High-Q_0/High-E_{acc} and ILC Cost Reduction Status

Daniel Bafia

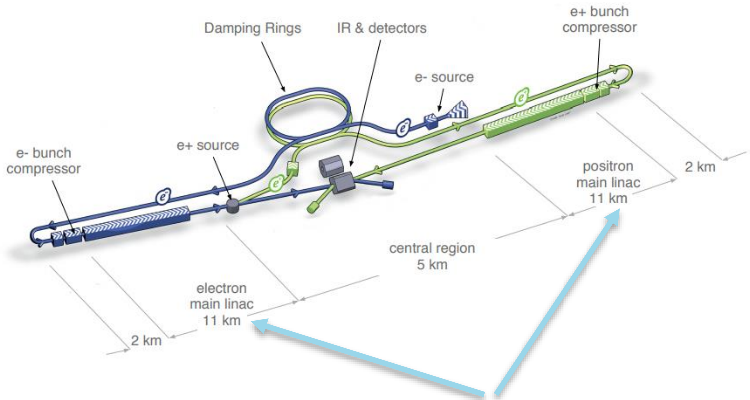
International Workshop on Future Linear Colliders

31 October, 2019

Necessity of High Gradient/High Q_0 for ILC Realization

https://ilchome.web.cern.ch/ilc/possible-benefits-ilc-technology

- The world needs a new Higgs factory for BSM physics
- ILC is a ready to go technology:
  - SRF is a proven to be capable of:
    - High Q_0 (LCLS-II)
    - High gradient (XFEL)
  - Easy to upgrade in energy
  - **<u>Relatively</u>** low cost
- Average accelerating gradient of main SRF LINAC is the largest cost driver
- Higher gradients = fewer cryomodules ➔ less $$
- Higher Q_0 = lower cryogenic costs

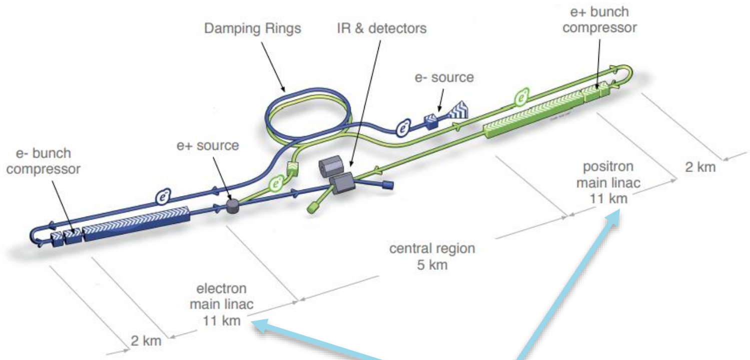


Baseline design:
Q_0=1x10^{10} @
$E_{acc,avg}$=31.5 MV/m

Necessity of High Gradient/High Q_0 for ILC Realization

https://ilchome.web.cern.ch/ilc/possible-benefits-ilc-technology

- The world needs a new Higgs factory for BSM physics
- ILC is a ready to go technology:
  - SRF is a proven to be capable of:
    - High Q_0 (LCLS-II)
    - High gradient (XFEL)
  - Easy to upgrade in energy
  - **Relatively** low cost
- Average accelerating gradient of main SRF LINAC is the largest cost driver
- Higher gradients = fewer cryomodules ➔ less $$
- Higher Q_0 = lower cryogenic costs

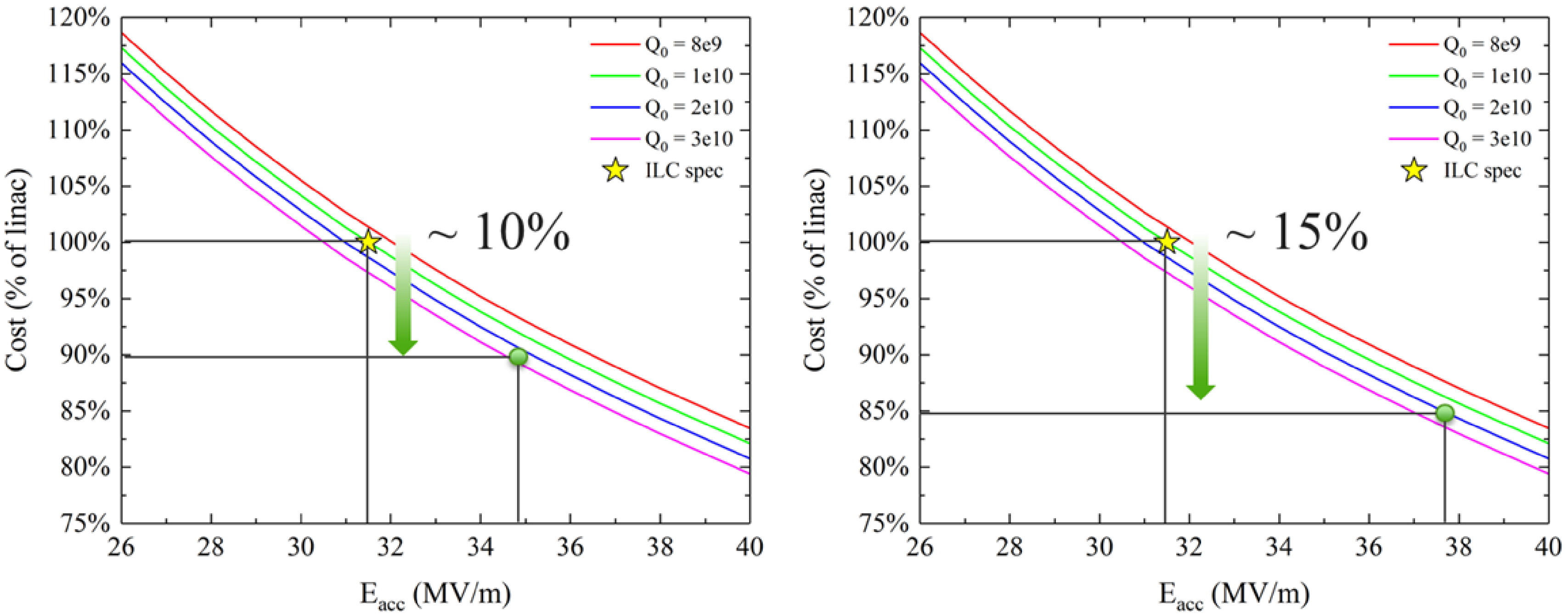


Baseline design:
$Q_0=1\text{x}10^{10}$ @
$E_{acc,avg}=31.5$ MV/m

Goal: create cryomodules that exceed these specs

Cost Estimation of a 250 GeV ILC LINAC

Courtesy of M. Checchin, US-Japan Coll. Worksh., 2017



Increasing cavity specs to Q_0=2e10 and 34.8 MV/m (37.7 MV/m) allows for a ~10% (~15%) decrease in LINAC cost

Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Overview of High Gradient/High Q_0 Work at FNAL

Part I: Single cell studies:

- Findings:
  1) Achieving 50 MV/m in 1.3 GHz TESLA – shaped Nb single cells
  2) Curious bifurcation in cavity performance
  3) Changes in cavity performance with different cavity cooldown protocols
- Cryo-AFM studies: Nano-hydride growth and dissolution

Part II: 9-cell studies

- High G/HighQ_0 TESLA-shaped 9-cell cavities

Part III: Plans for High G/High Q_0 ILC Style Cryomodule:

- Refurbishing plan
- International collaboration

Conclusion

Overview of High Gradient/High Q_0 Work at FNAL

Part I: Single cell studies:

- Findings:
  1) Achieving 50 MV/m in 1.3 GHz TESLA – shaped Nb single cells
  2) Curious bifurcation in cavity performance
  3) Changes in cavity performance with different cavity cooldown protocols
- Cryo-AFM studies: Nano-hydride growth and dissolution

Part II: 9-cell studies

- High G/HighQ_0 TESLA-shaped 9-cell cavities

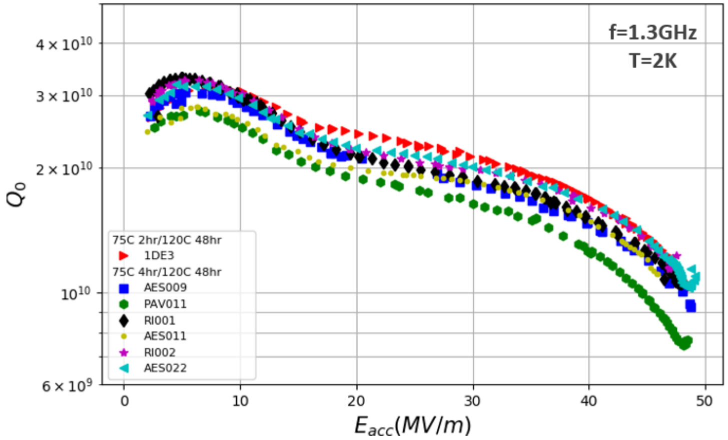
Part III: Plans for High G/High Q_0 ILC Style Cryomodule:

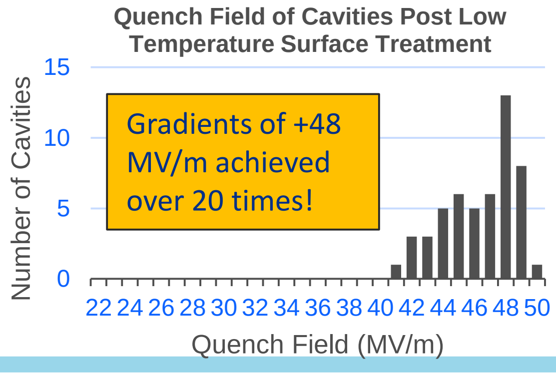
- Refurbishing plan
- International collaboration

Conclusion

New Finding #1: 50MV/m in TESLA-shaped Nb Cavities

Systematic achievement of unprecedented gradients ~48-50 MV/m (~210 mT)!

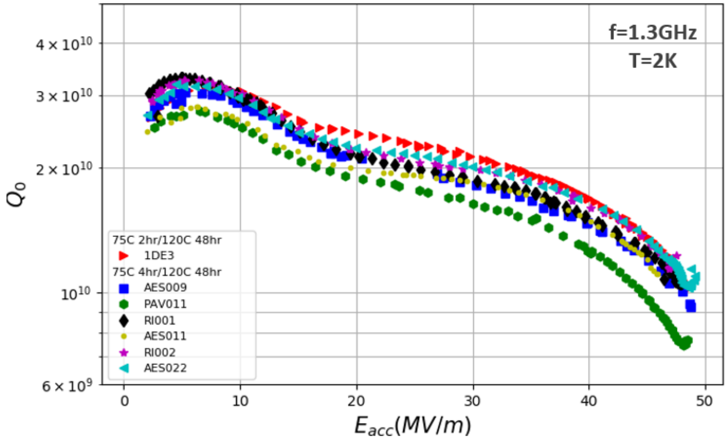


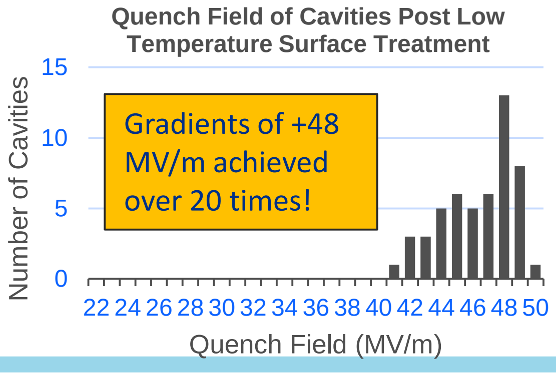


Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

New Finding #1: 50MV/m in TESLA-shaped Nb Cavities

Systematic achievement of unprecedented gradients ~48-50 MV/m (~210 mT)!





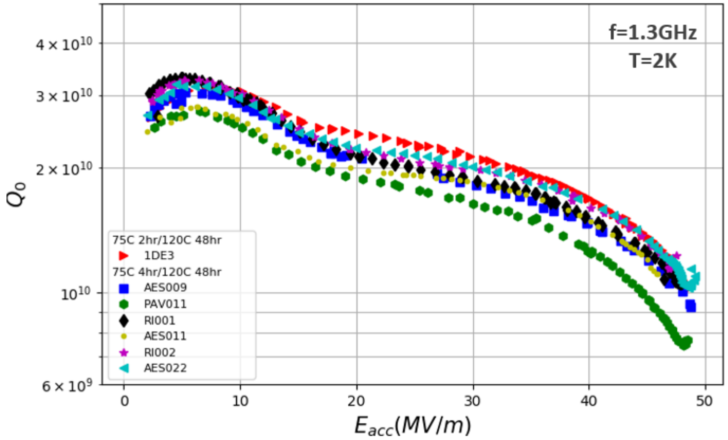
Performance linked to 2 peculiarities under study:

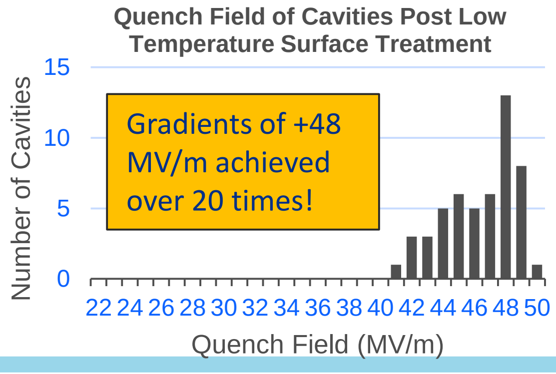
1) Ultra cold final EP that gives:

- Very smooth finish
- Little hydrogen uptake

New Finding #1: 50MV/m in TESLA-shaped Nb Cavities

Systematic achievement of unprecedented gradients ~48-50 MV/m (~210 mT)!



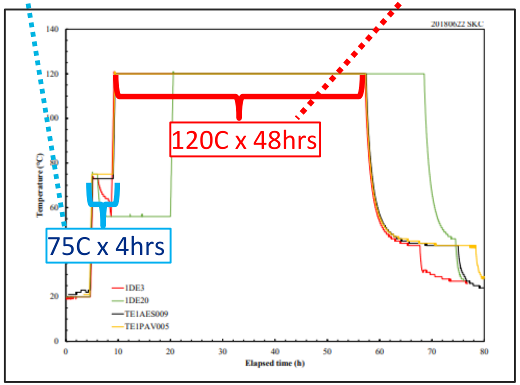


Performance linked to 2 peculiarities under study:

1) Ultra cold final EP that gives:

- Very smooth finish
- Little hydrogen uptake

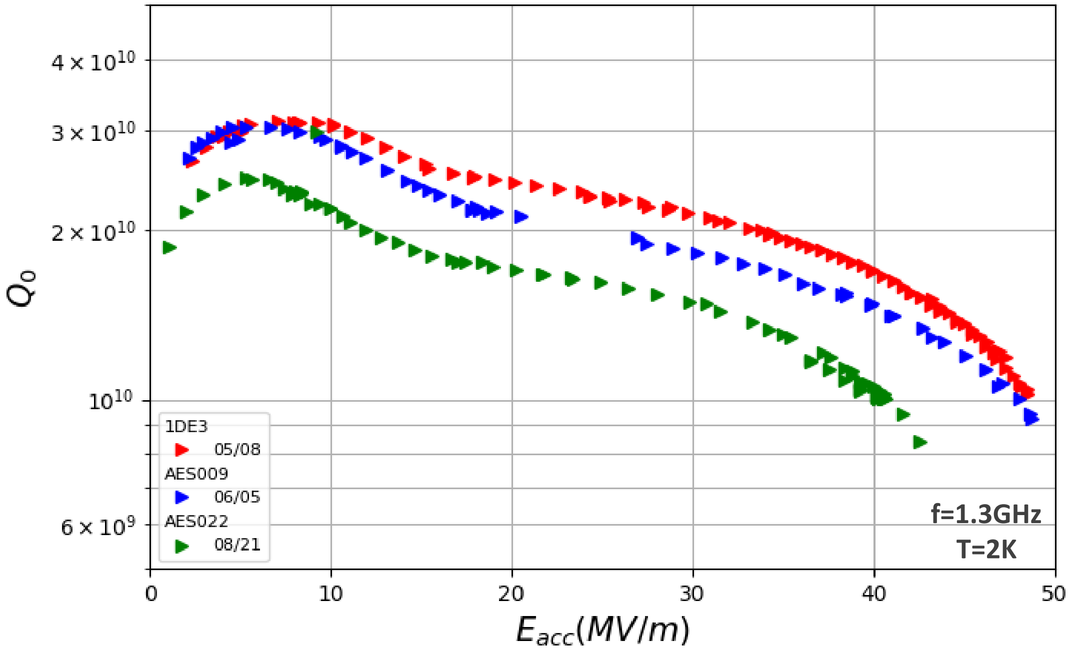
2) Addition of 75C bake before 120C in-situ bake



Studies ongoing to decouple effects of these treatments

Finding #2: Curious Branching in Performance

3 single-cell cavities post cold EP + 75/120C baking
were tested several times without disassembly

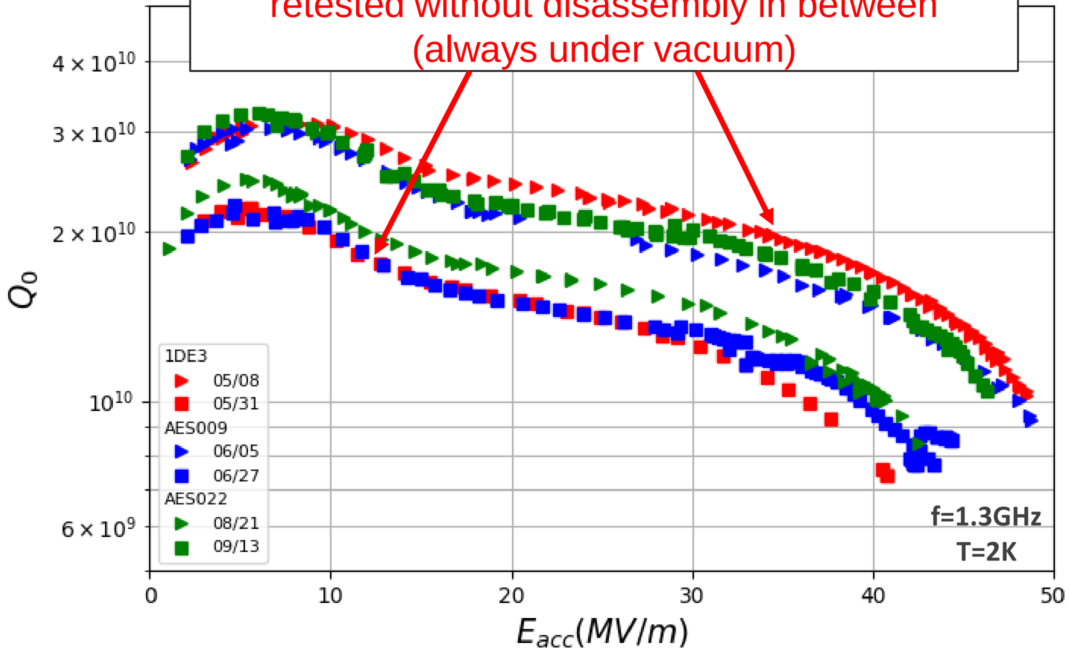


Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Finding #2: Curious Branching in Performance

3 single-cell cavities post cold EP + 75/120C baking were tested several times without disassembly

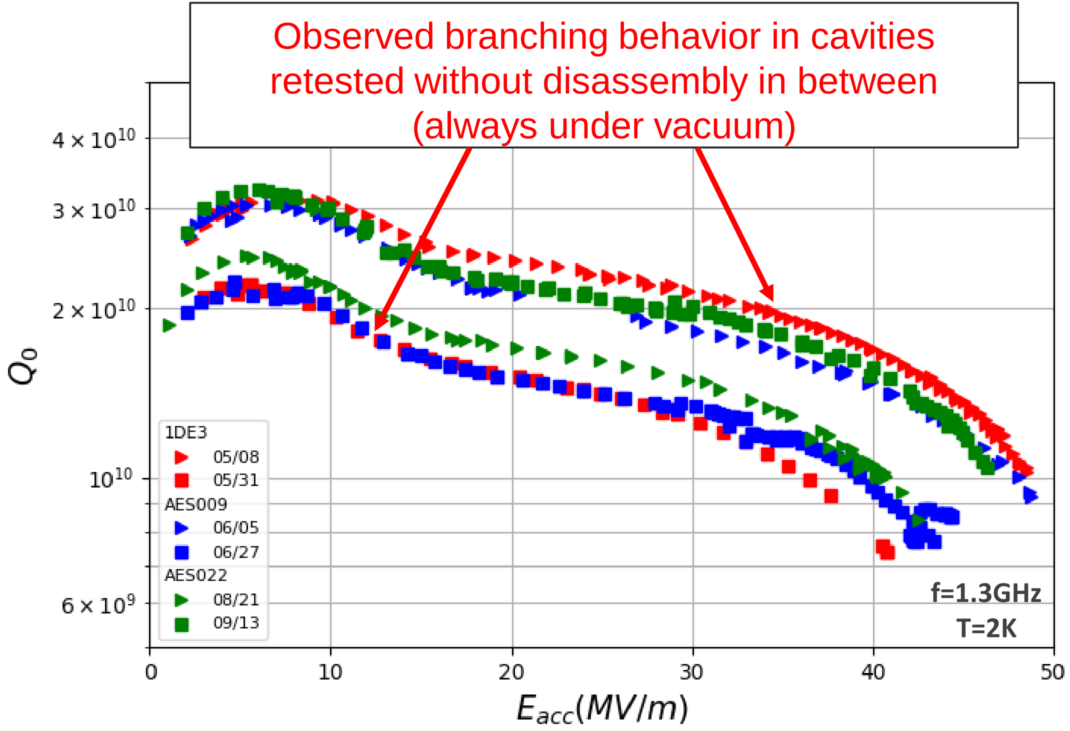
Observed branching behavior in cavities retested without disassembly in between (always under vacuum)



Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Finding #2: Curious Branching in Performance

3 single-cell cavities post cold EP + 75/120C baking were tested several times without disassembly

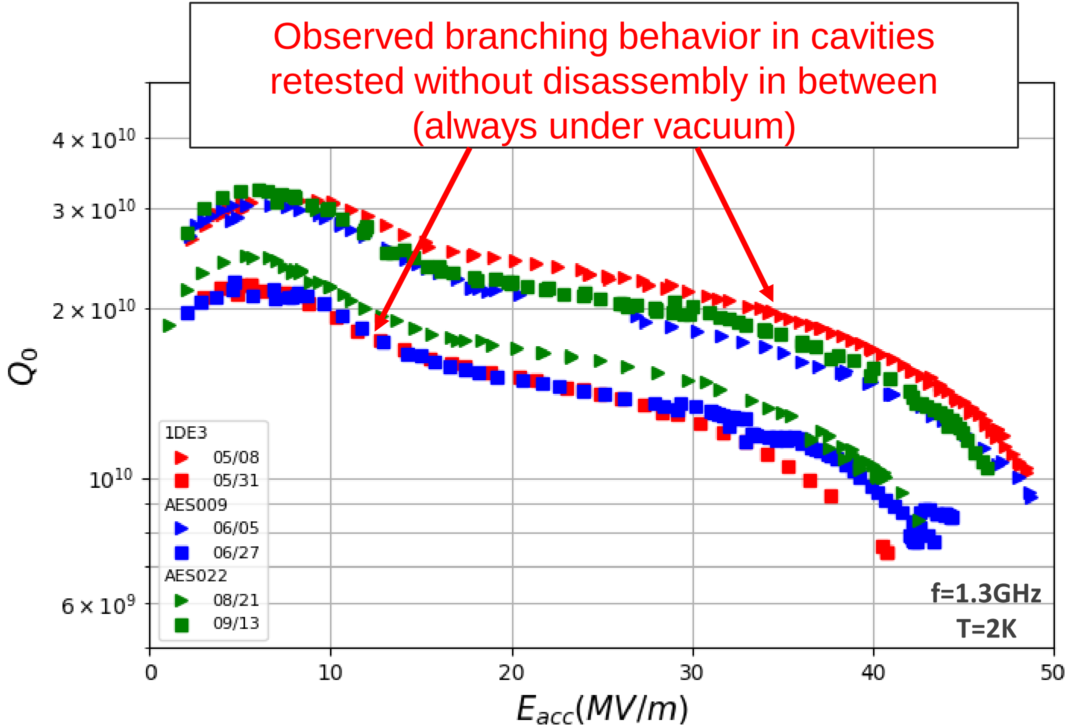


Possible Causes for Branching	Likely Candidate?
Dewar	**NO –** observed in 2 separate dewars
Top Plate	**NO**
Cables	**NO**
Calibration	**NO -** Qext 2 does not explain branching in Q and G
Flux trapping	**NO – MOST** were cooled in zero compensated field

Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Finding #2: Curious Branching in Performance

3 single-cell cavities post cold EP + 75/120C baking were tested several times without disassembly



Possible Causes for Branching	Likely Candidate?
Dewar	**NO –** observed in 2 separate dewars
Top Plate	**NO**
Cables	**NO**
Calibration	**NO -** Qext 2 does not explain branching in Q and G
Flux trapping	**NO – MOST** were cooled in zero compensated field

$B_{trapped}$ = 5.88mG to account for branching; not possible with compensation coils in VTS

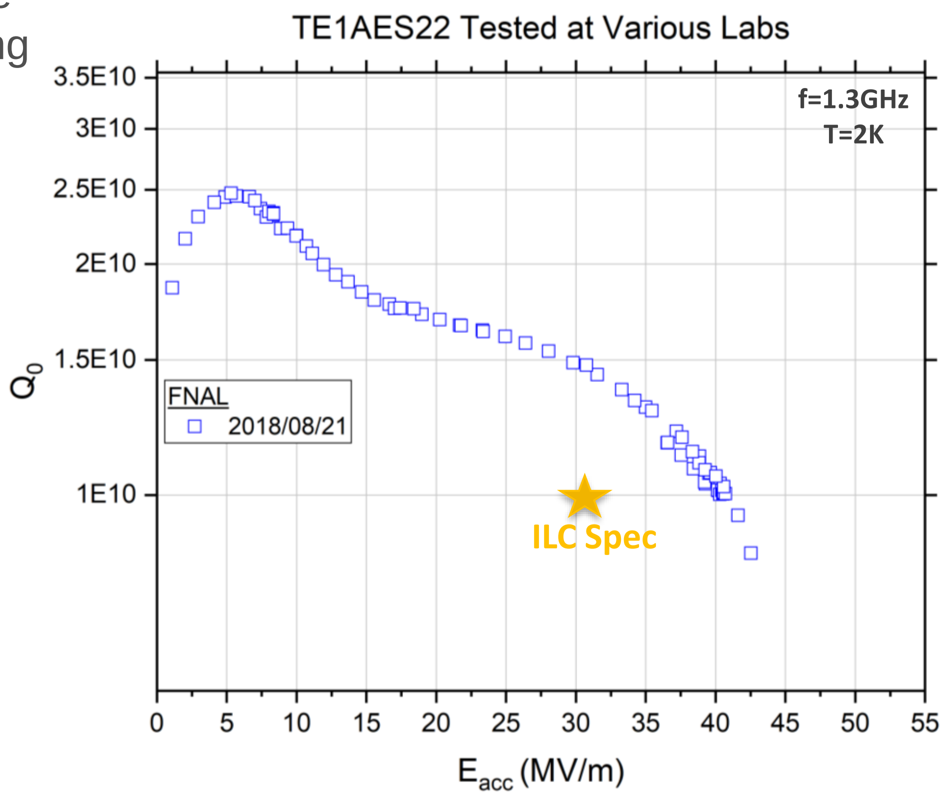
Fermilab ILLINOIS INSTITUTE OF TECHNOLOGY

50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m

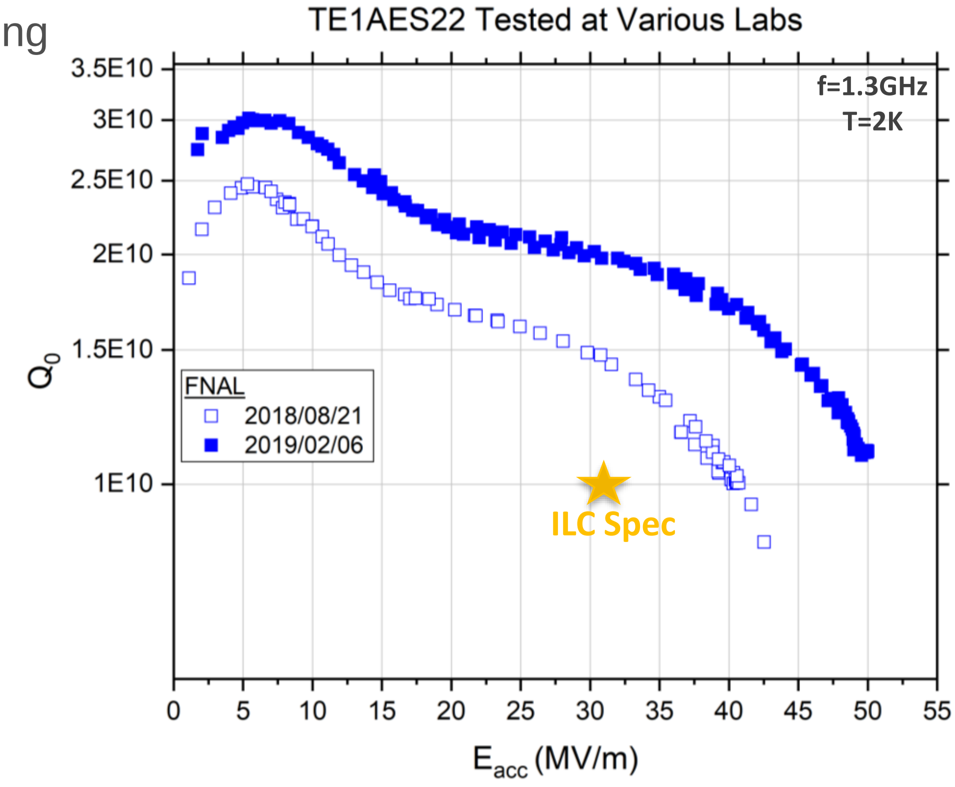


50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!



50 MV/m Single Cell Cavity Sent Around the World for Verification

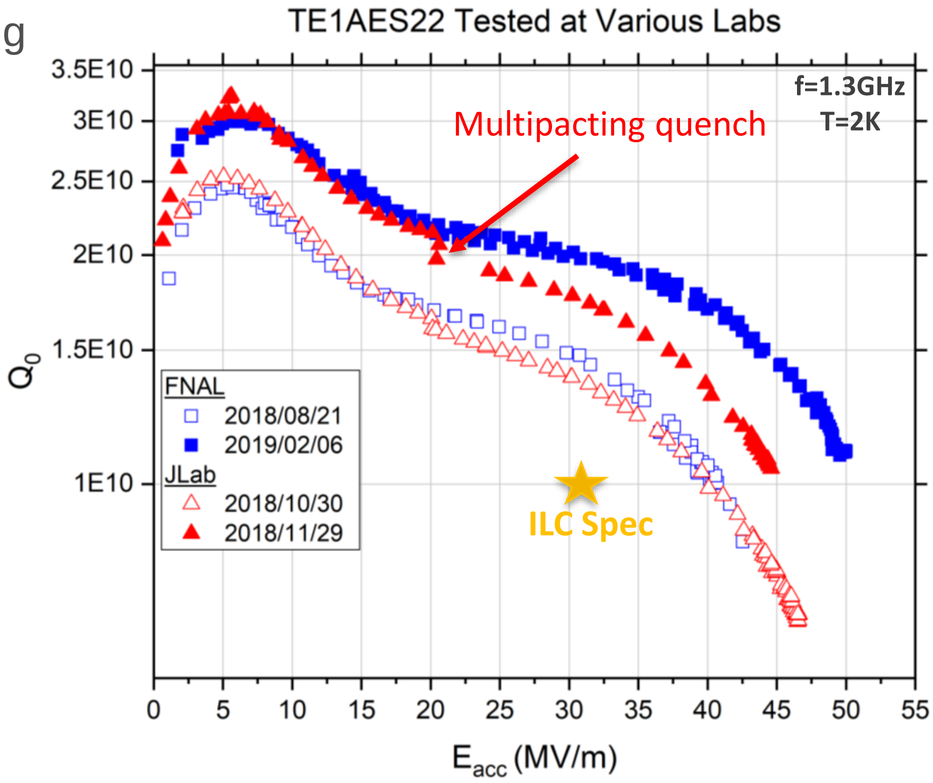
Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia

- Lower and Upper branch obtained



Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

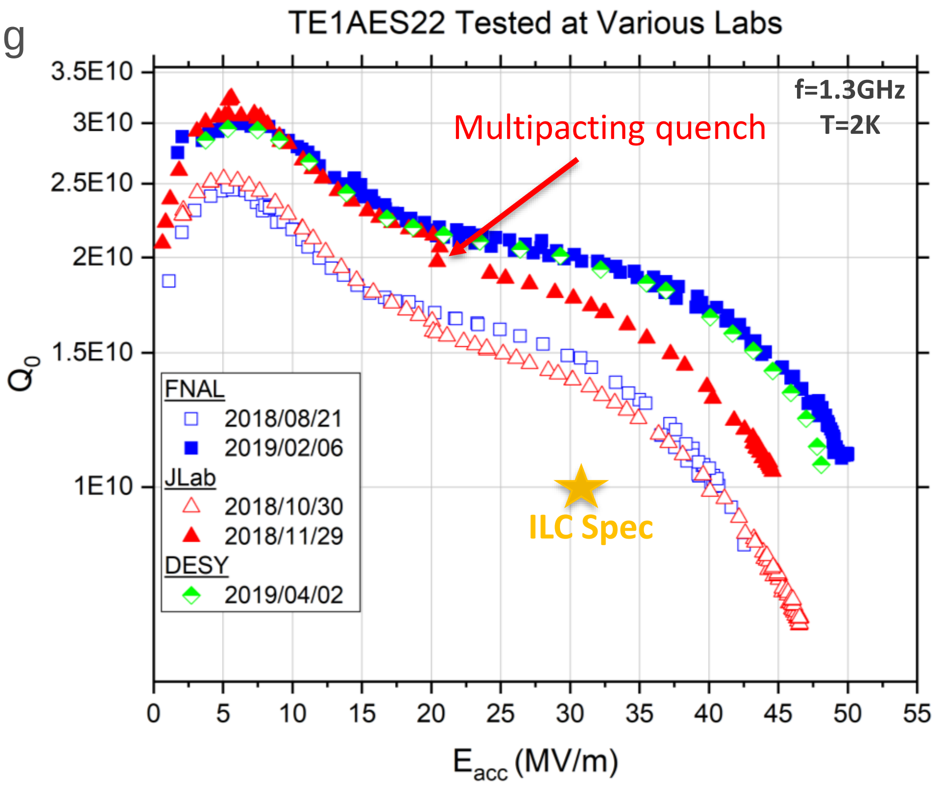
- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia

- Lower and Upper branch obtained

DESY – Hamburg, Germany

- Upper branch: +48MV/m confirmed



Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia

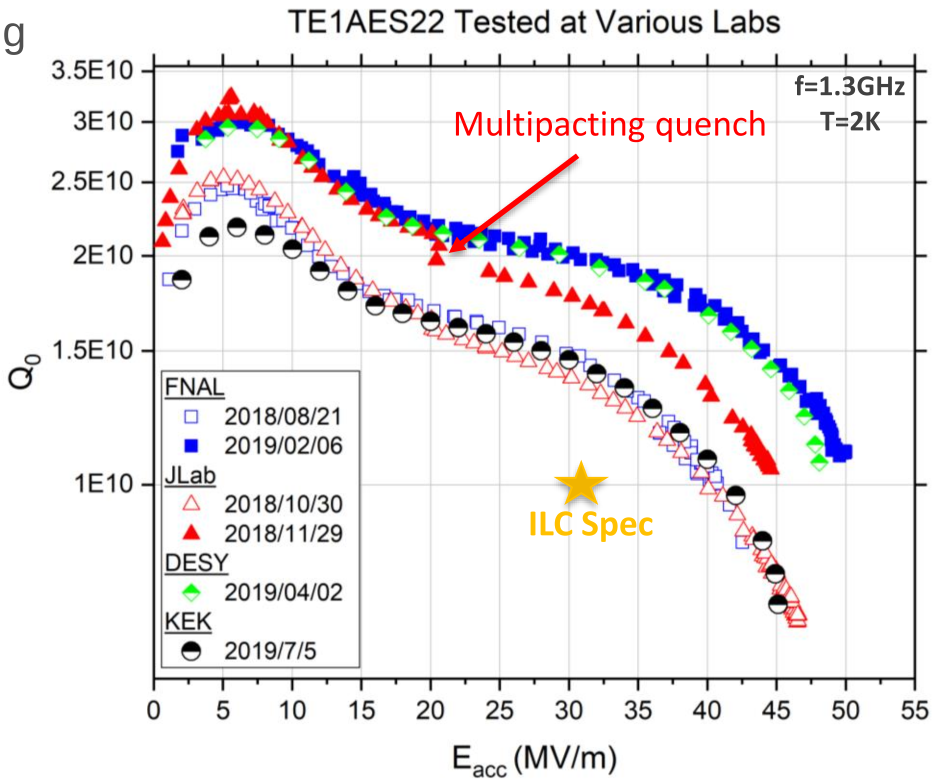
- Lower and Upper branch obtained

DESY – Hamburg, Germany

- Upper branch: +48MV/m confirmed

KEK – Tsukuba, Japan

- Lower Branch: +45MV/m confirmed



50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia

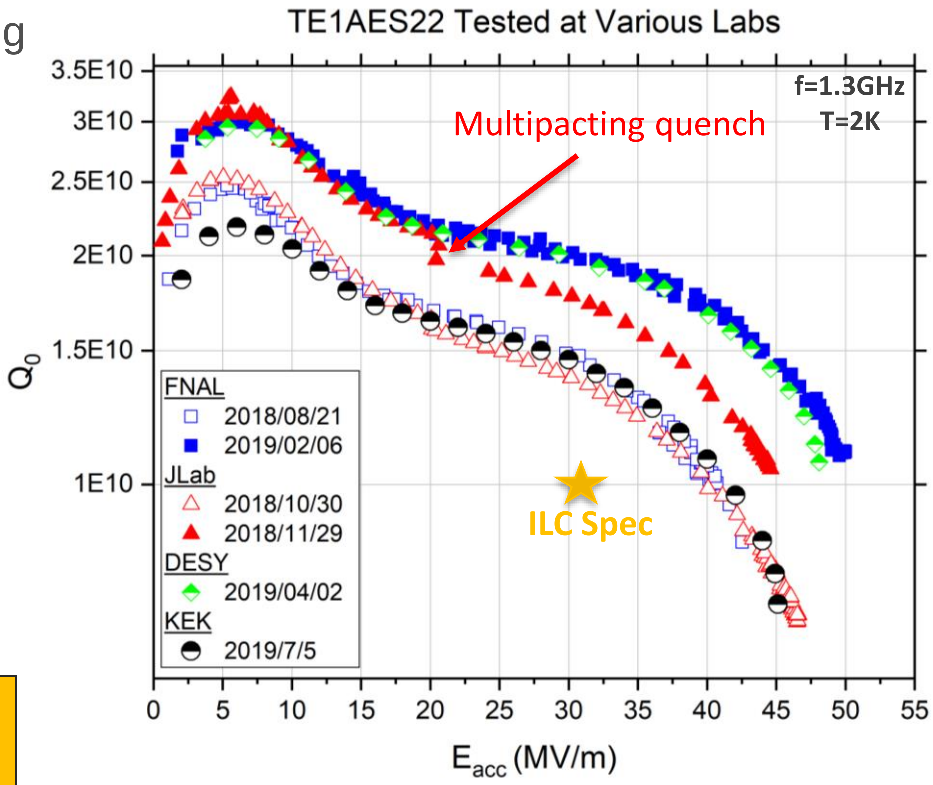
- Lower and Upper branch obtained

DESY – Hamburg, Germany

- Upper branch: +48MV/m confirmed

KEK – Tsukuba, Japan

- Lower Branch: +45MV/m confirmed



DESY and FNAL measure 2x Q_0 ILC spec!
Branching observed in other laboratories!

Fermilab ILLINOIS INSTITUTE OF TECHNOLOGY

50 MV/m Single Cell Cavity Sent Around the World for Verification

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

FNAL – Batavia, IL

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

Jlab – Newport News, Virginia

- Lower ...

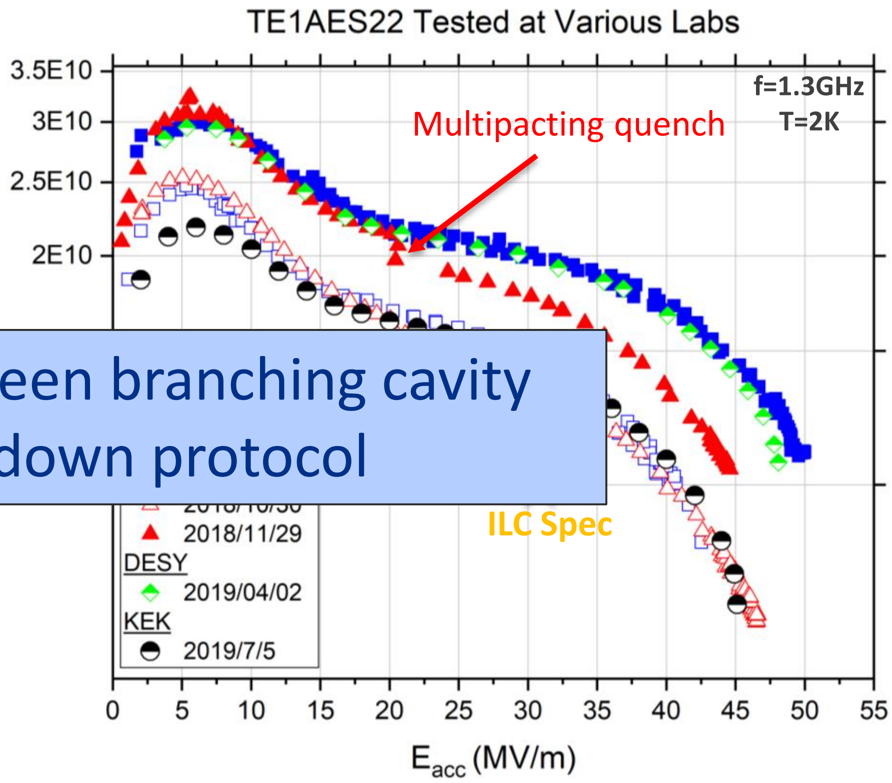
DESY – H...

- Upper branch: +48MV/m confirmed

KEK – Tsukuba, Japan

- Lower Branch: +45MV/m confirmed

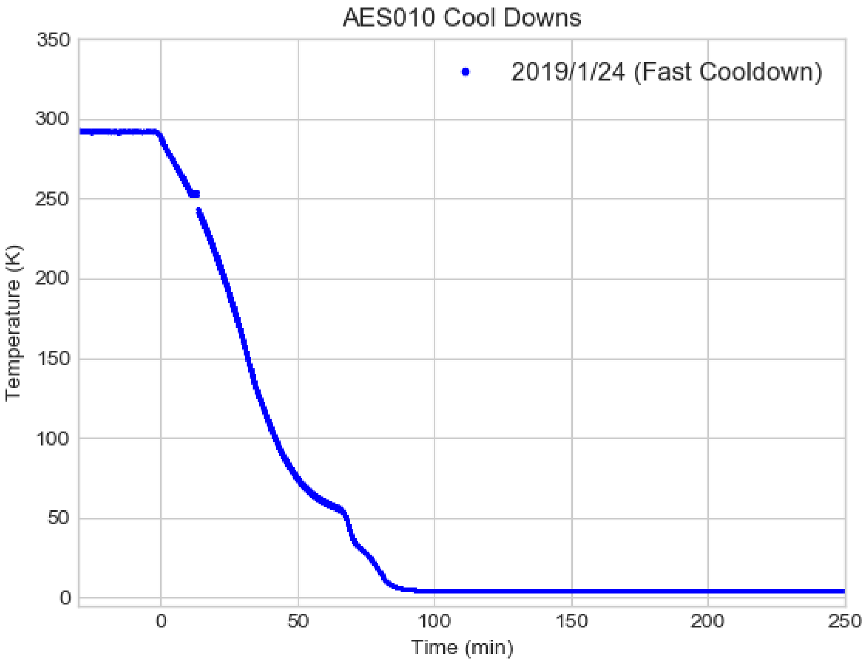
DESY and FNAL measure 2x Q_0 ILC spec!
Branching observed in other laboratories!

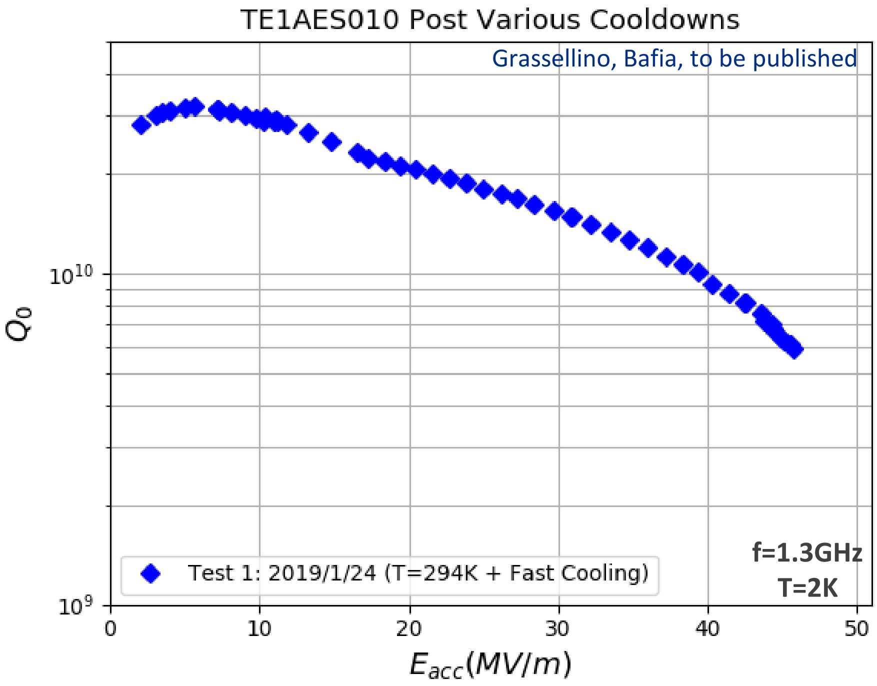


Some correlation found between branching cavity performance and cavity cooldown protocol

Finding #3: Performance Changes with Cooldown Protocol

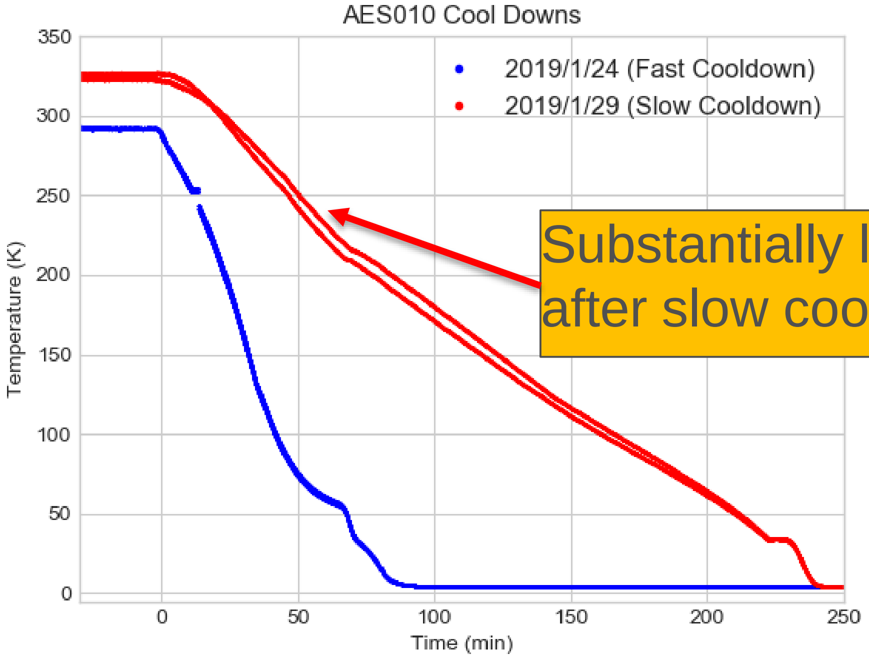
- Cavity TE1AES010 post **degassing @ 800C + 120C baking** was tested after different two different dewar cooldown protocols:



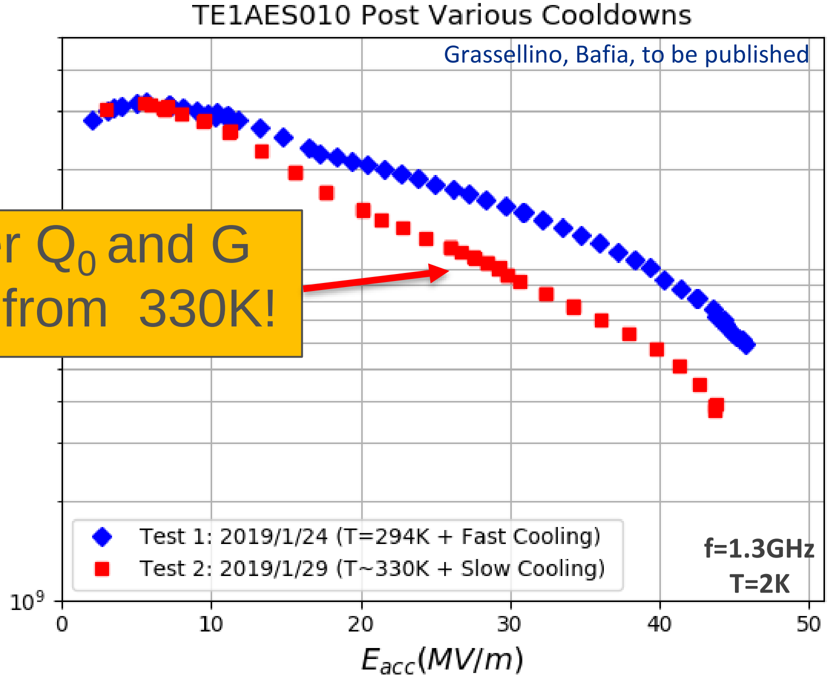


Finding #3: Performance Changes with Cooldown Protocol

- Cavity TE1AES010 post **degassing @ 800C + 120C baking** was tested after different two different dewar cooldown protocols:

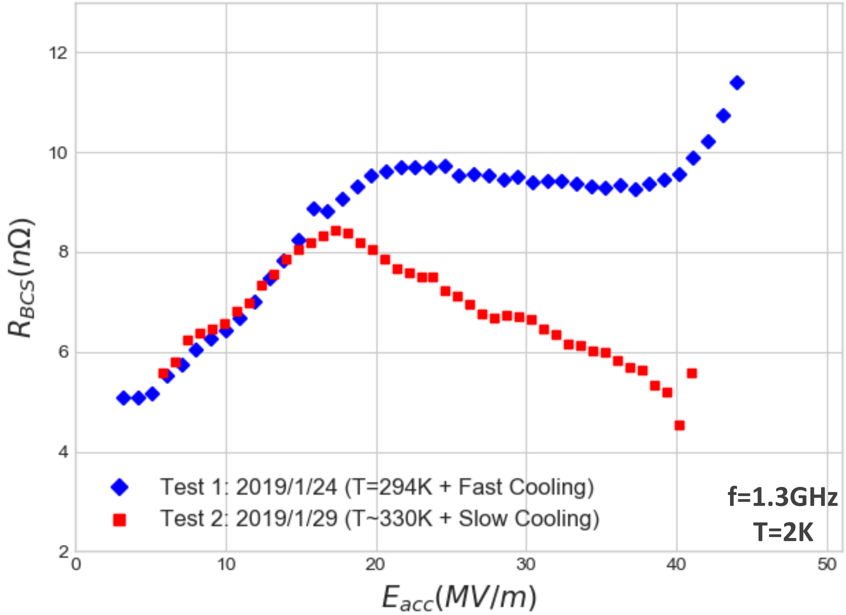


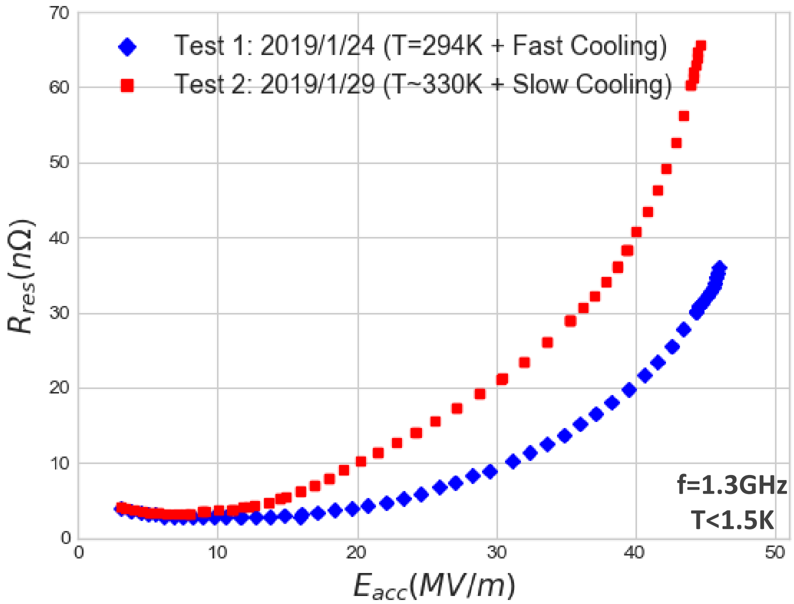
Substantially lower Q_0 and G after slow cooling from 330K!



Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

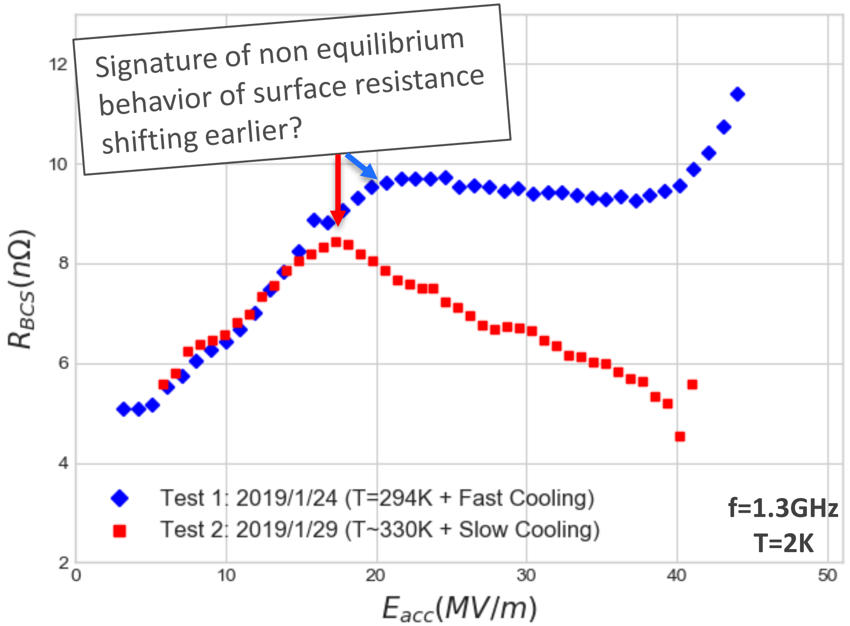
Finding #3.2: Surface Resistance Changes with Cooldown Protocol

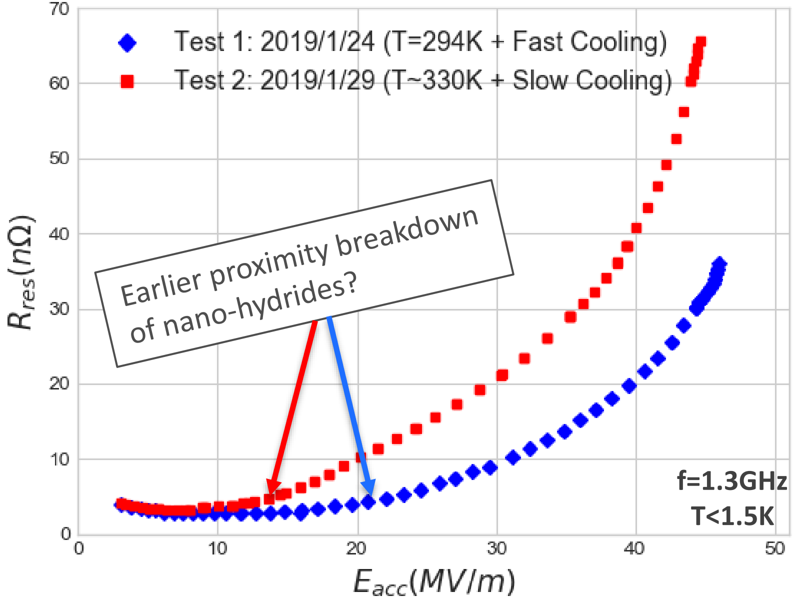




- Branching exists in the surface resistance - fundamental change R_s behavior

Finding #3.2: Surface Resistance Changes with Cooldown Protocol



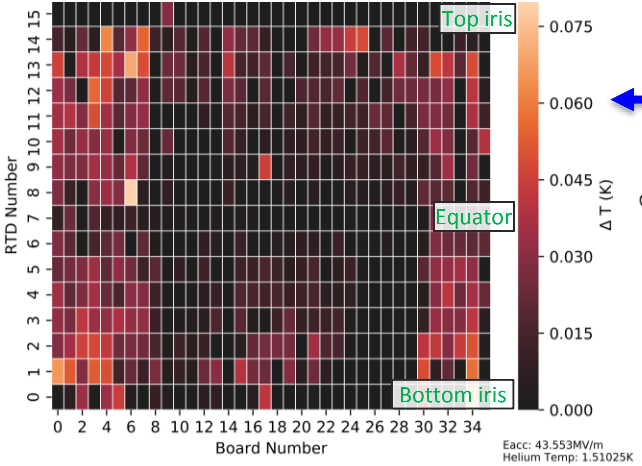


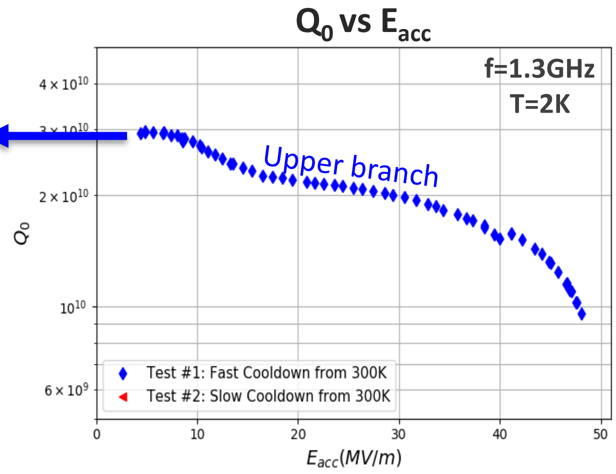
- Branching exists in the surface resistance - fundamental change R_s behavior
- “Knees” move at corresponding points with a ‘breakdown’ field compatible with the proximity effect model of nano-hydrides as introduced by A. Romanenko in Superconductor Science and Technology, Volume 26, Number 3

Repeat Experiment with TMAP: Effect of Cooldown

- Another cavity post **degas + 120C bake** (TE1AES017) was tested after slow and fast cool down from 300K:

TMAP of AES017 Post Fast Cooldown



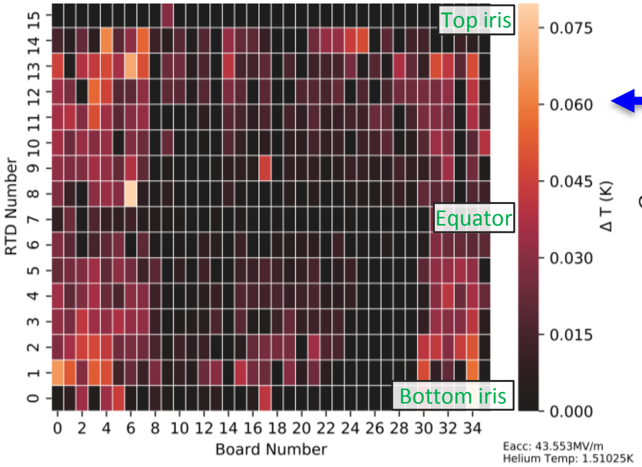


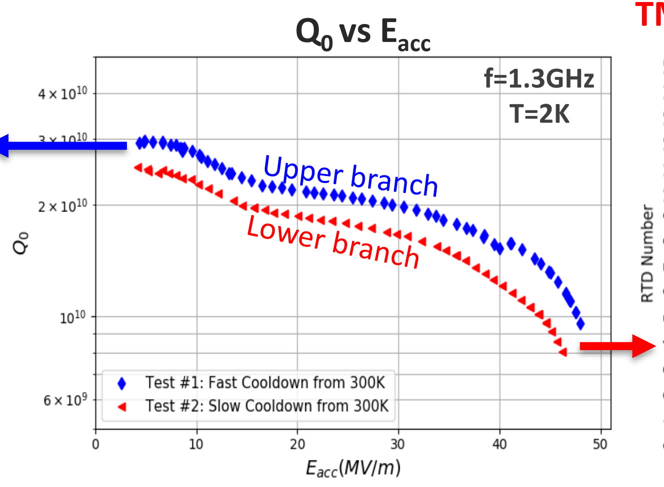
Grassellino, Bafia, to be published

Repeat Experiment with TMAP: Effect of Cooldown

- Another cavity post **degas + 120C bake** (TE1AES017) was tested after slow and fast cool down from 300K:

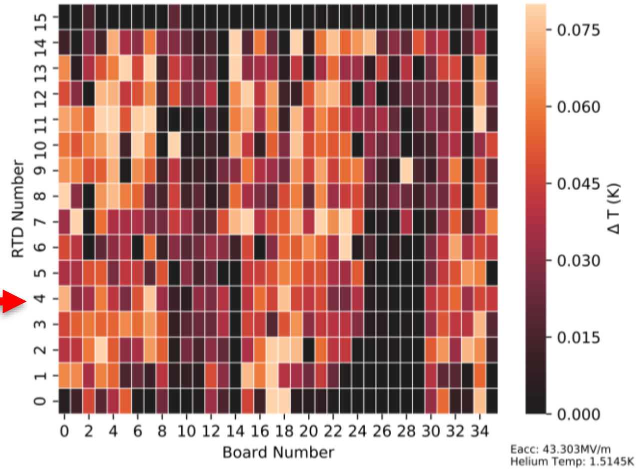
TMAP of AES017 Post Fast Cooldown





Grassellino, Bafia, to be published

TMAP of AES017 Post Slow Cool down

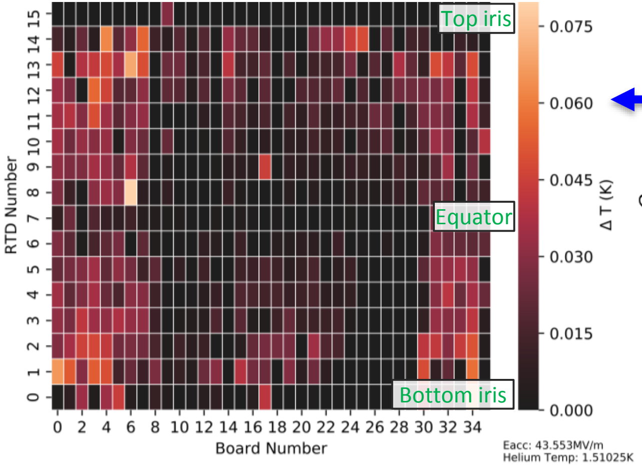


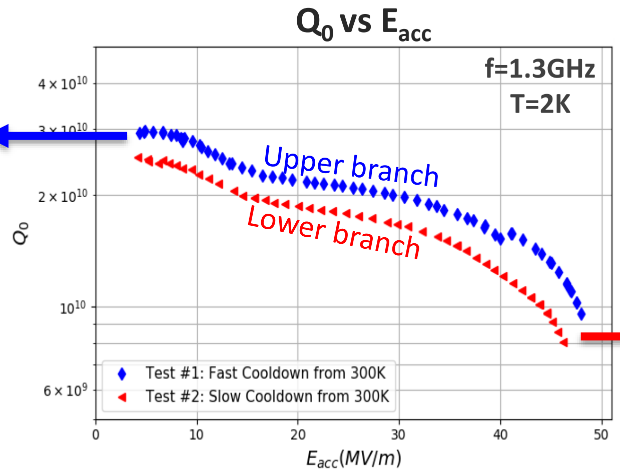
Significantly stronger heating near equatorial region post slow cooling!

Repeat Experiment with TMAP: Effect of Cooldown

- Another cavity post **degas + 120C bake** (TE1AES017) was tested after slow and fast cool down from 300K:

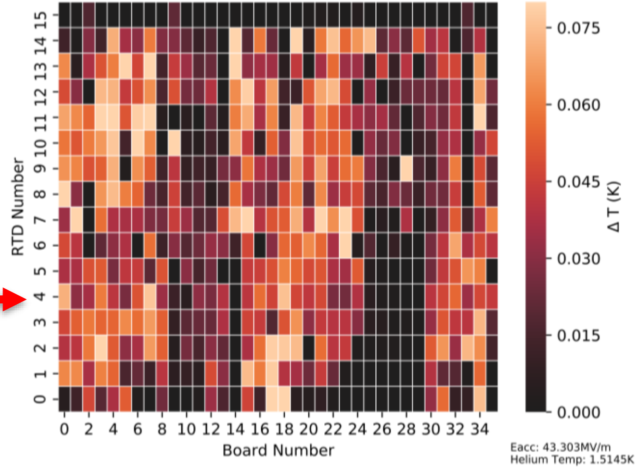
TMAP of AES017 Post Fast Cooldown





Grassellino, Bafia, to be published

TMAP of AES017 Post Slow Cool down



Significantly stronger heating near equatorial region post slow cooling!

Stronger heating post slow cooling suggests:

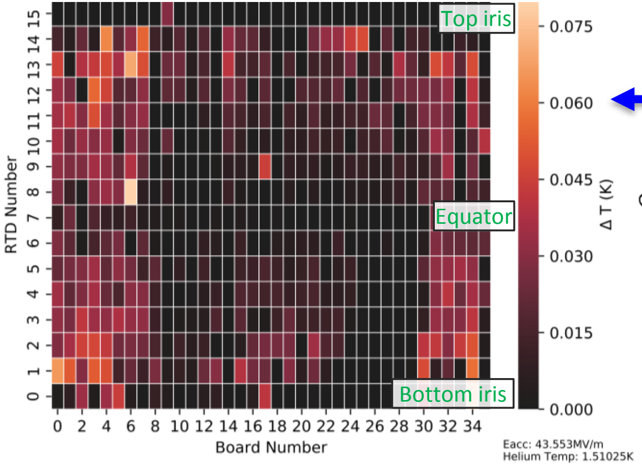
1) Nano-hydride precipitation in this region
2) Condensation of gases on the surface - relevant for cryomodules

Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

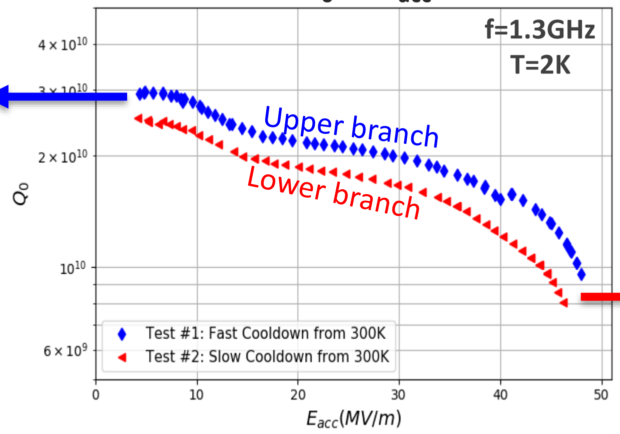
Repeat Experiment with TMAP: Effect of Cooldown

- Another cavity post **degas + 120C bake** (TE1AES017) was tested after slow and fast cool down from 300K:

TMAP of AES017 Post Fast Cooldown

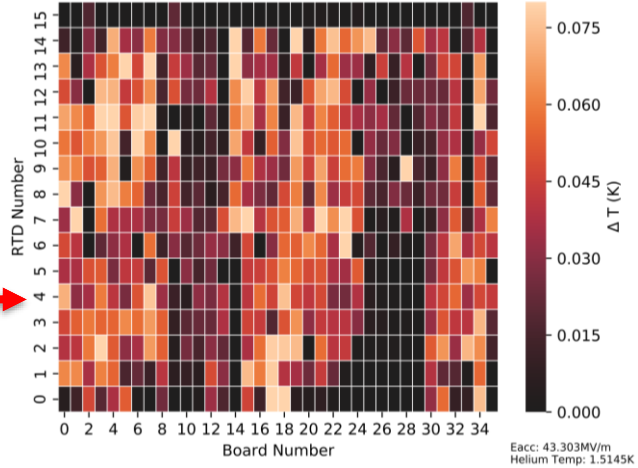


Q_0 vs E_{acc}



Grassellino, Bafia, to be published

TMAP of AES017 Post Slow Cool down



Significantly stronger heating near equatorial region post slow cooling!

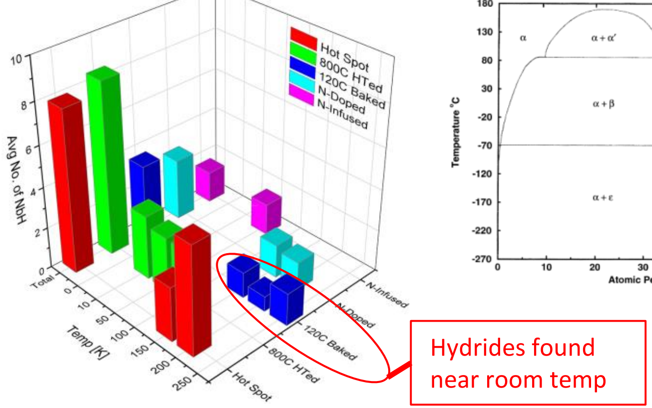
Stronger heating post slow cooling suggests:

1) Nano-hydride precipitation in this region
2) Condensation of gases on the surface - relevant for cryomodules

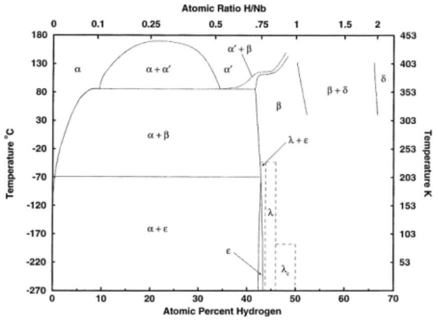
Cryo-AFM Studies on 120C Bake Cavity Cutout: Nano-hydride Precipitation

- Different recipes produce different amounts of hydrogen capture sites (vacancies, nitrogen, dislocations, etc)
- Amount of captured hydrogen could vary the dangerous temperature region in which hydrides form
- Dwelling in this "dangerous" temperature region could be detrimental to cavity performance – **cool down rate could affect 120C bake cavity performance**

Avg. No. of NbH Precipitates within 10 x 10 µm² unit area during cooling



Nb-H Phase Diagram



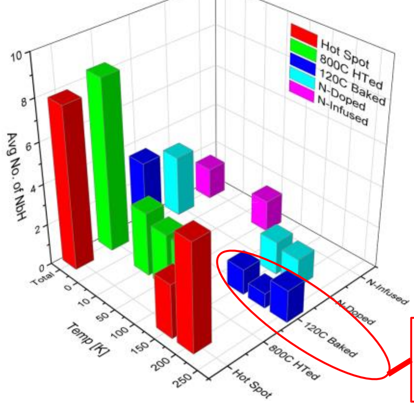
Plots courtesy of Zuhawn Sung

Fermilab
ILLINOIS INSTITUTE OF TECHNOLOGY

Cryo-AFM Studies on 120C Bake Cavity Cutout: Nano-hydride Precipitation

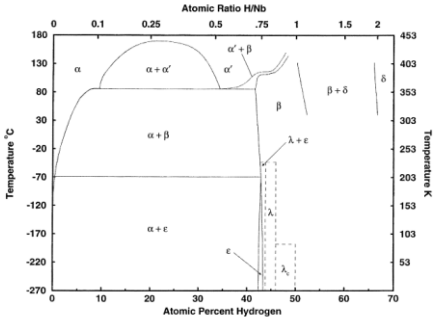
- Different recipes produce different amounts of hydrogen capture sites (vacancies, nitrogen, dislocations, etc)
- Amount of captured hydrogen could vary the dangerous temperature region in which hydrides form
- Dwelling in this "dangerous" temperature region could be detrimental to cavity performance – **cool down rate could affect 120C bake cavity performance**

Avg. No. of NbH Precipitates within 10 x 10 μm² unit area during cooling

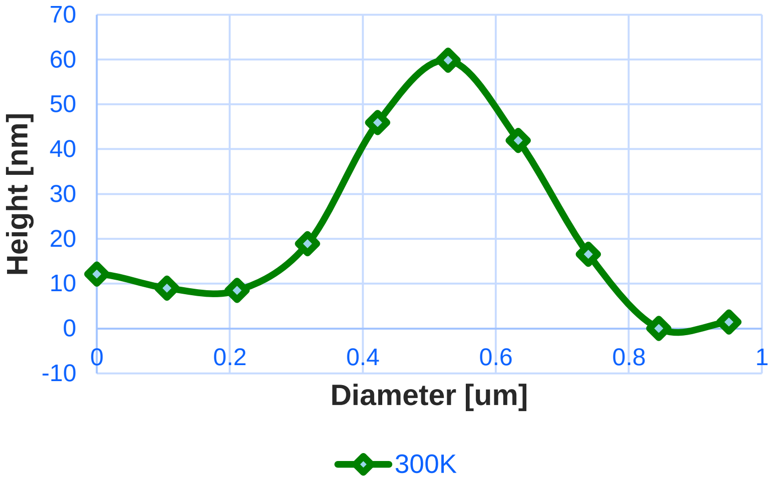


Hydrides found near room temp

Nb-H Phase Diagram



Hydride Size Through Warm Up of 120C Baked Cavity Cutout

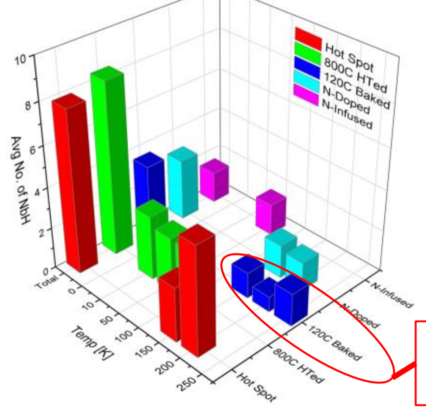


Plots courtesy of Zuhawn Sung

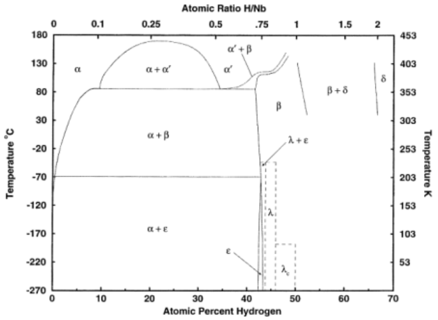
Cryo-AFM Studies on 120C Bake Cavity Cutout: Nano-hydride Precipitation

- Different recipes produce different amounts of hydrogen capture sites (vacancies, nitrogen, dislocations, etc)
- Amount of captured hydrogen could vary the dangerous temperature region in which hydrides form
- Dwelling in this "dangerous" temperature region could be detrimental to cavity performance – **cool down rate could affect 120C bake cavity performance**

Avg. No. of NbH Precipitates within 10 x 10 μm² unit area during cooling

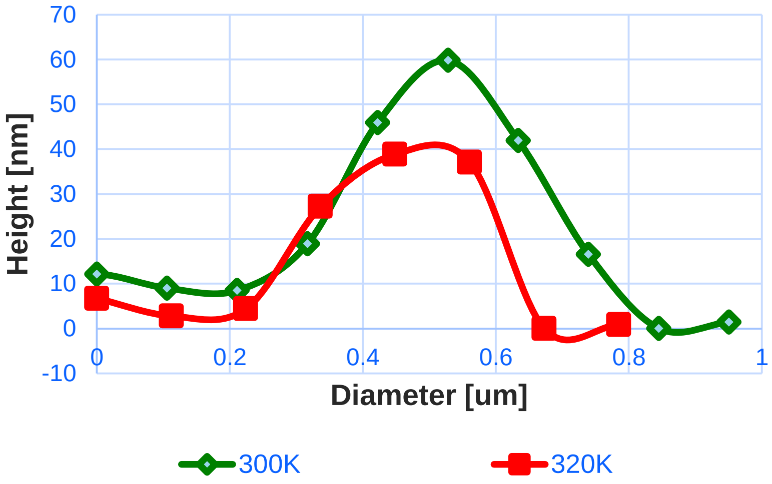


Nb-H Phase Diagram



Hydrides found near room temp

Hydride Size Through Warm Up of 120C Baked Cavity Cutout



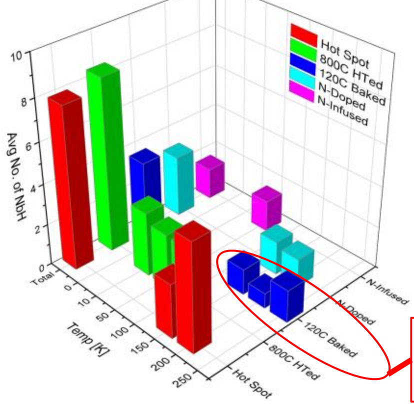
- For a 120C baked cavity cutout, hydrides appear to decrease in size when the sample is heated to 320K

Plots courtesy of Zuhawn Sung

Cryo-AFM Studies on 120C Bake Cavity Cutout: Nano-hydride Precipitation

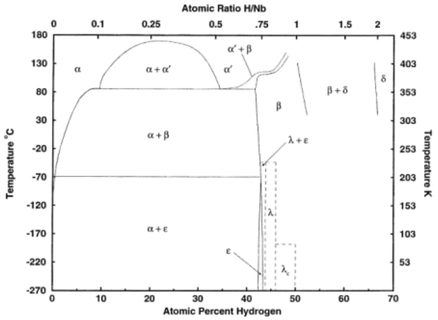
- Different recipes produce different amounts of hydrogen capture sites (vacancies, nitrogen, dislocations, etc)
- Amount of captured hydrogen could vary the dangerous temperature region in which hydrides form
- Dwelling in this “dangerous” temperature region could be detrimental to cavity performance – **cool down rate could affect 120C bake cavity performance**

Avg. No. of NbH Precipitates within 10 x 10 μm² unit area during cooling

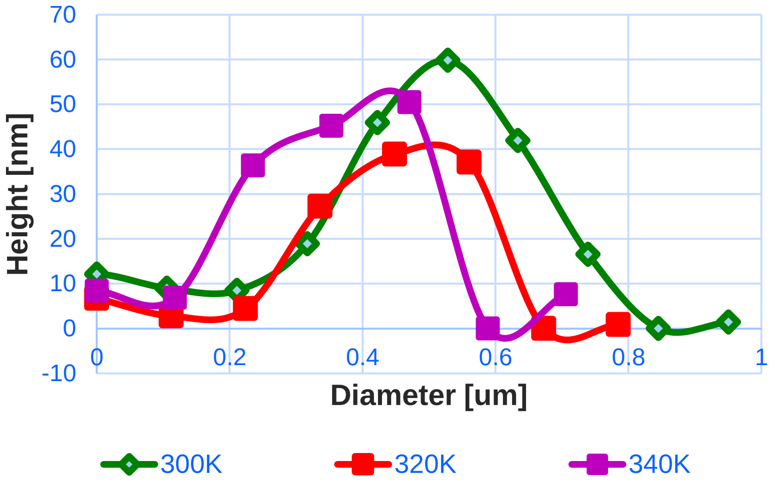


Hydrides found near room temp

Nb-H Phase Diagram



Hydride Size Through Warm Up of 120C Baked Cavity Cutout



- For a 120C baked cavity cutout, hydrides appear to decrease in size when the sample is heated to 320K
- Heating to 340K appears to INCREASE hydride size.
- **Elevated initial dewar temperatures may also affect the performance of 120C bake cavities**

Plots courtesy of Zuhawn Sung

Fermilab ILLINOIS INSTITUTE OF TECHNOLOGY

Overview of High Gradient/High Q_0 Work at FNAL

Part I: Single cell studies:

- Findings:
  1) Achieving 50 MV/m in 1.3 GHz TESLA – shaped Nb single cells
  2) Curious bifurcation in cavity performance
  3) Changes in cavity performance with different cavity cooldown protocols
- Cryo-AFM studies: Nano-hydride growth and dissolution

Part II: 9-cell studies

- High G/HighQ_0 TESLA-shaped 9-cell cavities

Part III: Plans for High G/High Q_0 ILC Style Cryomodule:

- Refurbishing plan
- International collaboration

Conclusion

High Gradient 9-Cell TESLA-shaped Nb cavities

Recent lessons learned:

1) High temperature annealing – flux expulsion

2) Low temperature electropolishing

3) 75/120C low temperature bake

High Gradient 9-Cell TESLA-shaped Nb cavities

Recent lessons learned:

1) High temperature annealing – flux expulsion

2) Low temperature electropolishing

3) 75/120C low temperature bake

- As part of the LCLS II-HE R&D effort, four TESLA shaped 9-cell cavities subject to:
  - High temp annealing
  - Electropolishing
  - In-situ 120C x 48hr bake

High Gradient 9-Cell TESLA-shaped Nb cavities

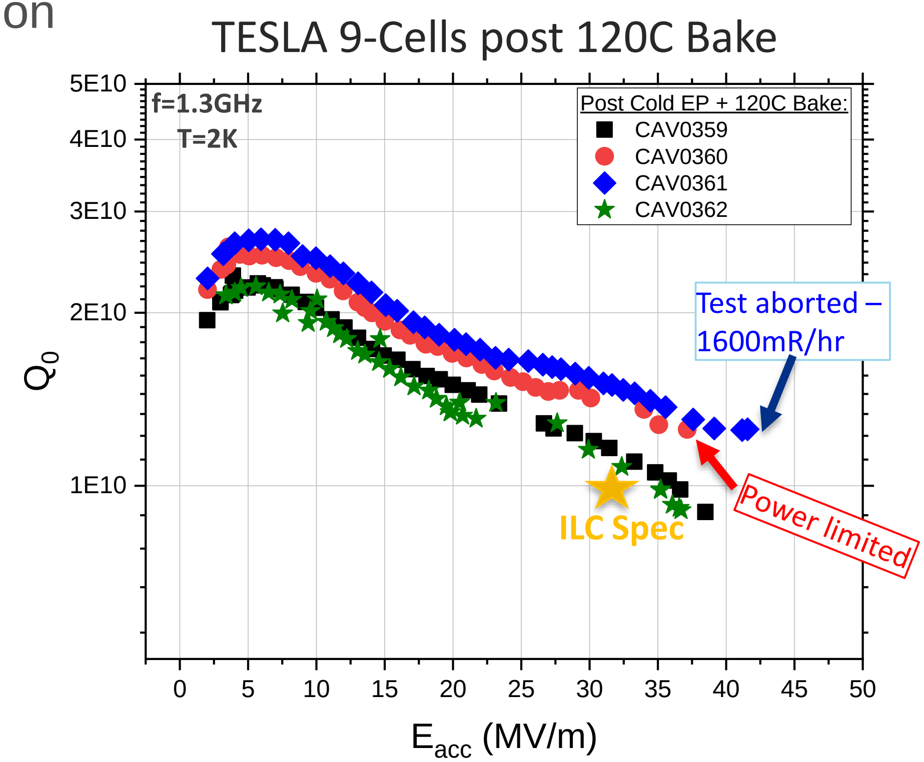
Recent lessons learned:

1) High temperature annealing – flux expulsion

2) Low temperature electropolishing

3) 75/120C low temperature bake

- As part of the LCLS II-HE R&D effort, four TESLA shaped 9-cell cavities subject to:
  - High temp annealing
  - Electropolishing
  - In-situ 120C x 48hr bake



LCLS-II-HE

Fermilab

ILLINOIS INSTITUTE OF TECHNOLOGY

High Gradient 9-Cell TESLA-shaped Nb cavities

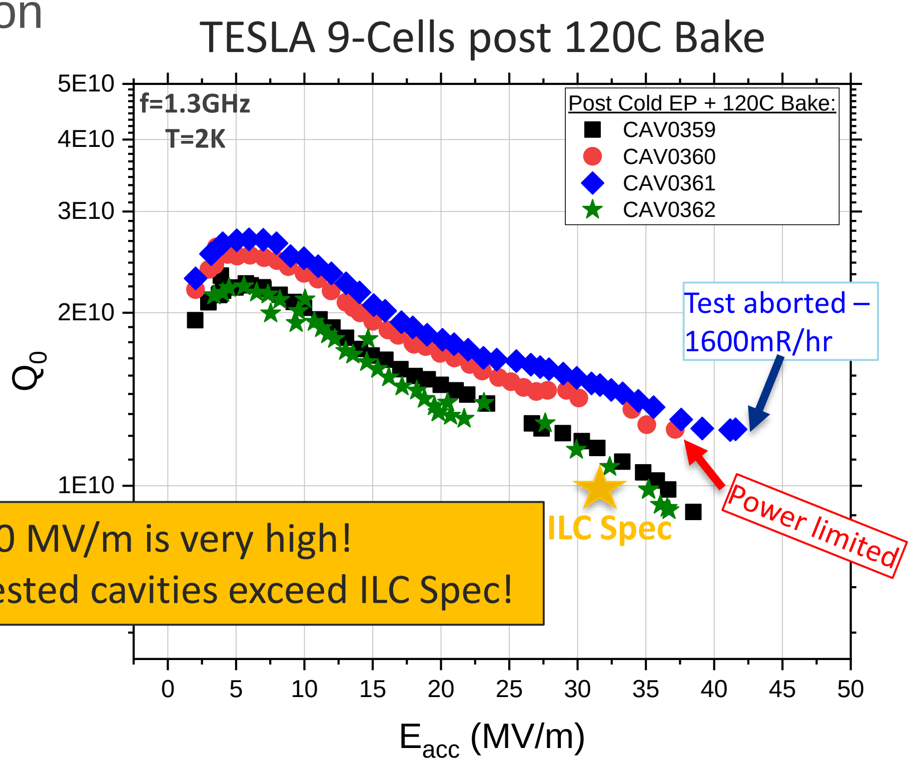
Recent lessons learned:

1) High temperature annealing – flux expulsion

2) Low temperature electropolishing

3) 75/120C low temperature bake

- As part of the LCLS II-HE R&D effort, four TESLA shaped 9-cell cavities subject to:
  - High temp annealing
  - Electropolishing
  - In-situ 120C x 48hr bake



Yield at 40 MV/m is very high!
All four tested cavities exceed ILC Spec!

High Gradient 9-Cell TESLA-shaped Nb cavities

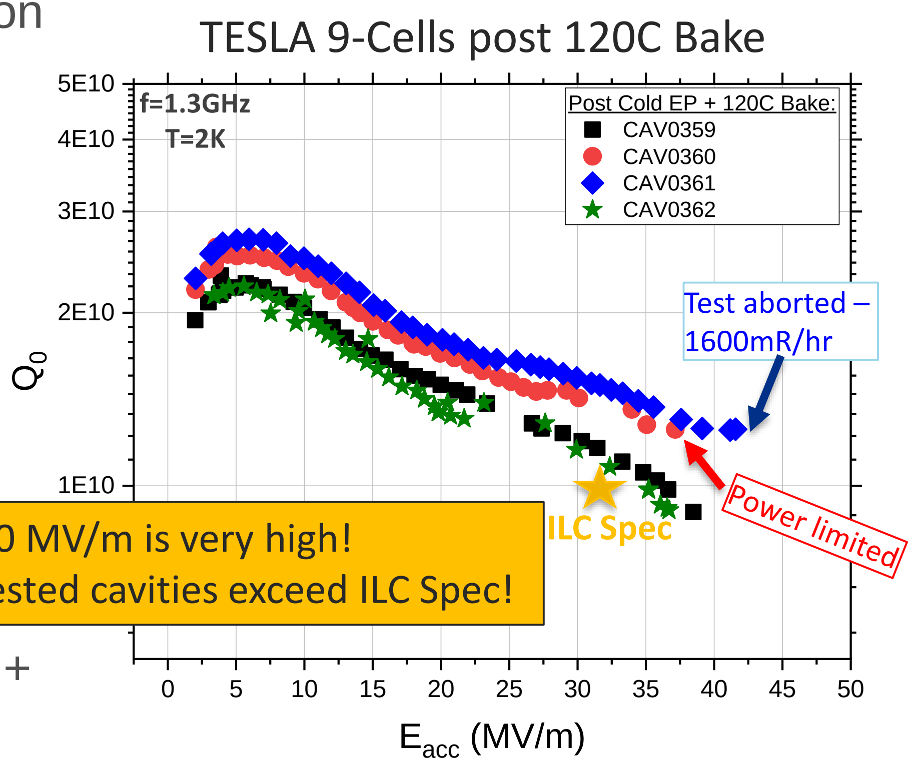
Recent lessons learned:

1) High temperature annealing – flux expulsion

2) Low temperature electropolishing

3) 75/120C low temperature bake

- As part of the LCLS II-HE R&D effort, four TESLA shaped 9-cell cavities subject to:
  - High temp annealing
  - Electropolishing
  - In-situ 120C x 48hr bake



Yield at 40 MV/m is very high!
All four tested cavities exceed ILC Spec!

- Next steps: repeat process with colder EP + 75/120C bake

Overview of High Gradient/High Q_0 Work at FNAL

Part I: Single cell studies:

- Findings:
  1) Achieving 50 MV/m in 1.3 GHz TESLA – shaped Nb single cells
  2) Curious bifurcation in cavity performance
  3) Changes in cavity performance with different cavity cooldown protocols
- Cryo-AFM studies: Nano-hydride growth and dissolution

Part II: 9-cell studies

- High G/HighQ_0 TESLA-shaped 9-cell cavities

Part III: Plans for High G/High Q_0 ILC Style Cryomodule:

- Refurbishing plan
- International collaboration

Conclusion

Plans for 2020-2021: High G/High Q_0 ILC Style Cryomodule

- With ILC Cost Reduction R&D funds from DOE, FNAL plans to assemble a High G/High Q_0 CM
- Goal: demonstrate an **$E_{acc,avg}$= 38MV/m @ Q_0= 1E10** in a CM test with a stretch goal of **40MV/m**
- Refurbish CM1, the first SRF cryomodule assembled at Fermilab in 2007, as a part of a collaboration between Fermilab, DESY, and LASA
- Reuse structural elements (vacuum vessel, support posts, cryogenic piping)
- Improved magnetic shielding will be implemented
- Encapsulated piezo tuner designs
- Cavities will be replaced by cavities that had achieved ILC spec and were set aside ~10 years ago for future modules

- Baseline treatment plan:
  - High temperature furnace treatment - flux expulsion
  - New low temperature EP
  - New 2-step low temperature baking treatment

Assembly will be carried out in FY20

Testing will take place in FY21 using existing facilities at FAST

High G/High Q_0 International Collaboration for ILC HL-HG

- As part of assembling this High Gradient Cryomodule, Fermilab reached out to potential partners to make this a more collaborative, international effort
- Success would mean that not just Fermilab, but multiple institutions capable of exceeding performance from TDR specifications
- Partners connected with: Jefferson Lab, Cornell, KEK, CEA, DESY, TRIUMF
- Partner contributions will vary depending on the institution, and will include
  - Contributions of treated and VTS qualified high gradient/high Q0 cavities
  - Treatment and/or testing of cavities
  - Magnetic shielding design/procurement
  - 10 years ago DESY already contributed kit for CM1

High G/High Q_0 International Collaboration for ILC HL-HG

- As part of assembling this High Gradient Cryomodule, Fermilab reached out to potential partners to make this a more collaborative, international effort
- Success would mean that not just Fermilab, but multiple institutions capable of exceeding performance from TDR specifications
- Partners connected with: Jefferson Lab, Cornell, KEK, CEA, DESY, TRIUMF
- Partner contributions will vary depending on the institution, and will include
  - Contributions of treated and VTS qualified high gradient/high Q0 cavities
  - Treatment and/or testing of cavities
  - Magnetic shielding design/procurement
  - 10 years ago DESY already contributed kit for CM1
- Fermilab Workshop on ILC HL-HG
  - Proposed High Luminosity – High Gradient ILC specs enabled by progress made in High G/High Q_0 R&D
  - Details can be found at: https://arxiv.org/abs/1910.01276

Conclusion

- Both High G/High Q_0 have been demonstrated at different laboratories, with **Q_0~2E10 at 31.5 MV/m achieved, 2X the ILC spec**, and **+48 MV/m (~210mT) while still maintaining Q_0 above 1E10** for 1.3 GHz single cell TESLA shaped Nb cavities post cold EP + 75/120 C baking.
- Bifurcation in cavity performance may be due to the **growth and dissociation of nano-hydrides** or the **condensation of gases.**
- 9-cell cavities post high temperature annealing and 120 C baking show a high gradient yield at 40 MV/m.
- The first cryomodule with an average accelerating gradient of 38-40 MV/m with Q=1E10 is expected to be assembled and tested by fiscal year 2021. Success would mean that production of CMs above ILC TDR specs are possible!

Thank you!