Estimated Gradient Limitation Insights for Different Surface Processing from Klystron Measurements

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TTC Meeting, July 2016

Insights from Klystron Measurements

- Klystron testing overview
- N-doped niobium
- 120^{o}C-baked niobium
- Nb_3Sn

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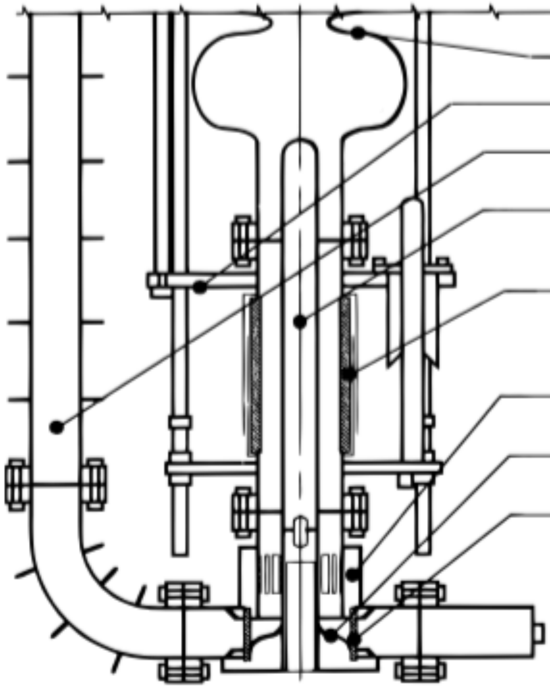
Insights from Klystron Measurements

- Klystron testing – motivation:
  - Escape global thermal effects by filling and quenching the cavity extremely quickly
    - Still limited by local effects
  - Probe higher fields than CW quench field
    - Probe fundamental fields in some cases (when heating not too strong)

Insights from Klystron Measurements

- Klystron testing – apparatus

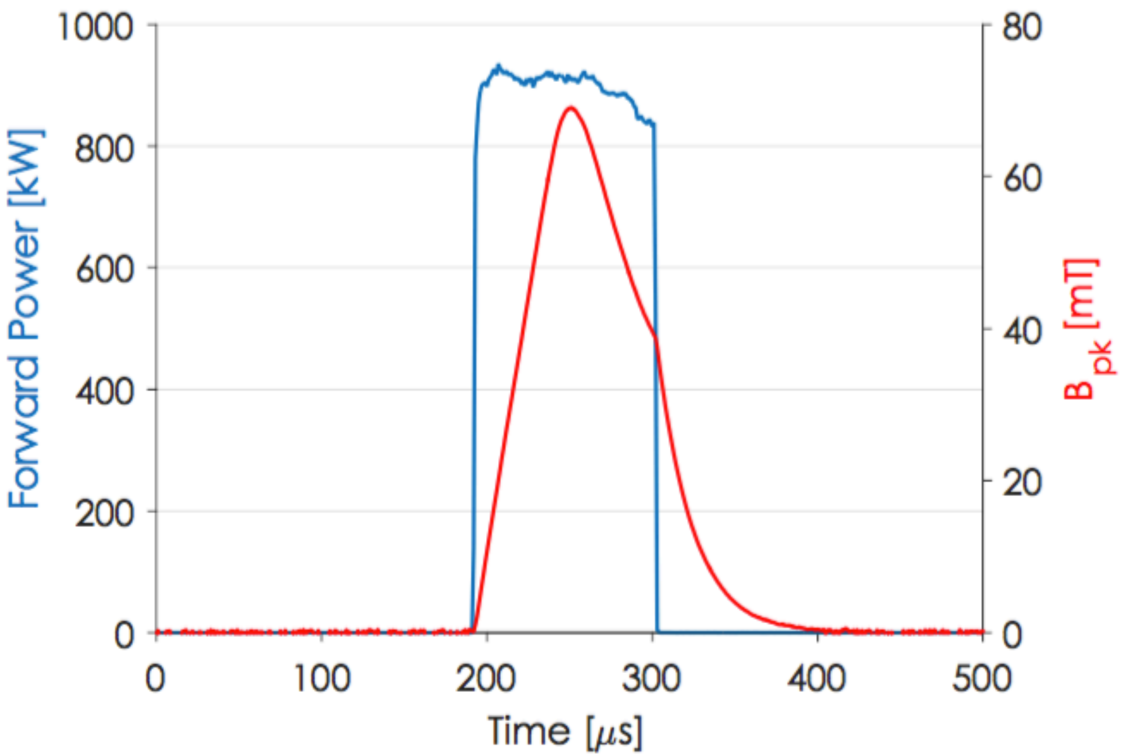


Insights from Klystron Measurements

- Klystron testing – procedure
  - Typically preceded by CW test to calculate material properties
    - F vs. T → λ vs. T, ℓ, T_c
    - Q_0 vs. T → R_0, Δ
    - Q_0 vs. E → R_{BCS} vs. E
  - Pulsed testing:
    - Short (~ 100 us) pulses, up to 1 MW each P_f
    - Very strong coupling: $Q_{ext} \sim 10^6$

Insights from Klystron Measurements

- Klystron testing – typical pulse
  - P_f, P_r, P_t
  - Quench field
    - Not necessarily the peak!
  - Time to quench
  - Q(t)



  - Reminder:
    - $Q \propto U/P_{diss}$

Insights from Klystron Measurements

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Insights from Klystron Measurements

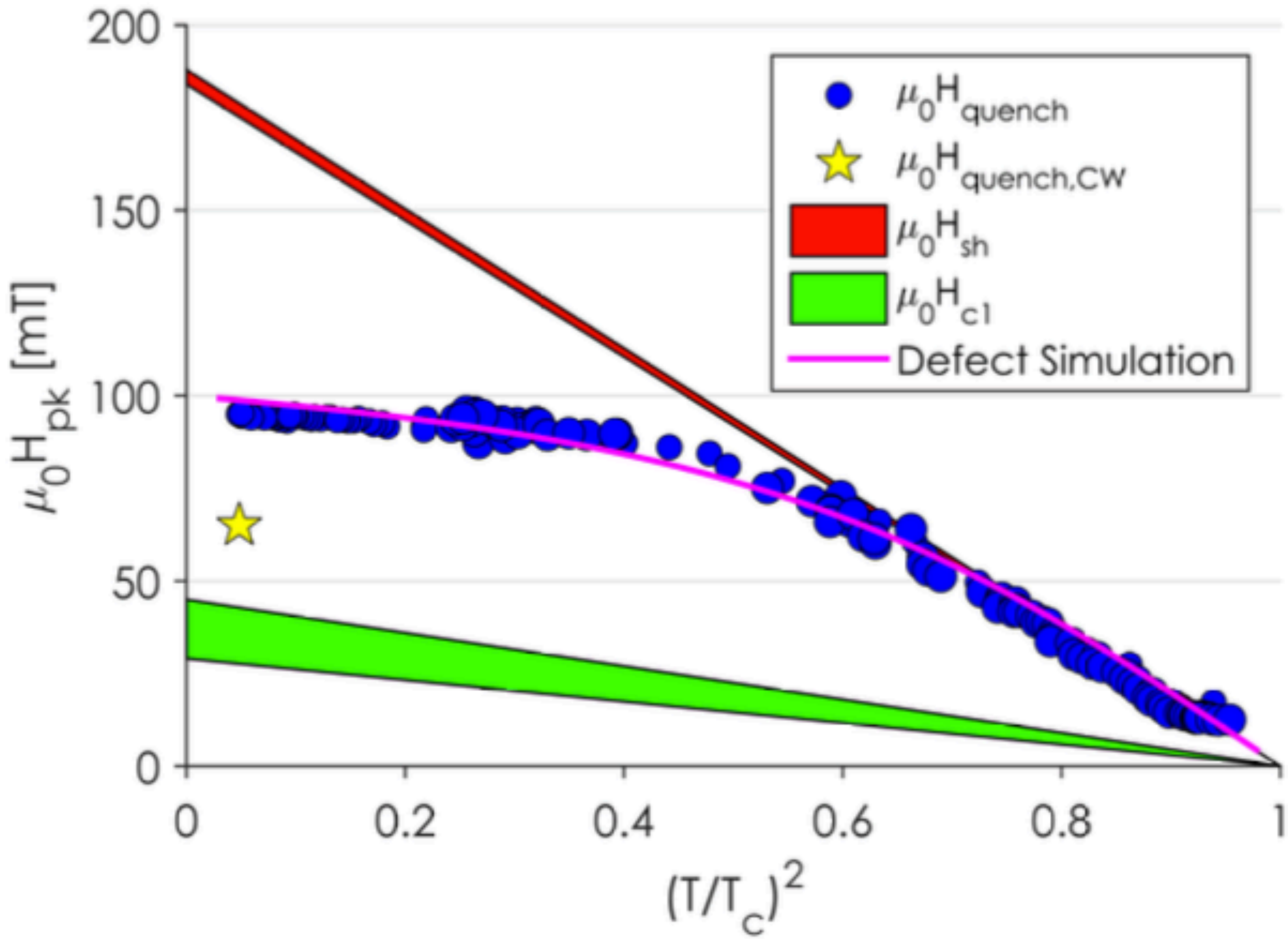
- N-doped cavities
  - LTE1-2
    - 900°C N-doping + 18 um VEP
    - Mean free path = 6 nm
    - B_{c1} = 37±8 mT, B_{sh} = 186±2 mT
    - CW quench field = 64±4 mT
  - LTE1-3
    - 990°C N-doping + 5 um VEP
    - Mean free path = 4 nm
    - B_{c1} = 26±9 mT, B_{sh} = 179±3 mT
    - CW quench field = 40±2 mT

NB: Critical fields are given at T=0

Critical fields lowered (B_{c1} strongly, B_{sh} somewhat) in doped niobium

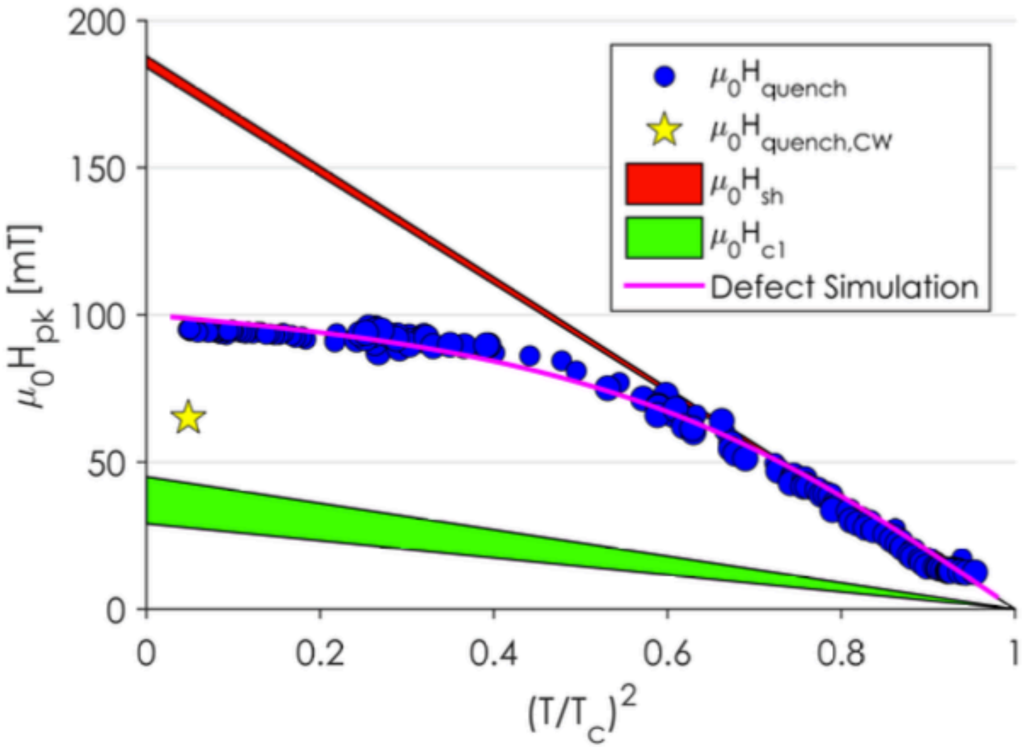
Insights from Klystron Measurements

- LTE1-2 N-doped results



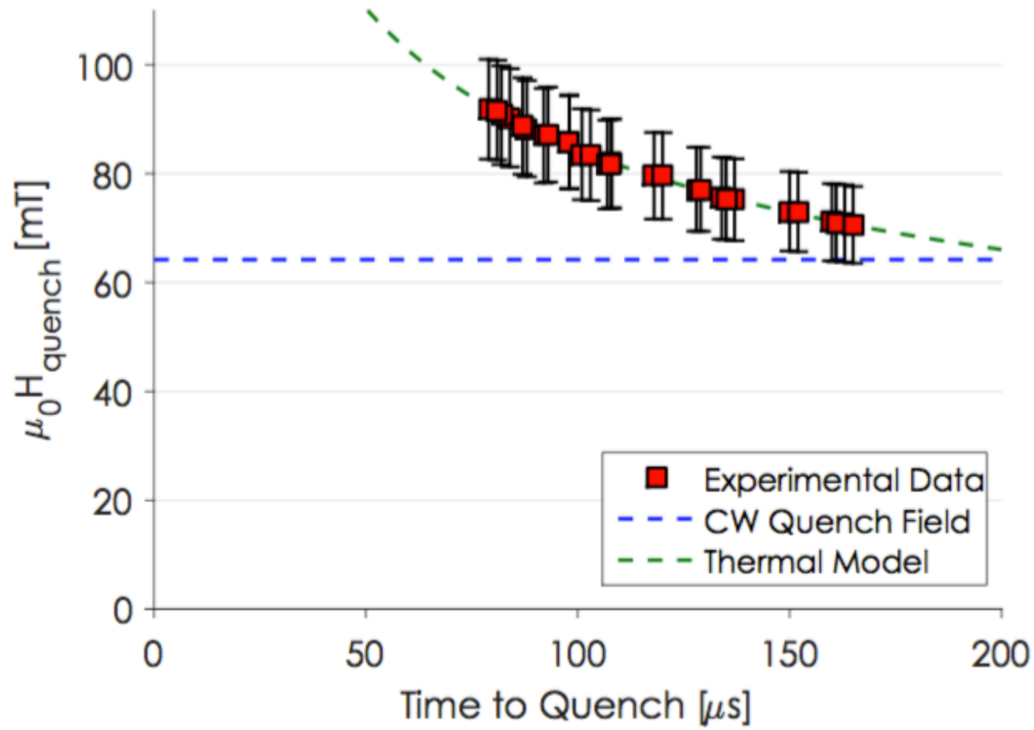
Insights from Klystron Measurements

- LTE1-2 N-doped results
  - High T: limited by flux entry at B_{sh}
  - As T decreases, B_{pk} diverges, indicating thermal effects
  - Consistent with thermal model of localized surface defect limitations – either flux entry or thermal runaway
  - Not a fundamental limit!



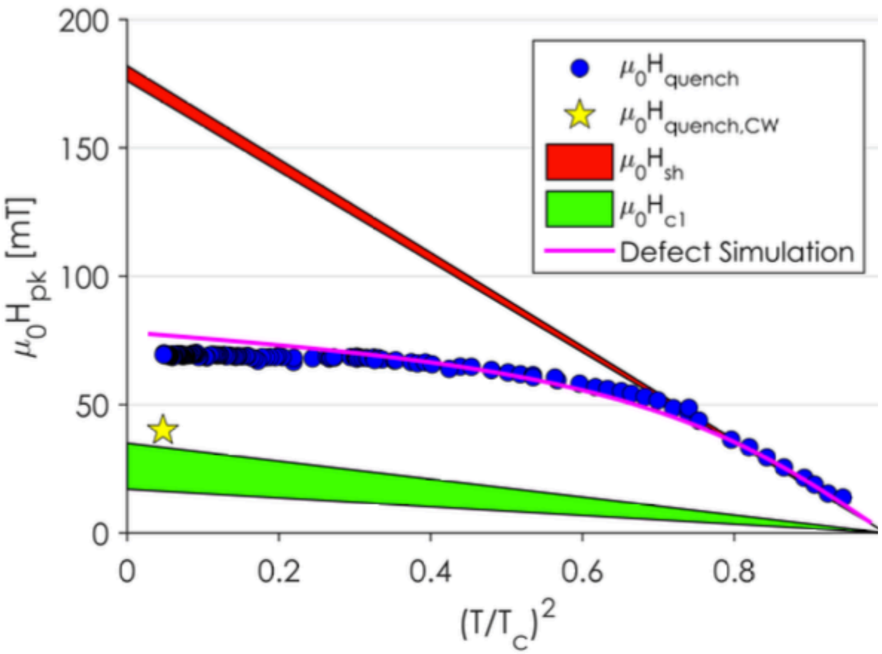
Insights from Klystron Measurements

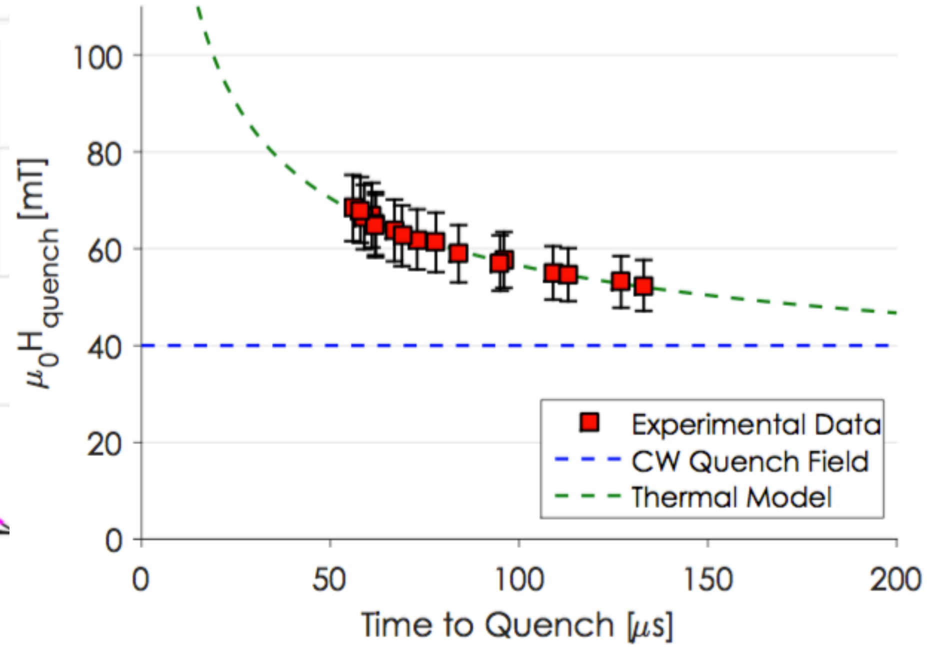
- LTE1-2 N-doped results
  - B_{pk} vs time to quench: asymptotically approaches B_{CW} for long quench times
  - Again, consistent with local surface defects: reaching a fundamental limit would be constant w.r.t. quench time.



Insights from Klystron Measurements

- LTE1-3 N-doped results

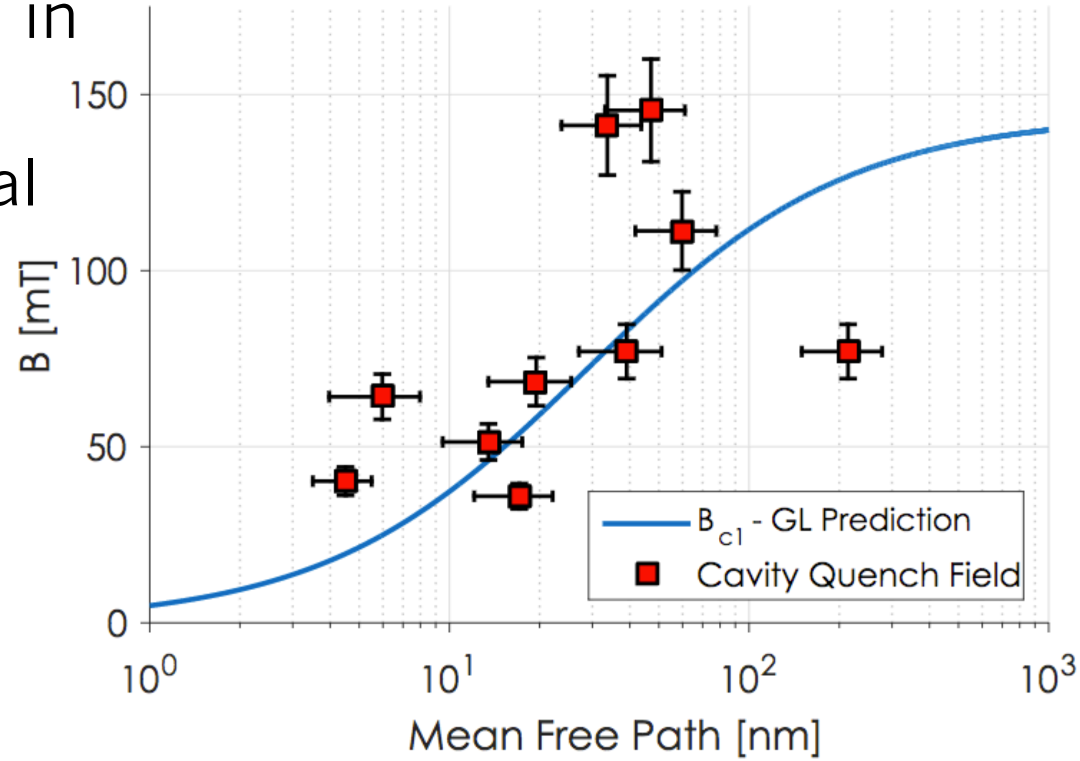




- Qualitatively very similar to LTE1-2, essentially same conclusions: limited by local surface defects, either flux entry or thermal runaway
- Quantitative differences in CW quench field, critical fields, pulsed quench field

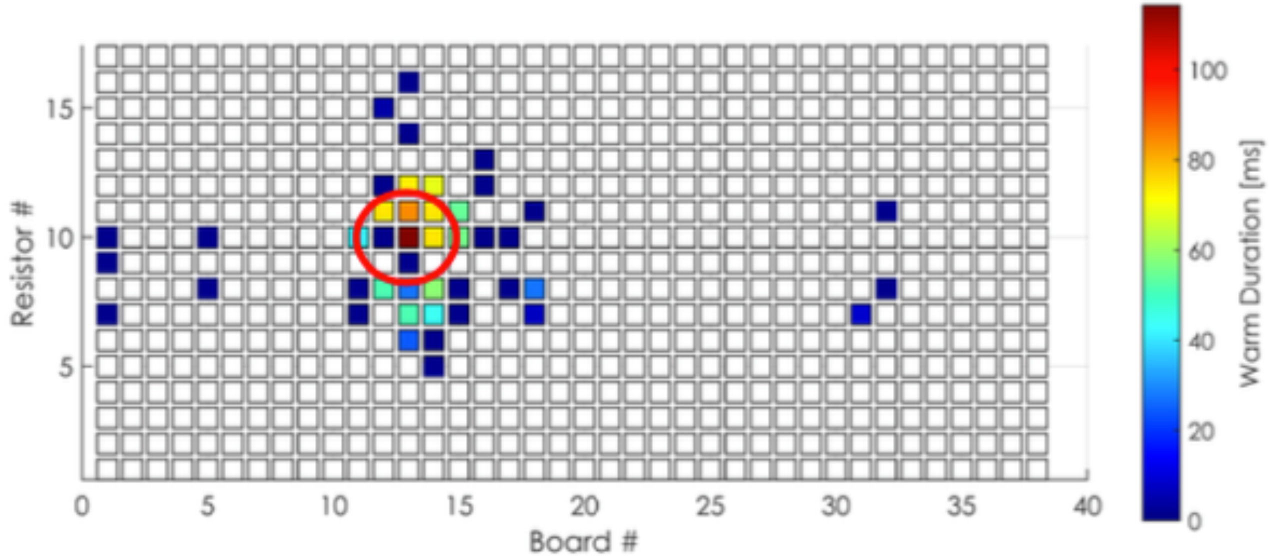
Insights from Klystron Measurements

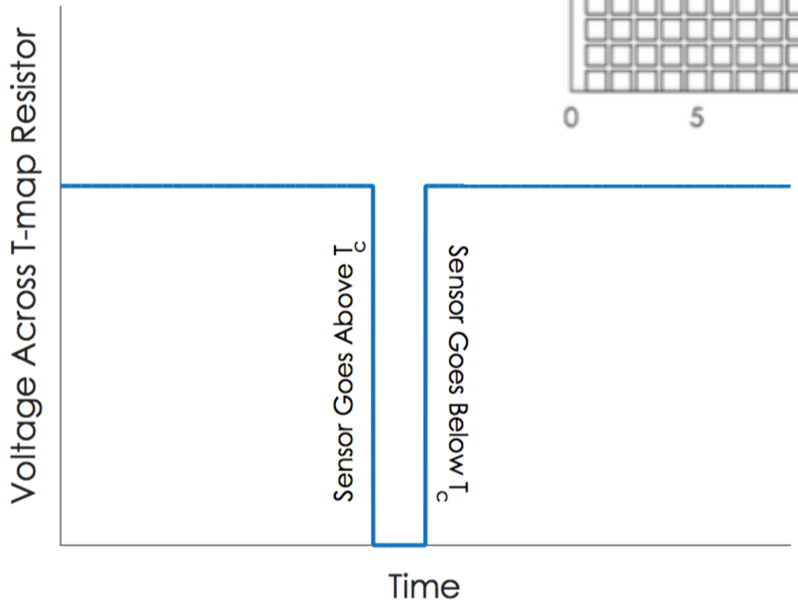
- N-doping – exceeding B_{c1}
  - Reached above lower critical field often in CW tests
  - Not a fundamental limit



Insights from Klystron Measurements

- N-doping – T-mapping local quench spots





Confirming local defect limitation

Insights from Klystron Measurements

- N-doped results – takeaway:
  - Cavities limited by localized effects on surface defects, either flux entry or thermal runaway
  - B_{sh} is ultimate limit as indicated by high-temperature data
    - Need to mitigate effects of surface defects!
  - We can get above B_{c1} in both pulsed and CW operation

Insights from Klystron Measurements

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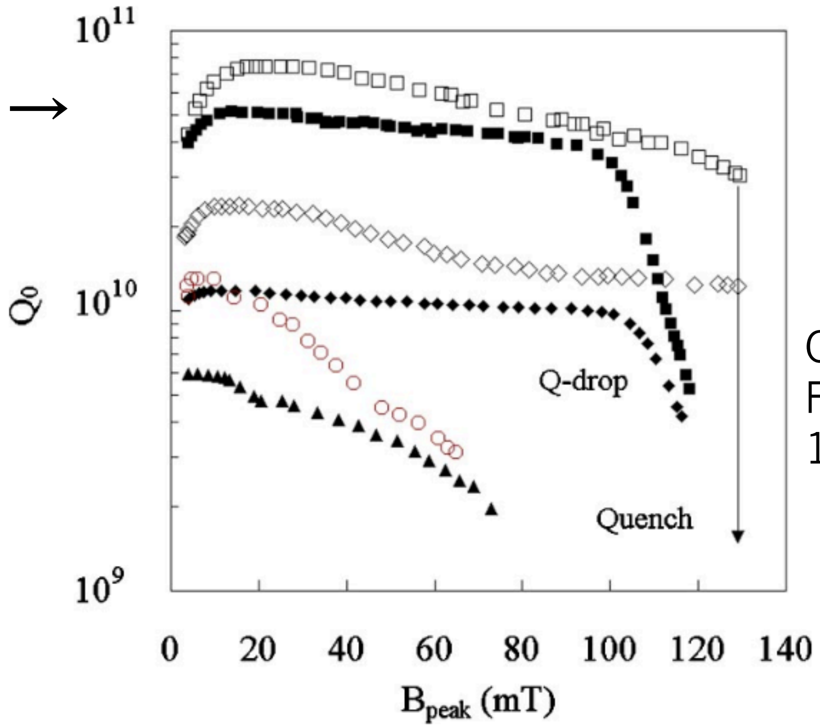
Insights from Klystron Measurements

- 120°C-baked cavities
  - Compared to standard bulk Nb:
    - Unbaked Nb sees HFQS, largely eliminated in low-T baking. This allows us to reach the fundamental limit of B_{sh}.
  - CW test →

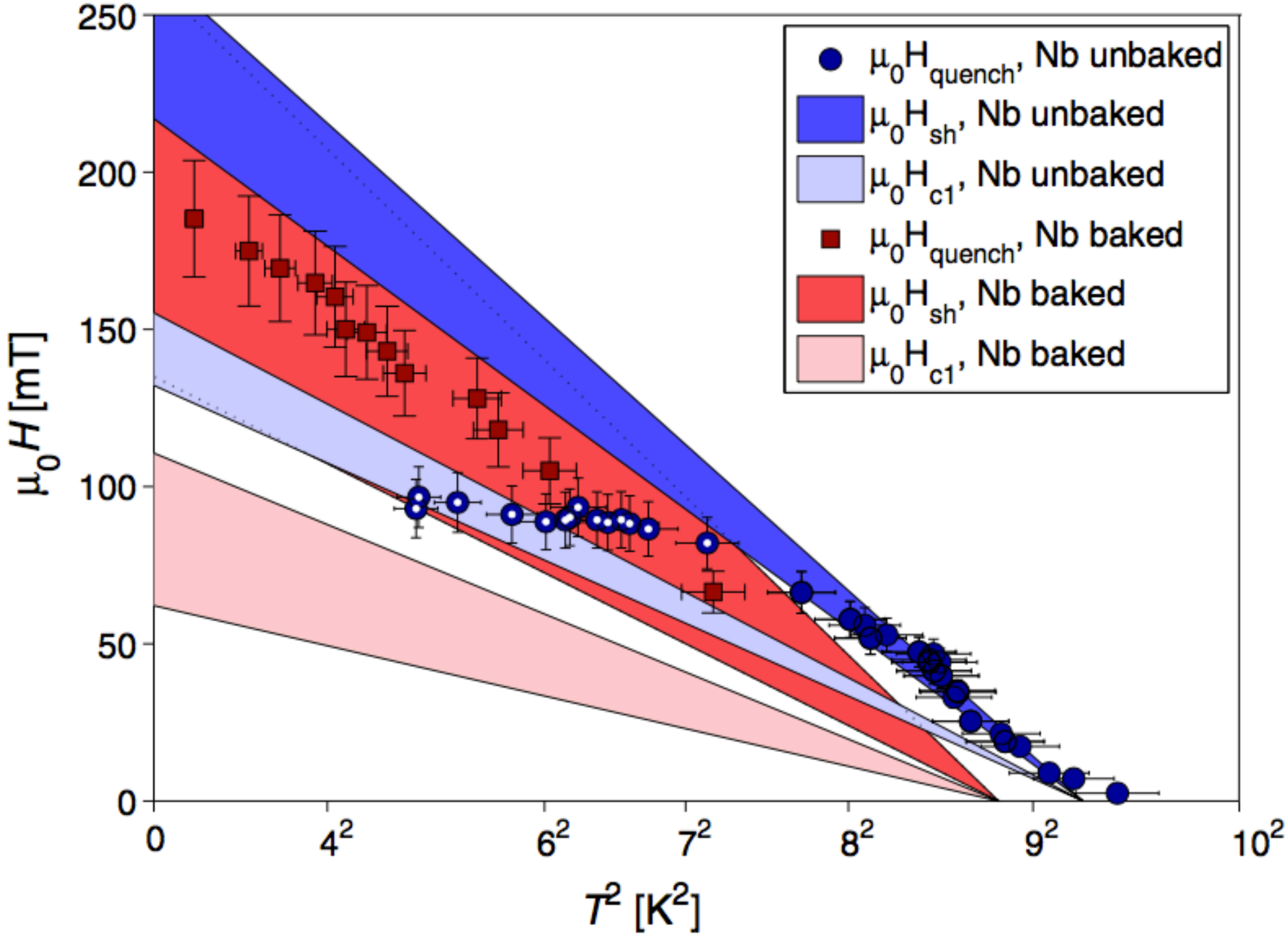


Open points – 120°C bake
Filled points – unbaked Nb
1.37 K, 2 K, 2.2 K

G. Ciovati, J. Appl. Phys. 2004

Insights from Klystron Measurements

- 120°C-baked cavities



Insights from Klystron Measurements

- 120^{o}C-baked cavities – takeaway
  - Reach B_{sh}! Limit is flux entry quench
  - Eliminate the HFQS/thermal quench of Nb
  - No free lunch – B_{sh} reduced, T_c as well

Insights from Klystron Measurements

- Klystron testing overview
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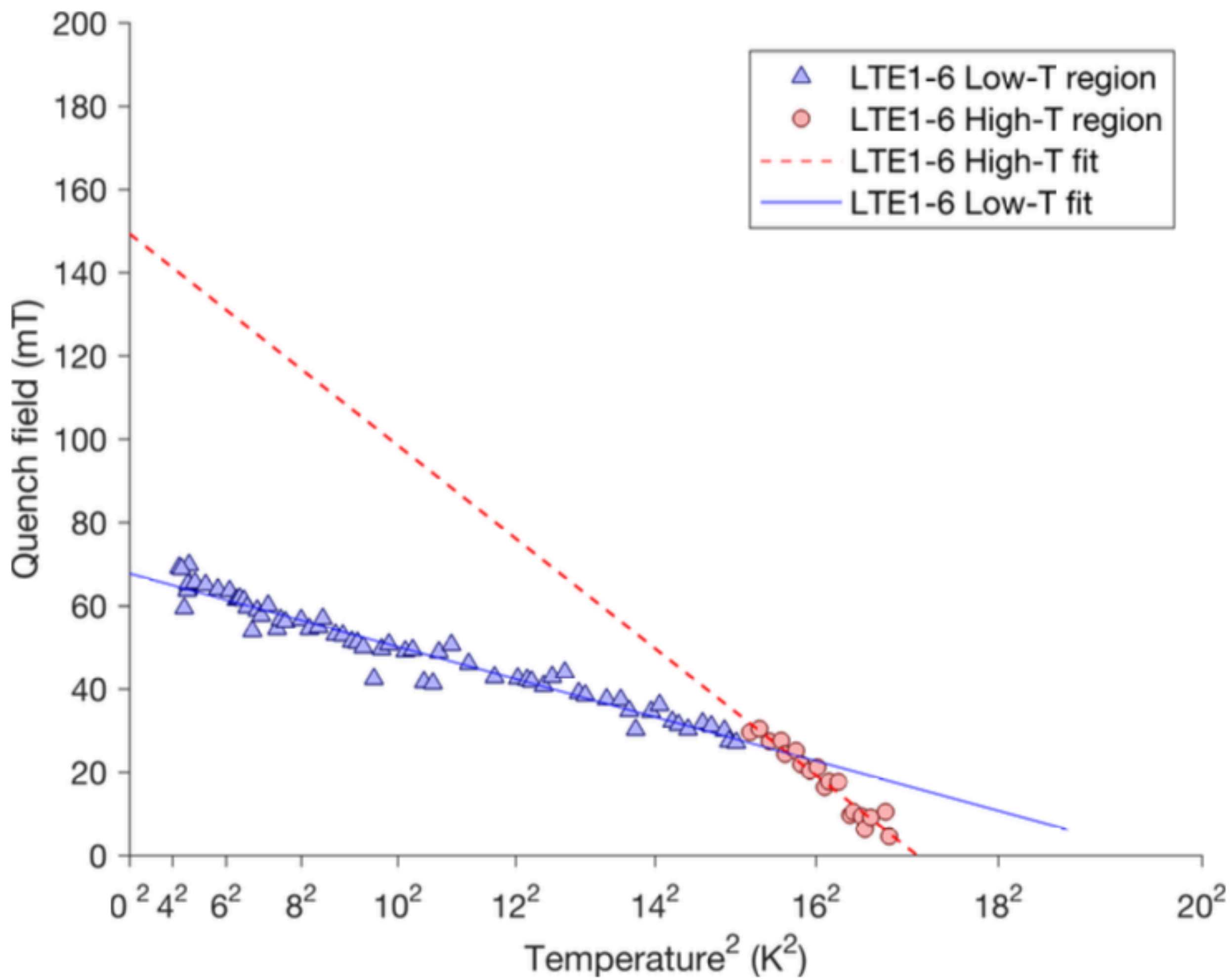
- Nb_3Sn

Insights from Klystron Measurements

- Nb_3Sn cavities
  - LTE1-6
    - CW quench field: 55 mT (~ 13 MV/m)
    - T_c ~ 17 K
  - ERL1-4
    - CW quench field: 65 mT (~ 15 MV/m)
    - T_c ~ 18 K
  - Older data
    - Campisi and Hays
  - Critical fields:
    - B_{c1} typically ~ 25 mT (strongly type-II)
      - exceeding by far in pulsed and CW tests
    - B_{sh} expected ~ 400 mT

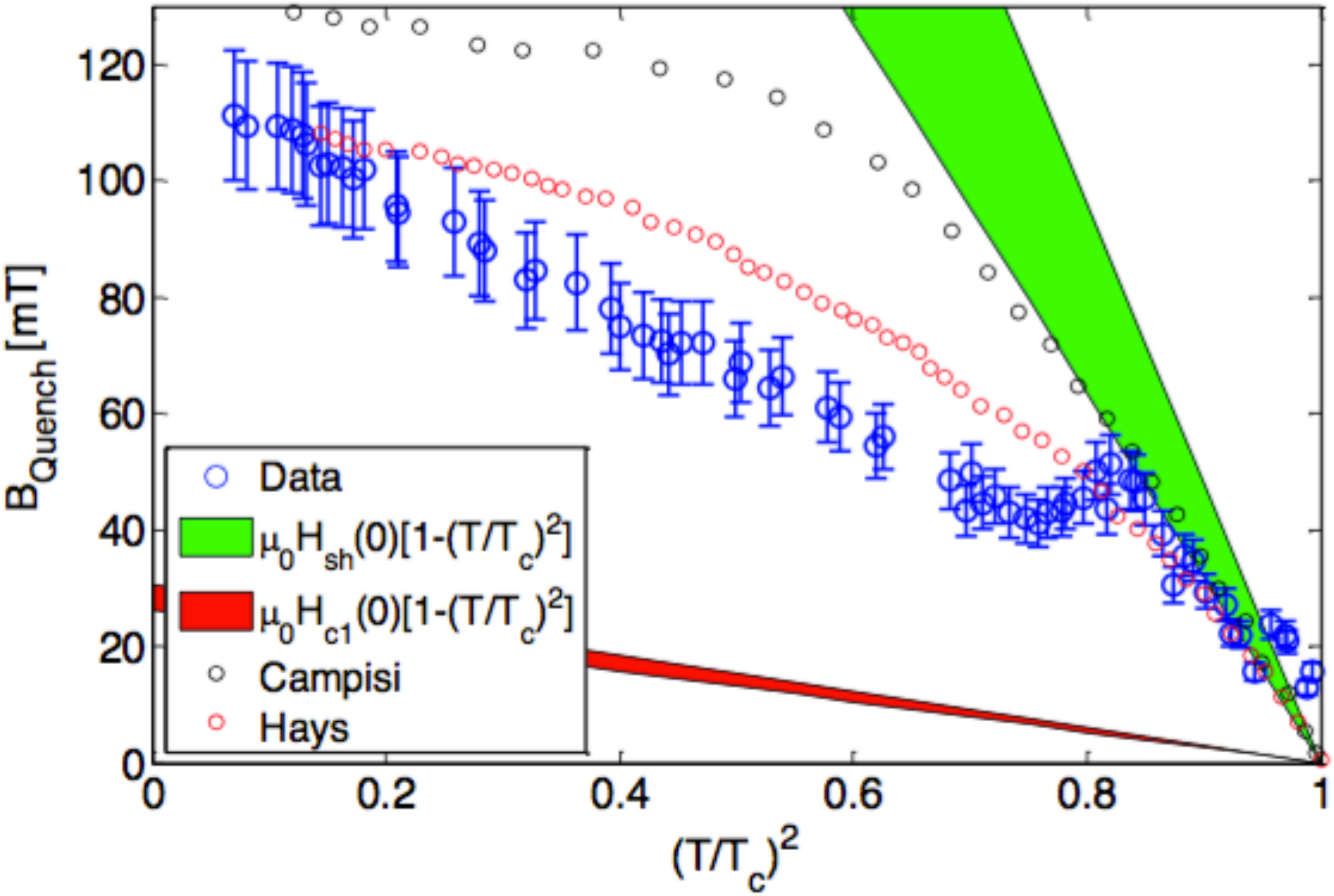
Insights from Klystron Measurements

- LTE1-6 Nb_3Sn results



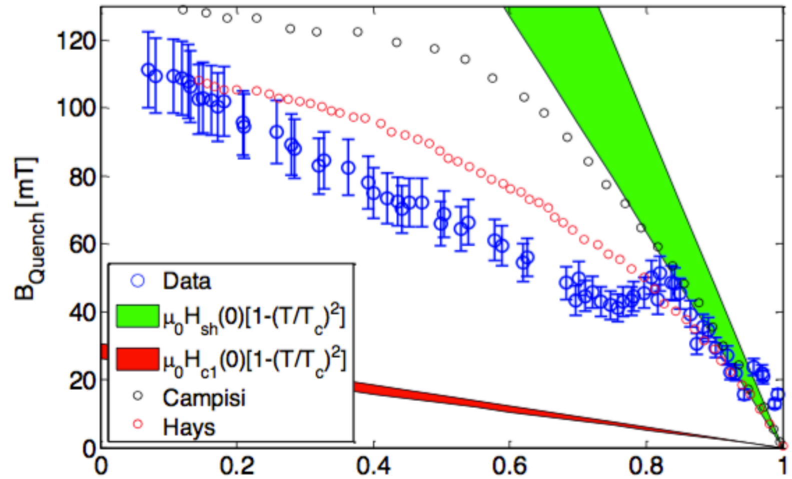
Insights from Klystron Measurements

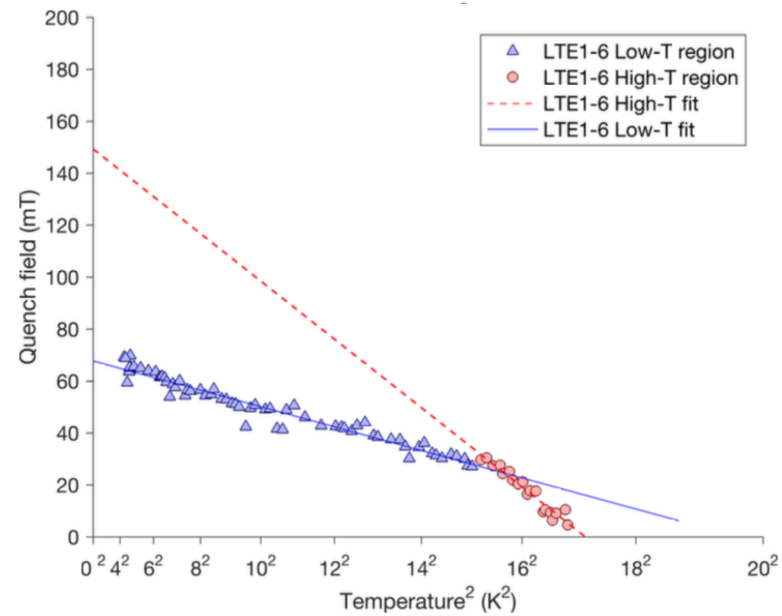
- ERL1-4 + older Nb_3Sn results



Insights from Klystron Measurements

- Nb_3Sn results
  - Bi-regional data indicate two separate regions with distinct limiting critical fields
  - Possibly corresponds with tin-depleted regions or with thin Nb_3Sn regions
  - Lower effective B_{sh} – field enhancement due to surface roughness?
  - Current R&D addressing these issues

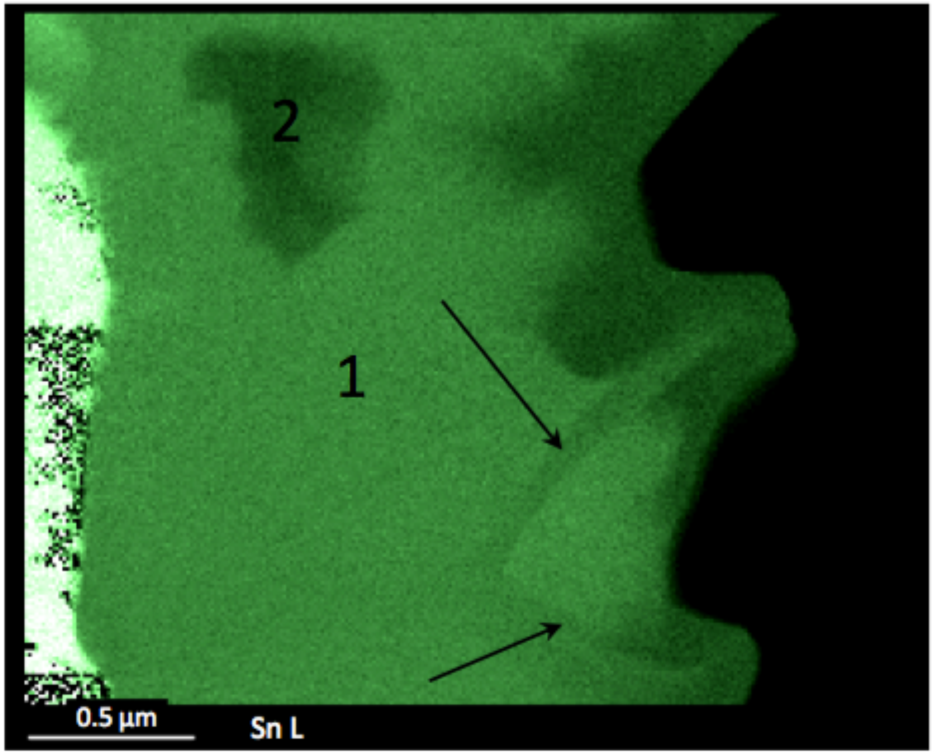


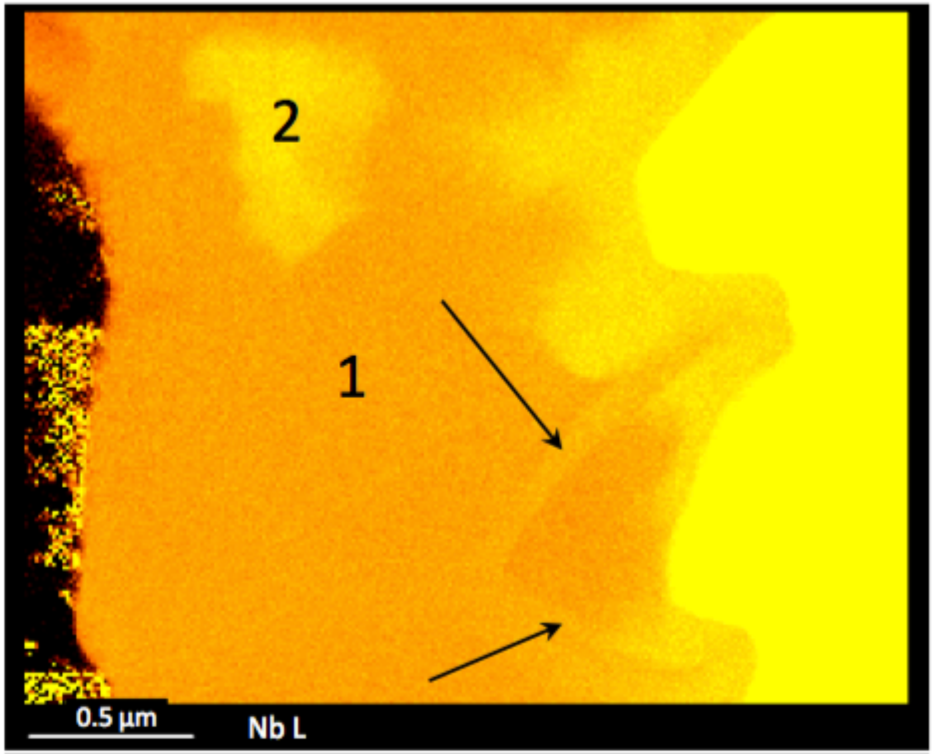


Insights from Klystron Measurements

- Nb_3Sn results
  - Tin-depleted regions

Data from T. Proslier, ANL

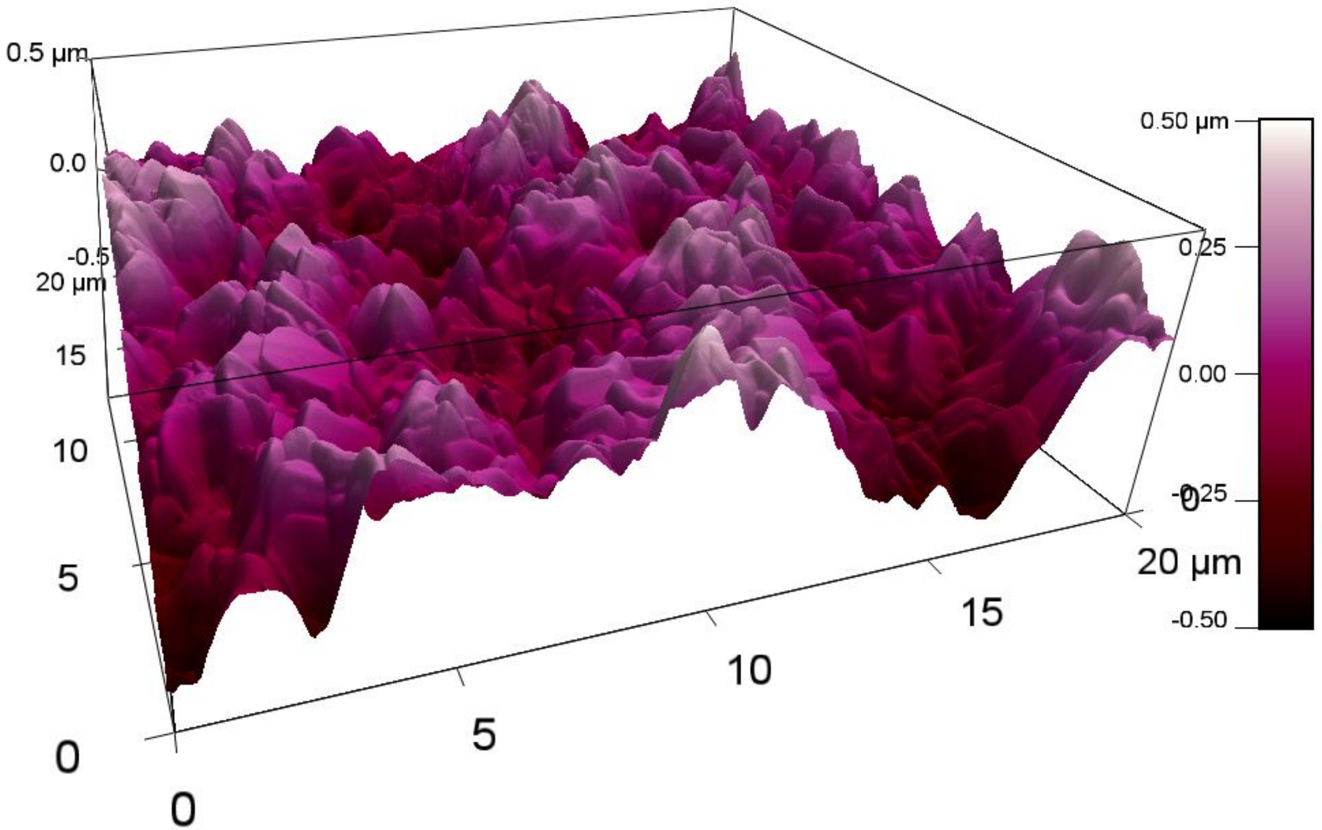




Area 1: 24 at.% Sn; Area 2: 16 at.% Sn

Insights from Klystron Measurements

- Nb_3Sn results
  - Surface roughness → field enhancement



Insights from Klystron Measurements

- Nb_3Sn results – takeaway:
  - Cavities limited by localized effects on bad regions (thin or tin-depleted), either flux entry or thermal runaway.
  - Ultimate limit B_{sh} effectively lowered due to field enhancement from surface roughness
  - Highly exceeding B_{c1} in CW and pulsed tests

Insights from Klystron Measurements

- Concluding thoughts:
  - Ultimate gradient limit is B_{sh}
  - N-doped cavities limited by surface defects
  - Nb_3Sn limited by thin and tin-depleted areas
  - 120°C baked cavities show how we might expect other materials to perform if we can get to B_{sh}.
  - In a perfect world… limiting gradients from B_{sh}:
    - 120°C bake: 200 mT → 47 MV/m
    - N-doped: 170 mT → 40 MV/m
    - Nb_3Sn: 400 mT → 100 MV/m!
      - With surface roughness: ~ 300 mT → 75 MV/m

Thank you for your attention!

- References / further reading:
  - S. Posen, N. Valles, and M. Liepe, Phys. Rev. Lett. 115, 047001 (2015).
  - IPAC 2016 papers from J.T. Maniscalco, D. Gonnella, and D.L. Hall

Insights from Klystron Measurements

- Backup slide – critical fields