Efficient Magnetic Flux Expulsion During Cooldown

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17th International Conference on RF Superconductivity
14 Sep 2015

Main points

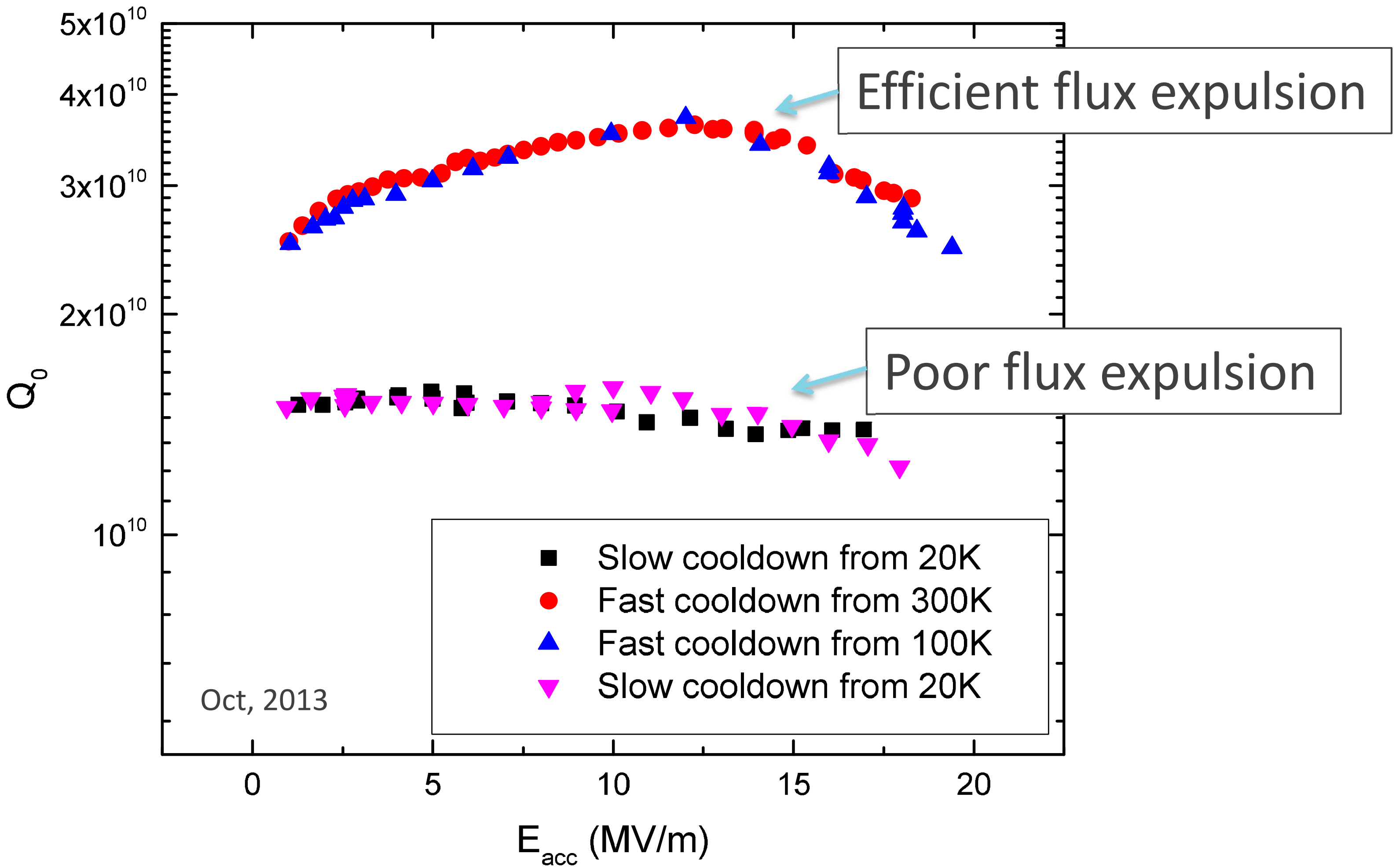
- Discovery at Fermilab in 2013 -> Cooling through T_c strongly affects Meissner expulsion efficiency [J. Appl. Phys. **115**, 184903 (2014)]
  - Slow cooling traps ALL flux
  - Efficient cooling exploited
    - $Q = 2.7\times10^{11}$ in 27 mG ambient field;
    - $Q > 5.5\times10^{10}$ in 190 mG ambient field
  - Effect is independent on the field source = static or generated by thermal currents etc
    - SRF'2013 recommendation for slow cooldown as best to retain Q in dressed cavities had to be revisited
      - Record high Qs in horizontal tests of fully dressed cavities for LCLS-II using the optimal fast cooling: $Q = 3\times10^{10}$ at T=2K, Eacc=16 MV/m
- What have we learnt about physics of the effect since then?
  - Mechanism of expulsion, role of the bulk, geometry…

Correcting SRF'2013 recommendation

- ~~SLOW COOLDOWN = Best for Q~~

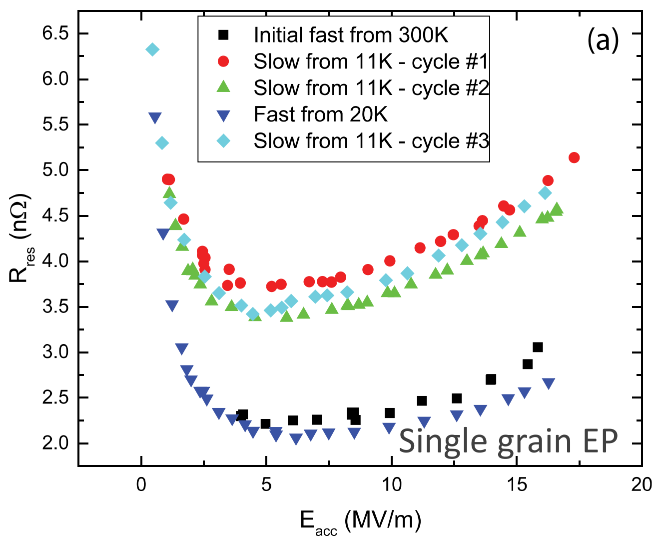
Reason: slow cooldown traps ALL magnetic field making it unsuitable for current magnetic environments in accelerators (e.g. 5 mG ambient field for LCLS-II = the most stringent specification ever)

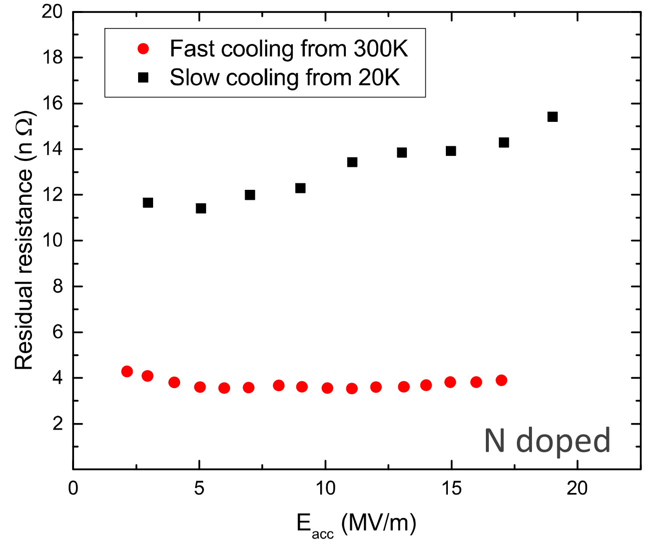
Bare N doped 9-cell in vertical test

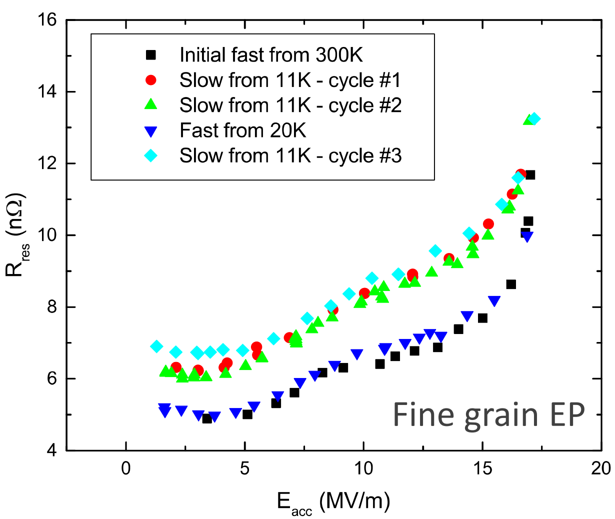


Fermilab

Systematic effect for all cavity treatments



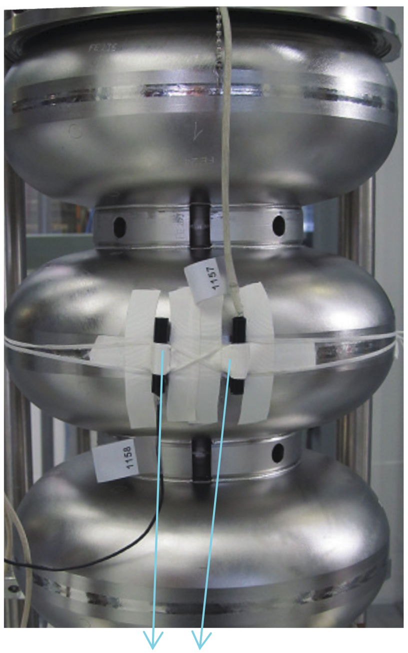




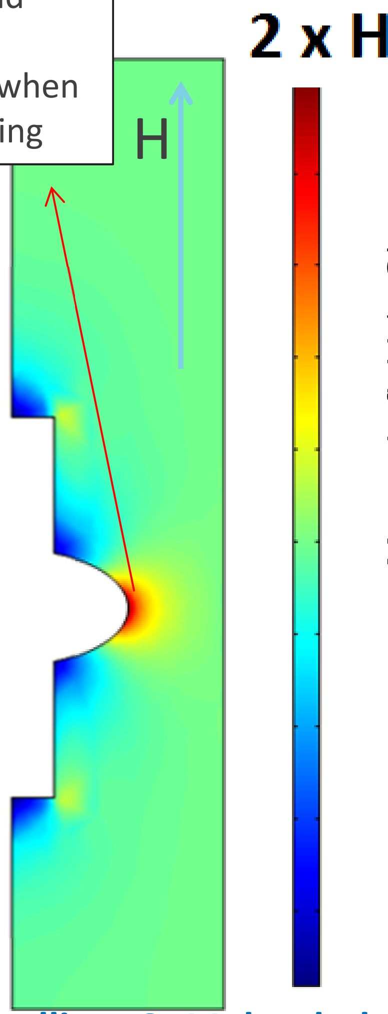
By only varying the parameters of cavity cooling through T_c=9.25K the residual surface resistance can be systematically and reversibly varied

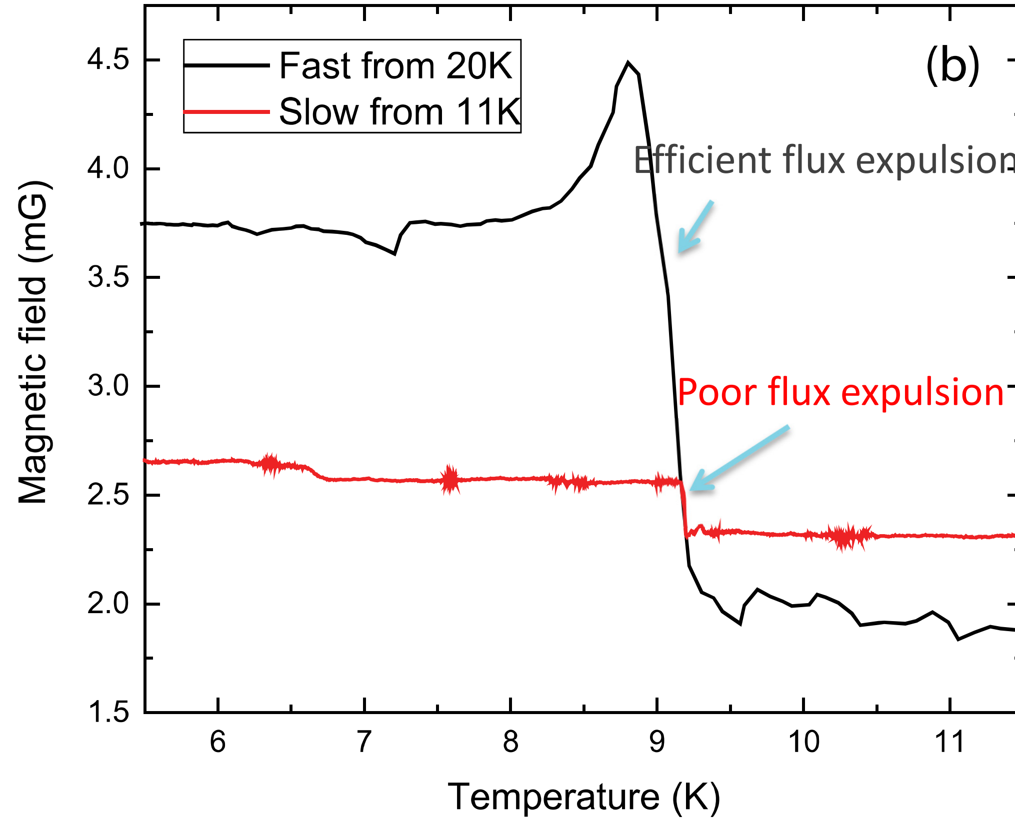
Magnetic probes reveal the new physics

Full expulsion of the magnetic field should increase the field at equator ~1.8 times when going superconducting



Fluxgate magnetometers

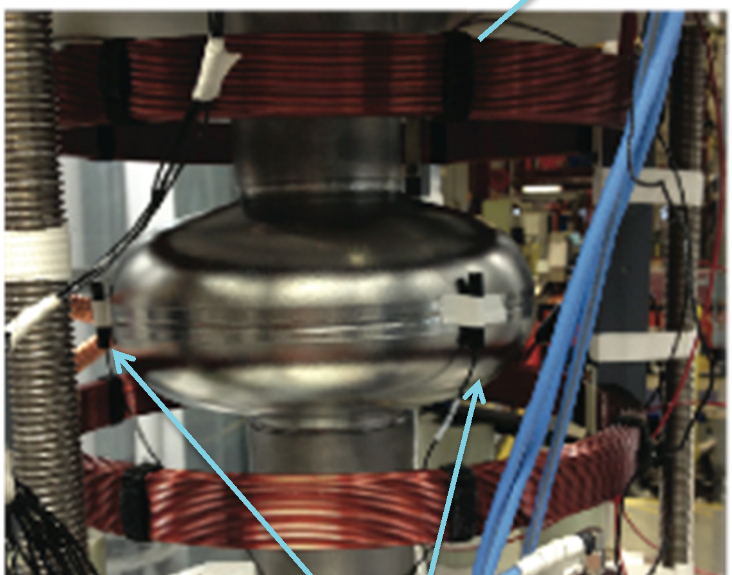


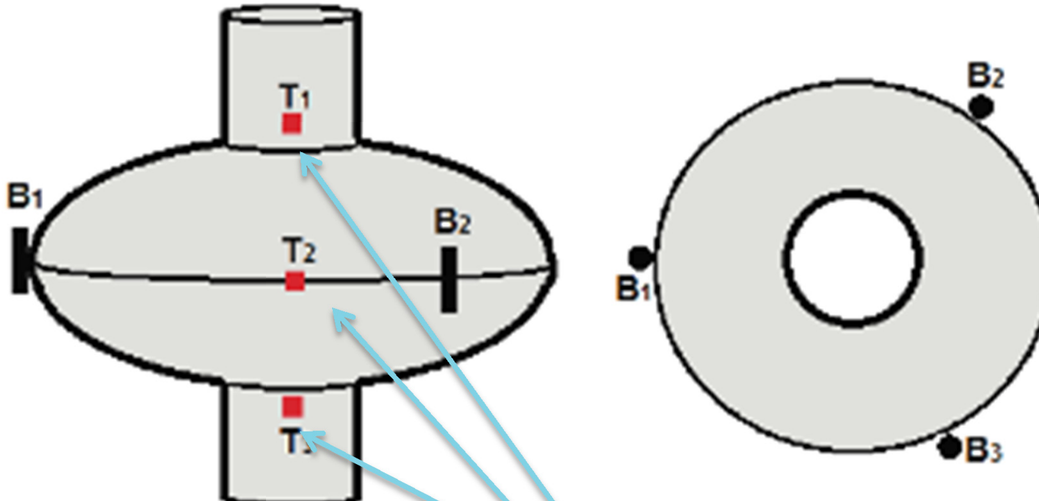


A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. 115, 184903 (2014)

Typical setup on 1-cell used for studies of expulsion

Helmholtz coils to control magnetic field



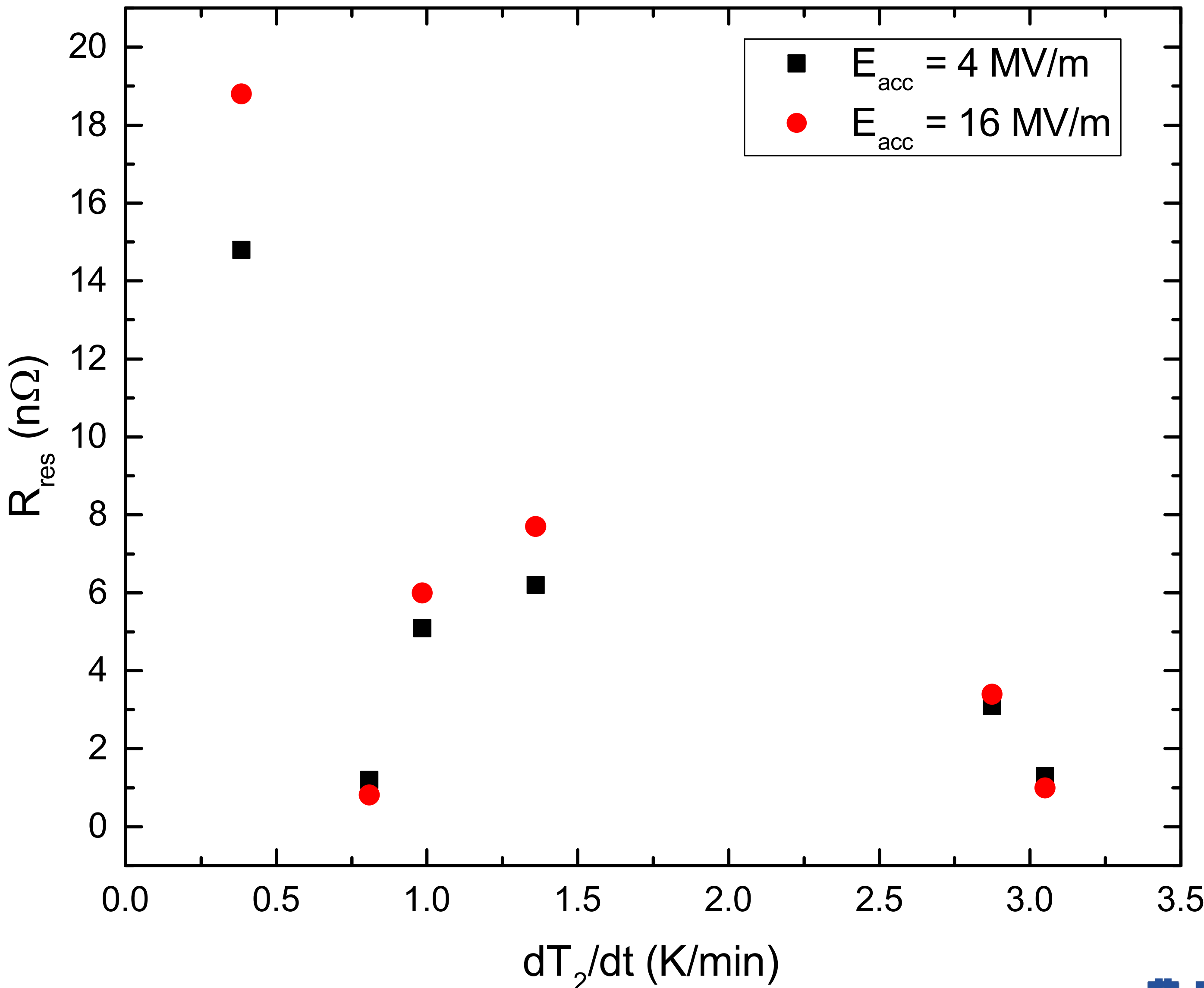


Temperature sensors

Single axis fluxgate magnetometers
(measure magnetic field)

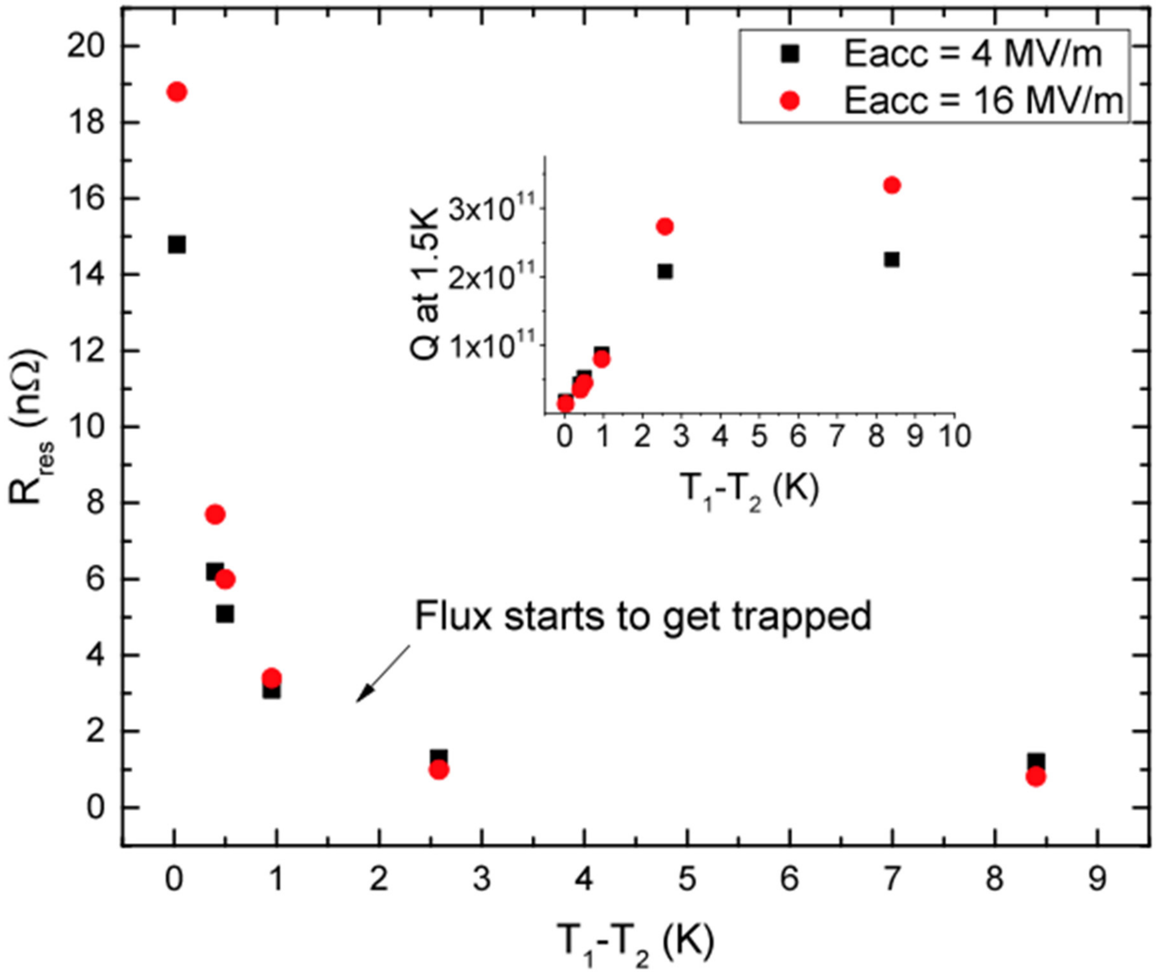
- What is the driving factor for better/worse flux expulsion? What makes “fast” cooldown efficient?

Cooldown rate dT/dt is not the main driving parameter



Thermogradient at NC/SC interface is key

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)

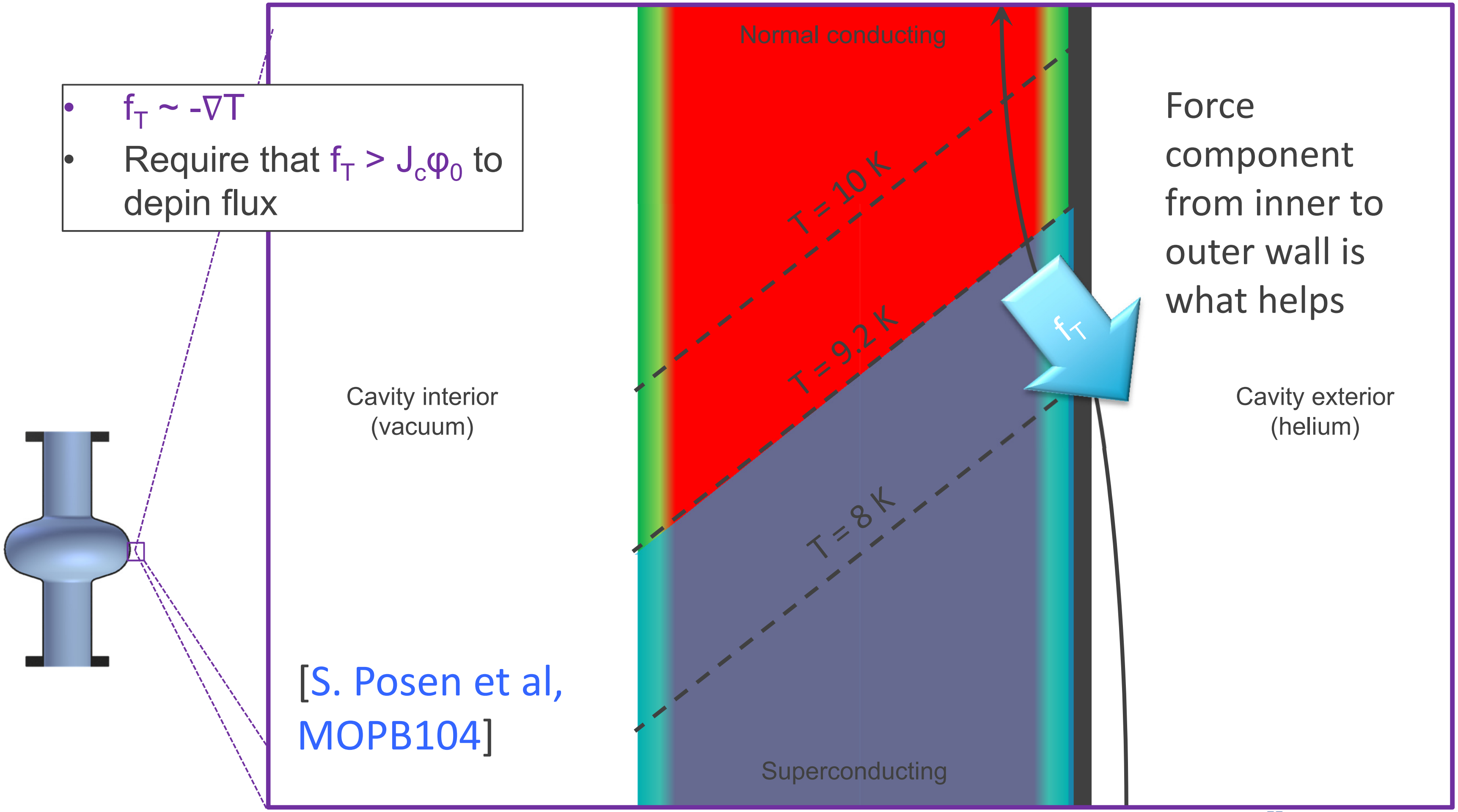


Temperature gradient at the phase front (dT/dx)

- Why is flux expulsion better for larger thermal gradient?
- Why is slow cooldown worse?

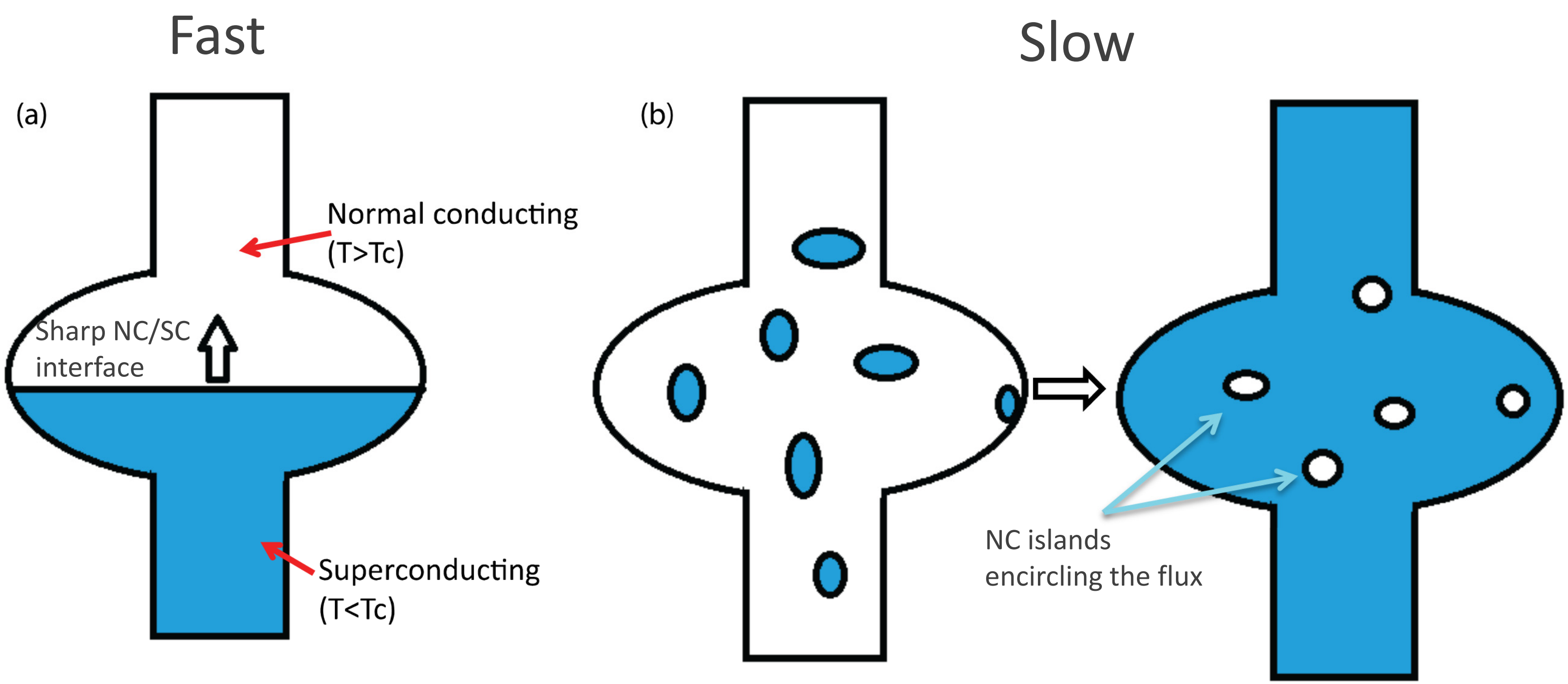
Mechanism#1: Depinning by Thermal Gradient

- Thermal gradient at the superconducting/normal conducting boundary creates a depinning force [J. Appl. Phys. 115, 184903 (2014)]



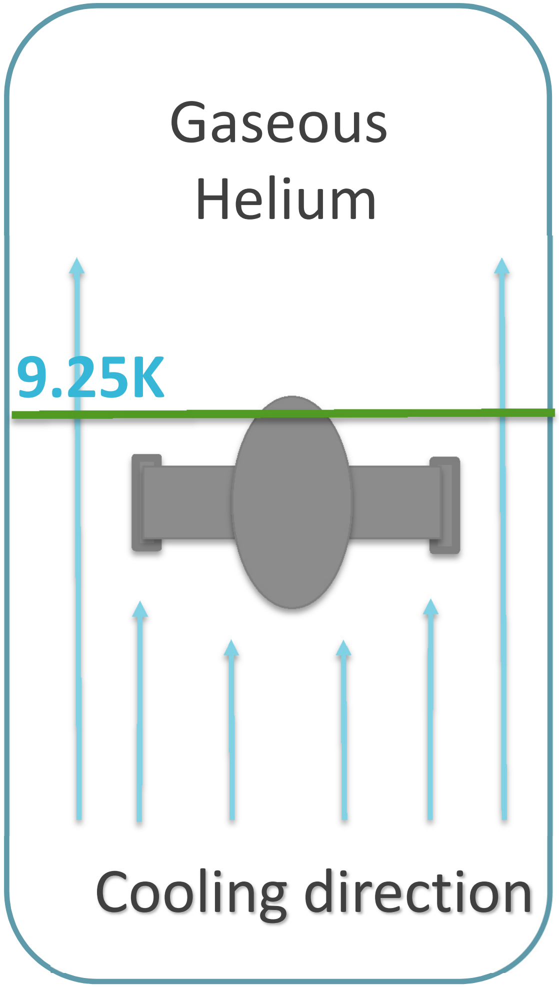
Mechanism #2: Unfavourable geometry of SC phase nucleation

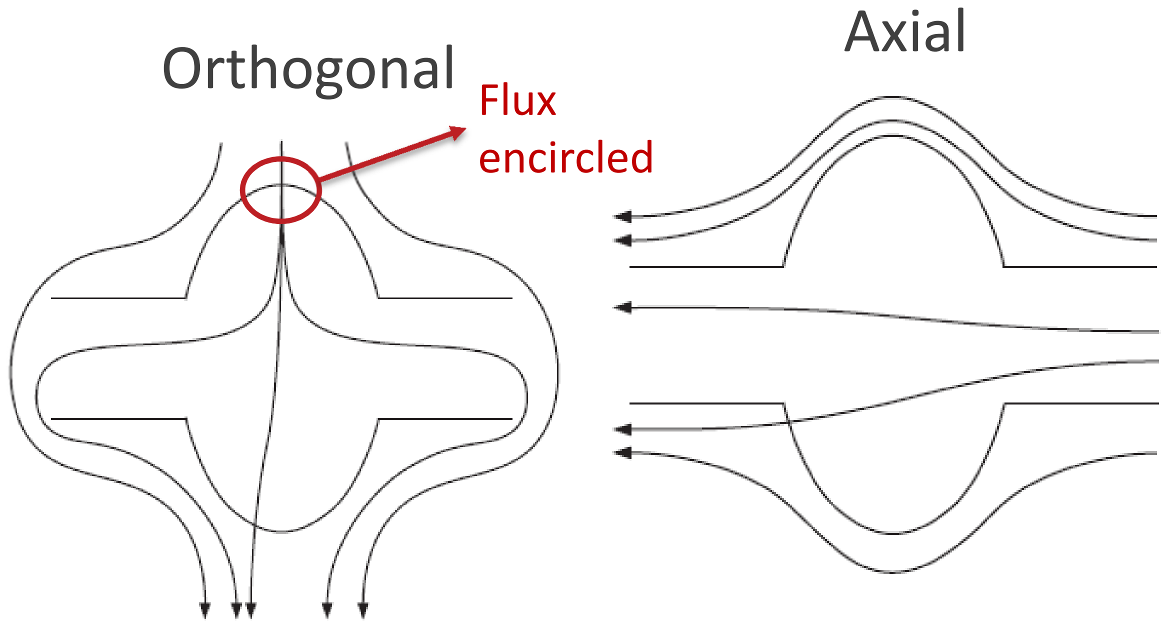
- See [**J. Appl. Phys. 115, 184903 (2014)**] for details



For this mechanism uniformity is “bad” -> leads to islands

More Geometrical Considerations: horizontal cavity



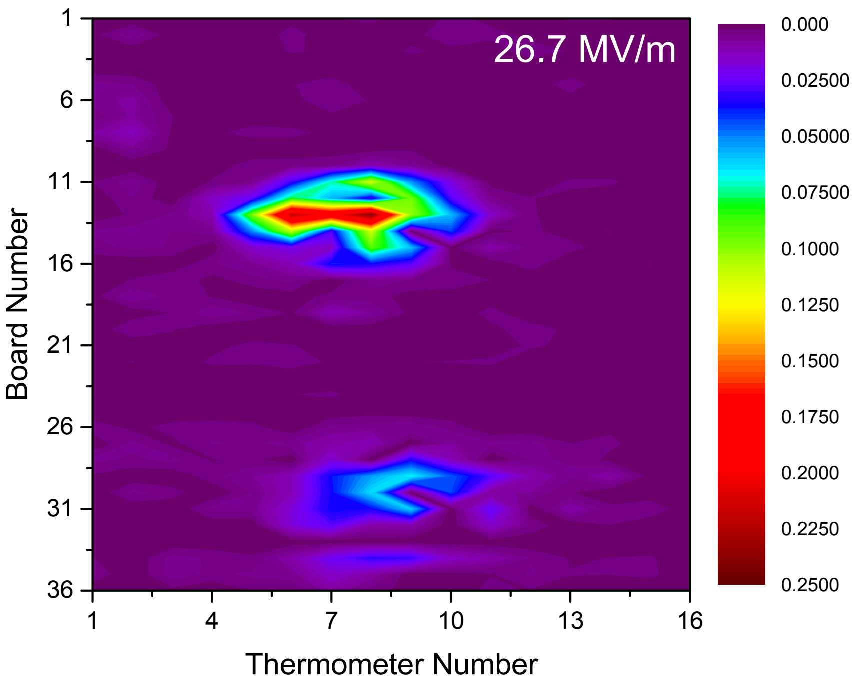


- Orthogonal magnetic field concentrated on top during the cool-down can not be expelled ()
  → **flux-hole** on top on the cavity equator
- Axial magnetic field concentrated on top can be expelled with fast cool-down

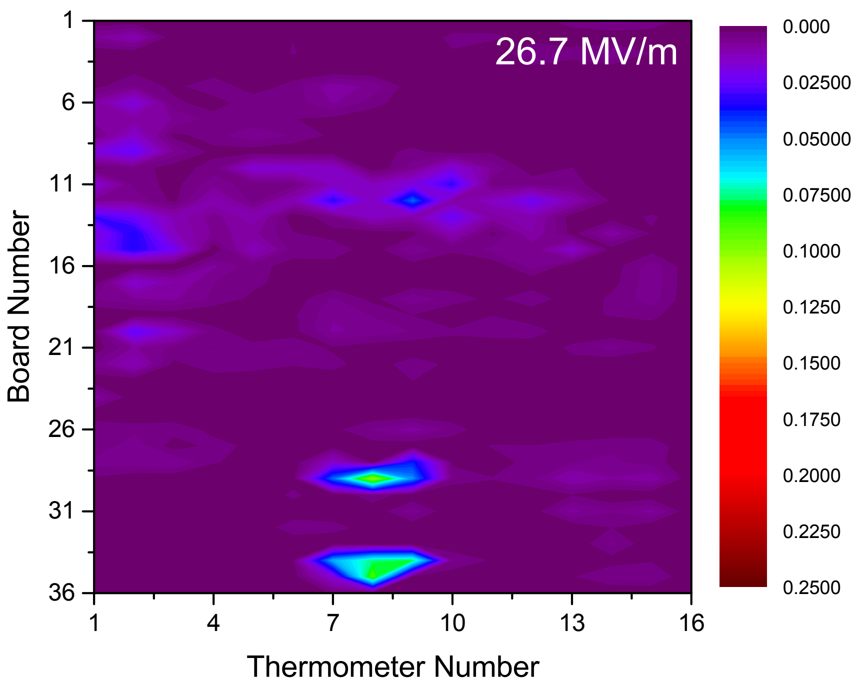
M. Martinello et, al, J. Appl. Phys. **118**, 044505 (2015)

Orthogonal vs Axial ~ 27 MV/m

Orthogonal field – Fast Cool-down



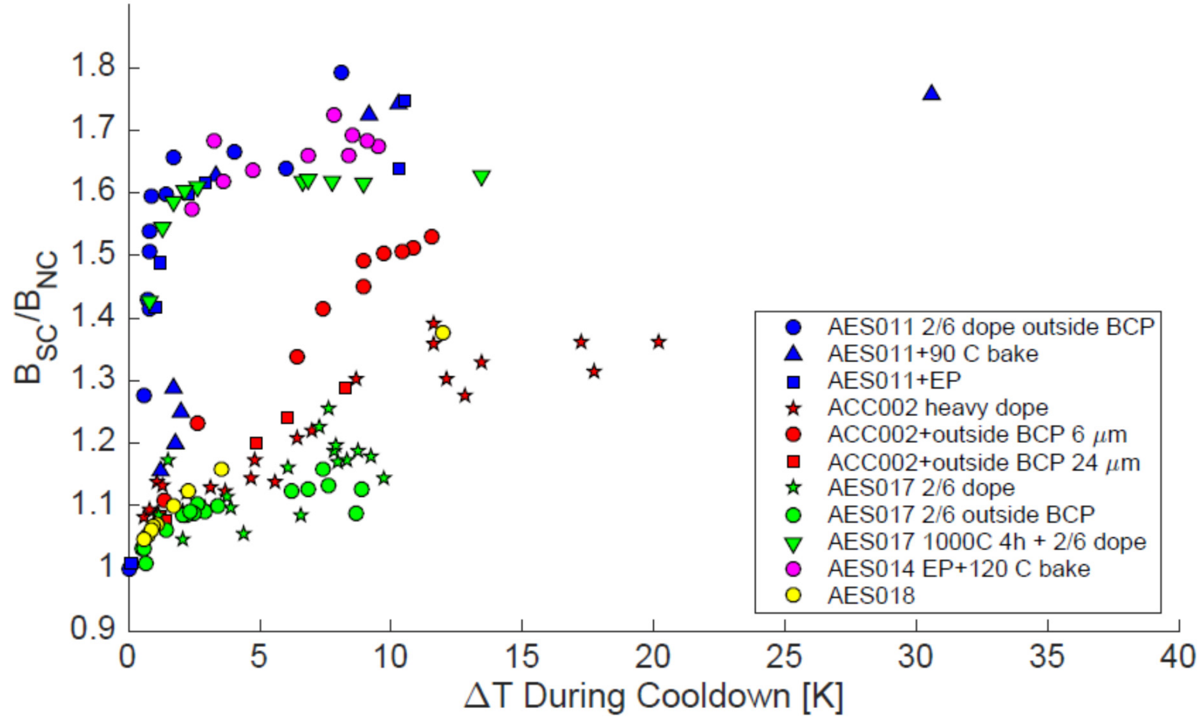
Axial field – Fast Cool-down



[M. Martinello et al, MOPB014]

Trapping Efficiency vs Trapped Flux Sensitivity

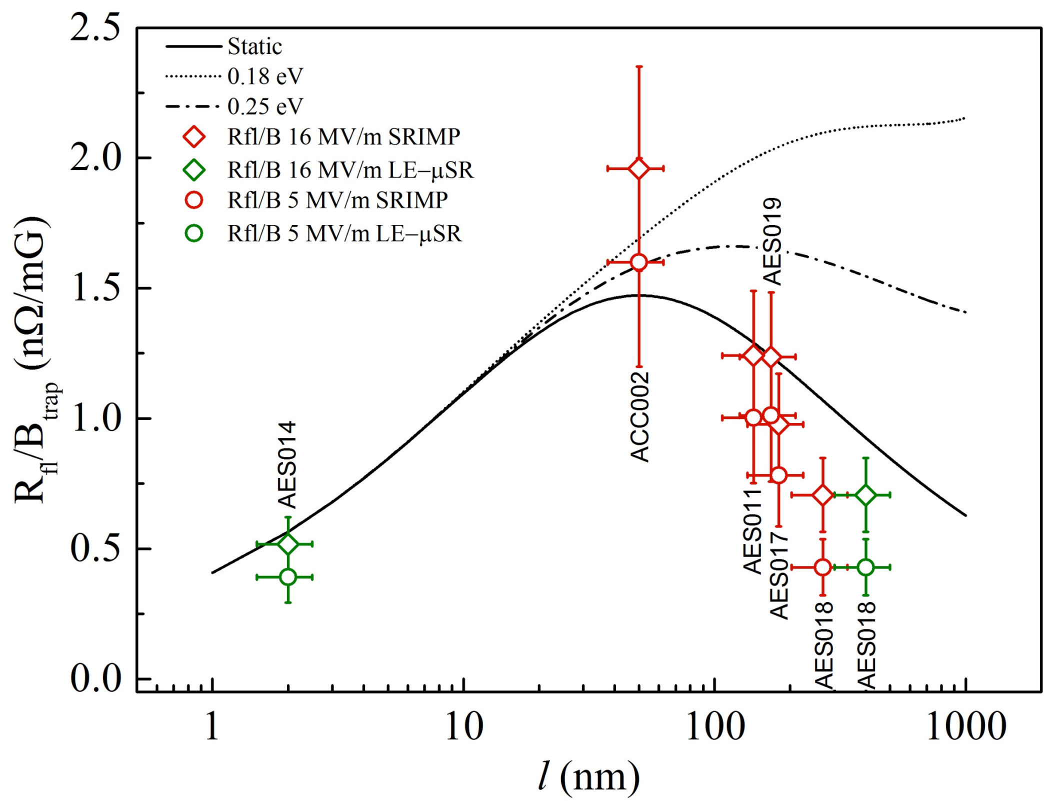
- <u>Trapping Efficiency</u>
  - How much of the magnetic field gets trapped for the given ambient magnetic field at Tc
    - Studied in detail -> [S. Posen et al, MOPB104]
      - Bulk treatment is the driving factor
        - Small grain/more dislocations cavities trap more



Fermilab

Trapping Efficiency vs Trapped Flux Sensitivity

- Trapped Flux Sensitivity
  - For the given amount of trapped flux how much additional dissipation (surface resistance) emerges
    - Studied in detail -> [M. Martinello et al, MOPB015]
      - Surface treatment is the driving factor
        - Nitrogen doped cavities are more sensitive



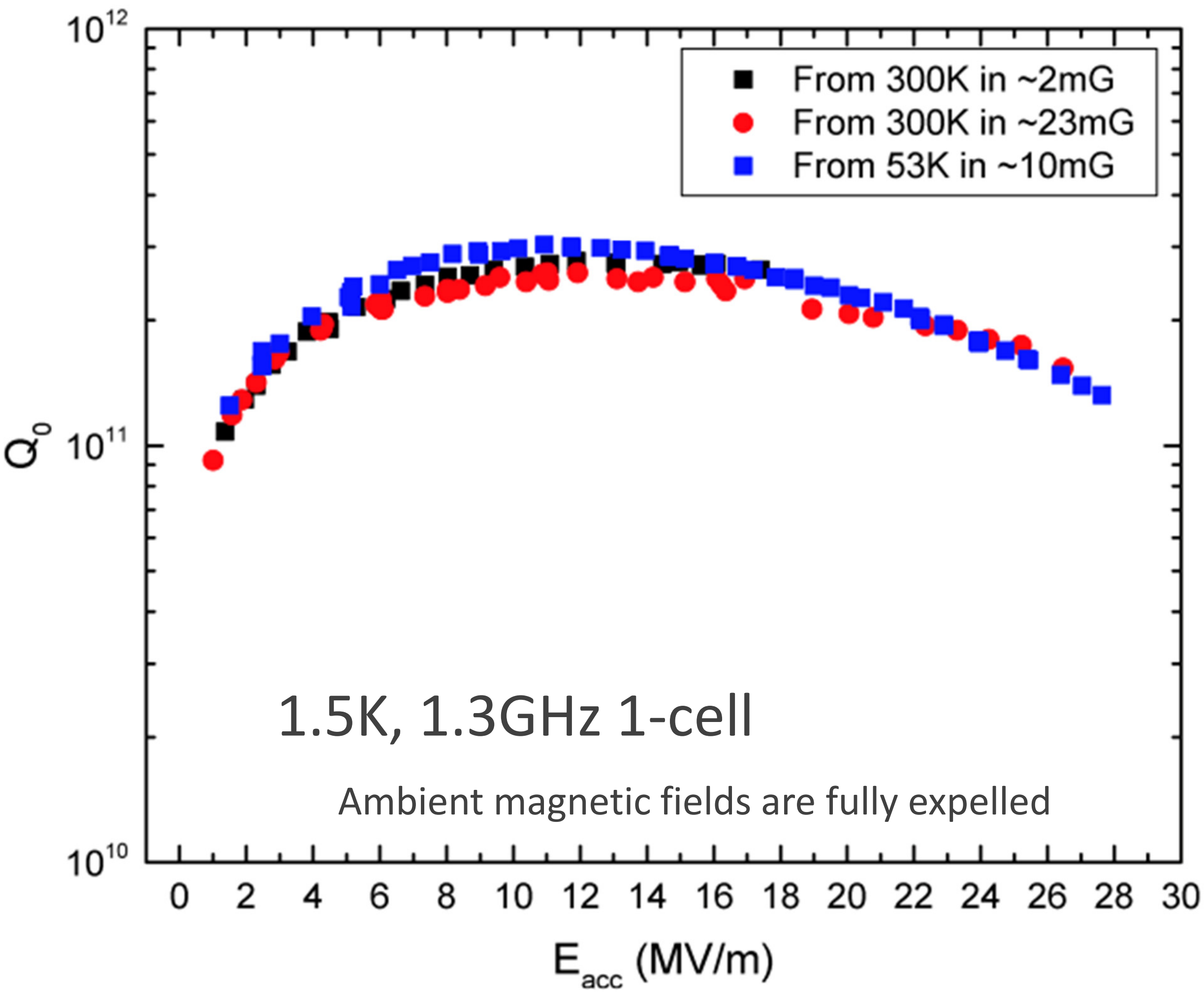
BEST to find out optimal cooling conditions to maximize Q (bare, dressed/cryomodule) as they reveal trapped flux the best

- Whatever is best for N-doped is best for EP, EP/120C etc

Use slow cooling to trap all flux and then measure dissipation

- Utilizing expulsion physics for record Qs

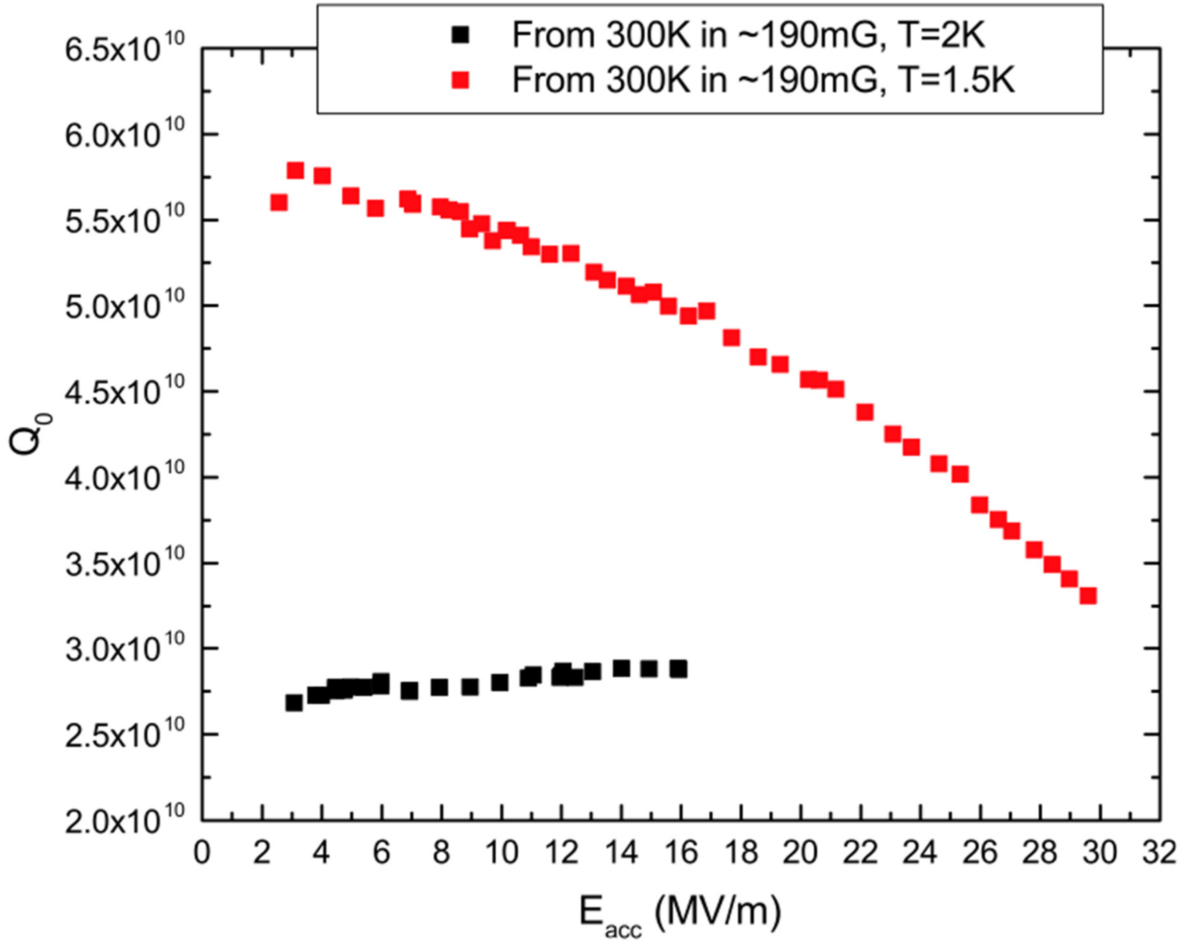
Utilizing new physics for record high Qs – bare 1-cell



Combination of nitrogen doping and efficient flux expulsion =>
Record high Q >1e11 up to 28 MV/m in SRF cavities

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)

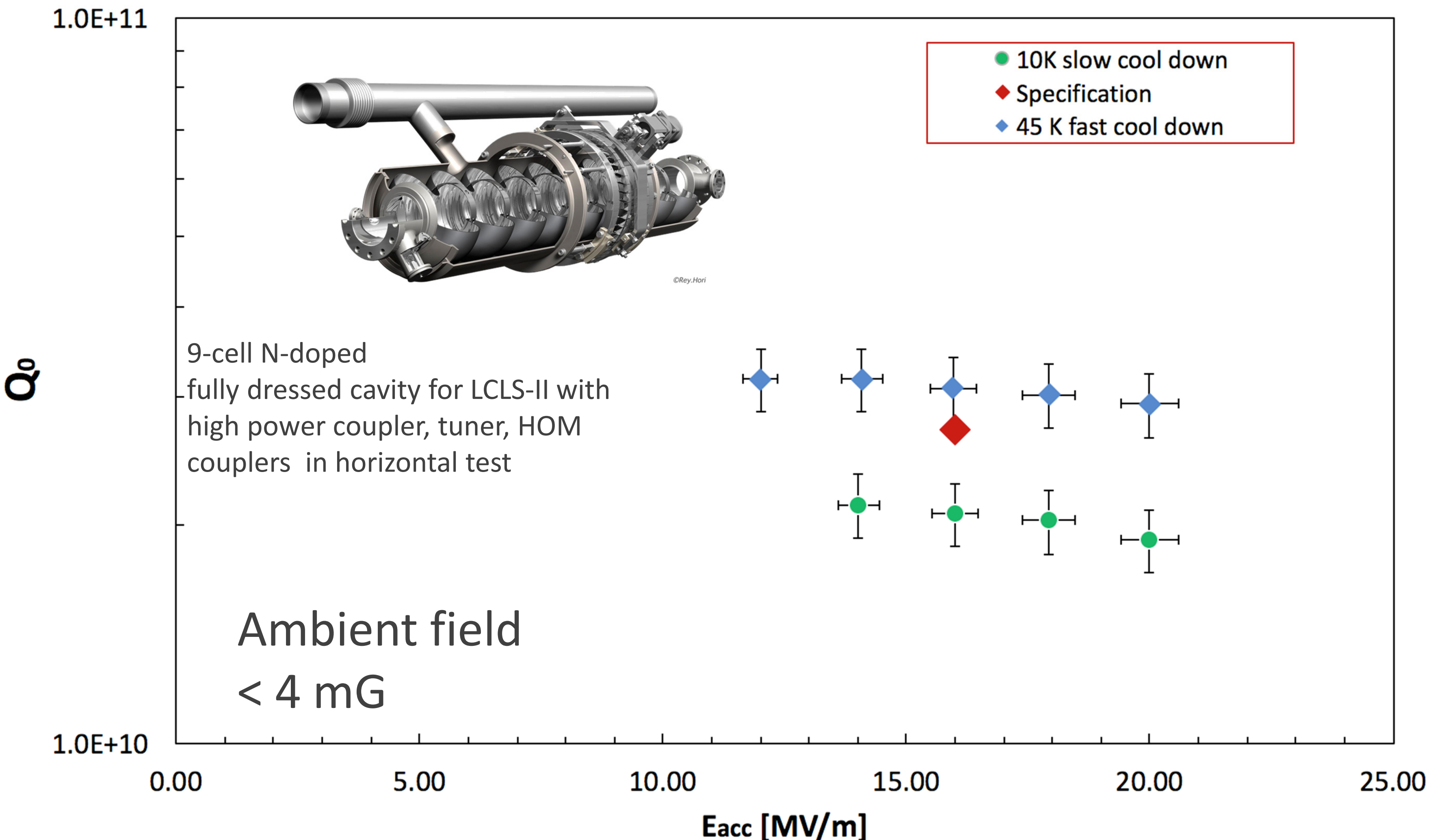
Expelling 190 mG



Q > 2.7e10 at 2K, 16MV/m in 190 (!) mG ambient field

A. Romanenko, A. Grassellino, A. C. Crawford, D. A. Sergatskov, and O. Melnychuk, Appl. Phys. Lett. **105**, 234103 (2014)

Bringing it all together: N-doped dressed cavity in cryomodule environment



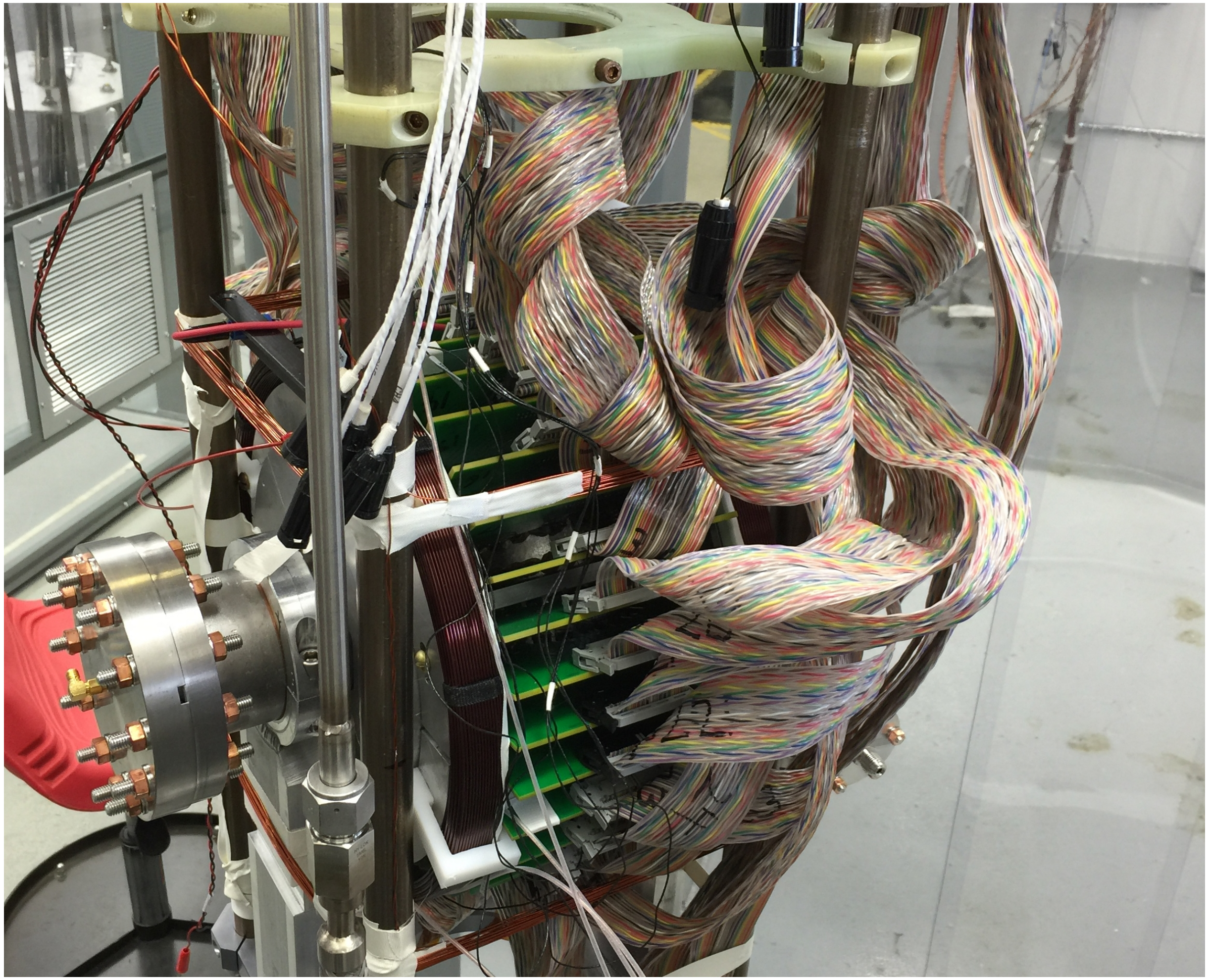
[see MOBA06, MOP028, THBA06, MOPB087]

Summary

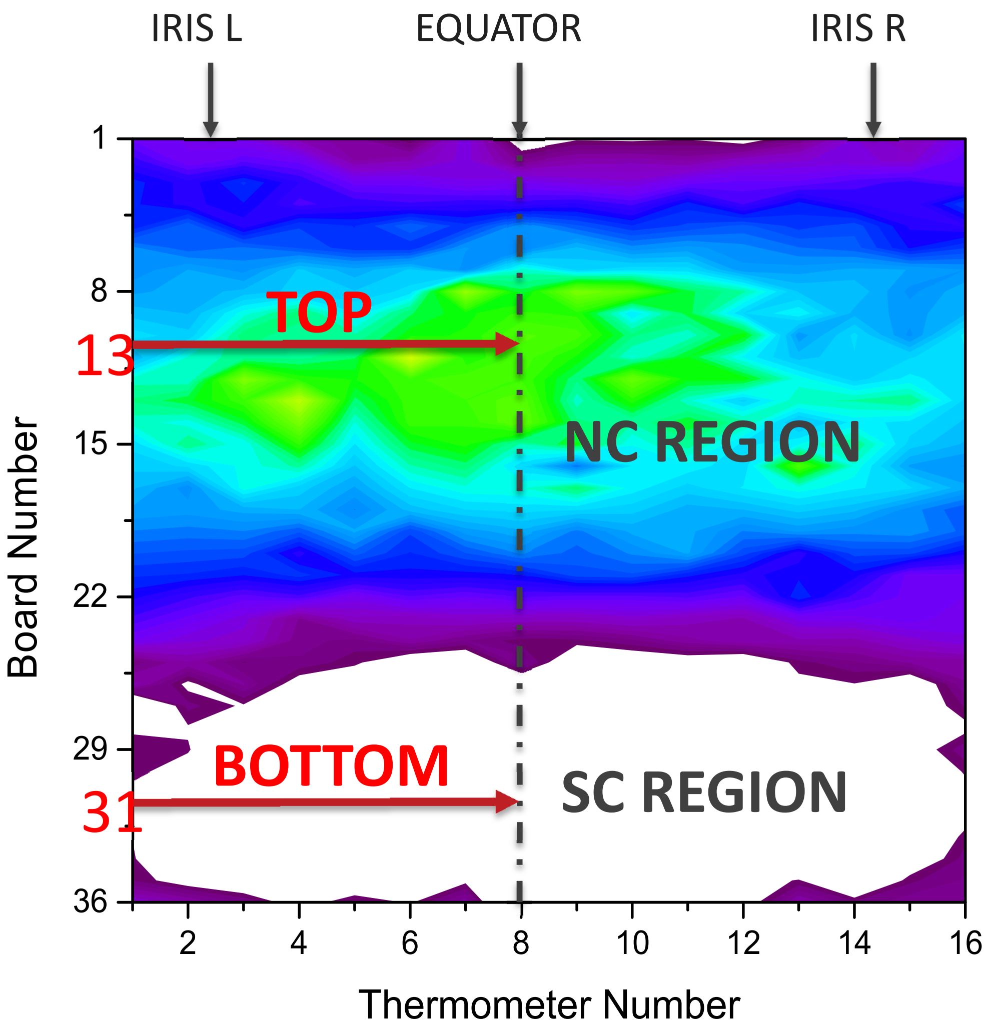
- Discovery at Fermilab
  - Magnetic flux can be expelled from cavity walls by fast/high thermal gradient cooldown
  - Allows achieving record low residual resistances
    - Examples:
      - $Q = 2.7 \times 10^{11}$ in 27 mG ambient field;
      - $Q > 5.5 \times 10^{10}$ in 190 mG ambient field
- Understanding has much progress
  - Mechanism of expulsion (or non-trapping) [MOPB104]
  - Importance of bulk properties [MOPB104]
  - Surface treatment effect [MOPB015, MOPB020]
  - Geometry effect (horizontal vs vertical) [MOPB014]
  - Is cryomodule configuration/performance any different? [MOBA06, MOP028, THBA06]
- Slow cooldown = best (SRF'2013)?
  - Not true for current magnetic environments

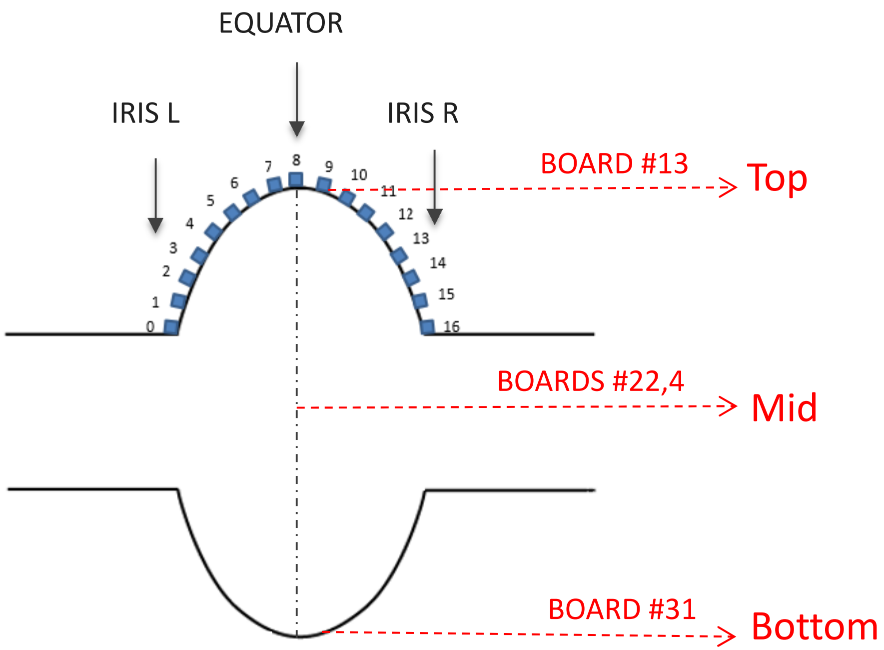
THANK YOU

Observing fast and slow cooldown dynamics



T-map cooling capturing

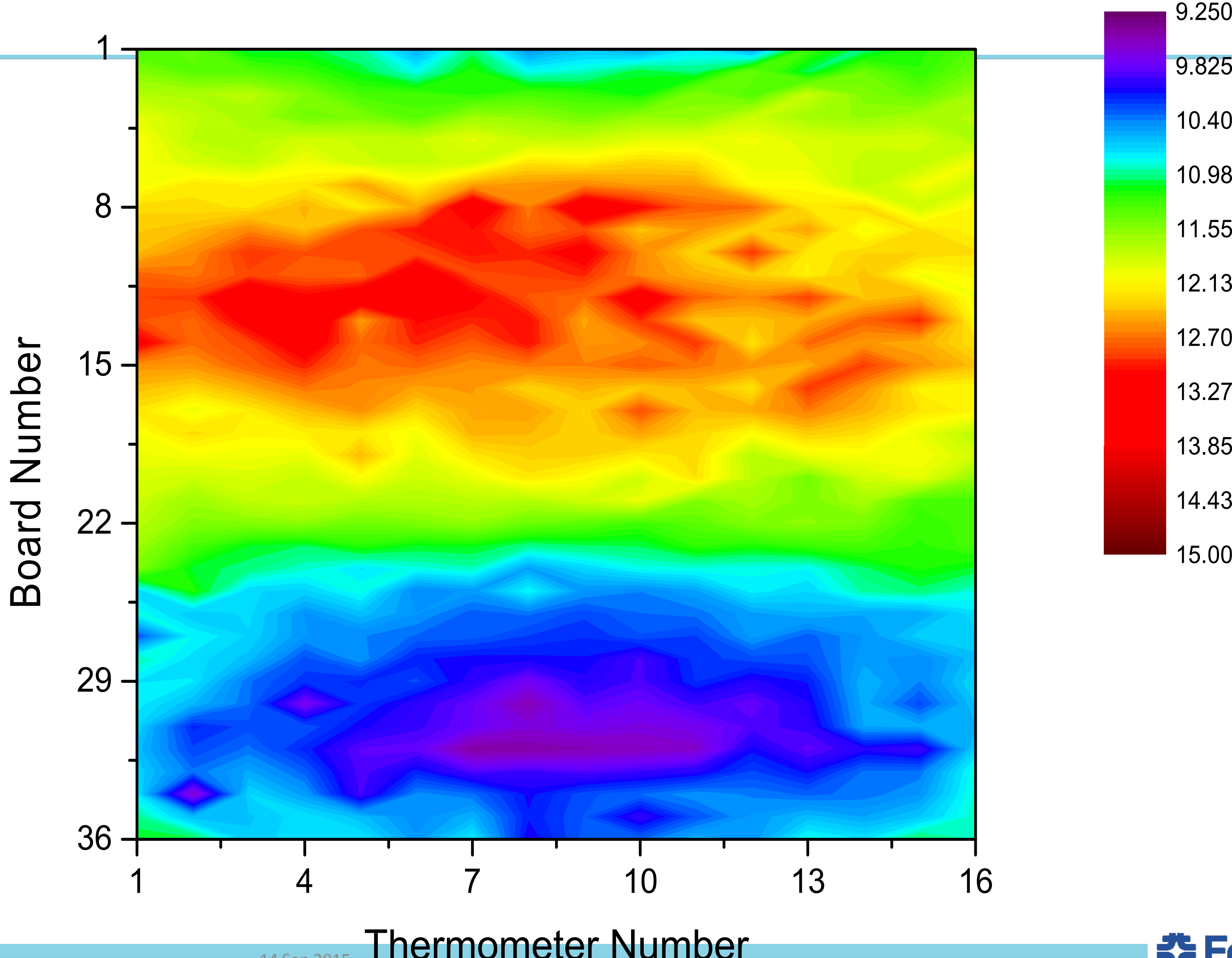




Fast Cool-down T-map

Starting T: 250K

Fast Cool-down From 250K



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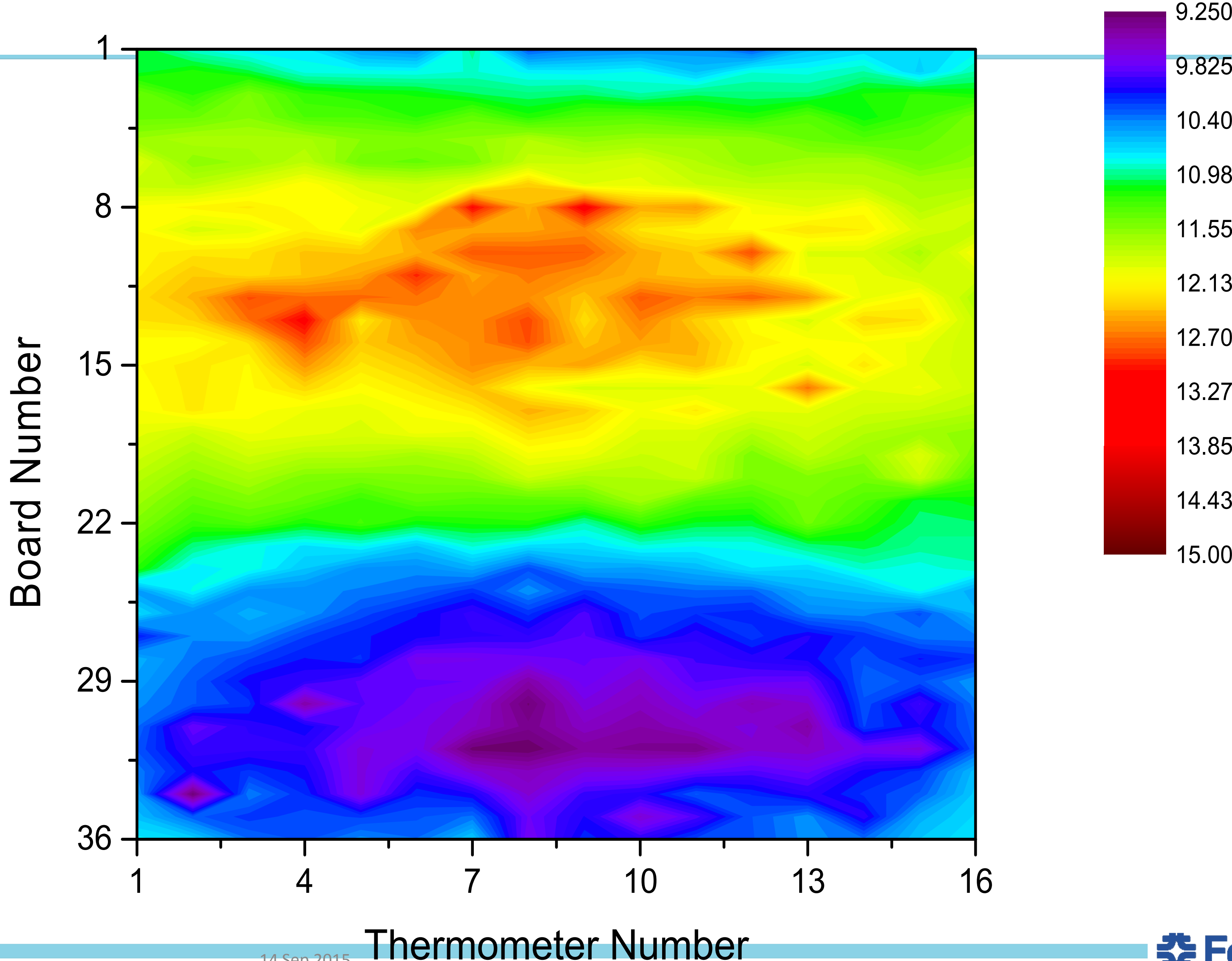

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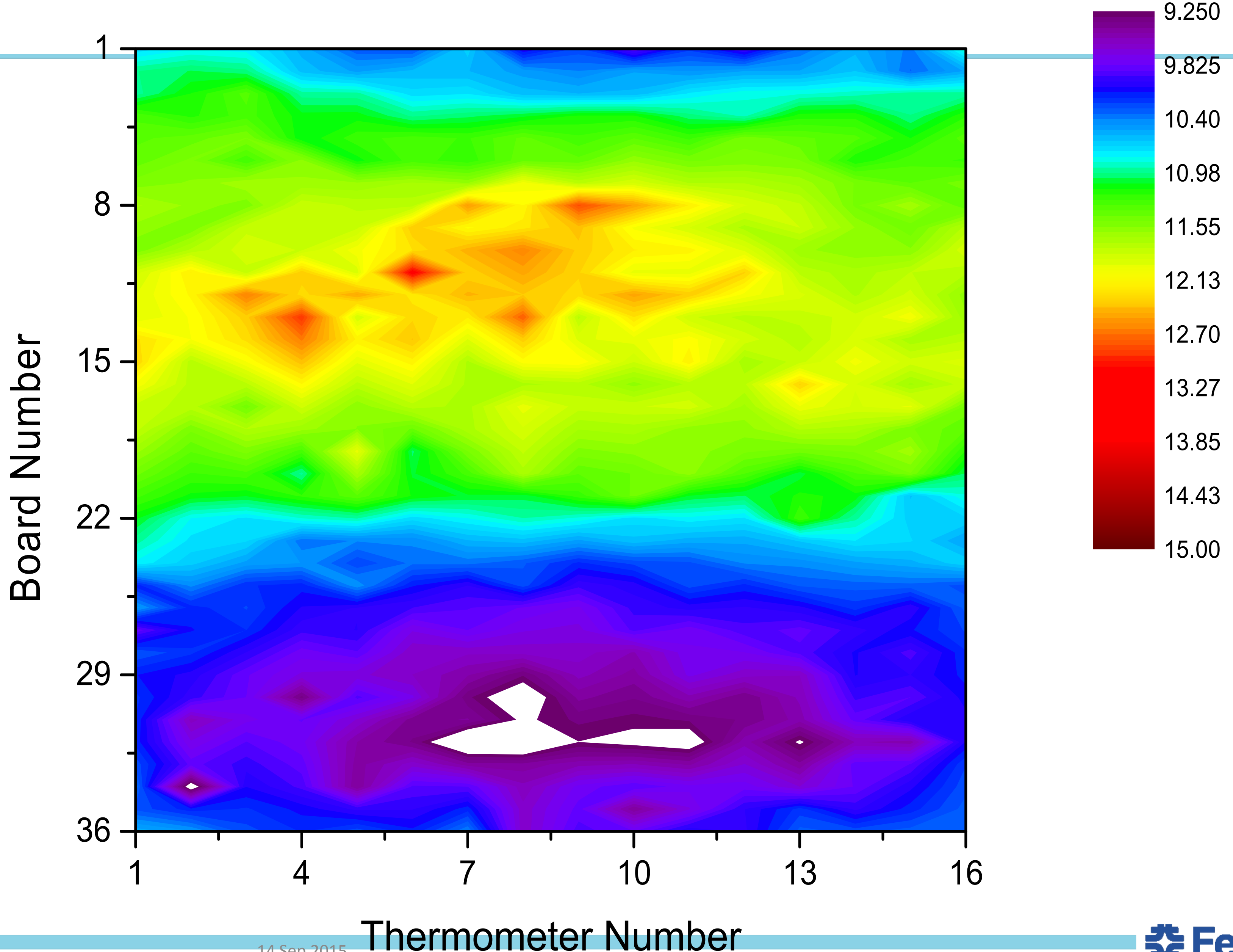

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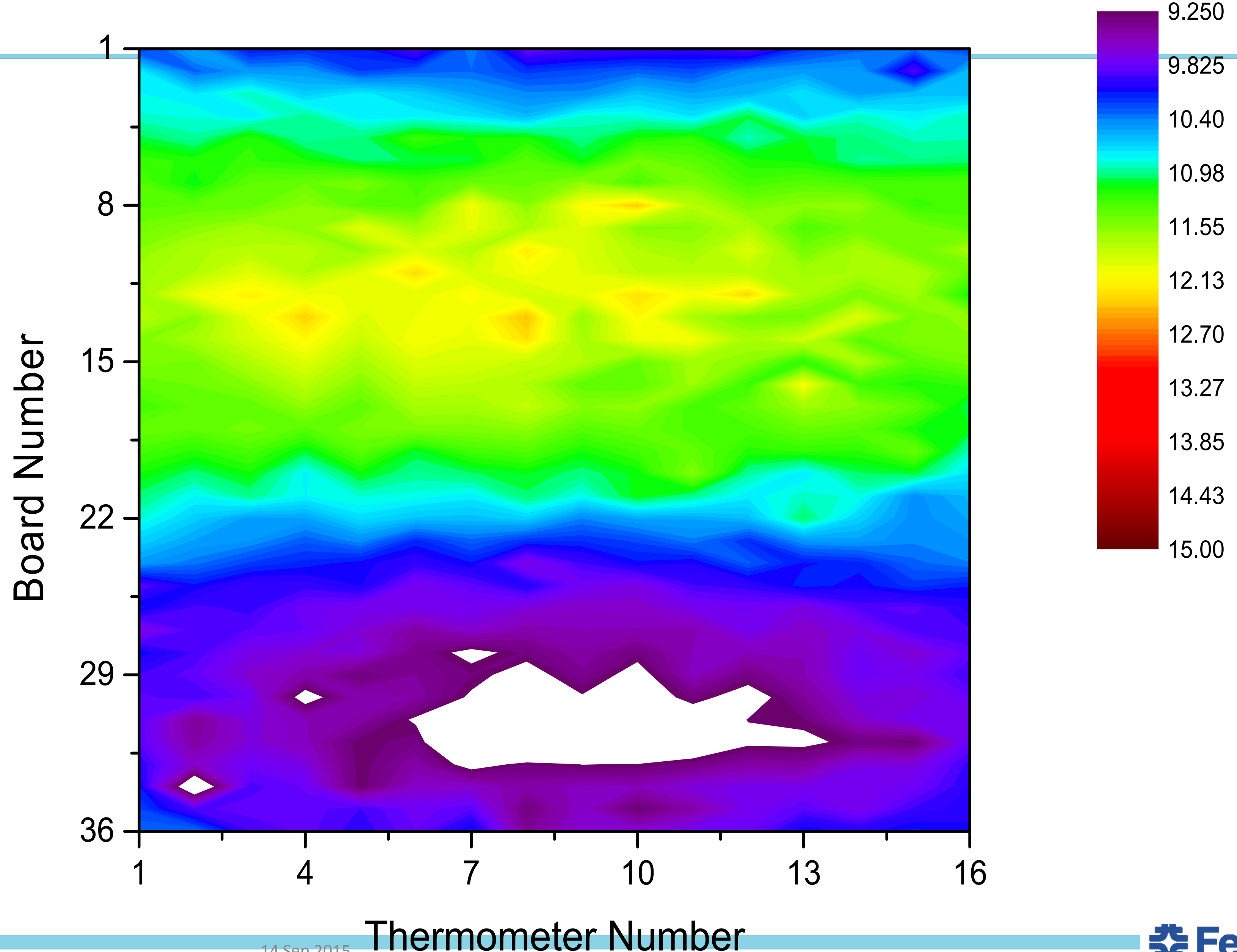

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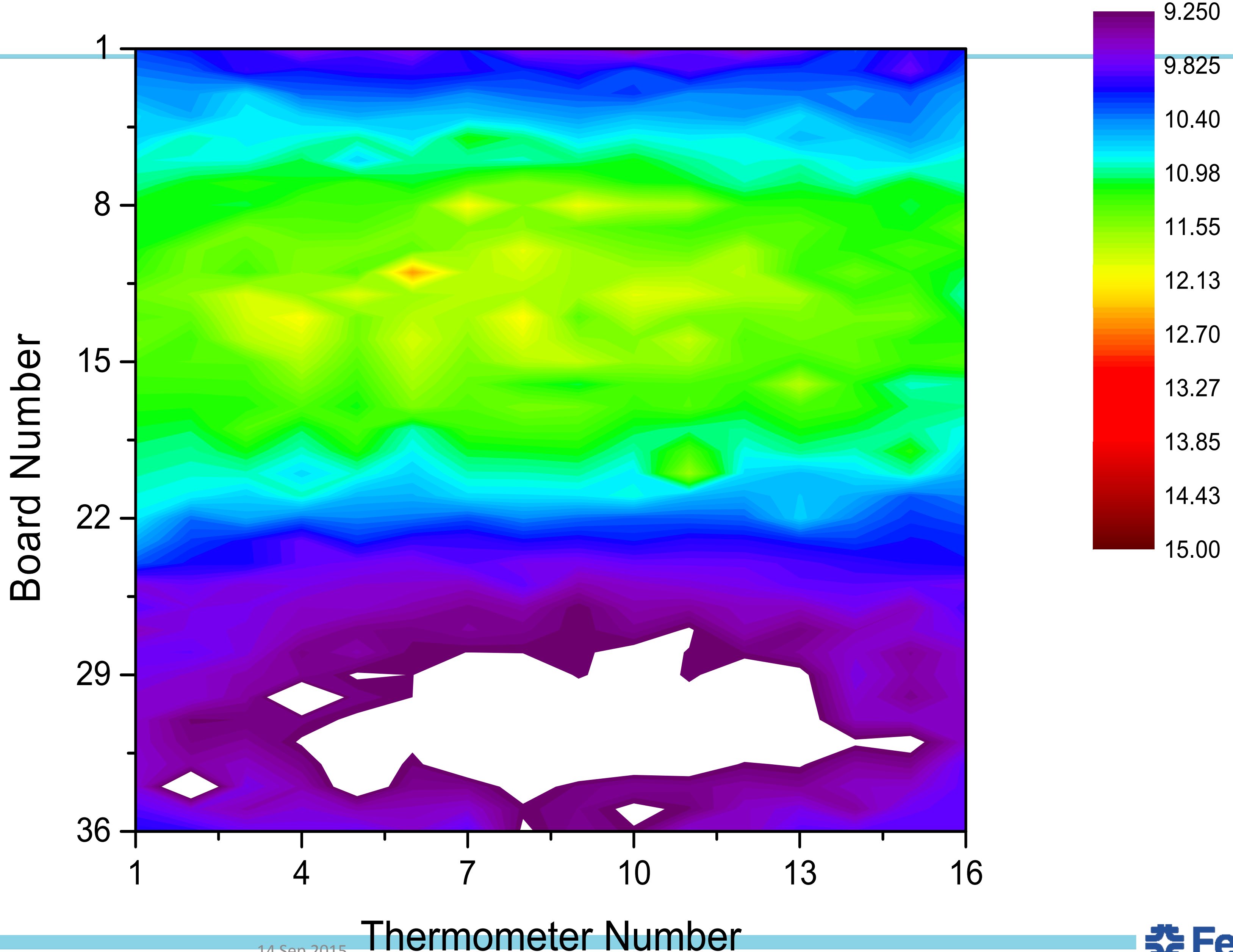

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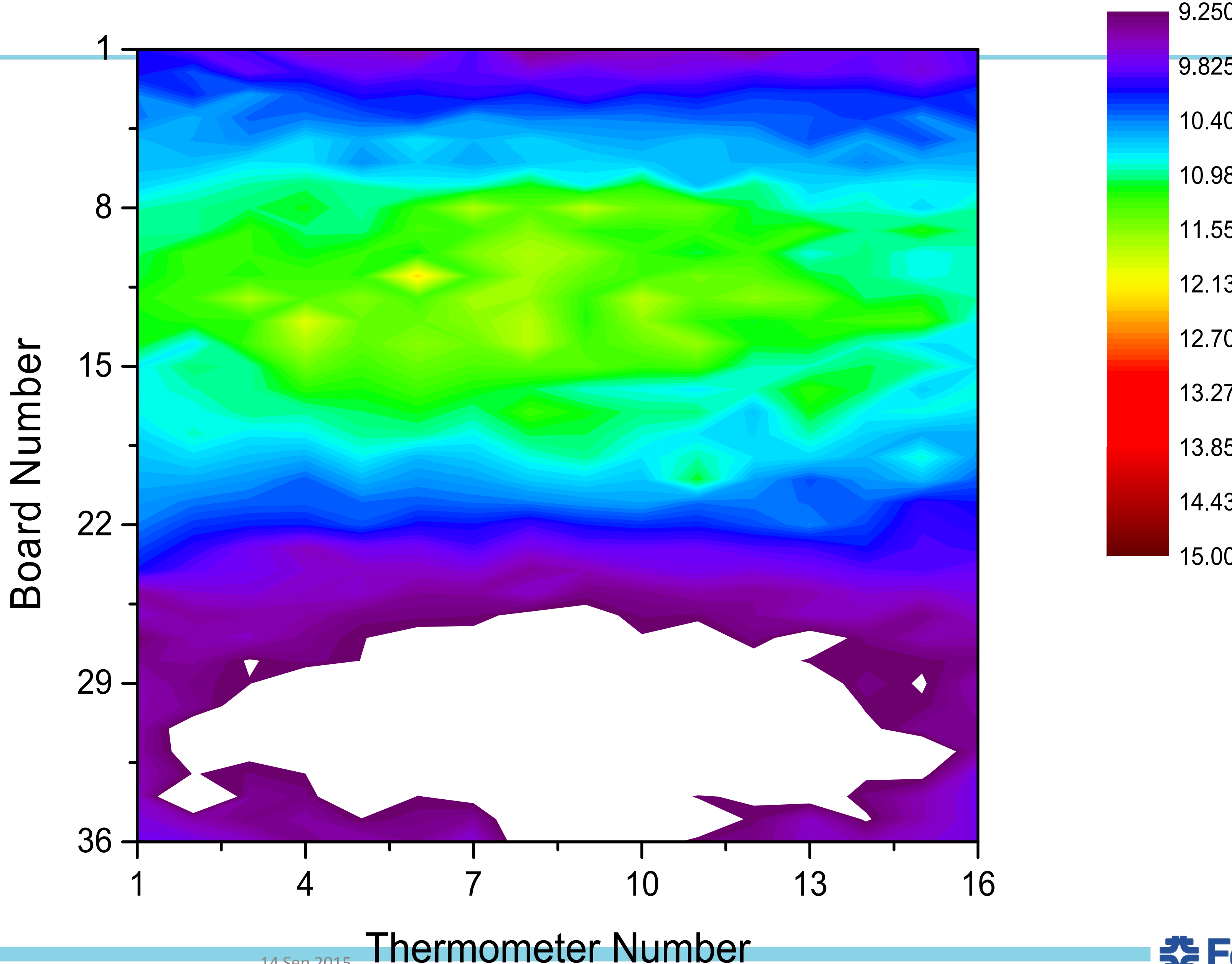

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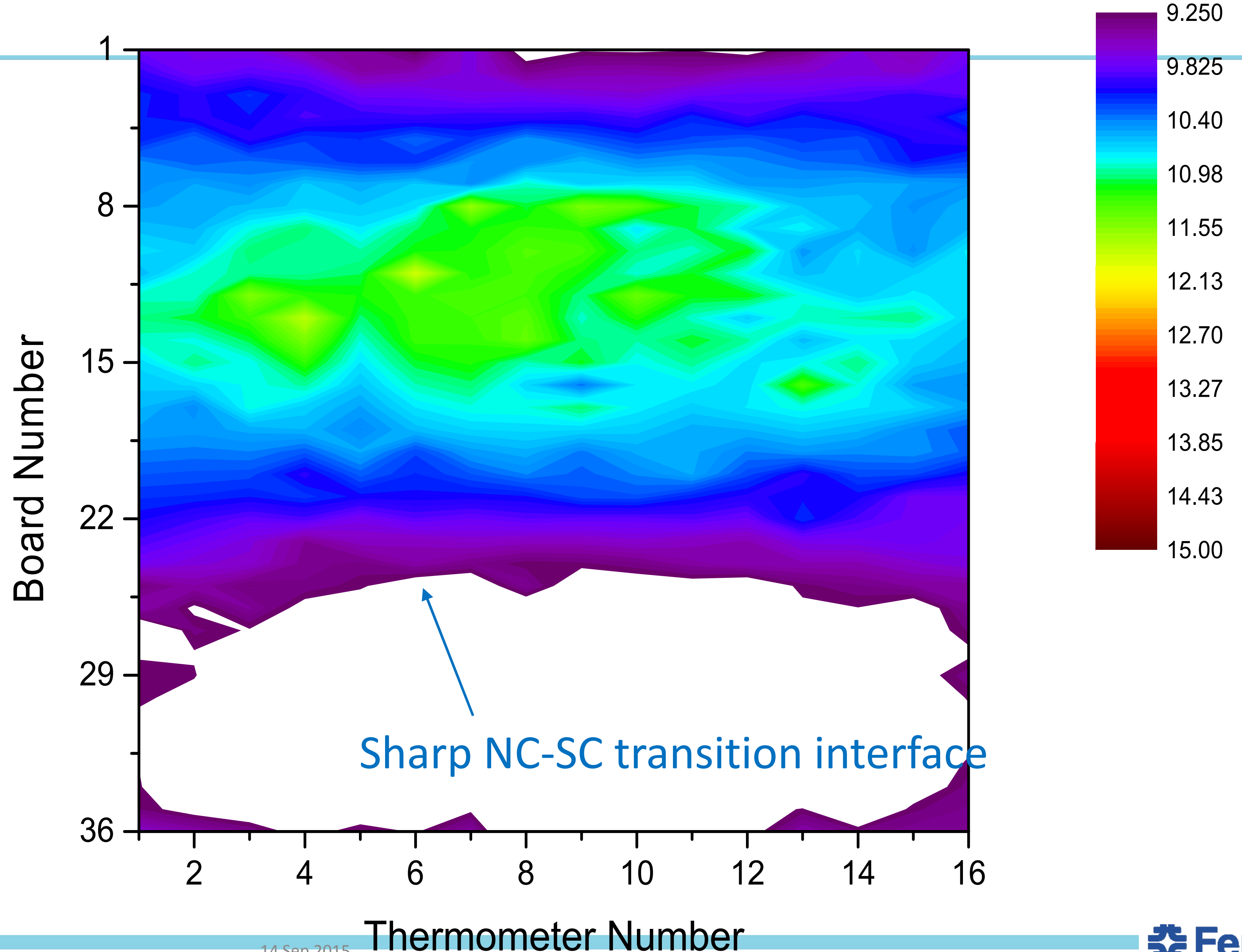

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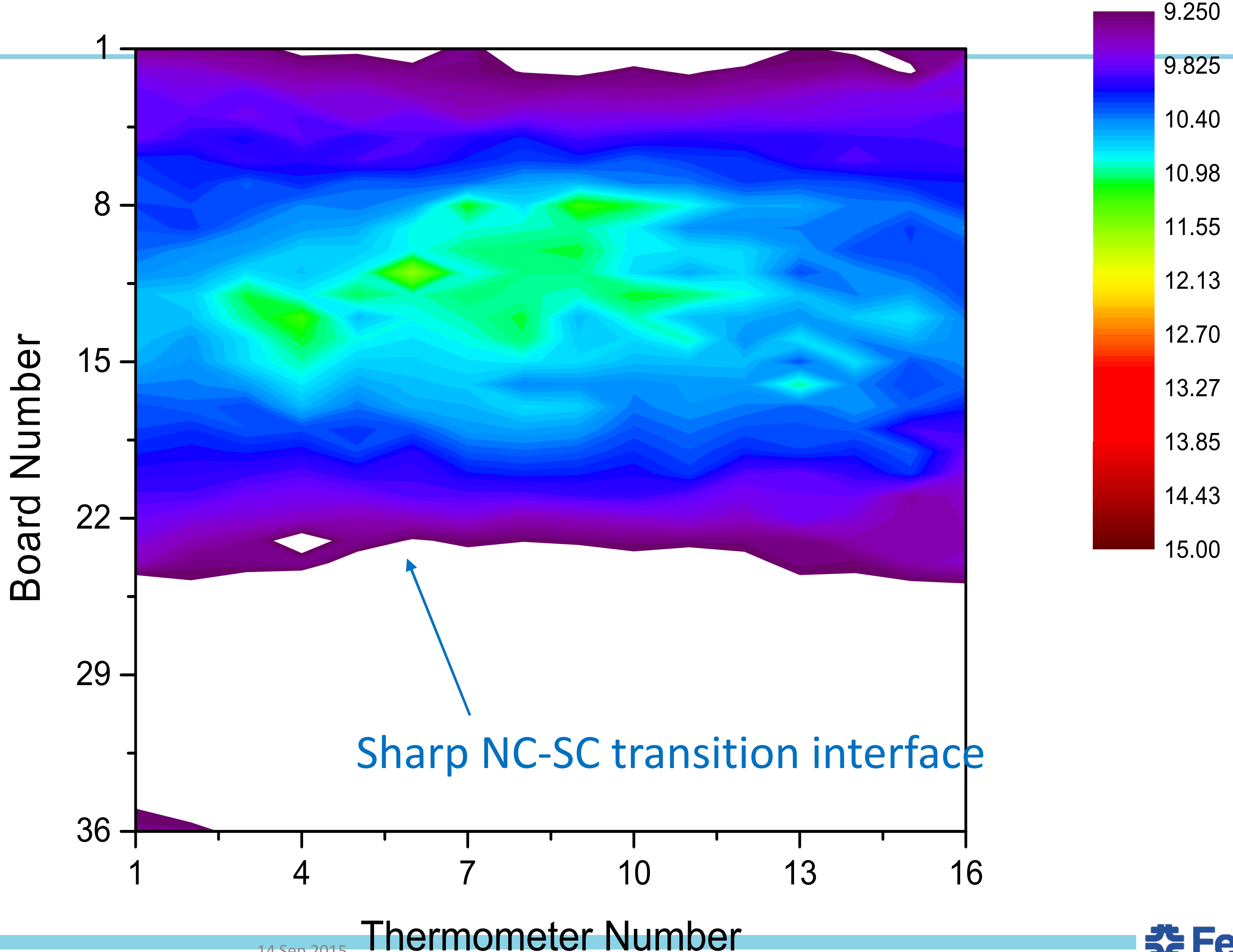

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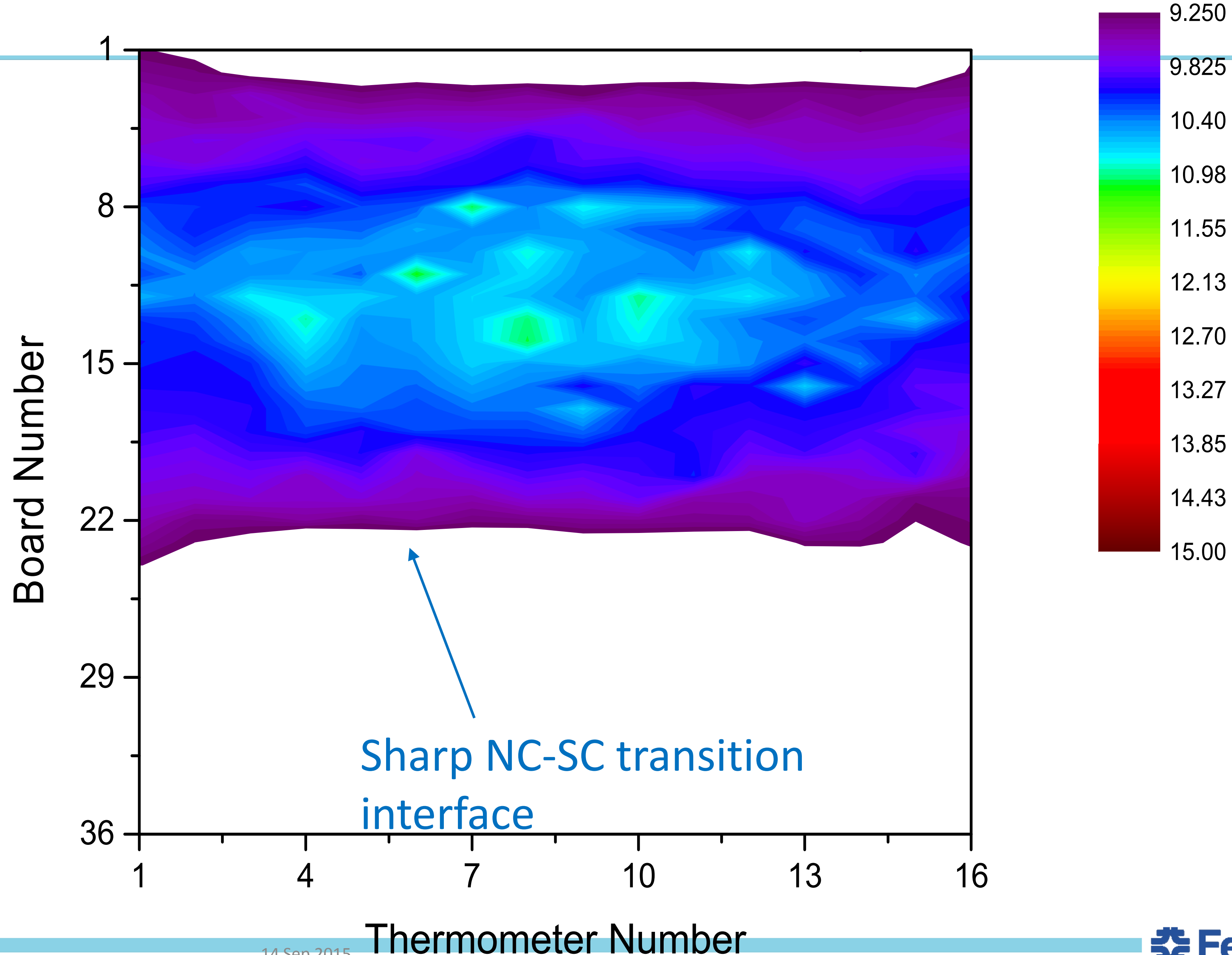

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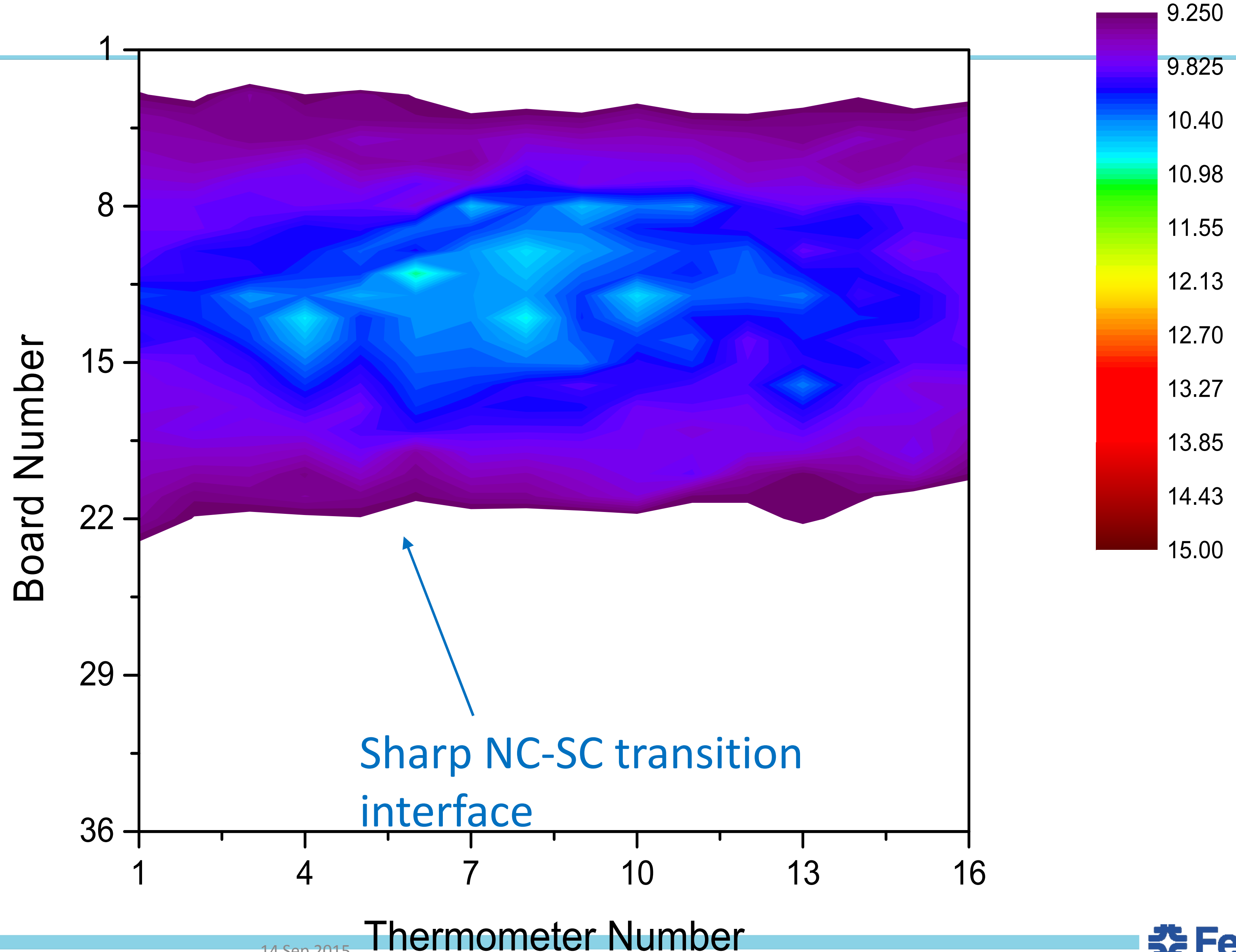

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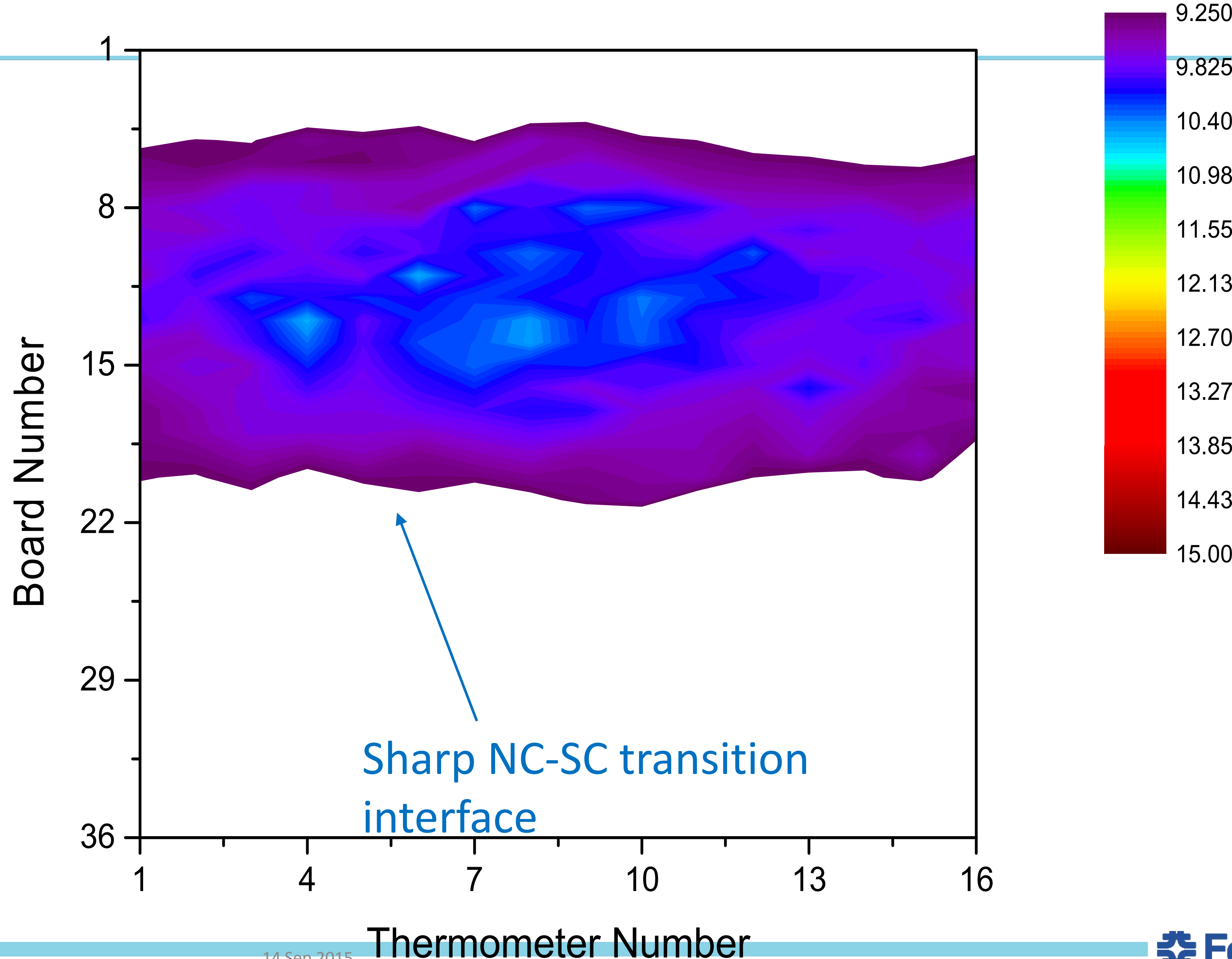

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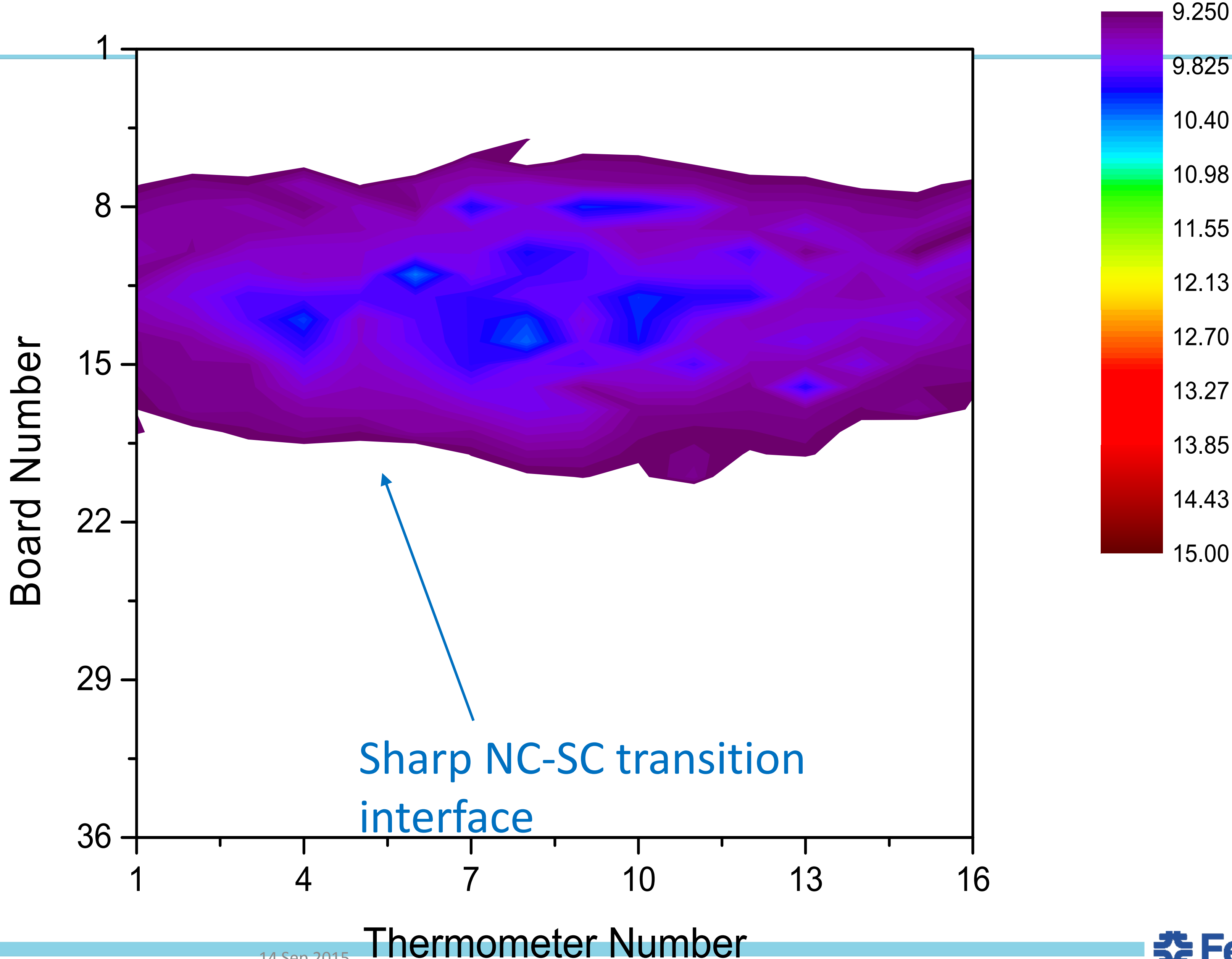

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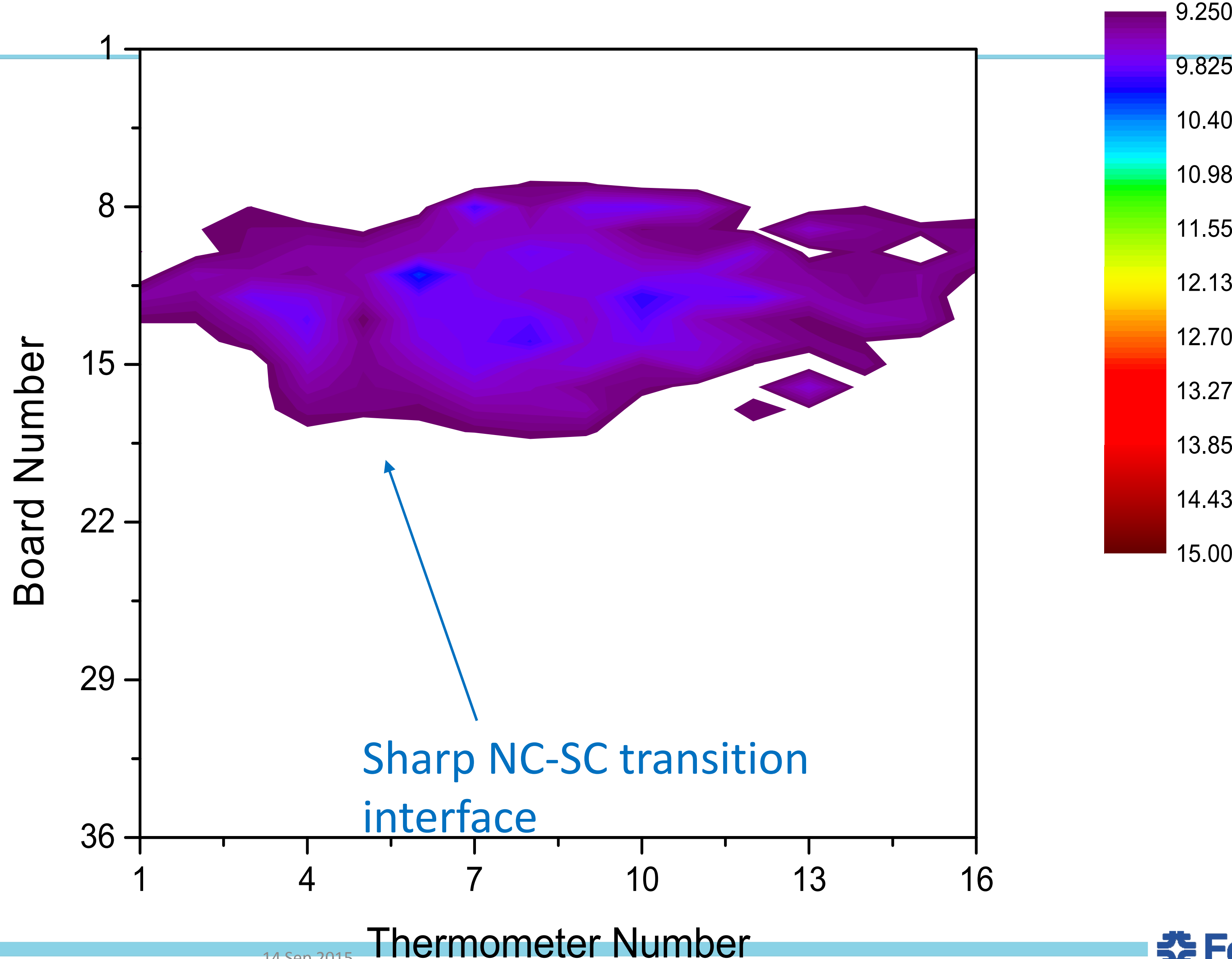

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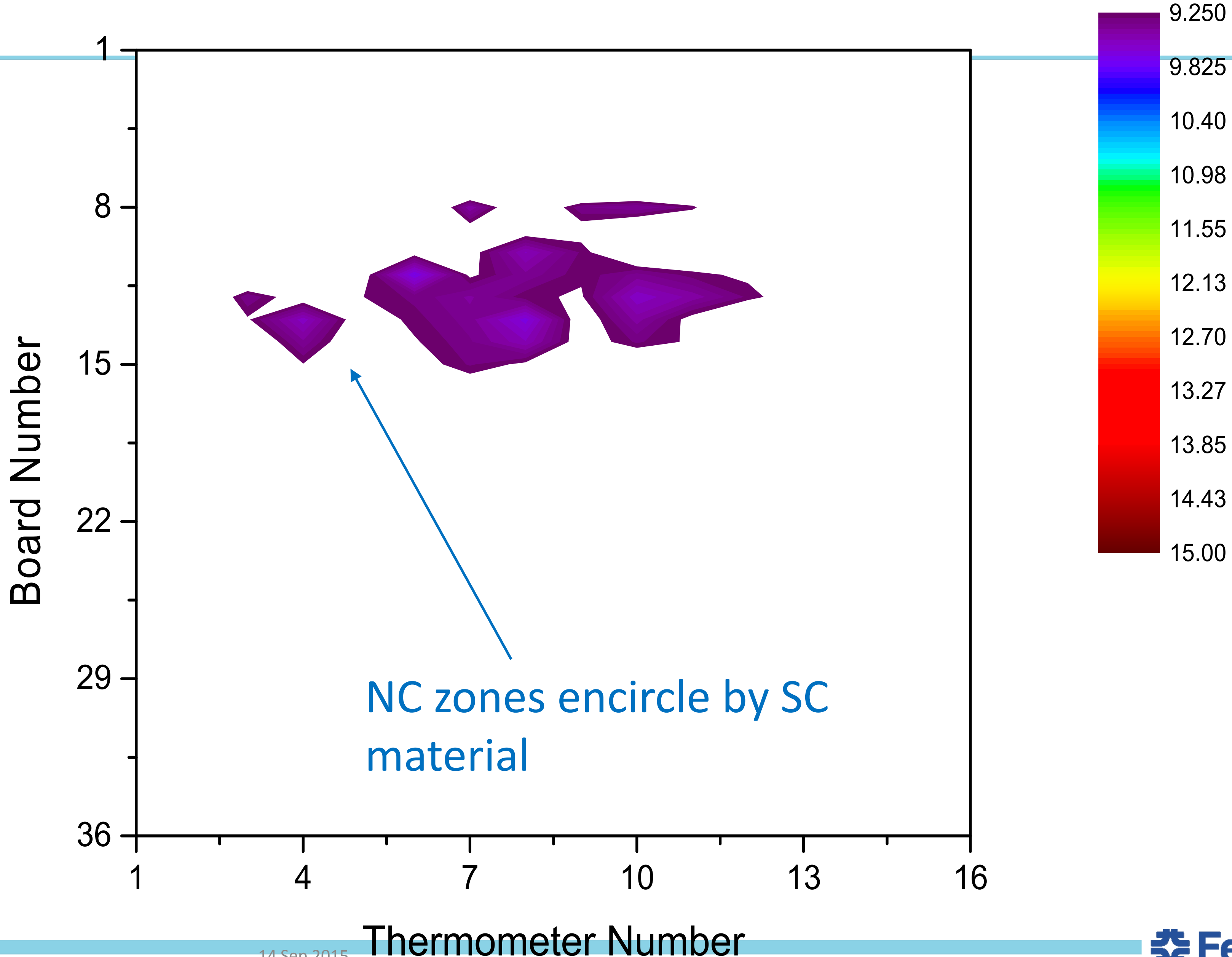

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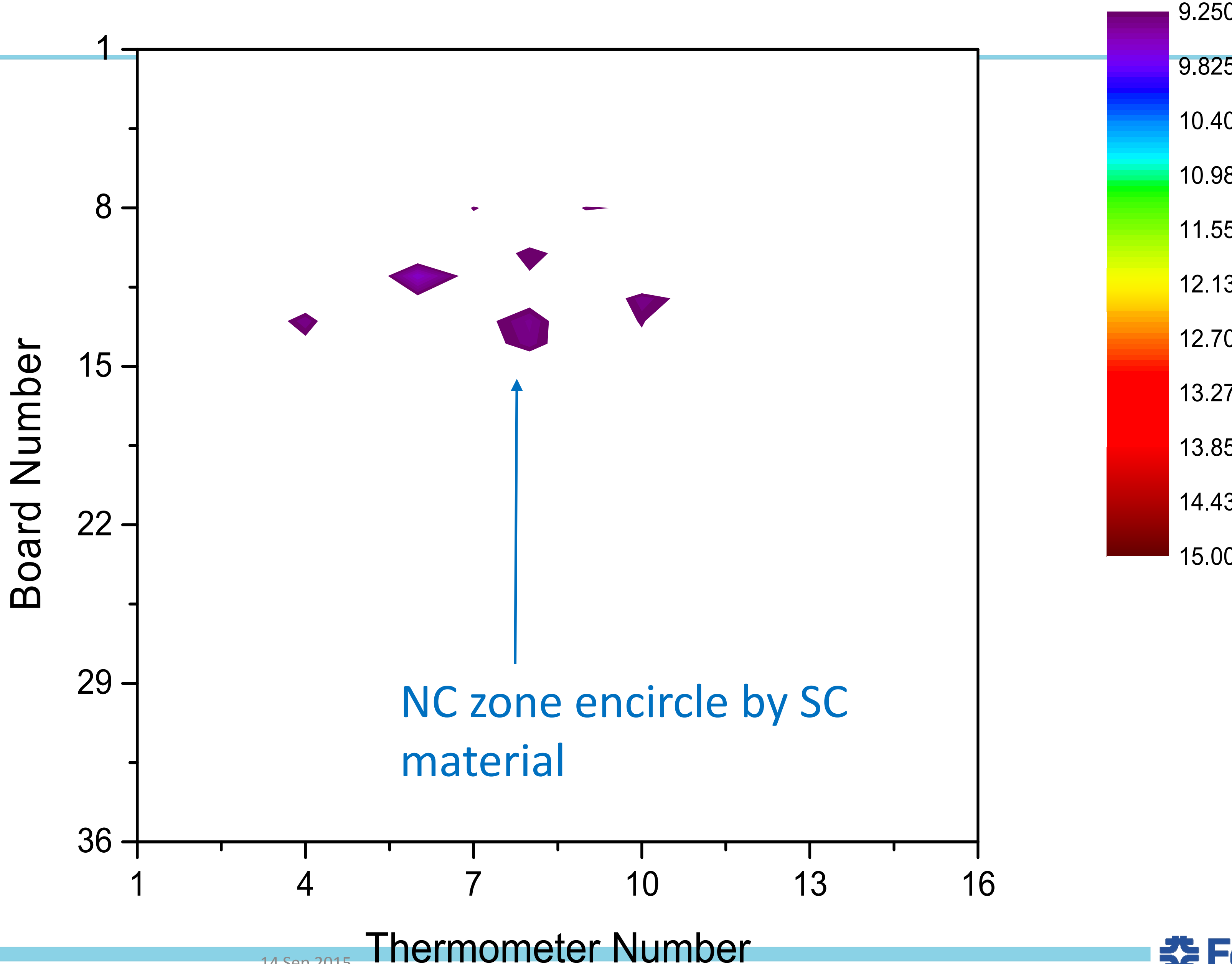

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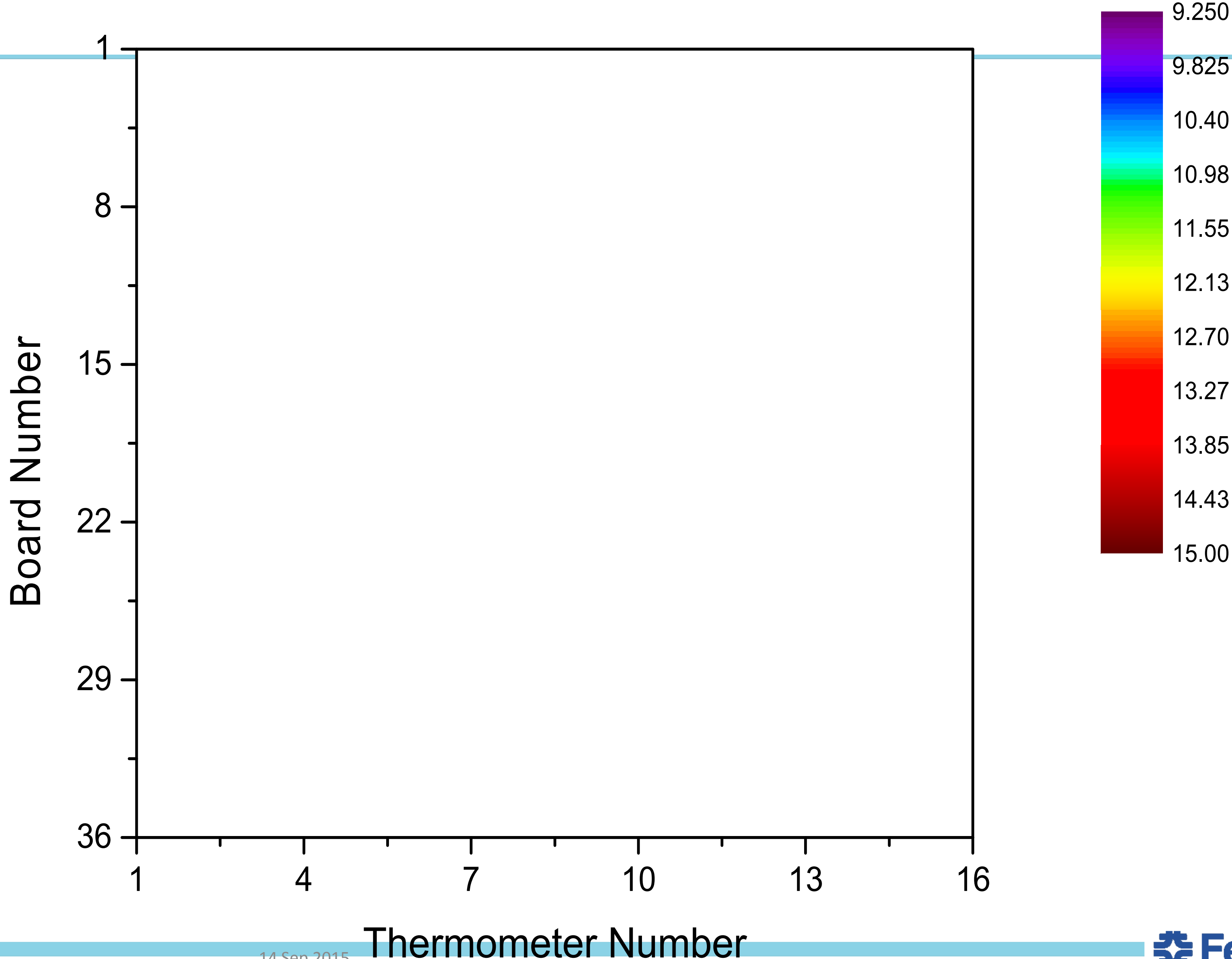
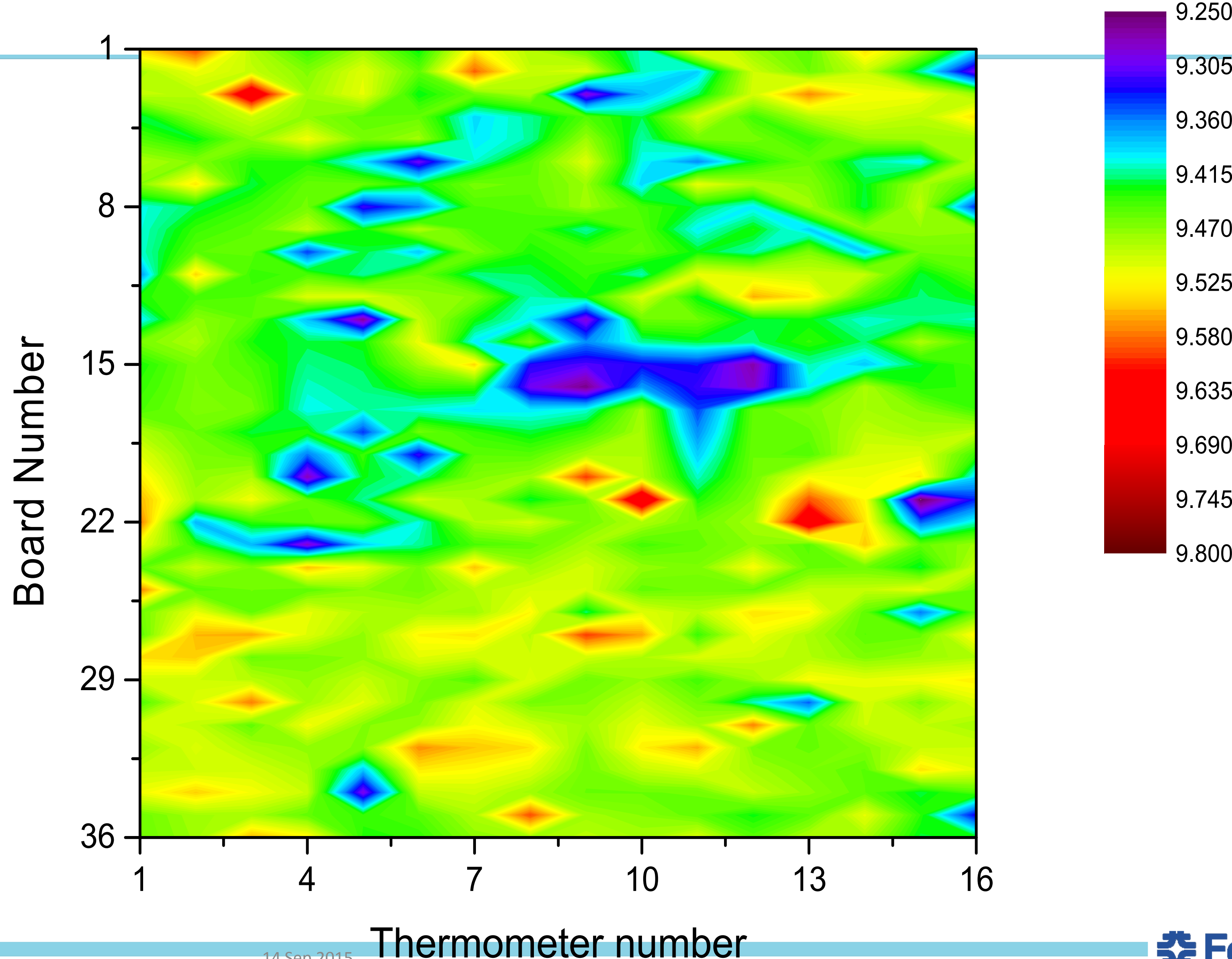


Slow Cool-down T-map

Starting T: 12K

Slow Cool-down From 12K



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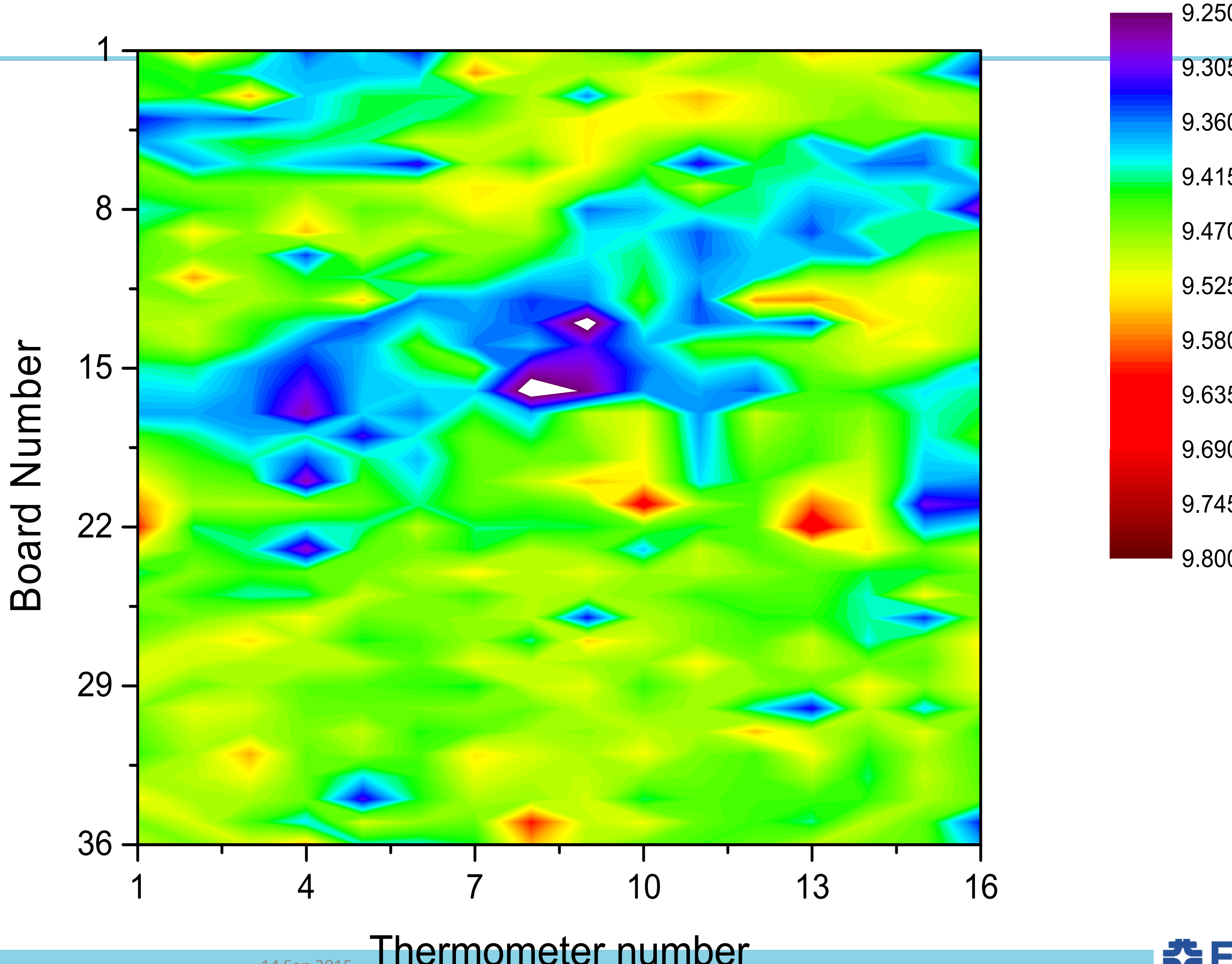

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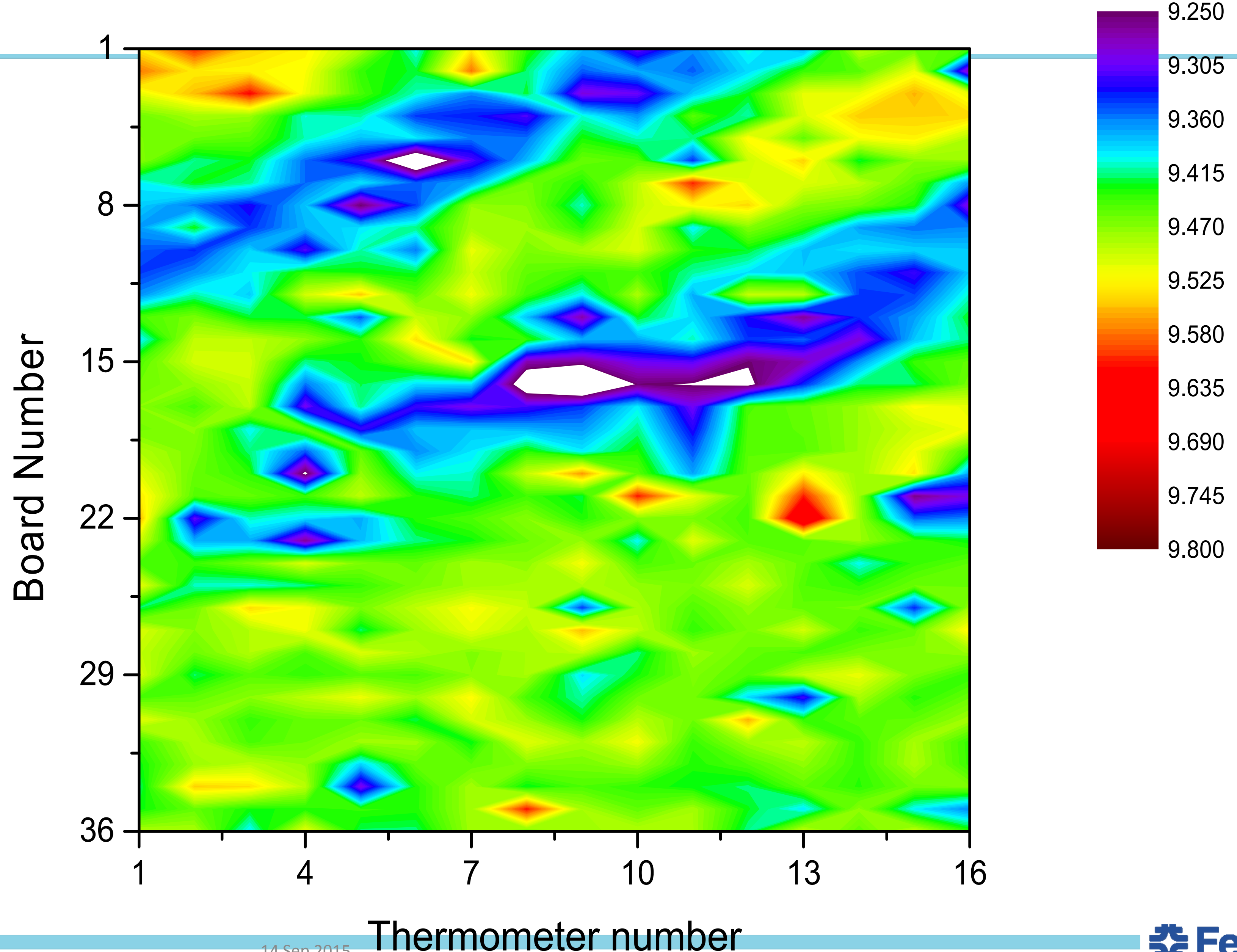

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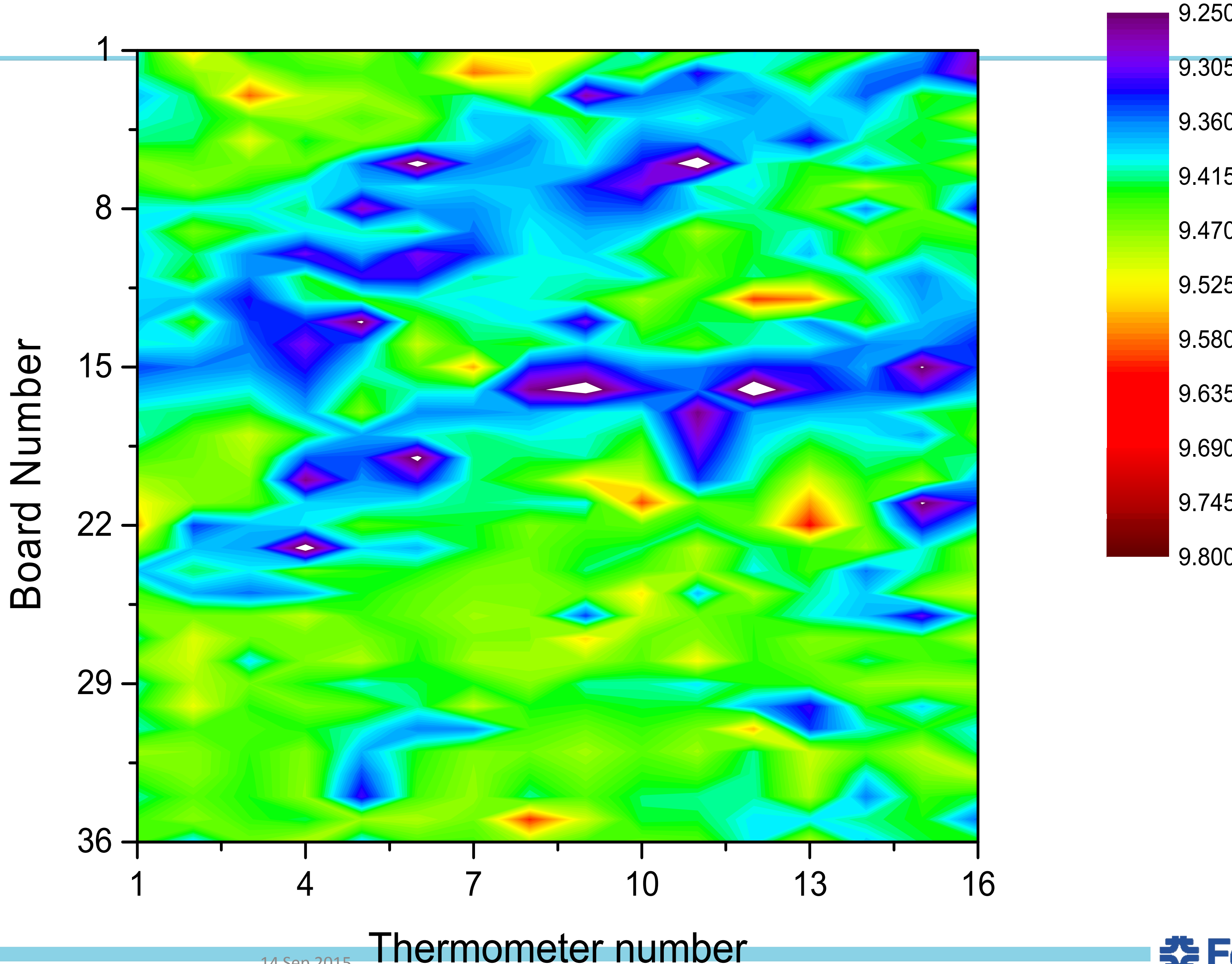

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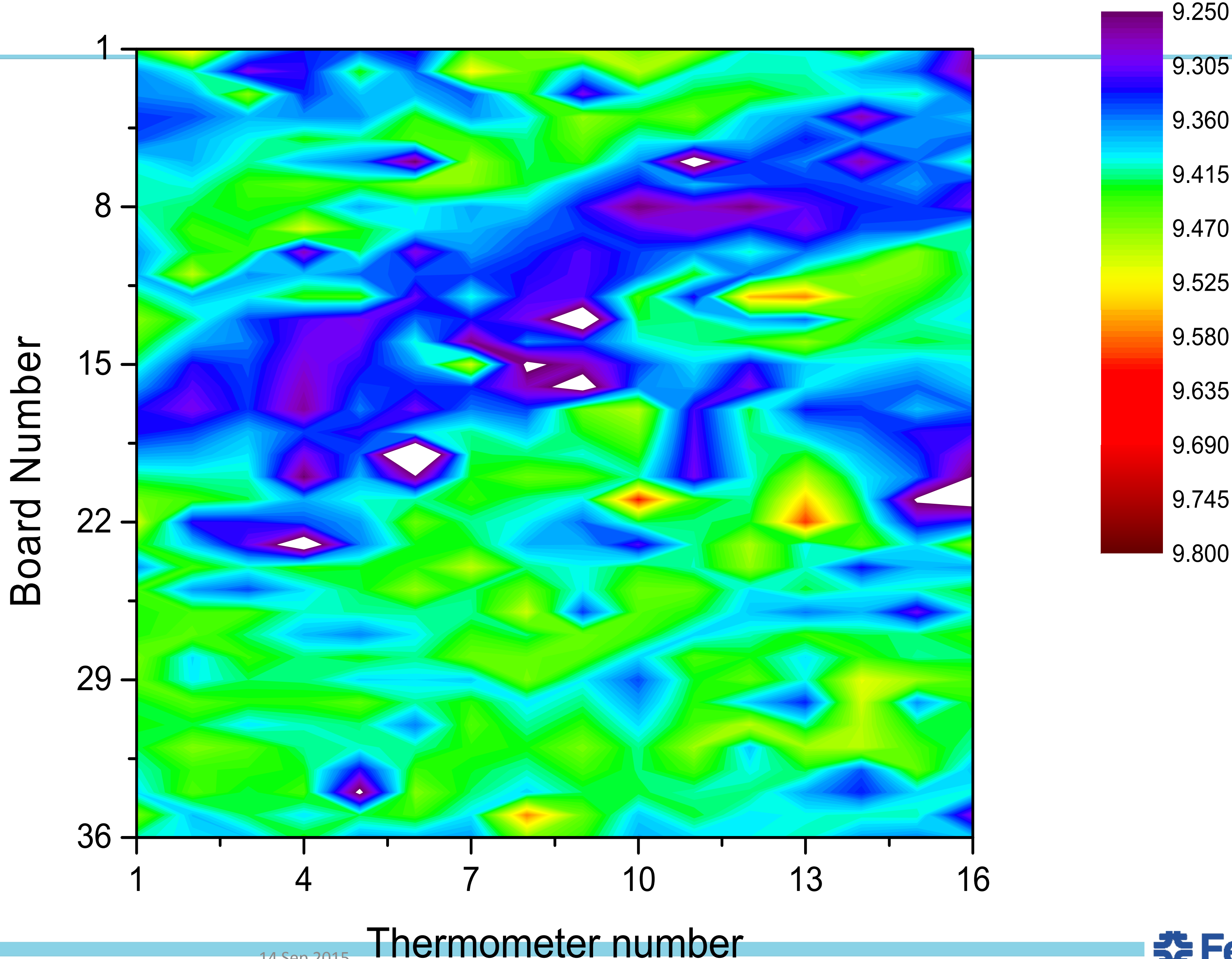

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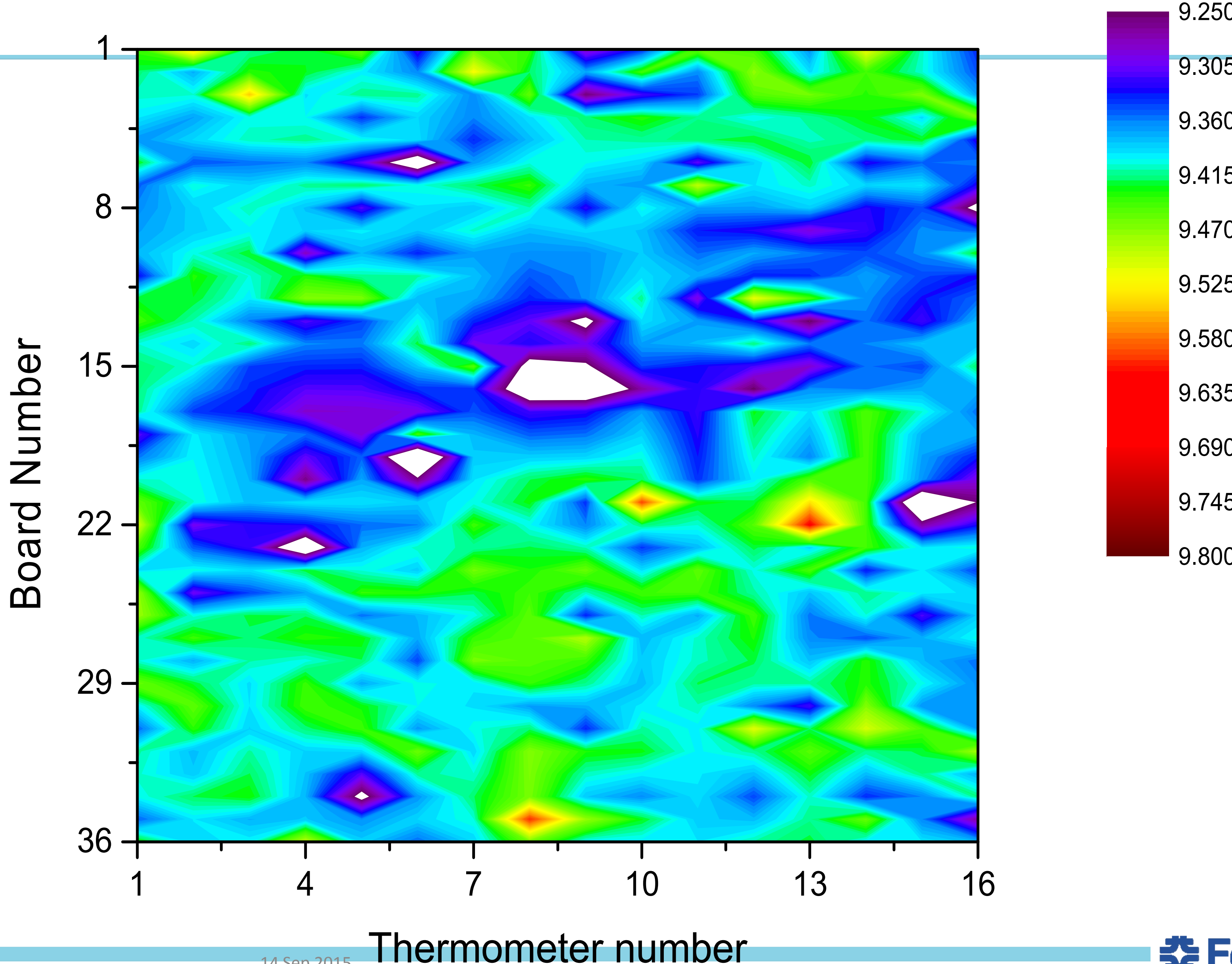

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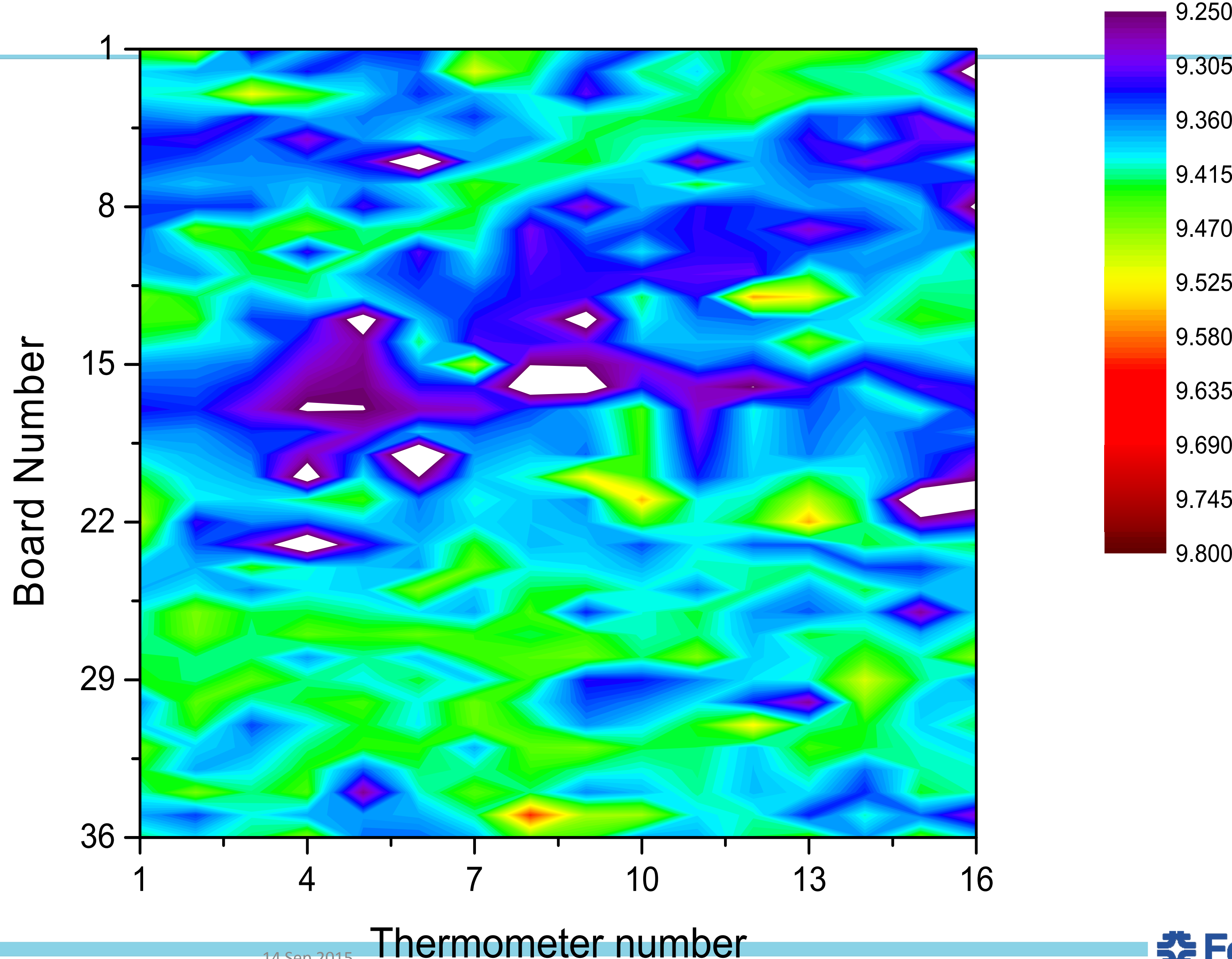

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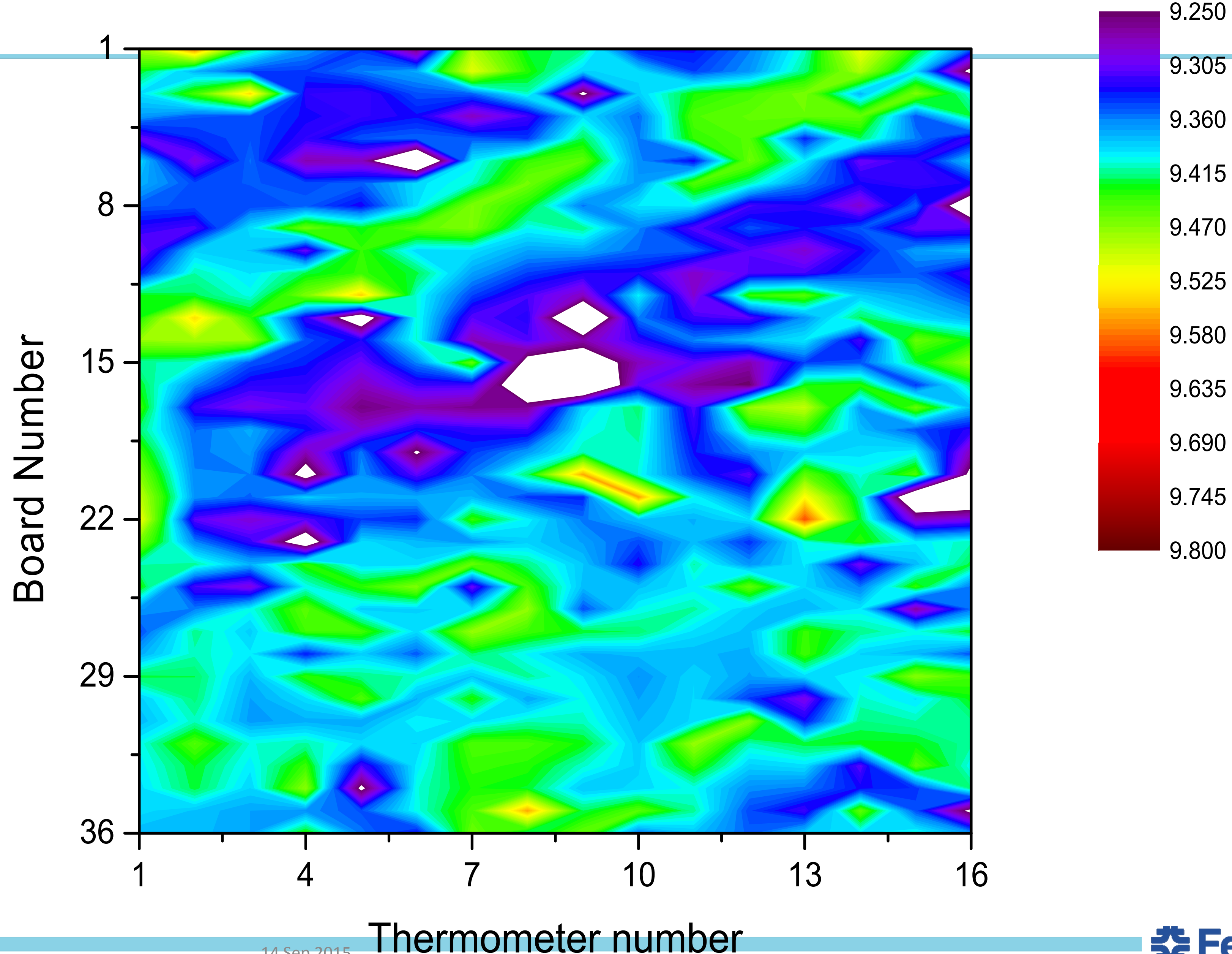

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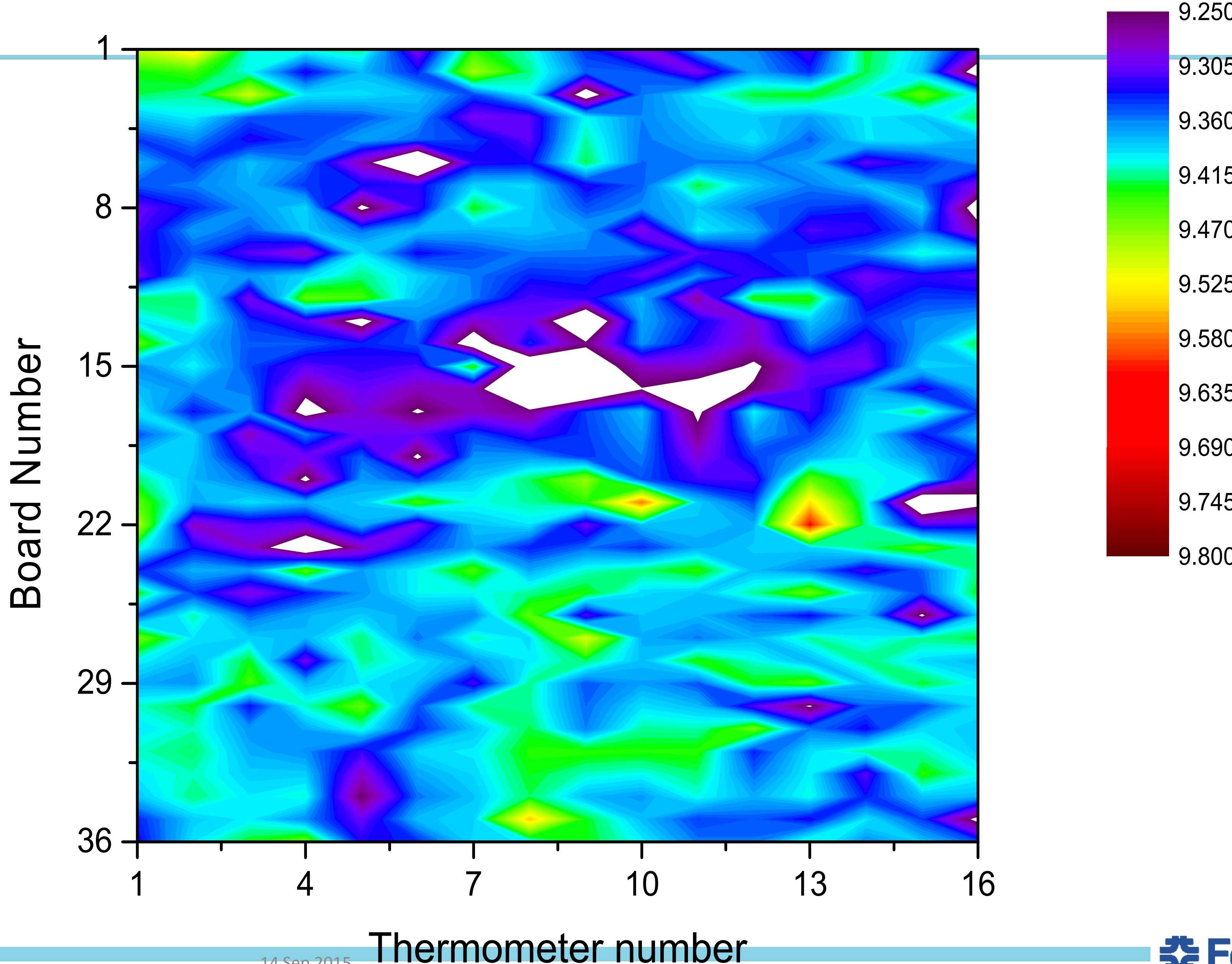

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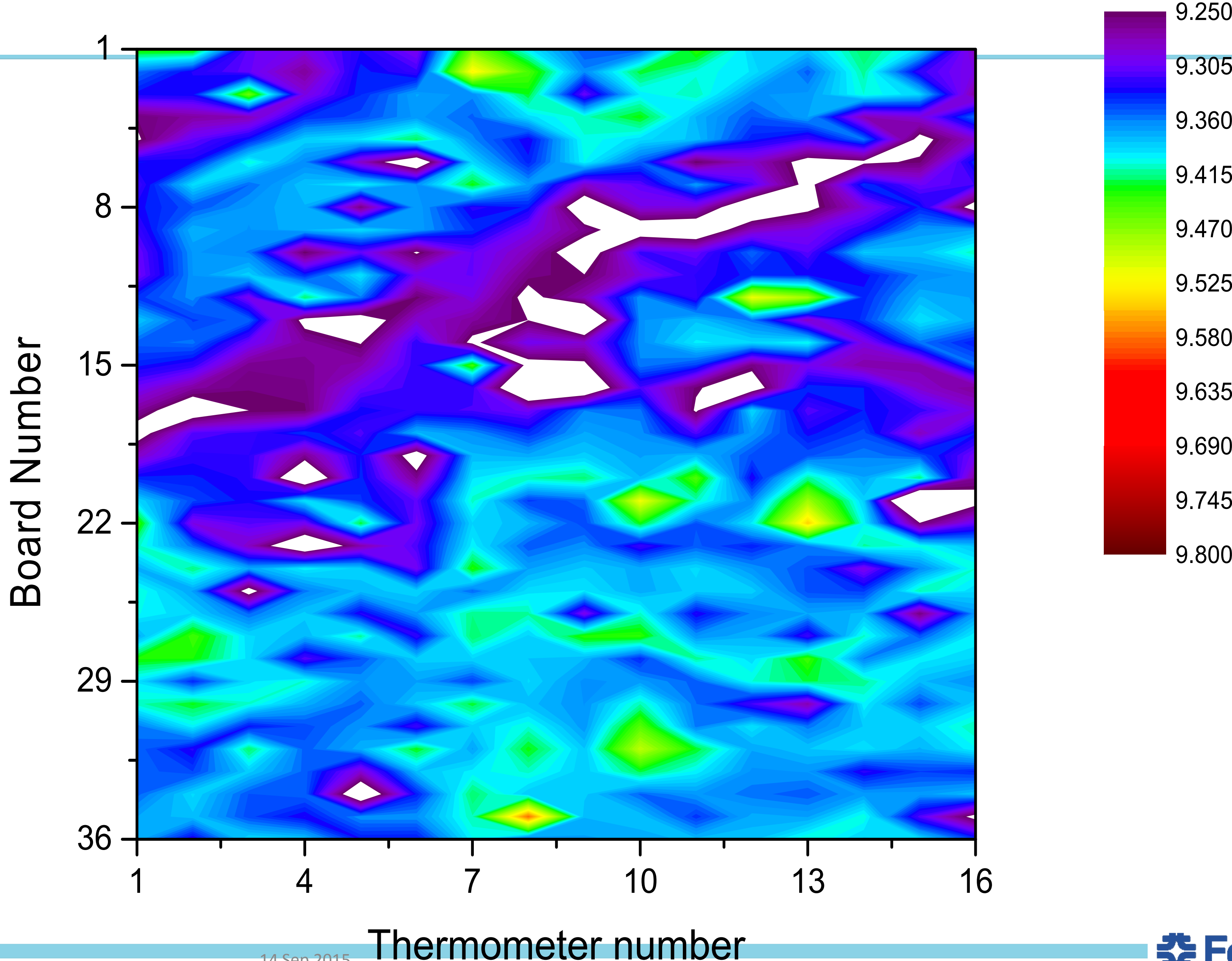

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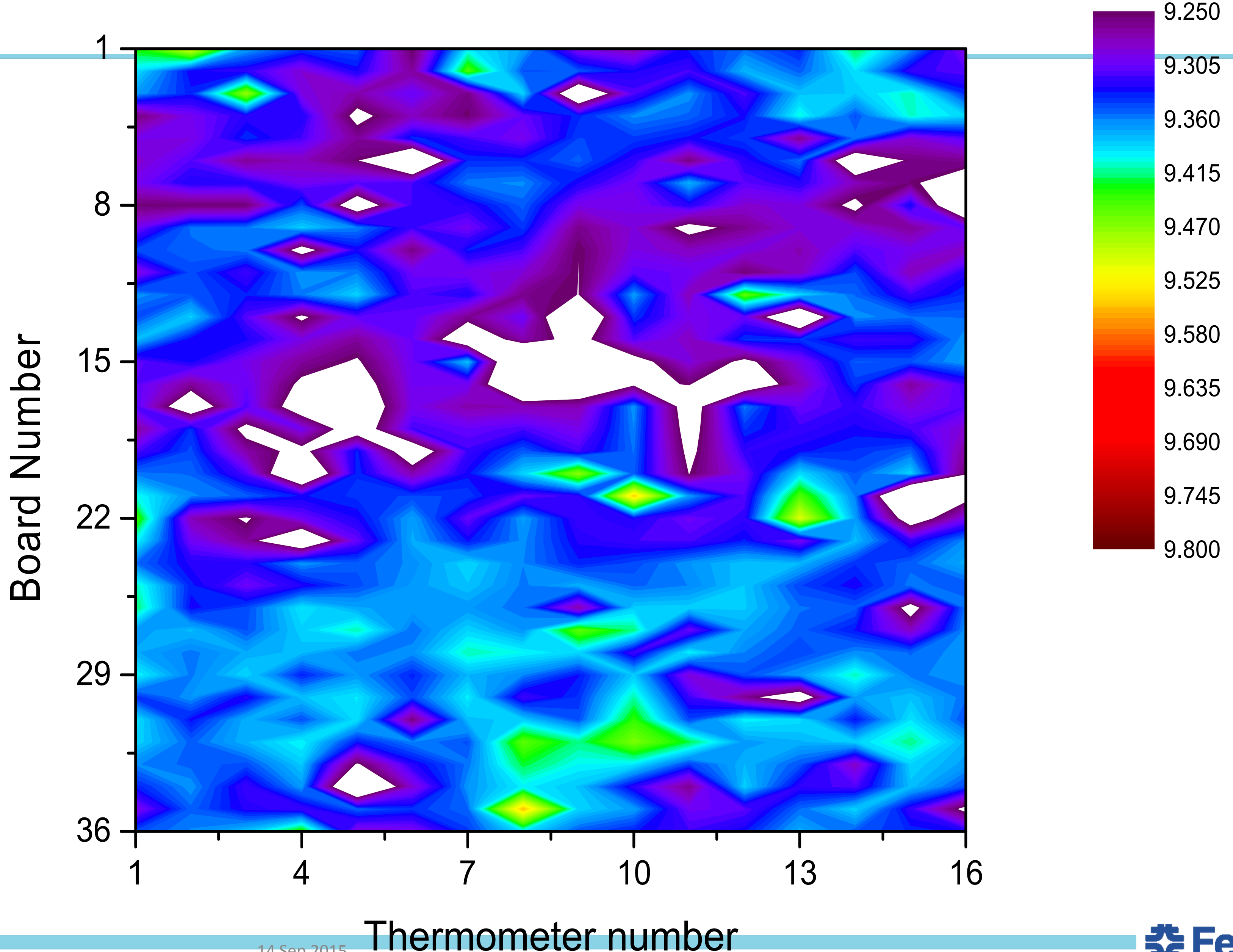

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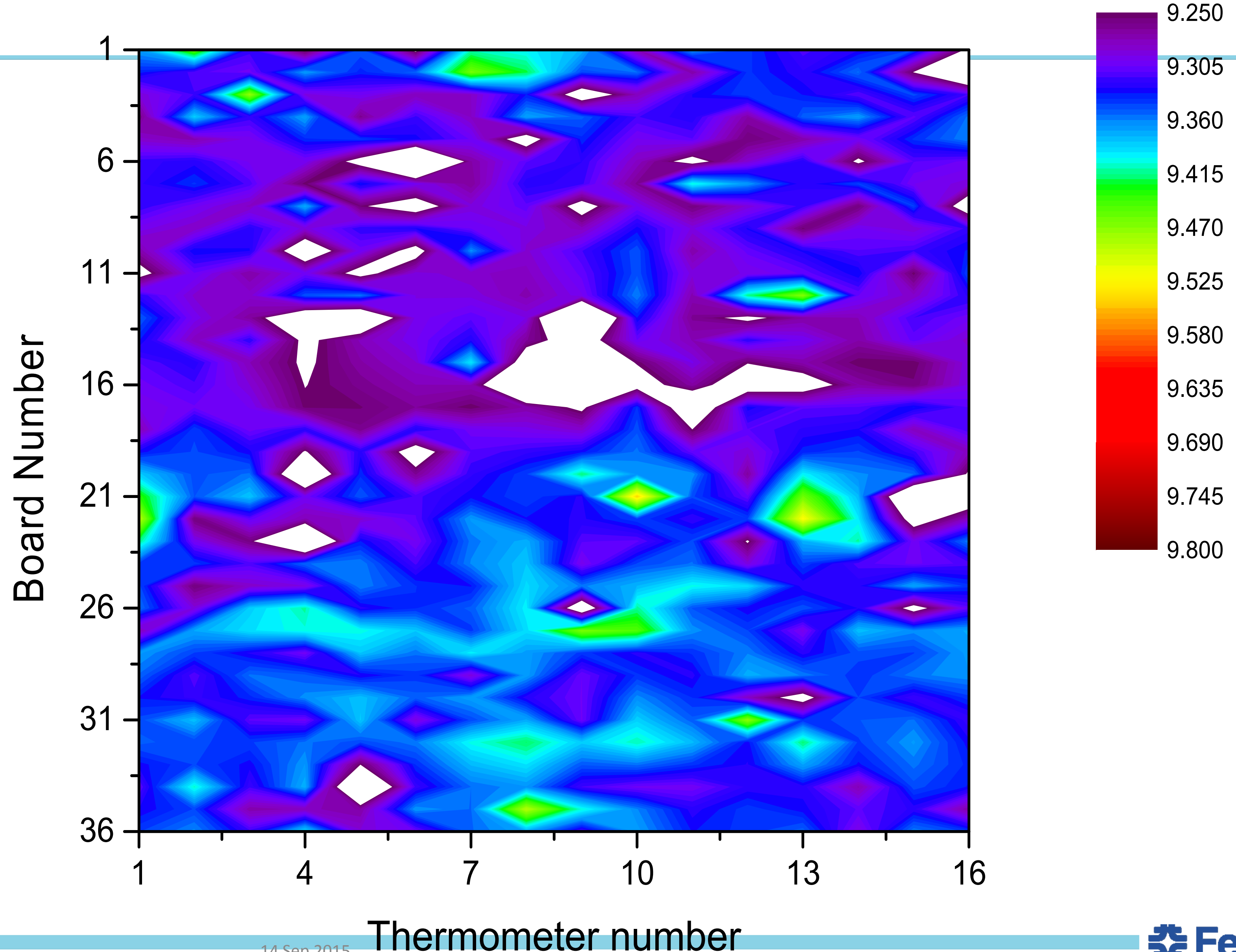

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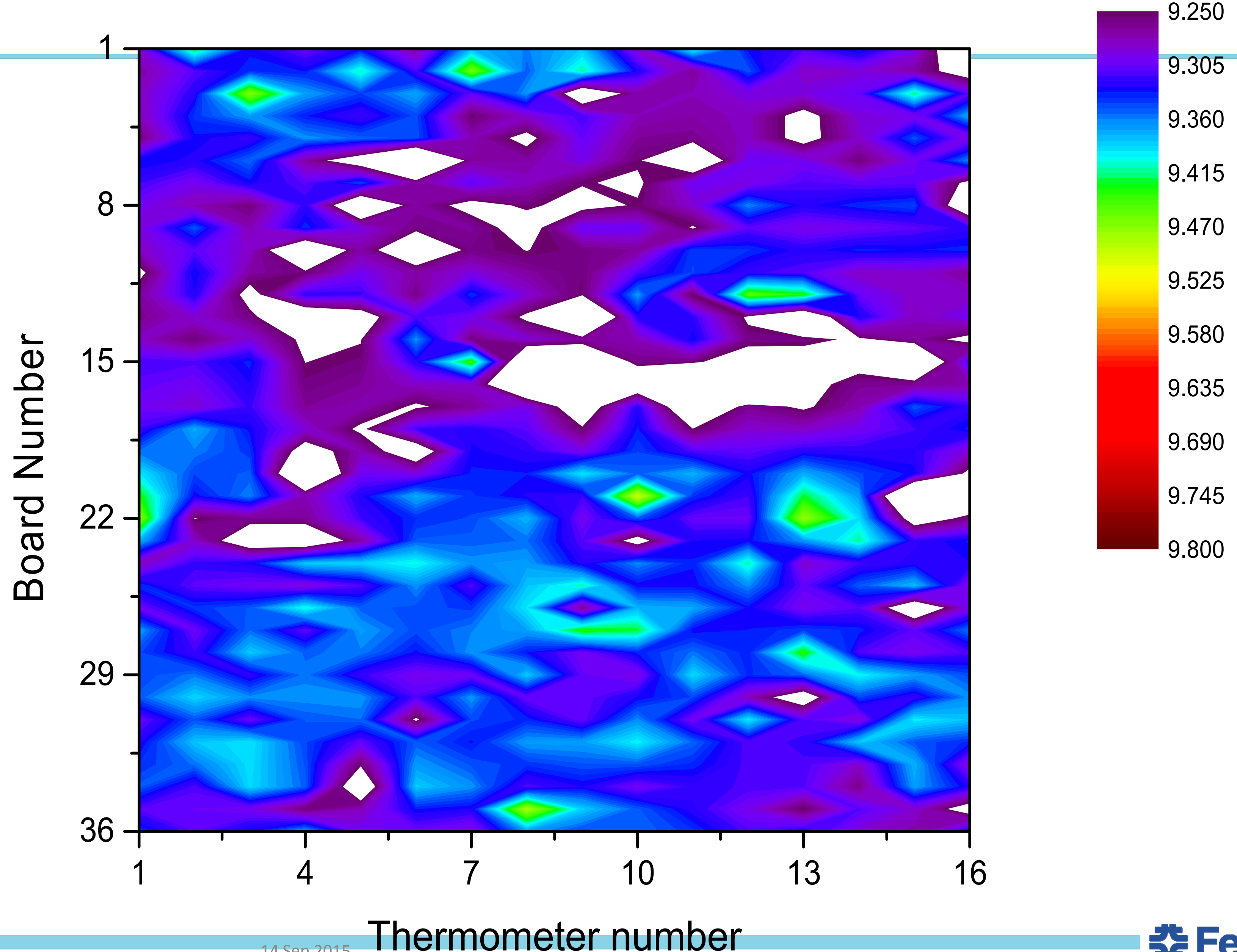

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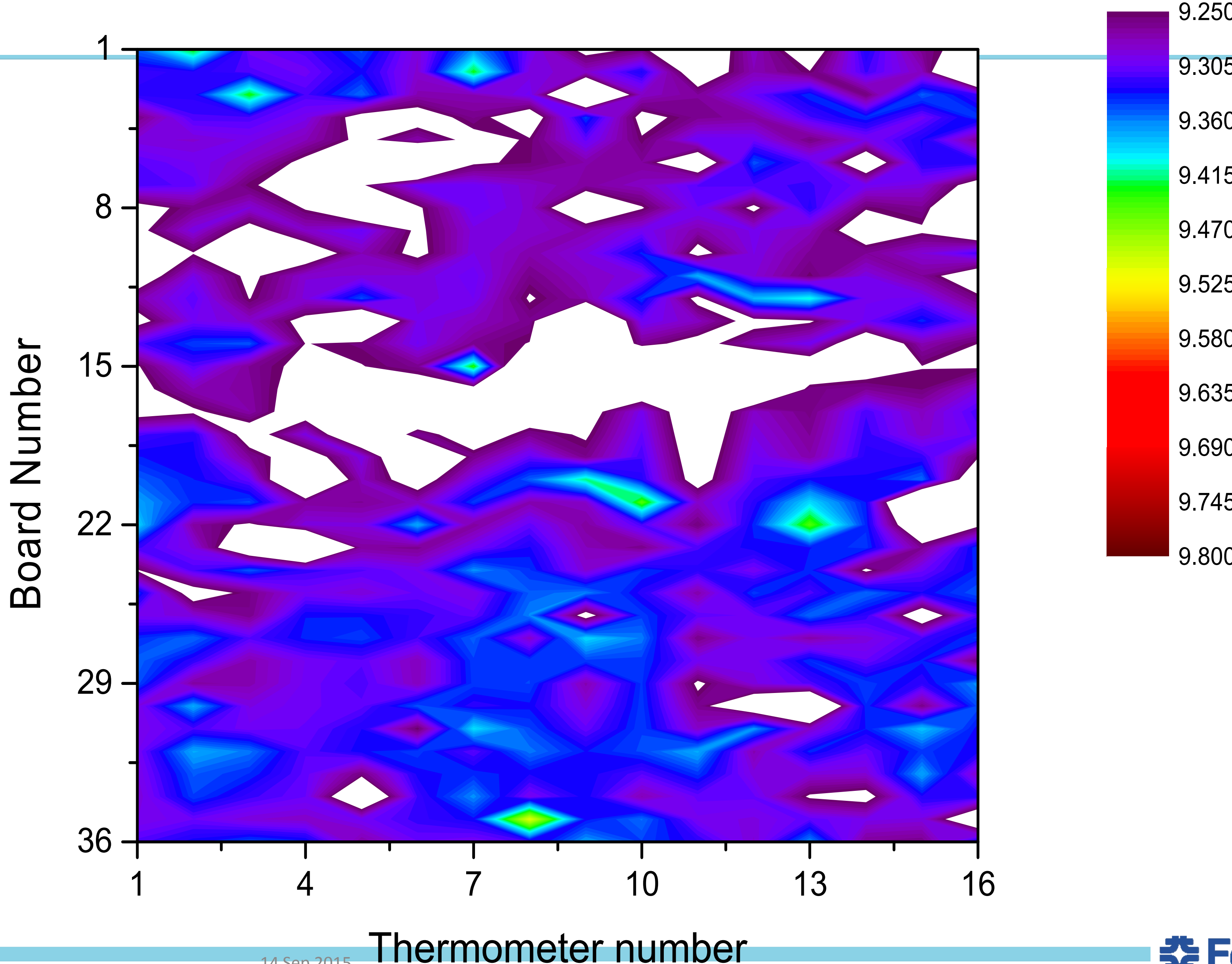

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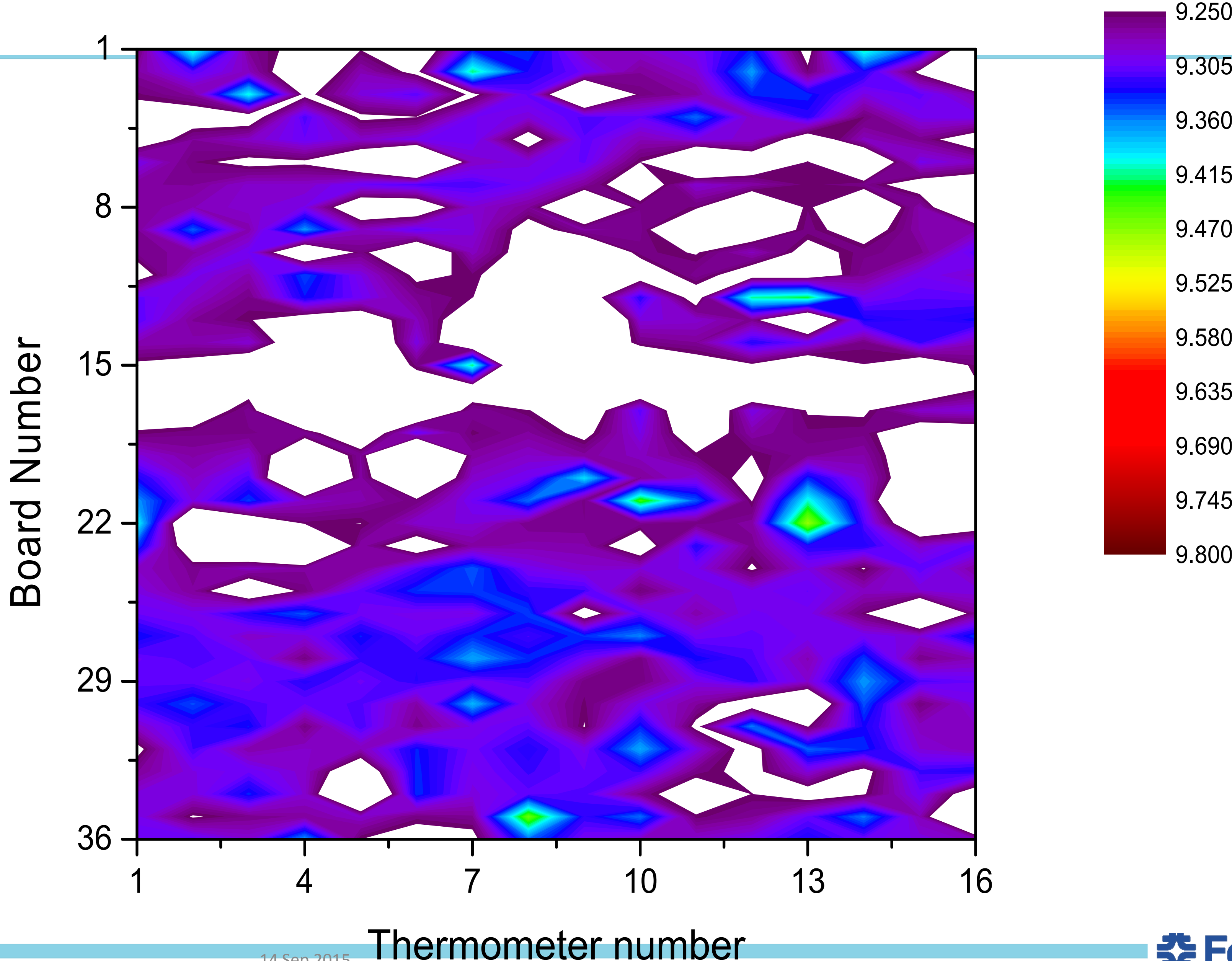

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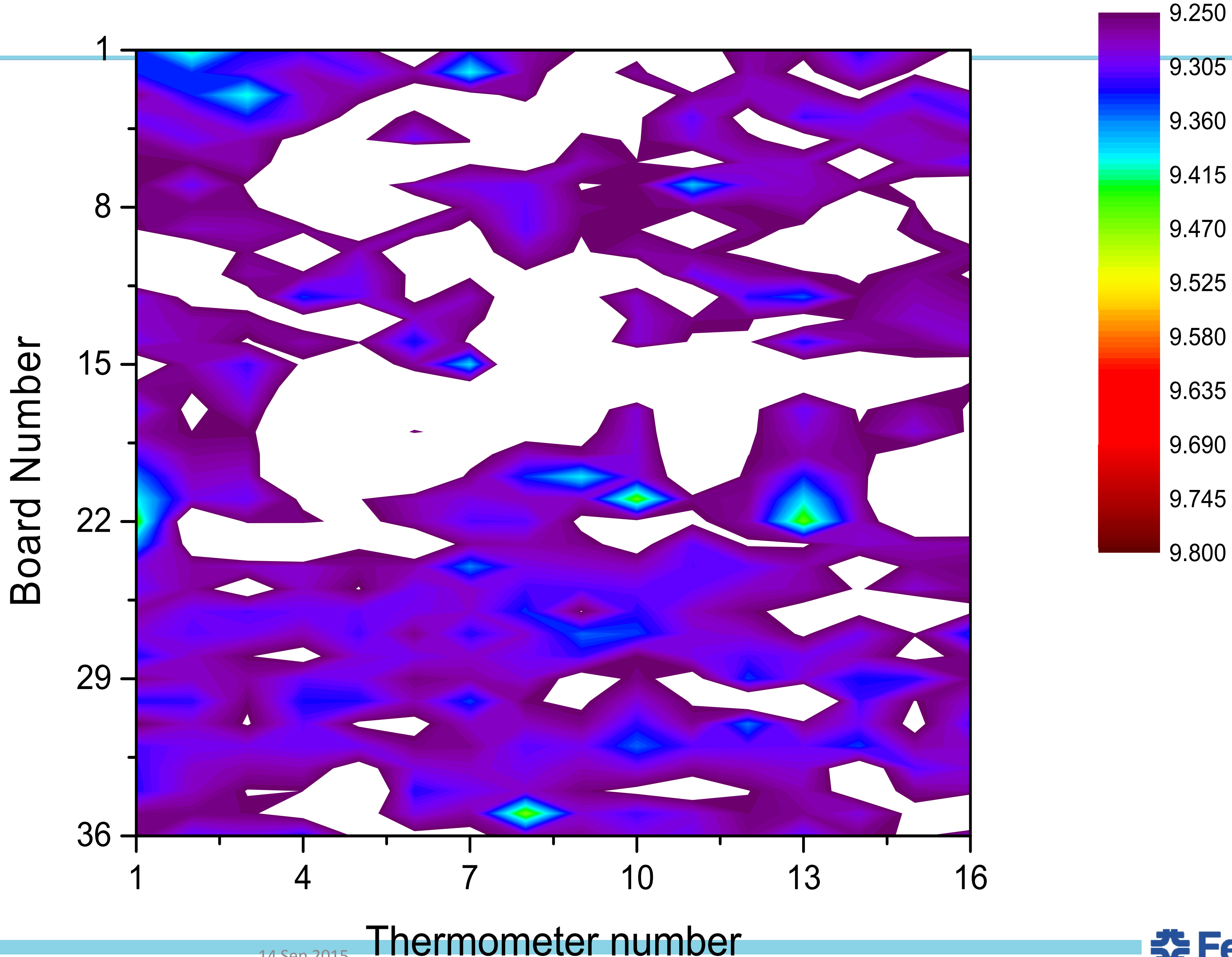

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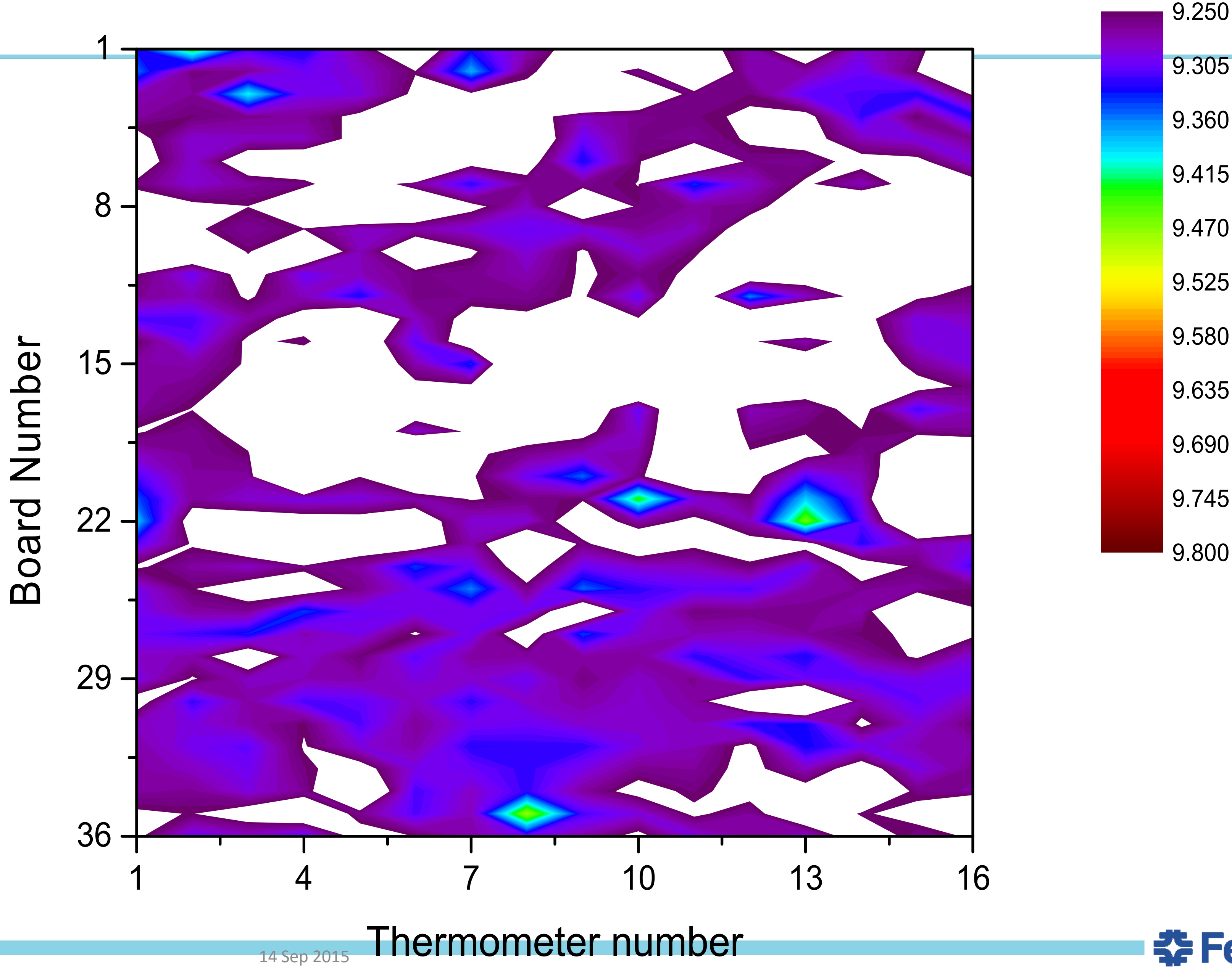

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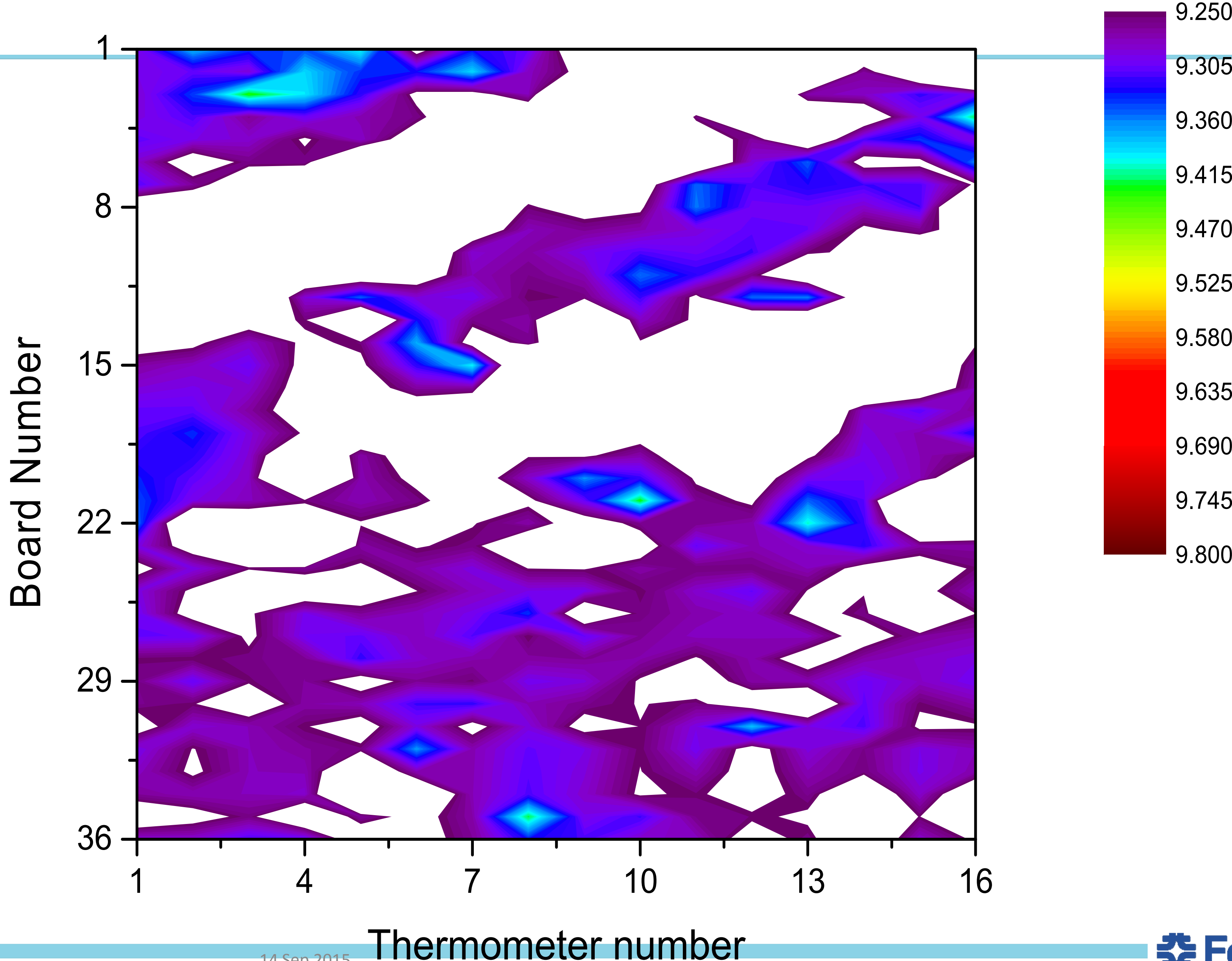
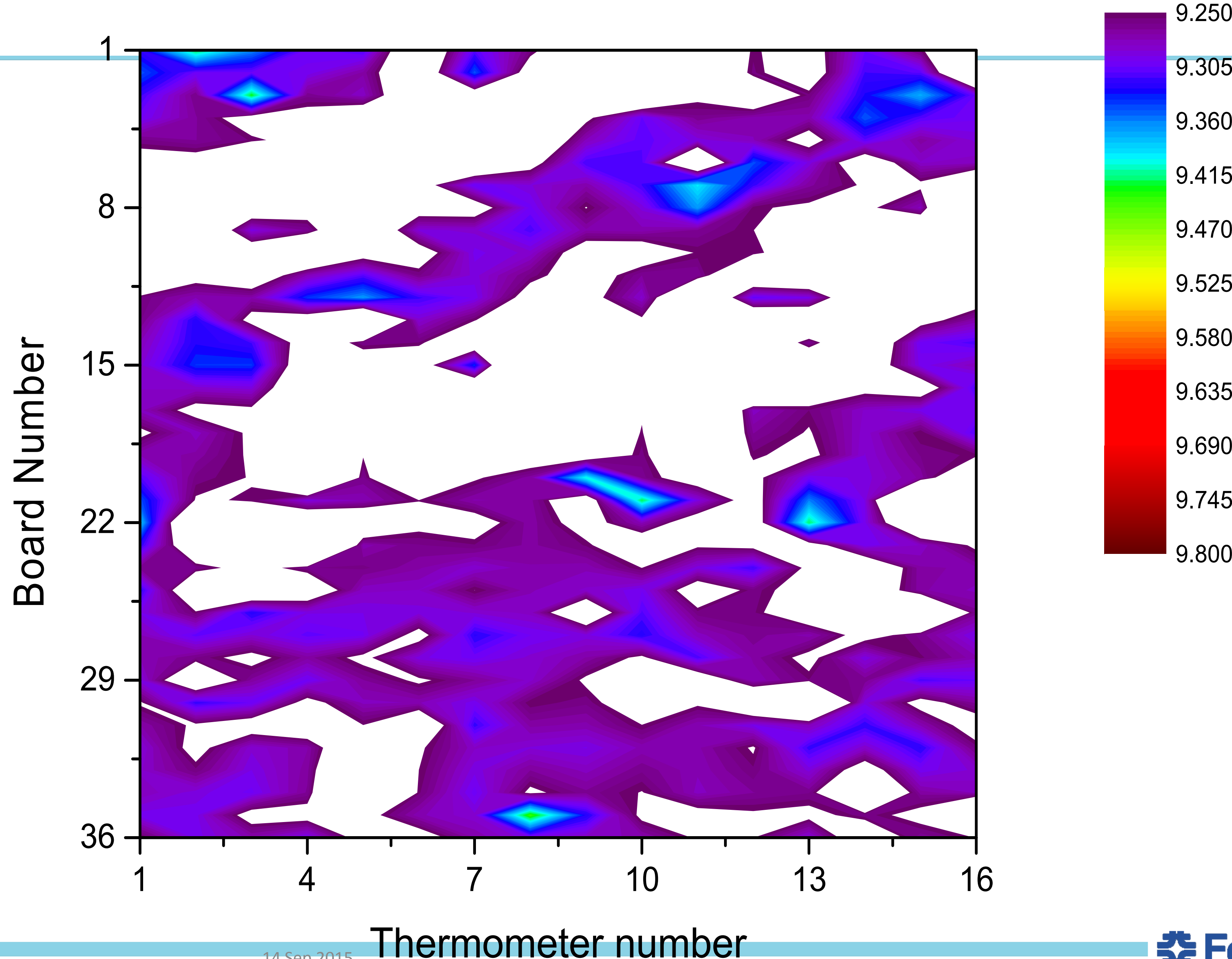


Slow Cool-down From 12K



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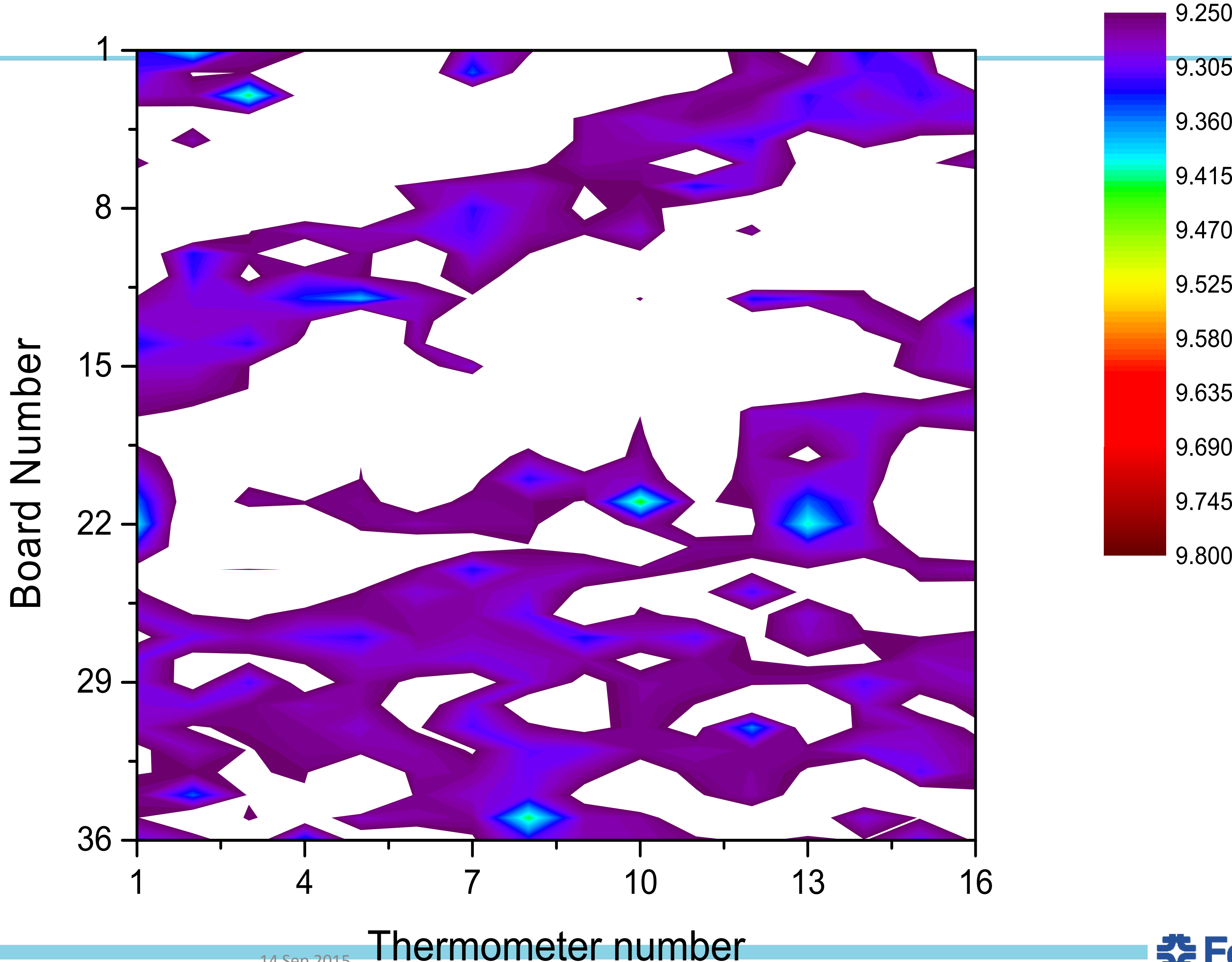

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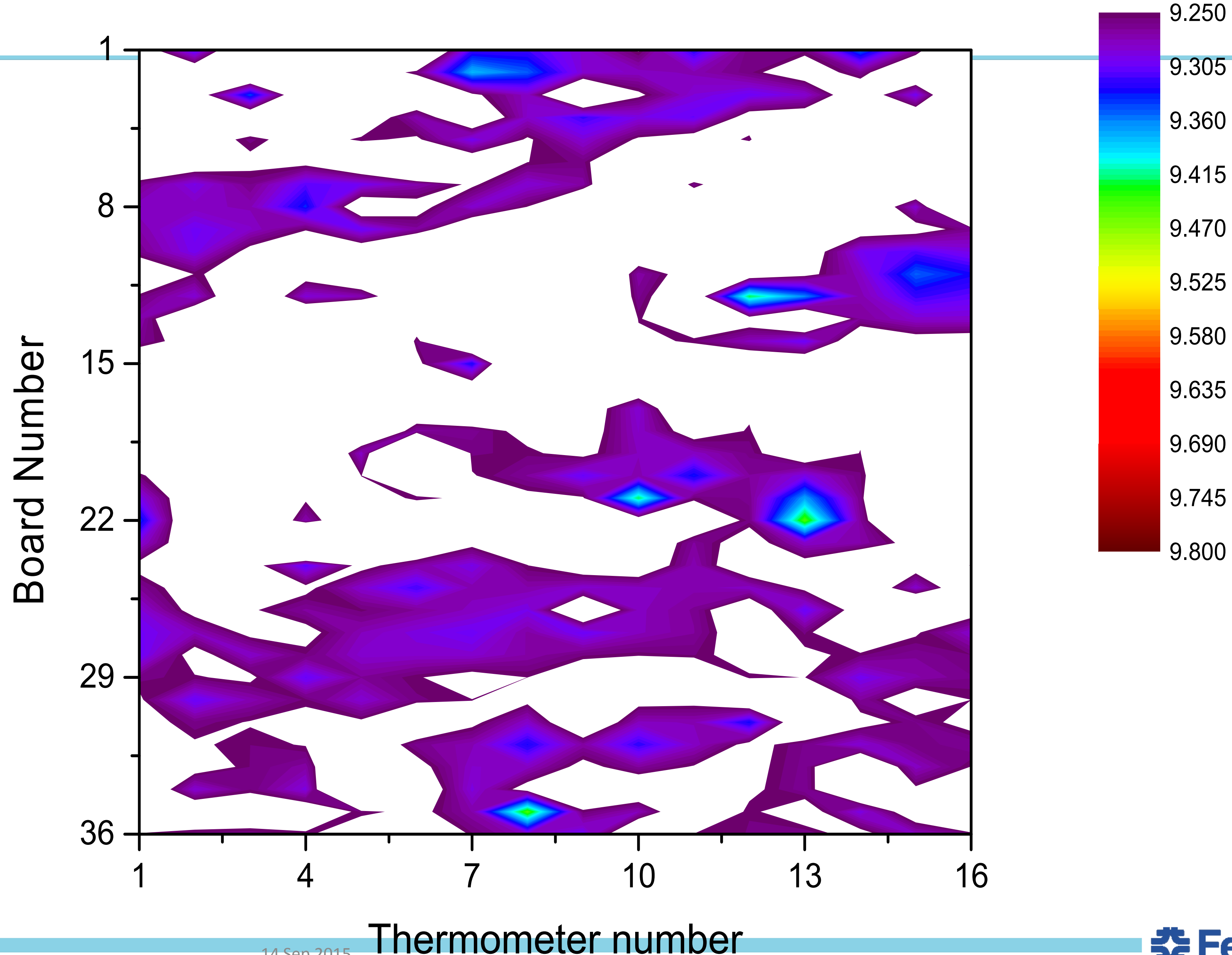

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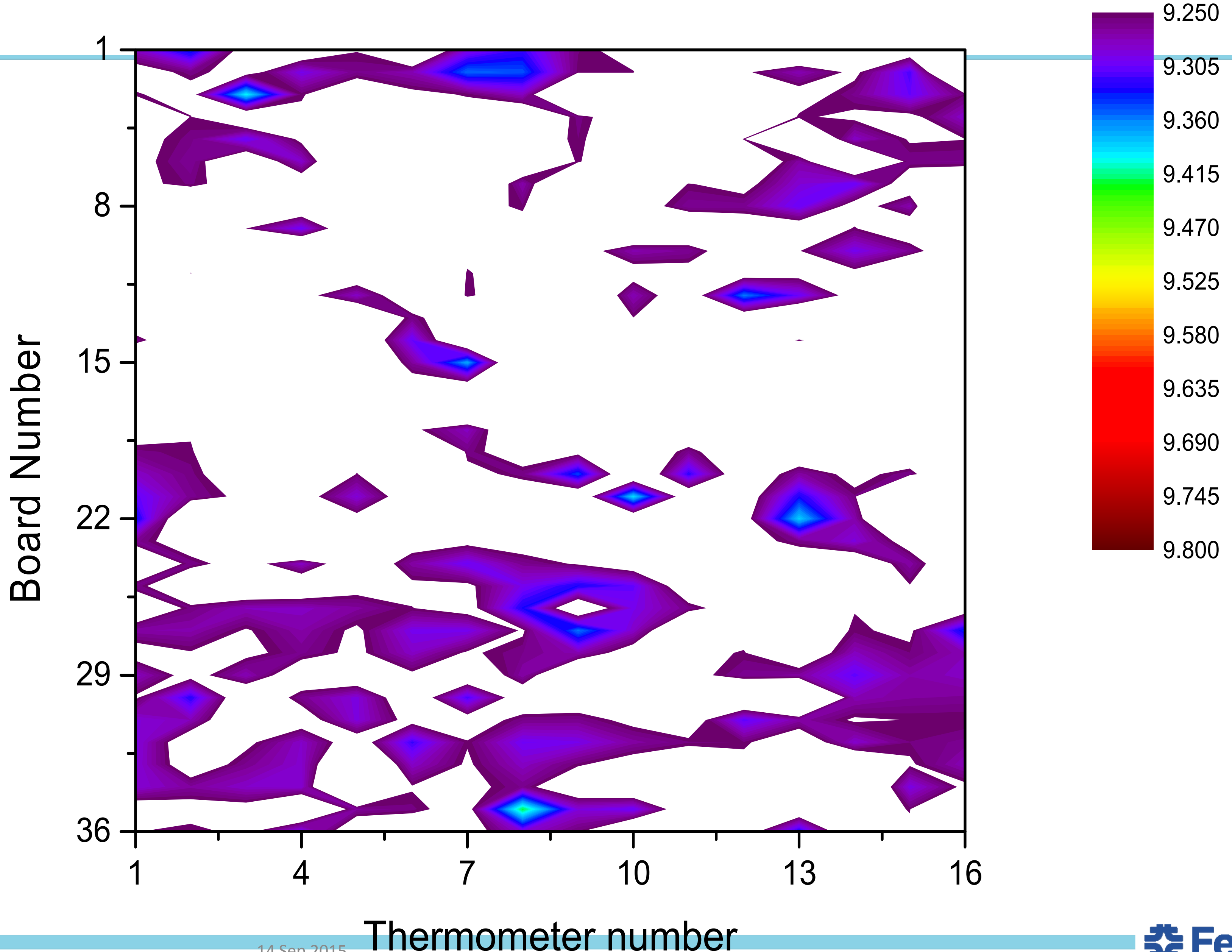

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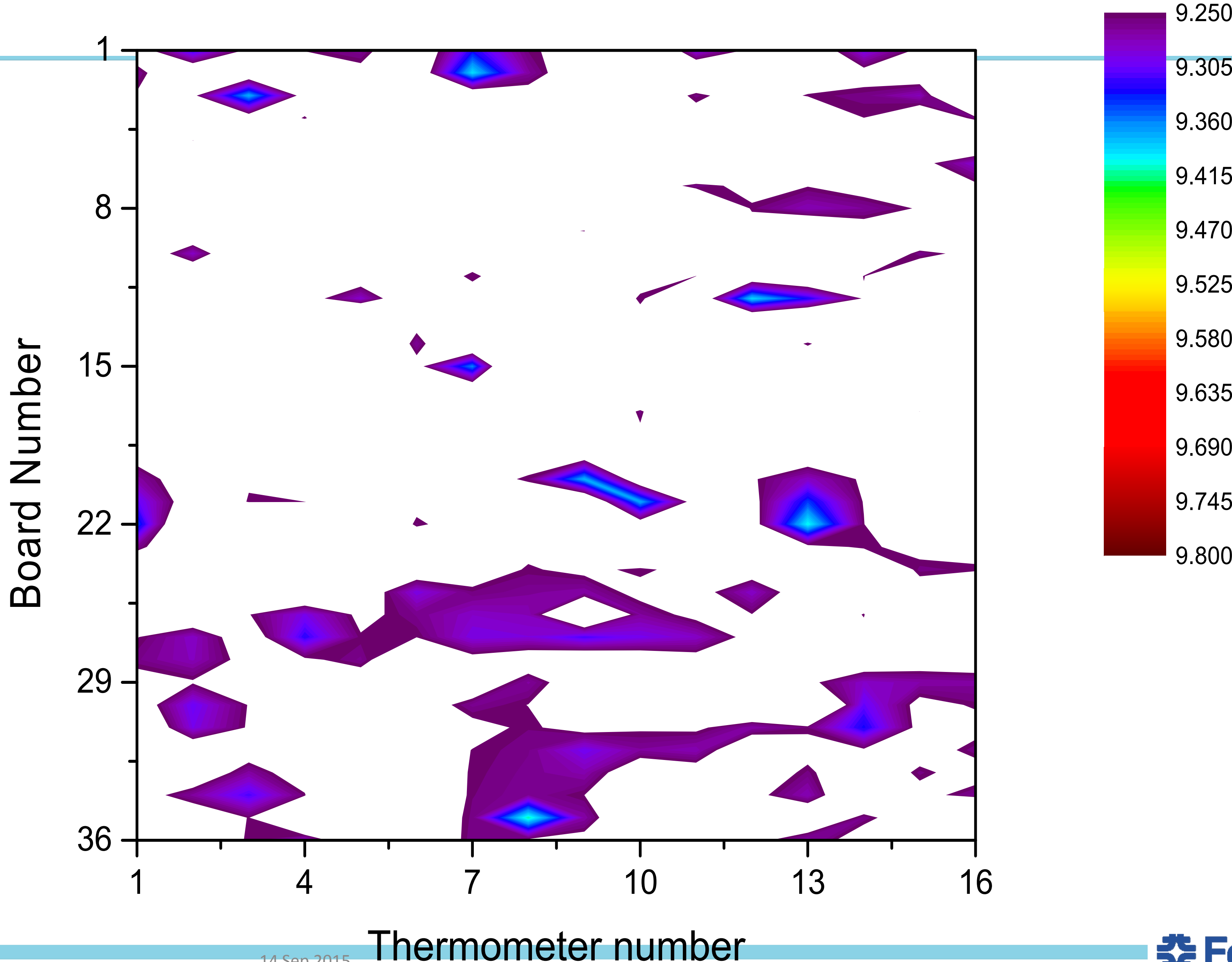

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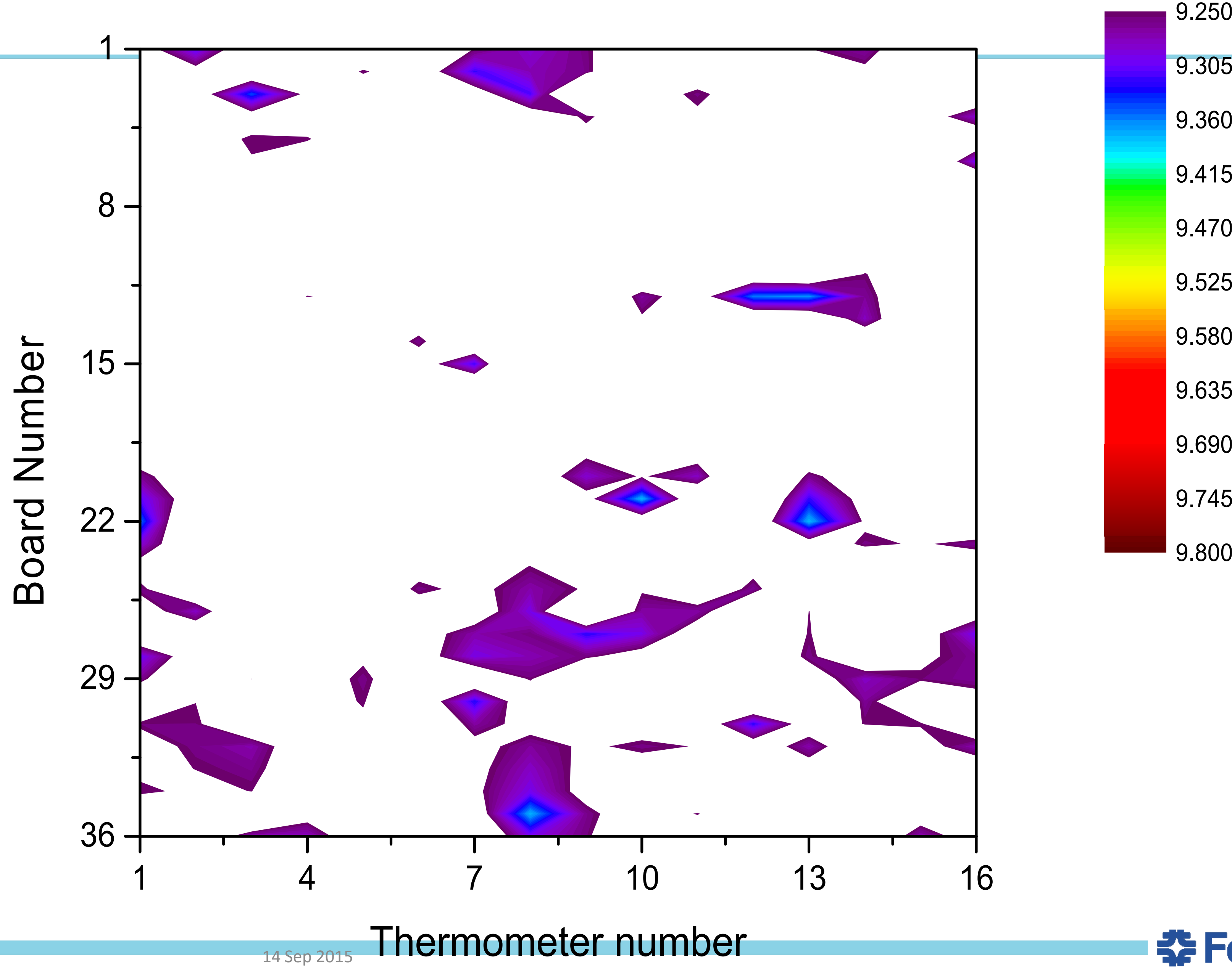

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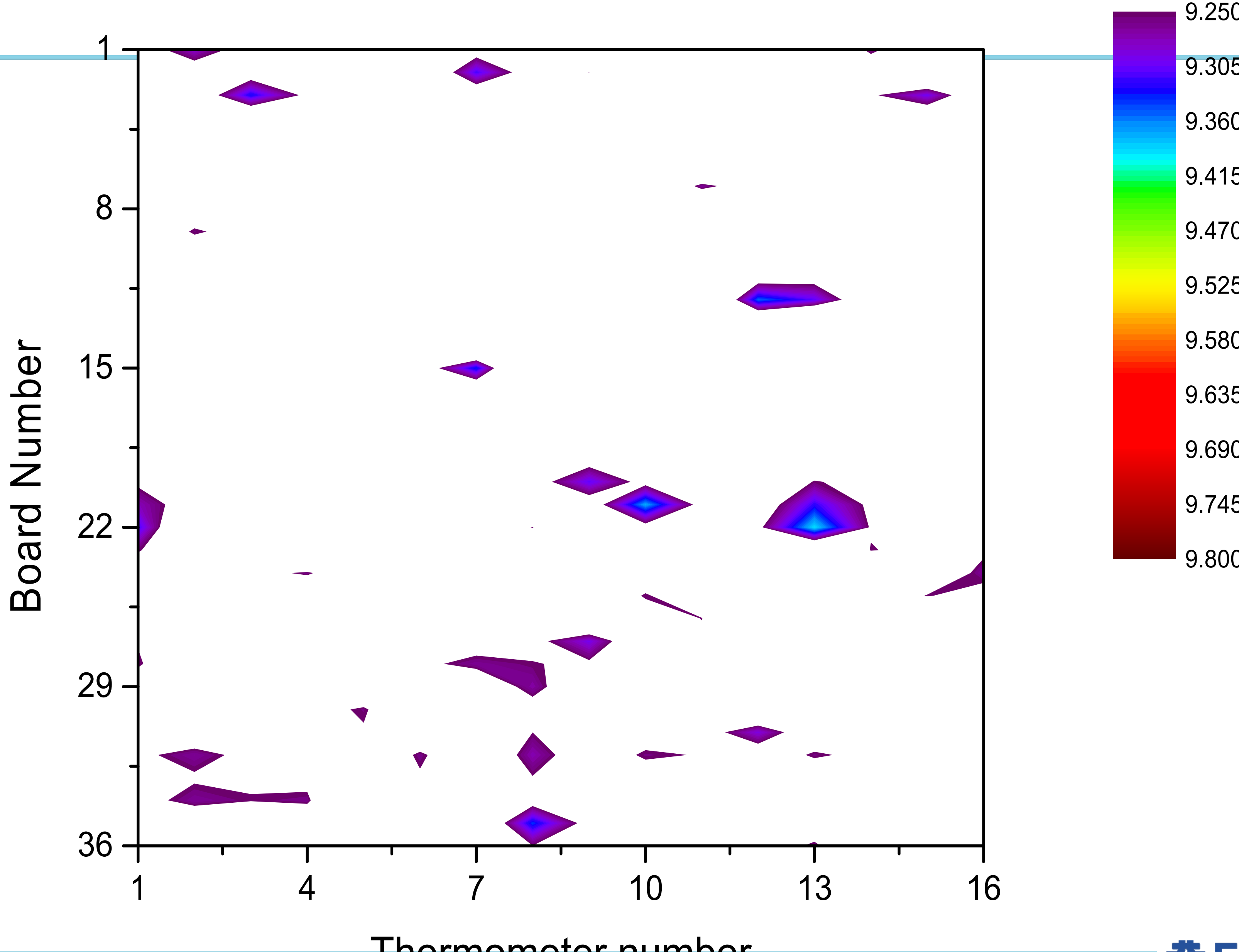

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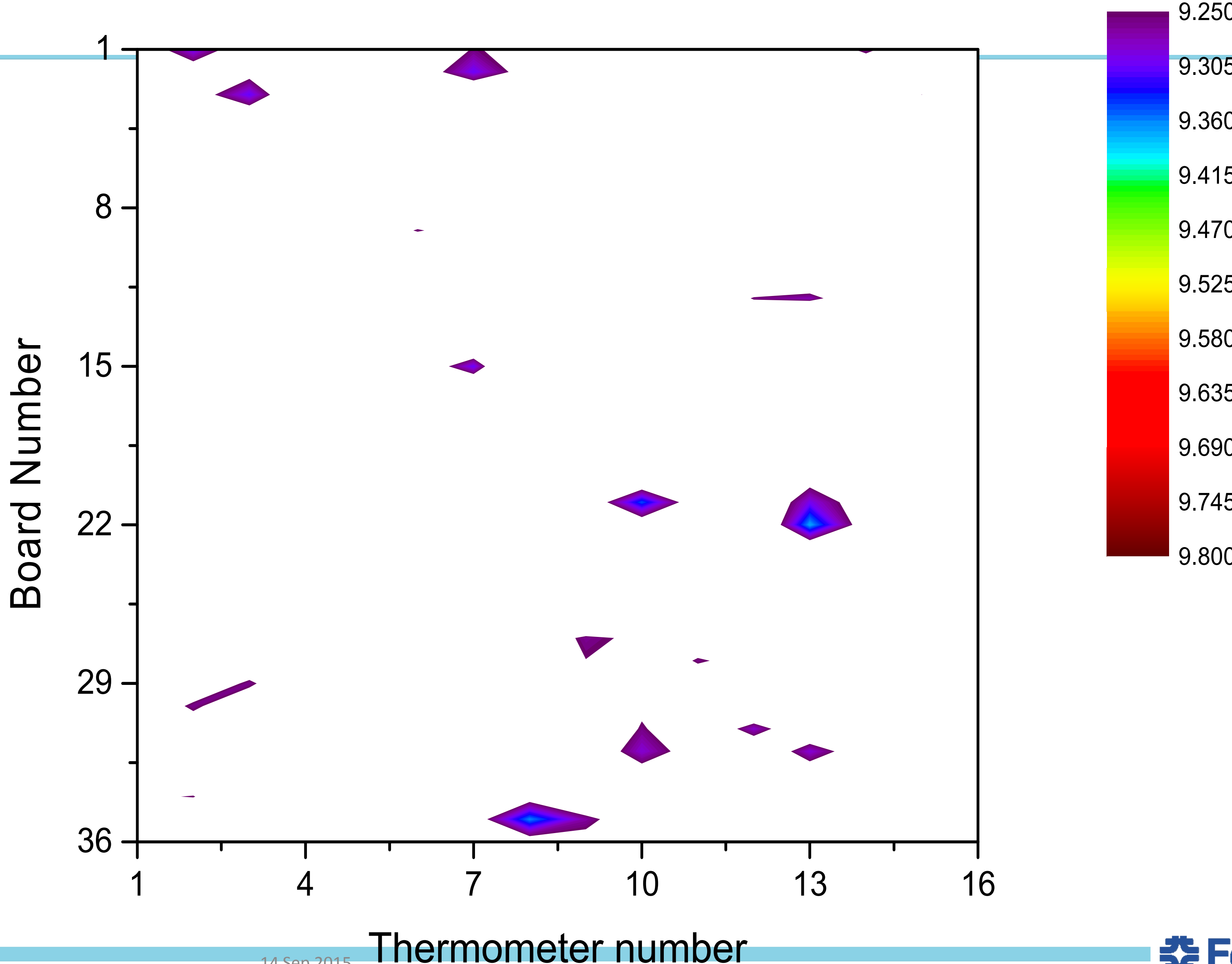

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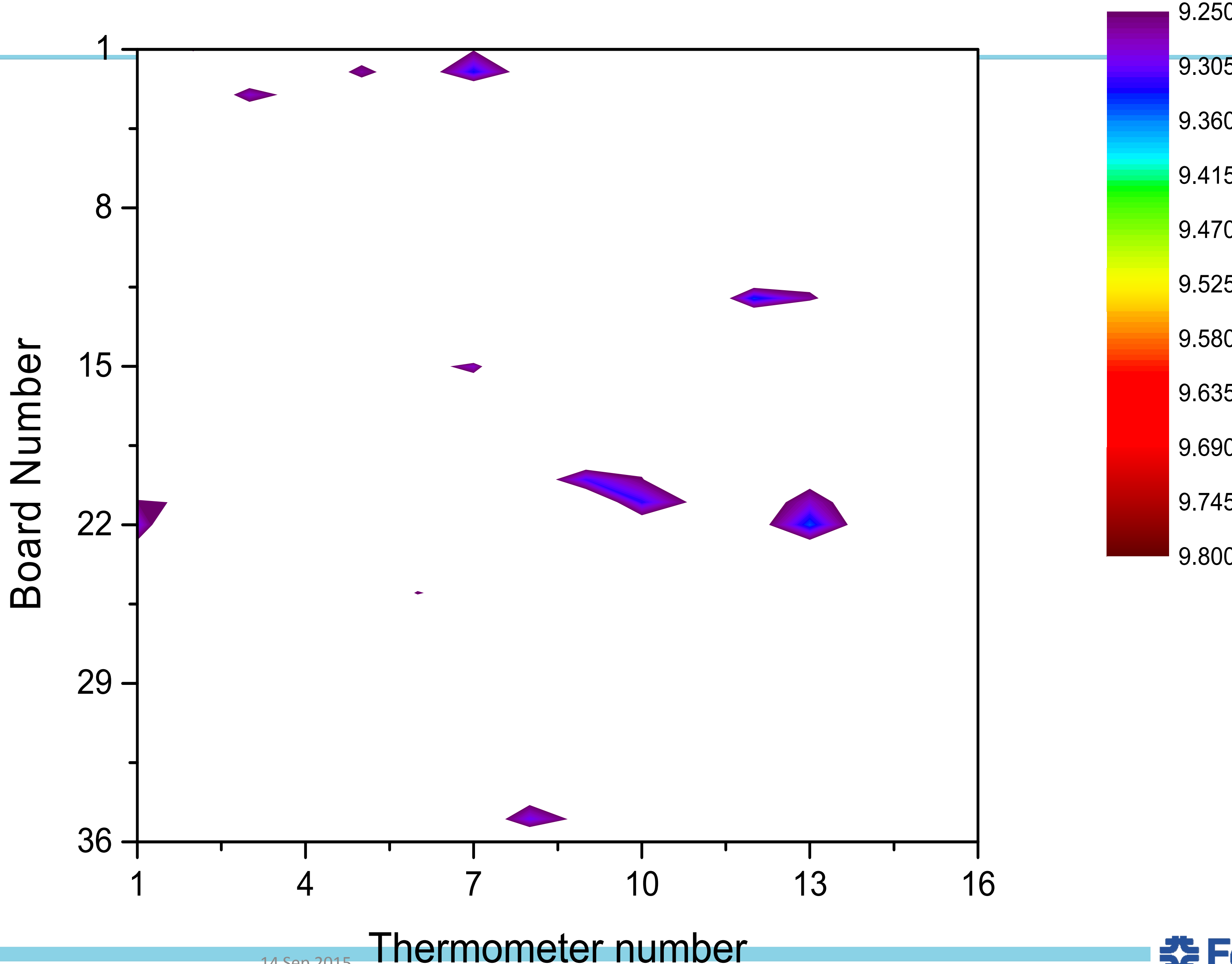

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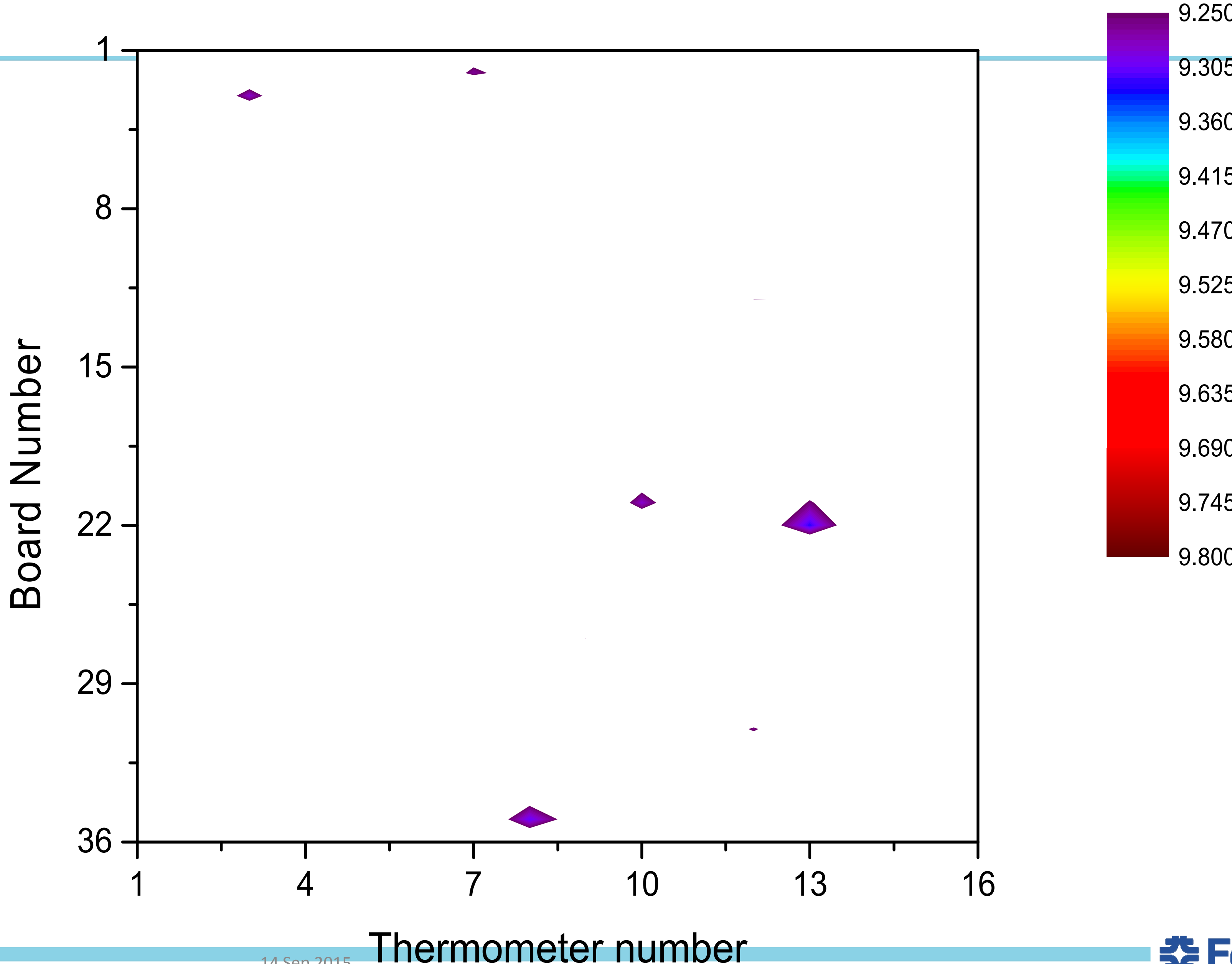

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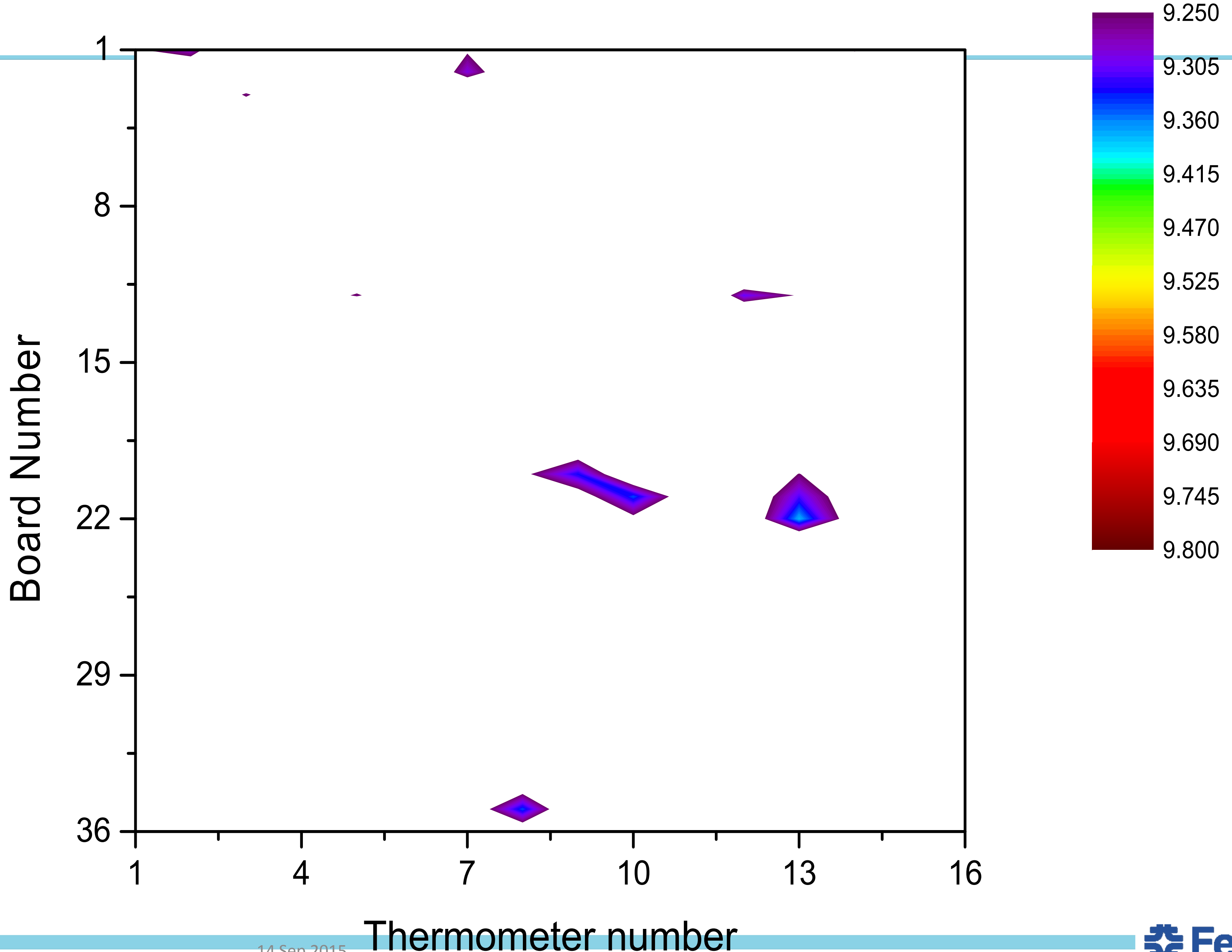

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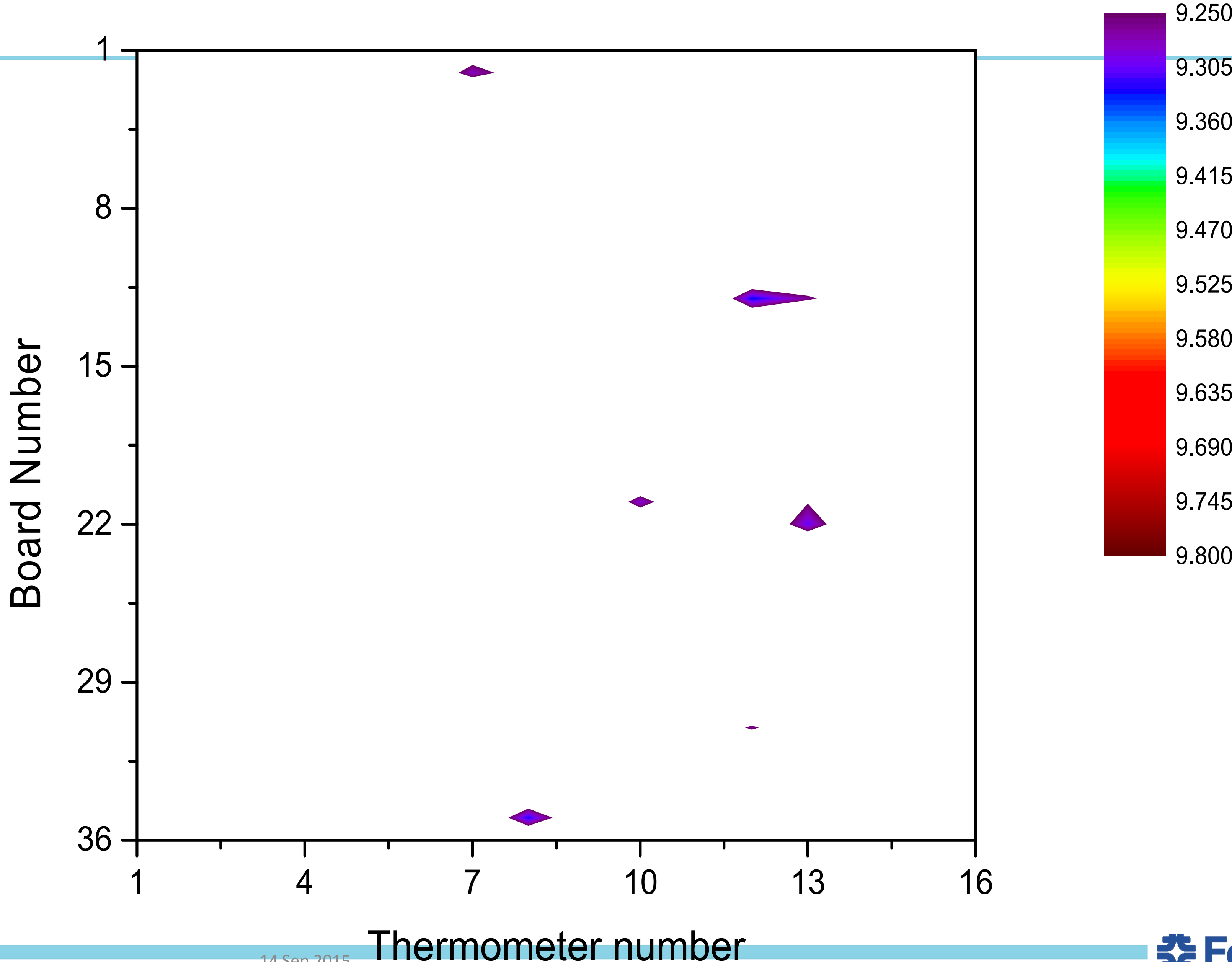

Slow Cool-down From 12K