STATUS OF C-BAND ACCELERATING SECTION DEVELOPMENT AT THE KEKB INJECTOR LINAC

T. Kamitani*, T. Sugimura, K. Yokoyama, T. Takatomi, K. Kakihara, S. Ohsawa, M. Ikeda, T. Higo, N. Kudoh, KEK, Tsukuba, Ibaraki 305-0801, Japan

Abstract

This paper reports on the recent status of the development of a C-band accelerating section for a future upgrade of the KEKB injector linac for the SuperKEKB project. Four prototypes of C-band accelerating sections were developed and installed in the KEKB linac in the summer of 2005. They have been driven by a 50-MW klystron and an rf-pulse compressor and operated for ten months as an accelerator module in the linac. This paper describes the present configuration of the accelerator module and its performance. Also given is the status of the development of a fifth prototype of the accelerating section, which was recently completed.

C-BAND ACCELERATOR MODULE FOR SUPERKEKB

In the SuperKEKB project, the injector linac is required to raise the positron injection energy from the present 3.5 GeV to 8.0 GeV. In order to achieve this, we have been developing a C-band accelerator module which can generate a 42 MV/m accelerating field gradient. This is twice higher than that generated by the existing S-band modules. In this upgrade, it is planned to replace some of the existing S-band accelerator modules (24 out of 58) in the injector linac by C-band counterparts. The length of a C-band module is designed to be half of the S-band equivalent in both the accelerating sections in the linac tunnel and the rf power source in the klystron gallery. The typical energy gain of an S-band module is 160 MeV. It is replaced by two C-band modules, each having 160 MeV energy gain. Thus, the total energy gain of the accelerator modules for positron acceleration is doubled.

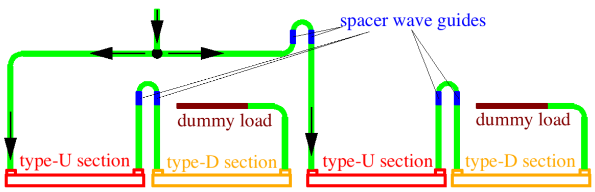

Figure 1: Design layout of accelerating sections.

A C-band accelerator module designed for the SuperKEKB injector is composed of a 50-MW klystron, a compact pulse modulator, a SLED-type of pulse compressor and four 1m-long accelerating sections. In the following, the accelerating section is just denoted as "section". As shown in Fig.1, the four sections are lined up as two pairs of tandem-connected sections through U-shaped wave-guides. The rf power from the pulse compressor split evenly to feed these tandems. The section was initially designed as a single 2m-long structure instead of two 1m-long sections. However, because of constraints in fabrication and the rf-measurement facilities, we adopted tandem-connected 1m-long sections fabricated independently. The weight of a 1m-long section is approximately 30 kg, and one person can lift it up. It is quite easy to handle during installation. Concerning the rf properties, that pair of sections is equivalent to a 2m-long constant-gradient structure. As a whole of the two sections, the disk aperture diameter is reduced linearly along the structures; accordingly, the shunt impedance goes higher, making up for the rf power loss, and producing a constant field gradient. Thus, the section in the upstream part (type-U) and that in the downstream part (type-D) have different rf properties, as listed in Table 1.

Table 1: Accelerating section parameters

	type-U	**type-D**
$2a$, disk aperture [mm]	14.5 → 12.5	12.5 → 10.5
$2b$, cavity diameter [mm]	42.1 → 41.5	41.5 → 41.0
shunt imped. [MΩ/m]	65 → 75	75 → 85
filling time [ns]	135	243
power loss [%]	45	61

C-BAND ACCELERATOR MODULE OPERATED IN THE KEKB LINAC

Since the start of C-band R & D for SuperKEKB in 2002, we have been developed five prototypes of the C-band accelerating section. The fifth prototype has recently been completed, as described in the next section of this paper. In the summer of 2005, we had four sections completed, which were installed in the KEKB linac to form a full set of an accelerator module. Until then, only one section had been installed and tested. Details of these four prototypes are described in [1]. As a consequence of the development of the sections started from the prototype No.1 as a type-D, the prototypes No.2 and No.4 are also the same type. Meanwhile, the prototype No.3 has large disk aperture like type-U. However, due to a limited development period for installing in the KEKB linac, we adopted a constant-impedance structure in order to make the input

* takuya.kamitani@kek.jp

coupler and output coupler dimensions common, as well as the dimensions of all accelerating cavities common. The disk aperture diameter was decided to be 14.5 mm, which corresponds to the dimension of the most upstream part in type-U. As a result, the rf property is different from the original type-U and it is called as type-U0 and has a 106 ns filling time and a 35 percent power loss. Thus, though it was a full set of an accelerator module formally, the configuration of the sections was different from the design layout of two sets of the type-U and type-D pair.

This irregular configuration has two problems. The first one is that the filling time of the first and the second sections (349 ns) differs from that of the third and the fourth sections (486 ns). Rf-pulse from a SLED-type pulse compressor has the shape of a sharp rise and slow down-slope in its time dependence. Thus, the beam-energy gain from the accelerator module is dependent on the arrival timing of an rf-pulse with respect to the beam passage. Generally, the optimum timing is when the peak of the rf-pulse reaches to the end of the tandem accelerating sections. In our case of unbalanced filling times, the optimization cannot be satisfactory.

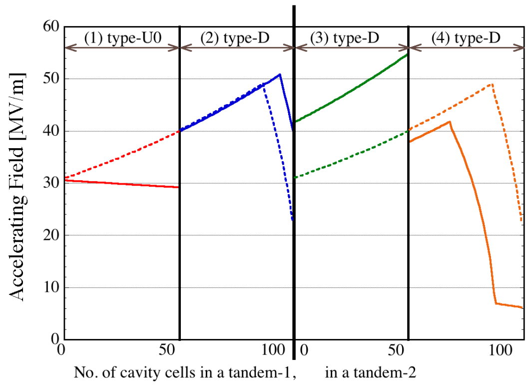

Figure 2: Accelerating field distribution in the accelerator module. Dashed: design configuration case, Solid: present configuration case

Fig.2 shows the accelerating field distribution in the sections for the compromisingly optimized timing. It was evaluated from a calculation based on the cavity cell parameters (shunt impedances, Q factors, group velocities) of the sections and on the measured data of an rf-pulse from the pulse compressor. As can be seen from Fig. 2, the rf power is not sufficiently filled in the latter half of the fourth section, whereas the peak power is close to the end of the second section. If the beam comes in at a later timing, the fourth section is more sufficiently filled, but in the second section the peak power has already gone out. Thus, this unbalanced filling time gives only a compromising optimum. Meanwhile, the field distribution for the design configuration is also shown in Fig. 2 as dashed lines. In that situation, the total energy gain is 3 percent higher. This detriment from the compromise is partly compensated by a higher field strength in the third section. However, there is another problem of the present configuration. Because the shunt impedance in the third section is higher than the design value, the electric field induced there is higher than the design as shown in Fig. 2. This leads to frequent rf breakdowns. Actually, after long-term rf-processing of the sections in the C-band accelerator module, more than half of the breakdowns occurred in the input coupler of the third section.

When plural accelerating sections are driven by a single rf power source, like our C-band accelerator module, it is important to synchronize the accelerating phases in the sections with respect to the beam arrival timings by adjusting the phase lengths to each section. For that the C-band module has no movable phase shifters, the phase lengths were adjusted by fixed-length wave-guide spacers placed in three U-shaped wave-guides as shown in Fig. 1. The lengths of the spacers were determined by a calculation. The coupler structure of the four sections are not the same, because the shape has been improved. Therefore, the phase lengths from the entrance of the input coupler to the accelerating cavity were estimated from data of nodal-shift measurements for each section under some assumption in the detuned short position. However, this assumption was not correct and it resulted in approximately 90 degree phase adjustment error in the phase relationships between the first and second sections, and also between the third and fourth sections. It was evaluated by two measurements. One was an observation of a beam-loading effect in the output rf pulse for each section as a dependence on the input rf phase. The other was a measurement of the rf phases from the beam-induced field and from the input rf. These measurement gave consistent results which clarified the phase adjustment error. Some of the wave guide spacers were replaced by those with re-adjusted lengths. Finally, the phase lengths in synchronous to beam arrival were adjusted within an error of 15 degrees.

Since installation of this full-set accelerator module, it has been operated for ten months. A recent beam-acceleration study showed that the beam energy gain from this accelerator module is 141 MeV at a klystron output power of 42 MW, which corresponds to 36.5 MV/m of the average field gradient. This is almost consistent with a prediction of 144 MeV from the calculation. After a modification to the design configuration of two sets of type-U and type-D pairs, the gain is expected to be 149 MeV. This is slightly less than the specification of 160 MeV for SuperKEKB. We will consider an improvement in the rf power multiplication factor of the pulse compressor. After rf-processing in this long-term operation, the recent klystron trip frequency due to rf breakdown is approximately once a day at a klystron output power of 36 MW. It is the same level of trip frequency compared with other S-band modules in the KEKB linac. The estimated field gradient is 34 MV/m at this rf power. At a higher power level, the frequency increases. At 42 MW klystron output power, where we carried out a beam-acceleration study, the frequency is more than 20 times a day.

FABRICATION OF THE PROTOTYPE NO.5 ACCELERATING SECTION

In pararell with the long-term operation test of the C-band accelerator module, the prototype No.5 accelerating section was developed. It is a type-U section in order to replace the present third section of type-D which suffers from a too-high electric field. The coupler structure and the fabrication technique of prototype No.5 are almost similar to those of prototype No.3, which has a smooth shape around the coupler iris, and its coupler cavity surface was electropolished. We believe that the shape and the surface treatment are effective for reducing the breakdown frequency.

Regular accelerating cavity cells of the C-band accelerating sections are connected by copper electroforming conducted at room temperature. It has a merit that the electroformed copper layer has higher rigidity compared with that fabricated by silver- or gold-brazing conducted at high temperature. Instead, the resonant frequencies of the cells cannot be changed by deforming. As a result, prior to the electroforming process, the frequencies should be adjusted by tuning the cavity diameter to a precision of 1 micrometer by ultraprecision lathe machining. In a constant-gradient type section, disk aperture of the cavities gradually decreases along the section, and the shunt impedance rises to keep the field gradient at the same level. According to the disk aperture diameter (2a) decreases, the cavity diameters (2b) also decreases to have the correct resonant frequency. To avoid multiple trials and errors during fabrication, it is important to have precise information of this 2a-2b relationship. For the case of the type-D section, it was originally designed as the precise half-scale dimension of an existing S-band section, the relationship had been known, and given as a polynomial function. However, for the case of type-U section, it does not have such a correspondence. The relationship was estimated by interpolating the data for the type-D section and type-U0 section as a form of fitted polynomial function. Considering that this estimation has a finite error, all of the cavity diameters were machined to be 20 micrometer smaller than the predefined design values in order to check the precision of frequency tuning by nodal-shift measurements. The data are given in Fig. 3(a).

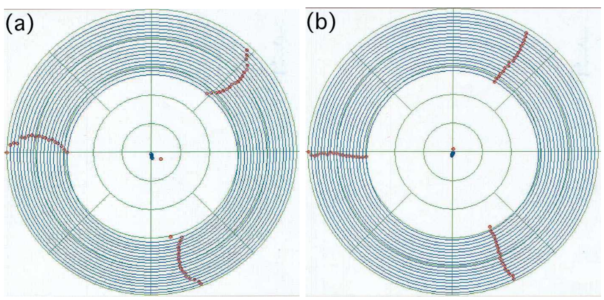

Figure 3: Nodal shift data of prototype No.5: (a) before the correction in the 2a-2b relationship and (b) after the correction.

Because the cells are $2\pi/3$-mode cavities, the data points are aligned as three series of straight lines separated by 120 degrees in phase angle in a well-tuned condition. The measured data has curved lines of the points. This reflects that the phase advance is not uniform, and that the resonant frequency is not well tuned, except for the overall shift by 20 micrometer smaller dimensions. To correct for this error, at first the correlation factor of the phase advance upon the resonant frequency is estimated by comparing data taken at two different frequencies. Then, in each of three series of data points, the correction factors in phase angles were estimated to obtain a straight alignment. The dominant tendency of the correction factors is expressed as a linear function. From these two kinds of factors, any errors in resonant frequencies and correction in cavity diameter 2b were estimated. The corrections in 2b dimensions were approximately -2 micrometer in the most upstream cell of the section and +2 micrometer in the most downstream cell. Taking this correction into account, final machining was conducted and the nodal-shift data after it is shown in Fig. 3(b). It shows that the data series line up almost in straight lines, and the differences in resonant frequencies were corrected.

After copper electroforming and TIG-welding of the water-cooling jacket and of the beam-hole plunger to the structure, prototype No.5 was completed. Then, rf processing of the section was carried out in a test stand in June, 2006. A klystron feeds its whole output power in this section; however, because the pulse compressor is not equipped in the test stand, the maximum rf power is 46 MW. The pulse width was changed in three steps: 100, 300, 500 ns. The klystron trip frequency was less than ten times a day after four weeks of rf processing. This section was installed in July, 2006 to replace the third section, which has been operated in the KEKB linac. Operation in this new configuration will start in Setember, 2006. By this replacement, an excessive high field in the third section is reduced, and it will contribute to reduce the rf breakdown frequency. The unbalance of the filling times is also partly improved. The energy gain will increase by a few percent by rf pulse timing optimization.

SUMMARY

Four prototype C-band accelerating sections were installed in the KEKB linac in the summer of 2005 and have been operated for ten months. The average acceleration field gradient of 36.5 MV/m has been achieved so far. Improvements in the breakdown frequency and in the energy gain are expected by replacing one of the installed sections by the fifth prototype section in July, 2006.

REFERENCES

[1] T. Kamitani et al., "R&D status of C-band Accelerating section for SuperKEKB", PAC2005 conference, Knoxville, Tennessee, USA, June May 16-20, 2005.