paper, brief description of the entire system proposed for this scheme and recent progress results are presented.

2. SCHEME CONSIDERATION

The present KEKB injector linac accelerates electrons to 8 GeV with 59 accelerator units, including a few stand-by units[2]. The electrons are injected directly into the High Energy Ring (HER) of KEKB. For positron injection, the electrons are accelerated to 4 GeV in the first four sectors (26 units), and then converted to positrons by the metal target. The generated positrons are accelerated to 3.5 GeV in the last four sectors (29 units), and injected into the Low Energy Ring (LER) of KEKB.

For the SuperKEKB plan, which requires an energy change between the electrons and the positrons, the positrons are accelerated to 8 GeV. However the maximum energy gain achieved by all of the existing positron acceleration units is not sufficient for 8 GeV injection. A simple way to achieve the positron energy increase is to use C-band accelerating structures, which have a higher acceleration gradient. The upgrade scheme presently being considered is shown in Fig. 1. In order not to degrade the beam quality as a result of the transition from S-band to C-

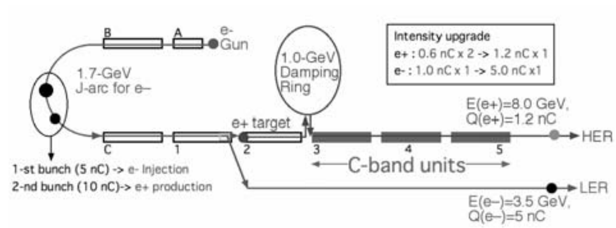

Figure 1 Proposed scheme using C-band system

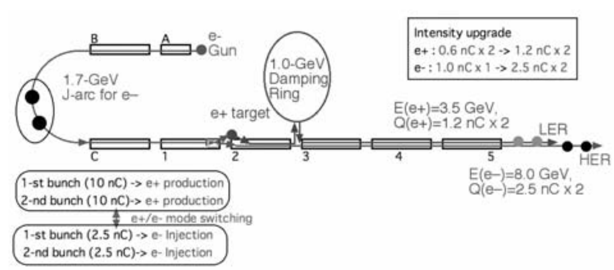

Figure 2 Simultaneous injection scheme using C-band system

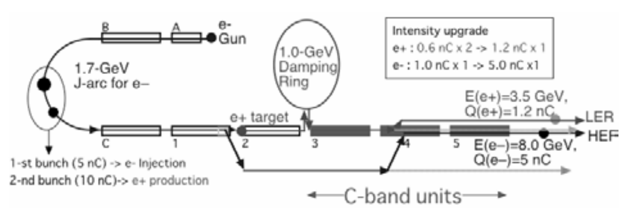

Figure 3 One of the possible schemes using a C-band system if there is no energy change

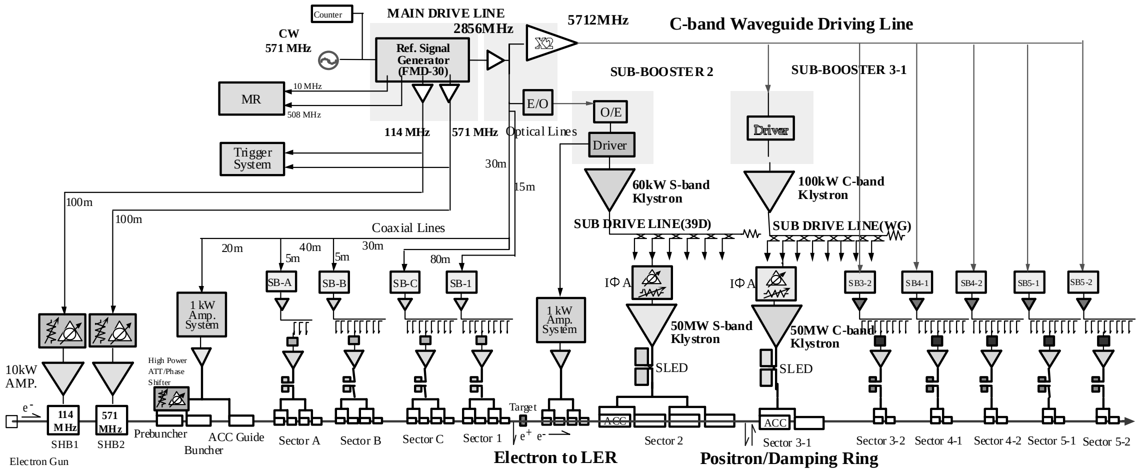

Figure 4 Block diagram of C-band system for SuperKEKB upgrade

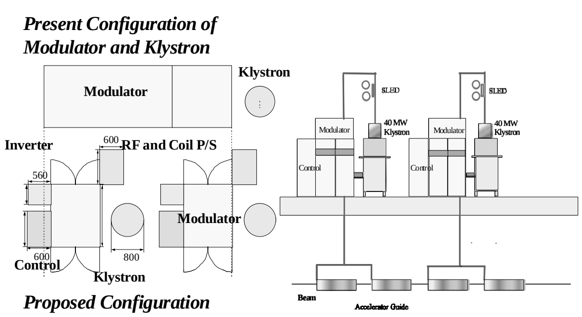

Figure 5 Comparison between the old and new modulators (left) and RF feeding scheme (right)

band structures, a 1.0 GeV damping ring and a buncher are also being considered. Figure 2 shows another scheme involving simultaneous injection of the positrons and electrons to raise the efficiency of injection to the KEKB ring. If the two-bunch operation currently performed in the present S-band system, is also possible in the scheme of Fig. 1, this will be useful for meeting the current increase requirement, which is another requirement of the injector linac for SuperKEKB. If the energy change between the positrons and the electrons is not needed, the C-band scheme is evitable, while there is difficulty in increasing the beam current and it is possible to introduce yet another scheme such as a recirculating beam scheme. Figure 3 shows one of the possible plans using a C-band system for the case of no energy change.

3. PROPOSED UPGRADE PLAN

The plan currently in progress is based on the scheme schematically shown in Fig. 1. The expected RF system is considered to be a complex similar to the current S-band system, as shown in Fig. 4. In order to make use of the existing infrastructures, the modulator is changed so as to use a compact inverter power supply, which charges the existing discharging circuits. This enables us to decrease the modulator size to one-third that of the existing modulator, as shown in Fig. 5, and to install 48 modulators in the existing klystron gallery. In order to utilize the existing building, the development of this compact modulator is inevitable. High-power klystrons required to output 50MW power are commercially available. It is also planned to reuse klystron sockets, such as pulse transformers and oil tanks, since the operating voltage for 50MW output is almost the same condition as for the present S-band klystron operations. The currently designed RF system has a 100kW sub-booster (SB) klystron that drives eight 50MW klystrons to suppress the cost of the individual driver amplifiers.

The accelerator guide is half the scale of that in the current S-band structures and has a 40MV/m acceleration gradient; reuse of the accelerator girders is also being considered. In order to obtain a 40MV/m acceleration gradient, the 40MW output power from the klystron is multiplied by a SLED (a power multiplication of 3.4 at a pulse width of 2 μs), and then fed to two 2 m- long C-band accelerators, which are halh-scale versions of those in the S-band structure. Assuming a filling time of 380 ns and an attenuation constant of 0.703, a peak power of about 59 MW at the entrance of the accelerator guide and an average acceleration gradient of 40 MV/m have been obtained. The SLED is considered to be a CERN-LIPS type[3], which uses the TE_{038} mode having a reasonably high Q-value. This compressor is almost the same size as the current S-band SLED and is expected to effectively utilize the prior manufacturing experience. Table 1 shows a comparison between the S-band SLED and the proposed SLED.

4. C-BAND R&D STATUS

C-band R&D started in the spring of 2002. The short-term goal was to install an accelerator guide in the KEKB linac of #4-4 (where no accelerator was installed) during the shutdown period in the summer of 2003 and to conduct a beam test in the autumn of 2003. We started by purchasing C-band components, since we had no components of the C-band frequency. Several important items for this project were the design and manufacturing of the C-band accelerator, a SiC dummy load, and a waveguide vacuum flange, as well as the construction of an RF system including the development of an SB klystron, a high-power RF window, and a compact modulator. These components were successfully completed by the summer of 2003. A high-power test of the system and processing of the accelerator guide were also completed, and the guide was installed in the beamline of the KEKB linac on schedule.

Table 1 Comparison between S-band SLED and proposed C-band SLED.

	KEKB-SLED	**LIPS-Type**
Resonant mode	TE015	TE038
Diameter	20.51cm	22.19cm(scaled)
Length	33.59cm	29.8cm(scaled)
Frequency	2856MHz	5712MHz
Cavity Q (theory)	107000	146970
Cavity Q (measured.)	97000	127800 (Expected)
Coupling β	6.4	9-11

4.1. Compact Modulator

A compact modulator was a key issue in order to install all of the required units in the existing klystron gallery. A prototype was manufactured using a DC inverter power supply, which charged the Pulse Forming Network (PFN). This inverter's maximum charging voltage was 50 kV, the peak charging current was 1.5 A, and the charging power was 30 kJ. In the PFN, two circuits with 14 inductances (1.55 nH) and 14 capacitances (15.5 μF) each were placed in parallel. The designed flat top was 2 μs and the characteristic impedance of the PFN was 5 ohms. A pulse transformer having a 1:15 step-up ratio gave a 350 kV pulse at maximum to the high-power klystron. Although we faced many problems, which caused the IGBT to break down in the first stage, it has been stably operating for more than 1000 hours up to now. At the same time, R&D work to achieve more stable operation of the inverter power supply has been proceeding.

4.2. 50MW Klystron and Driving System

A simple RF system was used in the test stand, which comprised a 2856MHz signal generator, a frequency doubler, a pulse modulator, an 8 W-transistor amplifier, and an SB klystron. The SB klystron was manufactured by retuning a weather-satellite klystron. From the SB klystron, an RF was fed through a WR-5 waveguide to a Toshiba 50MW klystron (E3746). The klystron socket was used in the same way as in the S-band system, which was possible up to 350 kV if the pulse transformer was rewound from 1:13.5 to 1:15.

4.3. High-Power RF Window

It was necessary to use the RF window to separate the vacuum system between the klystron and the accelerator guide. Although the high-power klystron was equipped with two windows, because of the simplicity of the vacuum system we developed a high-power RF window that was capable of being used at the 50MW power level. This was a mixed-mode window (TE_{11}+TM_{11}) proposed by Kazakov[4]. Using the mixed mode, the field decreased at the ceramic surface and on the edge, where brazing was conducted.

4.4. SiC Dummy Load

It was necessary to develop a dry load, which absorbed the RF power at the exit of the accelerator guide. A SiC dummy load was developed by loading SiC cylindrical materials on the waveguide surface of the E-plane. Two SiC dummy loads set in parallel were successfully tested, as described below.

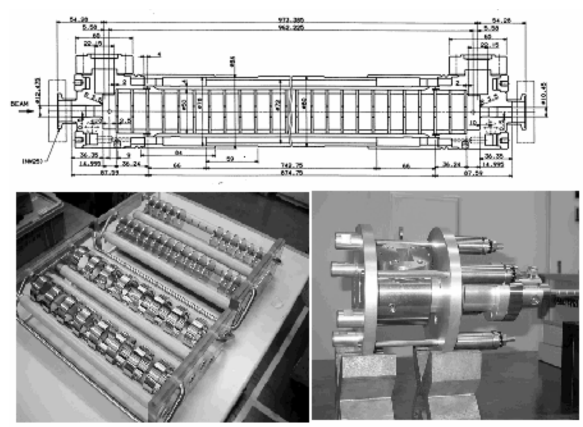

Figure 6 Cutaway view of accelerator (top), disks and cylinders (bottom left), and coupler (bottom right)

4.5. Development of Accelerator Guide

Although the basic design assumed the use of a 2 m-long accelerator guide, a 1 m-long C-band accelerator guide, which was half the scale of the current S-band guide, was manufactured as a prototype. This structure had the same electric property of the last half section of the proposed 2 m-long guide, and 2a (inner bore diameter of accelerator guide) was varied from 12.44 to 10.41 mm. The filling time was 234 ns and the attenuation constant was 0.434. With the conditions of no SLED and 40 MW output power from the klystron, an acceleration gradient of about 39 MV/m was expected. The design was implemented using the HFSS and MAFIA-3D codes. Disks and cylinders were manufactured at KEK and Mitsubishi Heavy Industry (MHI), and electroplating of the regular cells and electron beam welding of the couplers were carried out at MHI. Fig. 6 shows a drawing and photos of the cell and coupler. The second model accelerator guide, which is also 1 m long, is currently being manufactured at the KEK machine factory.

4.6. Test Bench and Test Results

A C-band test station was set in the accelerator assembly hall next to the S-band klystron test hall in the KEKB linac, in consideration of the short distance from the RF source to the shielding room. In this stand, a modulator test was performed in February 2003, and a C-band klystron test was conducted up to an Es (PFN voltage) of 42.5 kV with

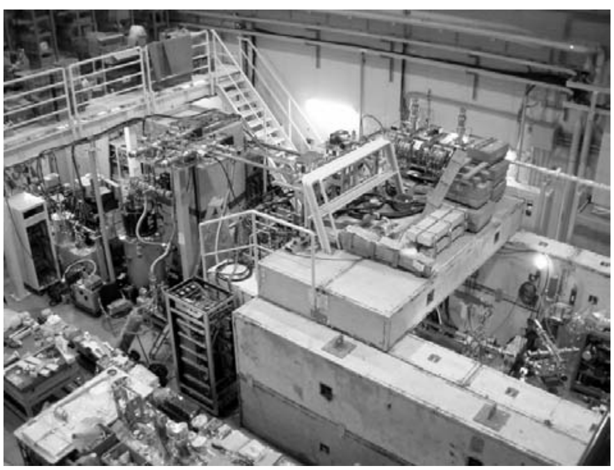

Figure 7 Birds-eye view of test hall

a pulse repetition of 50 pps and a pulse width of 2 μs in March 2003. An output power of 43 MW was measured with two water-loads. Then the klystron output characteristics were measured. We also adjusted the pulse flat top by changing the PFN inductance. Tentatively, 1.3% flatness was obtained. Another adjustment led to a flatness corresponding to a phase variation of 2.6 degrees. Fig. 7 shows photos of the test hall and Fig. 8 shows various waveforms obtained. A resonant ring test of an RF window with a forward traveling wave of up to 160 MW was performed in March 2003, as shown in Fig. 9, which confirmed the high-power capability of a mixed-mode RF window. A high-power test of a SiC dummy load up to 43 MW was then successfully conducted in June 2003.

High-power processing of the 1 m-long accelerator guide was conducted from July to August 2003. This processing was performed under a pattern determined by the program. Interlocks of the internal pressure and the VSWR were used to ensure that the accelerator guide was processed properly. Data such as the processing history, the generated dark current, and waveforms of the reflected power were automatically saved to memory to be used for analysis of this processing. A vibration sensor to detect the arcing position in the guide was set and its data were also saved. Conditioning up to 43.7 MW (corresponding to 42 MV/m) with 50 pps repetition and a 500 ns pulse width (this corresponds to the SLED output power width) was successfully achieved with a reasonable fault rate. Before installation in the beamline, phase shift measurements were performed to confirm no serious damage to the guide. Fig. 10 shows the processing history as a function of the pulse shot numbers.

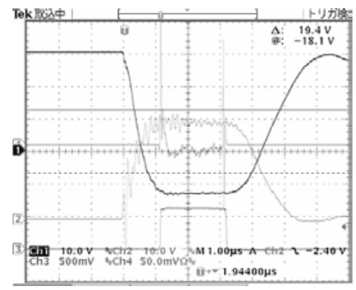

Figure 8 Waveforms: Voltage pulse (top), phase (second), current (third), and output RF (bottom). The horizontal scale is 1μs/div

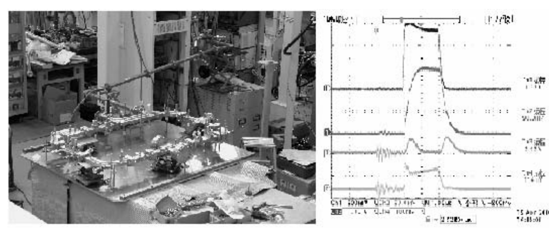

Figure 9 Resonant ring test and waveforms. The second waveform is that of the forward travelling wave

5. BEAM ACCELERATION

After the successful processing and checking of the phase measurement at MHI, the accelerator guide was installed at the end of the summer shut-down period[5]. A second new compact modulator had been manufactured and was already set at #4-4 in summer and tested with a resistive load. The 50 MW high-power klystron assembly and associated driver system were moved from the test stand and installed at #4-4. Figures 11 and 12 show the accelerator guide and the klystron unit installed in the linac tunnel and klystron gallery, respectively. Processing of the accelerator guide was started from the end of

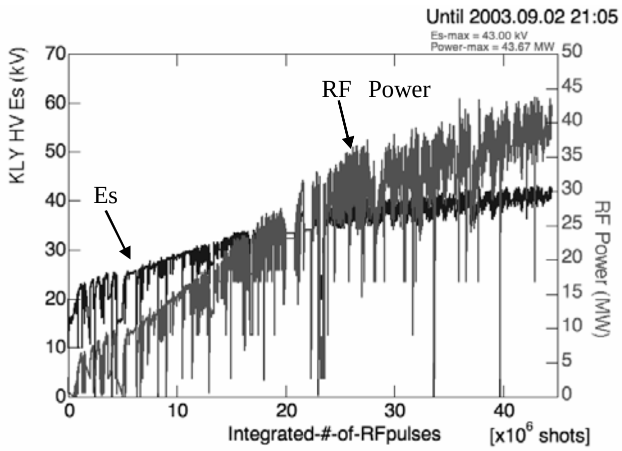

Figure 10 Processing history of the accelerator guide as a function of the RF pulse shot numbers

September 2003 and it was found that the reprocessing was performed quickly even though the structure was exposed to the atmosphere. After a week of processing, the final goal of the 42 MW level was achieved and a beam acceleration using the C-band structure was performed. This beam test was successfully conducted before the KEKB operation started, and the energy gain was analyzed by the analyzer at the linac end in the beam-switching yard. The preliminary data show that the installed 1 m C-band accelerator guide produced an energy of 40 MeV with an estimated measuring error of 5%. This corresponds to an average energy gradient of 40 MV/m at the output power of 42 MW from the klystron, thus we confirmed the design value. Figure 13 shows measuring data of the energy gain with the function of the RF phase and the sinusoidal fitting results. Since this accelerator guide has been kept operating as part of the KEKB injector linac, its long-term reliability has also been able to be investigated. So far it has been observed that the trip rate due to the VSWR is about 5 per hour, which is higher than the existing S-band cases. From the measurements of the acoustic sensor and analysis of the timing of reflected power during the processing, it was found that arcing occurs mainly at the input coupler section. It is therefore necessary to change the input coupler design for the next structure, and this is already under consideration.

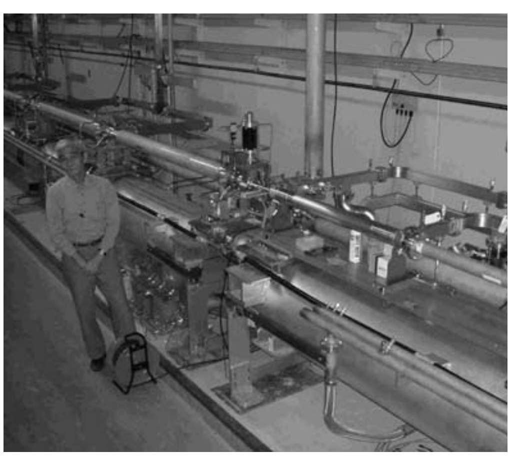

Figure 11 Accelerator guide installed at the #4-4 position

6. SUMMARY

The first test of the C-band accelerator unit, including the RF driving system, klystron, waveguide components, and 1 m-long accelerator guide, was successfully performed for the linac upgrade of SuperKEKB. We installed the accelerator guide in the KEKB linac beamline, and also successfully performed beam acceleration up to 40 MV/m. This C-band system has been operating in the KEKB linac beamline as part of the routine machine operation, and operating data have been accumulated. At the same time, we will prepare a new test stand to test the next accelerator guide and an RF compressor. We plan to install two 2 m-long accelerator guides fed by a 50 MW klystron or four 2 m-long accelerator guides fed by two 50 MW klystrons in the #4-4 station of the klystron gallery This will give us important C-band operation experience as well as an energy contribution to the KEKB operation.

7. ACKNOWLEDGMENT

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Figure 12 Modulator, 50 MW klystron assembly, and SB klystron installed in the klystron gallery

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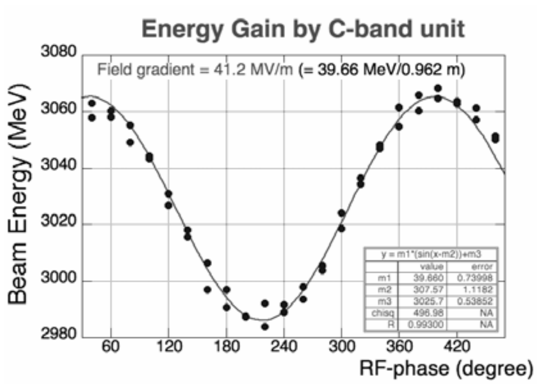

Figure 13 Energy gain measured by changing the RF phase when the output power from the klystron was 42 MW