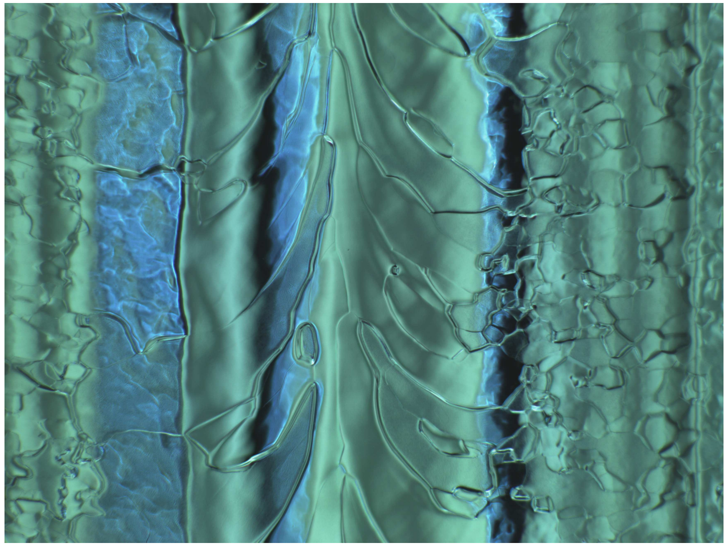
# Optical analysis of SCRF niobium cavities

## Status Report



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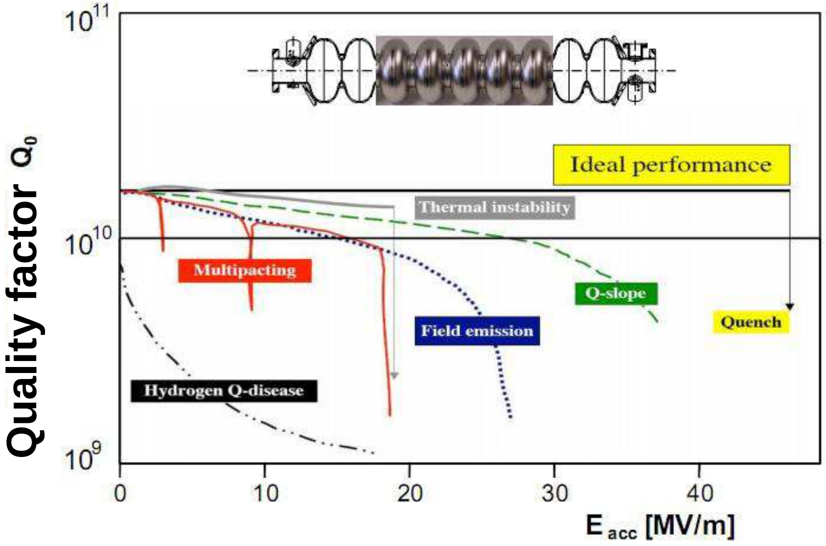
# SCRF Fundamentals

- Electromagnetic field oscillates inside volume bounded by superconducting surface
- Surface currents shield the external fields from bulk niobium (~30 nm skin depth).
- The highest magnetic field is located at equator region ⟶ highest current densities occur in this region.
- Surface roughness, a geometrical defect or an impurity lead to a local breakdown of superconductivity



# Goals

> Surface classification

- Deduce a minimal set of image variables to
  - Understand the influence of a chemical polishing of the cavity surface
  - Connect surface properties with operational behavior of the cavities

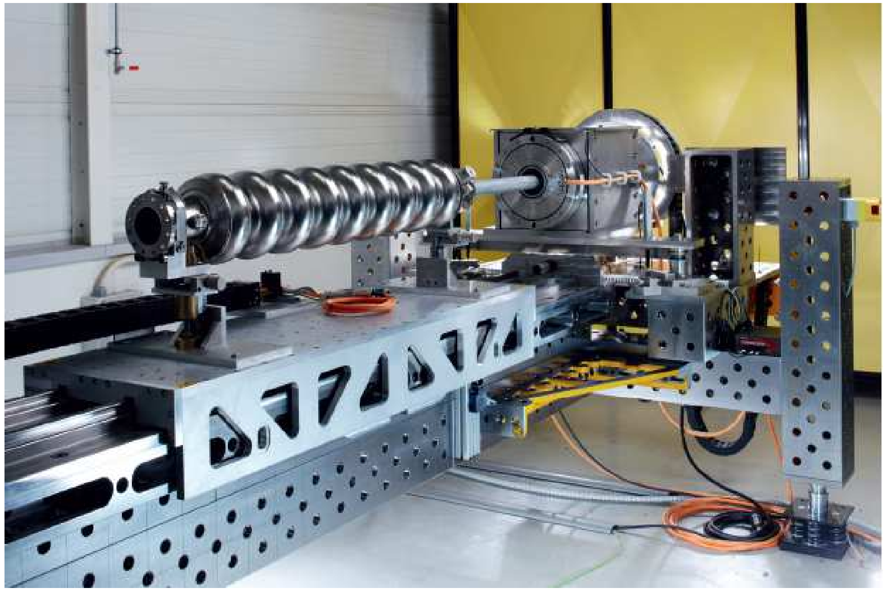
- Define a specification of surface and welding seam properties for quality assurance during industrial mass production of cavities

> Defect detection

- Development of automated detection and classification of irregularities as possible operational limiting heat spots (quench, Q-drop)

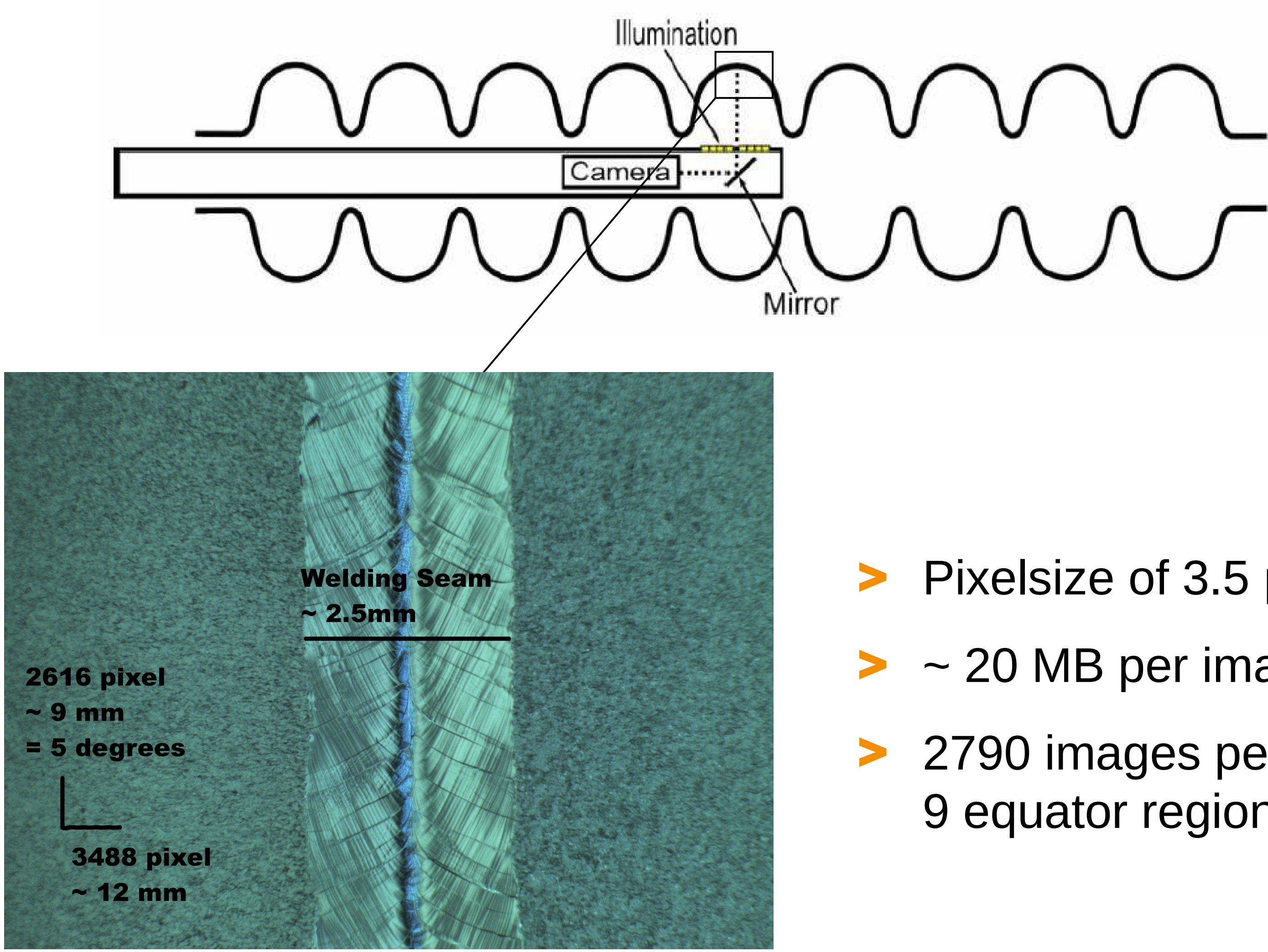
# OBACHT

- **O**ptical **b**ench for **a**utomated **c**avity inspection with **h**igh resolution and short **t**imescales



- Fully automated optical inspection: camera position, illumination, image taking and image storing, (auto focus)
- Timescale for single inspection decreased from the order of days to 8-10h
- Image processing for variable deduction runs in parallel using stored images

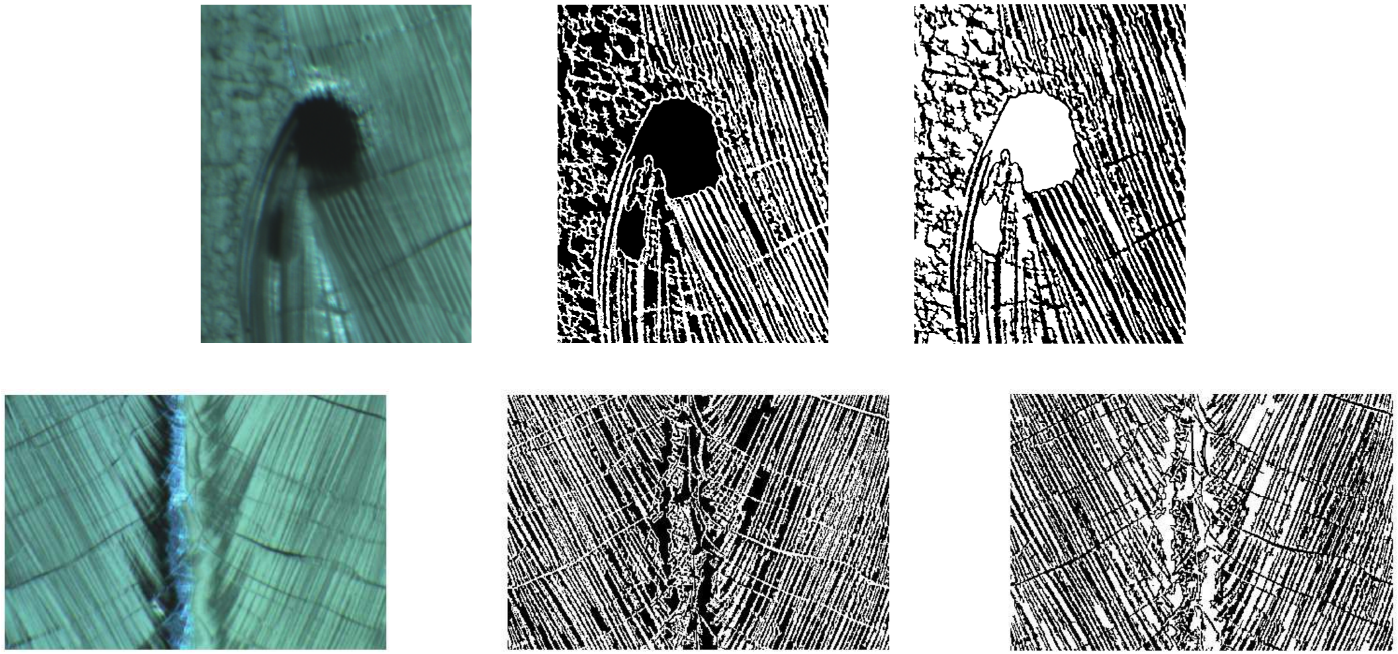
# Optical inspection




- Pixelsize of 3.5 µm x 3.5 µm
- ~ 20 MB per image
- 2790 images per cavity
  9 equator regions + 10 irides

# Image processing

- Image processing steps are applied to original color image
- Two binary images are derived (edge and object representation)

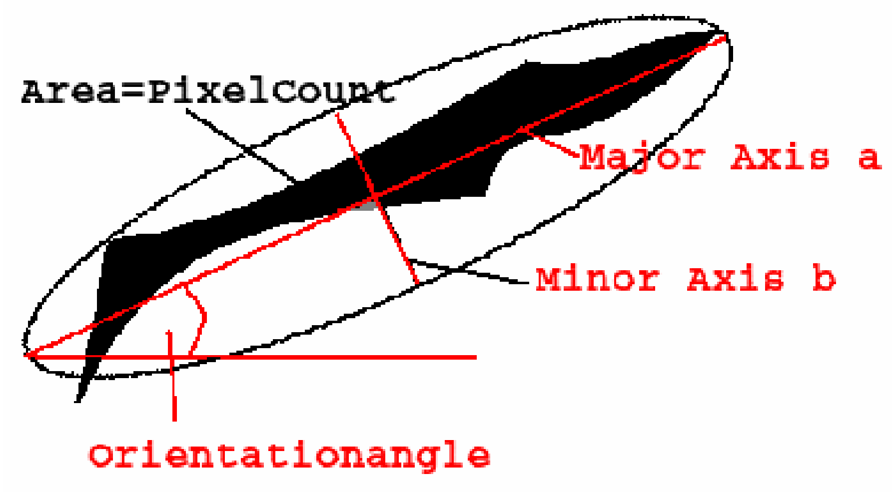


- Grayscale image is used and surface profile is optional
- Sets of variables are deduced using the image representations

# Key variables

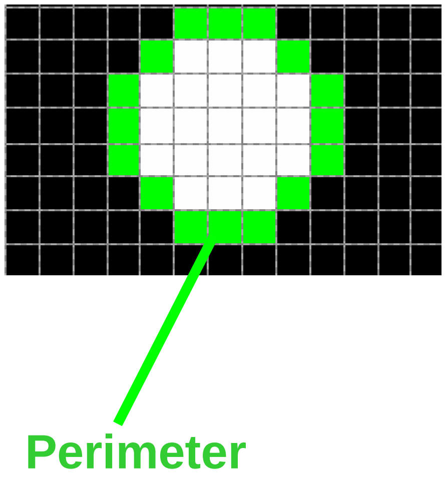
> Derived from the binary image

- Area
- Major & minor axis length
- Perimeter
- Orientation




> Derived with binary and grayscale image

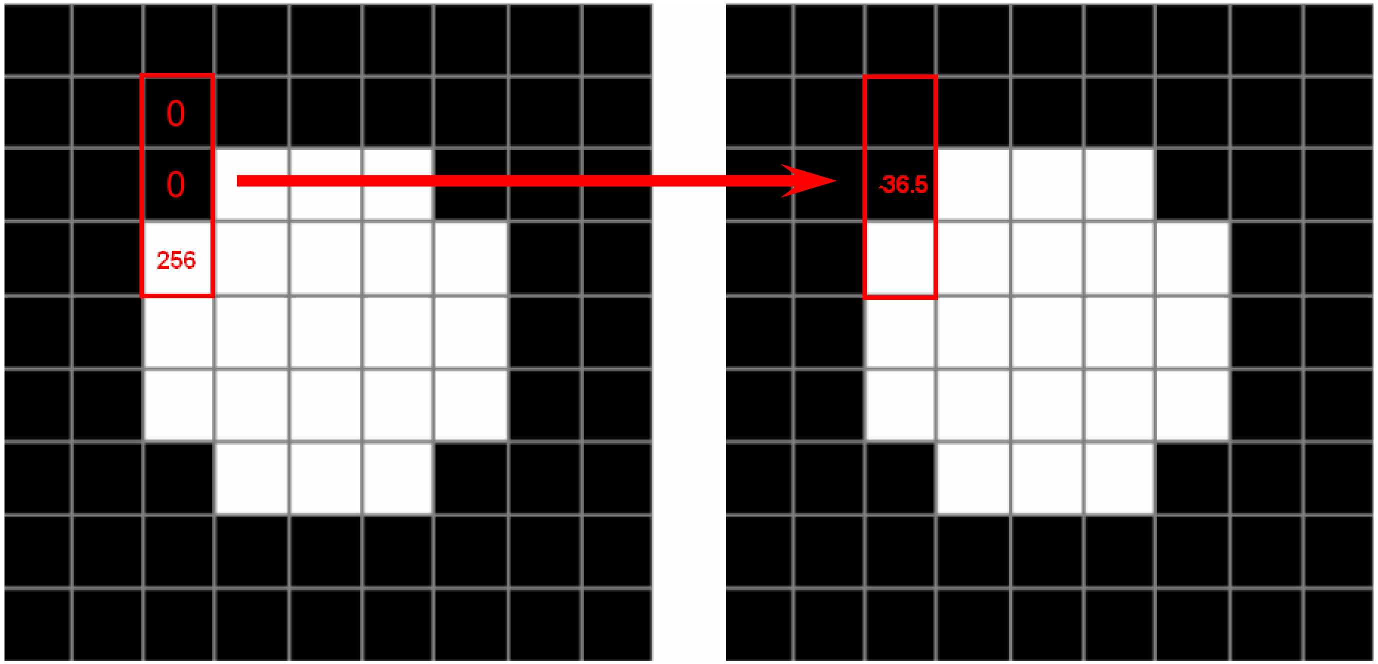
- Surface Roughness $R_{dq}$



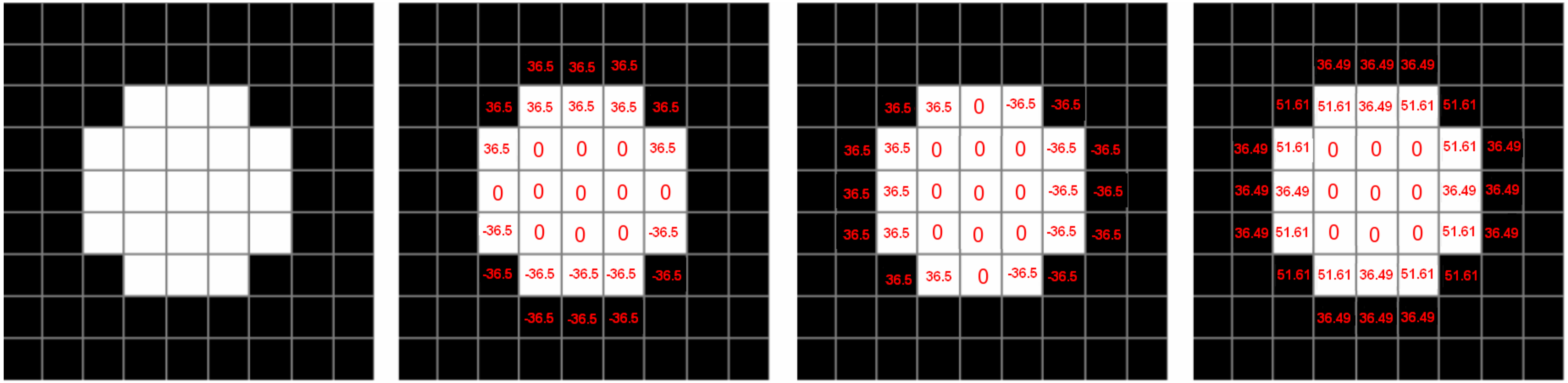
# Surface Roughness

- Pixel to pixel intensity difference is calculated (intensity gradient) for the x and for the y direction using the finite central difference

$$\Delta_{y_i} = \frac{I(x, y+1) - I(x, y-1)}{(y+1)-(y-1)} = \frac{256-0}{7}\frac{Bit}{\mu m} = 36.57\frac{Bit}{\mu m}$$



# Surface Roughness




(1) Object (2) Gradient in x direction (3) Gradient in y direction (4) Δi per pixel

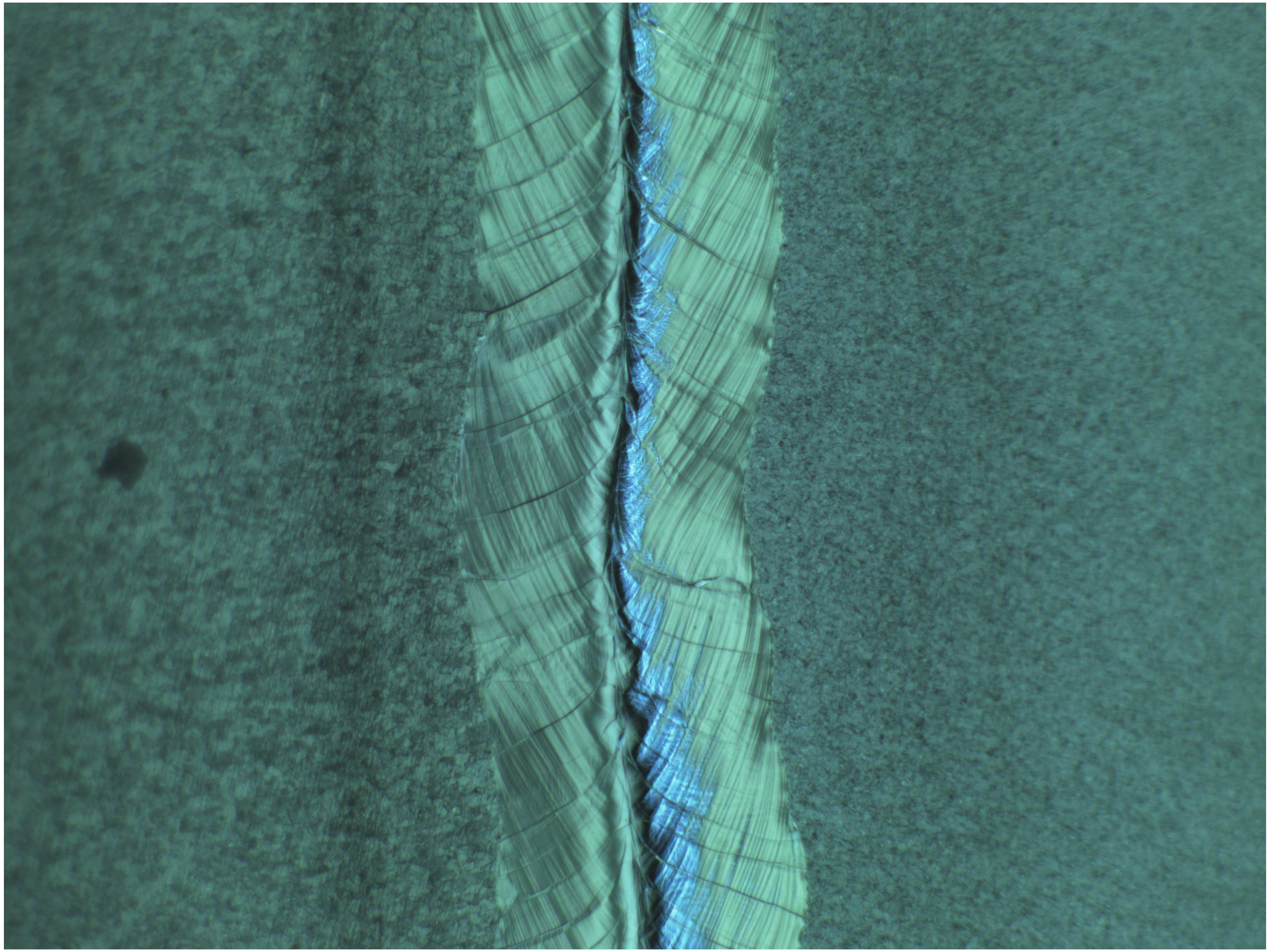
> x and y values for each pixels are used to derive a single scalar value $\Delta_{pi}$ (4)

$$\Delta_{P_i} = \sqrt{\Delta_{x_i}^2 + \Delta_{y_i}^2}$$

> Define object based $R_{dq}$: $R_{dq} = \frac{1}{N} \sum_p \Delta_{P_i}$

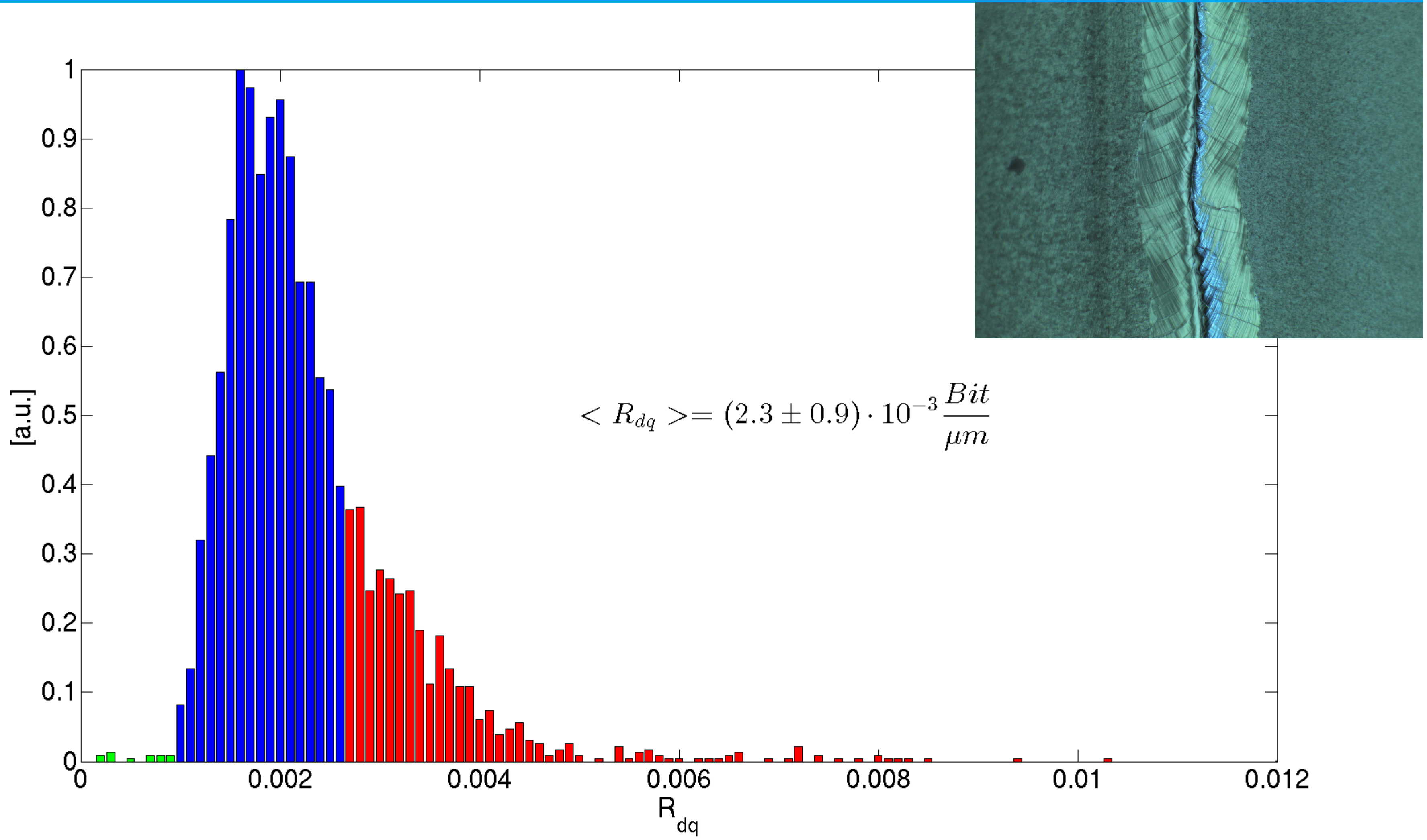
Example: $R_{dq}$ = 26.61 Bit/μm

# Surface Roughness - before electro polishing (ep)

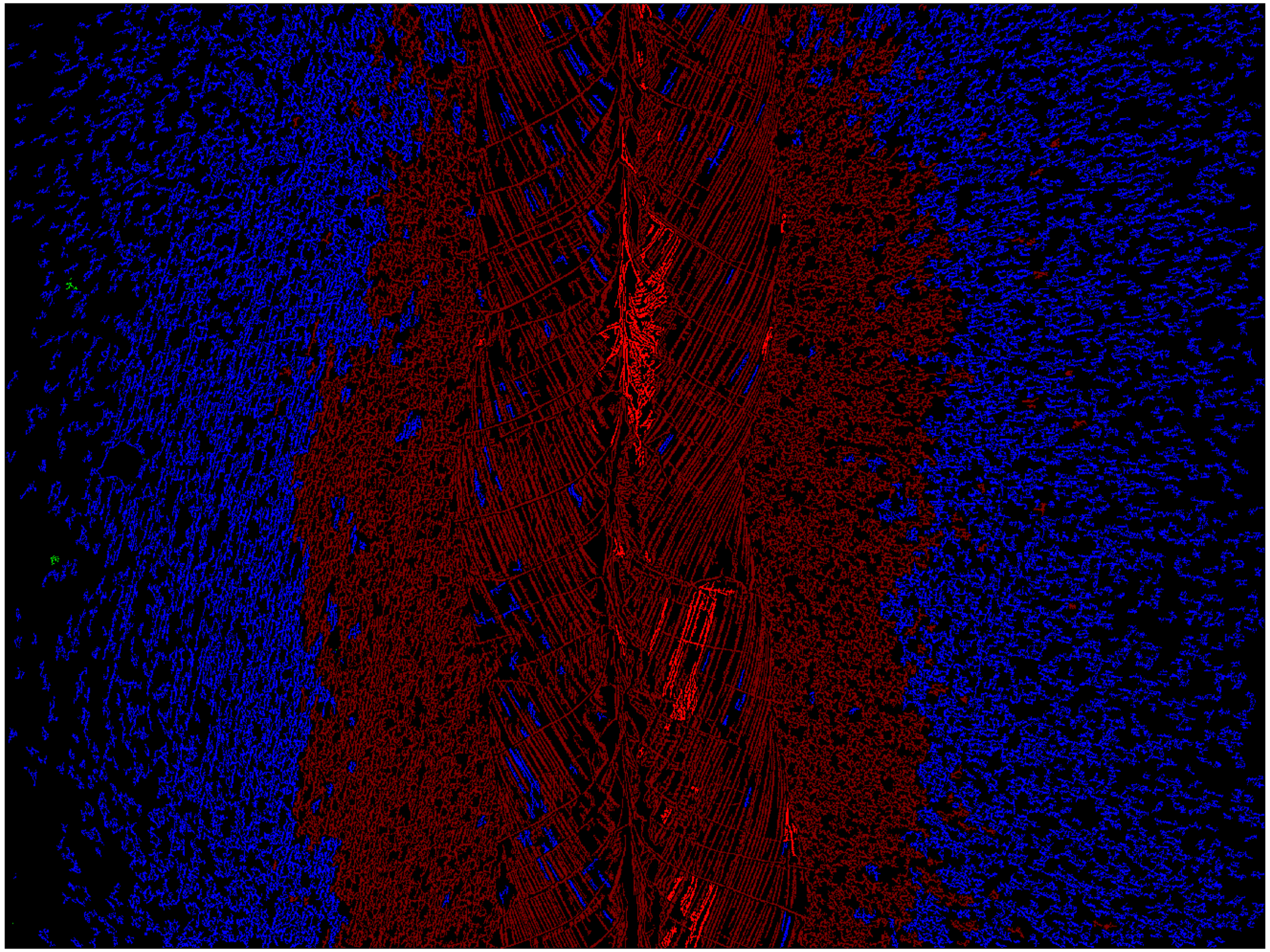


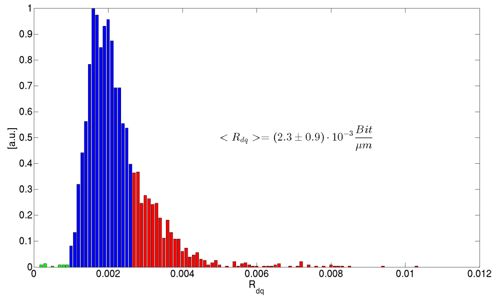
**Z161 – E3 – 117°**

# Surface Roughness - before ep



# Surface Roughness + edge length - before ep

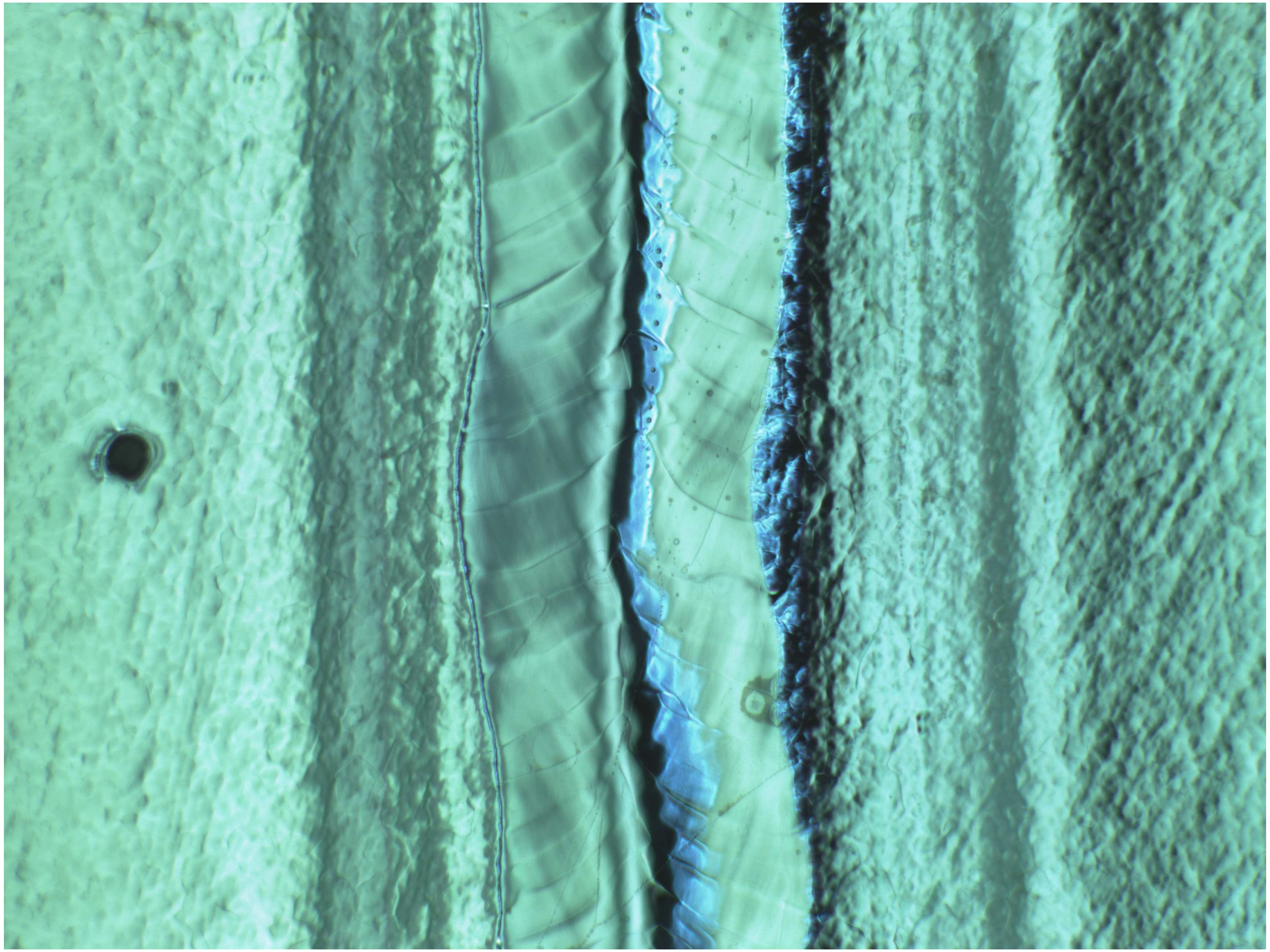





**Total length of edges found: 437 cm**

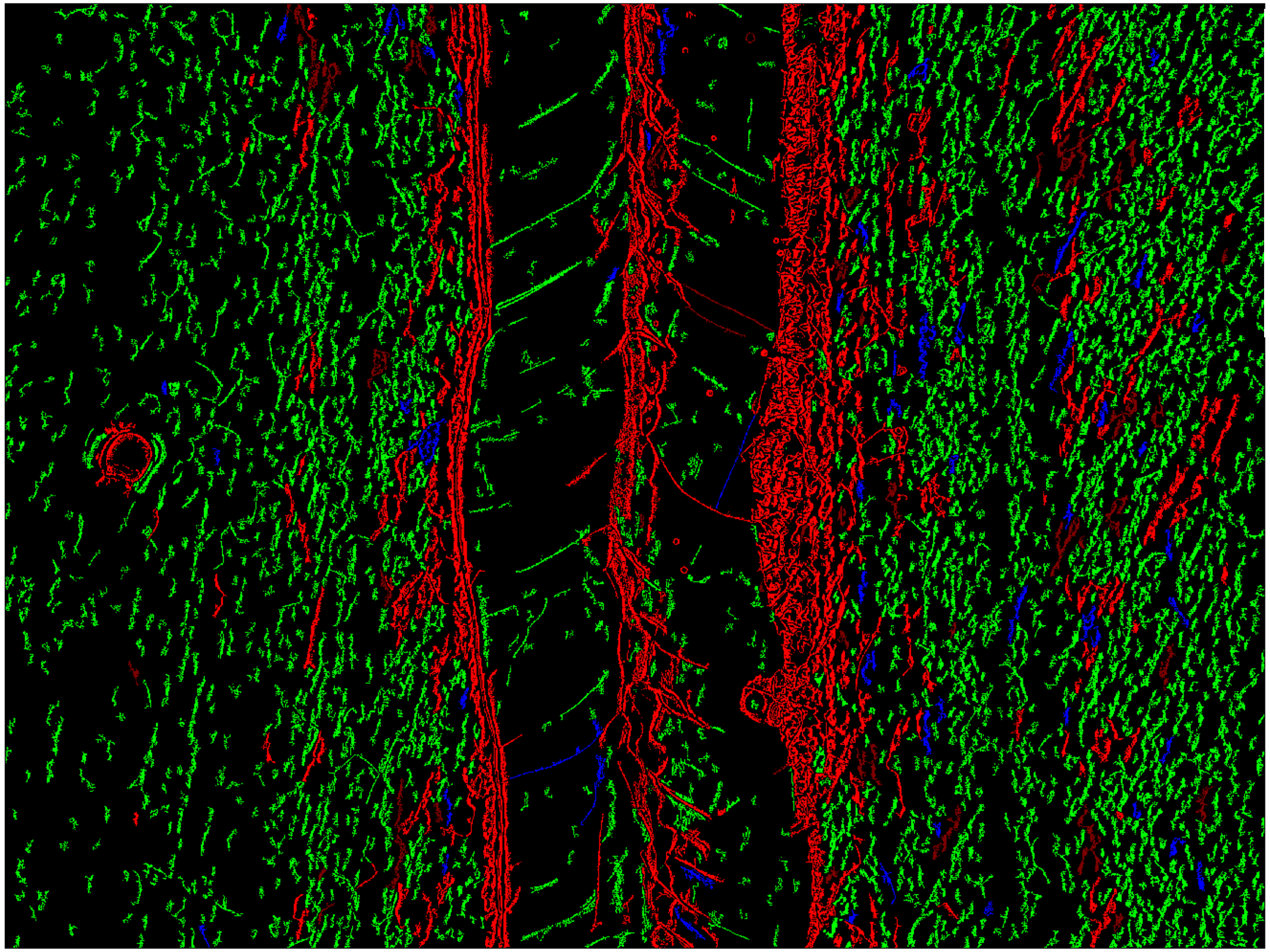
**Length of edges in welding seam region: 112 cm**

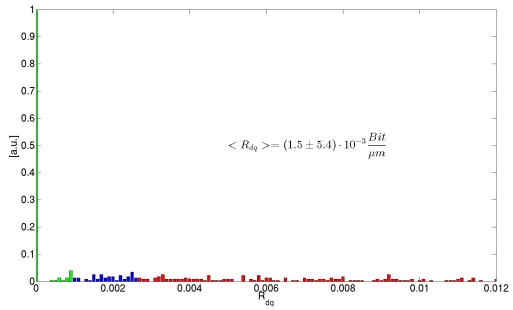
# Surface Roughness - after ep



**Z161 – E3 – 117°**

# Surface Roughness + edge length - after ep






**After ep:**

**Total: 257 cm**
**or 41.1%**

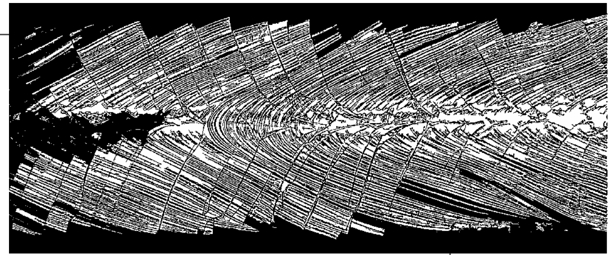
**Welding seam region:**
**42 cm**
**or 62.5%**

**$\langle R_{dq} \rangle$ reduced by 34 %**

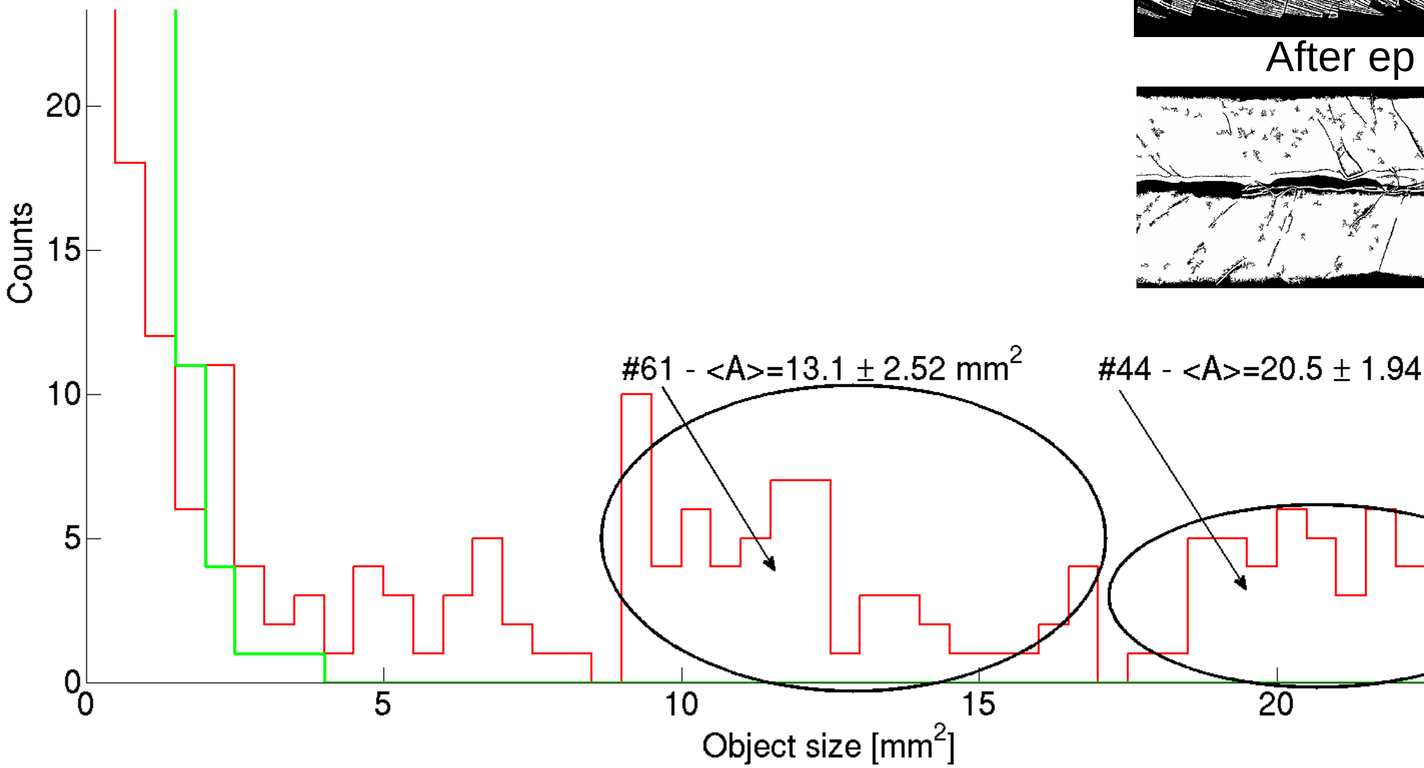
# Object size during treatment

- Histogram shows object size on welding seam region for complete equator (90 pics) before and after ep

Before ep



After ep



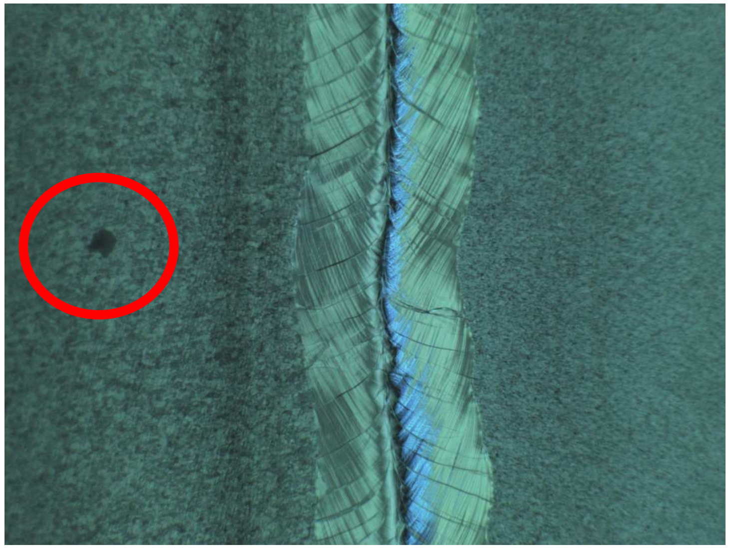

Total welding seam area found: 1607 mm² - total welding seam area expected: 1622 mm²

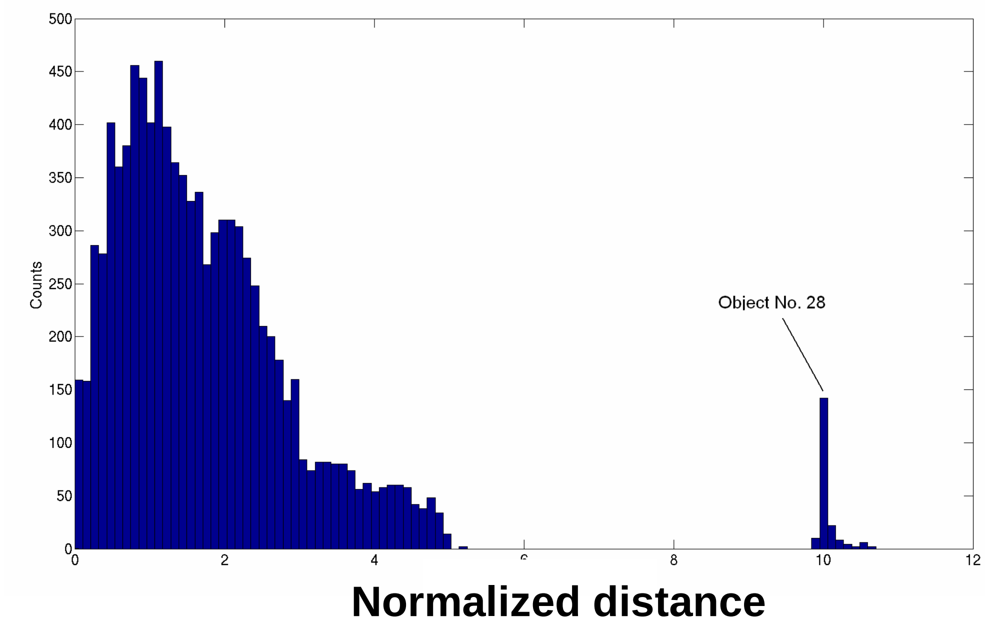
# Defect detection

- n=4 variables used to compare an object with the neighborhood
  - $\vec{x}$ = [Major axis length, eccentricity, area, color]
- Introduce normalized Euclidean metric with $\sigma_i$ variance of the variable

$$d(\vec{x},\vec{y}) = \sqrt{\sum_{i=1}^{4} \frac{(x_i - y_i)^2}{\sigma_i^2}}$$

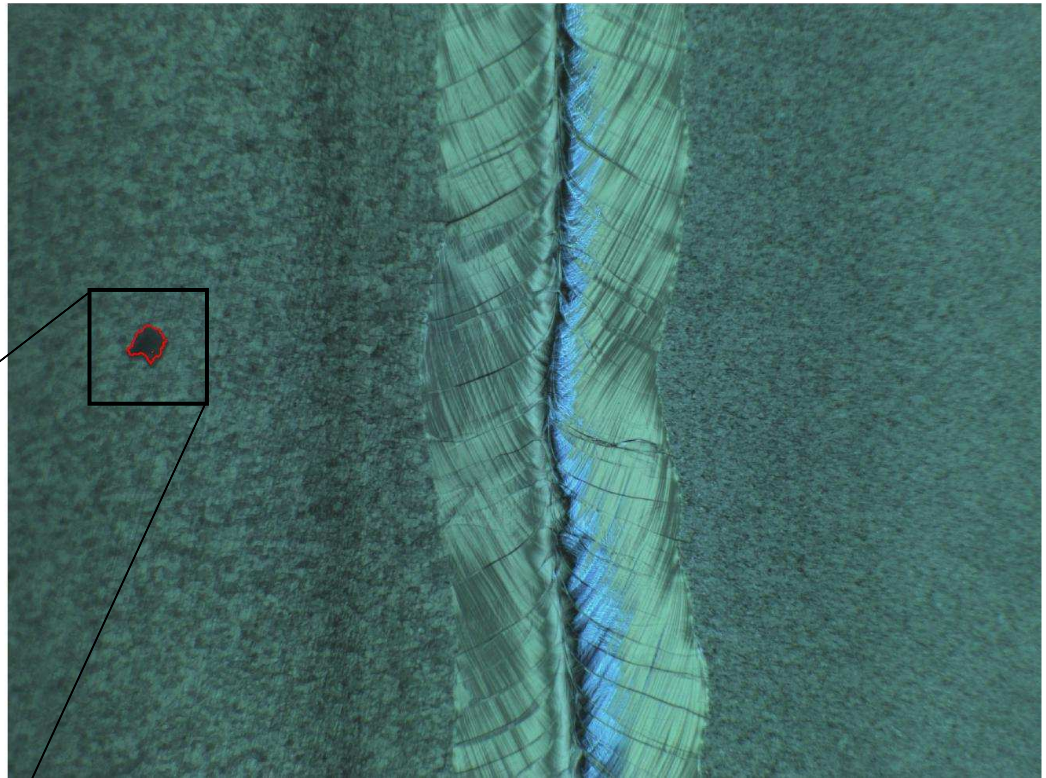
- Object is compared to its neighborhood: objects inside a circle of radius 3.5 * major axis length (red circle)
- Calculate distance d of object to neighborhood objects. If its above threshold, mark as irregularity

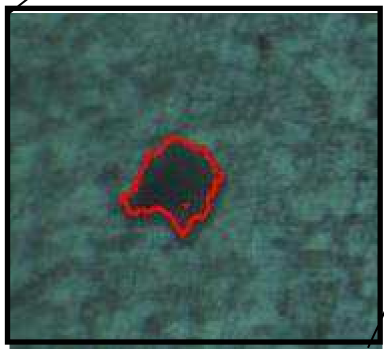




# Defect detection

- One object was identified as irregularity (d ~ 416 µm)
- Defect led to a quench (13 MV/m – location confirmed with T-map and Second Sound)
- Algorithm running on set of test images (9 confirmed defects) shows promising results





# Summary

- Optical inspection has become an established tool for quality control of SCRF cavities and is key in recognizing gradient limiting defects
- Automatic processing of cavity images
  - Provides an objective measurement of cavity surface properties
  - Allows for search of explicit surface defects
- Examples were shown for surface roughness and measurements of feature sizes and length
- Chemical surface treatment of cavities reduces number of features and diminishes feature size and area, which helps to support higher accelerating fields.



DESY

# Outlook

> Statistics will be improved with the 24 HiGrade cavities with same production scheme like the 800 XFEL cavities

- Influence of treatment onto image variables should become more obvious
- Correlations between image variables and performance of cavities should become clearer and a prediction of performance after inspection could become possible

> A minimal set of variables describing/classifying the cavity surface will be defined

- Vendor classification
- Treatment step identification
- Prediction for operational key values (max. Eacc / Quality-factor performance)

> Algorithm for defect detection and classification will be improved

- Find set of variables to minimize false classification
- Predict performance of irregularity