Cavity R&D Status and Future Plans

- with a partial summary of SRF2009

Rongli Geng
Jefferson Lab

Global Gradient R&D Highlights

- Americas
  - **1st US industry built 9-cell cavity passed ILC spec and reached 41 MV/m.**
  - **ANL/FNAL joint facility validated by EP proc. & testing of 1-cell cavity > 40 MV/m.**
  - **Improved understanding of quench limit by T-mapping and inspection.**
- Asia
  - **MHI#9 reached 27 MV/m during first RF test.**
  - **Improved understanding by T-mapping and optical inspection of 9-cell cavities.**
  - **Successful multi-wire slicing of ingot niobium.**
- Europe
  - **Improved understanding by optical inspection and T-mapping of 9-cell cavities.**
  - **Microscopic understanding of defect by cutting 9-cell cavities.**
  - **XFEL cavity call for tenders.**
- GDE SCRF Cavity Technical Area
  - **Yield evaluation method proposed (1st-pass and 2nd-pass production).**
  - **Formed global cavity database team toward global gradient yield curve.**

New 9-cell Cavity Results

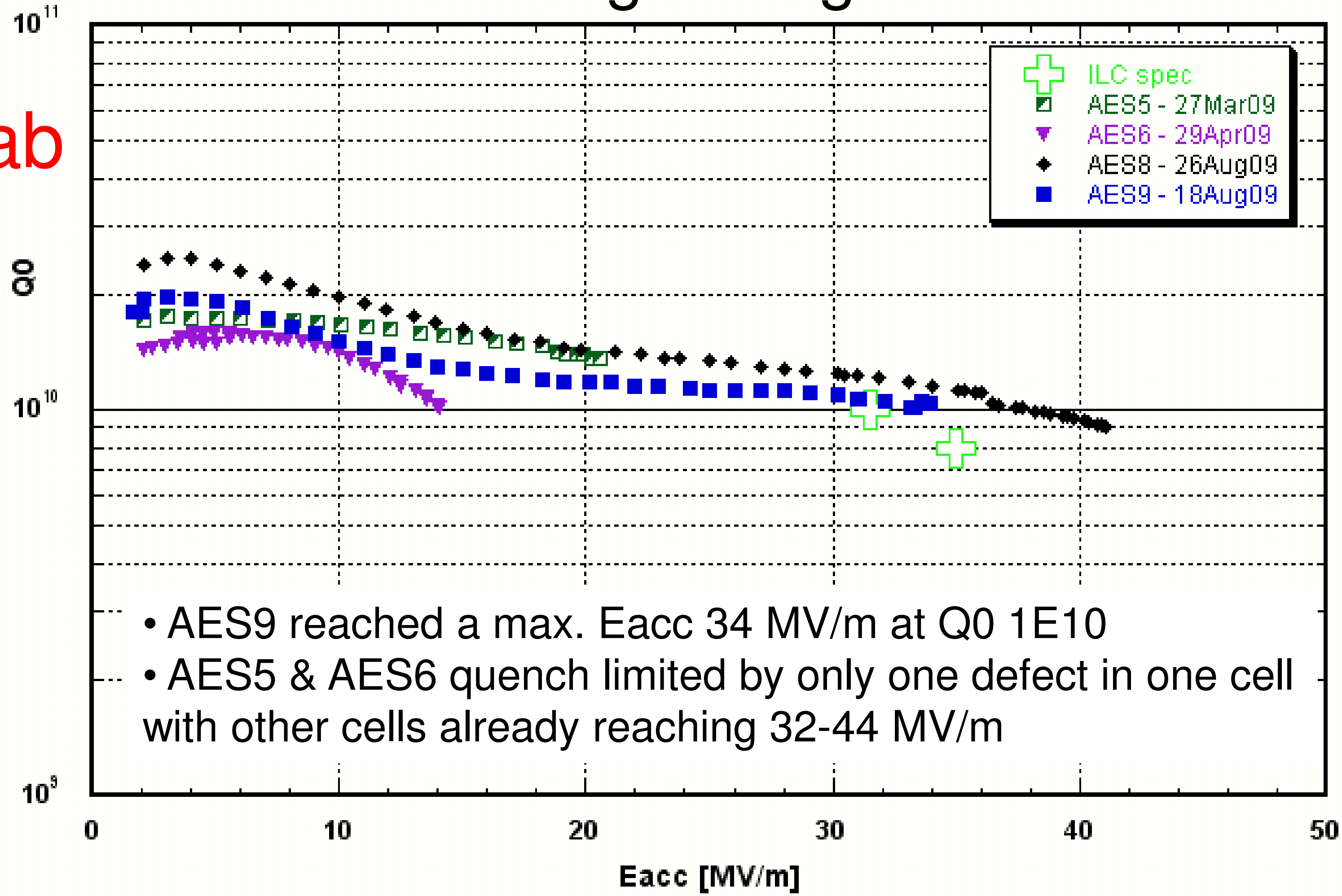
- US industry AES built 9-cell cavity passes ILC spec in JLab processing and testing

- Japan industry MHI built 9-cell cavity making progress 27 MV/m in KEK processing and testing

AES8 achieved 41 MV/m

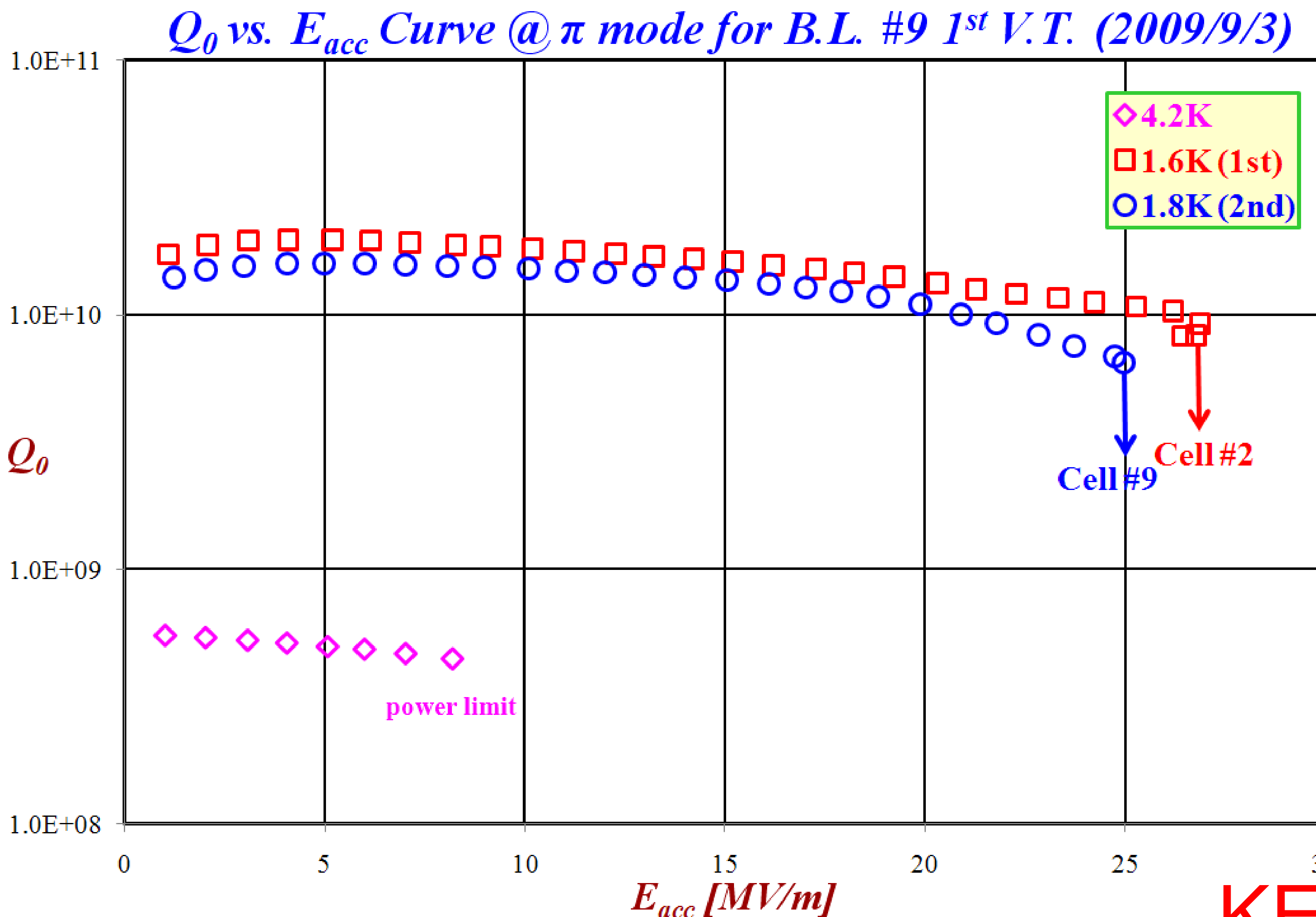
4 out of 6 second production 9-cell cavities by AES
First RF test following first light EP at JLab

JLab



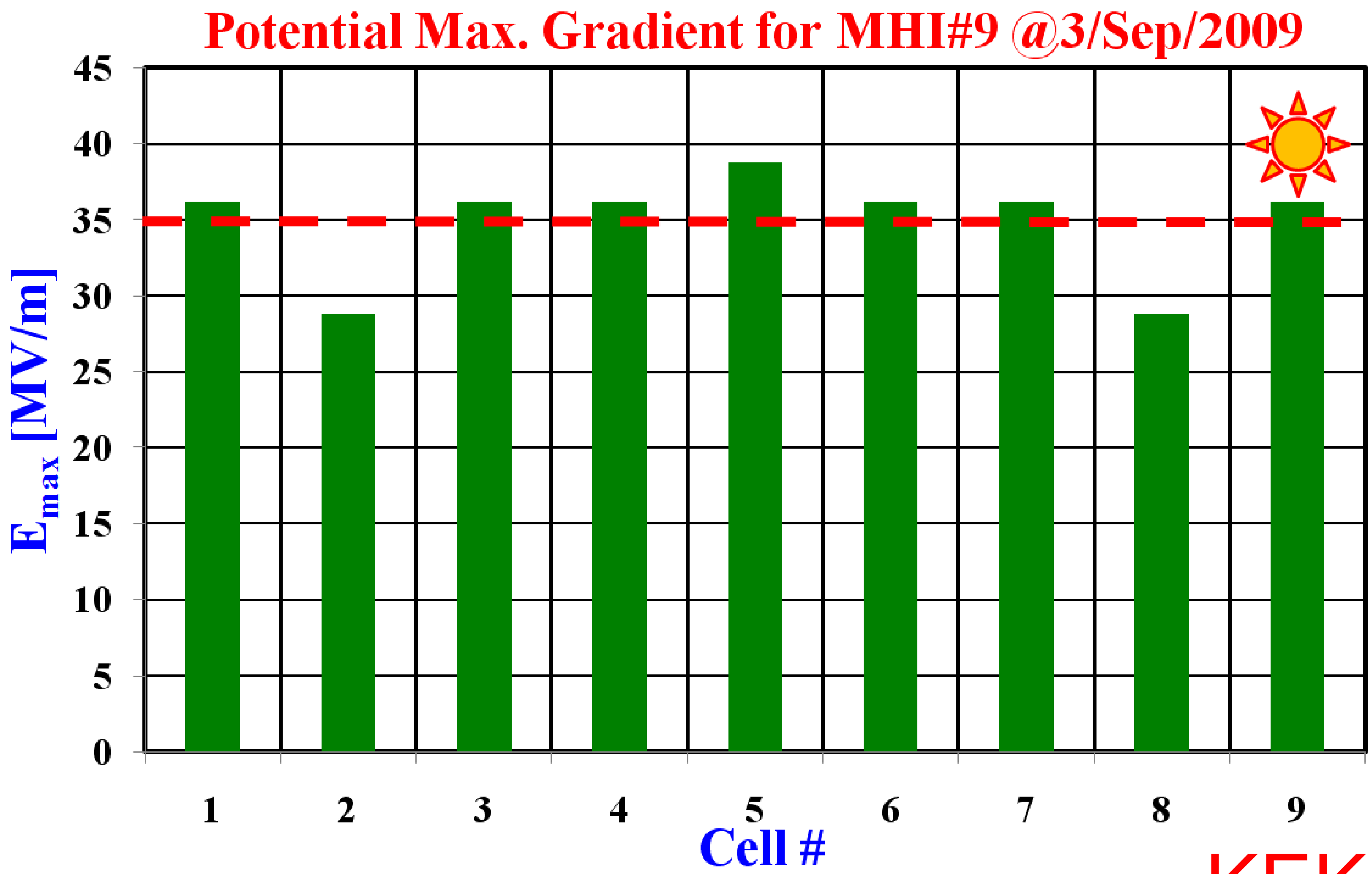
- AES9 reached a max. Eacc 34 MV/m at Q0 1E10
- AES5 & AES6 quench limited by only one defect in one cell with other cells already reaching 32-44 MV/m

MHI#9 reached 27 MV/m @ 1st test



KEK

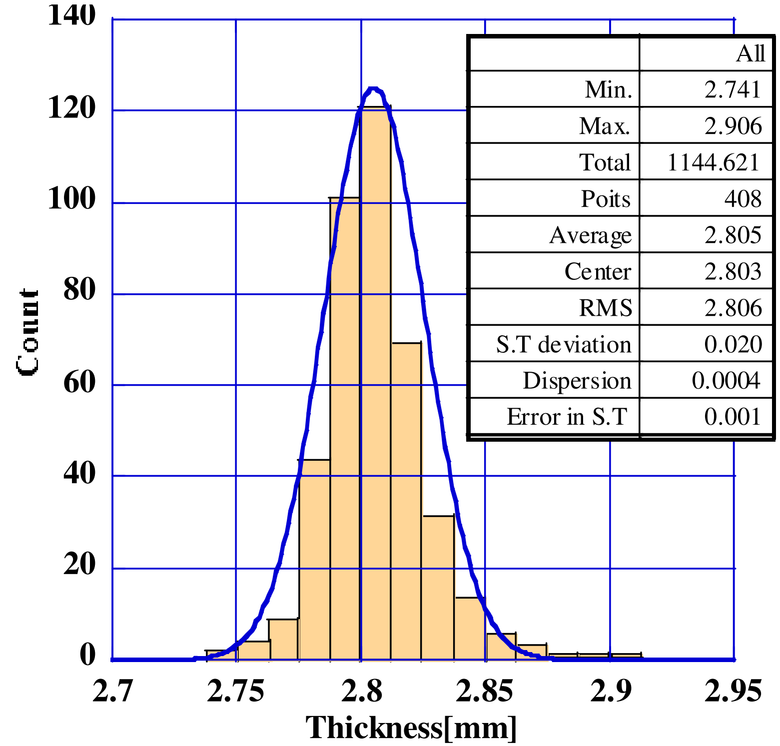
MHI9 most cells exceeded 35 MV/m



KEK

ACD progress

Multi-cell slicing of ingot material



	All
Min.	2.741
Max.	2.906
Total	1144.621
Poits	408
Average	2.805
Center	2.803
RMS	2.806
S.T deviation	0.020
Dispersion	0.0004
Error in S.T	0.001

Cost saving potential - also opportunity for material exploration as compared to rolled/annealed sheets

KEK

More ACD progress reports

- Large-crystal niobium cavity – W. Singer
- Re-entrant cavity – Z. Conway
- Low-Loss cavity – F. Furuta

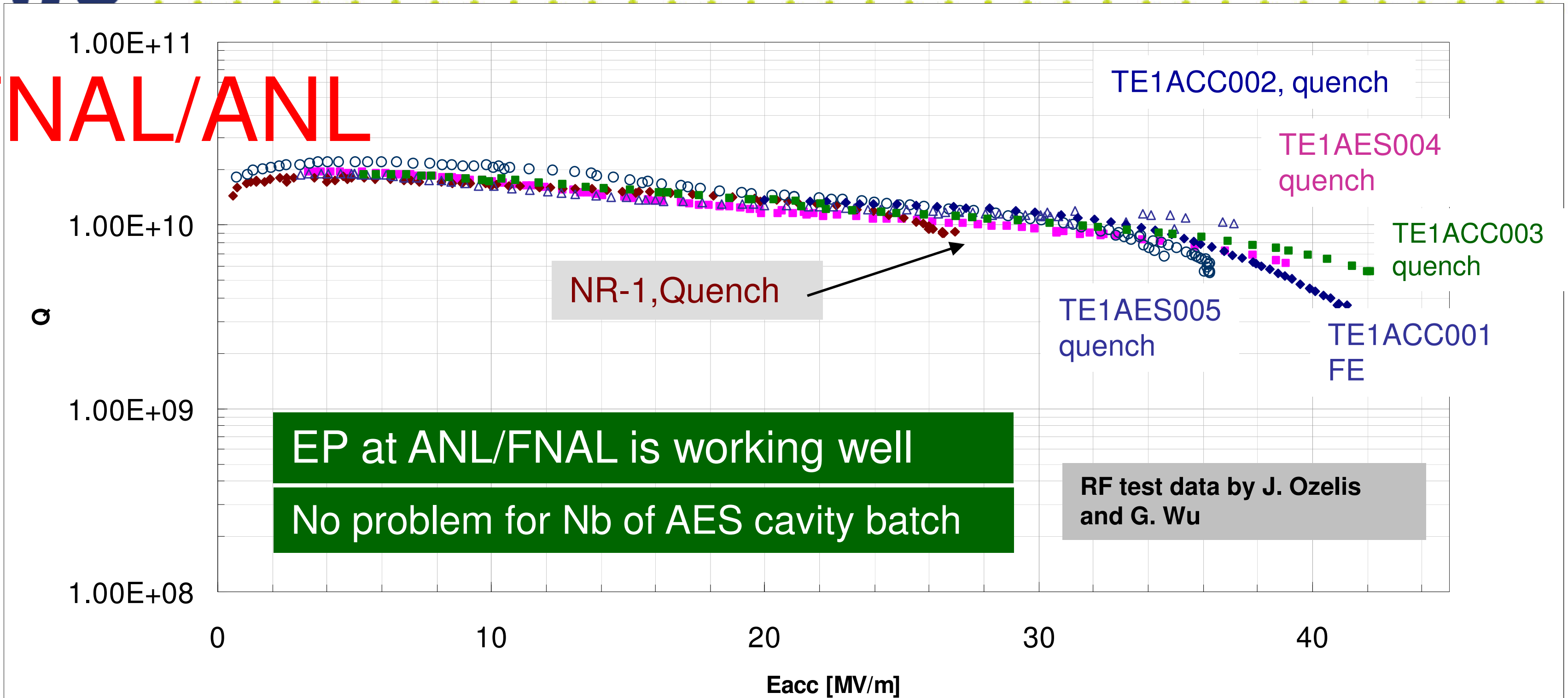
KEK 9-cell low-loss shape ICHIRO#7 arrived at JLab for EP and RF test

KEK built and tested first large-crystal 9-cell low-loss shape cavity

8 large-crystal 9-cell cavities built at DESY

Cavity Proc. Facility Validation

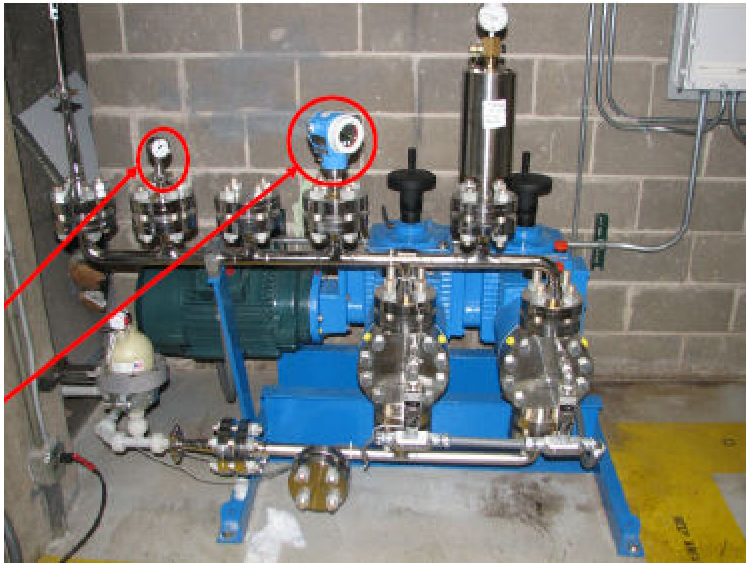
> 40 MV/m in 1-cells @ ANL/FNAL



	BCP*	EP	Ethanol	Eacc [MV/m]	Notes
NR-1	150	93		26.5	No distinguishing feature
TE1AES004	107	65		39.2	Equator large pit present
TE1AES005	104	100	Yes	36.3	Oxidation by HPR water
TE1ACC001		99	Yes	41.3	FE appeared due to vacuum handling
TE1ACC002		112		37.1	No distinguishing feature
TE1ACC003		119		42.1	Pits present

* BCP done at Cornell University

ANL/FNAL HPR machine



Bacteria causing field emission?

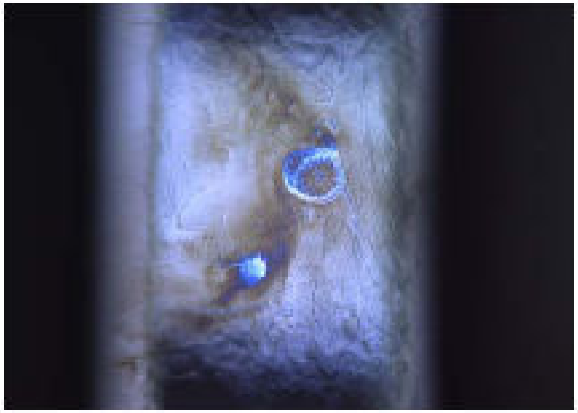
More details by A.Rowe

FNAL

KEK STF EP machine

MHI-06 cell#1 equator, t = 306 deg.
Downstream : off welding area

MHI-06, #9BP, t = 241 deg. -1



MHI-06, #9BP, t = 241 deg. -2

Stain causing field emission?
Detailed report by T. Saeki

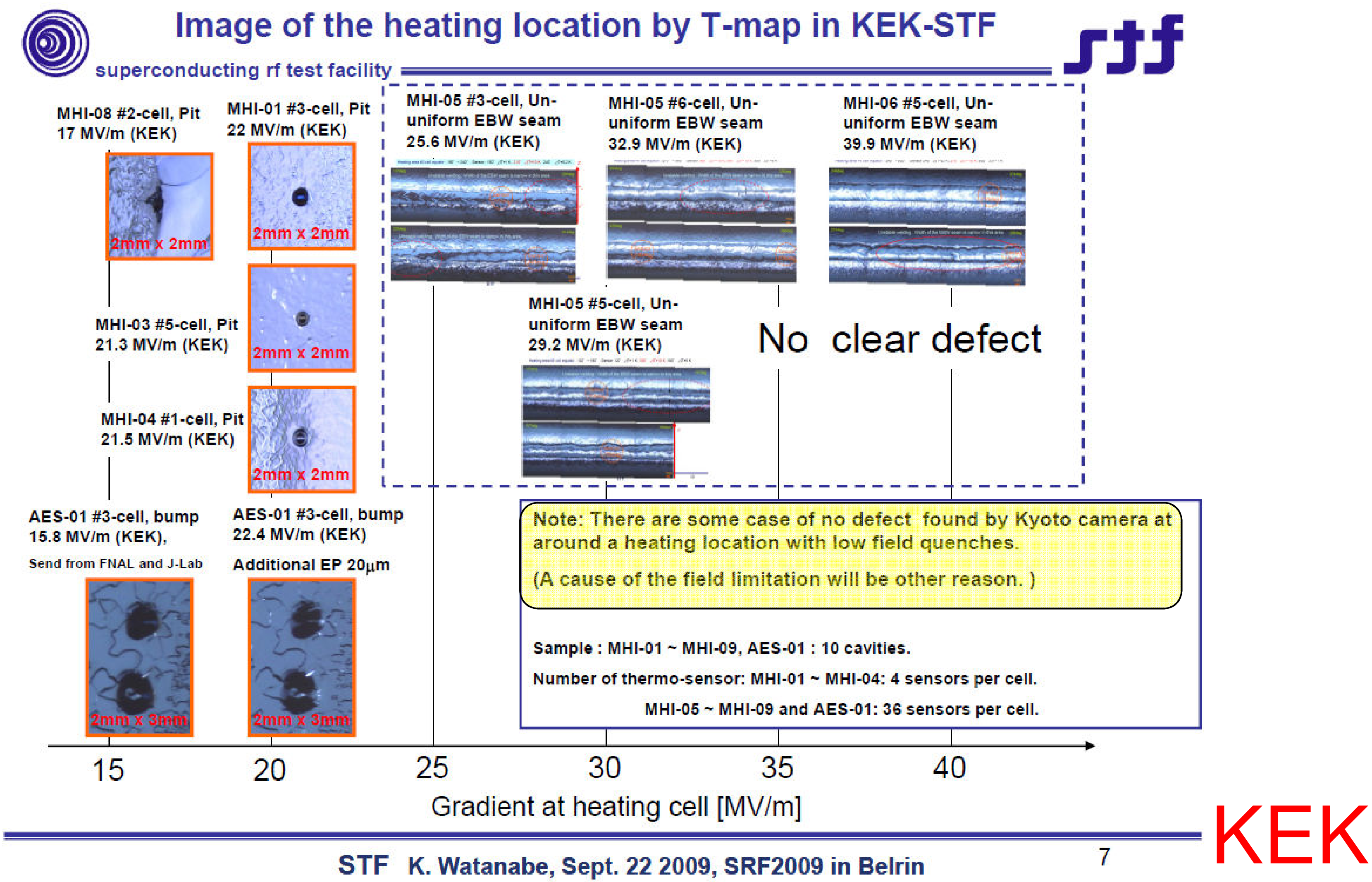
KEK

A proposal for proc. facility validation

- Separate processing validation from fabrication validation.
- Send previously qualified 9-cell cavity to new processing and testing facility.
  - This already happened within US region.
  - JLab qualified 9-cell cavities sent to FNAL under vacuum, re-test first for RF system cross calibration; re-processing later for facility validation.
- **This is yet to happen across regions.**
- Equally important, a global cross calibration of RF test results is necessarily required to justify a confident global gradient yield evaluation.

Defect/quench correlation toward quench prediction and improved fabrication QC

Initial defect & quench correlation

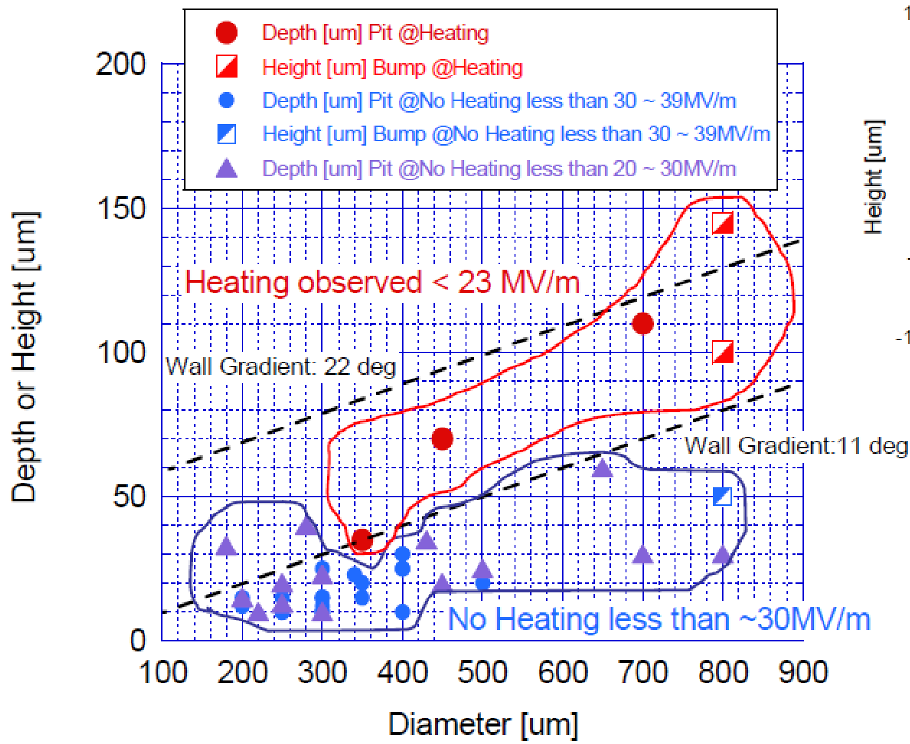


Initial size/profile & quench correlation

Correlation of spot size and heating (Rough estimation)

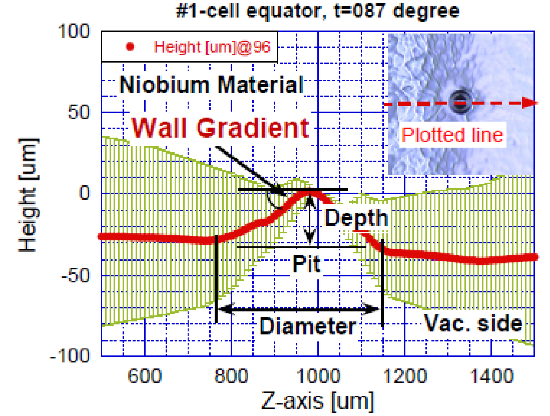
superconducting rf test facility

Relation of Spot size and Heating detected by T-map
(Preliminary result)



Sample: MHI-01 ~ MHI-09, AES-01 : 10 cavities.
Number of cell = 90 cells, Number of detected spot = 49 spots.

STF Baseline cavity #4 : After Phase 1.0 project
#1-cell equator, t=087 degree



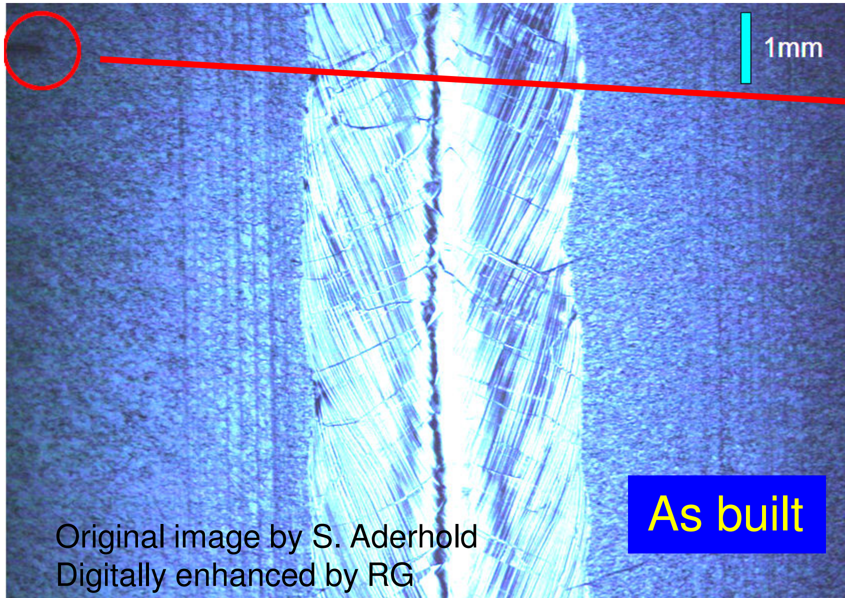
Larger, deeper (or higher) pits (or bumps) seem to cause quenches.

However,
*** Not all of the optically observed defects lead to problems.**
*** Note: preliminary results of analysis which utilizes *both* the pi-mode and pass-band measurements.**

STF K. Watanabe, Sept. 22 2009, SRF2009 in Belrin 8

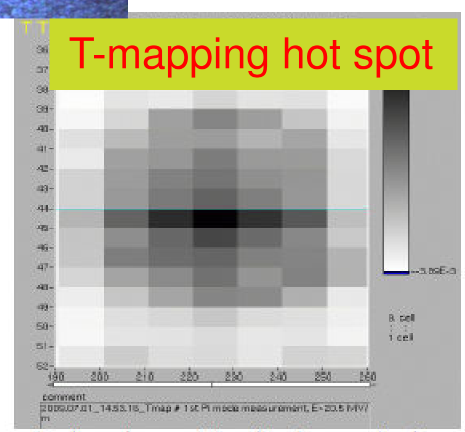
KEK

First predictive inspection at DESY

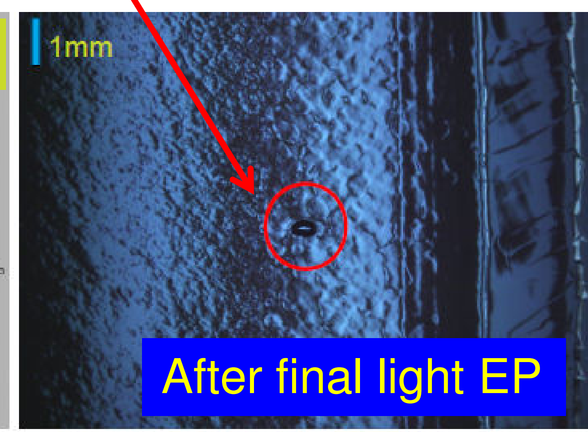


- More than 20 cavities inspected.
- Several cavities are tracked over the processing steps.
- First quench prediction based on optical inspection of as-received surface.

DESY

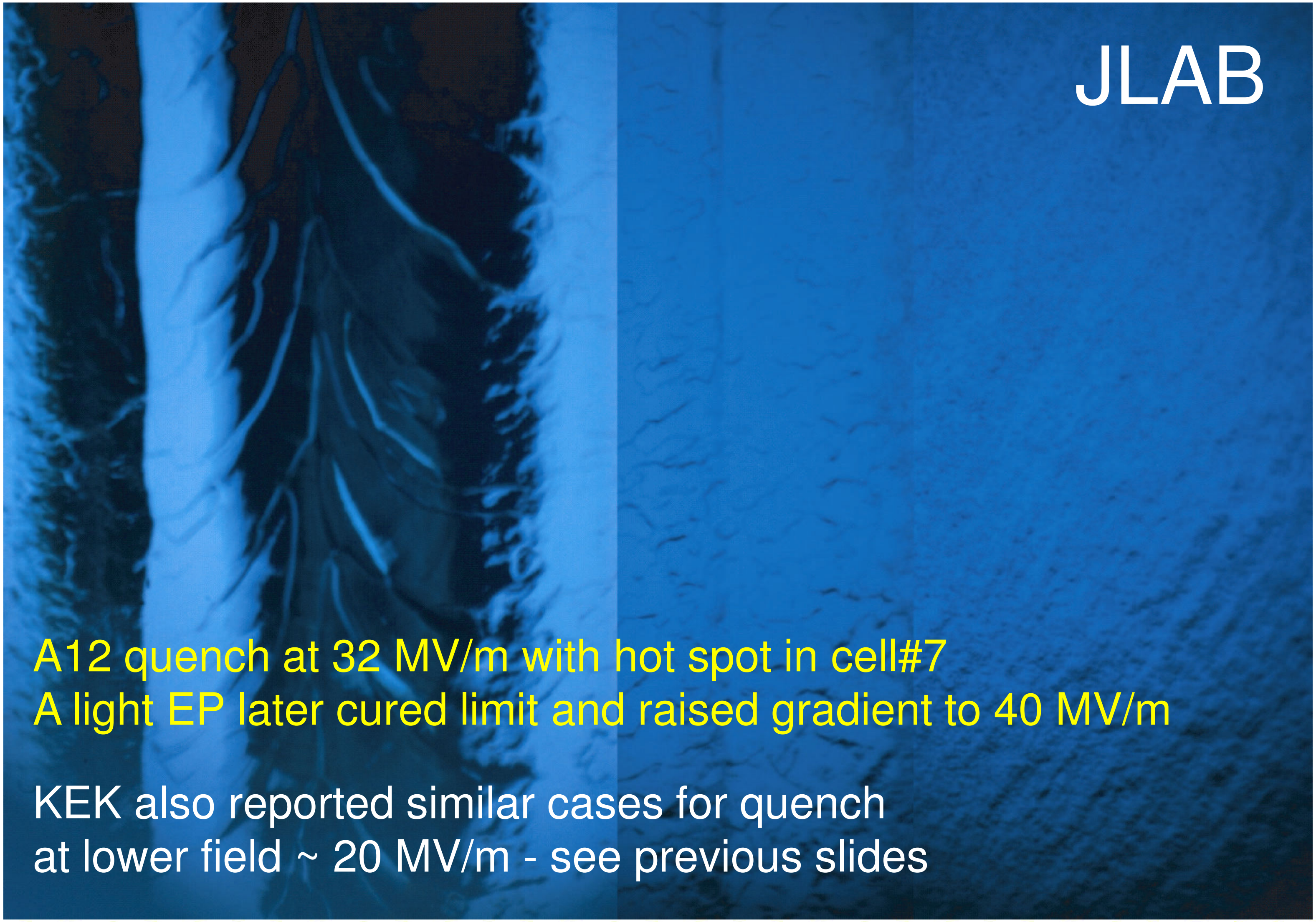


Heating at quench location in π-mode at 20 MV/m, observed at equator of cell 6



Defect in optical inspection picture of corresponding area of inner surface

Quench without observable defects



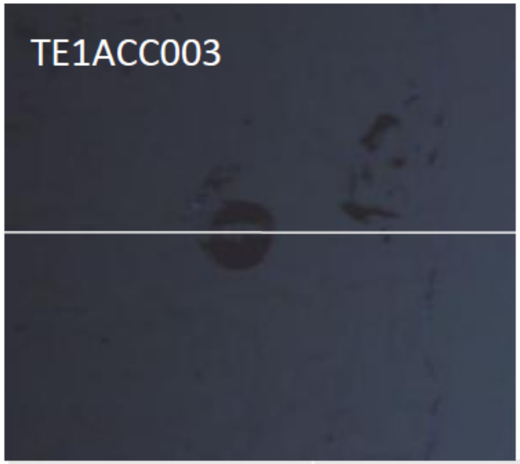
JLAB

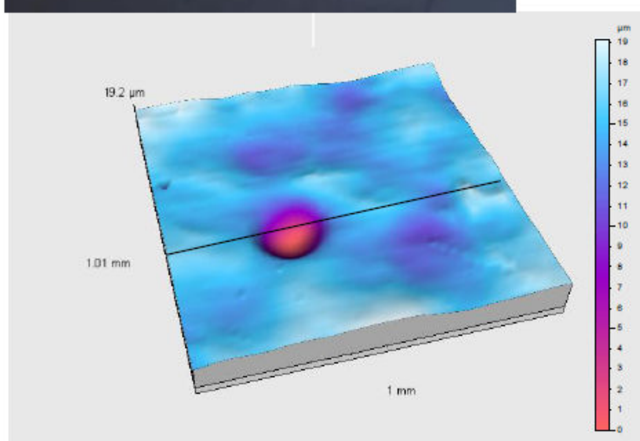
A12 quench at 32 MV/m with hot spot in cell#7
A light EP later cured limit and raised gradient to 40 MV/m

KEK also reported similar cases for quench
at lower field ~ 20 MV/m - see previous slides

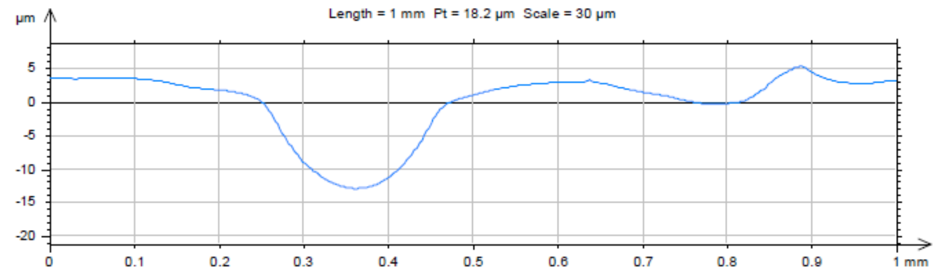
Defect profiling

Surface Geometry of a Replicated Defect

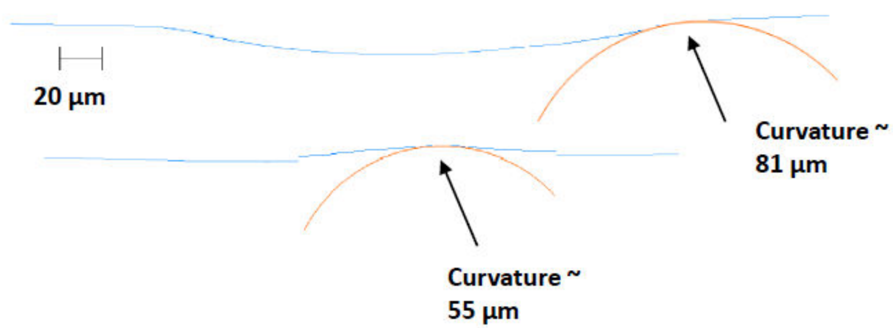




ϕ230 µm x 18 µm



Profilometer line scan



Zoomed to linear scale

FNAL

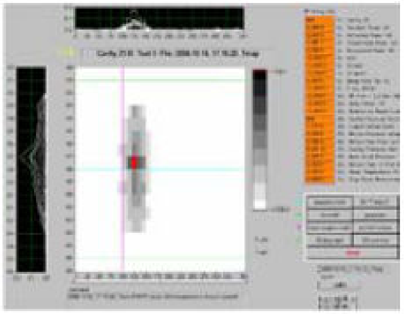
Microscopic studies of defects cut from 9-cell cavities

Cavity 1

Preparation:
90 µm EP (ACCEL), alcohol rinsing, HT 800° C, 60 µm EP (DESY), HPR, alcohol rinsing, 6 x HPR, tank welding, 6x HPR, bakingat 126° C.

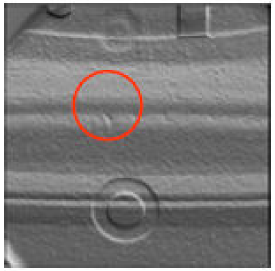
Results:
Eacc = 16.6 MV/m, Qo=$1.8 \cdot 10^{10}$ limited by quench, small FE in some modes, no Q disease.

Cell 5, Quench at 23,3 MV/m on equator

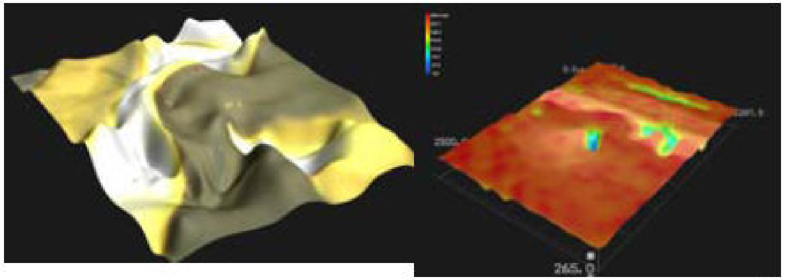


T-map: quench found in cell 5

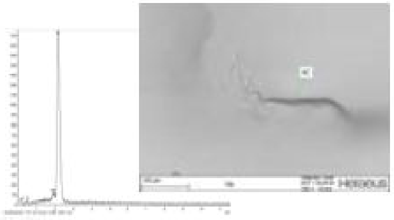
High resolution Kyoto-Camera. Spot on the equator of the cell 5



X-Ray imaging. Spot area marked. Washer as a reference



Sample 1, equator, 3D images. Bump and hole up to 200 µm deep in the spot area



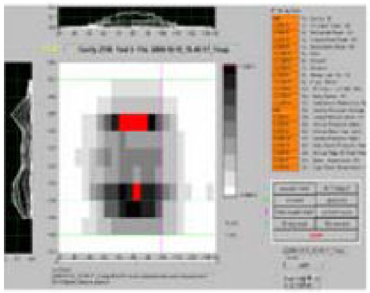
No foreign material inclusions detected by EDX. Defect is probably something like welding beard

No foreign material
Complex geometrical features

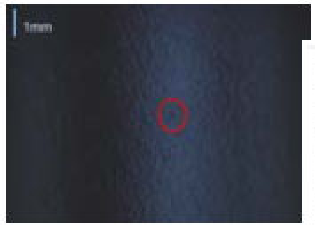
DESY

2nd 9-cell cut for defect studies

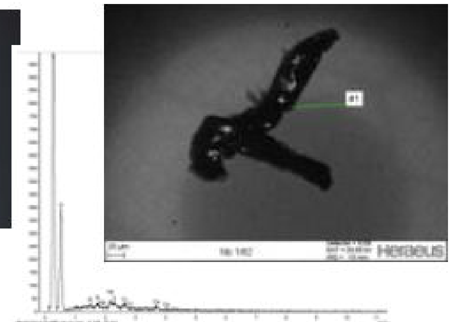
Cell 1, Quench at 16 MV/m



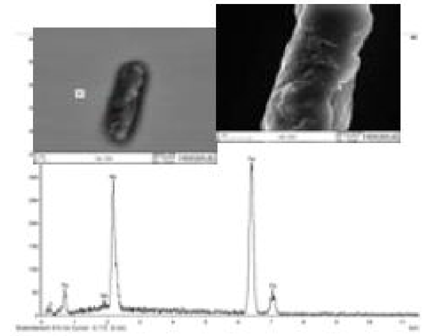
T-map of cell 1



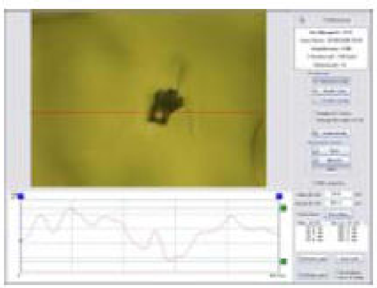
High resolution
optical cavity control

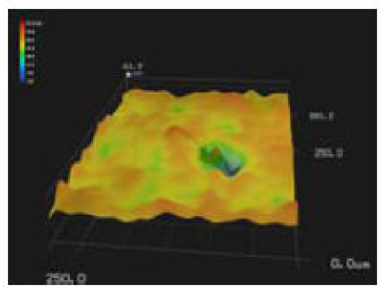


Sample 62 (away of equator): Many spots are detected. EDX of the biggest spot: C and O found

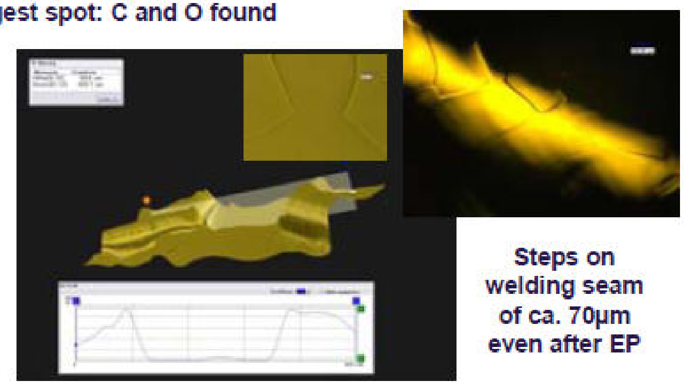


Sample 62: Iron found





Cell 1, Sample 25 (equator). In many cases spots seem to be like cavern.

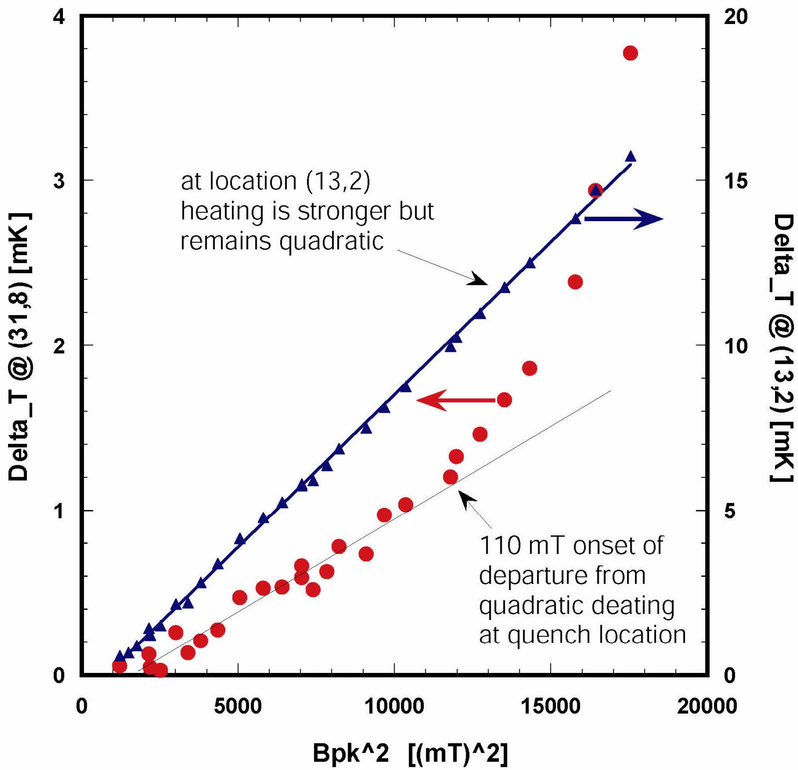


Steps on welding seam of ca. 70µm even after EP

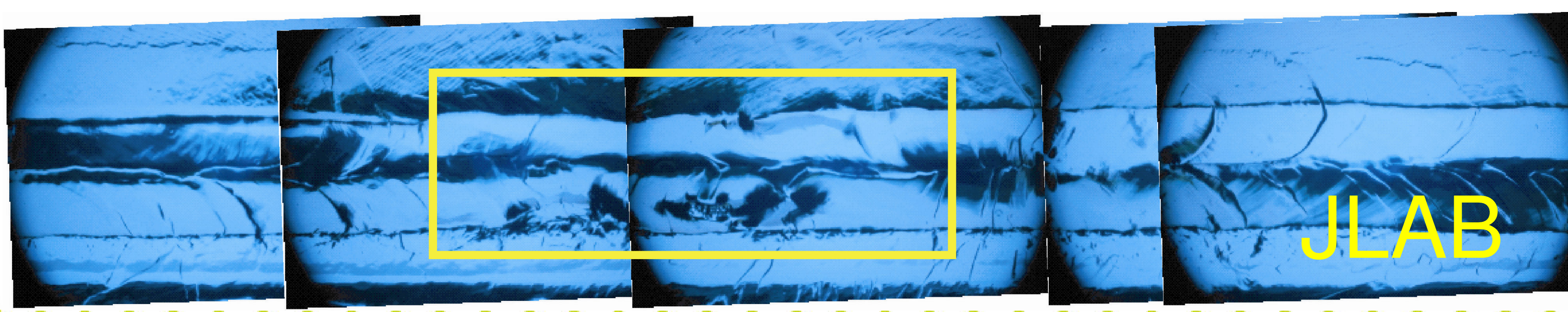
DESY

Heating behaviors at quench location

Preheating suggests phase transition - I

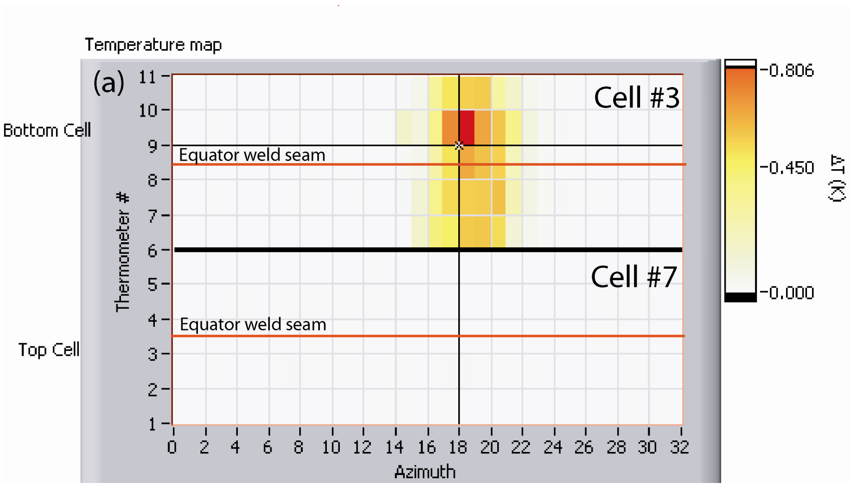


- JLab 9-cell LG1 after EP
- Quench at 30 MV/m
- Heating at weld repair
- magnetic field enhancement effect is a reasonable explain

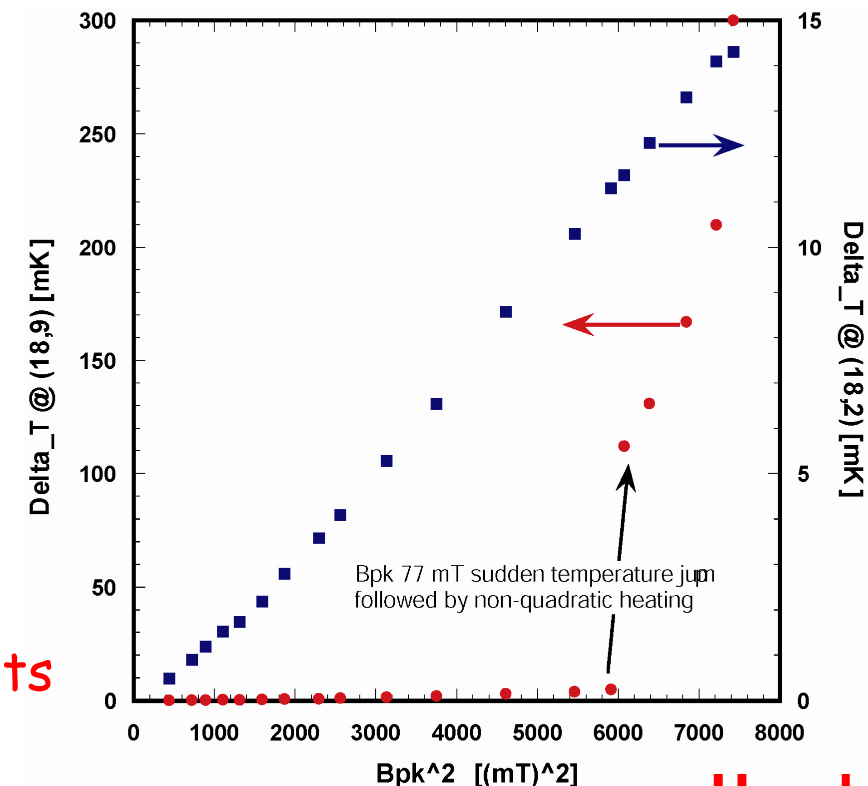


Preheating suggests phase transition - II

Hot spot captured during quench



Preheating at quench location (18,9) and random location (18,2)

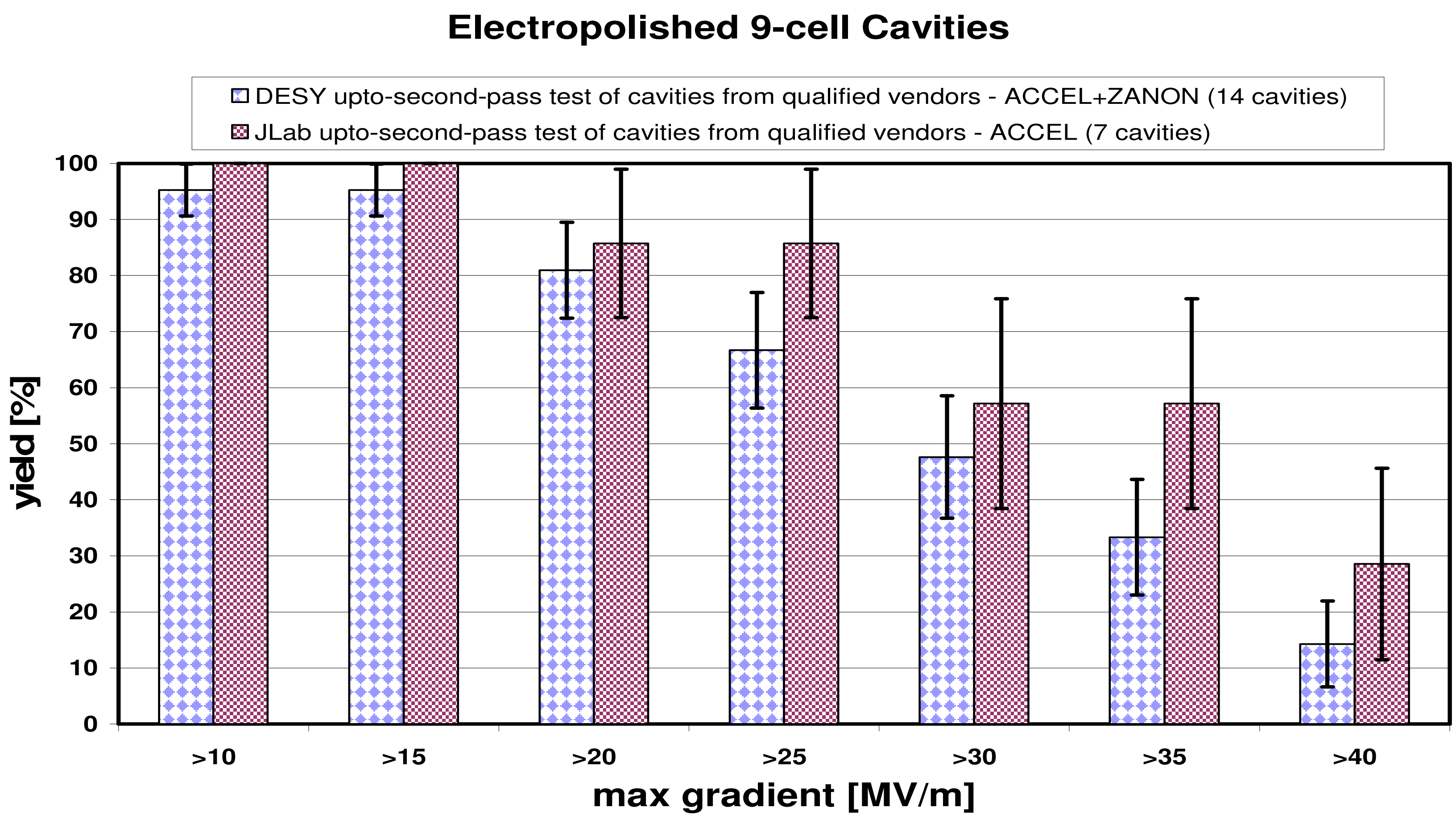


Local Magnetic field enhancement alone not enough to explain exp. facts

JLab

Yield plot

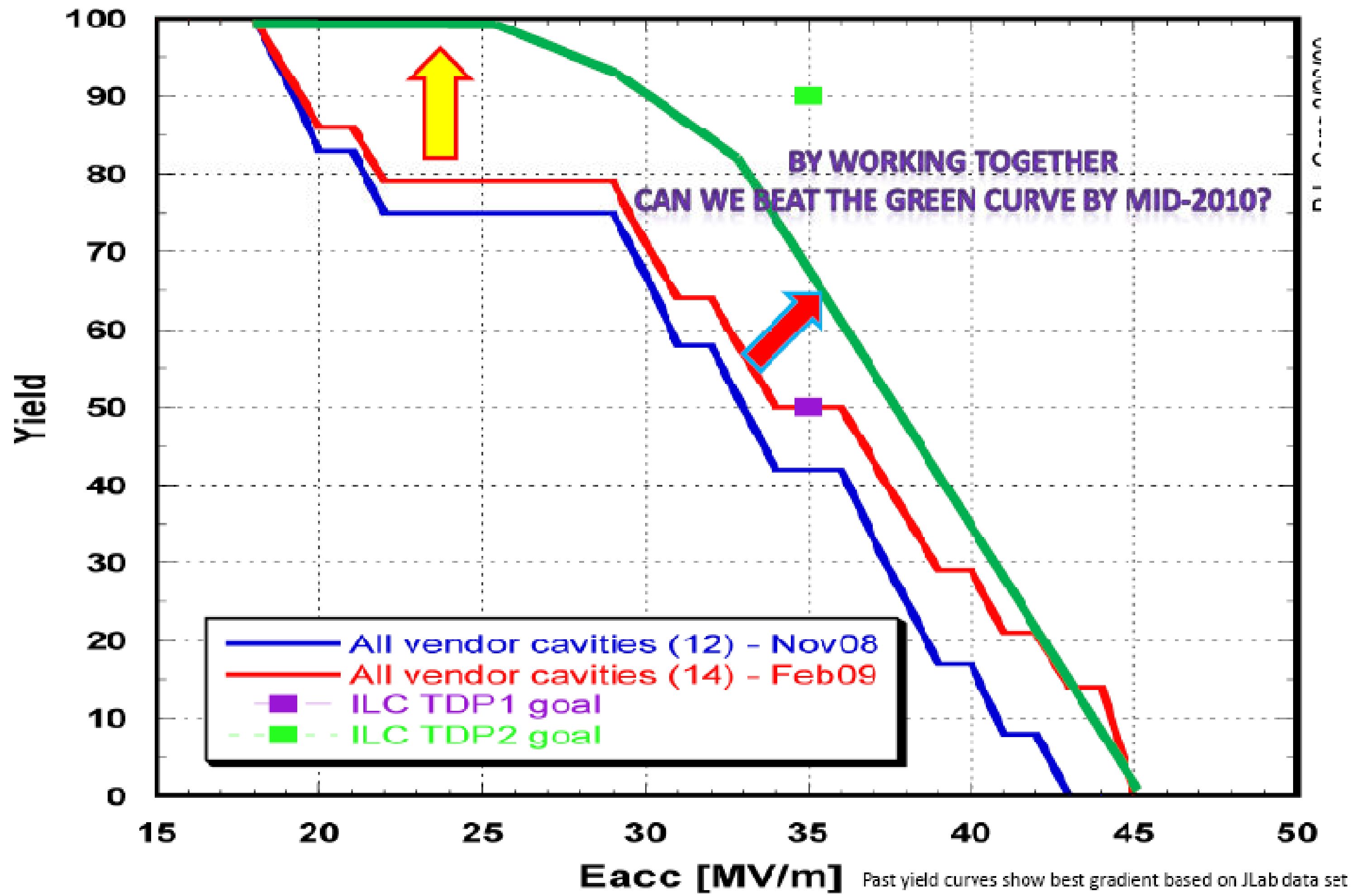
Gradient yield – up to 2nd pass



More by Camille Ginsburg's talk

New yield plot confirms need for two pushes

Two Big Pushes Ahead…



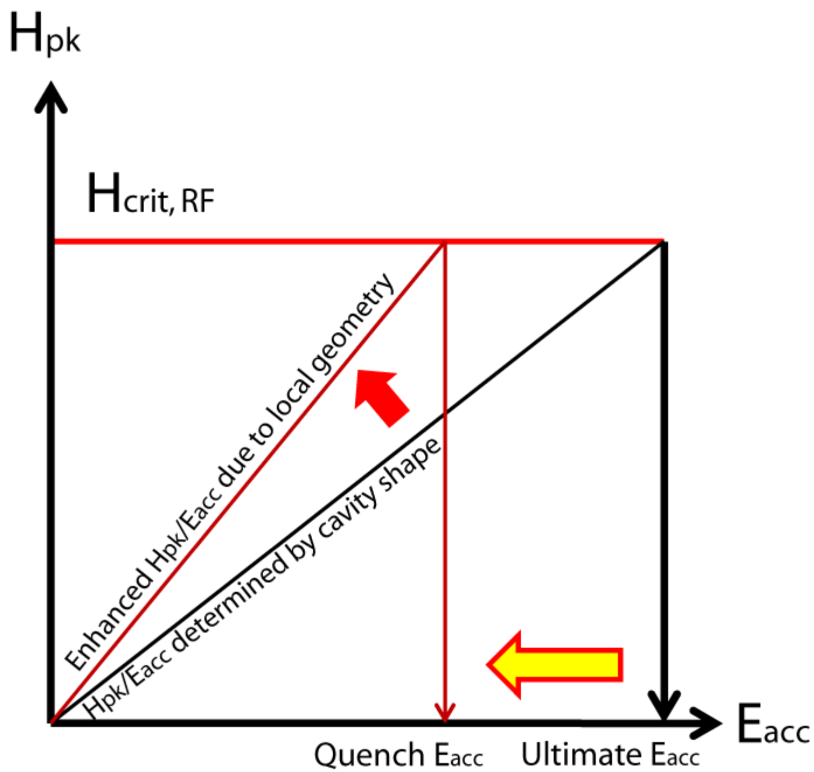
First presented at cavity vendor meeting at FNAL, March 6, 2009

overcoming quench limit
for
improved gradient yield

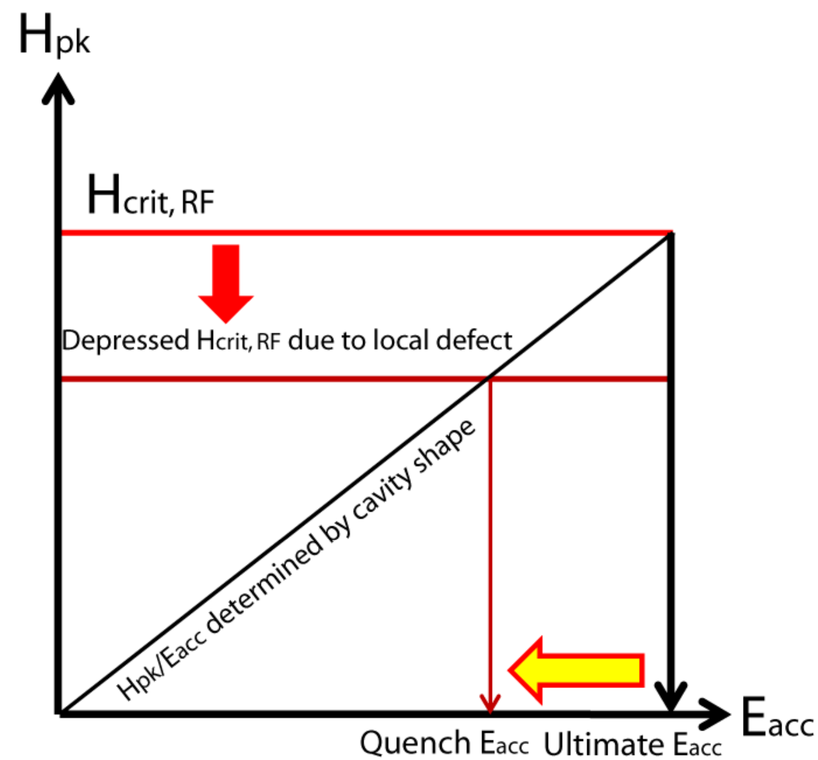
New: Understanding Quench Limit

- We now have improved understanding about quench limit ~ 20 MV/m because of T-mapping and optical inspection.
- Location: Gradient limited by one defect in one cell (near equator EBW) with other cells already reaching high gradients.
- Dynamics: Pre-heating data suggest magnetic field enhancement alone not enough to explain quench behavior.
- Two models for H-driven quench (next slides)

H-driven Breakdown Models

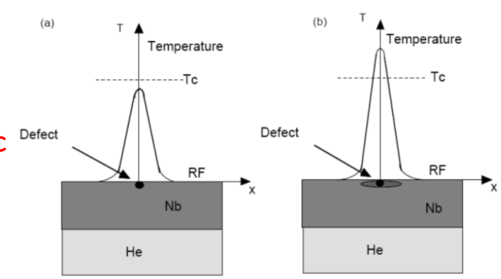


Local magnetic field enhancement model



Local critical field depression model

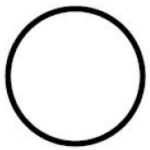
SC-NC phase transition front defined by $H_{crit,RF}$, instead of T_c as suggested in H^2-driven breakdown model



Magnetic field enhancement

1. sharper pits and
2. larger pits.

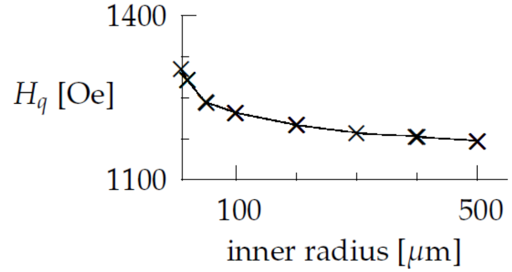
New Simulations for Ring-like Defects



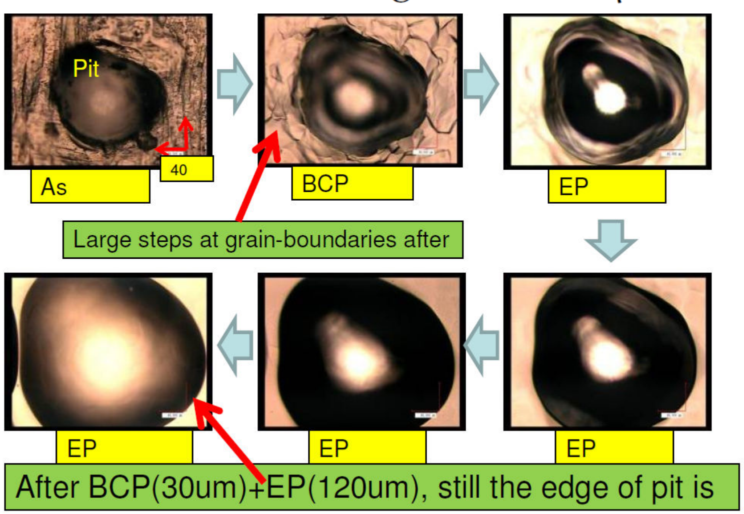
ring-shape defect modelling a pit

disc-shape defect used in previous simulations

Y. Xie et al., TUPPO048

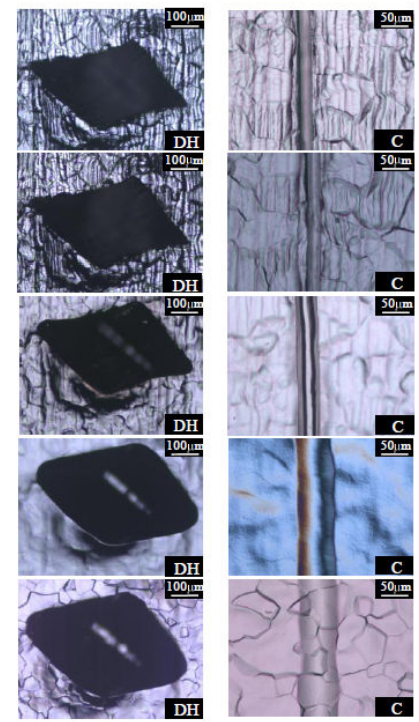


Larger ring diameters increase the NC area and lower the quench field. The quench field increases rapidly for ring sizes < 50 μm.



T. Saeki et al., THPPO085

Artificial defect tracking: Some defect not eliminated by repeated EP

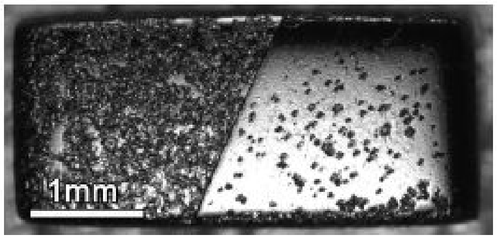


P.M. Michelato, L. Monaco, THPPO091

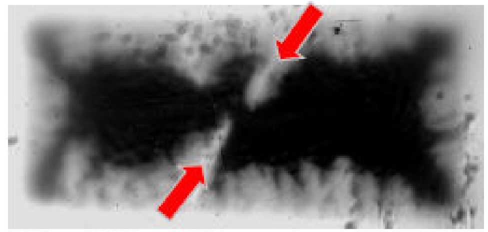
Suppressed superconductivity across GB

Reduced thickness sample (GB//H_{ext})

BCP'ed

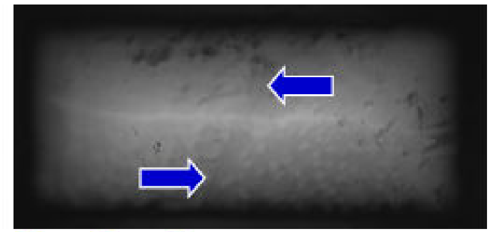


ZFC T=6K



H = 58 mT

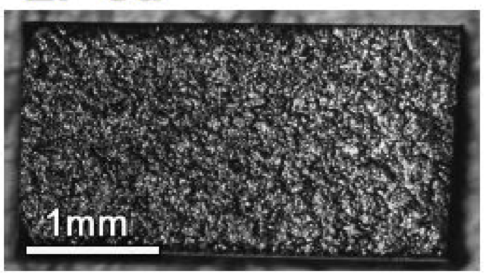
FC T=6K



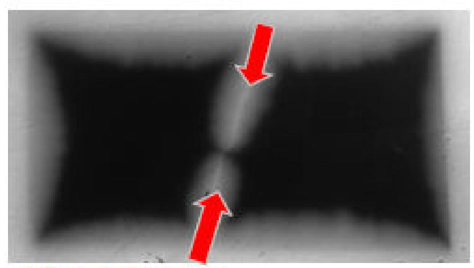
H = 0 mT

Same GB & thickness sample (GB//H_{ext})

EP'ed

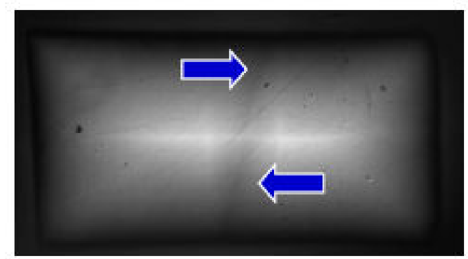


ZFC T=6.5K



H = 72 mT

FC T=6.5K



H = 0 mT

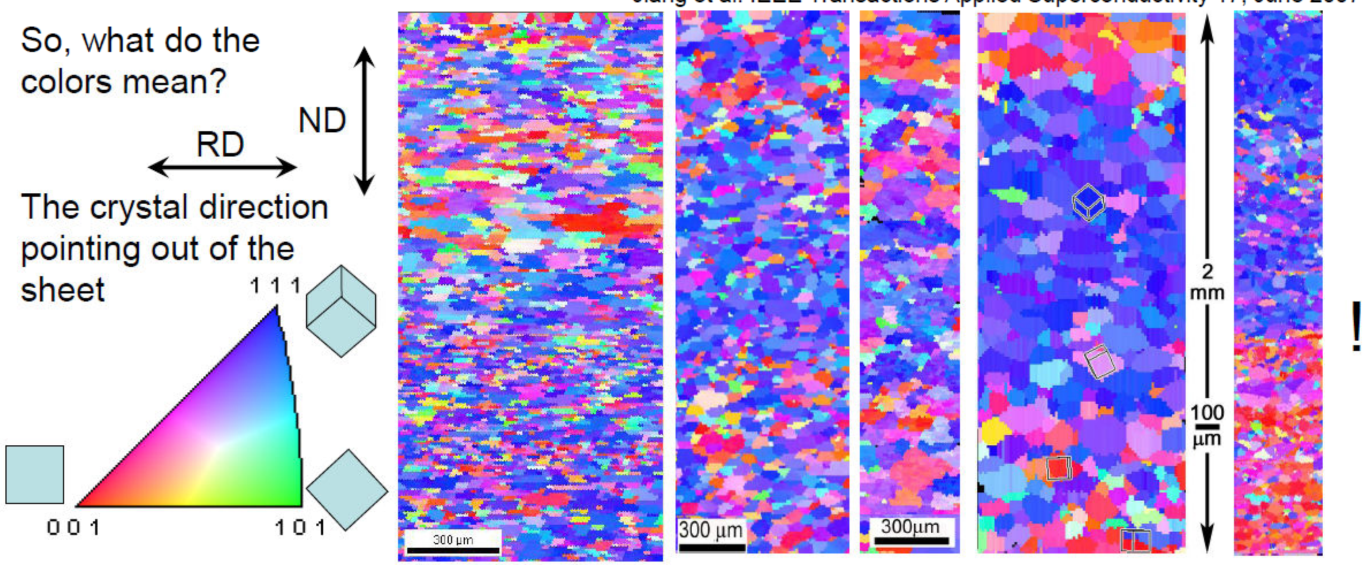
Z.H. Sung et al., TUPPO076

Complexity in Nb metallurgical

Rolling to make sheet metal - hard to control **microstructure** and **texture** (grain orientations)

- Consistency is a challenge… Producers start with a hunk of ingot, and then use combination of breakdown forging, annealing, rolling to hopefully get a uniform microstructure
  - does initial ingot orientation haunt the microstructure to the end ?
- We have never seen the same texture/microstructure twice…

Jiang et al. IEEE Transactions Applied Superconductivity 17, June 2007



T. R. Bileler, TUOAAU03

Gradient Limit Equation

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

• $H_{crit,RF}$: the intrinsic RF critical field – material
• r: a dimensionless factor representing the depression effect on the *local critical field* ***within the penetration depth***, due to impurity or lattice imperfection ($r \leq 1$) – metallurgical and surface chemistry
• β_{MAG}: a dimensionless factor representing the magnetic field enhancement effect due to local geometry ($\beta_{MAG} \geq 1$) – fabrication and processing
• H_{pk}/E_{acc}:the peak surface magnetic field to accelerating gradient ratio, determined by cavity shape – reason for new shapes such as Re-entrant and low-loss shapes
• d: a dimensionless factor representing the thermal stabilization effect – bulk material

Strategy for raising limiting gradient

- Raise *r*
  - **Optimize surface chemistry.**
  - **Optimize surface metallurgical properties.**
- Suppress β_{MAG}
  - **Optimize EP for *defect correction*.**
  - **Mechanical polishing before EP as demonstrated and suggested by Kenji Saito several years ago?**
- Raise *d*
  - **Thermal conductivity near EBW.**
  - **Starting material property optimization.**
  - **Restore phonon peak by recovering/annealing?**

Summary

- T-mapping and optical inspection improved understanding of quench limit 15-30 MV/m.
- Known facts about defects (mostly) limiting ~ 20 MV/m:
  - **One defect in one cell**
  - **Near equator EBW, 0.3 -1 mm in dia.**
  - **Sharp transition in pre-heating**
- Most observed features on as-built surface not correlated to quench limit.
- It seems fabrication only plays a partial role in creation of limiting defects
- It is advisable to look into the role of the starting sheet material (thermal and metallurgical) and its interplay with fabrication and processing
- Raising first pass yield requires optimizing material, fabrication and processing as a package
- In the mean time, local repair worthwhile exploring to efficiently raise second-pass yield

Conclusion

- Encouraging progress in industry built cavities.
- Improved understanding of quench behaviors.
- Yet we still have to ask many questions:
  - **Why many 9-cell cavities (1m^2 surface) are limited < 20 MV/m by only one defect (< 1mm^2) in one cell while other cells already reaching 30-40 MV/m?**
  - **Why magnetic field enhancement alone is not sufficient to explain all quench behaviors?**
  - **Why no observable defects in some cases of quench limit?**
- Great opportunities ahead for finding answers as curious material/metallurgy researchers and eager industry partners are joining ILC SRF cavity community. Let's work together!

Conclusion (cont.)

- 9-cell cavity processing and testing opportunities in next 6 months for improving yield statistics
  - **3 BCD cavities + 8 large-crystal cavities at DESY**
  - **4 BCD cavities + x ICHIRO cavities at KEK**
  - **27 BCD cavities (3 from previous order + 24 new) + x ACD (Re-entrant, Large-crystal) cavities in US**
- Complementary 1-cell cavity program offers opportunities for creativity.
- And finally our effort is going to be stronger as we are joined by enthusiastic new contributors from Canada (TRIUMF), China (IHEP, PKU) and India (IUAC, RRCAT).