X-Ray Tomography Inspection of SRF Cavities

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15th International Conference on RF Superconductivity
25-29 July 2011

Outline

- Introduction
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- SRF application/Experiences to date
  - 3.9 GHz examples
  - 1.3 GHz single cell
  - Larger view possibilities
  - Conclusions to date
- Vendor experiences
- Future Prospects and Plans
- Conclusions & Summary

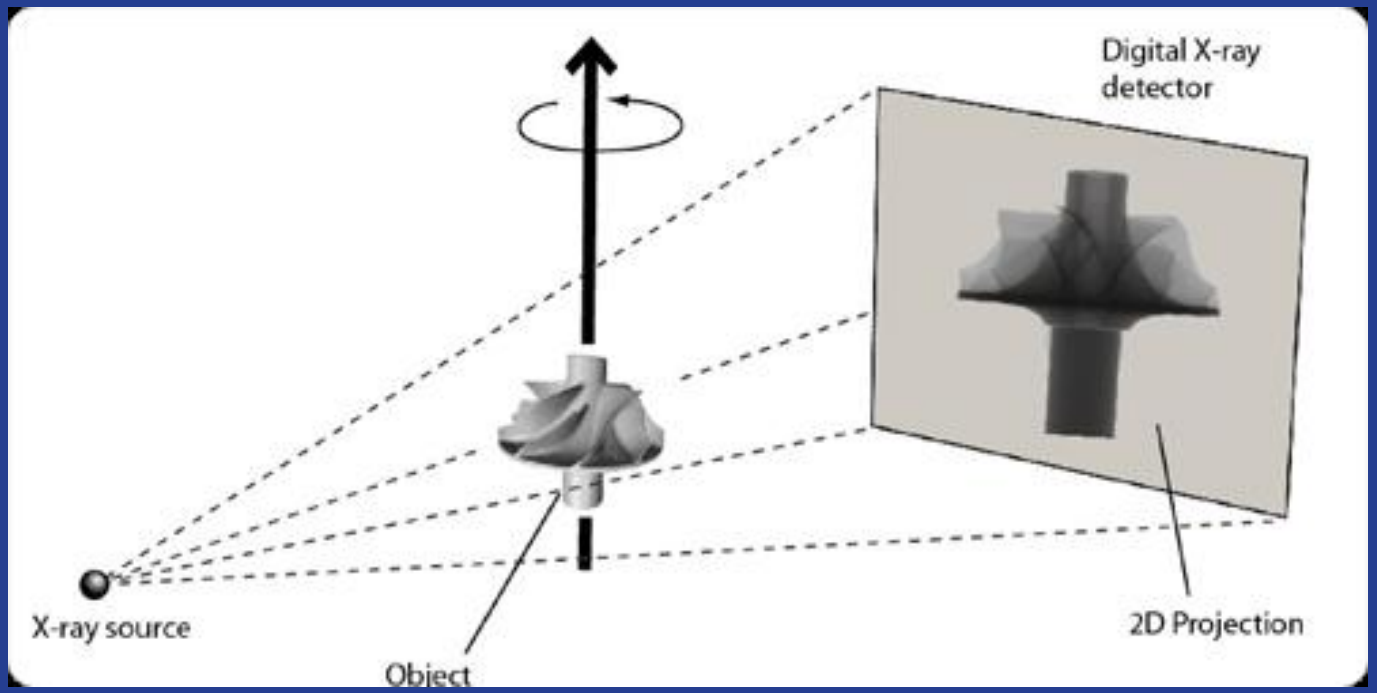
Introduction

- *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.*

- Our exposure to the capabilities and utility of 3-D X-ray Computed Tomography (CT) stemmed from degraded performance issues with two 3.9 GHz 9-cell cavities following a series of successful tests. Although multipacting and possible HOM damage were suspected based on previous experience, testing and attempts at visual inspection were fruitless. Only by means of 3-D x-ray CT was it possible to non-invasively determine that cracked Formteils were the root of the degraded performance.

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

Overview/How Computed Tomography works



The X-ray tube (open or sealed) produces a conic beam of electron that penetrates the object to be analyzed, and a digital signal is interpreted by the 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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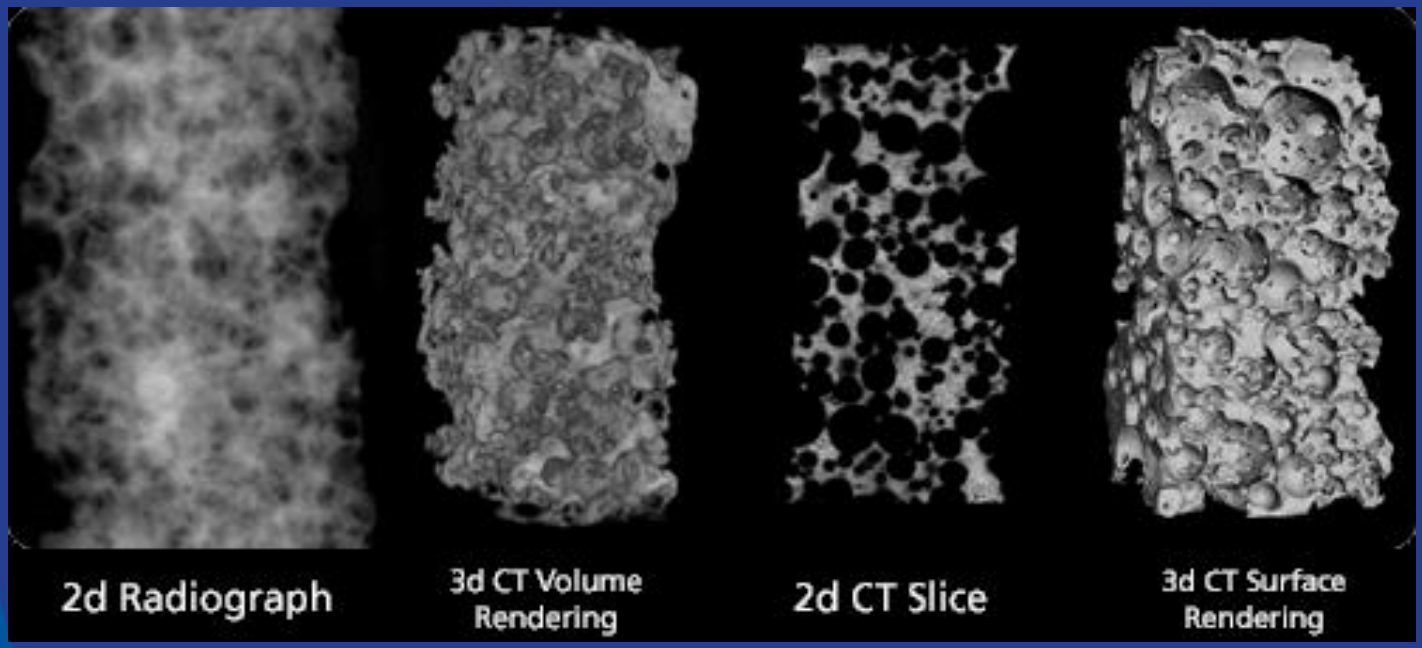
How Computed Tomography works



- From a series of 2D Radiographs and after calibration, the CT reconstruction software provides 3D volume results using 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 X-ray detector pixel size.

Courtesy of: NORTH STAR IMAGING, INC.

U.S. DEPARTMENT OF ENERGY

Fermilab

How Computed Tomography works

- Typical X-ray Energy = 225 kV
- Beam current = 350 μA
- Gun to Detector distance - 1 meter or less; gun close to object
- Detector pixel size - 127 microns
- Resolution depends on factors above plus material to be sampled
- Number of scans of order hundreds - images taken every 1/2 - 3 degrees about the selected axis of rotation
- Set-up + calibration + Scanning time = 4-6 hours
- Results ~1hour after scans completed

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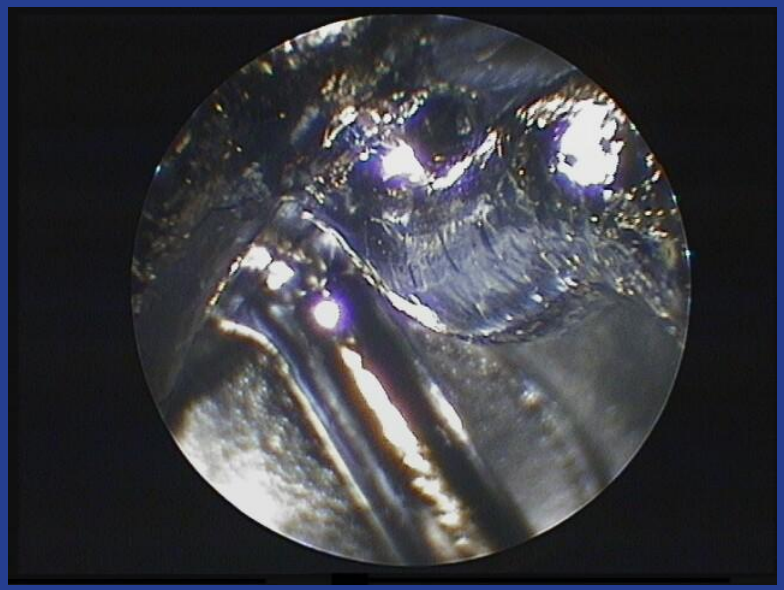
Fermilab Experience

- Degraded 3.9 GHz cavity performance
  - Inability to determine root cause
  - Visual inspection (with borescope) inconclusive
  - Destructive investigation not desirable
  - Sonic investigation inconclusive (Edwards & Schappert)
- Positive result leads to consideration of other imaging possibilities
  - Weld quality
  - Internal pits and underlying structure
  - Possible alternative to optical inspection



Fermilab Experience - 3.9 GHz Cavity HOM's

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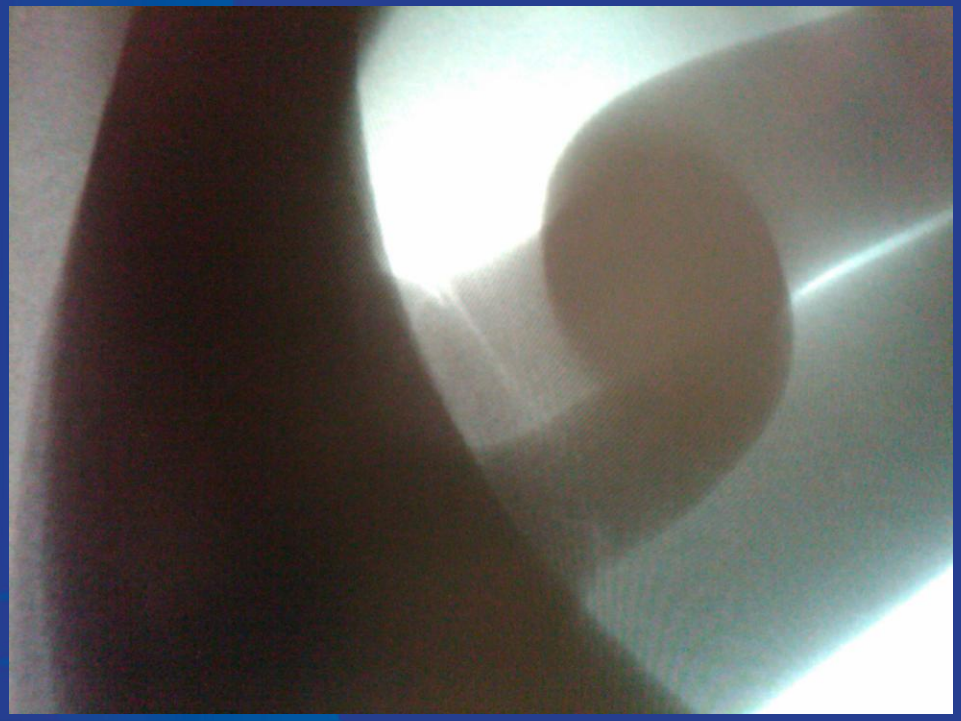
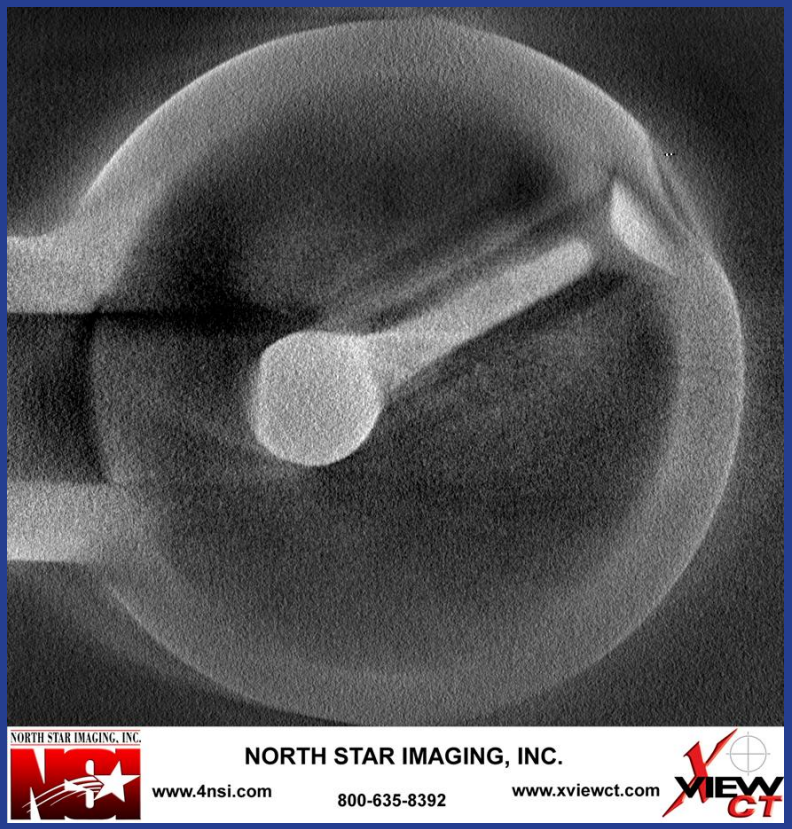
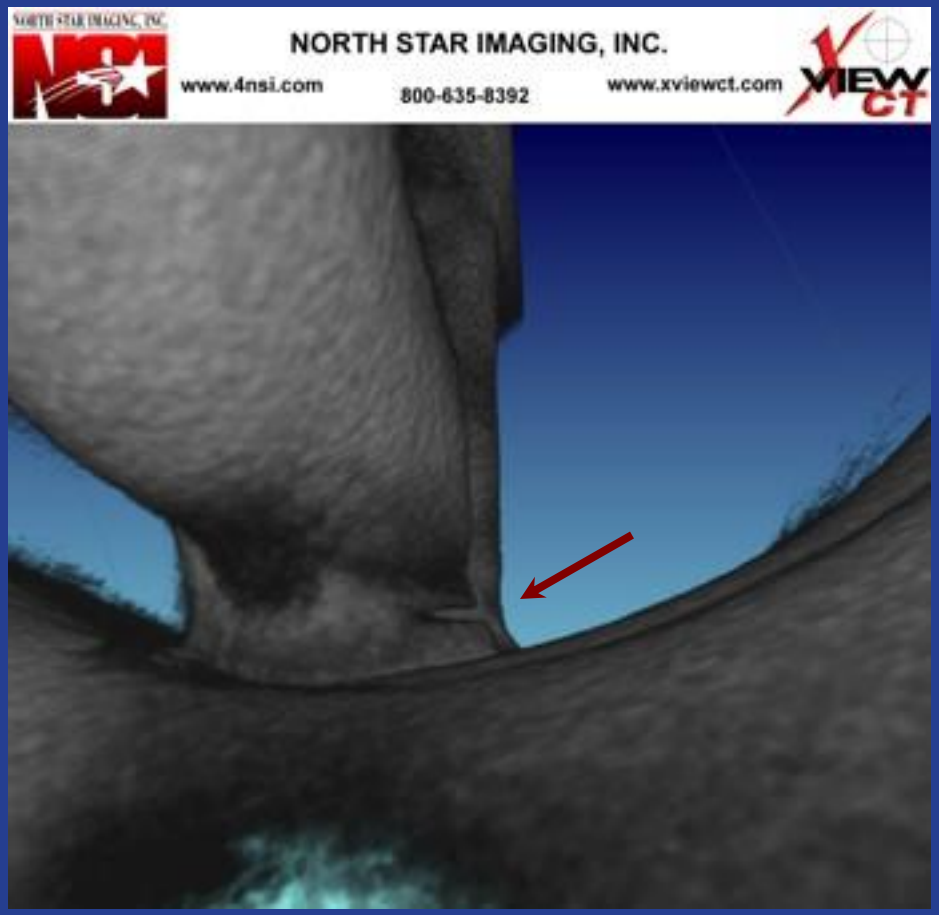




Fermilab Experience - 3.9 GHz Cavity HOM's

See me off-line to see a really cool movie of 2-D slice through a HOM can…

Fermilab Experience - 3.9 GHz Cavity HOM's



Fermilab Experience - 1.3 GHz Single Cell Welds

Fermilab Experience - 1.3 GHz Single Cell Welds

See me off-line to see a really cool move of 2-D scans through the equator showing weld voids…

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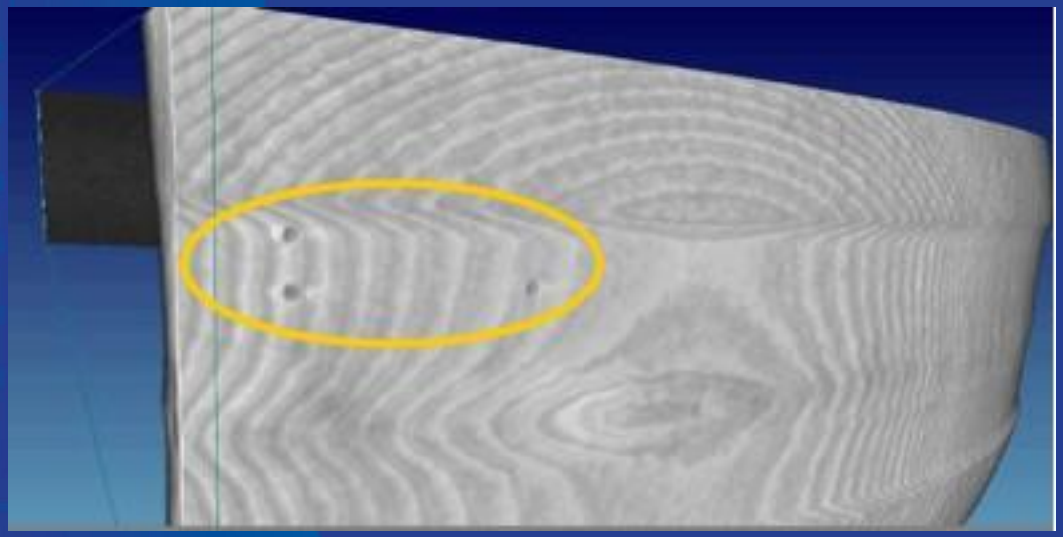
Fermilab Experience - 1.3 GHz Single Cell Welds



Imaging Episodes

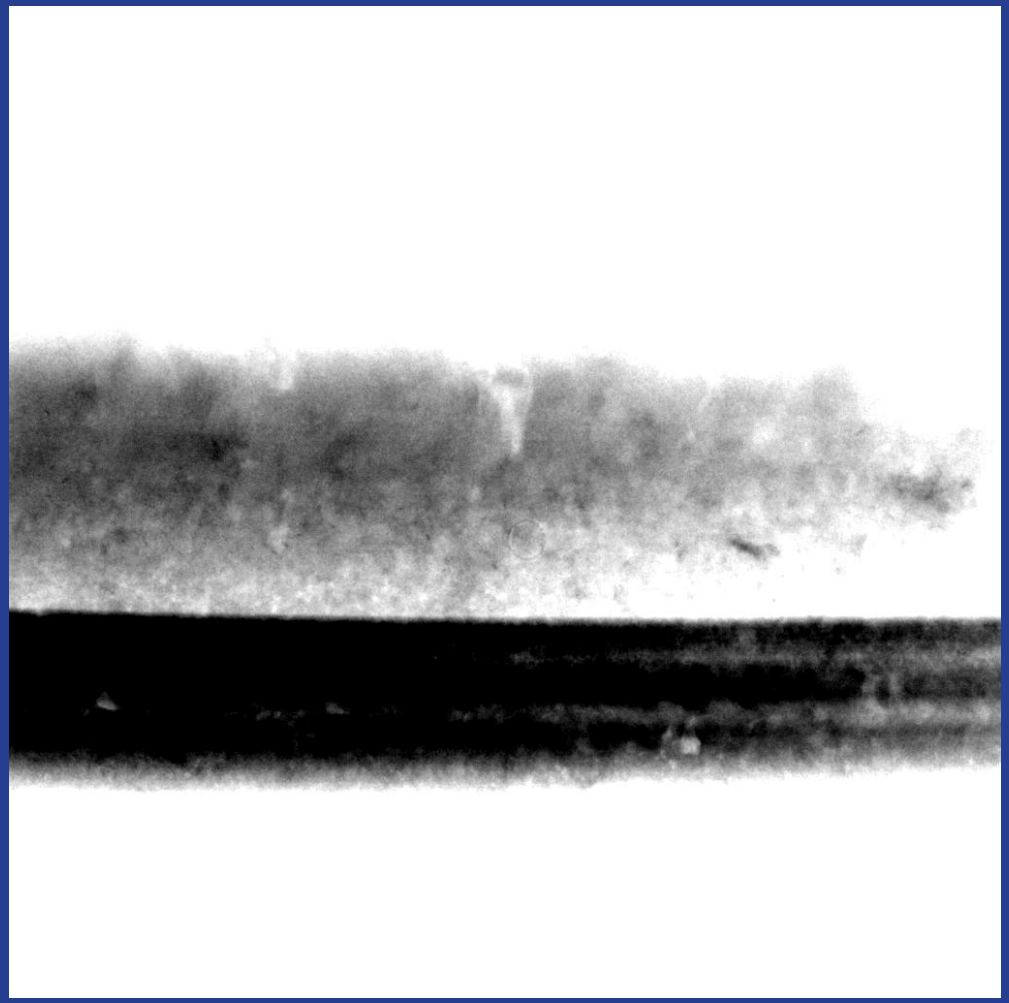
- 3.9 GHz 9-cell cavities
  - F3A4 - cracked Formteils
  - F3A6 - cracked Formteils
  - F3A9 - baseline imaging prior to BCP and testing
- 1.3 GHz single cell
  - RRCAT002 - evaluation of welds
  - TE1ACC004 - vendor evaluation/pit inspection
  - TE1CAT002 - vendor evaluation/pit inspection

Imaging Episodes

Imaging Episodes

‘far’ weld →

‘near’ weld →



Vendor Experiences

- Two ‘local’ vendors have provided their services
  - NorthStar Imaging - Rogers, Minnesota
  - Yxlon - Akron (Mogadore), Ohio
  - Imaging + Sales
- X-ray machines are very similar
- Fast turn-around
  - ‘Same day’ service
- Software capabilities
  - Resolution
  - Different visualizations
  - User/Owner needs

Observations

- CT can be a powerful tool for non-invasive inspection
- Analysis/Visualization Software is fundamental consideration
- Ease of analyzing images important
- Have some idea of what you are looking for
- Imaging internal surfaces is a challenge
- Trade-offs are inevitable
  - Resolution
  - Area of coverage
  - For internal surface views, 2-D *may be* best option

Future Prospects & Plans

- Continue to evaluate imaging techniques particularly on suspect cavities
- Discuss schemes to enhance internal imaging
  - 2D with internal detector
- Need to attempt a 1.3 GHz, 9-cell cavity series of scans

Conclusions & Summary

- 3-D X-ray CT can be a powerful tool for non-invasive inspection
  - Already proven itself to be capable of providing internal imaging of difficult geometries
- Mature technology in various industries
  - Aerospace
  - Automotive
  - Electronics
  - Military
  - Forensics
  - *CERN/LHC*
- Continued investigation needed for full exploitation in SRF field
  - Appropriate for special circumstances!
  - Appropriate for regular QA?

Acknowledgements

- Helen Edwards
- Warren Schappert - identifying North Star Imaging
- North Star Imaging
  - Jeff Diehm et al
- Yxlon/Comet Technologies
  - Chris Cherry, Chris Williams
- Bob Kephart - continued interest in this technique and its potential application to the field

Thank You!