REVIEW OF OPTICAL INSPECTION METHODS AND RESULTS

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Abstract

The inspection of inner surface of the superconducting rf cavities is essential in achieving high accelerating gradient. The high resolution camera system developed by Kyoto-KEK collaboration is a good tool to survey defect locations and to analyze a defect shapes in the inner surface of the cavities for boost accelerating gradient yield of 1.3 GHz superconducting 9-cell cavities. The heights or depths of observed surface defects can be estimated by examining the patterns of shades which are created by the lighting system which allows to illuminate the cavity surfaces with varying light angles by selecting a series of strip-line illuminators in steps. A good correlation has been so far observed between the hot spots localized by thermometry measurements in the vertical test and the positions of surface defects found by this system.

The cavity surface study with this camera system started in FY2008, and so far, the ACCEL, ZANON, AES and MHI cavities have been examined in KEK, DESY and FNAL. Other camera systems are developed in J-Lab, LosAlamos and Cornell etc.

This report will have a summary of inspection system in the world, and present the inspection method and results.

INTRODUCTION

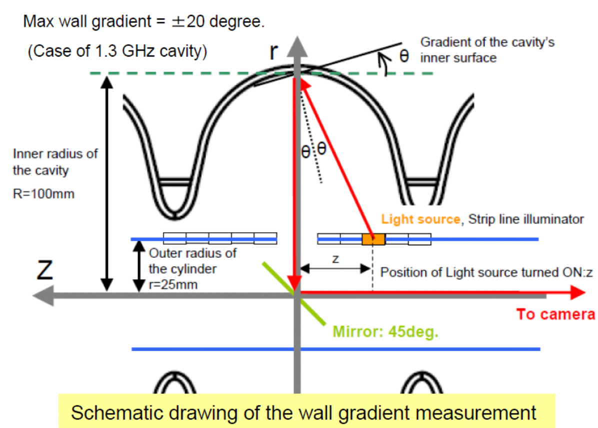
The high resolution optical inspection system is developed to search defects and measure the shape of them for better yield of accelerating gradient of superconducting 1.3 GHz 9-cell cavities. This method is useful tool to understand field limitation of one by combination of T-map. The goal of the study is to have reference to estimate a cavity performance by inspection.

The high resolution camera system is important for industrialization of cavity fabrication to make a suitable production control (Surface inspection of material, EBW inspection and surface treatment inspection etc.). So far, the inspection systems are adopted at labs around the world.

Kyoto Camera System

This inspection system is developed by a KEK-Kyoto-university collaboration with the goal of looking into the relation between the achievable field and the surface quality of the cavities in the context of technical R&D for the future International Linear Collider (ILC) project. The new KEK-Kyoto system has pushed forward this technique by implementing a mechanism that allows to semi-automatically examine the entire inner surfaces of multi-cell cavities with a much better resolution with the capability of measuring the three-dimensional sizes of the observed defects in a non-destructive measurement, which was very difficult in the past.

The system consists of a high resolution CMOS camera and a custom-made lighting system, and is built within a cylinder that has a diameter of 50 mm, fitting within the tight aperture of L-band (1300 MHz) 9-cell superconducting cavities. The achieved optical a resolution is about 7.5μm/pixel. Three dimensional sizes of observed surface defects are determined by examining the images obtained under varying light angles, which can be achieved by selecting a series of strip-line illuminators in steps [1, 2]. Image of the Kyoto camera system is shown in Figure 1. This system is adopted at KEK, DESY and FNAL from 2008 (see Figure 2, 3 and 4).



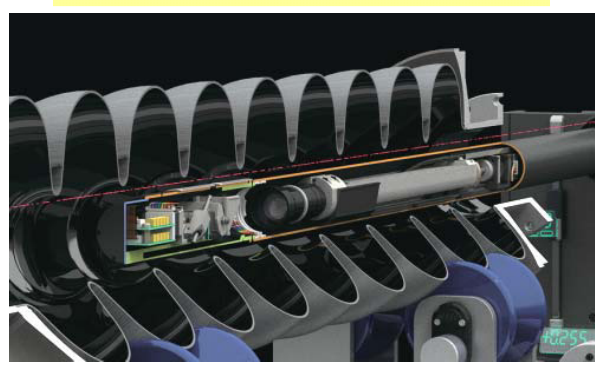


Figure 1: Image of Kyoto camera system

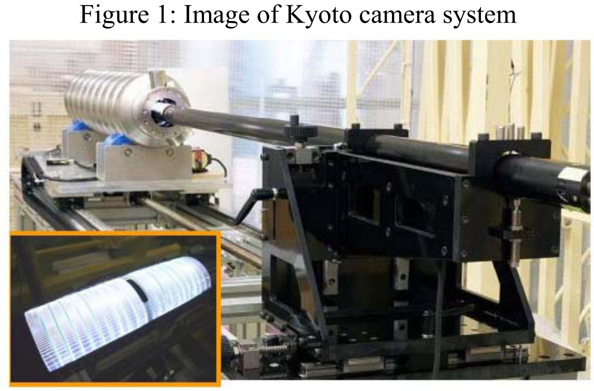


Figure 2: KEK system

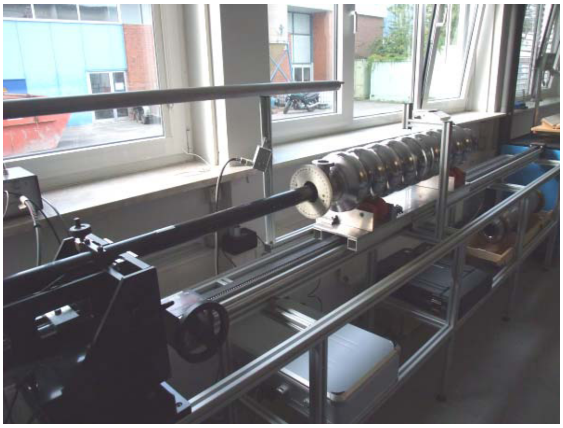


Figure 3: DESY system

Figure 4: FNAL system

J-Lab and Cornell-University System

J-lab inspection system is adopted the cavity inspection tool based on long-distance microscope. The J-lab system is shown in Figure 5 [3, 4]. The high resolution camera is putted in outside cavity, and inspected from end of beam pipe. The achieved optical a resolution is better than 3μm/pixel at 22 inches. The mirror and illuminators is equipped on the cylinder pipe, and this cylinder can moved z-axis by rail and step motor.

Cornell university inspection system is also adopted the questar long-distance microscope. The Cornell university system is shown in Figure 6 [5, 6]. The Questar long-distance microscope is on the left outside of cavity. Coaxial with the cavity is a white cylinder, which contains an integral mirror and light source for viewing the inner surface of the cavity.

Los Alamos System

LANL system is based on Karl Storz TechnoPack^{TM}X Videoscope inspection system [7]. The videoscope has 1/10 inches CCD with 250,000 pixels in an aspect ratio of 16:9 horizontal to vertical. There is a plan to motorize the rotation and the movement of scope tip with a computer. Also there is a plan to integrate the system with a high pressure rinsing (HPR) system so that the cavity can be inspected right after the HPR in the clean room. The LANL system is shown in Figure 7.

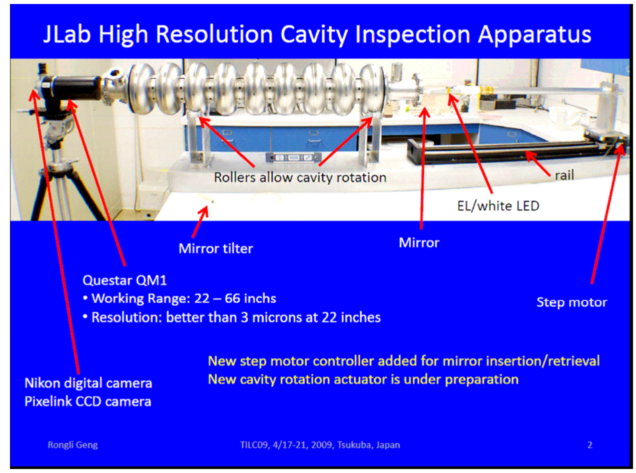


Figure 5: J-lab system

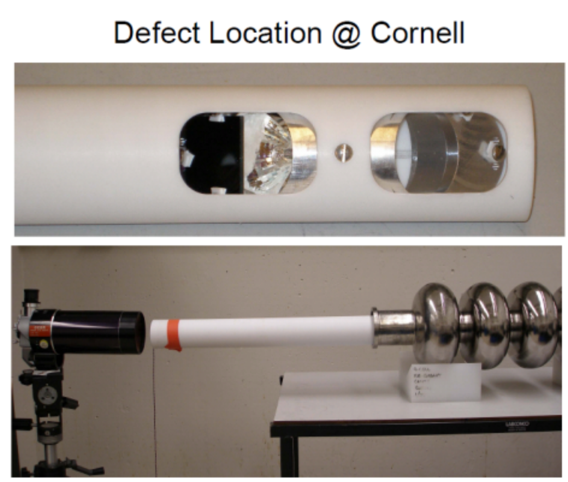


Figure 6: Cornell university system

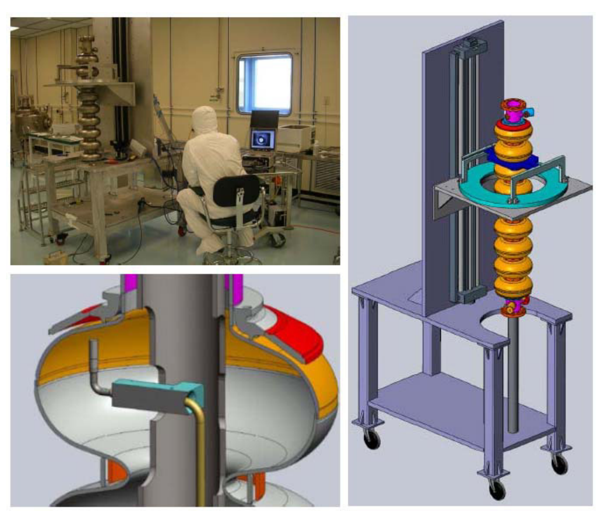


Figure 7: Los Alamos system

INSPECTION DURING CAVITY TEST

For example, the inspection method and procedure in KEK-STF will be explained in this section.

Inspection during cavity test after fabrication is shown as following,

1) 1st inspection at "As received".
2) 2nd inspection after bulk EP process then shape analysis and mark of suspicious spots. (See Figure 8)
3) 3rd inspection after vertical test with T-map results (in case of bad cavity performance and T-map detected a heating location).
4) Consider a counter measure for next test. Molding of defect, Local grinding and rinsing method etc.

Of course, all EBW seam of equator and iris and outside weld area are inspected all stages. The masureable of wall gradient by Kyoto camera system is about ±20 degree. Sometime, found a defect can not be measured the wall gradient due to very higher (or deeper) defect. In this case, the molding method is useful tool to make a shape analysis for the defect (see Figure 9). To use this replica, the shape analysis is very easy by using the laser microscope, and the test of local grinding for the defect also can be done to use this replica. Developed the local grinding machine is shown in Figure 10.

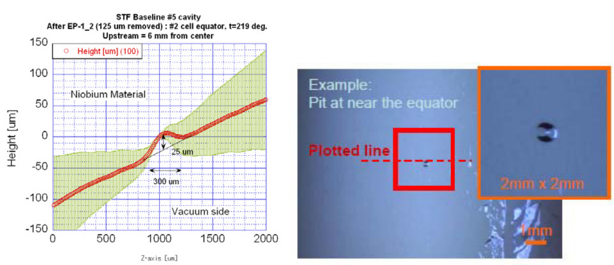


Figure 8: Example shape analysis of suspicious spot.

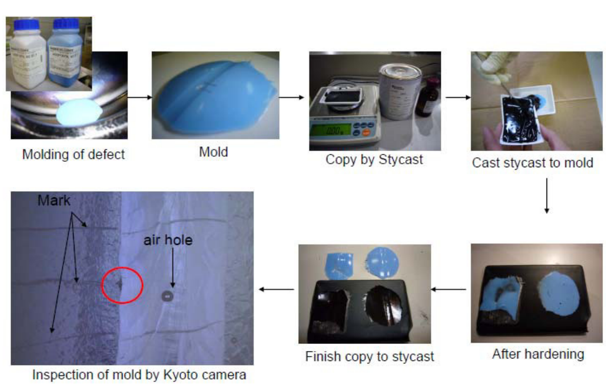


Figure 9: Molding and copy method.

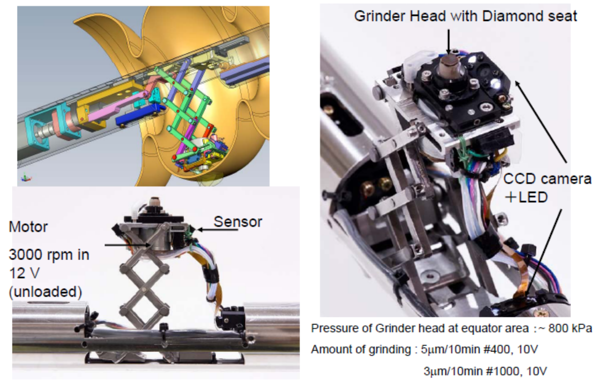


Figure 10: Local Grinding machine.

Inspection Before Vertical Test (Example of MHI-08)

All EBW seams of equator and iris and the outside weld area were inspected again before vertical test. If defect was observed, then make the shape analysis and mark on outer surface, and make a map of these defects. The map of defects of the MHI-08 is shown in Figure 11. The MHI-08 had two suspicious pits at outside weld area of equator. The EBW seams of the MHI-08 had no defect in this time. The thermo-sensors were attached on the mark of suspicious pits in the vertical test (see Figure 12) [8].

Inspection After Vertical Test with T-Map Results (Example of MHI-08)

The 1st vertical test of MHI-08 carried out at June 2009. Result of vertical test is shown in Figure 13, 14 [9]. The cavity performance was 16 MV/m in pi-mode. T-map detected a hot spot in pi-mode at 2-cell equator, and the angle which center of heating was about 180 degree. Reason of field limitation was quench at 2-cell equator. The performances of other cells were achieved more than 25 MV/m. Marked suspicious spots were no heating in vertical test. After vertical test, the cavity was disassembly, and inspected at hot spots with T-map result. The result of inspection is shown in Figure 15. A pit type defect was found at hot spot location by T-map. Size of defect was about 700 x 500 um, and the depth of defect could not measure by Kyoto camera system due to steeply wall gradient. However, the inspection before vertical test at this location was no defect. A pit was made after EP-2 process. A defect like this hot spot was not found at other EBW seam of equators.

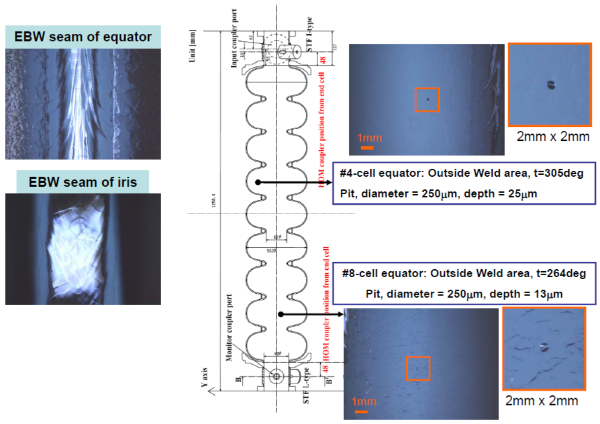


Figure 11: Make a map of suspicious spots before vertical test. (Before 1st vertical test of MHI-08).

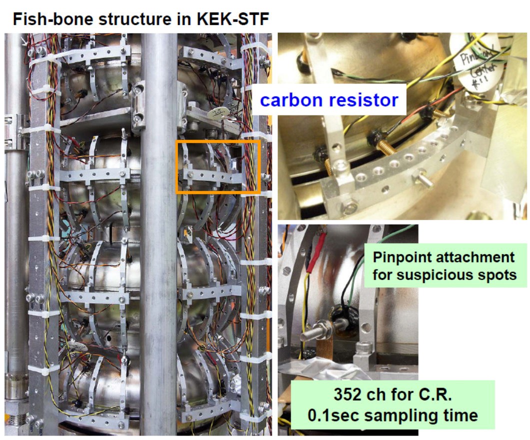


Figure 12: Setup of T-map.

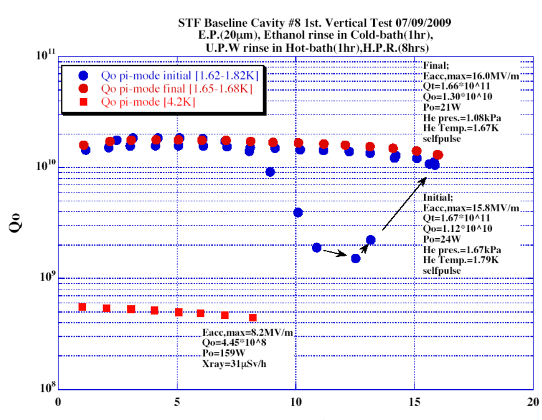


Figure 13: Result of 1st vertical test of MHI-08.

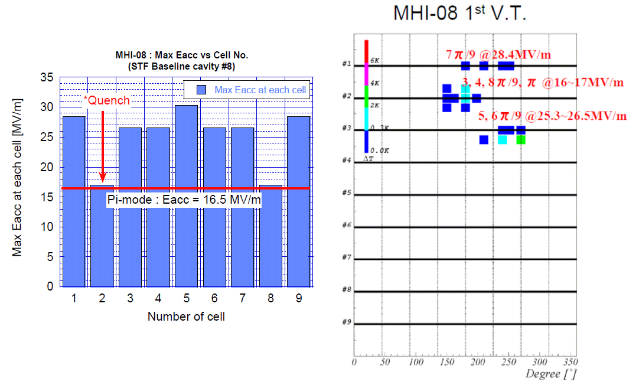


Figure 14: Results of passband measurement and T-map of MHI-08.

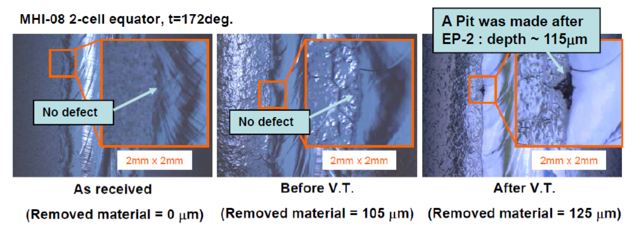


Figure 15: Inspection of after vertical test at hot spot location.

To obtain the information of the defect, the molding method was applied for MHI-08. The mold material used "WACER DENTAL ADS931" (the material is silicones.). The image of replica and result of shape analysis by laser microscope is shown in Figure 16. The depth of the defect was about 115um. "How to make a defect in this case" is not yet understood.

If a cause of field limitation for MHI-08 is really this pit type defect, then the cavity can repair to remove the defect by mechanical grinding method. The local grinding machine with diamond sheets was used to remove the defect. The process of grinding is shown in Figure 17. The location of defect is boundary between EBW seam and heat affected zone (red circle in Figure 17). To grind the defect in a short time, the diamond sheet #400 was used until removing the defect (Grinding time was 204 min). The diamond sheet #1000 used for polish after removing the defect (Polish time was 60 min).

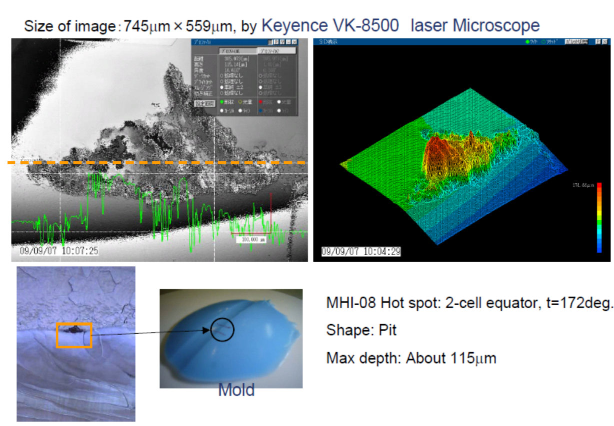


Figure 16: Image of replica and result of shape analysis.

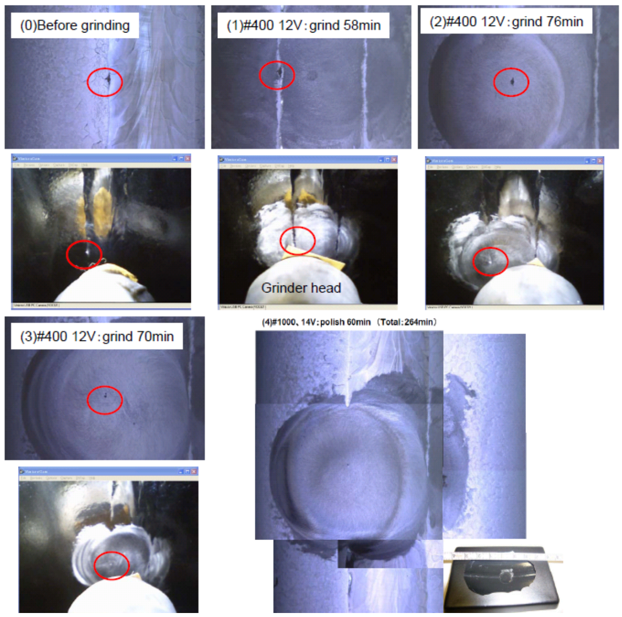


Figure 17: Apply the local grinding for MHI-08.

The defect was removed completely by the local grinding method. Next treatment will be EP process, and will be inspection after EP to check the grinded surface. The next vertical test of MHI-08 will be October 2009.

IMAGE OF HOT SPOT DETECTED BY T-MAP

Ten 9-cell cavities (MHI-01 ~ MHI-09 and AES-01) were inspected from April 2008 to September 2009. Figure 18 is summary of images of hot spot detected by T-map and the gradient at heating cells in KEK-STF. The clear defects were observed at quench location less than 23 MV/m. In the high gradient case, the quench location had no clear defect, the condition of surfaces were un-uniform EBW seam area. Note there are some cases of no defect found by inspection system at around a heating location with low field quenches. A cause of the field limitation will be other reason.

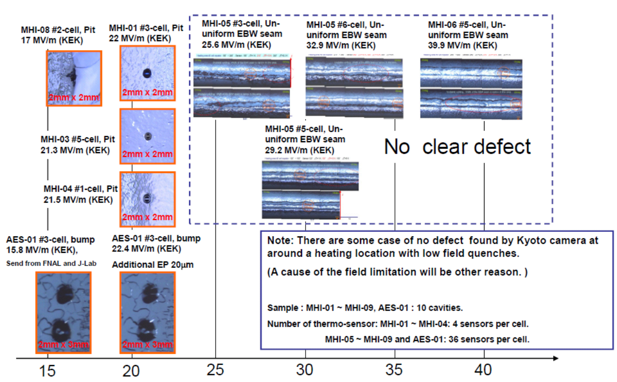


Figure 18: Images of hot spot detected by T-map in KEK-STF.

CORRELATION OF SPOT SIZE AND HEATING

The shape analysis of suspicious spots with ten 9-cell cavities (Number of cell = 90 cells, Number of detected spot = 49 spots) has been done from April 2008 to September 2009. The thermo-sensors attached on these suspicious spots every vertical test to study the correlation of spot size and heating. The parameters of defect size are defined in Figure 19. Relation of spot size and heating detected by T-map (Rough estimation) is shown in Figure 20. Red points are heating observed less than 23 MV/m. The type of defects which heating occurred low field were both pit and bump. Blue and purple points are no heating less than 30 MV/m. Larger, deeper (or higher) pits (or bumps) seem to cause quenches. However, not all of the optically observed defects lead to problems. Note preliminary results of analysis which utilizes both the pi-mode and passband measurements.

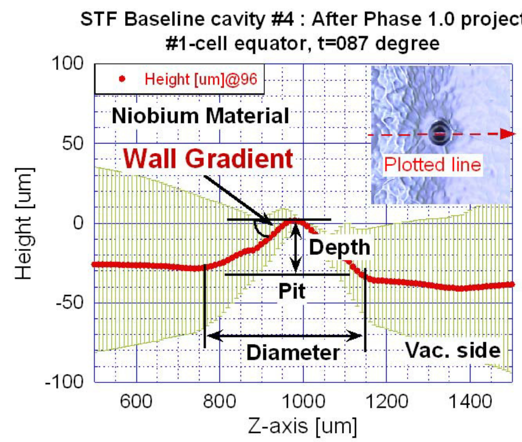


Figure 19: Define of parameter for shape of defect.

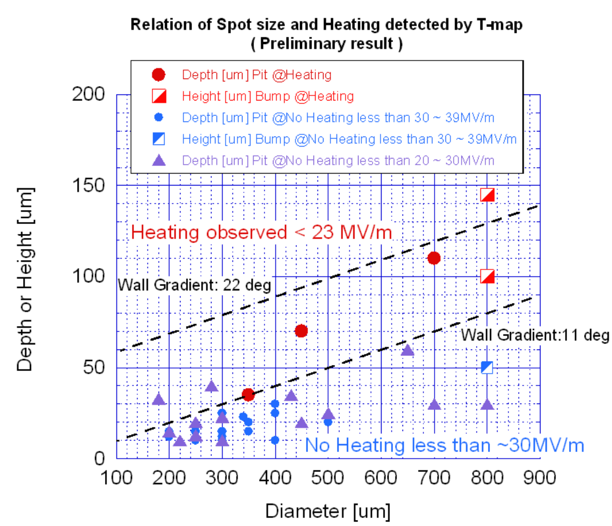


Figure 20: Relation of spot size and heating detected by T-map (Rough estimation).

SUMMARY

High resolution camera systems are used in labs world wide to make better yield of high gradient. Correction of defects size and quench field is under collecting by combination of inspection and T-map. Larger, deeper (or higher) pits (or bumps) seem to cause quenches. However, not all of the optically observed defects lead to problems. The development of the repair technique is promoted simultaneously with the inspection system.

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