ILC-HiGrade cavities as a tool of quality control for the EXFEL and further SRF R&D

- Motivation and goal
- European EXFEL/ILC-HiGrade program
- Results of cold RF test of the EXFEL/ILC-HiGrade cavities
- Quality control tools and actual results

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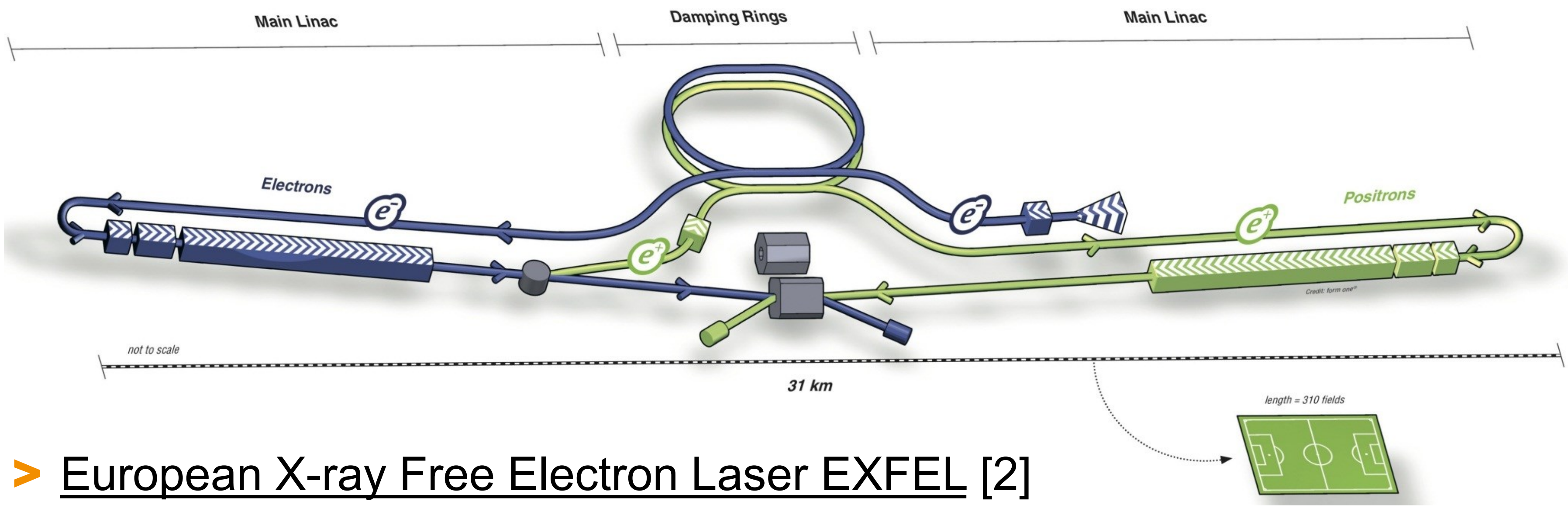
Motivation for high gradient superconducting (SC) cavities:

> The International Linear Collider ILC [1]

- Centre-of-mass energy 500 GeV, 31 km long, TDR 12 June 2013
- 16,000 1.3 GHz 9-cell Nb cavities, gradient E_{acc} at least 35 MV/m
- Average E_{acc} in the cryomodule: 31.5 MV/m @ quality factor $Q_0 > 10^{10}$

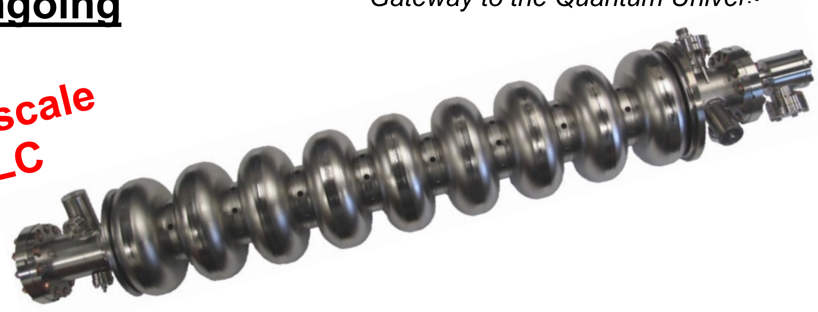


International Linear Collider – Gateway to the Quantum Universe

> European X-ray Free Electron Laser EXFEL [2]

- 800 SC 1.3 GHz 9-cell cavities, production **is ongoing**
- Nominal gradient E_{acc} = 23.6 MV/m @ $Q_0 > 10^{10}$
- 17.5 GeV beam energy, 3.4 km long

An excellent large-scale prototype for the ILC



[1] http://www.linearcollider.org [2] *www.xfel.eu*

European ILC-HiGrade programme

24 cavities are added to the EXFEL order:

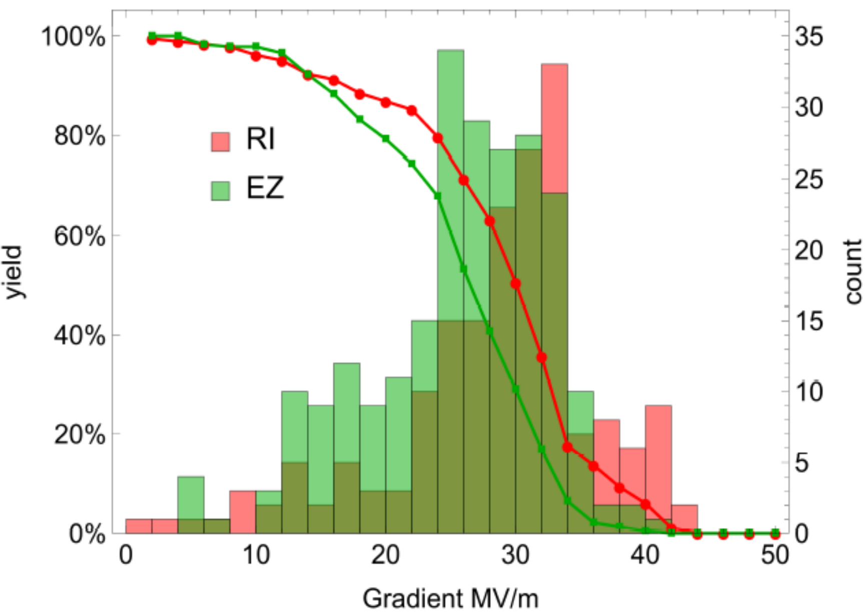
- Initially, serve as quality control (QC) sample for the EXFEL
  - extracted regularly, ~one cavity/month
  - after the normal acceptance test are taken out of the production flow --> R&D

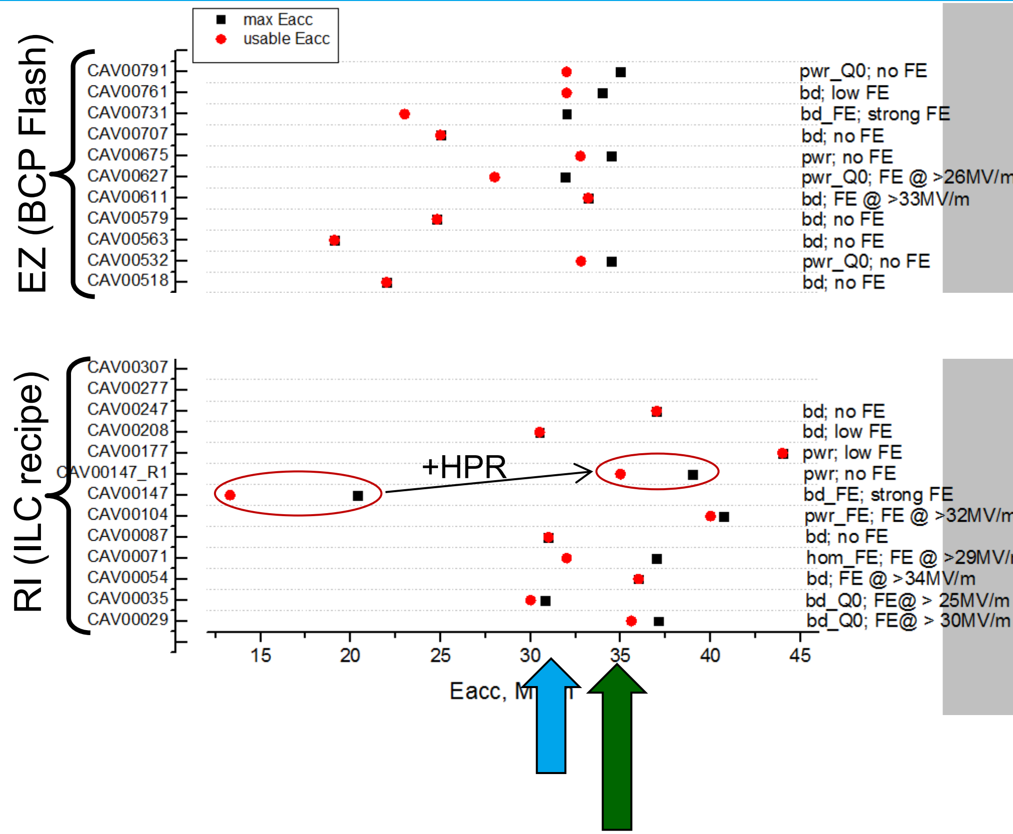
- Delivered with full treatment but no helium tank
  -> maximize the data output from the test

22 out of 24 already delivered

Cold RF results of EXFEL & ILC-HiGrade cavities

Usable gradient of EXFEL cavities (as received*)





	RI	EZ	Total
Tests	182	231	413
G_{AVG} (MV/m)	28.6	25.5	26.9
G_{RMS} (MV/m)	7.9	6.9	7.5
yield @ 20MV/m	87%	79%	83%
yield @ 26MV/m	71%	53%	61%
yield @ 28MV/m	63%	41%	51%

- “ILC recipe” provides cavities with usable gradient of ~31.9±8.2 MV/m (34.9±4.7 MV/m after retreatment)
- some achieve >40 MV/m

- Main limitation is FE

Usable gradient:
- E_{acc} of quench or
- E_{acc} at $Q_0 \leq 1 \times 10^{10}$ or
- E_{acc} at excess of X-ray radiation: >0.01 (0.12) mGy/min for upper(lower) detector

*D. Reschke, TTC Meeting KEK, Dec 2-5, 2014

Cold RF results of EXFEL & ILC-HiGrade cavities

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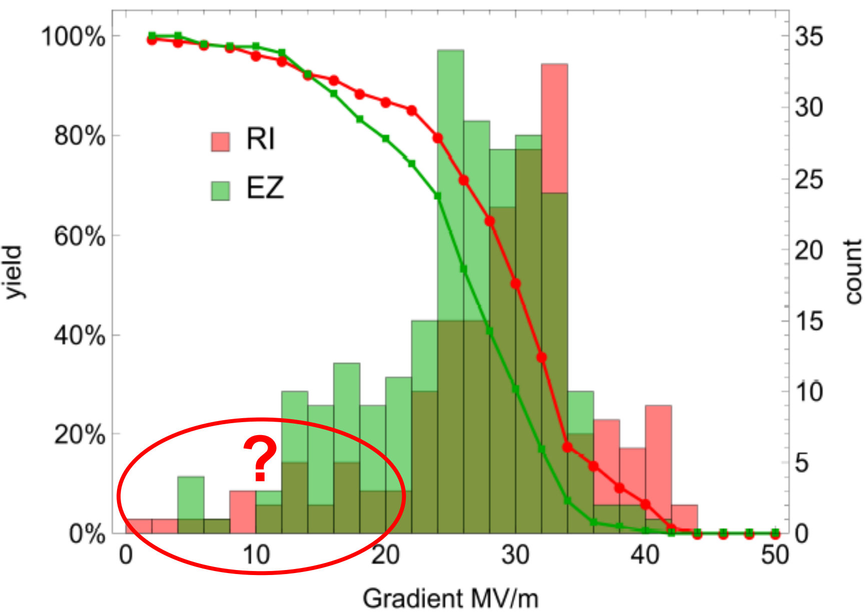

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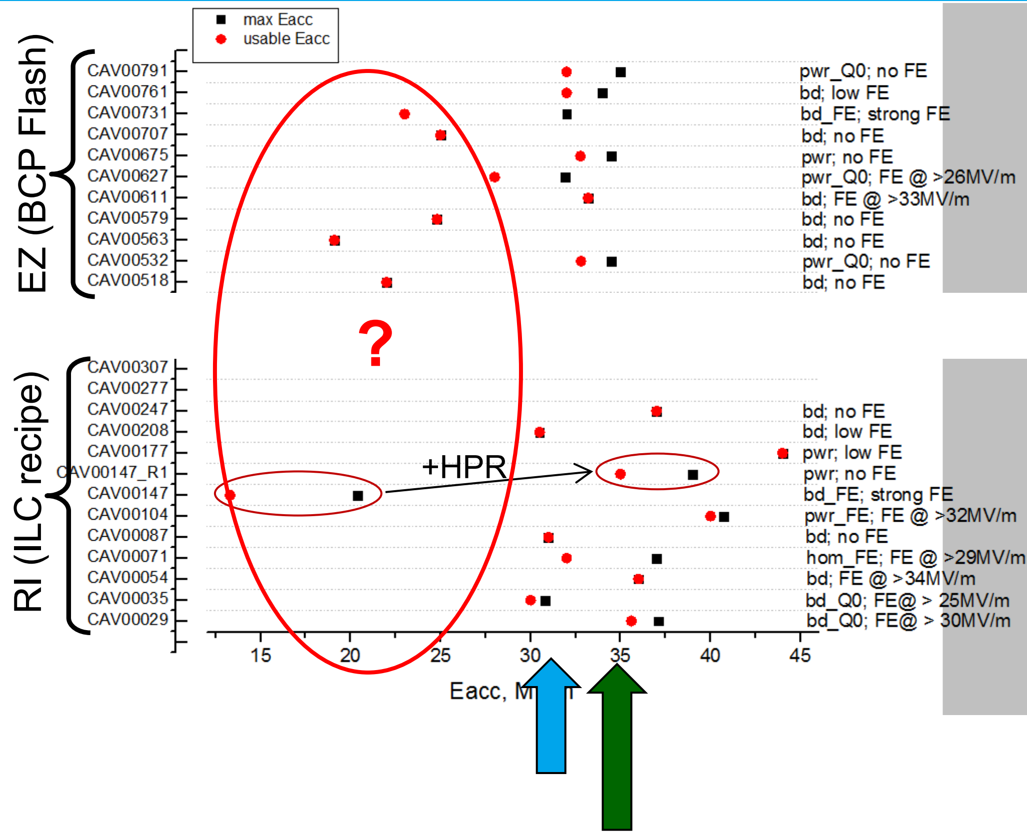

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*D. Reschke, TTC Meeting KEK, Dec 2-5, 2014

Goal

- Clear identification of the limiting factors:
  -> suspicious EXFEL cavities (mainly with usable E_{acc} ≤ 20 MV/m)
  -> all ILC-HiGrade cavities

  Additional techniques used:
  - Cold RF tests in different "passband modes" for localization of limiting cells
  - "2nd sound" and "T-mapping" for localization of thermal breakdowns (quenches)
  - Optical (OBACHT) and replica surface inspection

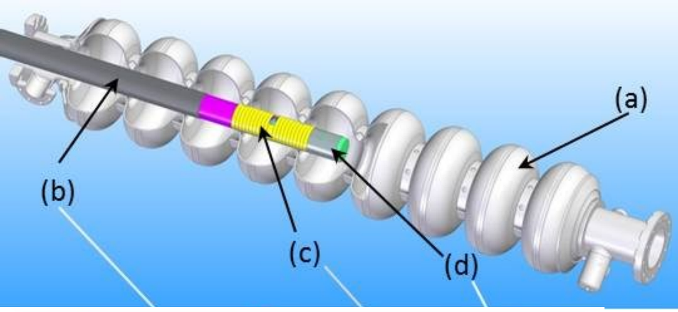
  *see more talk R. Laasch

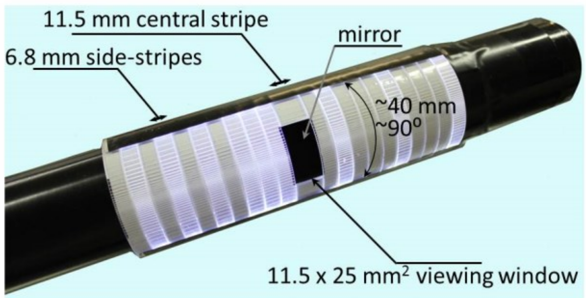
- Elaboration of further treatments:
  (providing e.g. E_{acc} ≥ 35 MV/m @ >90% yield as the ILC goal)
  - additional High Pressure ultrapure water Rinsing (HPR)
  - additional chemical polishing (BCP) or electropolishing (EP)
  - Centrifugal Barrel Polishing (CBP)
  - Local grinding repair

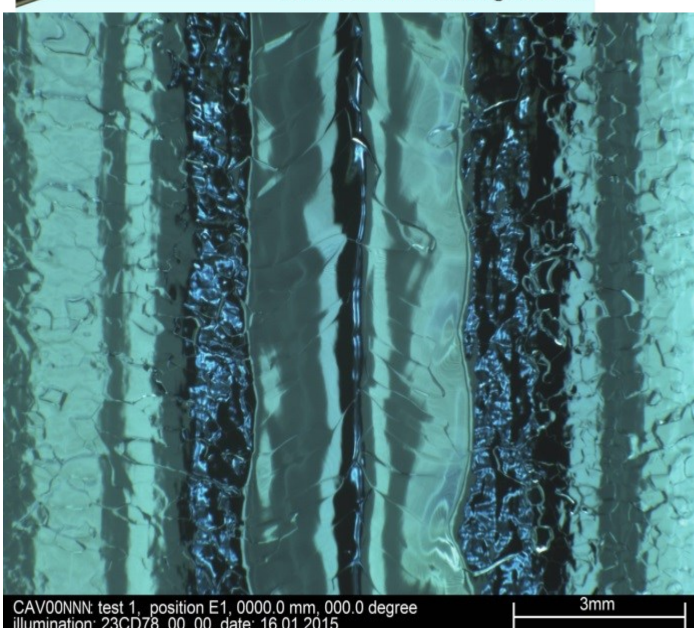
  *see more talk Y. Tamashevich

- Further improve quality control to reduce the retreatment rate

OBACHT – Optical Bench for Automated Cavity Inspection with High Resolution on Short Time Scales

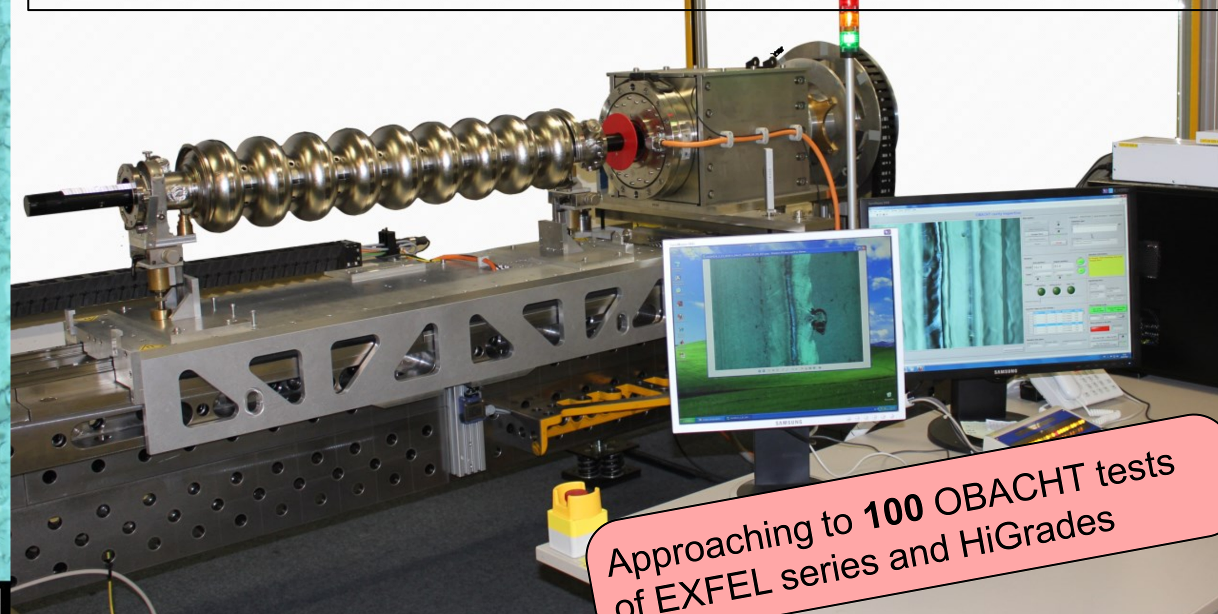






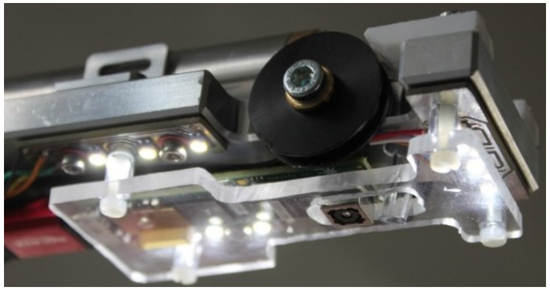
- Optical inspection tool for cavity inner surface (mainly welding seams)
- Semi-automated (LabView) tool based on "Kyoto camera" (Y. Iwashita, PRST AB, 11, 093501 (2008)):
  - ~10 µm resolution
  - special distributed illumination
- Automatic positioning, illumination, and image recording at predefined positions

⇒ Quality control and failures clarification
⇒ **Reduce significantly re-tests/re-treatments** by earlier failures detection



“Replica” surface profilometry

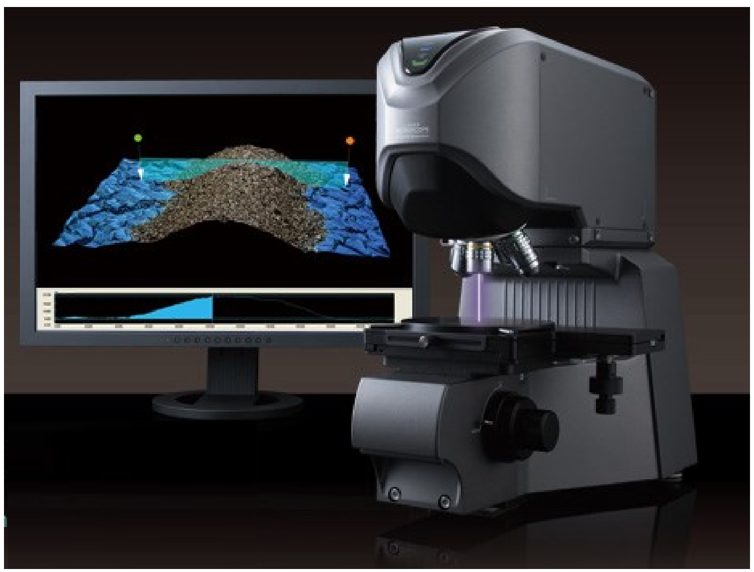
- “Replica” is used for non-destructive profilometry studies of inner surface: conspicuous surface features or defects



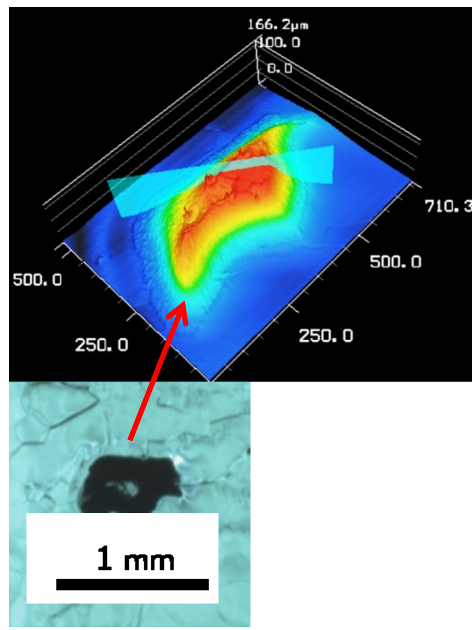
“Replica” tool with camera

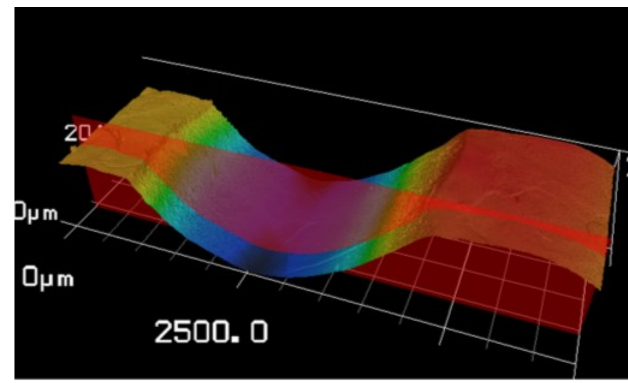
“Replica” tool in the cavity

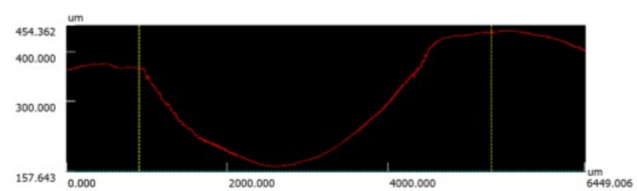
Silicon rubber on the surface



* Keyence 3D Laser scanning microscope



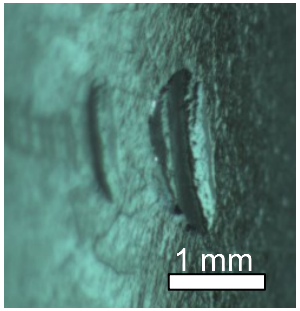




~1 μm resolution (3D topography) has been achieved
- no cavity degradation (no residues) if done correctly (at least after HPR)

Typical surface defects (EXFEL and ILC-HiGrade cavities)

Scratches

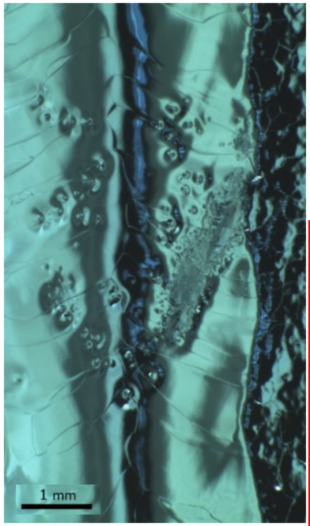


=> Handling failures:

- Strong x-ray radiation
- Complicated repair required (tank removal, mechanical polishing inside cavities, and 2nd whole surface prepare pass)
- Some failures identified and fixed

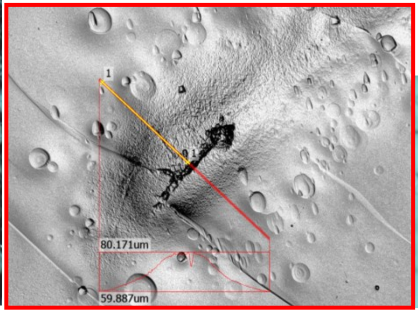
Typical surface defects (EXFEL and ILC-HiGrade cavities)

Pits or inclusions



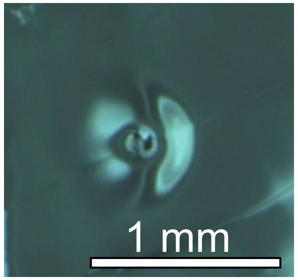
=> Foreign material inclusions:

- Low field quenches
- Influence polishing process
- Complicated repair required



Typical surface defects (EXFEL and ILC-HiGrade cavities)

"Etching pits"

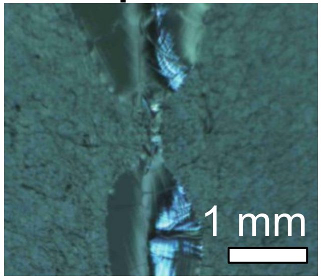


=> Etching effect (H_2 bubbles):

- No influence in high magnetic field regions (equators)
- Might lead to radiation in high electric field regions (irises)

Typical surface defects (EXFEL and ILC-HiGrade cavities)

Incomplete weld



=> Wrong welding parameters:

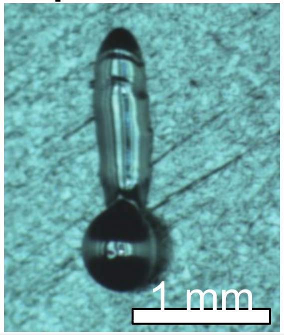
- Lead to low field quenches
- Complicated repair required
- Pressure issue

- Ruled out by electron-beam welding optimization

"Spatters"

Typical surface defects (EXFEL and ILC-HiGrade cavities)

"Spatters"



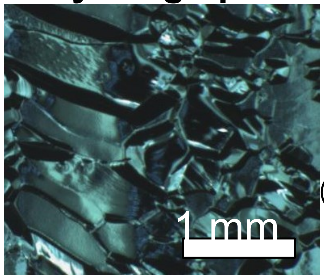
=> Welding failures due to sparks or presence of dust

⊖ Low field quenches

⊖ Mechanical polishing inside cavities required

Typical surface defects (EXFEL and ILC-HiGrade cavities)

"Very rough polishing"



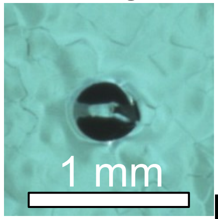
=> Wrong etching parameters

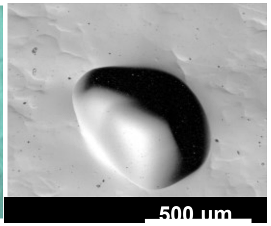
⊖ Lead to low Q_0 and low field quenches

⊕ Ruled out by better parameters optimization and control

Typical surface defects (EXFEL and ILC-HiGrade cavities)

"Cat eyes"

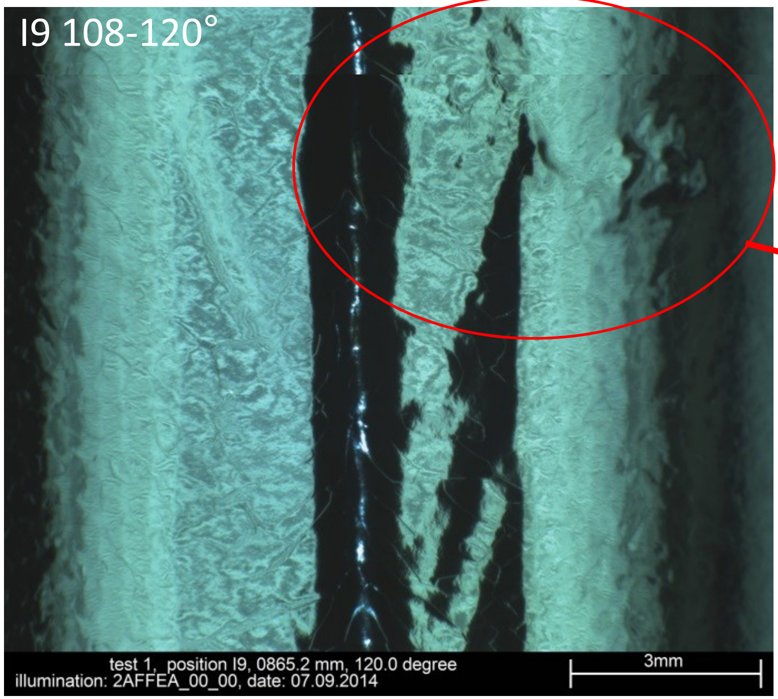


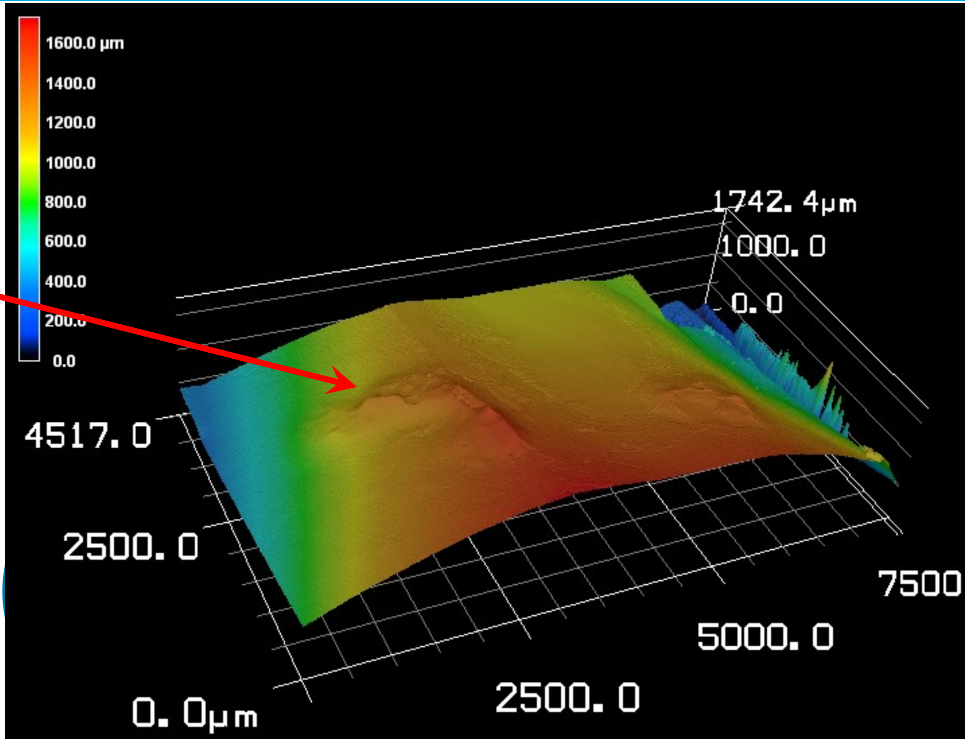


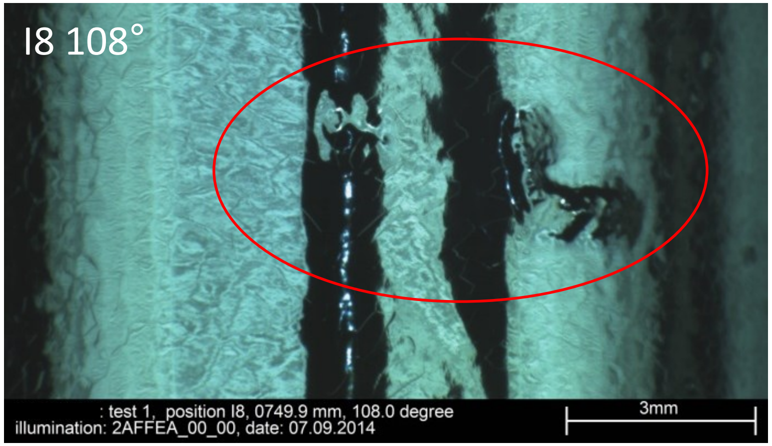
=> Voids in the surface

- Seems to be harmless
- No performance degradation observed

Typical surface defects: scratches



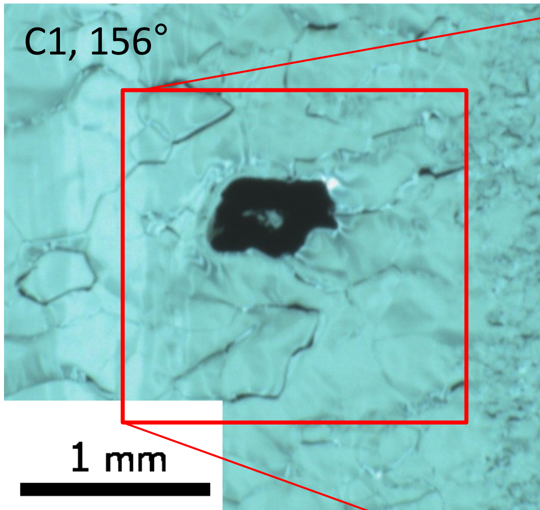


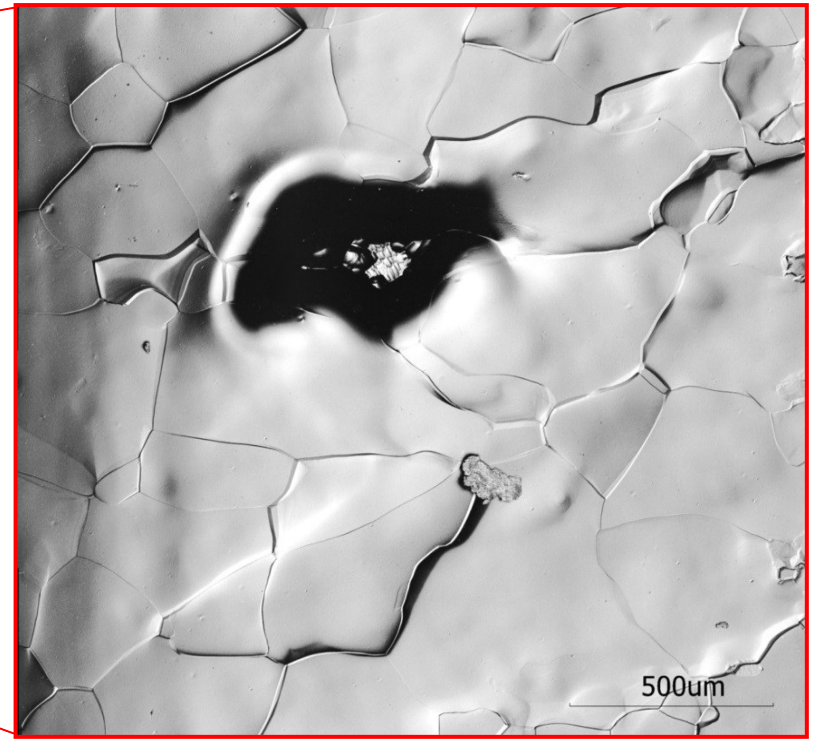


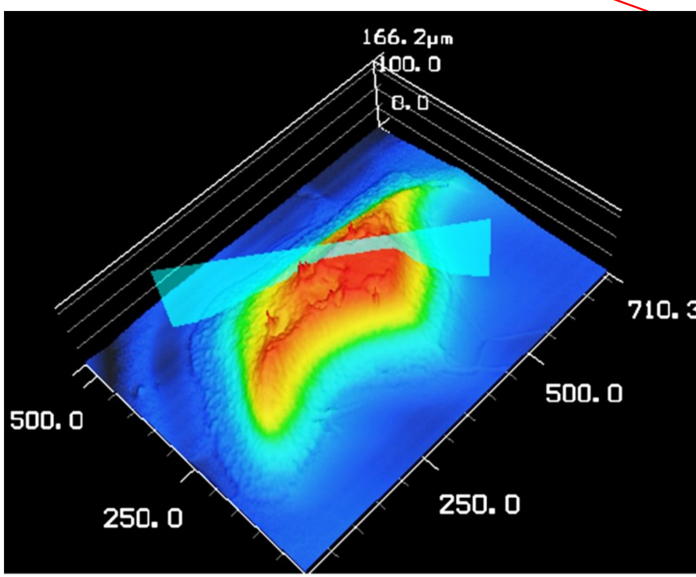
- $E_{acc,max}$ = 23 MV/m, limited by quench with strong radiation, $E_{acc,usable}$ = 16 MV/m
- Retreatment by add. HPR and 10 µm BCP did not improve the performance, made even worse
- Several mm-wide protrusions with at least 100 µm height found on almost all irises at the same angle
- Error: scratched by bent EP electrode

Typical surface defects: foreign inclusions

OBACHT image

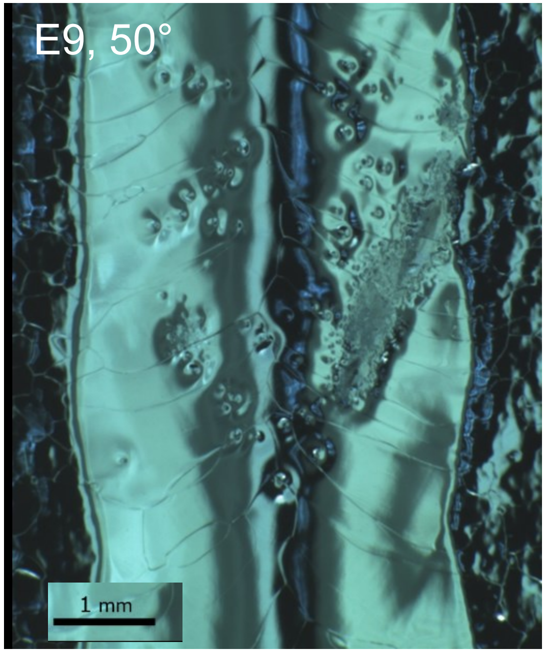


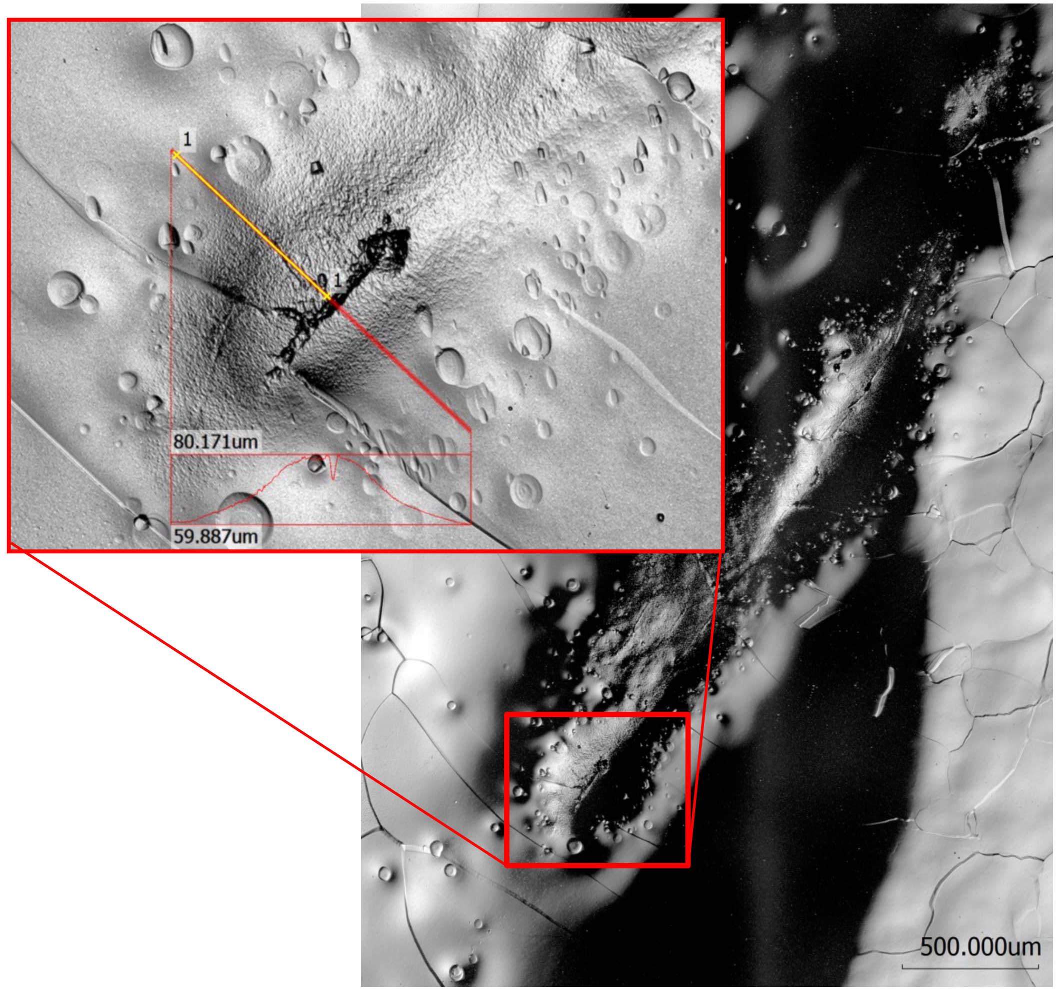


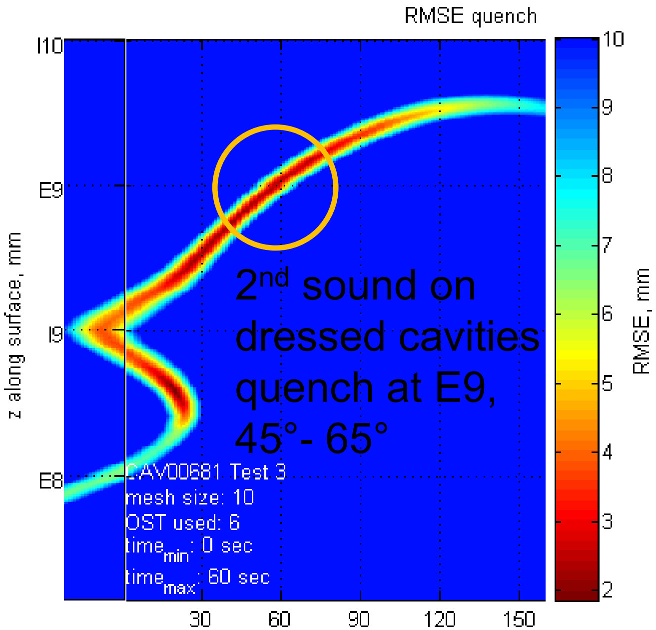


- $E_{acc,max}$ = 16 MV/m, limited by quench
- Height of the defect is ~124 µm
- Most probably a foreign inclusion not affected by polishing
- No deviations seen on the initial Nb sheet => defect appeared during fabrication

Typical surface defects: foreign inclusions







- $E_{acc,max}$ = 16 MV/m, limited by quench
- Etching defect due to contamination during welding
- Repair under discussion

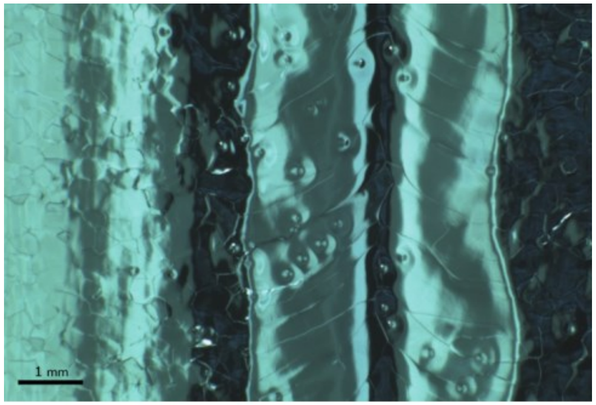
Cold RF tests vs. surface quality

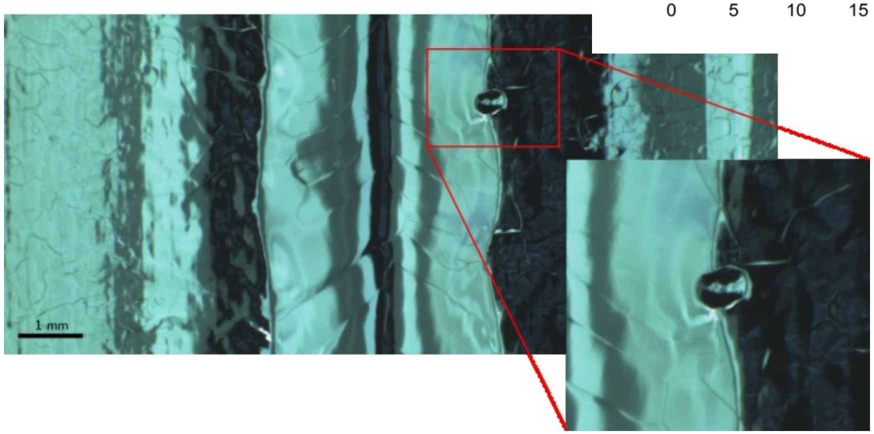
CAV00532:

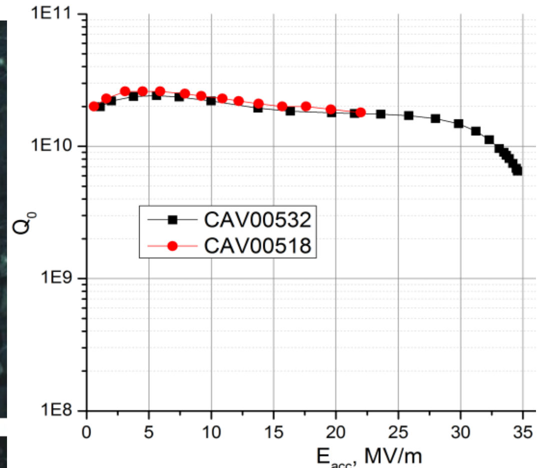
→ **Successful** cold RF test result with **no FE**, RF power limited at 200W P_{in})

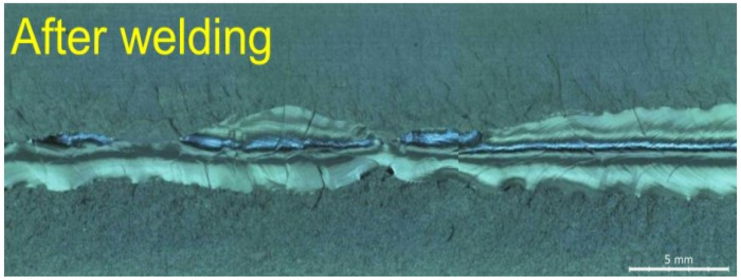
CAV00518:

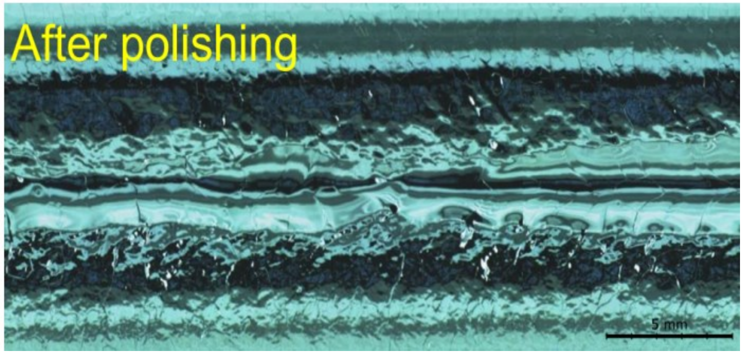
→ Unsuccessful cold RF test result with quench at **22 MV/m**, **no FE**











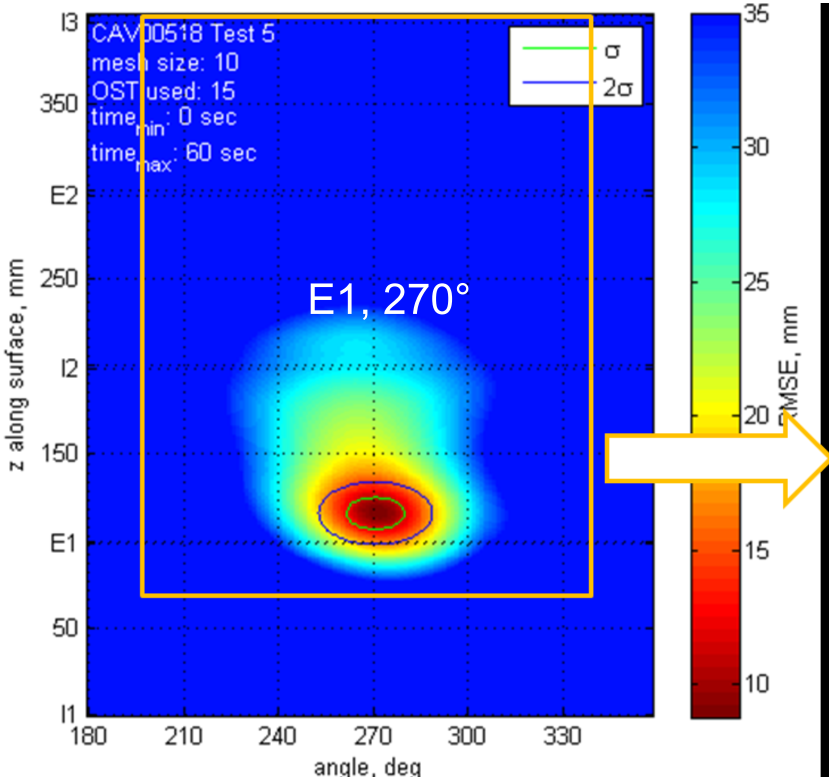
-> **Nice** RF result despite of "pits" and "cat-eyes" on the surface

-> OBACHT indicates defective welding as a possible quench reason

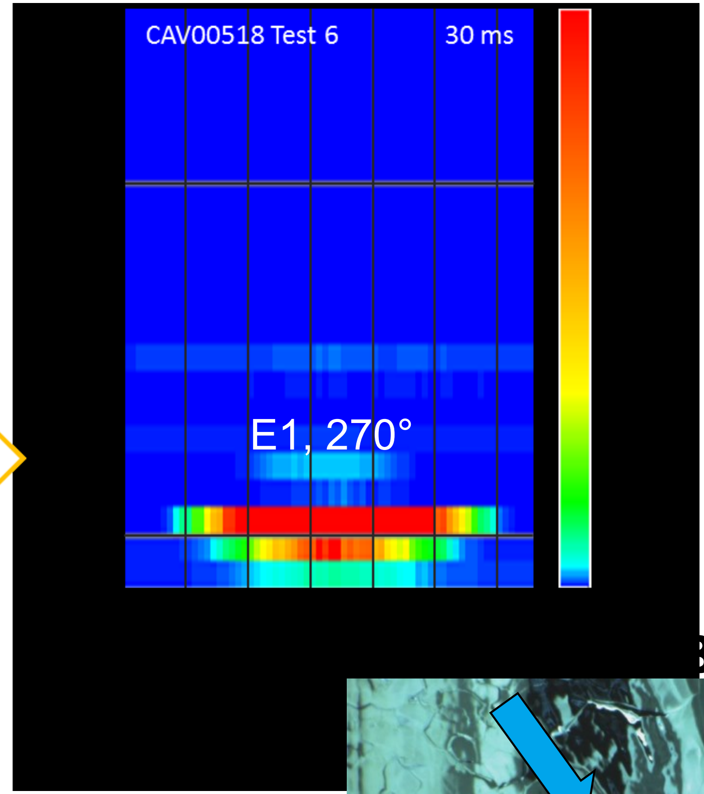
→ **"2nd Sound"** & **"T-mapping"** is applied for the quench localization and further studies

Welding errors: 2nd sound vs. T-mapping

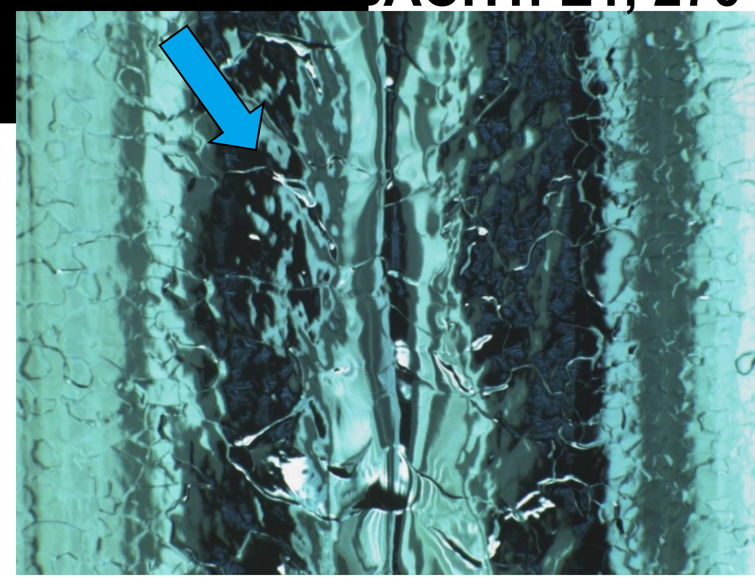
“2nd Sound “map”



Temperature map



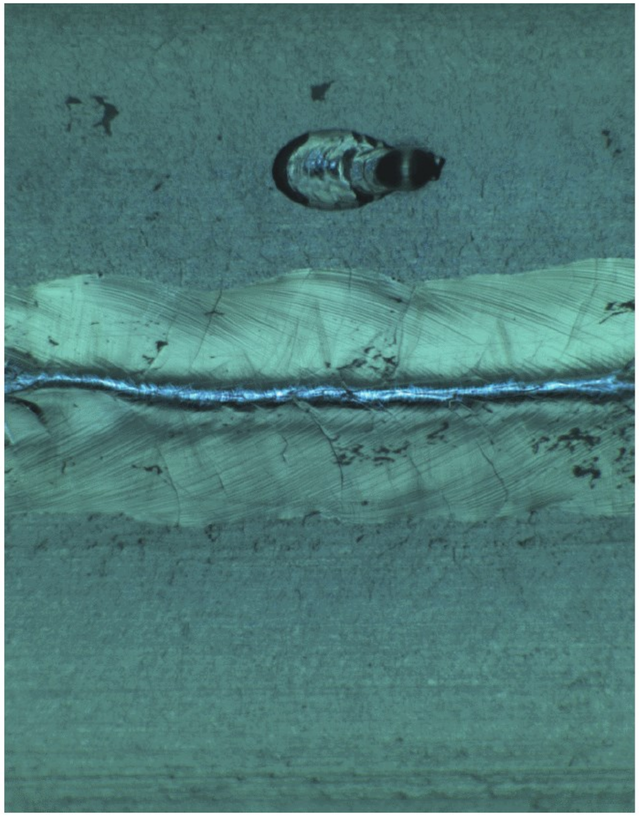
OBACHT: E1, 270°



- ⇒ *Quench at 24MV/m, localized on the E1, 270°*
- ⇒ *Good agreement between T- and 2nd-sound mapping*
- ⇒ *OBACHT* indicates **defective welding** as a possible quench reason

Typical surface defects: welding spatters

Endoscopes & **OBACHT** (shown here) inspections discover some **"spatters"** occasional occurring during the welding:



After final polishing:

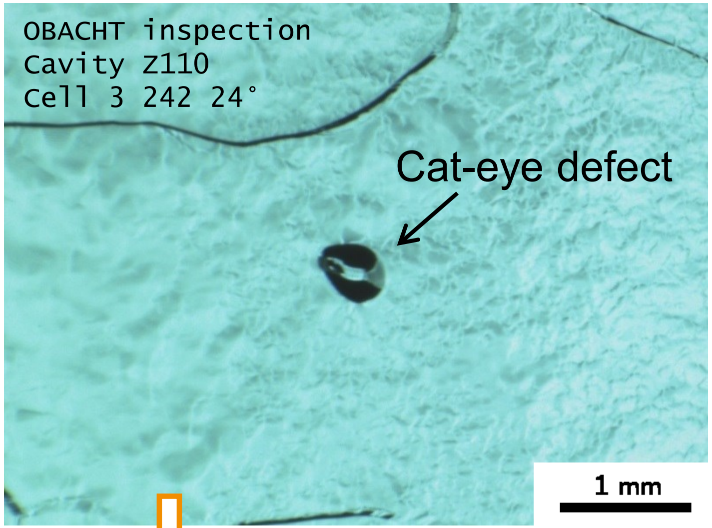
→ max **E_{acc} = 30.5 MV/m**
→ **no FE**

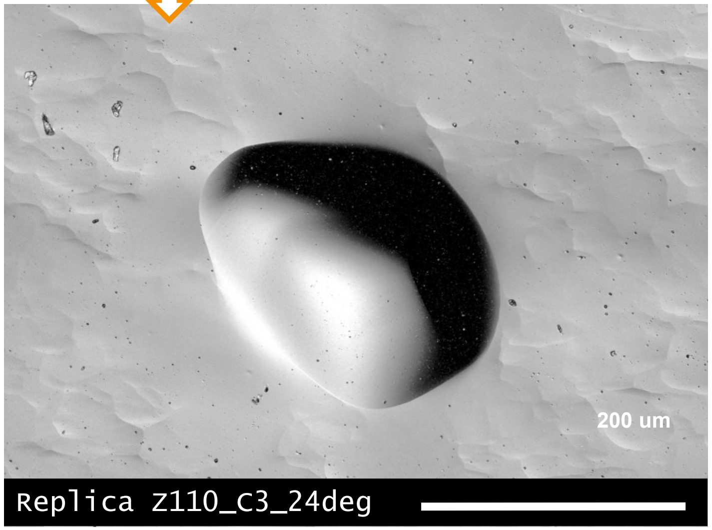
→**reasons**: - blasts due to contamination
- sparks due to defective high voltage regulation of the electron beam welding machine

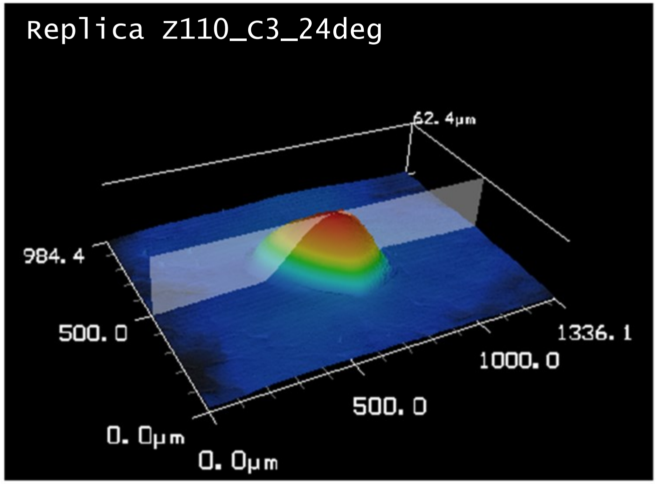
→ an **additional grinding/repair** is required

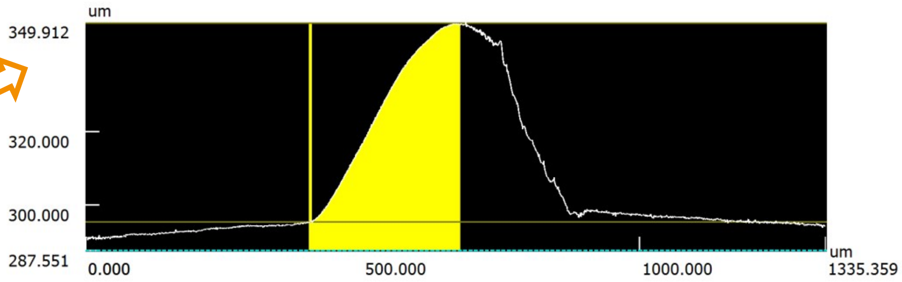
→ repair procedure using local grinder has been commission (manual one shown here)

Replica: defects investigation









Profile1	Horz. dist.	Hght. diff.	Hght. ave.	Angle	C.S. length	C.S. area	R	Comment
All	1335.359um	3.733um	306.016um	0.160°	1408.183um	24670.176u...		
Seg.1	268.152um	54.050um	325.731um	11.396°	278.242um	10276.218u...		

Pit in the surface. Depth 55 um

Thank you for your attention !

Acknowledgements:
- **FLA/ILC, MPL, MKS 1, MKS 3, and MHF-sl groups**

- **all DESY and INFN colleagues** involved in the XFEL cavity fabrication, treatment and tests

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