Quench and high field q-slope studies using a single-cell cavity with artificial pits

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This talk is adapted from part of my PhD defense presentation at Cornell University

Development of Superconducting RF Sample Host Cavities and Study of Pit-induced Cavity Quench

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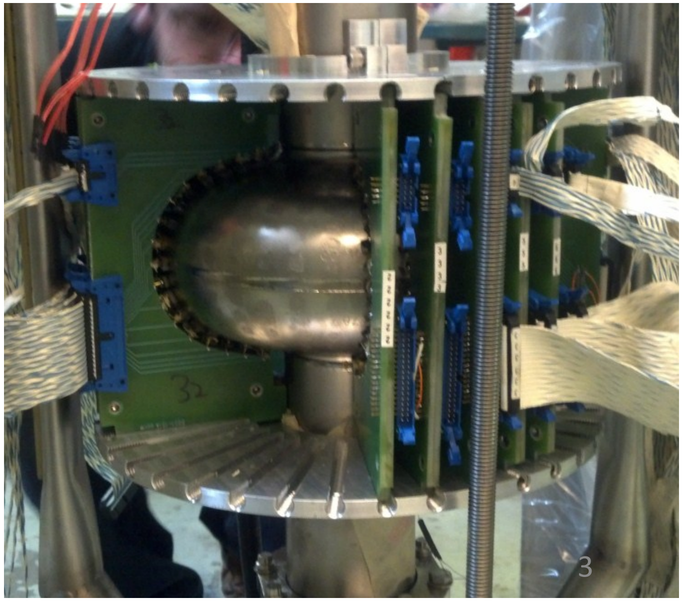
Jan 10, 2013



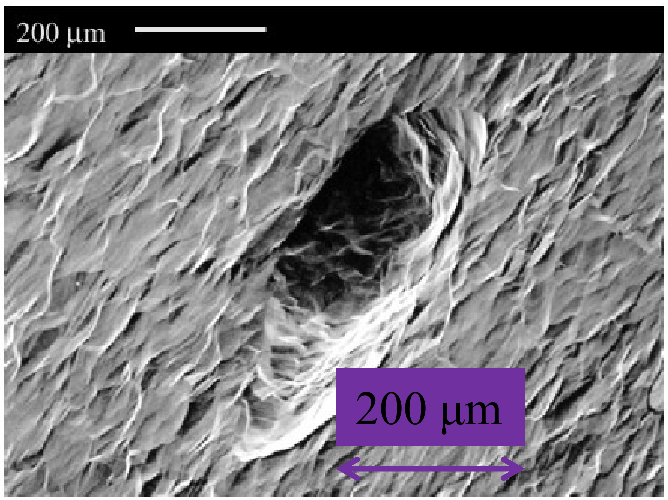
Outline

- Pit cavity experiment;
  - Motivation and experiment setup;
  - Experiment results and analysis;
  - **Key achievements:**

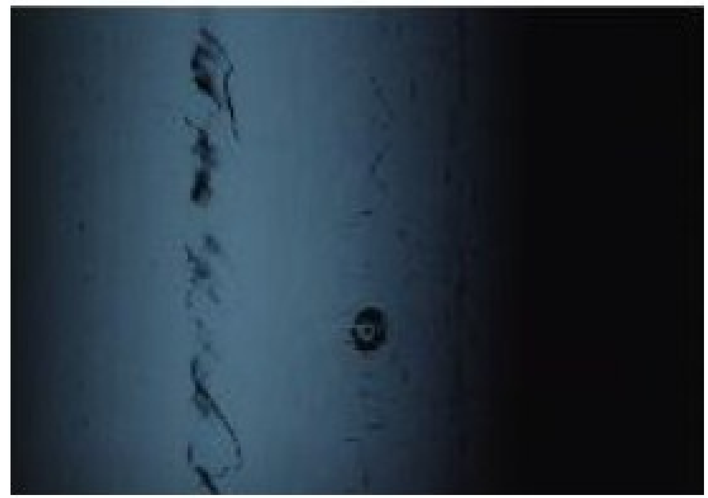
  Proves that pit with sharp edge will cause quench;
- Conclusions;
- A general rf heating simulation code for SRF community.

Why study pits

Pits are identified as sources of quench mostly below 25MV/m. Some pits will cause cavity to quench but some bigger pits don't cause quench.



Quenched at 22 MV/m (Cornell)



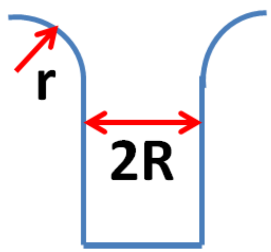
Φ~1mm pit, no quench (FNAL)

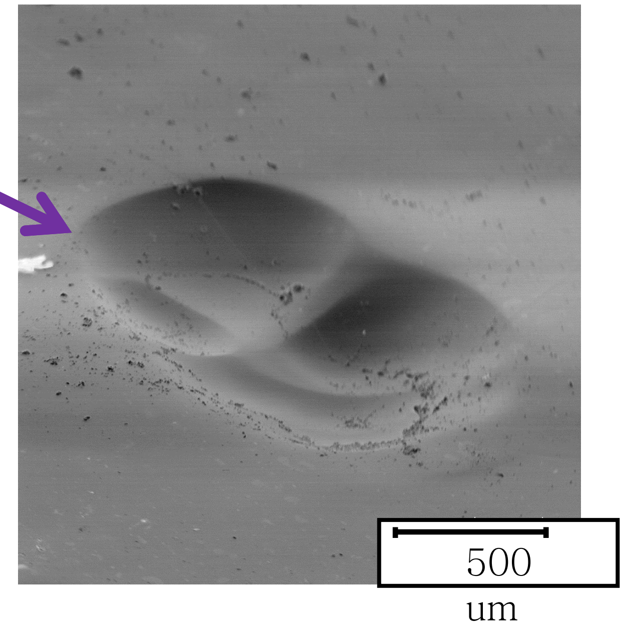
Open question: Why some pits cause quench, some are not? What are the relevant parameters?

A possible explanation: Magnetic field enhancement (MFE) at pit edges

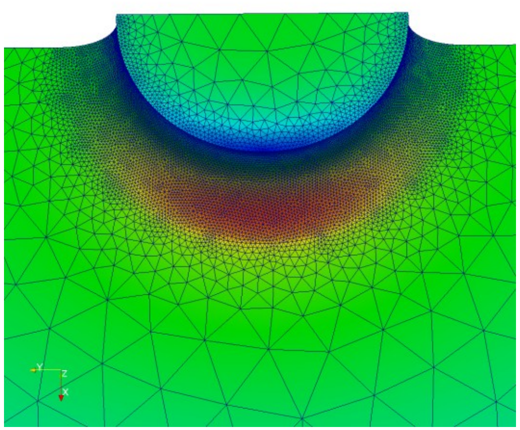
A possible explanation

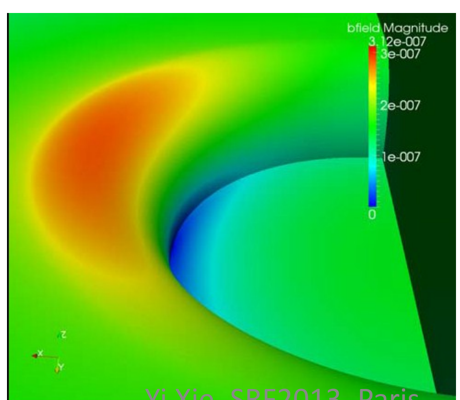
Due to magnetic field enhancements at the pits edge, some of the smaller pits with sharp edges may reach Nb superheating field earlier than some bigger pits with shallow edges;





Magnetic field enhancement factor: $\beta \propto \left(\frac{r}{R}\right)$^$(-1/3)$

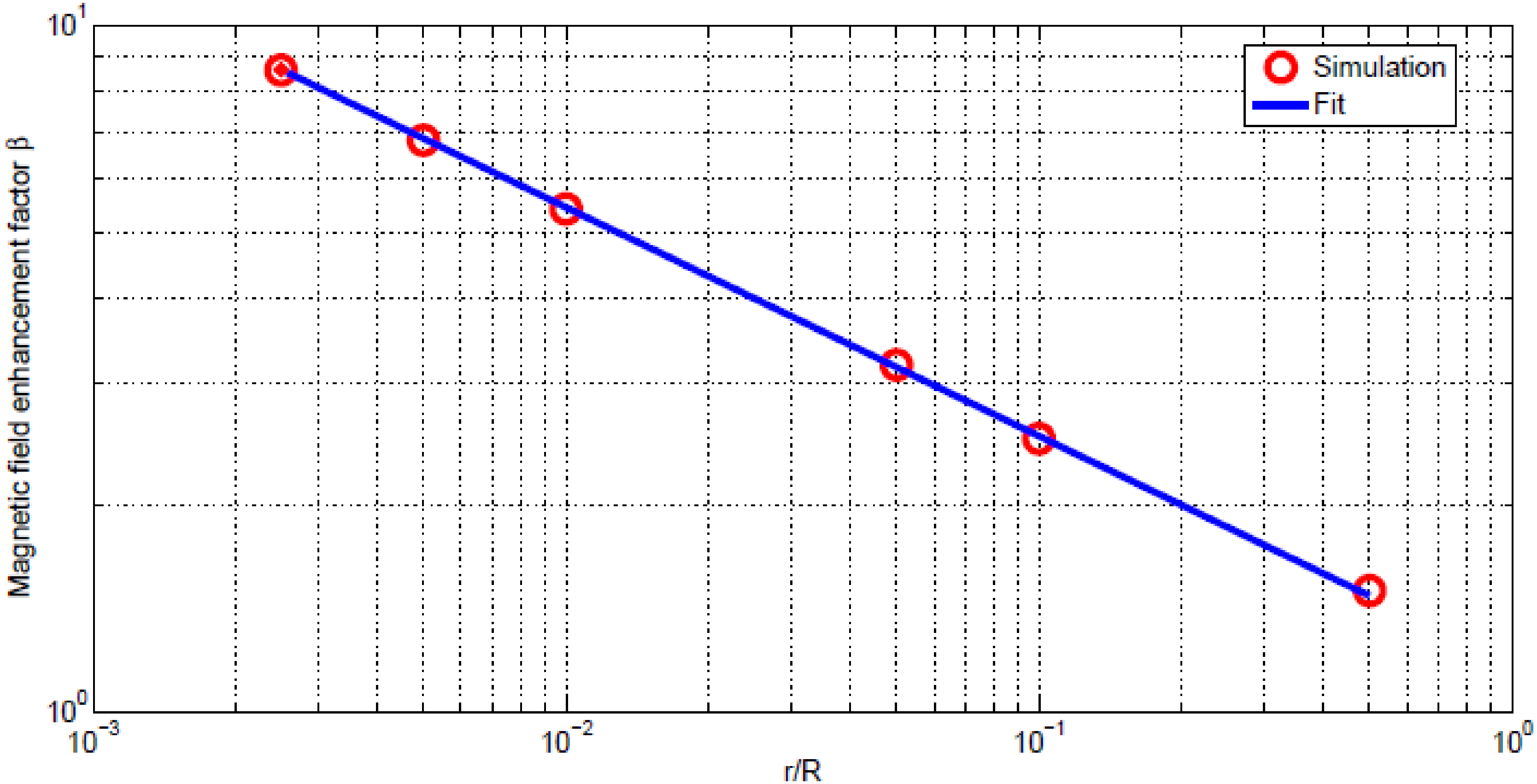




Valery Shemelin and Hasan Padamsee's initial idea and then I redid the pits simulation using ACE3P

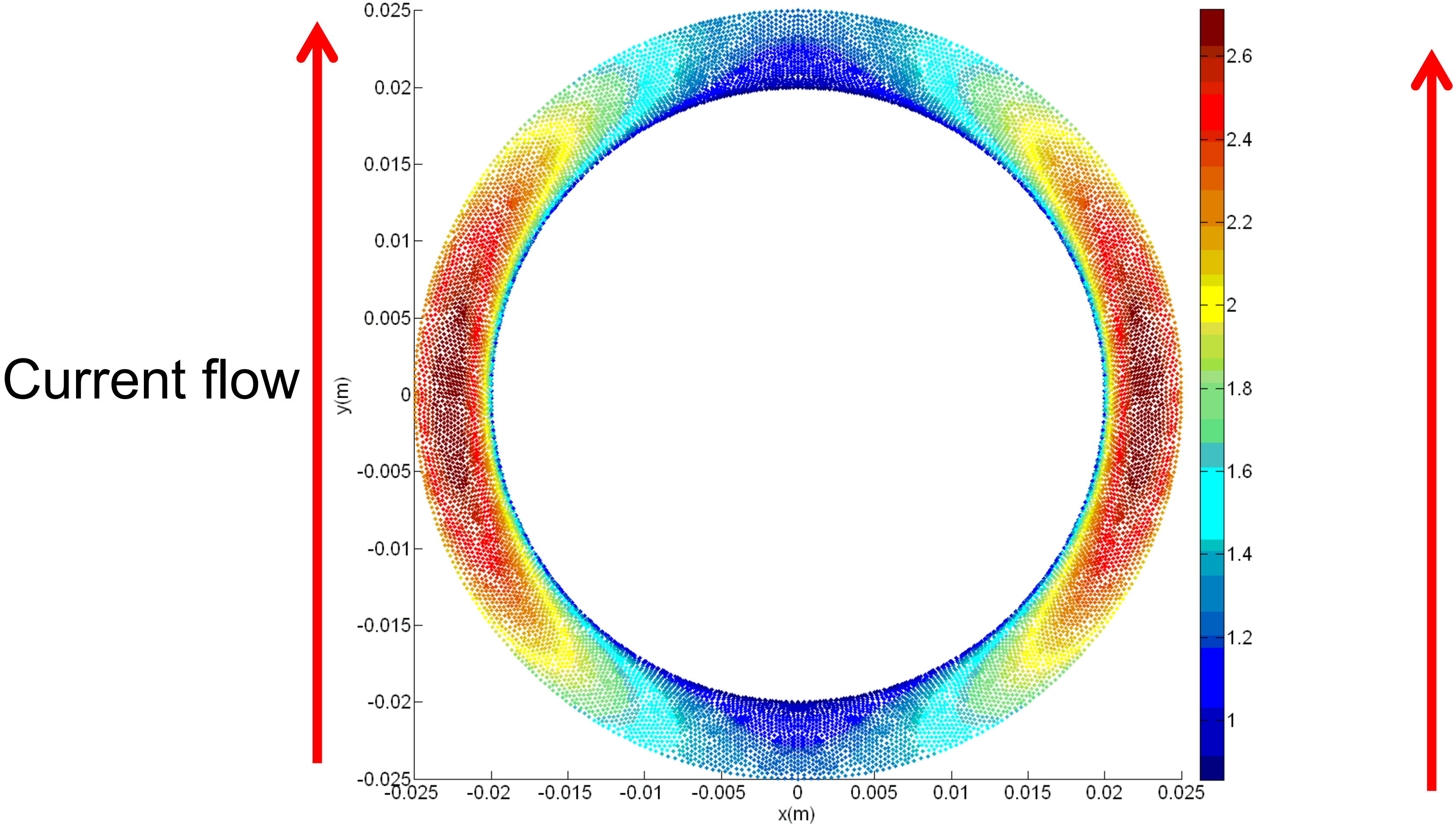
New calculation see TUP008

MFE



Magnetic field enhancement factor calculation by ACE3P using a 3-d model. The fit equation is $\beta = 1.17 * (r/R)^{-1/3}$.

MFE

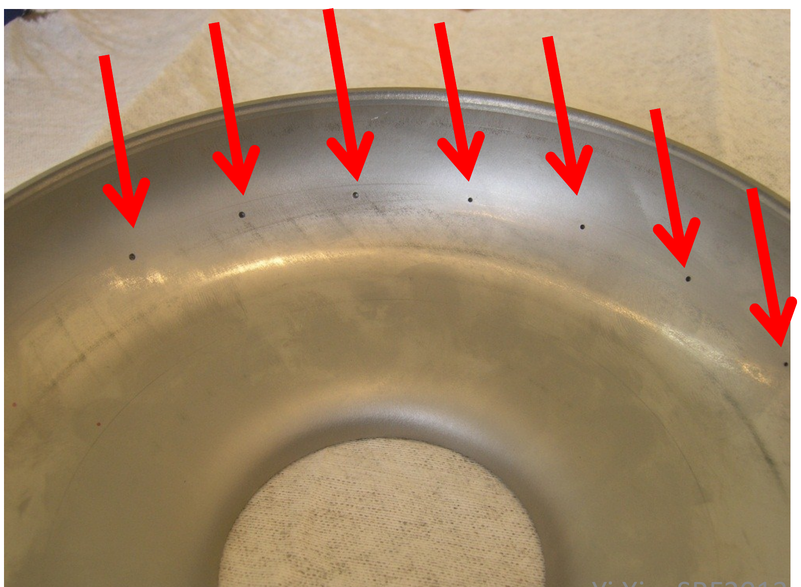


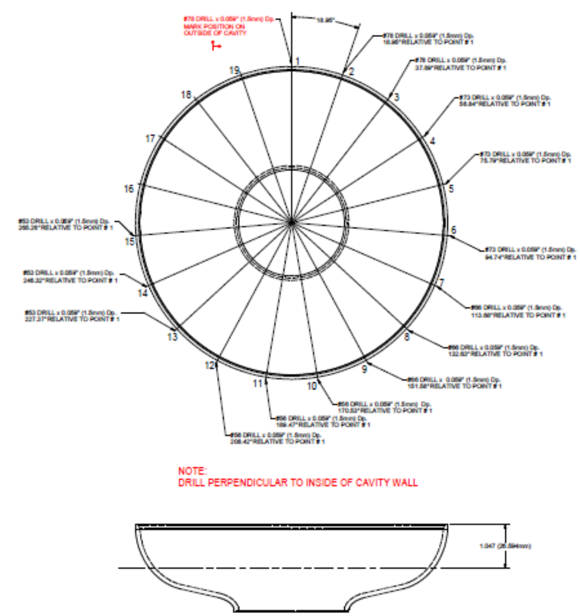
Magnetic field enhancement near the pit edge.

To systematically study pits, we need statistics, so I made a cavity with lots of artificial pits with different sizes R.

A pits cavity

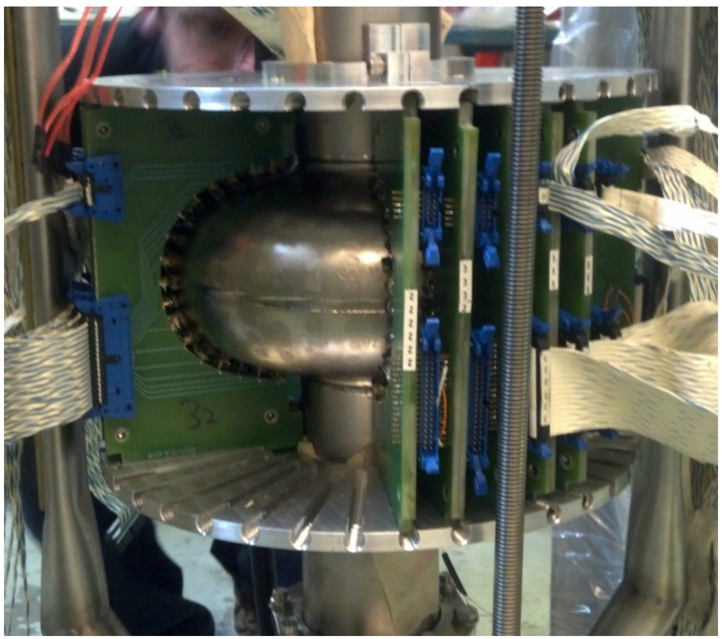
- I artificially created pits with five sizes on a single cell Nb cavity, three of them on each half cup before welding, all together 30 pits;
  - Radius: 200 μm, 300 μm, 400 μm, 600 μm, 750 μm;
  - Depth: 1.5mm;
- The cavity received 120um BCP and in-situ 120 C bake;



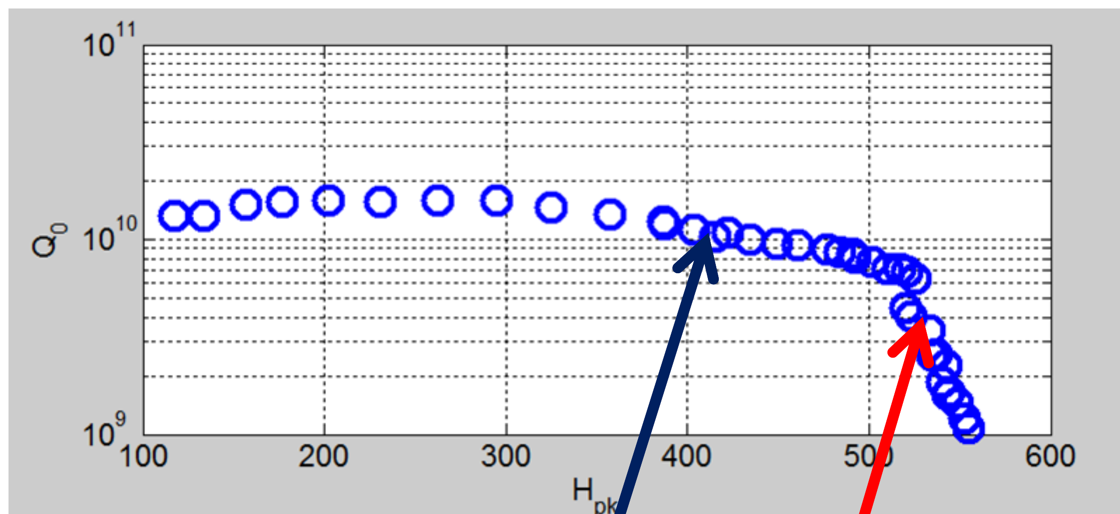


T-map

- For every pit, I used Cornell single-cell T-map system to record the temperature rise as a function of magnetic field;
- The cavity reached ~ 550 Oe (55 mT) on the quenched pits surface;



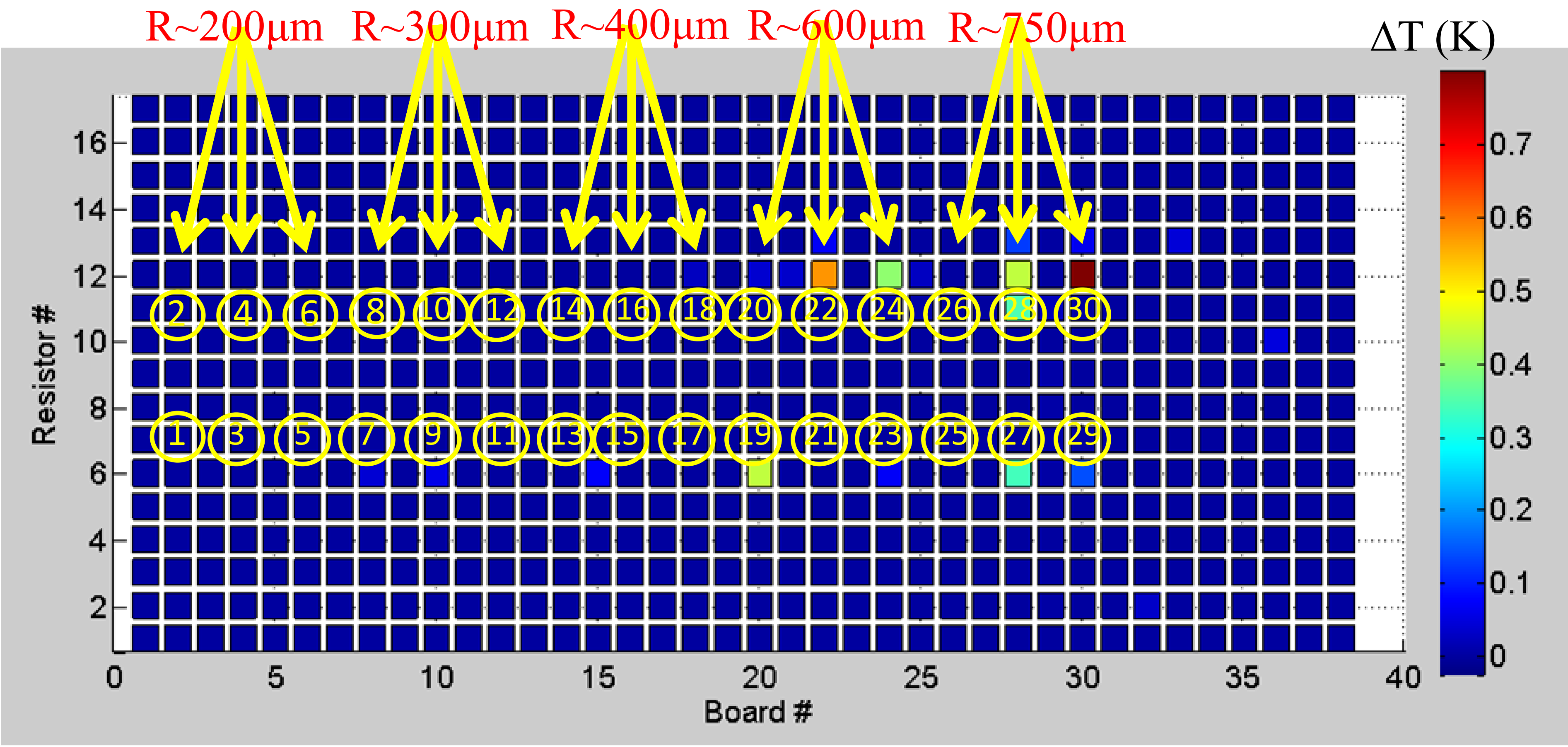
~ 650 sensors, nΩ sensitivity!



Some Q-drop effects kicks in

Huge Q-drop

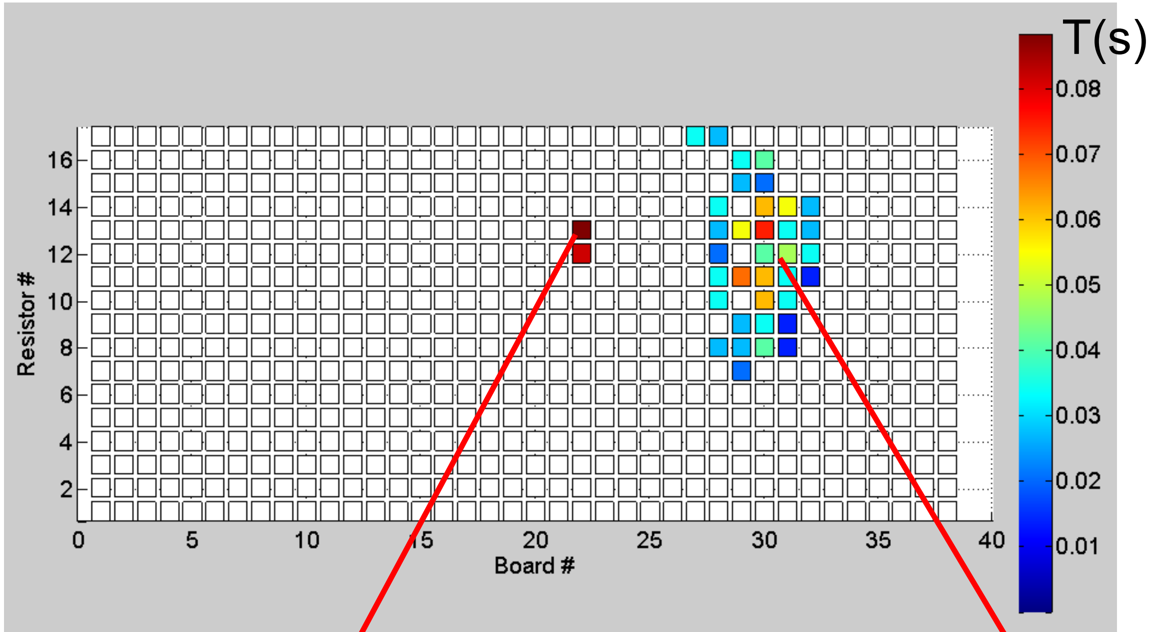
T-map



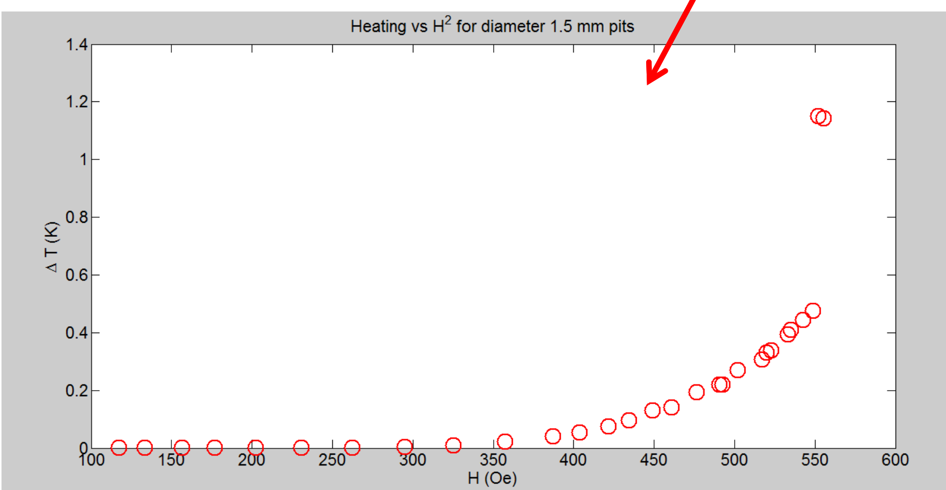
A typical T-map at ~ 500 Oe (50 mT)

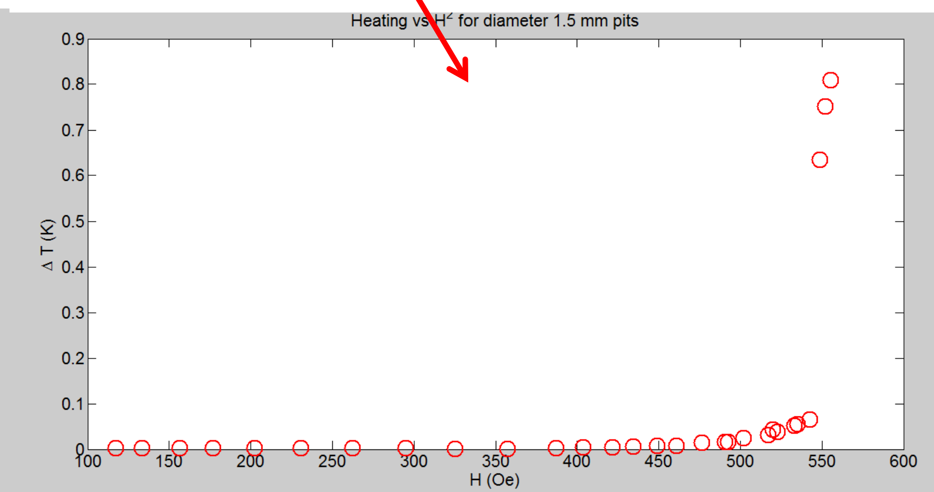
Note the bigger pits shows bigger heating

Quench locations

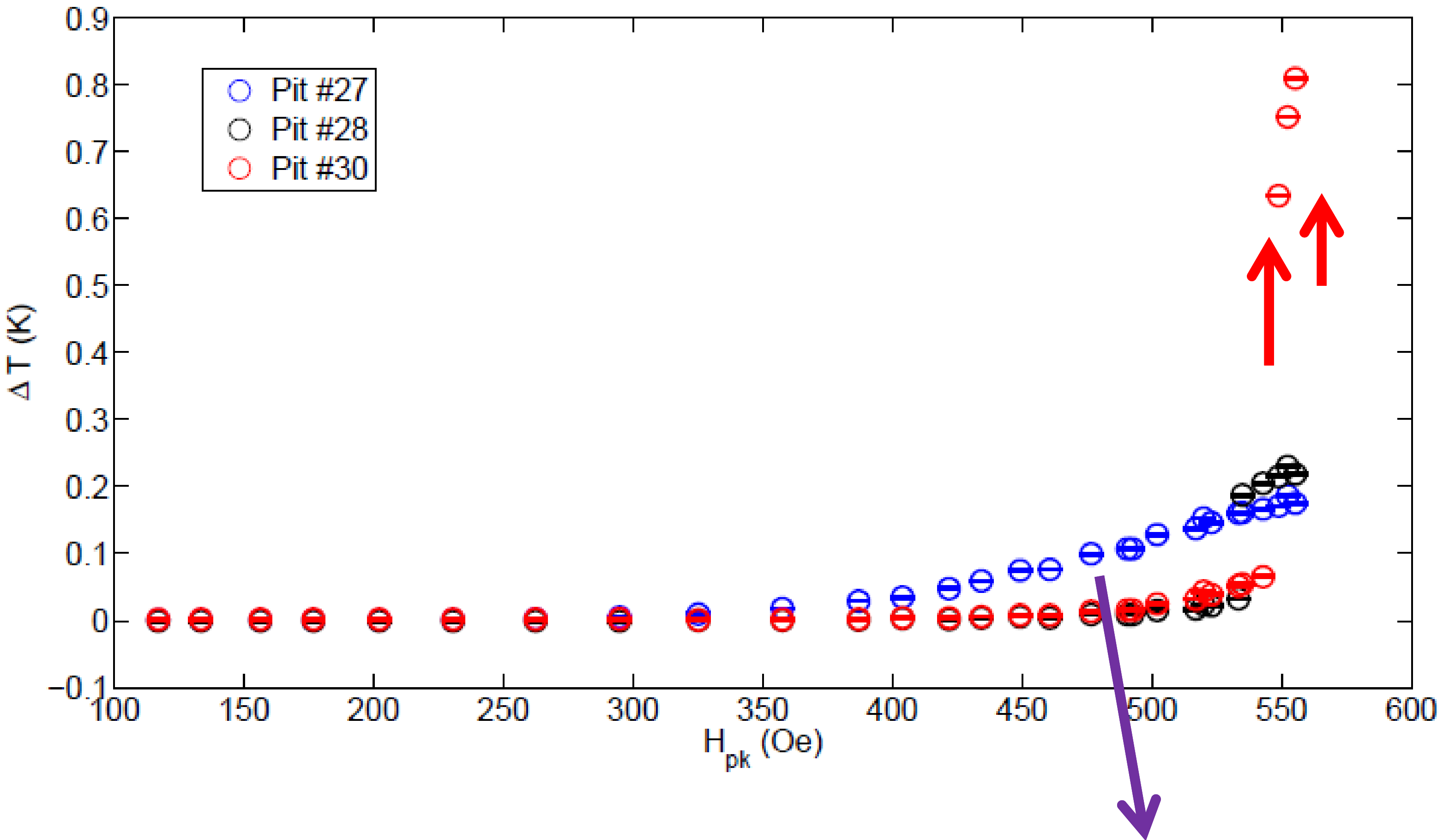


The quench locations were found by measuring the length of time that the resistors stayed warm after the quench of the cavity





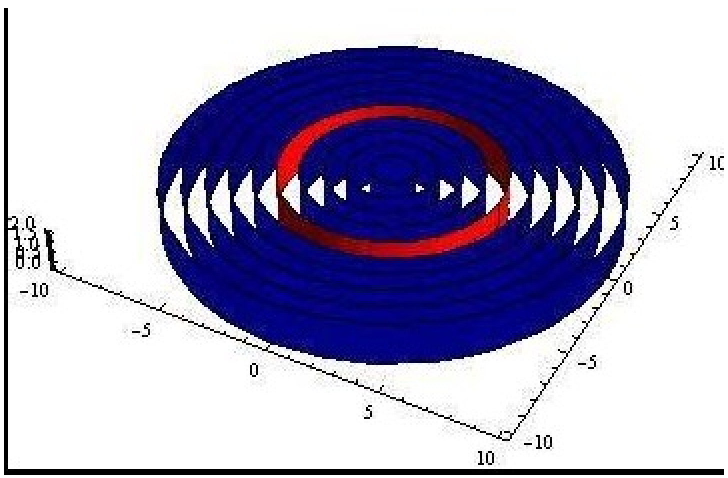
Quench pits



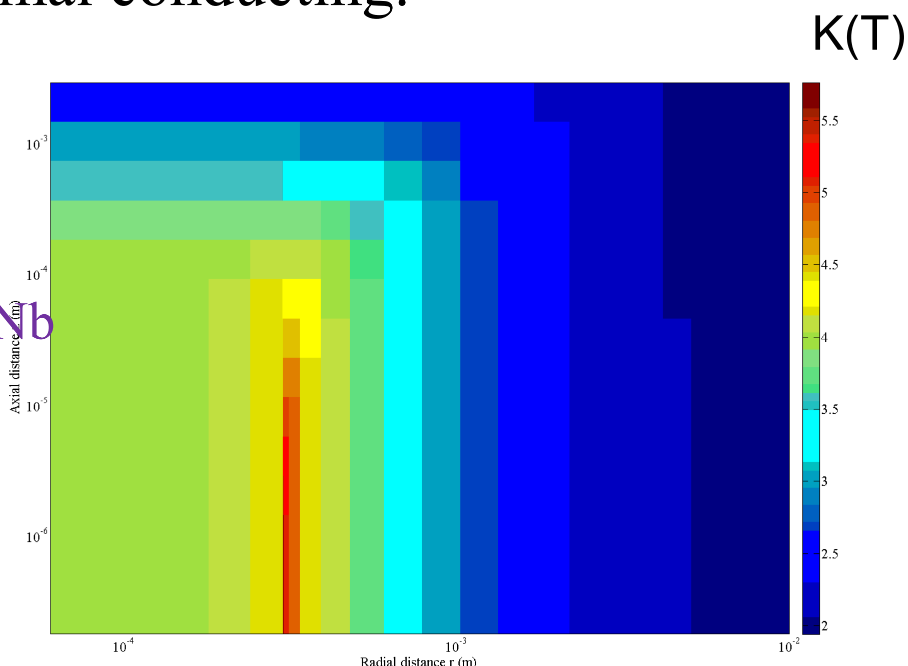
For two quenched pits, both show gradual heating until sudden jump to ~ 1K range, which may indicates pits go normal conducing;

Normal conducting region exists!

My ring-type defect model simulations show that there is a thermally meta-stable state below quench field for pit-like defects. At this state, only the edge of the pits will get normal conducting.



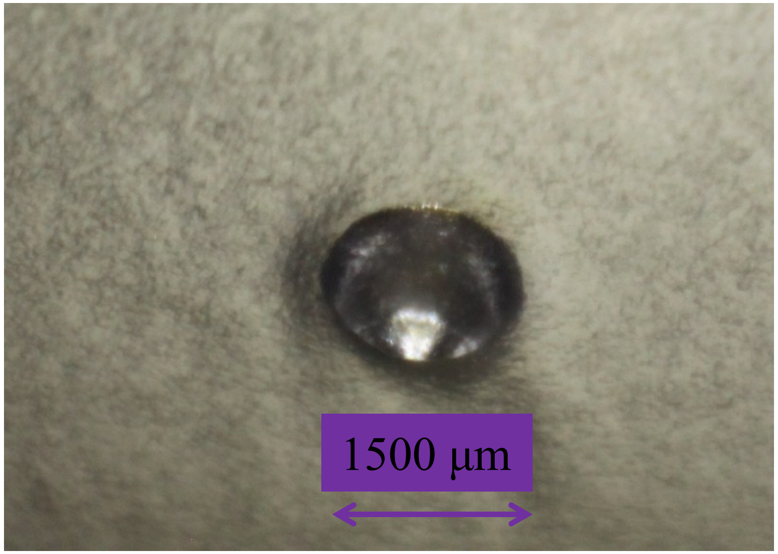
3mm Nb



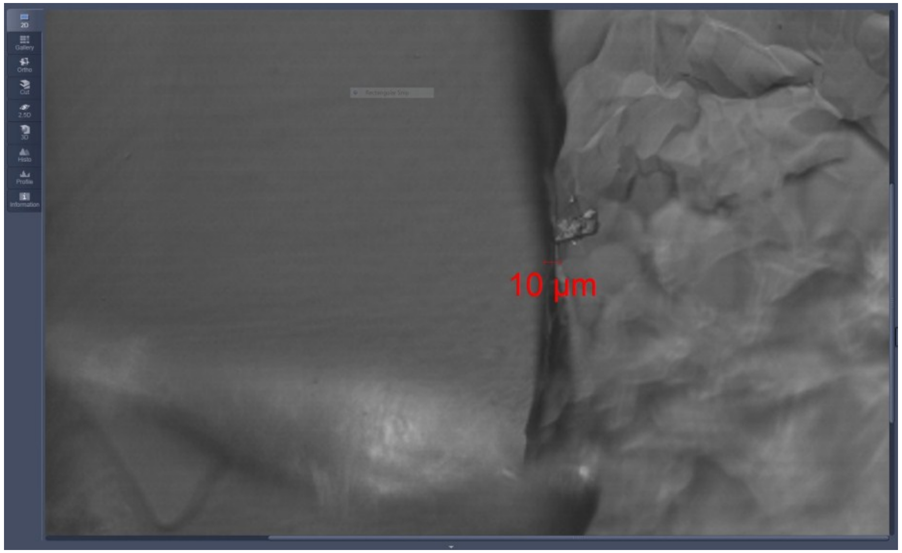
Radial distance from pit center

Normal conducting region, $T = 5.76K > T_c = T_{c0} * \mathrm{sqrt}(1 - H/H_0) = 5.4K$, Here H is slightly below quench field.

Optical images



Optical inspection after test



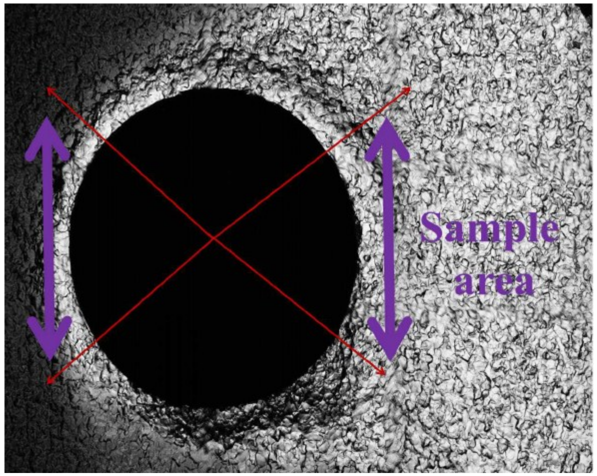
Laser confocal microscope of pit edge

For the quenched pits, R~750 um, r ~ 10 um, using MFE formula we can get MFE factor ~ **4**. Which is in good agreement with pits cavity quench field 55 mT (assuming Nb superheating field ~ 200 mT)!

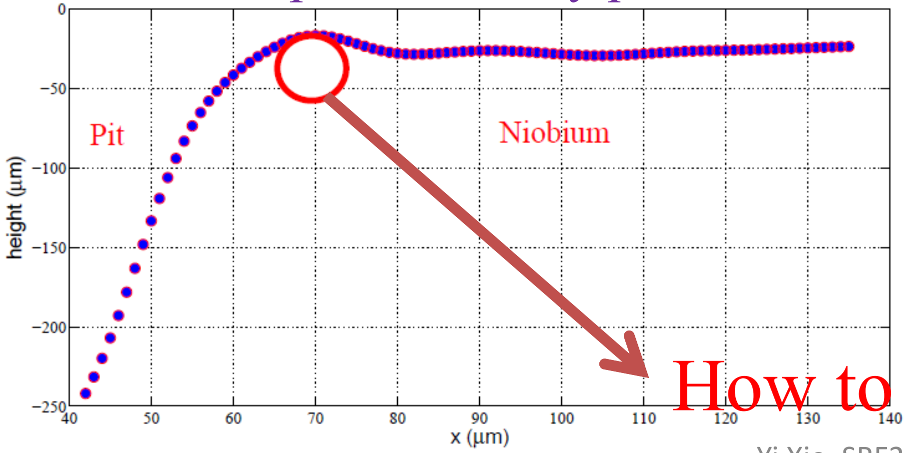
Laser confocal microscopy

Laser confocal microscopy was used to obtain the precise Values of pit edge radius r.

Replica of cavity pits



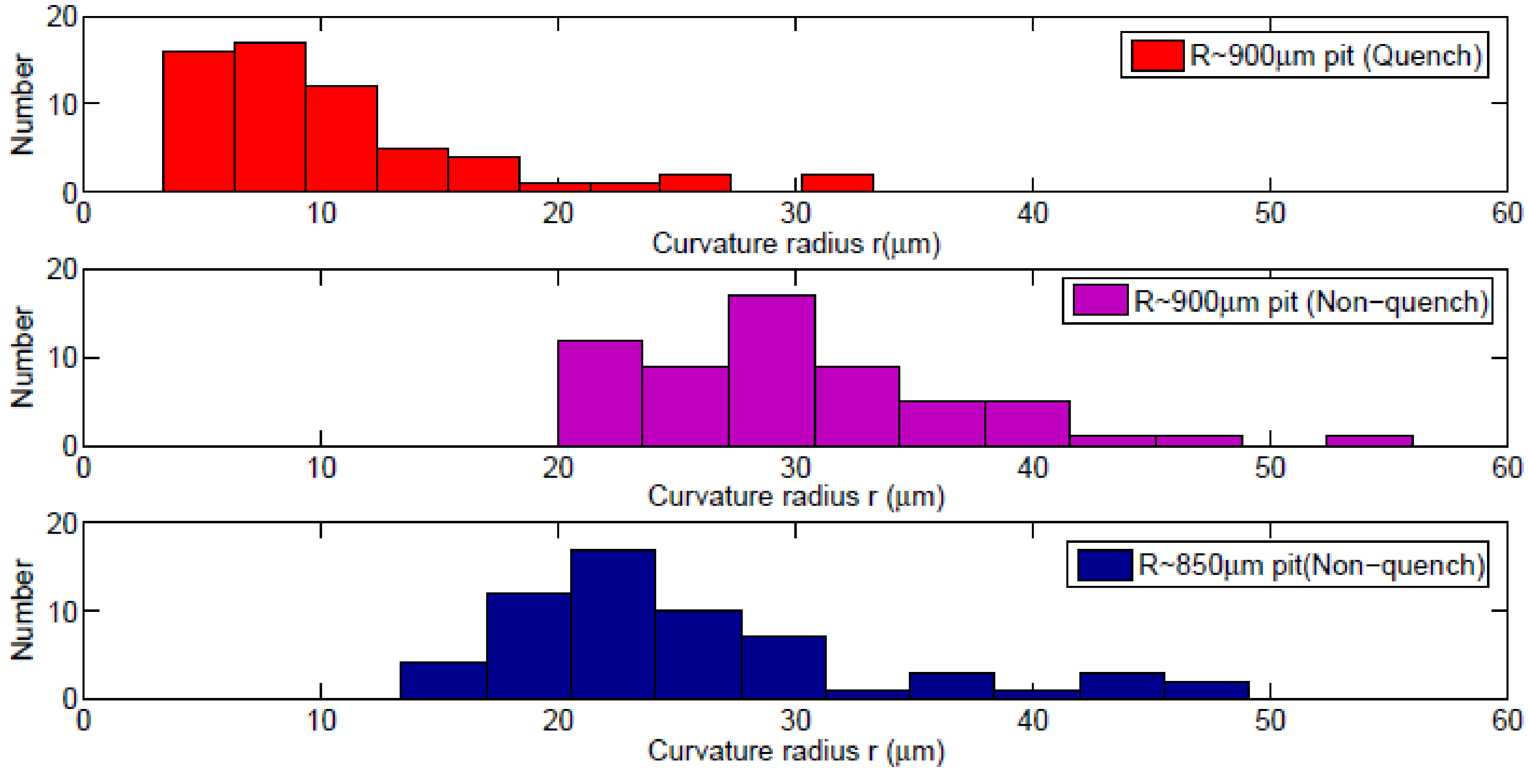
Pit sample area



Since magnetic field is parallel to cavity equator, so edges of pits perpendicular to the direction of the magnetic field show highest fields due to MFE effect. So we only sample area indicated above.

How to get pit edge radius r

Laser confocal microscopy



Range of pit edge radius r of three pits with the biggest drill bit radius R =750 µm

Laser confocal microscopy

Pit number	Pit drill radius (μm)	Range of pit edge radius r (μm)	Range of pit radius R (μm)
#30	750	5~30	850~900
#27	750	20~55	880~900
#28	750	15~45	820~850
#23	600	30~60	520~550
#24	600	25~60	580~610
#22	600	5~45	570~610
#19	600	20~55	550~600
#20	600	35~60	570~600
#7	300	20~50	280~310
#6	200	25~55	180~210
#2	200	35~60	190~200

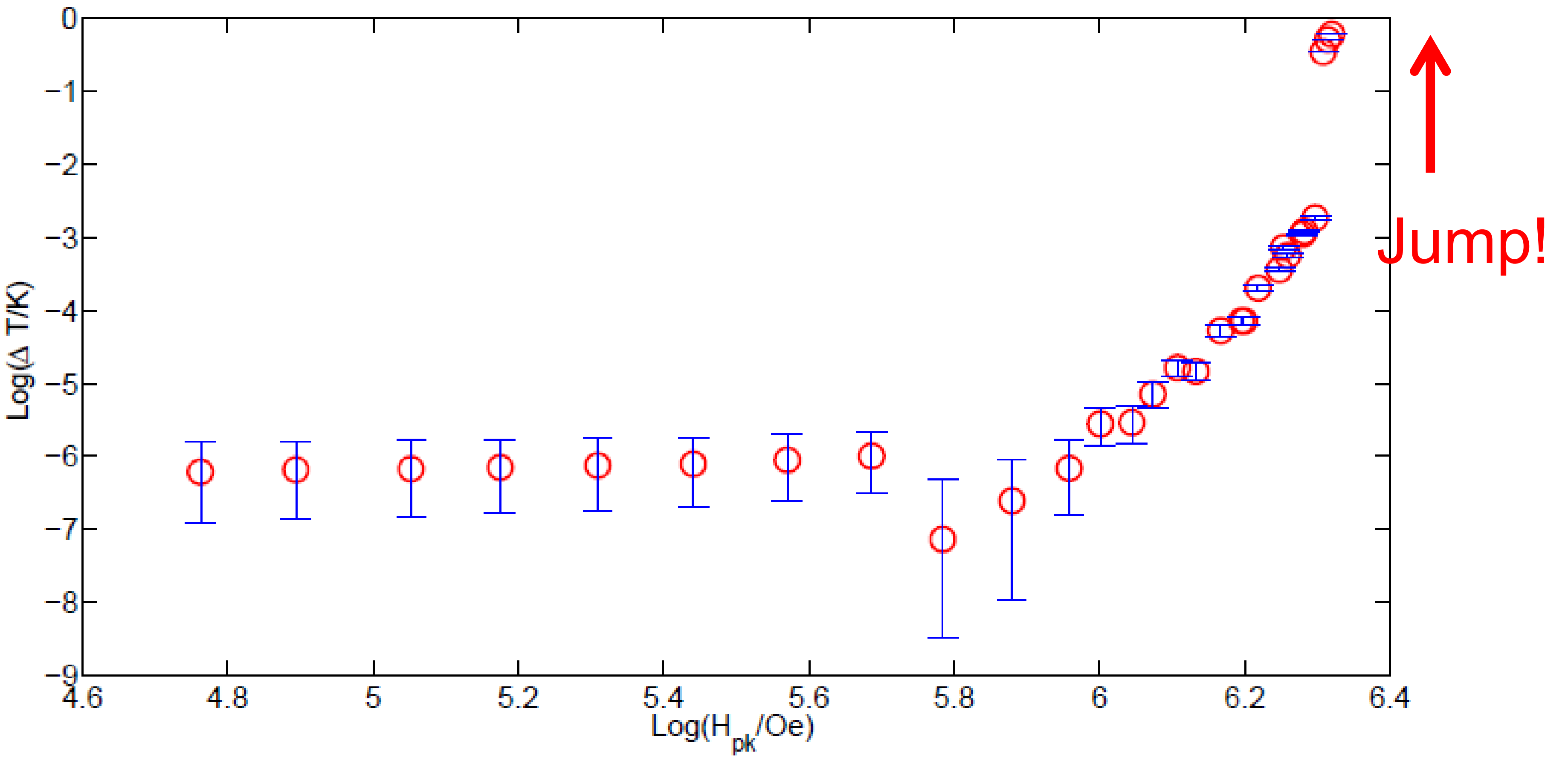
How does magnetic enhancement model apply to those pits geometrical information

MFE at pit edges

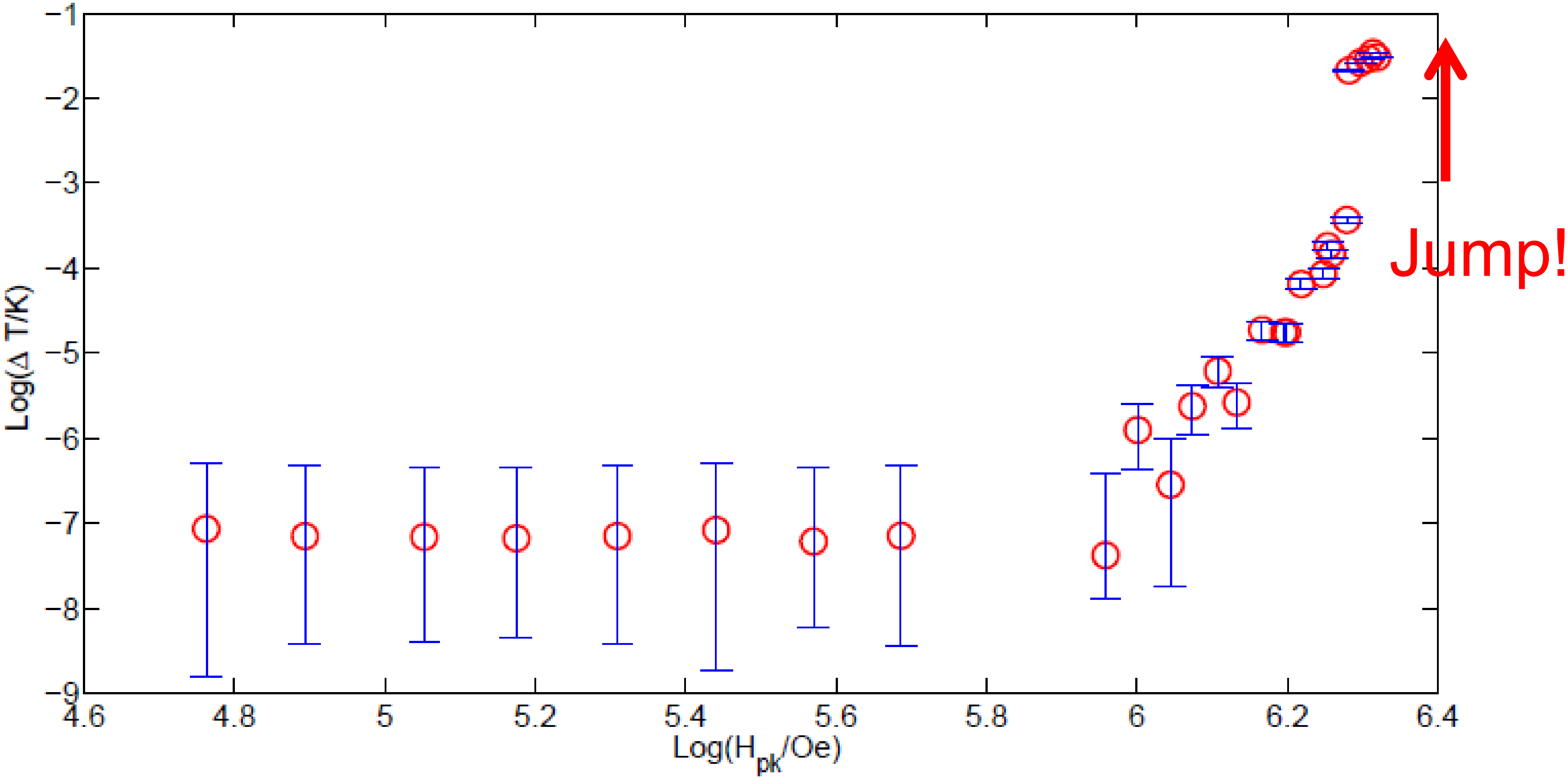
Pit number	Pit drill radius (μm)	Range of pit edge radius r (μm)	Range of pit radius R (μm)	Range of magnetic field enhancement factor $\beta = 1.17*(r/R)^{-1/3}$	Range of local magnetic fields at H_{pk} reached in the pit cavity (Oe)
#30	750	5~30	850~900	3.6~6.6	1940~3560
#27	750	20~55	800~850	2.9~4.1	1560~2210
#28	750	15~45	790~810	3.0~4.4	1620~2370
#23	600	30~60	520~550	2.4~3.1	1290~1670
#24	600	25~60	580~610	2.5~3.4	1350~1830
#22	600	5~45	570~610	2.7~5.8	1460~3130
#19	600	20~55	550~600	2.5~3.6	1350~1940
#20	600	35~60	570~600	2.5~3.0	1350~1620
#7	300	20~50	280~310	2.1~2.9	1130~1560
#6	200	25~55	180~210	1.7~2.4	910~1290
#2	200	35~60	190~200	1.7~2.1	910~1130

MFE theory suggests that the edge of pit #30, #28, #22 will go to normal conducting first,

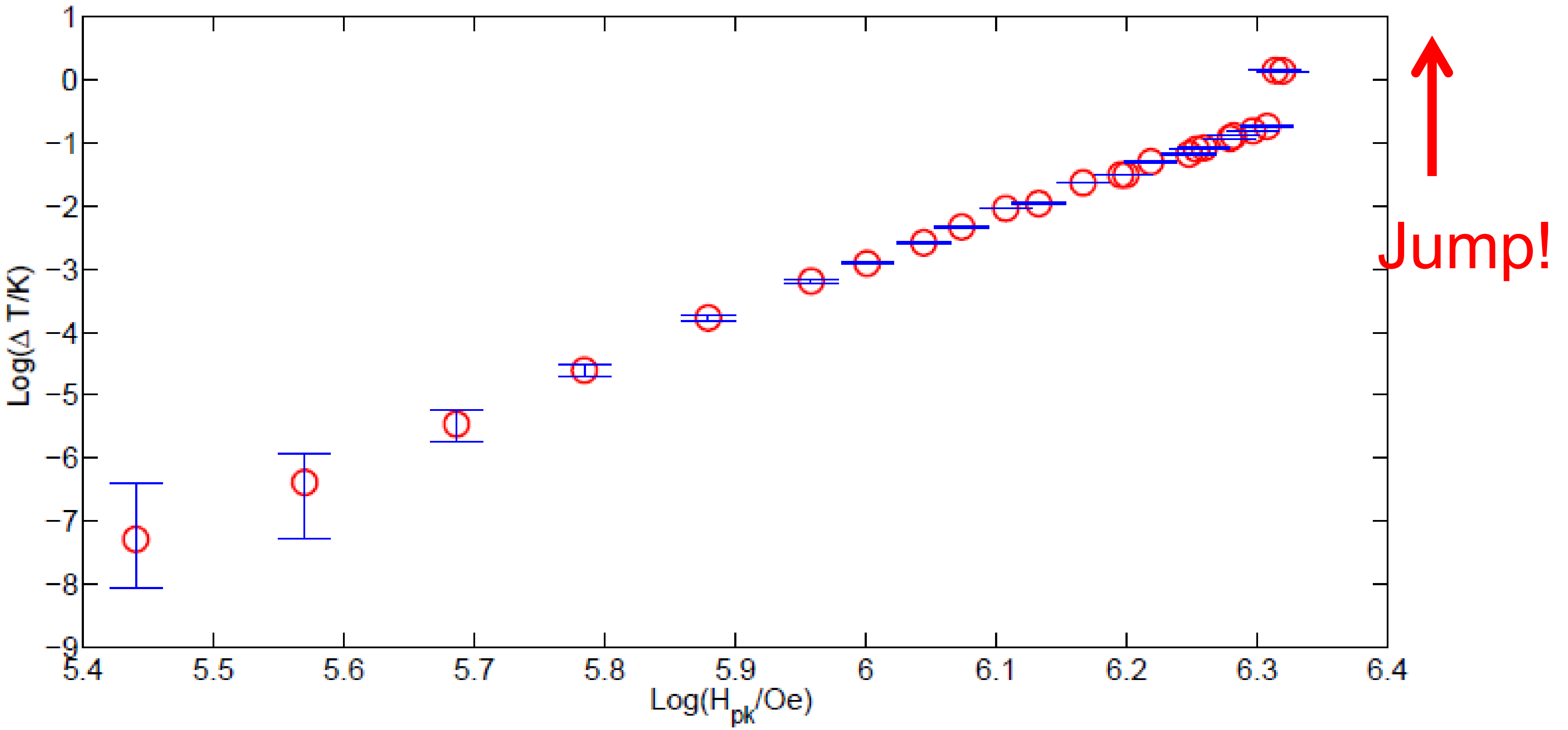
Is it that true?



Heating vs magnetic field level for pit #30



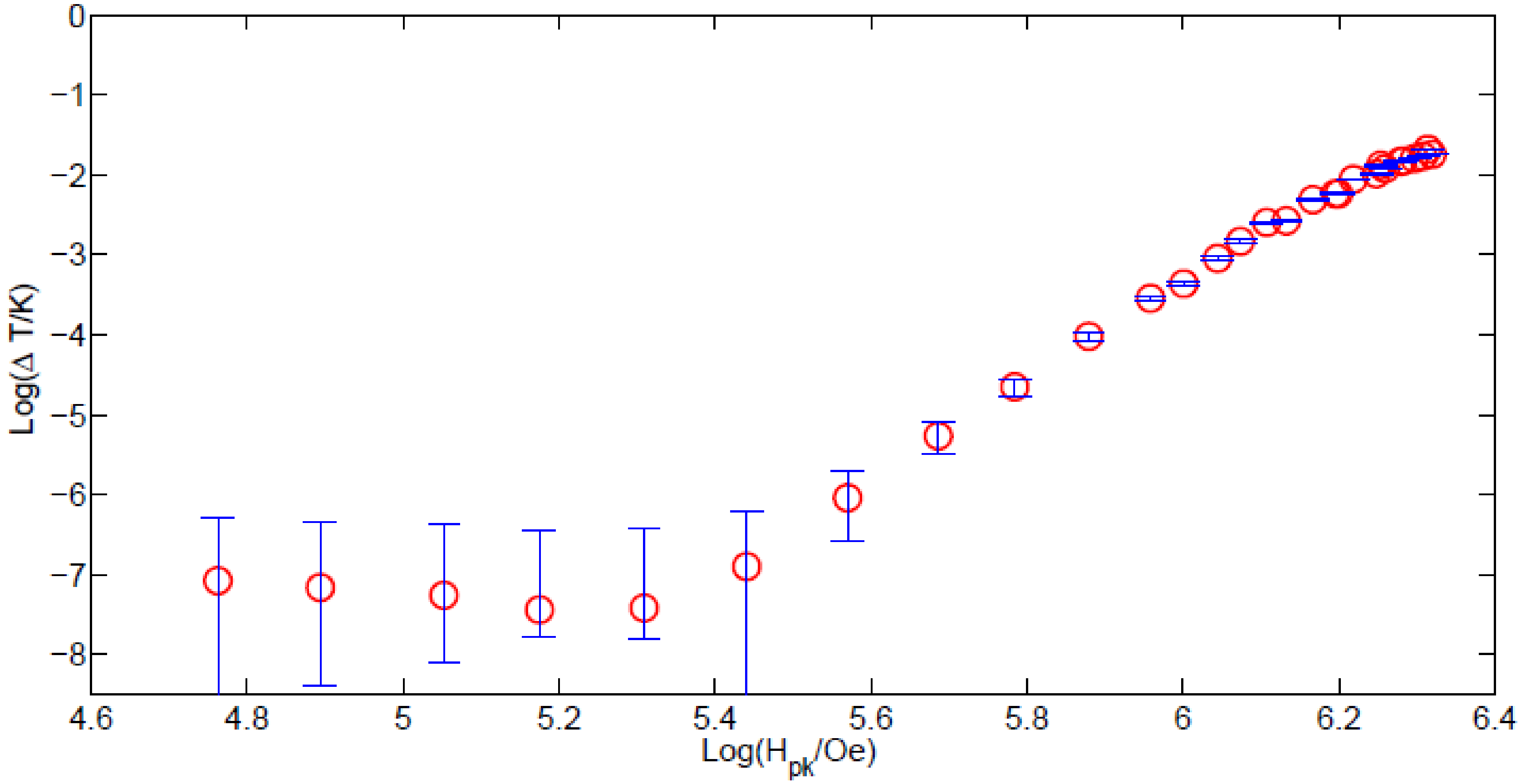
Heating vs magnetic field level for pit #28



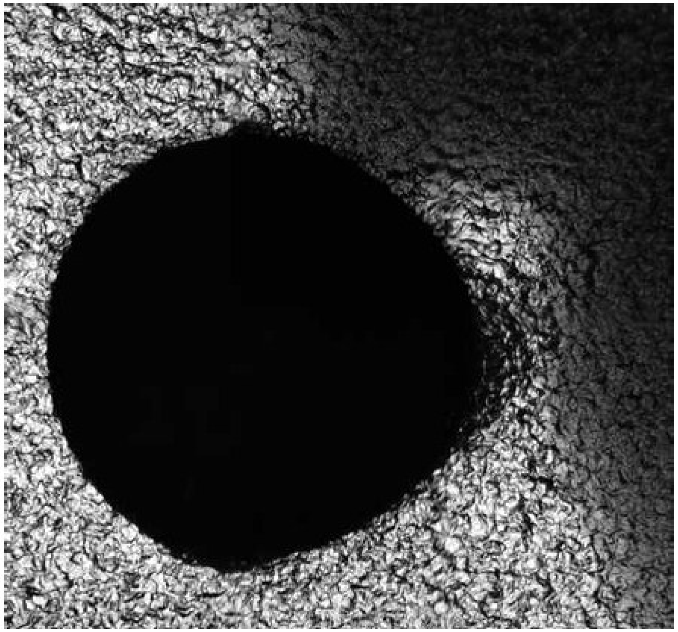
Heating vs magnetic field level for pit #22

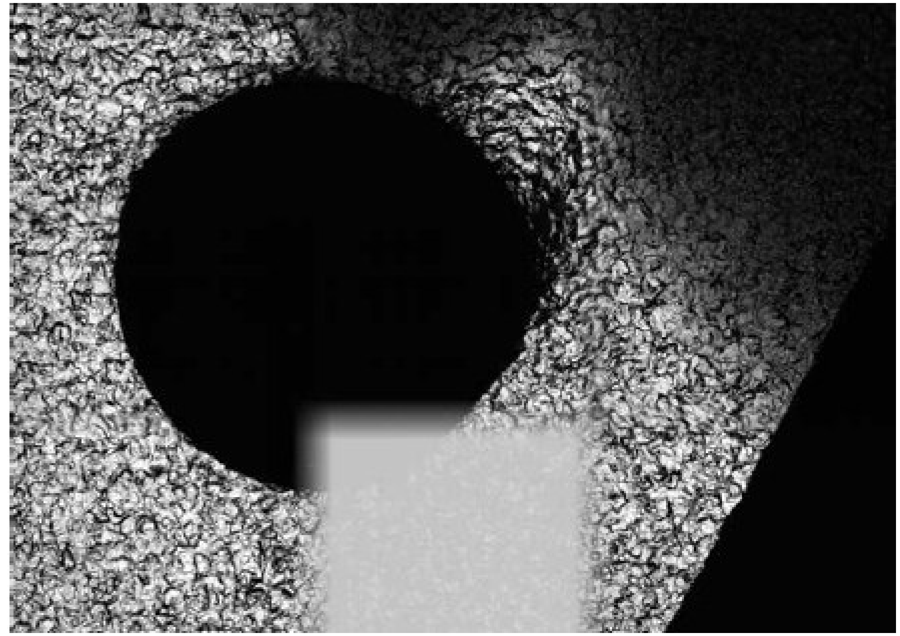
MFE theory suggests that the edge of pit #27 will go normal conducting at higher fields compared with pit #30, #28,

Is it that true?



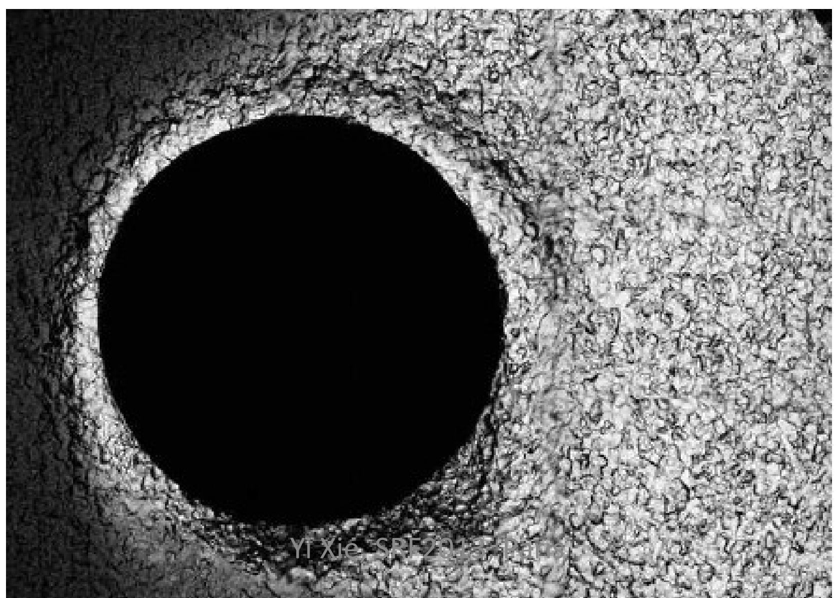
Heating vs magnetic field level for pit #27





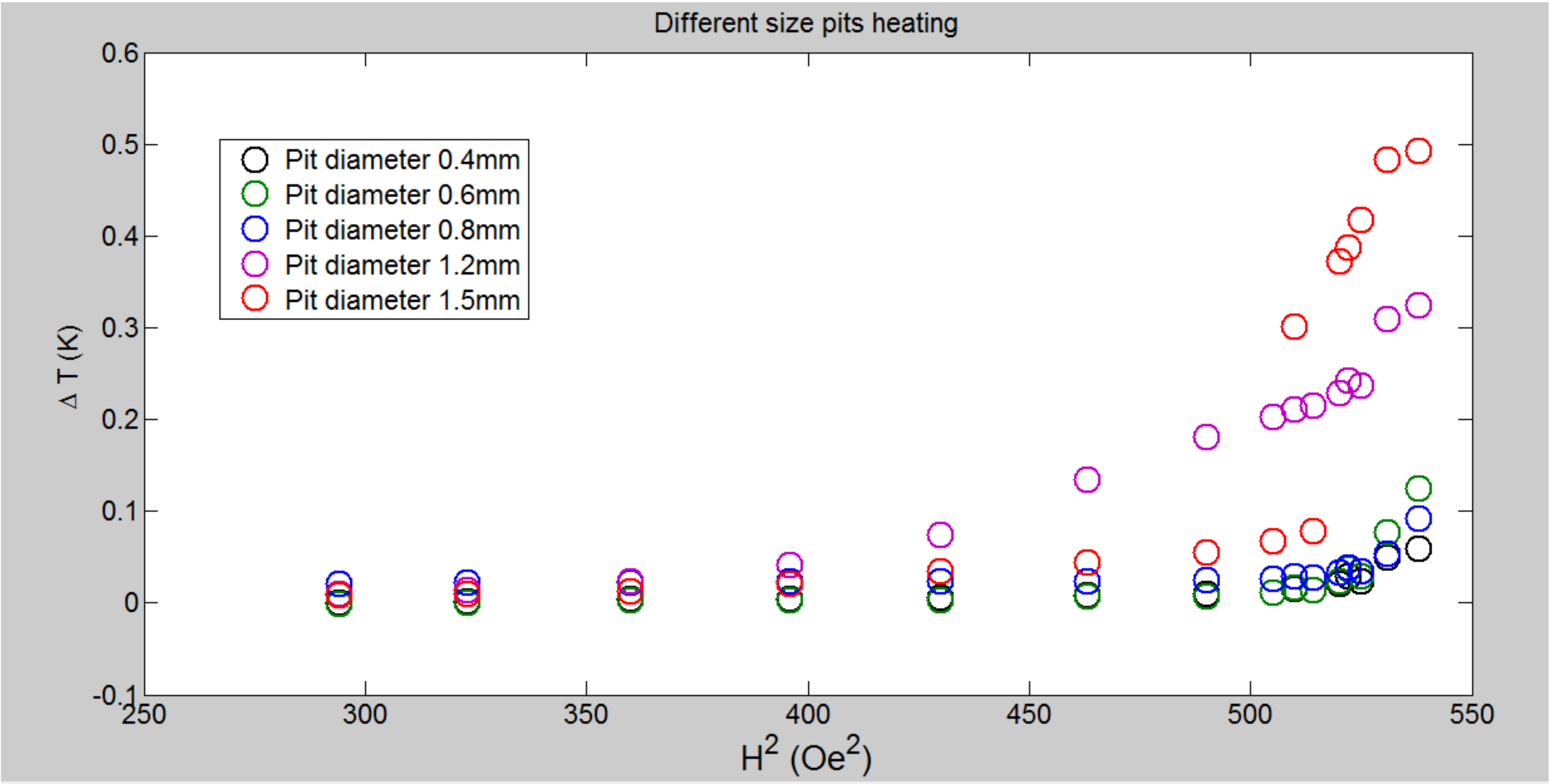
pit #30

pit #28



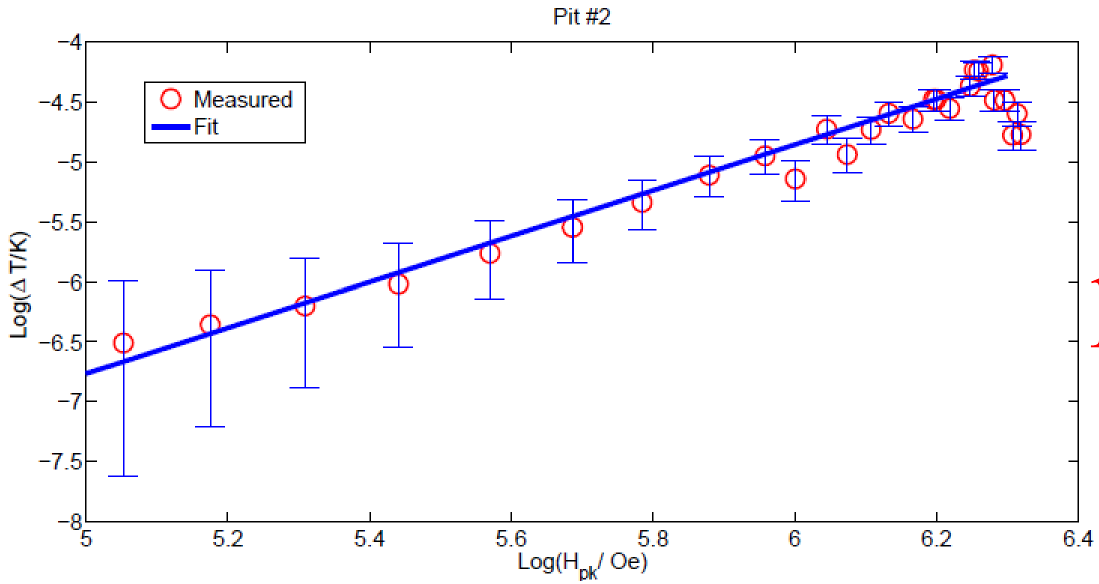
pit #27

Non-quench pits



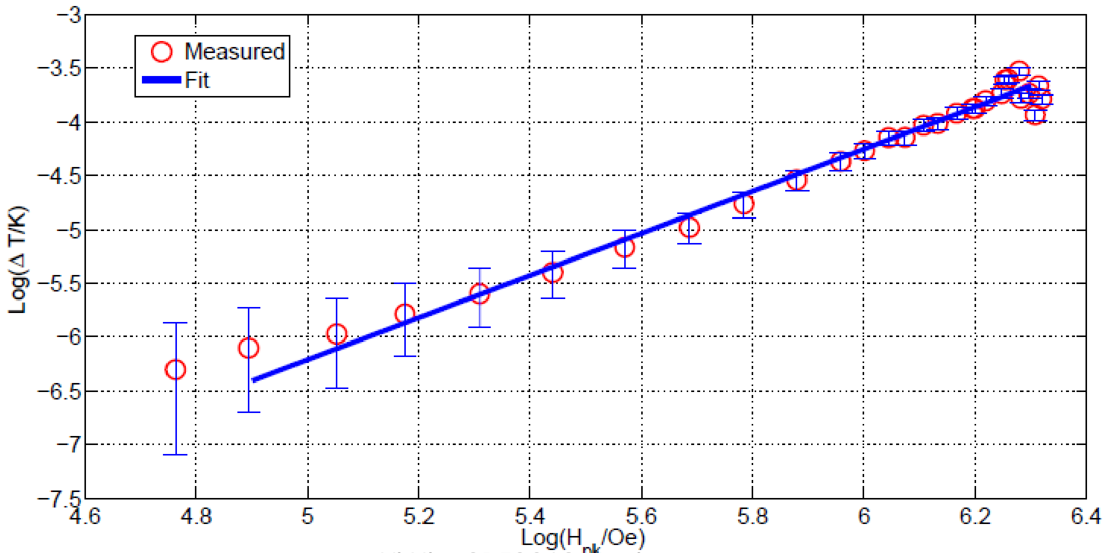
For different size pits, it appears heating generally increases along with pit diameter R which is also consistent with MFE model since our bigger pits have bigger MFE factor.

Non-quench pits



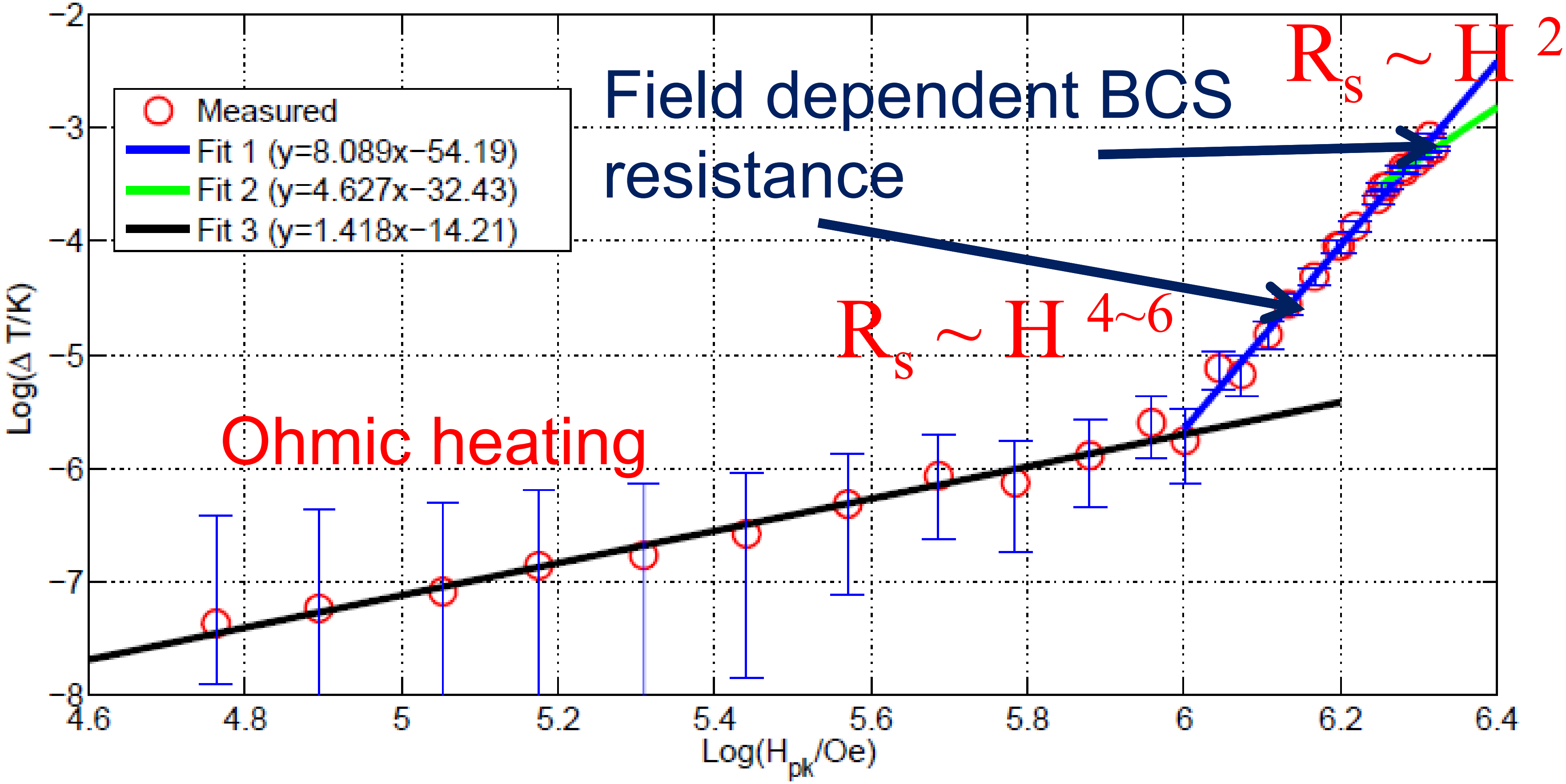
pit #2

Ohmic heating



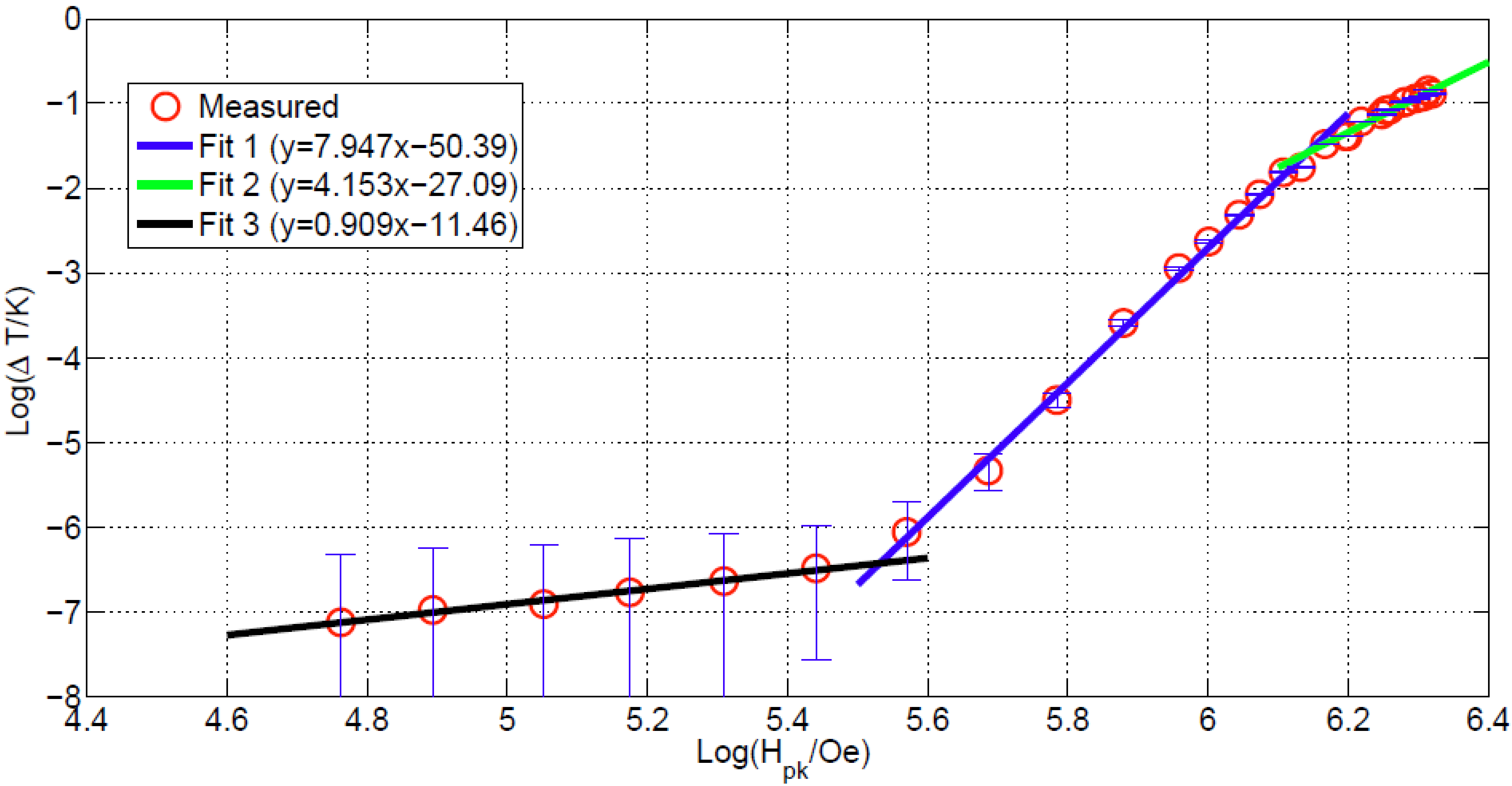
pit #6

Non-quench pits



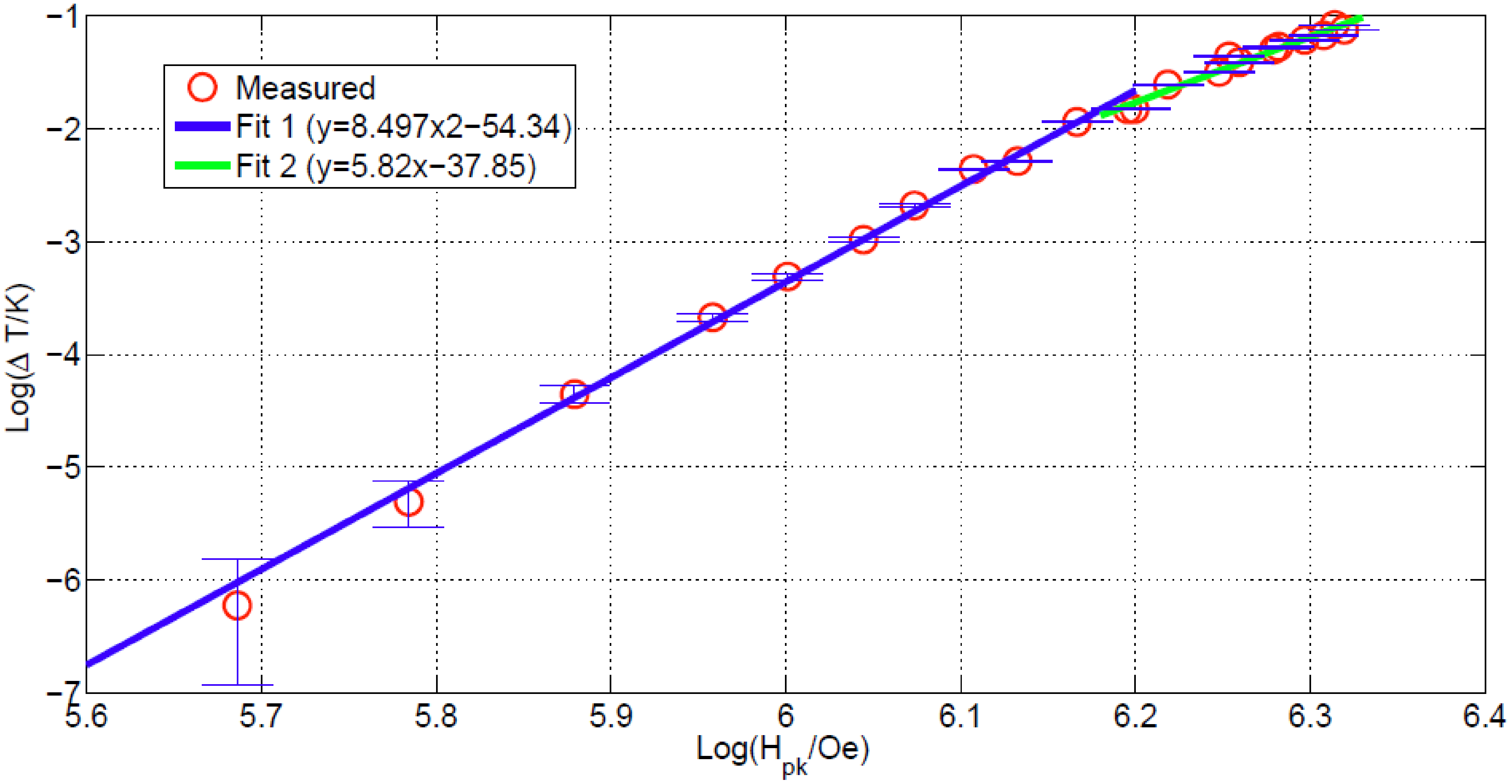
pit #20

Non-quench pits



pit #19

Non-quench pits



pit #24

Non-quench pits

Pit number	Slope of $ln(\Delta T/K)$ vs $ln(H_{pk}/Oe)$ in field region I (H_{local} < 800 Oe)	Slope of $ln(\Delta T/K)$ vs $ln(H_{pk}/Oe)$ in field region II (800 Oe < H_{local} < 1300 Oe)	Slope of $ln(\Delta T/K)$ vs $ln(H_{pk}/Oe)$ in field region III (H_{local} > 1300 Oe)
#27	~ 2	6.2	4.3
#28	~ 2	10.0	5.0
#23	~ 2	8.3	4.2
#24	~ 2	8.4	4.8
#19	~ 2	7.8	4.1
#20	~ 2	8.1	4.6
#7	~ 2	8.5	4.0
#6	1.92	N/A	N/A
#2	1.97	N/A	N/A

Non-quench pits

- Low field: H^2 heating;
- Higher field: with the magnetic field to a power of 4 to 6 at medium fields, and with a power of ~ 2 of the high fields above 1300 Oe;
- The transition to field dependent surface resistance happens at fields similar to where the high field Q-slope starts in BCP cavities (~ 900 Oe);
- The pit heating data shows that a BCP cavity surface can reach high fields close to the superheating field.

Summary & Outlook

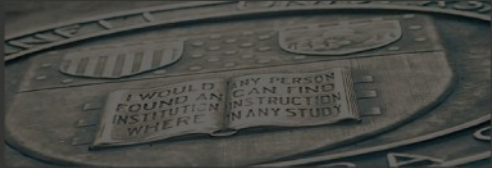
- Pit cavity experiments and simulations verify that MFE enhancement will cause pit edge nc first. Then the nc will spread and cause the whole cavity quench. Pit cavity is able to separate thermal effects from q-slope information.
- Pit cavity is a powerful tool to explore basic SRF niobium materials properties.
- Repeat what I did, just EP the cavity, see what the slope looks like.

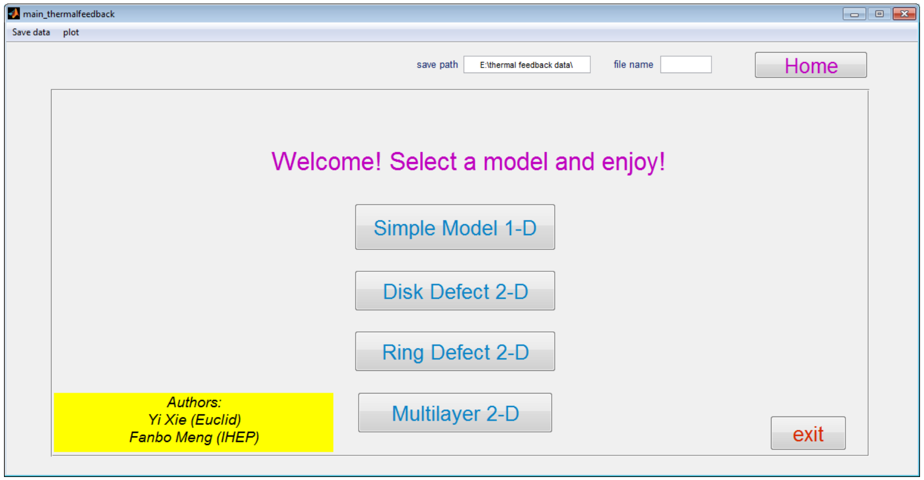
Acknowledgement

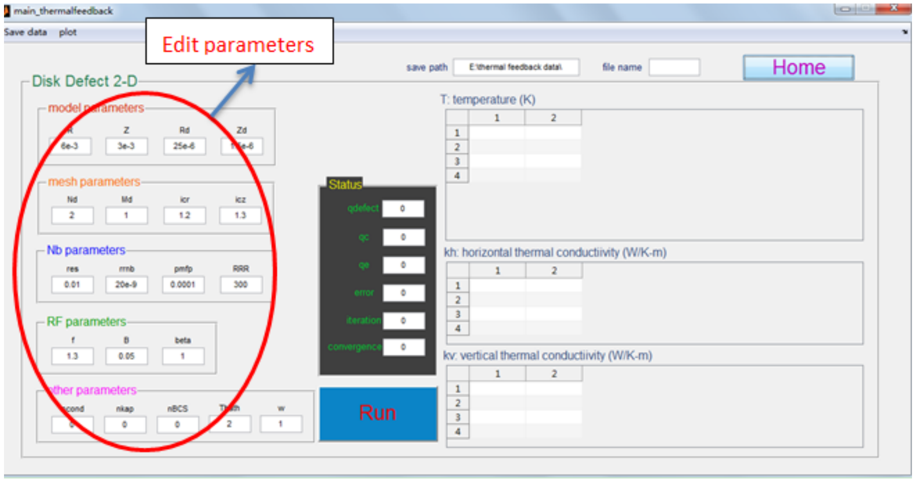
- Thanks to my advisors Profs. Matthias Liepe, Hasan Padamsee and Georg Hoffstaetter;
- Thanks to my fellow graduate students Dan Gonnella, Sam Posen for the help of pit cavity test, thermometry system; Thanks Ge Mingqi, F. Barkov and A. Romenenko for help on laser confocal microscopy.
- Thanks to entire Cornell SRF group!

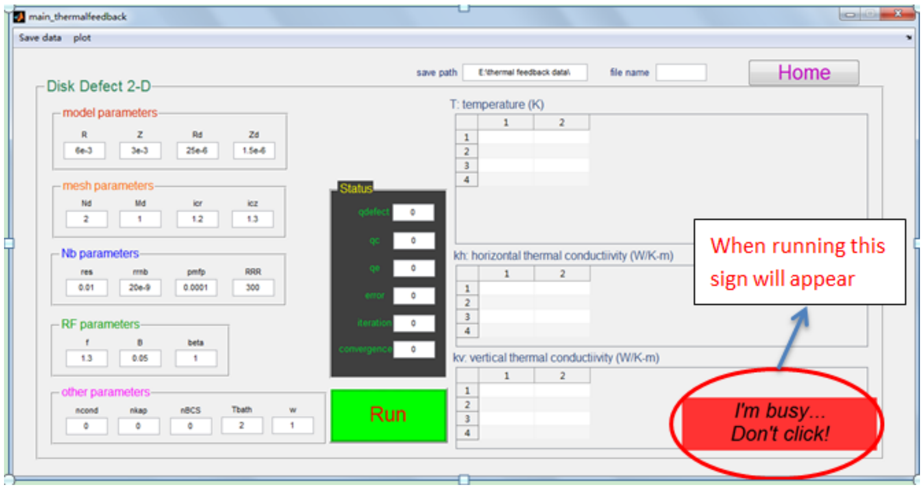
Thank you for your attention!

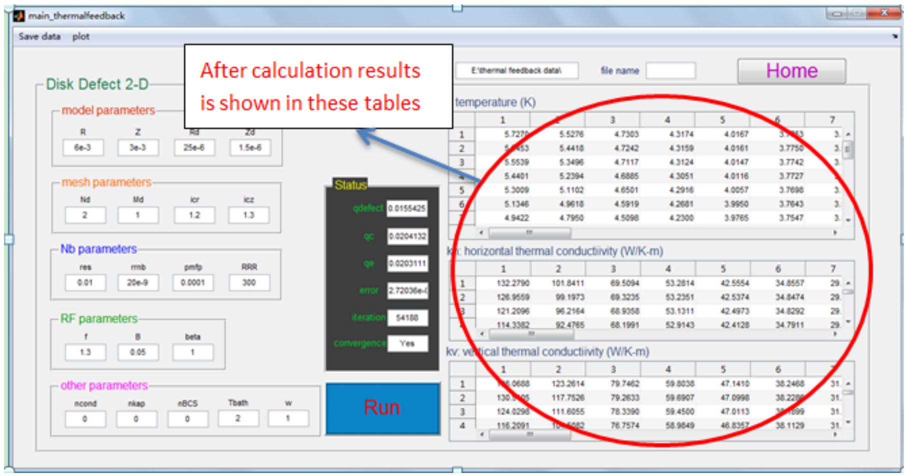
Advertisement for a general rf heating simulation code

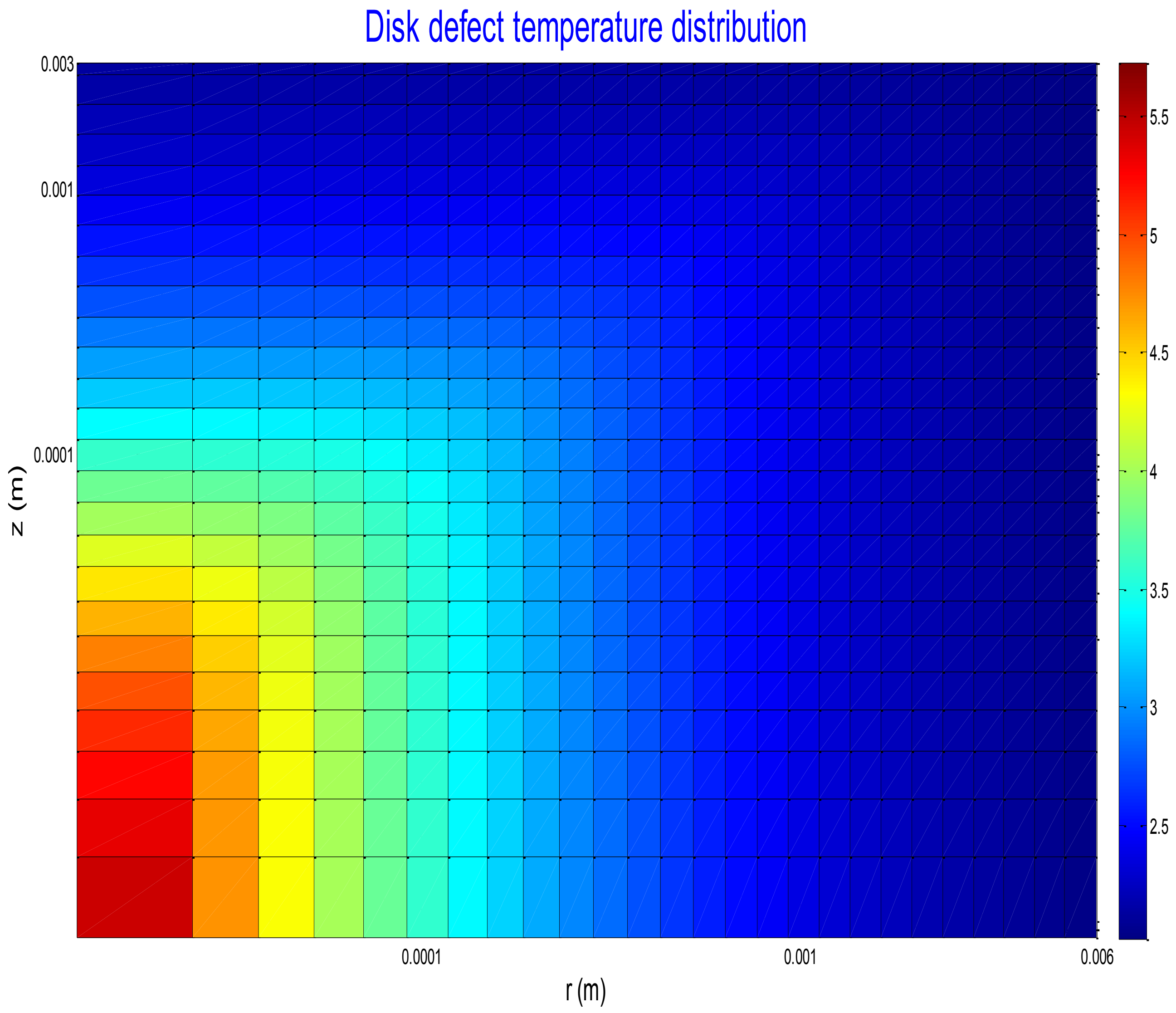



main_thermalfeedback
Save data plot
save path
E:\thermal feedback data\
file name
Home
Welcome! Select a model and enjoy!
Simple Model 1-D
Disk Defect 2-D
Ring Defect 2-D
Multilayer 2-D
Authors:
Yi Xie (Euclid)
Fanbo Meng (IHEP)
exit


Edit parameters
Disk Defect 2-D
model parameters
mesh parameters
Nb parameters
RF parameters
other parameters
Status
Run
Home
T: temperature (K)
kh: horizontal thermal conductivity (W/K-m)
kv: vertical thermal conductivity (W/K-m)


Disk Defect 2-D
model parameters
mesh parameters
Nb parameters
RF parameters
other parameters
Status
Run
Home
T: temperature (K)
kh: horizontal thermal conductivity (W/K-m)
kv: vertical thermal conductivity (W/K-m)
When running this
sign will appear
I'm busy...
Don't click!


After calculation results
is shown in these tables
Disk Defect 2-D
model parameters
mesh parameters
Nb parameters
RF parameters
other parameters
Status
Run
Home
temperature (K)
kh: horizontal thermal conductivity (W/K-m)
kv: vertical thermal conductivity (W/K-m)


Disk defect temperature distribution
0.003
0.001
0.0001
z (m)
0.0001
0.001
0.006
r (m)
5.5
5
4.5
4
3.5
3
2.5

Code capabilities

- Four running modes;
  - Simple defect free 1-D;
  - Defect case with disk-type and ring-type;
  - Multilayer cases: niobium on copper, Gurevich's coating;
- User can define niobium/helium properties (modular);
  - Basic: RRR, R0,f, PMFP => Rbcs, Kappa, Kapitza
  - Advanced: user can write their own Rbcs/Rres, Kappa and Kapitza resistance formula;
- User can define mesh configurations;
  - Flexible control mesh density near defects or the different layers;

Application examples

- Fermilab crab cavity version: wall thickness;
- Fermilab 650 MHz: RRR selection;
- Will nitrate coating affect niobium outside surface thermal properties?
- Material and thickness choices for niobium-copper and multilayer-coating;
- More important: defect and quench modeling;

You can download the whole code (include sources):
https://www.dropbox.com/sh/3qtzz4tpvq458hr/cNqY7UrLTc