A MACHINE FOR HIGH-RESOLUTION INSPECTION OF SRF CAVITIES AT JEFFERSON LAB*

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Abstract

A high-resolution cavity inspection machine has been built at JLab. It is based on a long-distance microscope with a spatial resolution down to 3 µm. This system has been a work horse in support of the on-going ILC cavity gradient R&D. More recently, this machine has been also used to inspect small aperture cavities including some 1497 MHz 7-cell CEBAF upgrade cavities and S-band single-cell crab cavities, demonstrating the capability and flexibility of the machine. We will describe the detailed features of the inspection machine along with some exemplary inspection results.

INTRODUCTION

Visual inspection is an inexpensive and useful means for identification of dangerous or suspicious features on the surface of cavity components such as dumb-bells. Unaided human eyes lack the ability to inspect places such as the inner surface of the equator region of an elliptical shape cavity. Tools such as a bore scope can come handy, but its use is often rather limited due to poor quality in image contrast and poor spatial resolution. A high-resolution optical inspection machine, as it turned out, is a necessary and useful tool for high quality inspection (for discovery) and documentation (for tracking) of features in any region of real SRF cavities.

Recently, high-resolution optical inspection of SRF cavities has received lots of attention primarily due to the advanced gradient R&D of real 9-cell cavities for the International Linear Collider (ILC). One important ILC cavity gradient R&D goal is to understand the nature of the quench causing defects and help develop solutions for defect treatment and prevention. As it turns out, high-resolution optical inspection has played an important role in these studies. It is hopeful that such a machine will become part of industrial fabrication QA/QC. The well-known optical inspection machine is the "Kyoto camera", developed by a KEK/Kyoto University collaboration, which is now also used at other labs [1][2]. At Jefferson Lab, development of high-resolution optical inspection of 9-cell ILC cavities started in 2008 [3][4]. This system is based on a long-distance microscope. Pictures in Fig. 1 show the evolution of the system from the simple line-of sight style inspection in 2008 to the advanced and automatic full-inner-surface inspection at the present time.

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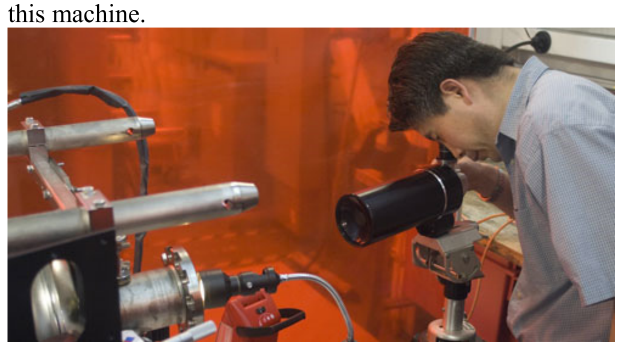
In this paper, we will describe the principle of the long-distance-microscope based optical inspection of SRF cavities as well as the detailed features of the machine components. Some exemplary inspection images will be given to show the capability of the system. It should be mentioned that this system has been a work horse in support the on-going ILC cavity gradient R&D at JLab since 2008. More recently, a variety of SRF cavities including CEBAF 12 GeV upgrade cavities and ANL crab cavities have also been successfully inspected by using this machine.



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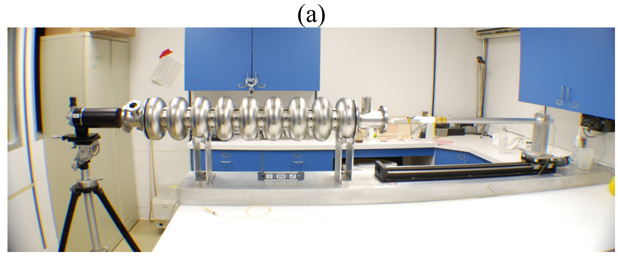

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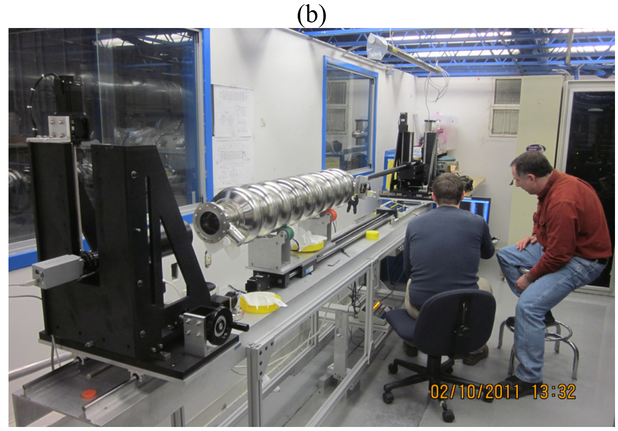


(c)

Figure 1: Development of JLab's high-resolution optical SRF cavity inspection system. (a) Direct line-of-sight inspection of end cell surface, circa April 2008. (b) Initial prototype of the full inner-surface inspection system, circa November 2008. (c) Present system with advanced automatic functions, February 2011.

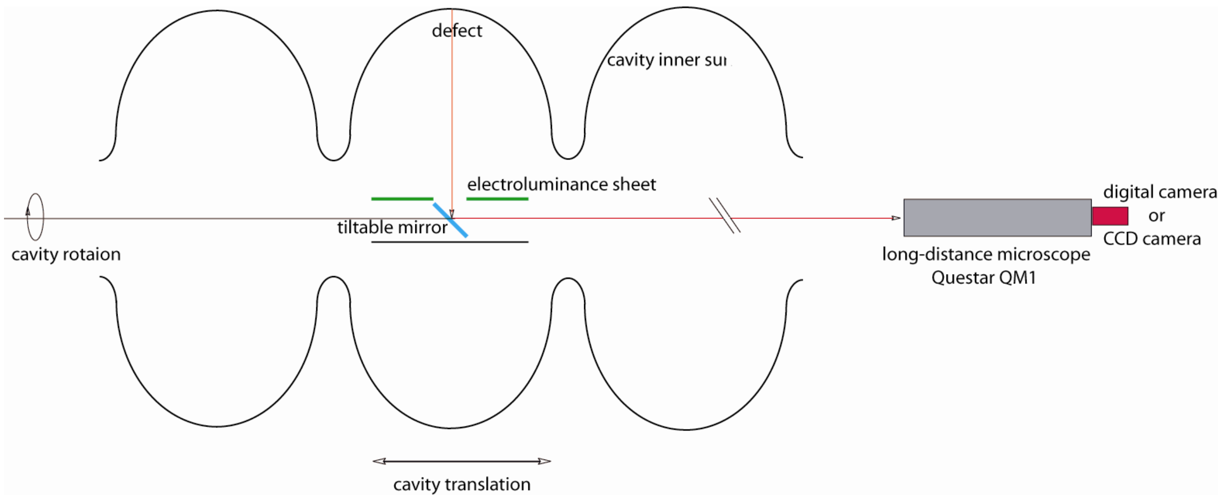


Figure 2: Principle of high-resolution SRF cavity inspection using a long-distance microscope.

PRINCIPLE OF INSPECTION

The principle of a long-distance-microscope based SRF cavity inspection is illustrated in Fig. 2. A mirror, supported by a long tube, penetrates into the cavity inner space. The tilting angle of the mirror with respect to the cavity axis is adjustable to allow inspection of the entire inner surface of a cavity. The nominal angle is 45° for optimal inspection of equator region and iris region. A defect on the cavity inner surface produces an on-axis image, which in turn is imaged by the long-distance microscope. Direct image observation or permanent image recording are made though an eye piece or an attached imaging device, respectively.

FEATURES OF MACHINE COMPONENTS

Mirror and Illumination

The mirror is carried by a long 38 mm OD tube, allowing the full penetration of a 9-cell 1300 MHz cavity. At the end of the mirror-bearing tube, an electroluminance (EL) sheet wraps around the tube, allowing illumination of the inner surface of the cavity. A rectangular window in the central region of the EL sheet ensures the mirror access (Fig. 3). This illumination scheme (following that in the Kyoto camera system) provides desirable effect for inspection of glossy cavity surfaces such as those of electropolished niobium.

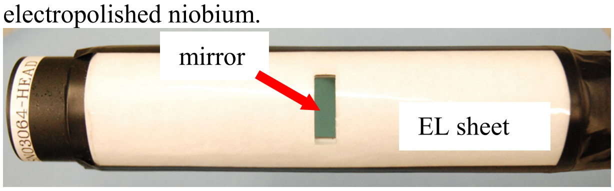
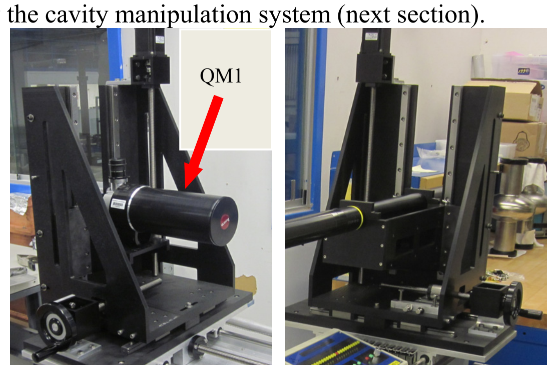


Figure 3: The mirror and electroluminance sheet at the end of the mirror-bearing tube.

Long-Distance Microscope

The long-distance microscope used in the JLab high-resolution SRF cavity inspection system is a Questar QM1. QM1 has two ports for viewing/imaging: one allows attachment of a digital camera (Nikon D80) or a CCD camera (Pixelink PL-B954U) for permanent image recording; the other allows direct observation of images through an eye piece. Nikon D80 saves images directly to a memory card, allowing easy data sharing and transportation. A laptop computer is needed to save the CCD camera images. The working distance of QM1 is in the range of 22-66 inches. The maximum resolution is 3 μm (at 22 inch working distance).

The Questar QM1 is mounted onto a manipulator assembly which rides on a pair of rails (Fig. 4a). This allows 3D movement of the scope. The mirror-bearing tube is mounted onto a similar manipulator assembly at the other end of the inspection system (Fig. 4b). The manipulation system has the following functions: (1) centering of the mirror tube with respect to the cavity beam tube; (2) alignment of the scope with respect to the mirror; (3) adjustment of the QM1 working distance. Once the scope-mirror system is set up for optimal inspection, the manipulators are locked down. Fine adjustment of the scope in longitudinal direction is still possible for optimal focus. In order to inspect different areas of a cavity, the cavity itself is rotated and translated by the cavity manipulation system (next section).



(a) (b)

Figure 4: Positioning system of the Questar QM1 (a) and the mirror-bearing tube (b).

Cavity Rotation and Translation

The cavity under inspection is horizontally placed on two pair of rubber wheels, attached to a plate mounted onto a linear motion gear system (Fig. 5). A step-motor drives one pair of wheels through a belt. These two wheels in turn drive the cavity to rotate through friction. Another step drives the linear motion gear system for cavity movement along its axial direction.

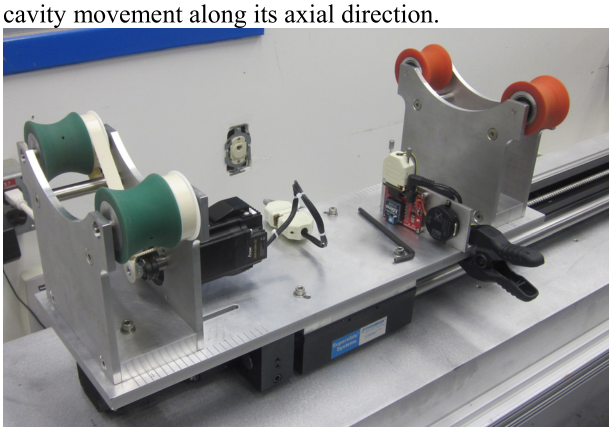


Figure 5: Cavity support, rotation and translation unit.

Control and Data Acquisition

The control and data acquisition are integrated into a computer system. An important part of the system control is to be able to determine a location on the cavity surface with repeatability. The longitudinal coordinate is derived from the step motor and the azimuthal coordinate is measured by a wireless sensor. The inspection image is saved on the computer hard disk.

Extension and Addition

The JLab high-resolution cavity optical inspection machine has the ability to accommodate the "Kyoto camera" (a unit on loan from KEK). More recently, collaboration between JLab and KEK has also demonstrated the possibility of adding the defect replica capability to the existing machine.

Example

Figure 6 gives an exemplary image of a defect discovered by our machine. This defect is at the high electric field region of the RF surface of the end cell loaded with strong field emission during RF test.

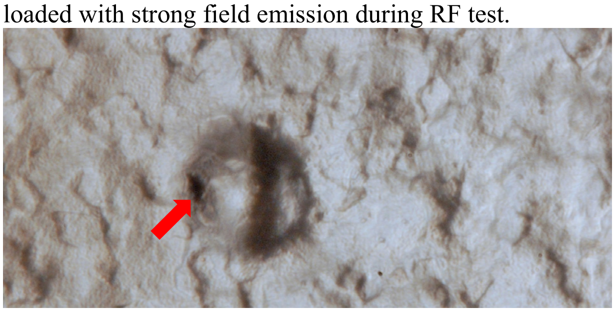


Figure 6: A circular defect with a ~ 10 µm core (indicated by arrow) discovered by JLab high-resolution SRF cavity inspection machine on a 9-cell cavity surface.

APPLICATIONS

The JLab high-resolution SRF cavity inspection system was initially developed for ILC cavity quench studies in association with temperature-mapping of 9-cell cavities. Some results can be found in Ref. [5]. Through inspection of quench areas predicted by the temperature mapping measurements, we are able to draw the following conclusion: quench limit at 20 MV/m or lower a gradient is correlated to sub-mm sized geometrical defect in the equator region of the quenching cell. Some inspection results of as-built cavities are used to provide feedback to cavities vendors for improved fabrication quality.

The application of our inspection machine has been recently extended for investigation of a variety of other cavities owing to the capability of the system. For example, a 7-cell 1497 MHz cavity (53 mm aperture) for CEBAF 12 GeV upgrade project was successfully inspected, providing clear evidence of iris damage [6]. The details of the damage (texture and color) allow the determination of the root cause of the damage. Figure 7 illustrates another example for inspection of a so called crab cavity with complex 3D shape. This inspection provides useful feedback to in-house cavity fabrication of new cavity developments.

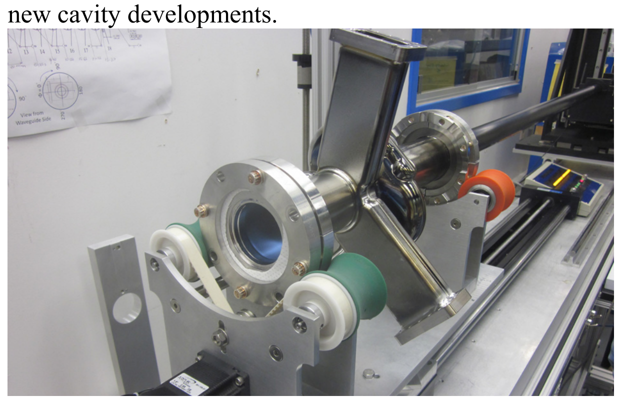


Figure 7: Inspection of a crab cavity being developed at JLab for ANL's APS upgrade project.

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