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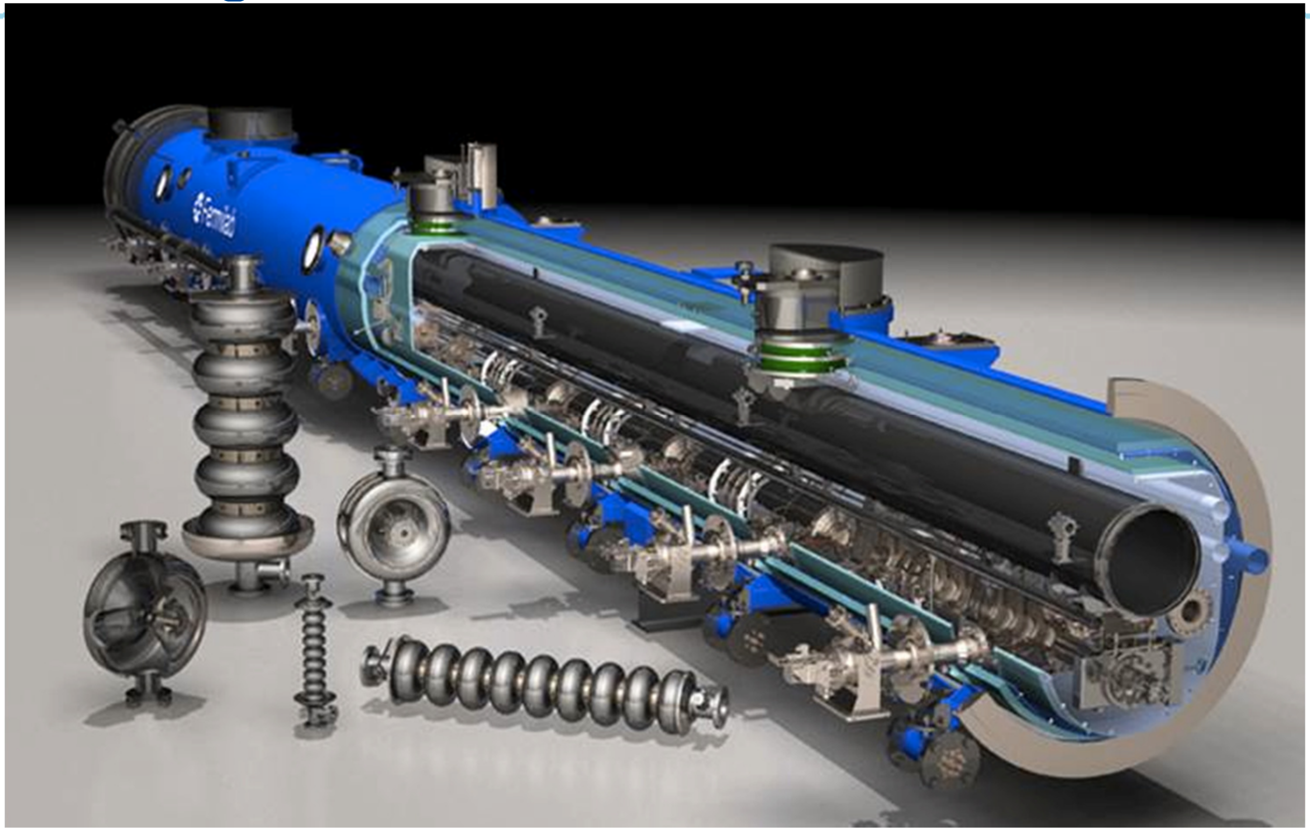
High Q Developments

Anna Grassellino
Fermilab
IPAC 2015, Richmond, Virginia

Outline

- Two recent breakthroughs have systematically and reproducibly changed the quality factor of niobium SRF cavities:
  1. *Nitrogen doping*
     - From discovery to cryomodule ready/transfer to industry ready technology (LCLS-2)
     - Why does it work? What is known and yet unknown (samples characterization, cavity measurements, theoretical models…)
  2. *Efficient Magnetic Flux Expulsion via fast cooling*
     - Discovery and progress in understanding with bare cavities
     - Practical implementation of lessons learned in cryomodules

Superconducting RF cavities

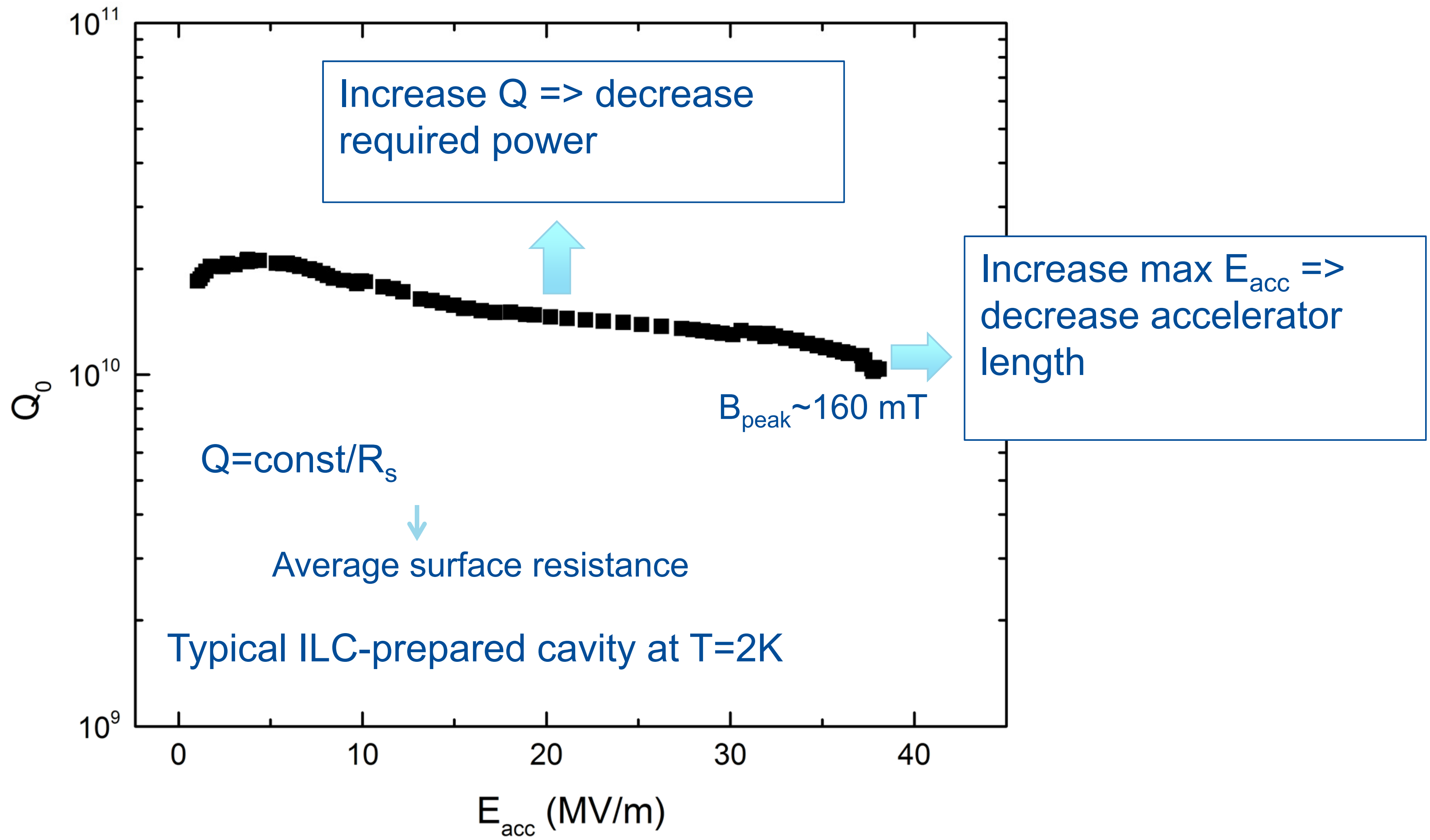


- Niobium is the material of choice (superconducting below 9.2K)
- Depending on different machines/applications:
  - Fundamental mode f = 50 MHz – 10 GHz
  - Operating temperature T = 1.8K to 4.2K
  - Achievable accelerating gradients ~50 MV/m

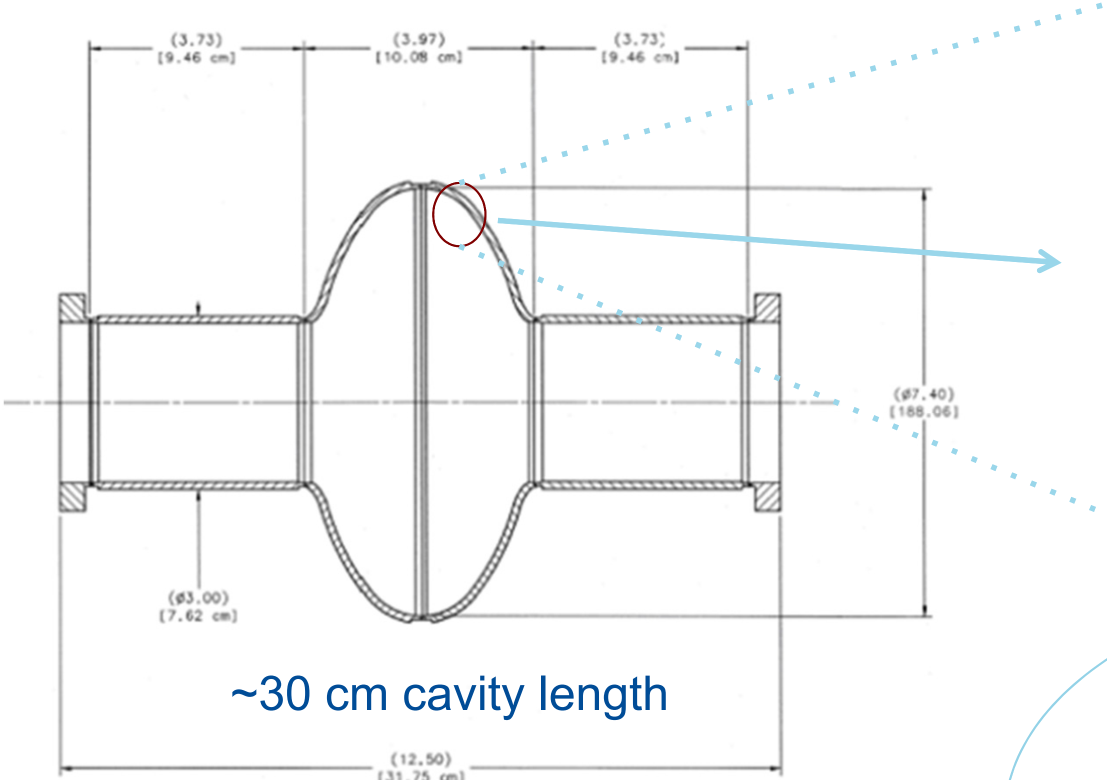
SRF cavities – advantages

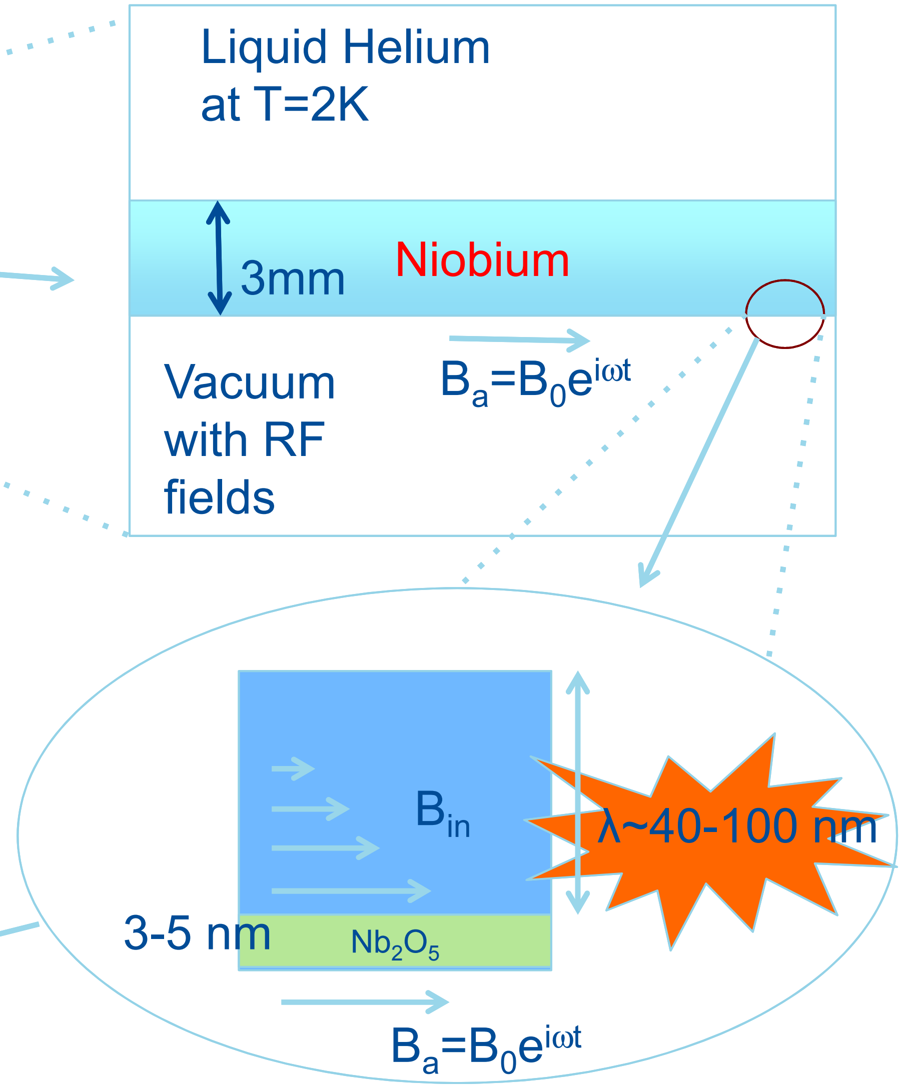
- Wall dissipation (proportional to surface resistance R_s) is reduced by many orders of magnitude over a normal conducting copper cavity
- Among highest quality factors Q in nature
  - $Q>10^{11}$ achieved, $Q=2x10^{10}$ – routine
- Affordable continuous wave and long pulse gradients
  - Field=acceleration can be ON all the time
- Larger aperture gives better beam quality

SRF cavities figures of merit: efficiency (Q) and quench field



What matters for SRF performance? Relevant scale is the nanoscopic





<u>Inner</u> surface nanostructure within ~ 2-100 nm completely determines RF losses in the cavity

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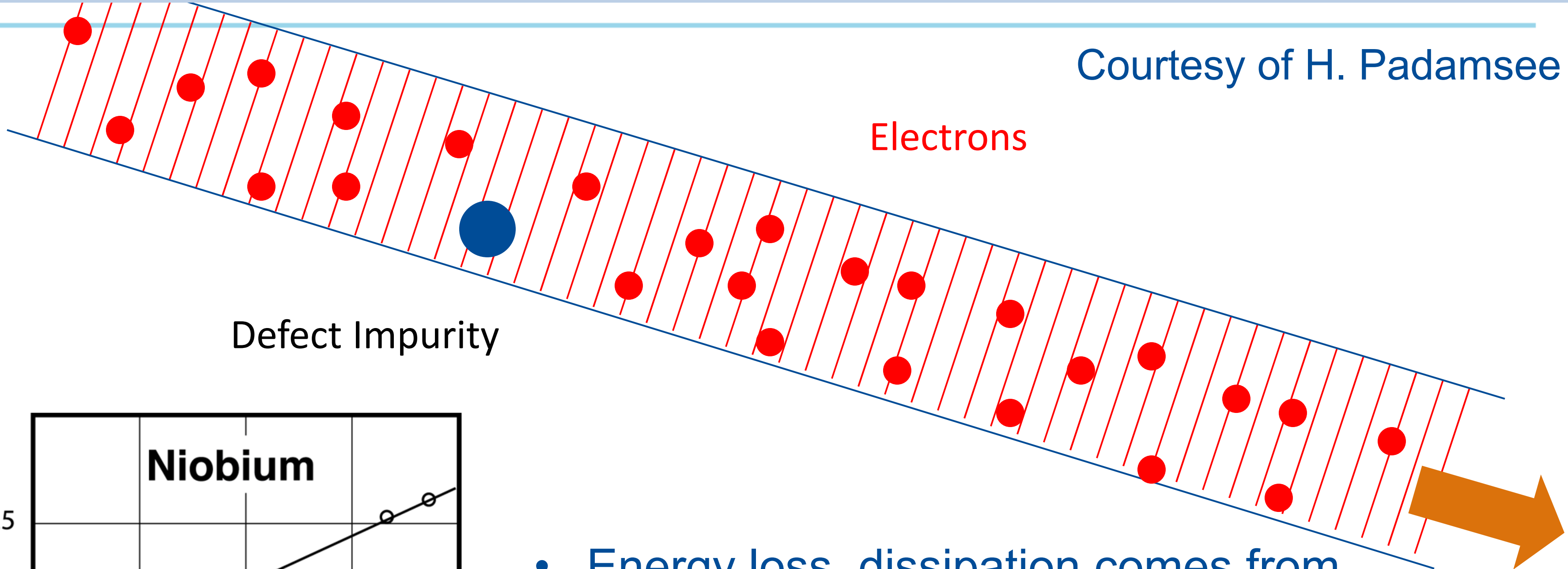
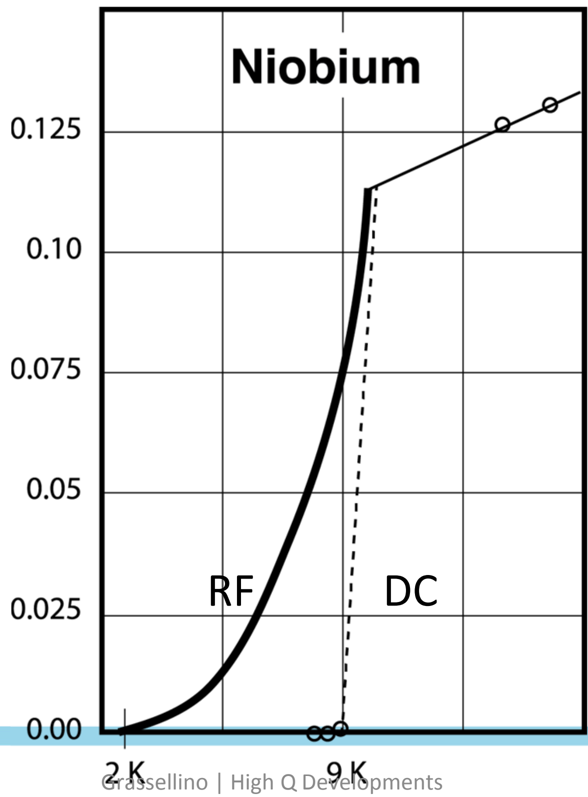
Superconductivity: DC case

Courtesy of H. Padamsee





- Energy loss, dissipation comes from scattering of electrons with defects or impurities
- In normal conducting state electrons scatter
- In superconducting state, cooper pairs form and move 'with no friction'

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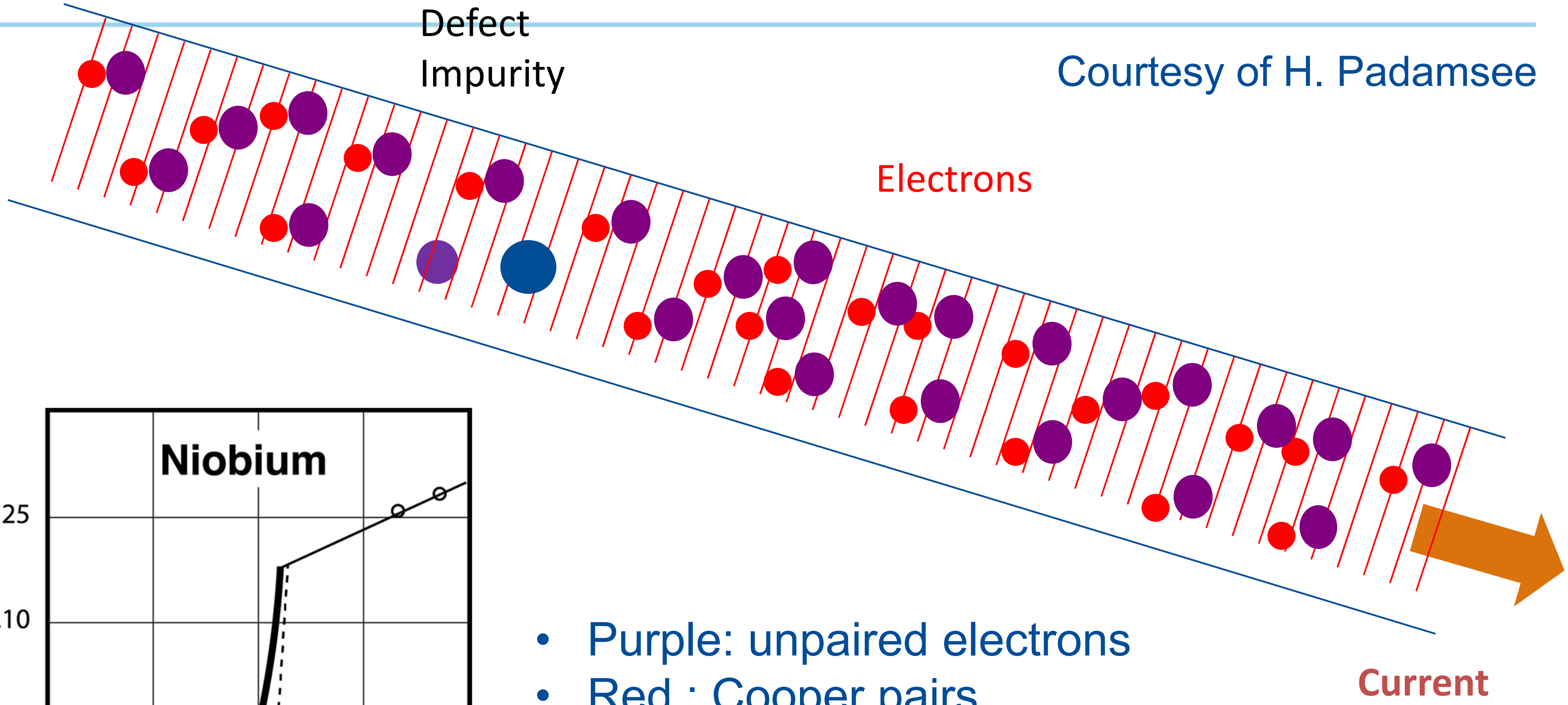
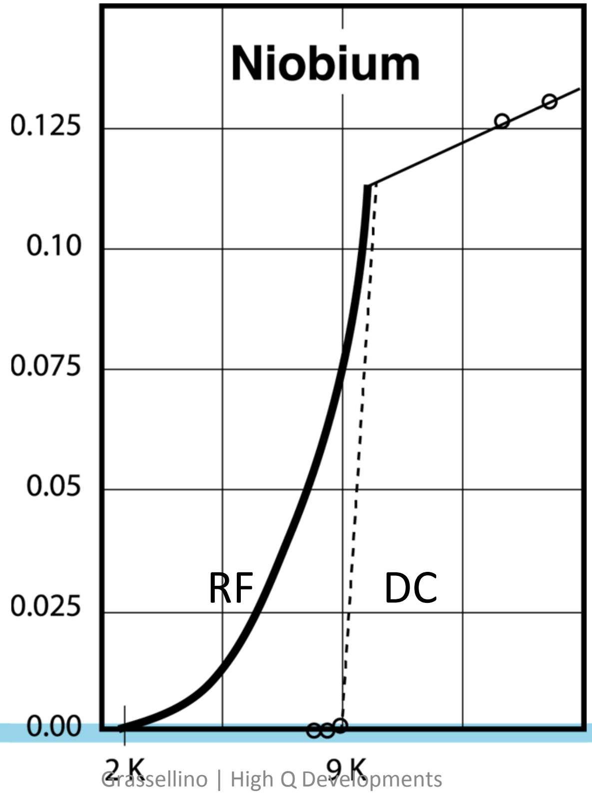
Superconductivity RF case- Small Non-Zero Resistance



Courtesy of H. Padamsee

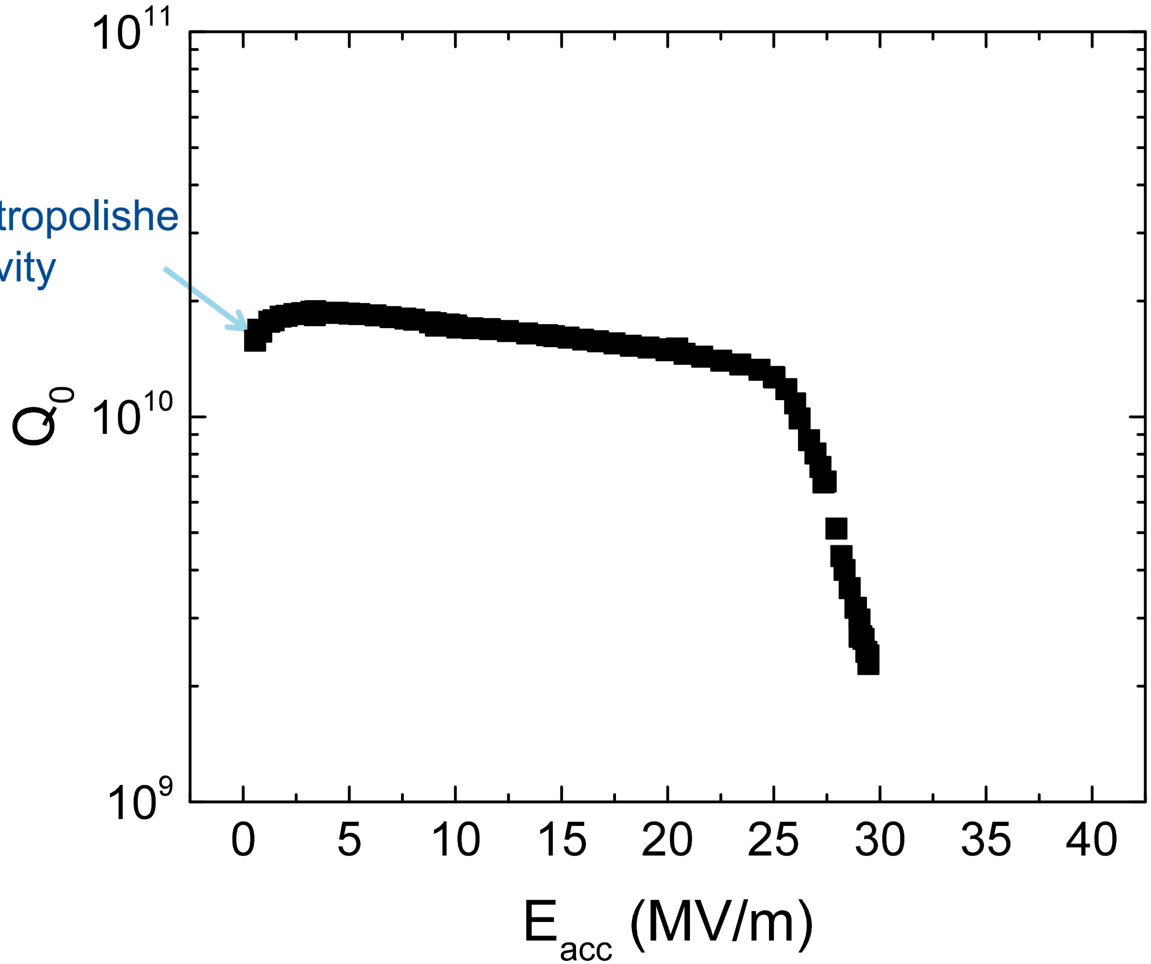


- Purple: unpaired electrons
- Red : Cooper pairs

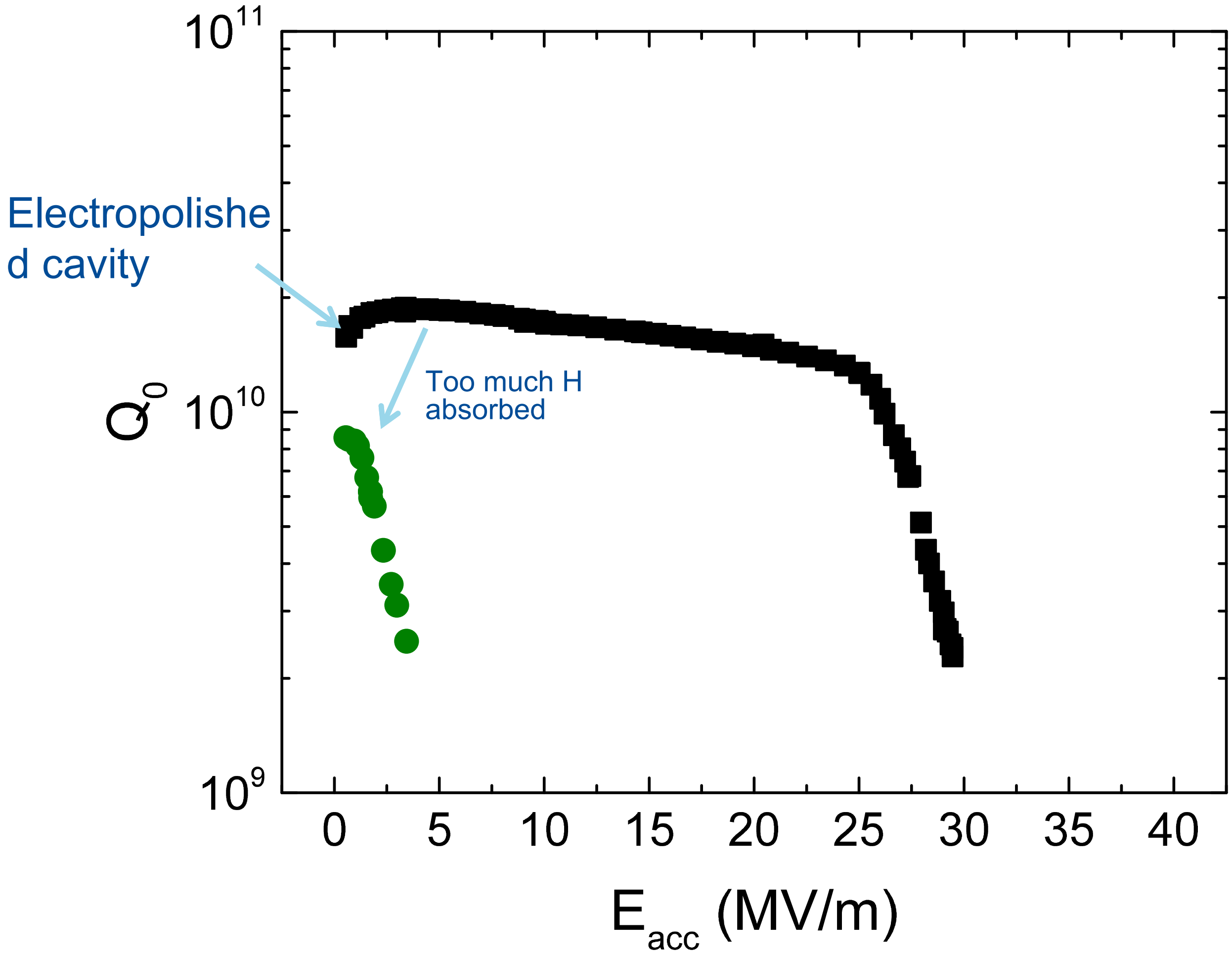
- Unpaired electrons can scatter and cause RF resistance and loss in efficiency (lower Q)

SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface

Electropolished cavity

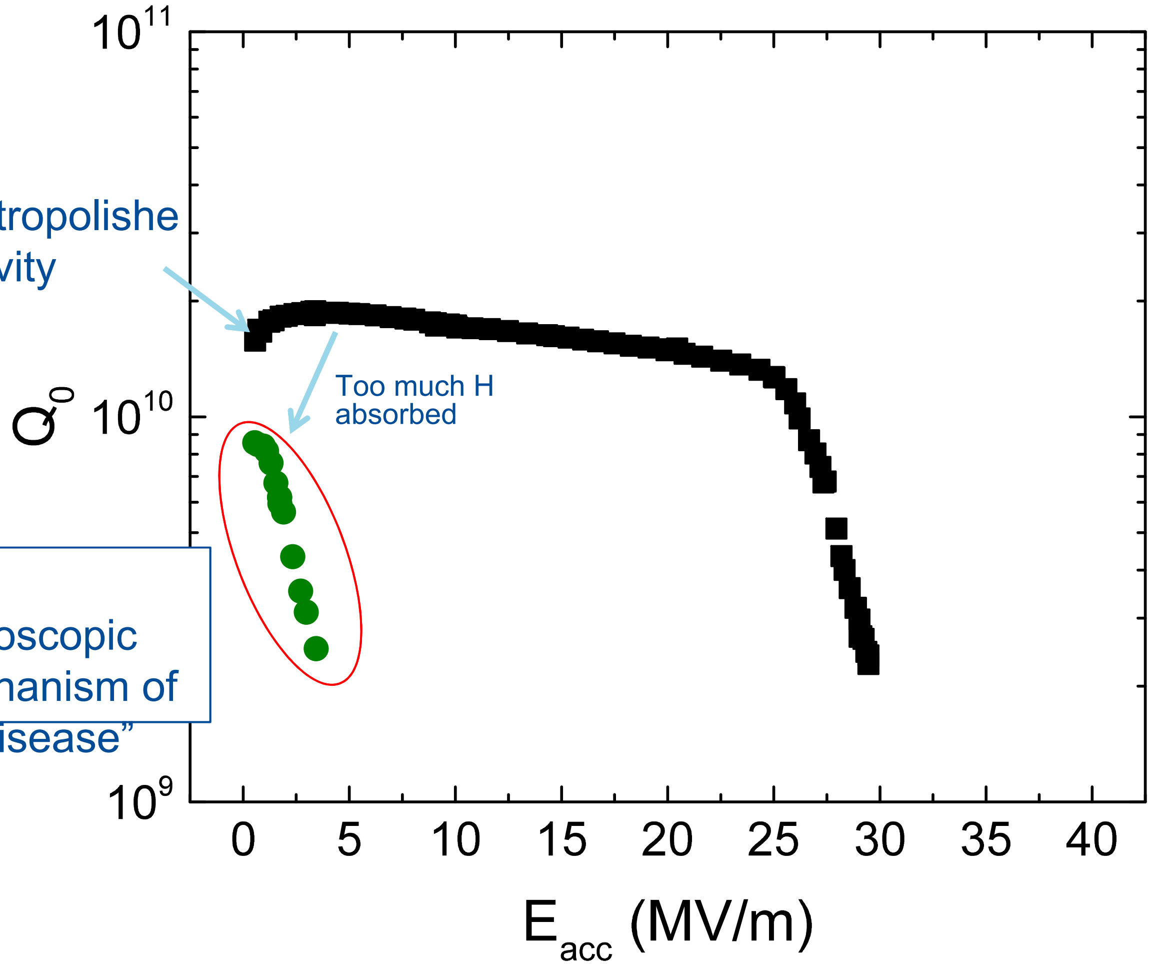


SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface



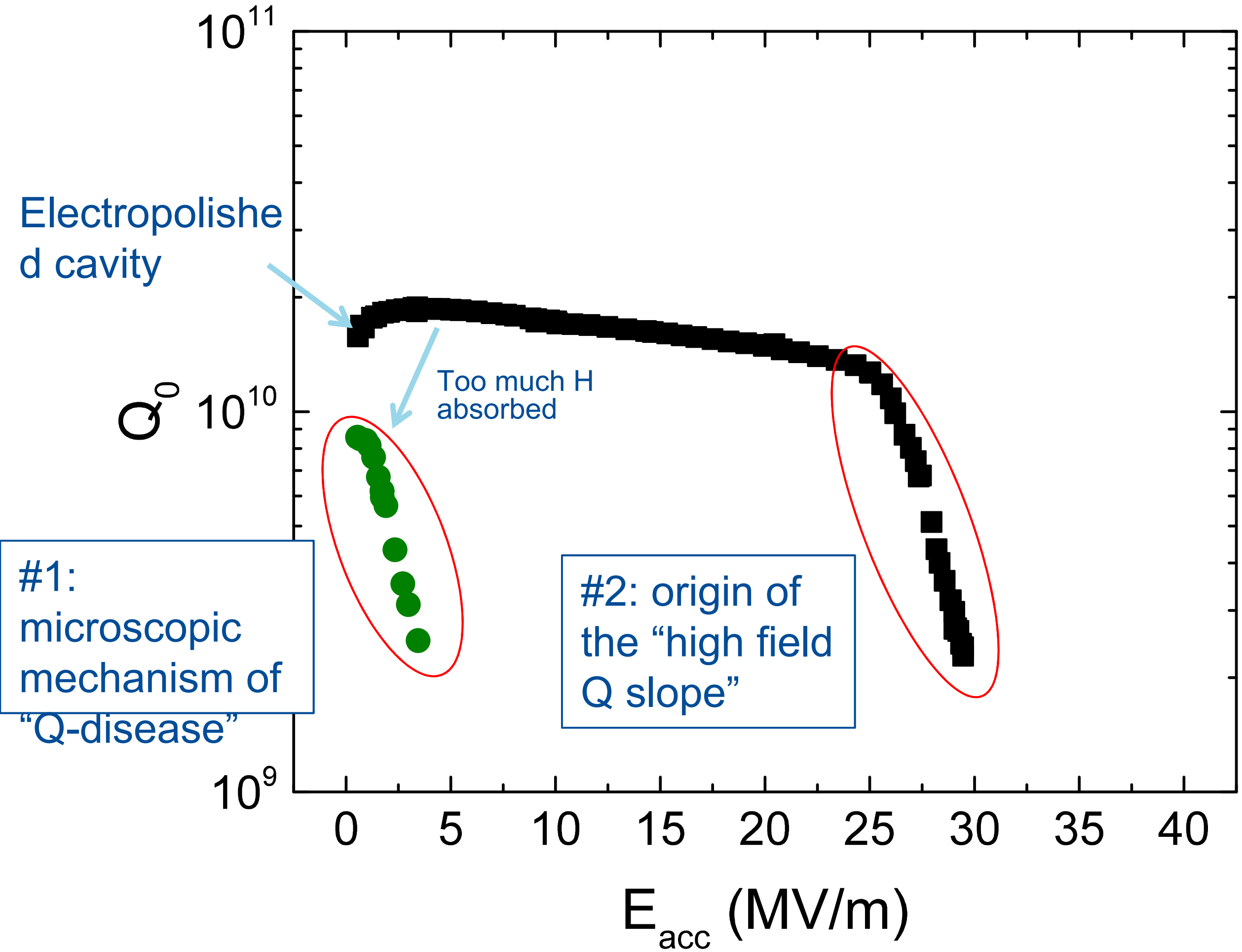
SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface

Electropolished cavity

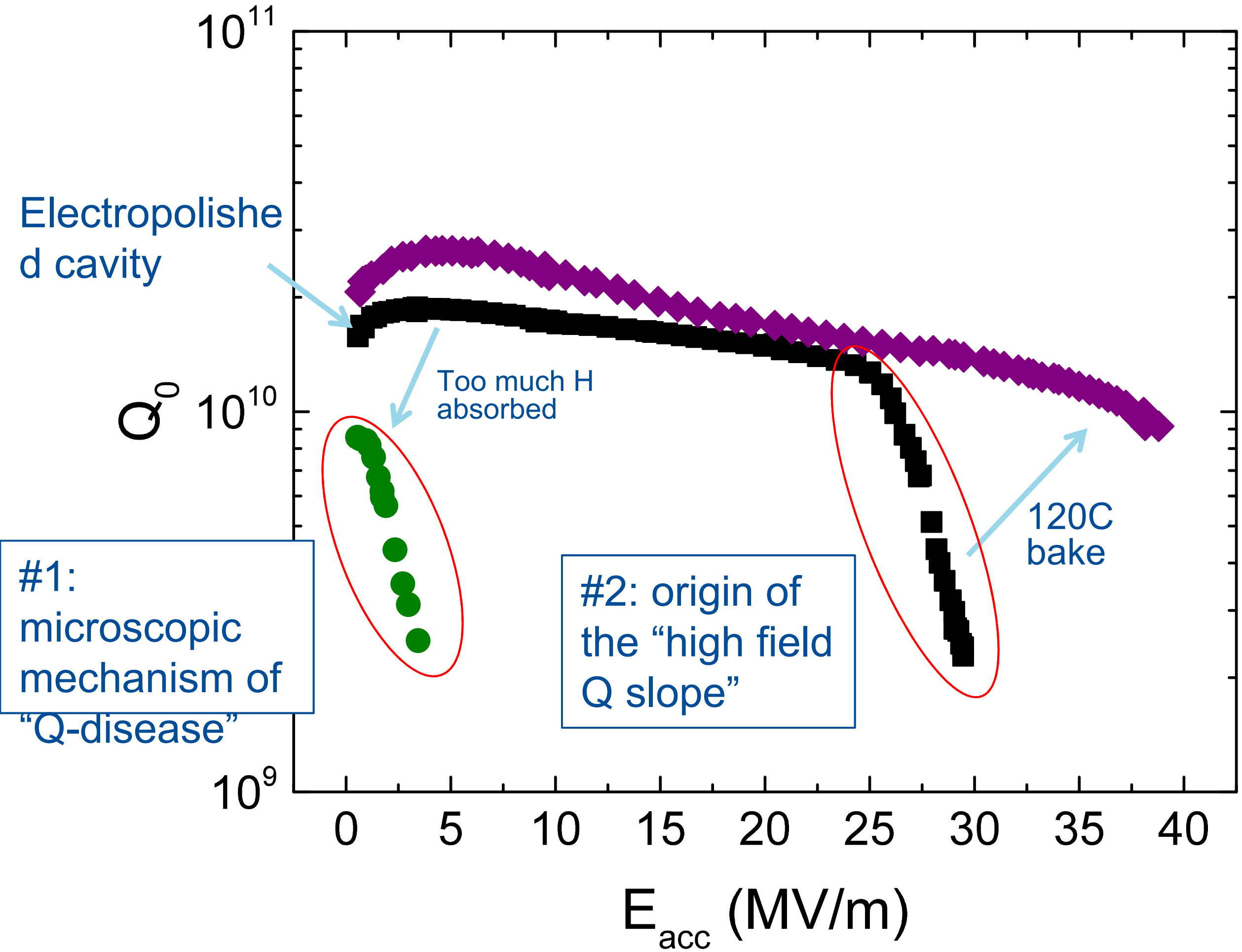


#1: microscopic mechanism of "Q-disease"

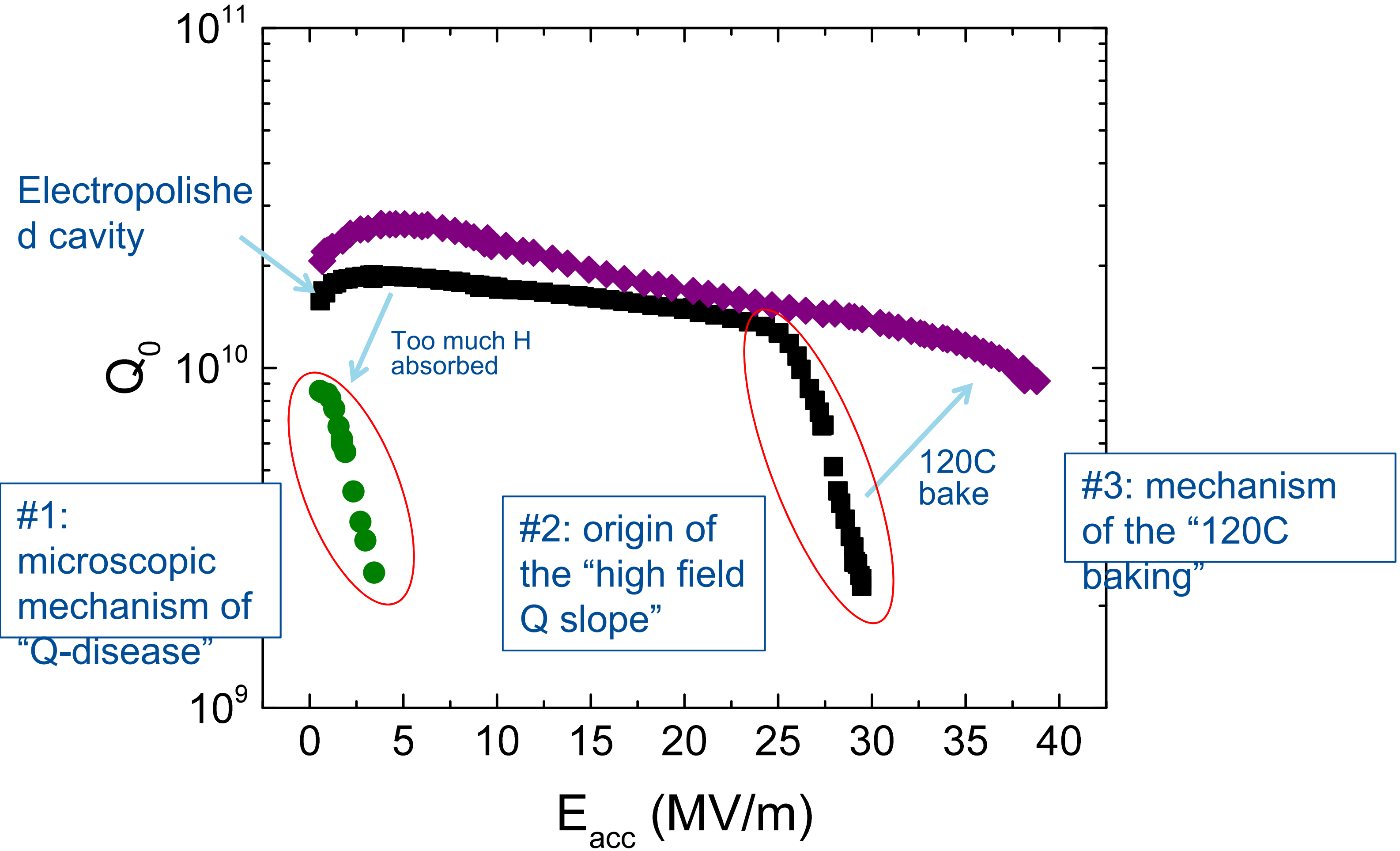
SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface



SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface



SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface



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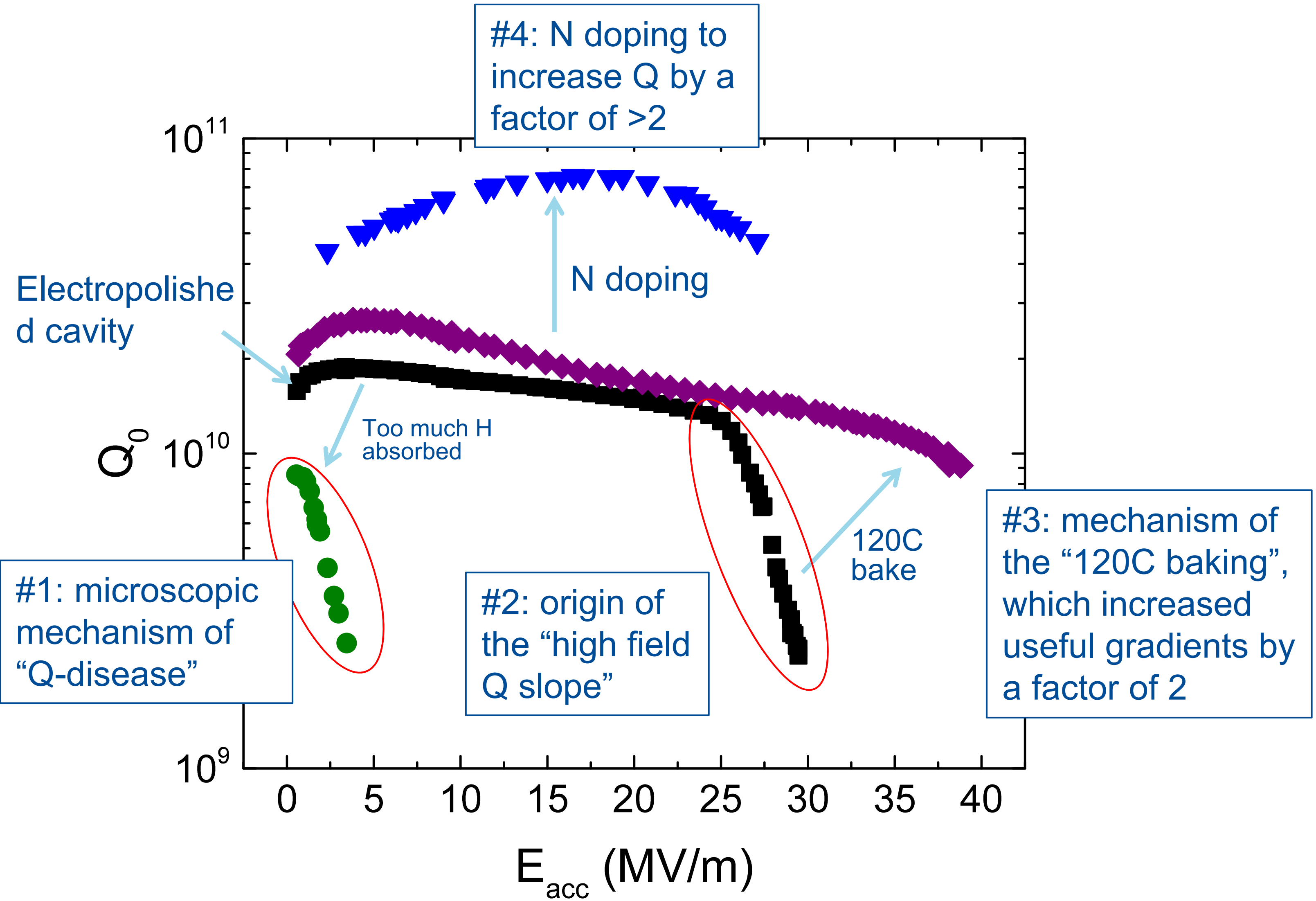
SRF advancements are driven by fundamental understanding of the underlying physics of cavity surface



N doping: results for LCLS-2, progress in understanding

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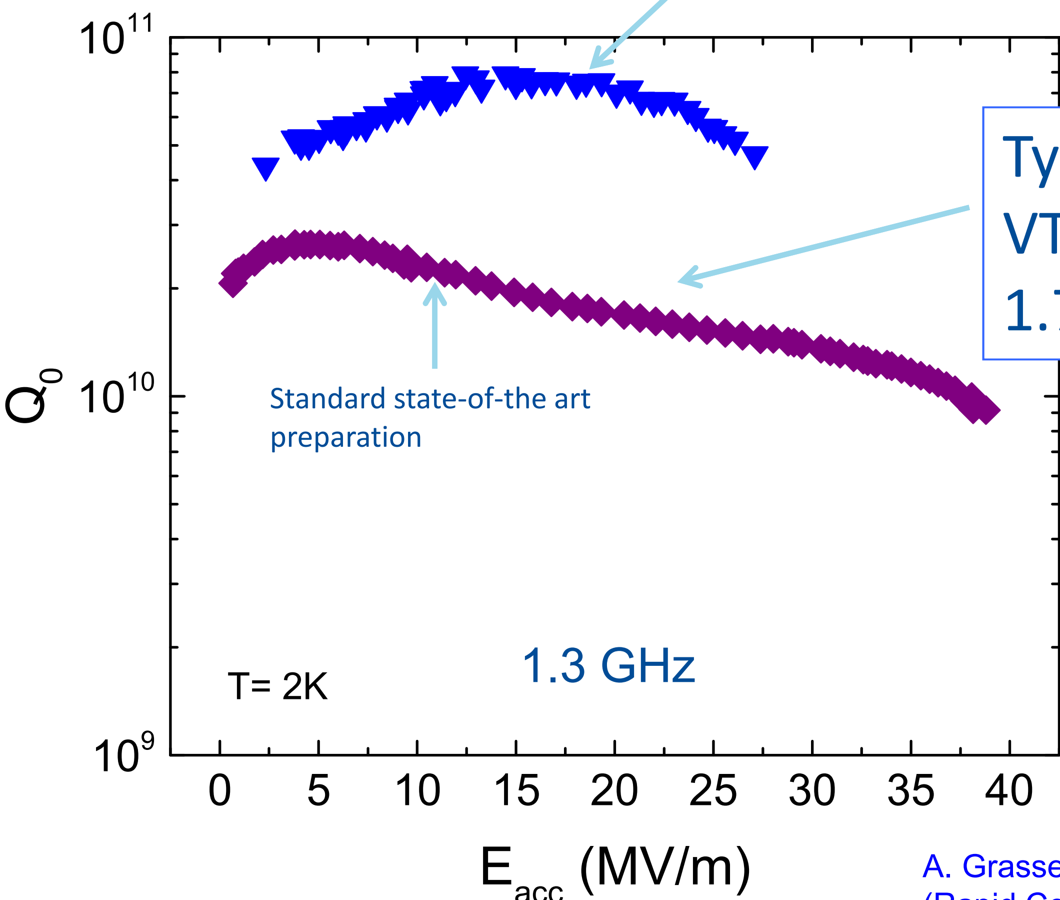
Nitrogen Doping: a breakthrough in Q

Record after nitrogen doping – up to 4 times higher Q! Average values obtained on nine cell Q(2K, 16MV/m)~ 3.5e10



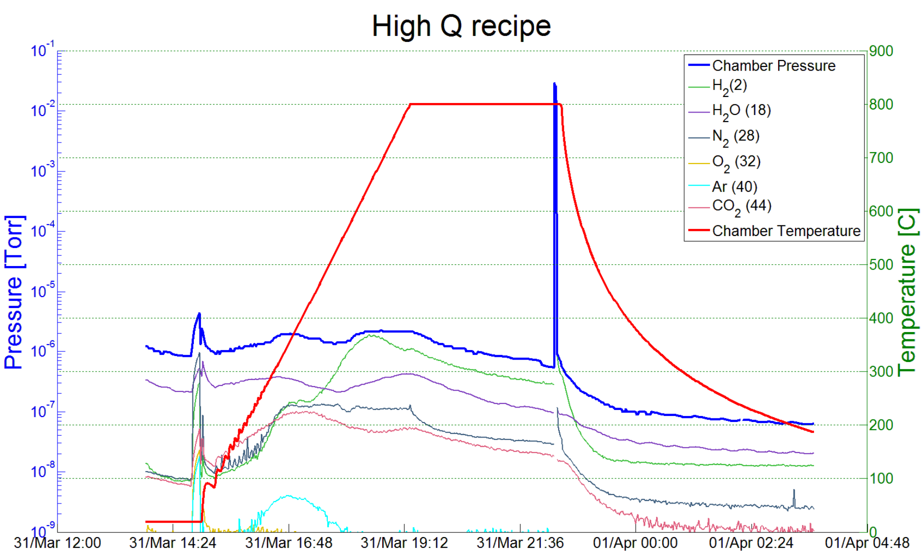
Typical Q obtained in VTS with 120C bake ~ 1.7e10 at 2K, 16 MV/m

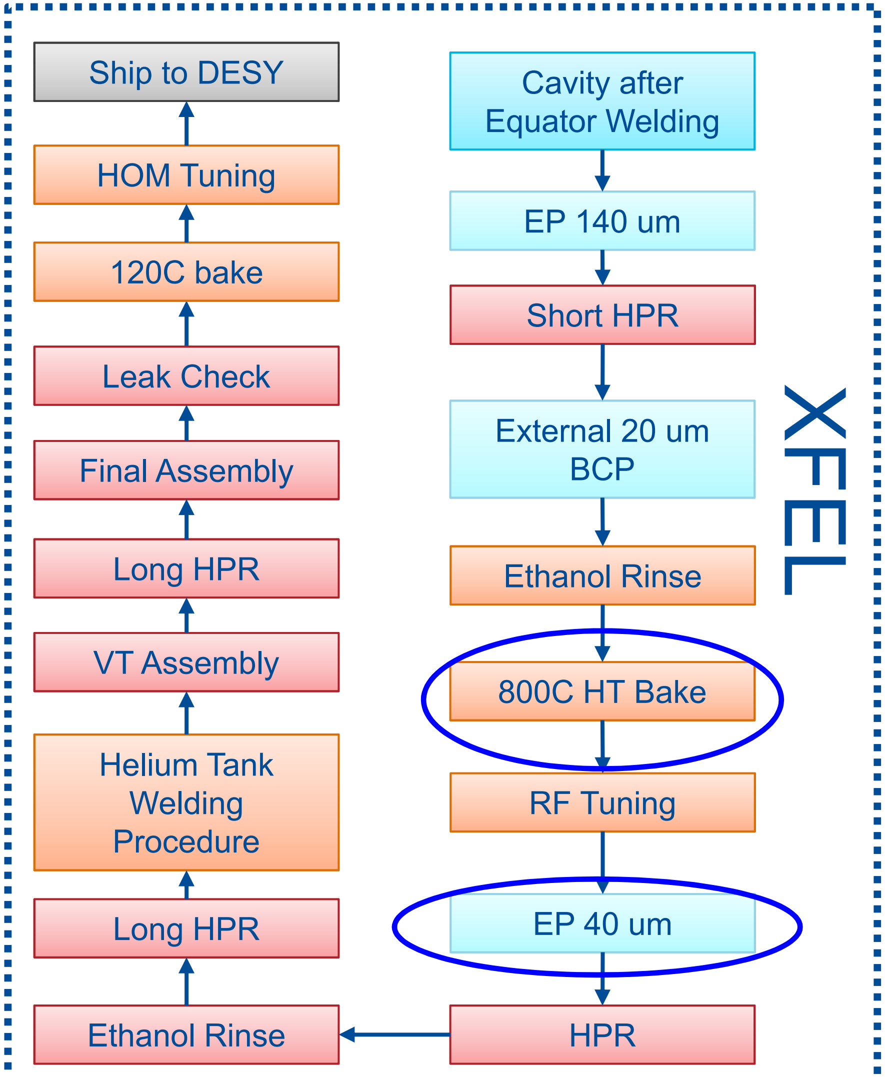
A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

Doping Treatment: small variation from standard protocol, large difference in performance

Example from a doping process developed for LCLS-2:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





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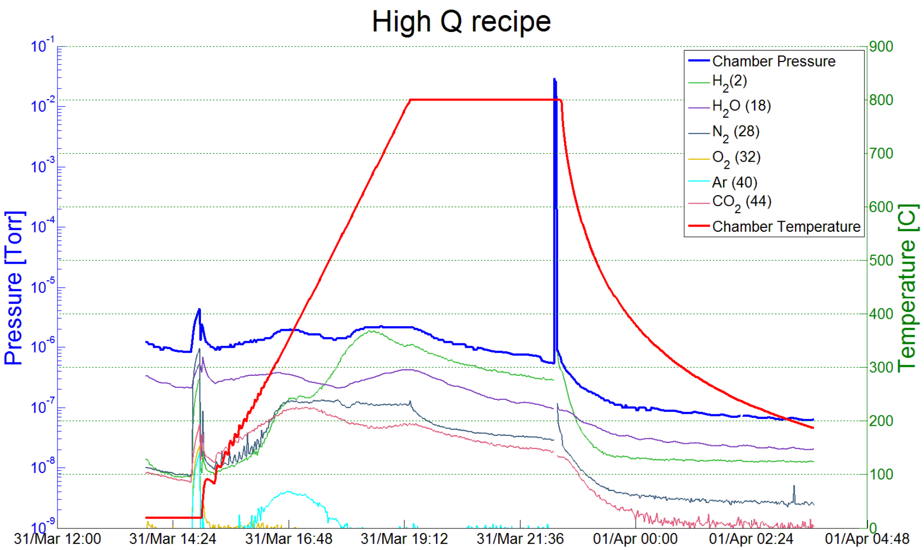
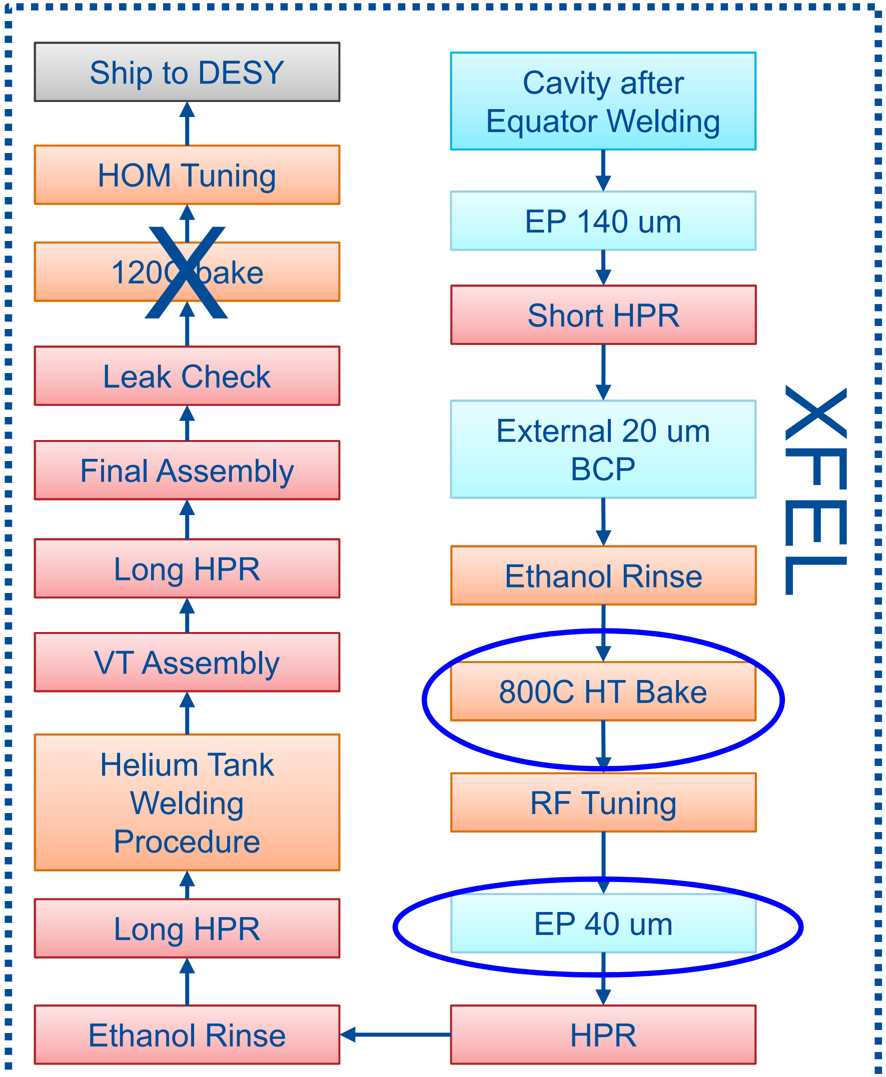
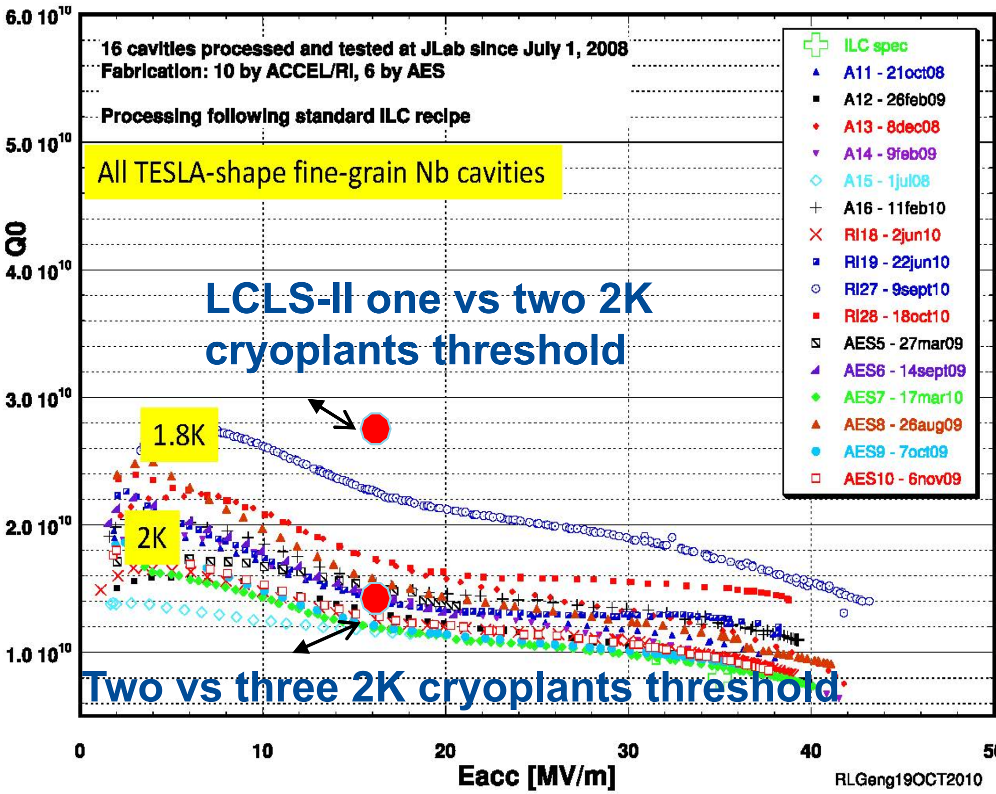




The importance of a high Q technology – the case of the CW machine LCLS-2

Example of 120C baked (standard ILC/XFEL technology)

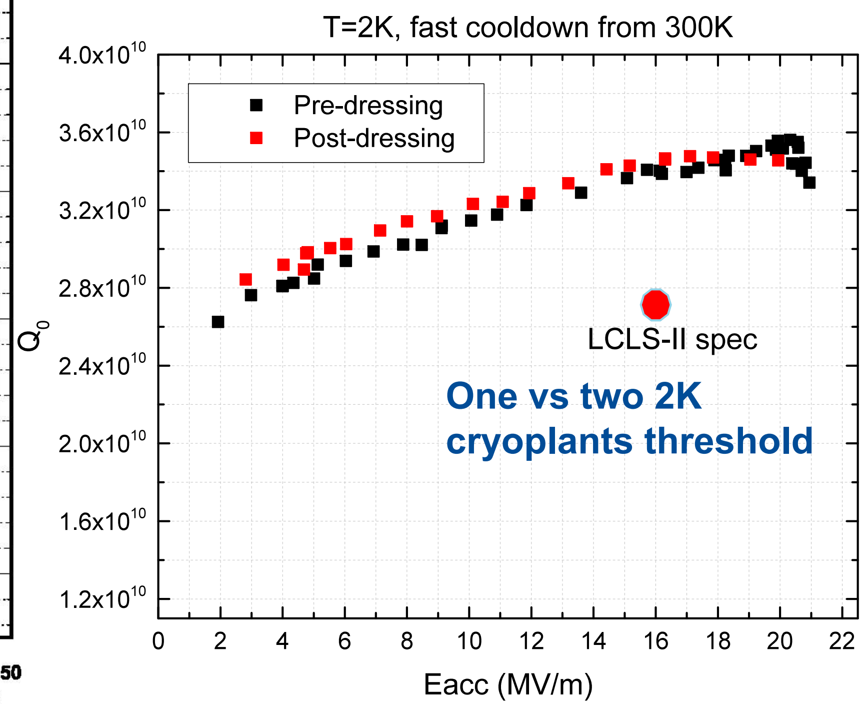
Would possibly require > 2 full cryoplants



Example of N doped

Dressed cavity for LCLS-2

Below the one cryoplant threshold



- N doping technology allows significantly lower refrigeration costs (capital, operating)
- Larger margin and possibility for an energy upgrade for same refrigeration cost

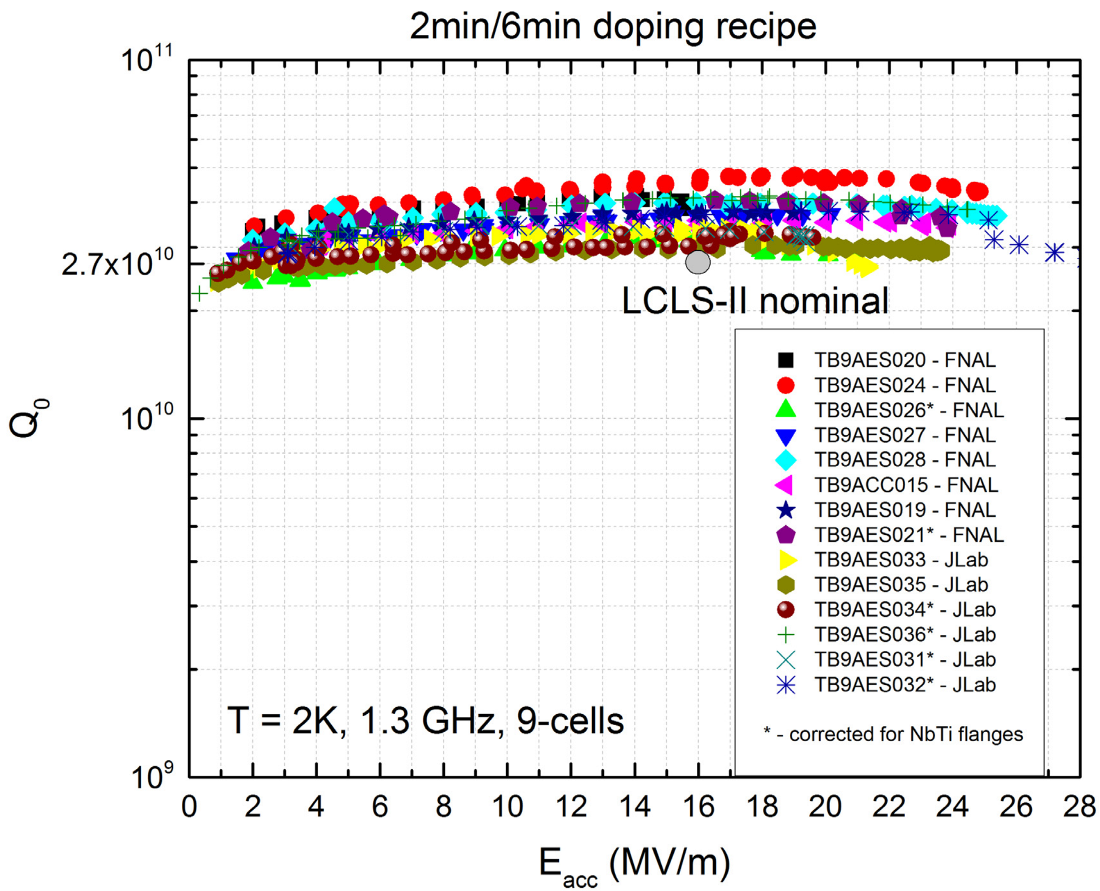
See also WEYC1 Technical Challenges of LCLS-II
Tor Raubenheimer

The High Q Collaboration for LCLS-II

- FNAL, Cornell, Jlab and SLAC together with one goal: bring the N doping technology from single cell R&D to nine cell production ready technology
- Technology transferred to FNAL to Cornell and Jlab; now is being transferred to industry, that will employ it in production stage for LCLS-II
- Target Q : 2.7e10 at 2K, 16 MV/m (1.3 GHz) – almost twice the state of the art (XFEL)
- High Q collaboration team leads:
  - SLAC – M. Ross (coordinator)
  - Jlab – C. Reece
  - Cornell – M. Liepe
  - FNAL – A.Grassellino

A. Crawford et al, WEPRI062, IPAC14

From single cell R&D to cryomodule ready technology: the two LCLS-II prototype cryomodules (FNAL and Jlab)



<Q>=3.6e10

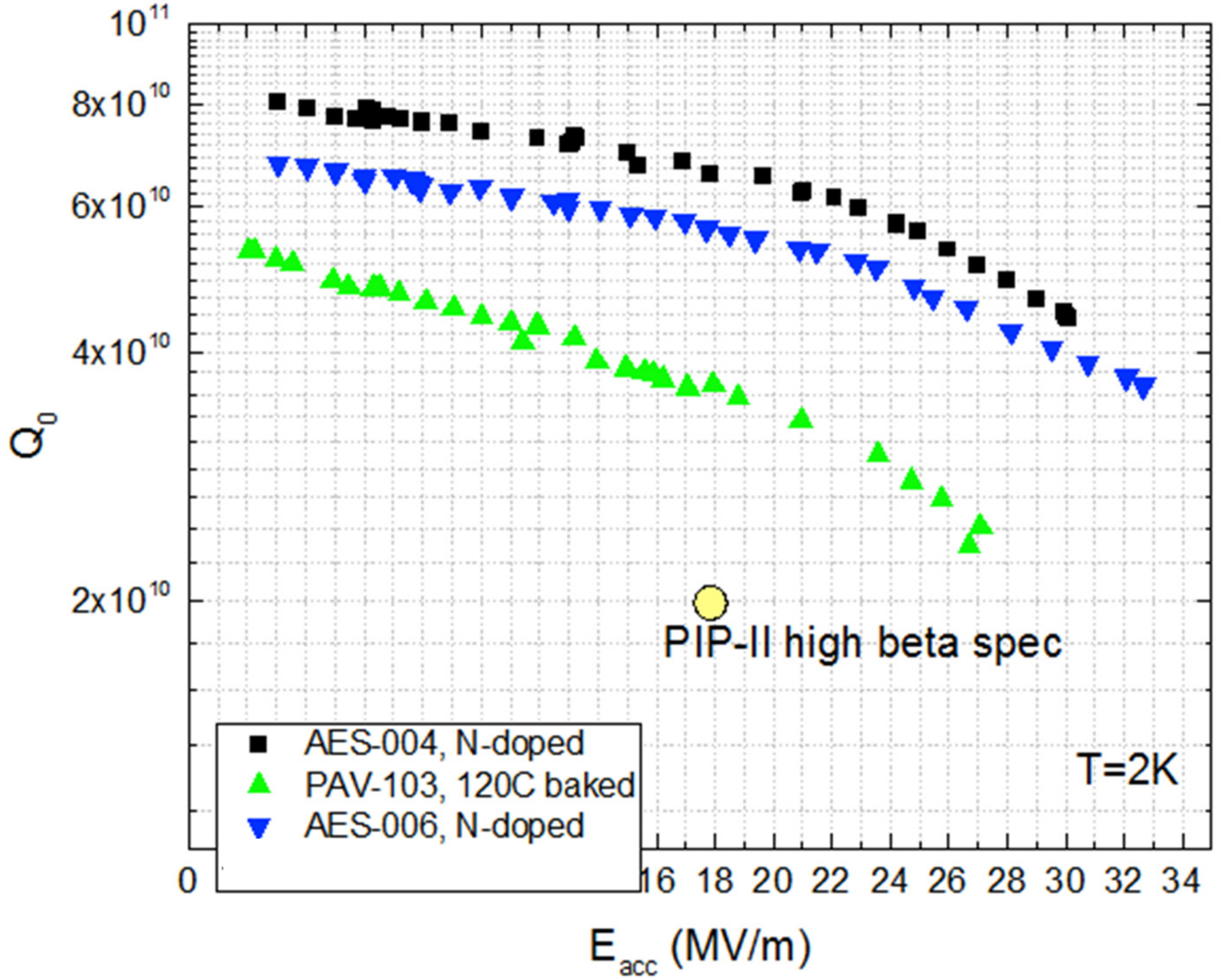
$\langle E_{max} \rangle$=22.2 MV/m

E_{max}median=22.8MV/m

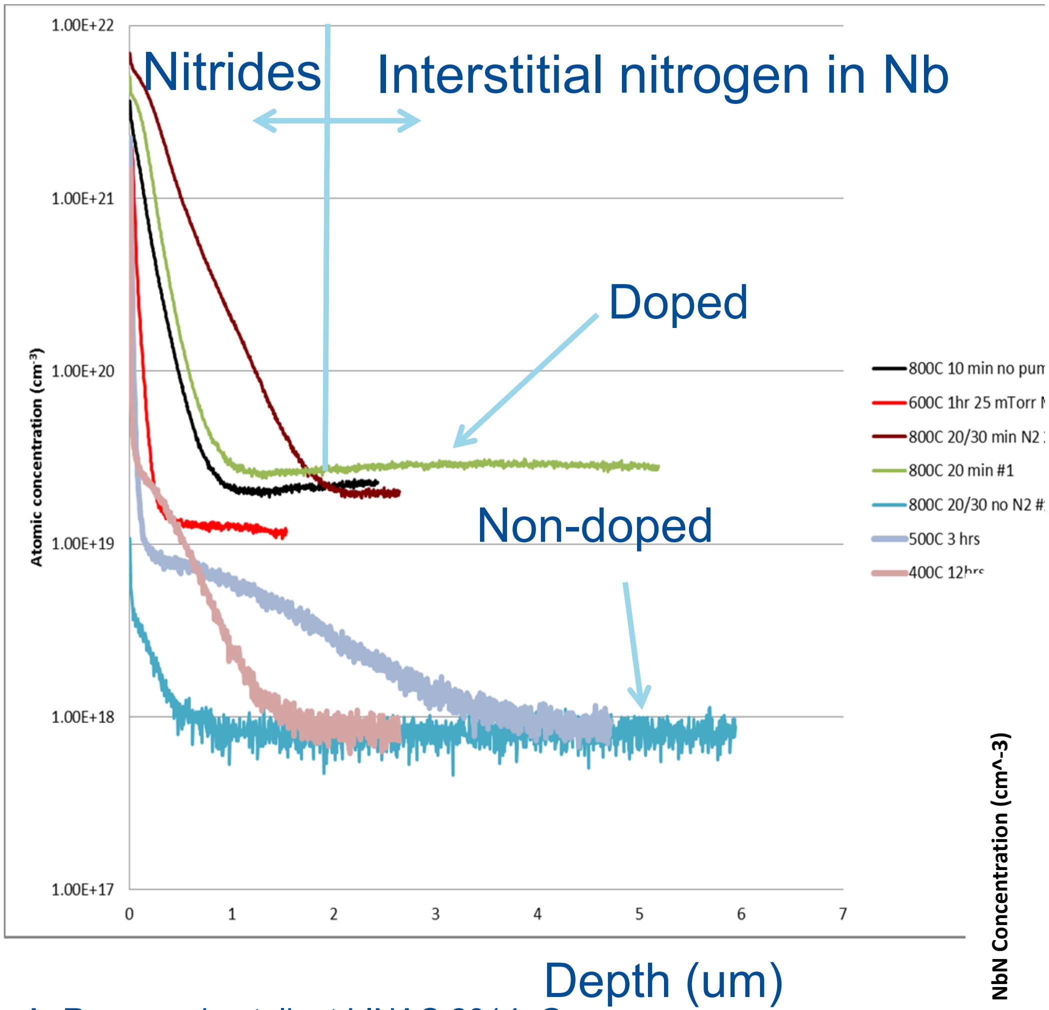
It is the highest average Q ever demonstrated in vertical test for 1.3 GHz nine cells at 2K, 16 MV/m in the history of SRF (larger than a factor of two the state of the art)

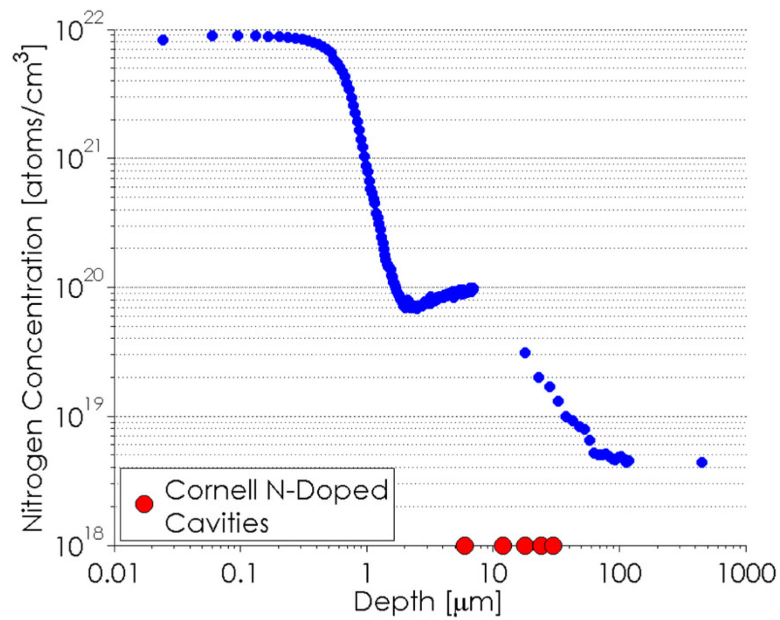
N doping applied to 650 MHz cavities at FNAL
Q~ 7e10 at 2K, 17 MV/m – record at this frequency!

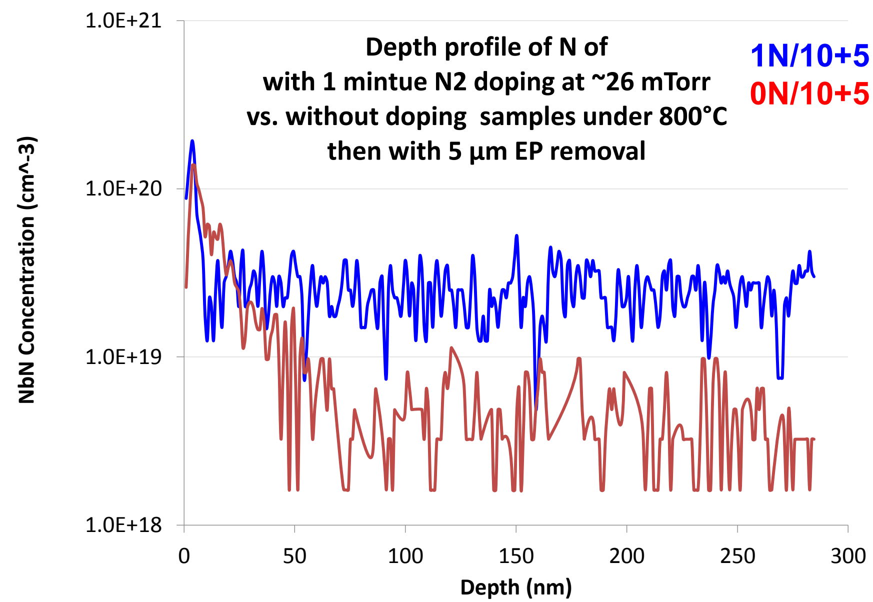
Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)



What does the N treatment do? N doping profiles via SIMS





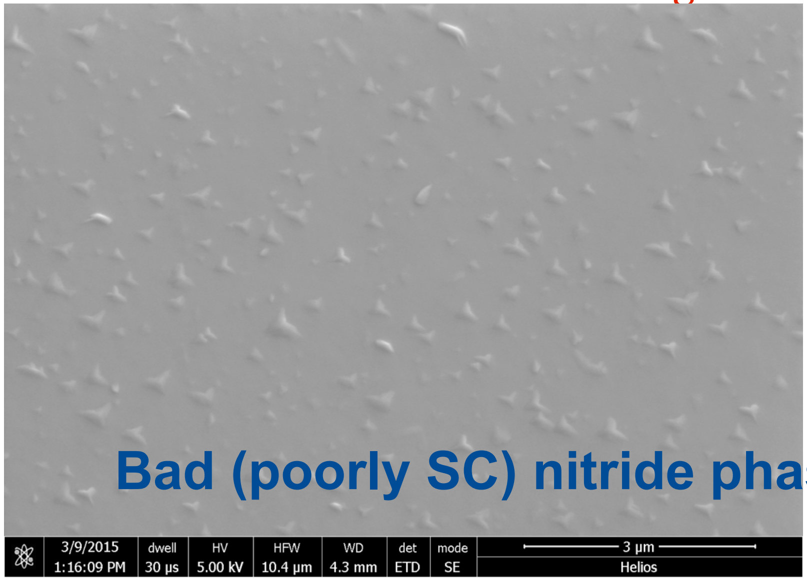


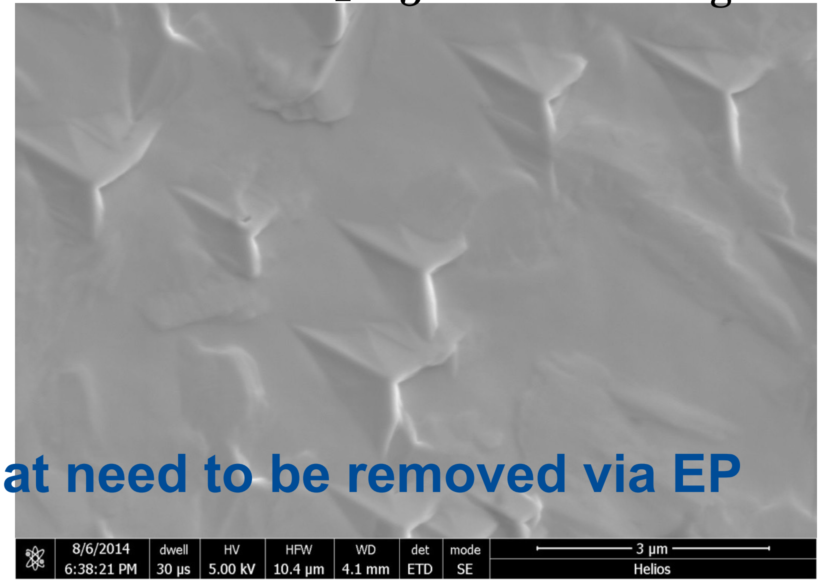
A. Romanenko, talk at LINAC 2014, Geneva
And D. Gonnella et al, LINAC 2014, Geneva
C. Reece et al, **WEPWI026**

Surface Nitrides (post bake, pre-EP) – imaged by SEM

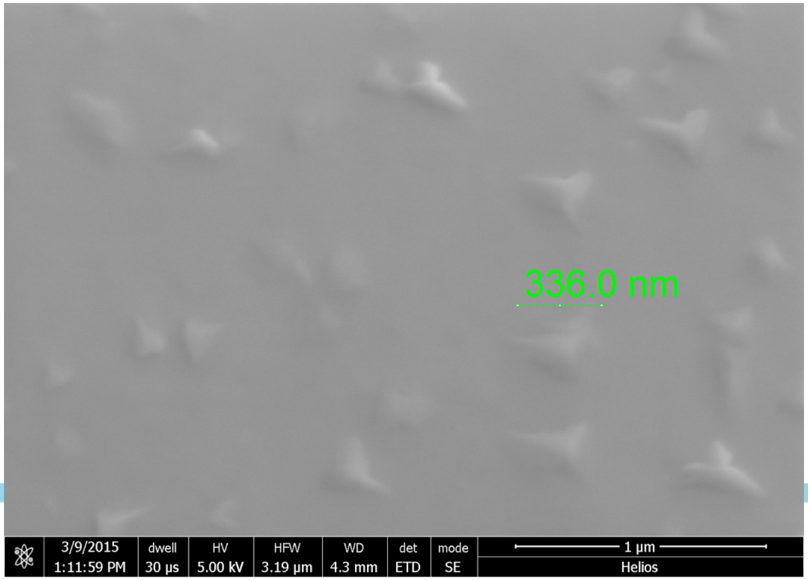
Flat Nb sample baked at 800C° for **2 min with N_2** + 6 min annealing

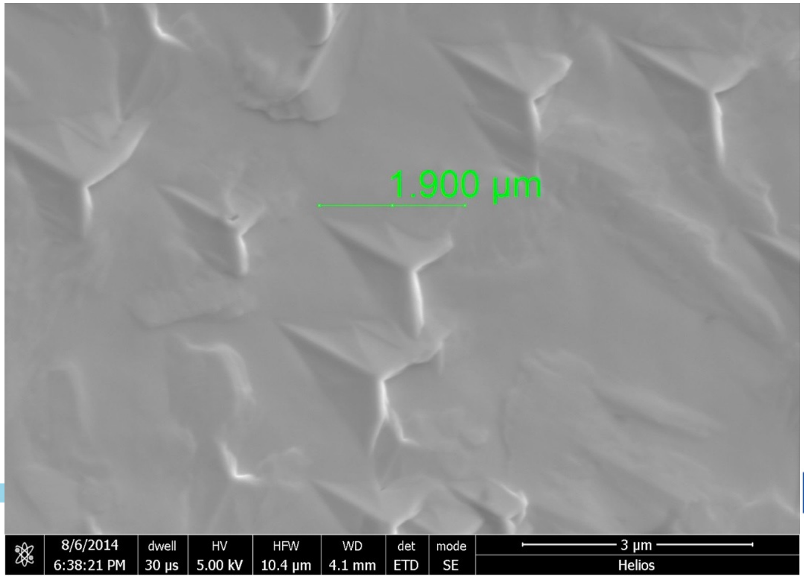
Flat Nb sample baked at 800C° for **20 min with N_2** + 30 min annealing





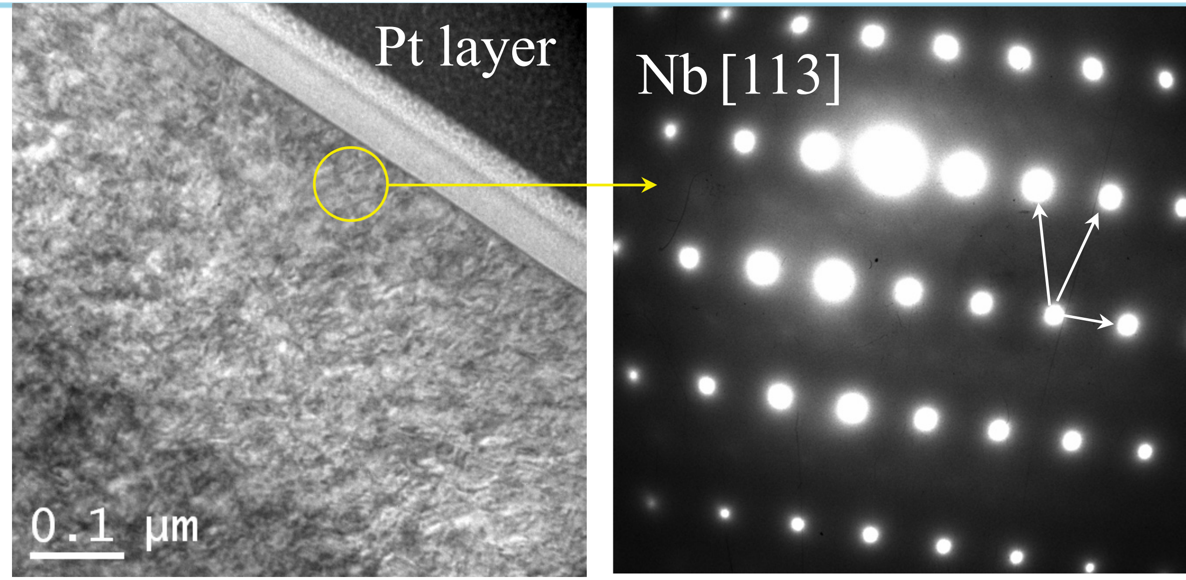
Bad (poorly SC) nitride phases that need to be removed via EP





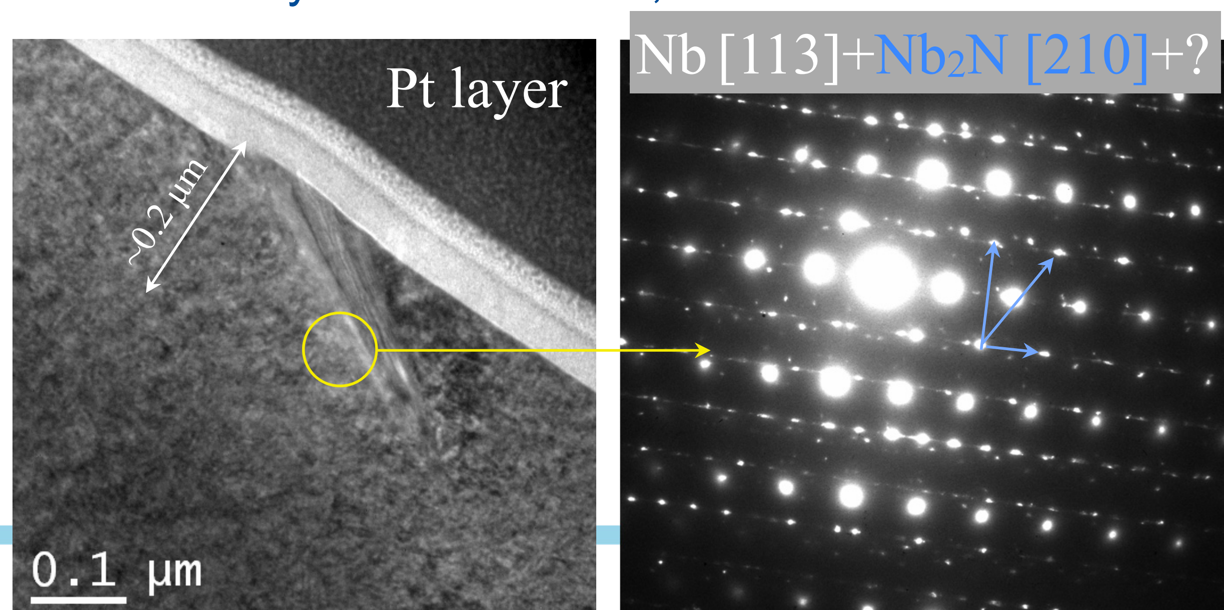
Room T TEM on post gas bake, pre-EP surface (2/6 recipe)

a) µm-sized areas of "uniform" contrast in near-surface show only Nb reflections



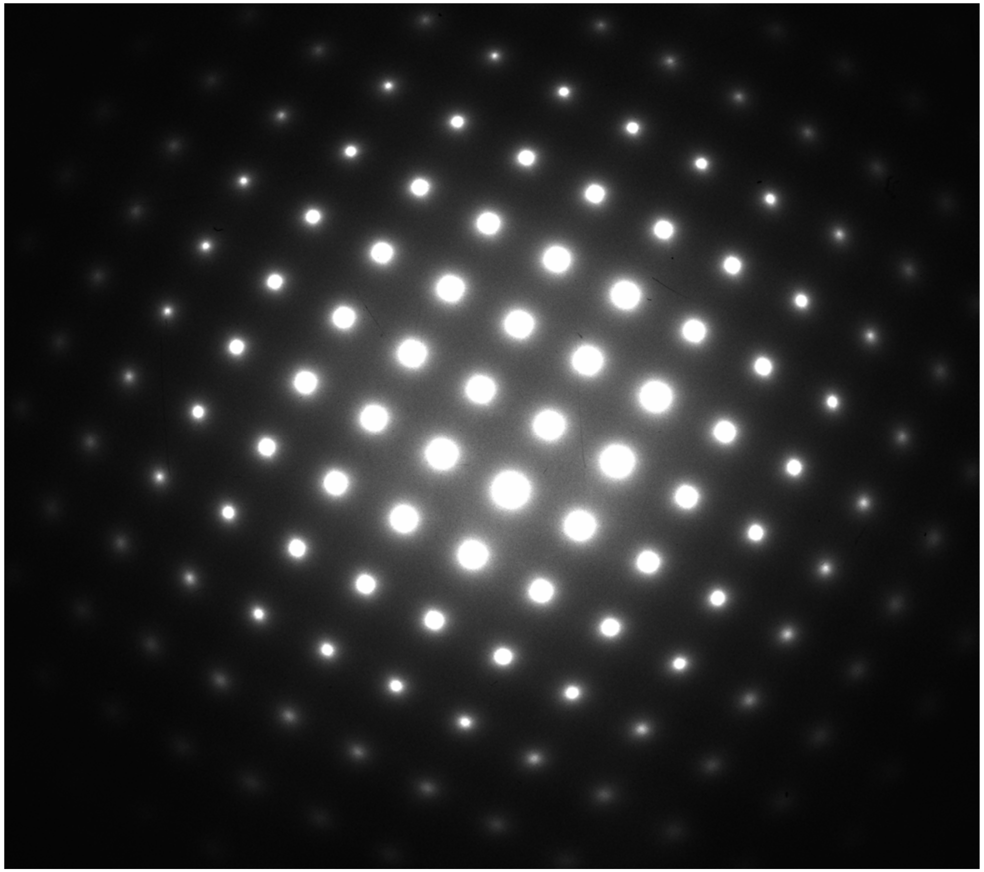
Courtesy of Y. Trenhikina, FNAL

b) few Nb nitrides-features (Nb_2N reflections) in Nb near-surface. Nitride "teeth" go ~0.2 µm deep



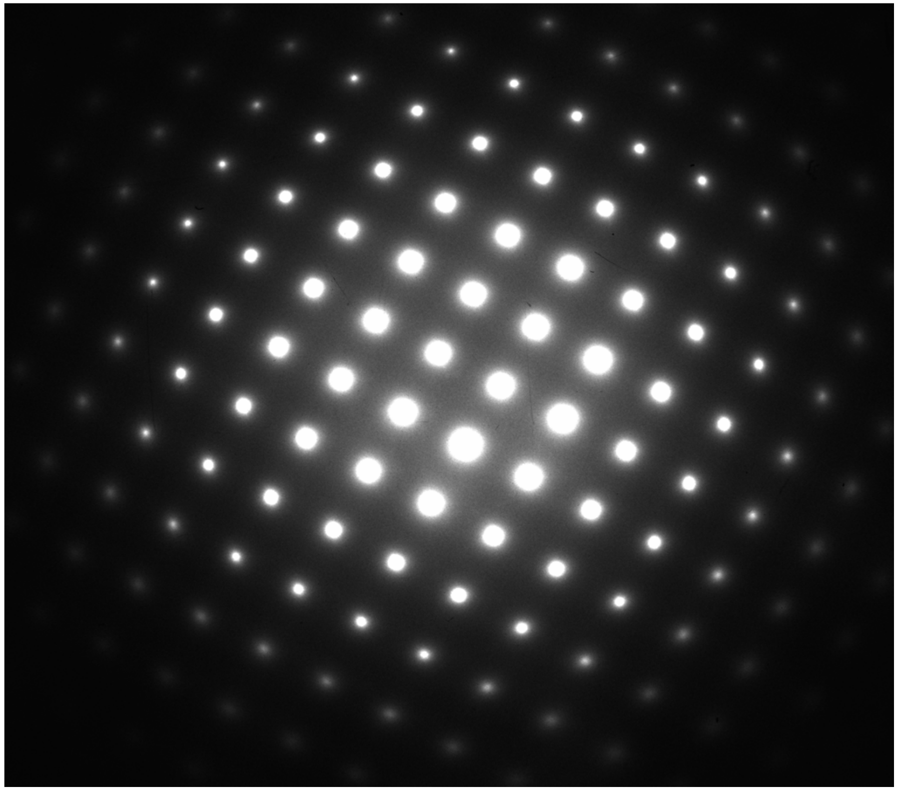
Room T TEM on N doped surface AFTER EP

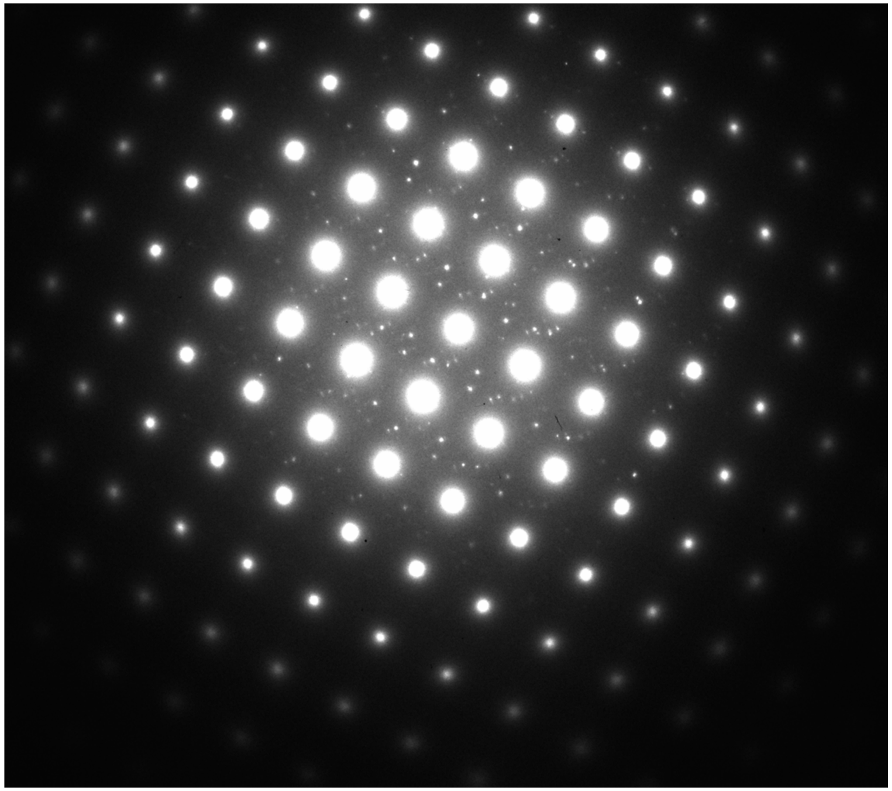
- Preliminary: no visible Nb nitrides-teeth in near-surface show only Nb reflections
- Confirms that root of improvement is from nitrogen as interstitial in the lattice



Cryogenic TEM on N doped surface AFTER EP

ROOM T → 90K

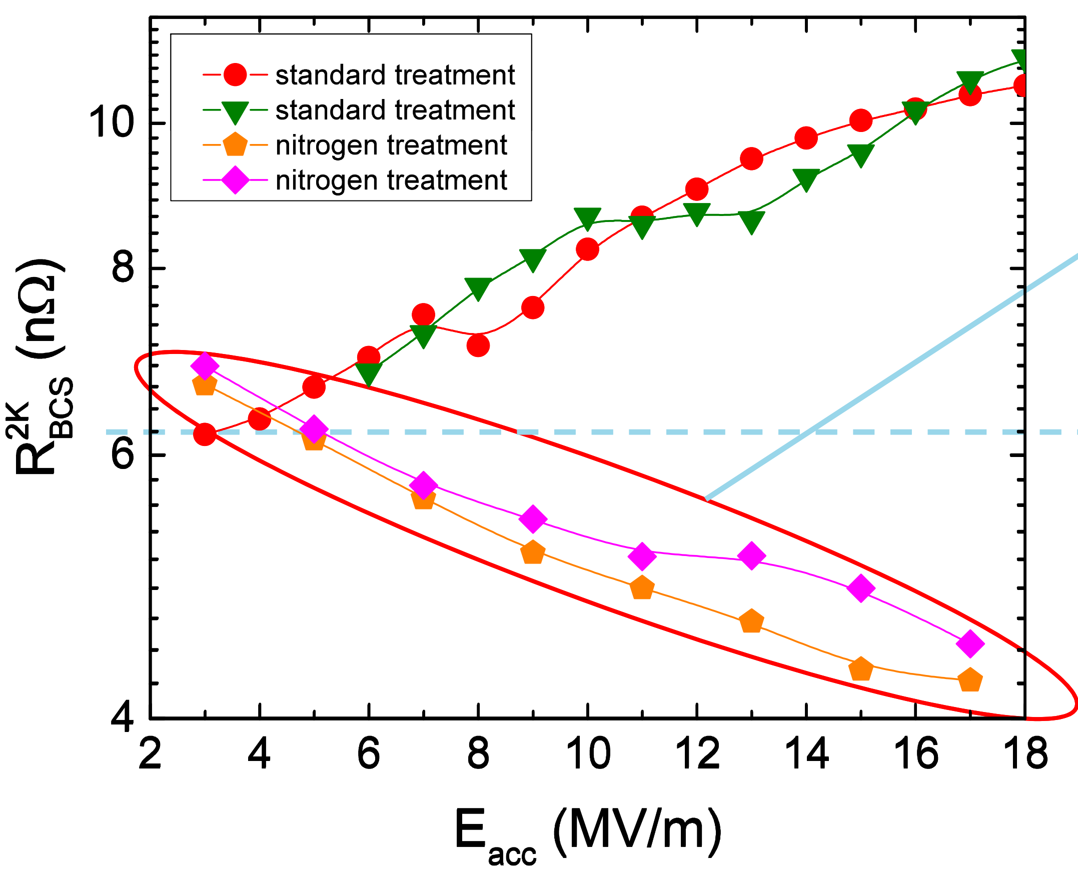




Preliminary: large near-surface area is affected by Nb nanohydride precipitation!
But different than typical: closely spaced, very small/thin Nb hydrides.

Nanohydrides in standardly treated samples: Trenikhina et. al. J. of Appl. Phys., 117, 154507 (2015).

Physics – perceived BCS limit has been overcome



Anti-Q-slope emerges from the BCS surface resistance <u>decreasing</u> with field

This is what BCS theory predicted to be the lowest possible surface resistance

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

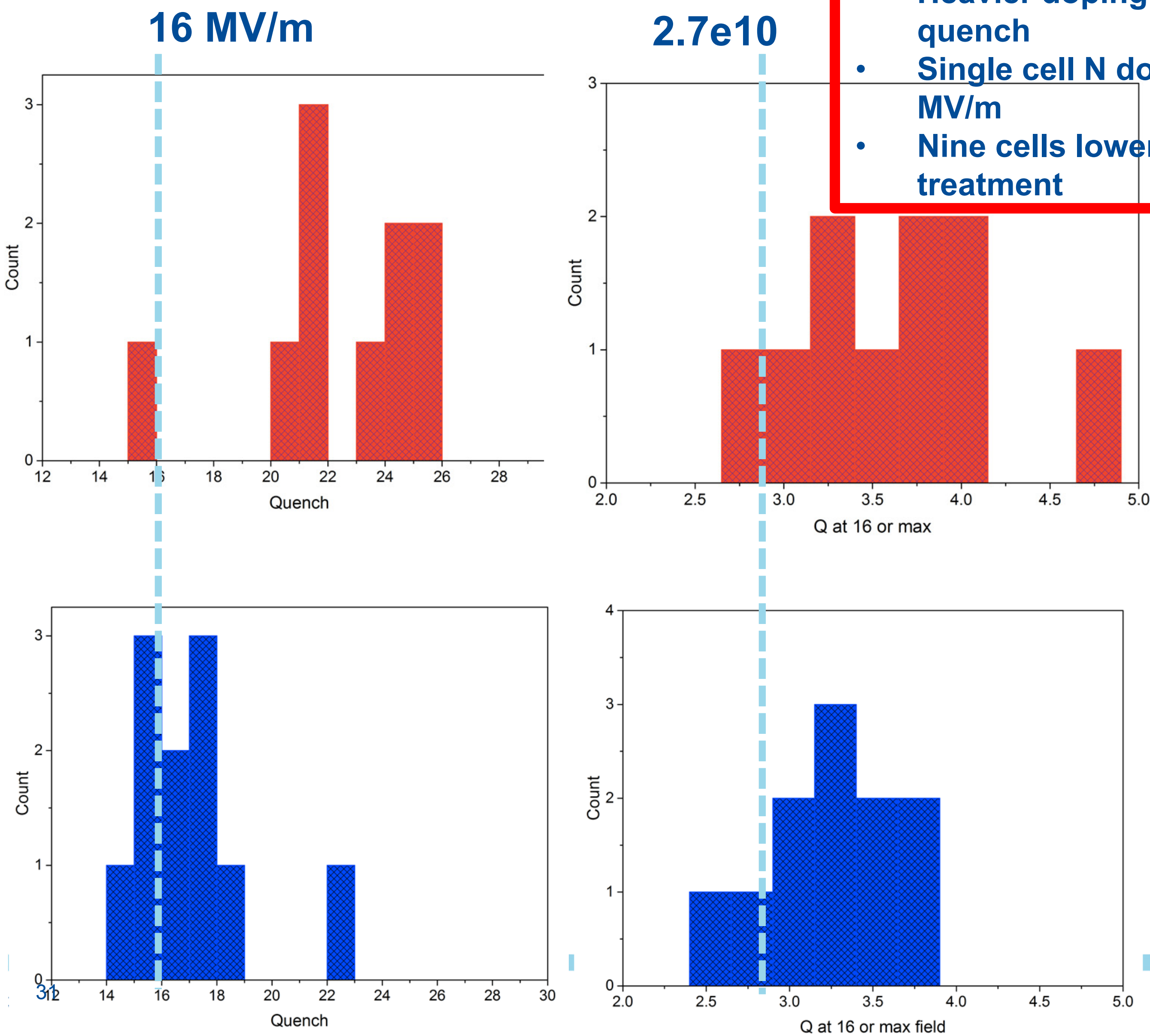
Models for explaining N doping $R_{BCS}(B)$

- B.P. Xiao, C. Reece, M. J. Kelley from JLab and College of William and Mary
  - Momentum of Cooper pairs leads to an inversed field dependence of R_{BCS}?
  - [B.P. Xiao et al, Physica C **490** (2013) 26-31]

- A. Gurevich from ODU
  - Time-dependent density of states leads to the effect?
  - [A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)]

Open questions: nature of premature quench in N doped

- **Heavier doping levels result in premature quench**
- **Single cell N doped demonstrated up to 39 MV/m**
- **Nine cells lower than single cell for same treatment**



Recipe 2/6 "light doping"

<Q>=3.6e10

$\langle E_{max} \rangle$=22.2 MV/m

E_{max}median=22.8MV/m

Recipe 20/30 "heavy doping"

<Q>=3.24e10

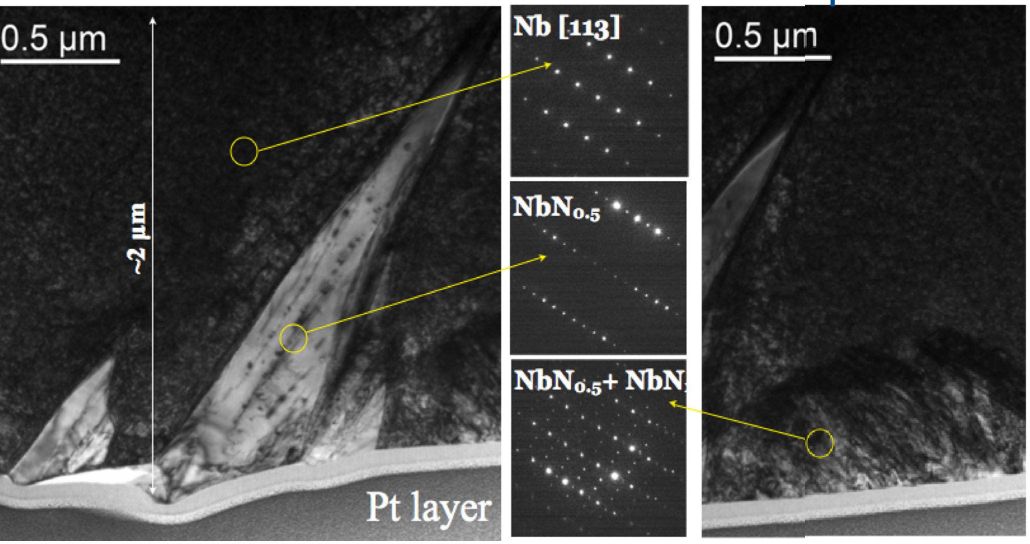
$\langle E_{max} \rangle$=16.3 MV/m

E_{max}median=16.5MV/m

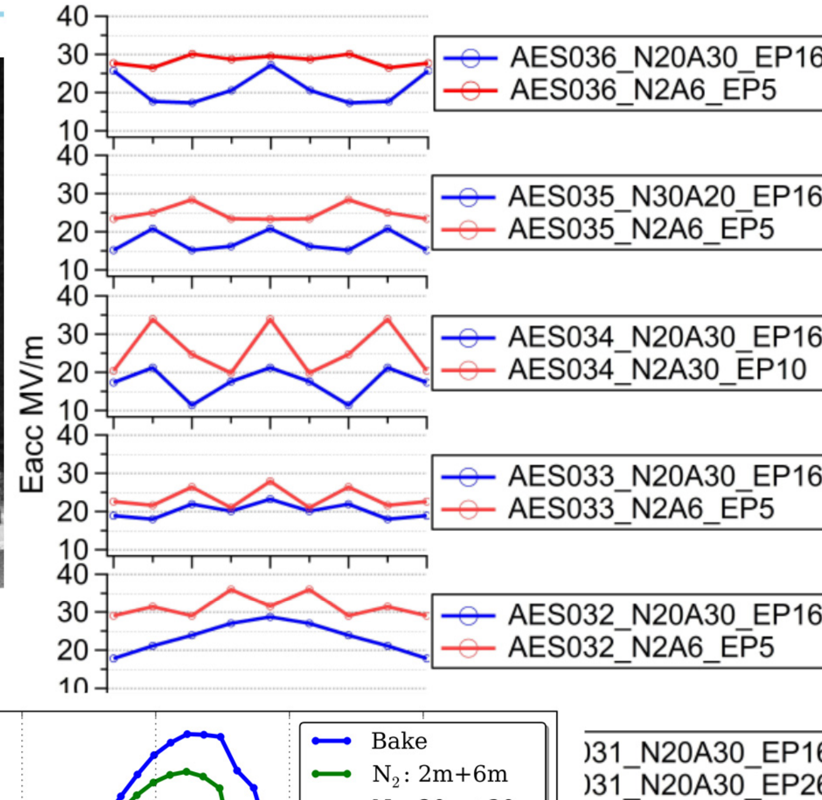
New insights on quench in N doped cavities

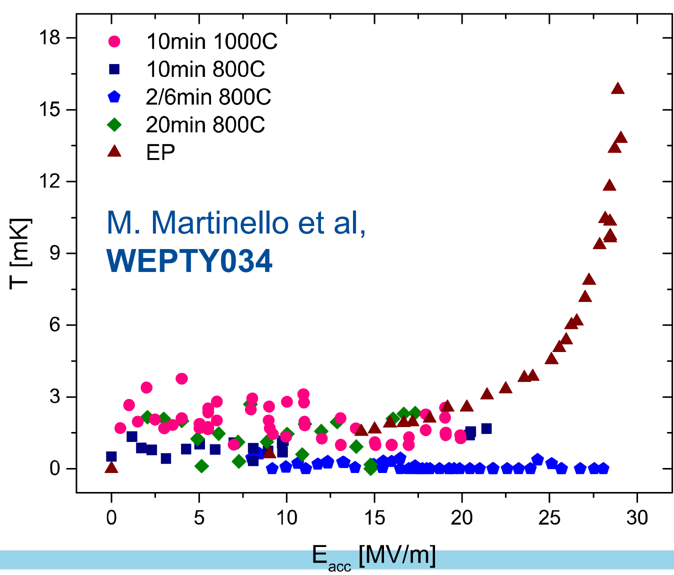
A. D. Palczewski et al, **WEPWI019**

Nitride teeth…residual nanonitrides post EP?

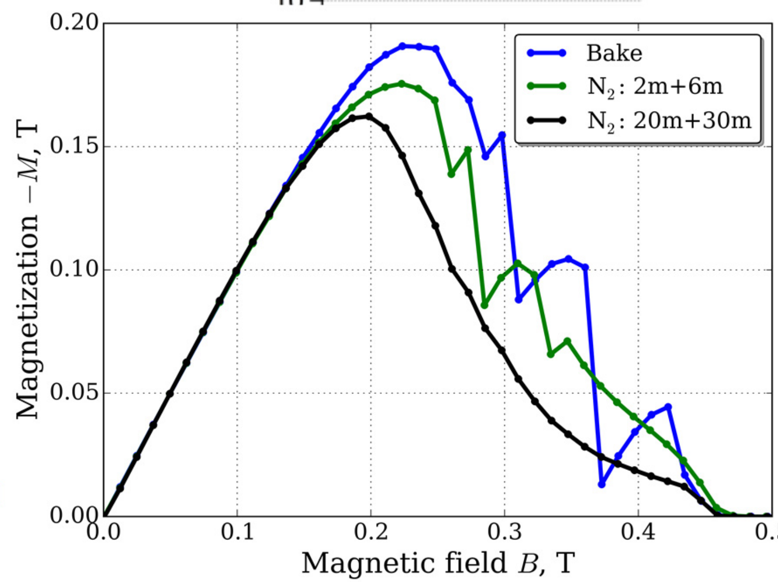


Passband mode Analysis





M. Martinello et al, **WEPTY034**

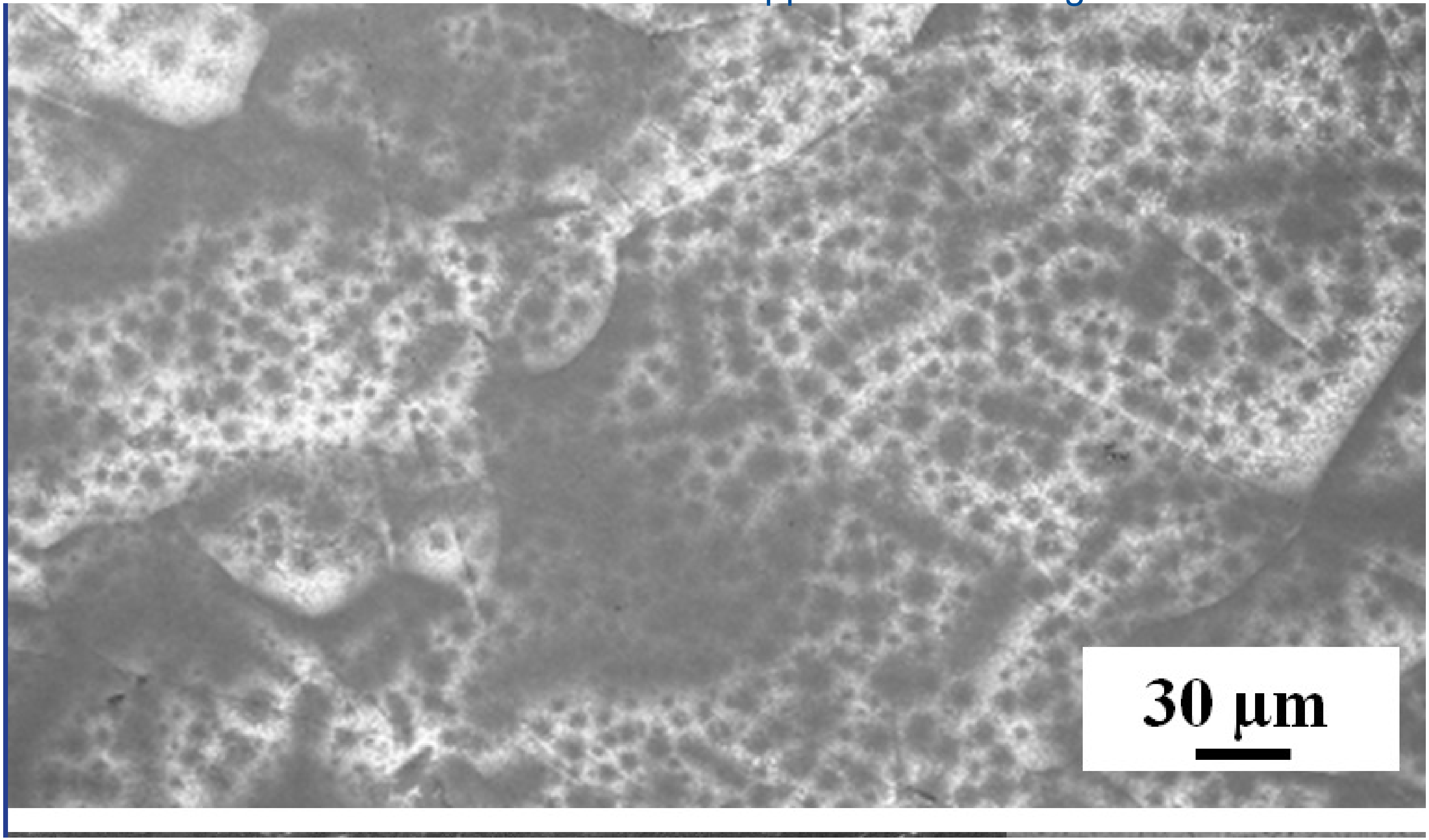


A. Vostrikov et al, **WEPTY022**

Efficient magnetic flux expulsion via fast cooling

Magnetic flux lines can be trapped and cause large RF losses

Trapped vortices imaged via Bitter Decoration



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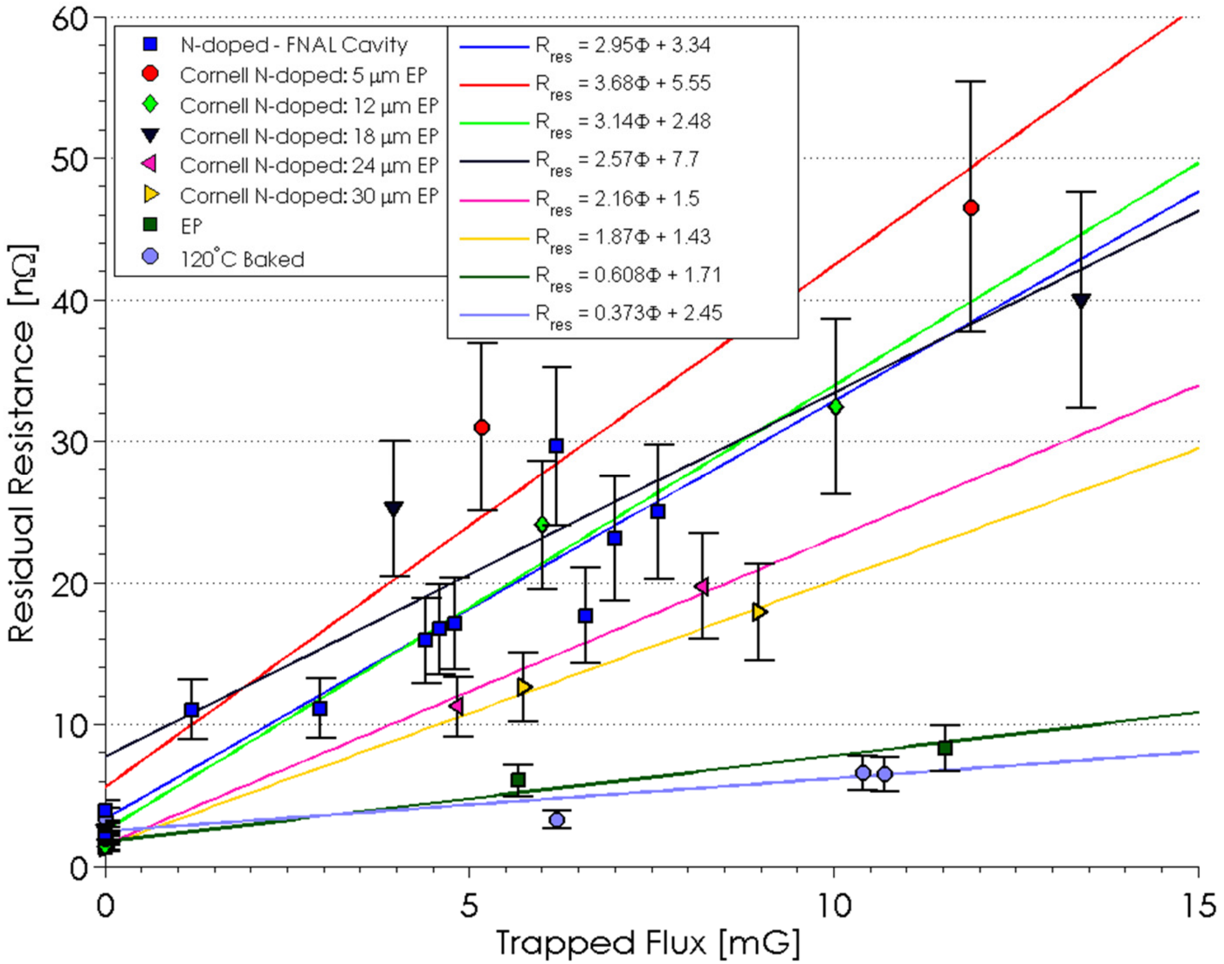
Enhanced sensitivity to magnetic field of N doped



D. Gonnella and M. Liepe. Cool Down and Flux Trapping Studies on SRF Cavities. Proceedings of LINAC 14, Geneva, Switzerland. MOPP017.

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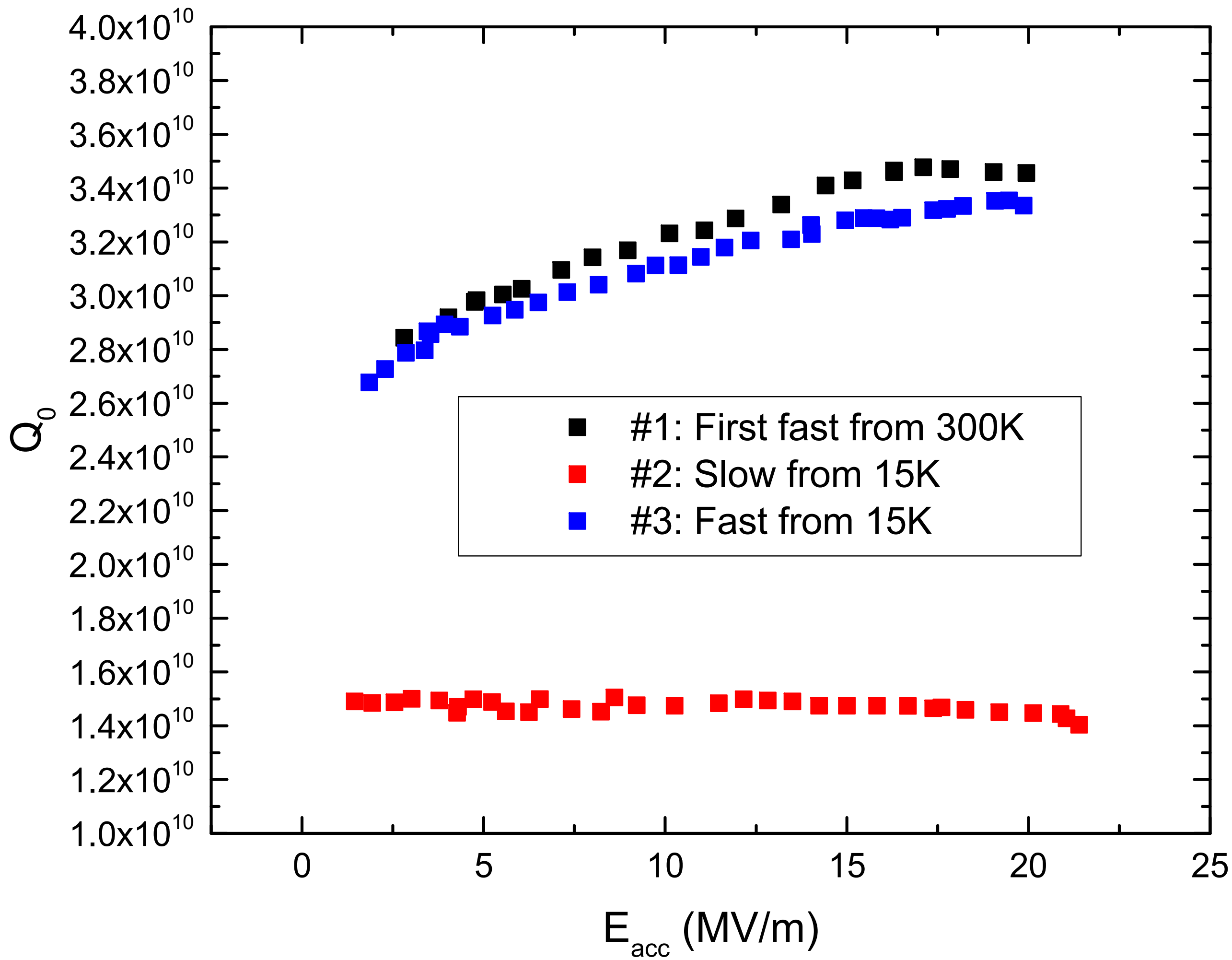
At FNAL, discovered that slow cooldown can kill high Q

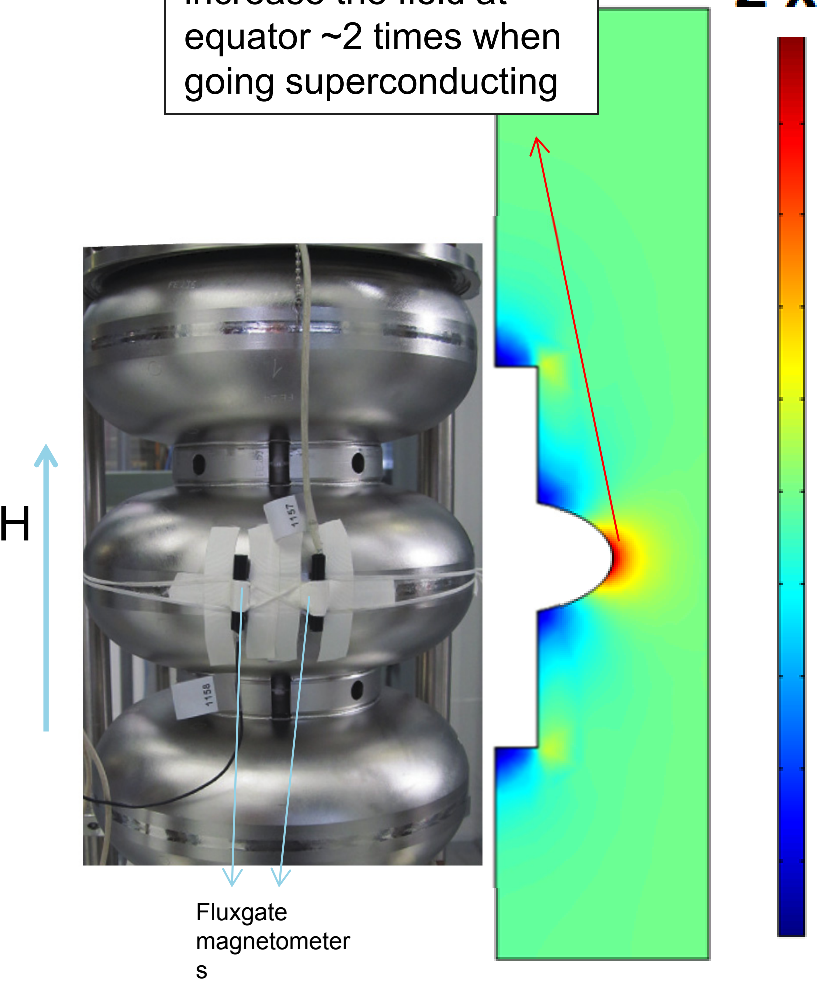


N doped nine cell in 5 mGauss!

A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. **115**, 184903 (2014)

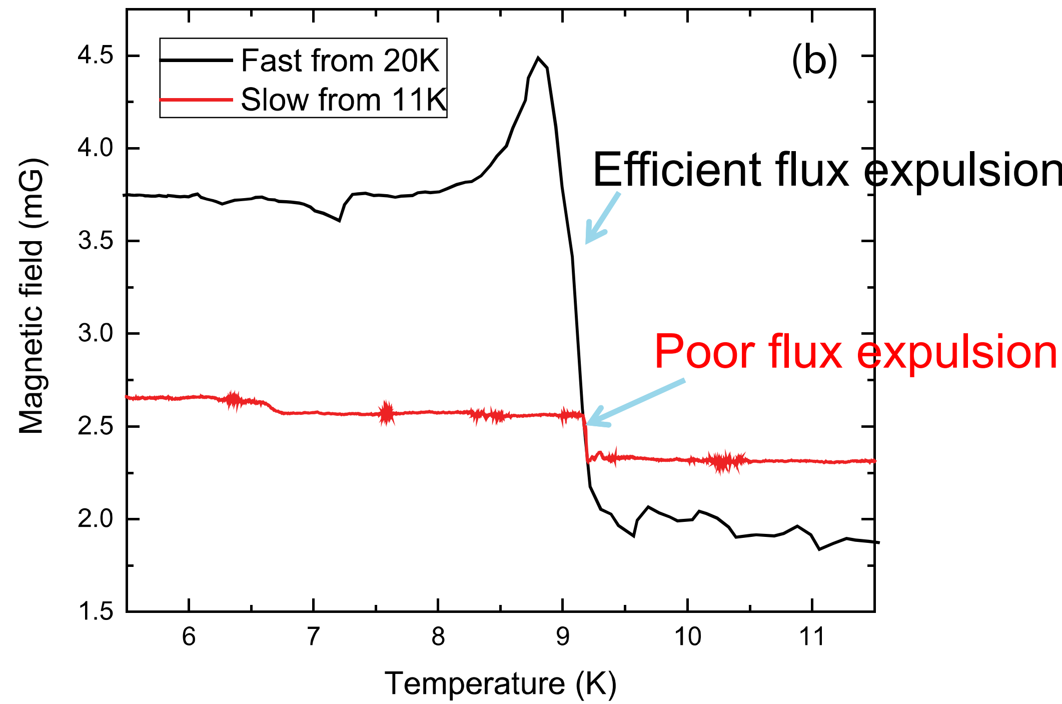
Magnetic probes revealed the new physics

Full expulsion of the magnetic field should increase the field at equator ~2 times when going superconducting



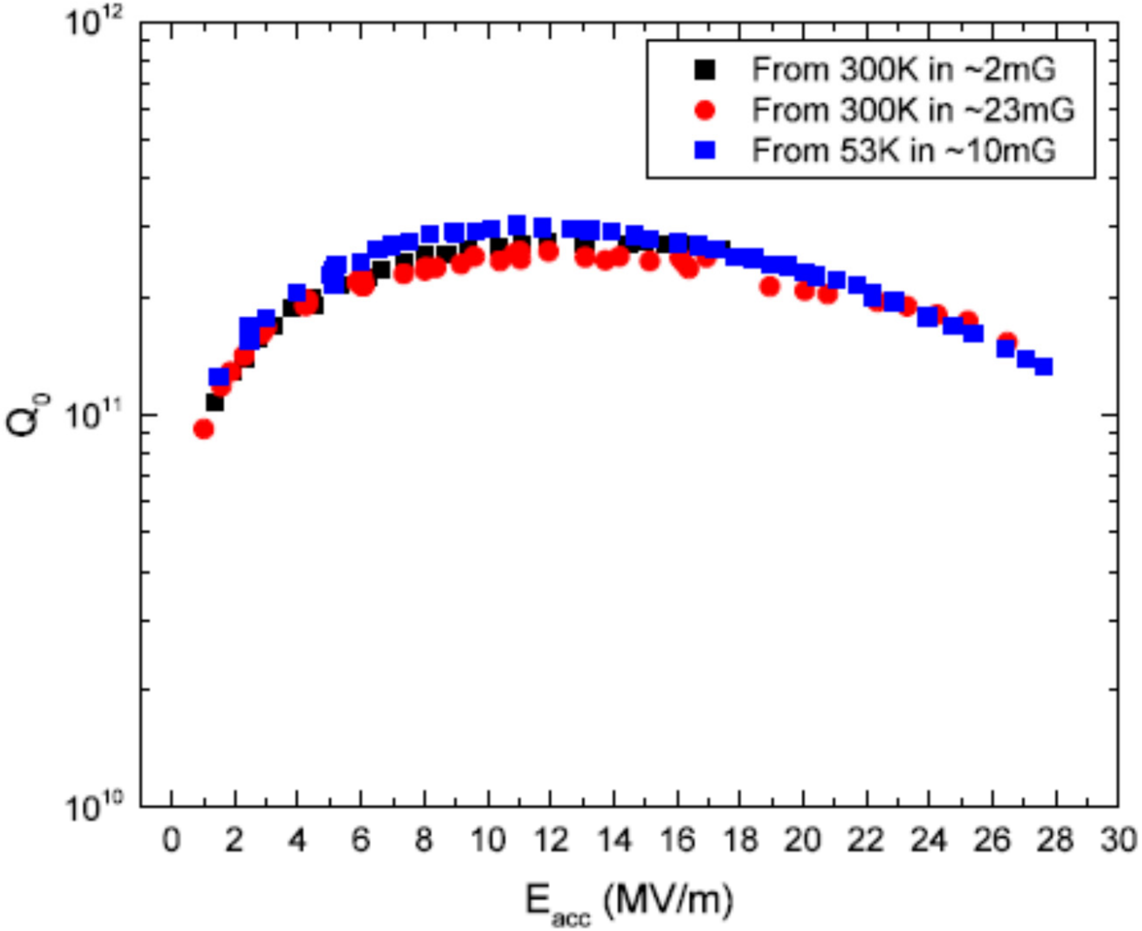
2 x H

It turns out the expulsion efficiency can be controlled by the cooldown procedure through Tc=9.2K (fast/slow, uniform or not)



<u>Same Meissner behavior for EP, EP+120C, N doping, fine/single grain, cooling is what matters</u>

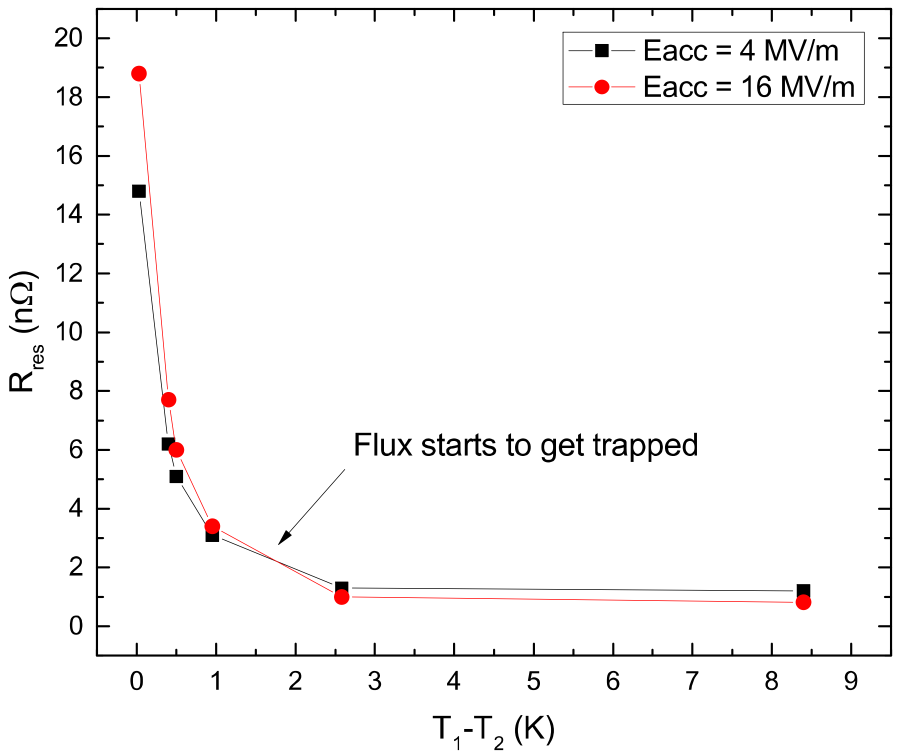
Record Q up to the highest fields combining N doping and efficient flux expulsion

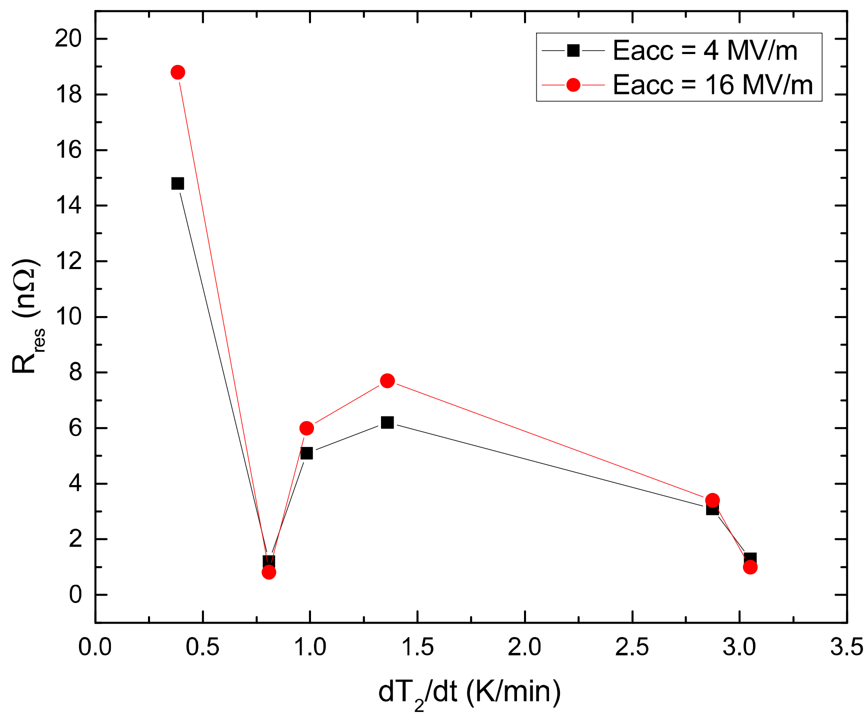


- High thermal gradient provides depinning force allowing efficient magnetic field expulsion
- Ultra-high Q_0 even in 190mG

A. Romanenko, A. Grassellino et al. J. Appl. Phys. 115, 184903 (2014)
A. Romanenko, A. Grassellino et al. Appl. Phys. Lett. 105, 234103 (2014)

It’s a matter of thermogradient along the cell (at the phase front) – and geometry of the problem has an effect, too…



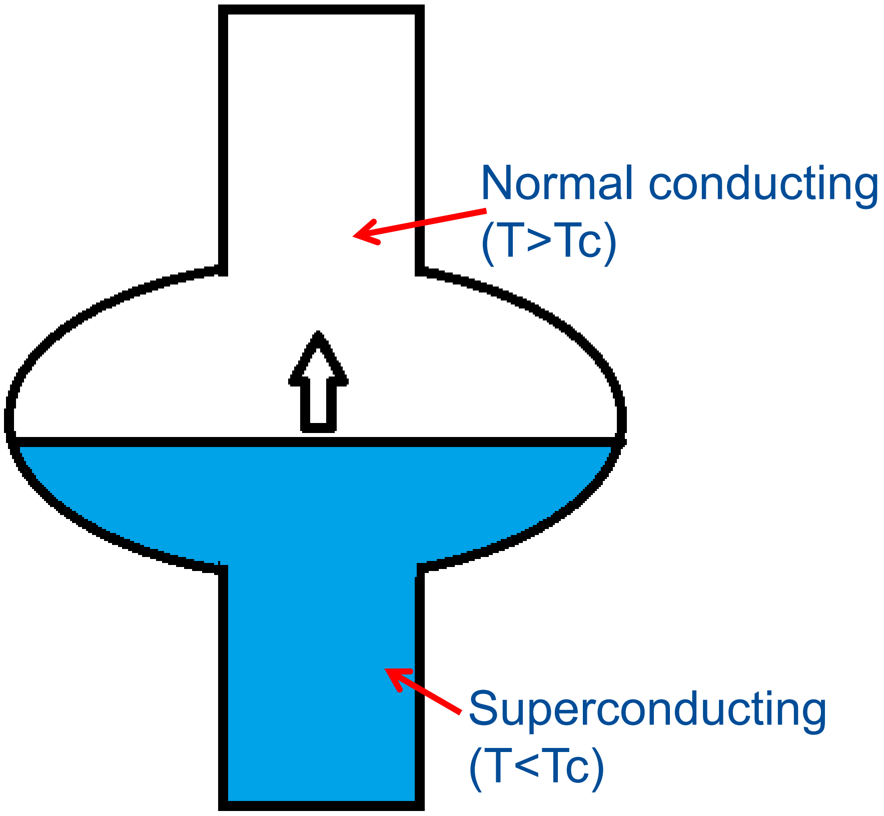


A. Romanenko, A. Grassellino, A.Crawford, D. A. Sergatskov, Appl. Phys. Lett. 105, 234103 (2014)

M. Martinello et al, **arXiv:1502.07291**

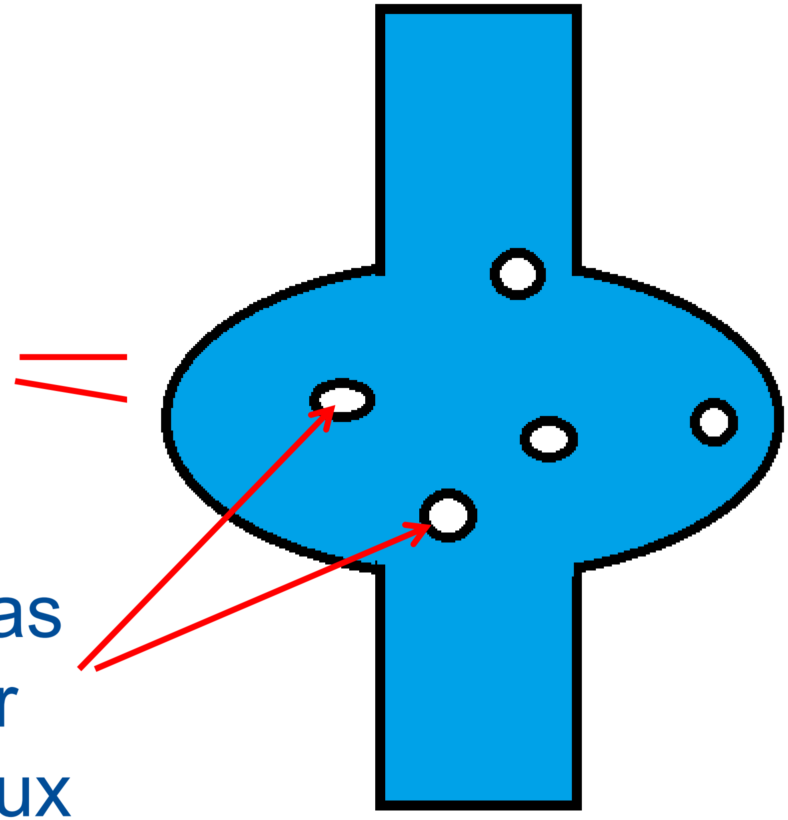
Details of superconductivity nucleation matter

Fast cooldown – well-defined superconducting/normal boundary is moving from bottom to the top => no energy barrier for flux to be expelled



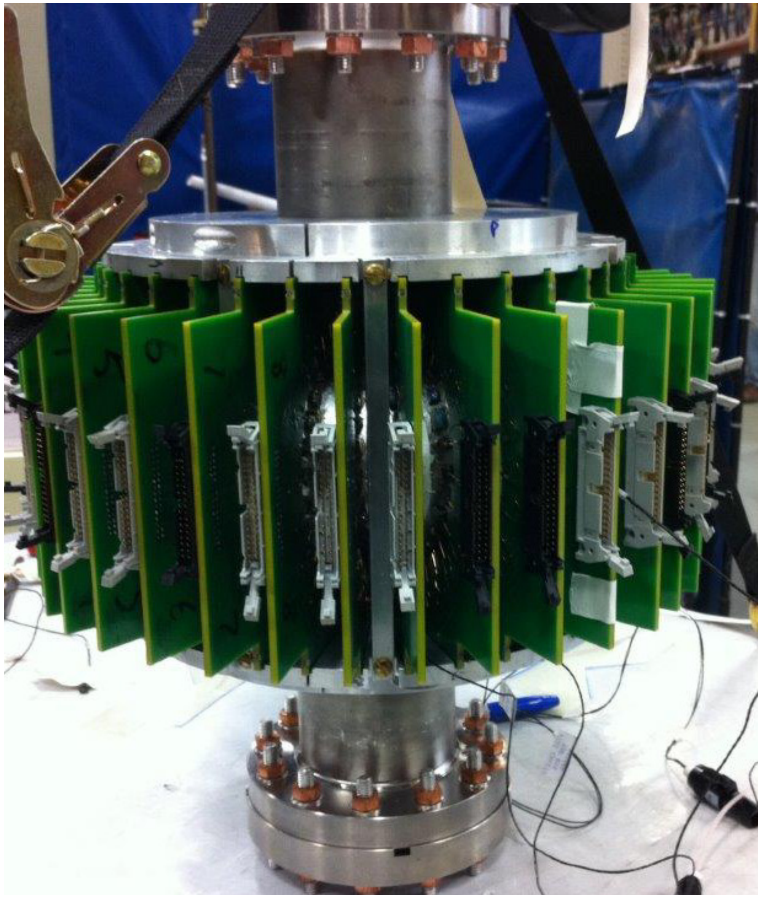
Details of superconductivity nucleation matter

Slow uniform cooldown – superconductivity is nucleated at multiple spots which reach T<Tc

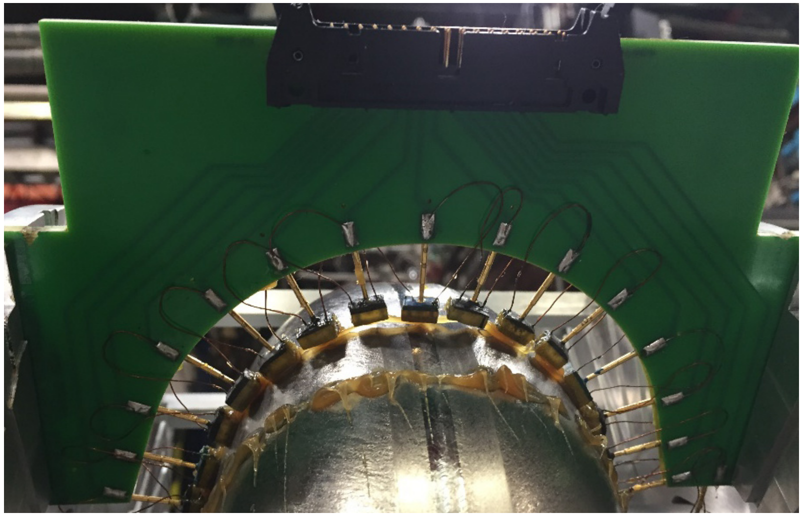


Flux surrounded by superconducting areas has an energy barrier for escape=> more flux trapping is possible

T-map apparatus



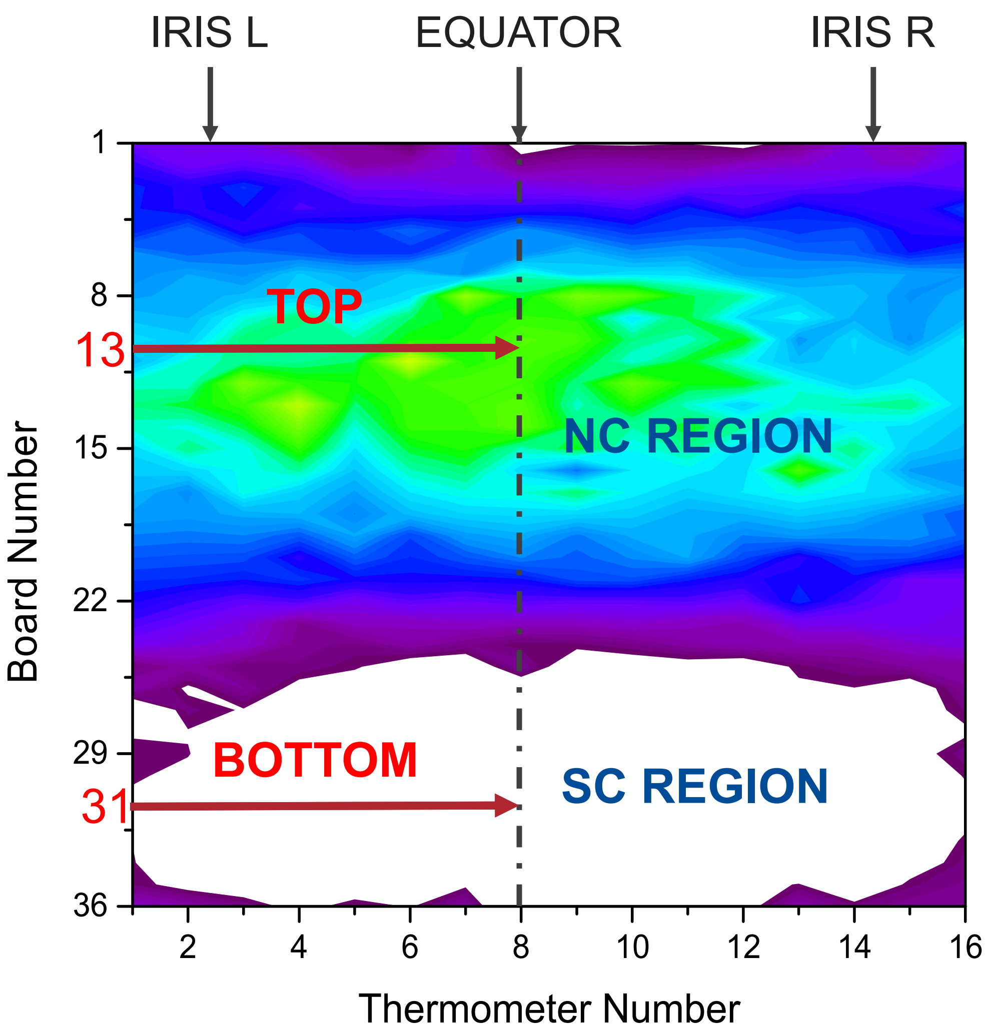
- Cornell-based T-map system
- 36 boards with 16 thermometers each

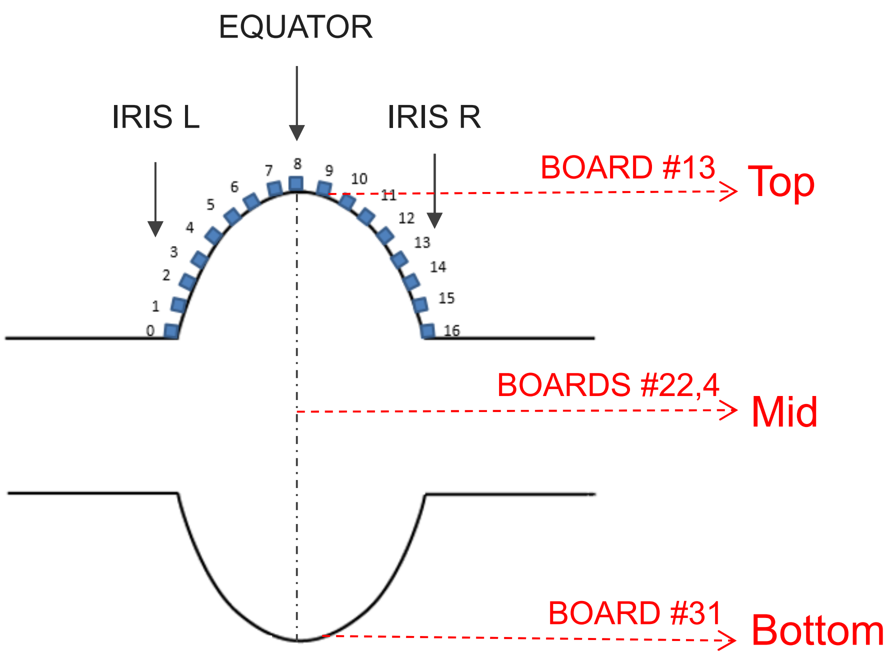


576 thermometers
all around the cavity

T-map images

M. Martinello and M. Checchin PhD thesis work (FNAL)

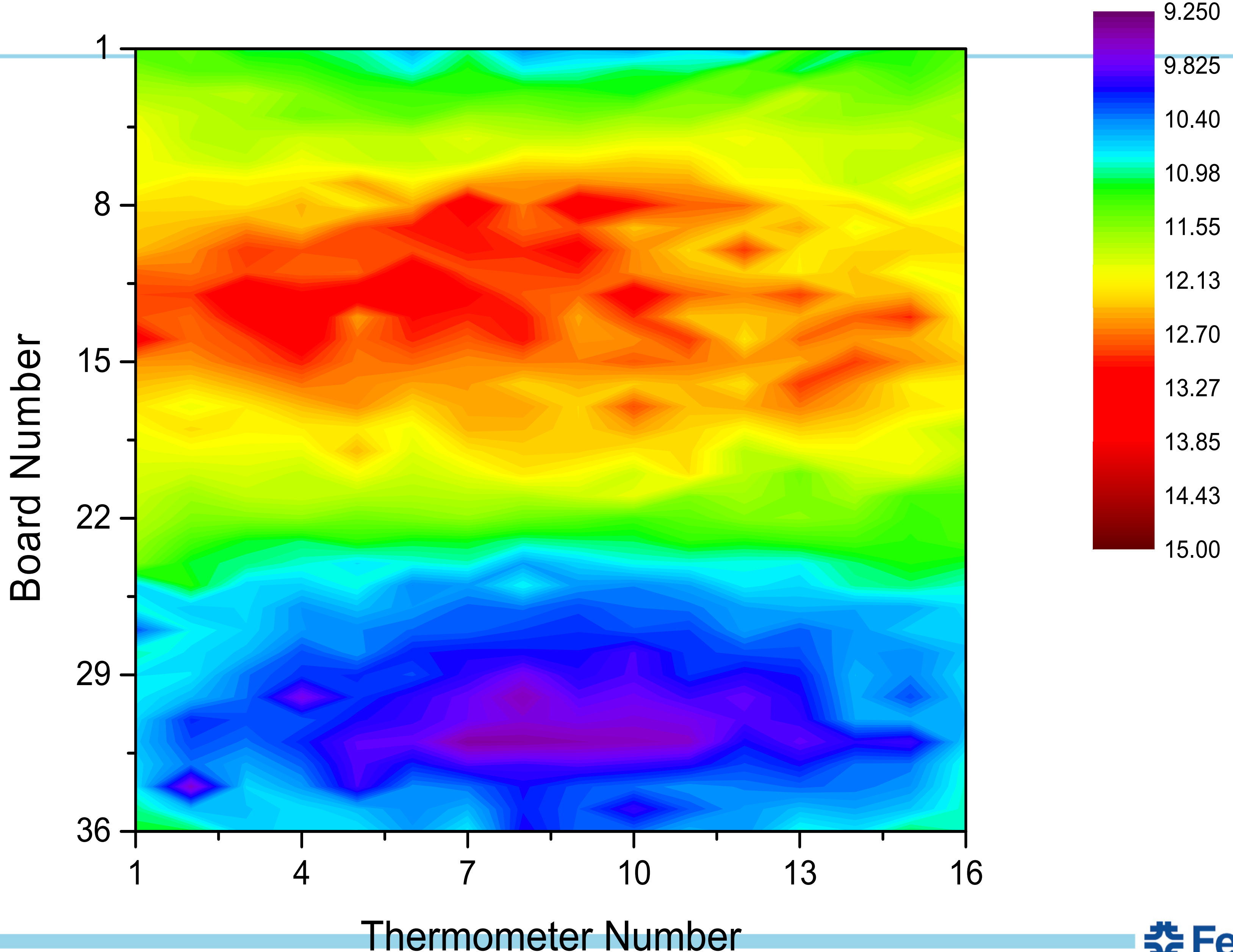




Fast Cool-down T-map

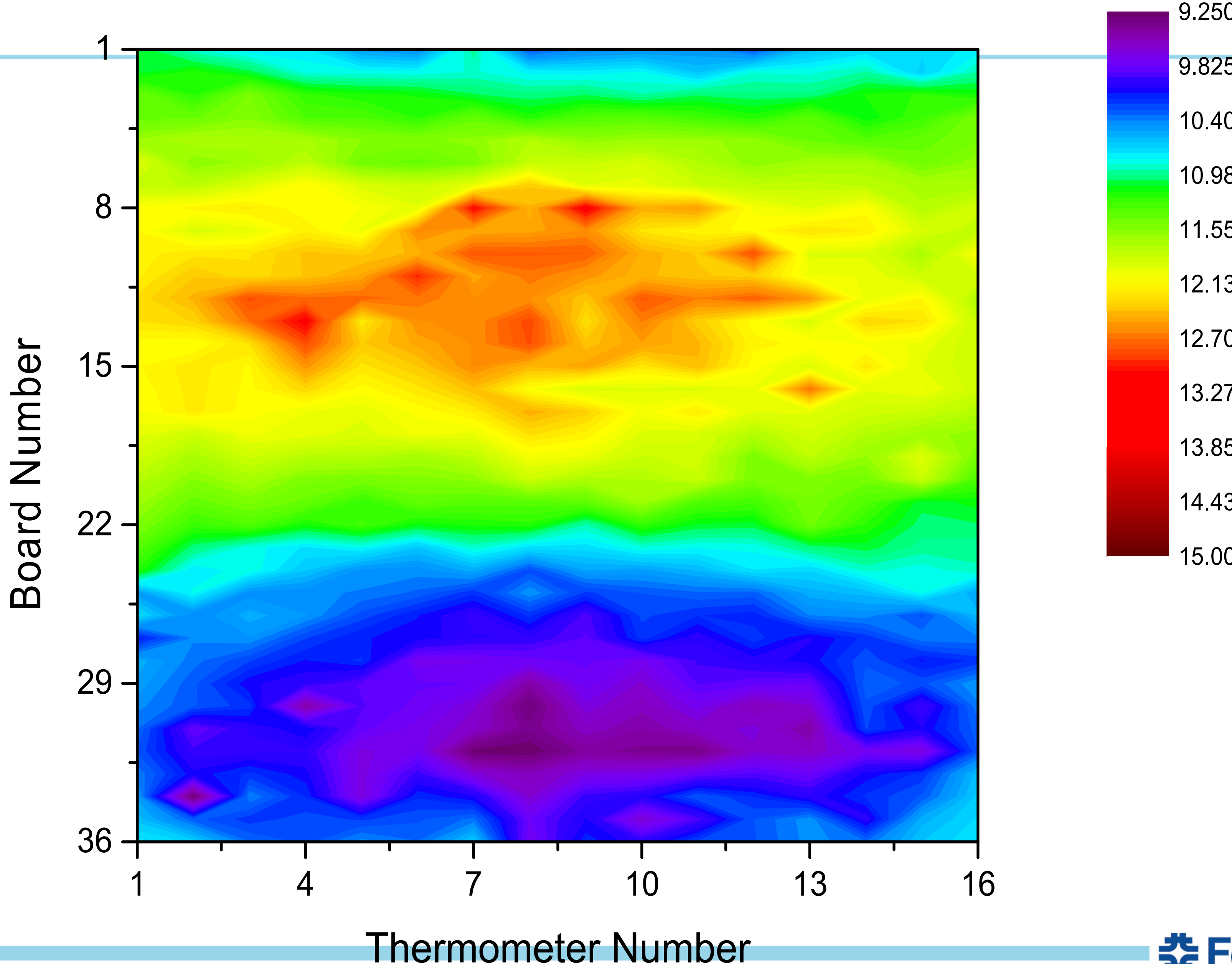
Starting T: 250K

Fast Cool-down From 250K



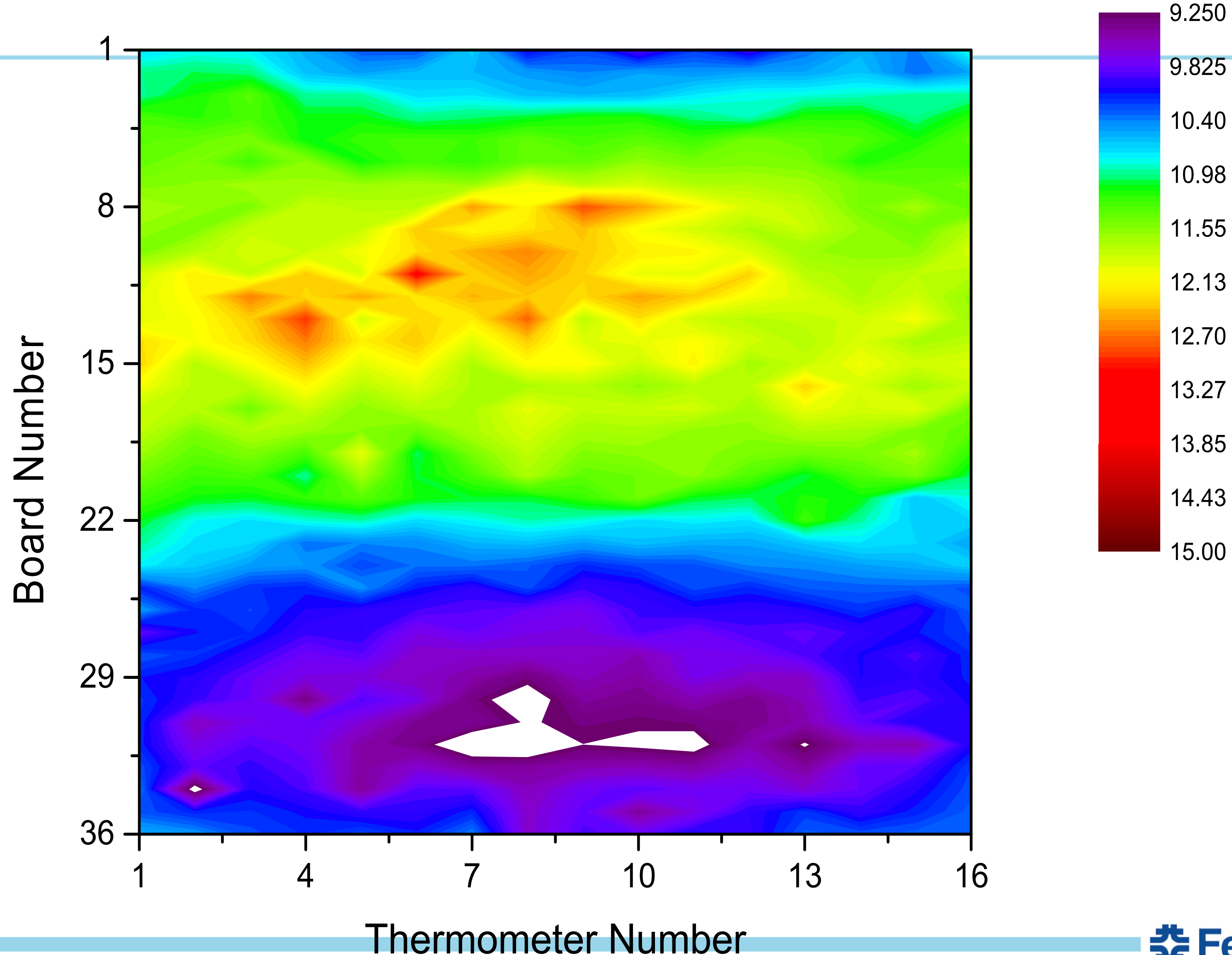
Fermilab

Fast Cool-down From 250K



Fermilab

Fast Cool-down From 250K



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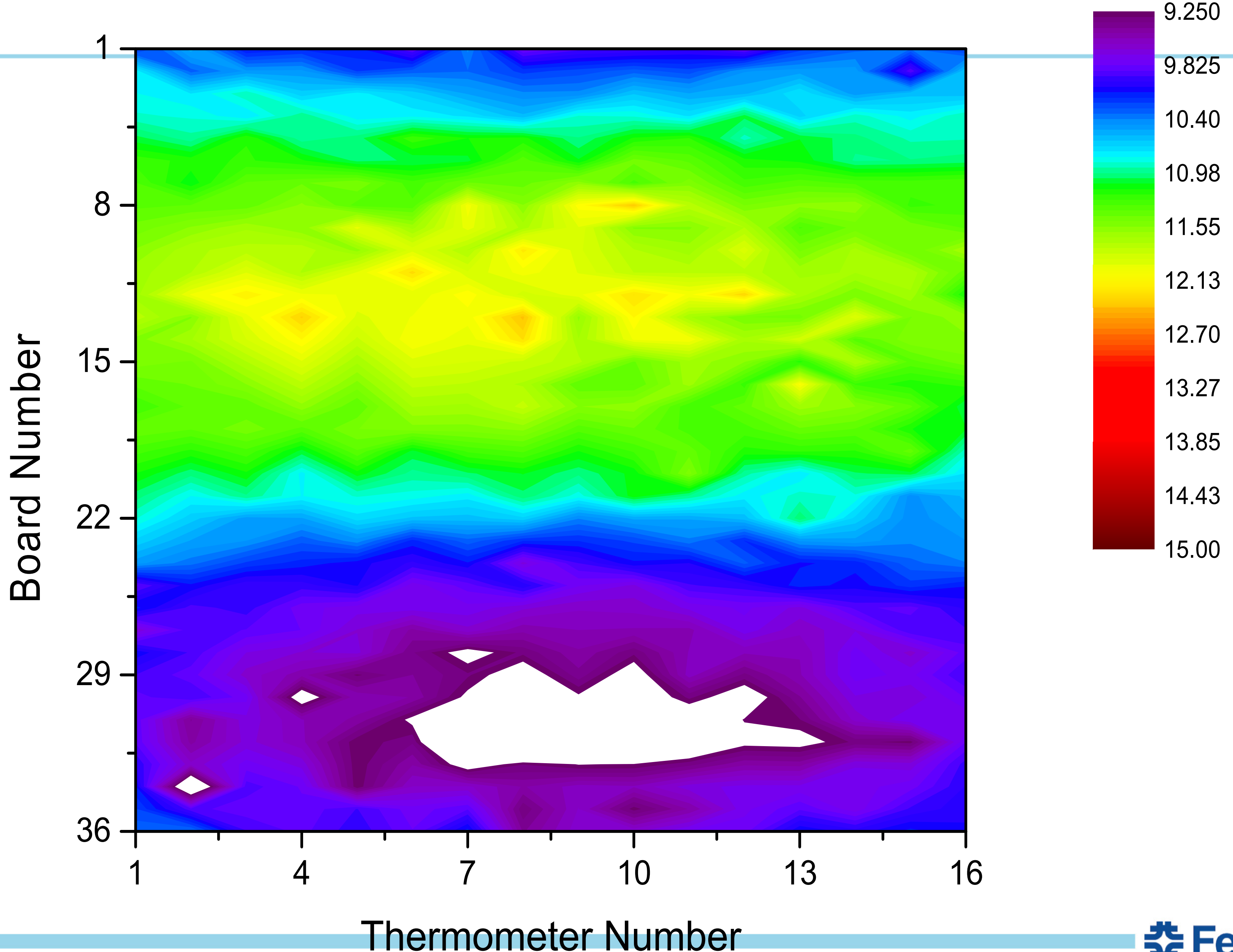
Fast Cool-down From 250K



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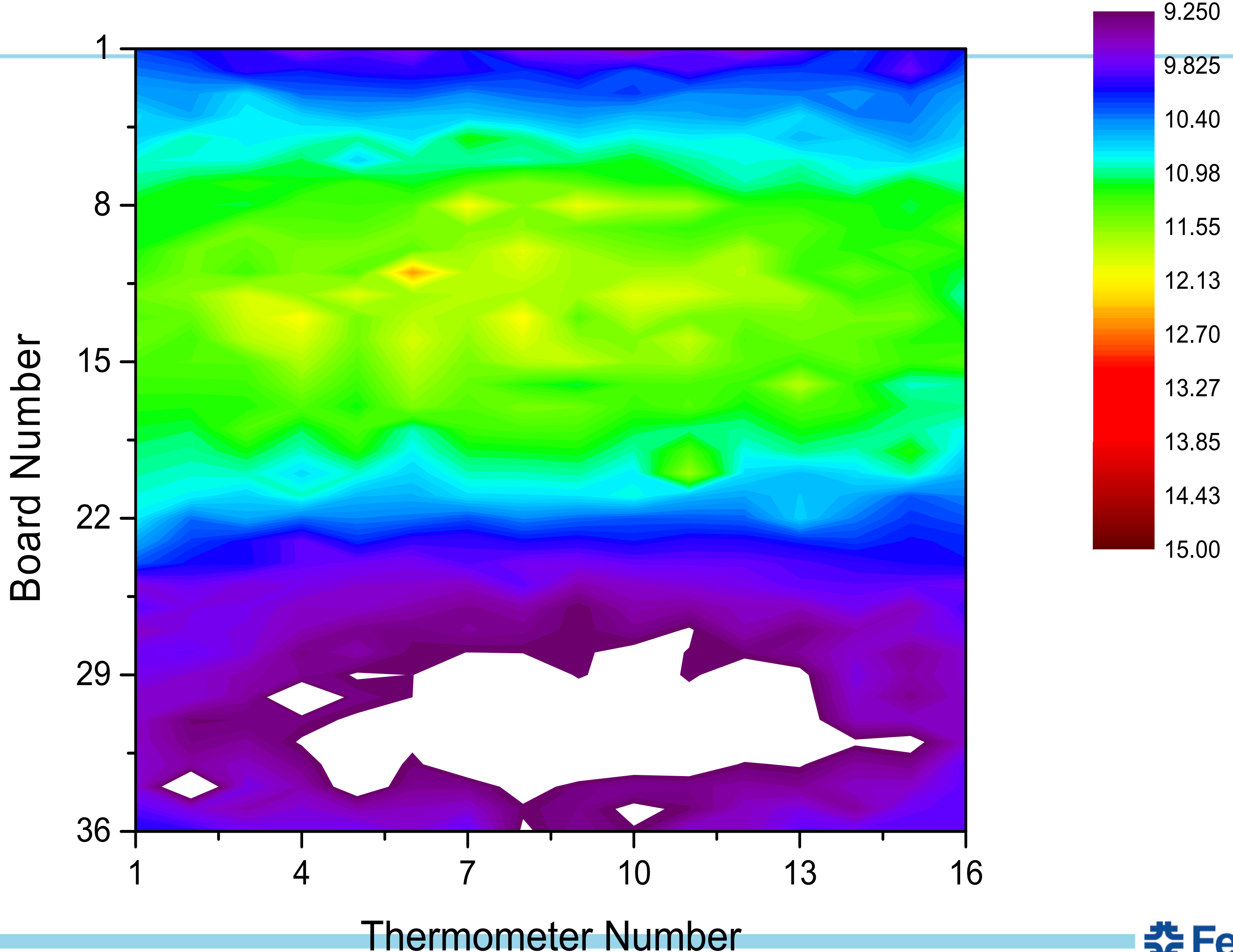

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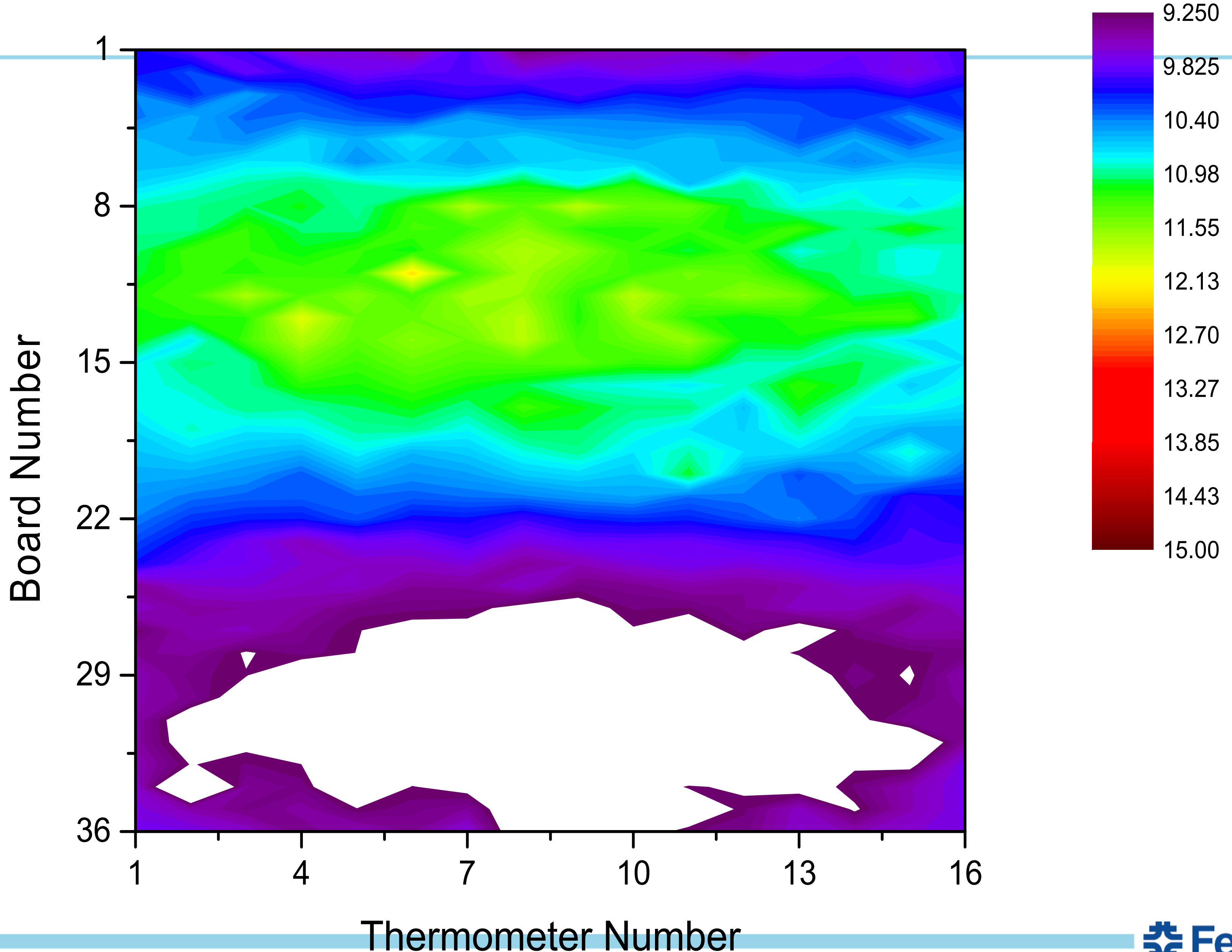
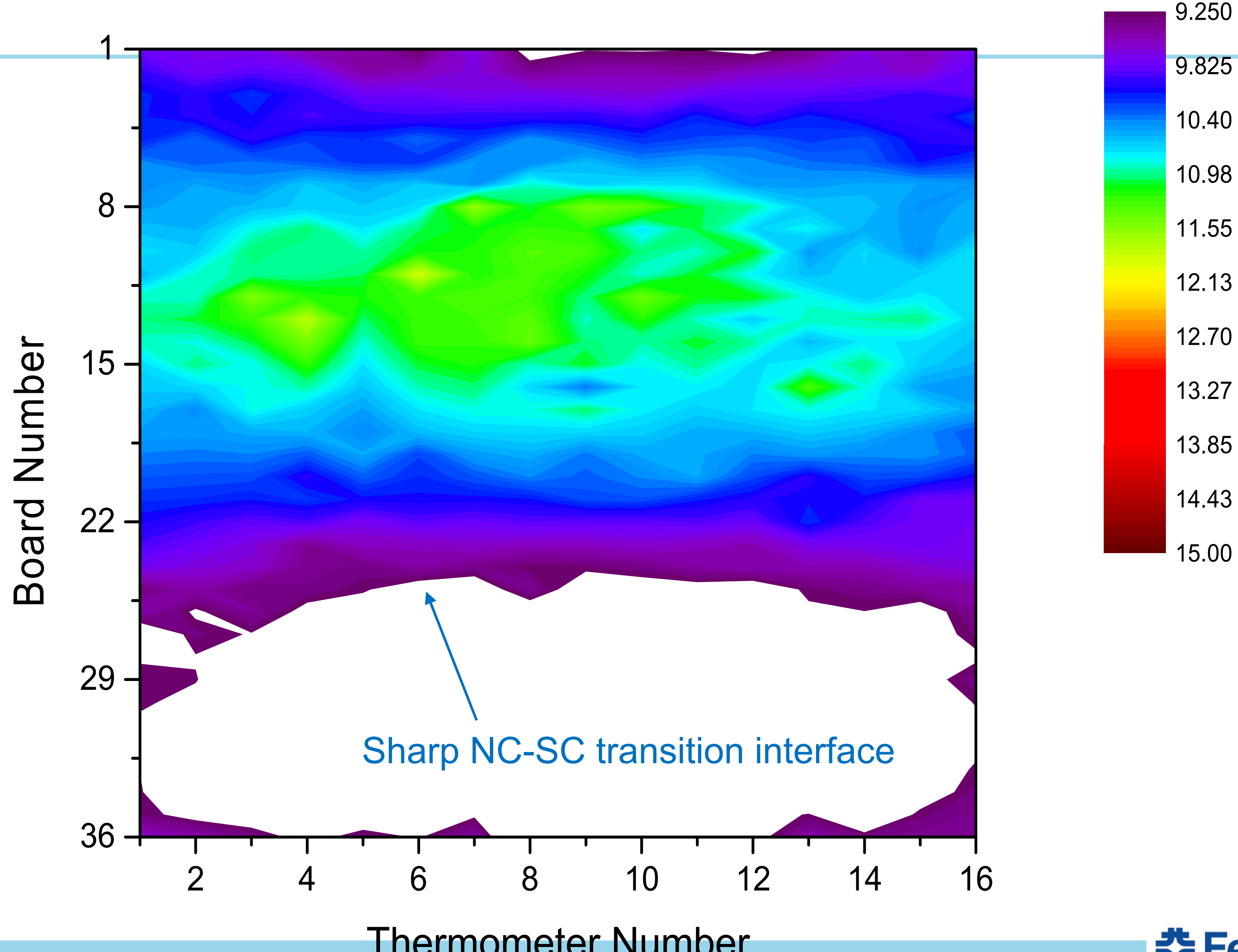
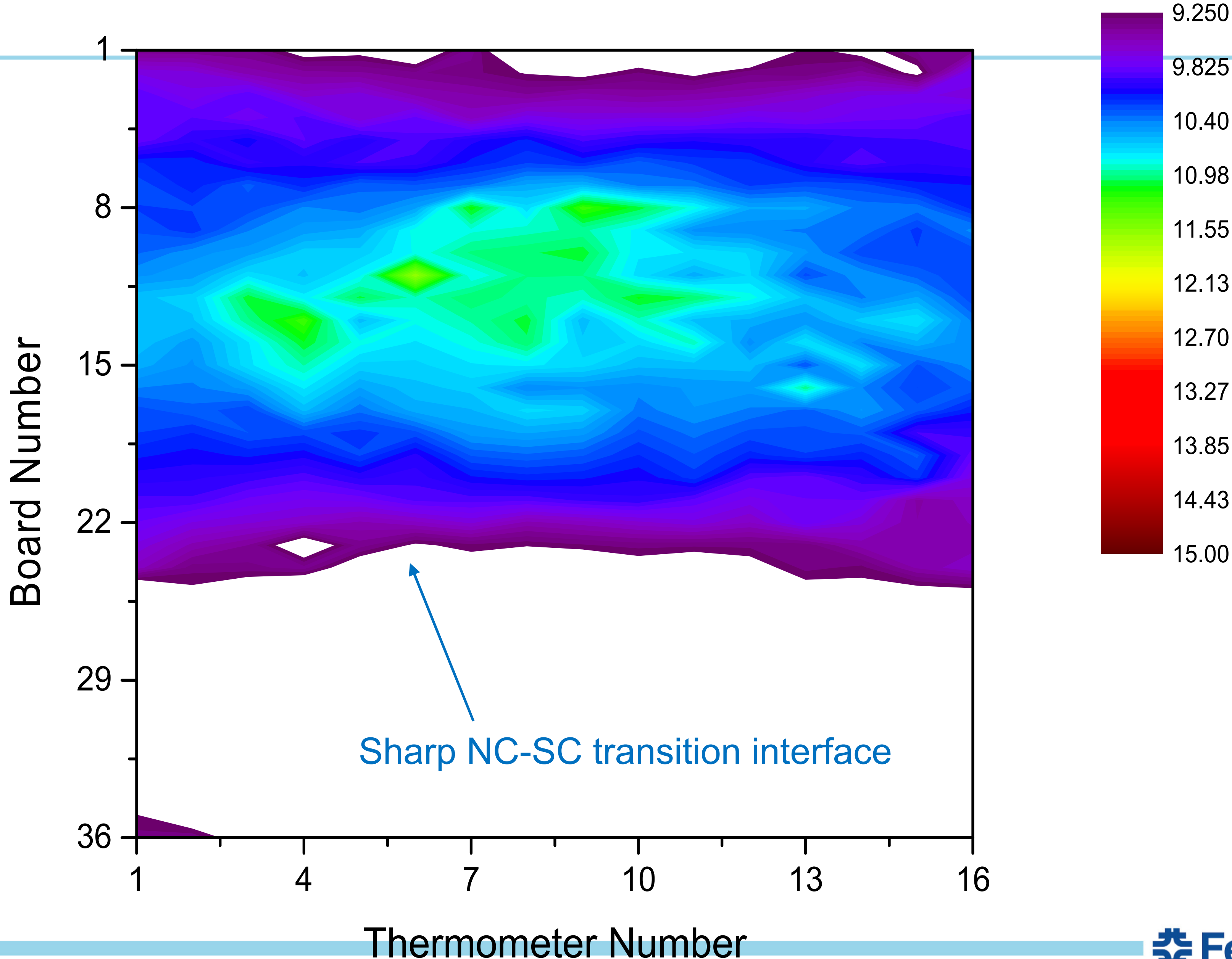


Fast Cool-down From 250K



Fermilab

Fast Cool-down From 250K



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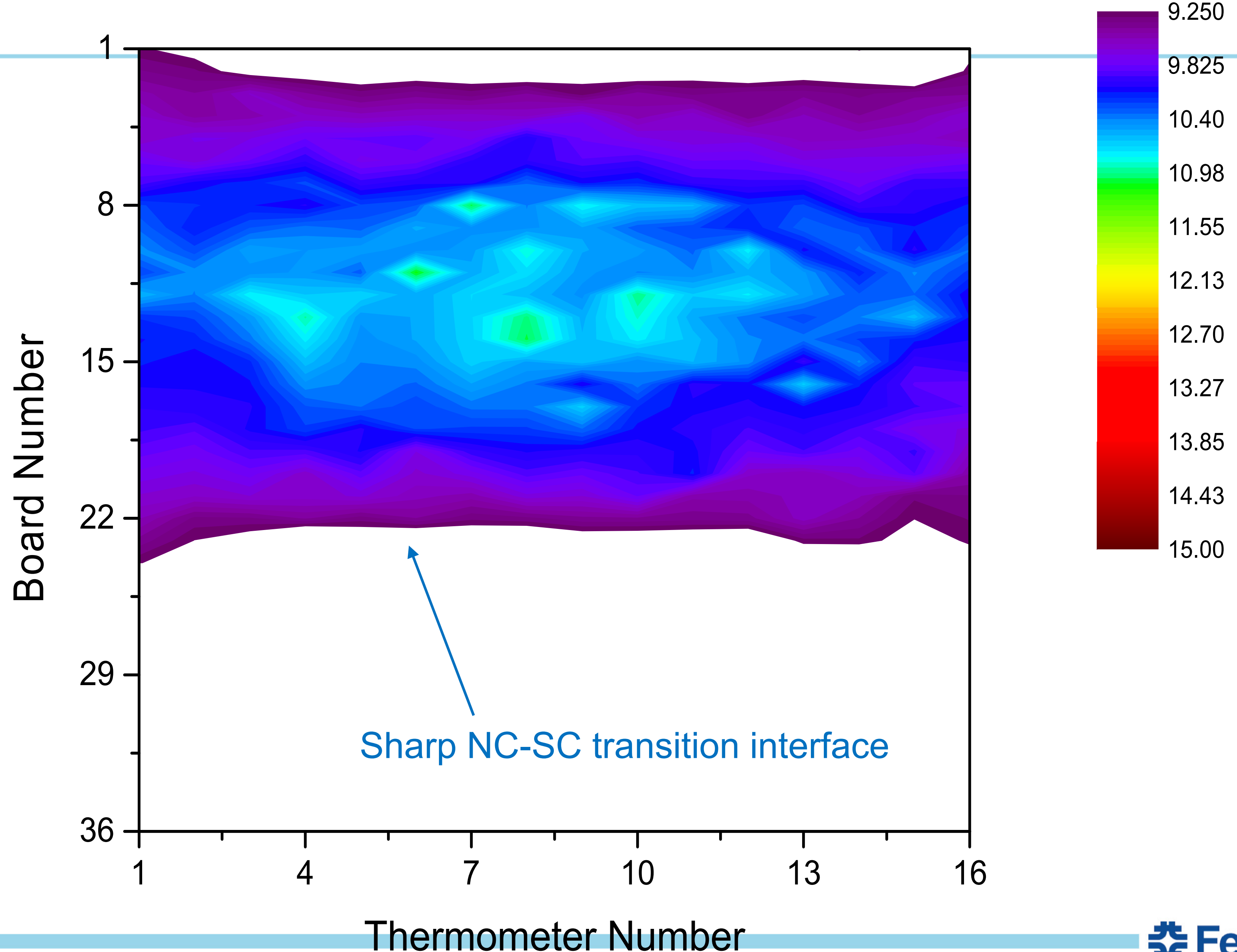
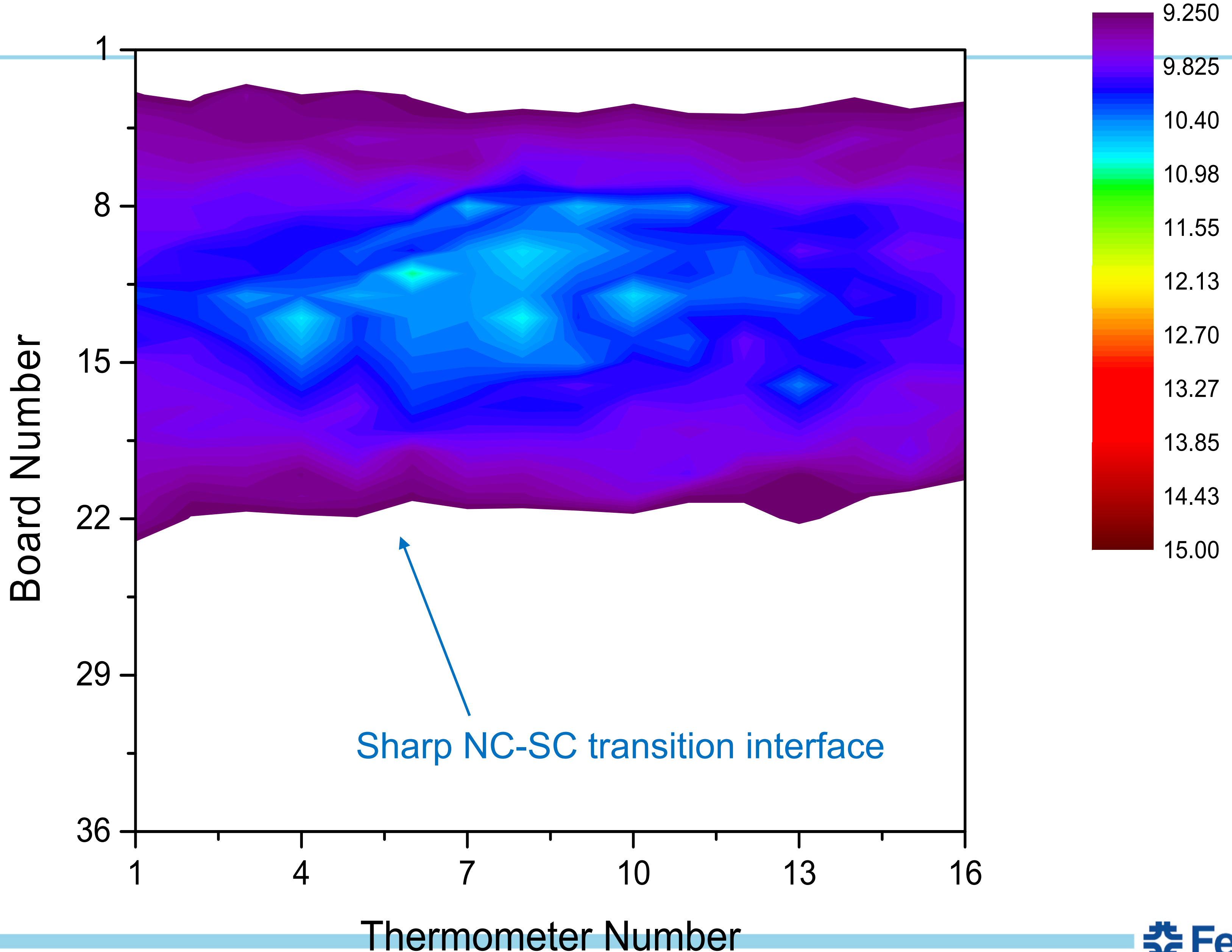


Fermilab

Fast Cool-down From 250K



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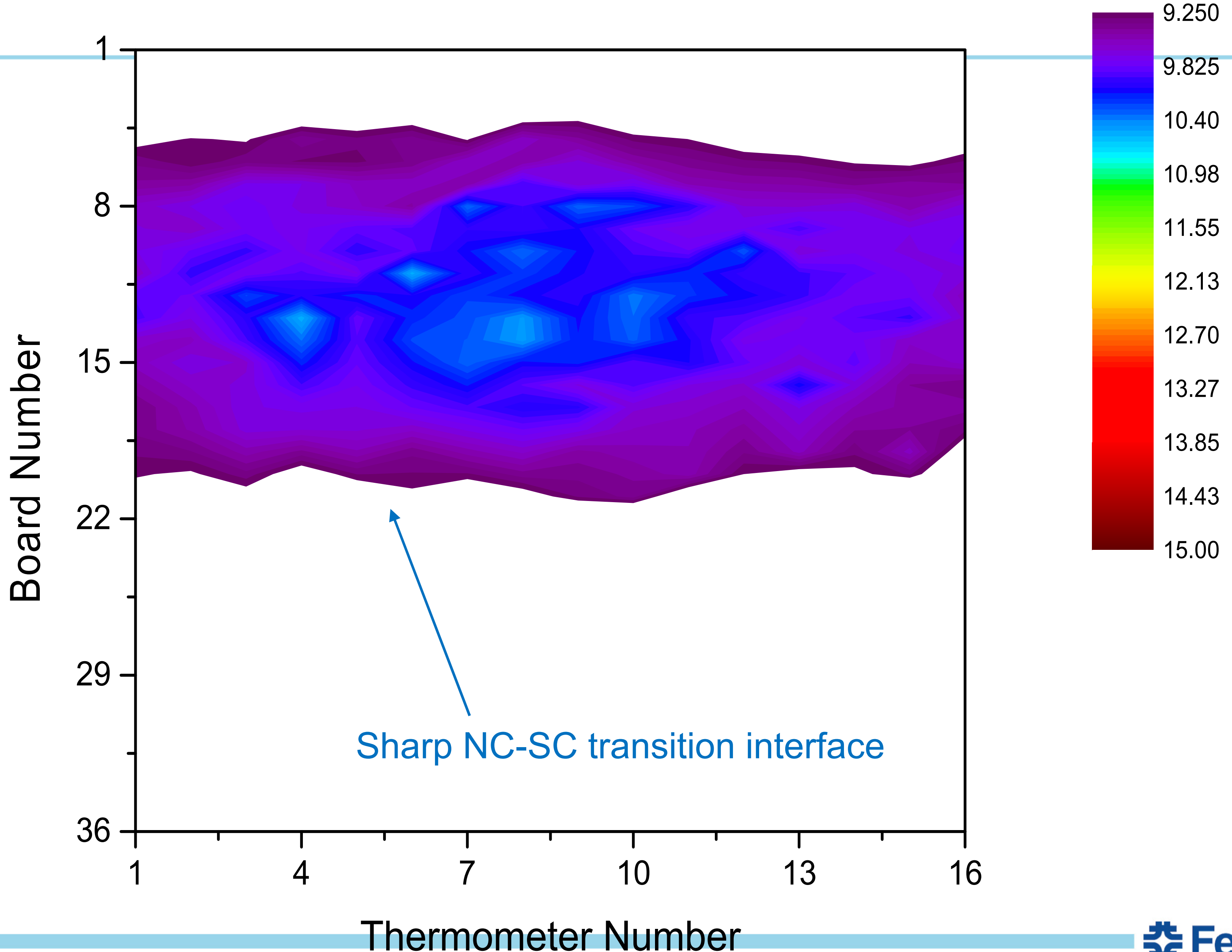

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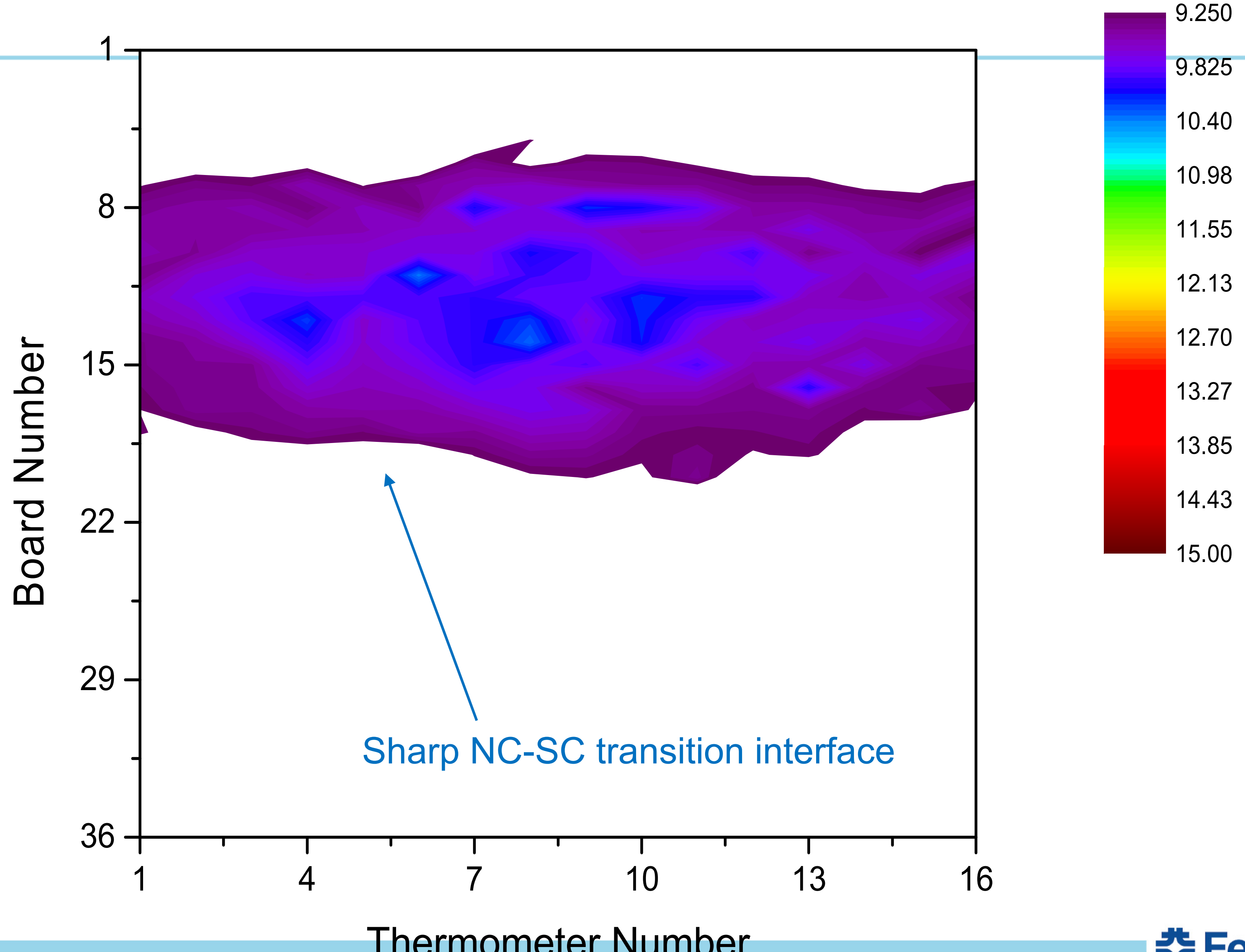
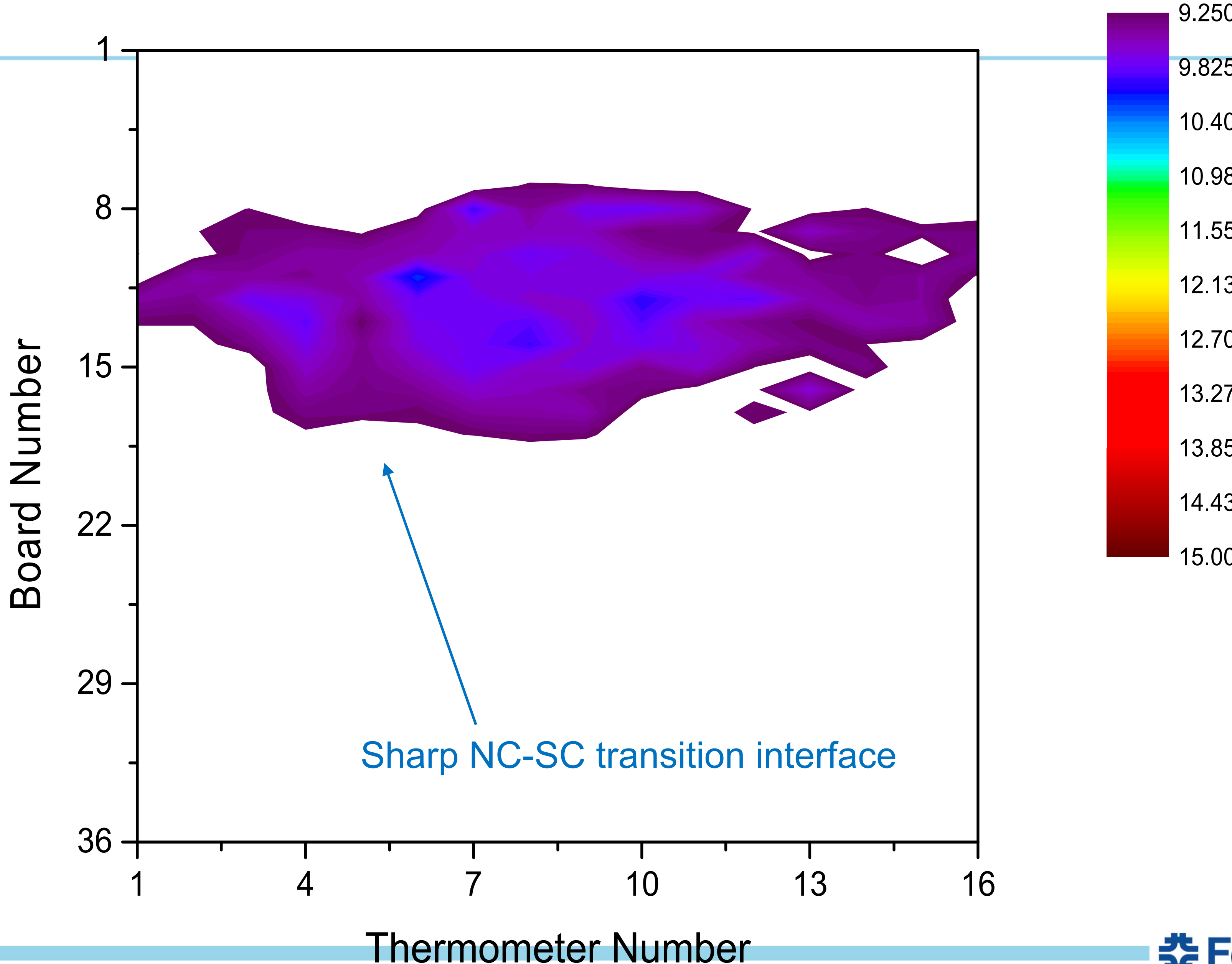
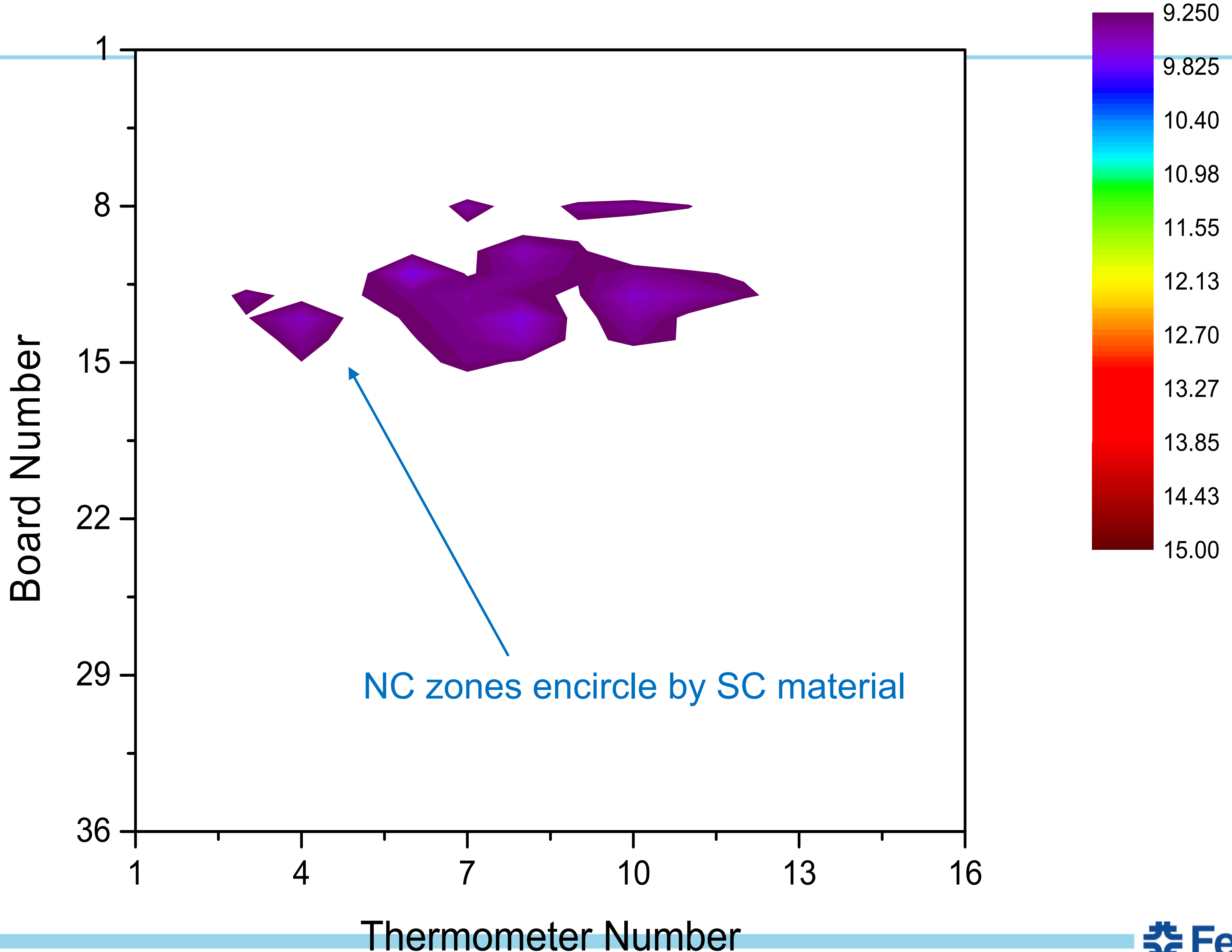


Fermilab

Fast Cool-down From 250K



Fast Cool-down From 250K



Fermilab

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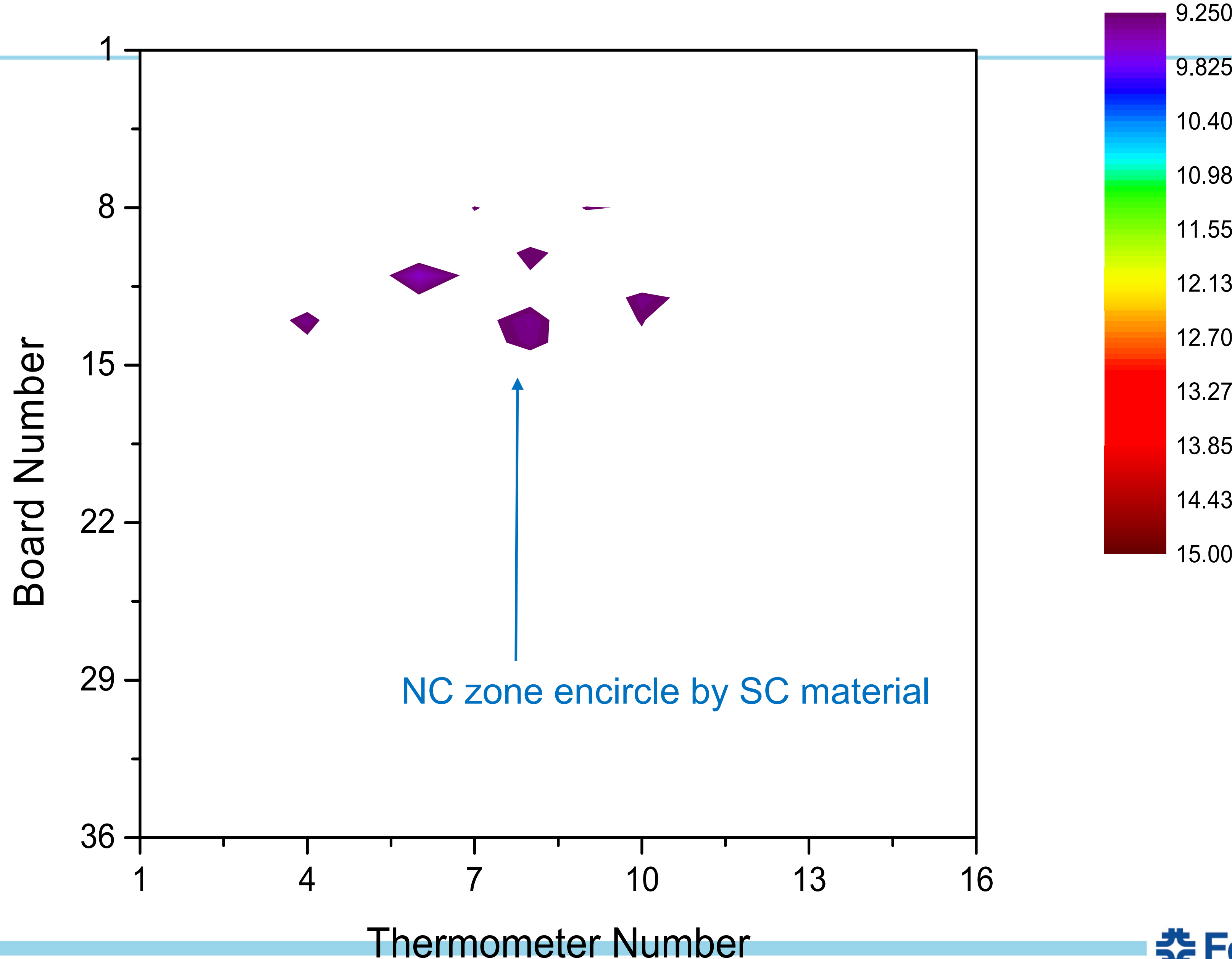

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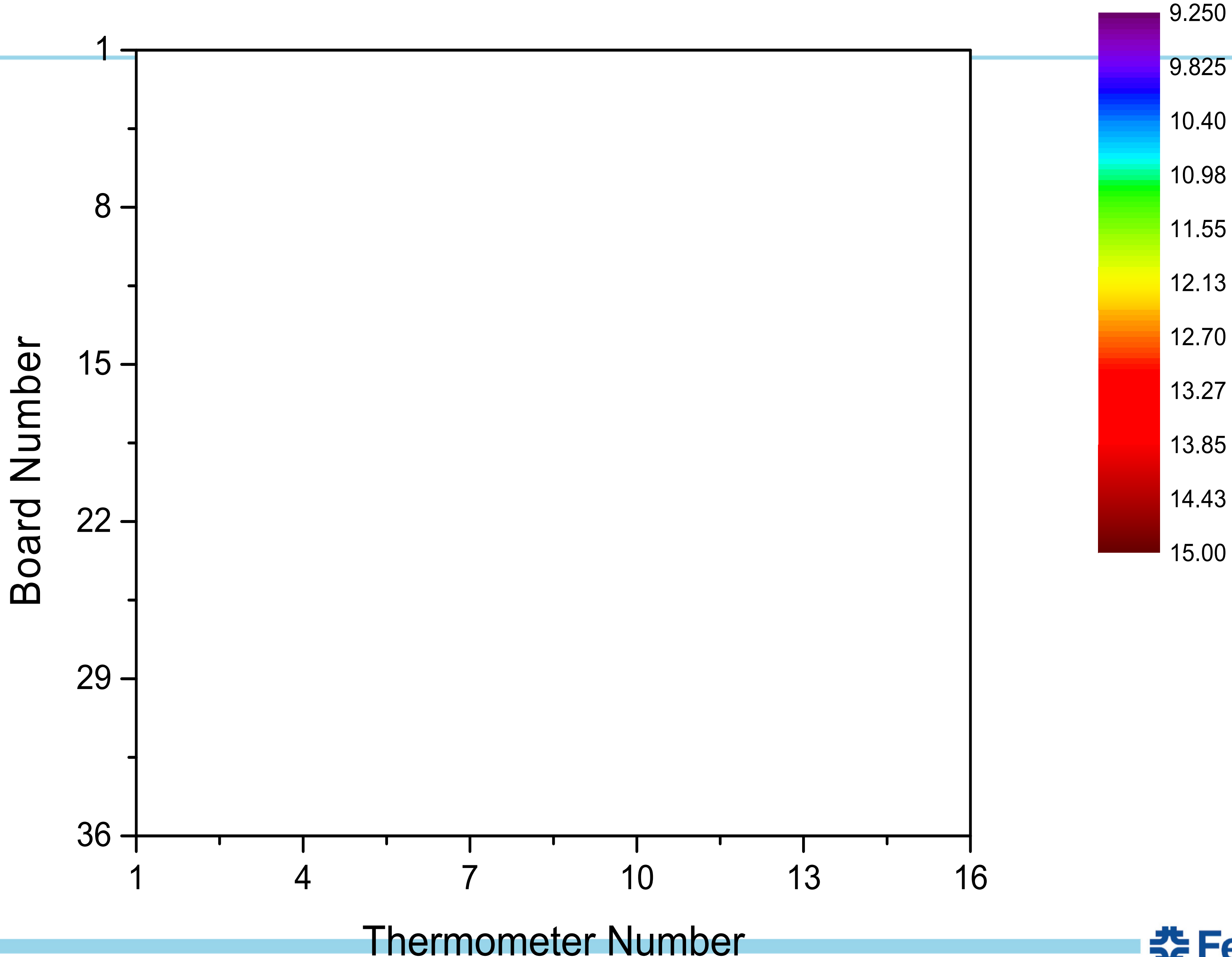
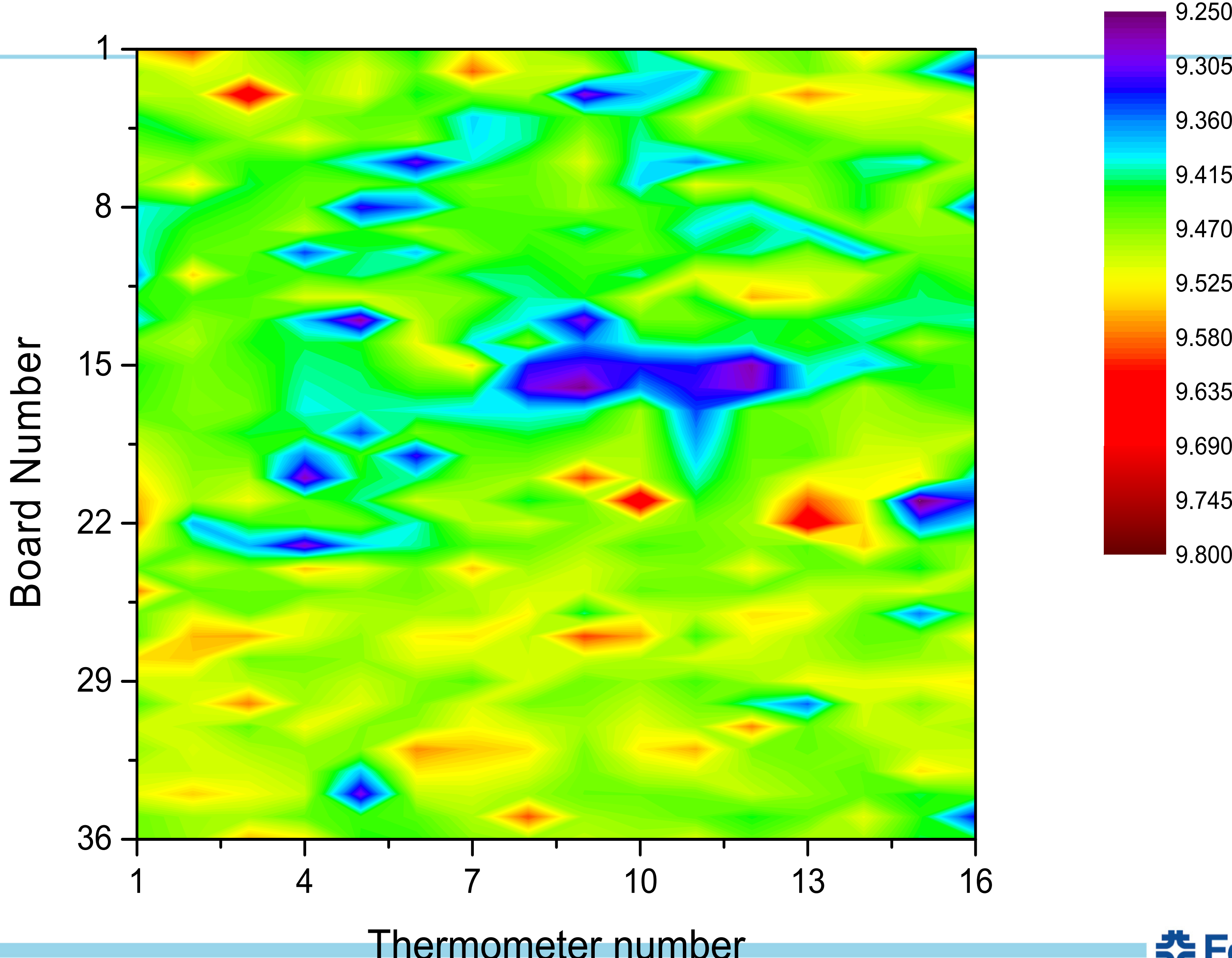


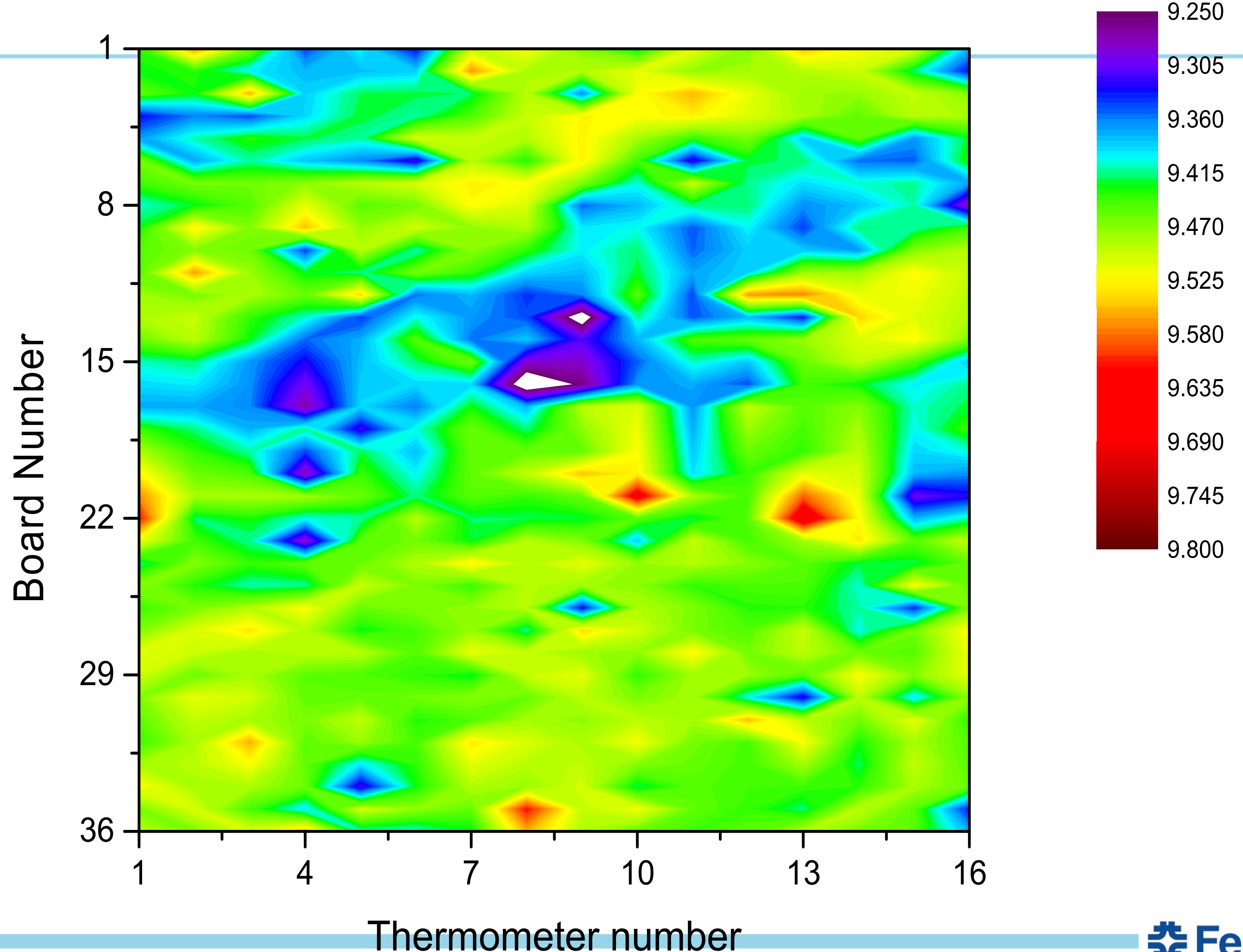
Slow Cool-down T-map

Starting T: 12K

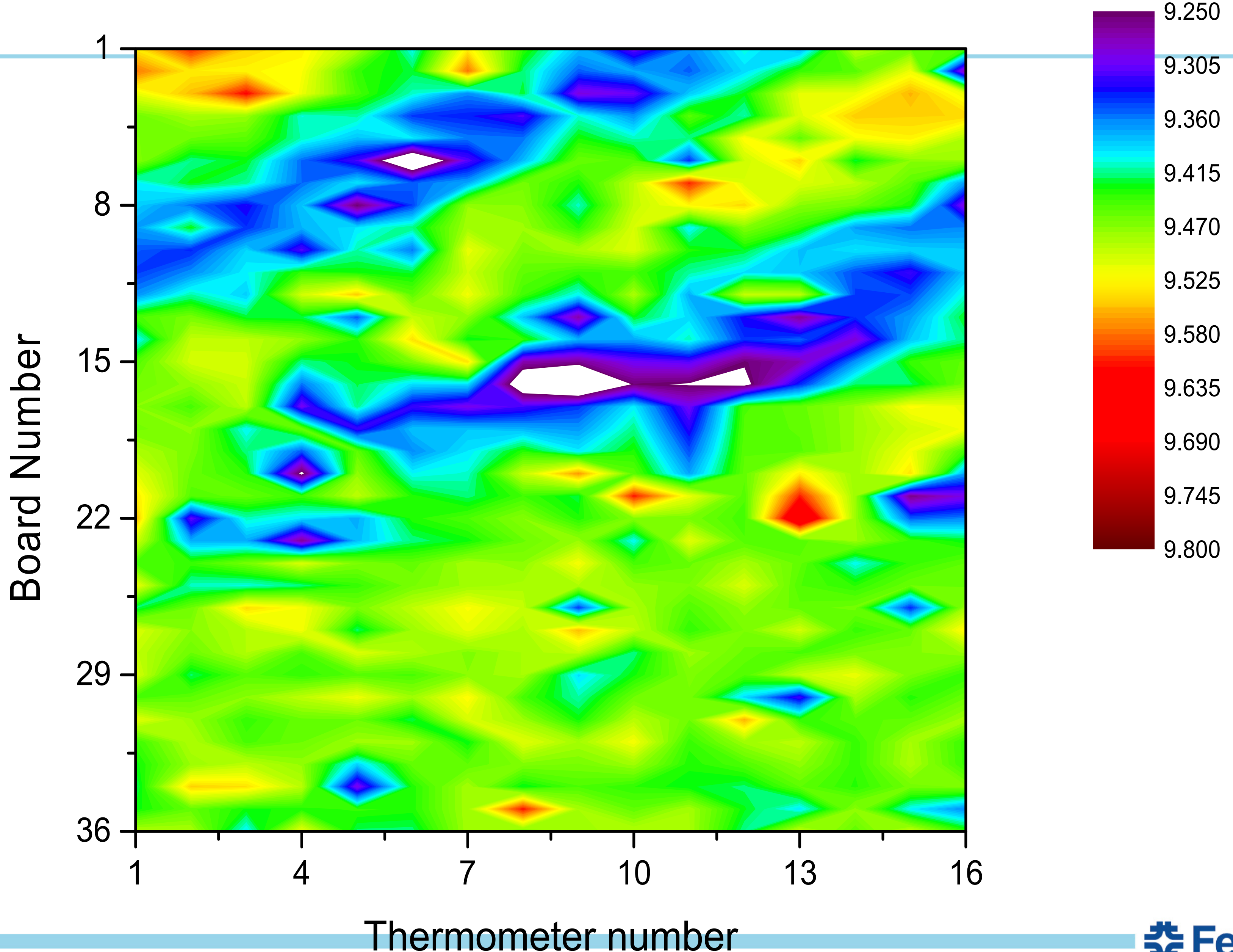
Slow Cool-down From 12K



Slow Cool-down From 12K



Slow Cool-down From 12K



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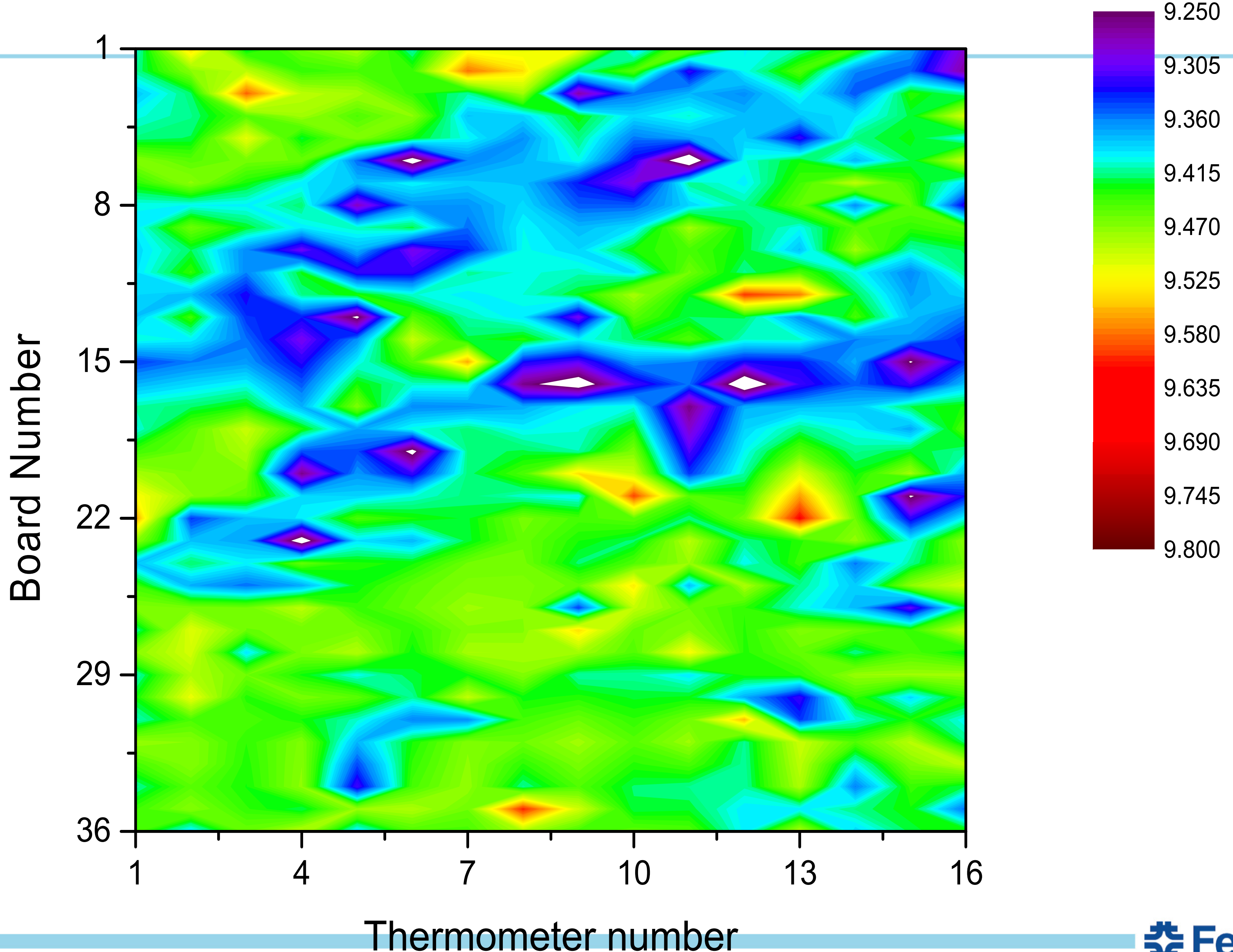

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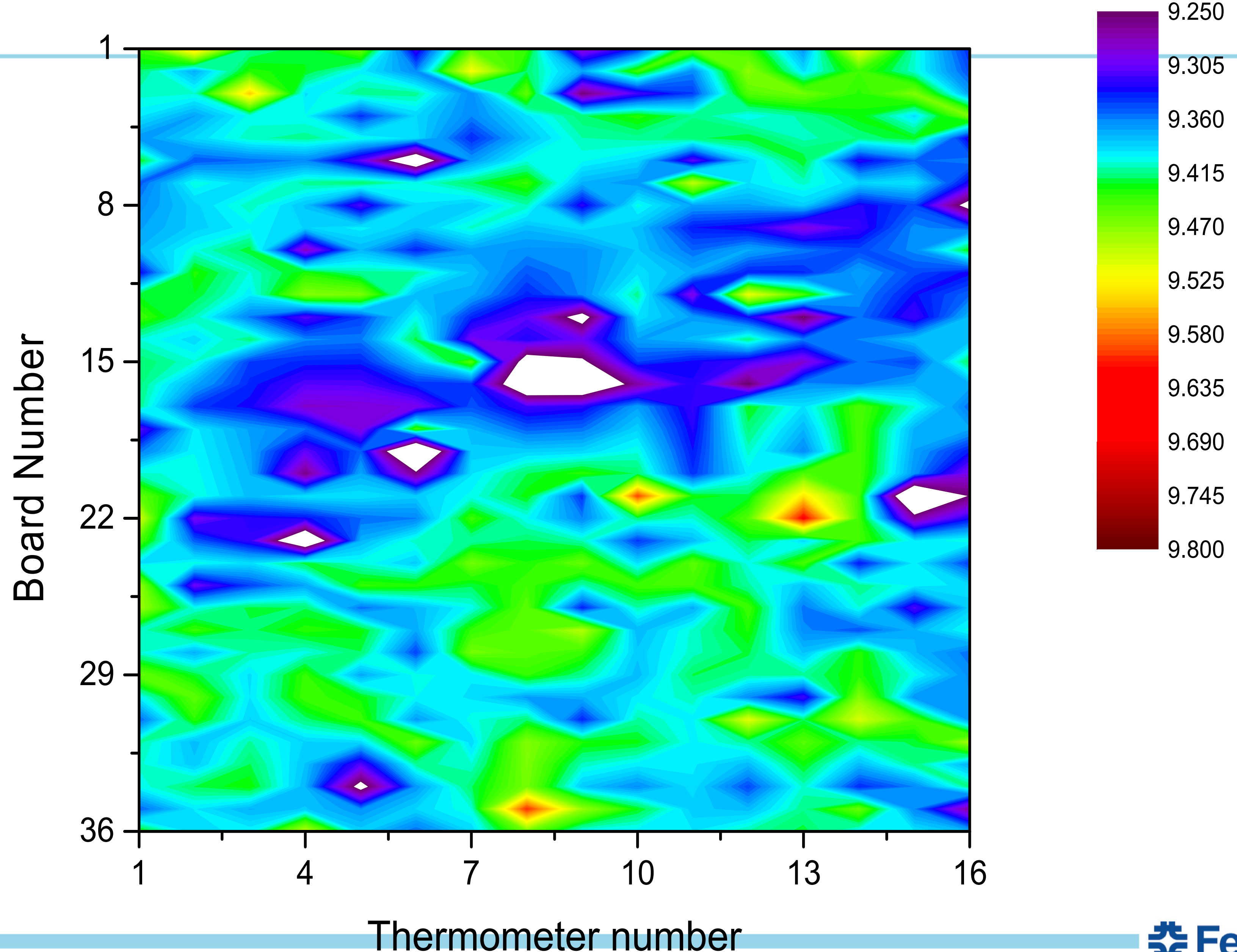

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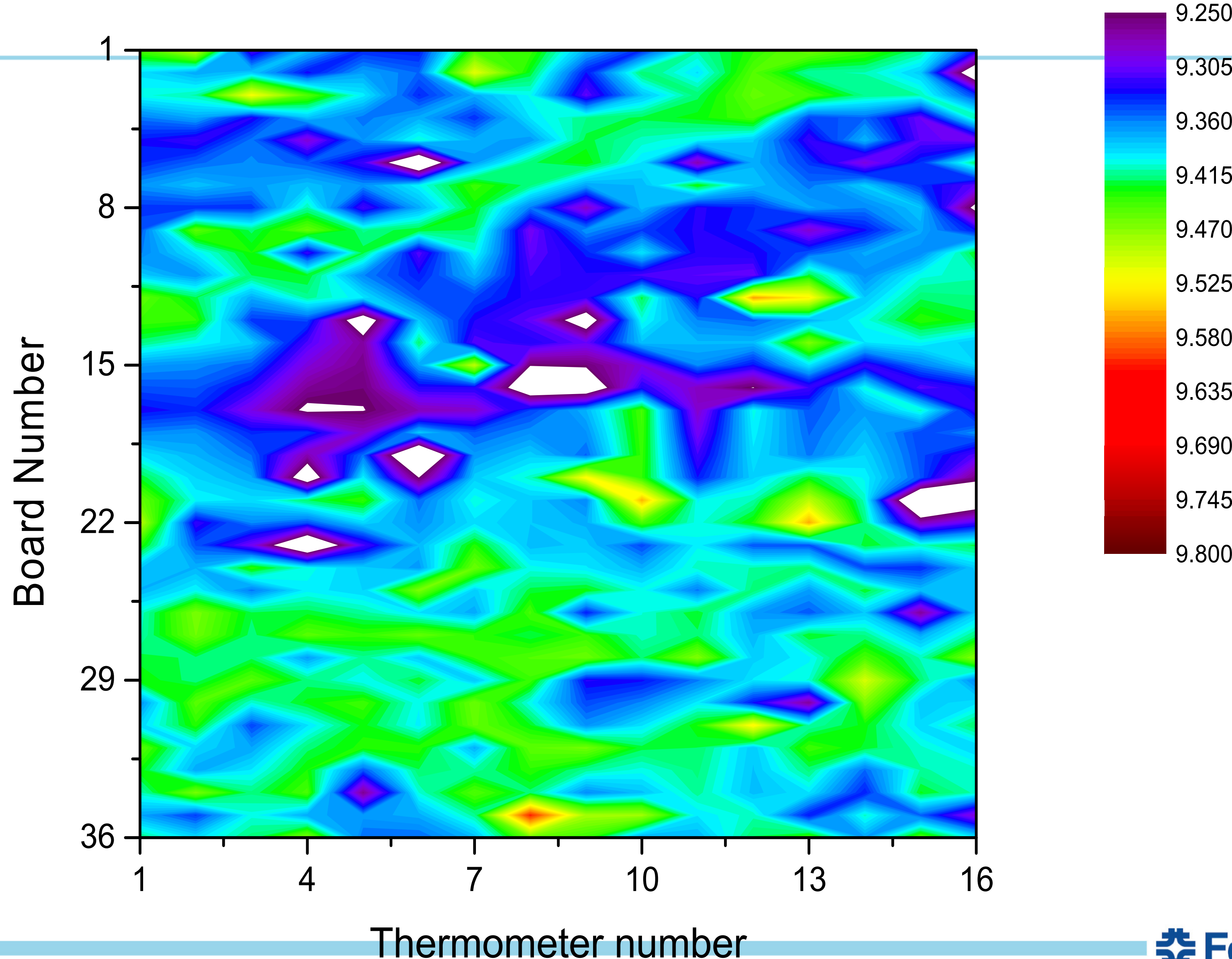

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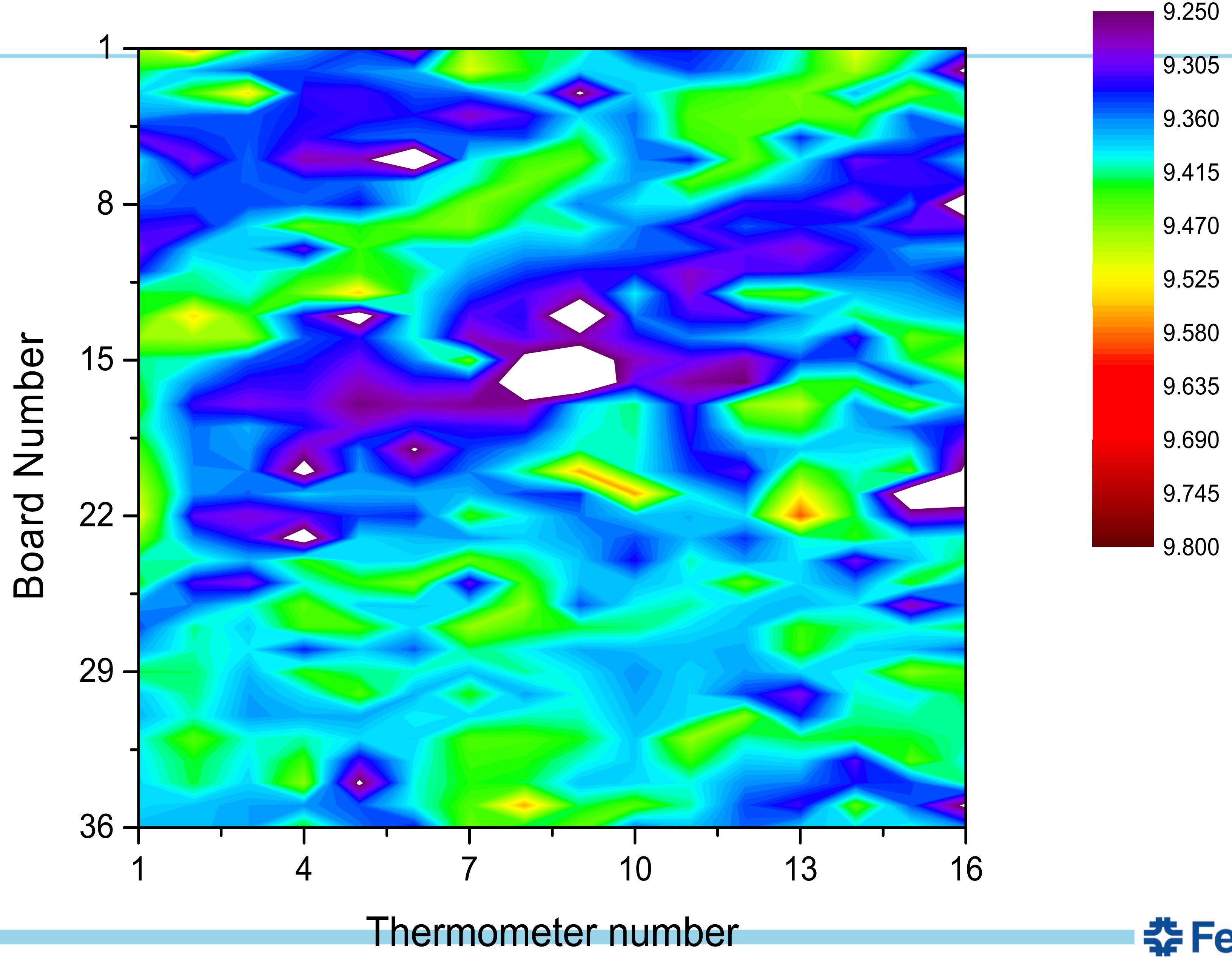

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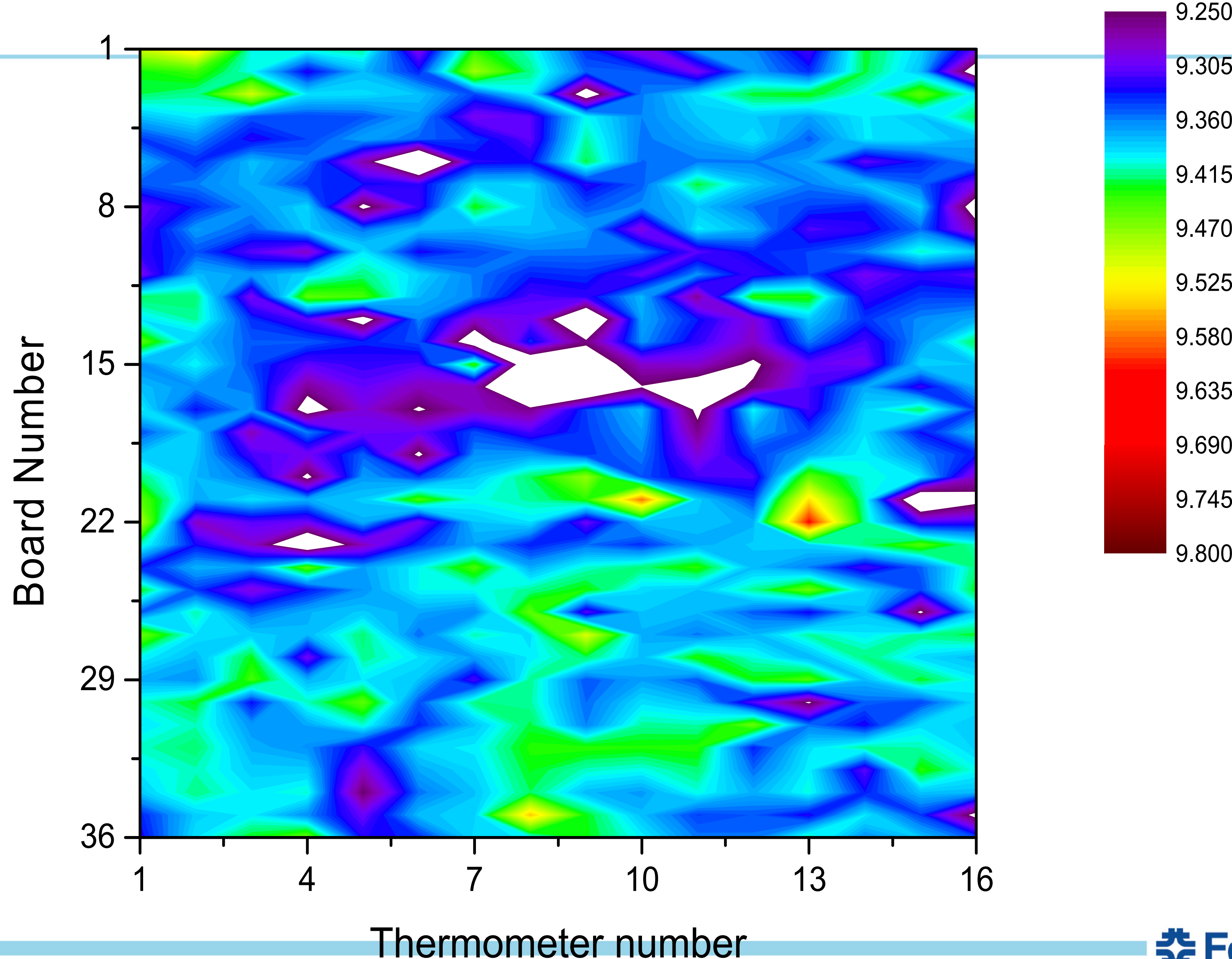
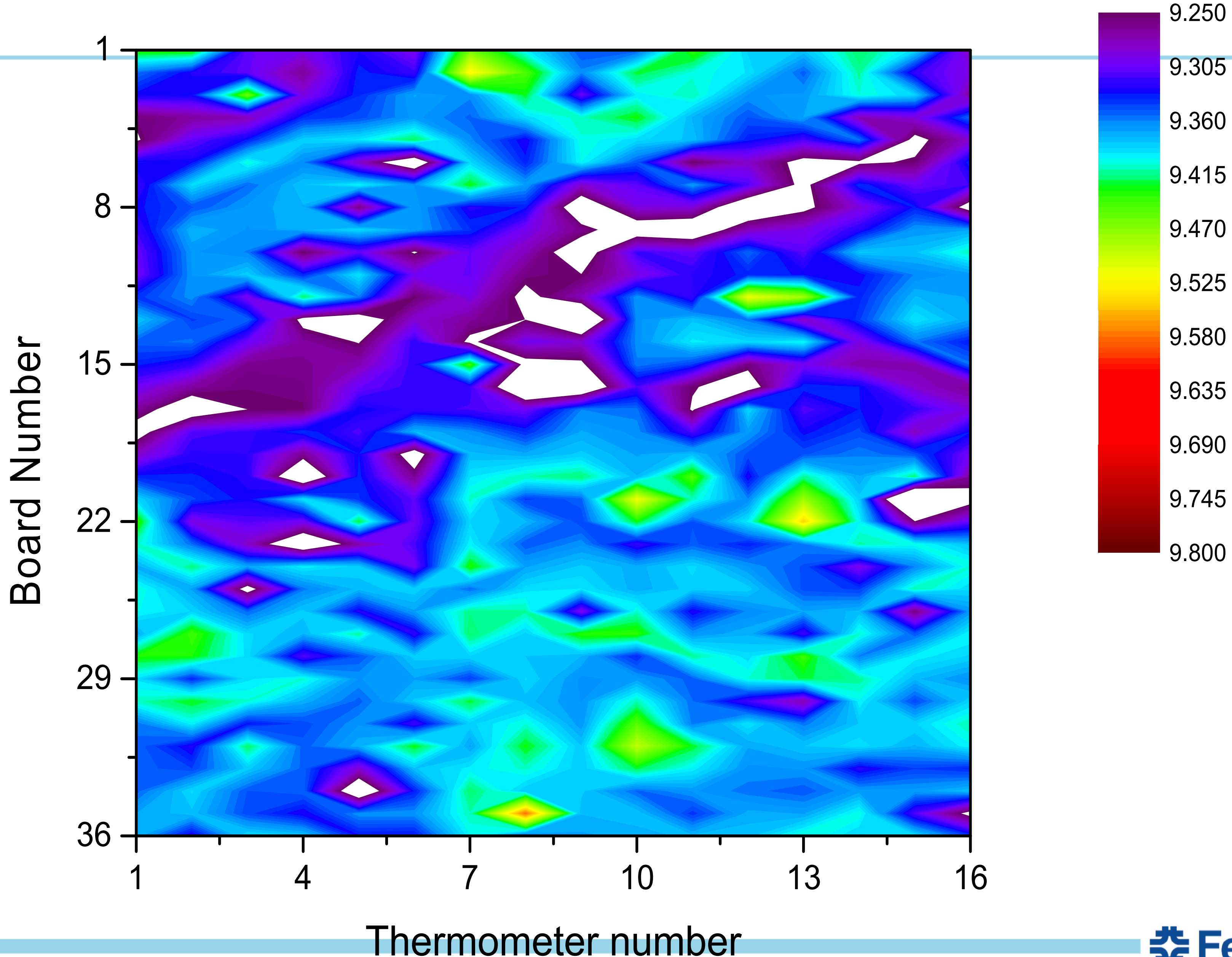


Fermilab

Slow Cool-down From 12K



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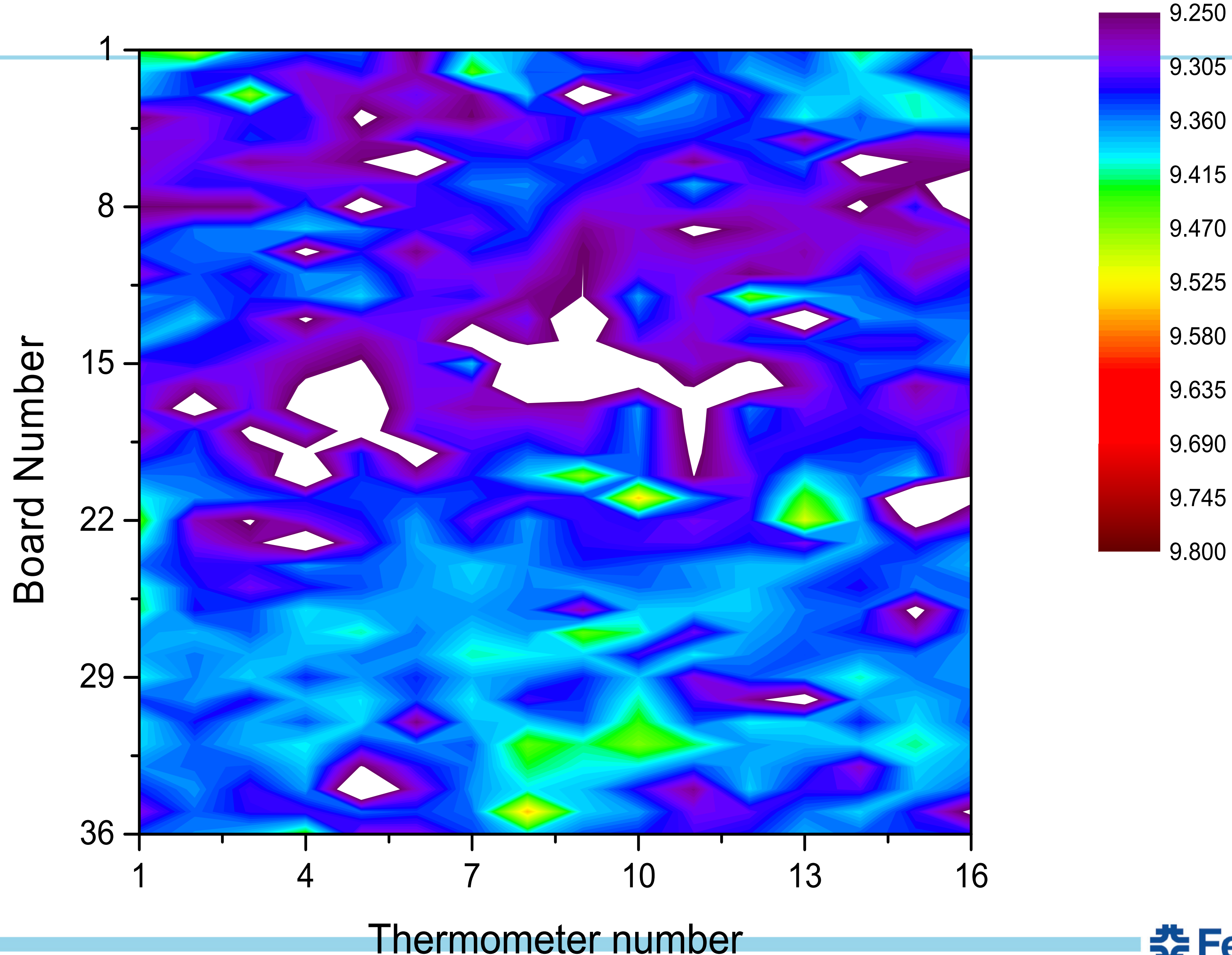
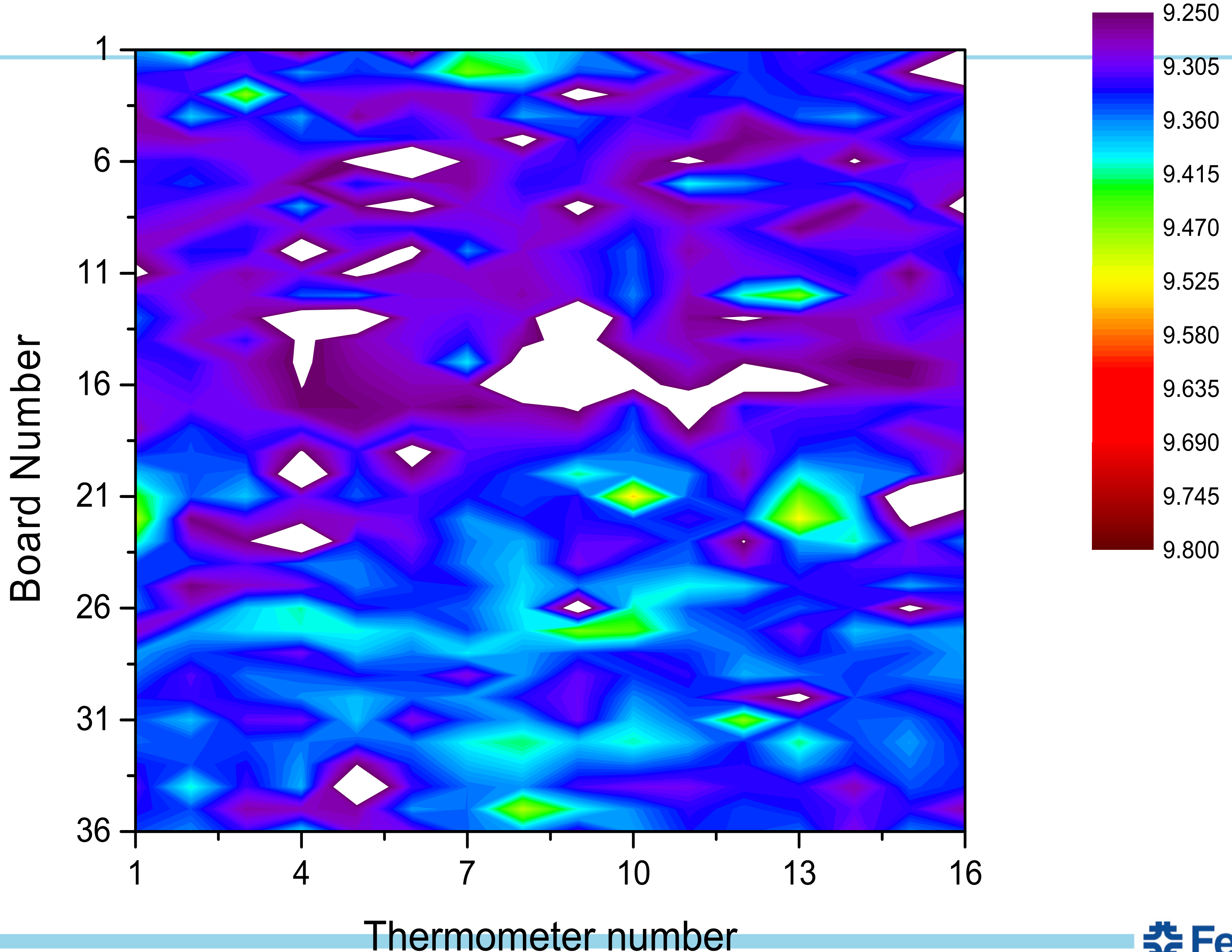


Slow Cool-down From 12K



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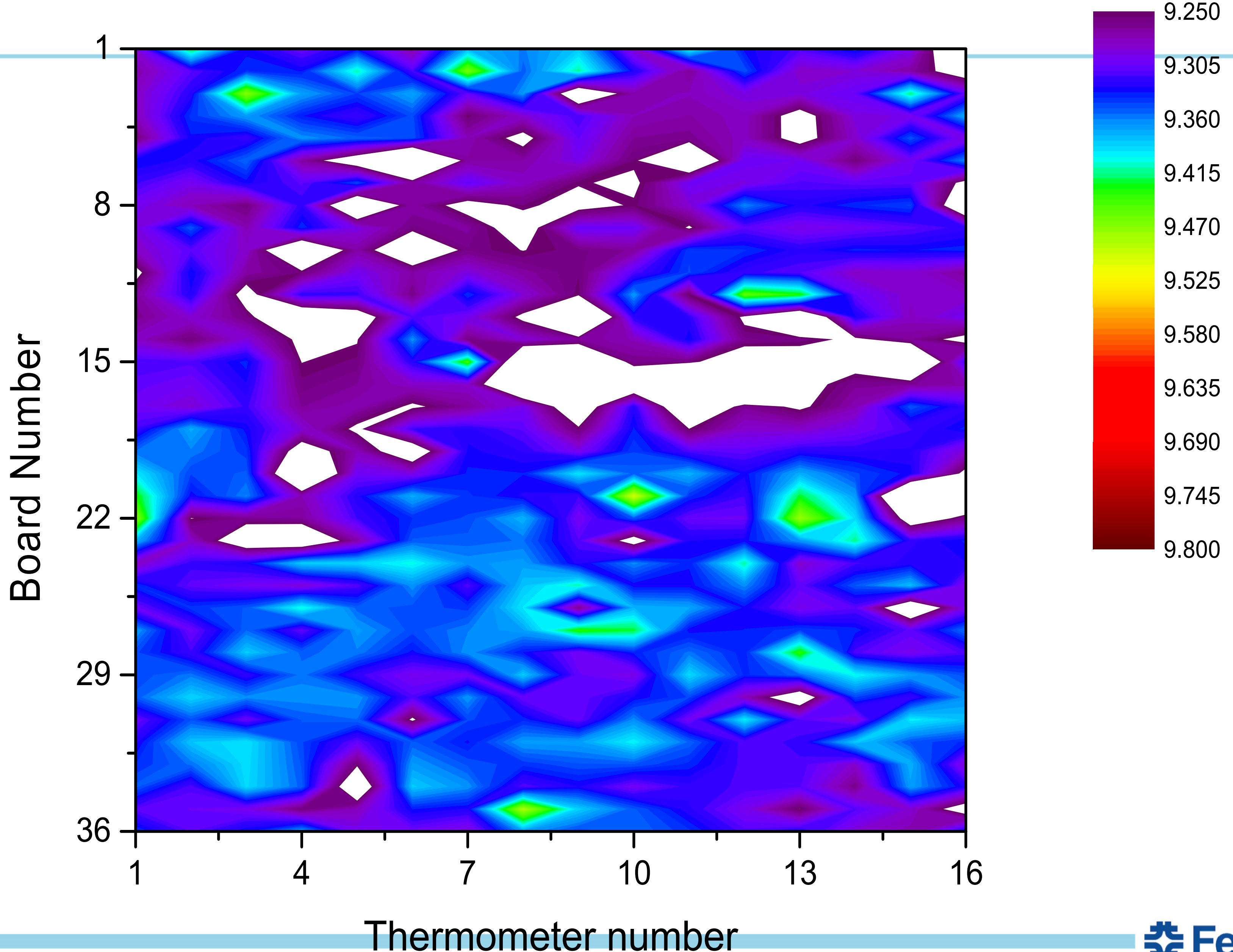

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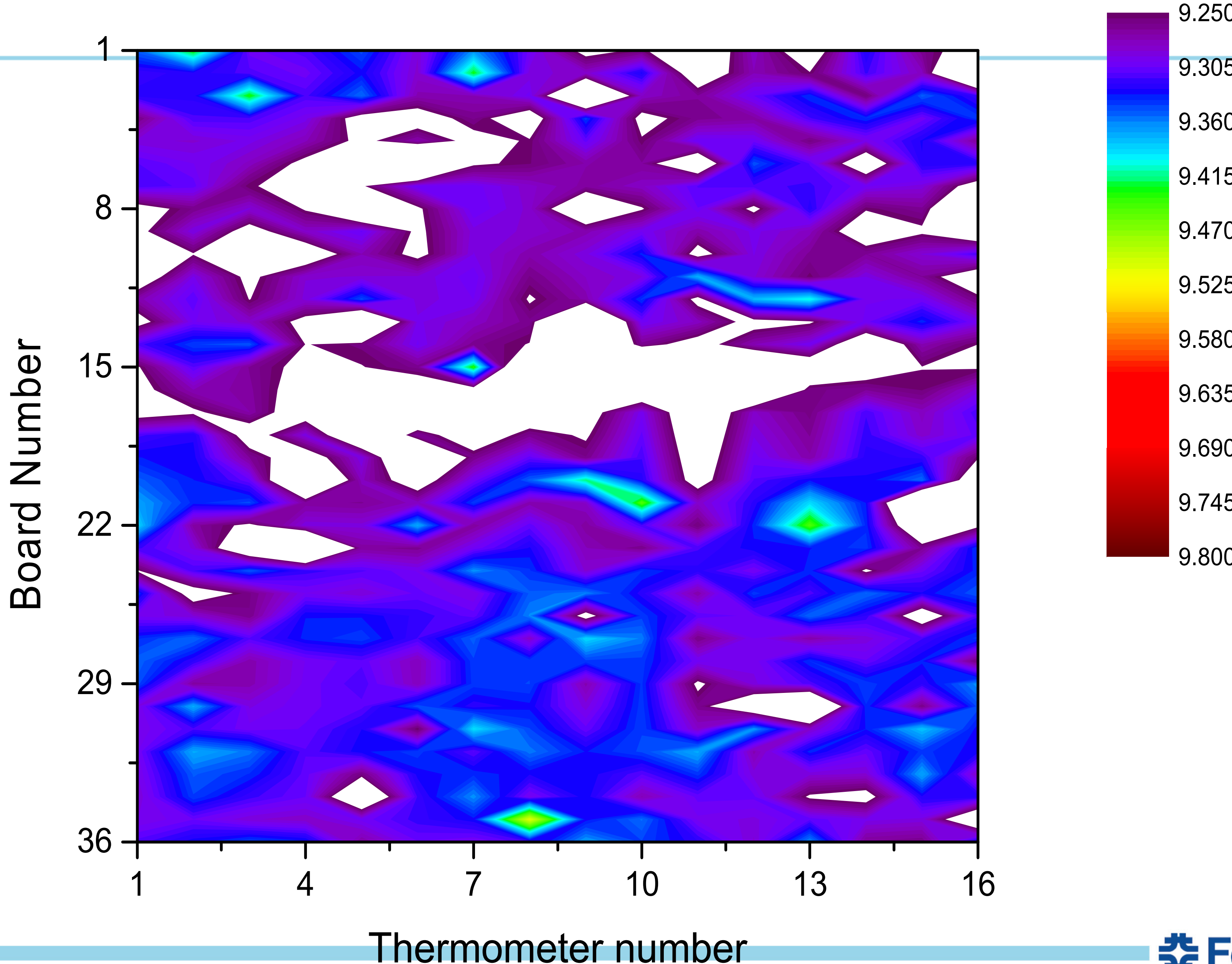

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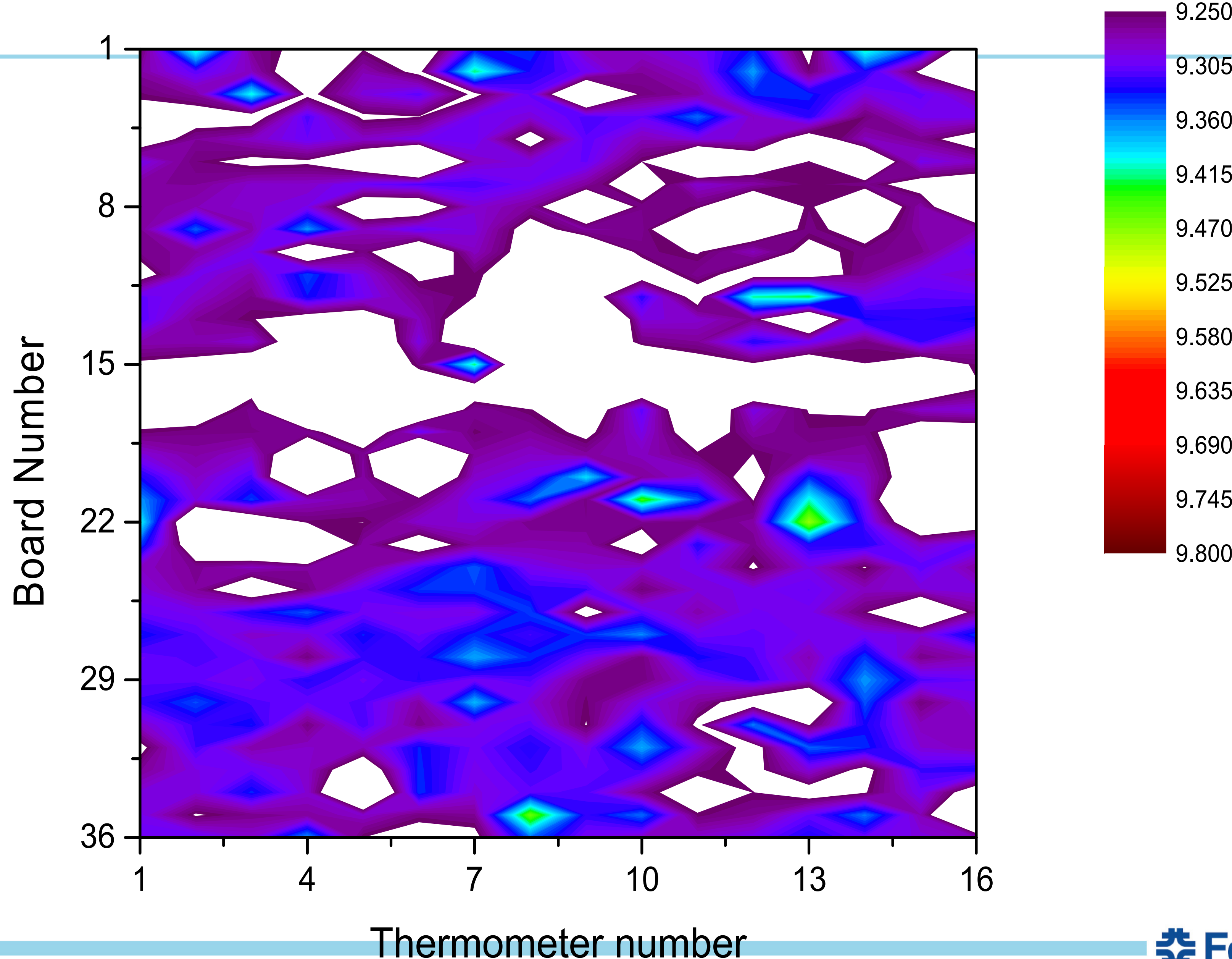

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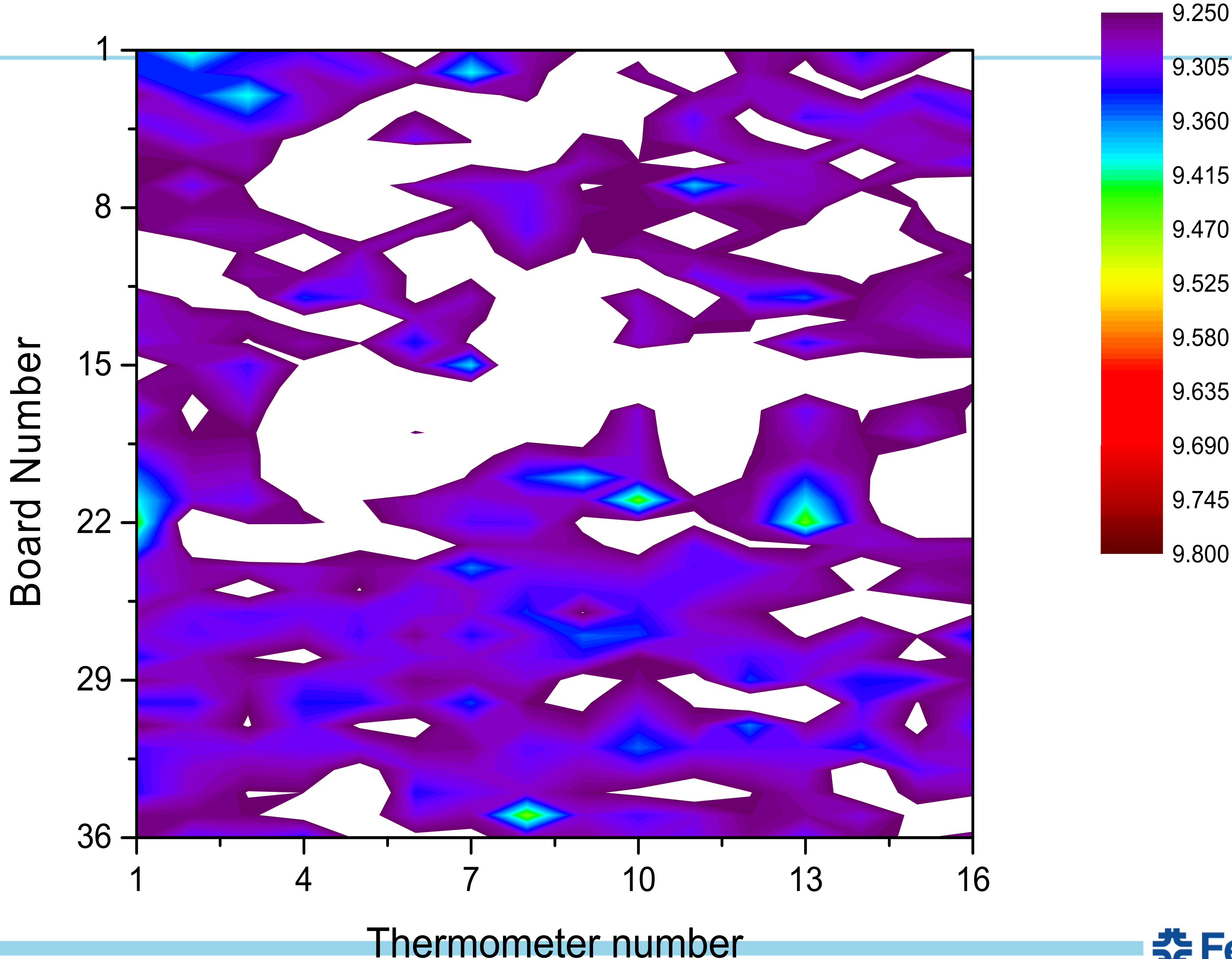

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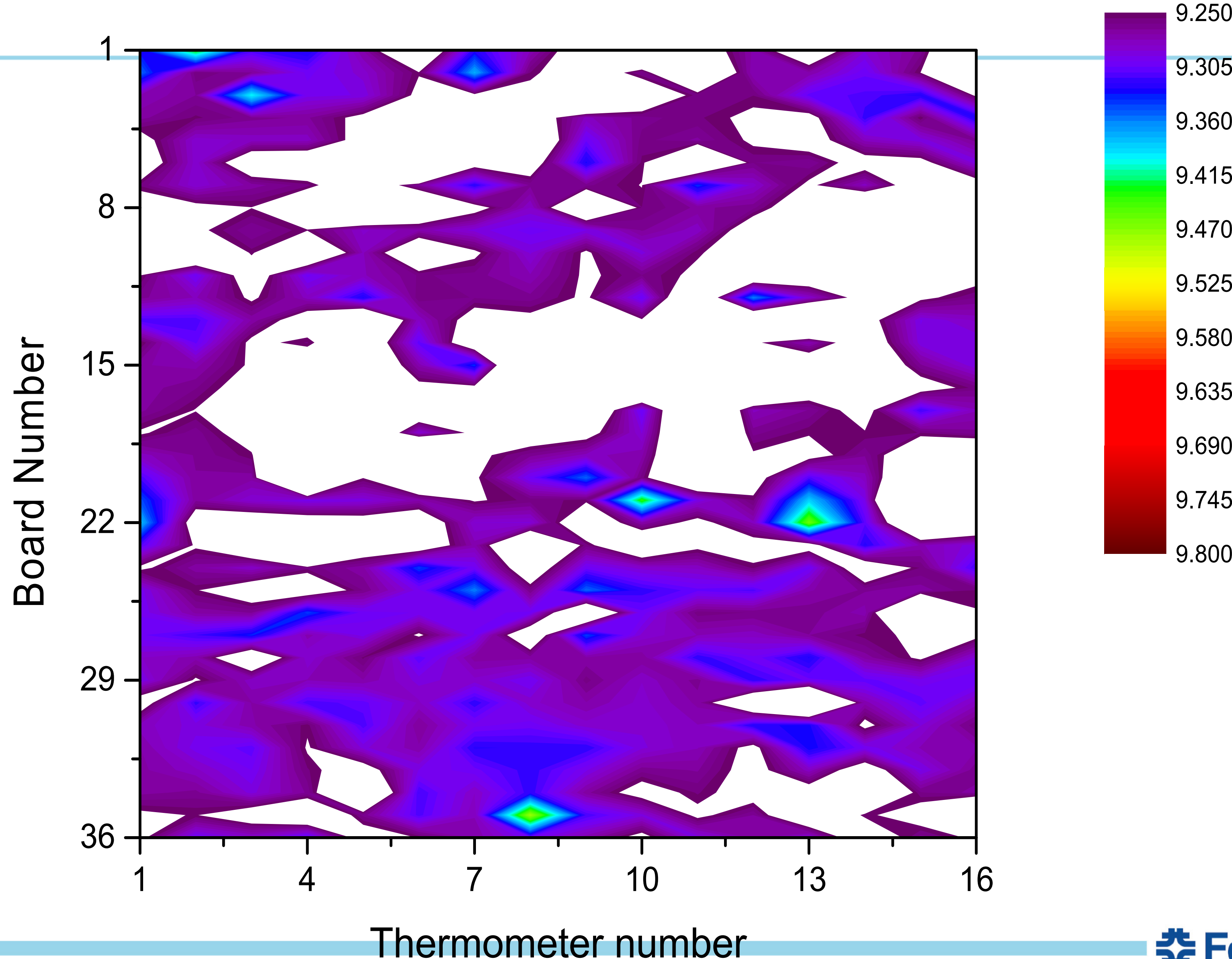

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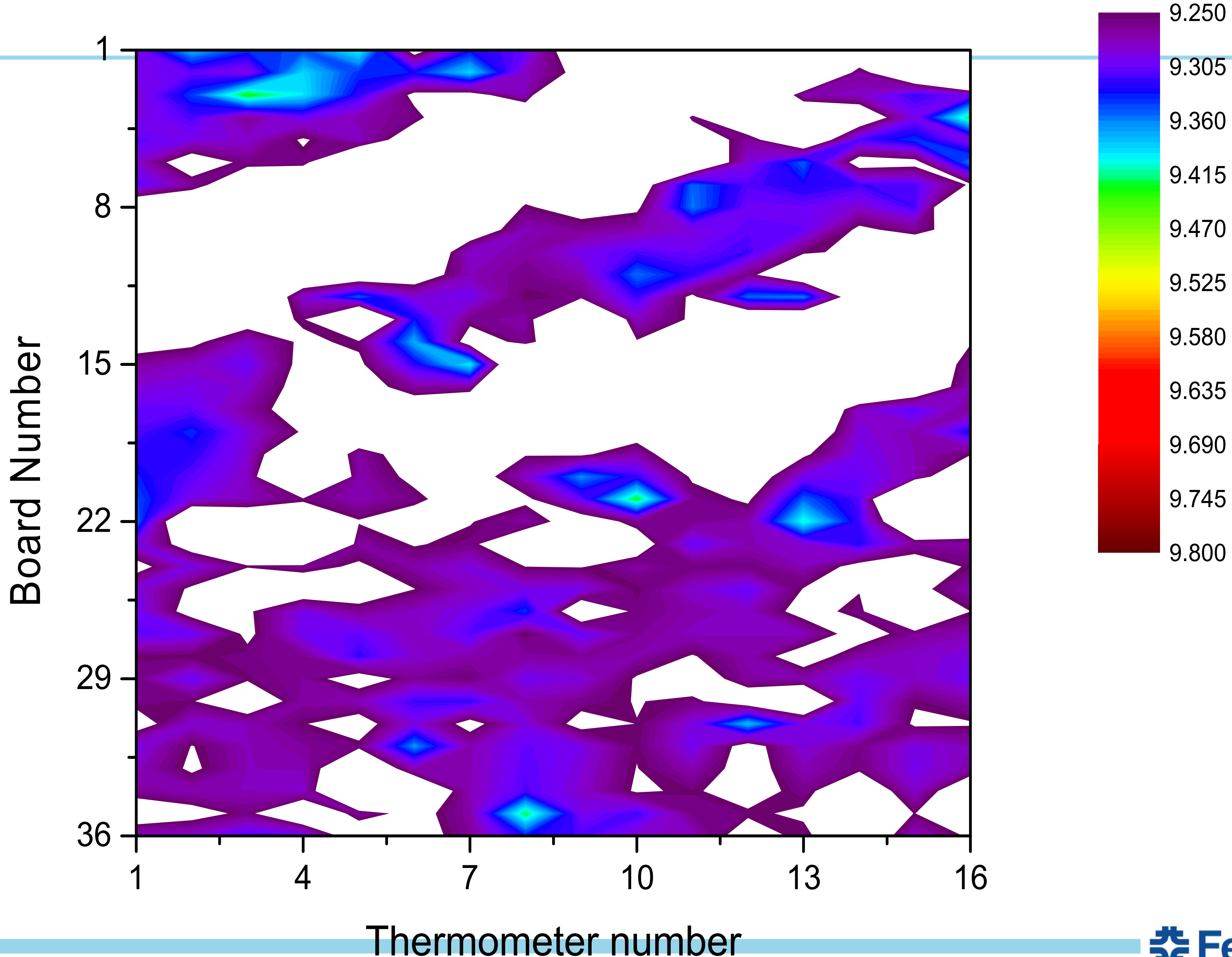

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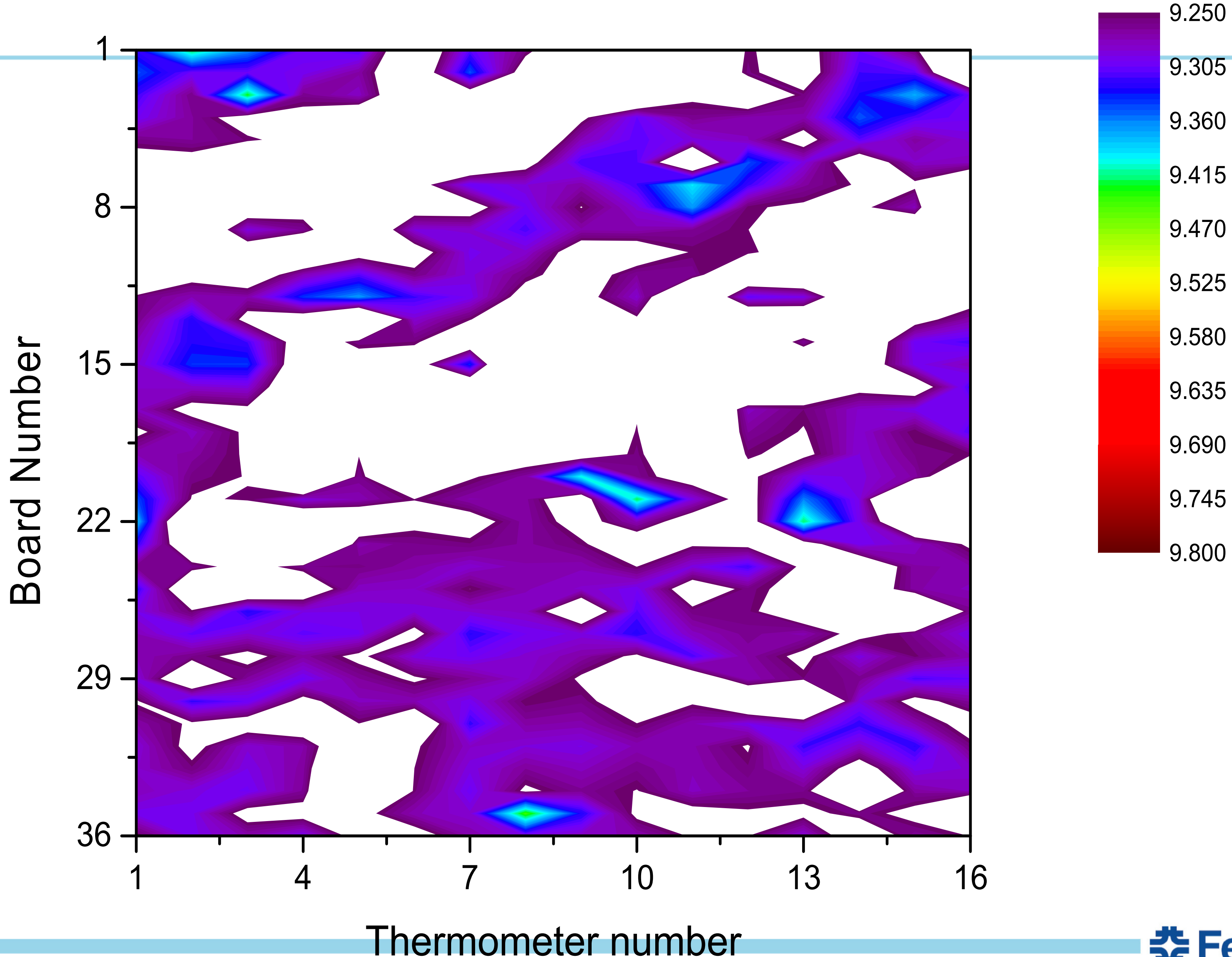

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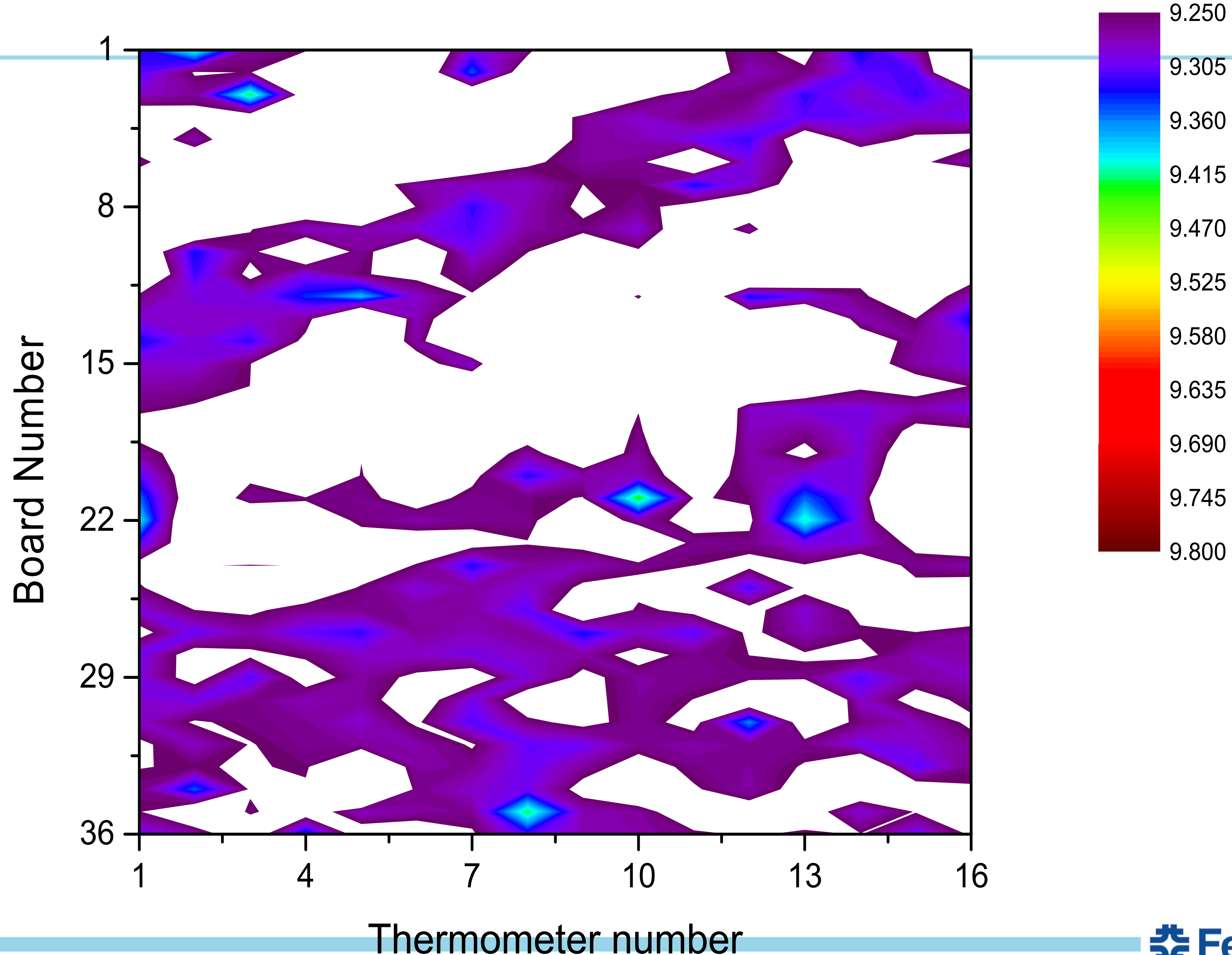

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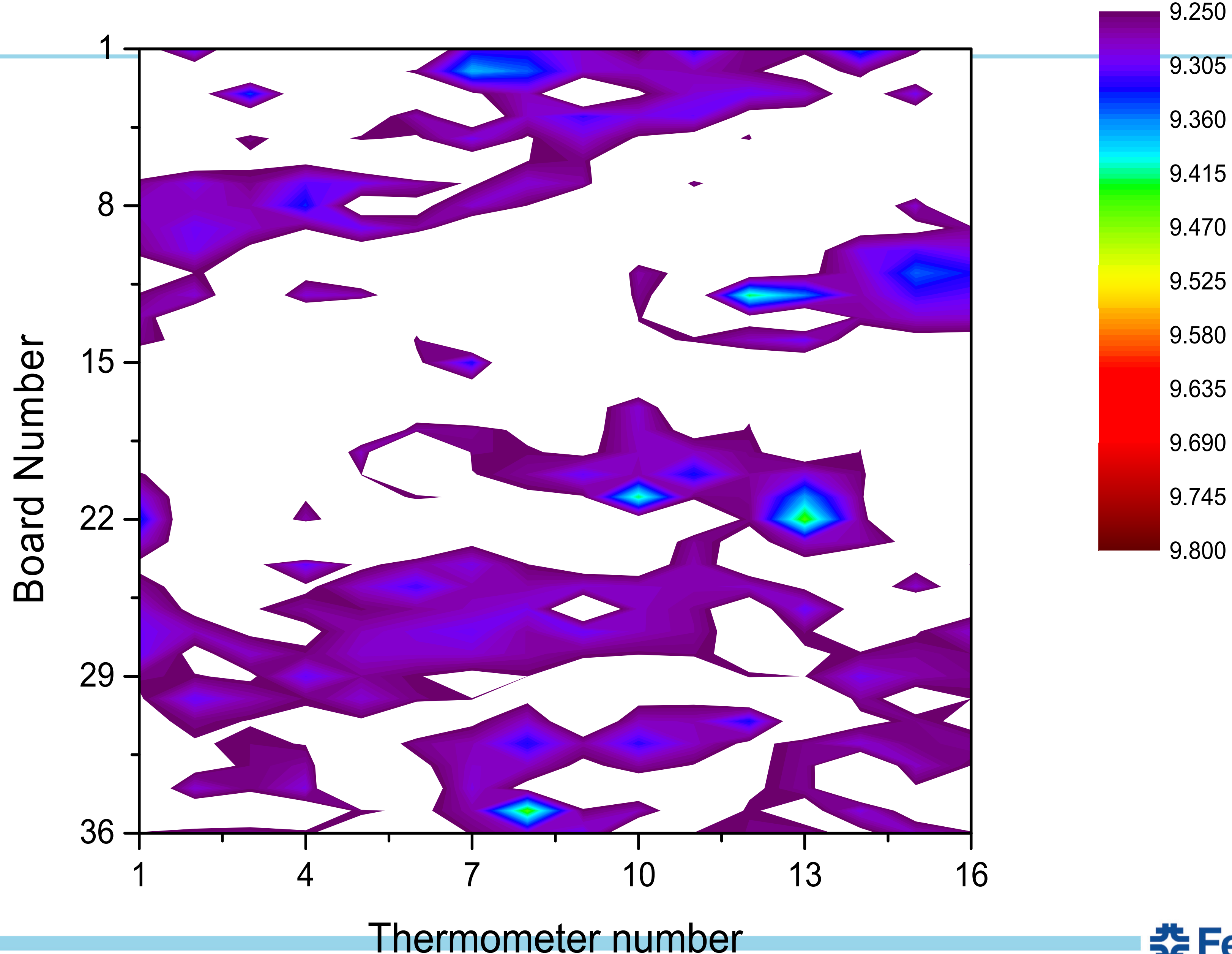

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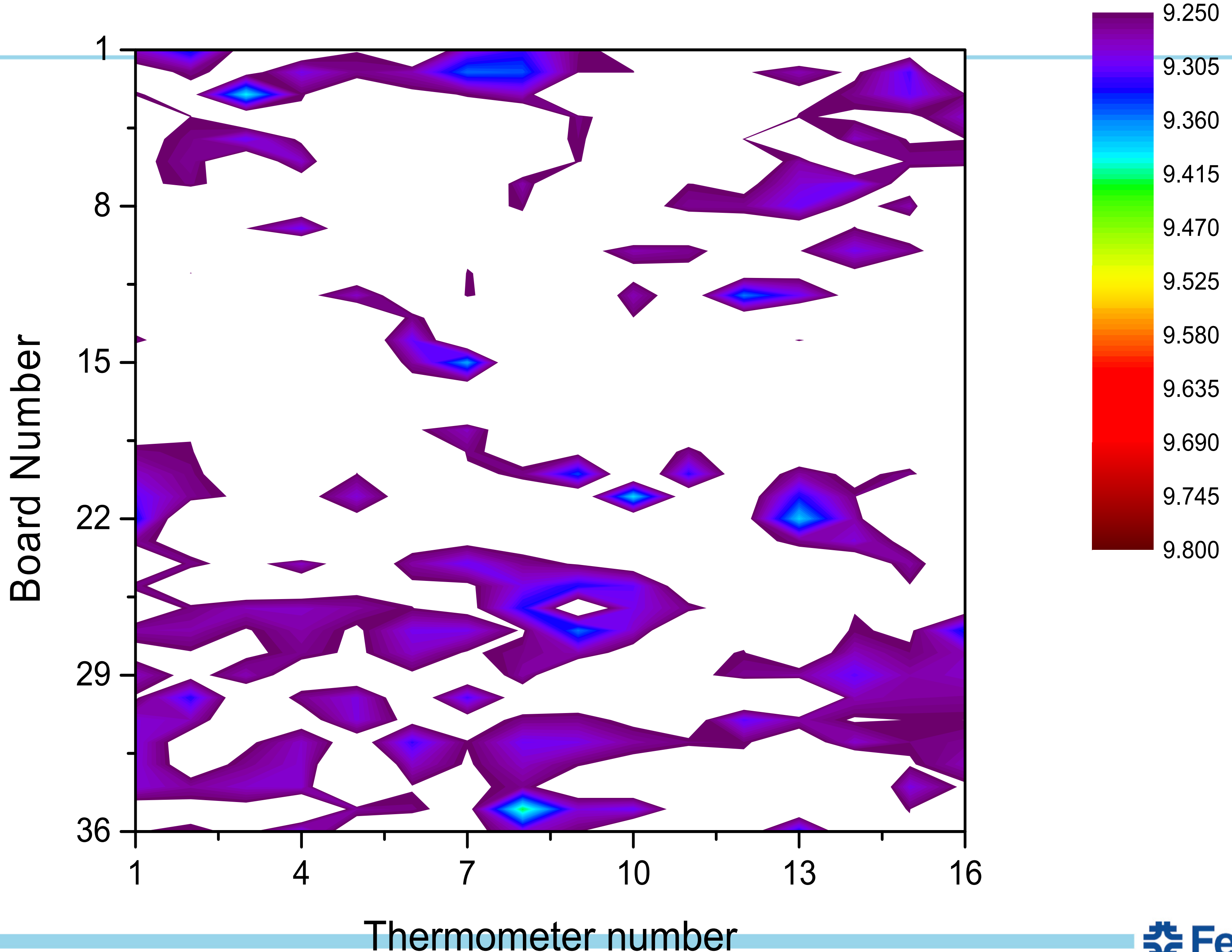

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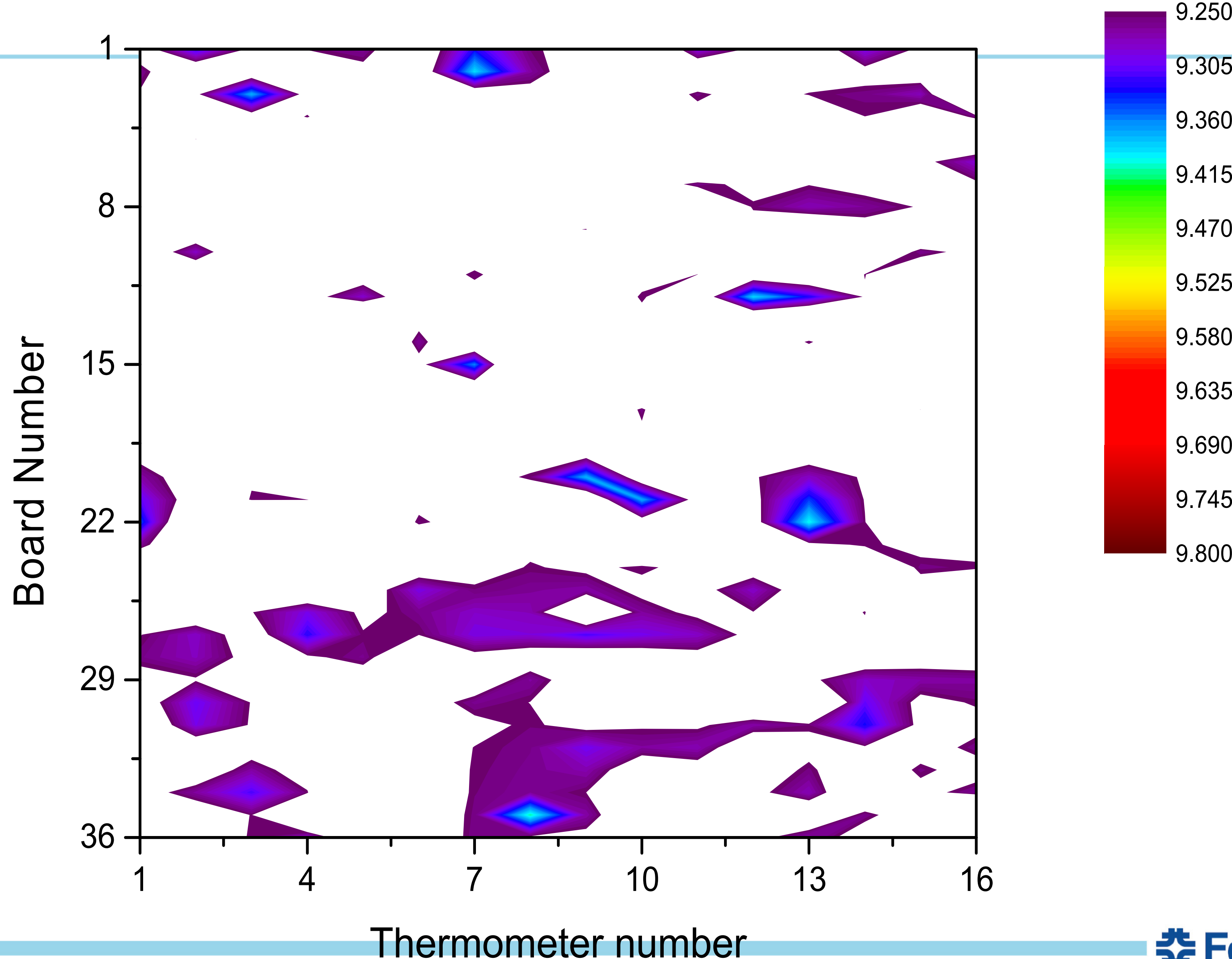

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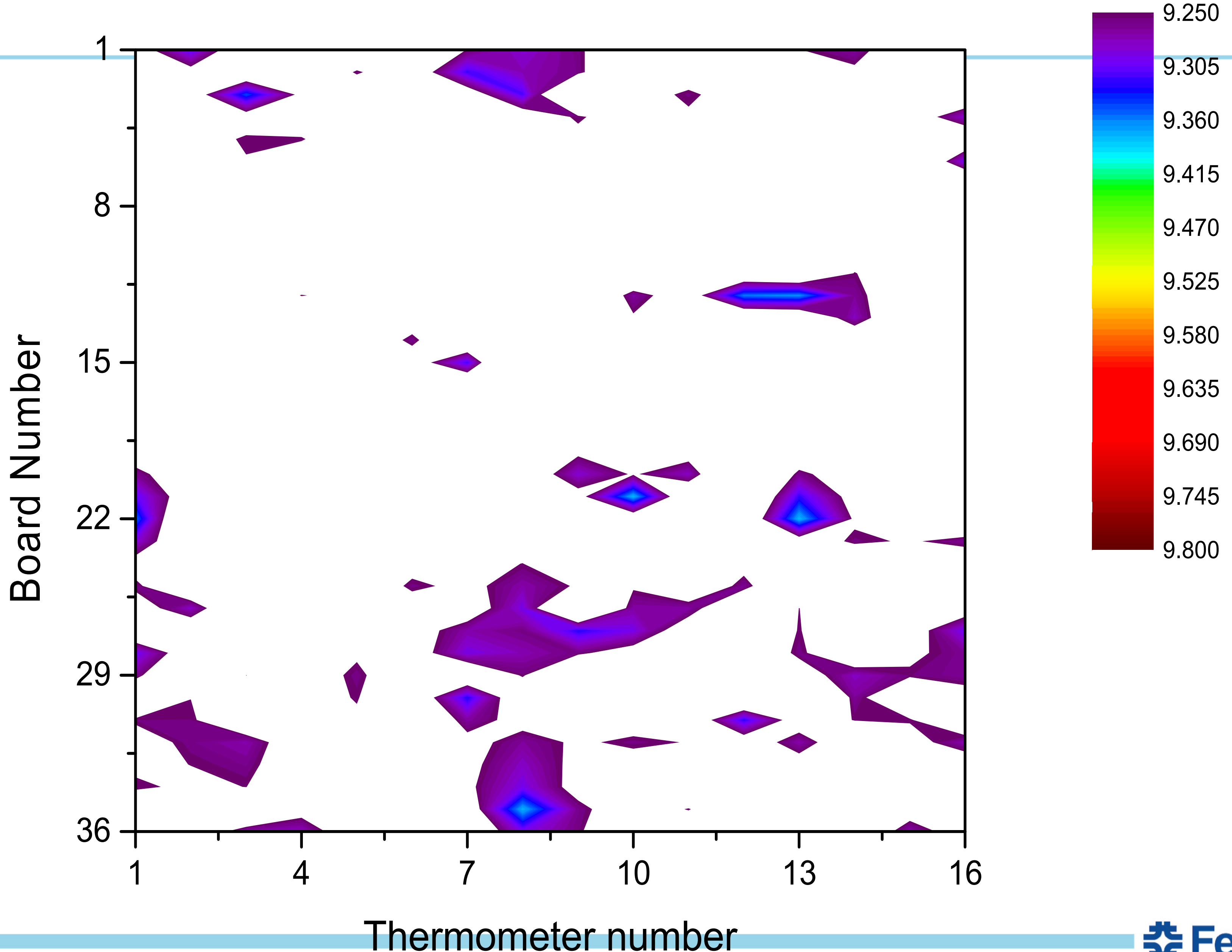

Fermilab

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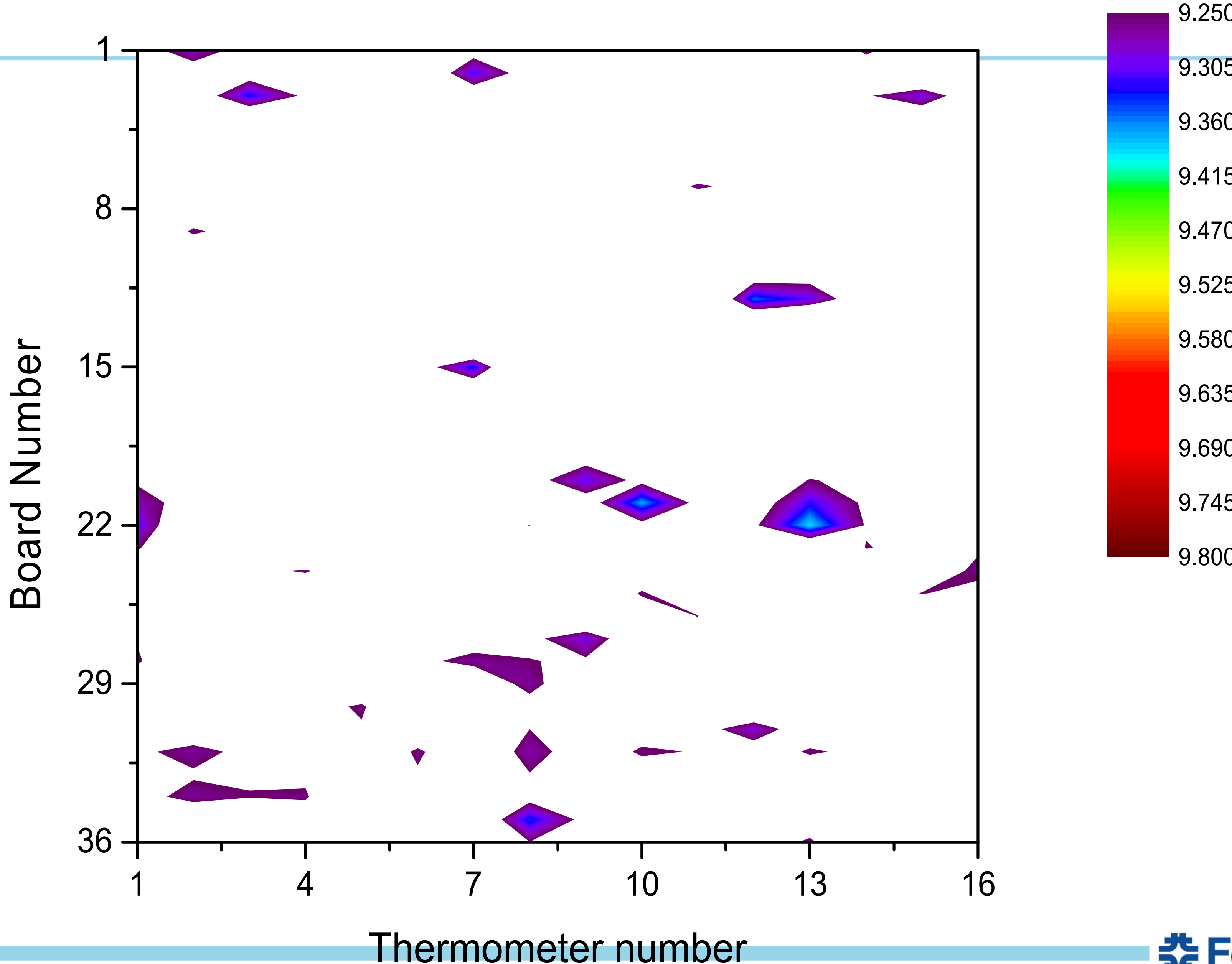

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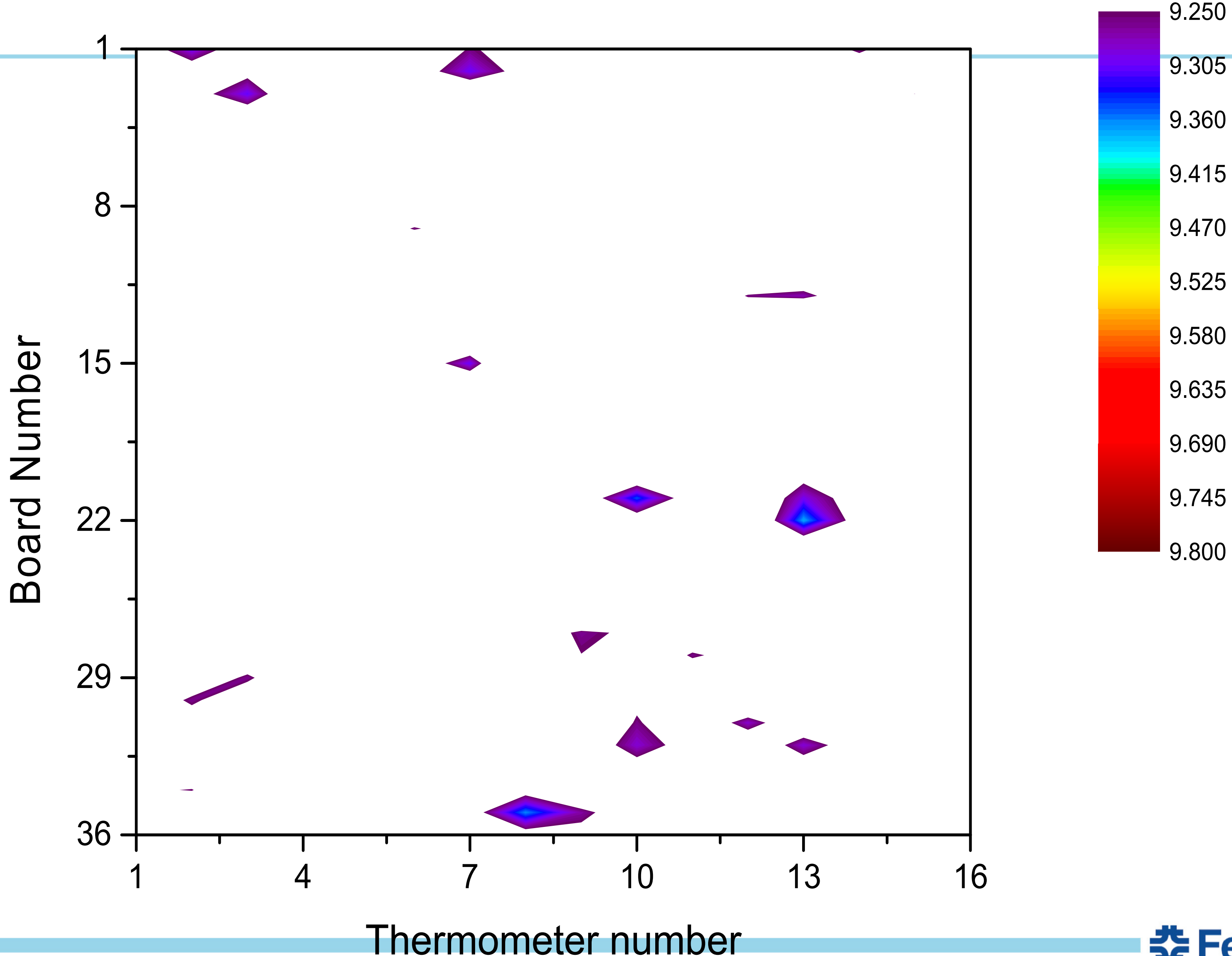

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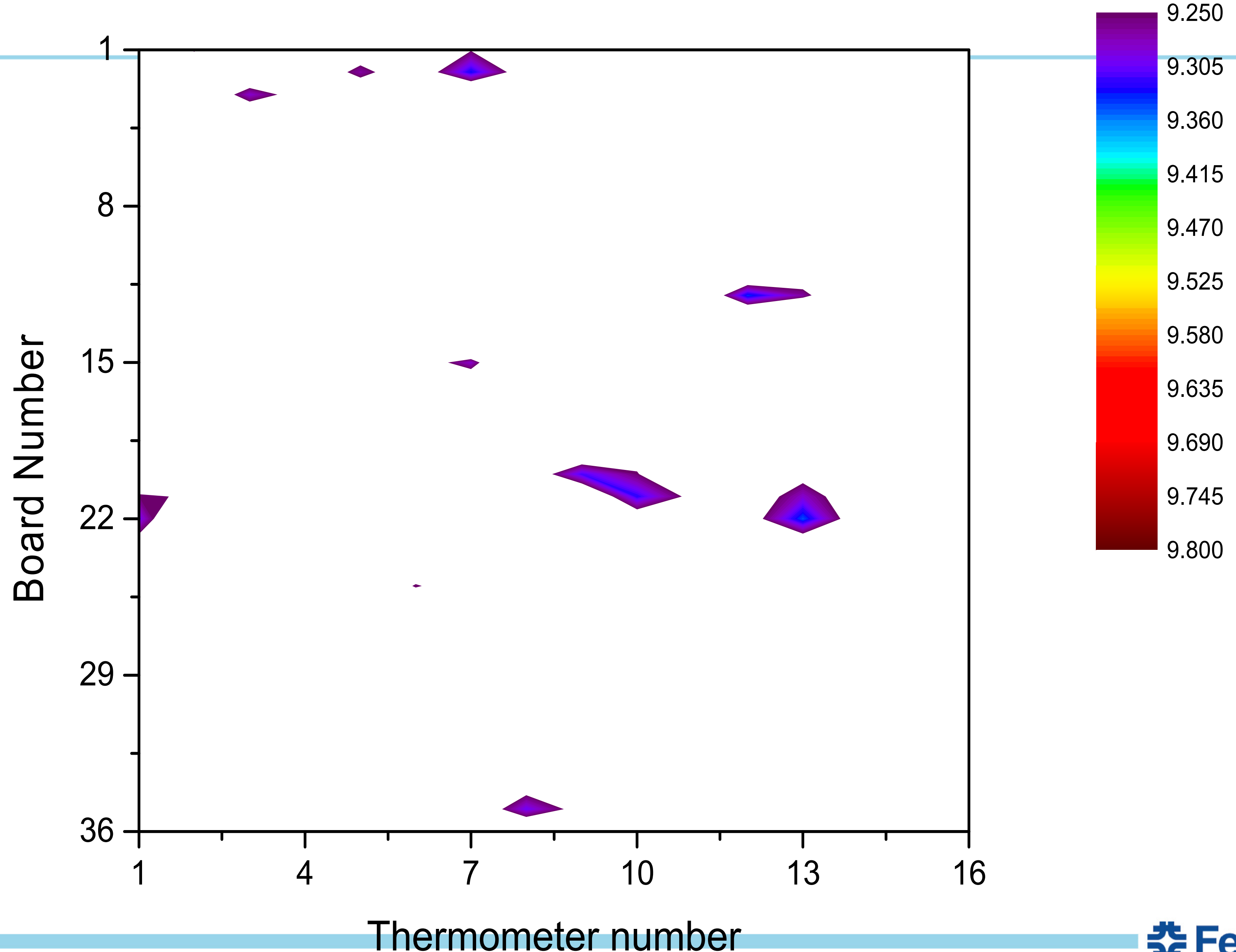

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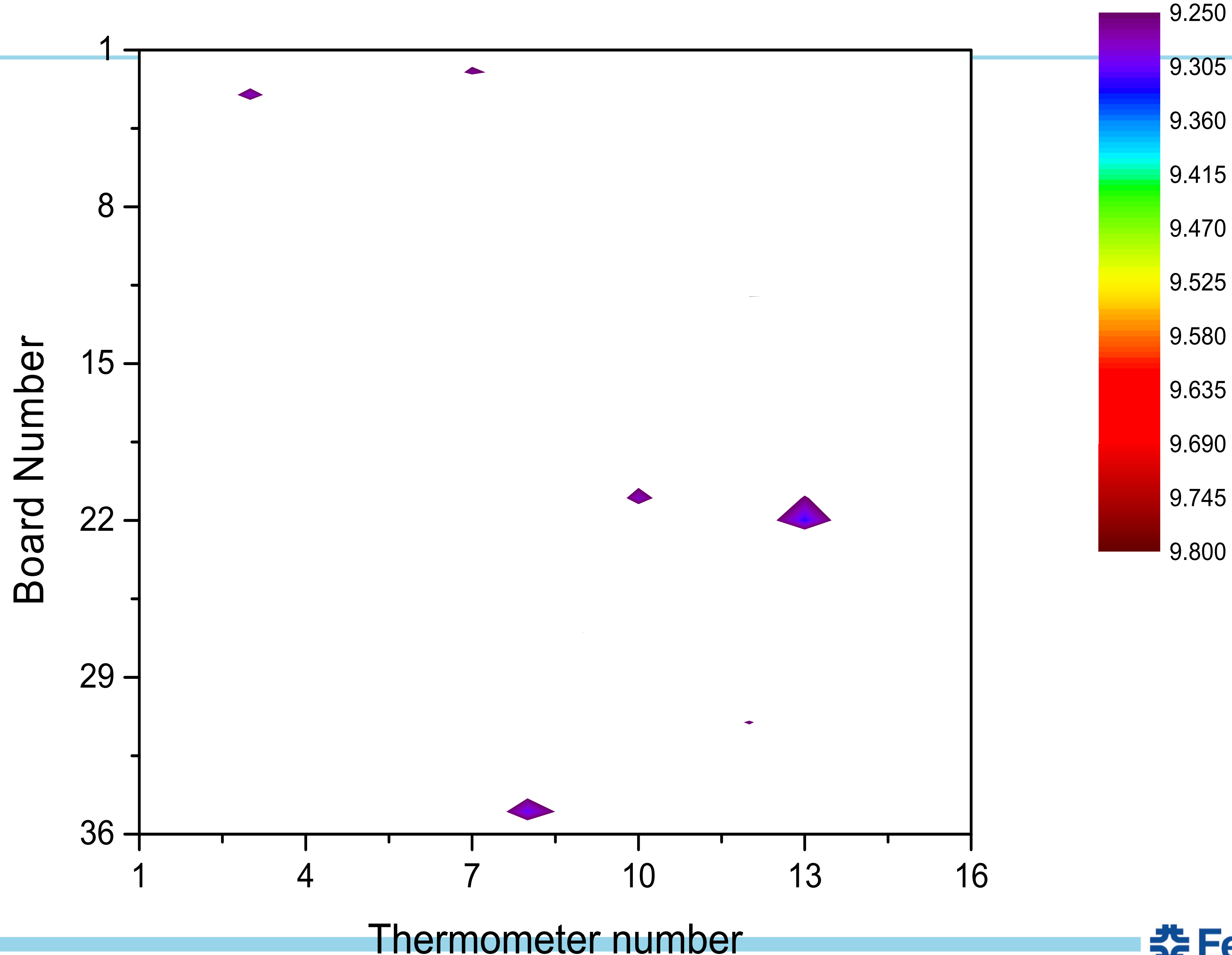

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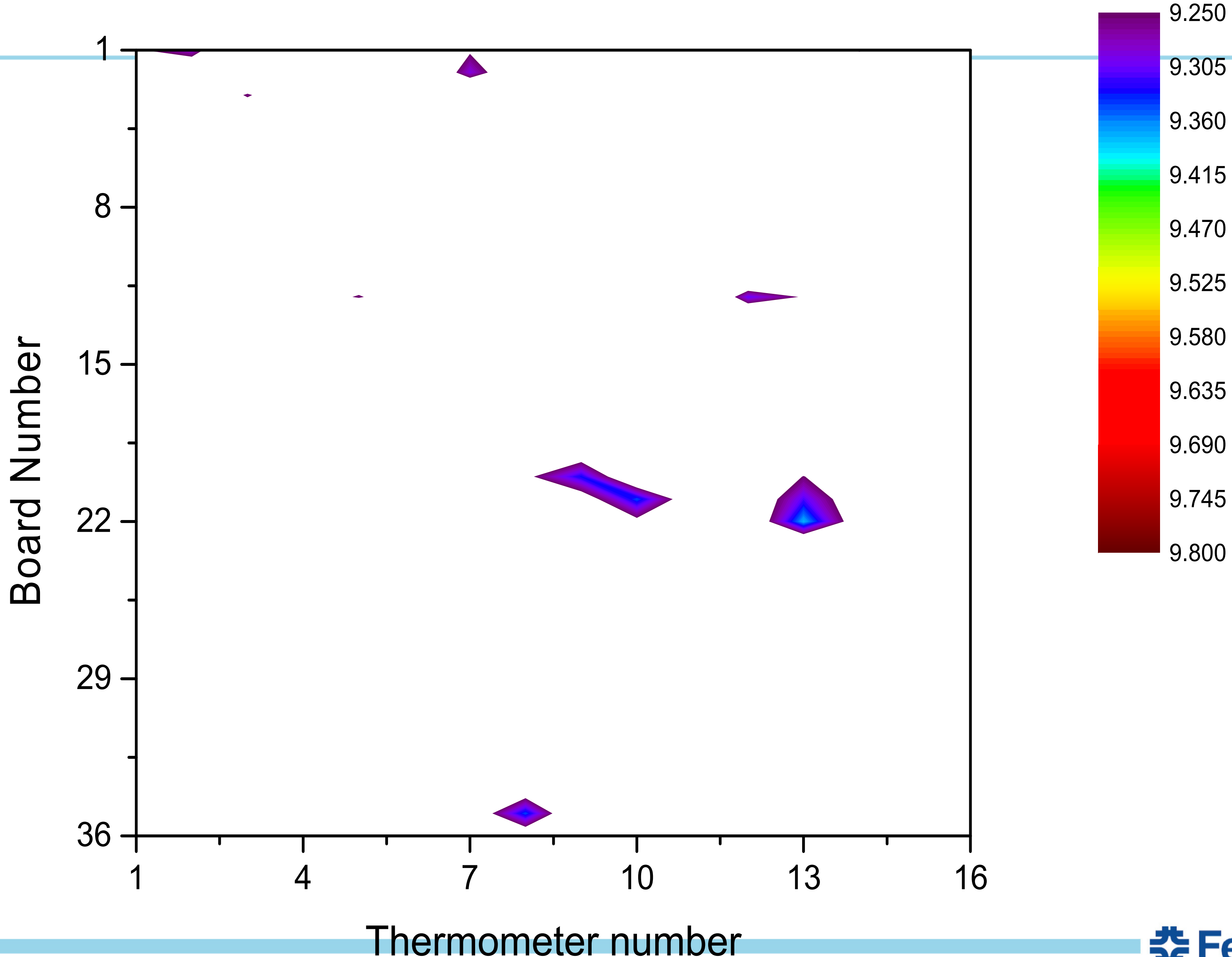

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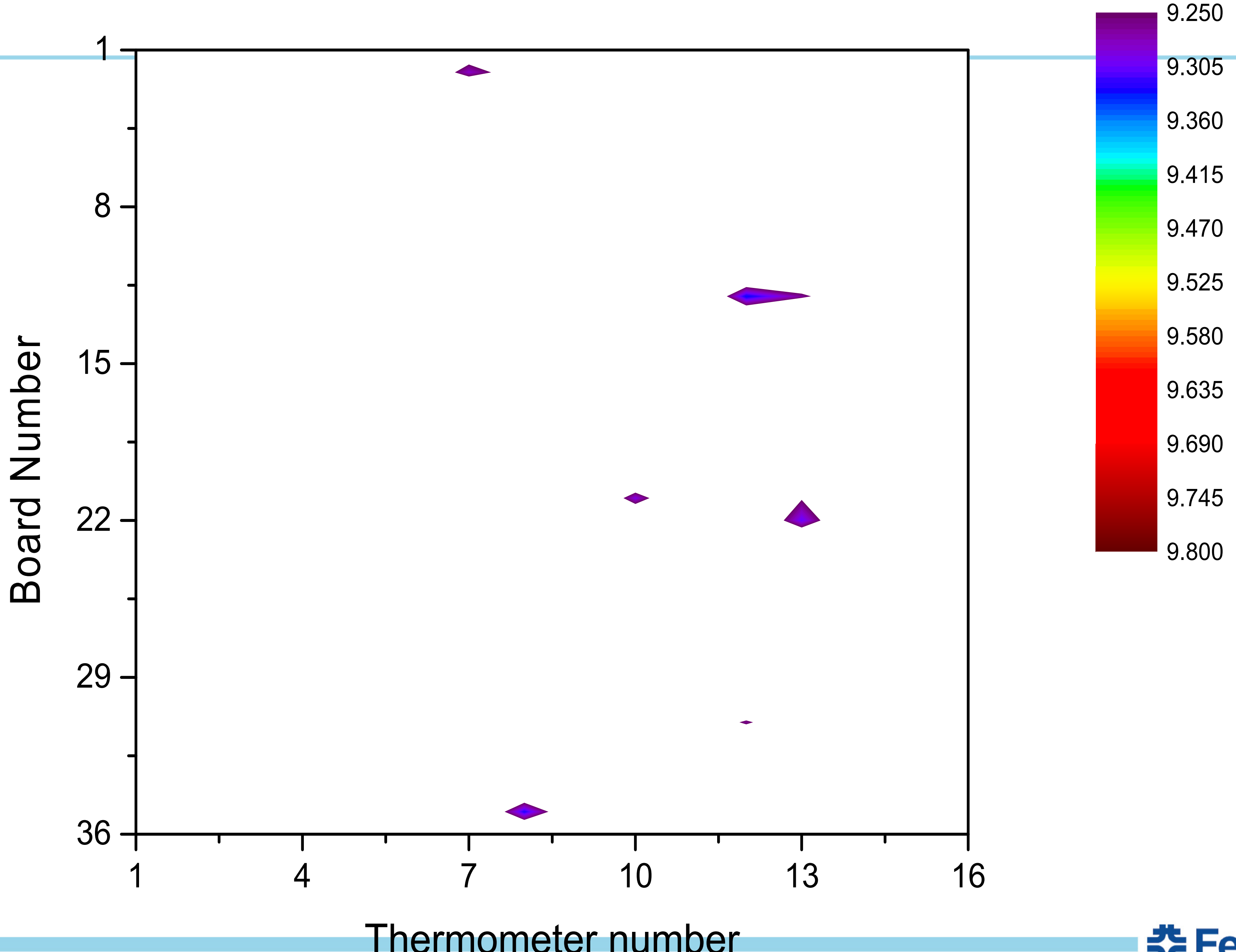

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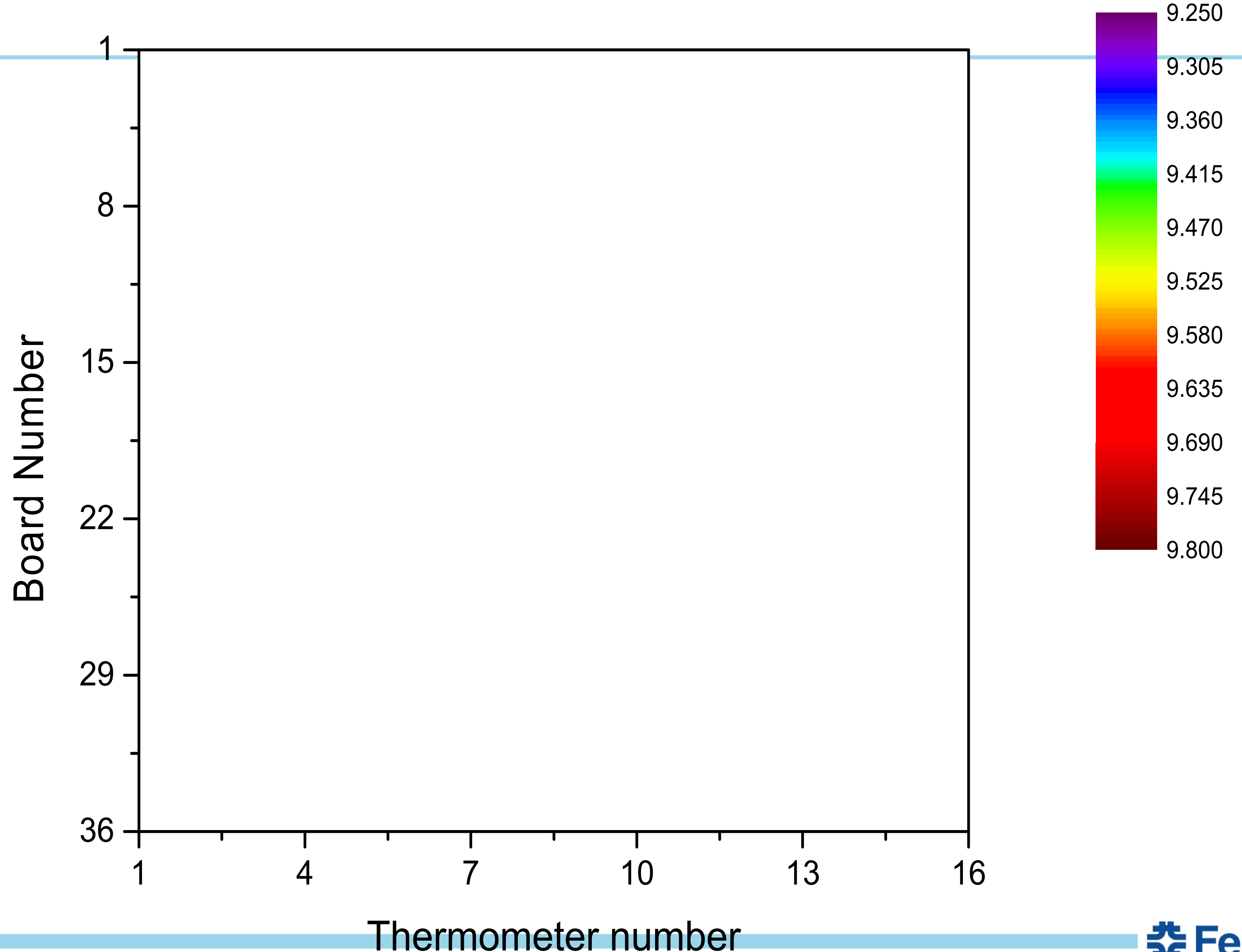

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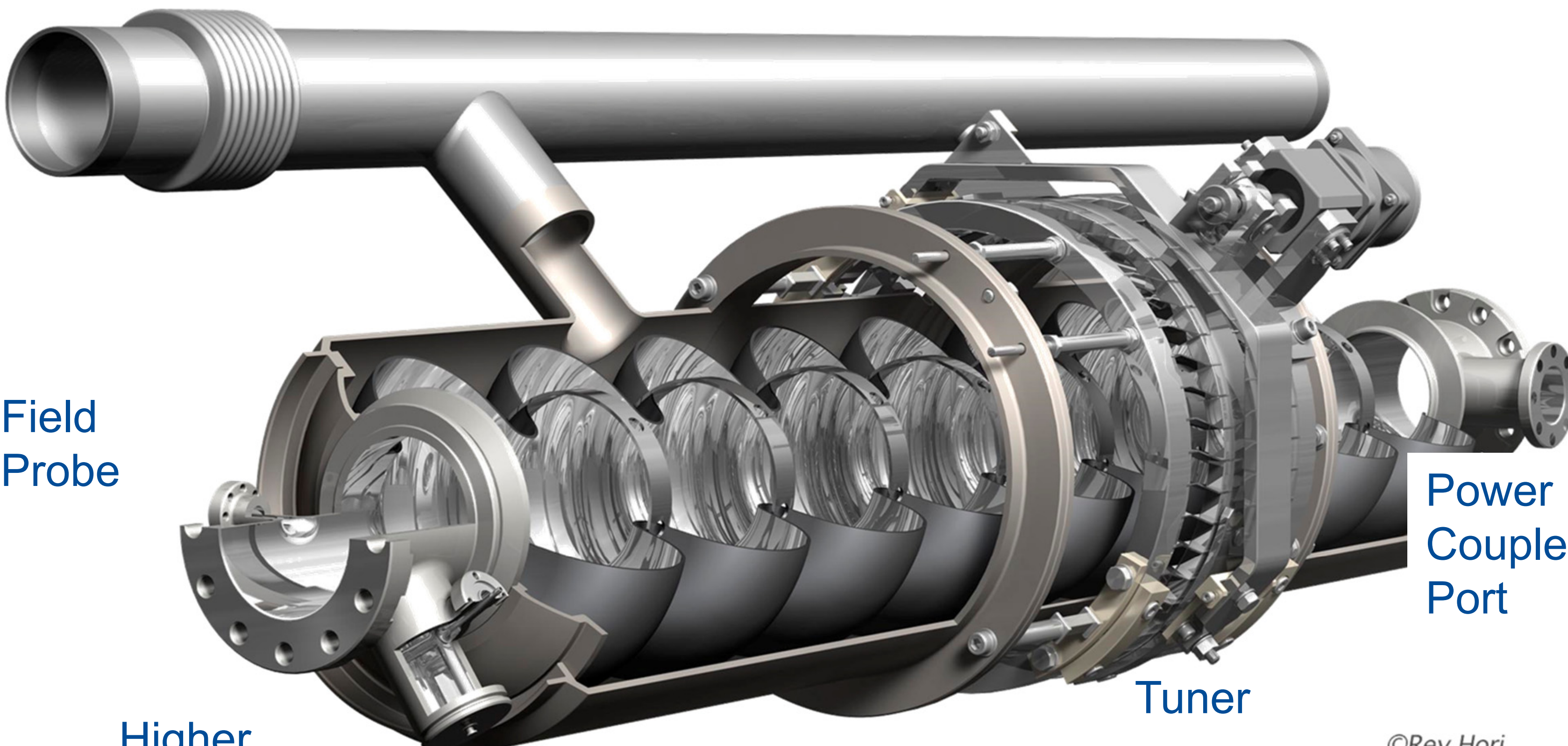
Bringing these very High Q
all the way down into the tunnel

Fermilab

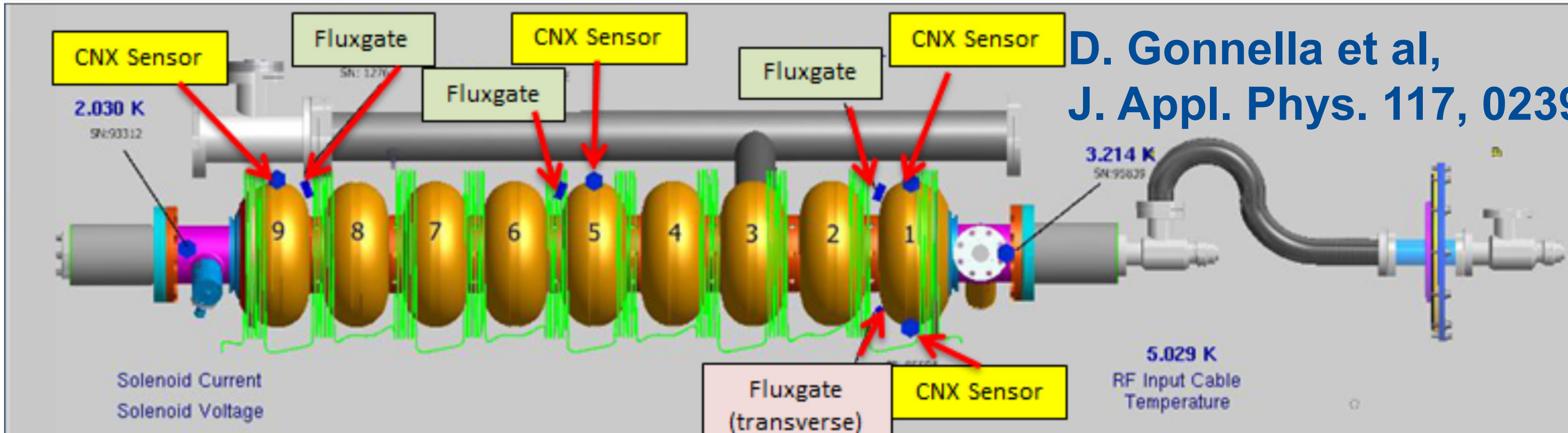
SRF cavity in its liquid helium filled tank: operating at 2 degrees above absolute zero (-456 deg F)

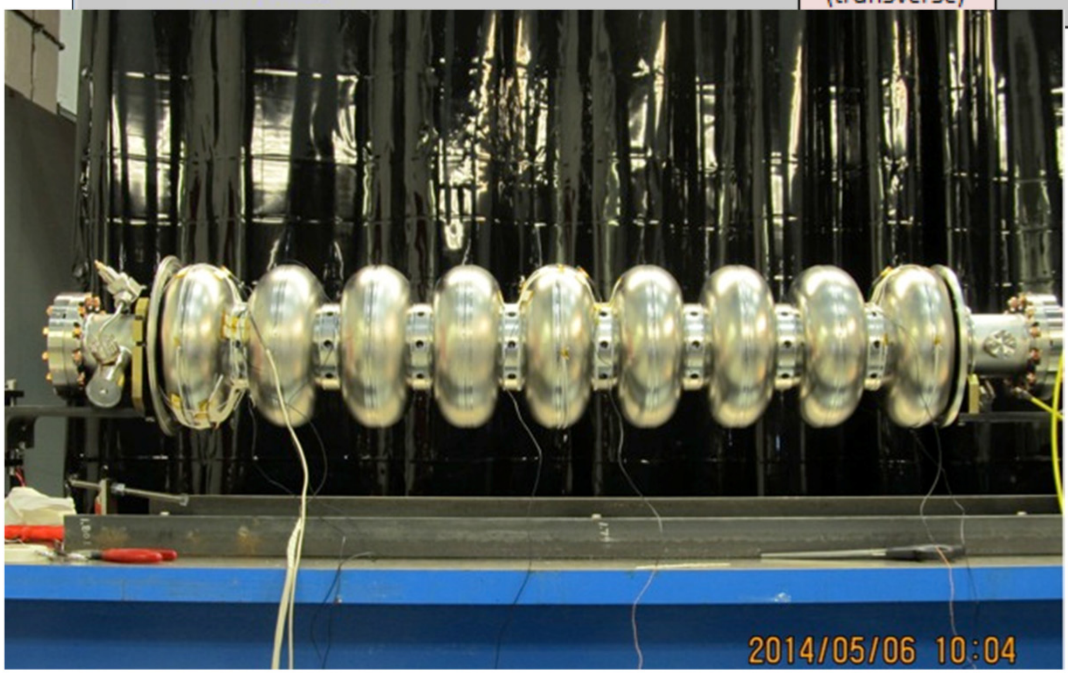


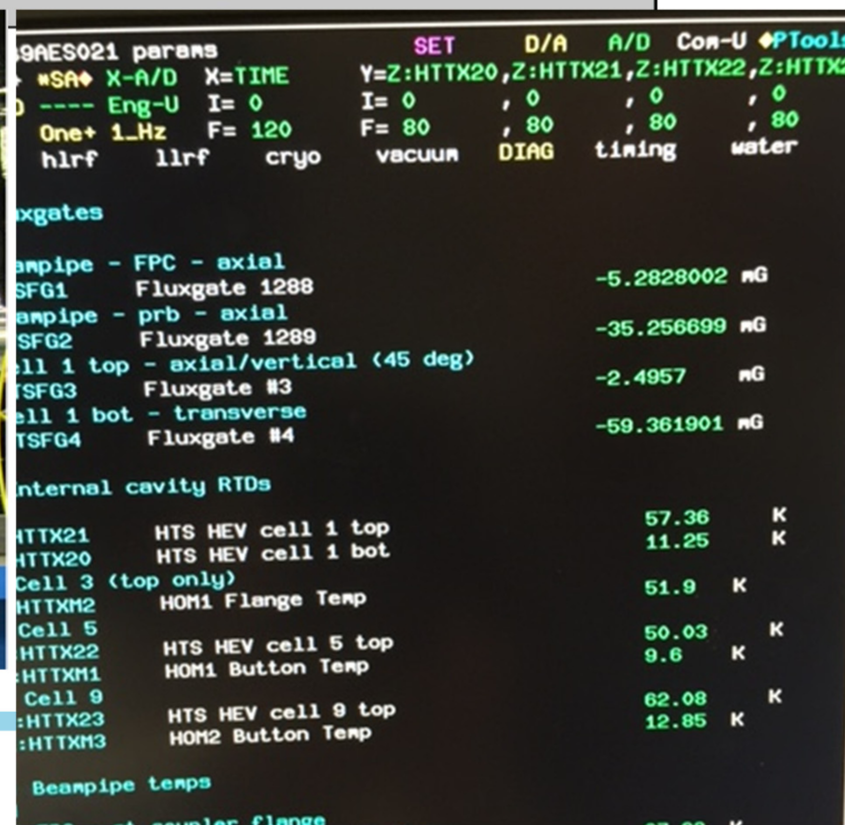
- Ports:
  - Beam in /out
  - Bring in power
  - Monitor field
  - Extract un-wanted frequencies

LCLS-2 cavities dressed with instrumentation inside vessel

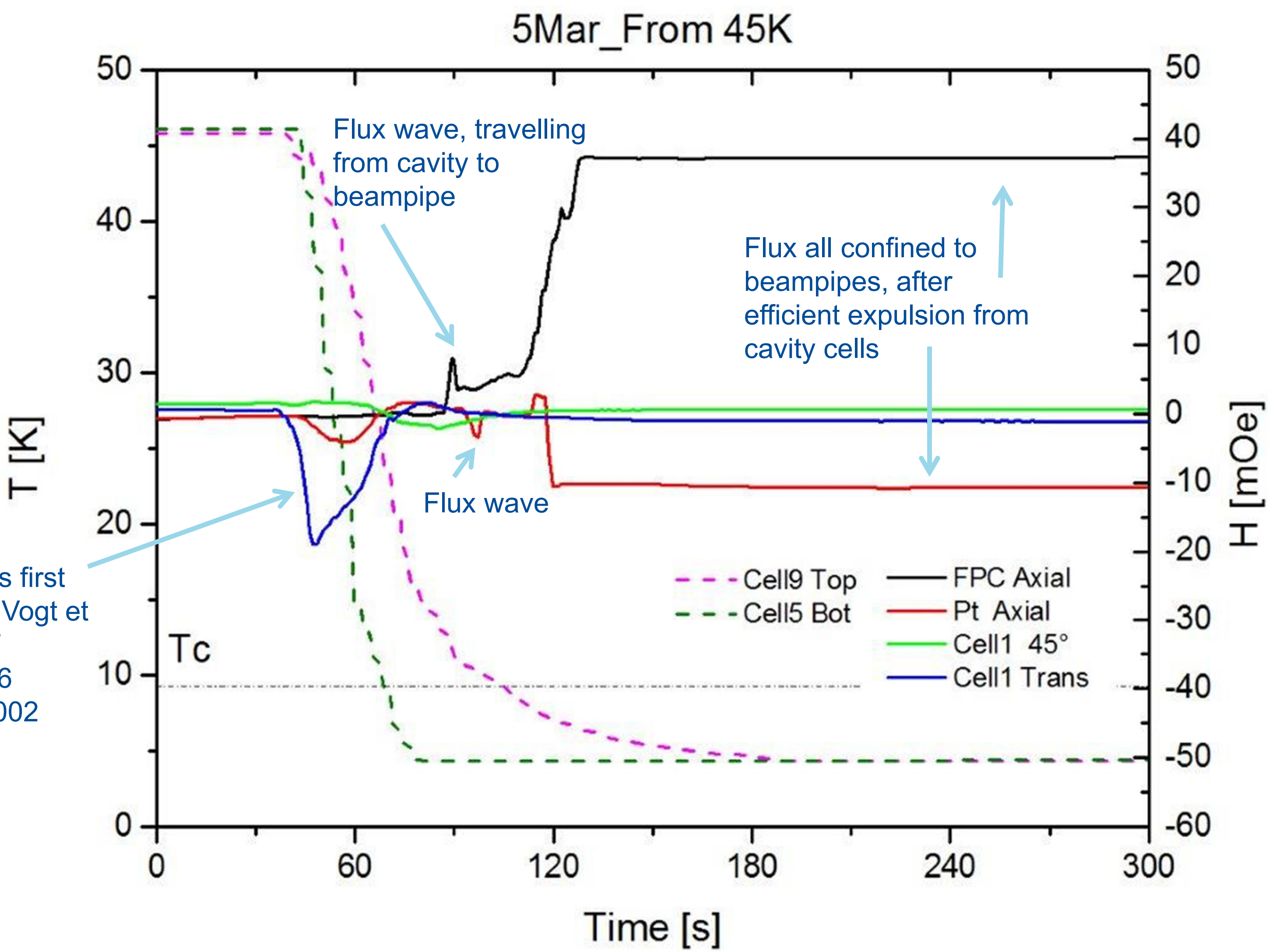
D. Gonnella et al,
J. Appl. Phys. 117, 023908 (2015





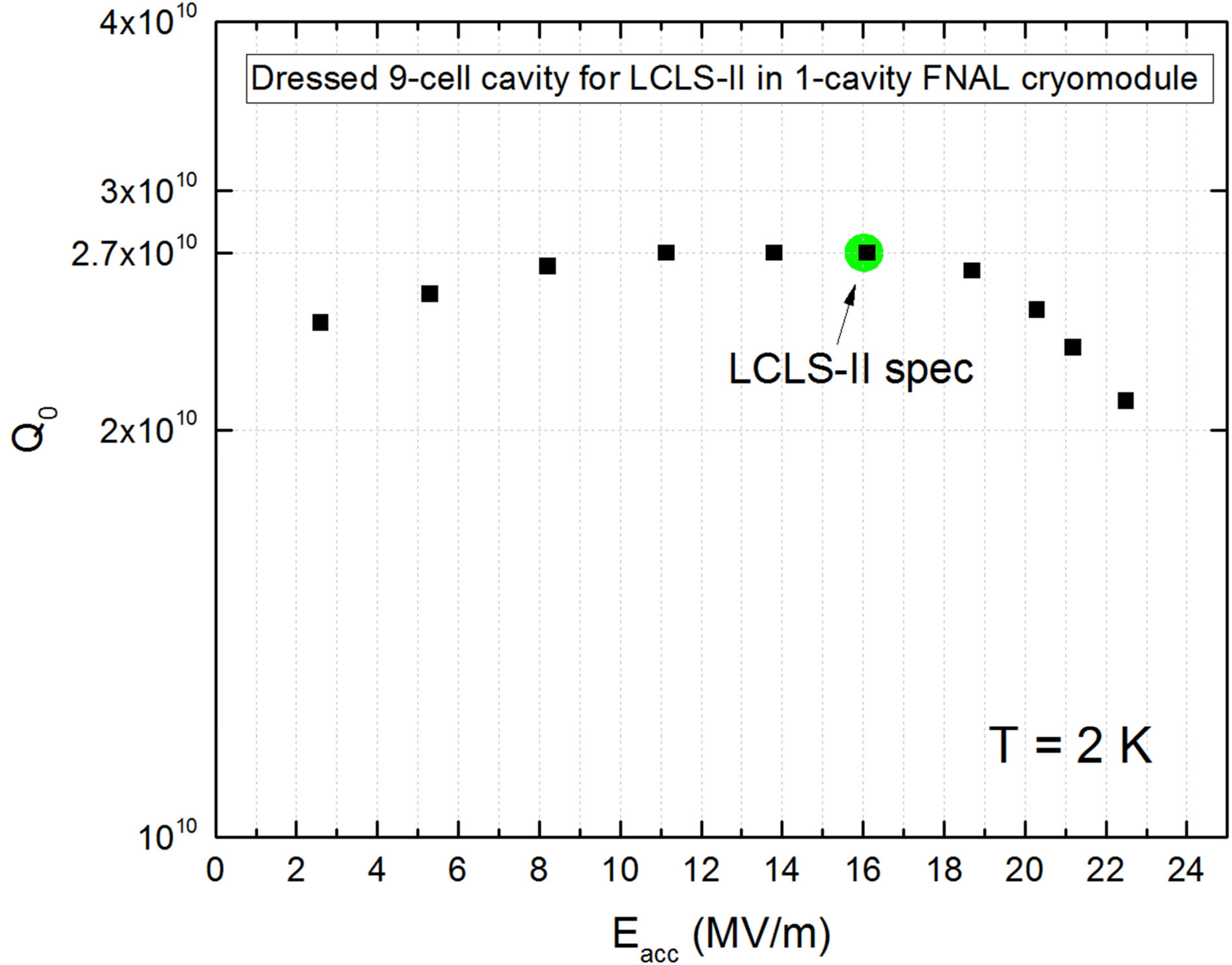


Sweeping the flux into the beampipes via fast cooling



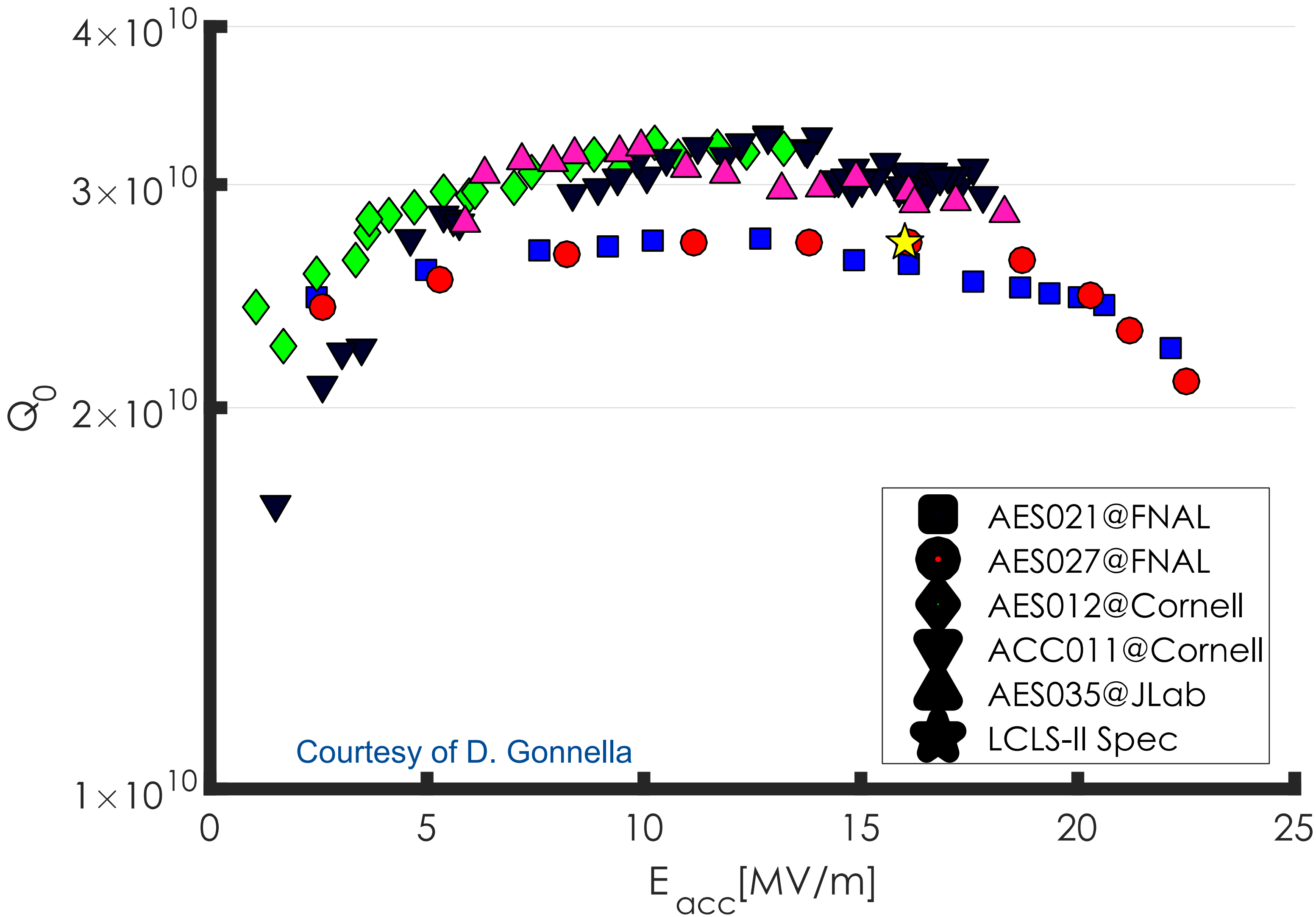
Thermoelectric induced field, as first discussed in J. Vogt et al Phys.Rev.ST Accel.Beams 16 (2013) 10, 102002

TB9AES027



Dressed 9-cell cavity for LCLS-II in 1-cavity FNAL cryomodule
4x10^10
3x10^10
2.7x10^10
2x10^10
10^10
Q_0
LCLS-II spec
T = 2 K
0
2
4
6
8
10
12
14
16
18
20
22
24
E_acc (MV/m)

Horizontal dressed cavity tests at FNAL, Cornell, Jlab Meeting final LCLS-2 specs in cryomodule environment!



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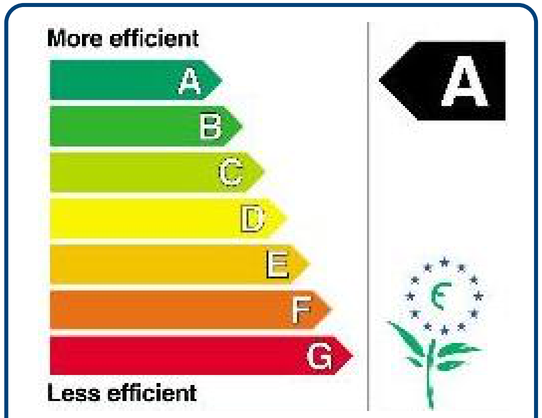
Conclusions

- Tremendous progress in the past two years in understanding of contributors to RF surface resistance
- Record Q achieved from bare cavity tests all the way down to cryomodule environment, by implementing N doping and understanding of flux expulsion via efficient cooling through Tc
- High Q at high gradient via doping is the frontier to be explored, the next battle already ongoing
- LCLS-2 nominal exceeded in vertical and horizontal test at three different institutions
- LCLS-2 has helped nurturing and developing a new high Q technology

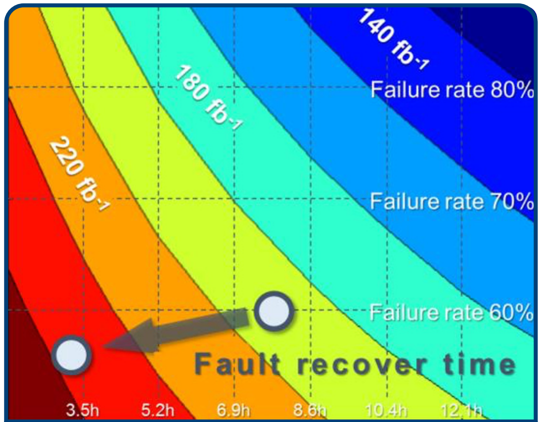
Scale Up versus Scale Out

- Scale-out of available technologies without advancement leads to unsustainable and inadequate performance
- Mandatory to use large projects to develop new technologies



Sustainability

Cost effective operation:
Personnel and material resources
Energy efficiency



Availability

Number of subsystems requires breakthrough in reliability, availability

Economy

Diversify technology sources to control risk
Economic return to society is mandatory

Thank you

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