PRECISE MEASUREMENT OF SUPERCONDUCTING CAVITY MOVEMENT IN CRYOMODULE BY THE POSITION MONITOR USING WHITE LIGHT INTERFEROMETER

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Abstract

Alignment of superconducting cavities is one of the important issues for linear collider and/or future light source like ERL and X-FEL. To measure the cavity displacement under cooling to liquid He temperature more precisely, we newly developed the position monitor by using white light interferometer. This monitor is based on the measurement of the interference of light between the measurement target and the reference point. It can measure the position from the outside of the cryomodule. We applied this monitor to the main linac cryomodule of Compact ERL (cERL) [1-3] and successfully measured the displacement during 2K cooling with the resolution of 10 μm.

INTRODUCTION AND MOTIVATION FOR DEVELOPING NEW MONITOR

R&D of superconducting cavity and cryomodules are in progress for next generation light source like energy recovery linac (ERL) and a future linear collider. For these accelerators, not only the cavity performance like high accelerating field and quality factor but also the precise cavity alignment for the beam axis is necessary to generate the high quality beam and keep highly stable beam operation. For example, linear collider requires the cavity alignment within 0.3 mm to the beam line to reduce the emittance growth by cavity misalignment. To set the superconducting cavity to the design orbit precisely, we need to know the displacement under cooling to He liquid temperature. The wire position monitor was developed to know the cavity movement precisely during cooling down and beam operation [4,5]. This monitor is based on a stretched wire in a coaxial transmission-line arrangement. Wire position monitor, which has two vertical strip-line electrodes and two horizontal strip-line electrodes and surrounds the wire, is equipped near the cavity inside the cryomodule. The wire are fixed at the two endcaps of the cryomodule, which are room temperature parts of the cryo-vessel. Like a beam position monitor, relative transverse movement of the cavity to the cryo-vessel is measured by detecting the relative transverse position between the cavity and wires. Its precision is a few μm. However, the measured data were unstable and not reliable because of the large thermal excursion of cable. connector and feedthrough of this monitor [6]. Furthermore, we have experienced the wire break under cooling of the cryomodule by thermal shrink.

Laser based position monitor based on the triangulation was used in commerce [7] and recently used for measurements of the displacements of the components like He gas return pipes set in cryomodule movements [6]. This laser based monitor can be set outside the cryomodule and viewed the components via the view-port of the cryo-vessel. It worked well with enough resolution (10 μmlevel), if the working distance between the cavity and the monitor is very short with several cm-length. However, in reality, cavity was set far from the outside of the cryo-vessel. Furthermore, the large aperture of view port for this monitor needs to measure the cavity position due to the principle of the triangulation technique and causesthe large thermal radiation to the superconducting cavity. It is difficult for this laser based monitor to measure the cavity displacements directly under cooling to He liq. temperature. This situation led us to develop a new position monitor based on the interference of laser and/or white light, named as WLI monitor. It makes possible to measure precise cavity position from the outside of the cryo-vessel, via a small view port.

In this paper, we first describe the principle of this monitor. Next we express the performance of this monitor tested at the test stand. Then, we show the results of the displacements of superconducting cavity in the cryomodule of cERL main-linac during 2K cooling. Finally, wesummarize the actual performance and future plan of this newly developed WLI monitor.

PRINCIPLE OF WLI MONITOR

The principle of WLI monitor is shown in Figure 1.

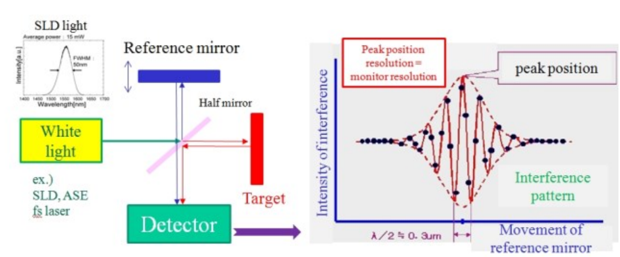

Figure 1: Principle of the WLI position monitor.

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White light with a broad spectrum is divided by a half mirror and one light is reflected by a target and the other by a reference mirror. These paths of two lights merged again at a half mirror and the interference pattern is detected by the detector during scanning the reference mirror. This method is called as "low-coherence interferometry" [8] and the interference pattern appeared when the optical path difference of two lights is smaller than the coherent length of white light source as shown in the right figure of Figure 1. Especially, the intensity of light of the interference is maximized only when the distance between the half mirror and reference mirror equals that between the target and half mirror. While we keep the peak detection under scanning the reference mirror precisely at every second, we know the relative displacement of the target at every second. The resolution was basically determined by the coherent length of white light. Recently, the interference measurements of long distance of more than 700 m can be achieved by using frequency-stabilized comb of fs laser with less than 10 μm resolution [9]. If we shorten the measurement length of less than 1 m, we'll achieve the resolution of 0.3 μm of a half of the wavelength of light.

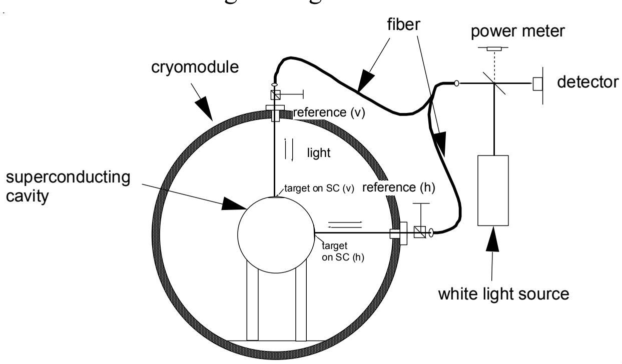

Figure 2: Schematic drawing of WLI monitor setting to cryomodule.

We show the schematic drawing of this monitor set to the cryomodule in Figure. 2. One white light source provides the two directional measurements of one superconducting cavity position by setting each reference target horizontally and vertically. The distance between cryo-vessel and the cavity is about 500 mm. The light source and the detector are set far from the cryomodule and light is transmitted via a fiber. There are many features and merits of WLI position monitor as follows.

1. Thanks to the white light interferometry, we can set the monitor and measure the cavity position directly from the outside the cryo-vessel even if the distance between the cavity and the cryo-vessel is far from more than one meter.
2. If the precise scanner is prepared for the movement of the reference mirror, the resolution of this monitor will be achieved less than 1 micron and the large dynamic range can be obtained by setting the movement of the scanner range larger.
3. When the monitor was broken, we easily repaired the sensor without opening the cryomodule.
4. Small aperture of view ports can be placed for monitoring and thus reduce the thermal radiation.
5. By using higher intensity white light and/or laser, we can improve the resolution of WLI monitor.

PERFORMANCE TEST OF WLI MONITOR AT A TEST STAND

Prior to setting of the WLI monitor to the cryomodule, we carried out the performance test at a test stand by using the critical optical components for the WLI monitor.

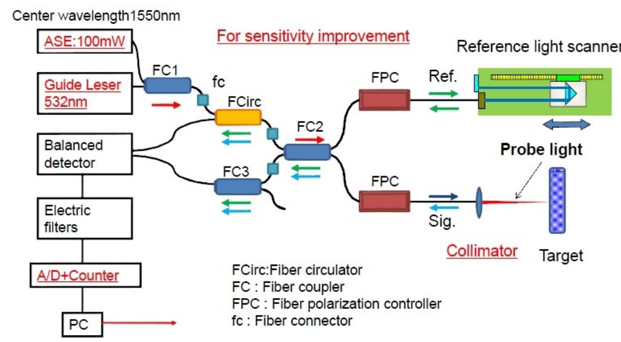

Figure 3: Setup of the WLI monitor at a test stand.

Figure 3 show the setup of test stand for WLI monitor. We used the ASE light source of 100 mW for a white light source to increase the laser power and satisfied our required resolution of less than 10 μm. All optical paths except for that near the target and the path of the reference light scanner are given by the optical fiber made of quartz. The power of light was divided by fiber coupler (FC) to the reference and to the target. The forward and reflected power adjusted by the fiber polarization controller (FPC) and fiber circulator (FCirc). Finally the path length of reference line was controlled by the scanner with less than 1 μm resolution and reproducibility. The dynamic range of more than 100 mm was obtained by moving this scanner. The interference of the reflected lights between the reference and the target was measured by the AD counter on PC via the balanced detector with the electric filter as a function of the position of the reference light scanner.

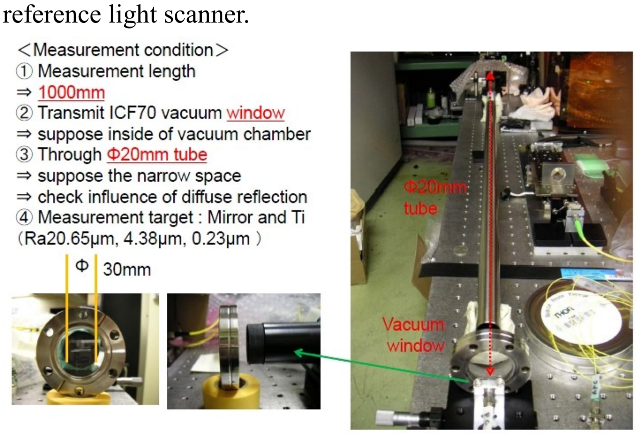

Figure 4: Picture of the setup from the collimator to the target of WLI monitor at the test stand.

Figure 4 shows the setup of WLI monitor especially from collimator to the target of WLI monitor at test stand. In order to demonstrate the performance of WLI monitor at the condition of cryomodule, the optical path from the collimator to the target kept 1 m length and were covered by the stainless steel tube with a small aperture of 20 mm diameter. We also set the view port of ICF70 flange with 30 mm diameter on this optical path. Target was made of Ti, which was same as the material of the He jacket of the superconducting cavity. We measured the interference pattern by changing the roughness of target and the incident angle of light to the target.

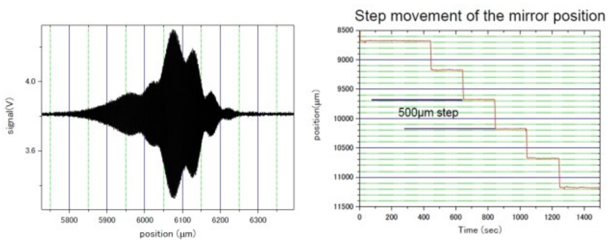

Figure 5: (Left) Measured interference pattern at a test stand. (Right) measured peak position of the interference pattern by changing the reference scanner.

The left figure of Figure 5 shows the measured interference pattern at a test stand by using Ti target with the roughness of 4.38 micron and the incident angle of 0 degree, which denoted that the incident light was perpendicular to the surface of the target. The interference pattern was not symmetry according to the position. This is because the spectrum of the ASE light was not the Gaussian shape. In spite of this asymmetric interference pattern, the peak position of the interference was stable under the continuous scanning. In order to check the accuracy of the measurement, we measure the peak position of this interference pattern by moving the reference scanner every 0.5 mm step as shown in the right figure of Figure 5. The relative peak position movement of the interference pattern perfectly matched the relative scanner movement. We found that the resolution of this monitor was 2 micron even if the optical path from the target to the collimator was as long as 1m length.

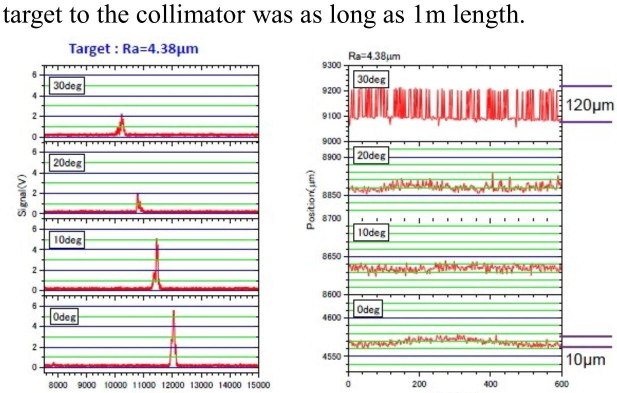

Figure 6: (Left) Measured interference pattern with the different incident angle. (Right) measured stability of the peak position of the different incident angle for 10 min.

We surveyed the dependence of the incident angle of the light to the target. The left figure of Figure 6 shows the interference pattern respect to the incident angle with same target as shown in Figure 5. As the incident angle larger, the peak intensity of the interference pattern became smaller. Due to the small intensity of larger incident angle of more than 30 degree, the resolution of this monitor became worse as shown in the right figure of Figure 6.

Table 1: Measurable peak intensity of interference pattern

Roughness of the target (Ra)	Range of incident angle
20.95 μm	0-30degree
4.38 μm	0-30 degree
0.23 μm	0-20 degree

We summarized the measurable peak intensity with the different parameters of the target as shown in Table 1. As the roughness was smaller, the sharper interference pattern was observed; the measurable range became smaller. We do not need the large incident angle for the cryomodule test. We, therefore, selected the smaller roughness of 4.38 μm to obtain higher resolution of WLI monitor. We noted that the resolution did not depend on the material of the target.

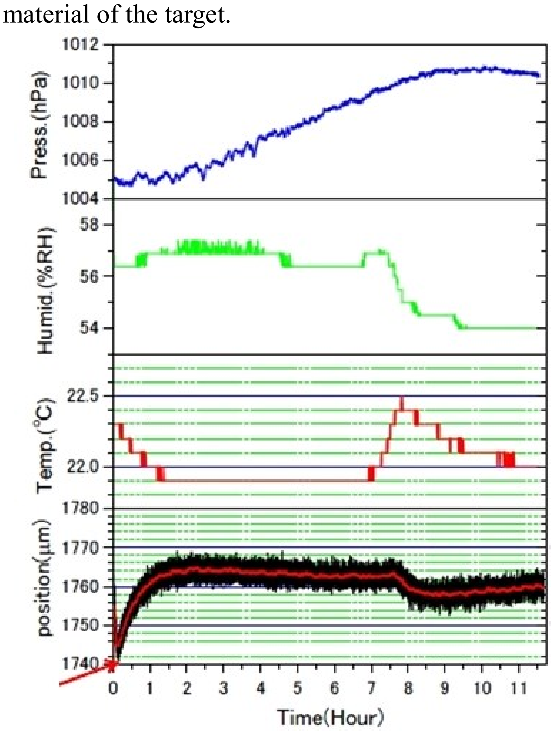

Figure 7: Long-term stability of the WLI monitor.

Finally, we measured the long-term stability by using same target at this test stand as shown in Figure 7. The bottom figure of Figure 7 shows the measurement of the position from the interference pattern. The above three figures from top side in Figure 7 show the pressure, humidity and temperature around a test stand, respectively. The initial movement of position monitor come from the warm-up of the ASE light. We have no correlation between the position and air pressure. But we found the correlation between the position and temperature and/or

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humidity. We could keep the measured accuracy with 5 μm for 12 hours and satisfy our requirement under controlling temperature of less than 0.6 degree accuracy. Especially, temperature dependence is severe for WLI monitor.

MEASUREMENT OF THE CAVITY DISPLACEMENT IN CRYOMODULE UNDER 2K COOLING

After the performance test, we installed the WLI monitor to the cERL main-linac cryomodule to measure the displacement of superconducting cavity under cooling down from room temperature to 2K.

cERL is a test facility, which is now being constructed on the ERL Test Facility in KEK. Its aim is to demonstrate technologies needed for future multi GeV class ERL. One of critical issues for ERL is development of the superconducting cavities. At the first stage of cERL, minimum version of ERL will be constructed and electron beams of 10 mA will be accelerated up to 35 MeV. One main linac cryomodule with two 9-cell cavities have been constructed.

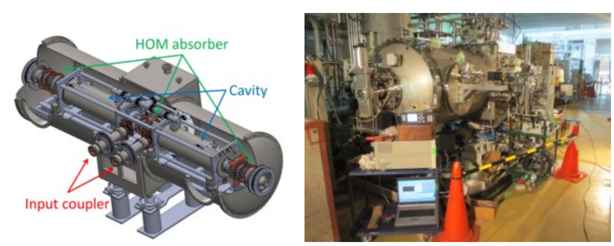

Figure 8: (Left) Schematic view of cERL main linac cryomodule (Right) Picture of cERL main linac cryomodule at cERL beam line.

Figure 8 shows a schematic view and a picture of the main linac cryomodule, which contains two 9-cell KEK ERL model-2 cavities [10,11] mounted with He jackets. Other important components like HOM absorbers [12] and coaxial input couplers [13] were equipped to perform the stable cERL beam operation. The detailed performance of this cryomodule including the high power test was shown in ref. [3]. The detailed structure and cooling parts of cryomodule, set at the deferent temperature regions, are explained below.

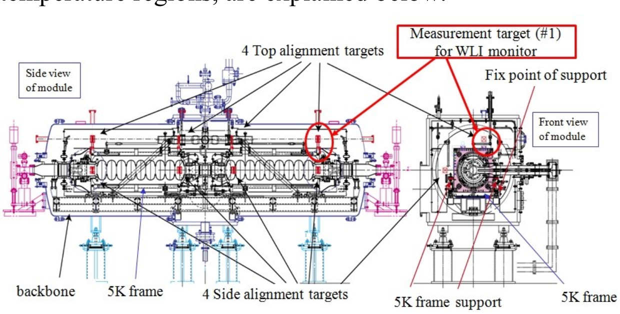

Figure 9: Detailed cross sections of the cERL main linac cyomodule with 8 alignment targets including the target (#1) for WLI monitor.

Figure 9 shows the detailed cryomodule structure of cERL main-linac with 8 alignment targets. Cooling pipes of 80K, 5K and 2K are extended throughout the cryomodule. The 80K line was cooled by Nitrogen, and 5K and 2K lines were cooled by Helium. After filling with 4K liquid He, insides of the He jackets were pumped down and the cavities were cooled down to 2K. To keep the precise alignment, two cavities were supported by Ti frame with 5K He line, called as 5K frame. And this 5K frame was supported by the large girder (backbone) set at 300K via 5k frame supports. The magnetic shield was equipped to this 5K frame.

The eight optical alignment targets were set at the known position on the 5K frame to measure the transverse movements of cavities. Four targets were set on the top part of 5K frame at each end of the cavities and arranged at the same transverse position to the beam axis. Other four targets were set the side parts of 5K frame with the same manner. These targets consisted of the quartz with a cross line and Al supports. Viewing the cross lines of these optical targets through the view port by the alignment telescope under cooling, we could catch up the movements of cavities. The resolution of the optical target was about 0.1 mm.

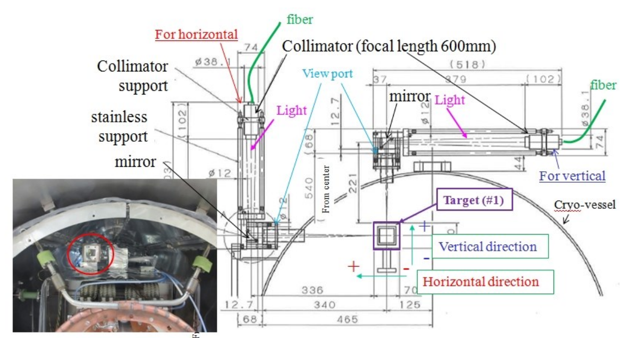

Figure 10: Setup of WLI monitor around cERL main-linac cryomodule. Red circle in the picture shows the optical target (#1) used for WLI monitor.

The target #1 in Figure 9 was used for monitoring the movement of cavities by the WLI monitor. Figure 10 shows the detailed setup of WLI monitor around the cERL main linac cryomodule. The horizontal and vertical side of the target #1 was monitored. The roughness of the side of the target made of Al was 1.6 μm. The both path lengths between the collimator and target were 600 mm, which equal the focal length of the collimator. The dynamic ranges of 30 mm for this WLI monitor were available. The collimators were fixed to the cryo-vessel of this cryomodule by the stainless supports. Other parts of WLI monitor were same as the setup of Figure 3 except for the fiber length between the FC2 and the collimator (the reference mirror), which was 3 m length. The white light of ASE light source of 30mW went through each fiber, mirror and view port and the reflected white light at the target #1 interfered with the reflected light at the reference mirror as shown in Figure 3. We note that the thermal and phase stabilized fiber was used for WLI monitor to improve the performance of this monitor.

The left figure of Figure 11 shows the measurement results of the horizontal and vertical movements under cooling to 2 K temperature with respect to the temperature of 5K frame for more than 3 weeks from the starting cooling down. The horizontal and vertical directions of target movements were explained by the green arrows near the target in Figure 10. The red and blue dots in Figure 11 show the horizontal and vertical movements measured by WLI monitor, respectively. The red open circles and blue open triangles in Figure 11 show the horizontal and vertical movement measured by the alignment telescope. The green line in Figure 11 shows the temperature at 5K frame. It took 2 weeks for cooling down to 2K because the following cooling strategy was required; (1) the HOM absorbers should be cooled down slowly, to avoid cracking on ferrite absorbers. Slope of 3K/hour was required. This rate was used for cooling test of the HOM absorbers. (2) Large temperature difference was avoided among each cooling lines. Typically it was required to be less than 50K. We noted that the cooling by liquid He stopped for about 8 hours in the midnight and the cooling by liquid nitrogen continued for 24 hours.

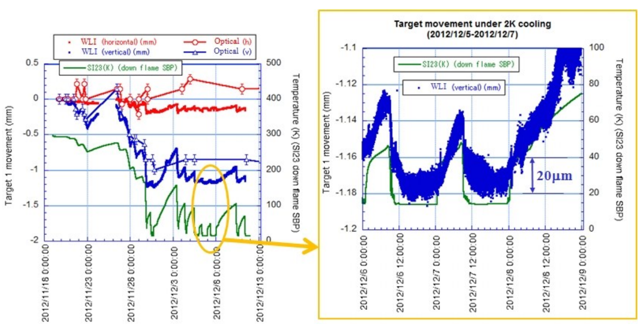

Figure 11: (Left) Measurement results of the movements of target #1 together with the 5K frame temperature (Right) Expanded view of the measurement results of left figure in orange circle. The left and right vertical axes of both figures show the measured target movements and the measured temperature of 5K frame, respectively.

We found that the horizontal and vertical movements of target #1 from room temperature to 2K were 0.2 mm and 1.1 mm, respectively. These values almost agreed well with the measurements by the alignment telescope as shown in the left figure of Figure 11. From these results including all target measurements [3], the displacements of cavity center, from room temperature to 2K, were estimated to be less than 0.5 mm. This value is within our alignment tolerance [14]. We show the measurement results under 2K cooling in detail as shown in the right figure of Figure 11. We found that the clear temperature correlation with temperature of 5K frame was observed and if the temperature of 5K frame was stable, superconducting cavity with 5K frame was stably set within 10 μm for 12 hours. This means our WLI monitor has less than +- 5μm for 12 hours.

There are some comments about these measurements using WLI monitor for cryomodule. The temperature of the cERL beam line was not stable for first 2 weeks under cooling from room temperature to 2K. Therefore, we found that the temperature dependence of WLI monitor was also appeared for first two weeks. Figure 12 shows the results of the measurement of target for first one week with respect to the temperature of the ASE light source and near the reference fiber and target as shown in Figure 12. We finally found that this temperature dependence of the measured position come from that of the spectrum of ASE light source. After keeping temperature stable, measured data was stable as shown in the right figure of Figure 11.

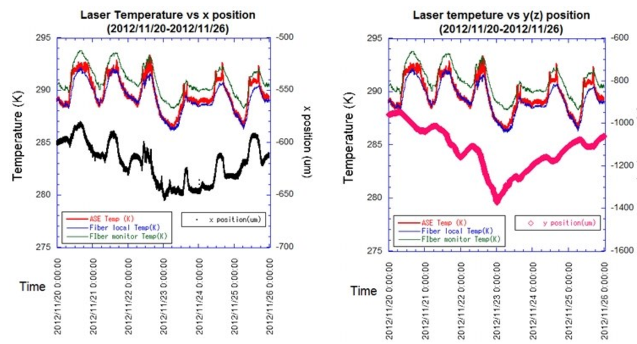

Figure 12: Measurement results of target #1 by WLI monitor (Left) horizontally and (Right) vertically.

This WLI monitor was set inside the cERL beam line to shorten the fiber length. Therefore, we needed to set the whole system including PC inside the cERL beam line. During high power test, unfortunately, we had to stop the measurement to escape them from the radiation come from the cryomodule. During warming up of the cryomodule, we restarted the position measurement of cryomodule. We noted that after warming up, the measured position returned to the original position.

SUMMARY AND FUTURE PLAN

We newly developed the position monitor based on white light interferometer. Prior to install WLI monitor to cERL cryomodule, we carried out the performance test at the test stand to demonstrate the performance of the WLI monitor. We found that the resolution of this monitor was 2 μm, in spite of the optical path from the target to the collimator of 1 m length. We also kept the measured accuracy with 5 μm for 12 hours under controlling temperature within 0.6 degree accuracy in this test stand. After the performance test, we installed the WLI monitor to the cERL main-linac cryomodule to measure the displacement of superconducting cavity under cooling down from room temperature to 2K. We found that the horizontal and vertical movements of target set in cryomodule from room temperature to 2K were 0.2 mm and 1.1 mm, respectively and agreed with the measurements by the alignment telescope. We also found that the clear temperature correlation of the measured position. This accuracy had 5 μm.

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In 2013, cERL will start the beam operation with main linac. To keep monitoring during beam operation, we plan to improve the WLI monitor to replace the whole monitoring system except for the collimator set the cryomodule to the outside of the radiation shield.

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REFERENCES

[1] S. Sakanaka et al., "Progress in Construction of the 35MeV Compact Energy Recovery Linac at KEK", IPAC'13, Shanhai, China, May 2013, p.2159-p.2161 (2013).
[2] K. Umemori et al., "Status of Main Linac Cryomodule Development for Compact ERL Project", IPAC'12, New Orleans, USA, May 2012, p.67(2012).
[3] H. Sakai et al., "High power CW tests of cERL Main-linac cryomodule" THIOC02 in these proceedings, Paris (2013).
[4] D. Giove et al., "A wire position monitor (WPM) system to control the cold mass movements inside the TTF cryomodule," Proceedings of PAC1997 (PAC97), pp.3657-3659.
[5] N. Eddy et al., "A Wire Position Monitor System for the 1.3GHz TESLA-Style Cryomodule at the FERMILAB new-muon-lab Accelerator", SRF'2011, Chicago, July, 2011, p.806 (2011).
[6] Edited by N.Toge et al., "S1-Grobal Report", KEK Report 2013-3 (2013).
[7] LK-2000 series; Keyence K.K., Higasiyodogawa-ku, Osaka, 533-8555, Japan.
[8] R.C. Youngquist, et al., Opt. Lett, 12 (1987) 158-160.
[9] J.Lee et al., Nature Photonics, 4 (2010), 716-720.
[10] K. Umemori et al., "Design of L-band superconducting cavity for the energy recovery linacs", APAC'07, Indore, India, Feb 2007, p.570 (2007).
[11] K. Umemori et al., "Vertical test results for ERL 9-cell cavities for compact ERL project", IPAC'12, New Orleans, USA, May 2012, p.2227(2012).
[12] M. Sawamura et al., "Cooling properties of HOM absorber model for cERL in Japan", SRF'2011, Chicago, July, 2011, p.350 (2011).
[13] H. Sakai et al., "High power tests of KEK-ERL input coupler for main linac under liquid nitrogen condition", SRF'2011, Chicago, July, 2011, p.356 (2011).
[14] N. Nakamura et al. proceedings of IPAC10, Kyoto, p2314 (2010).