UPGRADES OF S-BAND ACCELERATING STRUCTURES AND PULSE COMPRESORS IN THE ELECTRON AND POSITRON INJECTOR LINAC OF KEK

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Abstract

New S-band disc-loaded TM_{01}-2π/3-travelling-wave structures and pulse compressors have been developed for upgrades of the injector linac for SuperKEKB and Photon-factory storage rings in KEK. The structures 2-m long have ingenious disc irises with oval fillets reducing discharge in high-power operation and modulations in radius suppressing beam break-up instabilities arising from HEM_{11} wake fields. The pulse compressors are of compact spherical-cavity-type resonating at the degenerate TE_{112} dipole mode with a high Q-value of 98,000 and yield a peak power gain of 6.2. The structures generate an acceleration gradient of 25.9 MV/m in power operation of 40 MW by using the pulse compressor and stably accelerate a two-bunch beam with a bunch charge of 4 nC.

INTRODUCTION

S-band accelerating structures were produced about 40 years ago and have been operated in the KEK electron/positron injector linac [1]. Recently a lot of them have suffered from frequent discharges and water leaks due to aging deterioration. They are the obstacles to stable beam injection to the rings. The inside observation of the structures with a rigid scope [2] and the cutting investigation into severely damaged ones [3] demonstrated that repairing or reconditioning to recover them would be severely difficult. Therefore, we started to develop a new S-band accelerating structure as a substitute for the deteriorated.

SLED-type pulse compressors (KEK-SLED) have been used for about 30 years and enhance peak power for the structures to generate an accelerating gradient of 20 MV/m for the KEKB project [1]. Since the SLED structure is complicate and its production cost is high, we have developed an S-band spherical-cavity-type pulse compressor (SCPC) since 2020 approximately at half the cost of the KEK-SLED [4]. At the rated RF operation (2856 MHz, 40 MW, 4 μs, 50 Hz) in the linac, we need a pulse compression ratio of 4 on average for the structure filling time.

ACCELERATING STRUCTURE

RF Design

The specifications of the new disc-loaded structure are shown in Table 1. Figure 1 shows the schematic cross-sectional view and a photo of the structure. The body length and the connection flanges were the same as those of the old one in consideration of compatibility. The edges of the disc irises are formed elliptically with a ratio of 1:2 and reduce their electrical surface field strength by approximately 20% lower than the that of circular edge. A beam-accelerating electric field of 25.9 MV/m is generated with a rated input power of 40 MW.

Table 1: Structure Specifications

Operating frequency [MHz]	2,856
Accelerating mode	TM_{01}-2π/3
Type	Quasi-CG
Number of regular cells	54
Coupler	Single-feed type
Cell iris diameters [mm]	23.340 – 19.234
Attenuation constant [Neper]	0.366
Effective shunt impedance (mean) [MΩ/m]	61.7
Unloaded Q	14,000
Mean group velocity/speed of light	0.0117
Filling time [μs]	0.570
Energy gain [MeV/$MW^{1/2}$]	7.87
Flange-to-flange length [mm]	2,064

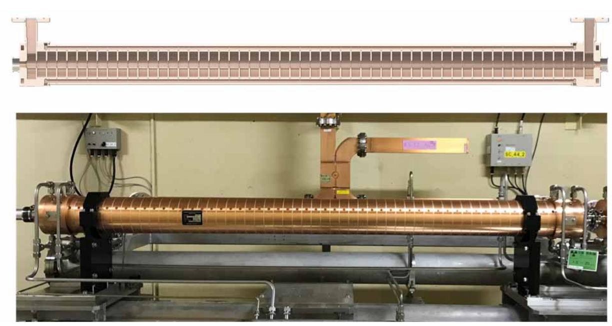

Figure 1: Cut-off schematics (Upper) and the structure installed in the injector tunnel (Lower).

Two-bunch beams with a maximum bunch charge of 4 nC should be accelerated and injected to the SuperKEKB storage rings. The time interval between the two bunches is 96.29 ns reflecting the operating frequency of a sub-harmonic buncher upstream of the injector. In order to stably accelerate the high-charge two-bunch beam, we must suppress the beam instability arising from coupling impedances of dangerous higher-order modes. The disc iris diameters were so elaborately set as to generate the sufficient beam-accelerating voltage and to suppress the instability. The HEM_{11}-π like modes of the cells have the highest

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transverse impedance near 4.3 GHz. The frequencies of the HEM_{11}-π like mode change linearly over 122.3 MHz so that the wake fields excited by the first bunch beat in the structure and make a node after 96.29 ns as shown in Fig. 2. Therefore, the next bunch feels the wake fields reduced by a factor of 1/1000 under coupled-mode approximation.

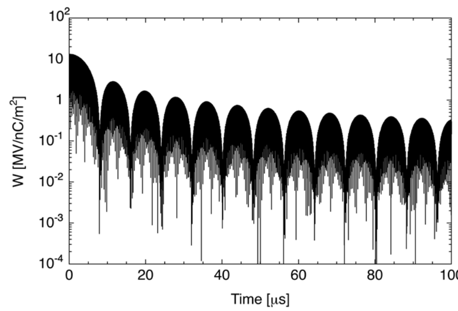

Figure 2: Wake function of HEM_{11}-π like modes.

The coupler has no sharp edges inside in order to decrease discharge and pulse heating over the inner surface of the coupler. The field asymmetry arising from the coupling iris is corrected by a recess on the other side of the power-feeding iris as shown in Fig. 3.

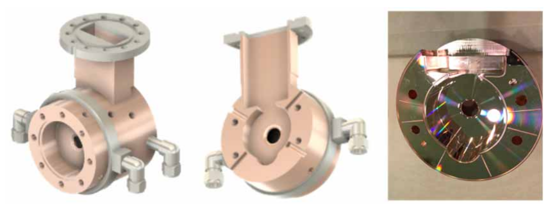

Figure 3: Schematics of the coupler and a photo of the coupler cell.

Fabrication and Low-power Measurement

HIP-treated class-1 OFHC copper was used as the material for the structure body. Machining with an ultra-precision lathe has a major dimension tolerance of ±5 μm or less, the surface roughness of discs and cylinders except their iris parts was less than Rz 0.1. The surface of the disc iris was finished at less than Rz 0.3. All the discs and cylinders were alternately piled up and jointed by silver brazing. After the brazing, we tuned the structure by dimpling each cell. The deterioration in unloaded Q by dimpling stays within 3%. The other RF parameters were equivalent to the designs.

High-power Operation

Four pilot structures were fabricated in 2020 and tested in a high-power test bench. After the structures were evacuated to a level of 10^{-6} Pa by ion pumps, they were conditioned by high-power RF waves. The rated operation power for the beam acceleration is 40 MW, but we plan to run them with a power of 80 MW or more in the future. The conditioning power was raised up to 100 MW but limited due to vacuum deterioration in a dummy load downstream of the structure. It took 463 hours (including the interlock pause time) to reach 100 MW with a pulse width of 0.5 μs, and 80 hours to reach 96 MW with a pulse width of 1 μs. The pilot structures, which have been conditioned up, were installed in the injector tunnel and are in beam acceleration as shown in the later section.

PULSE COMPRESSOR

RF and Mechanical Designs

The developed pulse compressor has a significantly different structure from the KEK-SLED currently used in the injector as shown in Fig. 4. The compressor comprises of a spherical single-cell cavity and a three-port waveguide polarizer. The cavity can store high energy and resonates in the TE_{112} mode with a high Q value. The input and output ports of the polarizer are WR-284 rectangular waveguides in TE_{10} mode. The input power flows into the ϕ72 cylindrical port of the polarizer in circularly polarized TE_{11} mode and excites rotating TE_{112} mode in the cavity. This rotating state can be regarded as degeneration of two TE_{112} modes whose planes of polarization are orthogonal to each other and whose phases are different by 90°. It is important to ensure the excitation of the degenerated resonance in order not to degrade the pulse compression ratio.

Table 2 shows the RF characteristics of the SCPC which have the same as those of the KEK-SLED in consideration of compatibility of RF operation [1].

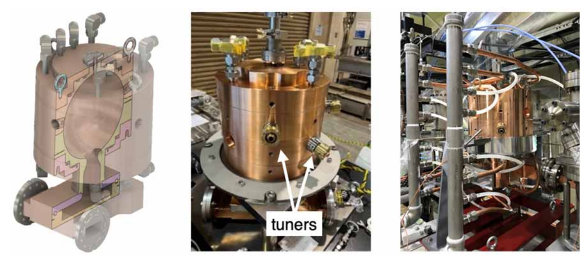

Figure 4: SCPC schematics with a cut-off view (Left), fabricated body (Center) and setting in the test-stand (Right).

Table 2: SCPC RF Characteristics

Operating frequency [MHz]	2,856
Resonant mode	Spherical TE_{112}
Unloaded Q	100,000
Coupling constant β	6.4
Peak compression ratio	6.2
Input pulse length [μs]	4.0
Phase-reversed length [μs]	1.0
Input power [MW]	40

Fabrication and Low-power Measurement

Figure 5 shows the manufacturing process. The SCPC consists of six main parts machined from class-1 OFHC copper by using a diamond-bit precision lathe. We took two-step silver brazing for the fabrication.

In the first step, we formed two hemispherical cavities and the polarizer. Cooling water channels were formed in the cavity bodies. The two hemispheres were temporarily assembled to form a spherical cavity with a cylindrical port in between. The RF characteristics of the temporary cavity were measured through the port by using a mode converter [4]. The resonant frequency was adjusted repeating the measurement and correction machining. The degenerate state was confirmed by rotating the mode converter and measuring the S_{11} parameter. When the mode is in degeneration, the measured unloaded Q is constant regardless of the rotation. After the tuning, the overall assembly was finished by the second step of silver-brazing. The frequency and degeneration changed by the brazing was precisely tuned by dimpling to the operating frequency with detachable dimpling tuners (up to eight locations as in Fig. 4) for pushing or pulling. Although the unloaded Q of the fabricated SCPC was 98,000 and approximately 2% lower than the design value, the effects on the compression ratio and energy gain were small.

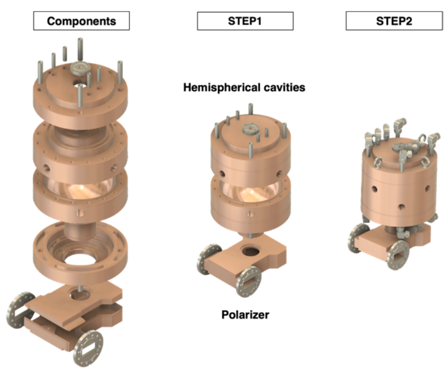

Figure 5: SCPC components and fabrication steps by silver brazing.

High-power Operation

The SCPC was conditioned in the high-power test stand. The high-power operation was successfully performed up to a peak output power of 80 MW with a compressed pulse width of 1 µs and a repetition of 50 Hz. It took 340 hours for the SCPC to steadily operate at the power. The maximum output power was restricted lower than the design value because of discharge in dummy loads installed downstream of the SCPC.

BEAM ACCELERATION

Before beam acceleration, the frequency of the SCPC installed in the injector was tuned again on site according to conditions such as operating cooling-water temperature and klystron output. As shown in Fig. 6, the measured output waveform of the SCPC was compared to that evaluated from the input during high-power operation. Monitoring these waveforms in real time, the measured was adjusted to overlap with the evaluated by the tuners and the reflection power from the SCPC was minimized. After completion of the tuning, we measured the beam-accelerating voltage by the two structures driven with the SCPC. Figure 7 shows the measured beam-energy gain by the two structures. The beam energy changed sinusoidally with respect to RF phases of the structures and the gain of the structure was exactly the set value of 40 MeV.

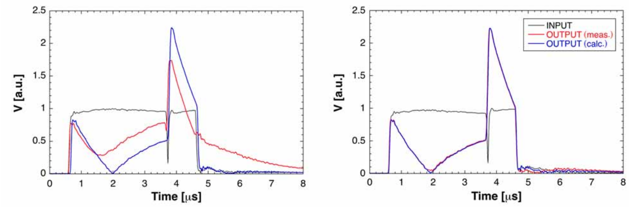

Figure 6: Input and output voltages of the SCPC before tuning (Left) and after tuning (Right) in the high-power RF operation. Black, red, blue lines are the input, measured output and evaluated waveforms, respectively.

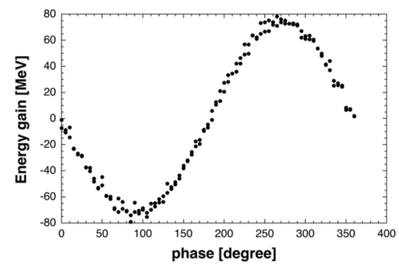

Figure 7: Beam energy gain by the two accelerating structures as a function of the RF phase of the structures.

CONCLUSIONS

We have developed new S-band accelerating structures to replace with the malfunctional old ones suffering from aging deterioration. The four pilot structures have the RF characteristics as expected. The S-band spherical single-cell cavity-type pulse compressor was also developed and tuned adequately. The operations at an RF power of 80 MW or more were succeeded for both the structure and the SCPC. They were installed in the injector and are stably in beam acceleration of 20 MV/m. We have finished mass-produced 12 structures in the spring of 2023 and plan to install them in the injector after conditioning.

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REFERENCES

[1] I. Sato *et al.*, "Design report on PF Injector Linac Upgrade for KEKB", KEK Report 95-18, Mar. 1996, in Japanese.

[2] T. Higo *et al.*, "Surface inspection and high gradient performance of S-band accelerator tubes used for 20-30 years at KEK," in *Proc. 13th Annual Meeting of Particle Accelerator Society of Japan*, Chiba, Japan, Aug. 2016, pp. 853-857.

[3] T. Higo *et al.*, "Inspection of inner surface of S-band accelerating structures of KEK electron-positron injector linac used for more than 30 years," in *Proc. 15th Annual Meeting of Particle Accelerator Society of Japan*, Nagaoka, Japan, Aug. 2018, pp. 455-459.

[4] T. Higo *et al.*, “RF characteristics view of construction of spherical-cavity-type pulse compressor,” in *Proc. 18th Annual Meeting of Particle Accelerator Society of Japan*, Takasaki, Japan, Aug. 2021, pp. 546-550.