# New Ideas & Approaches to Raise CEBAF $Q_0$ – Initial Results and Proposed Studies

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# Outline

- Introduction
- Factor of 2 change in $Q_0$ from evaluation at VTA to placement in CEBAF
- Sources of change and mitigation
  - Understanding from past and present effort
  - Mitigations implemented and planned
- New opportunities
  - Frozen flux reduction by Cryogenic Thermal Annealing (CTA)
  - Whole-module degaussing
  - Impurity doping refurbishment cavities?
- Proposal for new studies and tests
- Conclusion

# Introduction

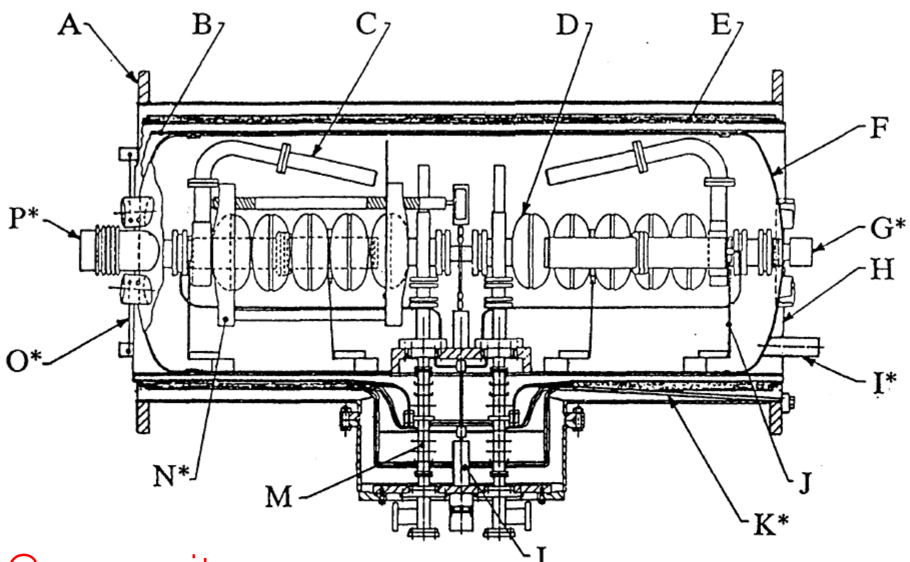
- Upgrade done. CEBAF has entered into new era of operation for NP.
  - 320 5-cell cavities plus 80 7-cell cavities in north- & south- linacs
  - High gradient (15-20 MV/m) in CW operation
    - Unprecedented
    - Unique large SRF linac – pushing reliability envelope
- Energy reach is crucial for CEBAF capability
  - Ultimate energy reach is constrained by $Q_0$ given fixed cavity shape and cryo-plant capacity (also RF source and LLRF)
- Energy efficiency is critical for sustainability
  - CEBAF needs to catch up in next few years for efficiency competitiveness
    - CEBAF: 2 GeV, 10 kW @ 2K
    - LCLS-II: 4 GeV, 8(4) kW @ 2K
- Seeking for establishment of new project to raise $Q_0$ of installed cavities in CEBAF: (a) without moving cryomodules out of tunnel;(b) within on-going C50 refurbishment effort.

# Original Cavity and Cryomodule

| | Design | Vertical testing | Cryomodule testing |
|---|---|---|---|
| <Eacc> | 5 | >5 | >5 |
| $Q_0$ at 2K at 5 MV/m | $2.4 \times 10^9$ | ~ $1 \times 10^{10}$ | ~ $5 \times 10^9$ |

Factor of 2 loss in $Q_0$

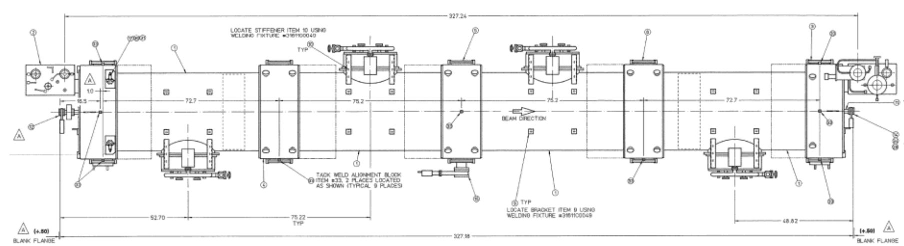
$Q_0$ met construction spec of $2.4 \times 10^9$




Cryo unit

A. Vacuum Shell Flange
B. Magnetic Shield and Inner Superinsulation
C. HOM Load
D. Cavity
E. Shield Superinsulation
F. Helium Vessel
G. Flange Surface on Isolation Valve
H. 40 to 50 K Radiation Shield
I. Shield Helium Supply Line
J. Outboard Cavity Support
K. Axial Support
L. Rotary Feedthrough
M. Fundamental Power Waveguide
N. Tuning Mechanism
O. Helium Vessel Support Rod
P. 2 K Helium Return

*Asterisked items shown only once to simplify illustration.



4x cryo unit -> cryomodule (8.25 m long)

# Sources of $Q_0$ Change and Mitigation

## Confirmed magnetic sources

| Source | Understanding | Mitigation | Mitigation implemented? |
|---|---|---|---|
| Magnetic strut springs | 302 SS, remanent magnetic flux, worse case 6 G at contact | Replace them by 316 SS springs | YES |
| Magnetic tuner drive shaft | 17-4 PH SS, remanent magnetic flux, worse case 1.7 G at contact | Replace them by 316 SS shaft | NO |
| Magnetic bearing | 440C SS, remanent magnetic flux typical 0.5 G at contact | Degauss first then re-use | YES |

## Other sources

| Source | Ruled out? |
|---|---|
| "Q-disease" from hydrogen in niobium material | YES |
| Window loss | TBD |

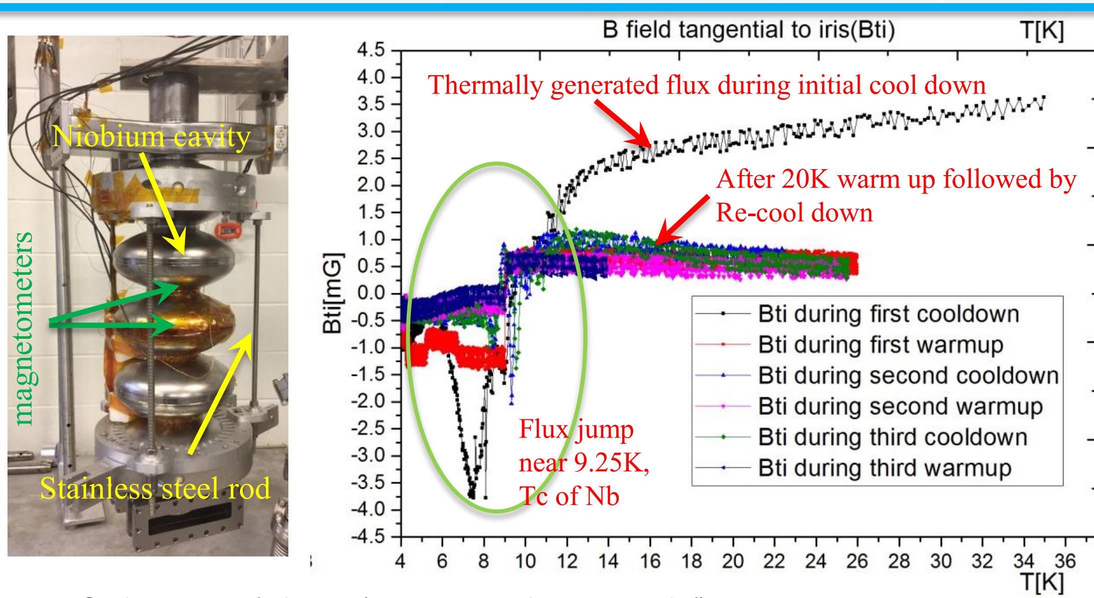
Work published at IPAC14 as a contributed talk, THOBB01 "Pursuing the Origin and Remediation of Low Q0 observed in the Original CEBAF Cryomodules"

# Sources of $Q_0$ Change and Mitigation (cont.)

## Sources under investigation/to be investigated

NEW

| Source | Testing result in hand? | Further test needed? | Potential benefit |
|---|---|---|---|
| Generated flux from thermal current effect | Initial testing result measured in VTA using a 5-cell dummy cavity | YES | May lead to a “thermal therapy” of in-situ $Q_0$ recovery in CEBAF tunnel |
| Additional flux trapping from repeated quenching events | NO | YES | May lead to an improved cryomodule testing procedure for full preservation of cavity $Q_0$ from VTA to tuunel |



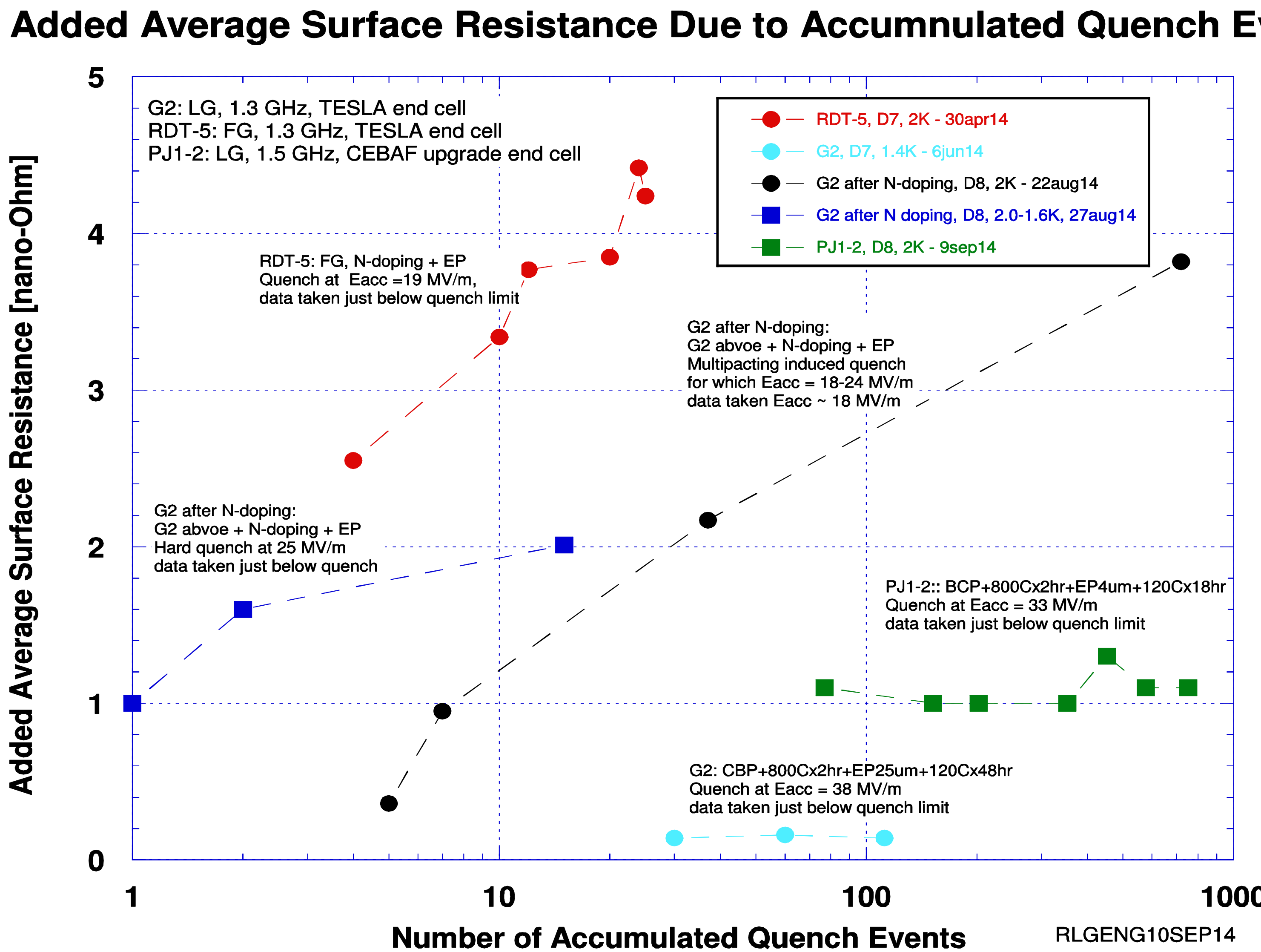

Series test of thermal current and generated flux using a 5-cell CEBAF cavity

Shichun Huang

Presently:

- Examination of magnetic flux *thermally generated* inside the loop formed between niobium cavity and stainless steels rods
- Developing a thermal current model for prediction of generated flux of cavity pair in a cryo-unit.
- A potential “thermal therapy” is being developed for zero out the thermally generated flux.

# Additional flux trapping from repeated quenching events




JLAB-TN-14-021

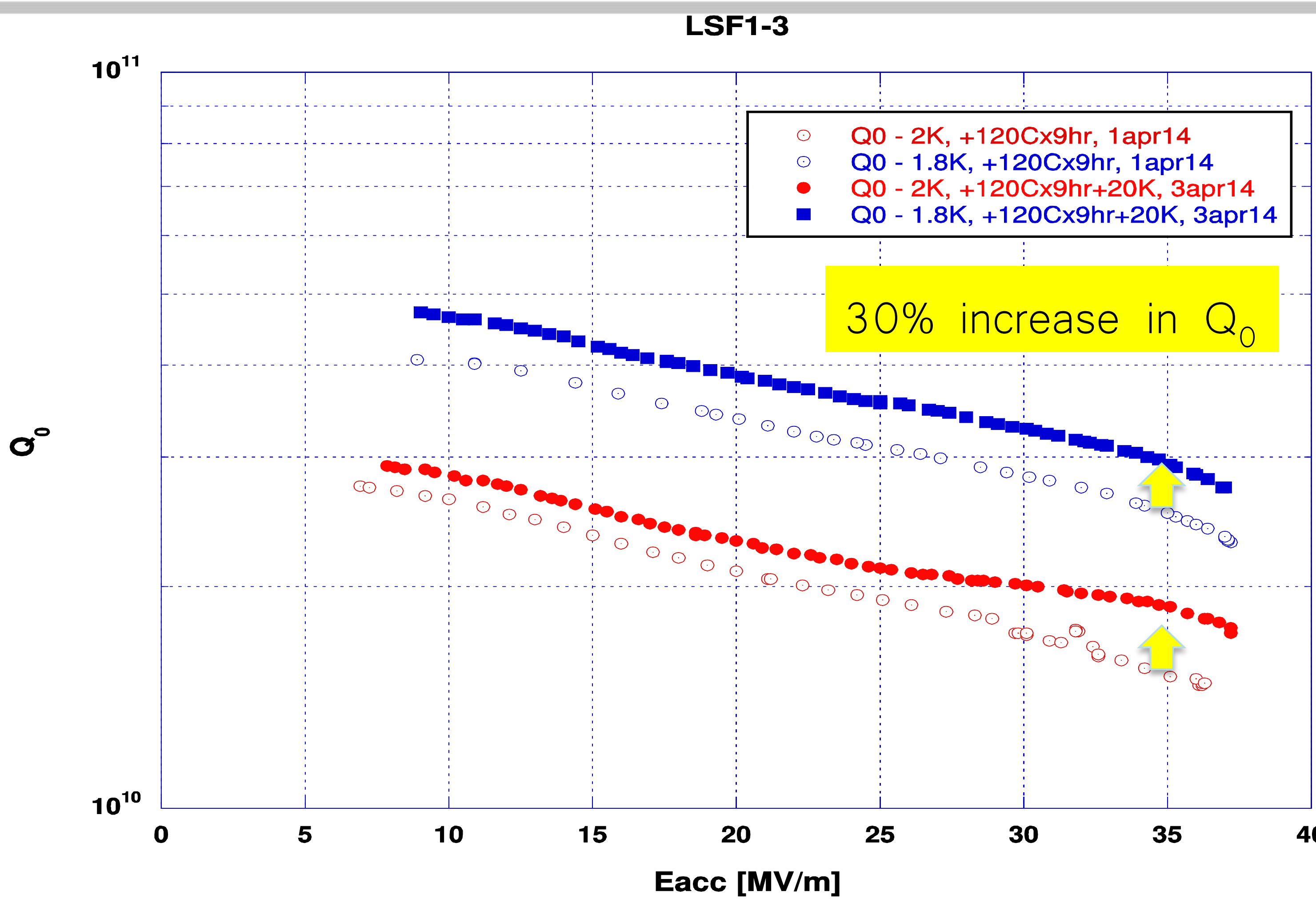
# Impact Factors

| SRF Machine | Duty Factor [%] | Design $Q_0$ [$10^{10}$] | Surface resistance [nΩ] | Relative increase for 4 nΩ added surface resistance | Number of high $Q_0$ cavities | Impact level |
|---|---|---|---|---|---|---|
| CEBAF-original | 100 | 0.24 | 114 | 4% | 338 | Negligible |
| CEBAF-upgrade | 100 | 0.72 | 39 | 10% | 80 | Low |
| XFEL | 0.65 | 1.0 | 27 | 15% | 800 | Medium |
| LCLS-II | 100 | 2.7 | 10 | 40% | ~300 | High |
| ILC-baseline | 0.65 | 1.0 | 27 | 15% | 16000 | Medium |
| ILC-low loss | 0.65 | 2.0 | 14 | 30% | 16000 | High |

# New Opportunities

- Frozen flux reduction by CTA
- Whole-module degaussing
- Impurity doping of re-furbished cavities

# 1-Cell Cavity Testing of CTA


LSF1-3

1.3 GHz

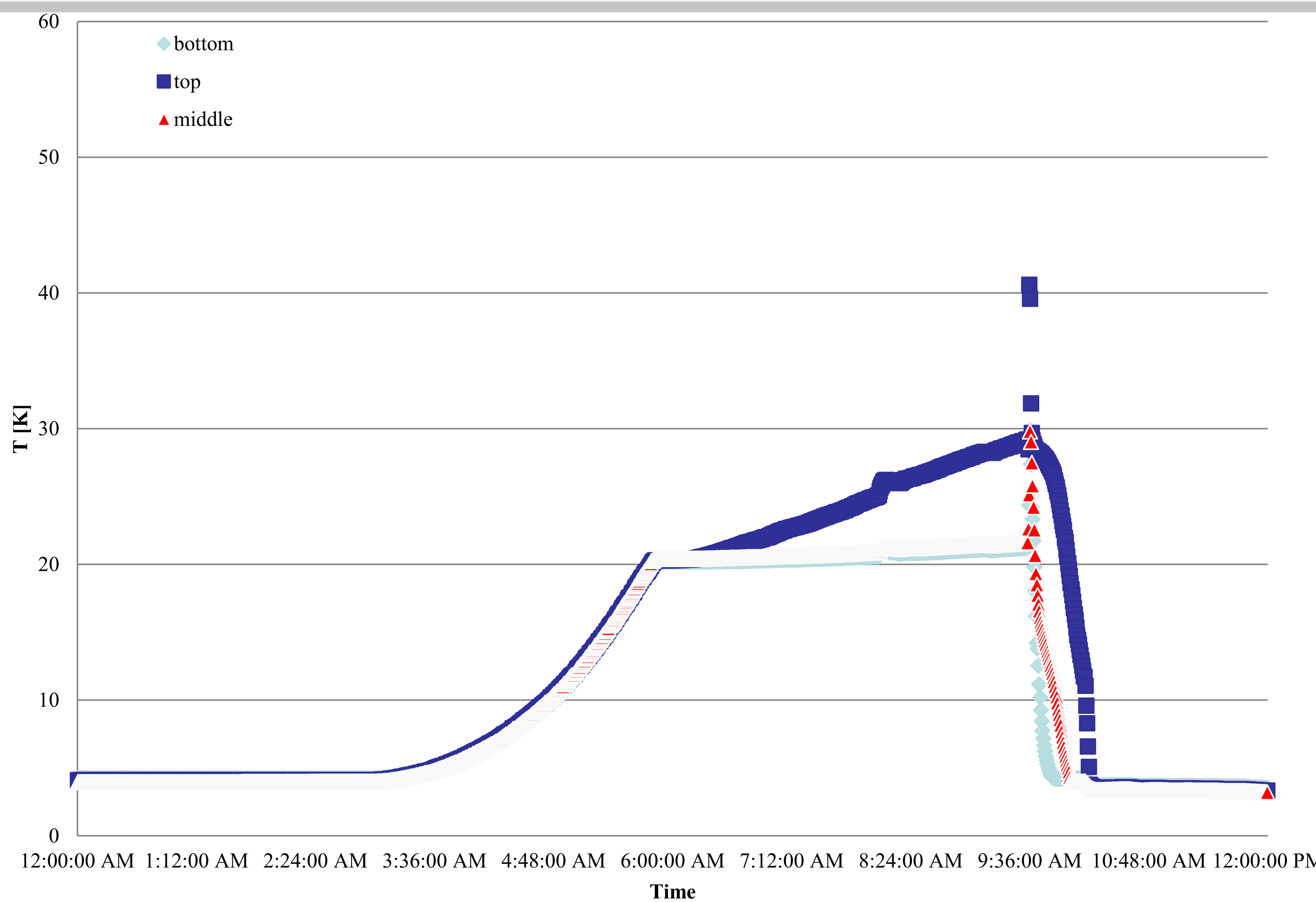
LSF Shape

Large-Grain Nb

Cavity processing:

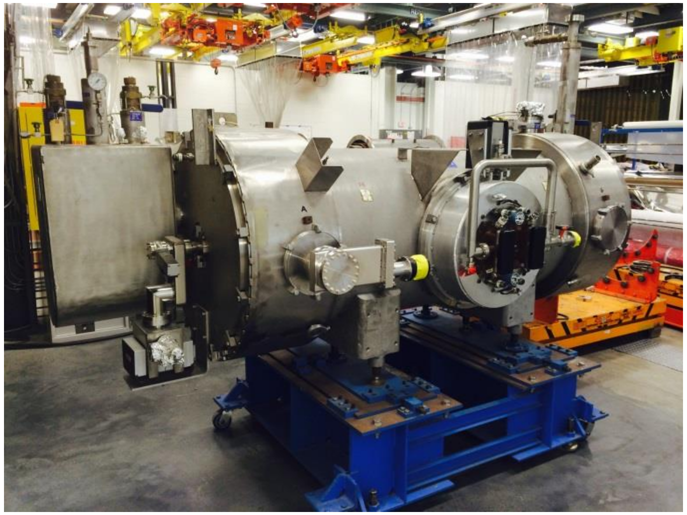
BCP 60 um + 800Cx2hr + BCP 20 um + 120Cx9hr

# LSF1-3 partial warm to 20 K then re-cool down



# Whole-module degaussing

- De-magnetize whole cryomoudle
  - Could lead to a solution applicable to cryomodules placed in CEBAF without moving them out of tunnel.
- Feasibility test with a cryo-unit or a quarter module



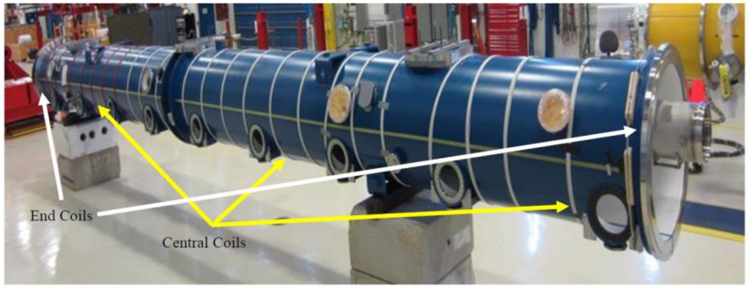



Figure 2. Coils used for De-magnetization

A. Crawford, Superconducting RF Cryomodule Demagnetization, arXiv:1503.04736

# Impurity Doping of Re-furbished Cavities

- Impurity doping (Ti, N) has shown benefit of raising $Q_0$.
- A workable procedure is now available in-house for nitrogen doping due to work for LCLS-II.
- A number of 9-cell XFEL/ILC cavities have been treated with nitrogen doping and tested at JLAB with good Q values up to the regime of 20 MV/m.
- A 7-cell C100-style was nitrogen doped and tested horizontally in a one-cavity cryomodule, with good Q values.
- Therefore...

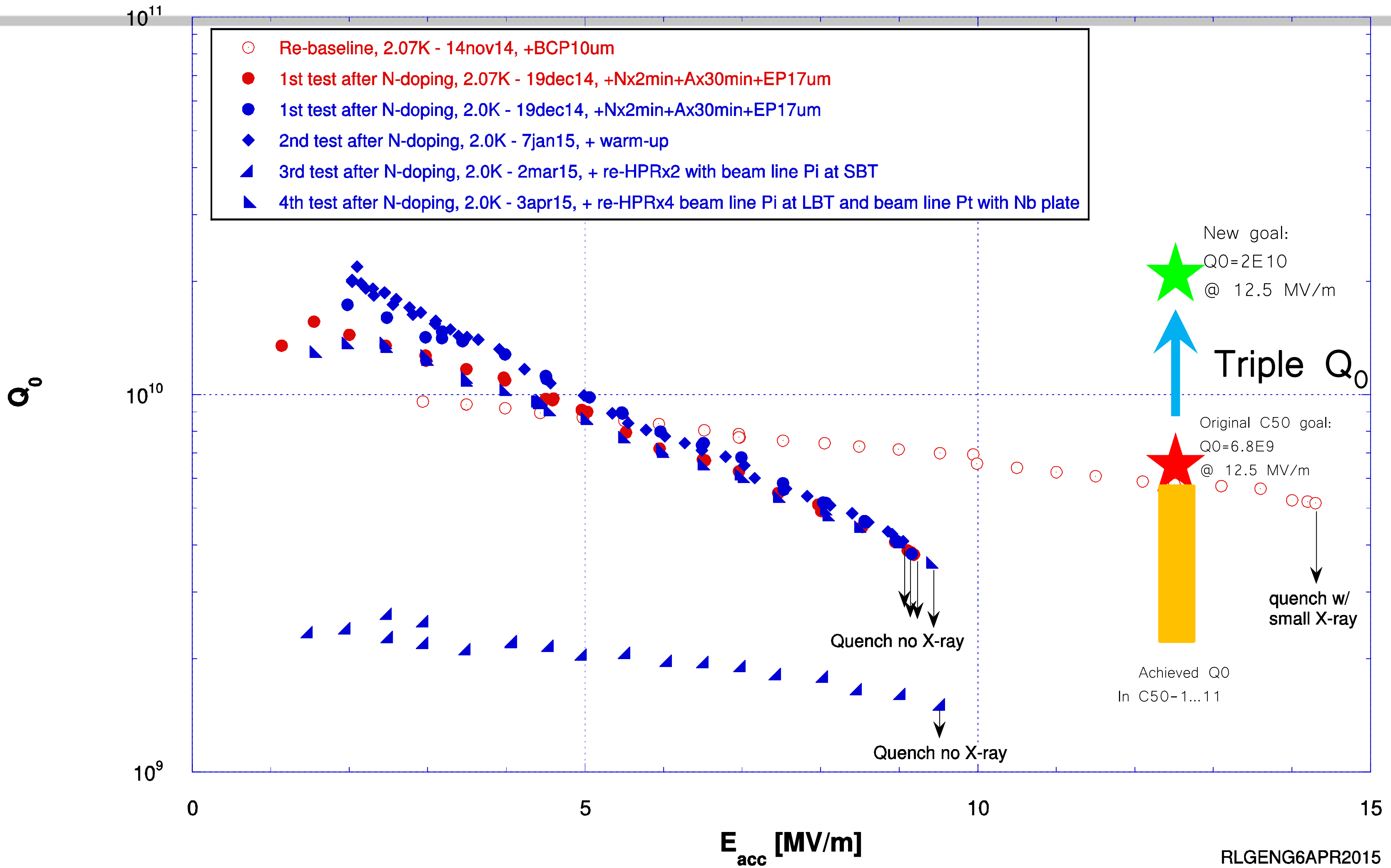
# Impurity Doping of Re-furbished Cavities (cont.)

- At September 22, 2014 C50-12 pre-kickoff meeting, a decision was made to test Nitrogen doping on a CEBAF 5-cell cavity.

- The goal is to raise cavity $Q_0$ in a CEBAF re-work cryomodule beyond what can be imagined before by exploitation of nitrogen doping technique that was made available in-house for LCLS-II $Q_0$ R&D.

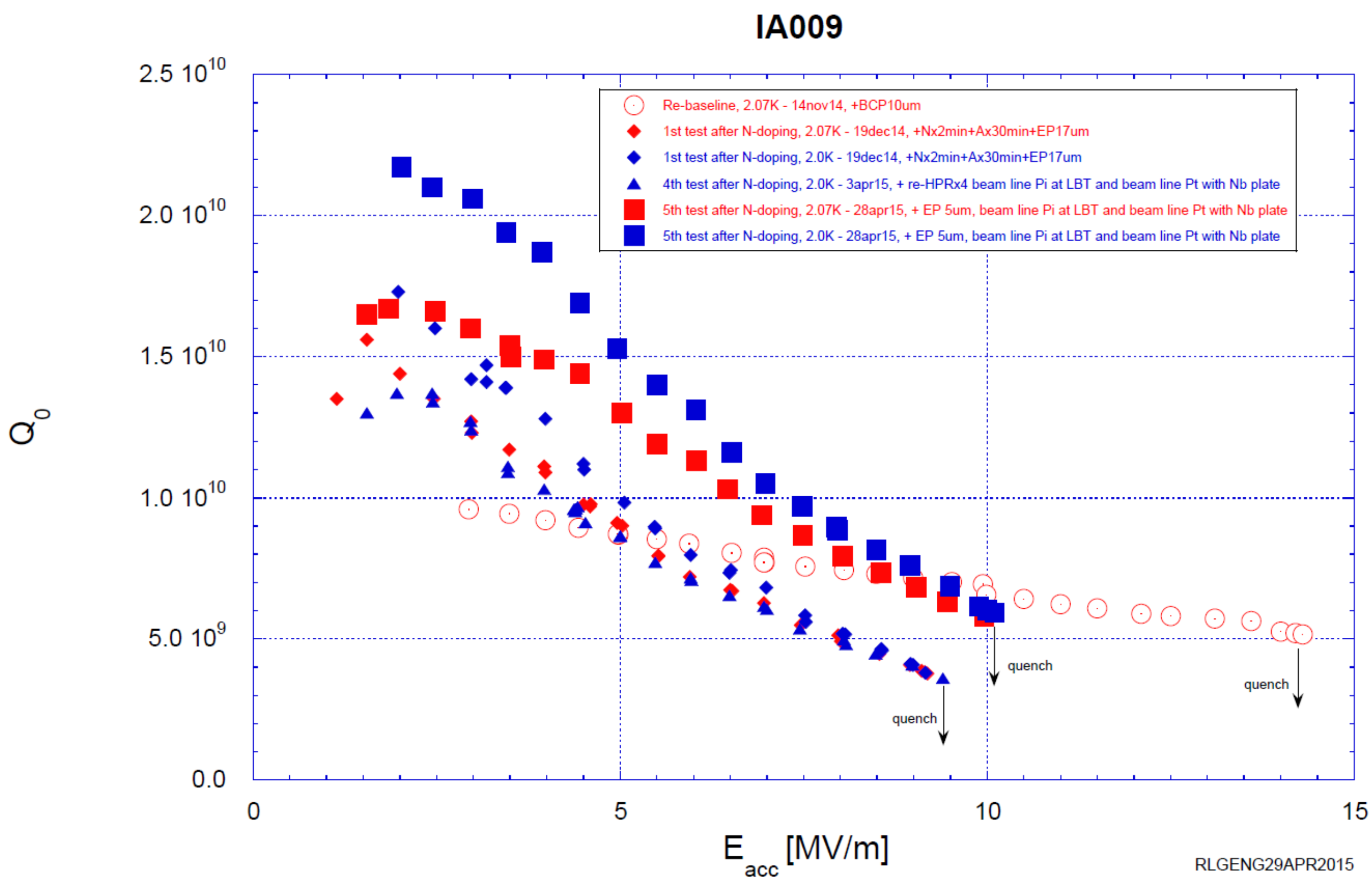
- Cavity IA009 was chosen for this study.

# CEBAF 5-Cell Cavity IA009

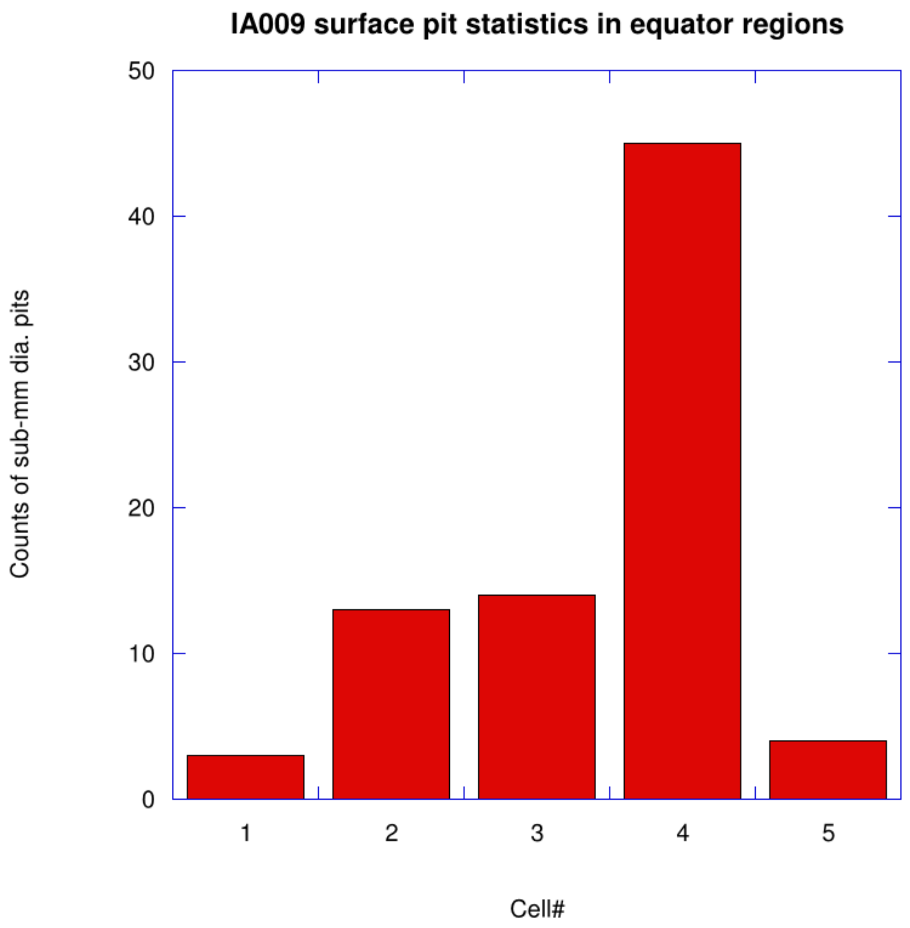


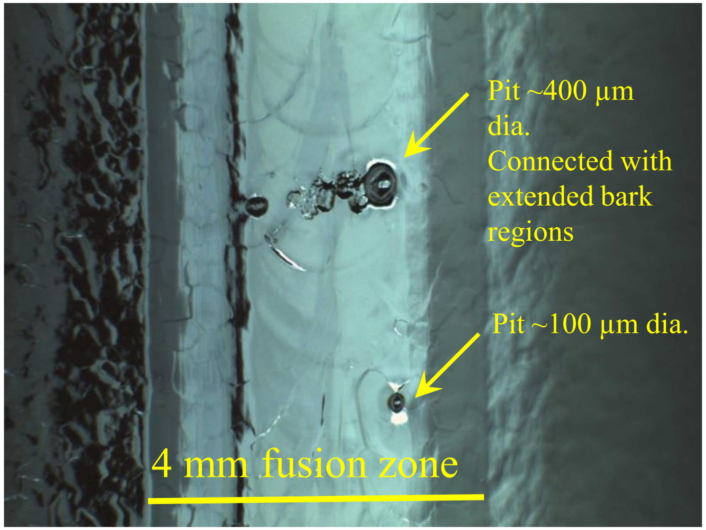

RLGENG6APR2015

# IA009 Performance Evolution since Re-baseline



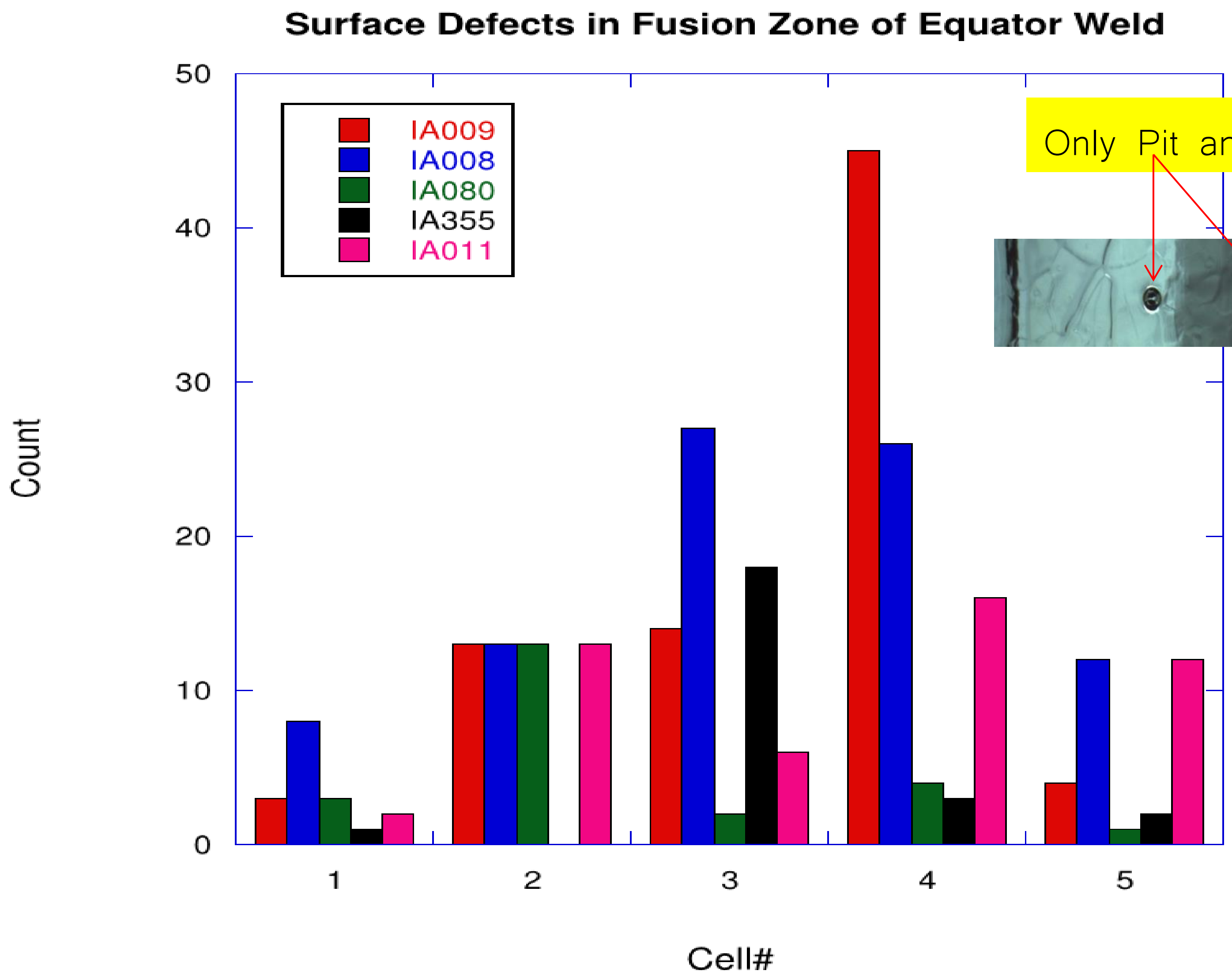
# Discovery of Surface Defects

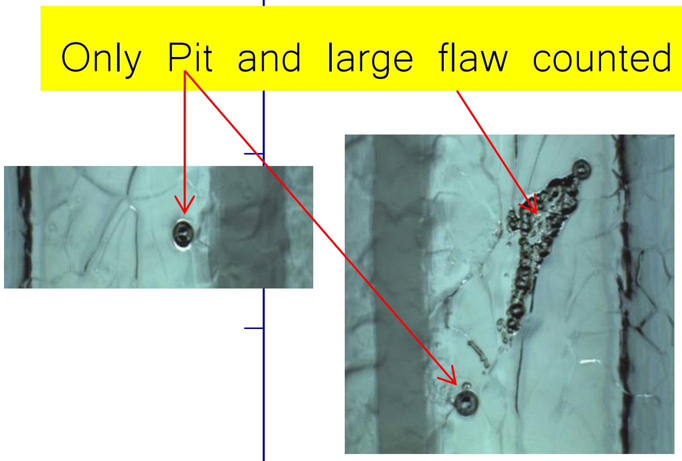



Outstanding defects in fusion zone of equator weld of cell #4

# Expanded Inspection of Surface Defects



# Conclusion on Preliminary 5-Cell N-doping

- First attempt in raising $Q_0$ by N-doping (IA009) is not successful, as a result of "grave" **F**usion **Z**one **D**efect (FZD).
- Optical inspection of 4 more 5-cell cavities revealed similar FZD's in similar amount.
- FZD's can be classified into three types: (1) pit; (2) ripple; (3) "large flaw". They are believed to originate from material/fabrication and therefore can be considered "genetic".
- FZD is rarely observable on modern-day Nb cavities.
- It seems that *"any attempt to further raise the $Q_0$ of these cavities by re-processing may face a brick wall"*.
  - Nature FZD and their interplay with N-doping deserve studies.
  - Cure FZD by barrels polishing may help and should be evaluated.

# Proposal for New Studies and Tests

- Systematic VTA cavity testing for frozen flux effect.
  - Test the CTA procedure for recovering $Q_0$ of cavities under the standard cavity pair configuration. (High impact potential)
    - Verify the thermal current model that has been developed from one 5-cell dummy cavity test.
    - Develop a CTA recipe of "thermal therapy" to be applied *in-situ* over all 5-cell cavities currently placed in tunnel.
  - Complete the unfinished C50-12 activities. (Impact the future re-furbishment cryomodules)
    - Progressive component addition to cavity pair to pin-point magnetized components.
    - Experiment "local shielding" over the center cells.
    - Assess window loss contribution.

# Proposal for New Studies and Tests (cont.)

- Test the feasibility of “whole module” de-magnetization.
  - Test with dummy cryo-unit.
    - Series tests with progressively added components around cavity.
    - Assess shielding factors of the inner shield and the outer shield
    - Characterize the magnetization of the shielding itself.
  - Cryogenic test of a cavity pair in a short cryomoudle
    - Mini-test of CTA.
    - Study added frozen flux from repeated quench events.

# Proposal for New Studies and Tests (cont.)

- Further evaluation of nitrogen-doping for raising $Q_0$ 5-cell cavities, including possible re-doping after barrel polishing.
  - Two cavites in hand:
    - IA008 (N-doping completed)
    - IA011
  - A clear conclusion on N-doping is useful
    - Positive answer sets solid ground for possible future path of $Nb_3Sn$ re-treatment.
    - Negative answer sets solid ground for possible future path of "LG cell transplant"
- Fundamental studies of defects in IA009
  - Dissect cavity, make 5 each 1-cell cavities, test with T-mapping, cut out quench area for material studies.
  - Recycle end groups for "C75" cavities with transplanted cells.

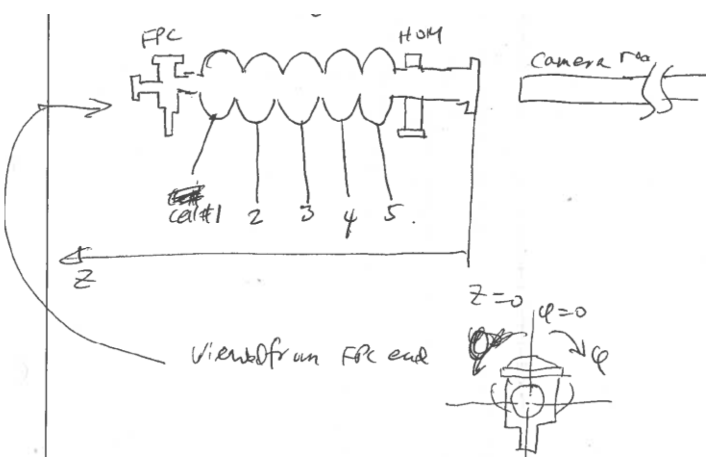
# Conclusion

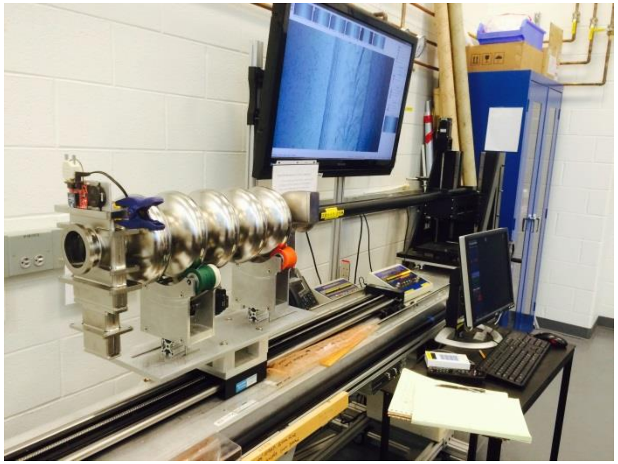
- The low $Q_0$ issue of 5-cell CEBAF cavities remains outstanding.
  - Understanding of $Q_0$ damage from magnetized components in hand, one change implemented in C50-11. One more change is to be implemented in C50-12.
- The effort in raising $Q_0$ of placed cavities in CEBAF has led us to explore inexpensive solutions applicable *in-situ* for raising *average* $Q_0$.
  - Cryogenic Thermal Annealing.
  - Whole-module degaussing.
- The effort in raising $Q_0$ for C50 refurbishment by N-doping 5-cell cavities met the issue of genetic FZDs. Further studies needed.
- Effort in $Q_0$ improvement and field emission reduction is related.
- Proposal is to establish a new project, whose objective is to raise $Q_0$ of installed cavities in CEBAF: (a) without moving cryomodules out of tunnel;(b) within on-going C50 refurbishment effort.
- A detailed cost of the proposed studies is being developed (< $150K).

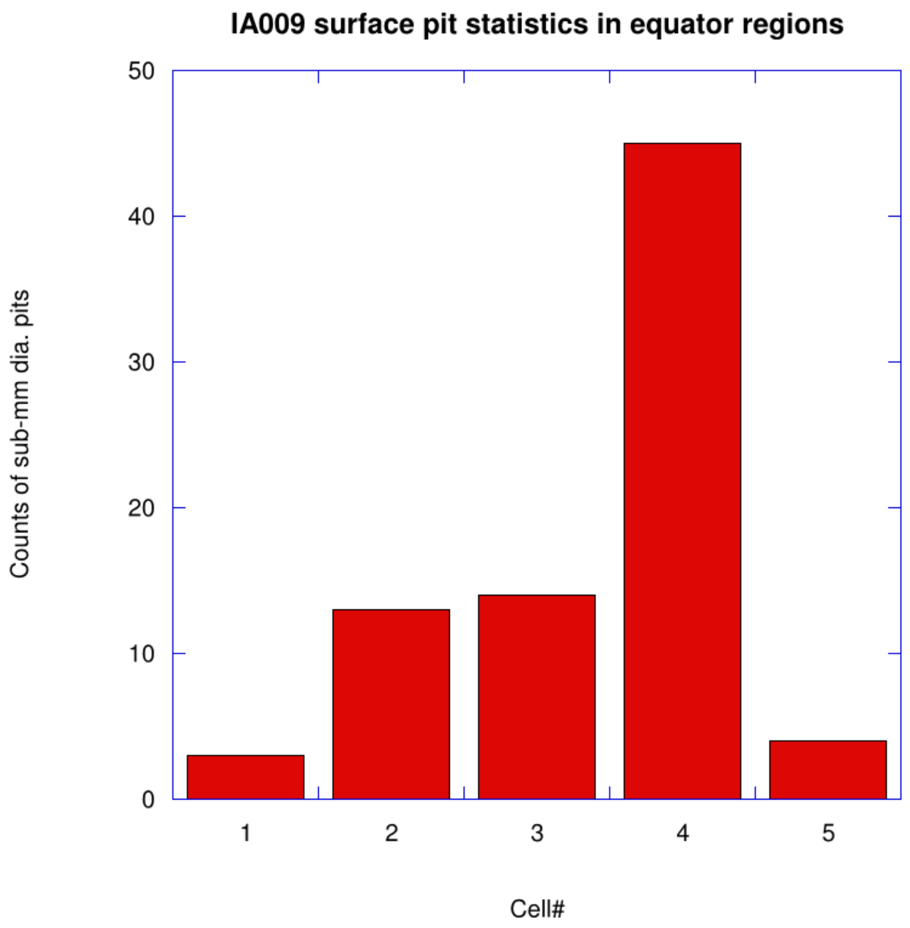
# Backup Slides

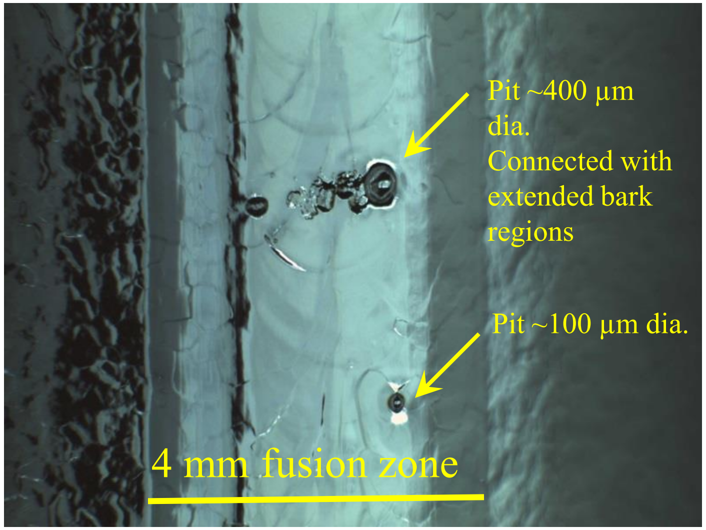
# IA009 Actions since 5/5/15

- Cavity vented, removed from test stand, fully dis-assembled.
- Optical inspection of equator regions.
  - Cell number starting at input power coupler side
  - Angle definition: 0°= 12 o'clock, direction=clock-wise



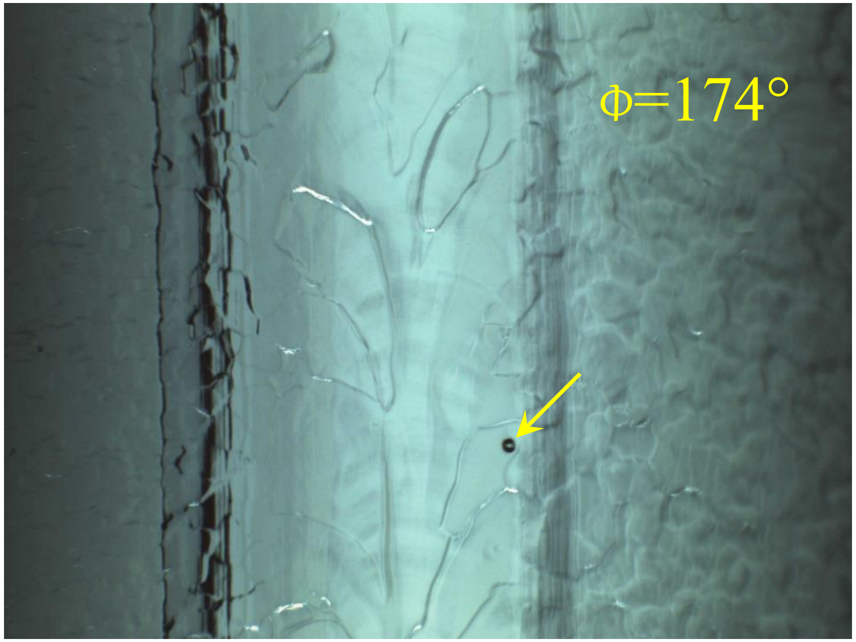


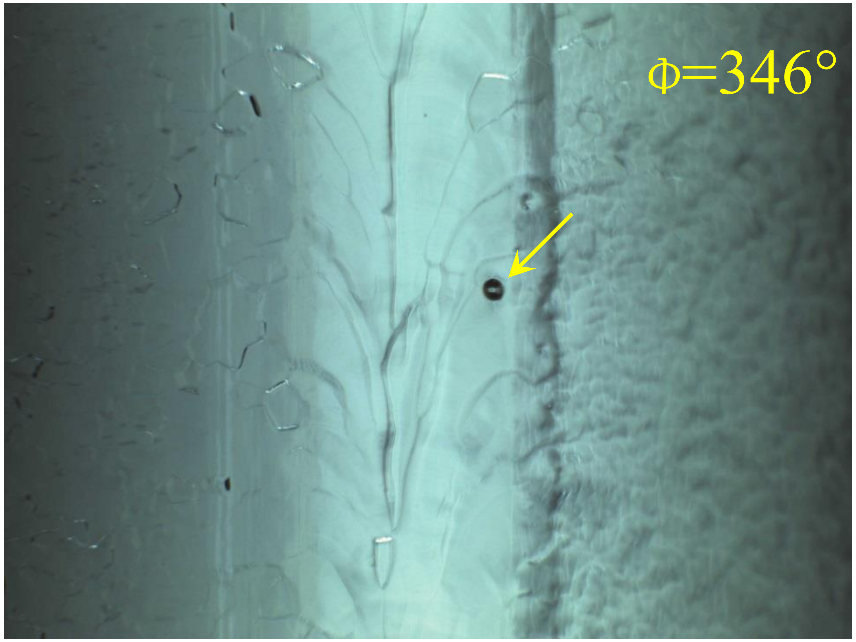




Outstanding defects in fusion zone of equator weld of cell #4

# Cell #1 Equator Weld

Pits (3 in total, smaller than average)

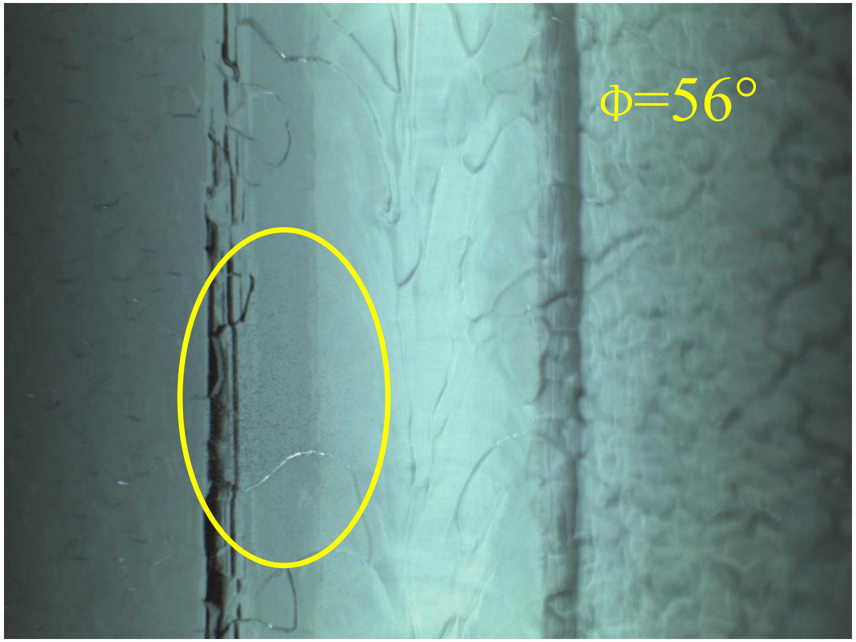


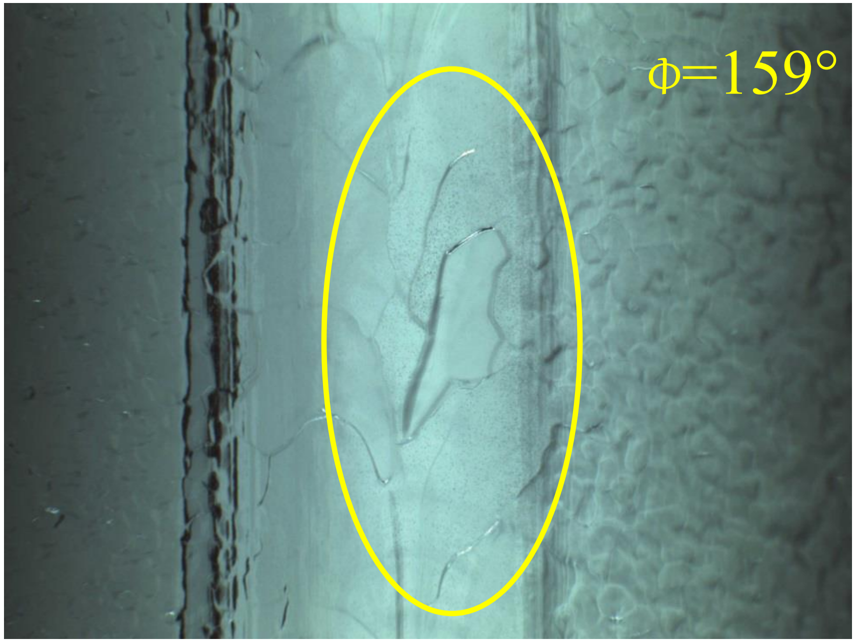



# Cell #1 Equator Weld

speckles (clustered in a few regions, only cell showing this)

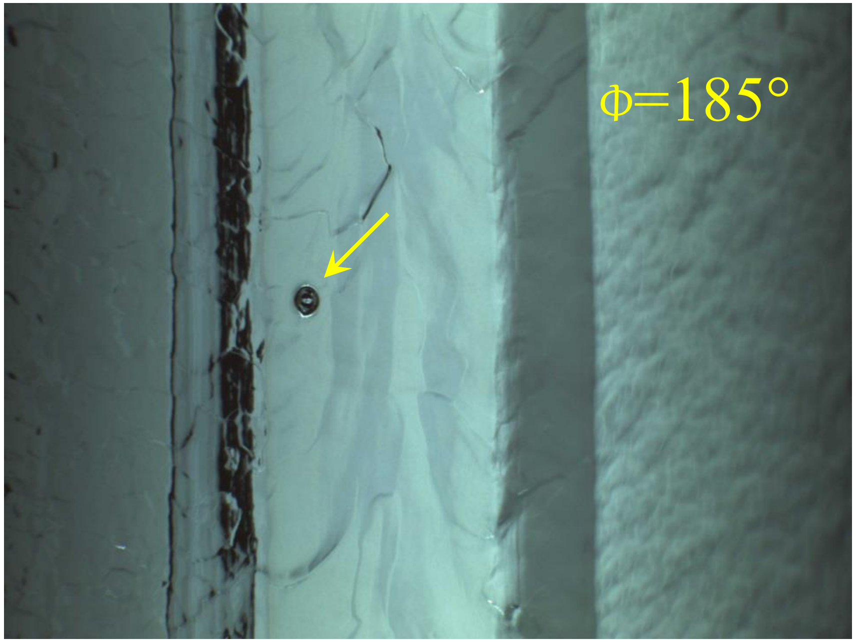
Nitrogen-rich islands due to insufficient surface removal?

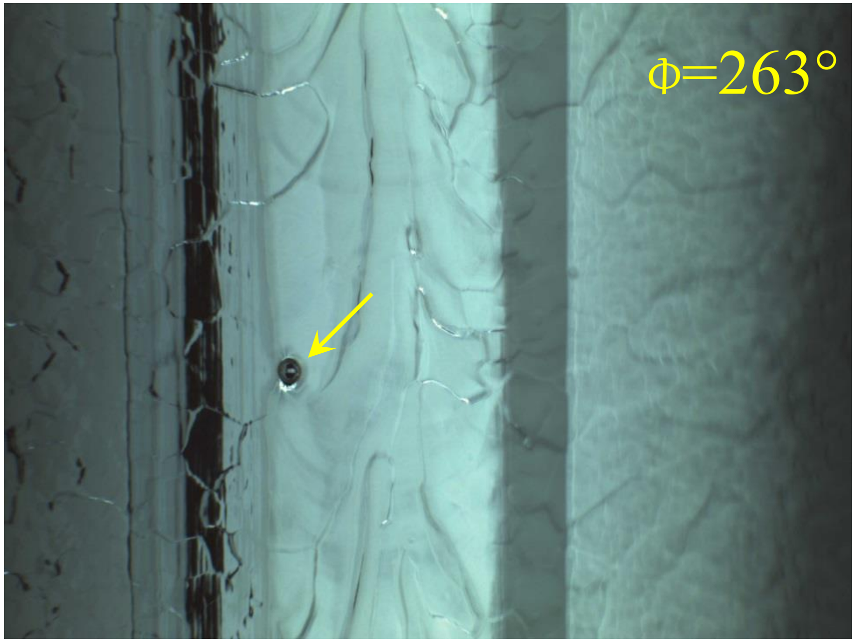


# Cell #2 Equator Weld

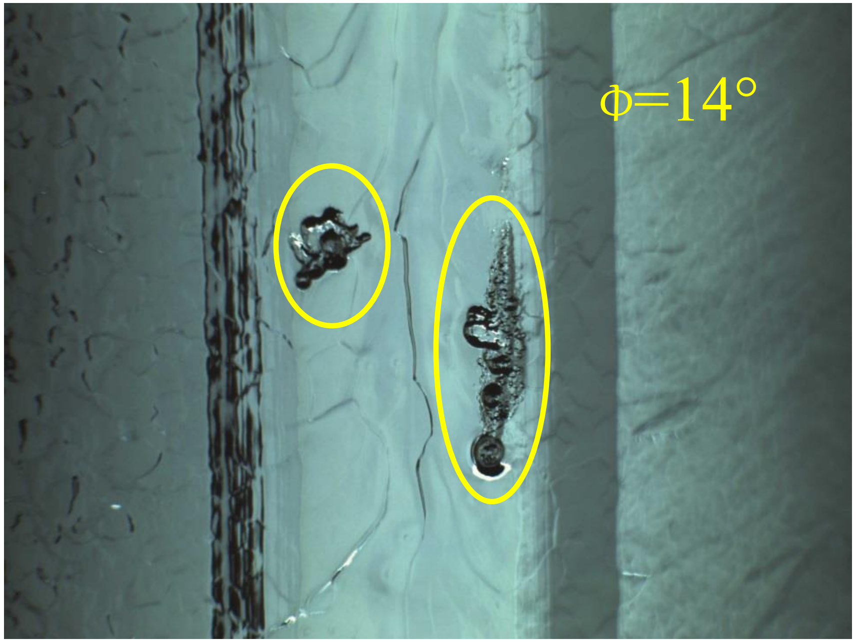
Pits (13 in total, 2 typical examples shown)

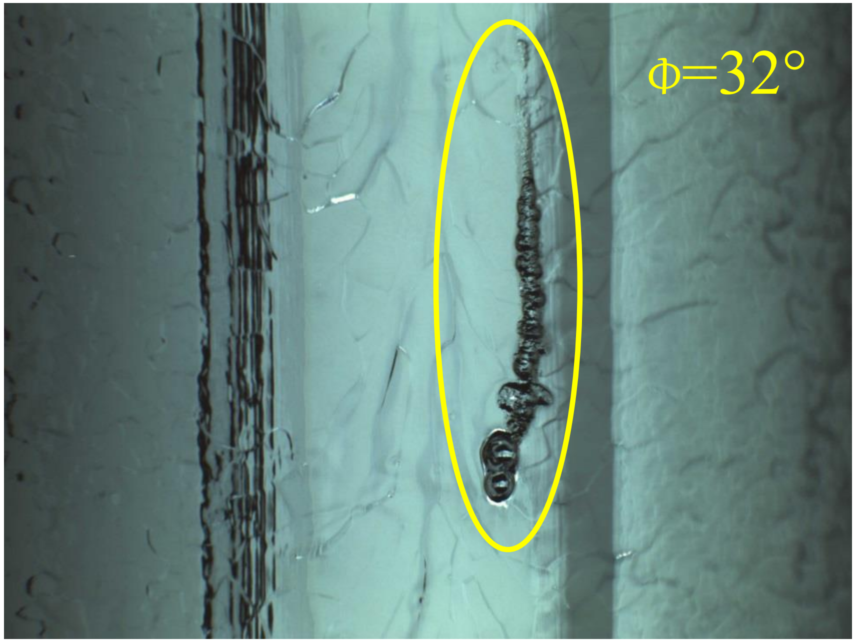


# Cell #2 Equator Weld

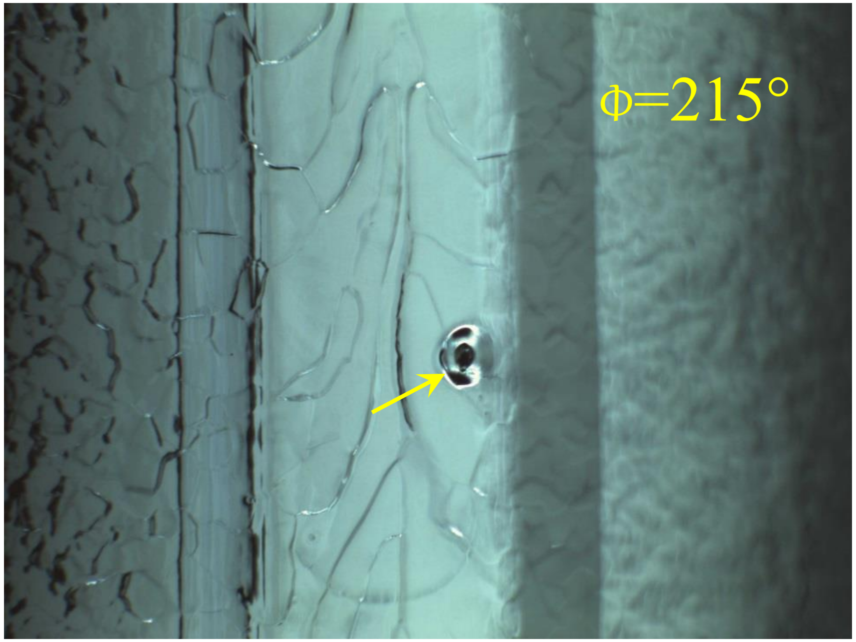
Large flaws



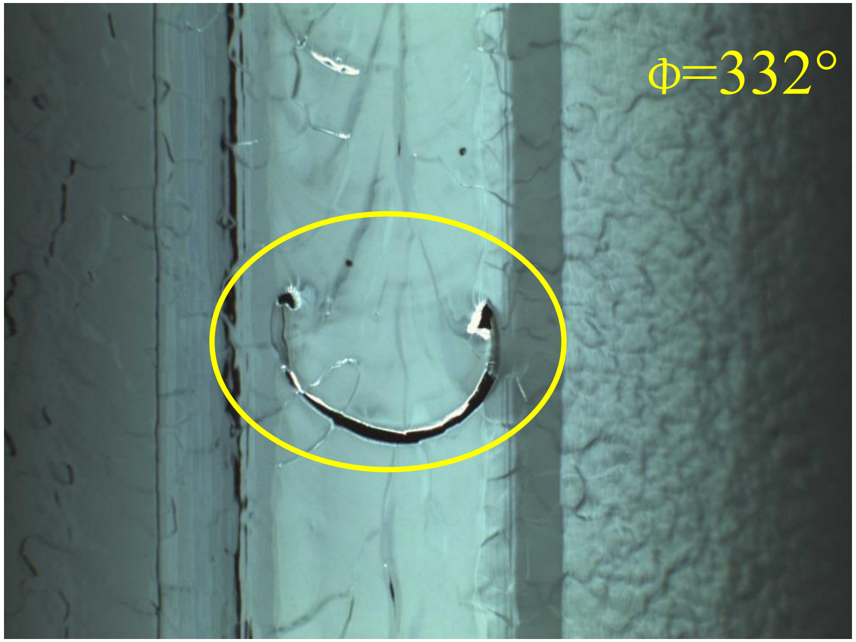



# Cell #3 Equator Weld

Pits (14 total, largest shown)

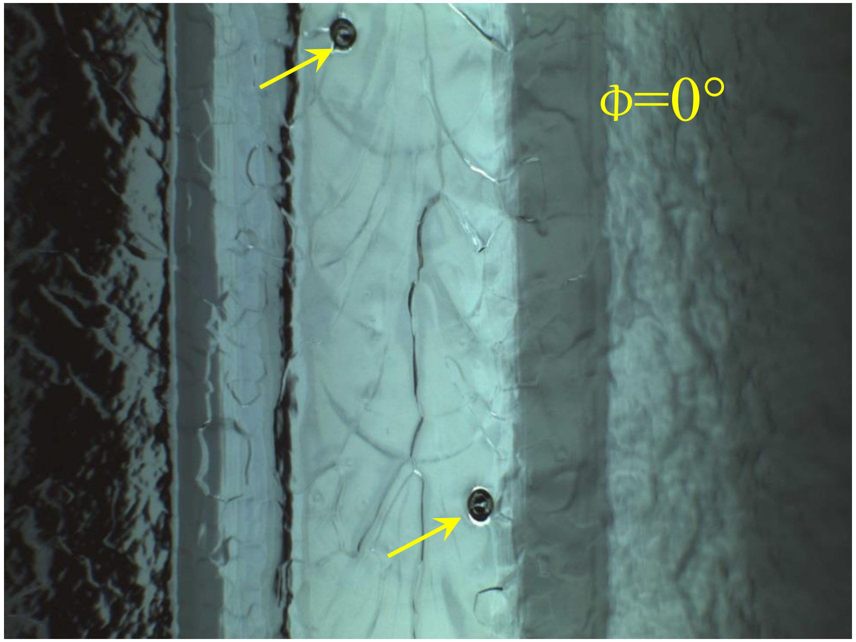


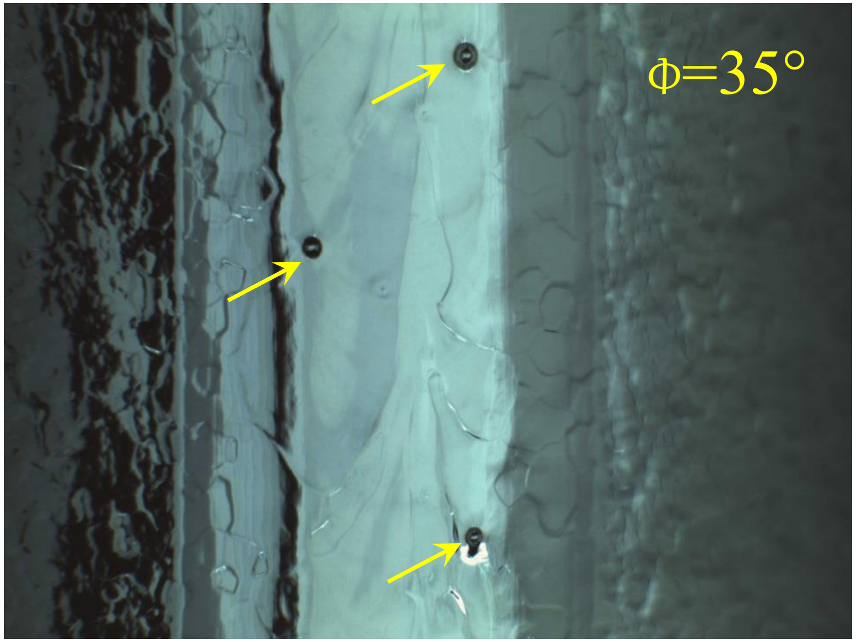

Curved linear feature (ripple of molten Nb?)



# Cell #4 Equator Weld

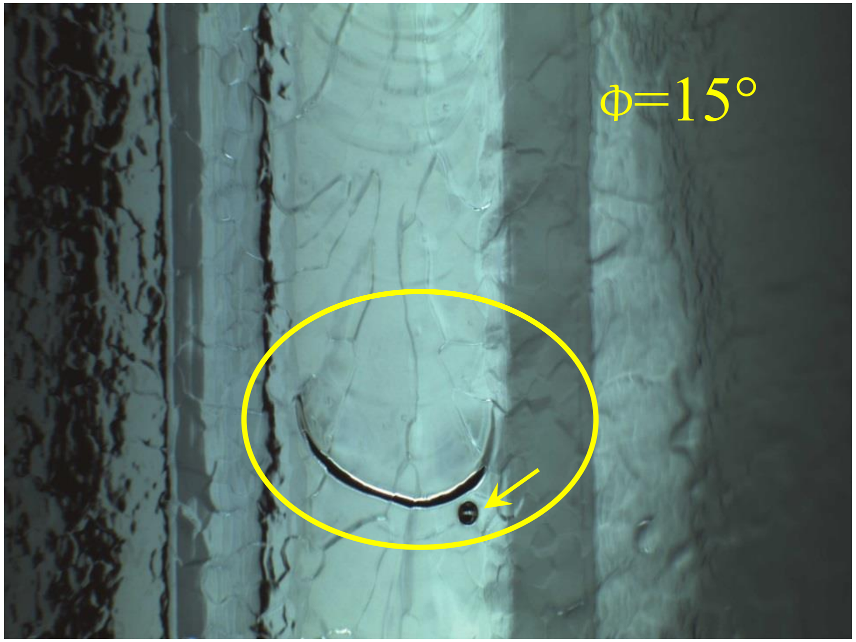
Pits (45 total, a few typical shown)

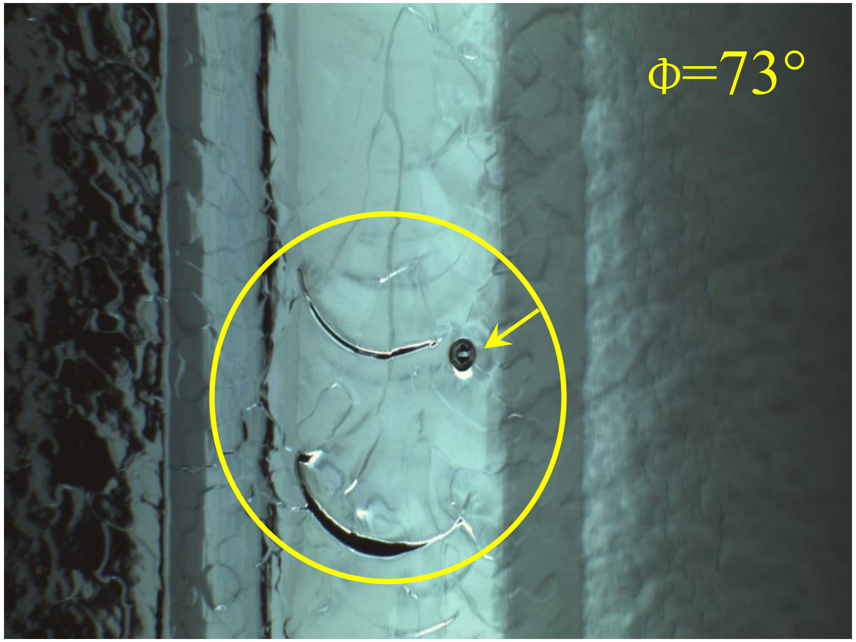


# Cell #4 Equator Weld

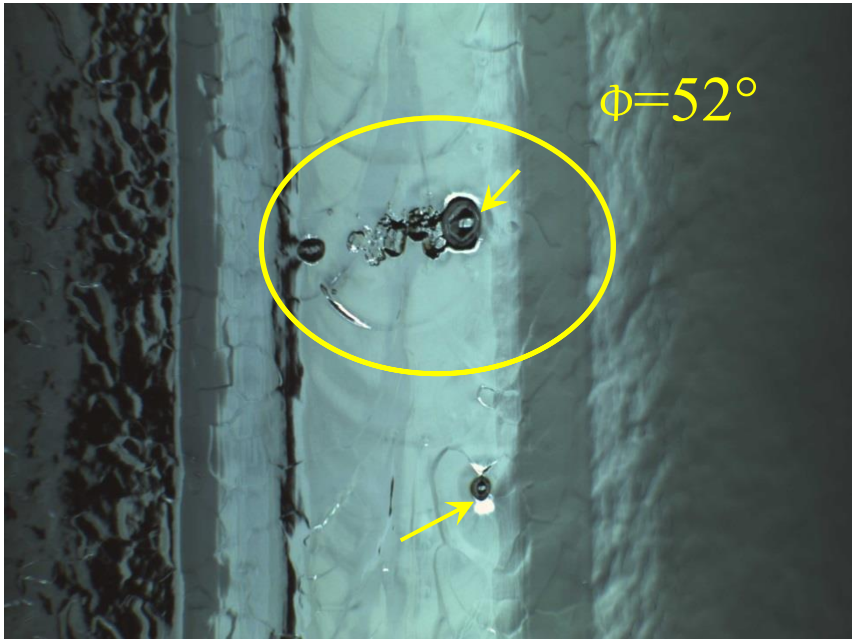
Pits next to ripple

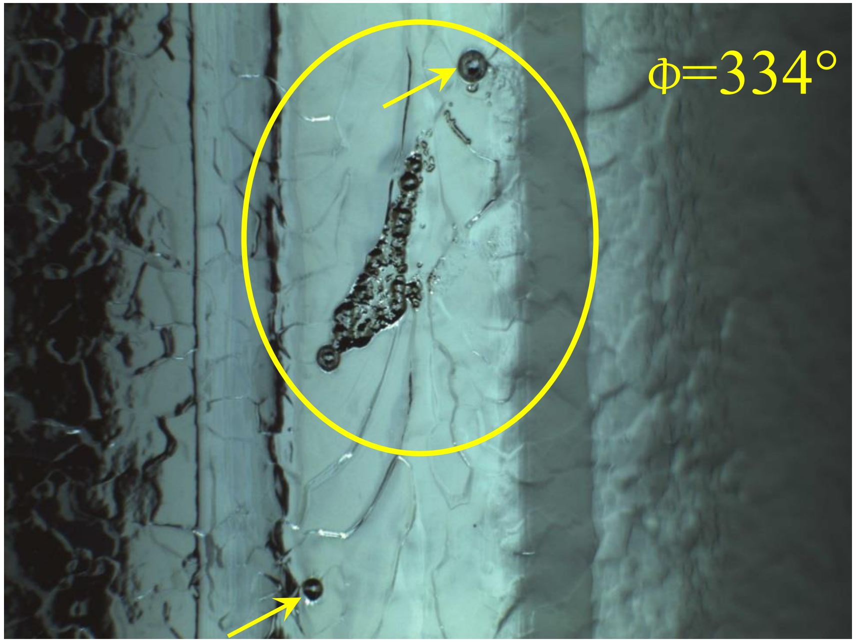


# Cell #4 Equator Weld

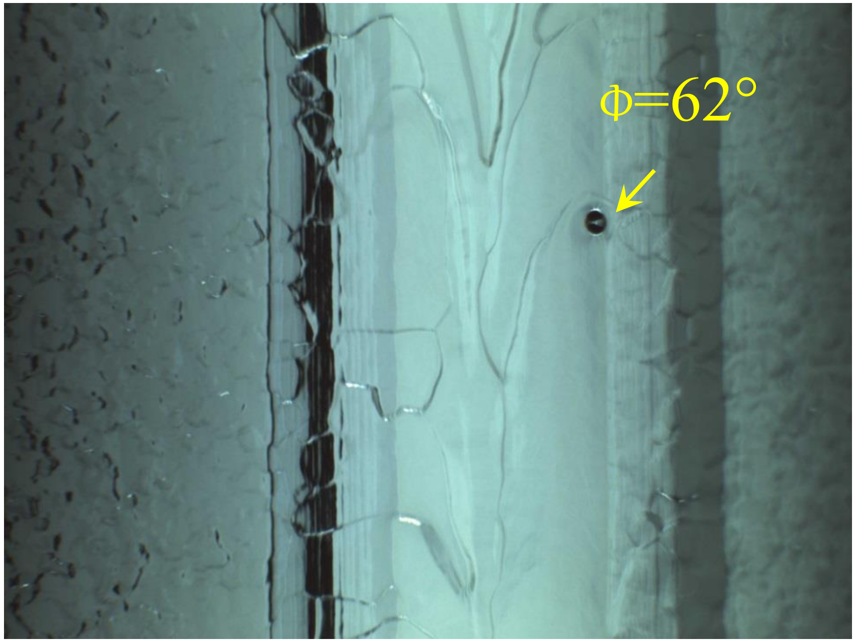
Large flaws



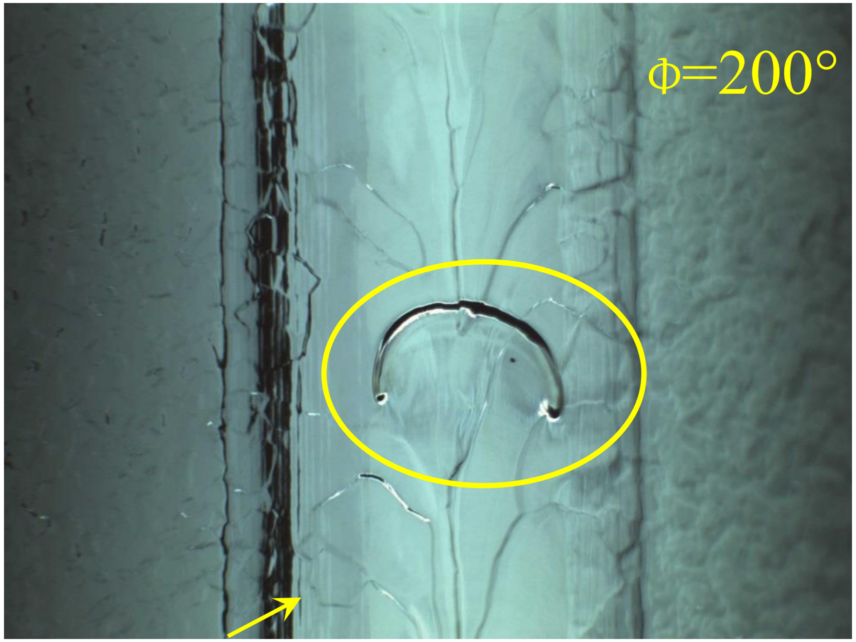



# Cell #4 Equator Weld

Pits (4 total, largest shown)




Curved linear feature (ripple of molten Nb?)



# 5/14/15 Conclusion

- Post VTA optical inspection revealed surprisingly large number of defects (pits, ripples and large flaws).
- Cell #2 & #4 are the worst – both have large flaws
- Cell #1 & #5 are the best; #3 in the middle.
- The heavy defect in cell #2 & #4 is consistent with previous finding of cell #2/4 being the most lossy; is also consistent with previous finding of cell #2/4 are among candidate cells responsible for quench at 9 MV/m.
- “Cloudy” speckles observed on cell #1 equator weld surface. We suspect these are nitrogen-rich islands due to insufficient EP removal.

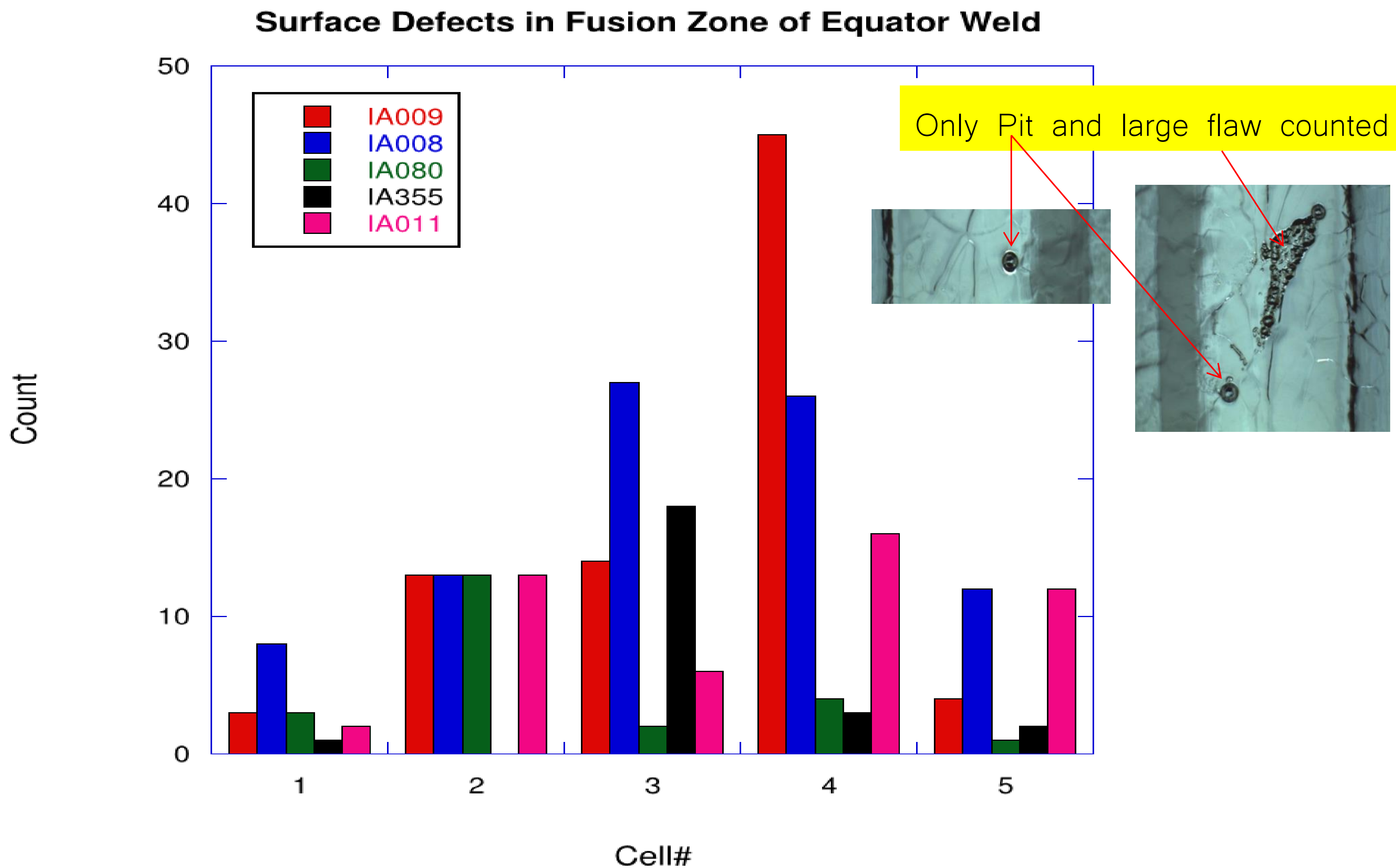
# 5/14/15 Conclusion (cont.)

- Based on good correlation between pass-band measurements and optical inspection results, we conclude both the premature quench and the strong Q-slope of IA009 after nitrogen doping was caused by grave defects in fusion zone of cell #2/4 equator welds.
- From RG's past experience, there is little chance of further improving the cavity performance by another EP.
- Based on optical inspection data of IA009 (2015) and IA015 (2008), we conclude the "fusion zone defect (FZD)" is a genetic character in all original CEBAF cavities, due to the then cavity EBW technology. Therefore, any attempt to further raise the $Q_0$ of these cavities by re-processing may face a brick wall. We propose to terminate the N-doping CEBAF cavity experiment. Instead, start to evaluate a cure to pit first.
- We seem to have a case of insufficient EP removal in cell #1 of a CEBAF 5-cell cavity.

# Actions since May 14

Carried out optical inspection of four 5-cell CEBAF cavities

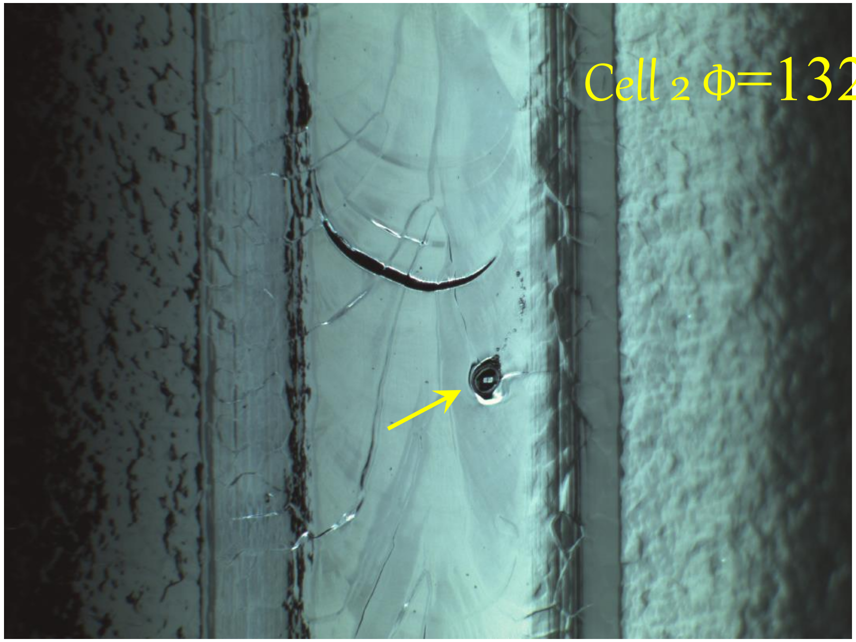
| Cavity | Last surface treatment and performance | Note |
|---|---|---|
| IA011 | Unknown (most likely BCP) | Cavity received from LP |
| IA080 | Unknown (most likely BCP) | Cavity dis-assembled from a cryomodule (FEL?) to be re-worked and become C50-12. Cavity have "large grains" all over places – apparently heat treated to high temperature (at least 1250 °C) in its past life. |
| IA355 | Unknown (most likely BCP) | ibid |
| IA008 | Nitrogen doping (no cryogenic RF test after nitrogen doping) | Pre-nitrogen doping processing history unknown. Latest cold test on 4/8/2013; 3/12/2013; 10/15/2008 |

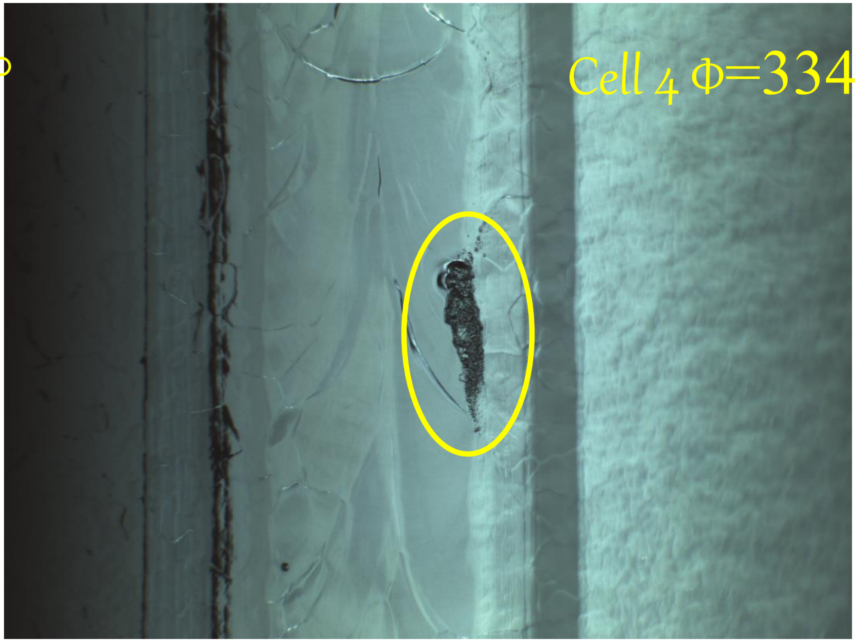

Surface Defects in Fusion Zone of Equator Weld
Count
Cell#
0
10
20
30
40
50
1
2
3
4
5
IA009
IA008
IA080
IA355
IA011
Only Pit and large flaw counted

# IA008 (Nitrogen doped)

pit

Large flaw

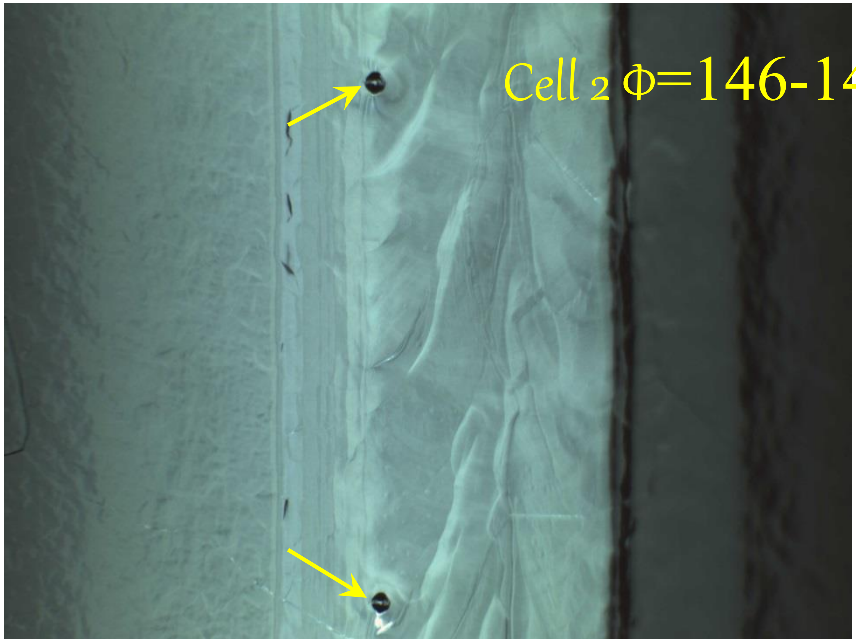


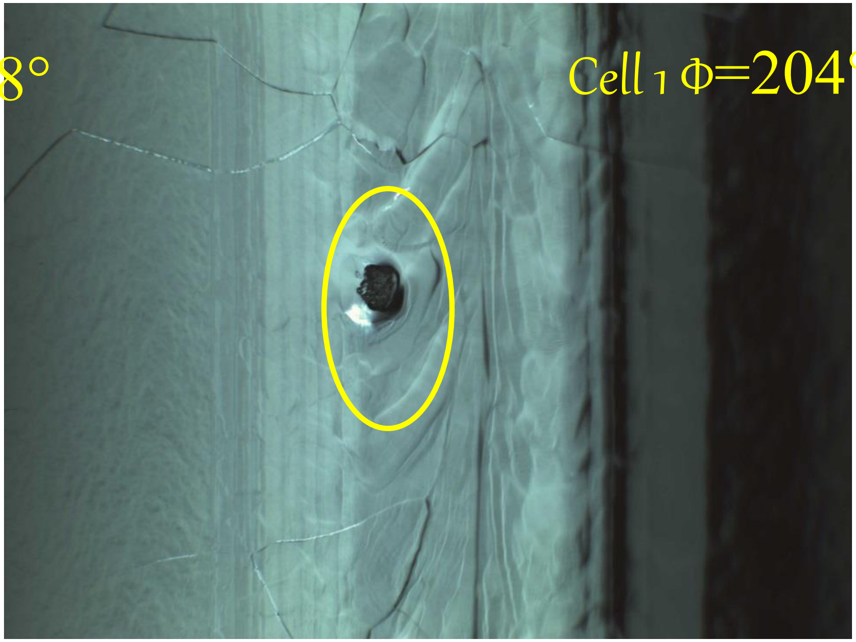
# IA080

(removed from module to be re-worked and become C50-12, "Large grain")

pit



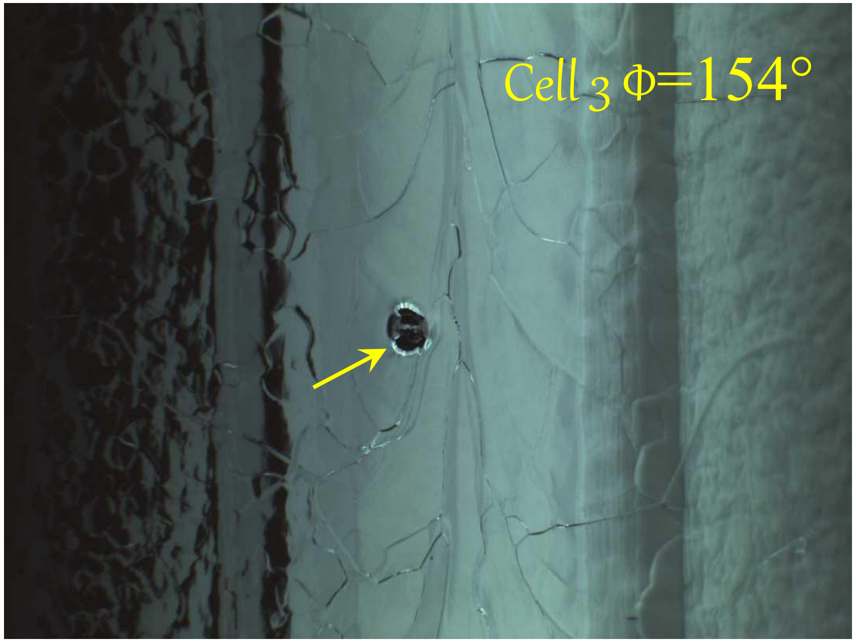

Large flaw



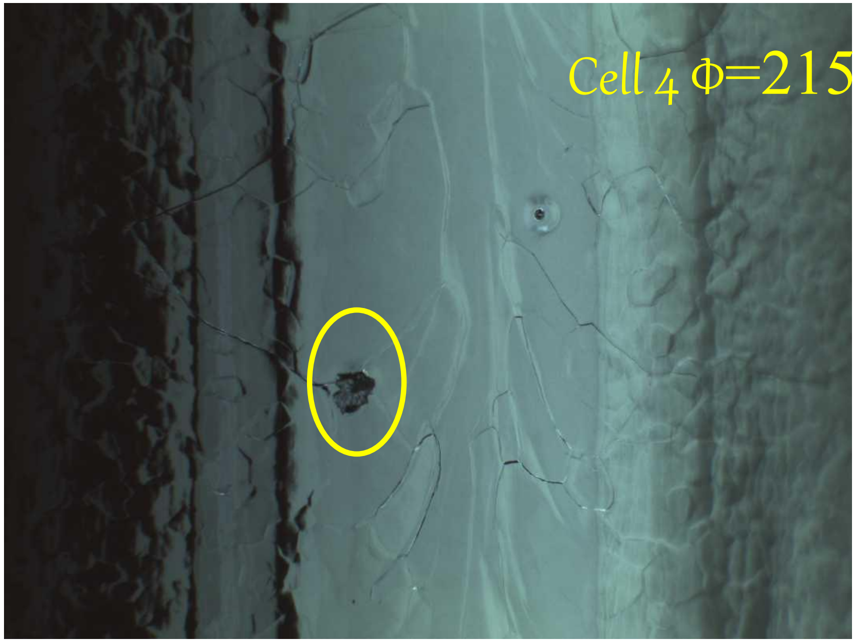
# IA355

(removed from module to be re-worked and become C50-12, "Large grain")

pit



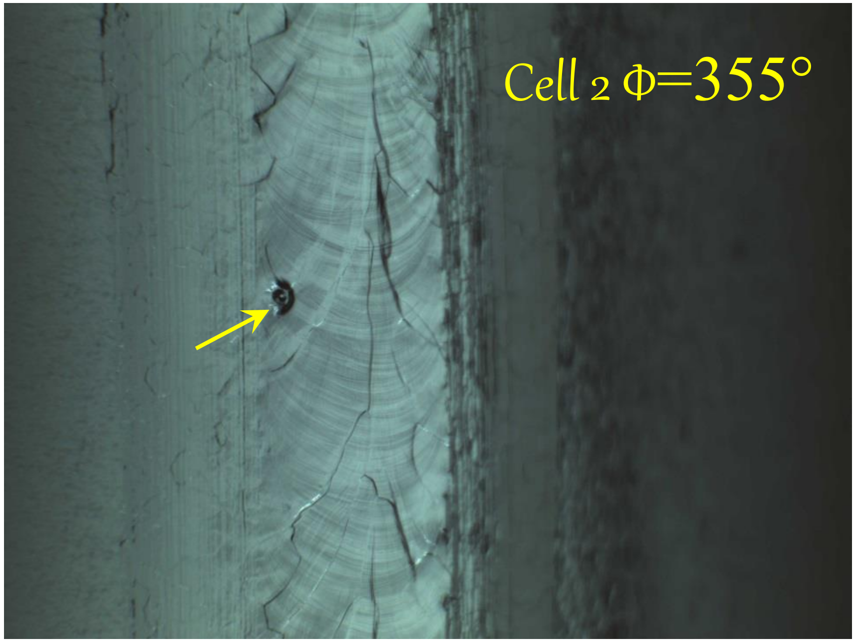

Large flaw

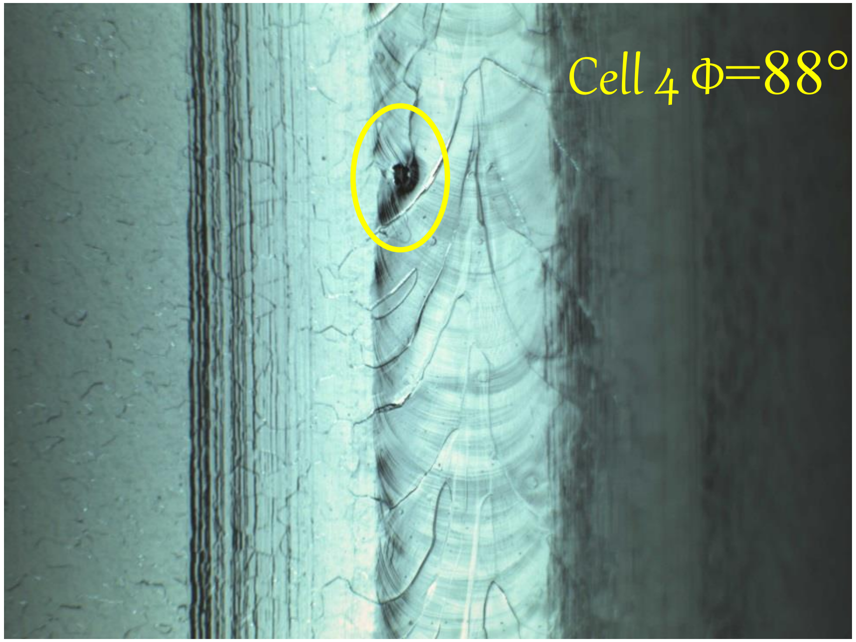


# IA011

pit

Pre-cursor large flaw?




- No apparent large flaw observed
- BCP etching of inner surface seems much less than other inspected cavities
  i. Visible molten pool ripples
  ii. Visible "blisters" on fusion zone surface