The development of new techniques for SRF cavity surface research at Fermilab

Mingqi Ge
Technical Division
Fermi National Accelerator laboratory
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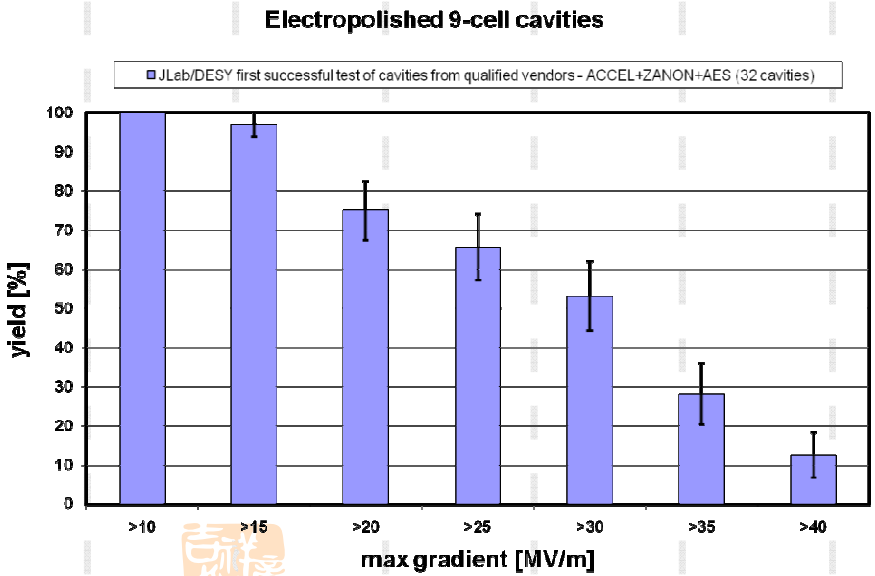
Outline

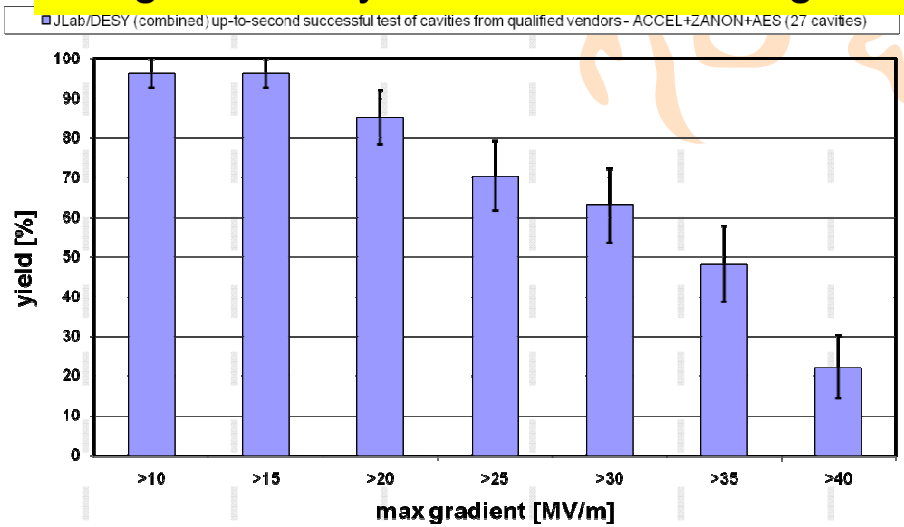
- Cavity optical inspection
- Surface replica technique
- Laser re-melting technique
- Laser welding study

Cavity RF performance statistic

Image courtesy of Camille Ginsburg



1st pass yield



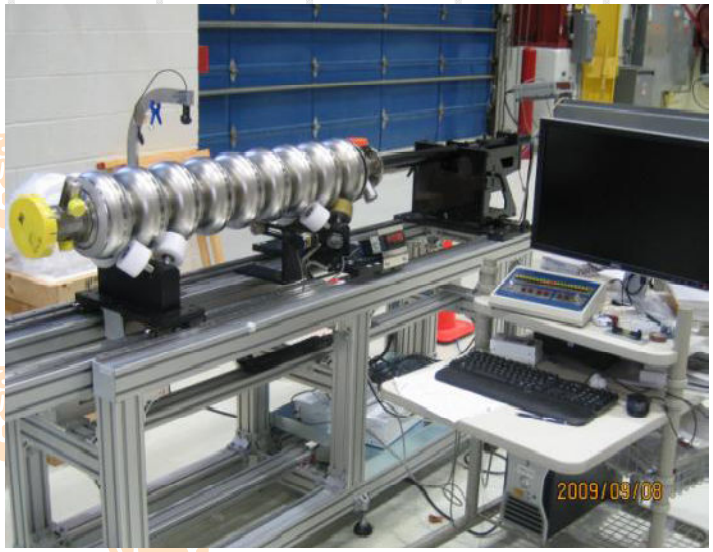
2nd pass yield

- Even after 2nd pass, less than 50% cavities yield at 35MV/m.
- Surface state affects SRF cavity superconductivity dramatically.
- Surface research is an important assignment for SRF material group in FNAL.

Optical inspection technique at Fermilab

Kyoto system:

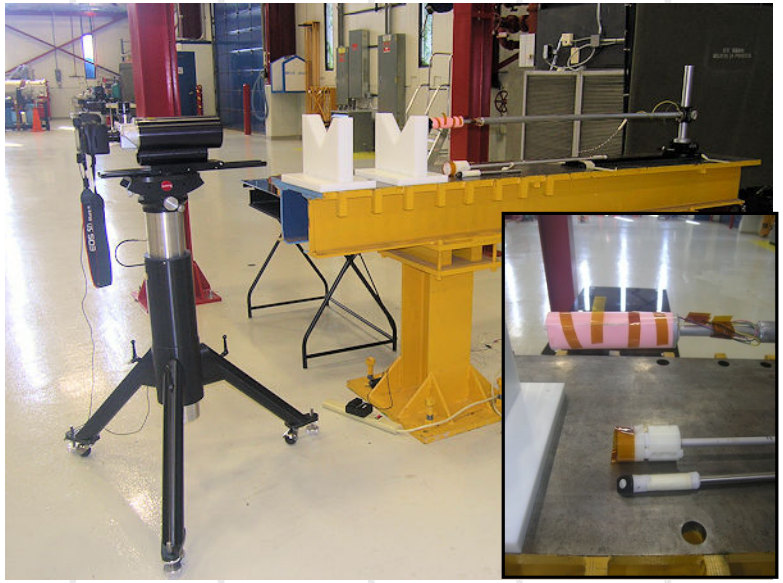
- 1.3GHz 9-cell cavity
- 1.3GHz single-cell cavity



Kyoto optical inspection system

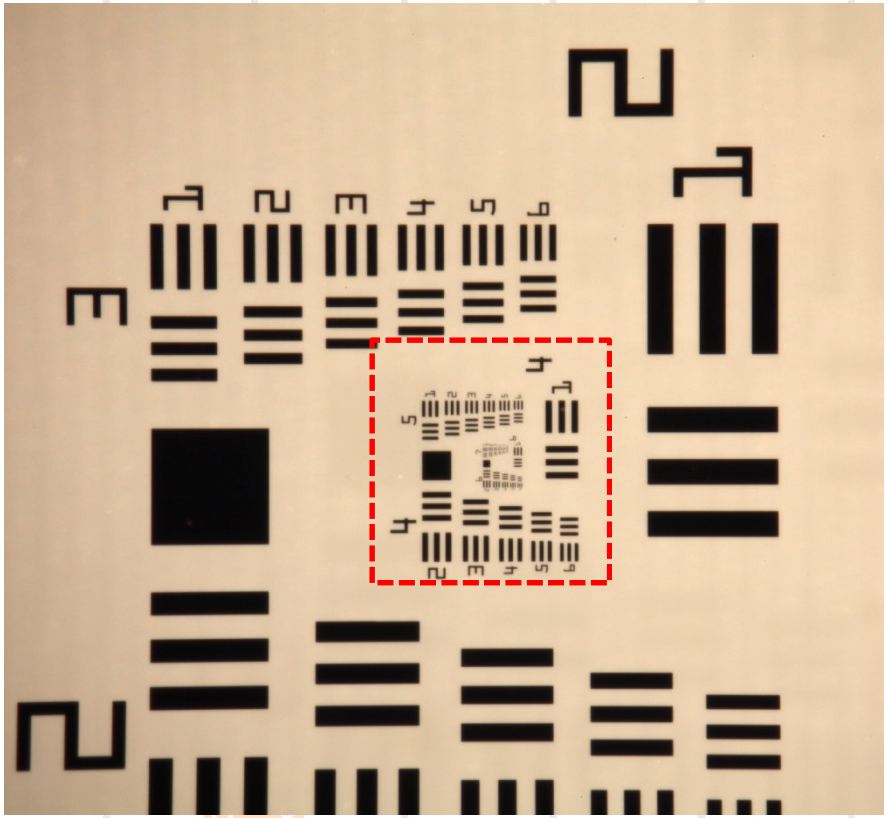
Questar system:

- 1.3GHz 9-cell dressed cavity
- 1.3GHz single-cell cavity
- 3.9GHz 9-cell cavity
- 3.9GHz single-cell cavity
- 1.3GHz Traveling wave cavity
- Spoke cavity
- 650MHz SRF cavity

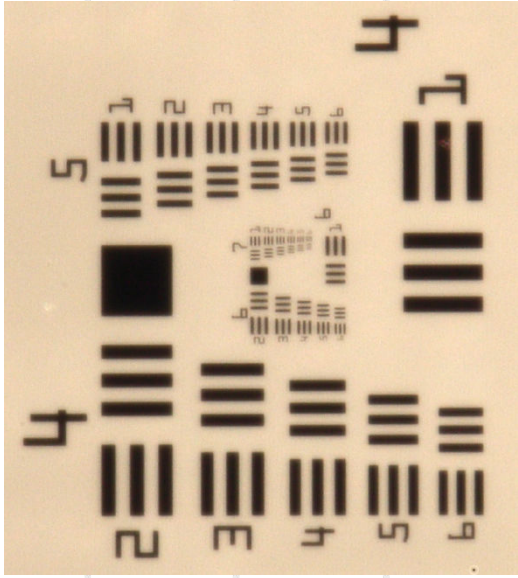


Questar inspection system

Resolution comparison between Kyoto and Questar system



100% cropped image from center



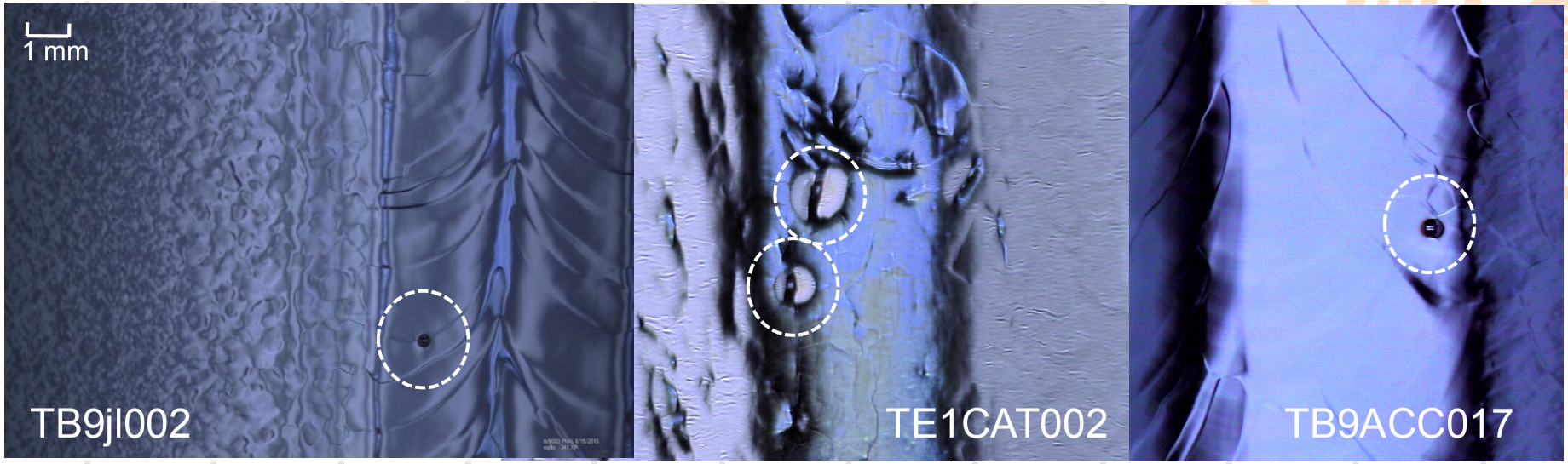
Questar system

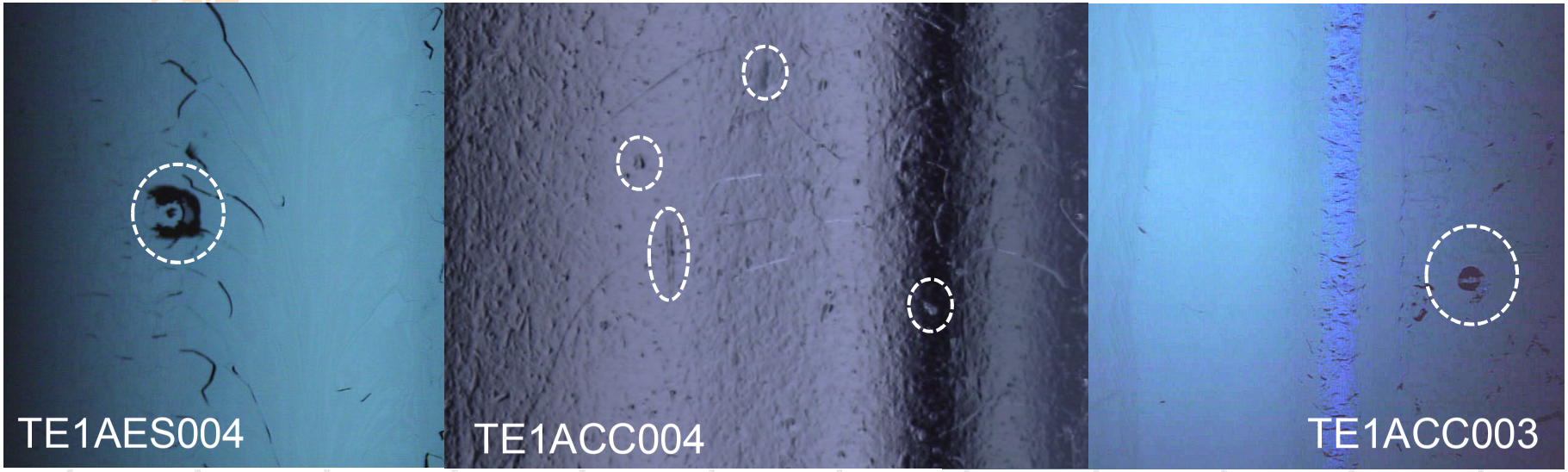
Kyoto system

$$Resolution\left(\frac{lp}{mm}\right) = 2x^{Group+(element-1)/6}$$

	Resolution (lp/mm)
Questar	181
Kyoto	32

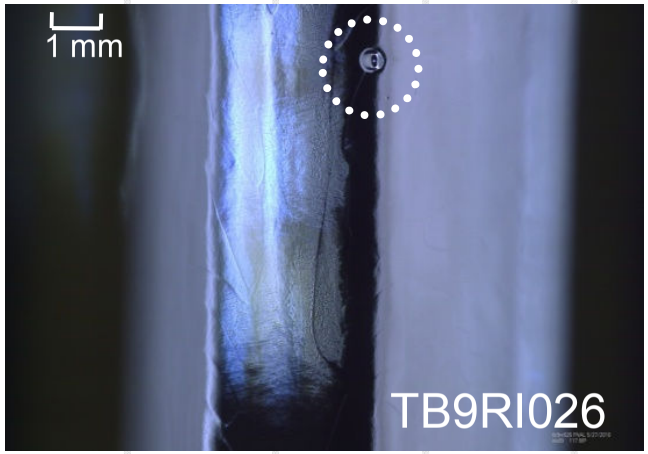
Defects observed in equator region

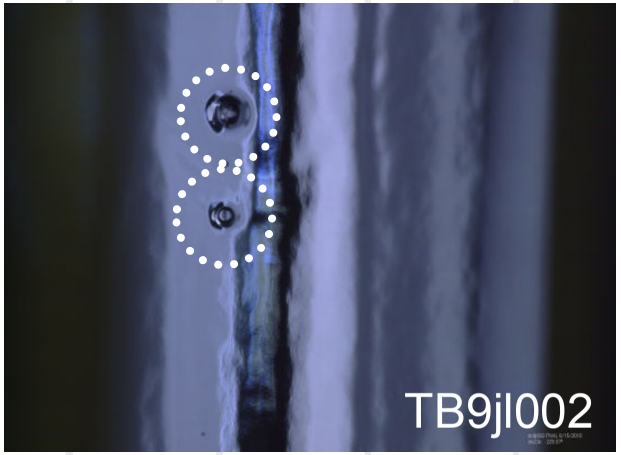


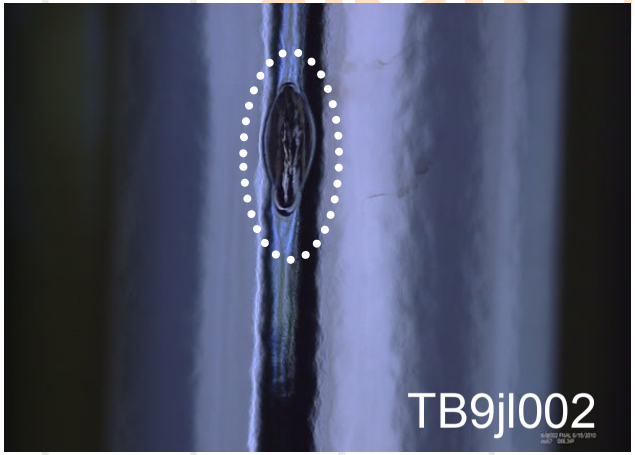


Defects observed in iris region

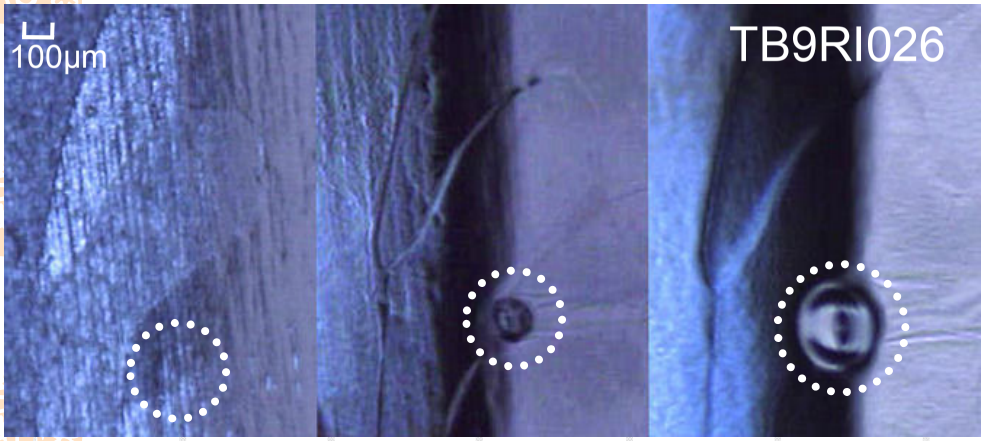
Image courtesy of Dmitri Sergatskov







Growth of pit observed by optical inspection



Brand new cavity | After 70µm EP | After another 70µm EP (total 140µm EP)

Some pits can not be removed by bulk EP!

Surface replica technique at Fermilab

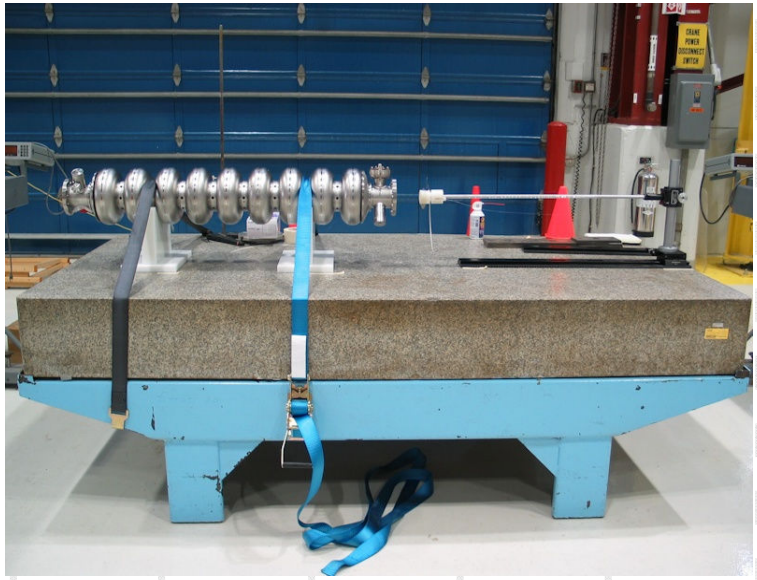
Motivation

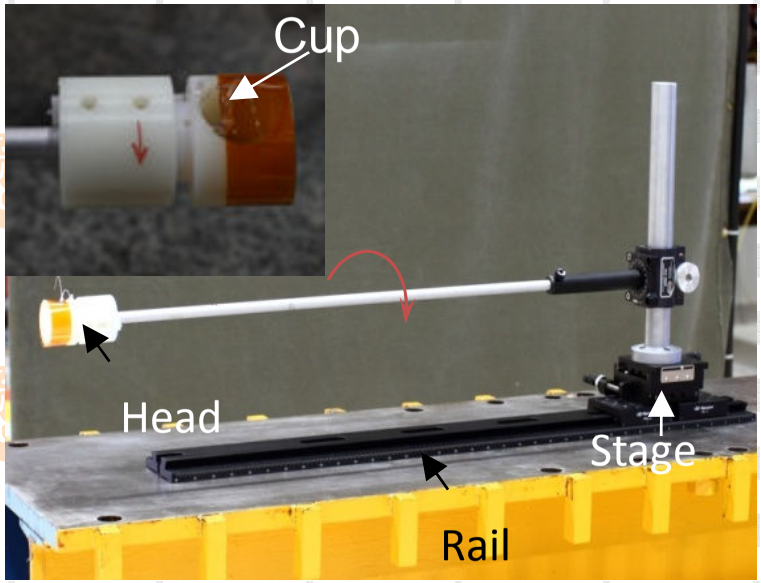
- To reveal the 3-D profile of pits.
- To provide topology information to establish the mechanism of local quench at the flaws.
- To assess surface preparation effectiveness by extracting surface roughness

Technical challenges

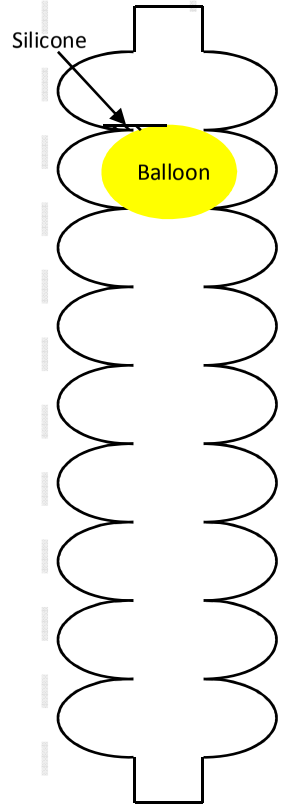
- Resolution *(to resolve features~ >100μm in diameter; >10μm in depth)*.
- Pouring silicone in and peeling it out from deep 9-cell cavity.
- No degradation for RF performance.

Technical approaching



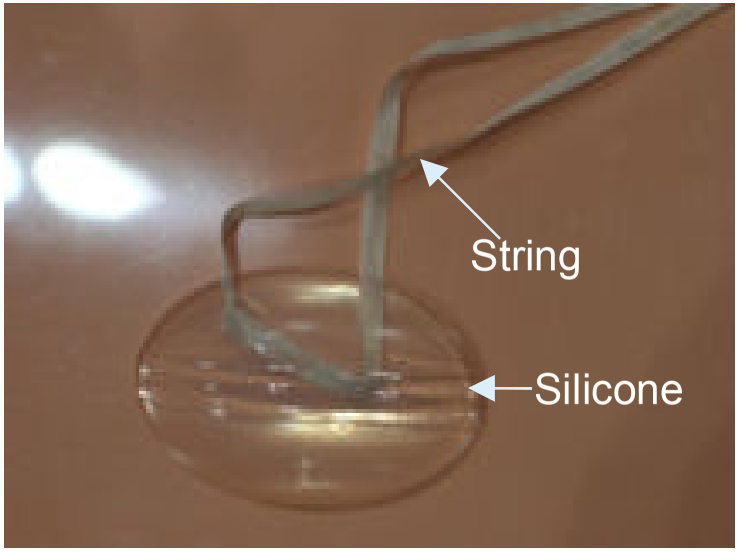


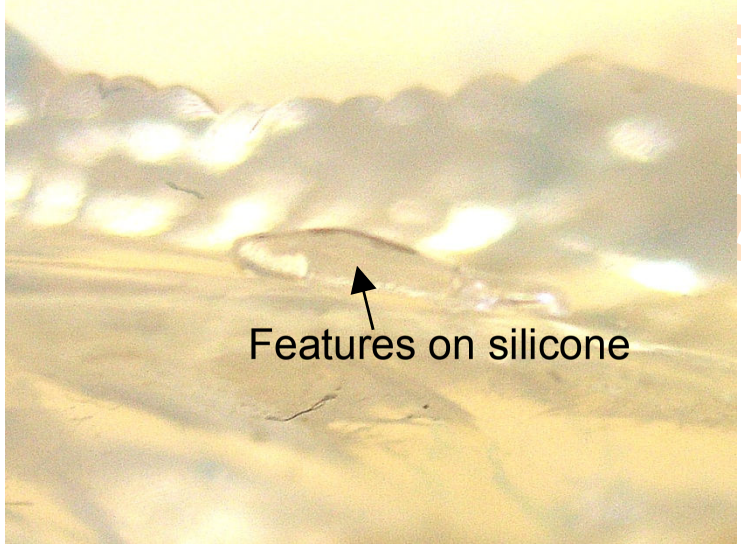
Molding equator region

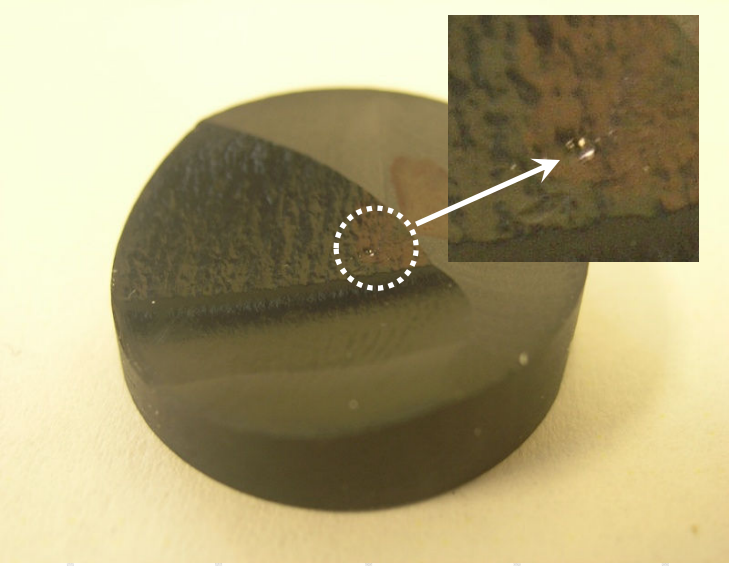


Molding iris region

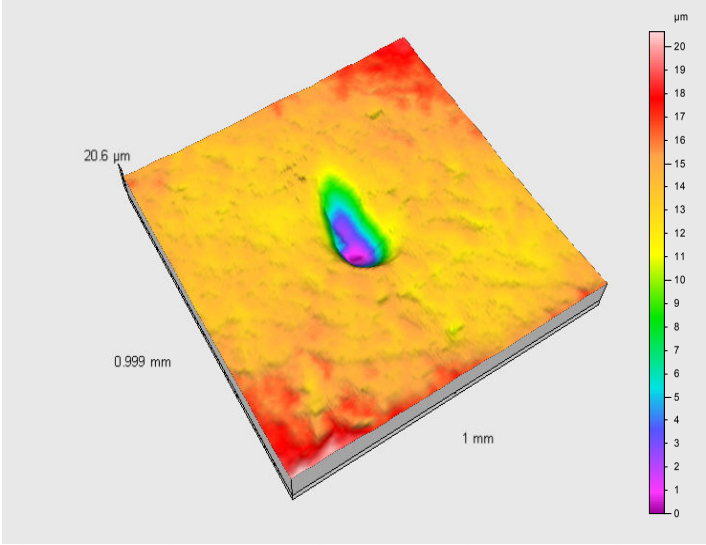
Technical approaching





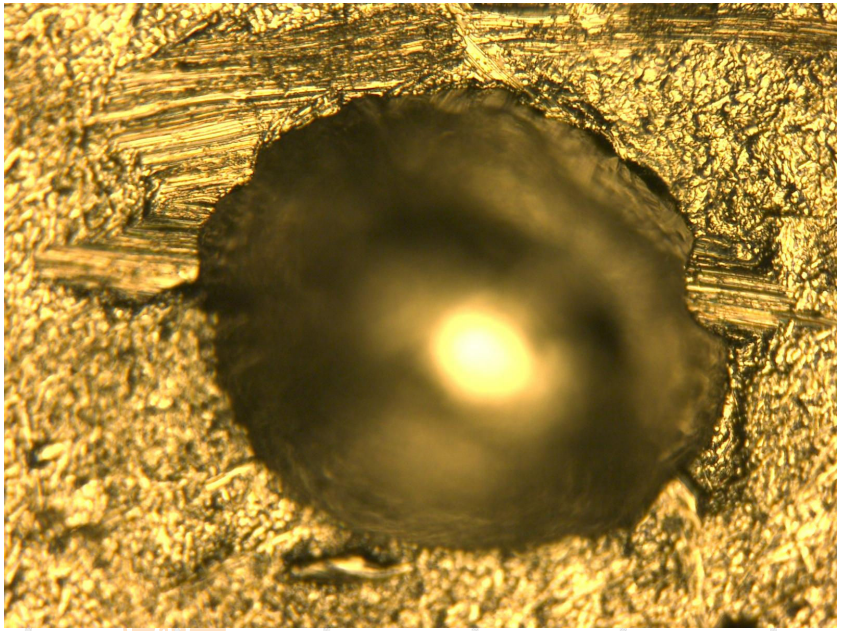


Epoxy after casting on silicone

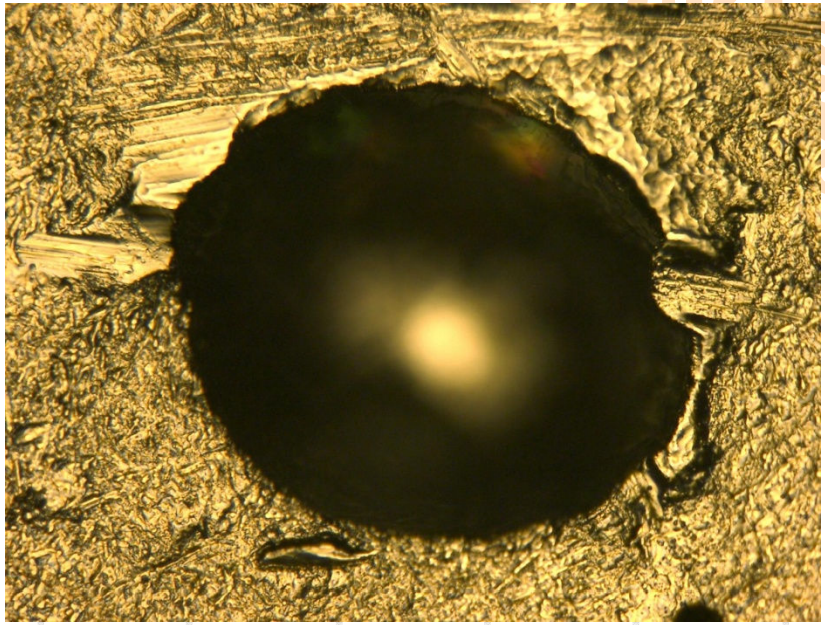


Feature's 3D shape after profilometry scanning

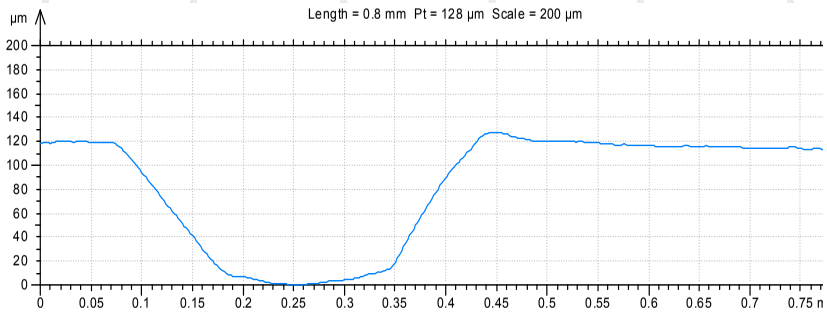
Resolution: 1 micron !



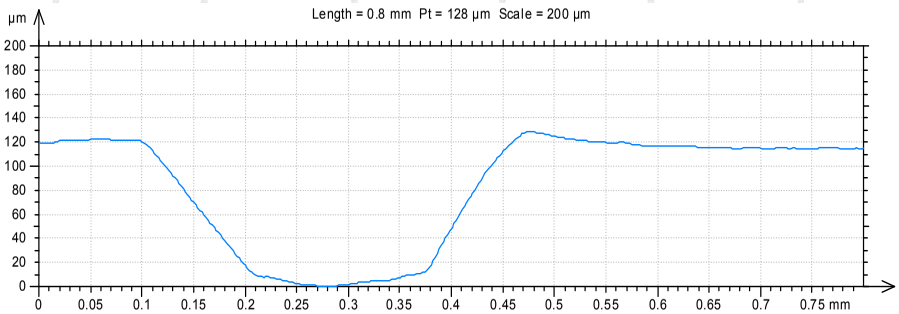
A man-made pit



Pit replica



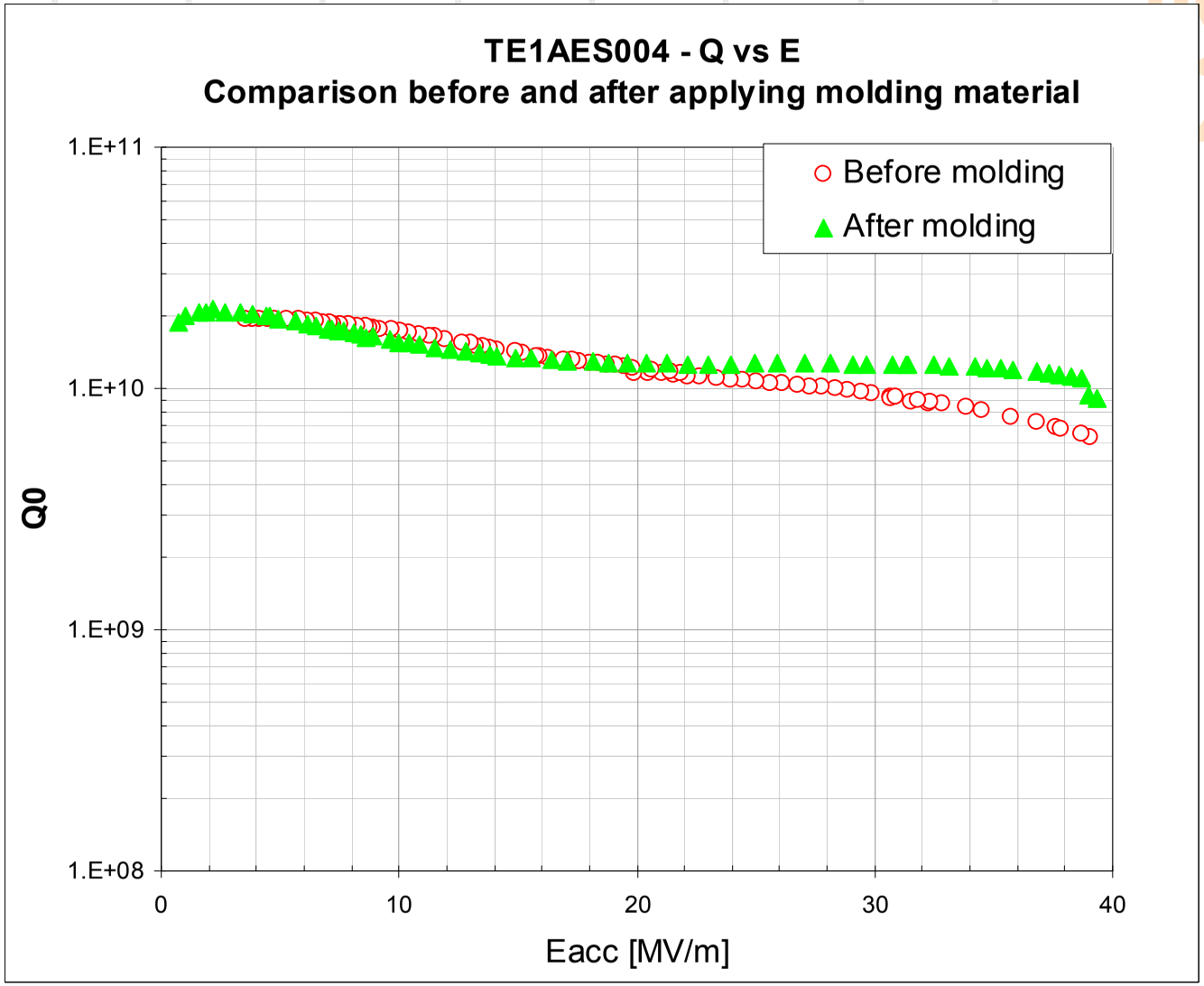
profile of a pit on the Nb coupon



profile of pit's replica

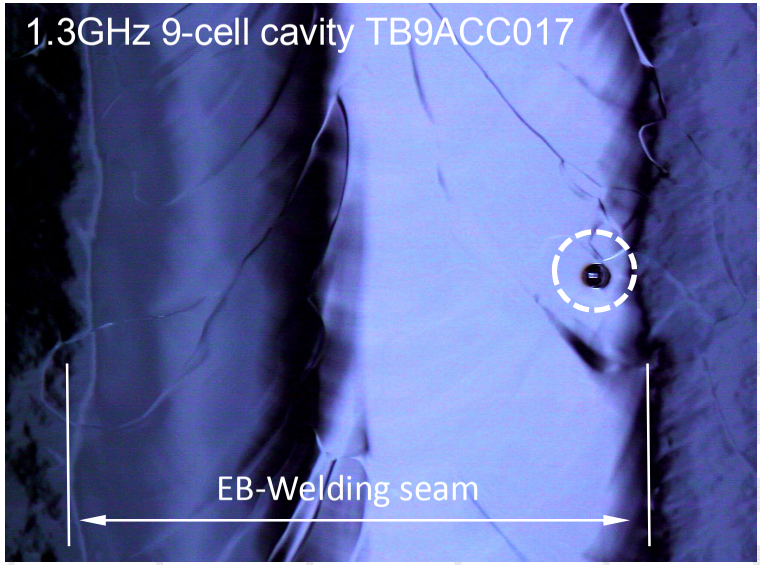
125µm deep, 300µm in diameter

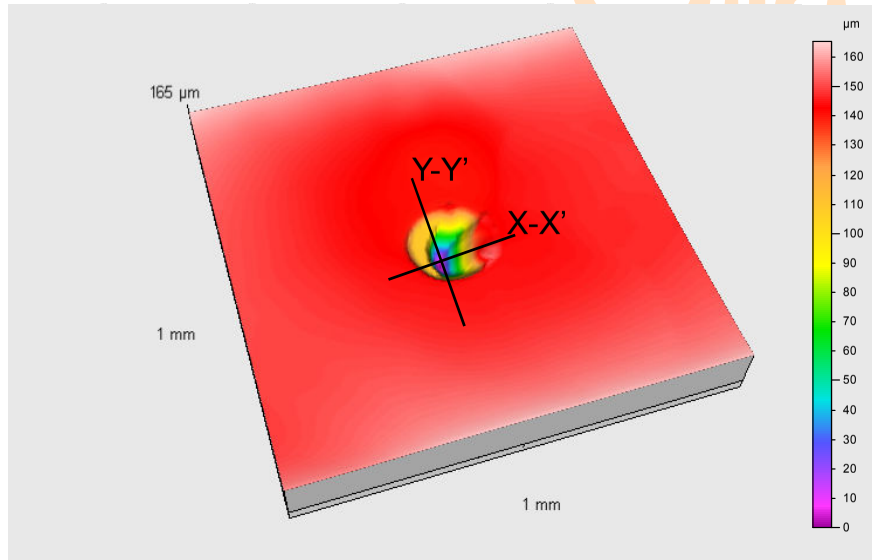
No degradation of cavity RF performance

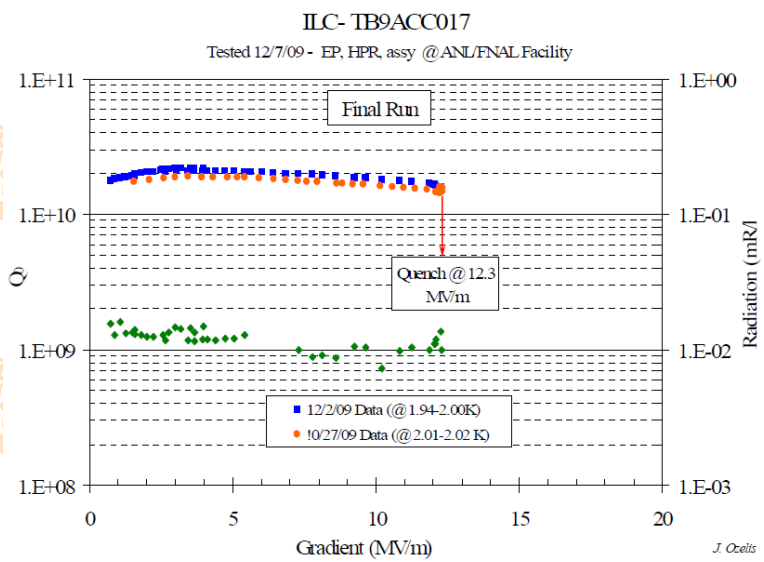


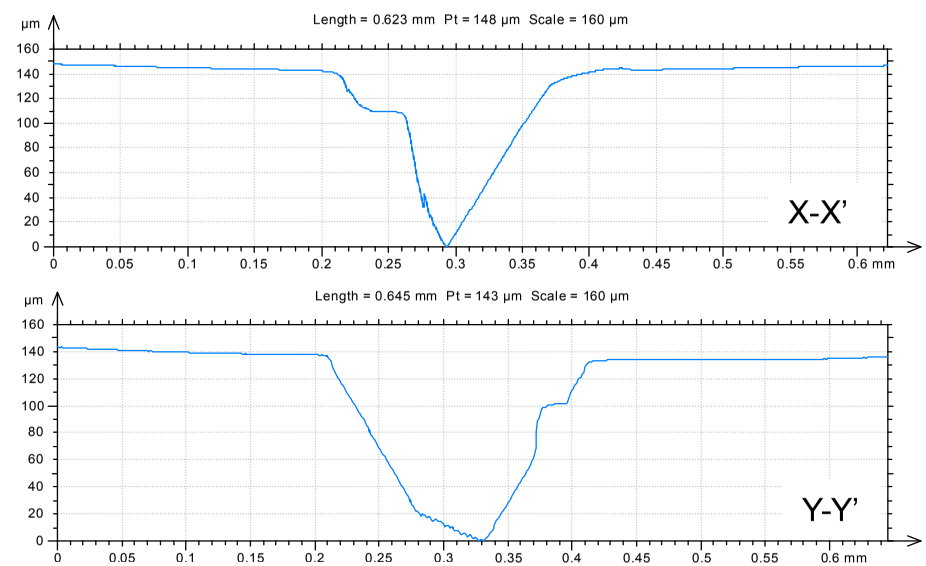
No light EP, just HPR after molding

Surface defect limits cavity performance at low field



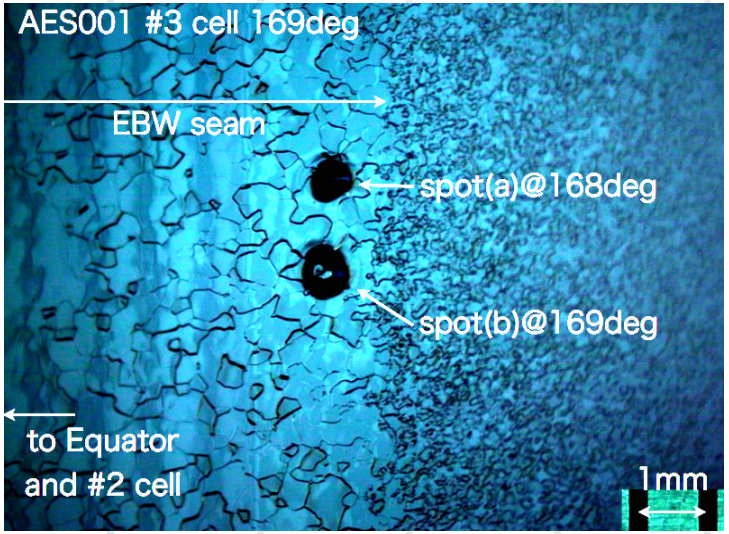


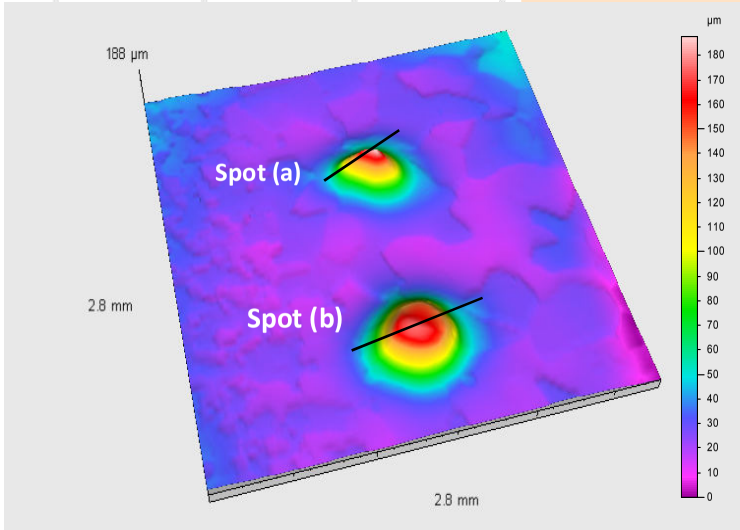


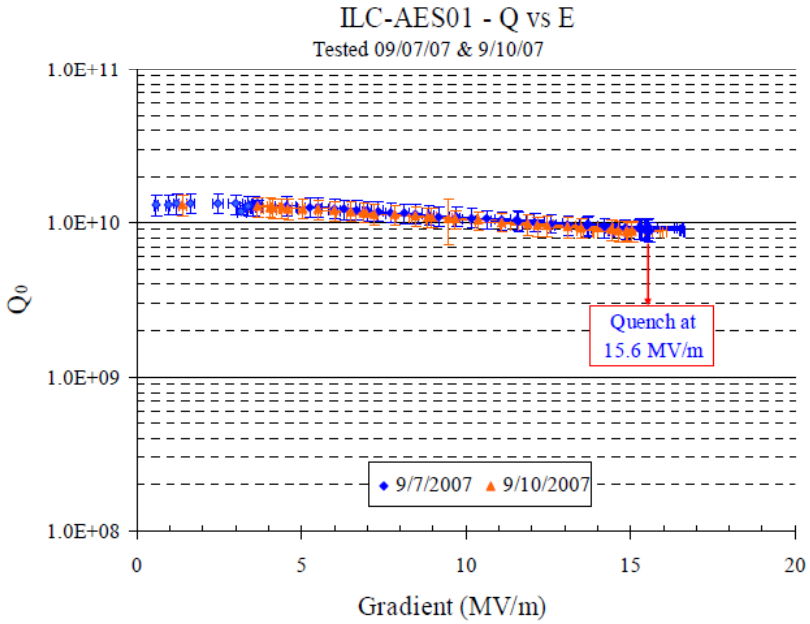


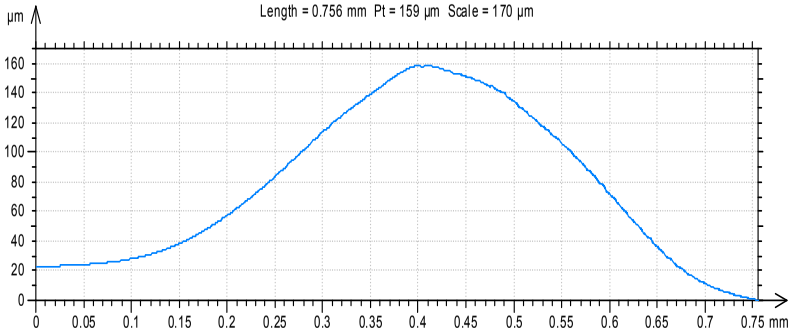
TB9ACC017 quenched at 12.3MV/m,
Pit was found at Cell #4 equator 180 deg region (quench location),
the pit is 150 µm deep and 200 µm wide on the top.

Surface defect limits cavity performance at low field

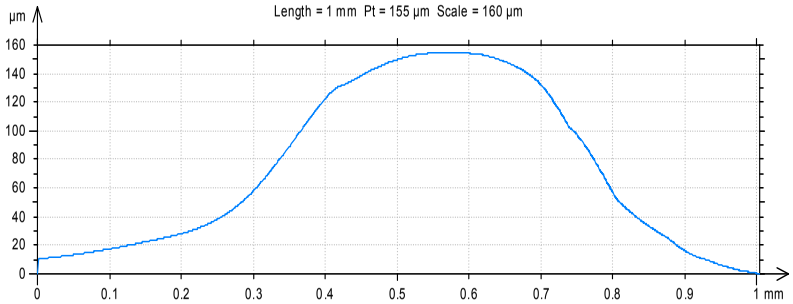








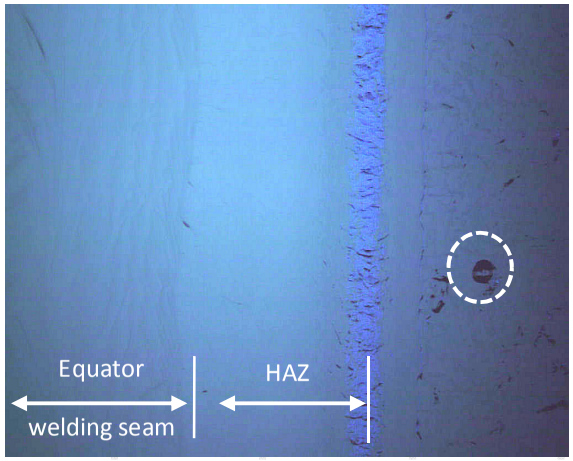
Spot A height 160µm, diameter 700µm on bottom



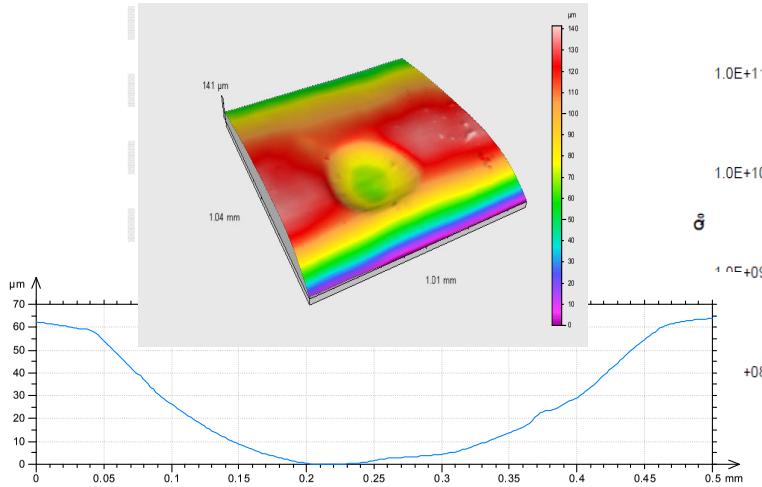
Spot B height 155µm, diameter 1000µm on bottom

AES001 quenched at 15.6~21MV/m,
Twin peaks were found at Cell #3 equator 169 deg region (quench location).

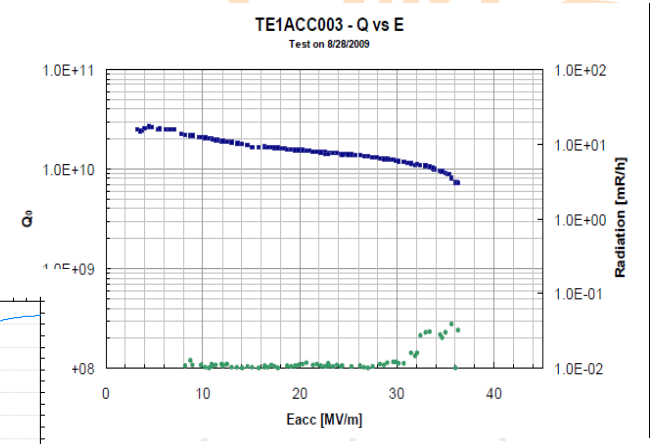
Surface defect limits cavity performance at high field
Single-cell cavity TE1ACC003 & TE1AES004



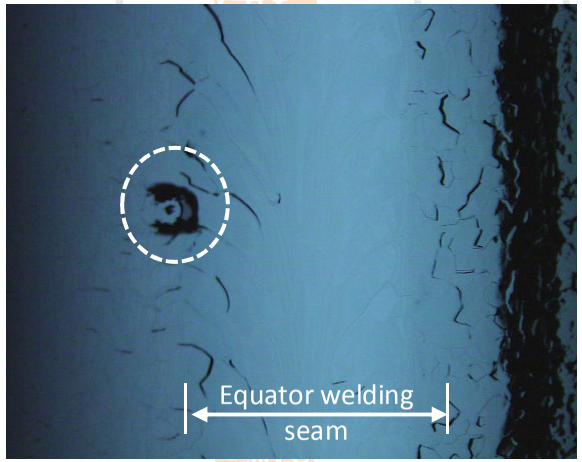
TE1ACC003



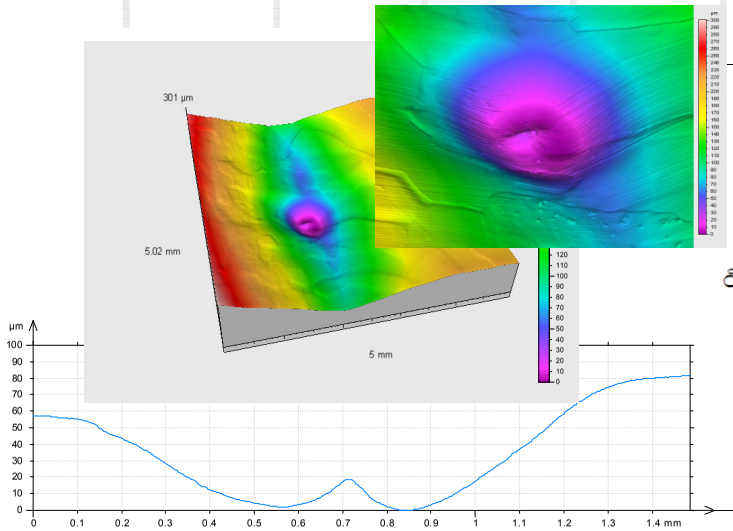
Diameter: 400µm,Depth: 60µm



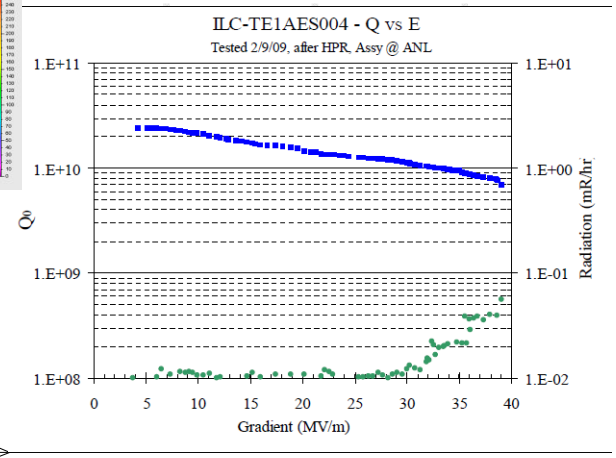
36MV/m quenched
at pit region



TE1AES004

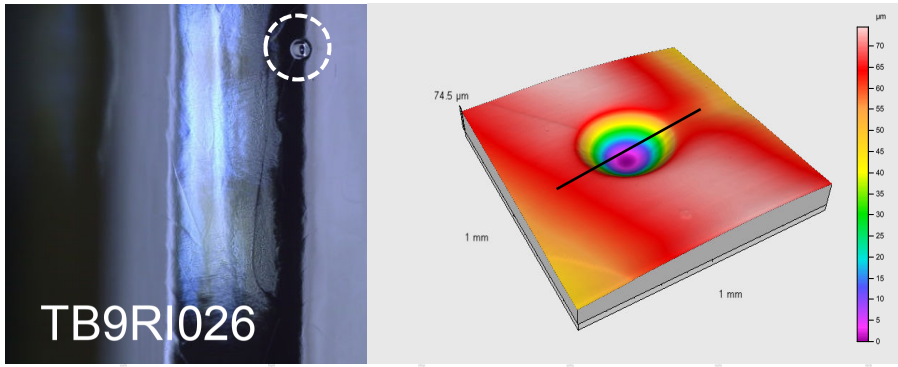


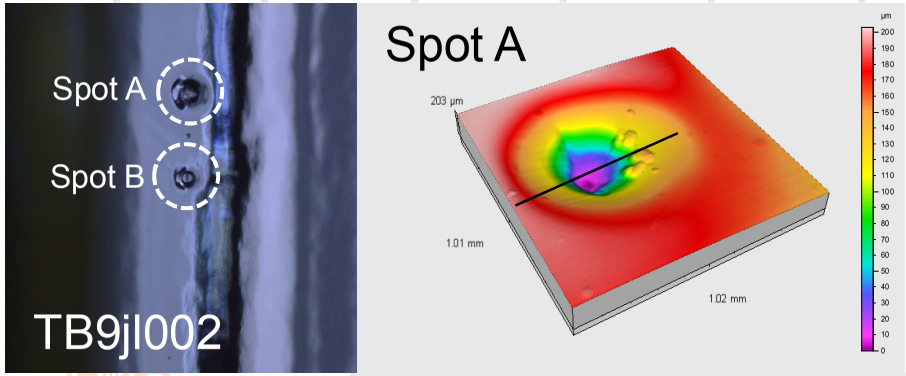
Diameter: 1300µm, Depth: 70µm
A 15µm high tiny bump in the center.

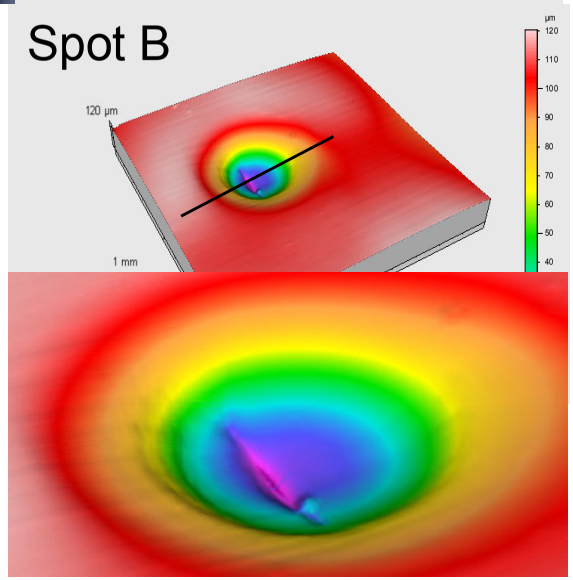


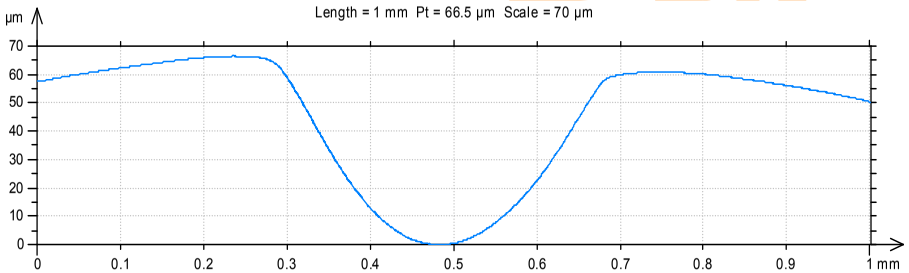
39MV/m quenched
at pit region

Reveal pits profile on iris region

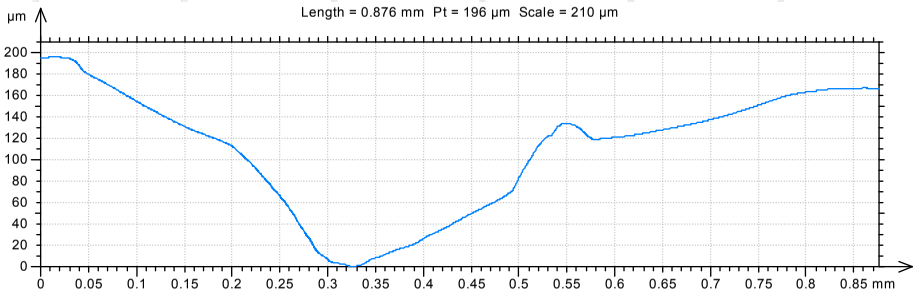




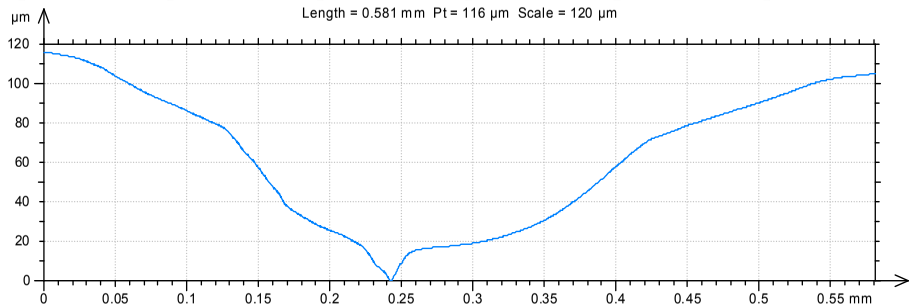




Diameter: 400µm,Depth: 70µm

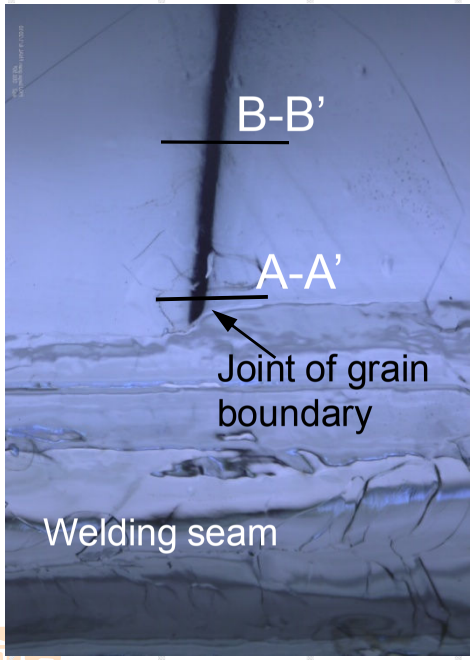


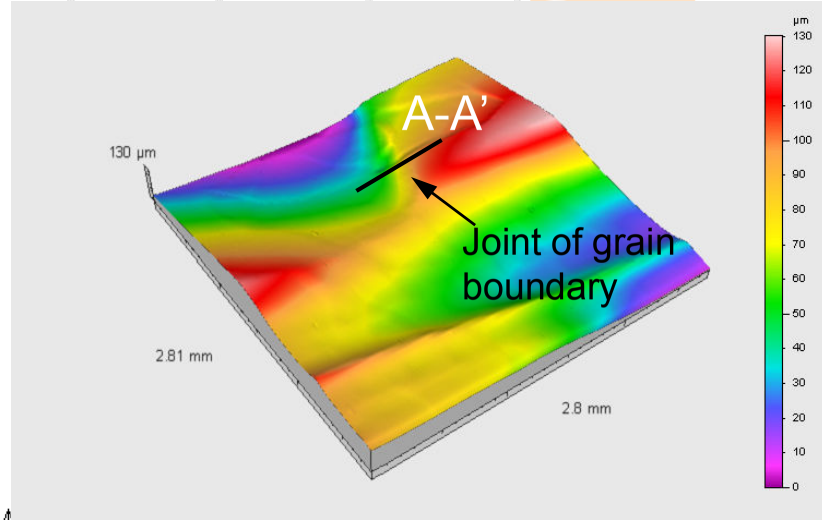
Spot A: Diameter: 800µm,Depth: 180µm

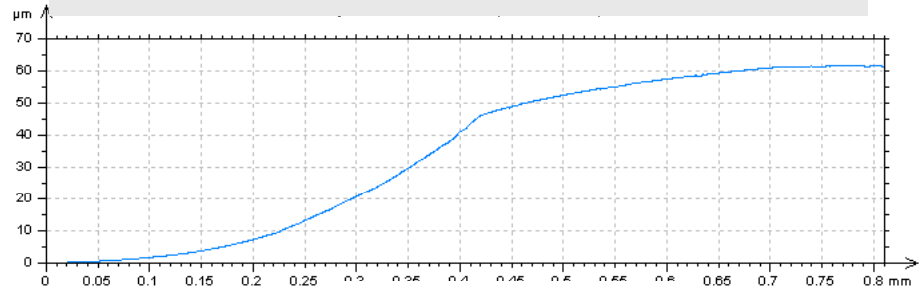


Spot B: Diameter: 550µm,Depth: 110µm
A 20µm deep crevice in center

The measurement of grain boundary step







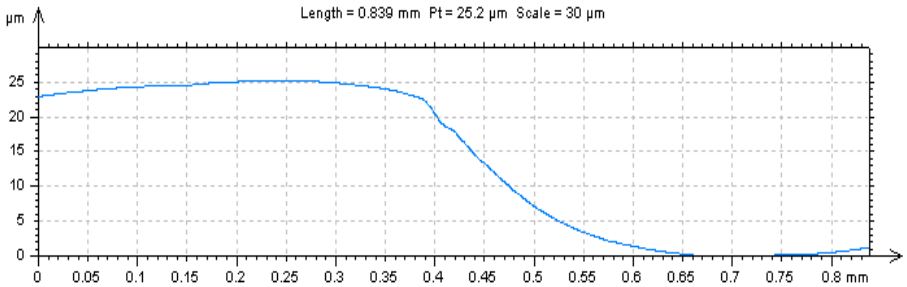
Profile on A-A'

The image depicts the joint of grain boundary.

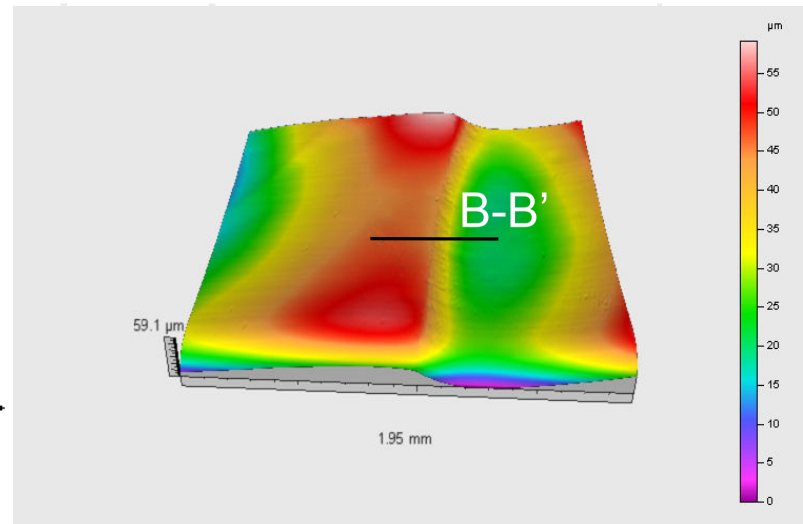
Eacc reached 43MV/m

The height of step on A-A': 60µm

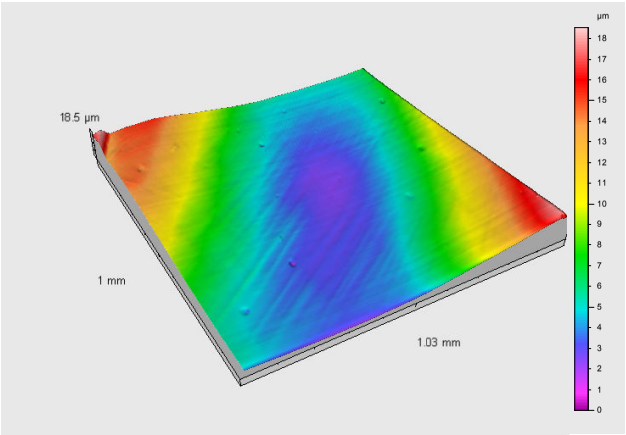
The height of step on B-B': 25µm



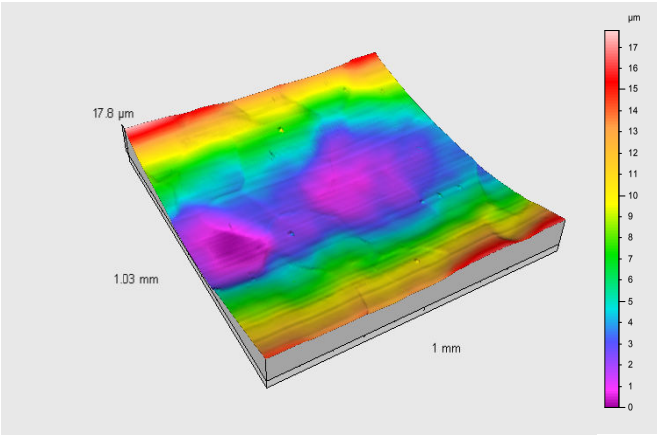
Profile on B-B'



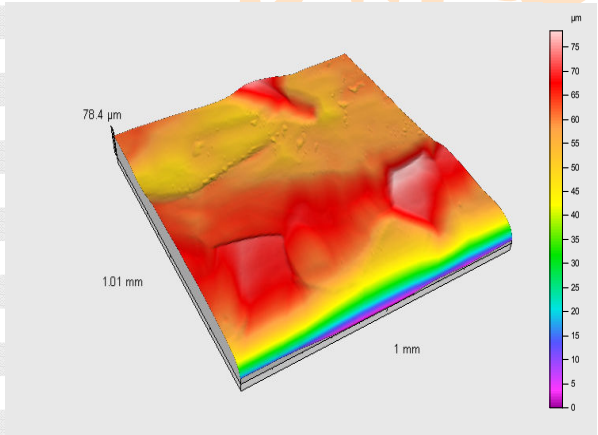
Roughness comparison between large grain BCP'd cavity and fine grain EP'd and BCP'd cavity.



Large grain BCP'd cavity
E_{acc} reached 43MV/m!



Fine grain EP'd cavity
E_{acc} reached 40MV/m!



Fine grain BCP'd cavity
E_{acc} reached 26MV/m!

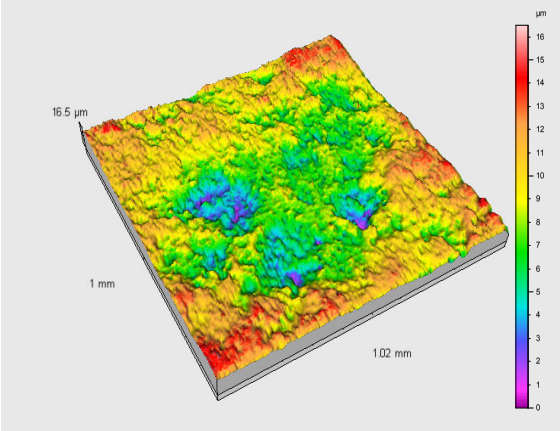
	Large grain BCP'd cavity	Fine grain EP'd cavity	Fine grain BCP'd cavity
Ra (µm)	0.0516	0.053	0.257
Rz (µm)	0.283	0.275	1.21
Rq (µm)	0.0648	0.0665	0.333

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i|$$

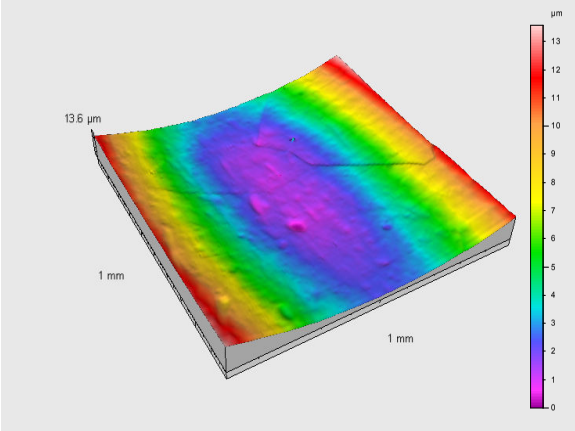
$$R_{zJIS} = \frac{1}{5}\sum_{i=1}^{5} R_{pi} - R_{vi}$$

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$$

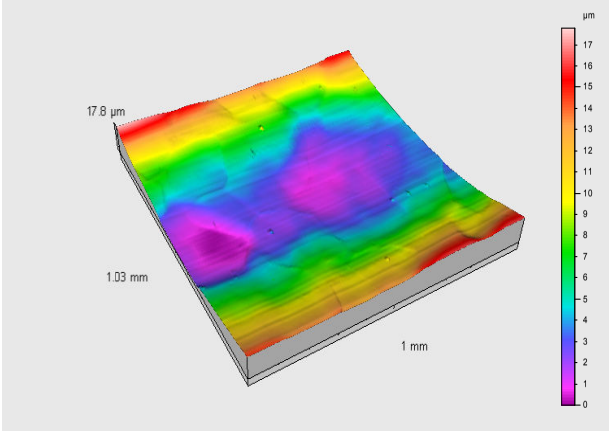
Tracking surface roughness from each preparation step



After 50µm tumbling surface



After final tumbling surface



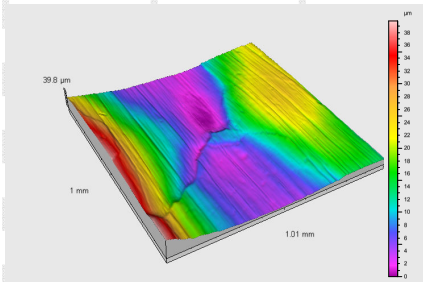
Fine grain EP'd cavity

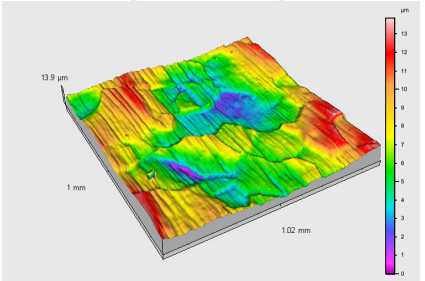
	After 50µm tumbling	After final tumbling	Fine grain EP'd cavity
Ra (µm)	0.512	0.0527	0.053
Rz (µm)	2.68	0.253	0.275
Rq (µm)	0.633	0.0669	0.0665

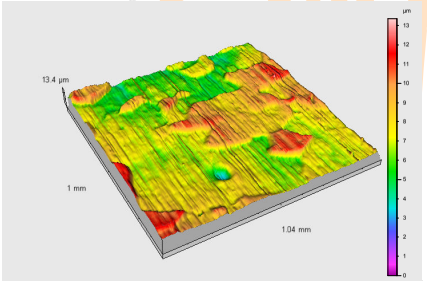
Cavity surface roughness

Welding seam | HAZ | Outside HAZ

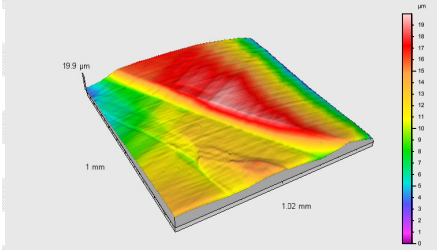
Brand new
TE1PAV001

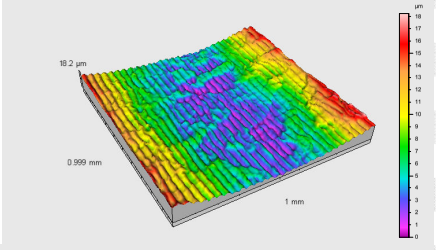


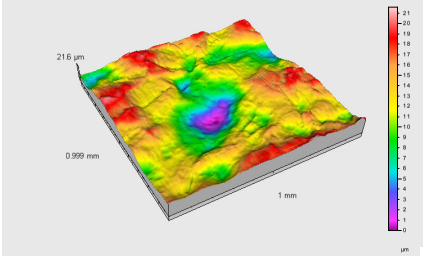




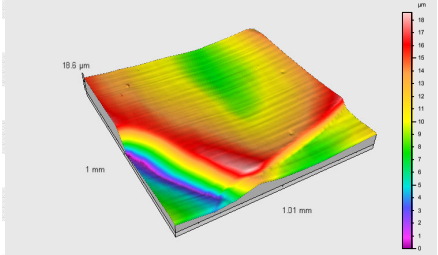
Brand new
TE1ACC006

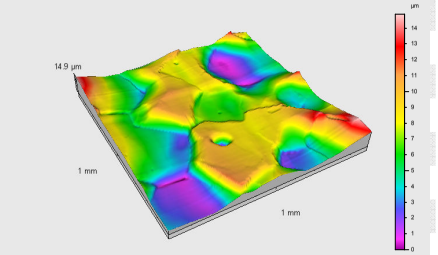


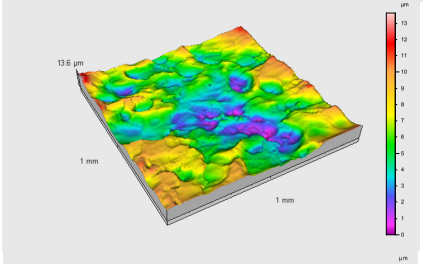




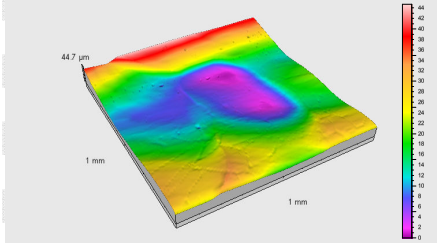
PKU single crystal
BCP'd cavity

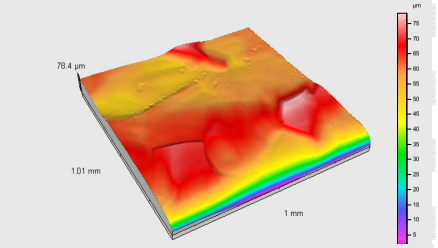


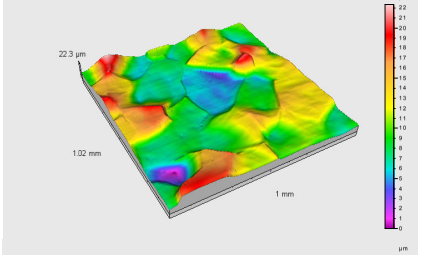




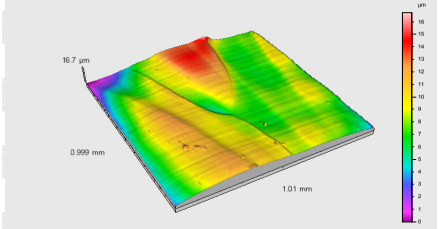
BCP'd 70µm
NR-6

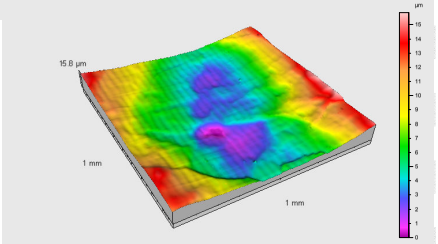


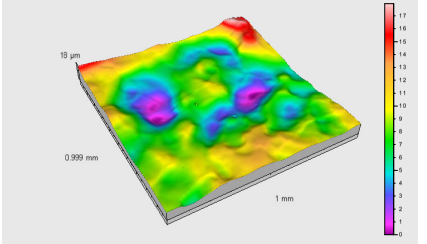




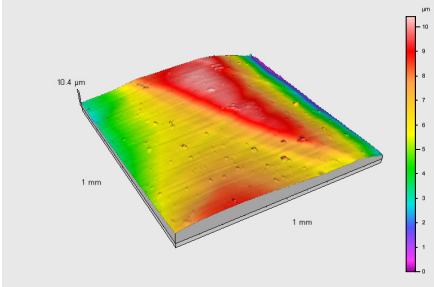
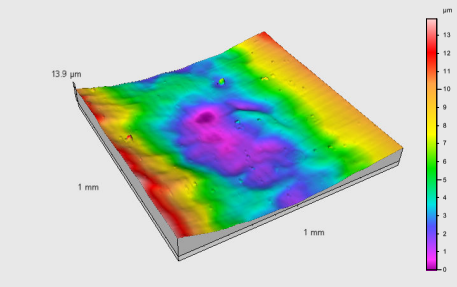
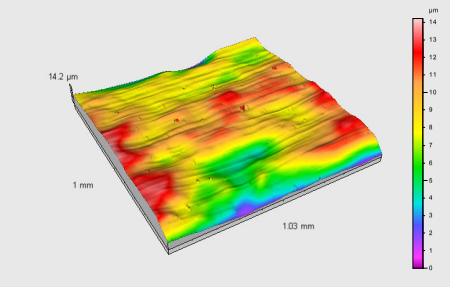
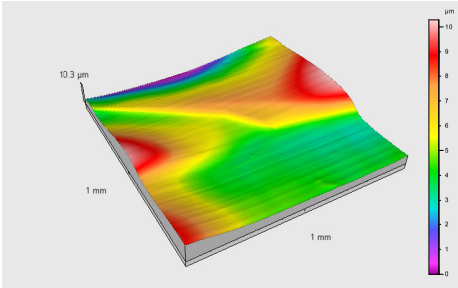
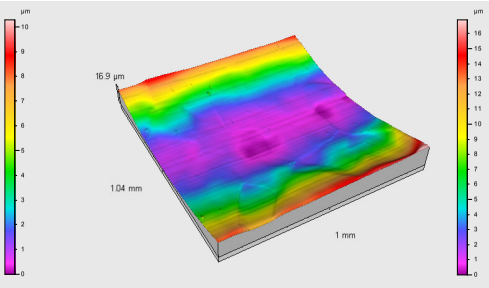
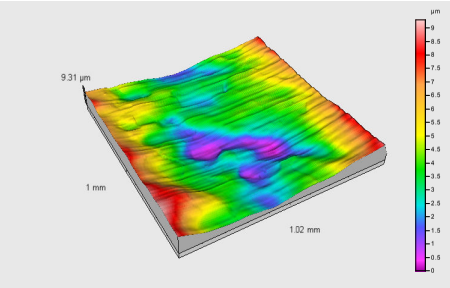
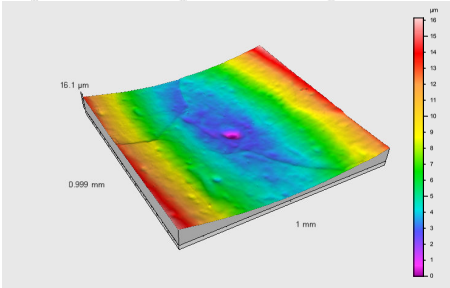
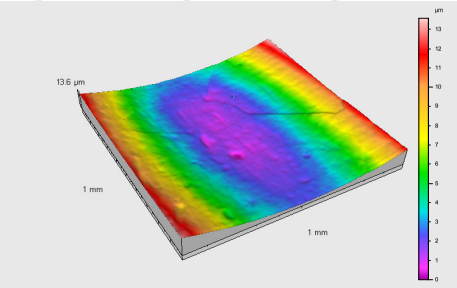
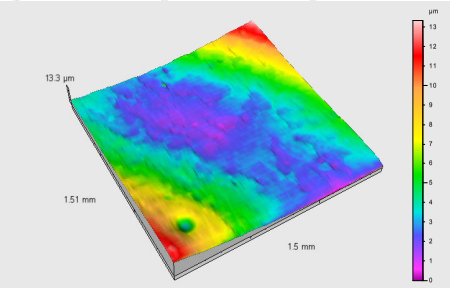
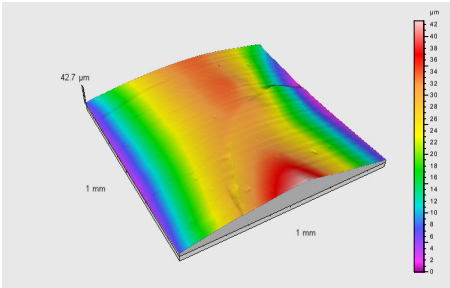
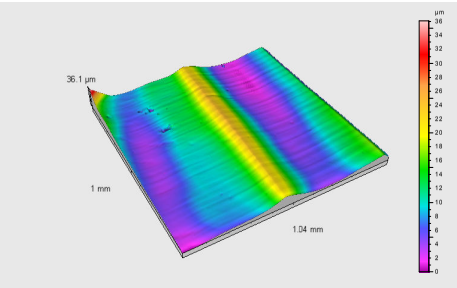
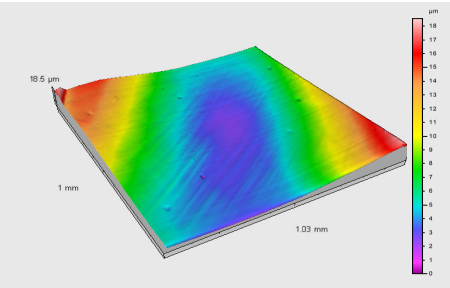
EP'd 40µm
TE1ACC005





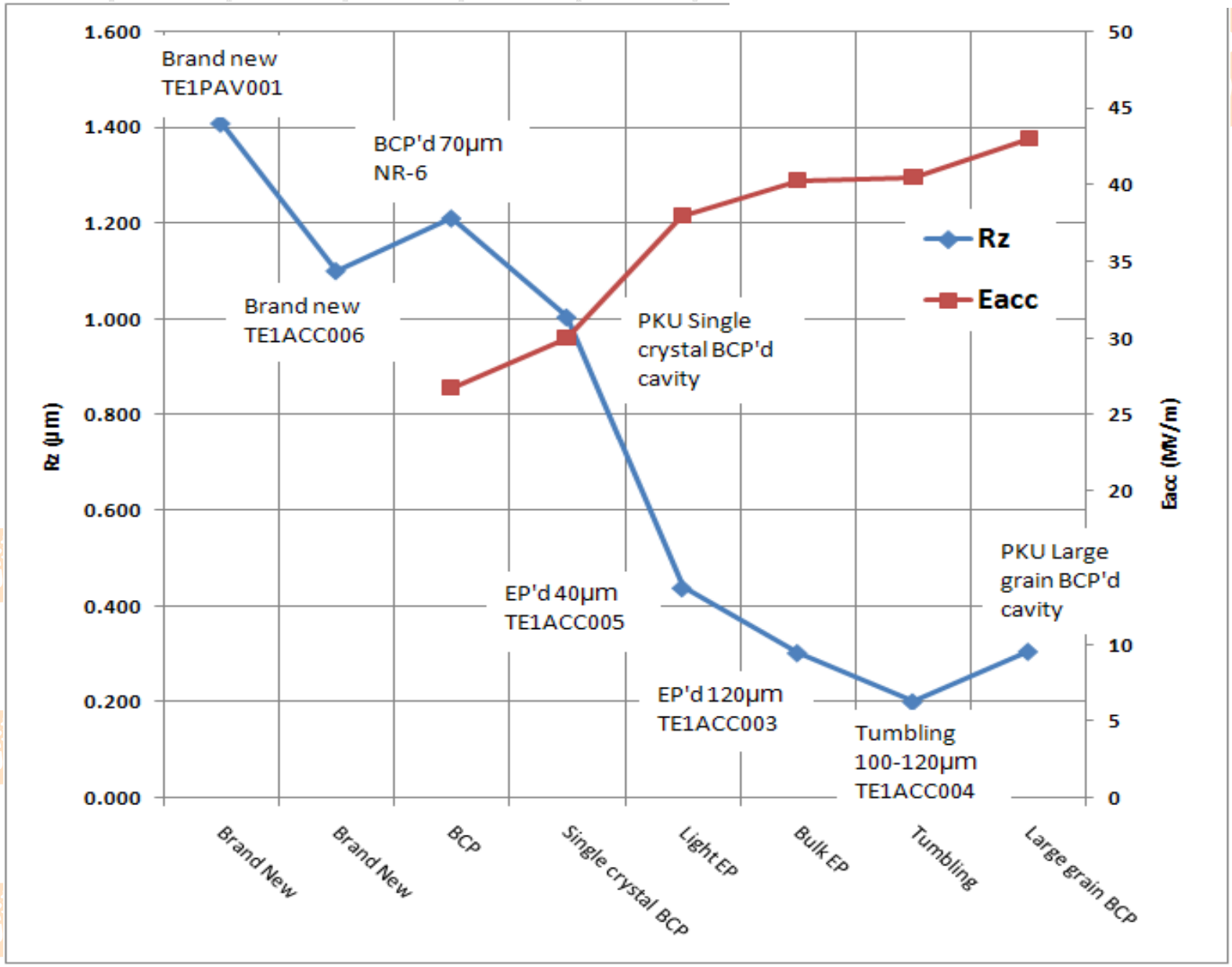


Cavity surface roughness

	Welding seam	HAZ	Outside HAZ
EP'd 120µm TE1ACC003			
EP'd 150µm TB9ACC017			
Tumbling 100-120µm TE1ACC004			
PKU Large grain BCP'd cavity			

Surface roughness vs. Gradient

TESLA shape ,quenched but no obvious defects



Summary of surface replica technique

- Surface replica technique has high resolution *(the substructure inside pits),* and no degradation of cavity RF performance.
- Revealed pit's 3-D shape from 9-cell cavity equator and iris region.
- Extracted surface roughness from six major categories of SRF cavities, representing the modern SRF cavity technologies.
- Topology information enables us to estimate the field enhancement factor, and to assess the effectiveness of surface preparation.

Laser re-melting technique at FNAL

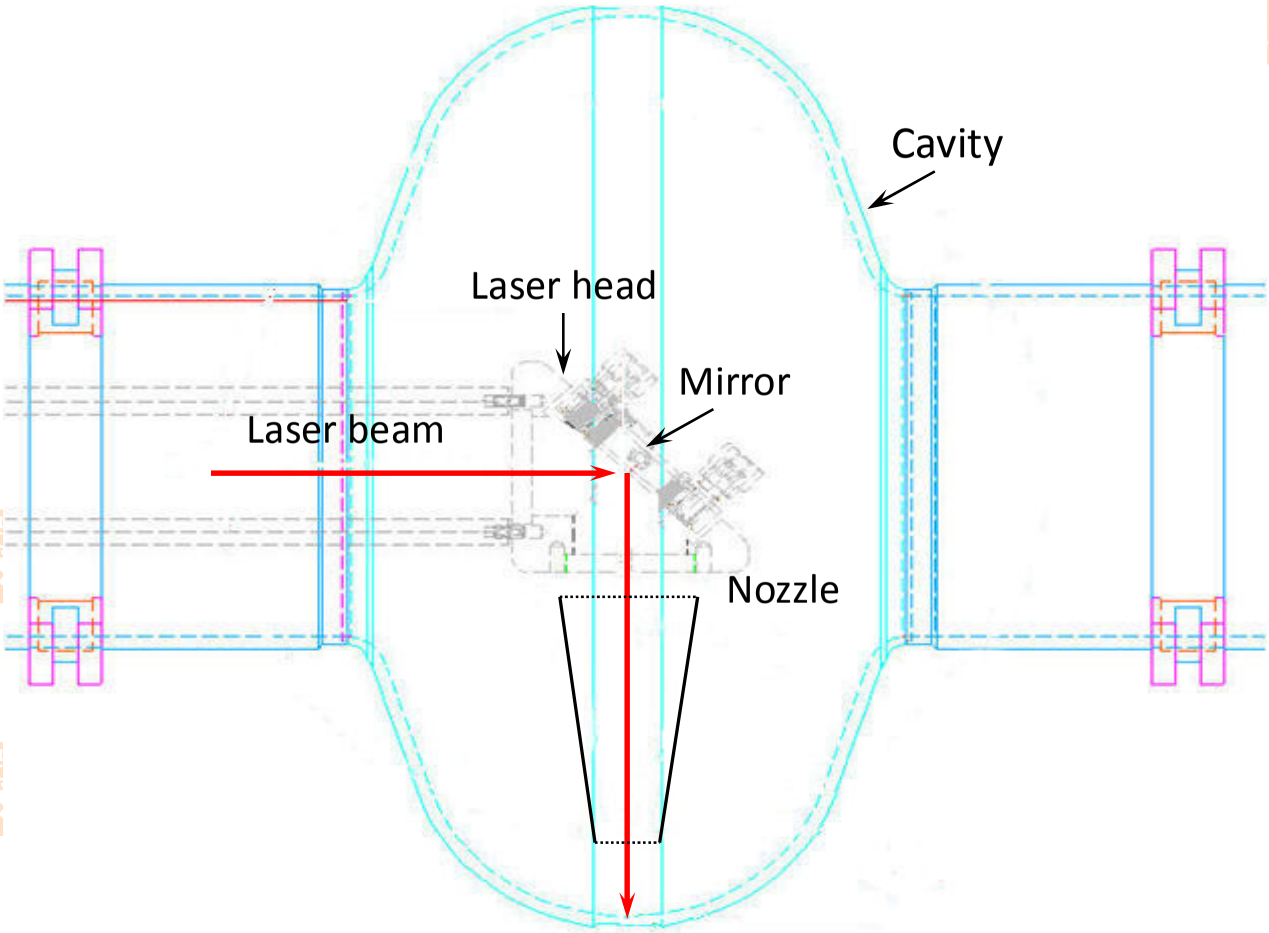
Motivation

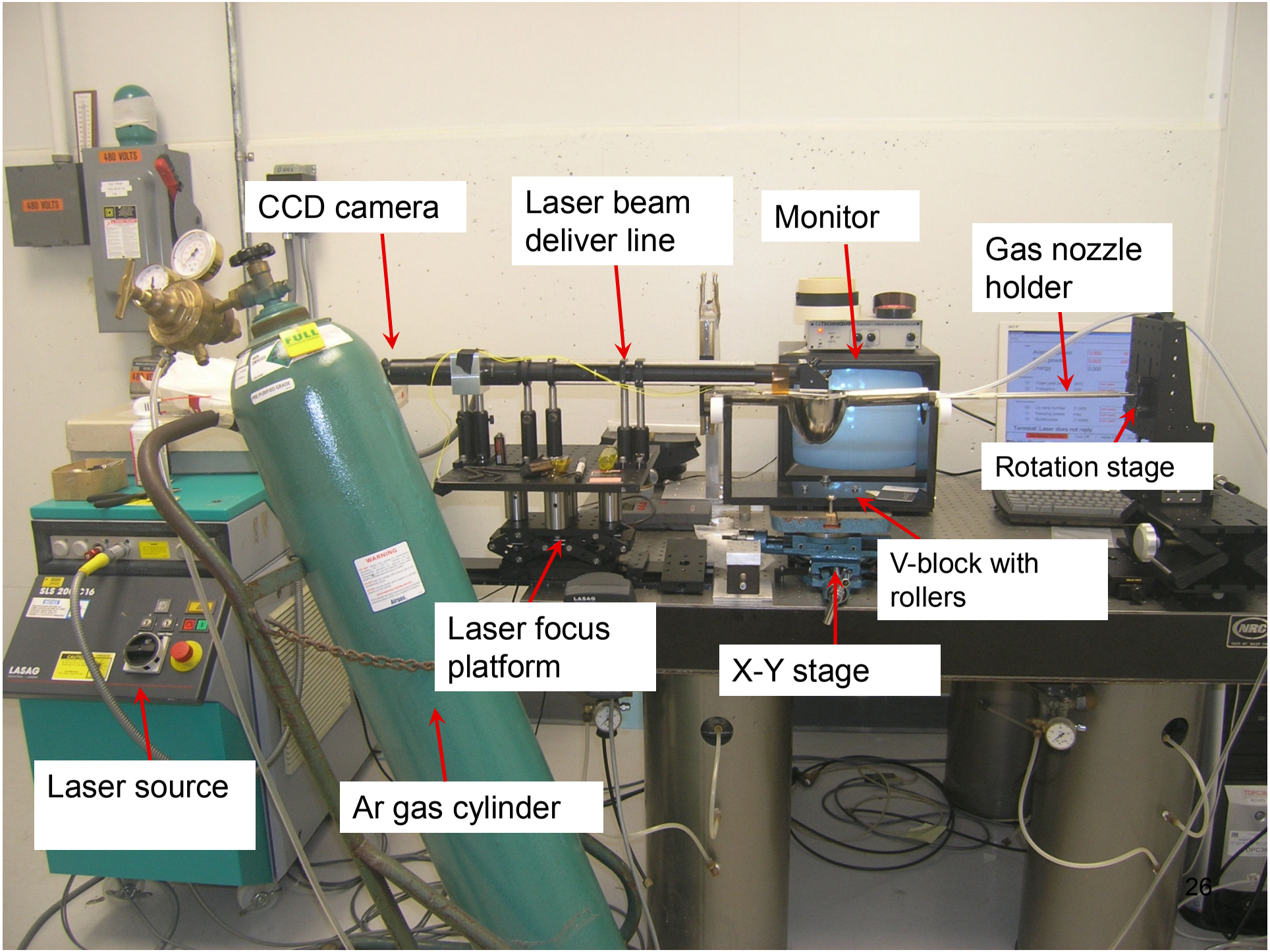
- Remove surface defects limiting cavity gradient below 20MV/m and improve gradient > 35MV/m.

Technical challenges

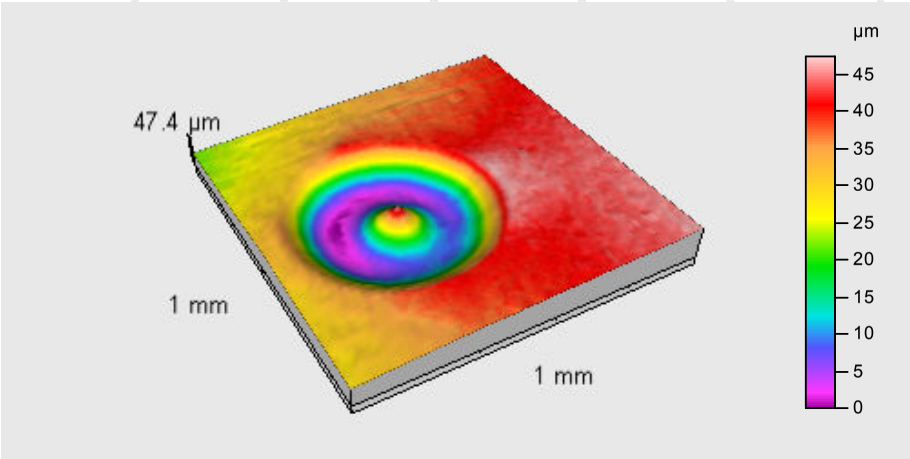
- Laser spot should be very smooth and flat.
- Focus Laser beam on pit accurately. (Pit ~ 100μm)
- High resolution camera and sheet lighting are needed for tracking pit.
- Molten region should be protected by pure Ar gas.

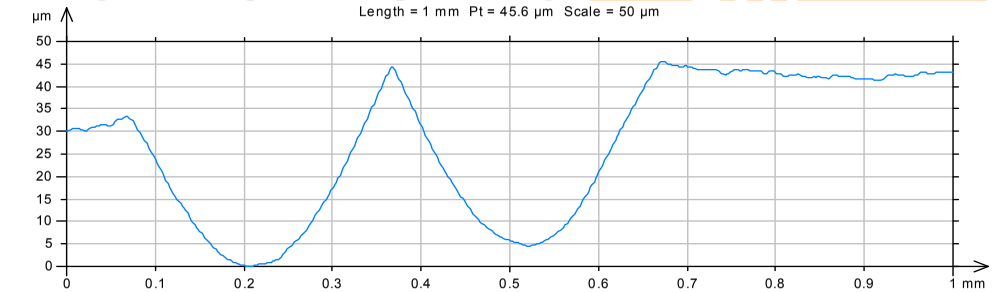
Laser re-melting system for single-cell cavity

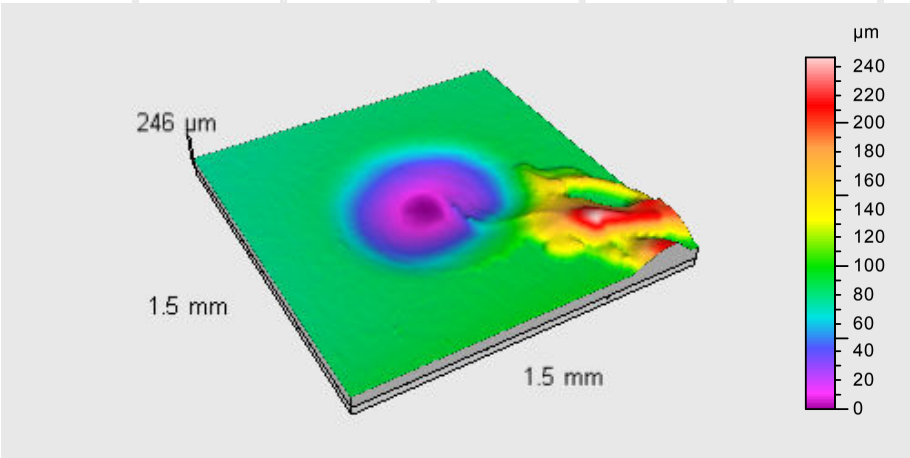


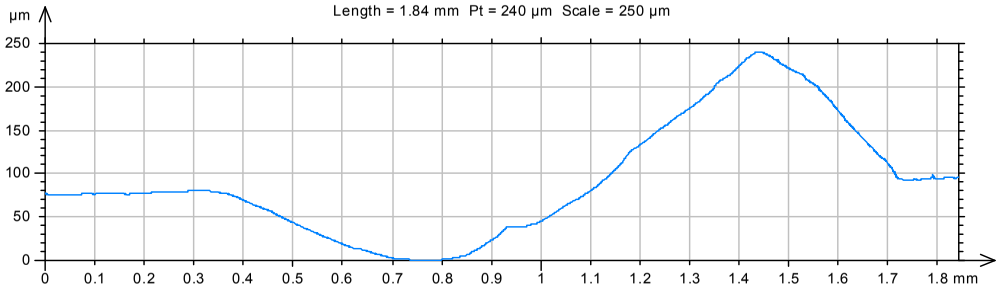

CCD camera
Laser beam deliver line
Monitor
Gas nozzle holder
Rotation stage
V-block with rollers
X-Y stage
Laser focus platform
Laser source
Ar gas cylinder

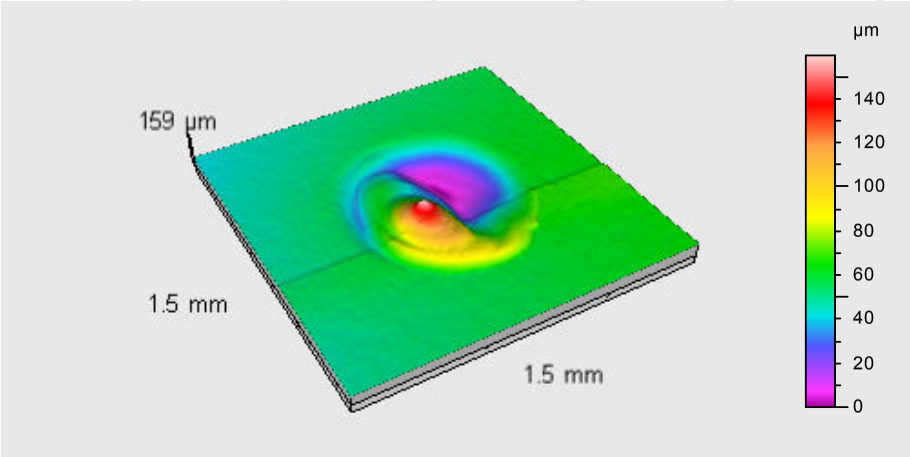
Laser parameters and gas pressure optimize via Nb coupon

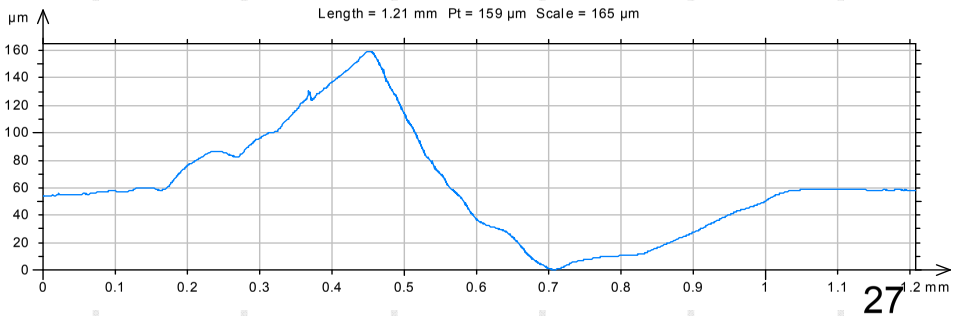




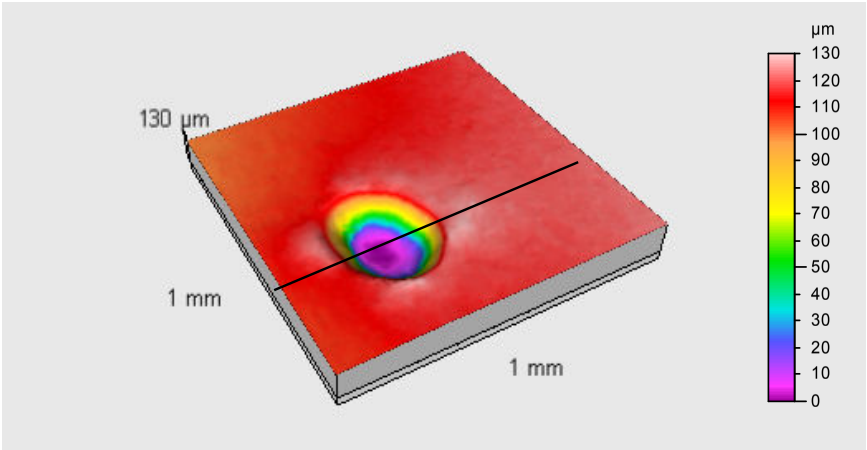


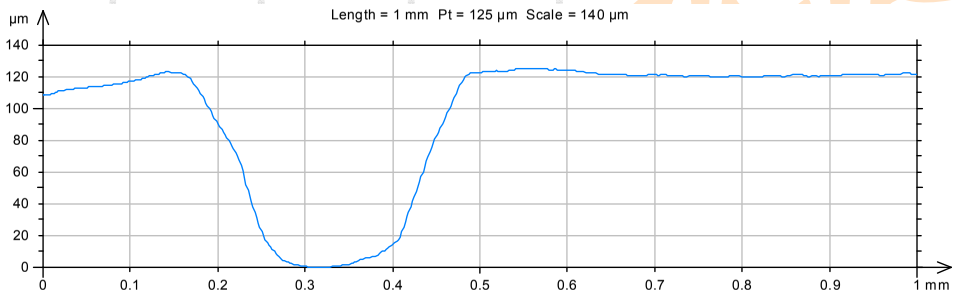




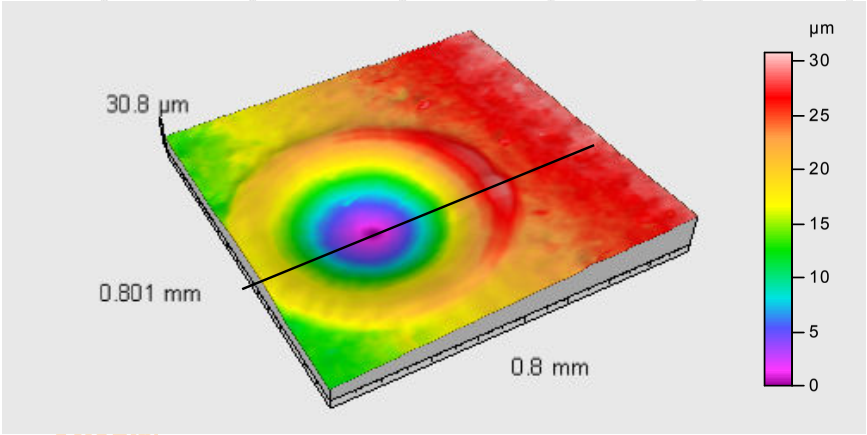


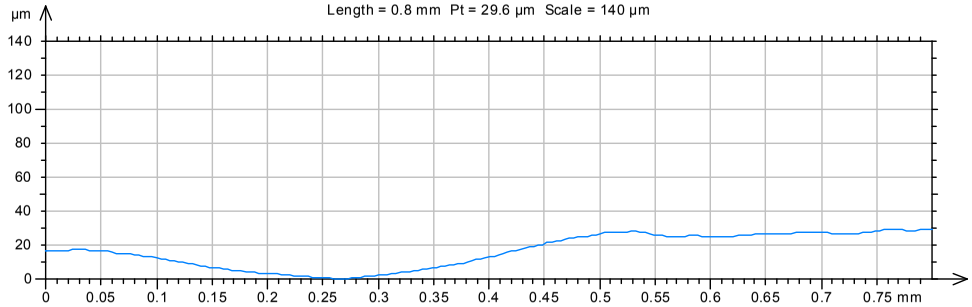
Profile Comparison before and after laser re-melting





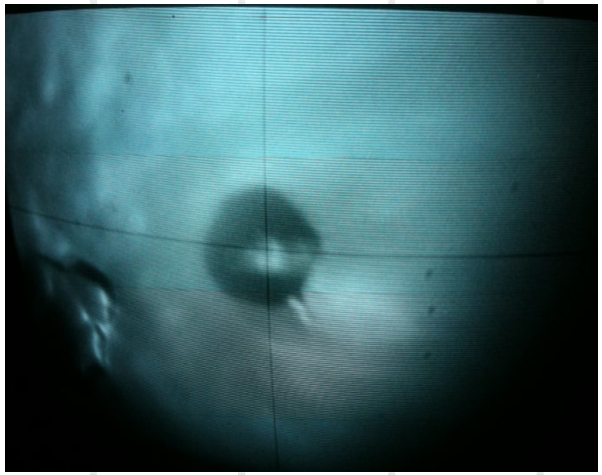
Man-made pit

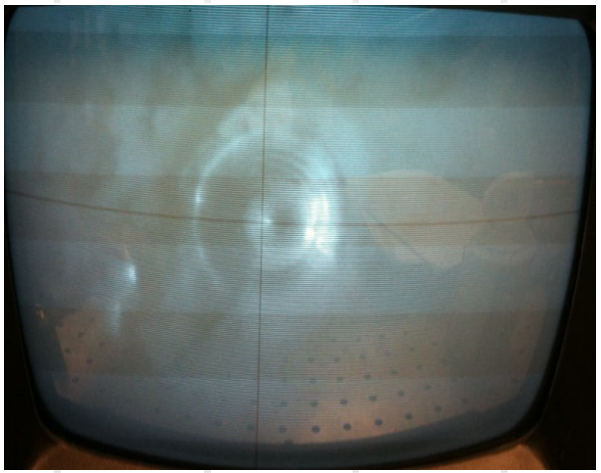


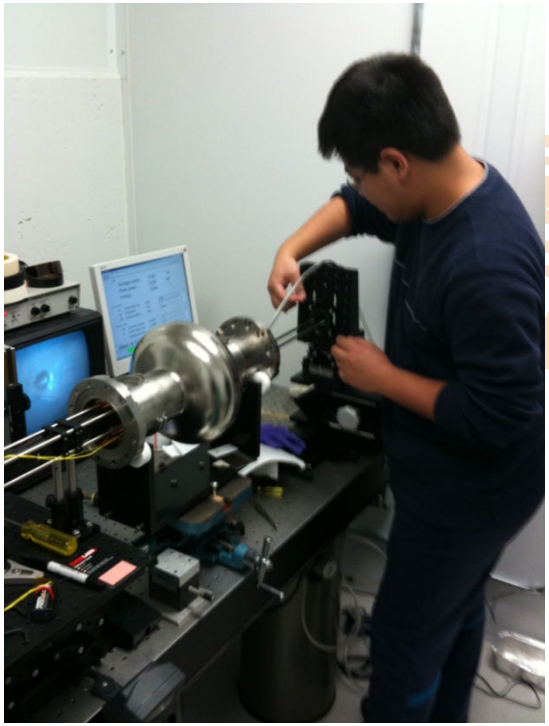


After re-melting the pit profile changed from 120µm deep to 30µm flat

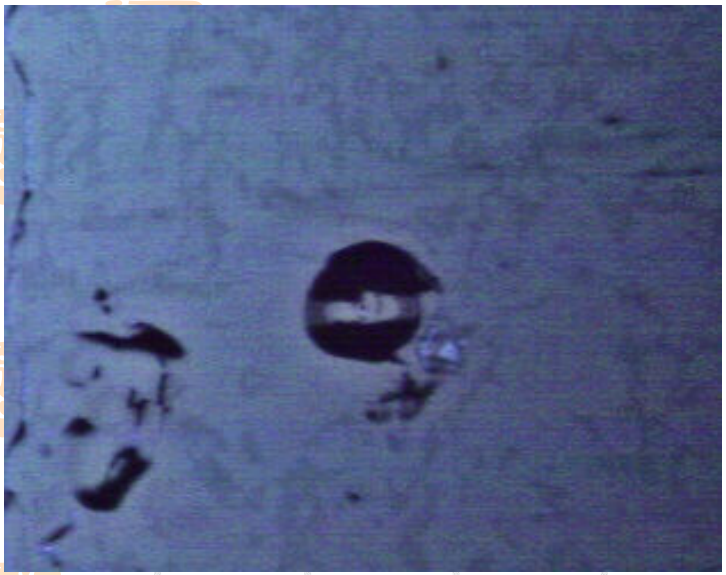
Laser processing of 1.3GHz single-cell cavity TE1ACC003

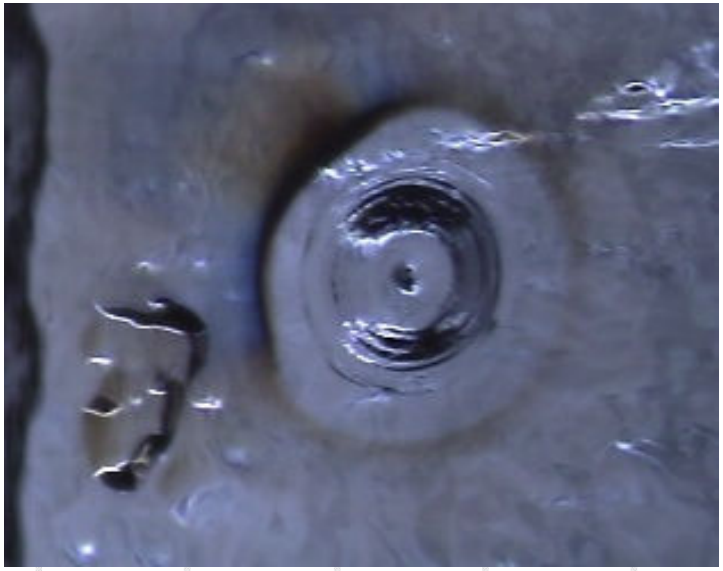






Screenshot of the monitor before and after laser re-melting



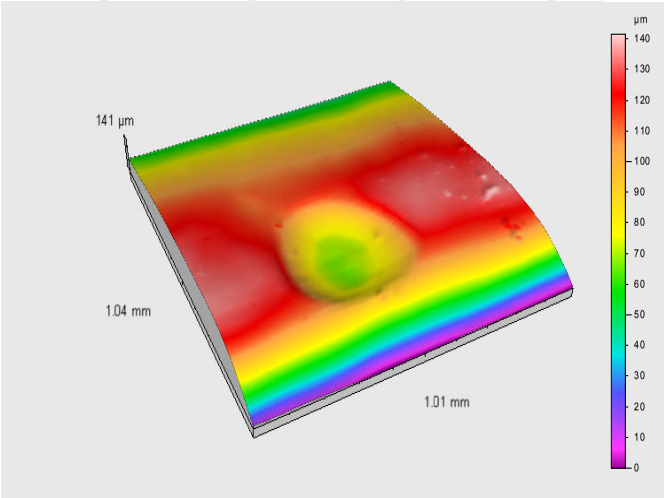


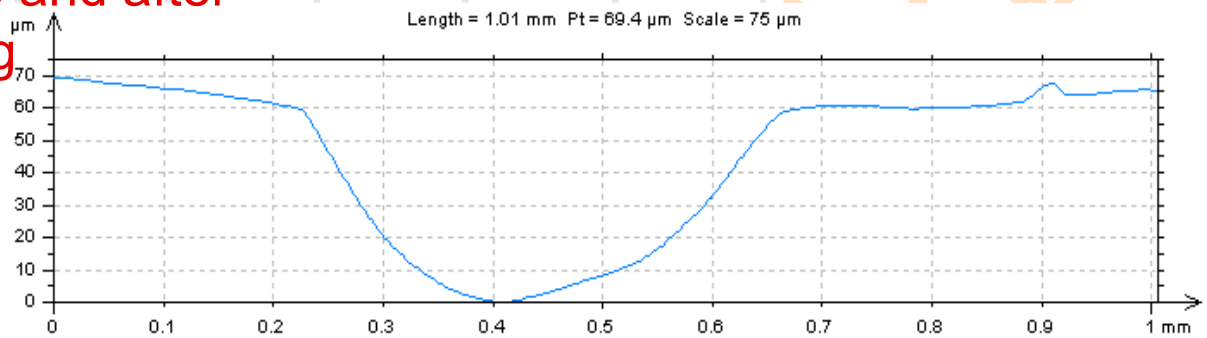
The Pit before re-melting

After re-melting

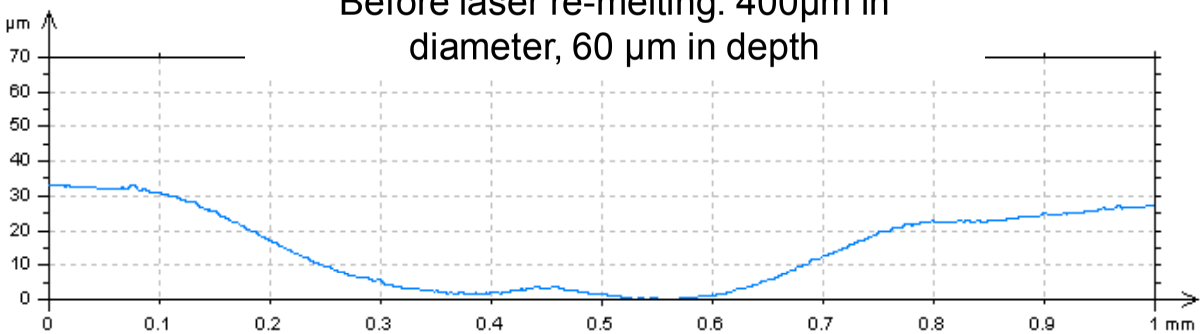
Images was taken from Kyoto Optical Inspection machine

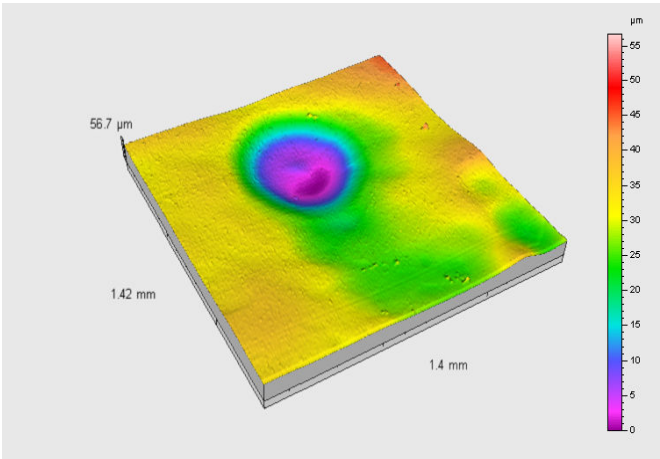
Profile comparison before and after Laser processing



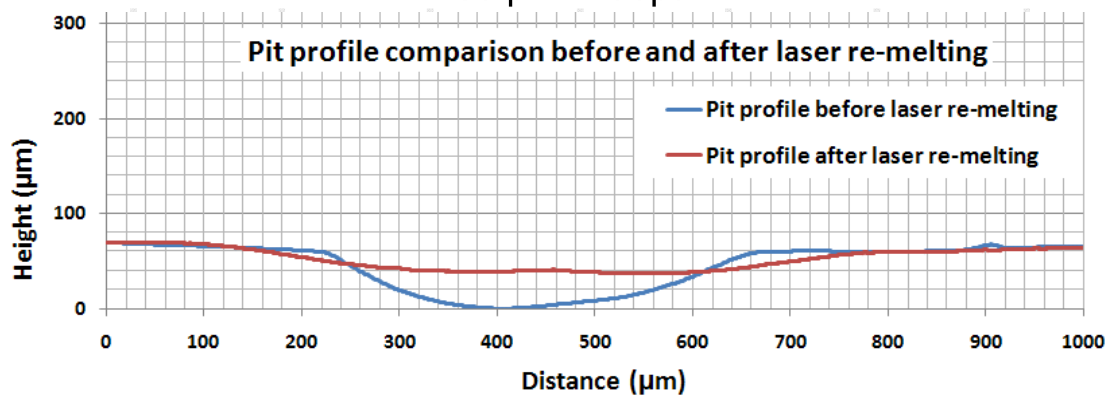


Before laser re-melting: 400µm in diameter, 60 µm in depth



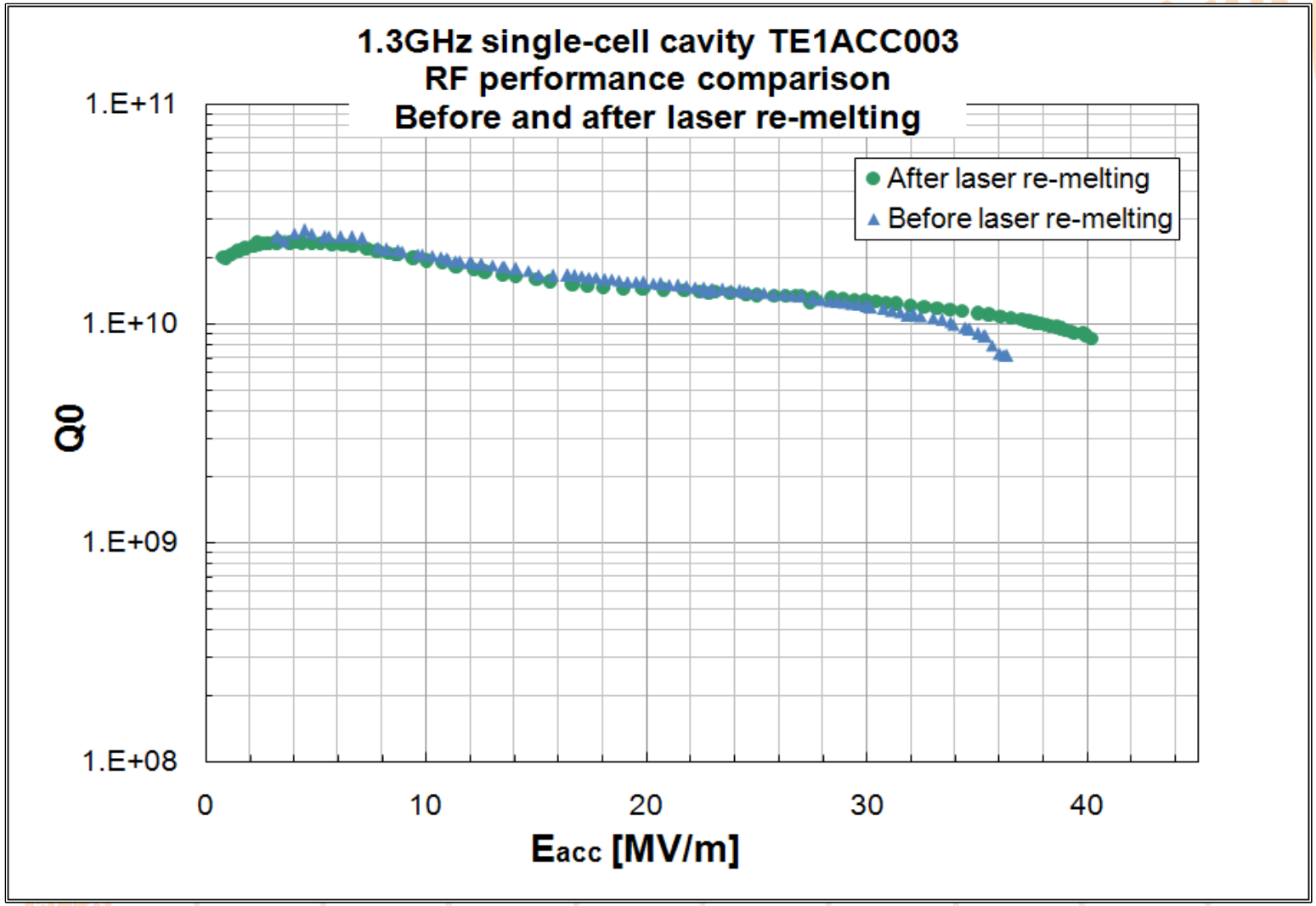


After laser re-melting: 700µm in diameter, 30 µm in depth



The pit profile changed from 60µm deep to 30µm flat after re-melting and 50µm light EP

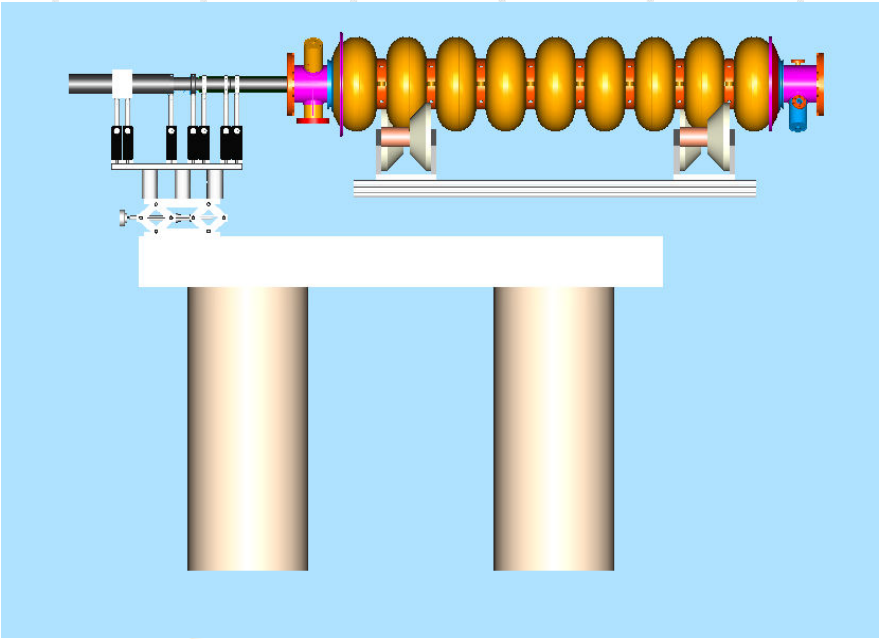
Cavity vertical test results before and after laser processing

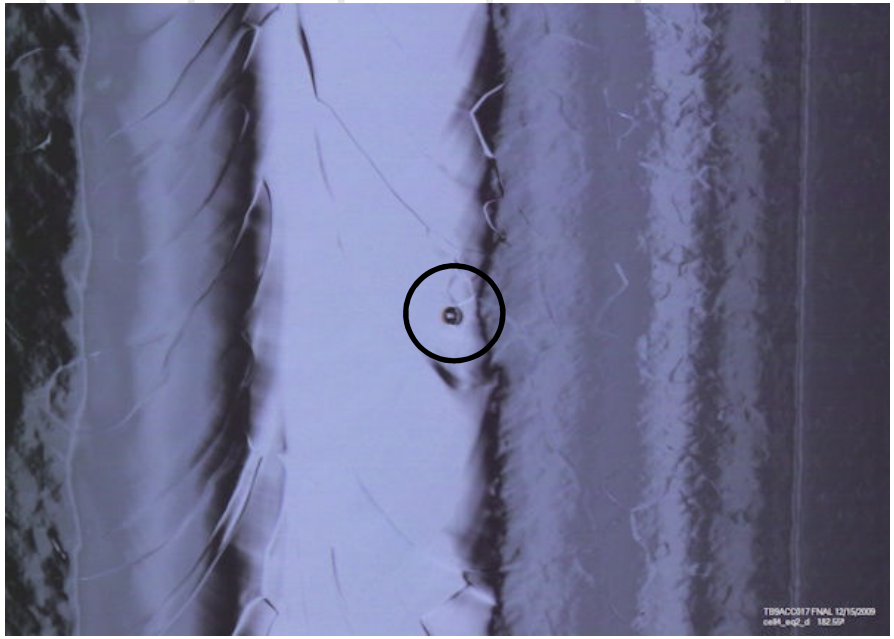


After Laser processing: EP 50μm+HPR+120C baking;
Eacc achieved 40.3MV/m, quenched at molten region.

The next step

- To develop 9-cell system.





Pit in 1.3GHz 9-cell cavity TB9ACC017
Quenched at 12.3MV/m.

Summary Laser re-melting technique

- Changed pit's profile to flat surface by high power laser pulse.
- Successfully re-melted a pit inside 1.3GHz single-cell cavity.
- Improved cavity gradient to 40.3MV/m after 50μm EP.
- Next step is to develop a system for 9-cell cavity.

Laser welding study

Motivation and Benefits

- Dramatically decrease HAZ area.

1. The laser pulse has very short duration ~10ms;

2. The potential benefit is to decrease the probability of welding pit generation.

- The weld could be very smooth and narrow.

1. Proved by laser re-melting technique (40MV/m);

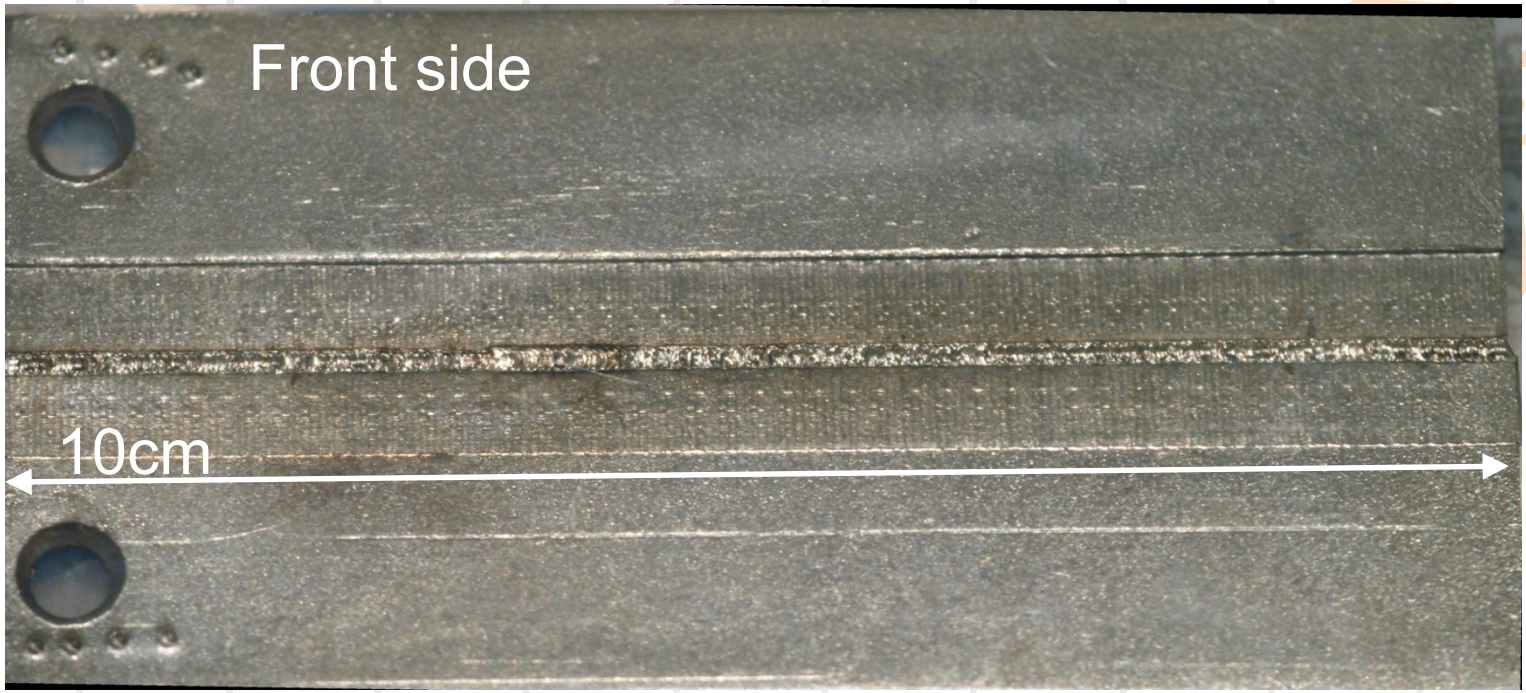
2. By changing different pulse form, we can change the ratio of weld width and depth.

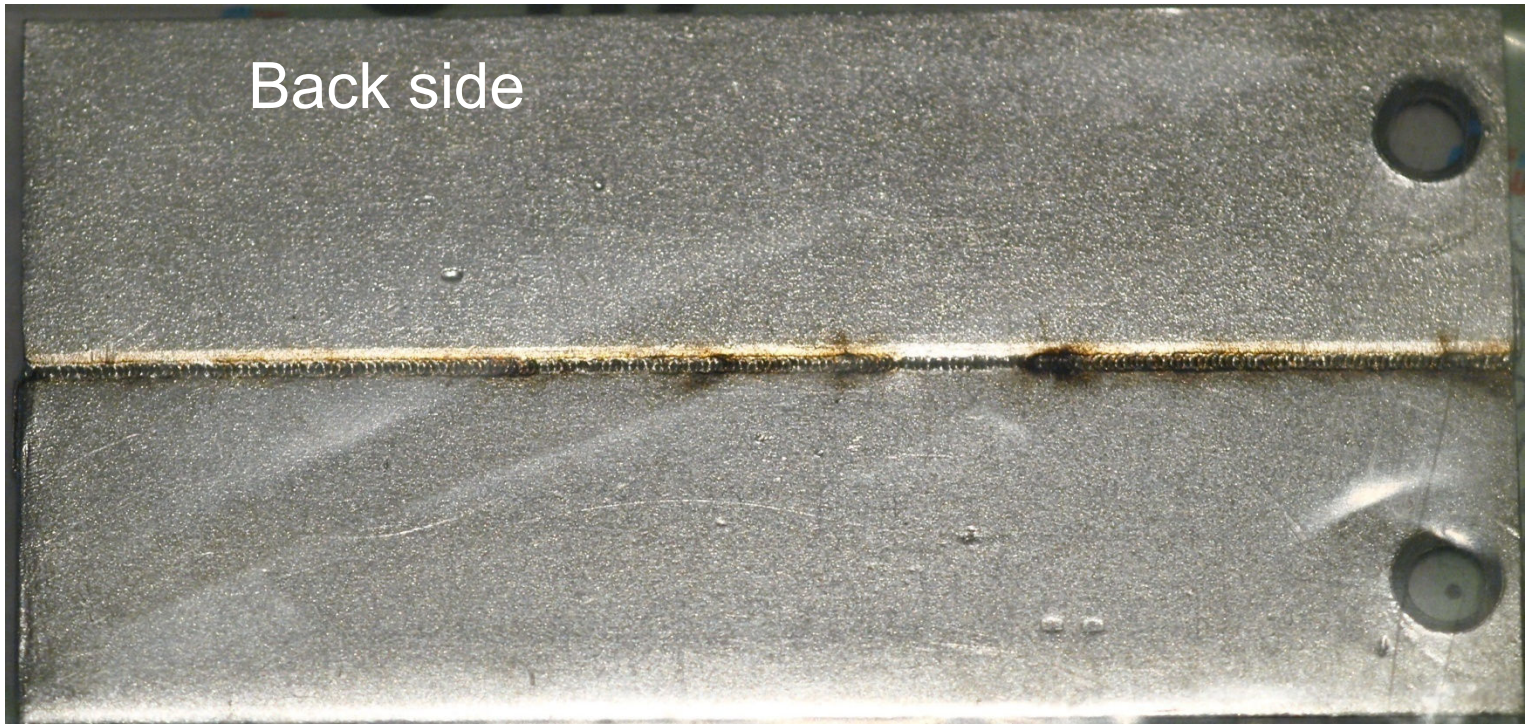
- Welding cavity in Air just with Ar gas protection

Proved by laser re-melting technique

- Welding very complicated structure.

Laser beam can be reflected and focused by optics as well as conducted by laser fibers without so much power loss.


Front side
10cm


Back side

RRR test results

Sample No.	RRR
1	326
3	348
4	286
5	234, 252

RRR value does not decrease so much!

Conclusion

- Several new techniques have been developed at Fermilab surrounding a topic: Surface.
- Optical Inspection locates the defects and links them to quench location via T-mapping.
- Surface replica technique exhibits 3-D shape of pit, and extracts surface roughness from SRF cavity.
- High power laser pulse is able to re-melt pit and restore cavity gradient up to 40MV/m.
- Laser welding has potential to avoid welding pits generation.

Thanks for your attention