X-RAY TOMOGRAPHY INSPECTION OF SRF CAVITIES*

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Abstract

Performance issues with superconducting cavities and a desire for an enhanced non-invasive view of the interior of a cavity compared to that provided by optical means has led us to inspection using 3-dimensional X-ray tomography. This technique has provided the necessary view of suspected faults in Higher Order Mode couplers. This success naturally leads to determining if x-ray inspection of welds and other potential cavity defects might prove to be helpful during cavity fabrication. Results of x-ray scans from commercial vendors and potential for this technique will be presented.

INTRODUCTION

It can be difficult to determine the root cause of poorly performing SRF cavities owing to the difficulty in performing non-invasive visual inspections. Welds, in particular, and hard to reach areas such as Higher Order Mode couplers are nearly impossible to inspect without slicing or cutting open these areas. Such was the case of two poorly performing 3.9 GHz cavities at Fermilab. After a series of successful ones, repeated tests indicated multipacting of the 'Formteils', the 2-post antennae which couple the higher order mode power out of a cavity, but it was impossible to conclusively inspect these pieces for possible failure. Only by means of 3-D X-ray computed tomography (CT) was it possible to positively identify fractured 'Formteils' as the root cause.

Additional internal issues, namely questionable welds and pits/imperfections, have been targeted as other candidates for this technique.

3-D COMPUTED TOMOGRAPHY OVERVIEW

Fundamentally, 3-D Tomography requires a large number of two-dimensional images about a given axis followed by the application of mathematical techniques to create three-dimensional images.

As seen in figure 1, the X-ray tube (open or sealed) produces a conic beam of electrons that penetrates the object to be analyzed, and a digital signal is interpreted by the two-dimensional (2D) detector as a Digital Radiograph image.

The object is positioned on a precision rotational stage and an image is acquired during the rotation at a constant step. The step is usually 0.25 degree to 1 degree (1440 to 360 images). The scan usually covers a rotation of 360 degrees, but for specific applications a limited angle scan can be performed.

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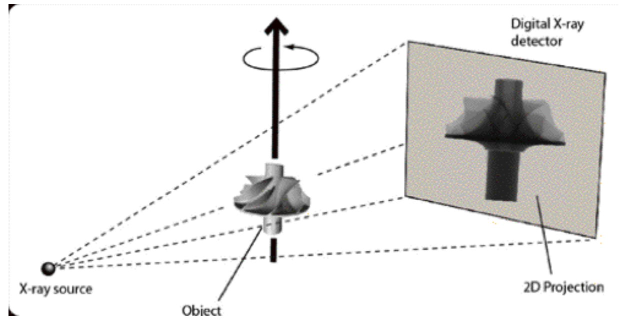


Figure 1: Overview of 2-dimensional imaging technique. Courtesy of *North Star Imaging, Inc.*

From a series of 2D Radiographs and after calibration, the CT reconstruction software provides 3D volume results using a 'Filtered Back-Projection' algorithm (Feldkamp). 3D CT data are rendered as 'voxels' (volume element) with three-dimensional resolution from a few micrometers (microCT) to hundreds of micrometers depending on the X-ray detector pixel size as shown in figure 2 [1].

What we have found particularly useful in this imaging process is the resulting 2-D slice views which are produced simultaneously in the x, y, and z planes from the series of original 2-D radiographs. Also key to quality imaging is uniform density of the object to be inspected.

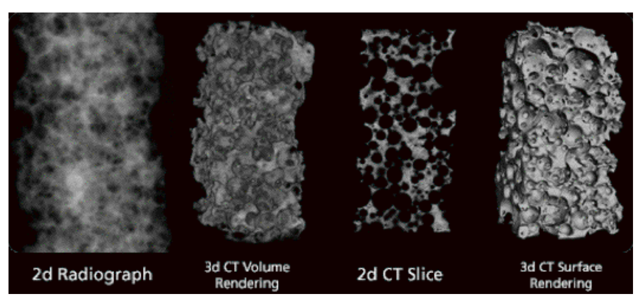


Figure 2: Steps taken in producing three-dimensional computed tomography images. Courtesy of *North Star Imaging, Inc.*

Typical parameters used for imaging cavities are:

- X-ray Energy = 225 kV
- Beam current = 350 μA
- Gun to Detector distance - 1 meter or less; gun closer to object
- Detector pixel size - 127 microns
- Resolution depends on factors above plus material (density) to be sampled
- Number of scans - variable, scans typically taken every ½ to 3 degrees over 360° of rotation
- Set-up + calibration + Scanning time - 4-6 hours
- Results available ~1hour after scans are completed.

CAVITY IMAGING MOTIVATION & EXPERIENCES

To date six cavities have been imaged for Fermilab by commercial vendors. These include three 3.9 GHz 9-cell cavities and three occurrences of studying 1.3 GHz single cell cavities.

3.9 GHz Cavities

As described above, two 3.9 GHz 9-cell cavities took a decided turn for the worse in terms of cavity performance following a series of successful tests. These early models include HOM 'Formteils' which are of an early 2-post design. Such cavities have a history of excessive mulitpacting and 'F-piece' fractures near weld regions.

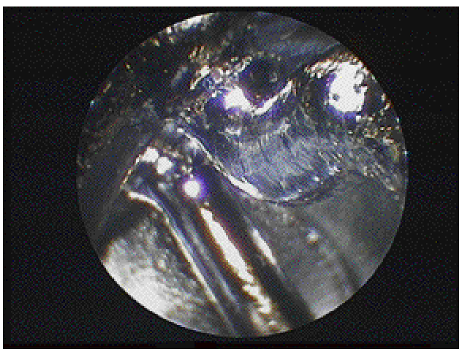
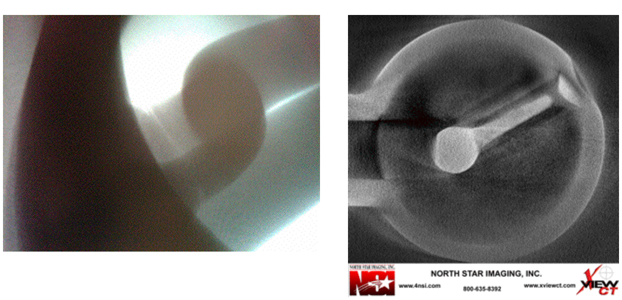


Figure 3: Borescope image of a 3.9 GHz HOM 'Formteil'.

Attempts to condition away the degraded performance, re-processing the internal surface and image suspect locations with a borescope were unsuccessful. Figure 3 is a photograph of inspection of such a piece in a suspect region. Attempts to make some assessment with sonic means proved to be inconclusive as well.

A vendor, *North Star Imaging, Inc.*, was identified and contacted regarding possible 3-D CT imaging. Figure 4 shows a 3.9 GHz cavity under analysis at North Star's Rogers, Minnesota facility with both Fermilab and North Star personnel present. Using the process described above a series of 2-D scans were made, every 0.5 degree, through 360° of rotation.



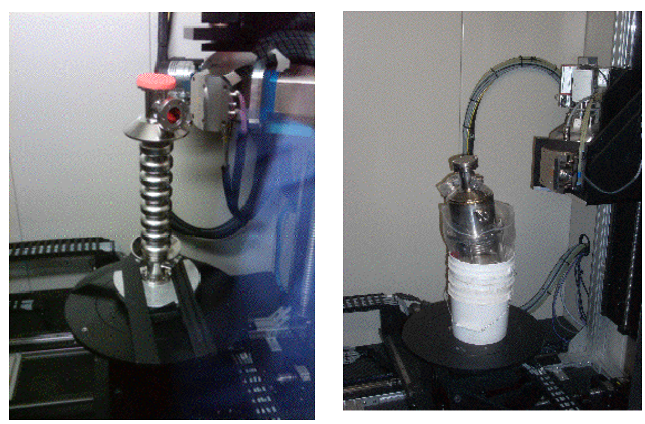
Figures 4 & 5: 2-D image (left) and 2-D reconstruction 'slice' view of a suspect HOM can.

Figures 4 and 5 respectively show one such 2-D radiograph and a slice reconstruction through the HOM can.

In figure 6 it is possible to see the size of the X-ray machine with Fermilab and North Star Imaging staff witnessing a 3.9 GHz 9-cell cavity under analysis.

Figure 6: 3.9 GHz dressed Cavity undergoing imaging at *North Star Imaging, Inc.*

Orientation of the device or area to be studied with respect to the incident X-ray beam and detector is critical to successful tomography. Figures 7 and 8 show both a bare and dressed 3.9 GHz cavity mounted for imaging with a slight tilt so as only minimal interference with the input coupler and HOM feed through flanges as well as conical end groups are encountered.



Figures 7 & 8: 3.9 GHz cavities in the X-ray machine mounted for imaging. The X-ray gun is to the right in both photos.

In both cases, the exercise proved to be successful as fractures near the weld joint of the back-side 'F-piece' leg were clearly visible. With CT reconstruction software it is possible to look at the result from virtually any angle or magnification. The size of the fracture in this case is estimated to be of order 0.1's of a mm.

Neither cavity has been opened to make a direct physical measurement. Figures 9 and 10 are two views of the same fracture. Since the fractured leg was on the back side of the HOM can with respect to the cavity bore it would have been impossible to see without invasively accessing the HOM can.

Figure 9: Clear evidence of a 3.9 GHz cavity fractured HOM 'Formteil'.

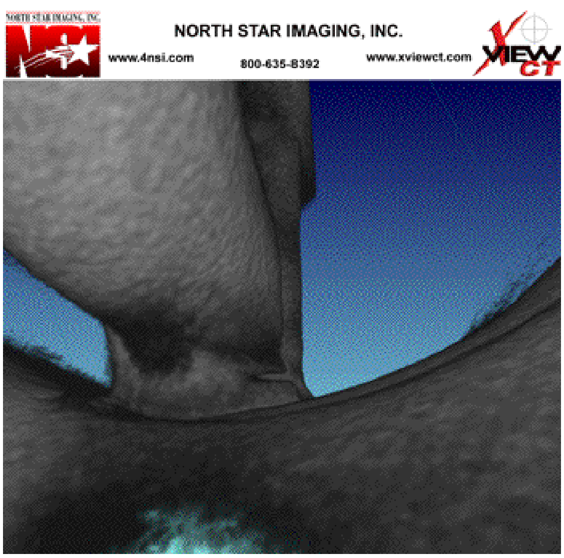


Figure 10: Alternate view of the same fracture as in Figure 9.

A spare 3.9 GHz cavity albeit with a 'modern' single-post 'Formteil' was fabricated and has undergone a baseline series of scans prior to chemical processing and testing.

1.3 GHz Single Cell Cavities

The definitive results described above naturally led to consideration of other imaging possibilities, namely checks of electron beam weld quality, inspection for internal pits, and identification of possible imperfections underlying the cavity surface. Thus there is motivation to determine if 3-D CT could complement or be an alternate technology to high resolution optical inspection.

The first candidate to be imaged was a cavity with a known low quality equator weld as evidenced by visual inspection. Figure 11 shows a representative cavity under assessment at *North Star Imaging*.

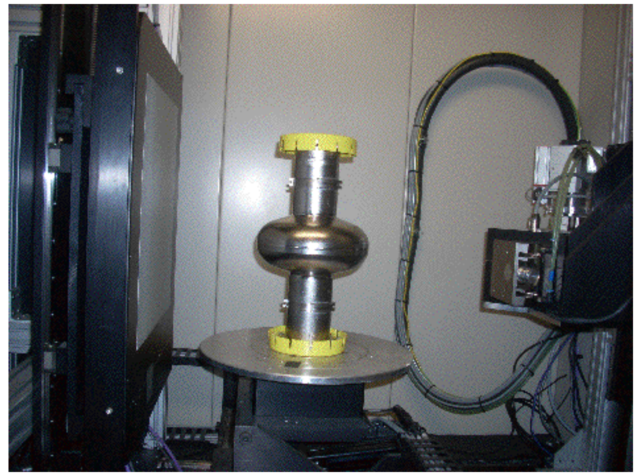


Figure 11: 1.3 GHz single cell cavity under test. To the cavity's left is the detector screen and to the right is the X-ray gun in its resting position.

2-D slice images showed a 'sparkling' pattern of alternating light and dark spots in the region of the equator weld. This response initially caused some consternation but was finally ascribed to the X-ray beam striking weld voids and scattering off of the surface surrounding the voids. Figures 12 and 13 are 3-D CT images clearly indicating voids in the equator weld from two locations. In fact, perusing the weld region in this way indicates that much of the weld was found to have an internal void. From these images it is possible to estimate the size of the void and its depth below the outer cavity surface. Actual physical sectioning has yet to be carried out to confirm these indications.

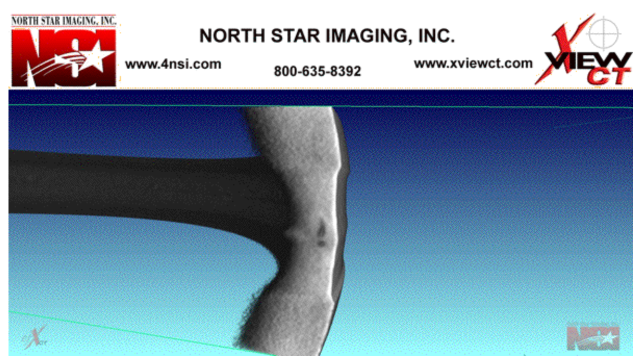
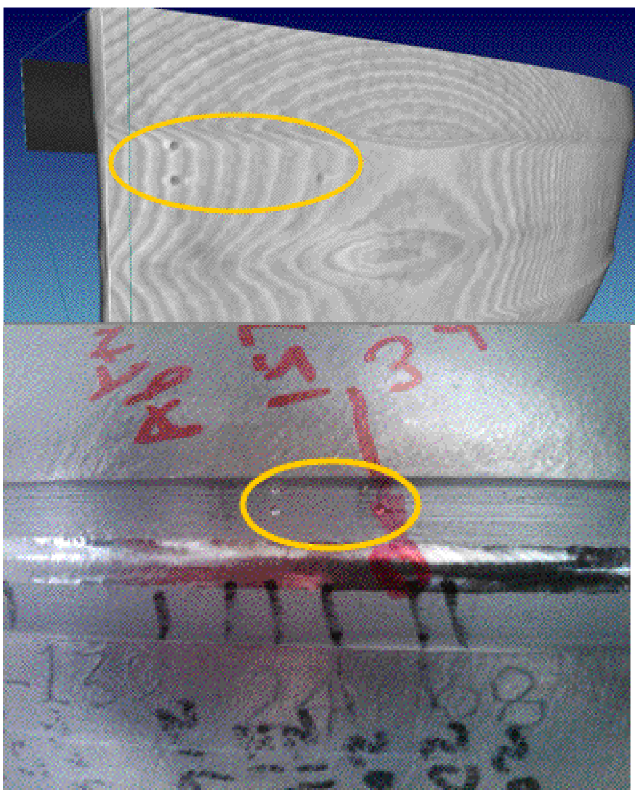


Figure 12: 3-D CT image of an equator weld void.

During an on-line consult with North Star's imaging expert pertaining to the cavity described above, three 'holes' were noted slightly under the outer surface of the cavity just above the weld region, as shown in Figure 14. This proved to be a quality check of sorts for the imaging process as visual inspection of the cavity revealed that a series of reference points had been scribed as shown in Figure 15.

Figure 13: Second view of the void in a 1.3 GHz single cell cavity equator weld.



Figures 14 & 15: Reconstructed view just under the surface of a 1.3 GHz single cell cavity and comparative photograph of the outer surface. Note the three scribe marks circled.

There have been two additional inspections of 1.3 GHz single cell cavities to assess the feasibility of using this technique to identify pits at or just below the internal surface of such cavities. This exercise also permitted the evaluation of another potential vendor, *YXLON/Comet Technologies*.

Figure 16 is a representative 2-D radiograph produced by their equipment. This view actually contains both a 'close' view of the weld region and a 'far' image of the opposite surface made possible by slightly tipping the cavity so that the incident X-ray beam is vertically off-normal to the cavity surface.

The resolution of this scan makes it is clear that 2-D images alone are insufficient to identify regions of pits and software reconstruction tools are critical in making clear views possible.

IMAGING SERVICE PROVIDERS

The quest to identify vendors able to supply our desired images has resulted in two 'local' companies i.e. within 500 miles of Fermilab:

- NorthStar Imaging, Inc. - Rogers, Minnesota
- YXLON/Comet Technologies - Akron (Mogadore), Ohio.

Both firms offer imaging and analysis services as well and also manufacture and sell their own lines of X-ray machines. The devices offered by each are very similar. Figures 17 and 18 are images of a cavity being prepared for test at *YXLON* and a view of their system. The *YXLON* hardware compares favorably to the *North Star Imaging* system seen in Figure 6. Both vendors offer relatively fast turn-around and availability and nearly 'same day' service in terms of producing image results. Similar techniques are offered as to how the imaging is performed and system operating parameters.

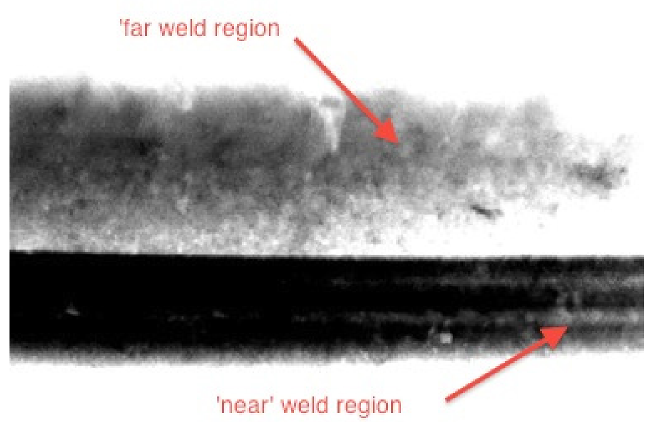


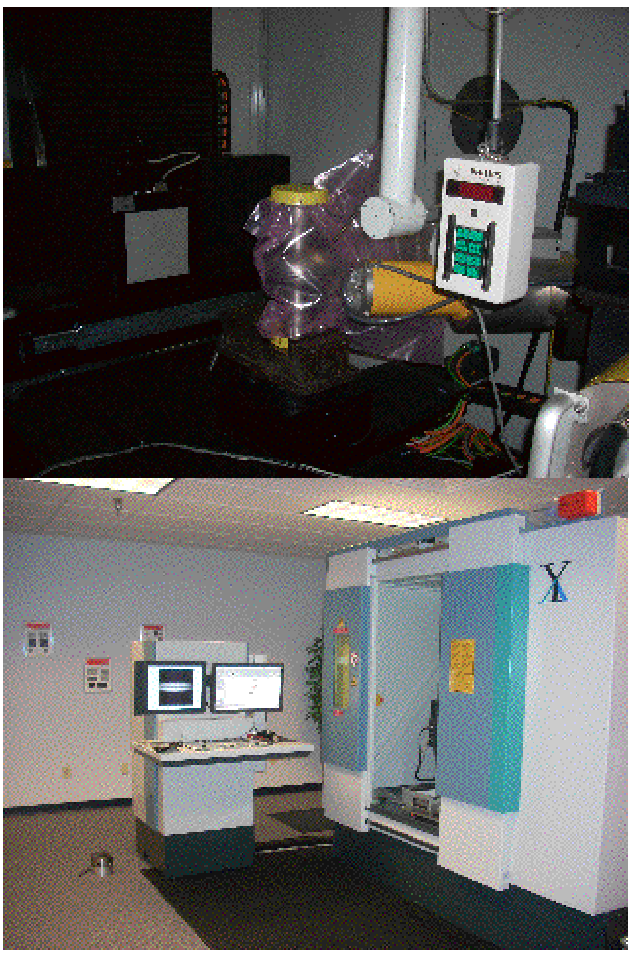
Figure 16: 2-D image of the equator weld of a 1.3 GHz single cell cavity. Two views of the weld are possible – the lower (darker) image is of the surface closest to the incident X-ray beam.

OBSERVATIONS

The following observations can be made based on our limited experience with this technology as applied to SRF cavities:

- 3-Dimensional X-ray Computed Tomography can be a powerful tool for non-invasive inspection,

- Analysis/Visualization Software is a fundamental need and consideration of its capabilities cannot be stressed enough,
- The ability to see x, y, and z 'slices' through the imaged device is a powerful tool in its own right,
- Ease of analyzing images is important,
- One must have some idea of what is being looked for so as to optimize imaging technique and device orientation,
- Imaging internal surfaces is a challenge due to the scattering of the incident beam through multiple surfaces,
- Trade-offs are inevitable in terms of resolution and area of coverage,
- For internal surface views, it is the opinion of the imaging experts were have discussed this with that high resolution 2-D *may be* best option.



Figures 17 & 18: X-ray imaging system at *YXLON/Comet Technologies* in Akron, Ohio.

FUTURE PROSPECTS & PLANS

This technique has yet to be fully evaluated as to its appropriateness for SRF cavities. To make progress in the short-term it is desirable to image cavities with suspect region(s) of defects and compare them to 'good' cavities. In order to improve the image resolution of the internal cavity surface discussions have begun as to the feasibility of placing a detector within the cavity or equivalent alternatives. Yet to be attempted, yet very important, is performing scans on a 1.3 GHz 9-cell cavity. Further experience with imaging software is also needed.

SUMMARY

We conclude that 3-D X-ray Computed Tomography can be a powerful tool for non-invasive inspection. It has already proven itself to be capable of providing internal imaging of difficult geometries as evidenced by identifying cracked HOM antennae on 3.9 GHz SRF cavities.

This is a mature technology in various industries including Aerospace, Automotive, Electronics, Military, and Forensics. This technique has also been employed at CERN to inspect LHC magnet interfaces [2].

Continued investigation is needed for full exploitation in the SRF field. Clearly it is an appropriate tool for special circumstances; it remains to be seen if it can be systematically employed for effective Quality Assurance/Control.

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- The staff at *YXLON/Comet Technologies* especially Chris Cherry and Chris Williams of Berg Engineering,
- Bob Kephart of Fermilab for his continued interest in this technique and its potential application to the field.

REFERENCES

[1] http://www.xviewct.com/computed-tomography-technology/how-ct-works.

[2] L. R. Williams et al., "Mobile CT-System for In–situ Inspection in the LHC at CERN", IPAC'10, Kyoto, May 2010, MOPEB076, p. 447 (2010); http://www.JACoW.org.