Optical cavity inspection

Vladislav Babitski, Belarusian state university of informatics and radioelectronics, Belarus

September 8, 2015

Supervisors: Aliaksandr Navitski
FLA/ILC, DESY, Hamburg

September 8, 2015

Abstract

Optical inspection system OBACHT and Replica have been used for systematic analyses of the quality of surface treatment of superconducting radiofrequency cavities. Description of the applied techniques and typical defects found on the cavity surface is presented. Settings of a newly installed camera of the OBACHT system have been systematically varied and optimum setting allowing the best picture quality and absence of artefacts and blurriness have been obtained and described here.

Contents

1 Introduction

Superconducting radio-frequency (SRF) niobium cavities (Fig. 1) are a key component of current and future efficient particle accelerators producing high-energy and high-intensity beams. The technology is a key to next generation light sources, accelerator-driven sub-critical nuclear reactors and nuclear-fuel treatment, and new accelerators for material science and medical applications. The SRF cavities are made from high-purity niobium and undergo a complex multi-step production process to achieve high accelerating gradient, E_{acc}, and unloaded quality factor, Q_0. These quantities, together with the manufacturing yield, drive cost and performance factors such as cryogenics, beam energy, and machine length.

The European X-ray Free Electron Laser (EXFEL), currently under construction in Hamburg, requires for example 800 Tesla-shape nine-cell 1.3 GHz SRF niobium cavities operating at nominal average E_{acc} of 23.6 MV/m with Q_0 of at least 10^{10}. The future International Linear Collider (ILC) would require the production of 16,000 such cavities operating at nominal average gradient of 31.5 MV/m with almost the same Q_0 factor. With such a quantity of cavities to be fabricated, an appropriate quality control (QC), failure reason clarification, possibilities for retreatment and repair of the SRF cavities, and the resulting manufacturing yield become very important issues.

Figure 1: Picture of Tesla-shape nine-cell SRF niobium cavity

The ability to detect performance-limiting defects on the inner surface leading to low Q_0 factor, thermal breakdowns (especially at the equator welding seams and the surrounding area), and x-ray radiation (mainly due to sharp geometric defects on irises) provides a tool of QC and failure reason clarification. Detection of failures and defects, especially in early production steps, would significantly reduce repetition of quite expensive cold RF tests and retreatments of the cavities.

Inspection of the inner cavity surface by an optical system is an inexpensive and useful means for surface control and identification of dangerous or suspicious features. The complicated shape of the SRF cavities and hidden inner surface, as a most critical one, require, however, development of a special device. Such tools as borescopes or videoscopes are handy, but poor quality in image contrast and poor spatial resolution often limits their use.

The systems based on a long-range microscope and a mirror provide better image quality remaining still almost fully manual. Industrial QC, documentation, and tracking of surface features at different production steps in any region of SRF cavities require a reliable automated inspection system.

A specially developed Optical Bench for Automated Cavity inspection with High resolution on short Timescales (OBACHT) and a surface analyses technique called replica together with the laser scanning microscopy are used for the QC of the inner cavity surface and described here. Settings of a newly installed camera of the OBACHT system have been systematically varied and optimum setting allowing the best picture quality and absence of artefacts and blurriness have been obtained and described here.

2 Measurement technique

2.1 OBACHT

OBACHT is a system for optical inspection and recording of the inner surface of 1.3 GHz niobium cavities of TESLA shape (Fig. 2a). The range of the optical inspection is able to cover the entire inner surface of such cavities. The set-up is suitable for inspections of cavities with and without helium tank (with 2-phase helium pipe as shown in Fig. 2b) as well as of semi-finished parts (SFP) such as dumbbells (Fig. 1c) and end-groups (first or last half-cell with beam-tubes and its accessories) of the cavities.

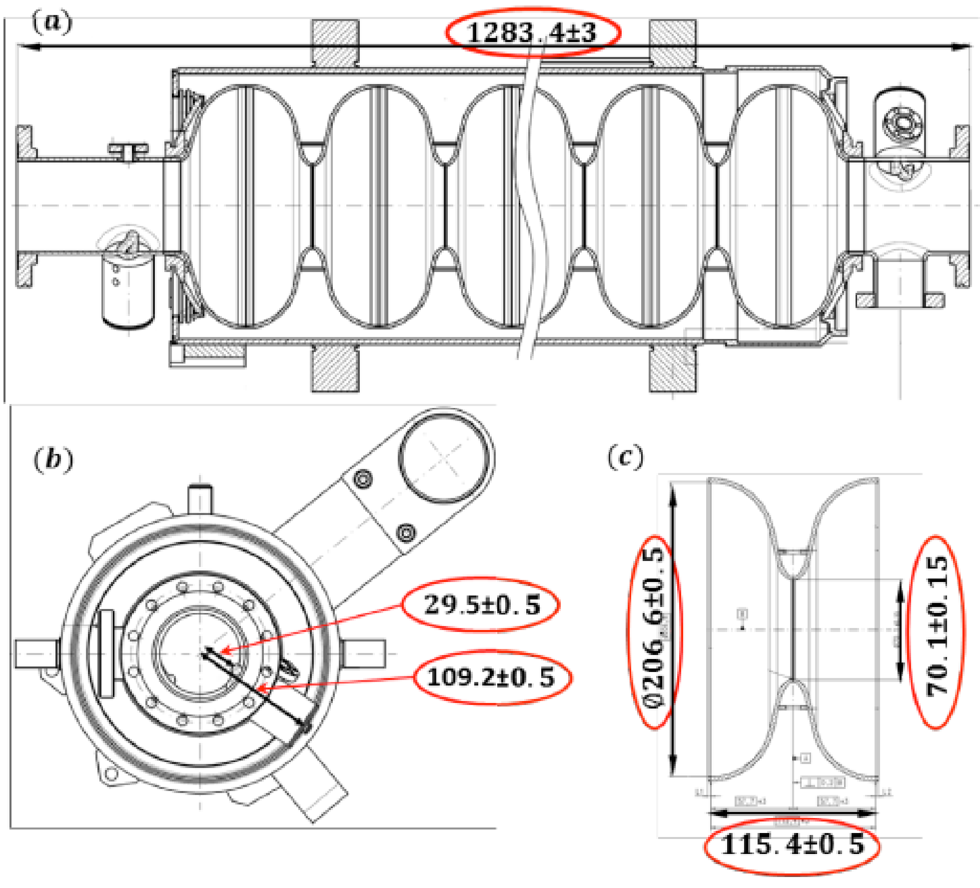

Figure 2: CAD drawings of 1.3 GHz cavity in the helium tank showing the most important dimensions for the optical system

The dimensions of the cavities and SFPs which are of the most importance for the optical inspection system are given in the Fig. 2. These are the length of the cavity of 1283.4±3 mm, diameter of the narrowest part to be inspected i.e. the irises 2 to 9 of the middle cells of the cavity of 70.1±0.15 mm and the widest part of the cells i.e. the equators of 206.6±0.5 mm, the spacing between neighboring equators and irises of 115.4±0.5 mm, and the distance between the bottom of the high (HOM) cans and the cavity center axis of 109.2±0.5 mm. The bore opening of the cavities is, however, reduced to around 60 mm due the HOM antennas sticking out of the cavity as can be seen on the drawings in Fig. 2b. Considering the presented dimensions, the optical inspection tool is able to reach any point within at least the 1286.4 mm length, able to acquire images of the surface in the range between ~34.9 and ~110 mm distance from the cavity center axis, and has outer diameter well below 60 mm considering additionally a safety margin between the inner surface, HOM antennas, and the inspection tool. Also there is an additional space on each side of the cavity in the longitudinal direction as a safety margin for mounting/dismounting of the cavities. The safety margin has been estimated to be around 25 cm between flanges of the cavity beam-tubes, supports, and the optical inspection tool in the extracted position. Despite to the shape of the cells the system is able to acquire images of the inclined planes of the inner surface of the cavity, too.

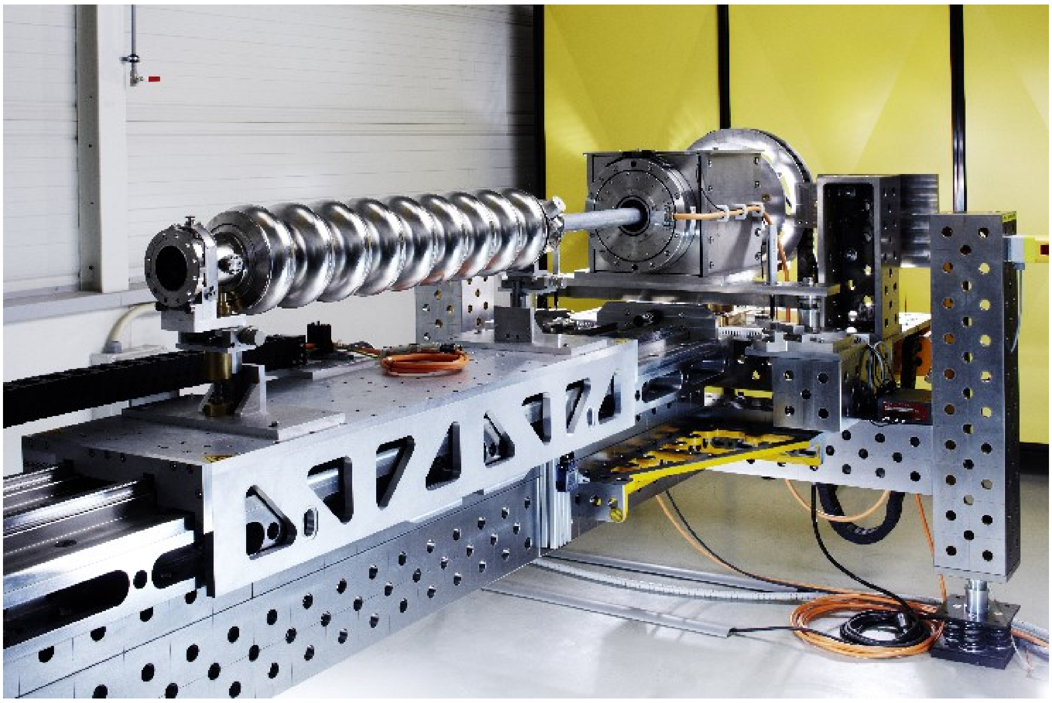

Figure 3: Picture of the OBACHT optical inspection system

The minimum possible step size for the rotation is approximately 0.03°, corresponding to a movement of the image of around 50 μm. The minimum possible step size and accuracy for the longitudinal movement is better than 50 μm. Settings of any reasonable step size are possible as well. Positioning of the tool and image acquisition are fully automatized. To minimize blurring of the images due to vibrational excitations of the optical inspection tool and of the inspected parts it is possible to adjust the speed and acceleration of the motor system, allowing smooth start and stop of the movement.

Since the length of the cavities varies in the order of 3 mm and mechanical fixation of the cavities with 50 μm reproducibility is very demanding, it requires a referencing of the position of the cavities and the parts for every new installation. Locations of the equator welding appear to be the most favorable reference points in the longitudinal direction, whilst the position of the center of the main coupler port is defined as a reference point for starting angle (zero degree) in the cavity coordinate system. To allow an easier referencing of the cavities a coarse mechanical reference system is applied to force installation and fixation of the cavities in well-defined longitudinal and azimuthal orientations. Furthermore, reproducible set-up of the inspection tool following maintenance or repair is guaranteed.

Safeguard measures have been introduced for personal protection, as well as for prevention of accidental damages of the parts to be inspected and of the inspection tool itself.

The system is suitable for investigations of cavities and SFPs after different surface preparation steps. After chemical or electro-chemical polishing the inner surface of superconducting cavities become mirror-like and, therefore, highly reflective. This makes the illumination for an optical inspection very difficult and requires a special lighting system.

The steering of OBACHT and control of the whole measurement process is done using a Graphical User Interface (GUI) written in LabView. The GUI runs on a dedicated Windows 7 PC and guides the user through all the tasks such as energizing the whole system, referencing the motors, referencing the cavities, choosing data paths, adjusting motor, focus and illumination settings, image taking in a manual or automatic mode, and finally checks of the performed inspection and shutting down the whole system. An example of the GUI for the automatic inspection mode is presented in Fig. 4.

Since the set-up should be suitable for inspections of cavities at different production steps, of individual parts, and of the cavities as a whole, the cavities or SFPs are fixed on a work bench and move longitudinally, whilst the optical inspection tool rotates azimuthally inside during the inspection. This mode has been verified with the “Kyoto camera” [Y] at DESY and allows flexible mounting of the cavities and SFPs.

Anticipating technological progress, the camera and its mechanical and electrical interface are chosen in such a way that they are suitable for future upgrades.

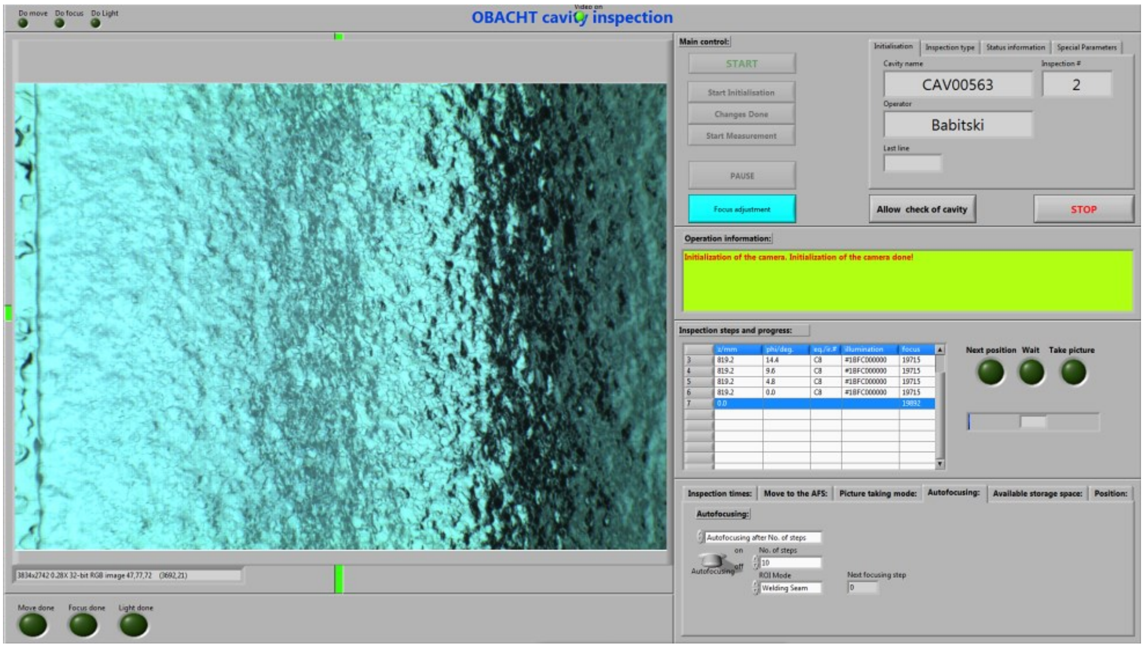

Figure 4: Interface of LabView Software to set up the inspection

2.1.1 Cavity inspection

A "standard" cavity inspection concentrates on welding seams at the equator and irises plus the area to the left and right of the equator welding seams and yields approximately 3500 images in 8 hours. One OBACHT image covers a cavity area of 12x9 mm^2 at the equator with at least 10 µm resolution. A design with linearly moving cavity and rotating camera has been chosen and results in the linear position accuracy of cavities up to 10 µm whilst the accuracy of the angular positioning of the camera is at least 0.01°.

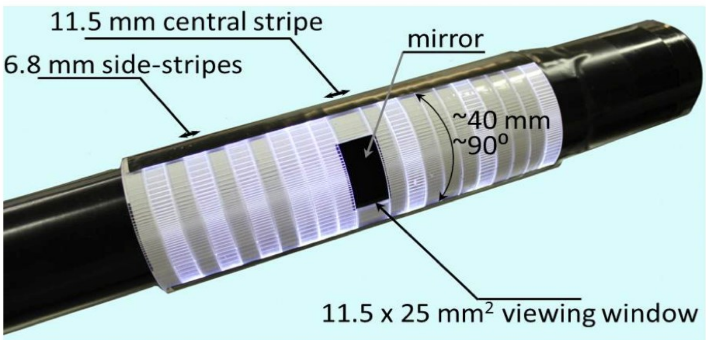

Figure 5: OBACHT illumination unit consisting of a central stripe with a viewing window and twenty sidestripes attached to the head of the camera cylinder.

The camera-cylinder (Fig. 5) is based on the Kyoto camera system with some modifications of the illumination unit, an upgraded camera, and more rigid construction using a different aluminum alloy. A schematic diagram of the camera-cylinder is presented in Fig. 6. The inner surface of the cavity is reflected in an imaging mirror and recorded by a camera aimed axially. Such construction was chosen in part due to space considerations, to account for the room required for the camera and attached lens, and in part due to the camera's inherent focusing range. In order to carry out a non-destructive observation and keep the inner surface as clean as possible, the camera system is housed in a cylinder with the outer diameter of 50 mm. This cylinder can be inserted into the beam-tube of the cavities.

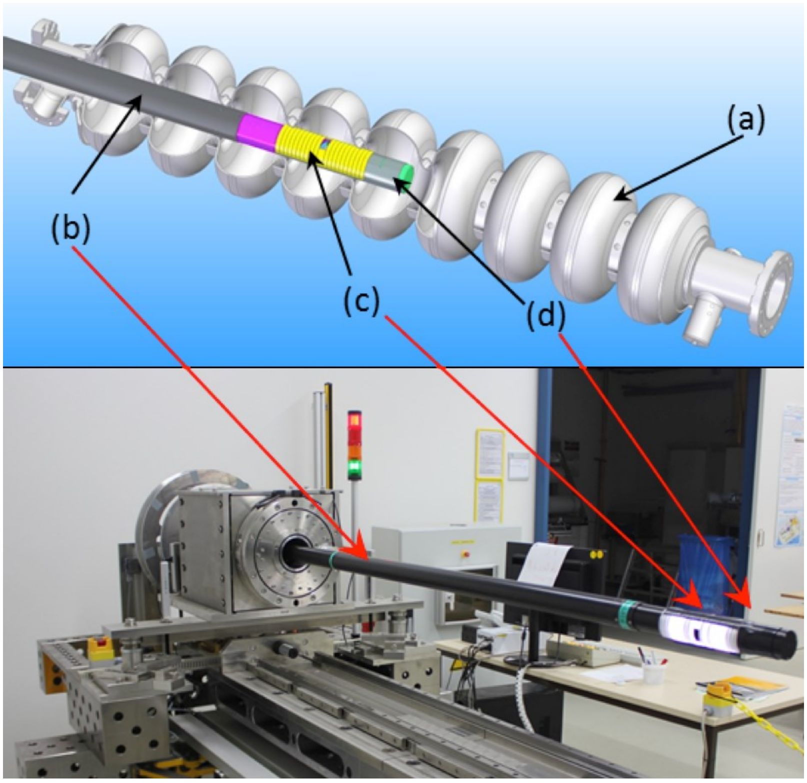

Figure 6: 3D CAD view of the camera-cylinder inserted into the nine-cell cavity and real picture of the camera cylinder: (a) nine-cell cavity, (b) camera-cylinder, (c) cylinder-head with a mirror mechanism, and illumination unit (d)

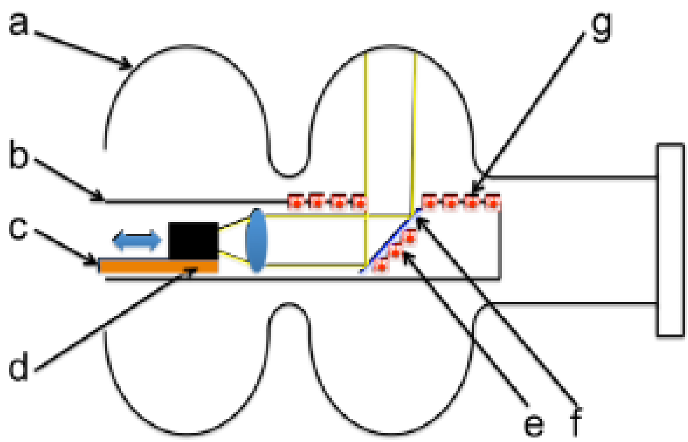

Figure 7: Schematic diagram of the camera-cylinder. The camera (d) is placed axially in a cylinder (b) and observes the inner surface of the cavities (a) through a tiltable semitransparent mirror (f). The focus is adjusted by moving the camera longitudinally (c). LEDs from stripes (g) on the surface of the cylinder and behind the mirror € provide the required illumination.

The imaging mirror (Fig. 7) can be tilted at least ±30° by a stepping motor to adjust the imaging plane of the camera with the inclined planes of the inner cavity surface.

2.2 Replica

To gain information about the 3D topography of surface features or defects, a replica technique has been applied additionally on some defects, especially if an unambiguous interpretation of defects could not be performed based on the OBACHT images. Replica is a non-destructive surface-study method reaching resolution down to 1 µm by imprinting the details of the surface onto a hardened rubber. The footprint is subsequently investigated with a microscope or profilometer. 3D laser scanning microscope (Keyence VK-X100K) has been applied for topographic investigations of the replica-samples and provide up to 0.2 µm lateral and 10 nm height resolution.

"Replica" is used for non-destructive profilometry studies of inner surface, conspicuous surface features, and defects.

To make a replica sample we have use a liquid 2-component silicon mixture in proportion 1:1. The mixture was placed onto the surface using a special tool (Fig. 7) equipped with a camera and illumination for defect localization and a dosing unit for fine controlled of the silicon amount. After the curing time of around 1 hour, the replica is removed from the cavity and inspected with the laser microscope. An example of surface defects observed with OBACHT and characterized by replica technique shown in Fig. 8.

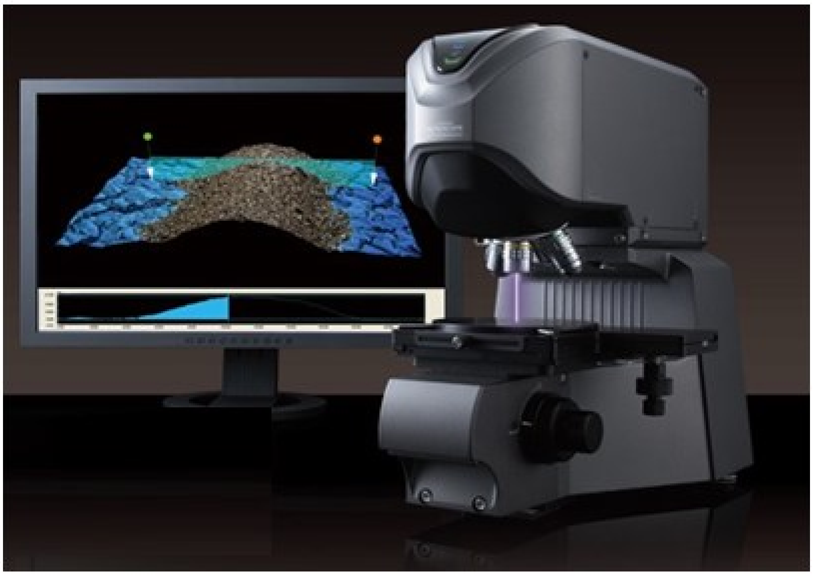

Figure 8: Laser microscope Keyence vk-x100

Picture 9: Picture of making replica process

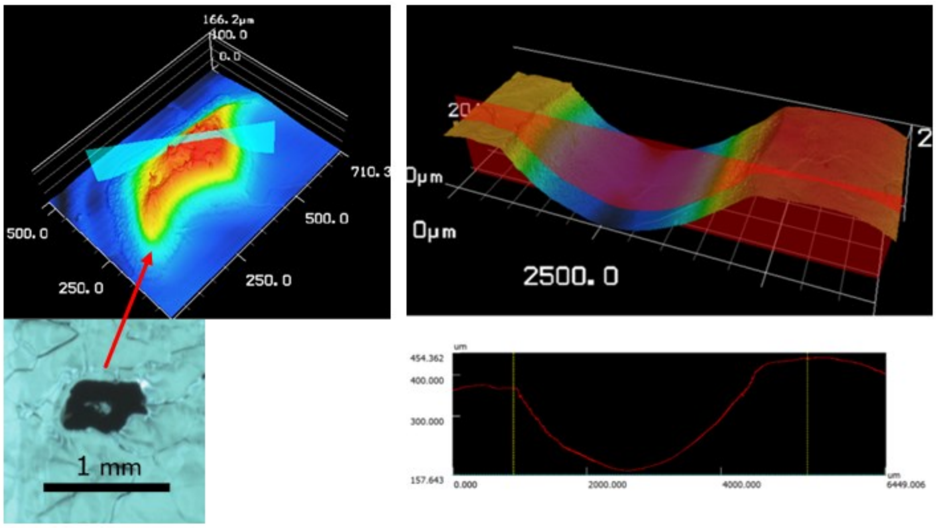

Figure 10: Profilometry of defect

3 Experimental results

3.1 New OBACHT camera

The camera of the OBACHT system was broken and has been replaced. An optimization of its settings to obtain the best picture and remove artifacts and blurriness was required.

The new camera used in the system is a 10 MP resolution colour camera Basler acA3800-14uc. It is equipped with USB 3.0 interface for data transfer, Aptina MT9J003 CMOS sensor, and can shoot 14 frames per second. One OBACHT image covers a cavity area of 12x9 mm^2 with 3856x2764 pixels.

Figure 11: Picture of Basler acA3800-14uc camera

Around 75 shots are required to record one 12 mm band region around the electron beam-welding seam at the equator, and 30 shots at the iris.

3.2 Parameters to be optimized

The following parameters were systematically varied:

- Pixel format
- Gain
- Exposure time
- Black level
- Gamma
- Digital shift

3.2.1 Pixel format

Pixel format is a mosaic of tiny color filters placed over the pixel sensors to capture color information. The filter pattern is 50% green, 25% red and 25% blue.

Pixel formats available for this camera:

- Bayer BG 8
- Bayer BG 12
- Bayer BG 12p
- YC_bC_r 422

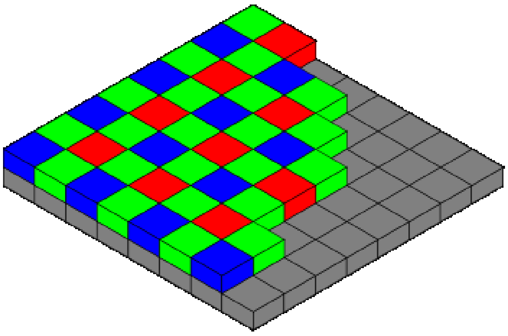

Figure 12: The Bayer arrangement of color filters on the pixel array of an image sensor

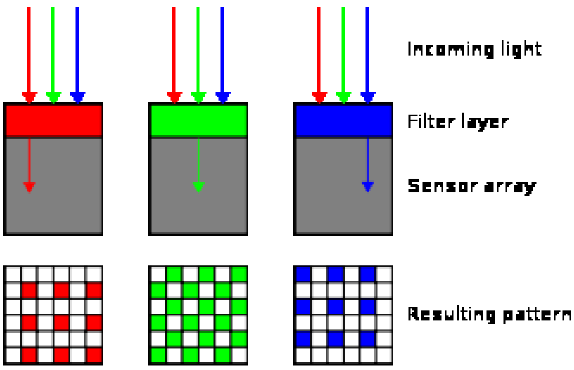

Figure 13: Profile/cross-section of sensor

3.2.2 Gain

Gain is an electronic amplification of the video signal. Signal is boosted adding more voltage to the pixels amplifying their intensity and brighten the image. This voltage increase is measured in decibels (dB).

Possible gain values: 0 - 16.67569 dB.

As we see from the image, the optimal value for gain parameter is approximately 7.

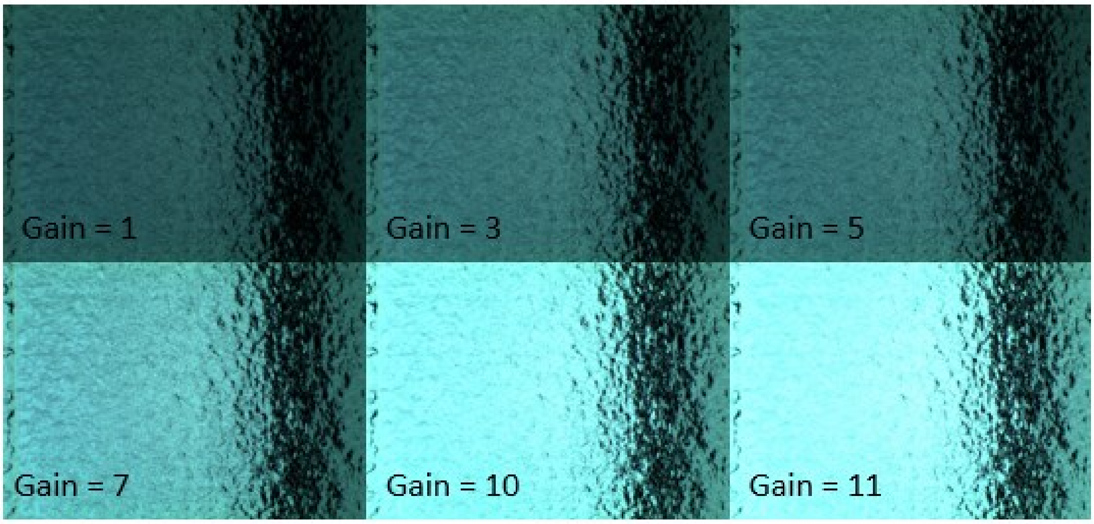

Figure 14: Pictures made with different gain value

3.2.3 Exposure time

Exposure time is an opening time of the camera's shutter while taking a photo. The amount of light that reaches the film or image sensor is proportional to the exposure time.

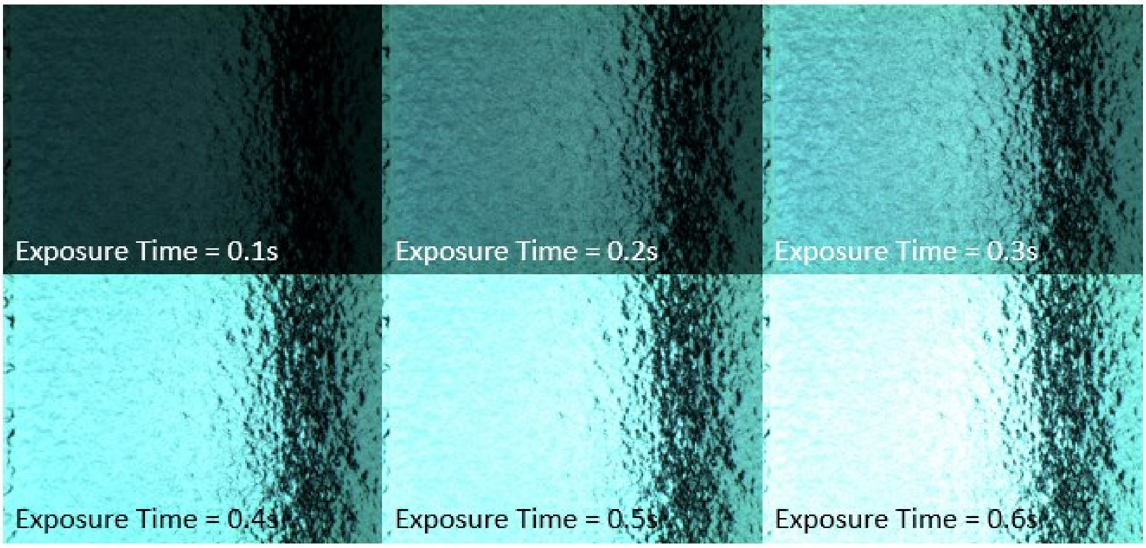

Figure 15: Pictures made with different exposure time value

As we see from the image, the optimal value for exposure time parameter is approximately 0.3-0.4s.

3.2.4 Black level

Black level is an offset (positive or negative) to the pixel values output by the camera. Allowed range for this camera is: 0 to 63.9375 for 8bit depth and from 0 to 1023 for 12bit depth.

As we see from the image, the optimal value for black level parameter is 1.25.

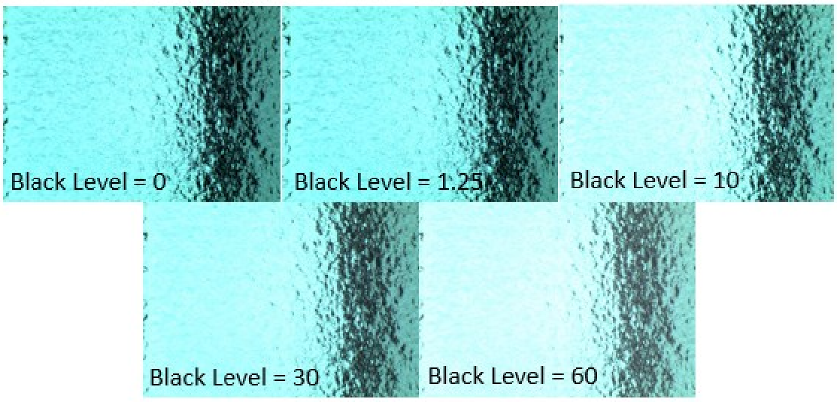

Figure 16: Pictures made with different black level value

3.2.5 Gamma

Gamma is a modification of the brightness of the pixel values output by the camera's sensor to account for a non-linearity in the human perception of brightness. Gamma correction is always performed in the RGB color space.

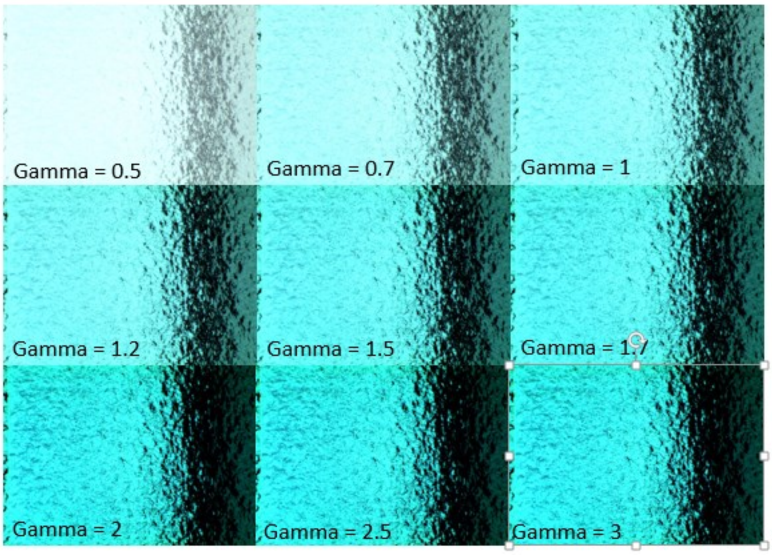

Figure 17: Pictures made with different gamma value

As we see from the image, the optimal value for black level parameter is 1.7.

3.2.6 Digital shift

Digital shift is a change of the group of bits that is output from the analog-digital conversion (ADC) in the camera. Using the digital shift feature will effectively multiply the output of the camera by 2 times, 4 times, 8 times, or 16 times.

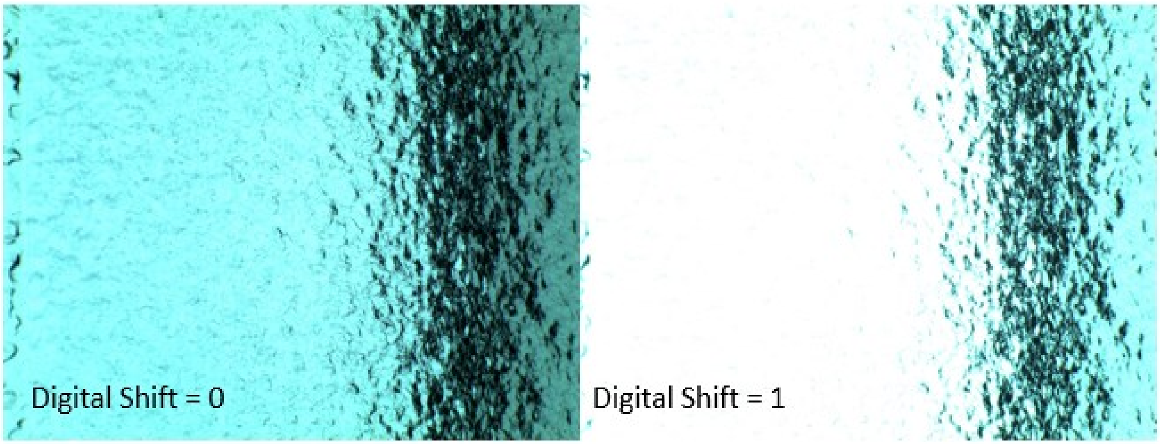

Figure 18: Pictures made with digital shift value

As we see from the image, the optimal value for black level parameter is 0.

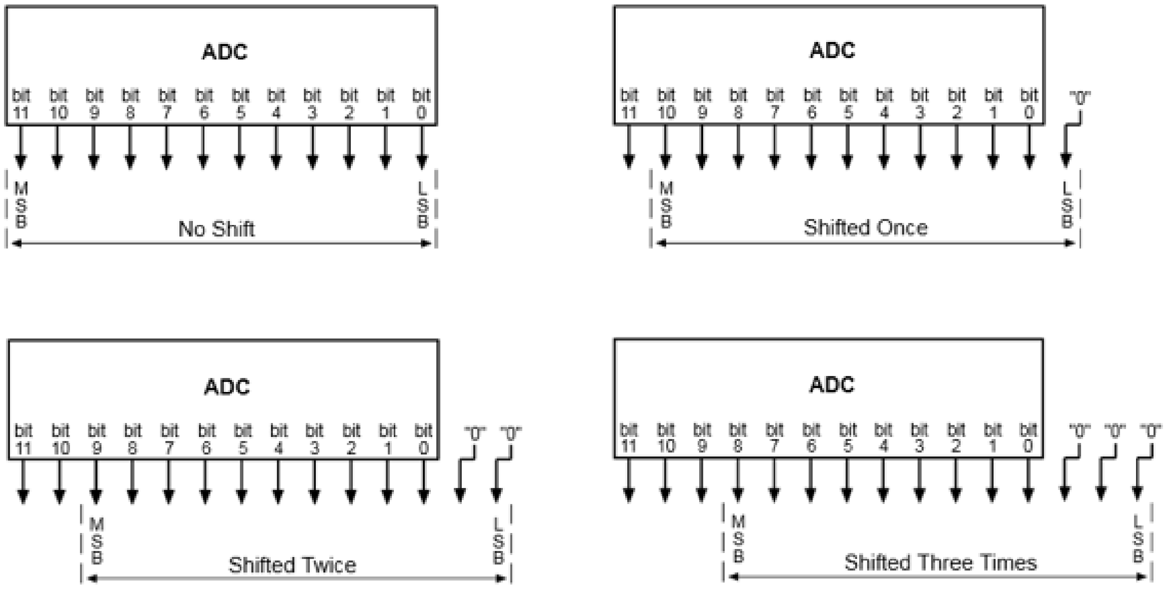

Figure 19: Analog-digital conversion with or without shift in 12 bit pixel formats

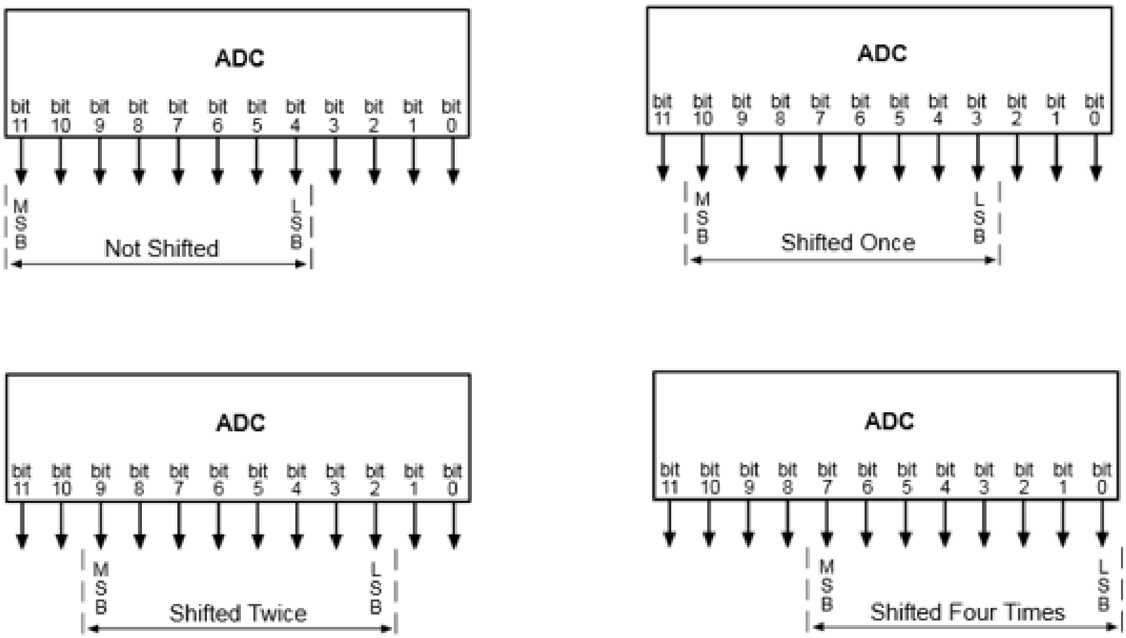

Figure 20: Analog-digital conversion with or without shift in 8 bit pixel formats

3.3 Cavity inspection results

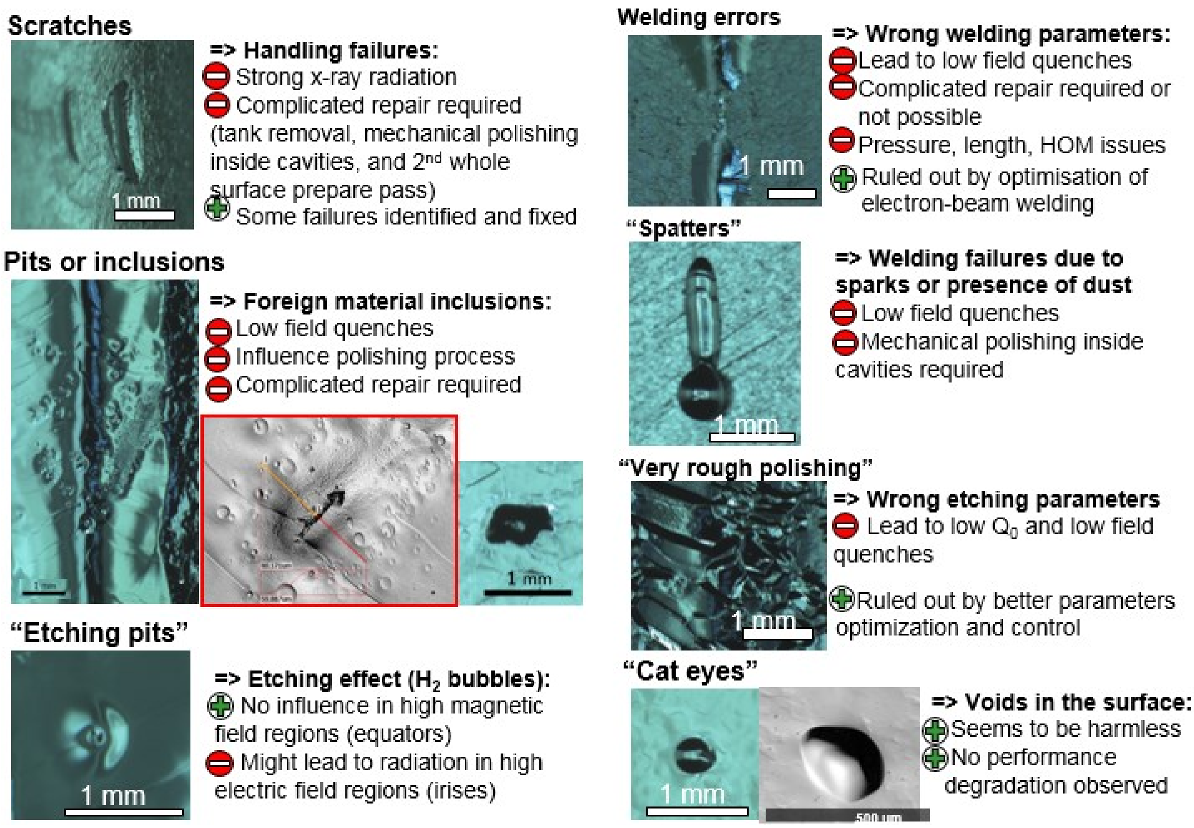

Figure 21: Picture of different defects and how they can influence on SRF cavity

There are different types of defects that can cause different problems (Fig. 19):

- Scratches
- Pits or inclusions
- “Etching pits”
- Welding errors
- “Spatters”
- “Very rough polishing”
- “Cat eyes”
- Dust

In order to perform optical inspection of a cavity with a good performance, CAV00247 has been chosen. In the cryogenic RF test the cavity achieved maximum accelerating gradient of 37 MV/m and unloaded quality factor Q_0 of $2.9 \cdot 10^{10}$ without any radiation.

Several “cat eyes” have been observed on the cavity surface (Fig. 22). Because of the excellent performance of the cavity, such “cat eyes” can be classified as harmless for the cavity performance.

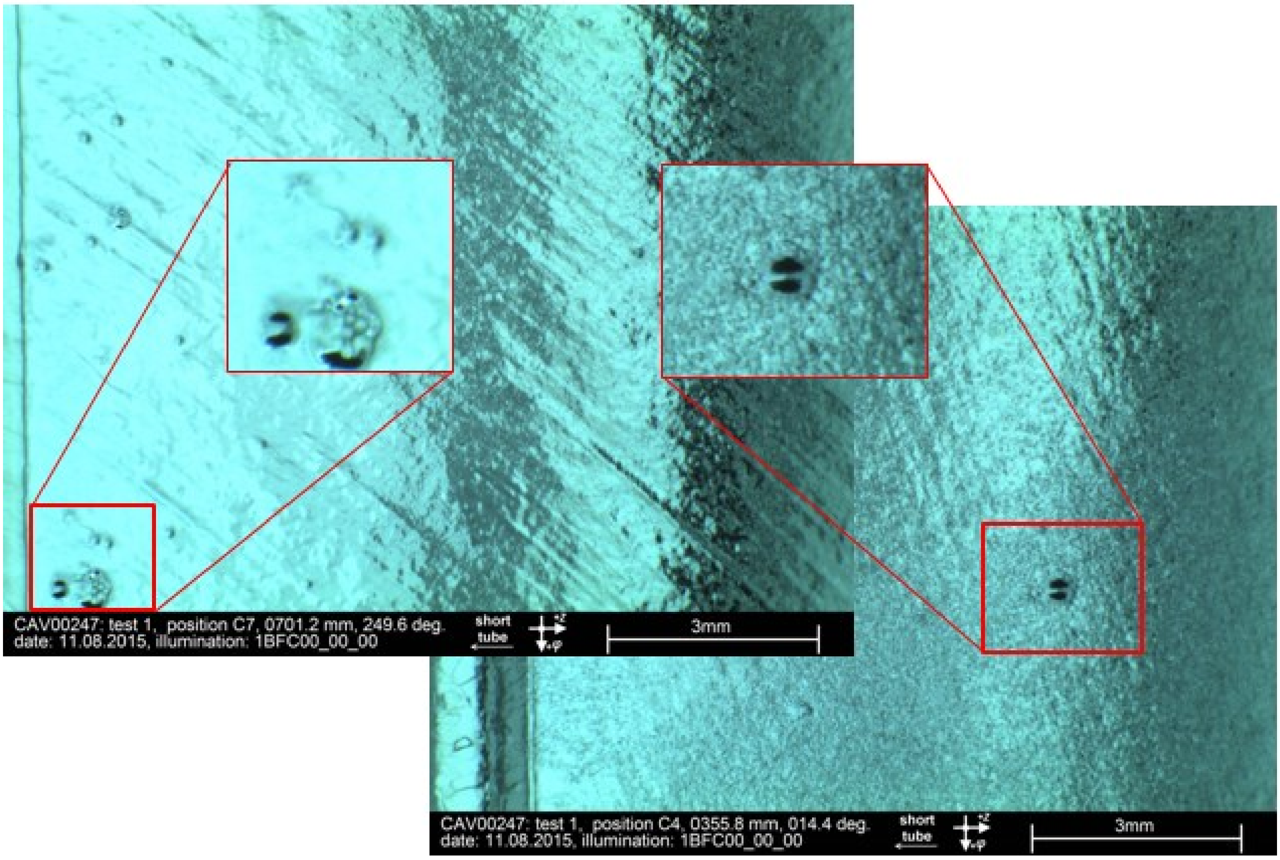

Figure 22: Example of “cat eye” defect, found on CAV00247

3.4 Replica surface study

In order to analyze the grain structure of Nb on the welding seam and surrounding heat affected zone, replica investigations on equator 1 and 9 of CAV00532 have been done (Fig 23-26).

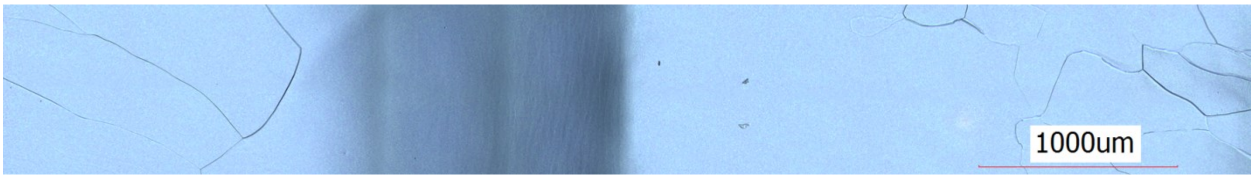

Figure 23: Grain structure on equator 1

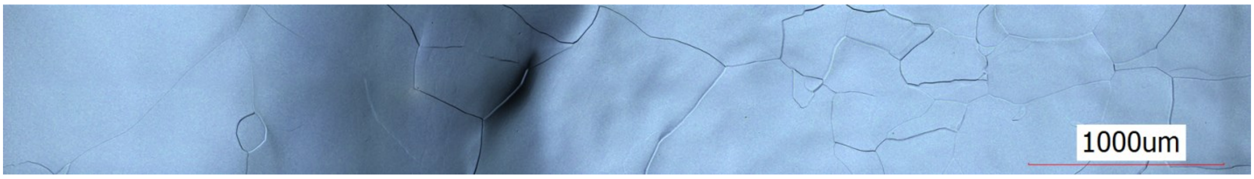

Figure 24: Grain structure on equator 9

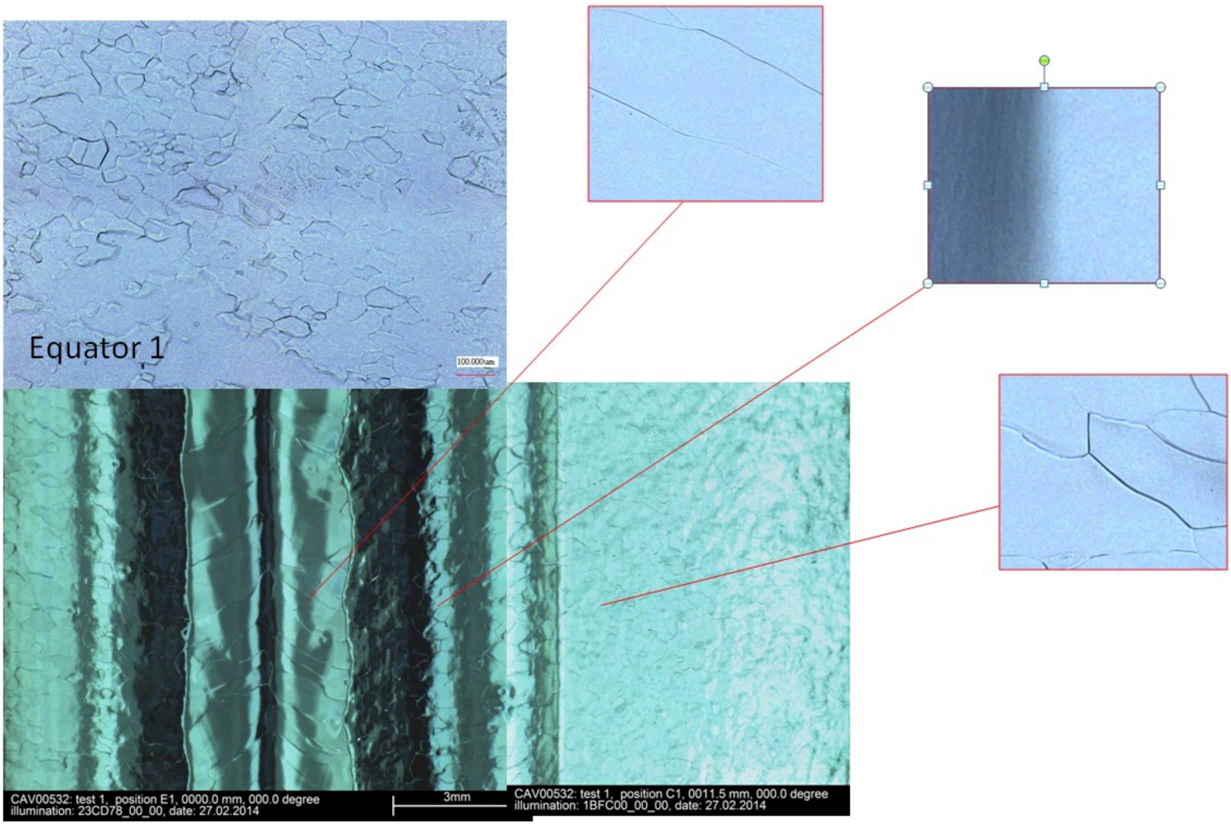

Figure 25: OBACHT and replica image of equator 1

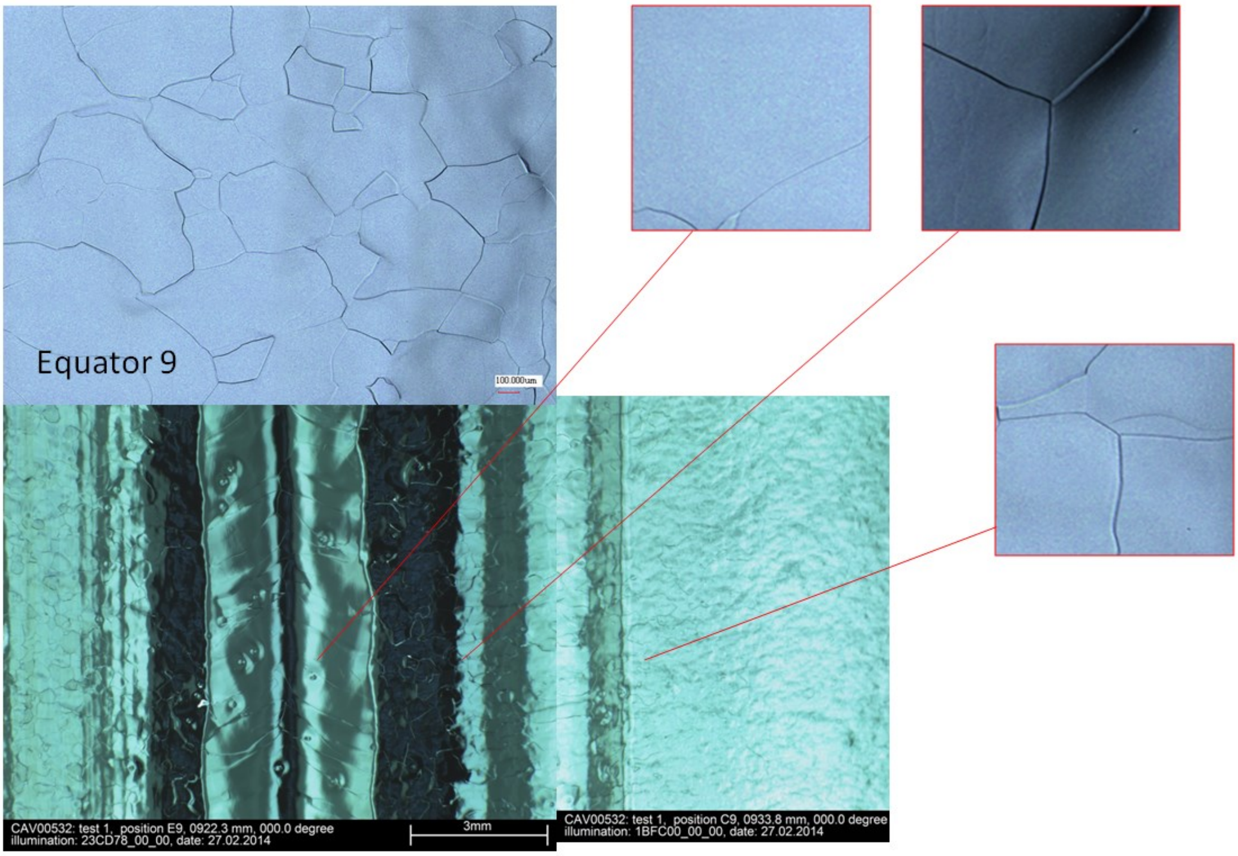

Figure 26: OBACHT and replica image of equator 9

The results indicate different granularity of Nb in the heat affected zone explaining different patterns on the OBACHT images.

4 Summary

Several inspections of cavities have been performed using OBACHT and replica. No significant defects observed.

Optimal parameters for the Basler acA3800-14uc camera have been obtained:

- Pixel format - YC_bC_r 422
- Gain ≈ 8 dB
- Exposure time ≈ 0.3-0.4s
- Black level – 1.25
- Gamma – 1.5
- Digital shift - 0

Replica results of CAV00532 showed different grain structure around welding seams of equator 1 and 9, what can be further used for surface classification and understanding of patterns on the OBACHT images and their influence on the cavity performance.

5 References

[1] A. Navitski, S. Aderhold, U. Cornett, E. Elsen, G. Falley, M. Lemke, J. Schaffran, L. Steder, H. Steel, Y. Tamashevich, Cavity inspection system OBACHT, DESY, 2015.
[2] A. Navitski, ILC-HiGrade and SRF R&D progress, DESY, 2015.
[3] Y. Ulrich, A. Navitski, L. Steder, M. Wenskat, Camera control for the OBACHT system, DESY, 2012.
[4] F. Schlander, OBACHT, DESY, 2011.
[5] L. Steder, Measurement manual for OBACHT, DESY, 2012.
[6] XFEL Technical Design Report, DESY 2006-097, Hamburg, July 2007, www.xfel.eu
[7] ILC Technical Design Report, 2013, www.linearcollider.org