Optical inspection by OBACHT (DESY) and other inspection elsewhere from other laboratories

- Motivation and main purpose of optical inspection systems
- Requirements and wishes
- Review of optical inspection systems for cavities worldwide with some outstanding results and typical surface defects
- OBACHT system at DESY and some examples from the EXFEL & ILC-HiGrade cavity production
- Summary and outlook

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Motivation & main purposes of the optical systems

Inner surface of SRF Nb cavities is a key factor for the performance

- surface quality control e.g. after the EB welding, polishing, etc. is of importance

Optical inspection is a fast and simple method, however, very demanding due to

- bright reflections and low contrast on smooth mirror-like surface after treatments
- limited space, complex shape, and big surface area (~1 m^2) of the cavities
- Industrially available optical systems mostly do not match

→ Development of specialized cavity inspection systems required

Several system have been developed/purchased for:

- ✓ Cavity inspection with a feedback to fabrication process
- ✓ Detailed studies/analysis of surface defects
- ✓ Tracking of surface modifications especially during cavity repair or commissioning of (new) surface treatment methods
- ✓ Post-cold-RF-test inspection as a feedback for localized examination of quench area predicted e.g. by thermometry, 2^{nd} sound, etc.

Requirements and wishes to optical systems

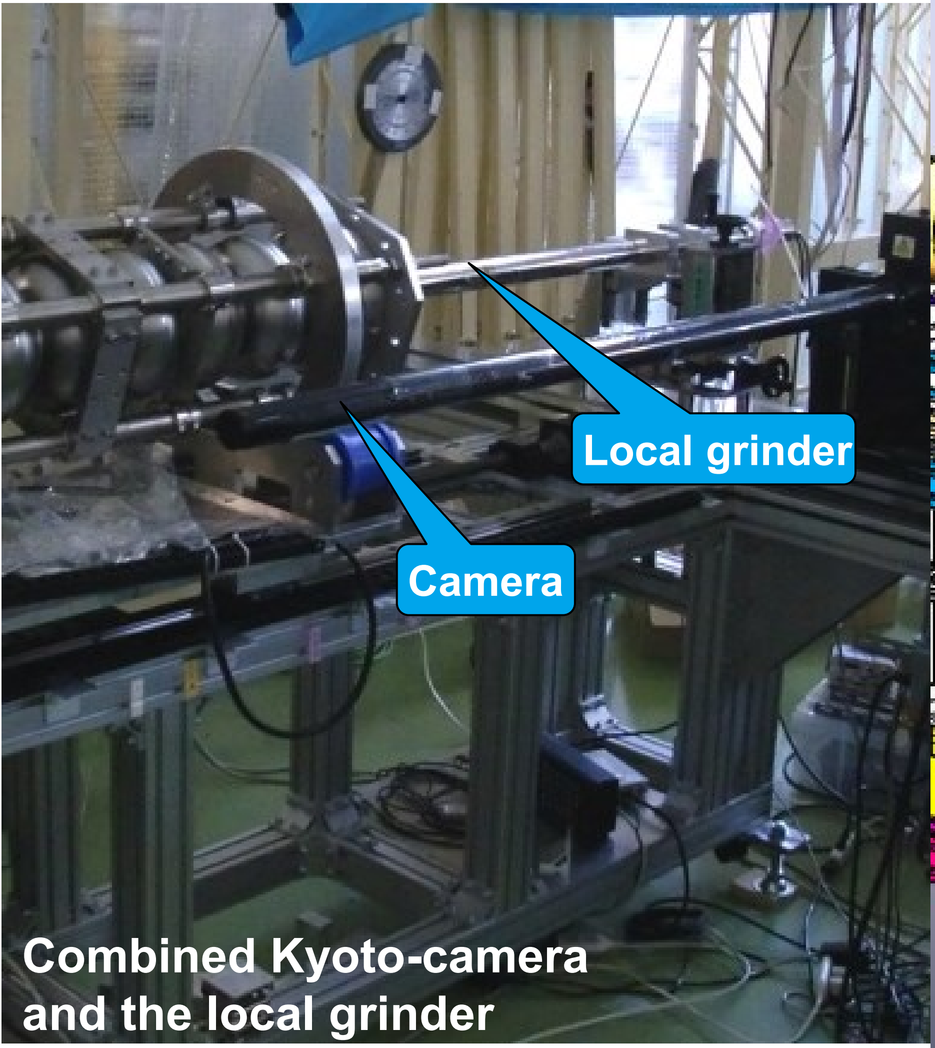
- Imaging of the surface with a resolution of ~10's of μm or better
- Illumination: - comprehensive light pattern and brightness control to avoid deterioration of the images by light reflections
  - side illumination for an estimation of height information
  - automatic light pattern and brightness adjustment
  - different colors, polarization
- Manual ← → auto focusing
- HDR function to display and equalize bright and dark areas
- Live imaging and image acquisition/storage for post processing
- Real time and post image processing for defect recognition and surface qualification
- Manual and automatic fast (a few hours e.g. for 9-cell cavity) inspections
- Positioning control with high reproducibility (at least 0.5 mm), vibration free
- Collision free movement, no surface pollution
- Optical system clean room compatible
- User and expert operation modes

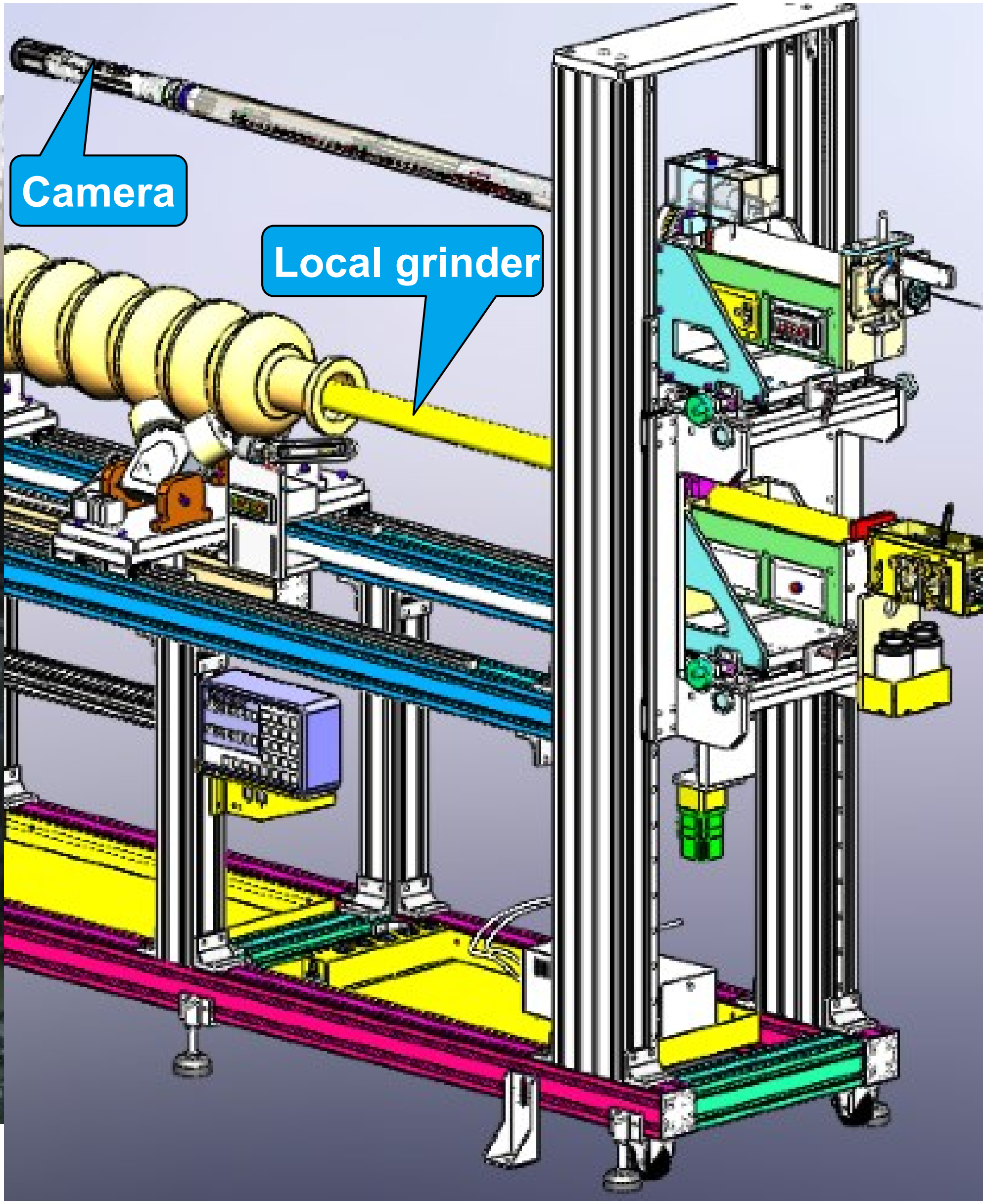
Review of optical inspection systems worldwide

- **KEK keep developing**:
  - a new multifunctional unit for cavity inspection/treatment comes soon
  - design of illumination unit reached Ver.5 and Ver.6 comes soon
  - total three working units: one at KEK, and the other two are loaned to JLAB&DESY
- **FNAL**:
  - one Kyoto system for Tesla and similar-shape cavities
  - one modified Kyoto system for 650MHz cavities (new LEDs and cavity support)
  - long-range microscope (Questar) based system for 3.9 GHz, 325MHz (spoke) cav.
- **JLAB**:
  - one Kyoto optical inspection system
  - one JLab's high-resolution long-range microscope based system
  - CYCLOPS
  - Olympus optical fibre system and a simple one with a mirror/microscope camera
- **CERN**: - one Kyoto optical inspection system for SPL 700MHz (ø70) cavities
- **Cornell**: - one long-range microscope (Questar) based optical inspection system
- **LANL**: - Videoscope based inspection system, no update on the status
- **DESY**: - Kyoto camera based OBACHT system
  - a mini USB-camera with autofocus and LEDs for replica control

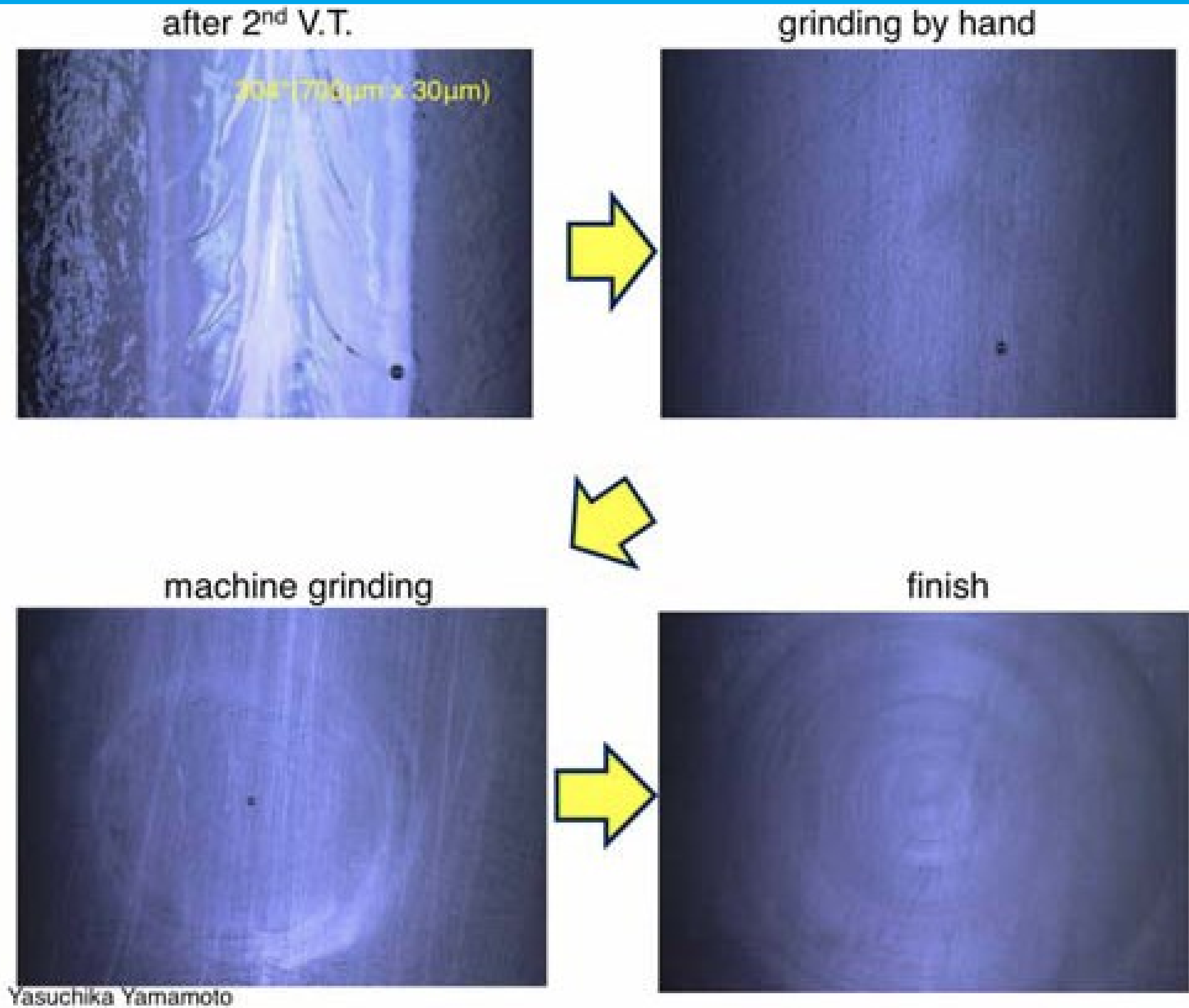
MFU* for cavity inspection/treatment at KEK

* Multifunctional Unit



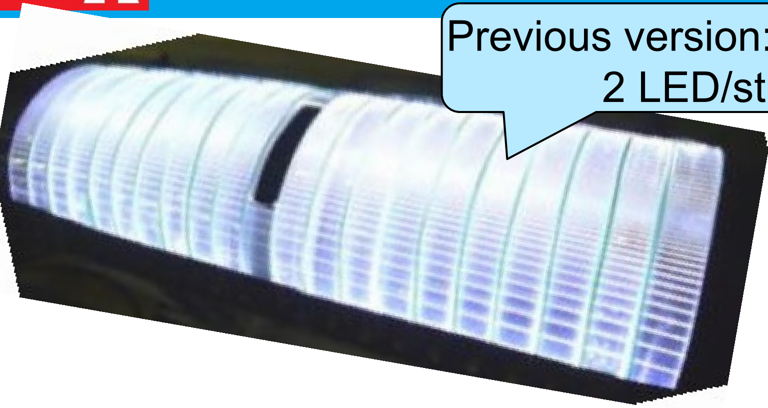


Local grinding process control/tracking

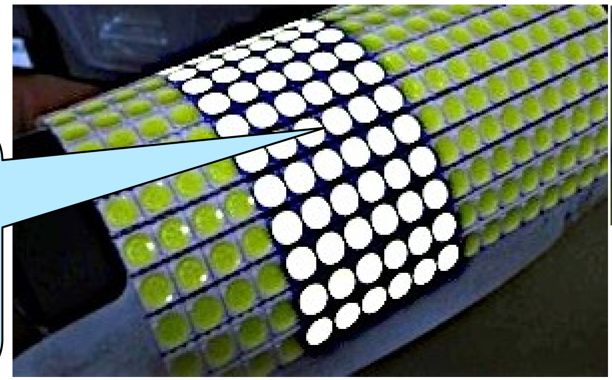


Progress in the illumination unit design at KEK

Previous version:
2 LED/strip



Enhanced (Armadillo) illumination (**V.5**)
for large cavity:
14 chips/line x 2 lines/strip x 10 strips/side
x 2 sides = 560 chips!
Stripe control only (not individual dots).



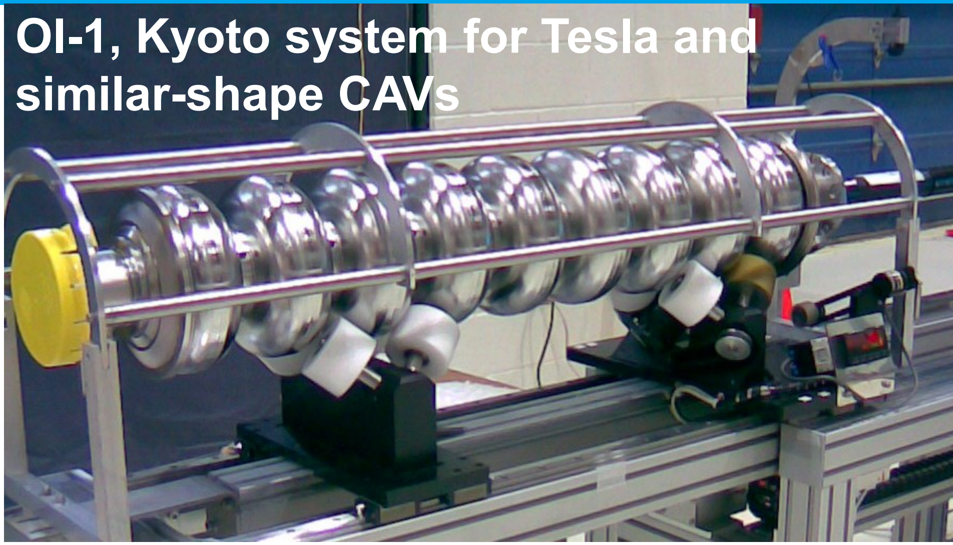
3 LED/chip!

Latest Illumination Unit (**V.6**):
Independent control of each
LED: horizontal or vertical line
or each dots

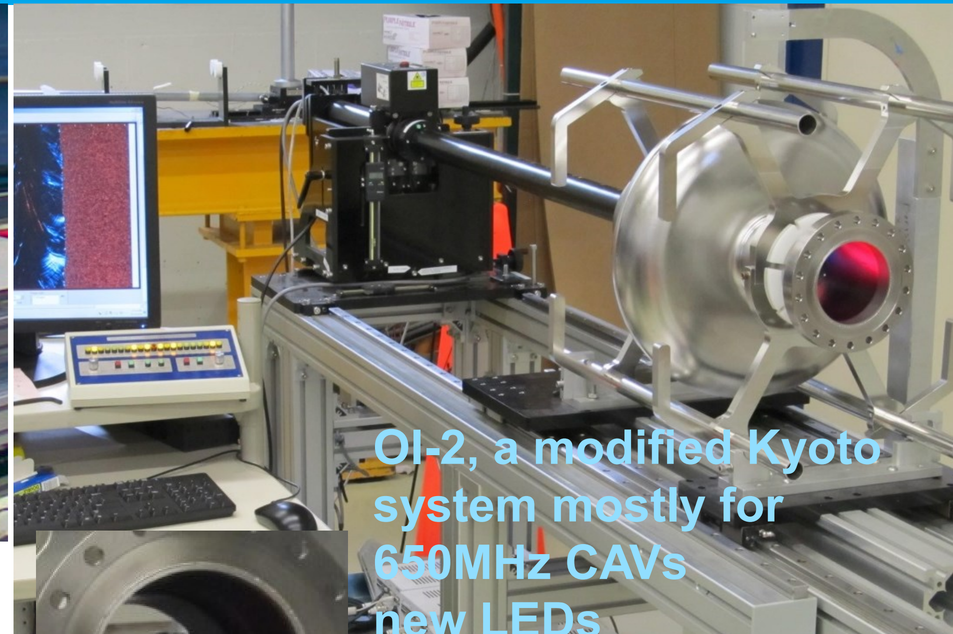
Automatization of the illumination pattern control and brightness adjustment is required!

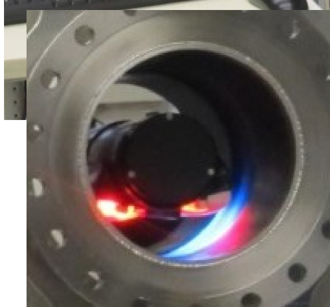
Cavity inspection systems at Fermilab

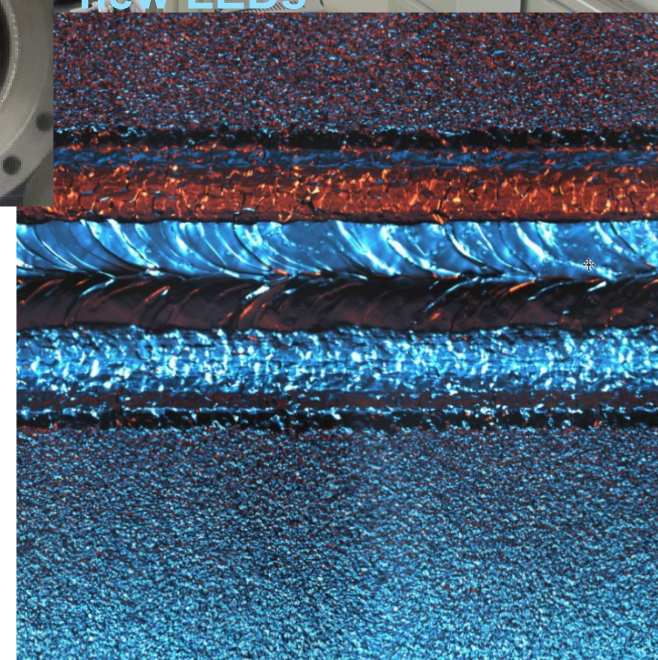
OI-1, Kyoto system for Tesla and similar-shape CAVs



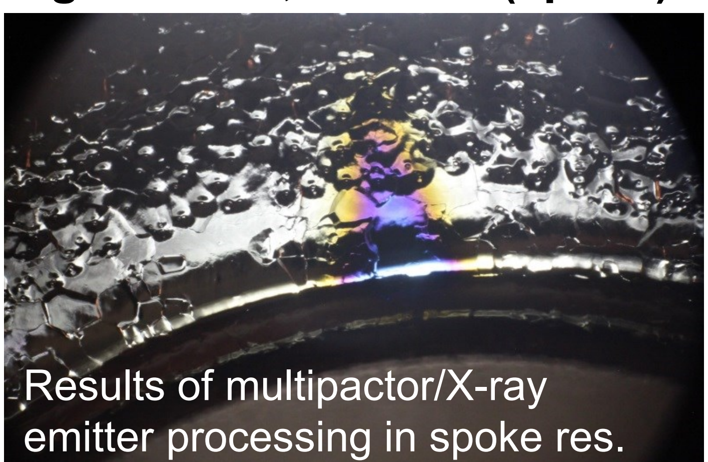
OI-2, a modified Kyoto system mostly for 650MHz CAVs new LEDs





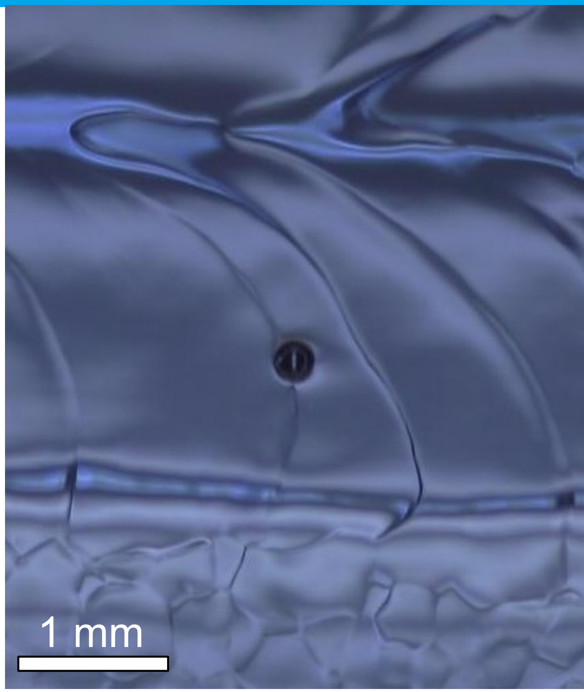


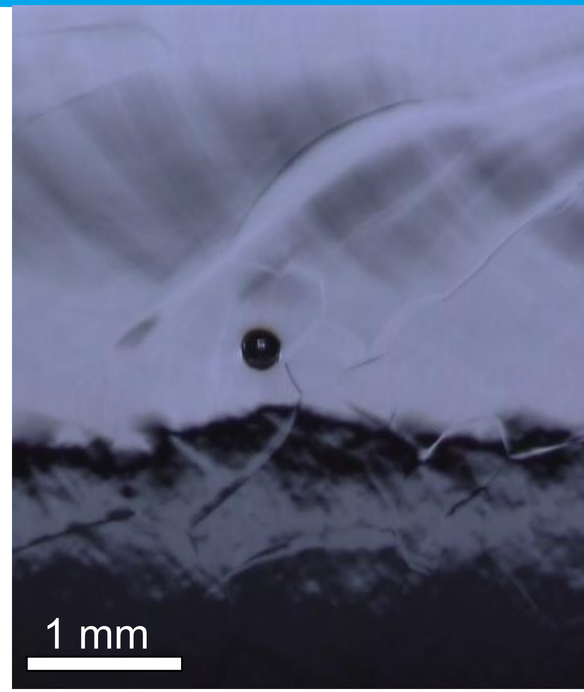
OI-3, Long-range microscope (Questar) based system for odd-ball inspections: e.g. 3.9 GHz, 325MHz (spoke) CAVs

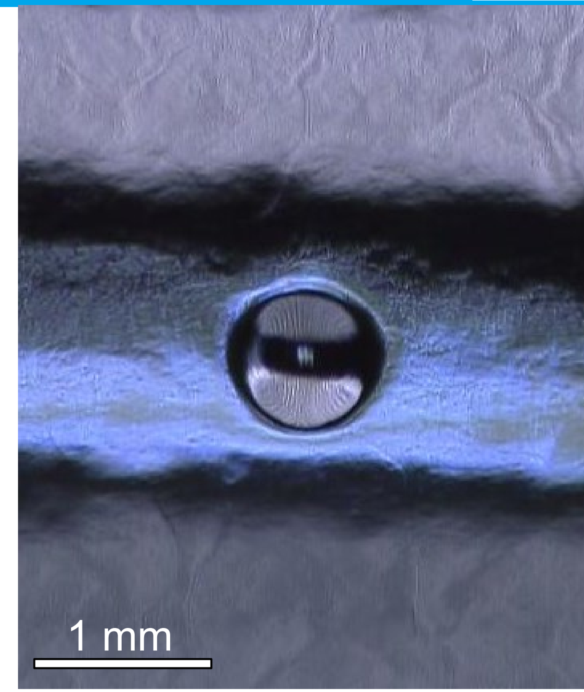


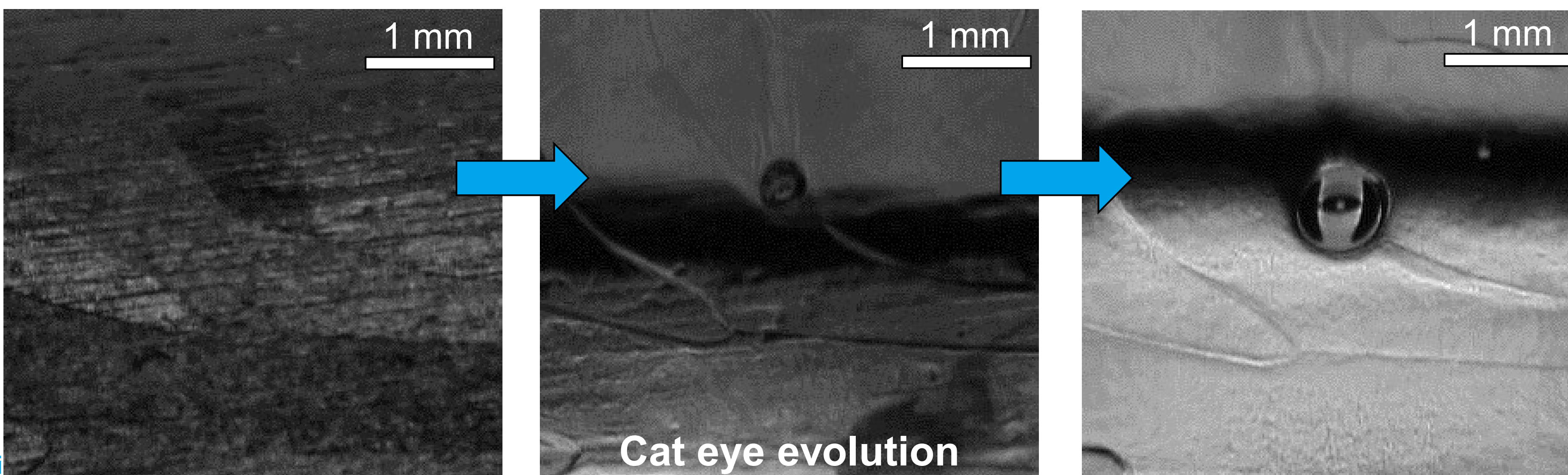
Results of multipactor/X-ray emitter processing in spoke res.

“Cat eye” examples on cavities (Fermilab)

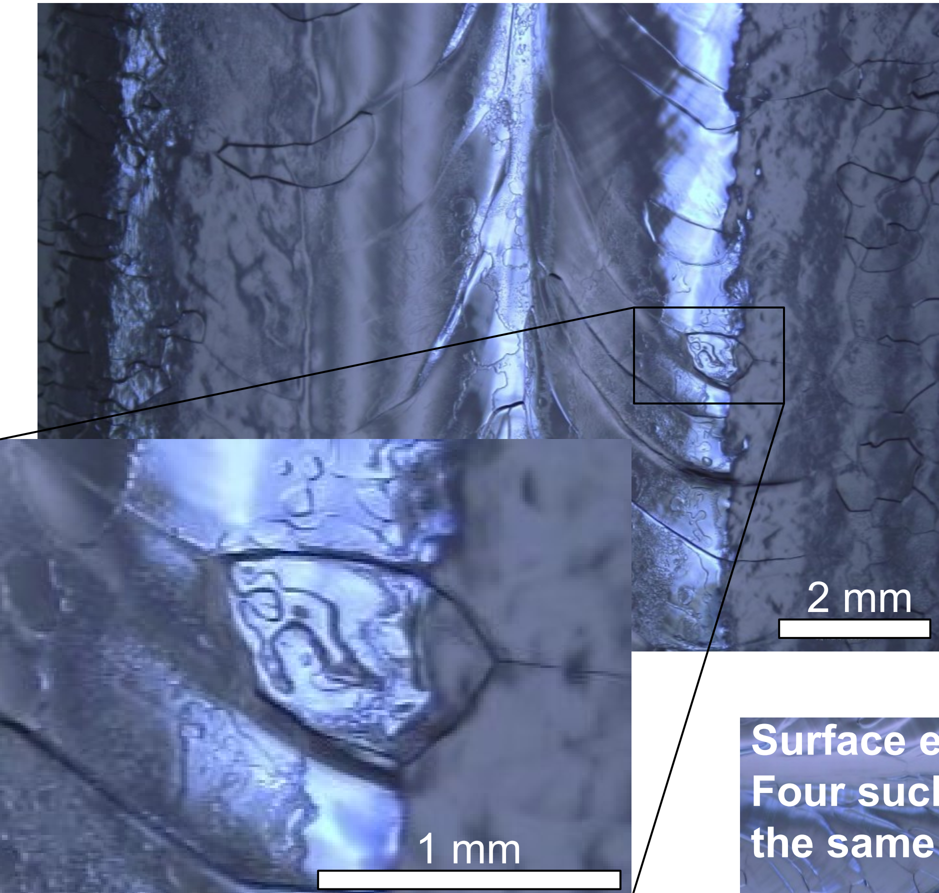




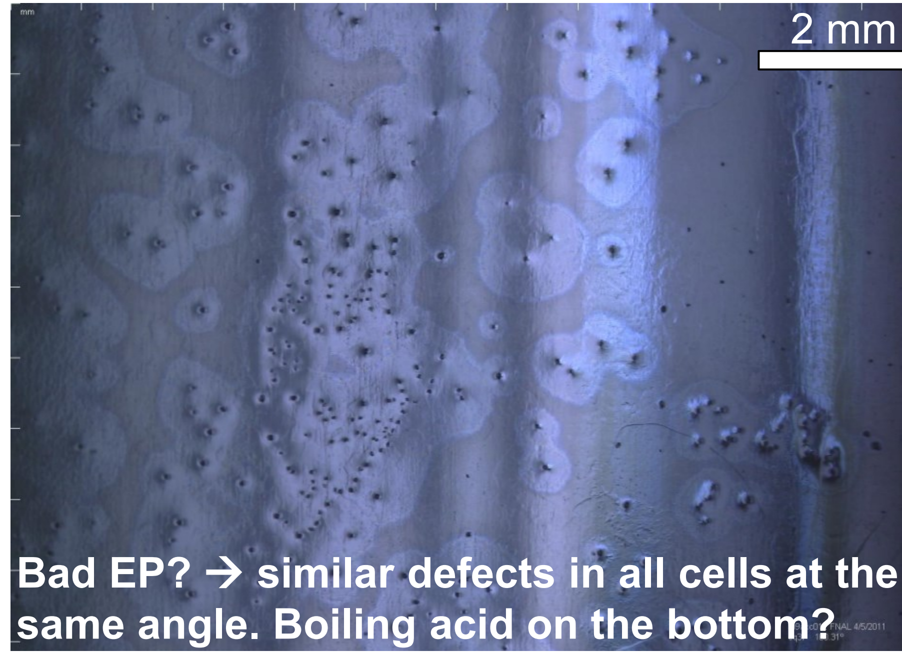


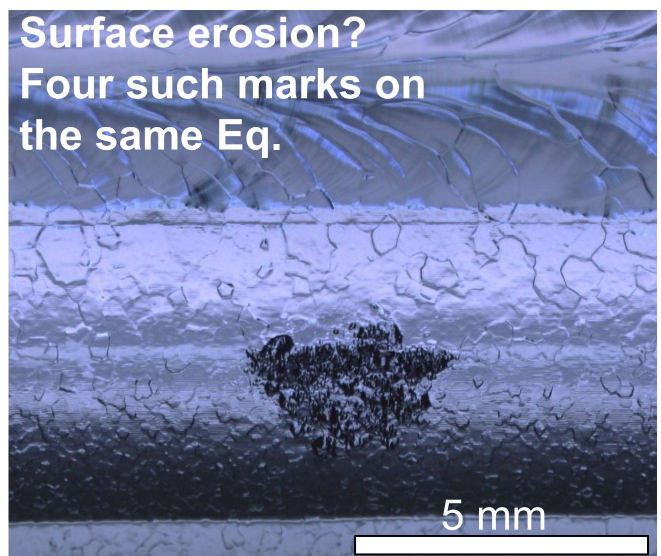


Polishing defects on cavities (Fermilab)



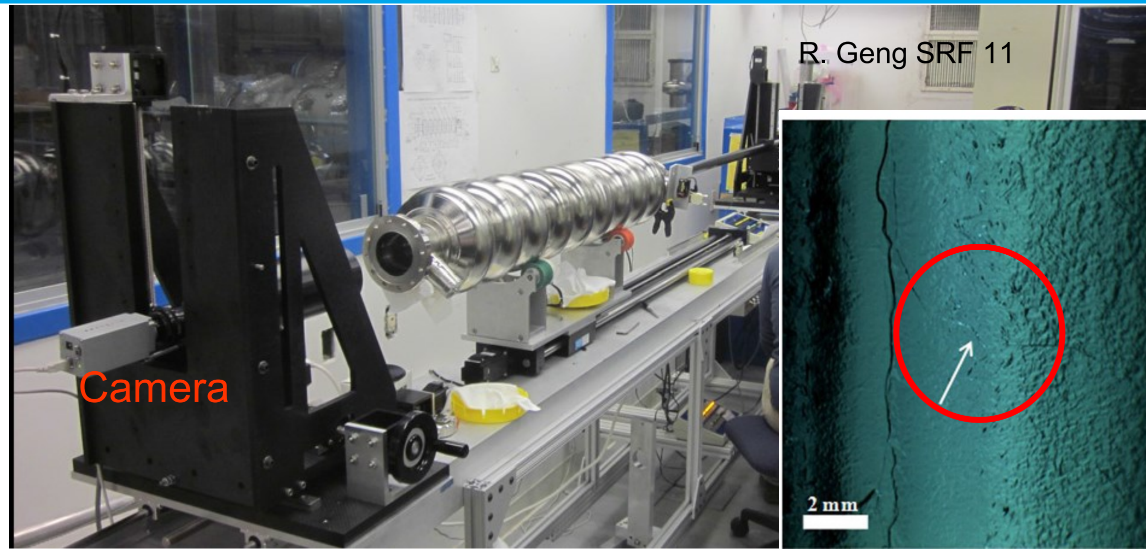
EP acid “jetting”?





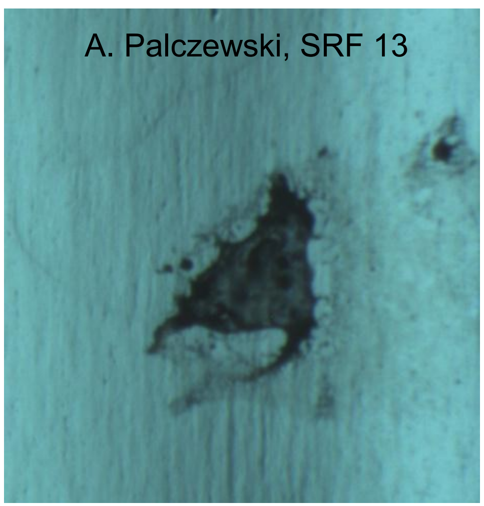
Cavity inspection systems at Jlab (1)

CYCLOPS

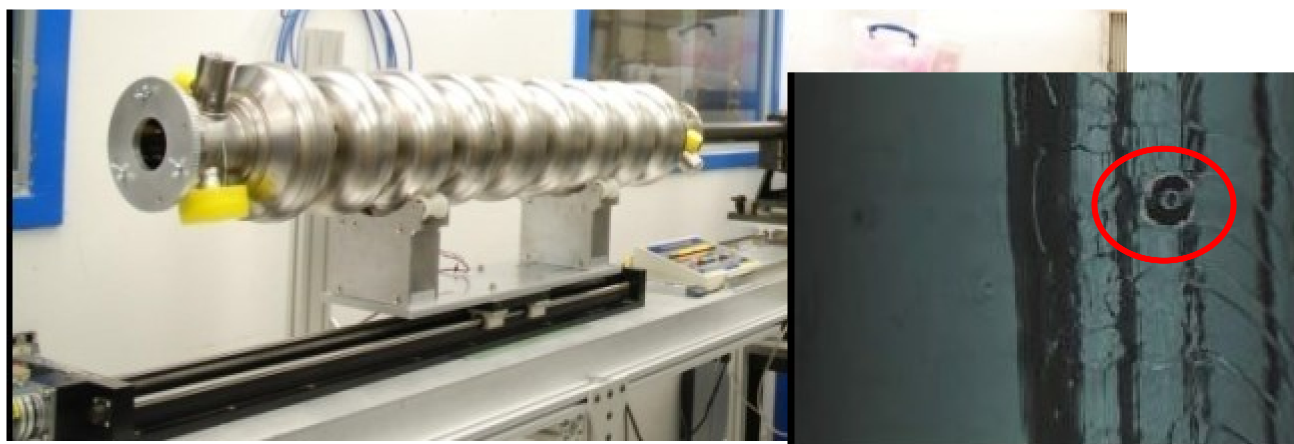


Quench location (~20 MV/m) identified by T-map on 1-cell cavity -> no clear defect found

JLab's high-resolution optical SRF cavity inspection system

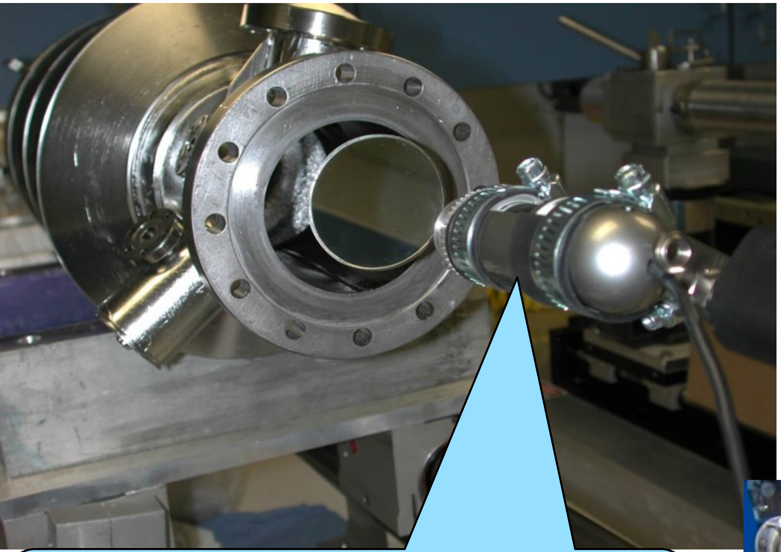


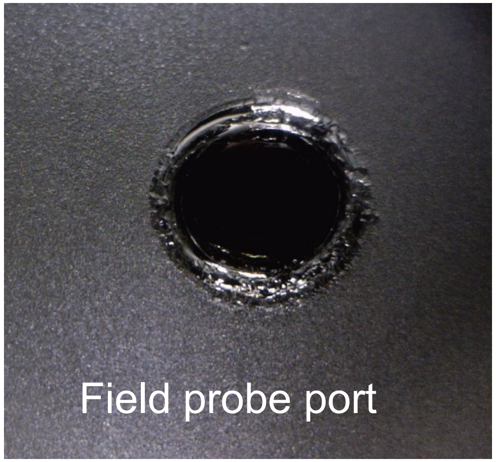
10-12 μm deeps feature measured by CYCLOPS



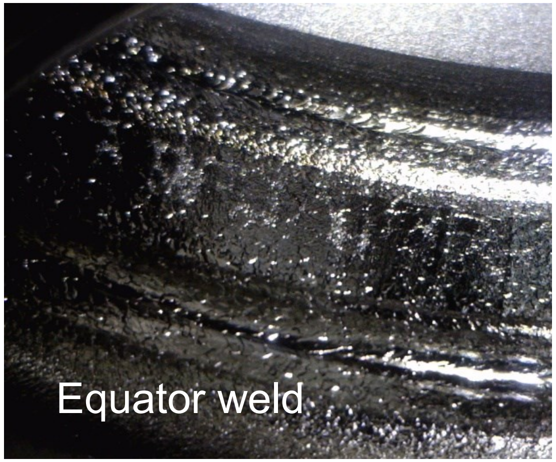
Kyoto camera optical inspection system

Cavity inspection systems at Jlab (2)



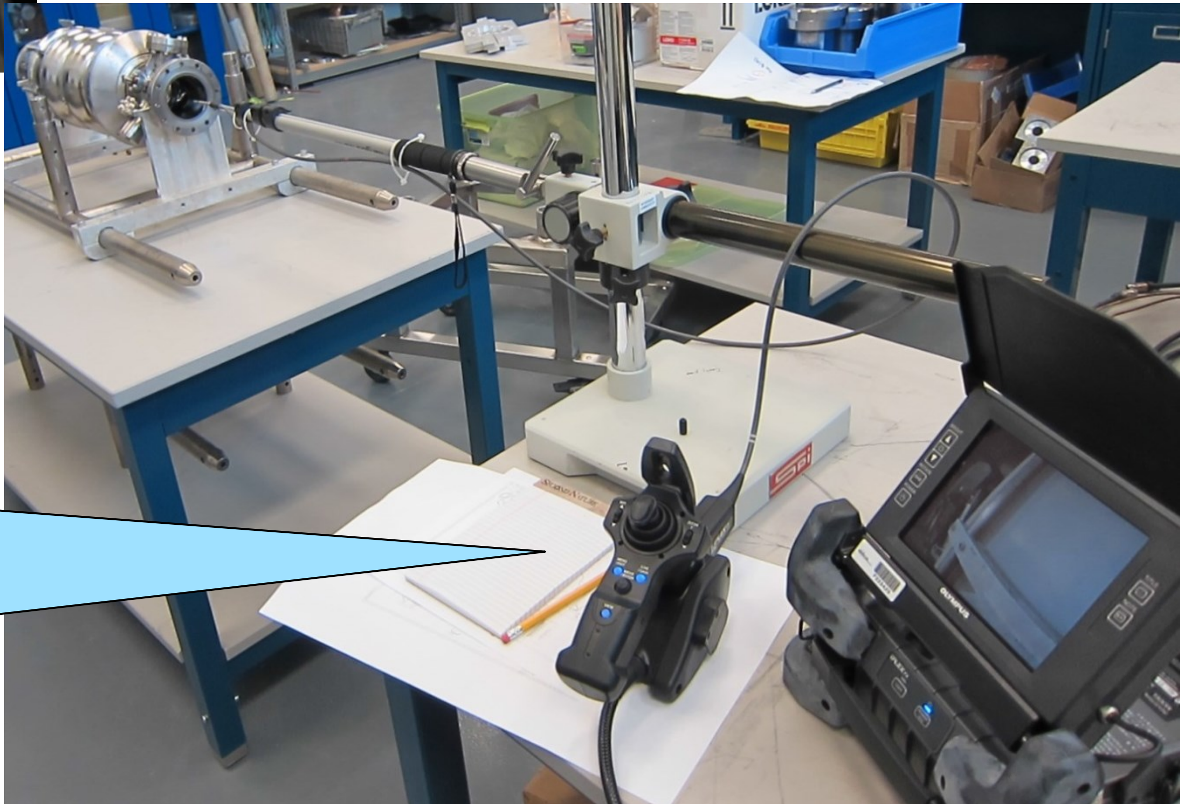


Field probe port



Equator weld

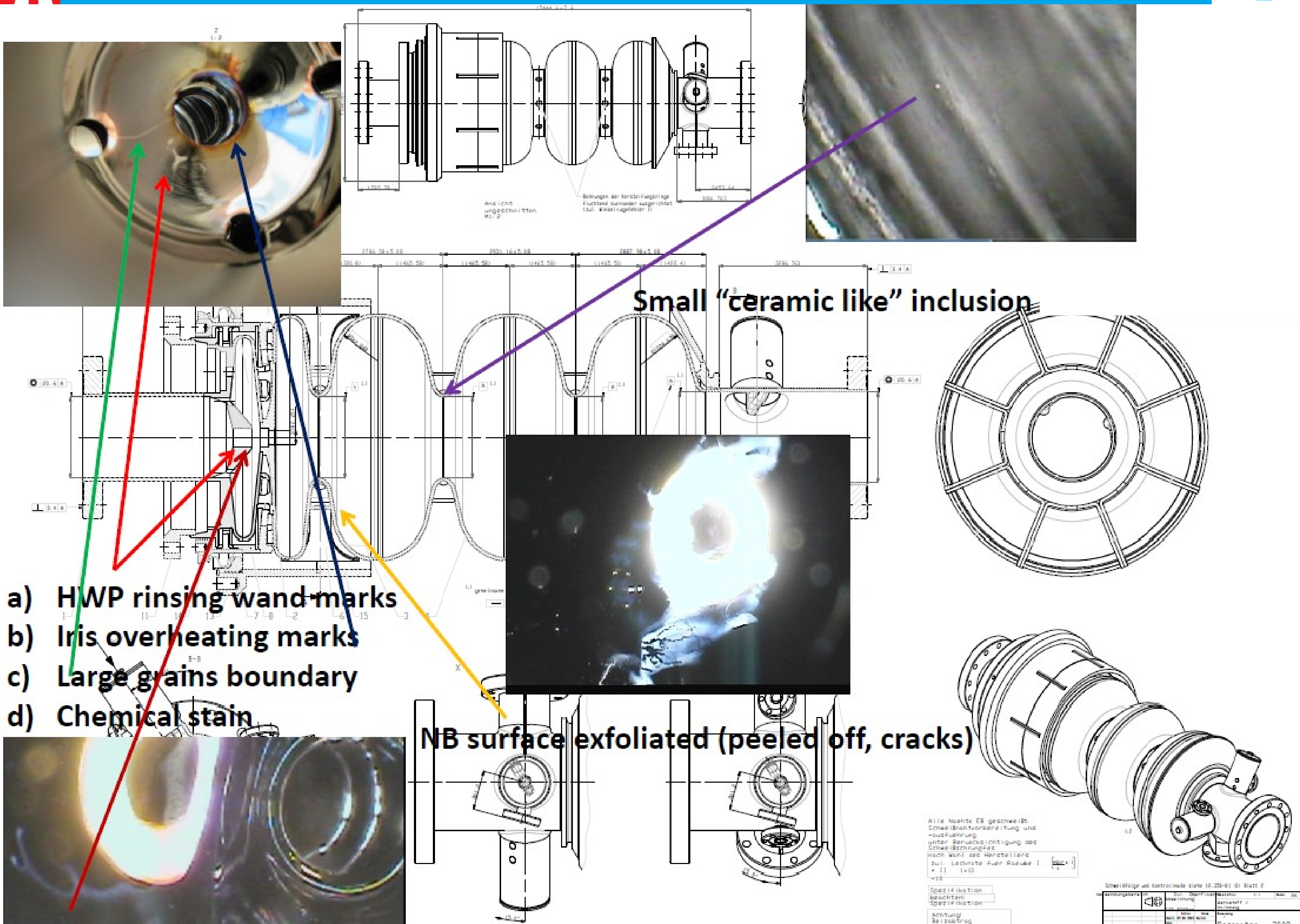
Optical system based on a **mirror** and **microscope camera** connected to a computer



Olympus system with **optical fiber** (quite **expensive** but the orientation of the optical fiber tip and focus can be **controlled pretty well** on a certain area inside the cavity)

Both operated fully manually

Resondorf gun inspection with Olympus at Jlab



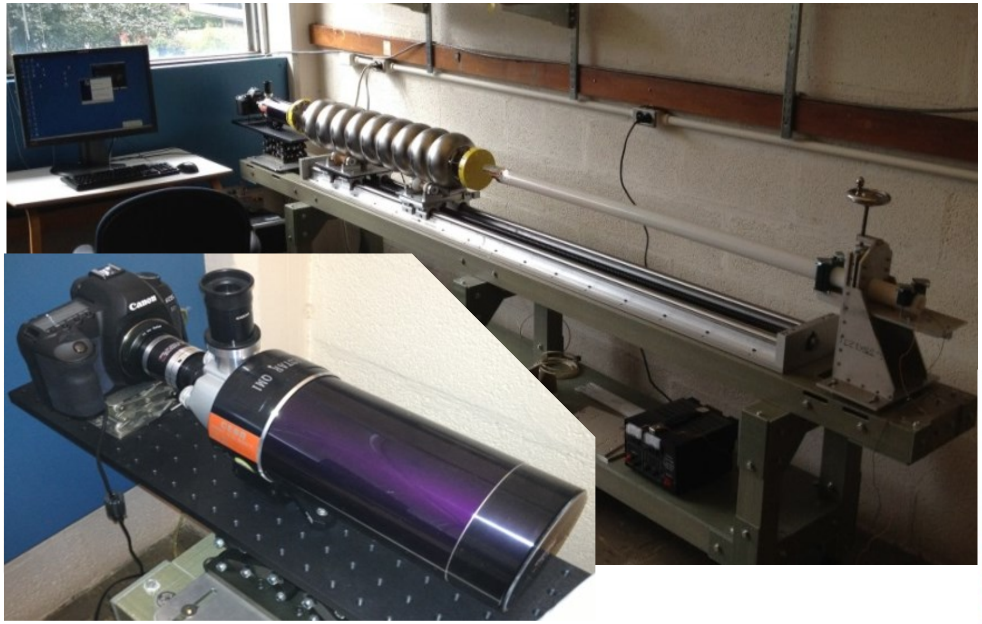
Small "ceramic like" inclusion

a) HWP rinsing wand marks
b) Iris overheating marks
c) Large grains boundary
d) Chemical stain

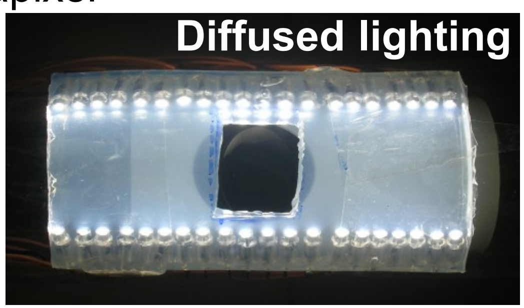
NB surface exfoliated (peeled off, cracks)

Cavity inspection system & examples from Cornell

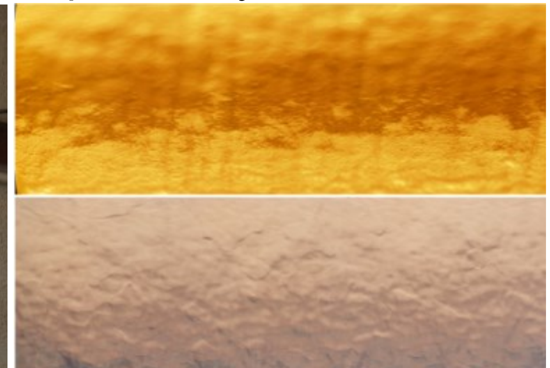
The Questar long-range microscope based optical inspection system



The Questar microscope and the DSLR with 21 Megapixel



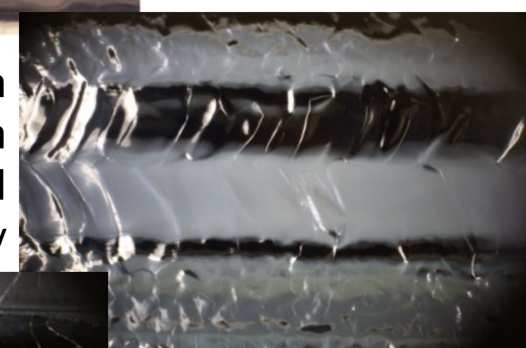
- Resolution: 5 μm
- Computer-controlled stage
- Diffused lighting



AES06
Quench locations*
at 30 MV/m
No defects identified optically

AES06
Defects causing no quench at 30 MV/m

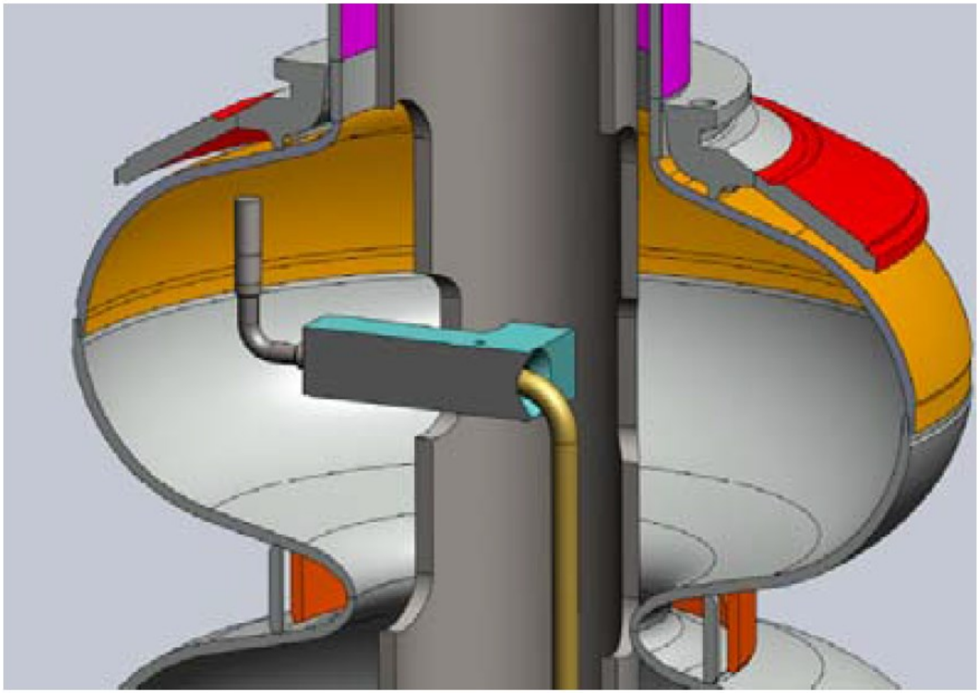
NR1-3 Quench location* at 36 MV/m
No defect identified optically



LR1-6
Quench location*
at 23 MV/m

*2nd sound based

Cavity inspection system at LANL



No update of the current status !

Figure 1: Conceptual drawing of the surface inspection using a videoscope.

MOPP158 Proceedings of EPAC08, Genoa, Italy

CONCEPTUAL DESIGN OF AUTOMATED SYSTEMS FOR SRF CAVITY OPTICAL INSPECTION AND ASSEMBLY*

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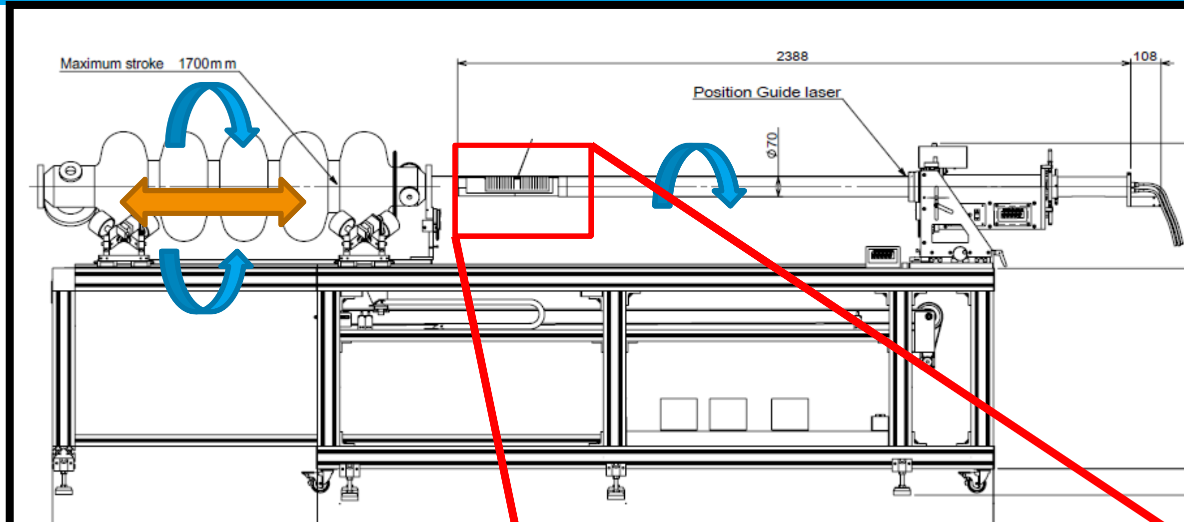
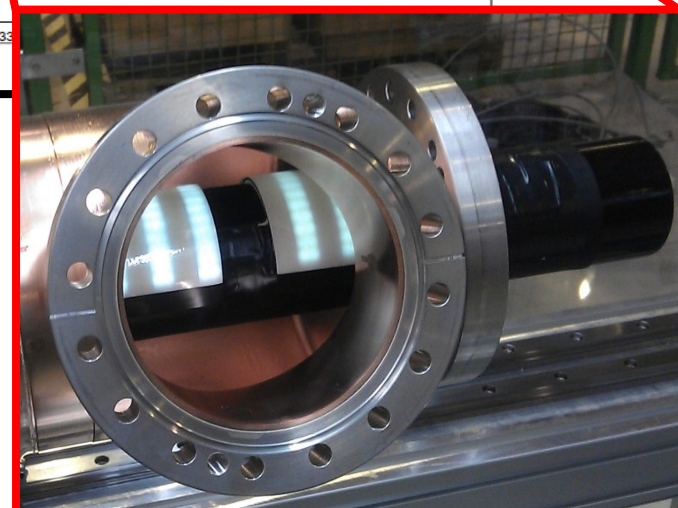
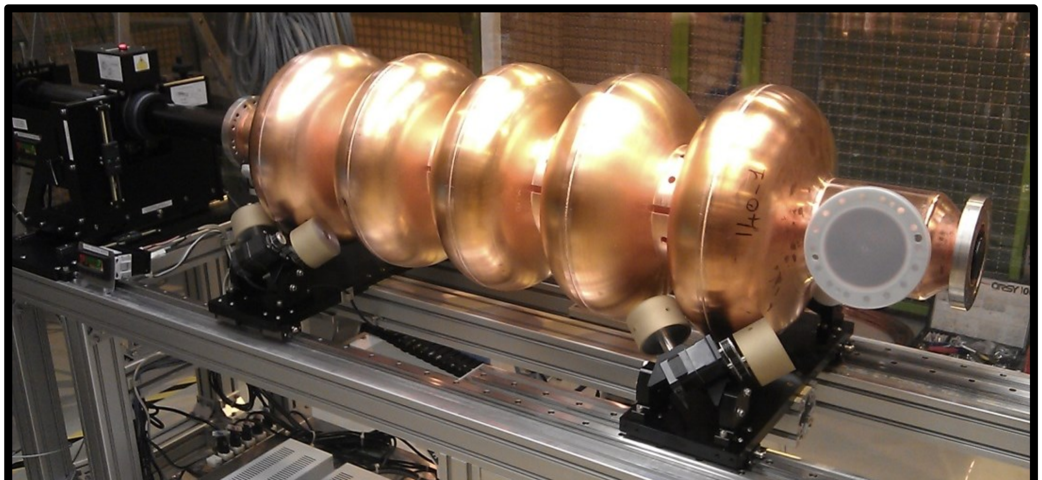
Optical Inspection SYSTEM at CERN

Equator EB welding (Cu cavity)



Kyoto/KEK system with an SPL cavity

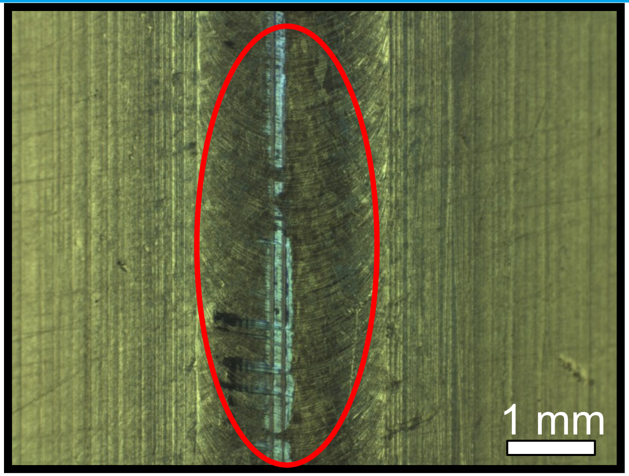




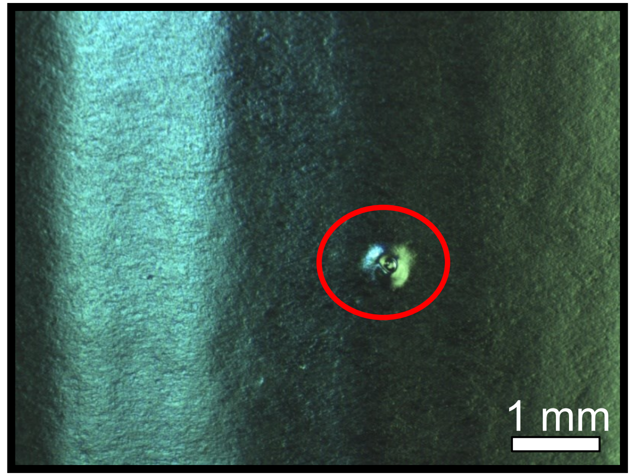
SPL copper mock up on the bench for the first test

Illumination system close-up
Camera: 3488 x 2616 pixel @ 2.5 fps
2 μm/pix, 26.1 MB/picture
Image size = 6.9 mm X 5.2 mm

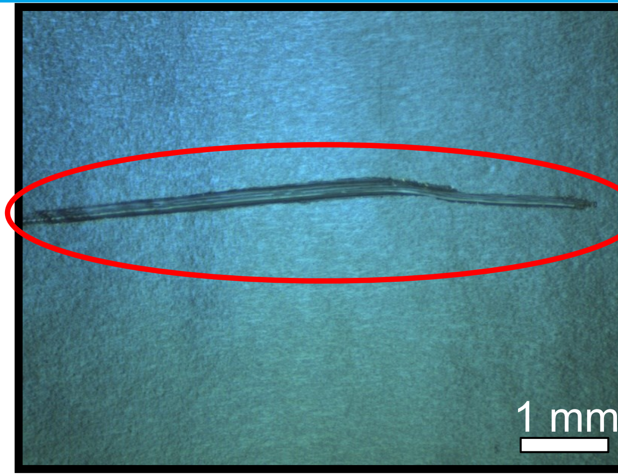
Optical Inspection: defect collection



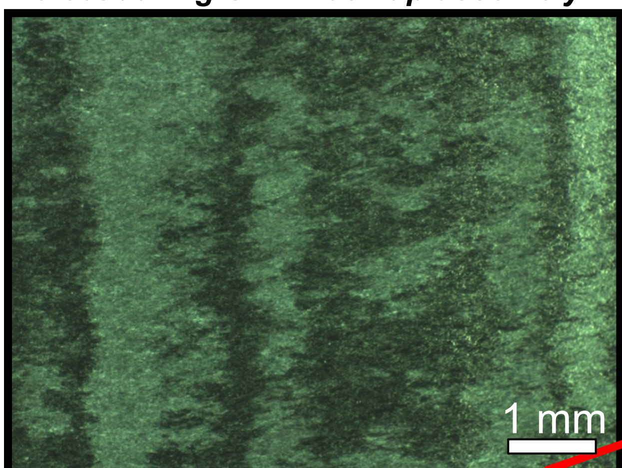
Defect during SPL mock up assembly



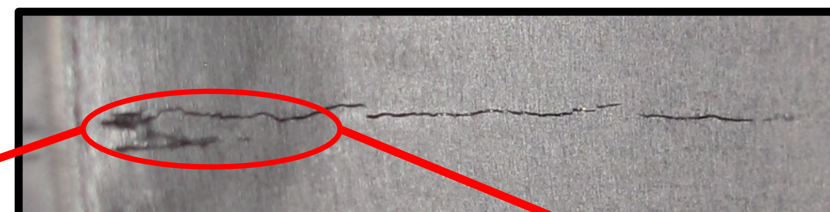
Cat eye defect on coated cavity (HIPIMS)



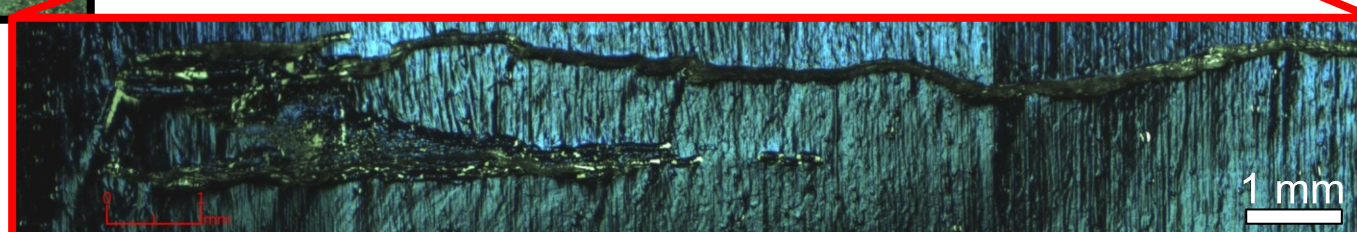
Scratch coated cavity (HIPIMS)



Black marks on coated cavity (HIPIMS)



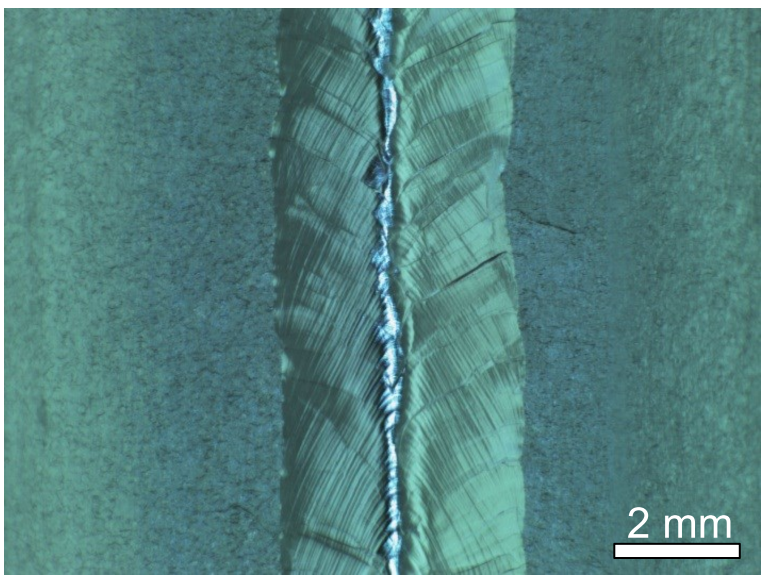
X-ray view of the defect

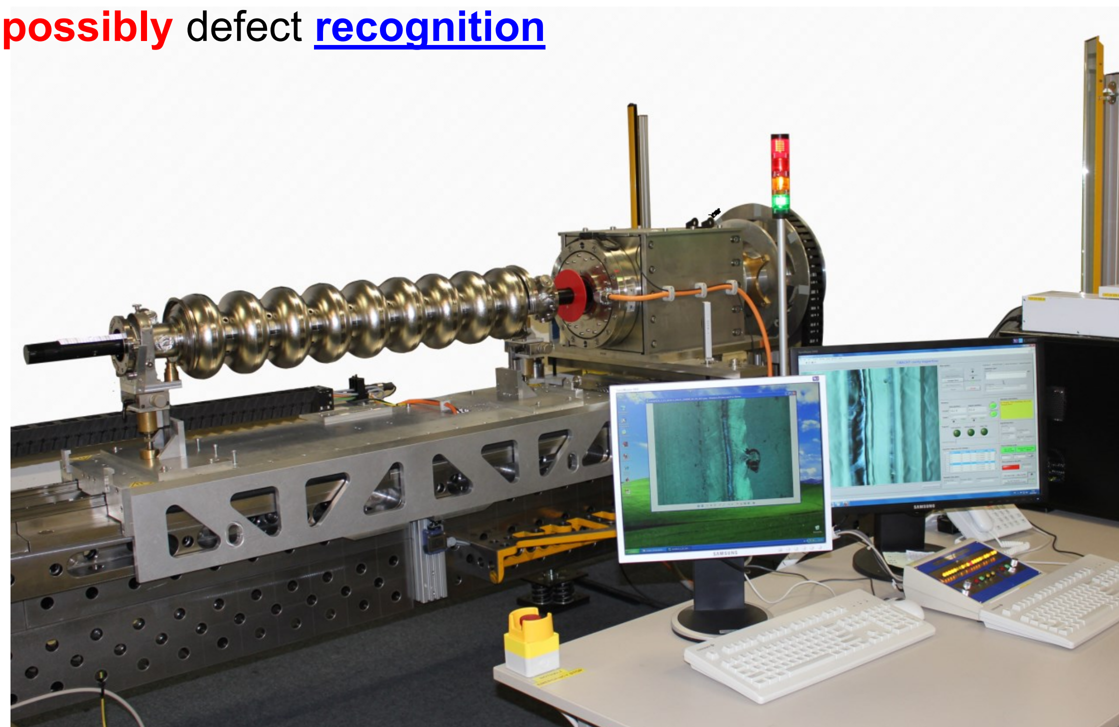


Crack on SPL01 Nb cut off

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

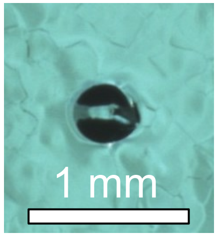
- **Large amount** of cavities (also dressed) can be **inspected**: European XFEL & ILC-HiGrade
- **Fully automated** (LabView) cavity inspection with Kyoto Camera System yields
  - 2790 pictures in ~8 hours: welding seems of equator (iris) every 4°(10°) + equator left/right
  - ~12 x 9 mm pictures (2488 x 2616 pixels, ~10 µm/pixel) in *.bmp, *.png and/or *.jpg
- Movable sled with cavity (axial posit. ~10 µm) and Kyoto camera (angular posit. ~0.01°),
- **Semi-automatic** cavity **positioning**, **illumination**, and image **recording**
- **Automatic** image **processing** and **possibly** defect **recognition**



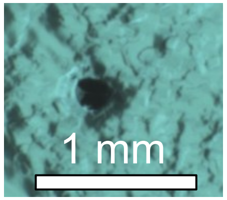


Typical surface defects

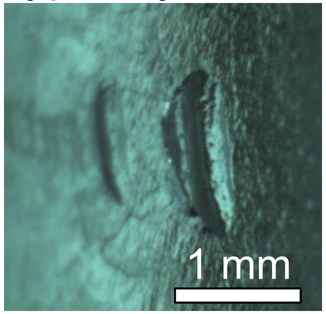
"Cat eyes"
typically on equators



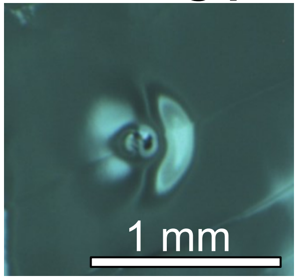
Pits or inclusions



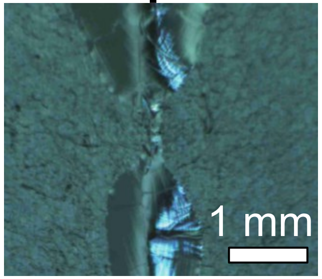
Scratches
typically on irises



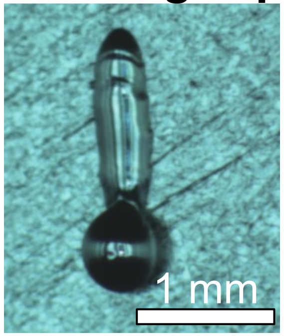
"Etching pits"



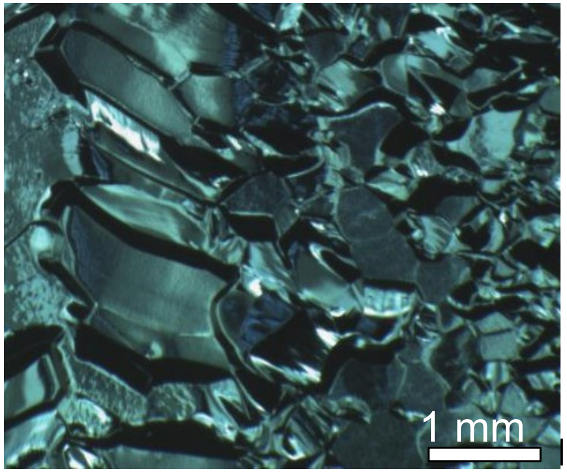
Incomplete welding



Welding "spatters"



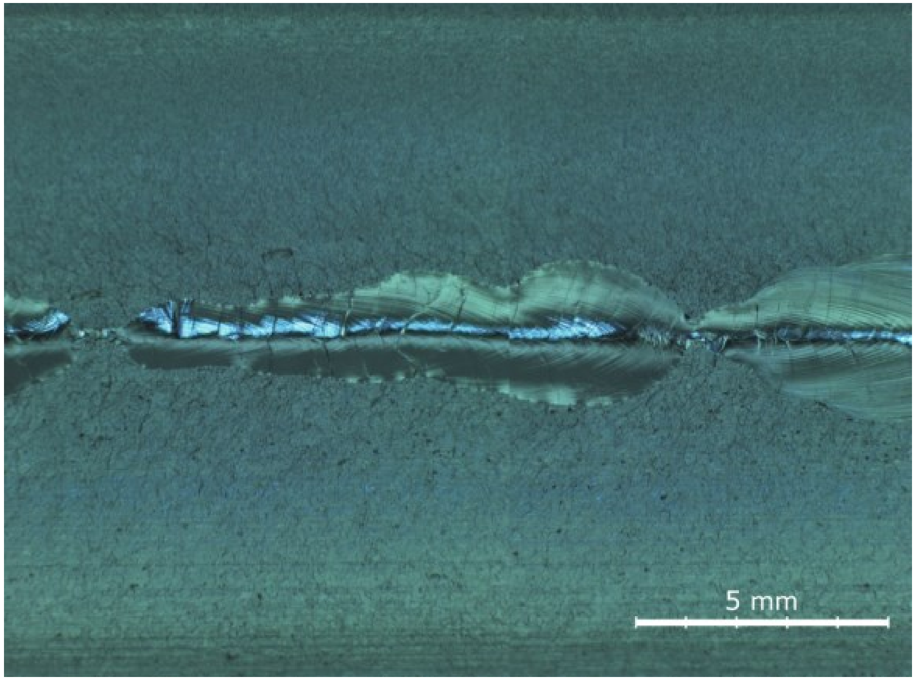
"Very rough polishing"

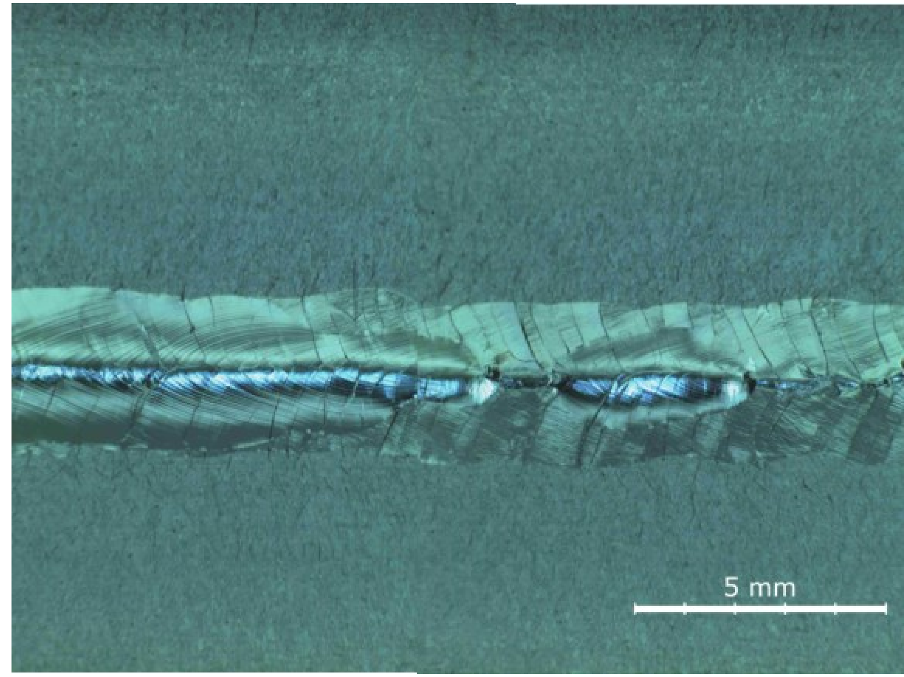


Examples of the OBACHT tests

> **Optimization** of equator welding parameters:

see WG1





Initial, **not optimized**

→ **e^- -beam not penetrated everywhere**

→ **strong variation of the seem- width**

→ **repair procedure to be established**

Final, **optimized**

→ **e^- -beam fully penetrated**

→ **homogeneous welding seem**

> **OBACHT** provides much **better resolution and image quality** as compared to the conventional **endoscopes**

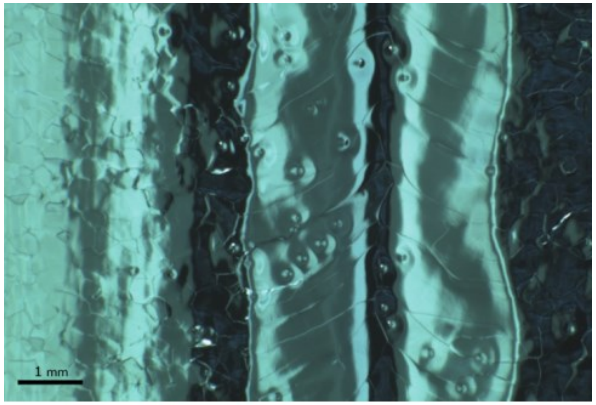
Cold RF tests vs. surface quality

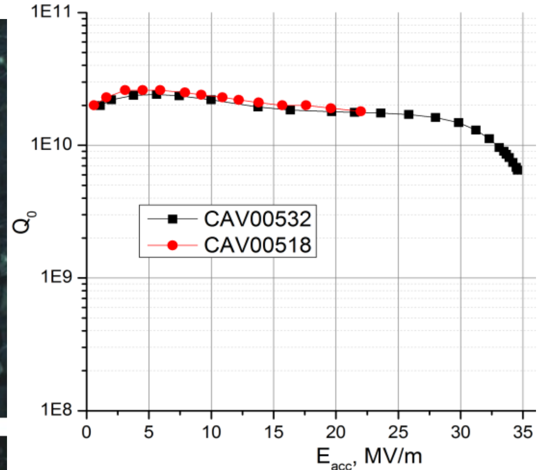
CAV00532:

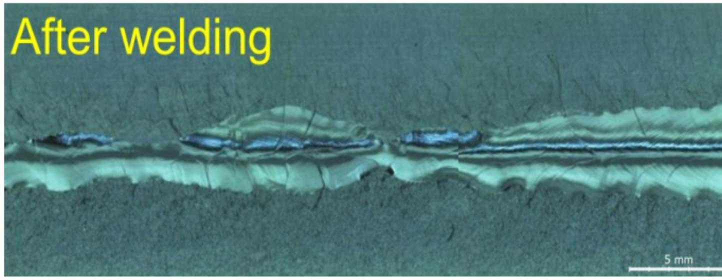
→ **Successful** cold RF test result with **no FE**, RF power limited at 200W P_{in})

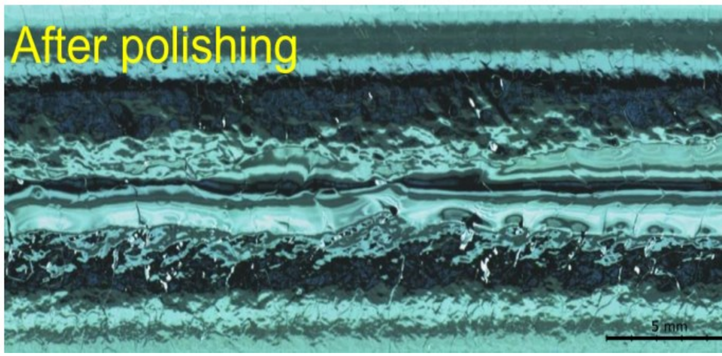
CAV00518:

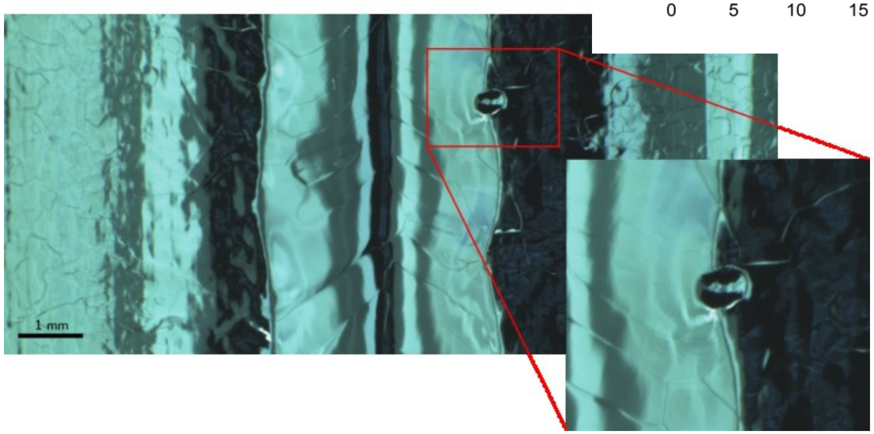
→ Unsuccessful cold RF test result with quench at **22 MV/m**, **no FE**











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

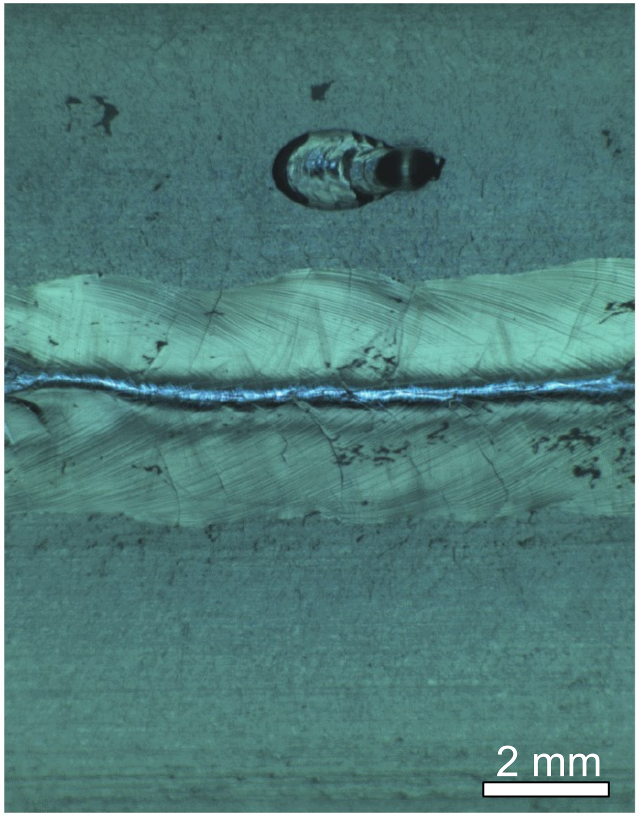
-> OBACHT indicates defective welding as a possible quench reason

→ **Second Sound** & **T-mapping** will be applied for the quench localization and further studies

Surface defects study and repair

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

see WG1



After final polishing:

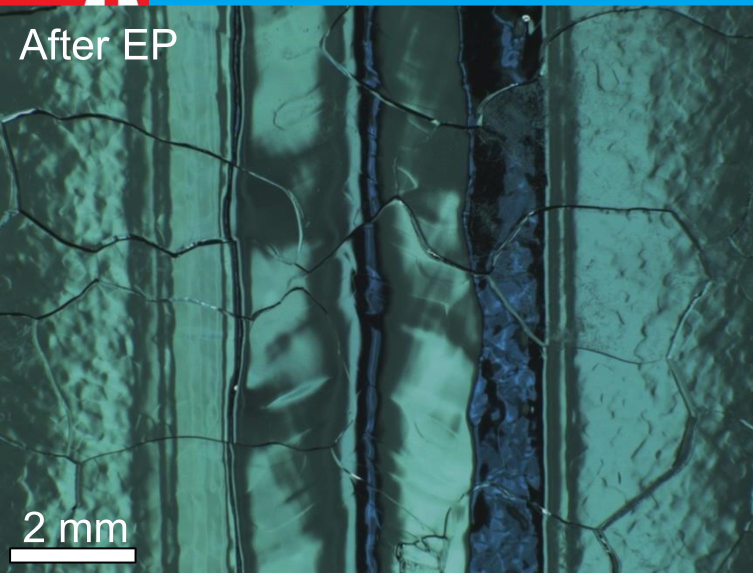
→ max **E_{acc} = 30.5 MV/m**
→ **no FE**

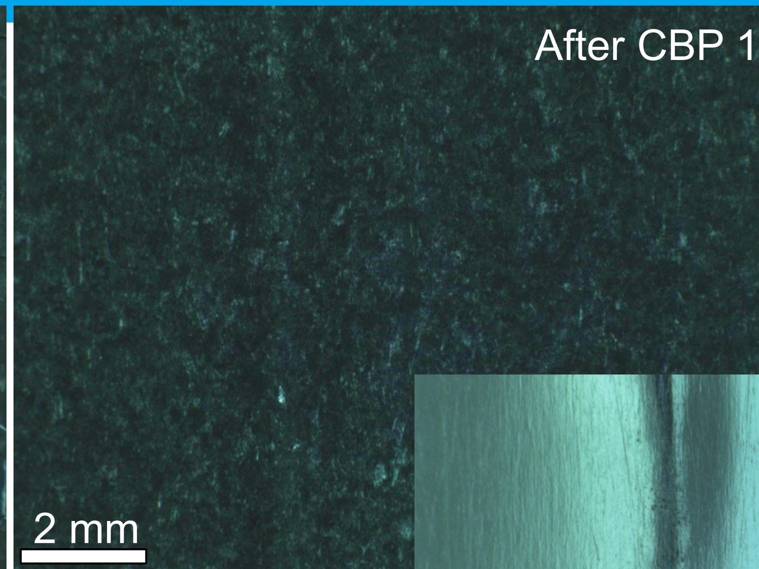
→ reason is under investigation

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

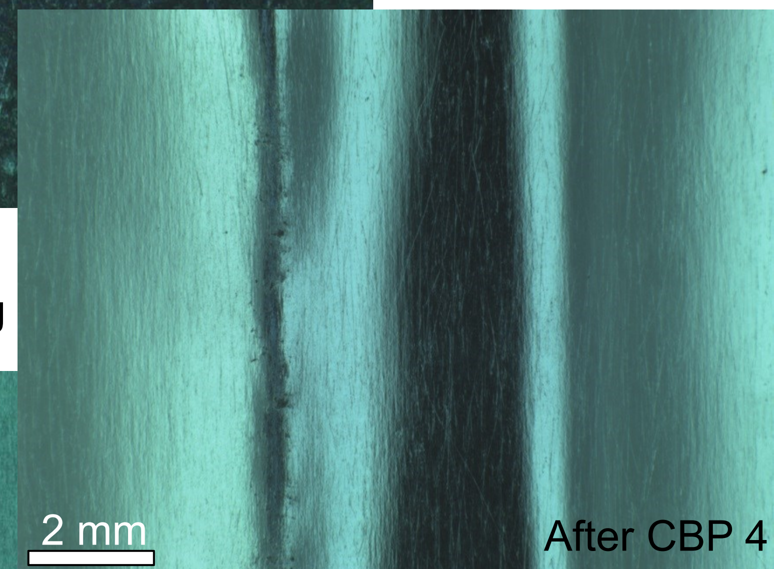
→ optimum repair procedure (here shown a manual one) is under study

Tracking of the CBP polishing



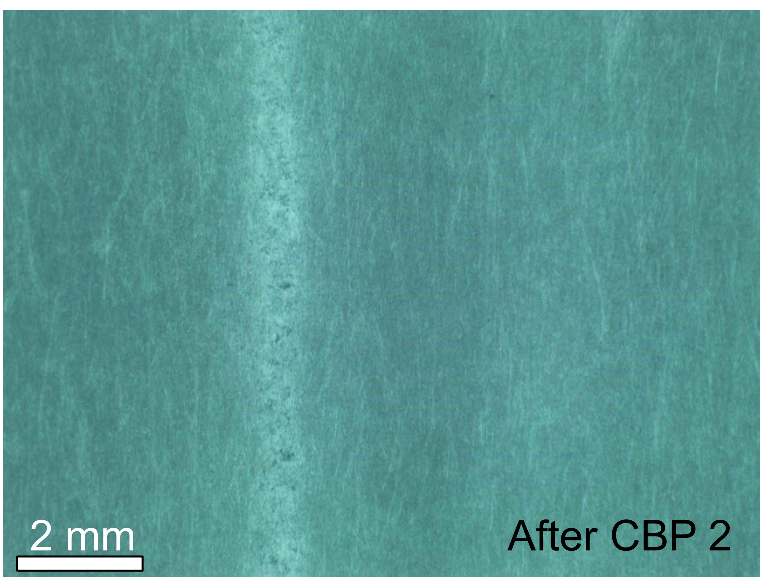


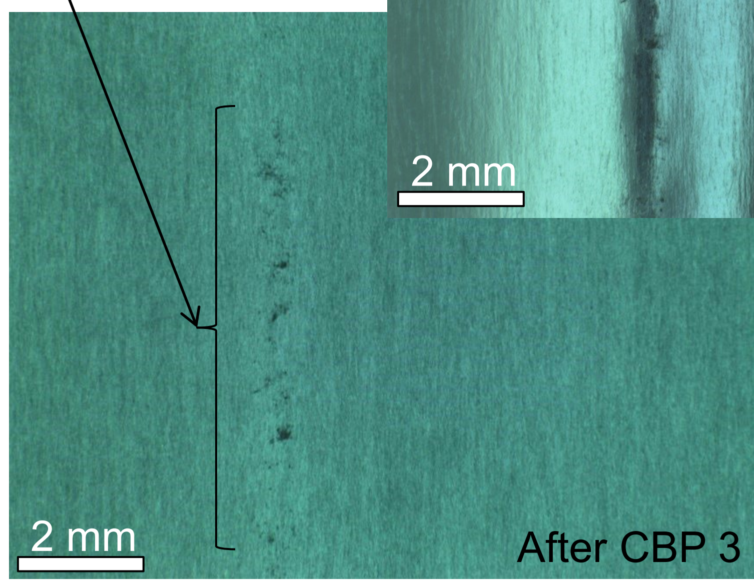
see WG3



Z110_E1, 14.4^0
E_{max} = 14 MV/m
despite of add. EP

Porosity close to welding seam
even after ~200µm CBP polishing

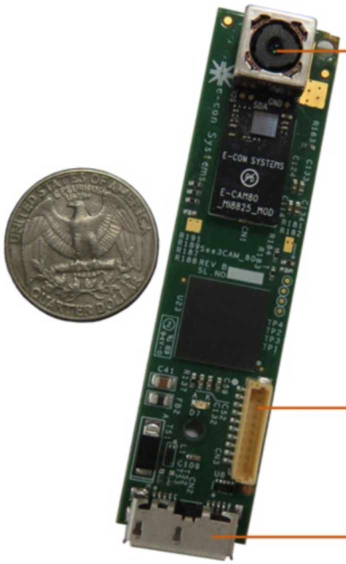


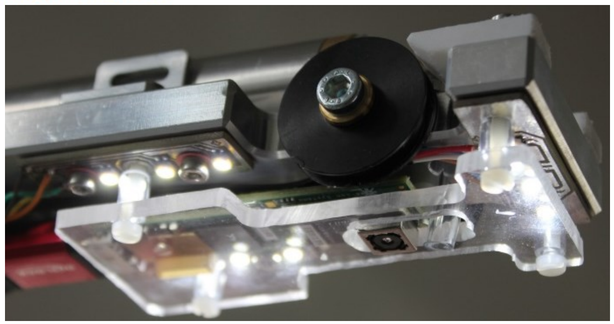


A mini USB-camera with autofocus and LEDs for Replica

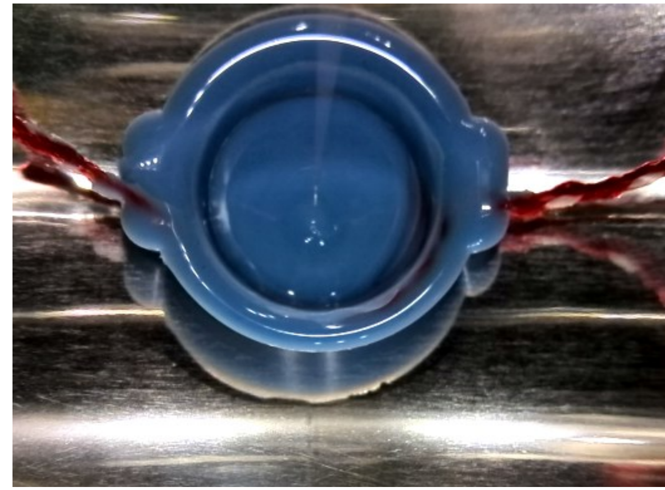
> **Replica** is non-destructive testing tool of inner cavity surface
- 3D topography (~1 µm resolution) and **correlation** to 2D images from OBACHT
- no cavity performance degradation (no residues) if done correctly (at least after HPR)

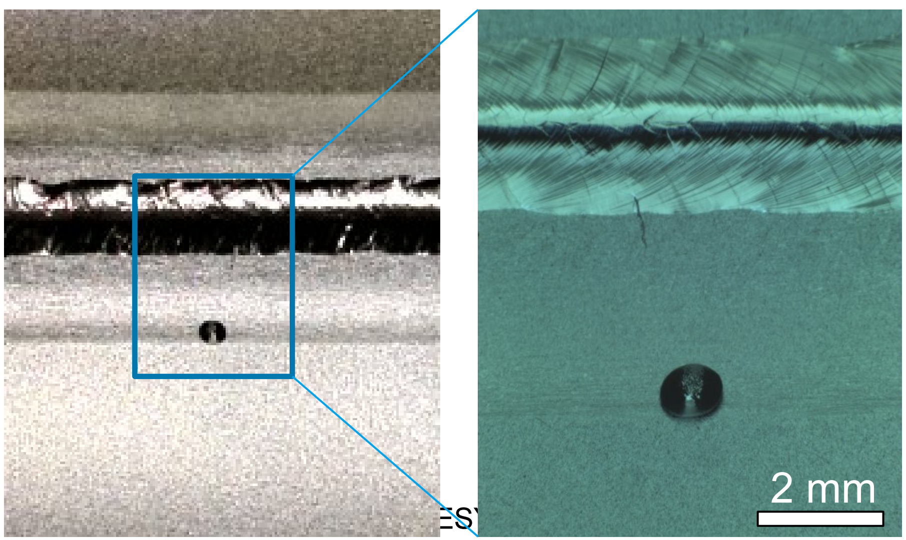
see WG3

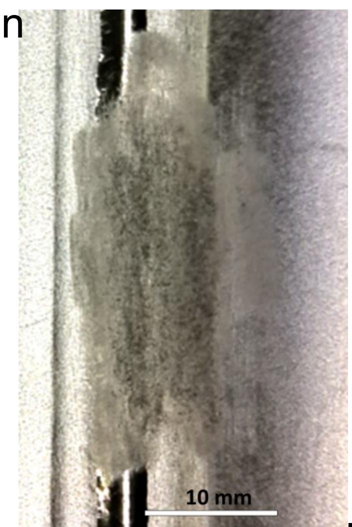




- Large field of view (8x6 cm^2)
- Autofocus
- Diffused illumination

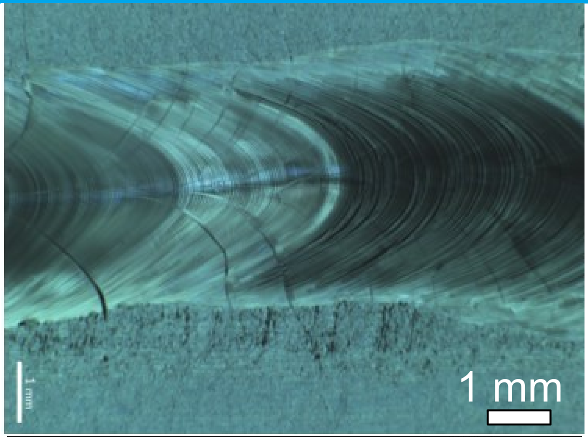


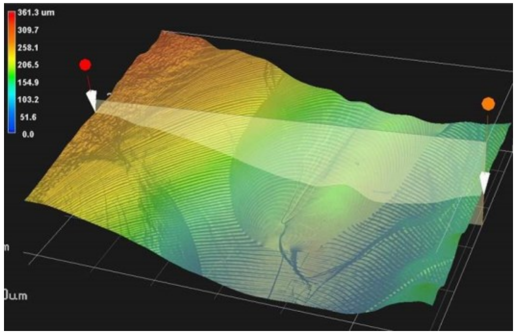


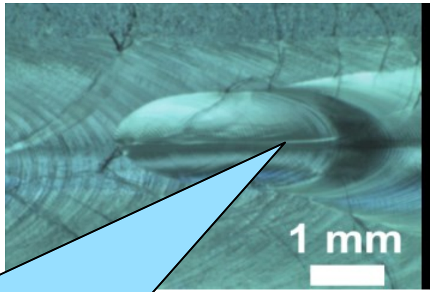


- Other area after local grinding

3D topography vs. 2D images of OBACHT

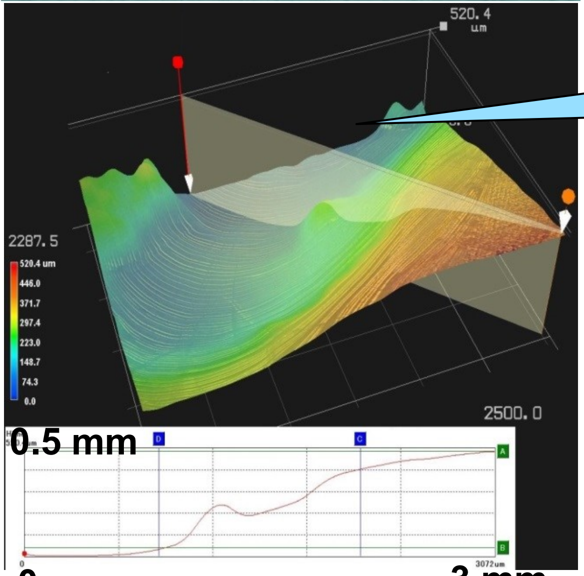






→ “snake head” at e⁻-beam welding exit is **not protruded** as it seams from the OBACHT images

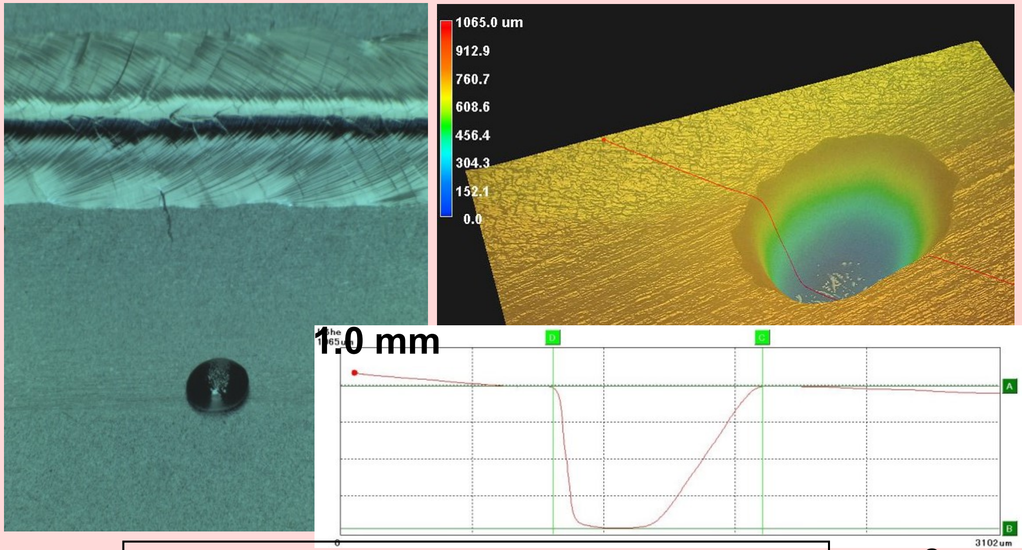
→ The whole welding seam (right) **protrudes >500 µm** (**<300 µm specified**)



After final assembly and polishing:

→ **max E_{acc} = 34.3 MV/m, BD limited**

→ **no FE**



→ 1 mm defect to be grinded

Summary and outlook

- The optical systems became **a very important tool** for analysis of inner cavity surface:
  - **Quality control** of cavities surface
  - **Detailed examination** of the quench areas possible
  - Give **valuable feedback** to the fabrication and (re-)treatment steps (e.g. great support to EXFEL cavity fabrication especially during the ramp-up phase and some cavities retreatment)
- The equator welding seems to be still a "**weak point**" as it is not easy accessible
  - An **additional grinding/repair tool** is required
- Although optical inspection in combination with 2nd Sound and T-mapping offers a **convenient method** to locate quenches, precise un-doubtful localisation and understanding of quenches in SRF cavities is still a **challenge**
  - Often **not clear correlation** of all diagnostic methods
  - **Additional** surface mapping **technique** (like Replica, XRF, etc.) or even destructive tests might be **required**

- Further **developments** of the system is **desirable** especially in such aspects as
  - Even more **faster** and **fully automatic inspections** what requires at least **autofocusing** function of the camera, **automatic** light **pattern** and **brightness adjustment**
  - **Automatic** image **processing** for defect **recognition** and **surface qualification** is still to be **optimized/developed** to analyse thousands of pictures

Thank you for your attention !

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European ILC-HiGrade programme

24 cavities are added to the ***EXFEL*** order as a part of the ILC-HiGrade program:

> Initially, serve as **quality control (QC)** sample for the ***EXFEL***
- extracted regularly, ~**one cavity/month: first few cavities arrived!**
- after the **normal acceptance test** will be **taken out** of the production flow --> **R&D**

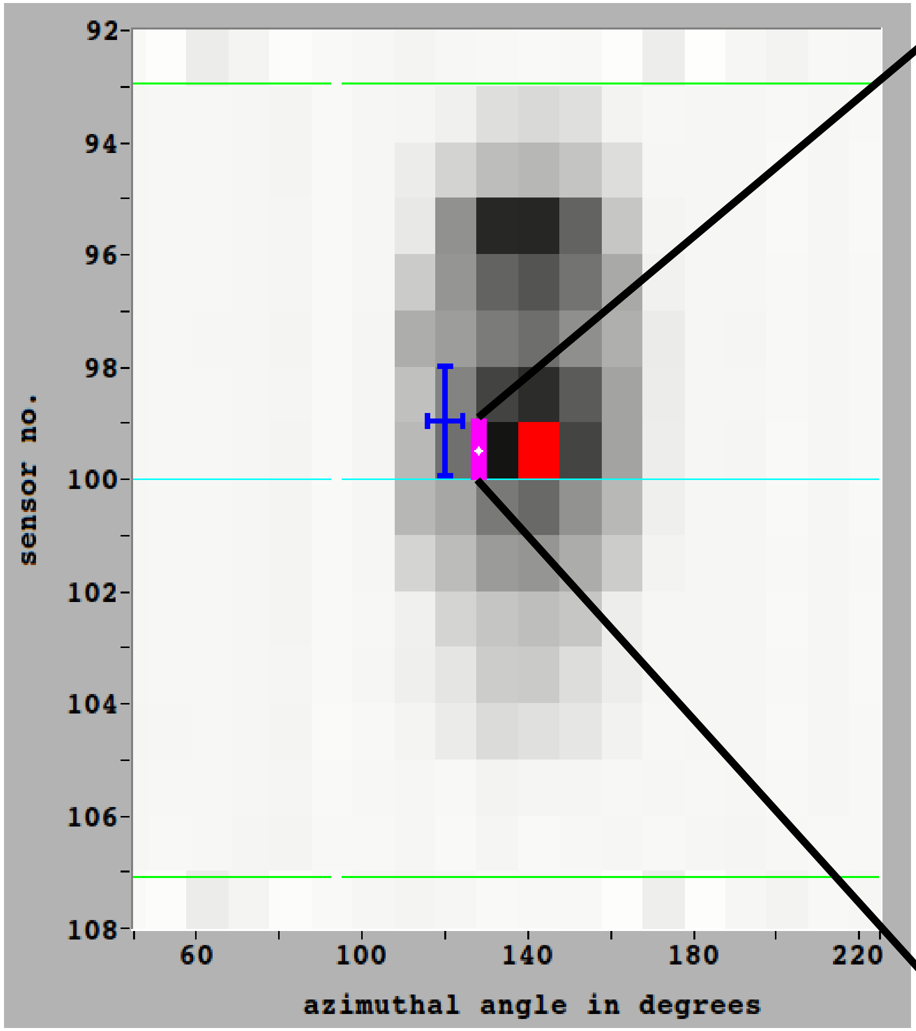
> Delivered with **full treatment** but **no helium tank**
-> **maximize** the data output from the test

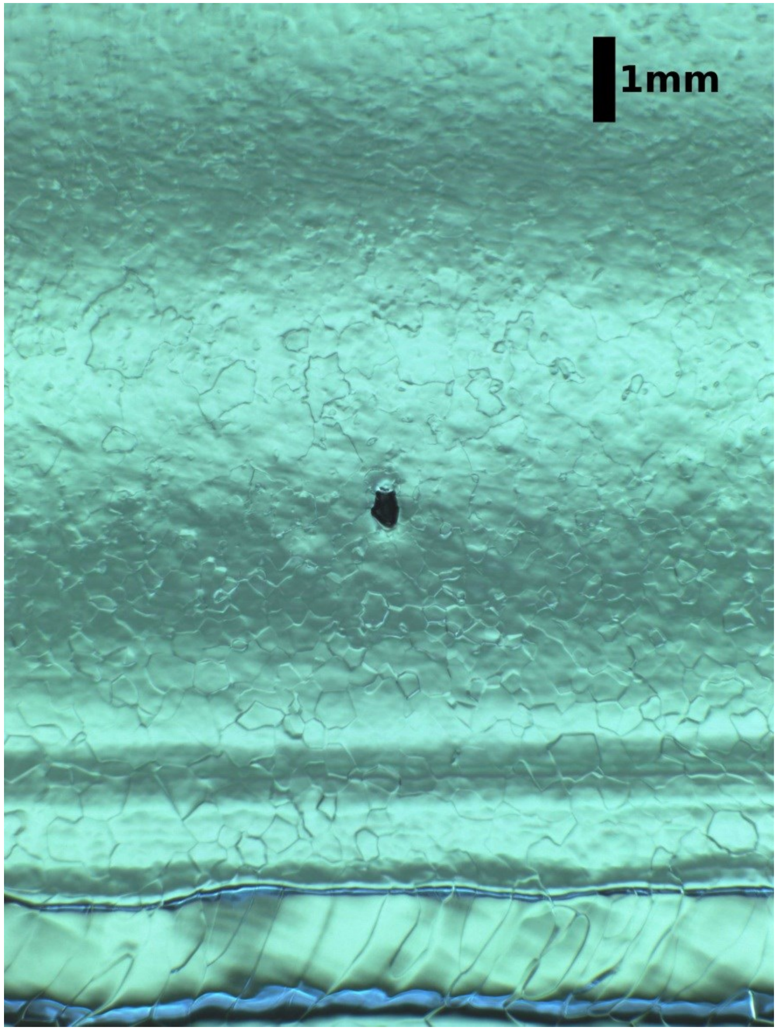
> Further handling within **ILC-HiGrade/CRISP** **as feasibility study** for **ILC goal**:
- "Second sound" and T-mapping from the 2nd cold RF test
- optical inspection (OBACHT) and replica
- Centrifugal Barrel Polishing (CBP)
- Local Grinding repair

> Eventually aim **3 world record modules** from the **24 ILC-HiGrade cavities**

Quench localization example

- Z161, cell #2 in pi-mode: Second sound (blue) vs. OBACHT (pink) and T-map (red)





ILC-HiGrade Lab

- ~150 m^2
- 2 laboratory rooms + 1 storage/technical room