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Progress in N-Doping at FNAL – New Higher Gradient Insights

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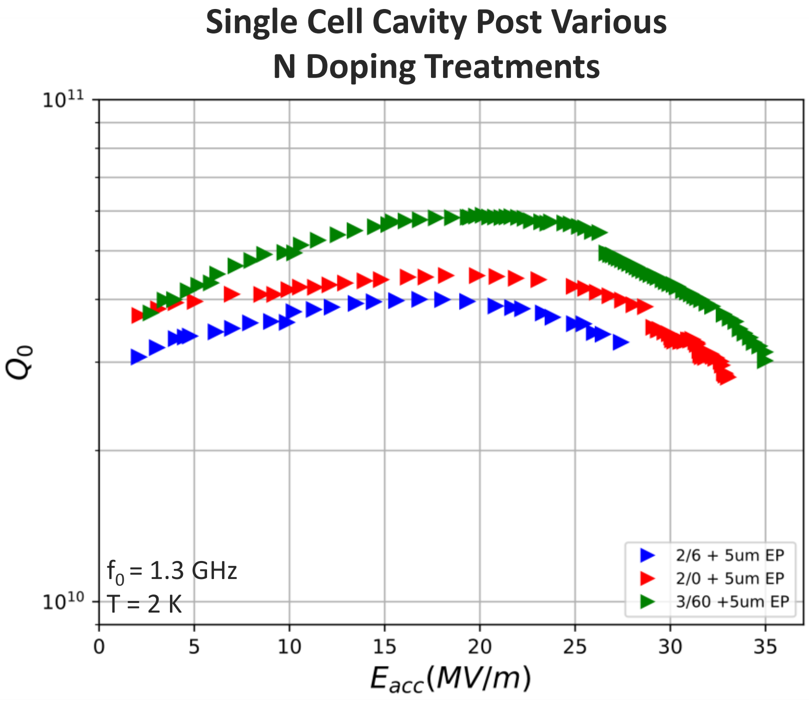
TTC’20 CERN

4 February 2020

Pushing the Performance of Nitrogen Doped SRF Cavities

- New optimized N-doping surface treatments of niobium SRF cavities have pushed the limits of performance
  - Q_0=3E10 above 30 MV/m
- To drive down the cost of future accelerators, need to improve further
- What are the **mechanisms responsible for high gradient** performance?
- This presentation will:
  - Present a study on the quench behavior in N-doped single cell cavities using thermometry mapping (TMAP)
  - Make a connection to early quench in 9-cell cavities



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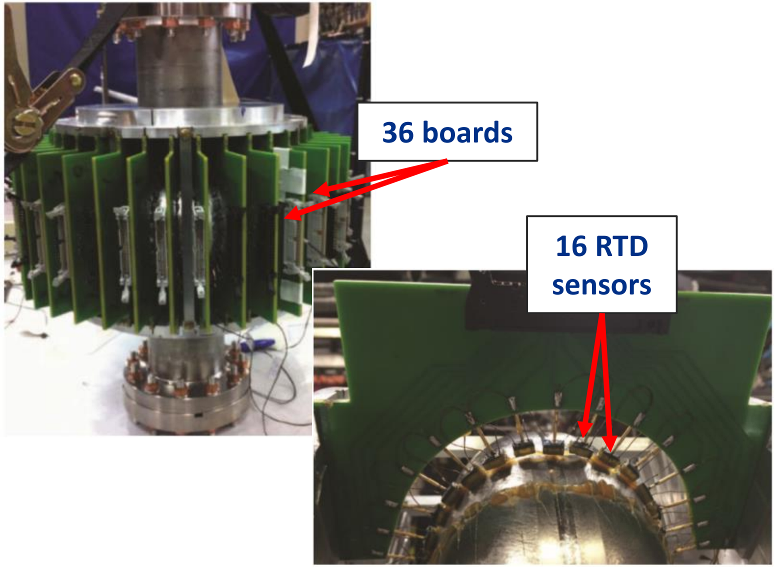
Sequential TMAP Study of a Single Cell Niobium Cavity Post Various N-Doping Surface Treatments

Sequential TMAP Study of a Cavity Post N-Doping treatments

- One 1.3 GHz single cell was subject to the following N-doping surface treatments
- Inner surface was reset between each treatment with 40 µm electropolish (EP)
- After each treatment, cavity was equipped and tested with TMAP to study the nature of quench at T_{Bath} = 2 K and T_{Bath} < 1.5 K



Photos courtesy of M. Martinello

Treatments Used in Sequential Study

Treatment 1: 3/60 + 10 µm	Treatment 2: 2/0 + 5 µm – Failed treatment	Treatment 3: 2/0 + 5 µm	Treatment 4: 2/0 + 7 µm
3min in 25 mTorr N @ 800 C	2min in 25 mTorr N @ 800 C	2min in 25 mTorr N @ 800 C	Add + 2 µm
60min in UHV @ 800 C	+5um EP	+5um EP	
+10um EP			

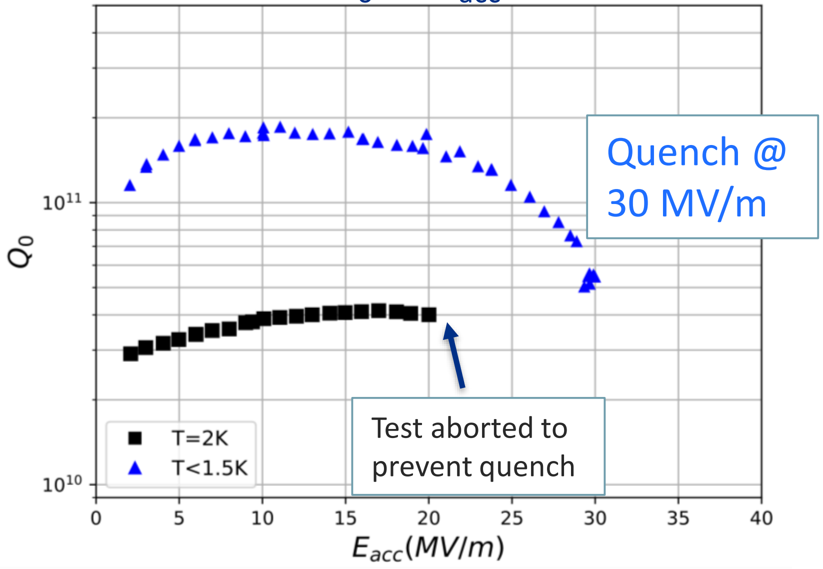
40 µm EP reset (between Treatment 1 and Treatment 2)

40 µm EP reset (between Treatment 2 and Treatment 3)

Sequential TMAP Study 1/4: 3/60 + 10 µm EP

- 1st treatment: JLab developed 3/60 N-doping surface treatment:
  - 3 min in 25mTorr of N at 800 C + 60 min in UHV at 800 C + 10 µm EP

Q_0 vs E_{acc}



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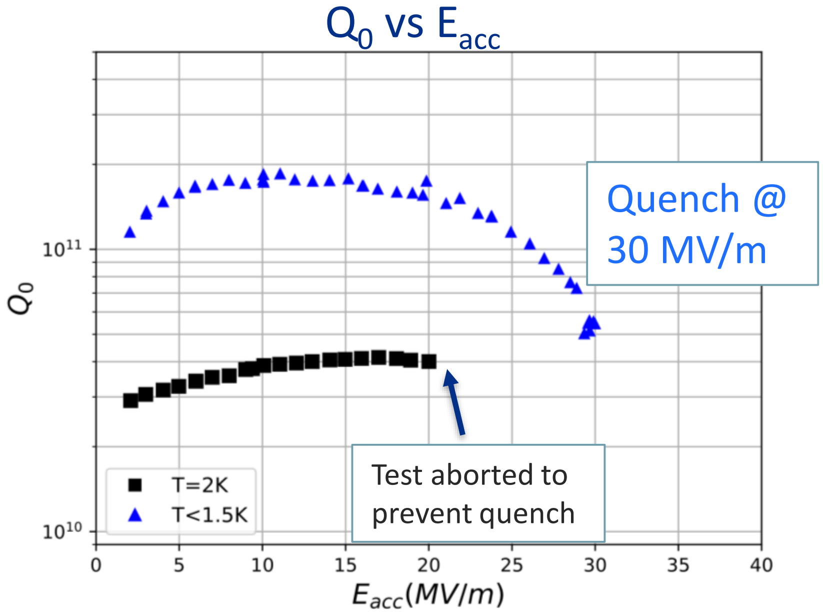

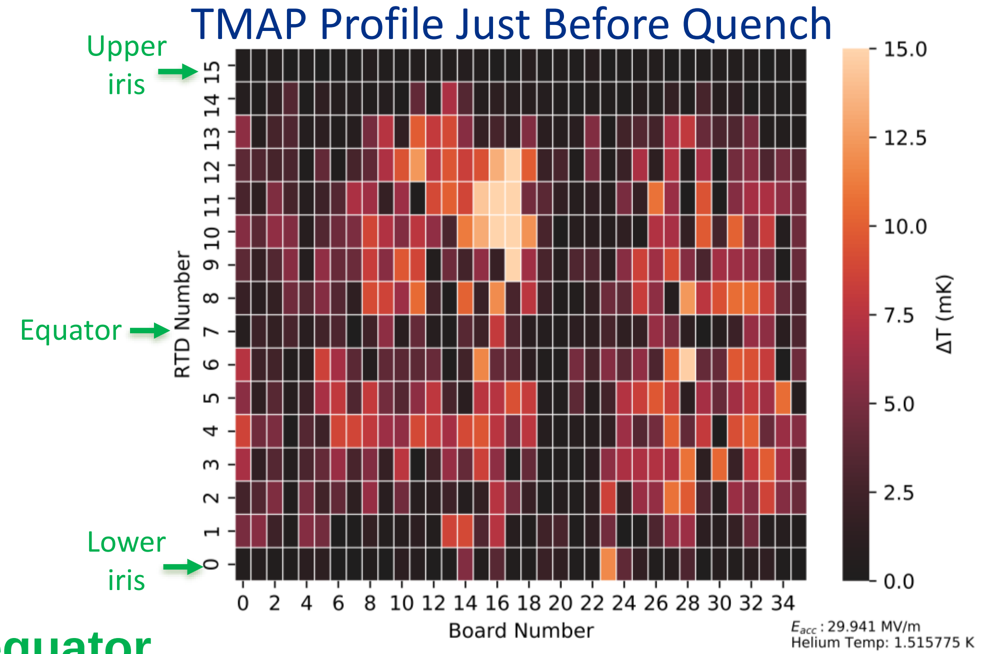

- Strong, localized pre-heating **above equator**

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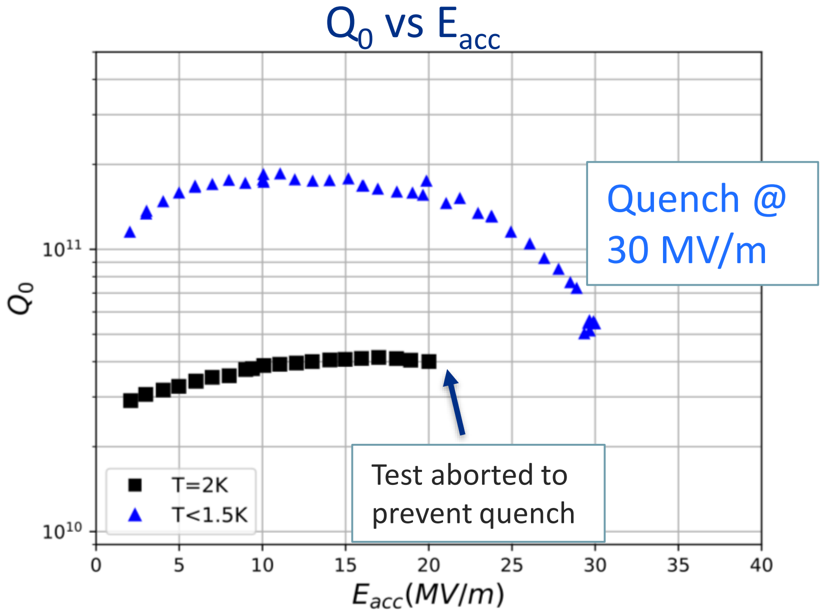
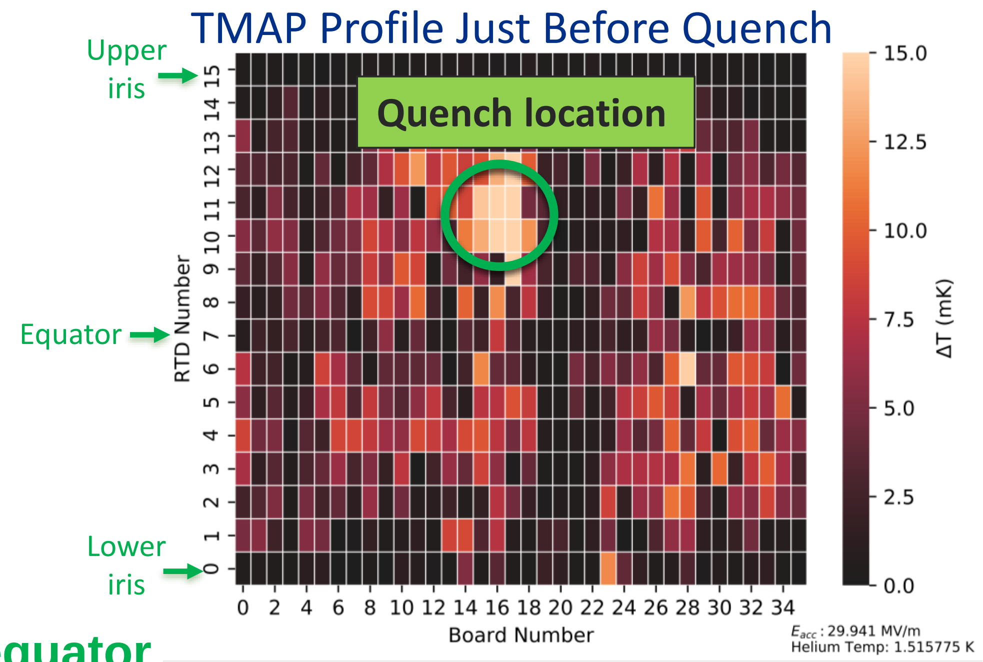
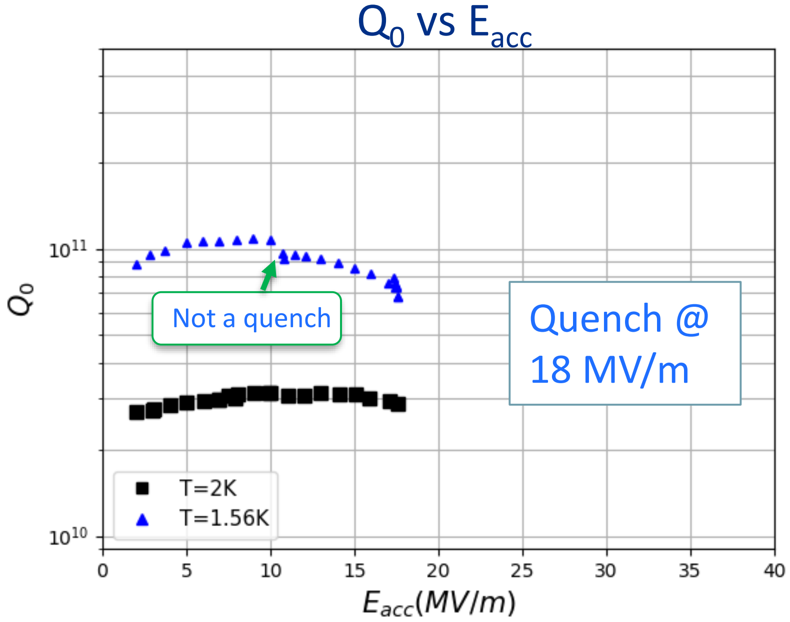




- Strong, localized pre-heating **above equator**
- Quench location coincides with area of strongest pre-heating

Sequential TMAP Study 2/4: 2/0 + 5 µm EP

- 2nd treatment: 40um EP reset + FNAL developed 2/0 N-doping surface treatment:
  - 2 min in 25mTorr of N at 800 C + 5 µm EP



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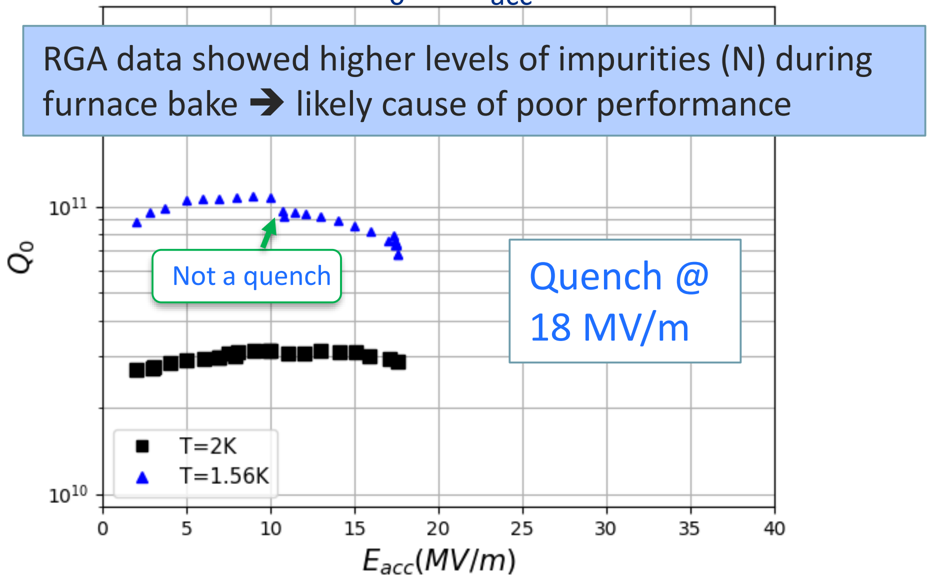
Q_0 vs E_{acc}



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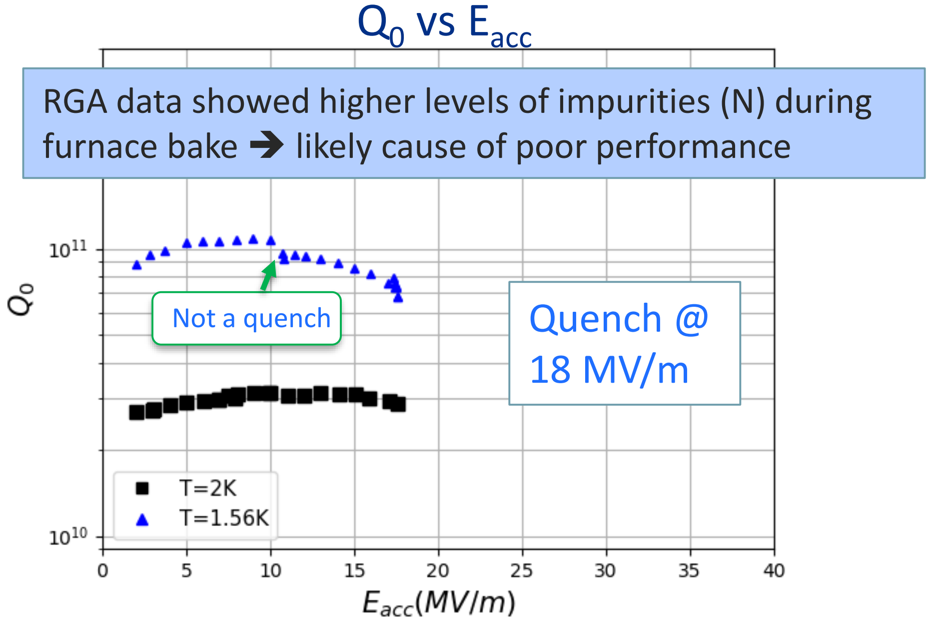

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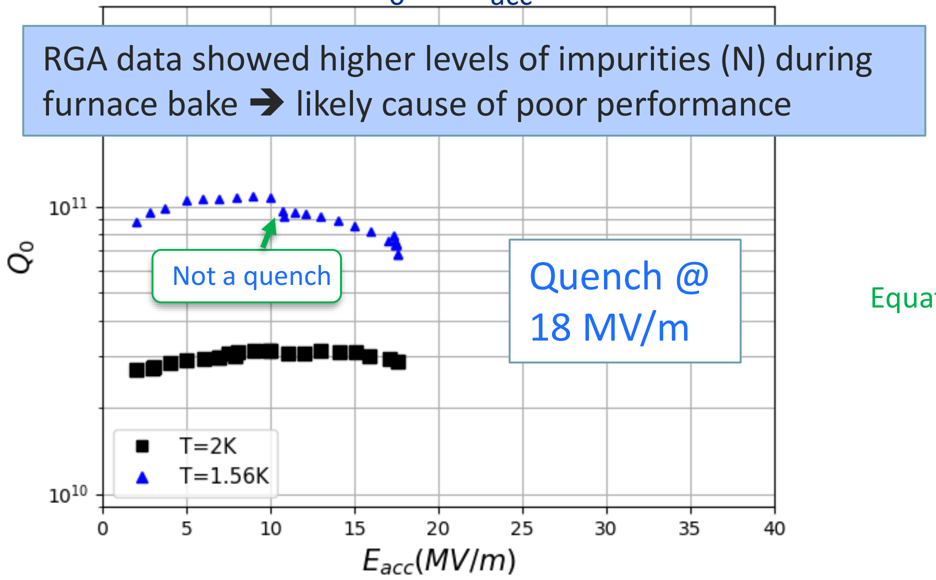
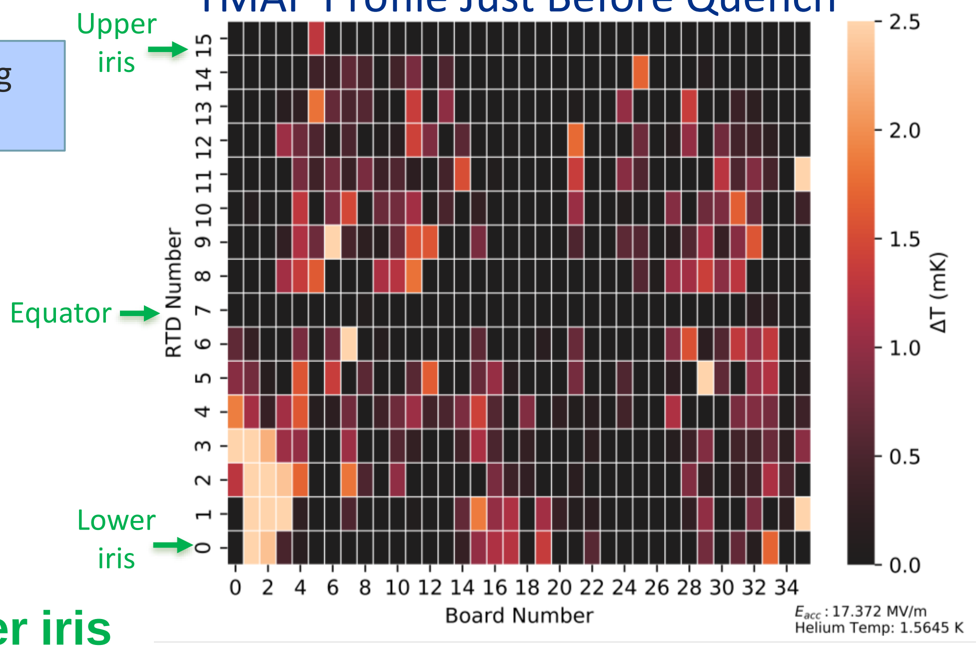


TMAP Profile Just Before Quench



- Highly localized pre-heating near **lower iris**

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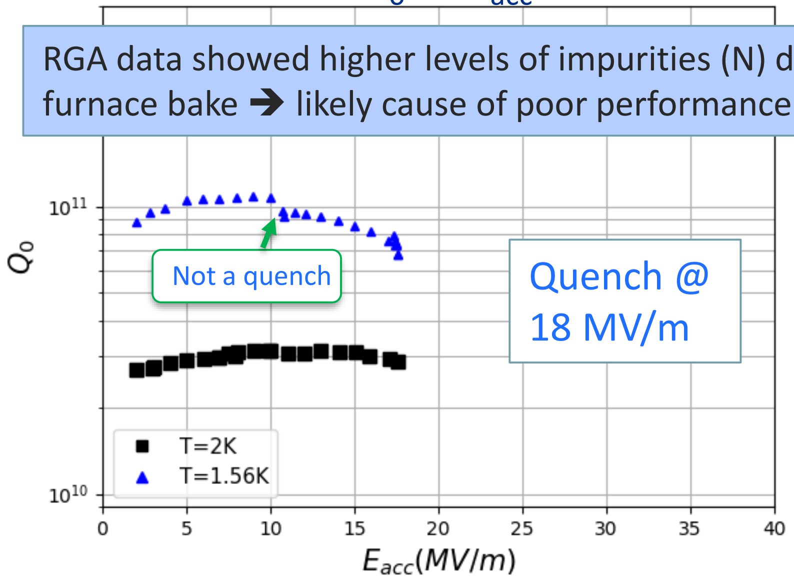
Q_0 vs E_{acc}

RGA data showed higher levels of impurities (N) during furnace bake ➔ likely cause of poor performance



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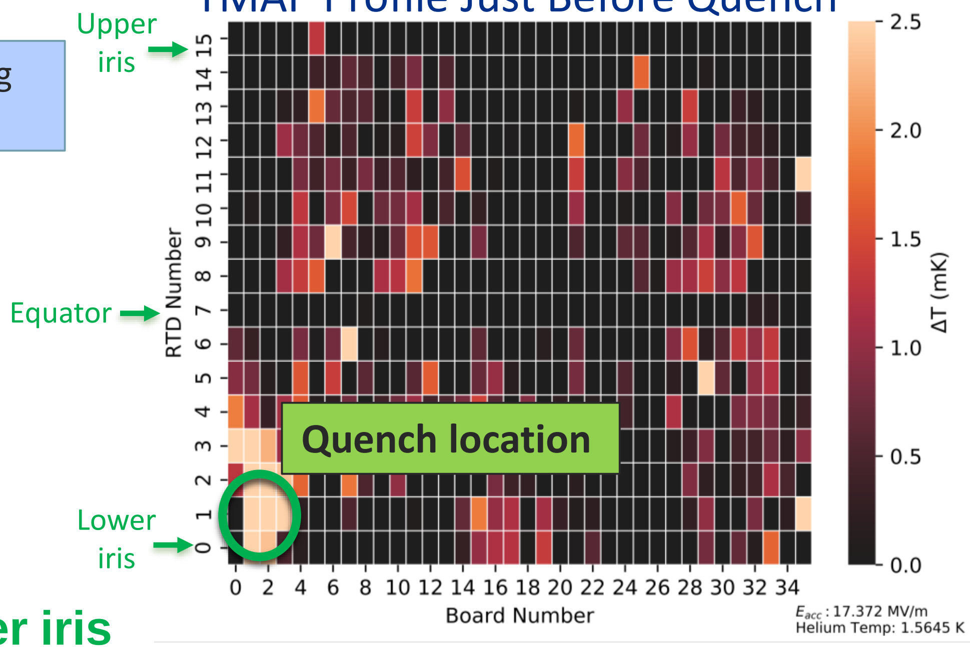

- Highly localized pre-heating near **lower iris**
- Quench location coincides with area of strongest pre-heating, due to **nitride?**

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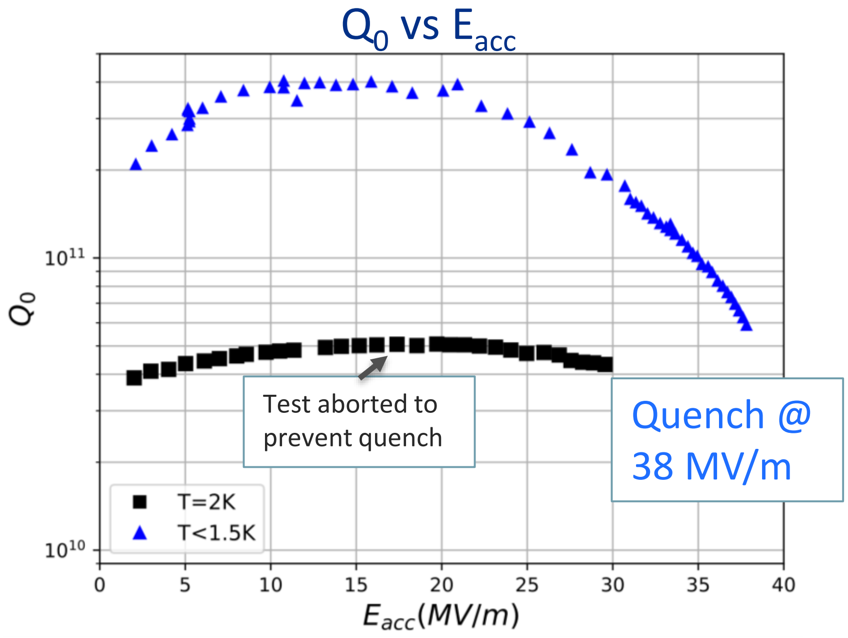
Sequential TMAP Study 3/4: 2/0 + 5 µm EP (Again)

- 3rd treatment: 40um EP reset + 2/0 N-doping surface treatment: Successful



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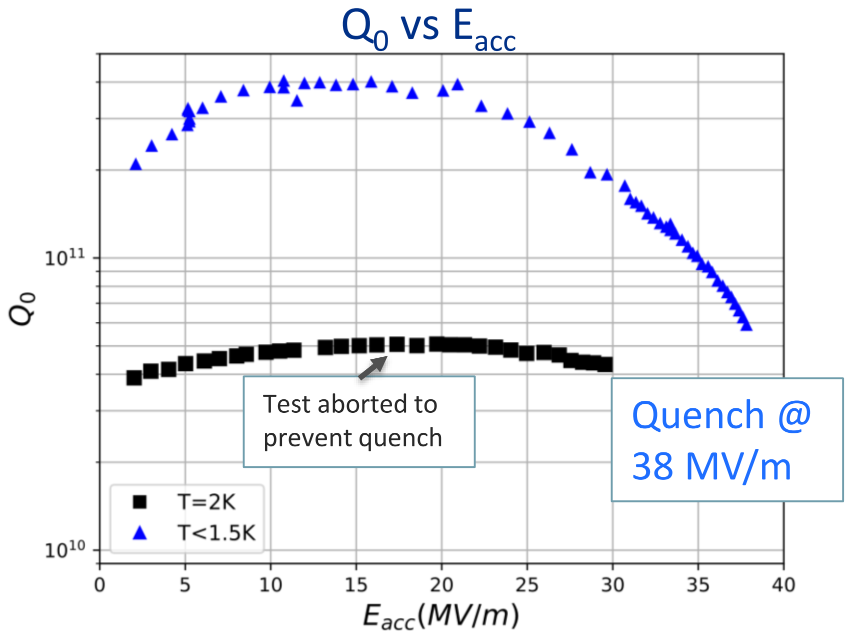

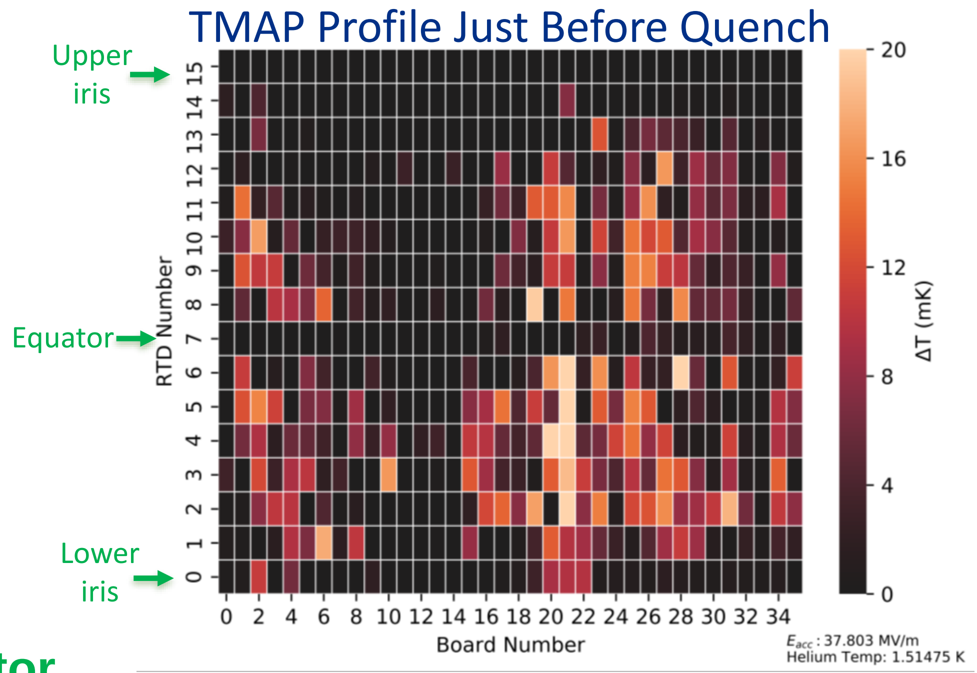

- High level of pre-heating **below equator**

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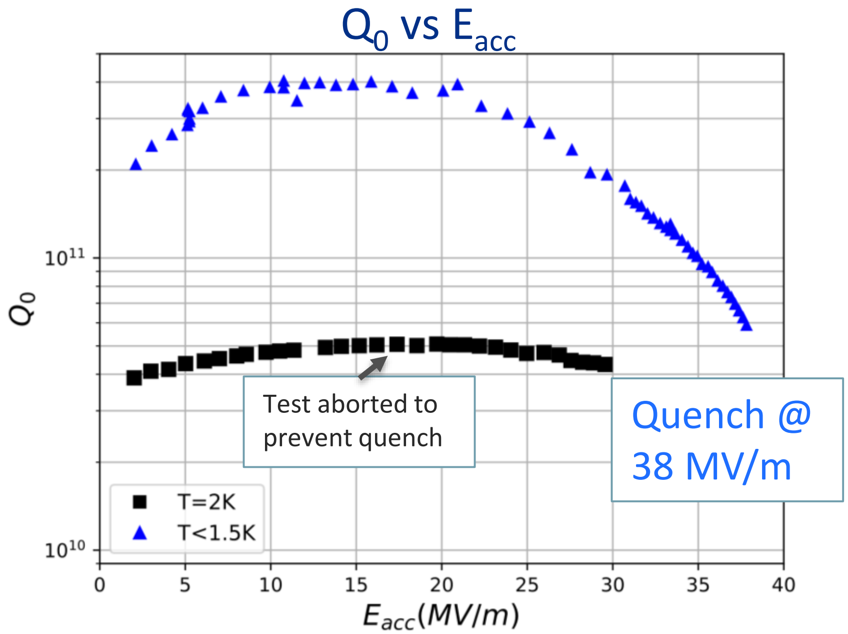

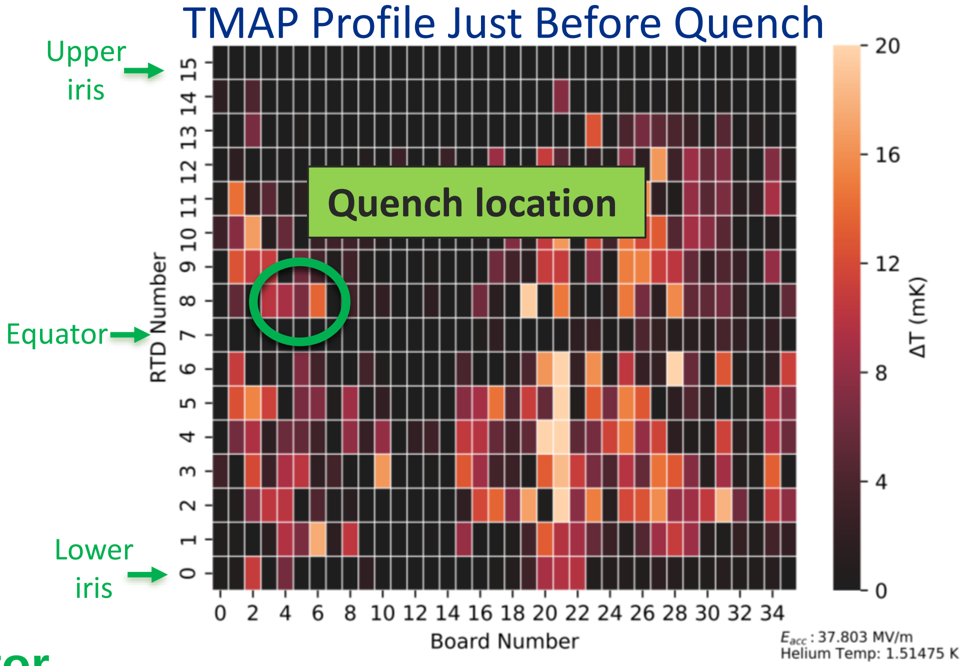

- High level of pre-heating **below equator**
- Quenches **near equator** - **DOES NOT** coincide with area of strongest pre-heating

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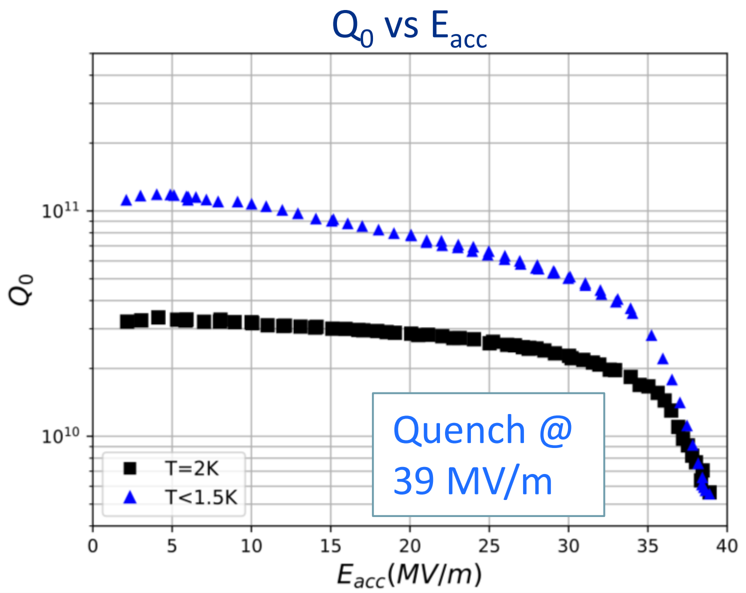
Sequential TMAP Study 4/4: 2/0 + 7 µm EP

- **Add +2 um EP on top** of the previous treatment: net treatment 2/0 + 7 µm EP



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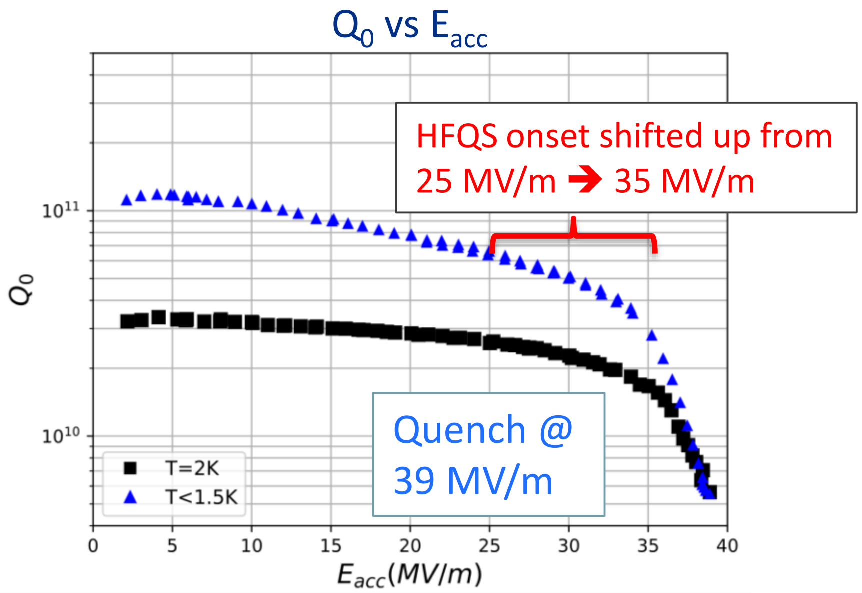
  - Losing benefit of doping – different mechanisms governing quench?



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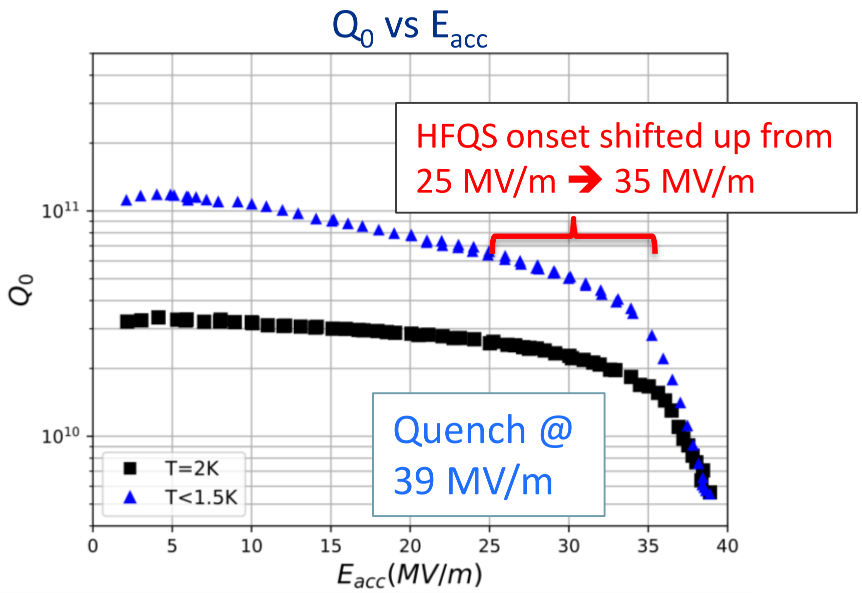

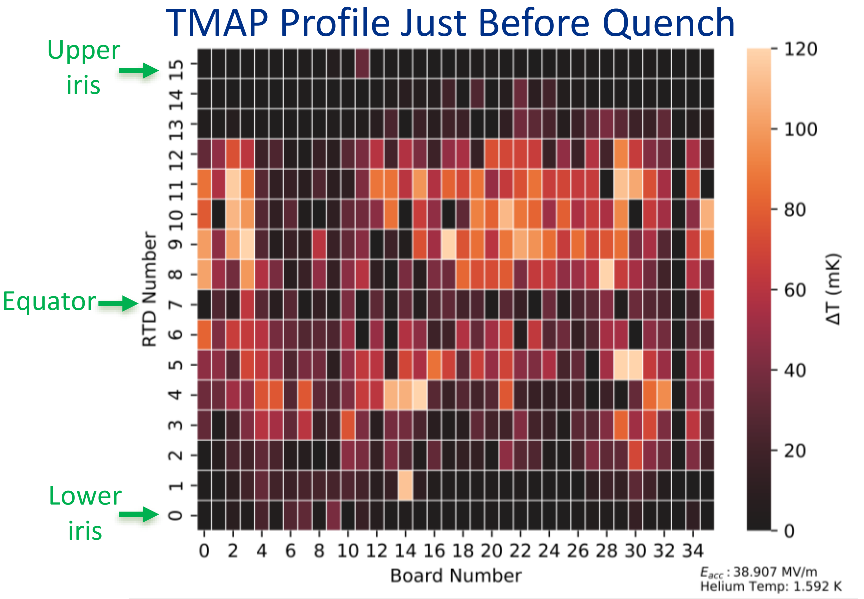

- TMAP profile shows **strong global heating** ➔ resembles EP cavity with HFQS

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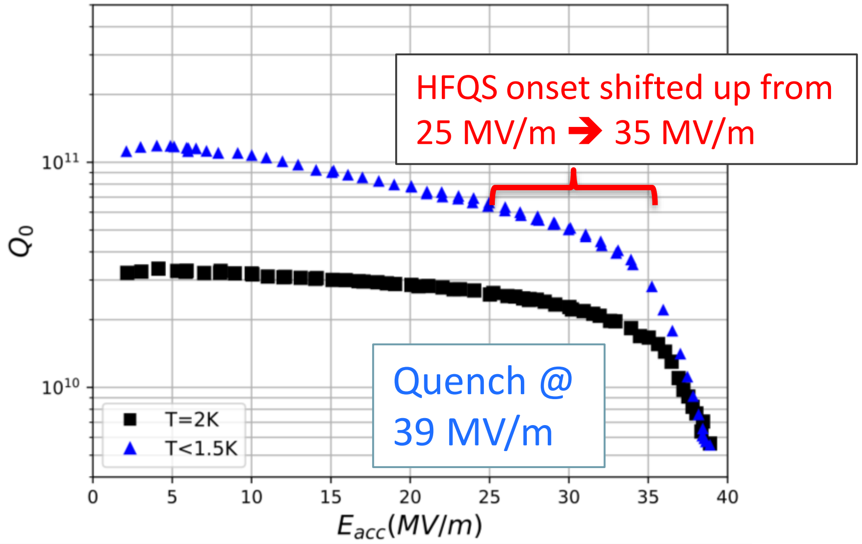

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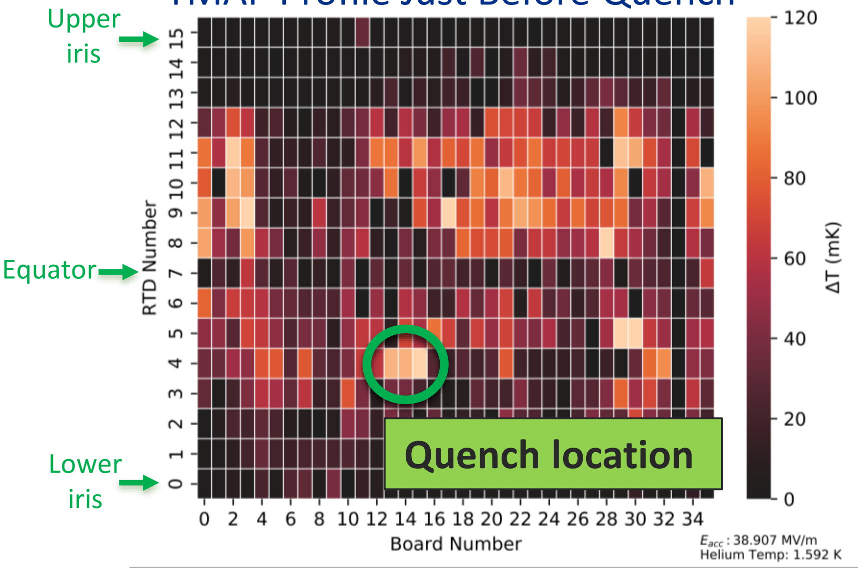

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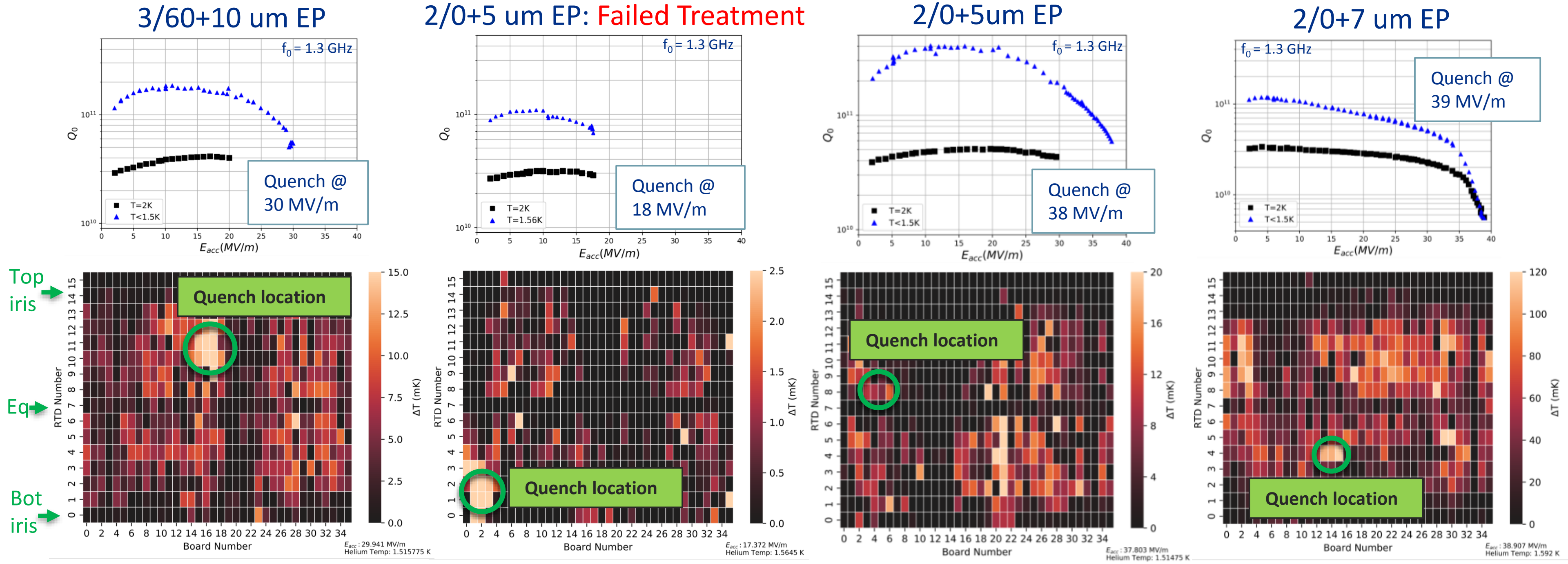
Comparison of TMAP Profiles



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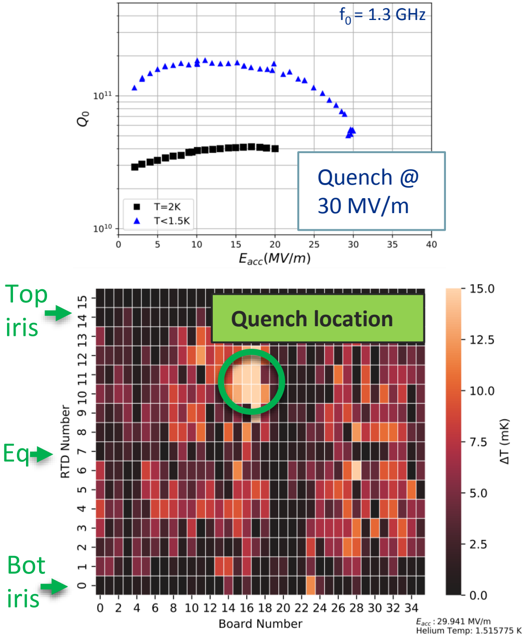
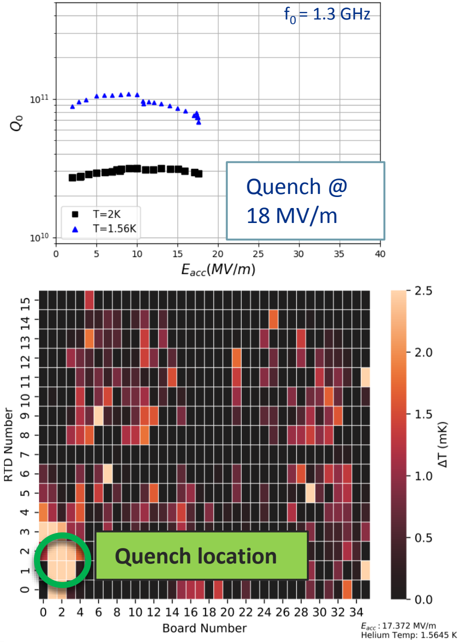


2/0+5 um EP: Failed Treatment



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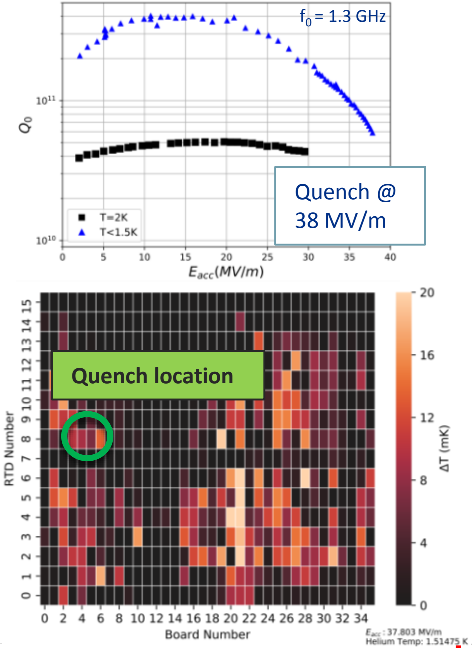
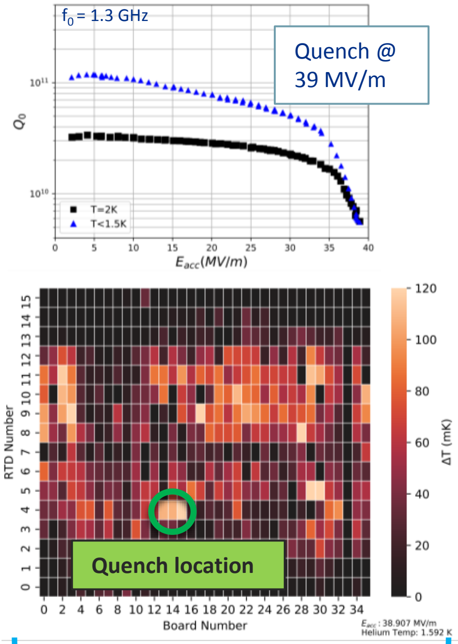


2/0+7 um EP



Higher quench fields tend to quench closer to the equator

Becomes HFQS-like

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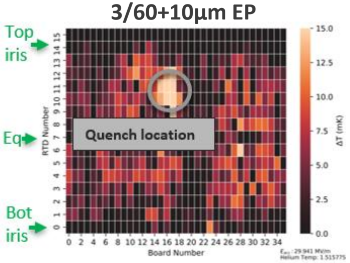
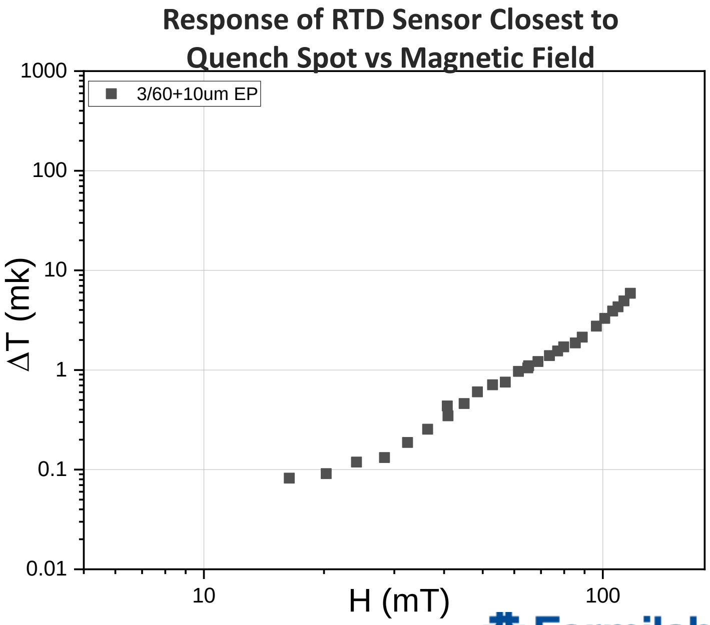
Comparison of Quench Spot Heating Profiles: ΔT (H)

Response of RTD sensor nearest to quench location is plotted as a function of magnetic field



- **3/60+10um EP:** Low pre-heating, sudden quench
  - Likely to be of magnetic origin



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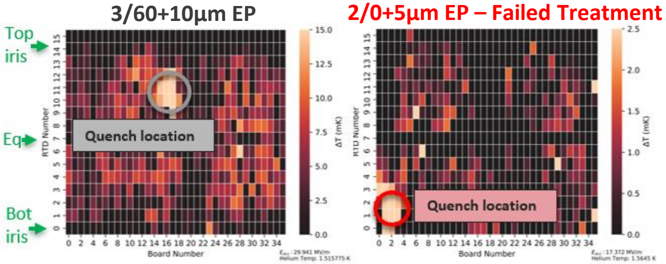

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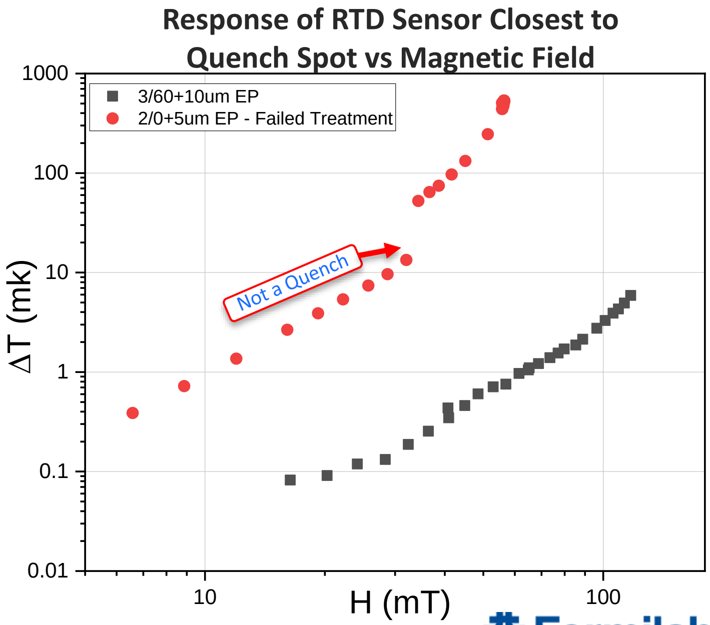

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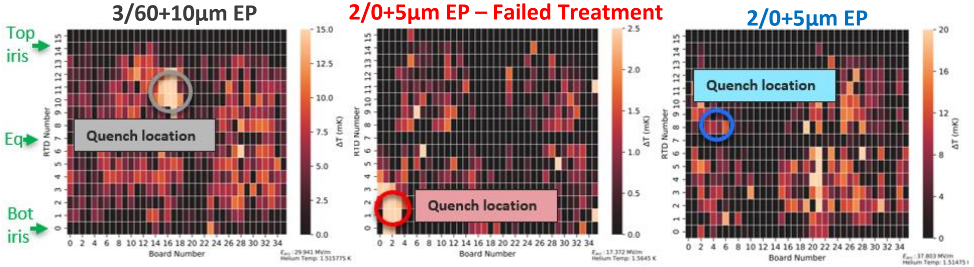

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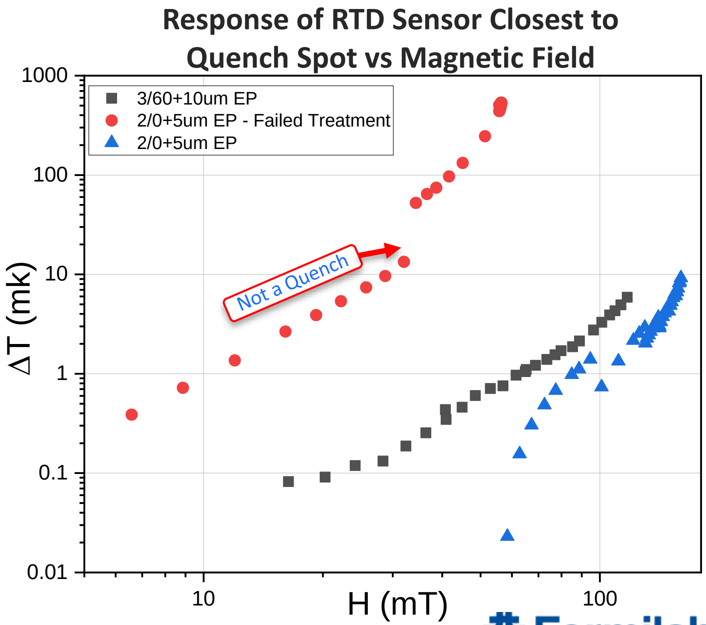

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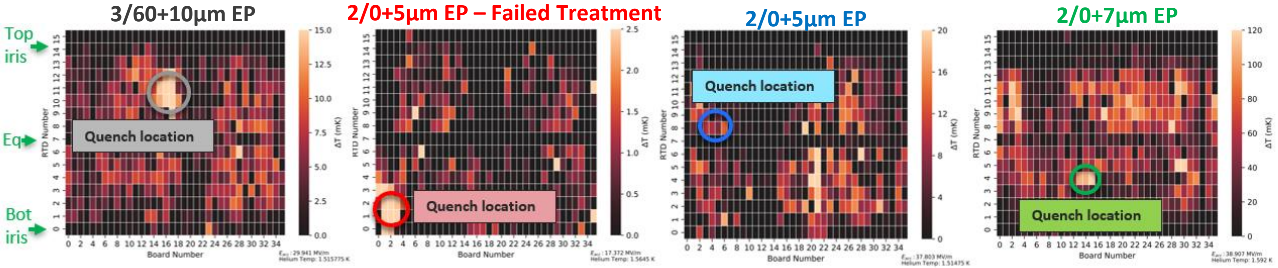

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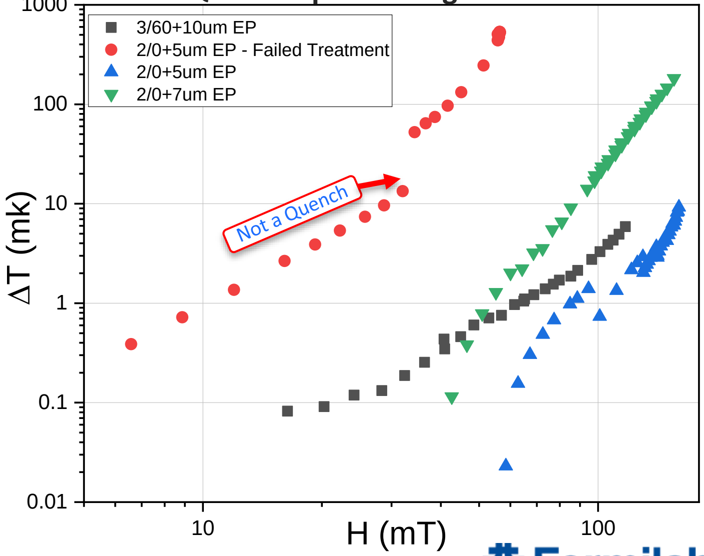
Response of RTD Sensor Closest to Quench Spot vs Magnetic Field



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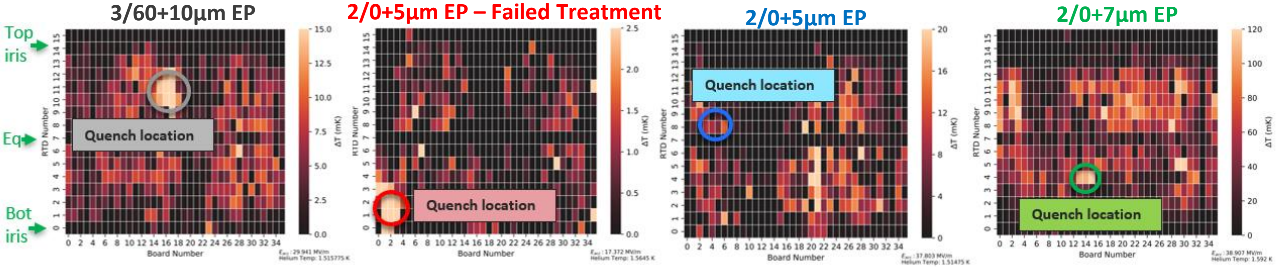

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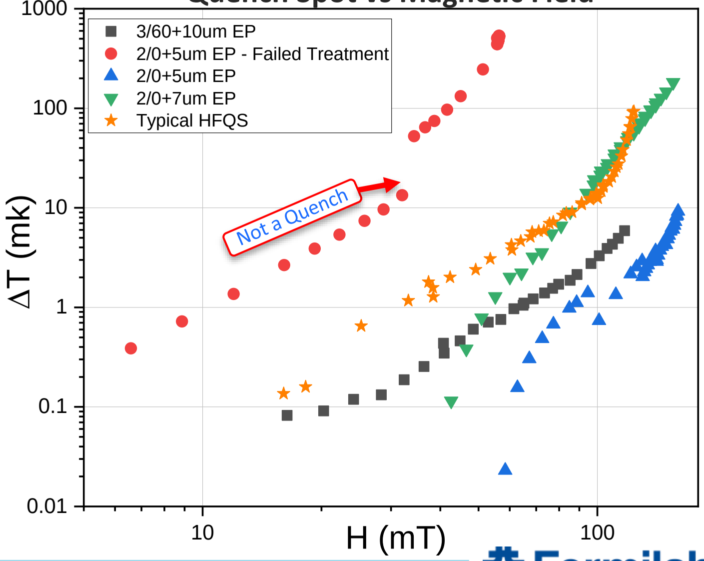
  - *Not @ point of strongest pre-heating:* likely magnetic origin
- **2/0+7um EP:** Steady pre-heating, sudden quench
  - Compared to **typical HFQS**, stronger slope, no change
  - Transition from N-doped to EP cavity
  - Quench is of thermo-magnetic origin

Response of RTD Sensor Closest to Quench Spot vs Magnetic Field



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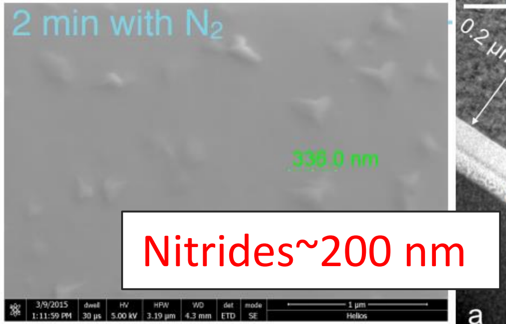
Possible Source of Low Quench Fields: Nitrides

- Results suggest that if N-doping "goes well," cavity will quench at point of **highest field (equator)**
- If N-doping "doesn't go well" (i.e., furnace contamination, poor EP, etc.), cavity will **quench at a low field closer to the iris** - could be due to localized defects such as **nitrides**:
  - Excess nitrogen near iris due to "line of sight"
  - Residual nitrides left post EP?

SEM and TEM Studies of Nitrogen Baked Samples – 2 min, NO EP



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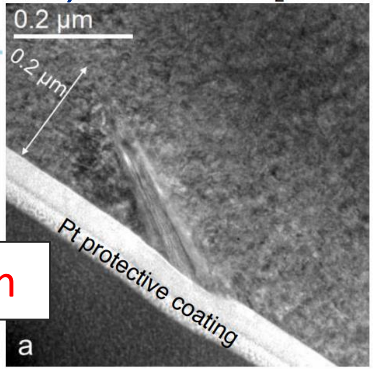

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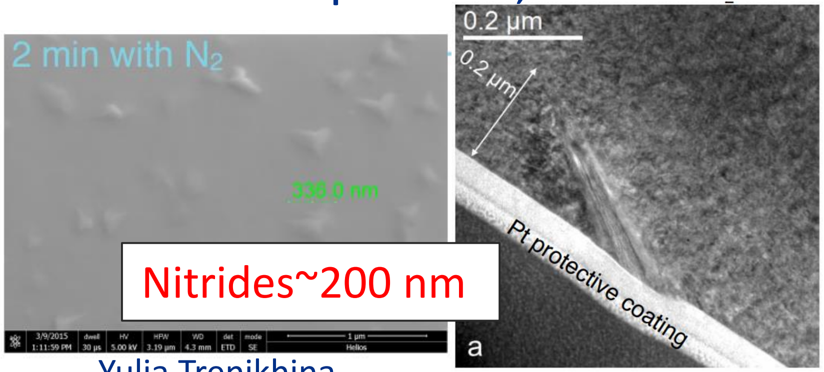

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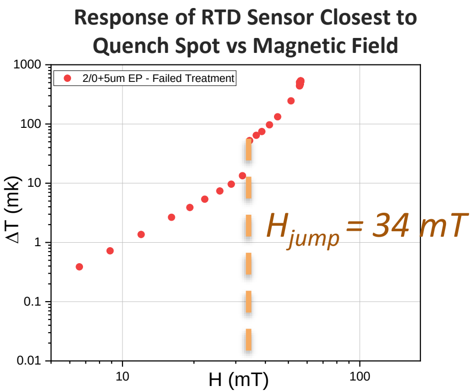


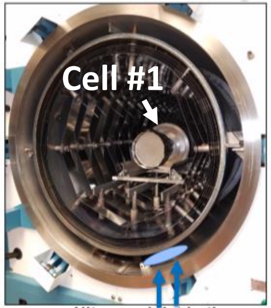
- Estimate of minimum nitride size for a proximity breakdown to occur @ H_{jump} = 34 mT (assuming values of Nb):

$$d \approx \frac{1}{6}\frac{\Phi_0}{\lambda_n H_{jump}} \approx 30nm$$

- Small, but above TEM and SEM images taken on samples that haven't received any final EP – 30 nm could be a reasonable approximation – topic of future study

Connection to Low Gradients in N-Doped 9-Cells

- Previously observed that **excess nitrogen** may cause **poor RF performance** and **surface quality** in 9-cell cavities



Nitrogen inlet in the furnace sits near the door

See talk by Arely Cano for more on this study

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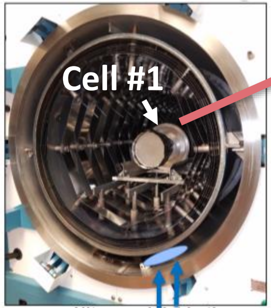
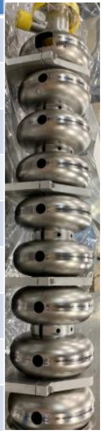
Cell closest to door/N inlet (Cell #1) quenched @ 19.5 MV/m; Cell #5 @ +30 MV/m
- **Difference in N concentration?**



Nitrogen inlet in the furnace sits near the door

CAV18 Quench Field-FPC Facing Front (MV/m)	Cell #
19.5	1
30.8	2
>25.3	3
>23.3	4
>30.8	5
>23.3	6
25.3	7
>30.8	8
>19.5	9



See talk by Arely Cano for more on this study

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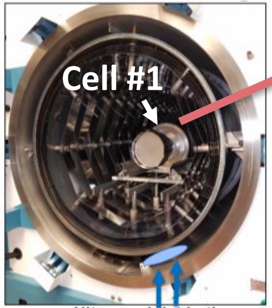
Samples cut from each cell



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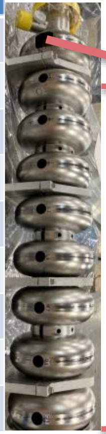
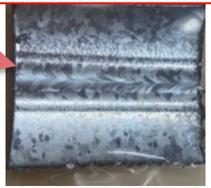
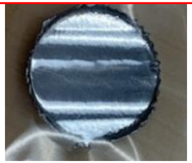


Cell# 1 cutout: clearly see individual grains



Cells # 2-9: pristine surface



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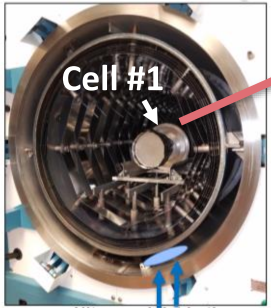

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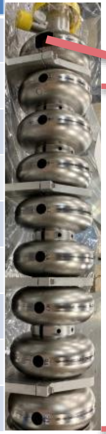

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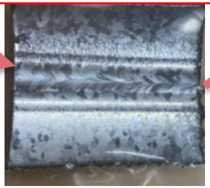
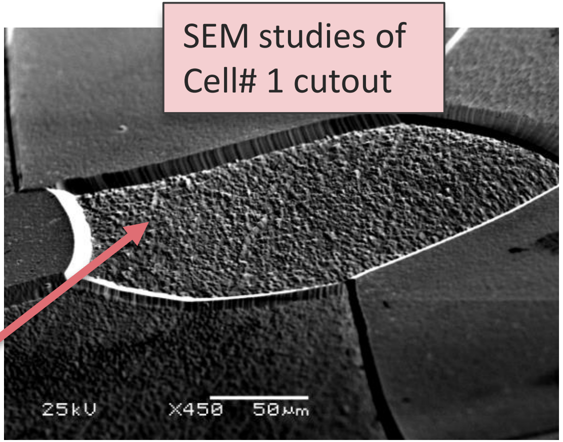


Cells # 2-9: pristine surface

SEM studies of Cell# 1 cutout



- Clearly etched grains
- Could **excess nitrogen** have left some grains subject to **preferential etching, and scoop out nitrides,** leaving a rough surface? – topic under study

See talk by Arely Cano for more on this study

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Conclusions & Future Work

Conclusions:

- For the N-doping surface treatments studied, the treatments that yielded **higher quench fields quenched closer to the equator** with a mechanism that is likely of **magnetic origin**
- The treatment that gave the **lowest quench field** (18MV/m) quenched **near the iris** and is likely due to the **heating of a nitride**
- Idea that an excess of nitrogen causes early quench is consistent with results from 9-cell cavity study
- Decreasing the concentration of nitrogen in an N-doped cavity via EP shows the **re-emergence of HFQS** at an elevated field (35 MV/m instead of 25 MV/m) and a heating behavior that is a combination of N-doped and standard EP cavities

Future Work:

- Get a better estimate for nitride size that corresponds with a certain breakdown field
- Perform this same TMAP study but with the sequential removal of the surface by EP
- More material science studies on N-doped 9 cell cutouts to pinpoint cause of early quench