Hot Topic Session

Maximizing Peak Surface Fields (H_{pk}) Time Barrier vs. Surface Barrier

- Chairs: H. Padamsee and C. Reece

Abstract

- Is $H_{super-heating}$ the limit to surface H_{pk}?
  - Surface energy barrier to the penetration of fluxoids above H_{c1}
- New: Is the time barrier to fluxoid formation the limit?
  - The time barrier is the time scale for order-parameter changes (pair-breaking).
- Order parameter change time scale is longer than the RF period
  - so fluxoids do not nucleate within the RF period.
- =>Which new materials to explore for SRF?
  - Nb_3Sn, MgB_2, overlayers…
- OR materials with a higher time barrier
  - V, Ta, Sn or such overlayers?

Anticipated Program

- 5 min Intro: Hasan Padamsee
- 10 min Alex Romanenko, time barrier
- 10 min: Review of H_{sh} calculations: Alden Pack
- 10 min: Experimental data on max H_{pk}, traditional treatments: Rongli Geng
- 10 min: Experimental data on max H_{pk}, exotic treatments: Mattia Checchin
- 15 min: Open Discussion moderated by Charlie & Hasan
    - So which matters most: time or surface barrier?

Hot Topic Talk 1

Alexander Romanenko

Time barrier – key to high gradients?

Alexander Romanenko

SRF'2019

4 July 2019

Main points

- KEY relevant question:
  - If the RF field exceeds a critical field (e.g.) how soon does the dissipation emerge?
- Time barrier = slow down the emergence of dissipation
  - Vortex formation takes a finite time => make it as long as possible
- **DC** fields of first flux penetration measured on niobium samples are lower than maximum RF fields in cavities
  - **DC** superheating cannot explain the highest gradients
    - It is used however as a guide for all new materials gradient research

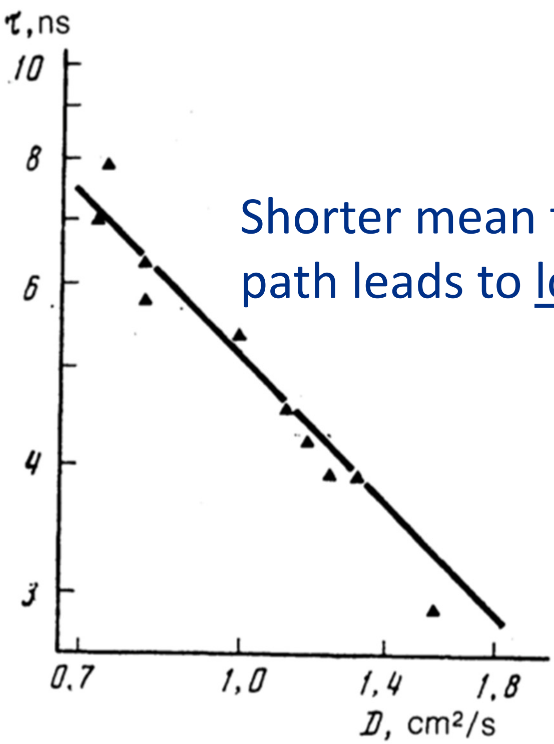
How soon do the vortices form?

- Vortex nucleation is governed by the characteristic time scale of order parameter changes, so-called τ_Δ
  - If flux penetration/dissipation is happening or not depends on the relation between τ_Δ and RF period T_{rf}
    - $\tau_\Delta > T_{rf}$ => vortex-induced dissipation is delayed beyond Hsh
    - $\tau_\Delta < T_{rf}$ => Hc1 and superheating become more relevant – more DC-like
    - $\tau_\Delta >> T_{rf}$ => vortices don't matter as they never form

- $\tau_\Delta \sim \tau_{GL} << 1$ ns is only relevant for gapless superconductors (which Nb is not) → was understood by e.g. Tinkham and Bezuglii in late 1980s

- For gapped superconductors at low T: **$\tau_\Delta \sim \tau_E \sim 1$ ns for Nb**

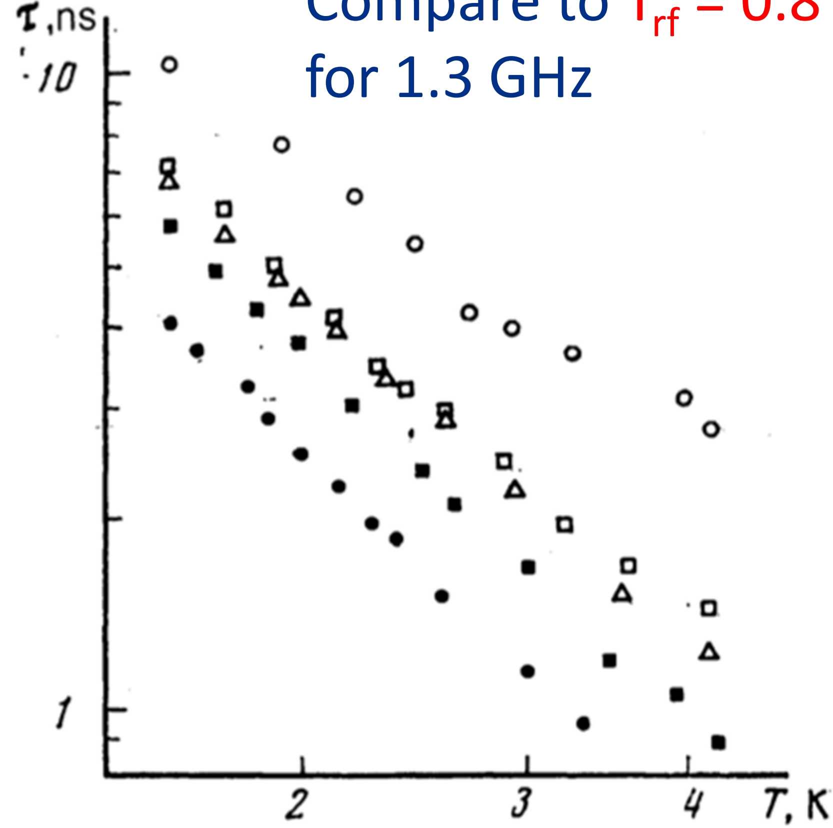
Experimental observations of gap relaxation time in Nb



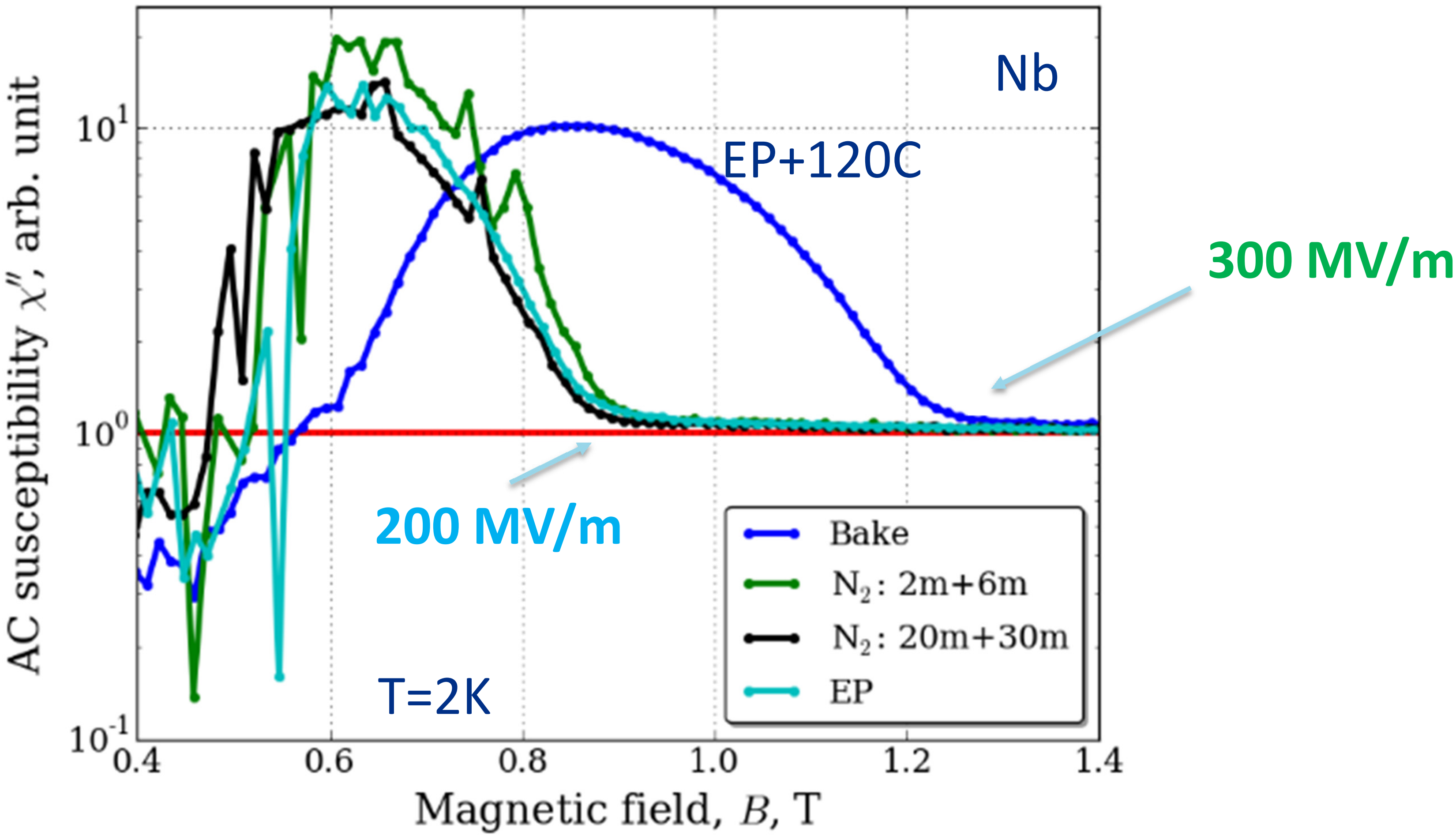
Shorter mean free path leads to longer τ

FIG. 4. Dependence $\tau(D)$ determined at $T = 1.6$ K for samp
ness $d \leqslant 200$ Å; the continuous curve represents the dependen

Compare to T_{rf} = 0.8 ns for 1.3 GHz



How far can the time barrier help extending the Eacc?



Fermilab

How to push the gradients using Time Barrier?

- Plenty of new opportunities!
  - Clean Nb Hc2 is ~100 MV/m, dirty is higher

- Make niobium surface "slower" by right impurities
  - Maybe this is already why 120C baked cavities go way beyond surface Hc1

- Use other "slower" (longer $\tau_{e\text{-}ph}$ scattering times) superconductors

- Increase frequency

Which materials could be better for “time barrier”?

Table 1. τ_0, the characteristic e–ph coupling time, calculated by using equation (8) for some metals, together with superconducting data from [21–23].

Metal	τ_0 (ns)	T_c (K)	T_D (K)	$2\Delta/kT_c$	$10^3 b$ (meV^{-2})
Nb	0.37	9.2	276	3.92	1.55
Tc	0.609	7.8	411	3.48	0.57
V	1.71	5.4	380	3.45	0.61
Ta	1.88	4.47	240	3.45	1.66
Sn	2.24	3.75	200	3.66	2.40
In	0.77	3.4	108	3.69	9.90
Tl	1.26	2.33	78	3.69	18.6
Re	92.5	1.697	415	3.38	0.36
Al	395	1.196	428	3.34	0.35
Mo	748	0.915	460	3.53	0.29
Zn	556	0.875	327	3.19	0.59
Os	2480	0.66	500	—	0.23
Zr	996	0.61	290	—	0.73
Ru	9220	0.49	600	3.42	0.15
Ti	7960	0.4	415	3.43	0.32
Hf	95700	0.128	252	3.63	0.82
Ir	414000	0.1125	420	—	0.28

Lower T_c => longer τ_0

Table 3. Characteristic e–ph coupling times, τ_0, of A-15 compounds, together with superconducting data from [21] and [23].

Compound	τ_0 (ns)	T_c (K)	T_D (K)	$2\Delta/kT_c$	$10^3 b$ (meV^{-2})
Nb_3Ge	0.006	23.2	300	4.05	2.18
Nb_3Si	0.013	19.0	300	—	1.87
Nb_3Al	0.013	18.8	300	4.16	1.85
Nb_3Sn	0.014	18.0	290	4.11	1.97
V_3Sn	0.016	17.9	300	—	1.79
V_3Si	0.079	17.1	530	3.37	0.41
V_3Ge	0.085	11.2	300	2.97	1.38
Mo_3Ge	76.8	1.80	430	—	0.37

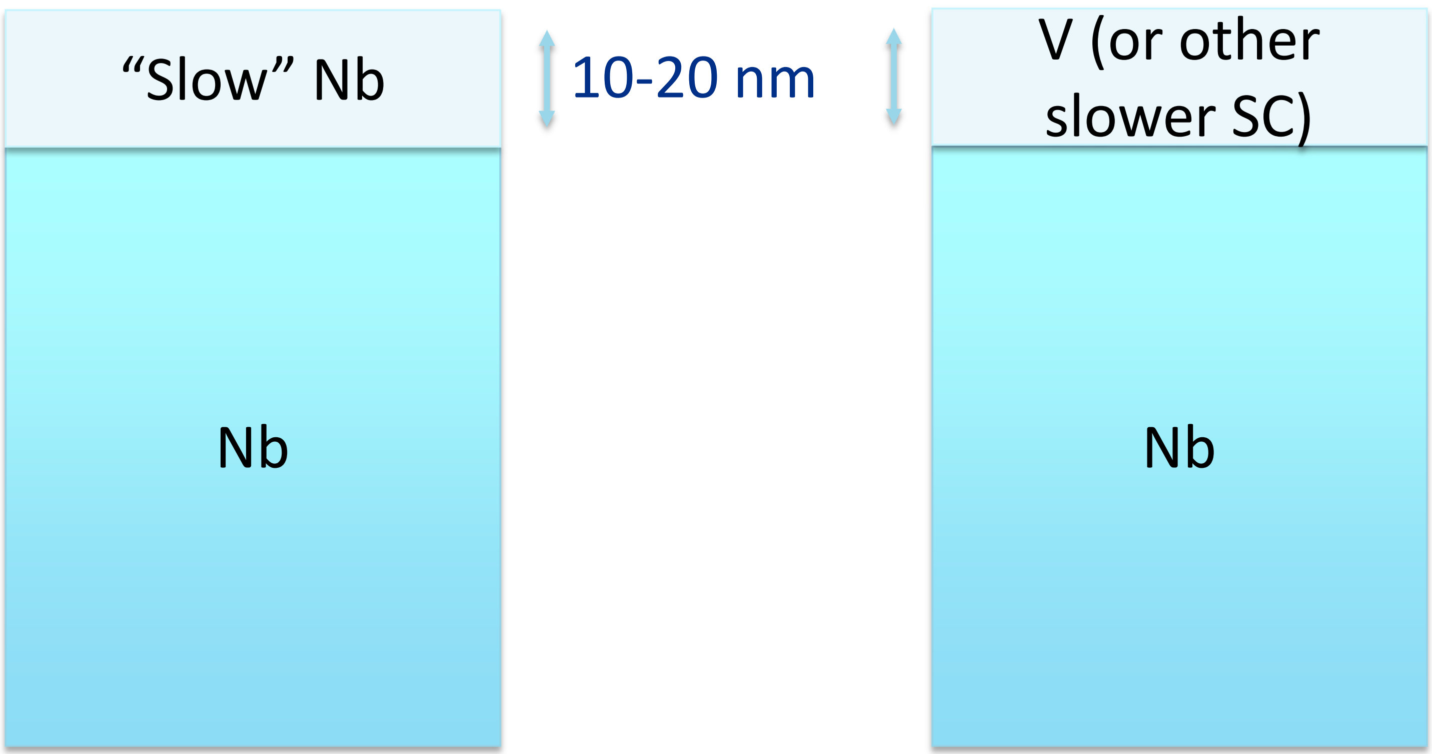
A15 are not good –too ”fast”

Table 4. Characteristic e–ph coupling times, τ_0, for B1-type superconductors.

Compound	T_c (K)	T_D (K)	$10^3 b$ (meV^{-2})	τ_0 (ns)
NbN[a]	15	400	0.78	0.06
$ZrN_{0.98}$[b]	10	360	0.85	0.19
VN[c]	8.5	465	0.44	0.61
$TiN_{0.98}$[d]	4.6	480	0.35	4.87

A thin layer of <u>slow</u> superconductor as a possible solution

Option 1 | Option 2

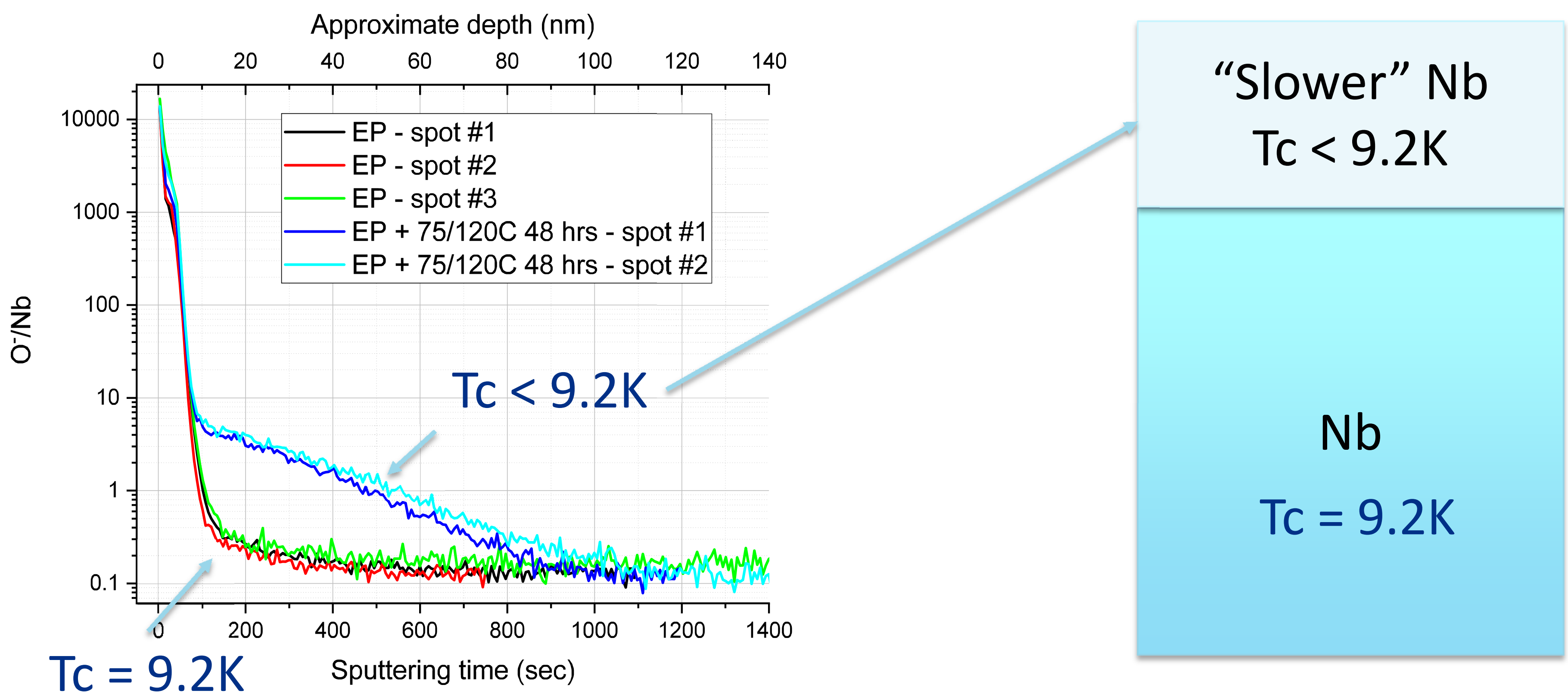


Is it how 120C baking or N infusion enables Hrf >> Hc1?

Explore techniques for lower Tc SC deposition

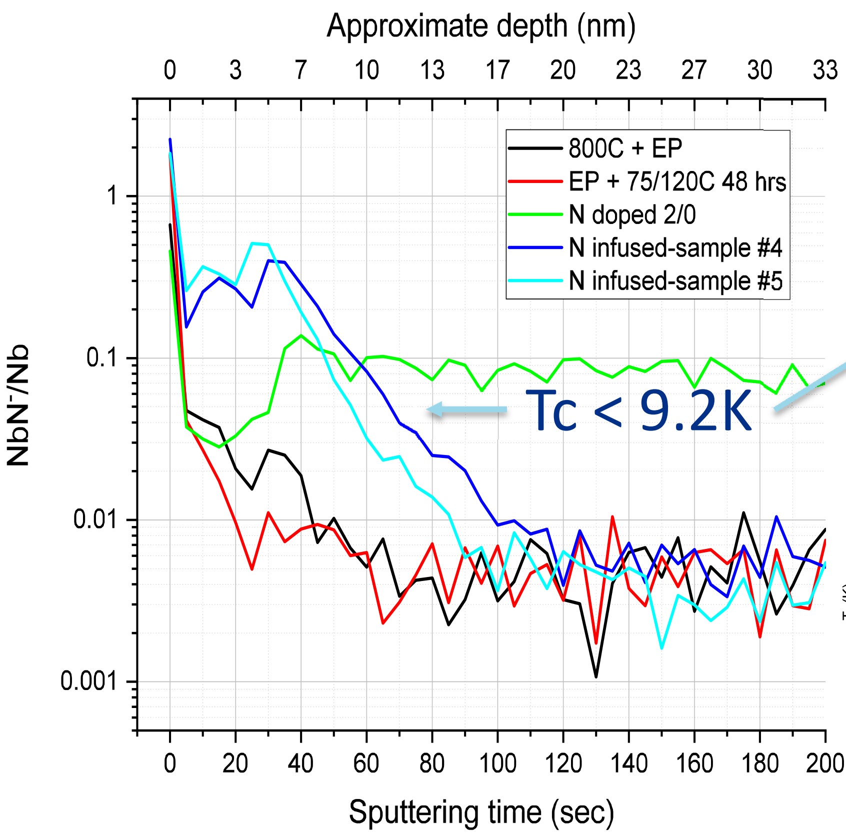
Oxygen-suppressed surface T_c in 120C baked cavities

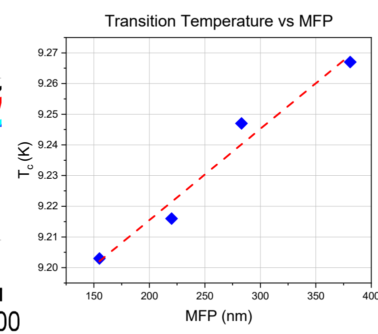
- NEW from highest performing cavity cutouts
  - 120C baking brings about an <u>oxygen-rich</u> layer (**THP014** this afternoon)



Nitrogen-suppressed surface T_c in 120C N infused cavities

- From highest performing cavity cutouts (**THP014**)
  - 120C N infusion => nitrogen-rich thin layer

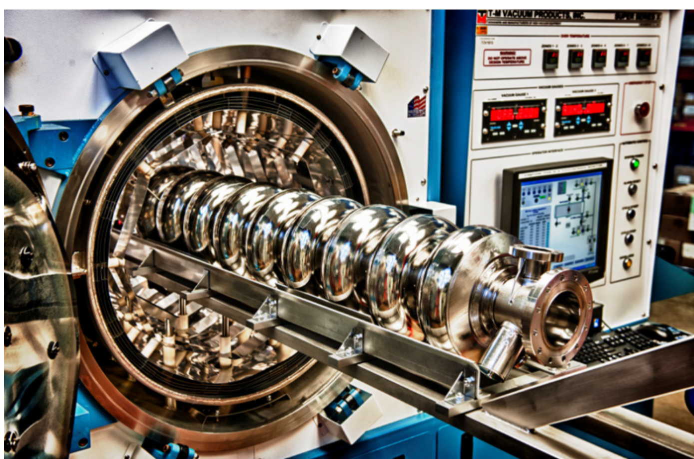




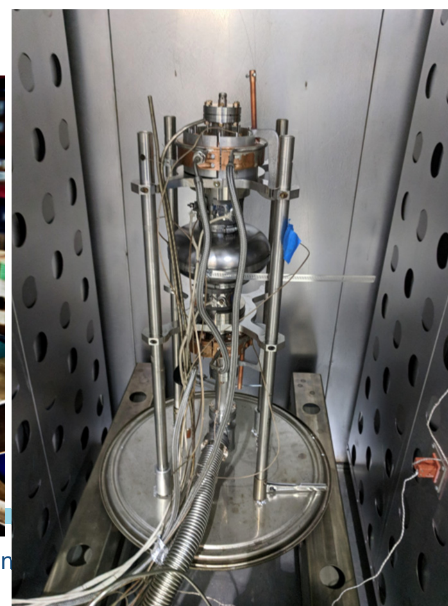
Experimental plans for studying S-S structures at FNAL

- Standard method to “infuse” nitrogen in surface layer is to utilize our very clean high temperature furnace → studies will continue to explore duration/pressure
- We have recently developed a new method for N-infusion in a low T oven, keeping cavity always under vacuum, never to see the heating chamber
- This new method involves in situ removal of the Niobium surface oxide, leaving the surface ‘naked’ and we find produces an effect of “self N-doping” → studies ongoing (bake + HF rinsing) => see https://arxiv.org/abs/1907.00147
- Next year FNAL will commission a new CVD/ALD furnace (multicells compatible) for state of the art S-S structures and doping with different gases

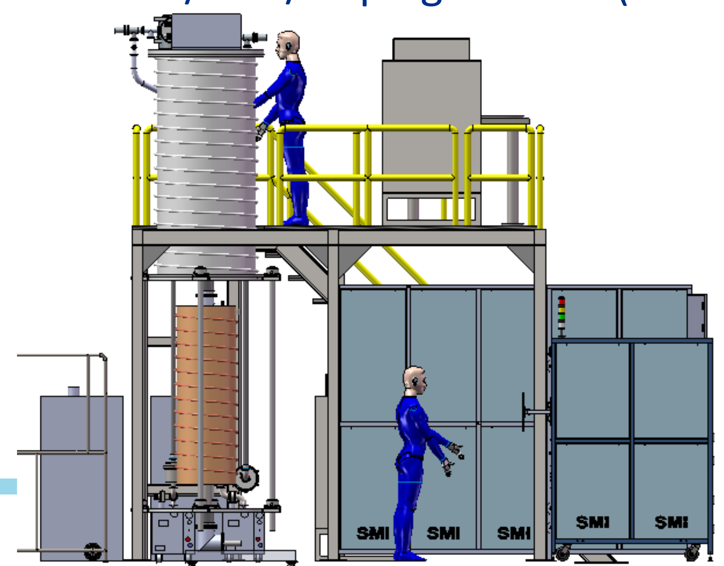
High T furnace infusion



New medium T bake “self infusion”



New ALD/CVD/Doping furnace (2020)



- What about DC superheating/surface energy barrier?

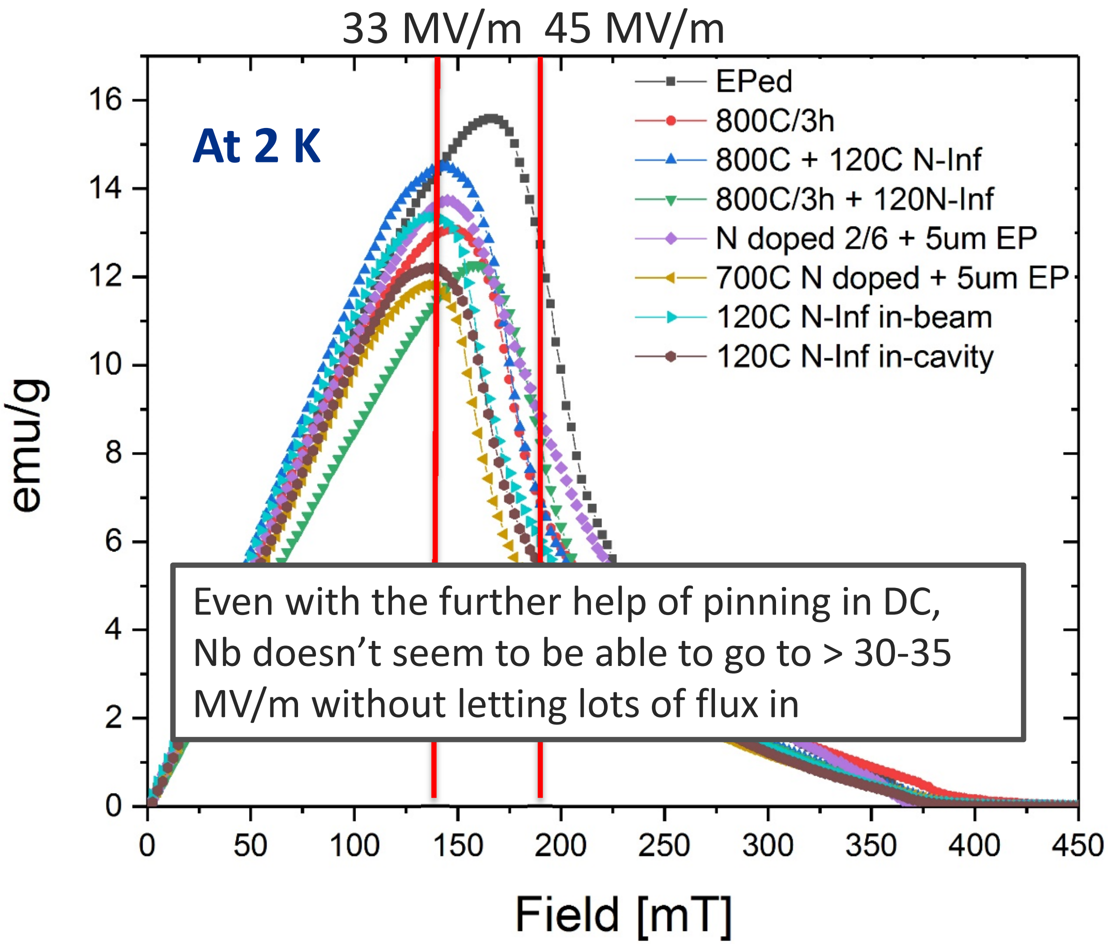
Currently the focus is heavily on DC superheating

- DC superheating field Bsh suggested as the "fundamental" limit (~240 mT for clean Nb)
  - NB: has no direct proof
- Lots of recent theoretical calculations of Bsh
- Exploring materials with higher Bsh than Nb (Nb3Sn, MgB2 etc)
- Various suggestions to improve Bsh
  - Multi (or single layers) of higher Bsh superconductor on top of Nb
  - Dirty layer on top of clean

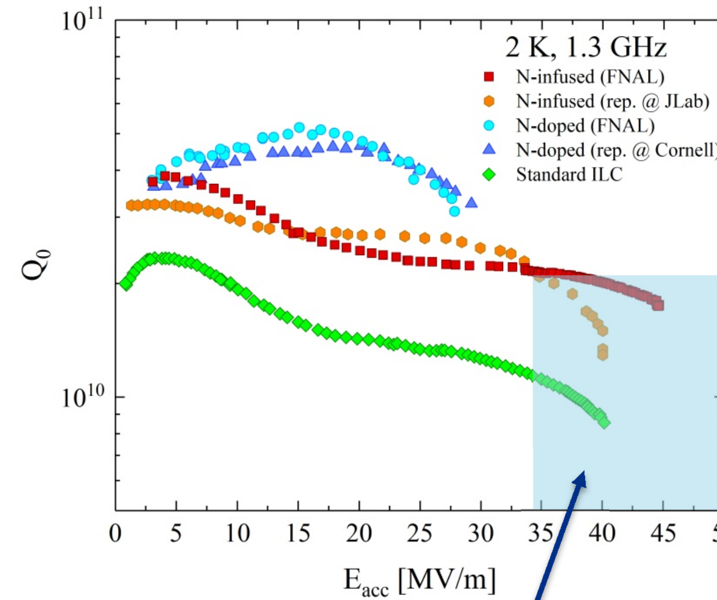
- **My view – while higher Bsh would not hurt, it may not be the most promising way for pushing the gradients in SRF cavities**
  - **Any non-ideal area -> entry way for flux -> superheating is not realized**

DC performance of samples vs SRF Cavities

DC Magnetization curve (m [H])



Even with the further help of pinning in DC, Nb doesn't seem to be able to go to > 30-35 MV/m without letting lots of flux in



Region of flux penetration suggested by DC measurements

- These results suggest that SRF cavities quench above the DC flux penetration threshold
  - Cannot be due to DC superheating

See also e.g. R. Laxdal et al, TUFUA7

Summary

- Relevant theory for a <u>gapped</u> superconductor suggests "time barrier" role in achieved fields

- Experimental data for Nb show that vortex nucleating times are comparable or longer than the rf periods considered
  - Counterintuitively -> LOWER Tc superconductors can give higher gradients (as they are slower!)
  - Explore higher frequencies – flux penetration is delayed
  - Lower Tc slower SC on top of niobium – another proposal

- If taken advantage of, fields Eacc > 100 MV/m can be on the horizon with Nb
  - Huge potential

Hot Topic Talk 2

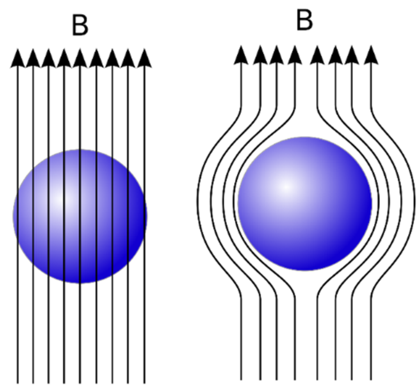
Alden Pack

H_{sh} Calculations

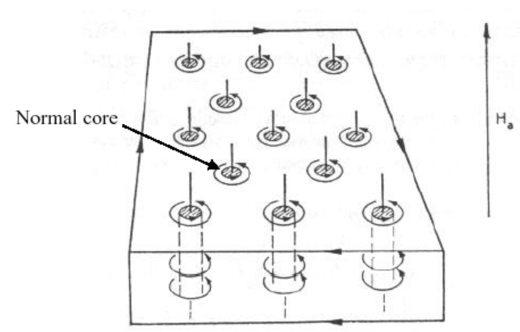
A brief and very incomplete review

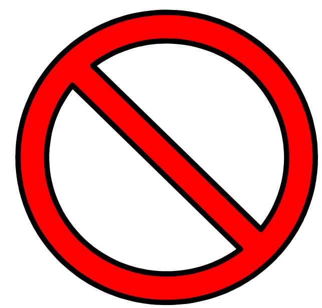
Superconductors and Magnetic Fields

- For relatively small applied magnetic fields, superconductors expel flux: Meissner state



- At higher fields, Type II superconductors allow flux to enter in packets: Vortex state

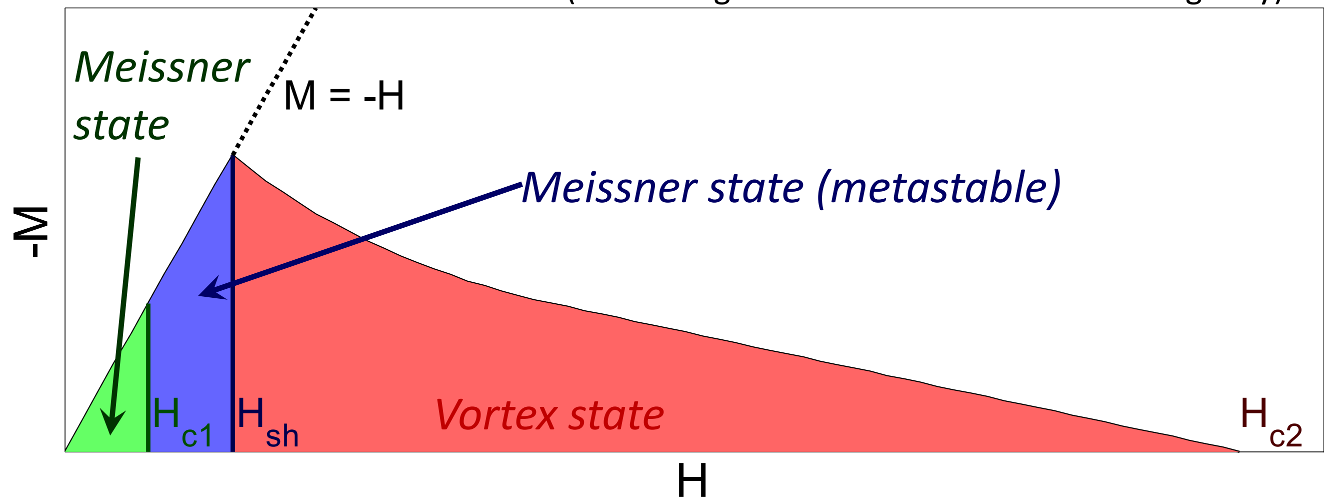




Images from Wikipedia and Rose-Innes and Roderick, Introduction to Superconductivity

The Superheating Field

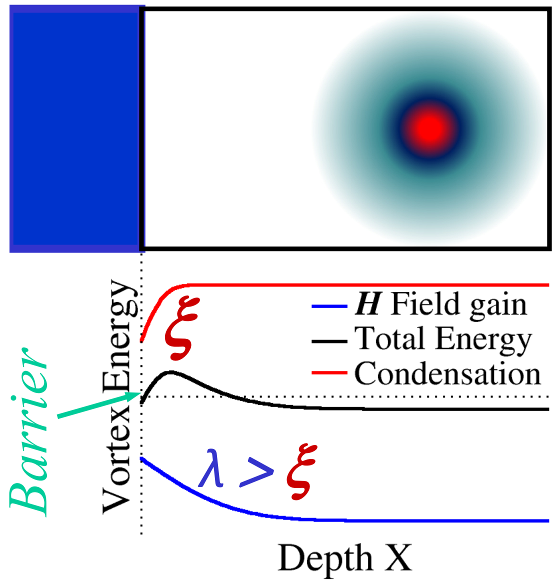
(Note: Magnetization curve for H increasing only)



- Flux free Meissner state is stable up to H_{c1}
- Favorable for flux to be deep in bulk above H_{c1}
- BUT surface energy barrier allows metastable state!

The Superheating Field

Why a superheating field?

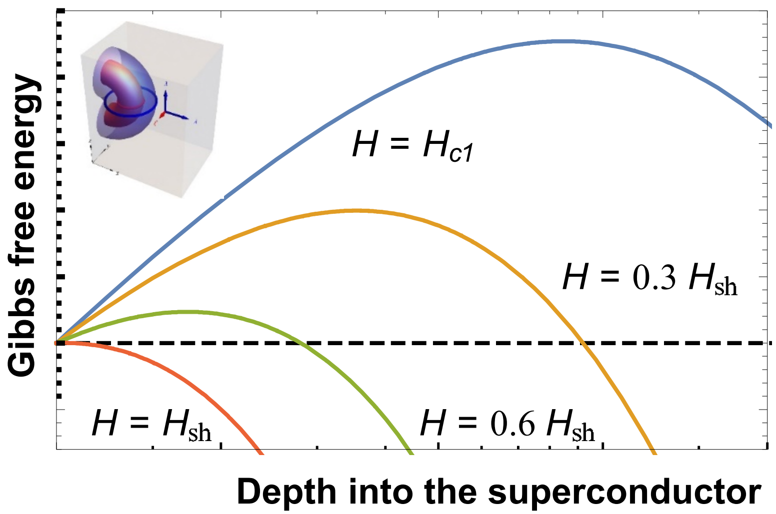


Costly core ξ enters first; gain from field λ later

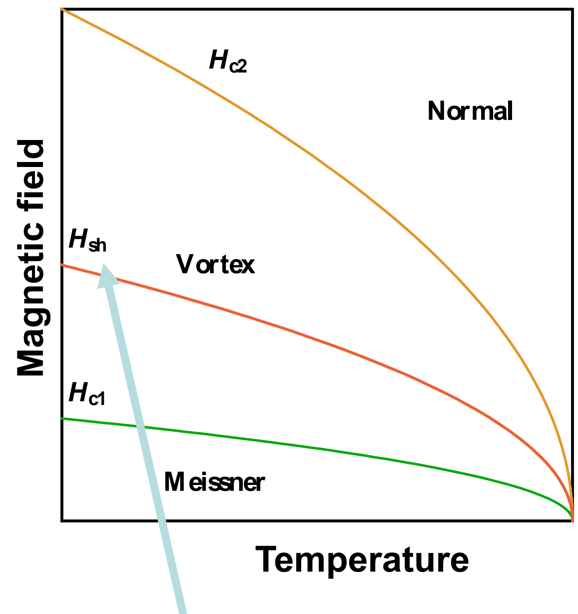
Energy benefit: flux from high magnetic field region into low magnetic field region

Energy cost: creation of normal conducting vortex core

Barrier to Vortex Entry and Stability Threshold

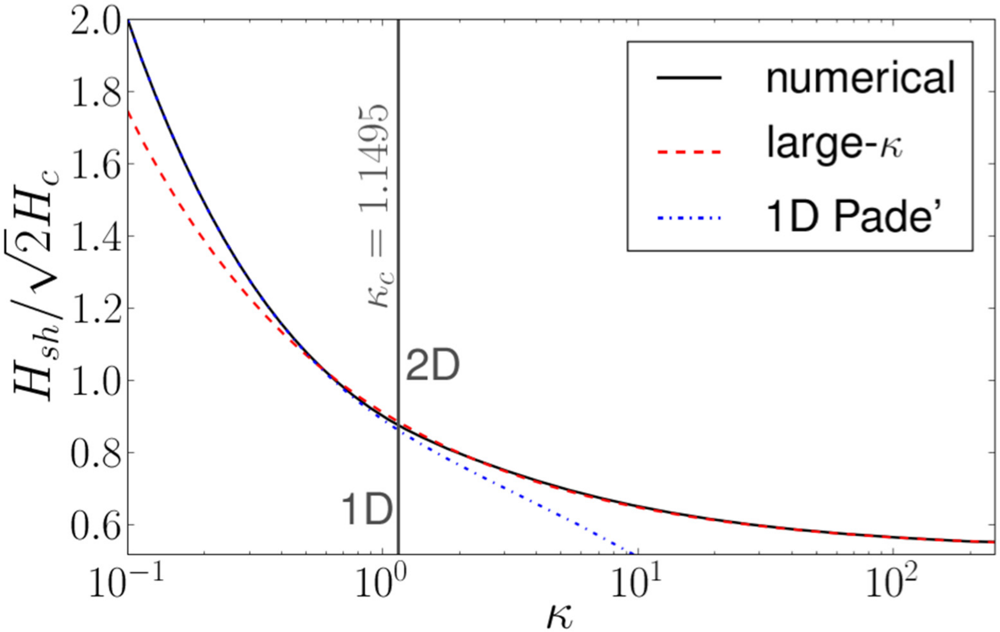


Bean & Livingston, *Phys. Rev. Lett.* 1964
Competition between magnetic pressure and attraction to the surface.



Superheating field:
Threshold of stability of the Meissner state

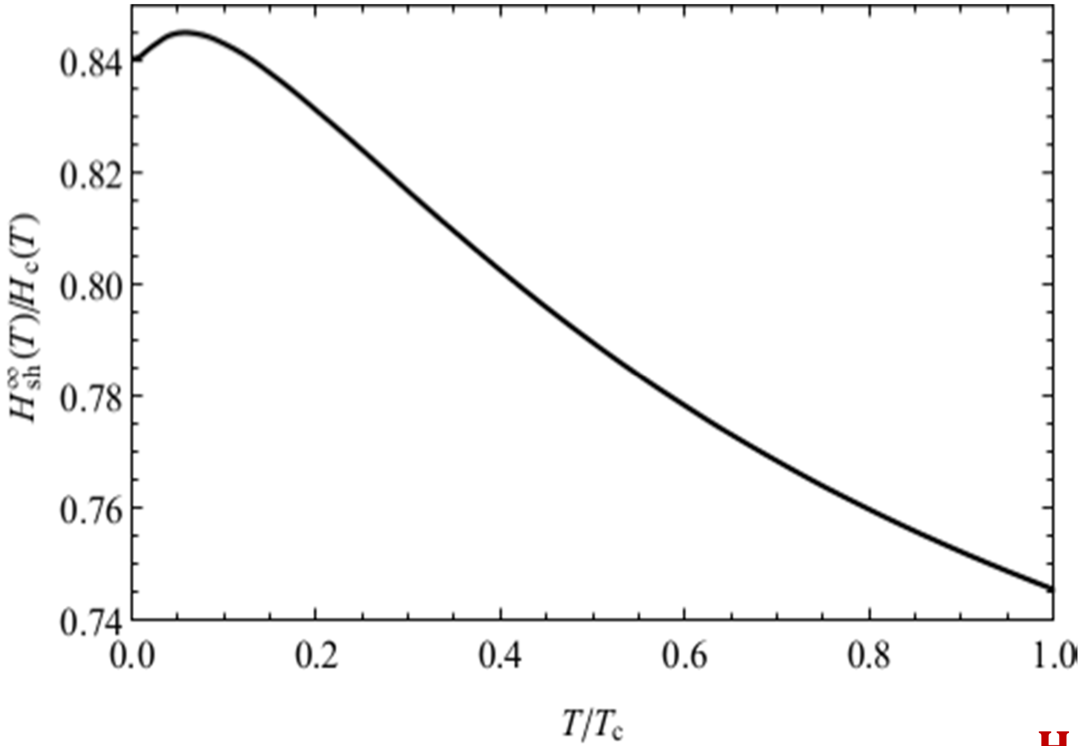
Some Calculations of the Superheating Field near T_c



Material	κ	H_{sh} / H_c
Nb	1.5	1.19
Nb_3Sn	26.4	0.86
MgB_2	37.8	0.84
NbN	129.3	0.79

Transtrum et al., *Phys. Rev. B* 2011
Ginzburg-Landau theory for H_{sh} as a function of κ for T near T_c.
Kramer, *Phys. Rev.* 1968, etc.

Some Calculations of H_{sh}/H_c vs T



Catelani & Sethna, *Phys. Rev. B* 2008
Quasiclassical Eilenberger theory for H_{sh} as a function of T for large κ.
Lin and Gurevich, *Phys. Rev. B* 2012

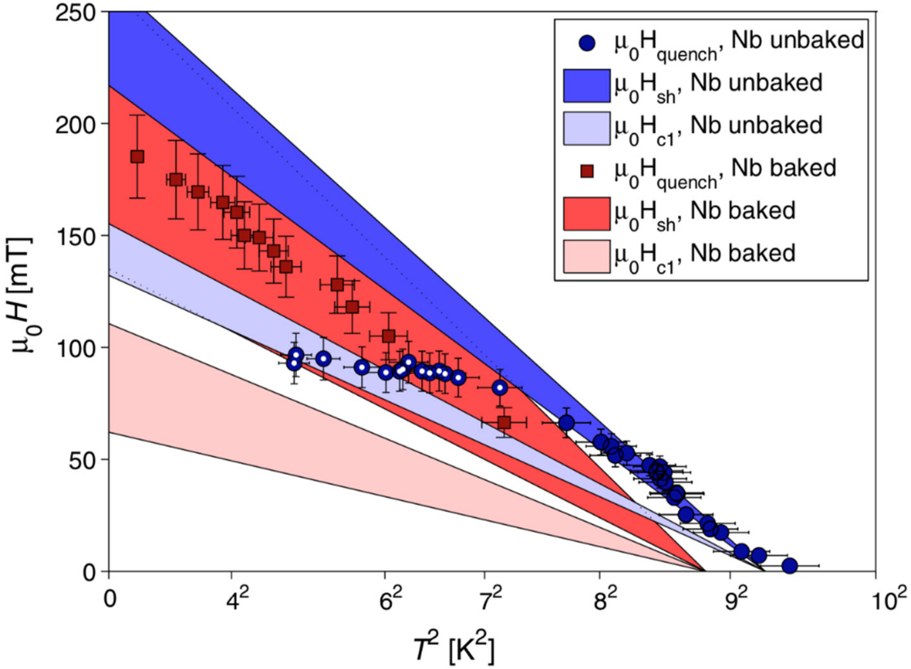
Note:

$$H_c(T) \approx H_c(0)\ [1\text{-}\ (T/T_c)^2]$$

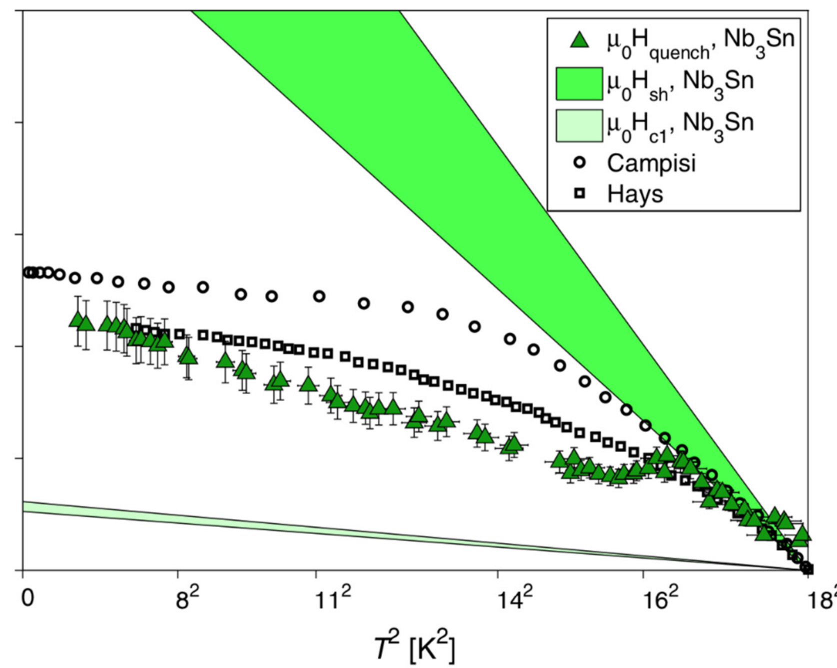
$$\mathbf{H_{sh}(T) = c(\kappa, T) \cdot H_c(0) \cdot \left[1 - \ (T/T_c)^2\right]}$$

RF Flux Entry / Quench Field vs T Measurements (Cornell, 1.3 GHz)

Niobium (EP and EP+120C)



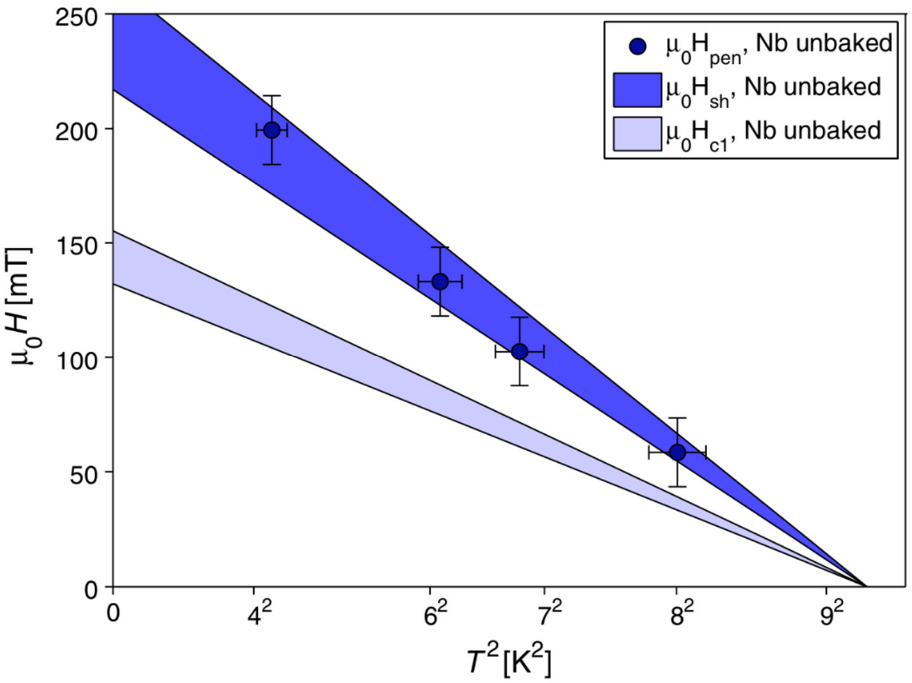
Nb_3Sn



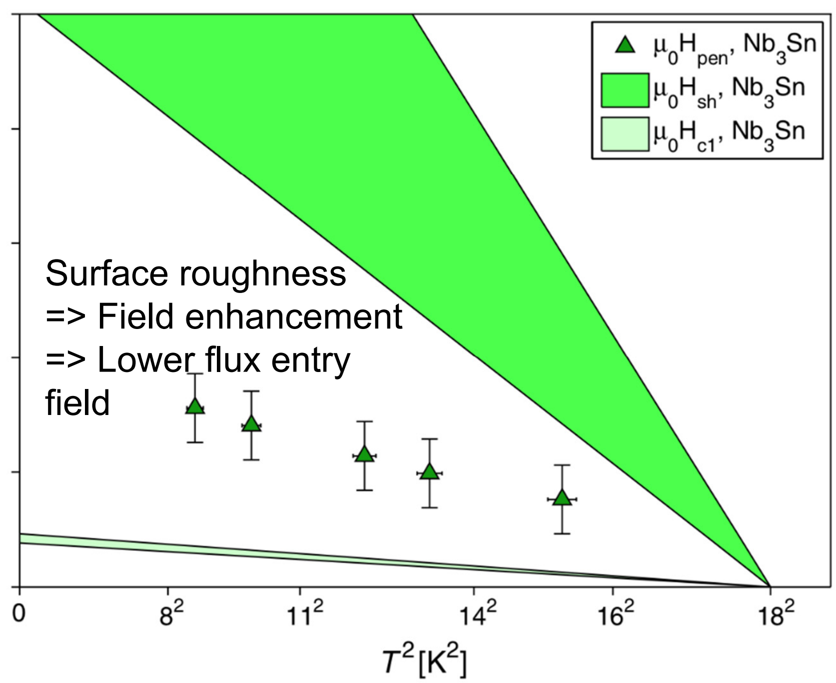
S. Posen, N. Valles, and M. Liepe, Phys. Rev. Lett. 115, 047001 (2015)

DC Flux Entry / Quench Field vs T Measurements (Cornell)

Niobium (EP and EP+120C)

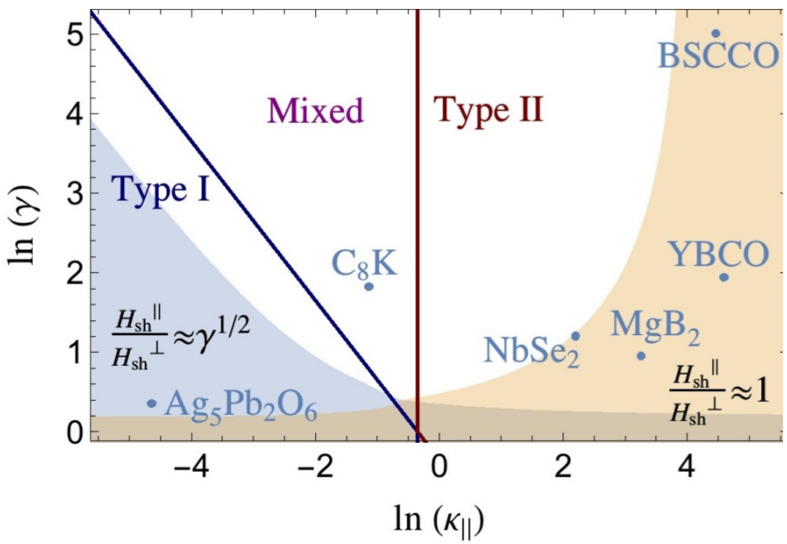


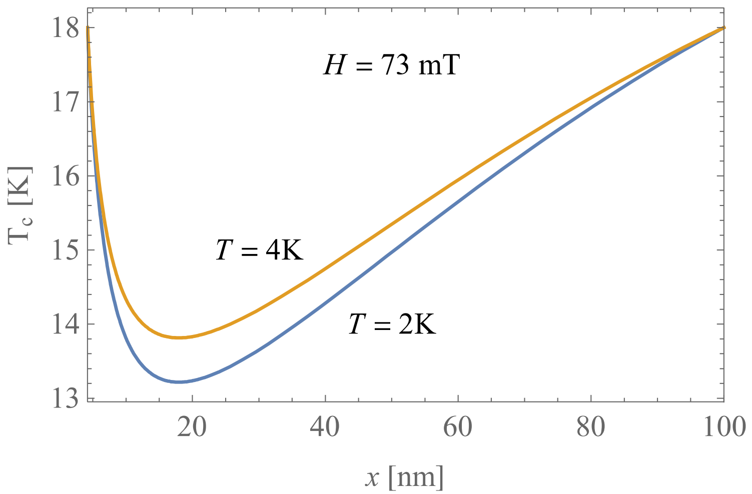
Nb_3Sn



S. Posen, N. Valles, and M. Liepe, Phys. Rev. Lett. 115, 047001 (2015)

Lower H_{sh}: Anisotropy and Disorder

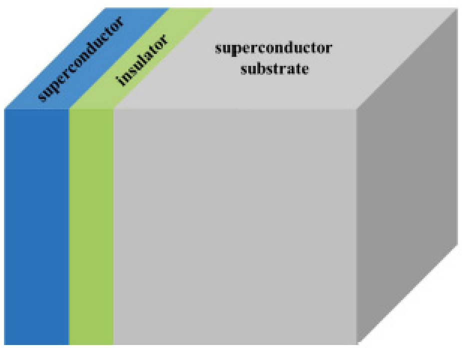




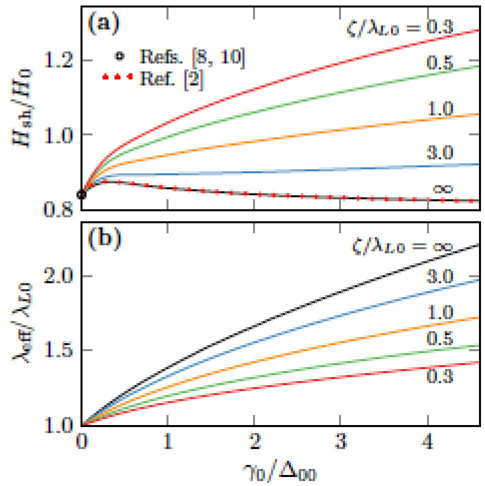
Liarte et al. *Phys. Rev. B* 2016
Anisotropic GL theory for diagram in terms of mass anisotropy and GL parameter showing regions where H_{sh} is isotropic (yellow). Low-T H_{sh} anisotropy is not known.

Liarte et al. *Superc. Sci. Tech.* 2017
Bean-Livingston barrier and critical droplet theory for T_c profile that allows vortex nucleation for Nb_3Sn at 73mT.

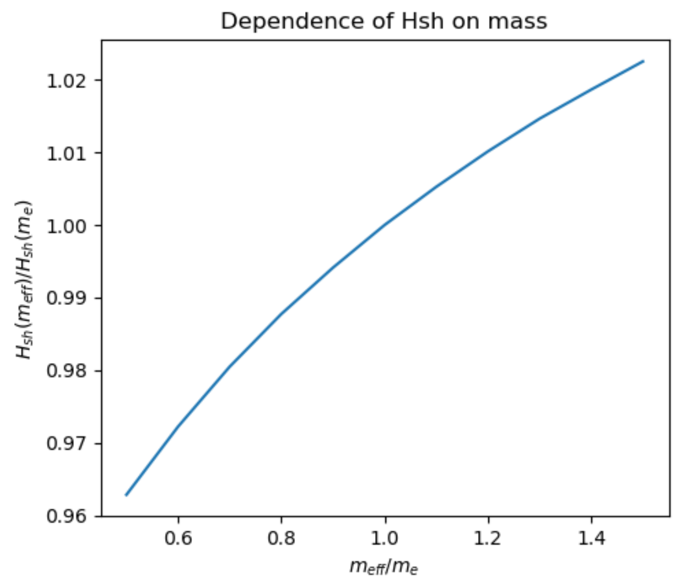
Higher H_{sh}: Laminates and Dirty Layer



Kubo, *Superc. Sci. Tech.* 2016
Optimization of thickness and material assessment
Gurevich Appl. Phys. Lett. 2006



Ngampruetikor & Sauls, 2018
Eilenberger theory optimizing dirty layer to increase H_{sh}.
Koshelev, 2019



Allowing spatial variations in the effective mass changes Hsh

Conclusion

- Hsh has been theorhetically evaluated for a bulk geometry in Eilenberger and Ginzburg-Landau Theory.
- Experimental work shows Nb cavities can operate above Hc1.
- Nb3Sn can operate above Hc1 but they are not yet optimized to reach Hsh.
- Anisotropies complicate defining type I and type II superconductors.
- Disorder can lower Hsh.
- SIS could potentially raise Hsh.
- As seen in Eilenberger and Ginzburg-Landau theory, dirty layers may raise Hsh.
- Is this the limit for SRF cavities?

Hot Topic Talk 3

Rongli Geng

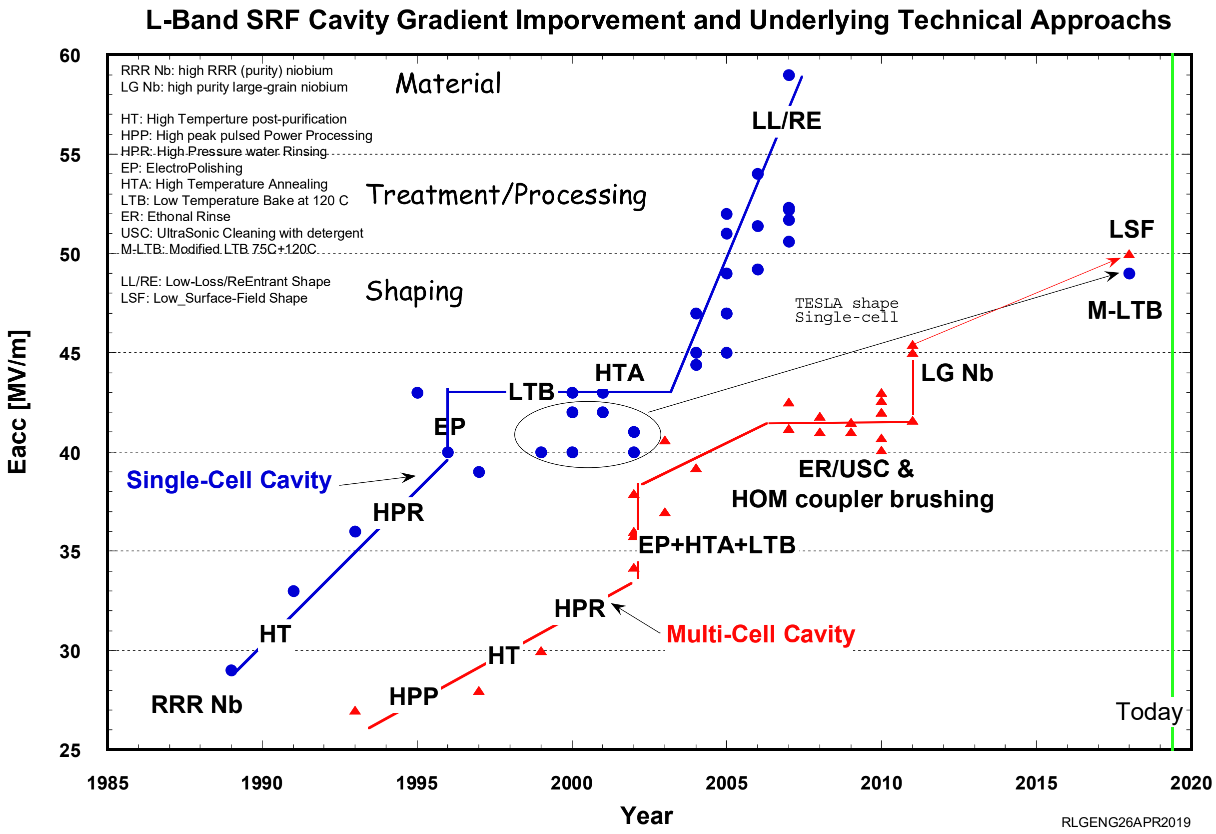
Experimental Data on Max Peak Field

Rongli Geng

SRF2019 "Hot Topic" discussion

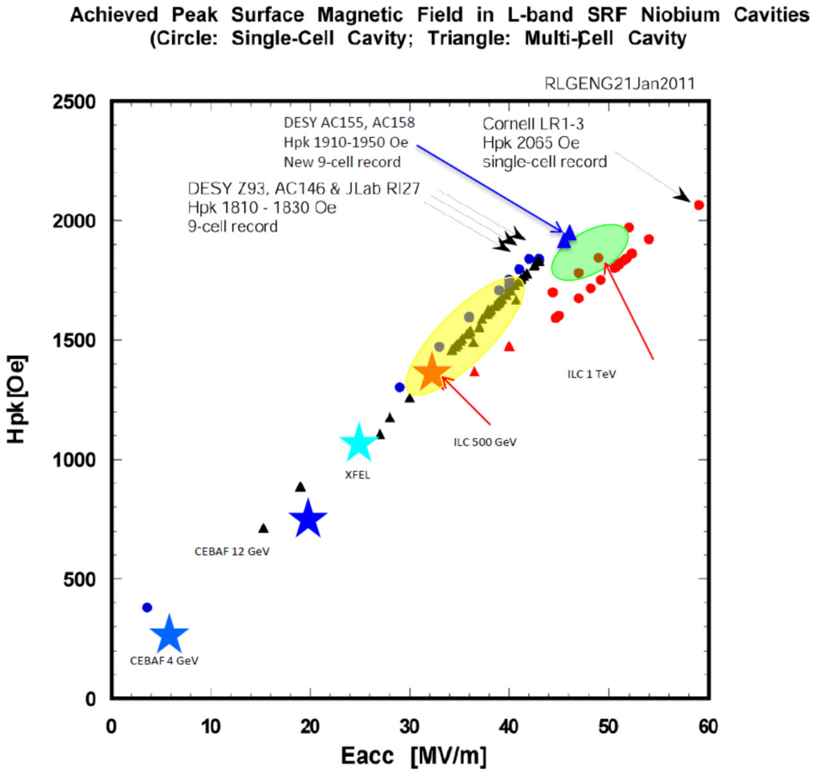
July 4, 2019, Dresden, Germany

Experimental Data on Max Peak Field, E_{pk} & H_{pk}, Driven by Pursuit for Higher E_{acc} in Practical Cavities



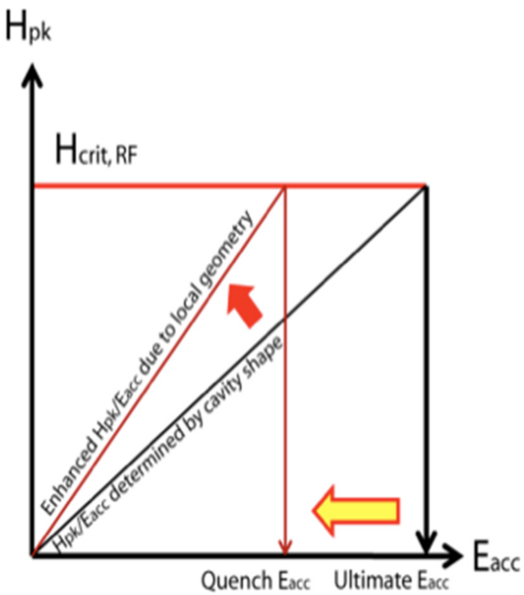
- Context for today's hot topic is H_{pk}, for which there is a fundamental limit $H_{crit,\ RF}$.
- E_{pk} is equally important for real cavities as it is met as a bottle neck often before a fundamental limit is hit.

Max Peak Field Values in Cavity Measurements Obtained by Multiplying Measured E_{acc} with Calculated Ratio α_H

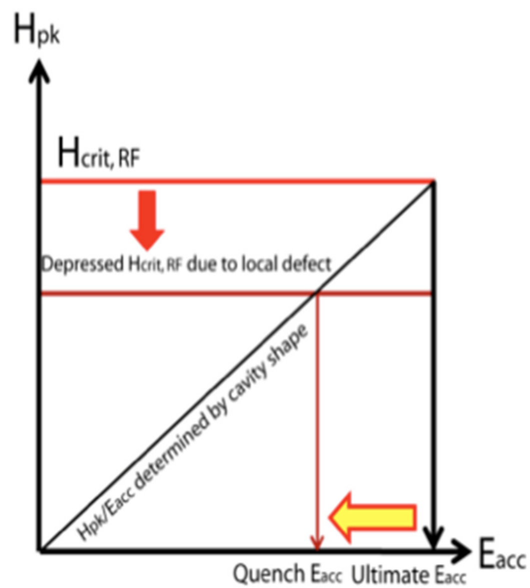


- Indirect measurement
- α_H is determined by cavity shape and can be calculated with codes
- Typically CW measurement in Q ~ 10^{10} – time constant ~ sec for ~ GHz cavity
- H_{pk} thus found represents surface field attained over large (>1000 mm^2) surface area
- The highest H_{pk} observed in L-band Nb cavities ~ 2100 Oe

The Ability of This Method for Probing $H_{crit,\,RF}$, a Material Property, is Limited by Extrinsic Factors



Local magnetic field enhancement model



Local critical field depression model

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

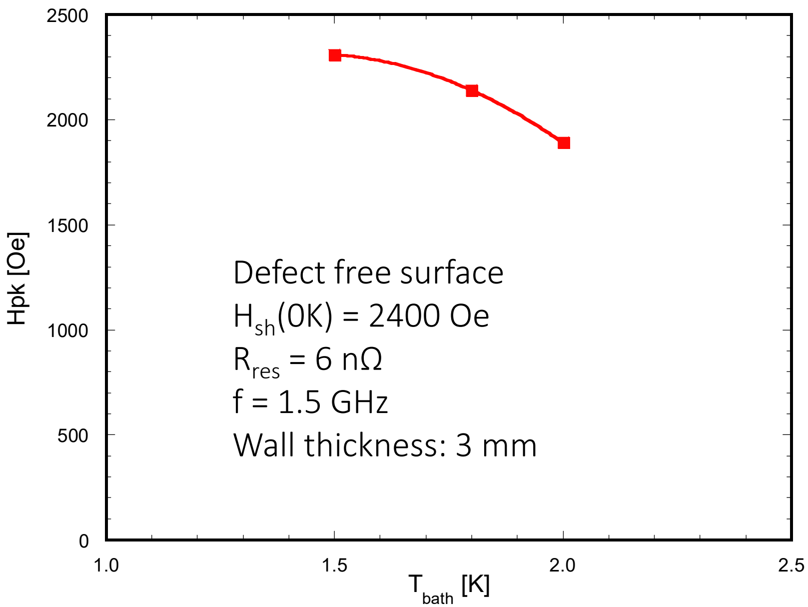
- Achievable gradient (E_{acc}^{max})
- Cavity surface chemistry (r)
- Nb: > 2000 Oe (exp.), 2400 Oe (the.); Nb_3Sn: > 4000 Oe (the.) ($H_{crit,RF}$)
- Cavity wall thermal conductance (d)
- Cavity surface smoothness (β_{MAG})
- Cavity shape (H_{pk}/E_{acc})

Pre-mature quench ignited by

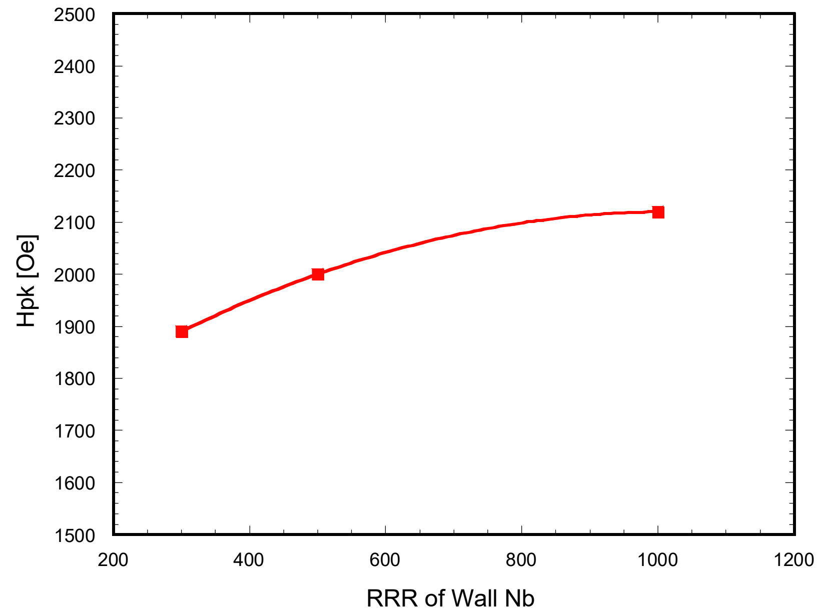
- local magnetic field enhancement
- Local depression of critical field

- Finite cavity wall thickness also play a role due to thermal bottle neck effect
- Decades of R&D + hundreds of M$ investment*, solutions in addressing (d, r, β_(MAG,)) for high gradient SRF now converged and in hand : Hi purity Nb, EBW, EP, LTB, HPR, elliptical shape

Raise Accessible H_{pk} by Tuning Overheating Effect Due to Thermal Impedance from Nb Wall and Interface to LHe

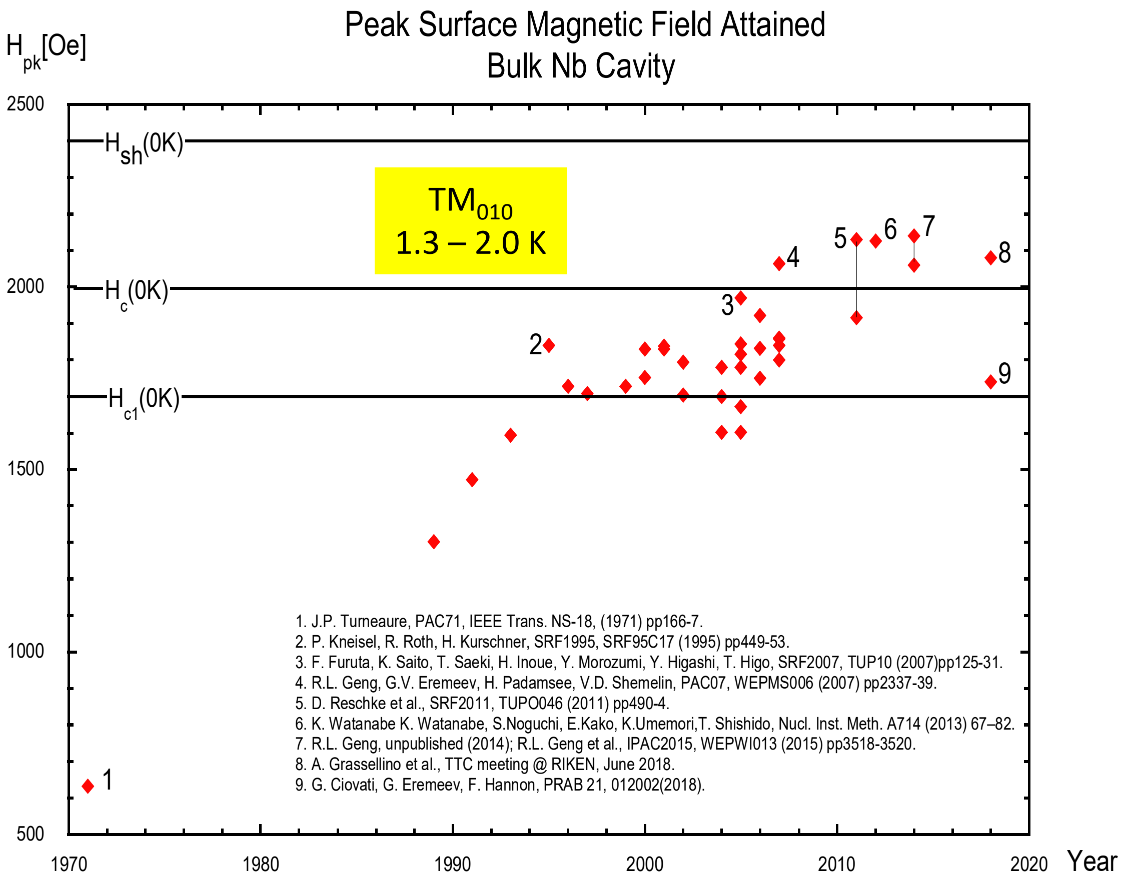


22% raise from 2K to 1.5 K



12% raise from 300 to 1000

J. Dai, Ph. D Thesis, Peking U., 2011



Data Point	material	Freq [GHz]	# of cells	Treatment
1	Nb	1.3	1	HT+LTB
2	Nb	1.3	1	BCP
3	Nb	1.3	1	EP+LTB
4	Nb	1.3	1	EP+LTB
5	LG Nb	1.3	9	EP+LTB
6	Nb	1.3	2	EP+LTB
7	LG Nb	1.5	1	EP+LTB
8	Nb	1.3	1	EP+M-LTB
9	Nb	3.0	1	EP+LTB

Nb: Fine-grain nNb
LG Nb: large grain ingot Nb
HT: UHV firing 1800 °C
CP: Buffered chemical Polishing (HNO_3+HF+H_2O)
EP: Electropolishing (HF+H_2O+H_2SO_4)
LTB: Low temperature bake 100-120 °C
M-LTB: Modified LTB (75°C + 120 °C)

Concluding Remarks and Open Questions

- Steady rise in observable H_{pk} in TM_{010} mode Nb cavities over decades
- Max. H_{pk} observed at 2K within 10% as compared to Superheating Theory prediction
- Quality of comparison between experimental data with Theoretical prediction can be improved in several ways:
  - Suppress field emission at $E_{pk} > 100$ MV/m – new techniques beyond HPR?
  - Reduce overheating on RF surface – thin wall, high purity, LG Nb?
  - Deliberate Kappa-engineering – homogeneous N-doping then progressive EP?
    - "Dirty Nb" as a model system for high Kappa material such as Nb_3Sn?
- "Special cavity" for H_{pk} concentrated small surface area?
- "Defect free cavity" testing at various T_{bath}?

Hot Topic Talk 4

Mattia Checchin

Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Hot Topic: Experimental Data on Max Peak Field

Mattia Checchin

19th International Conference on RF Superconductivity

04 Jul 2019

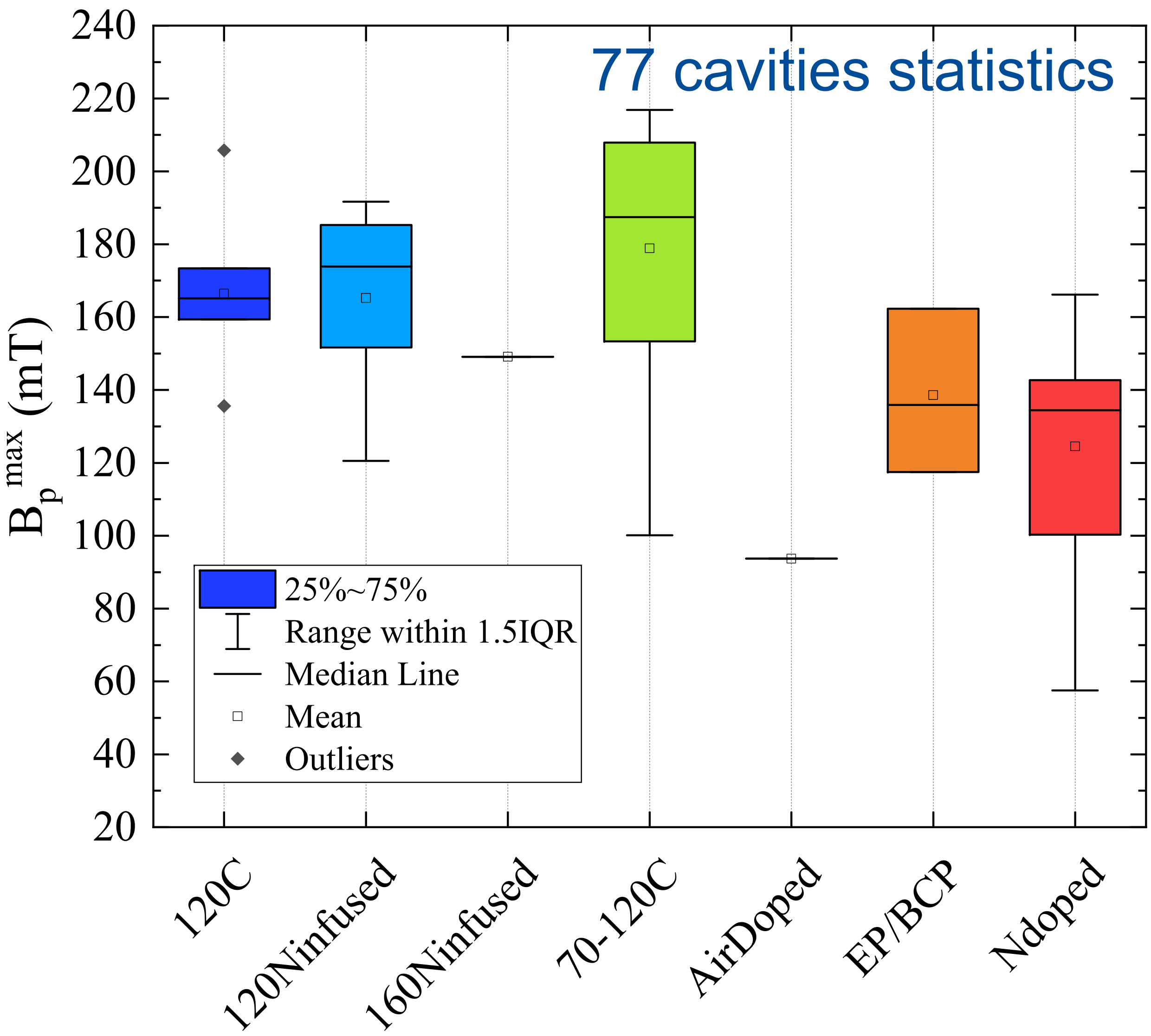
Cavity statistics

- We took the quench field of several single-cell cavities measured at Fermilab in between 2015 to 2019 for a total of **more than 70 cavities**
- Thermal treatments considered are:
  - 120 C baking
  - 120 C N-infusion
  - 160 C N-infusion
  - 70-120 C baking
  - N-doping (several recipes)
  - Air doping (one cavity doped with air)
  - EP and BCP

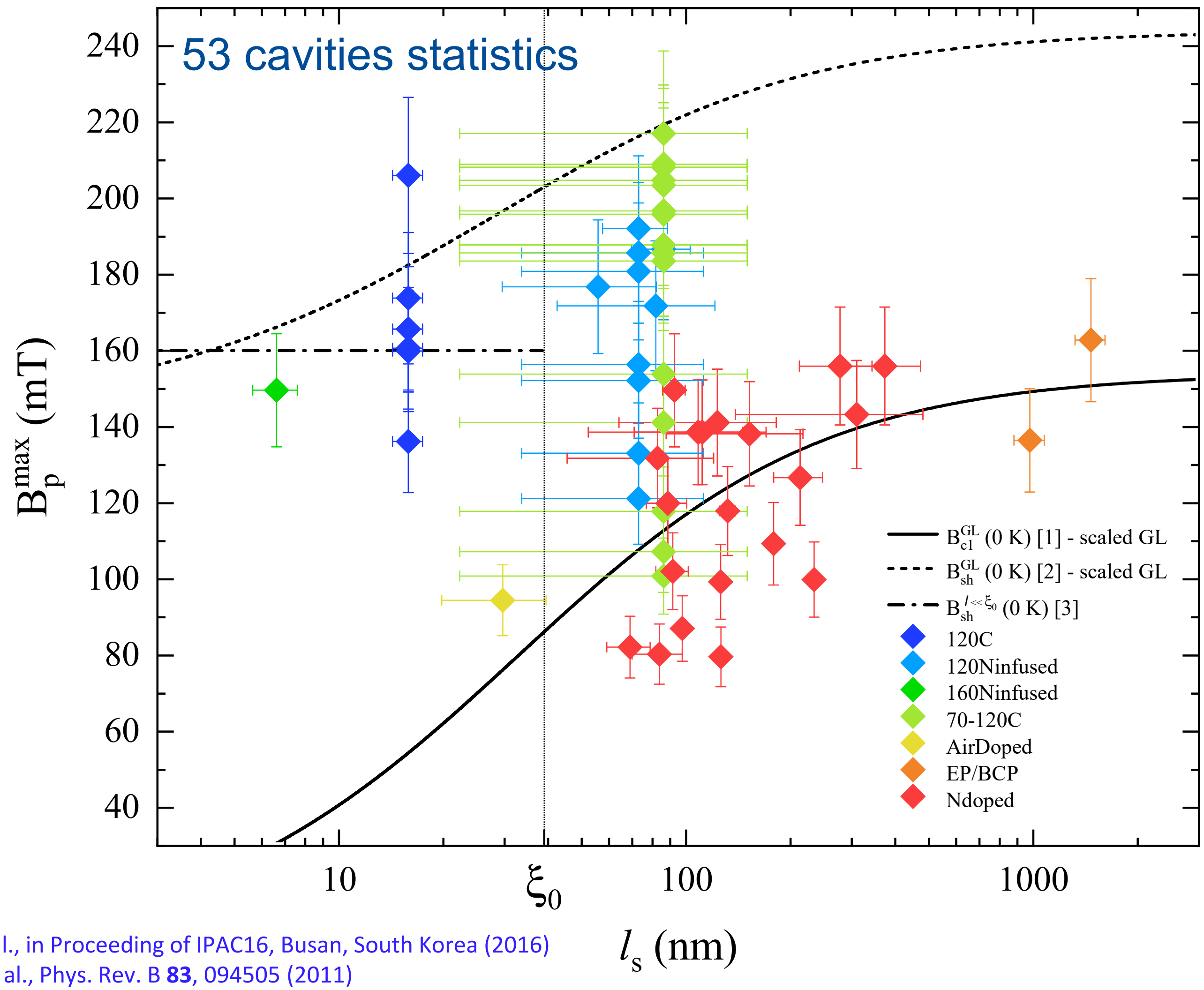
Relevant references for the experimental data

- M. Checchin et al. WEPMR002, IPAC 2016
- M. Checchin et al. TUPLR024, LINAC 2016
- M. Checchin et al. MOPOB20, NAPAC 2016
- Martinello et al., Appl. Phys. Lett. 109, 062601 (2016)
- A. Grassellino et al., Supercond. Sci. Technol. 30, 094004 (2017)
- A. Grassellino et al. arXiv:1806.09824 (2018)
- Bafia et al. TUP062, SRF 2019
- Bafia et al. TUP061, SRF 2019

Quench field statistics vs treatment

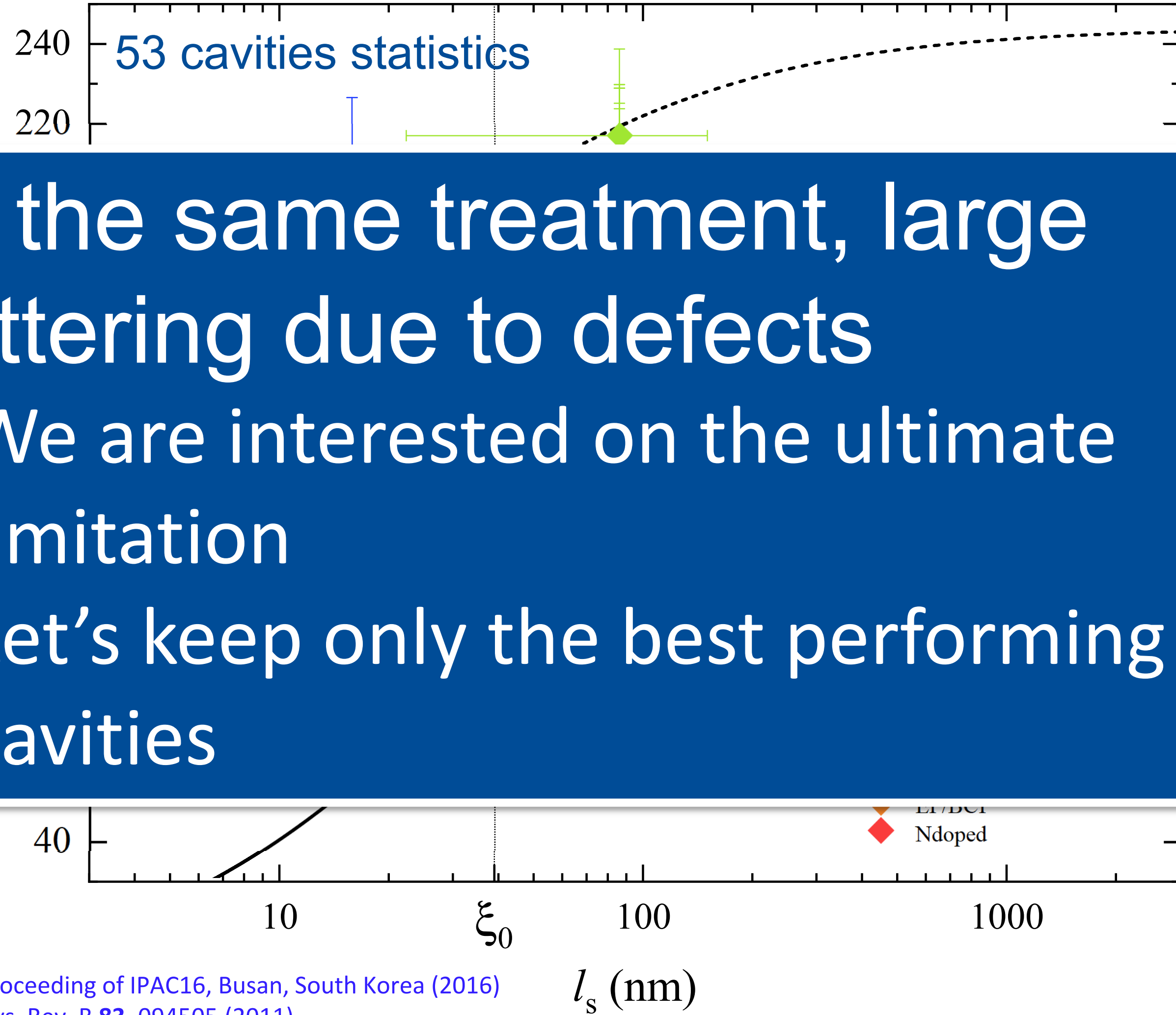


Quench field vs mean-free-path



[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

Quench field vs mean-free-path

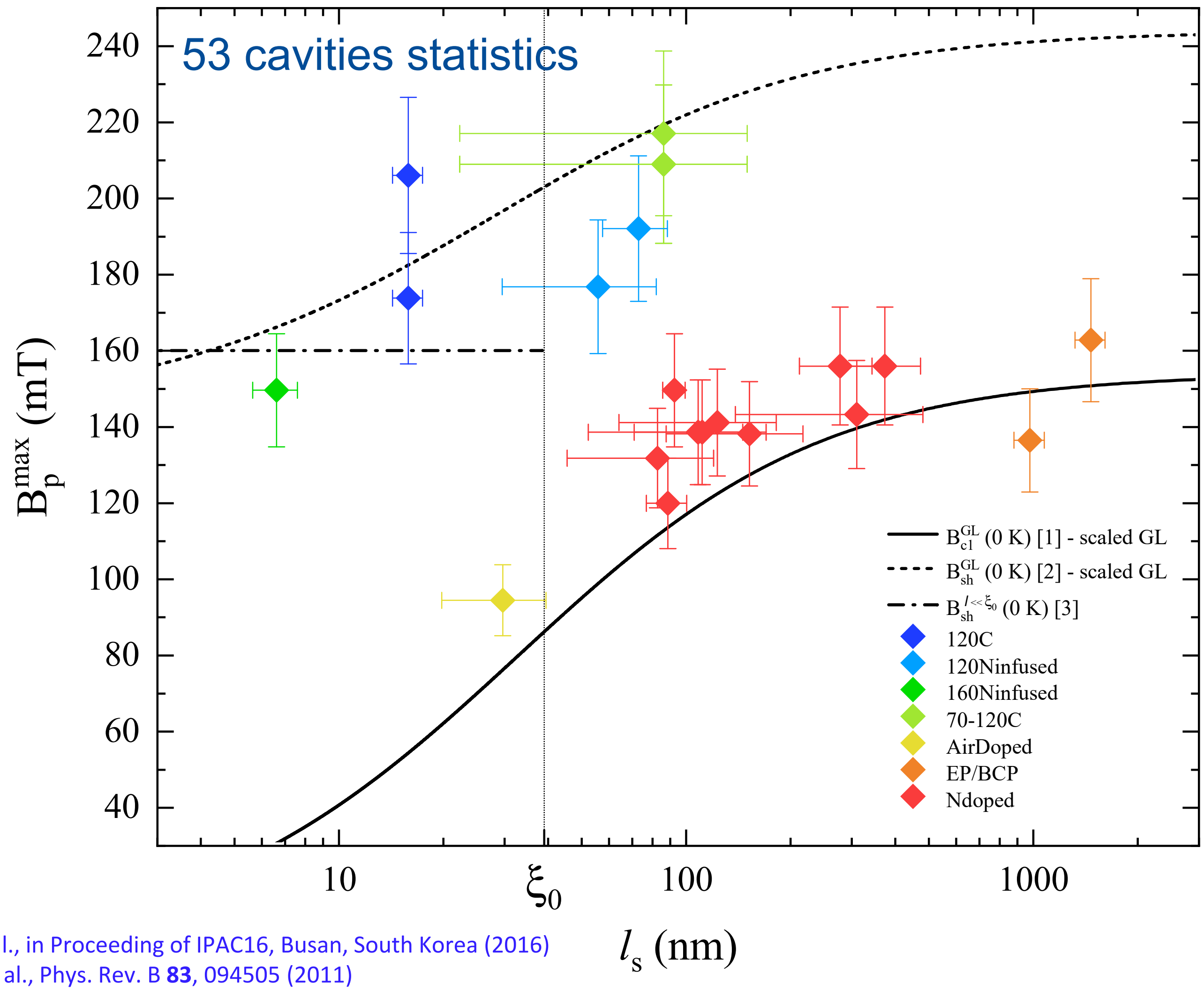


For the same treatment, large scattering due to defects

- ➪ We are interested on the ultimate limitation
- ➪ Let's keep only the best performing cavities

[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

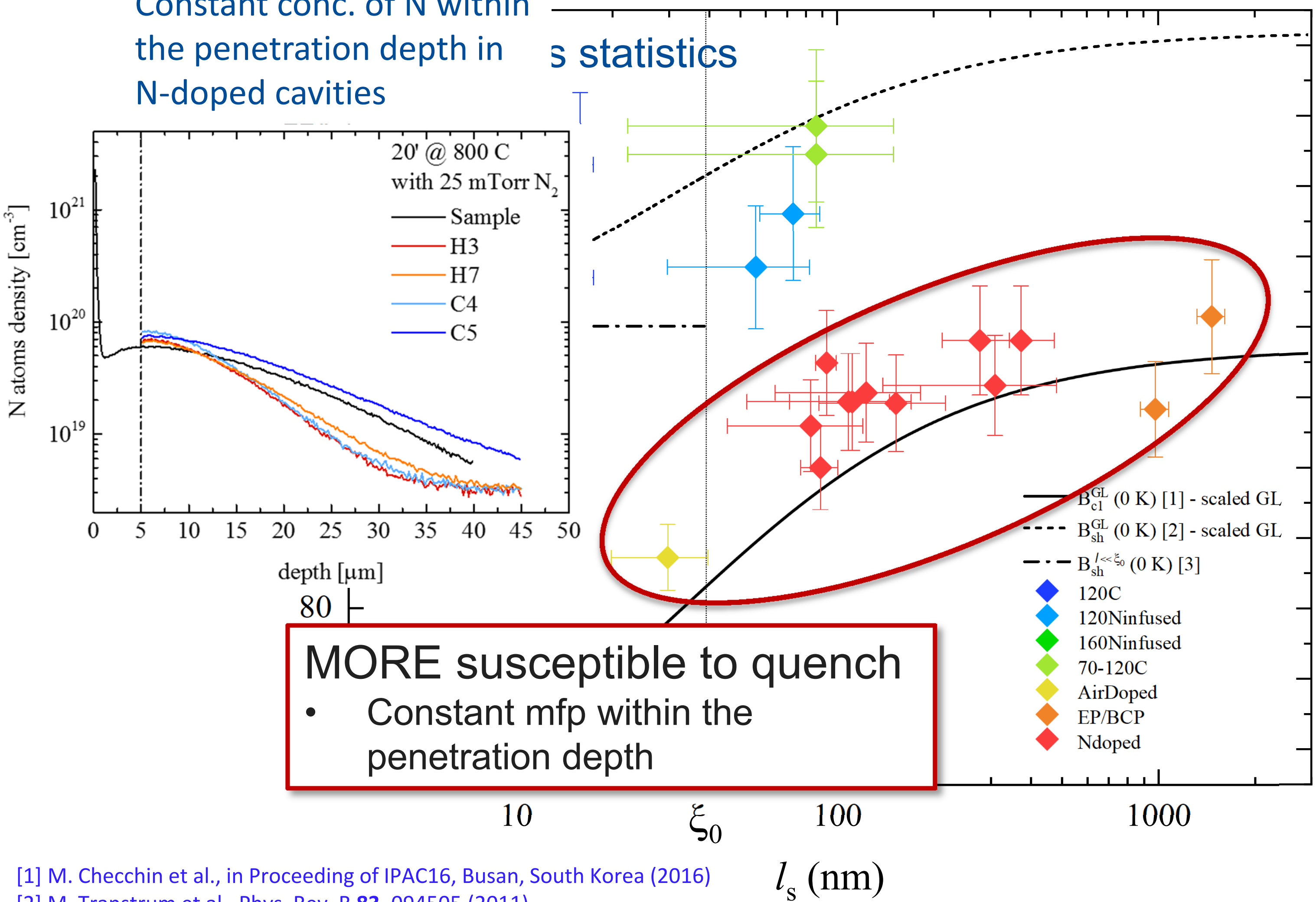
Quench field vs mfp – best cavities per treatment only



[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

Quench field vs mfp – best cavities per treatment only

Constant conc. of N within the penetration depth in N-doped cavities



MORE susceptible to quench

- Constant mfp within the penetration depth

[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

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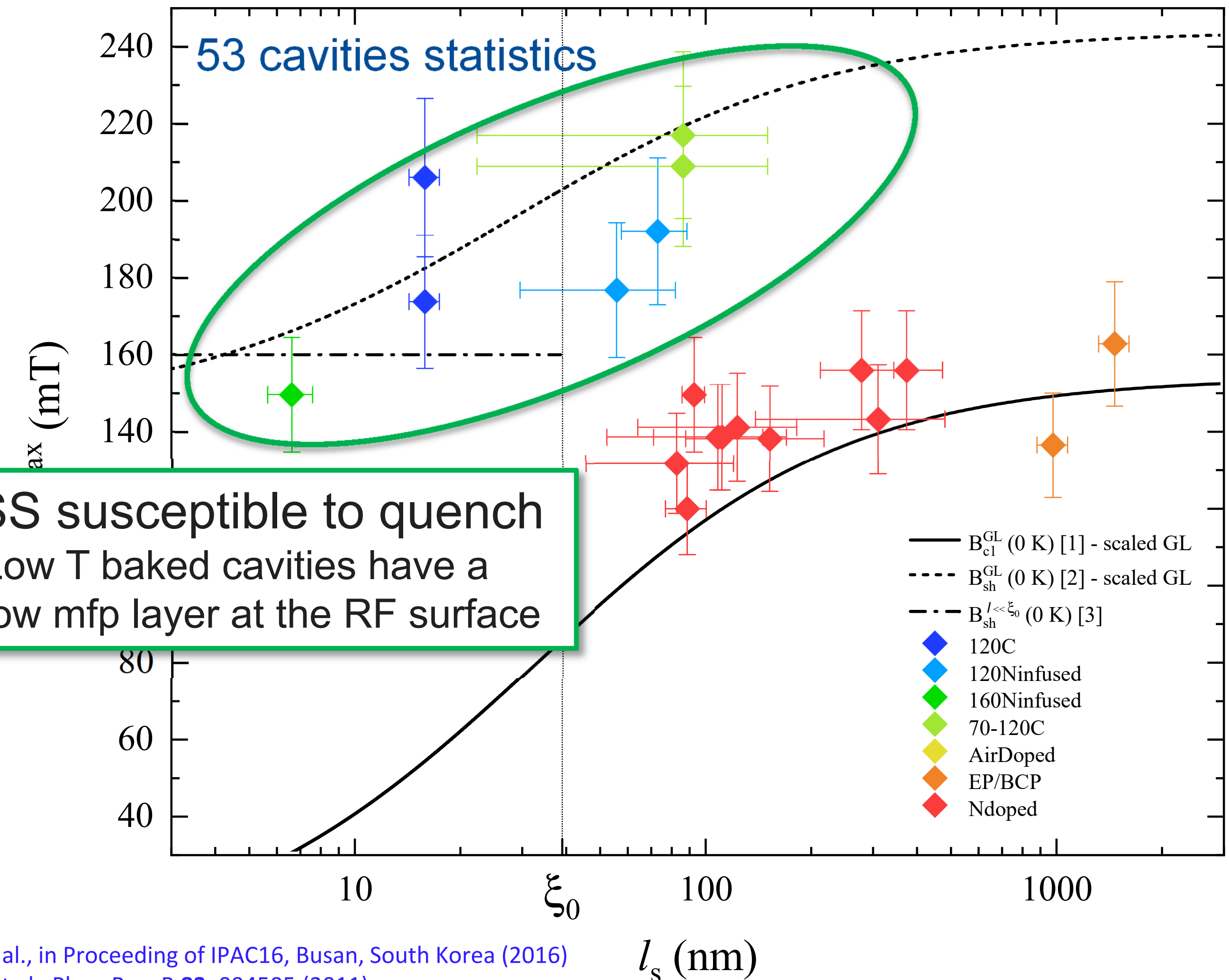
Quench field vs mfp – best cavities per treatment only



LESS susceptible to quench

- Low T baked cavities have a low mfp layer at the RF surface

[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
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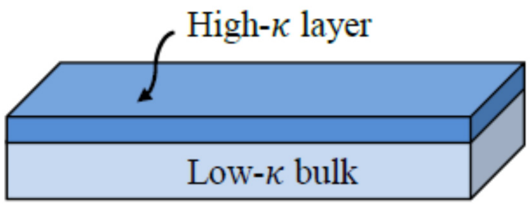
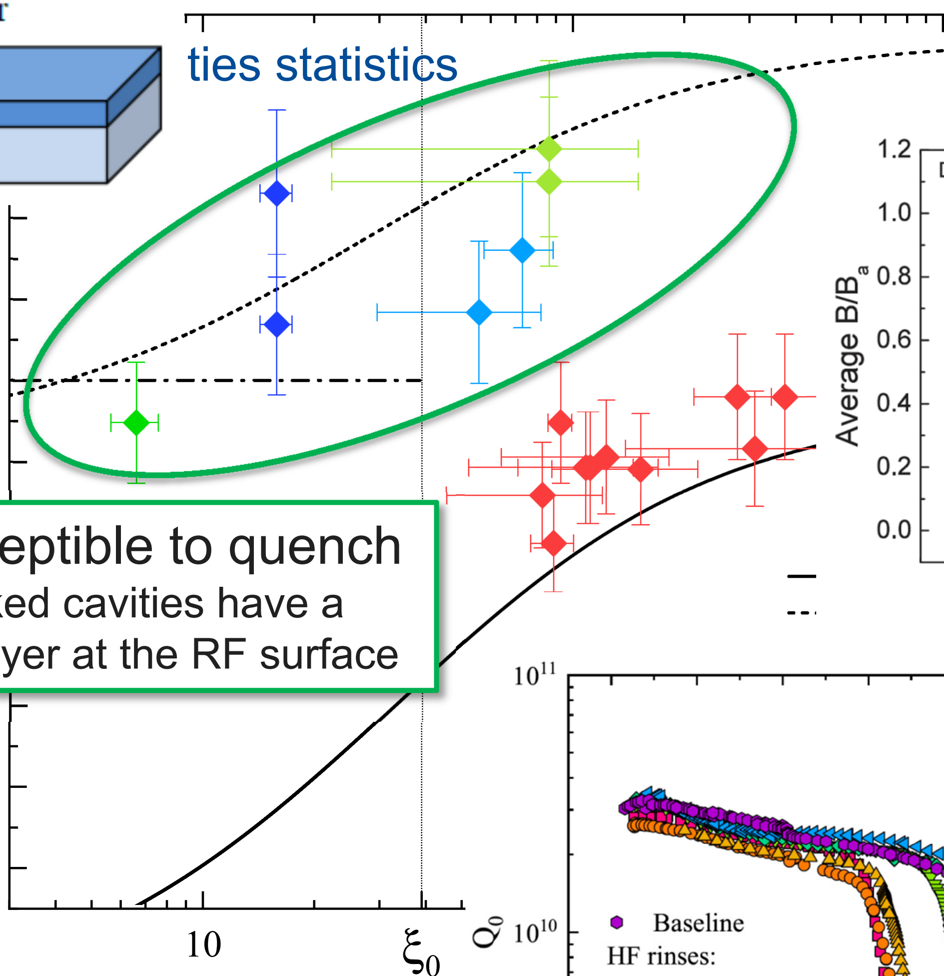
Quench field vs mfp – best cavities per treatment only



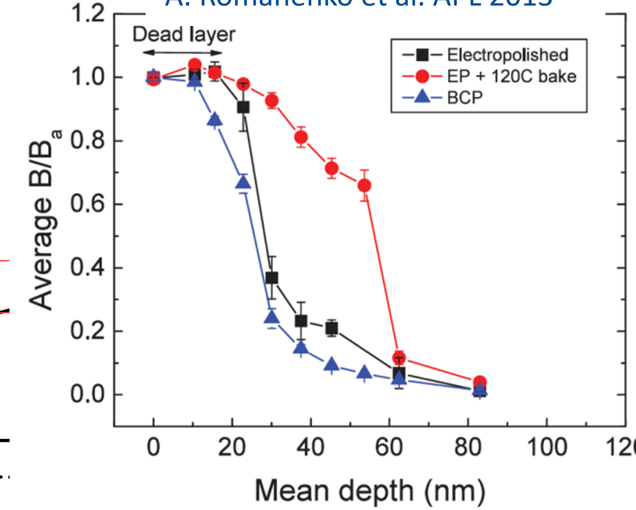


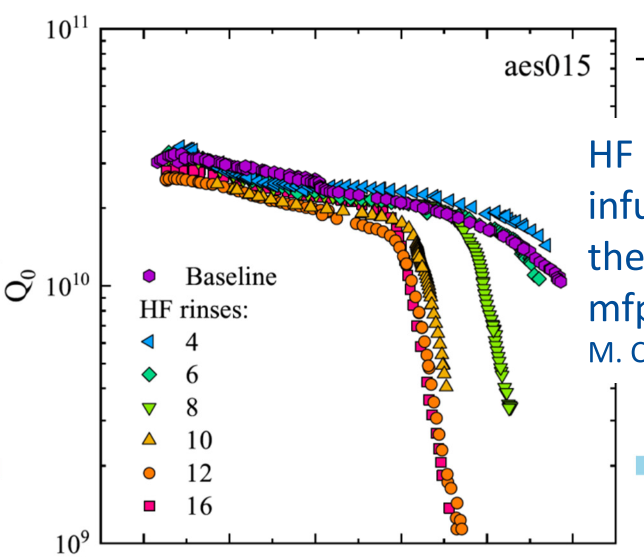
LESS susceptible to quench

- Low T baked cavities have a low mfp layer at the RF surface

Dirty layer observed in 120 C baked cut-outs with LE-μSR

A. Romanenko et al. APL 2013



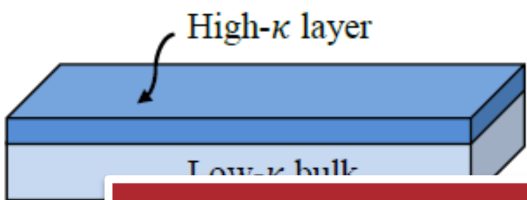


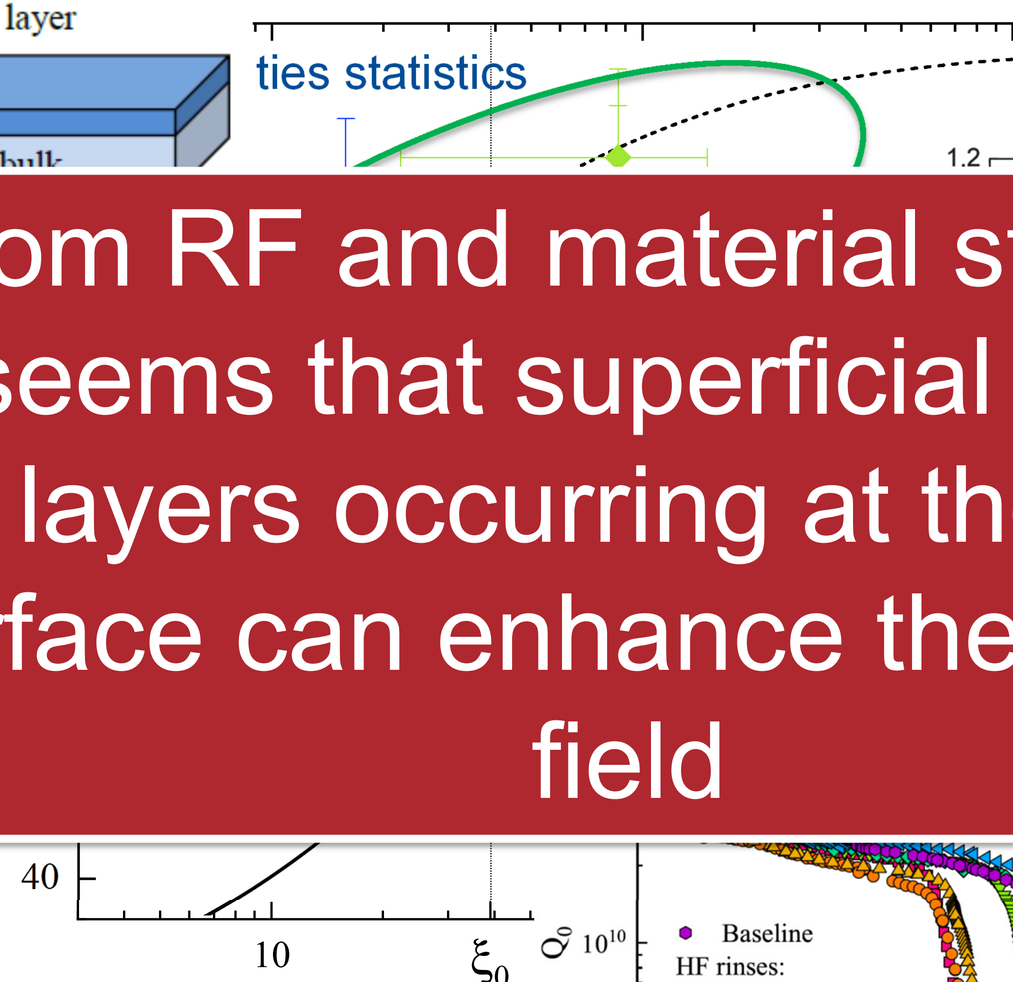
HF rinses on 120 C N-infused cavity revealed the existence of a low mfp layer at the surface

M. Checchin et al. IPAC 18

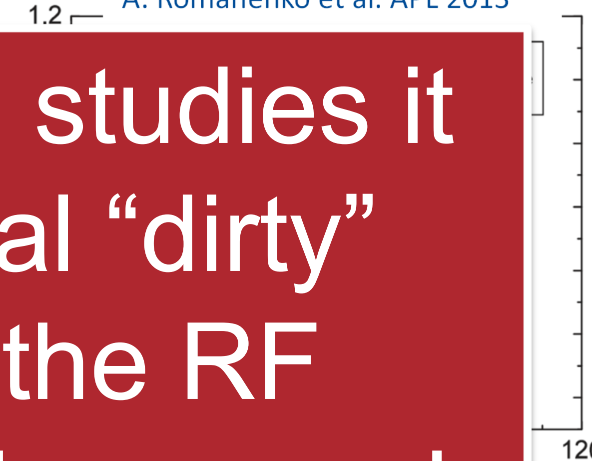
[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

Quench field vs mfp – best cavities per treatment only



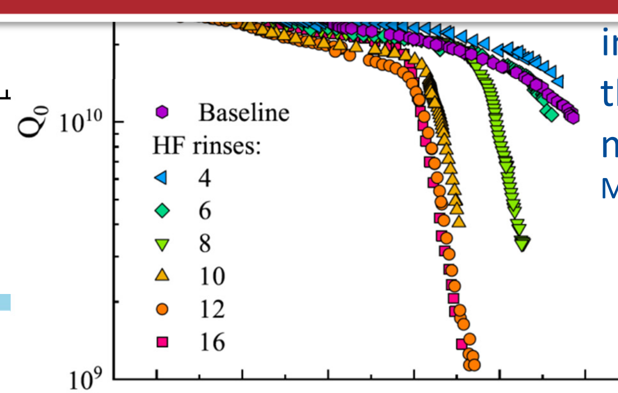


Dirty layer observed in 120 C baked cut-outs with LE-μSR
A. Romanenko et al. APL 2013



From RF and material studies it seems that superficial "dirty" layers occurring at the RF surface can enhance the quench field

N-infused cavity revealed the existence of a low mfp layer at the surface
M. Checchin et al. IPAC 18



[1] M. Checchin et al., in Proceeding of IPAC16, Busan, South Korea (2016)
[2] M. Transtrum et al., Phys. Rev. B **83**, 094505 (2011)
[3] G. Catelani and J. P. Sethna, Phys. Rev. B **78**, 224509 (2008)

Bulk μSR measurements of vortex penetration

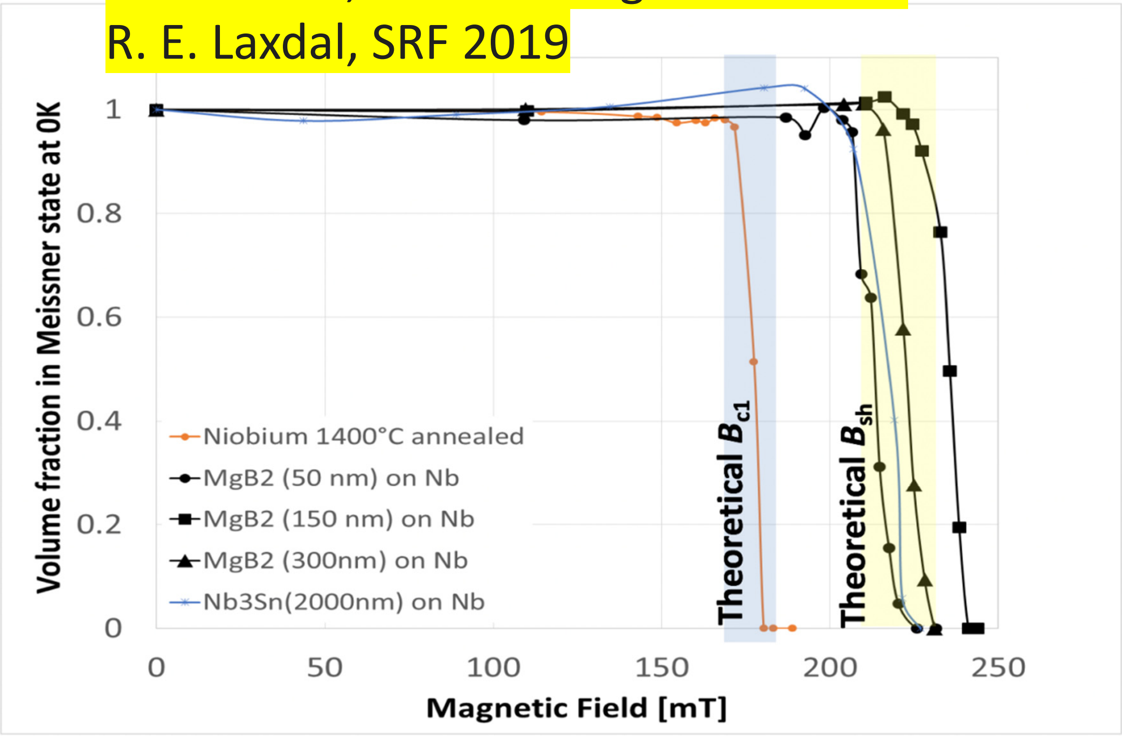
TRIUMF — Field of first flux entry on coated samples

Recently MgB_2 and Nb_3Sn on niobium samples of different thickness have been tested.

Findings: A layer of a higher T_c material on niobium can enhance the field of first entry by about 40% from a field consistent with H_{c1} to a field consistent with H_{sh}.

This enhancement does not depend on material or thickness suggesting that superheating is indeed induced in niobium by the overlayer

R. E. Laxdal, TTC Meeting RIKEN 2018
R. E. Laxdal, SRF 2019



Superheating in coated niobium, T Junginger, W Wasserman and R E Laxdal, Superconductor Science and Technology, Volume 30, Number 12, Published 7 November 2017

Bulk μSR measurements of vortex penetration

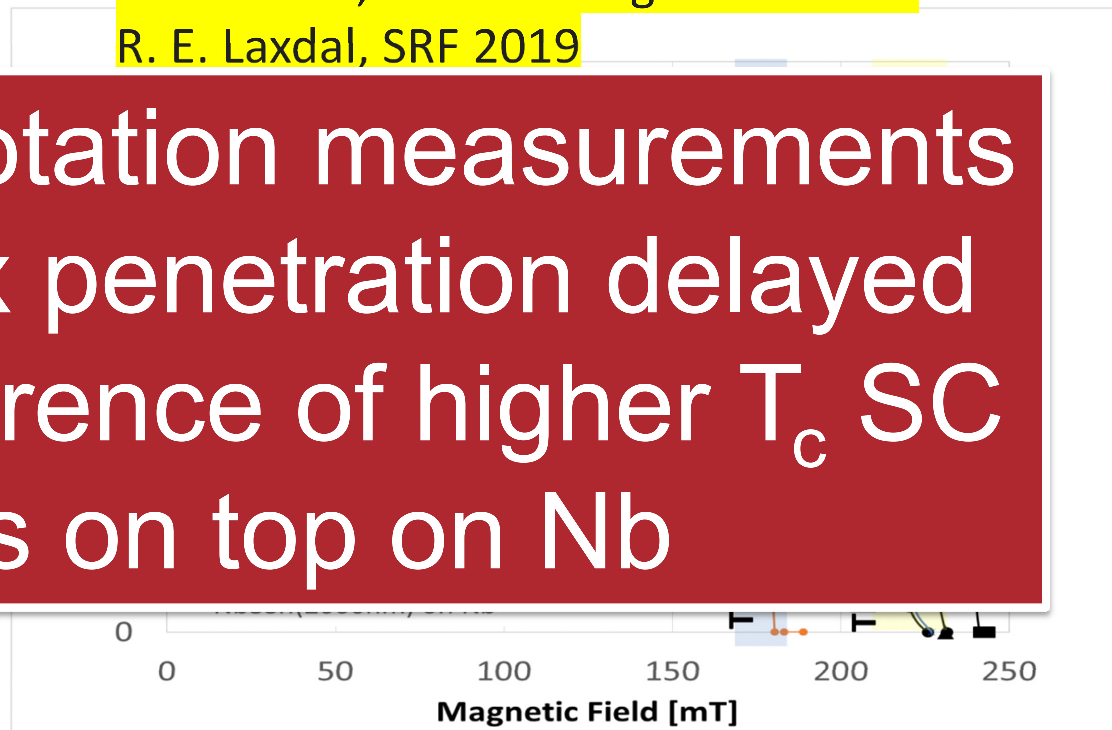
TRIUMF — Field of first flux entry on coated samples

R. E. Laxdal, TTC Meeting RIKEN 2018
R. E. Laxdal, SRF 2019

Recently MgB_2 and Nb_3Sn on nio… thi…

Fin… ma… en… by… co… co…

Thi… de… suggesting that superheating is indeed induced in niobium by the overlayer



Muon spin rotation measurements show vortex penetration delayed by the occurrence of higher T_c SC layers on top on Nb

Superheating in coated niobium, T Junginger, W Wasserman and R E Laxdal, Superconductor Science and Technology, Volume 30, Number 12, Published 7 November 2017

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What is the connection between RF and bulk μSR data?

- **"Dirty" layer** implies short mean-free-path, and therefore **long penetration depth at the surface** (compared to the bulk)
- **Higher T_c SC** layers means **longer penetration depth** (compared to the Nb substrate)
- The two systems can be described by same argumentations

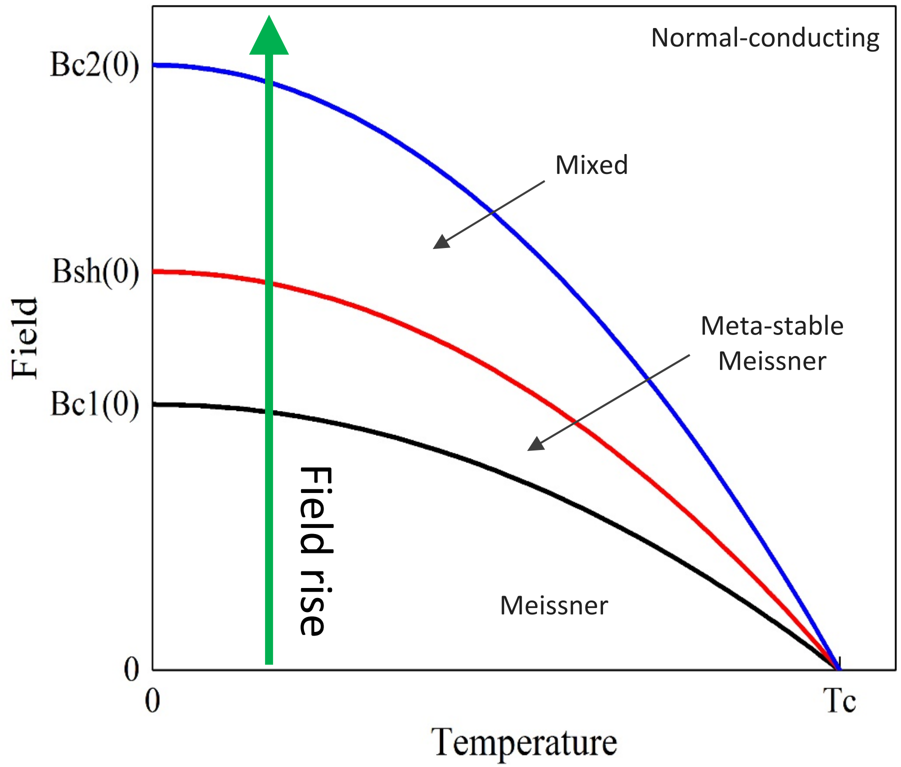
How does SS structures works?

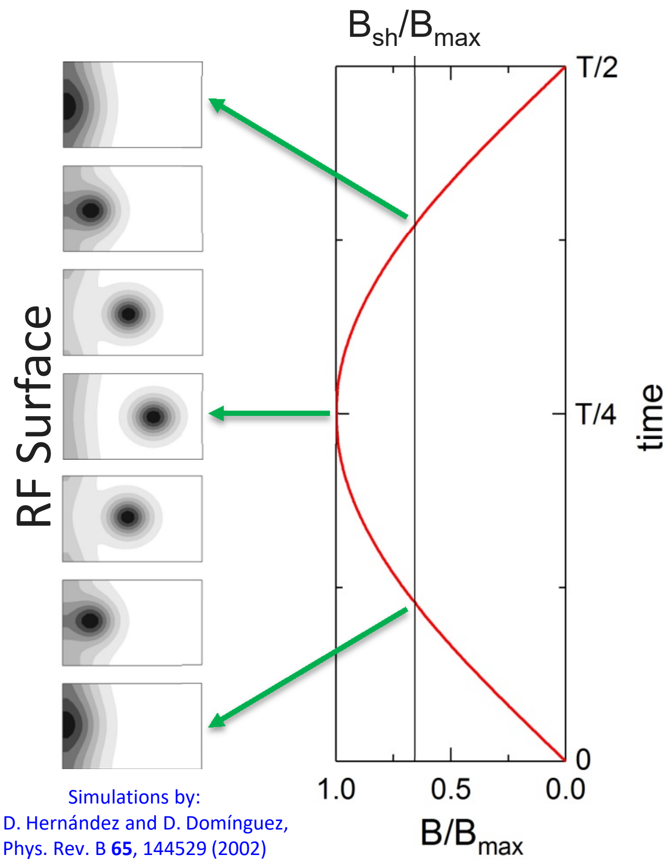
SS structure:

Energy barrier to vortex nucleation

Maximum theoretical gradient of SRF cavities

- Vortex penetration is considered to be the theoretical limit of the accelerating gradient achievable in SRF cavities
- For flawless surfaces, vortex flux lines can penetrate only for *B* larger than the superheating field B_{sh}

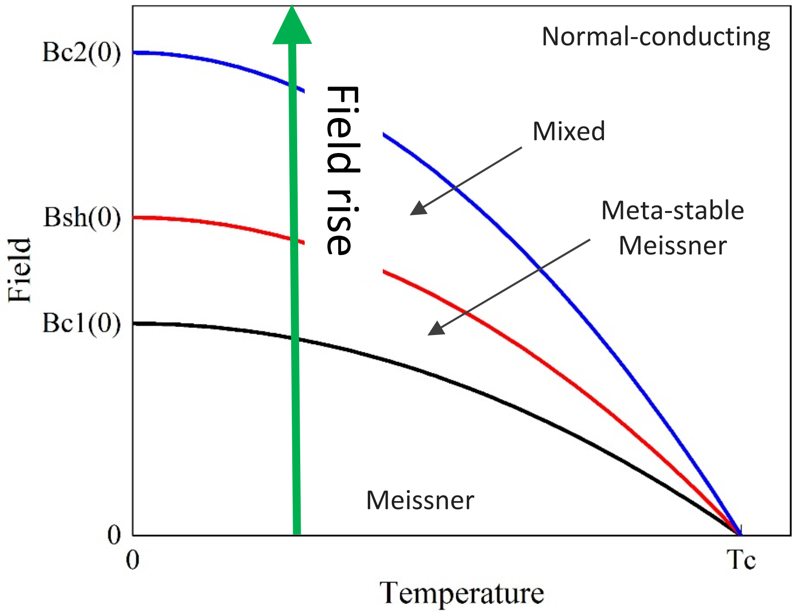


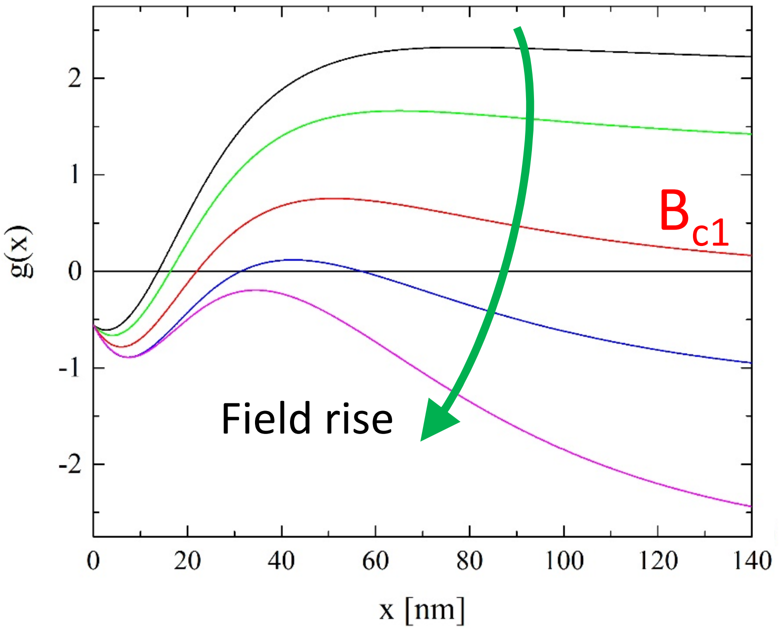


Simulations by:
A. D. Hernández and D. Domínguez,
Phys. Rev. B **65**, 144529 (2002)

Energy barrier to vortex nucleation

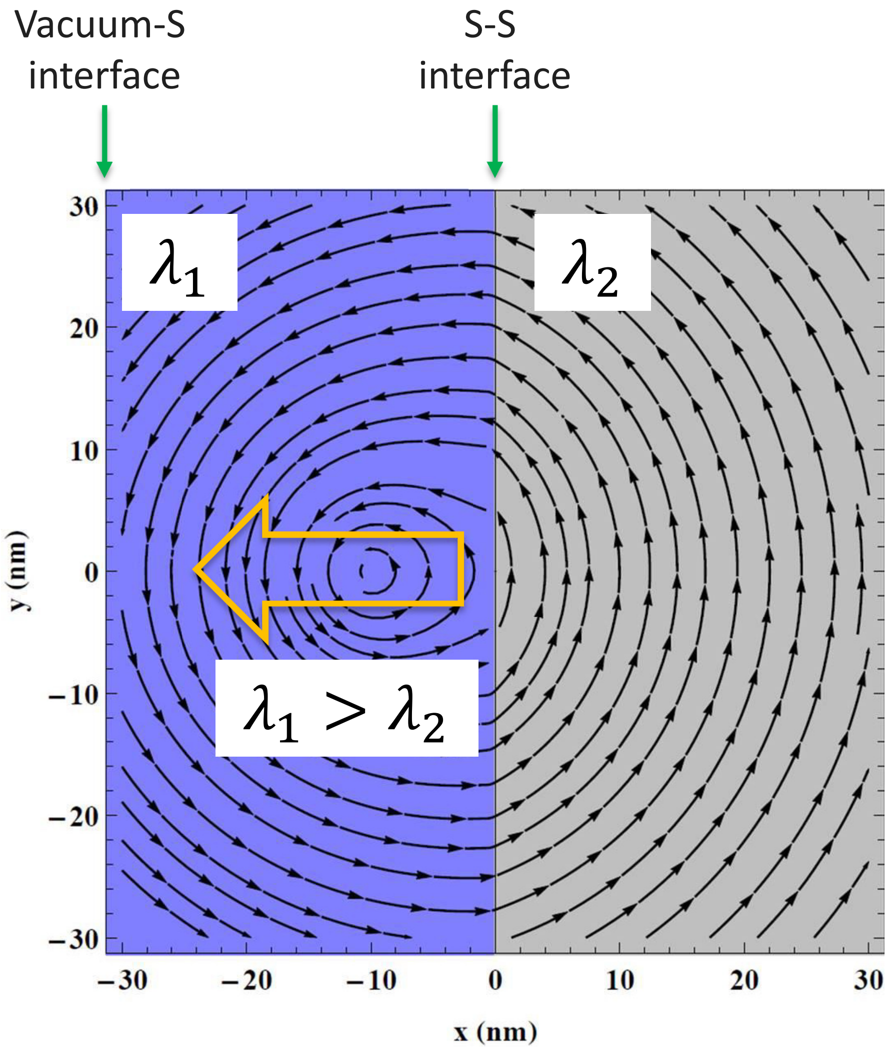
- The superheating field can be described in terms of energy barrier to vortex nucleation
- The energy barrier to vortex nucleation keeps the material in a meta-stable Meissner state up to $B_{sh} > B_{c1}$
- Defects at the surface can lower or completely destroy the barrier





C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964)

What does happen if another interface is added?

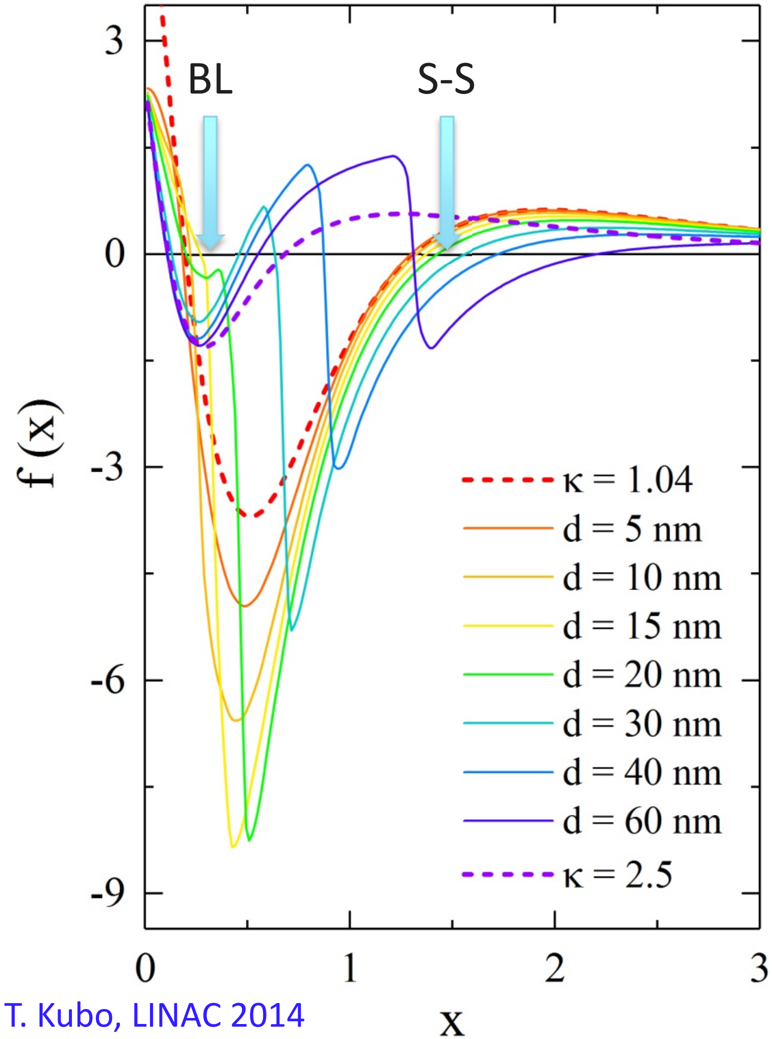


- The vortex is pushed by the S-S boundary in the direction of the material with larger λ.
- A second BL-like barrier is acting at the S-S interface
- The force acting on the vortex as a function of depth can be calculated in the London and GL framework

T. Kubo, LINAC 2014

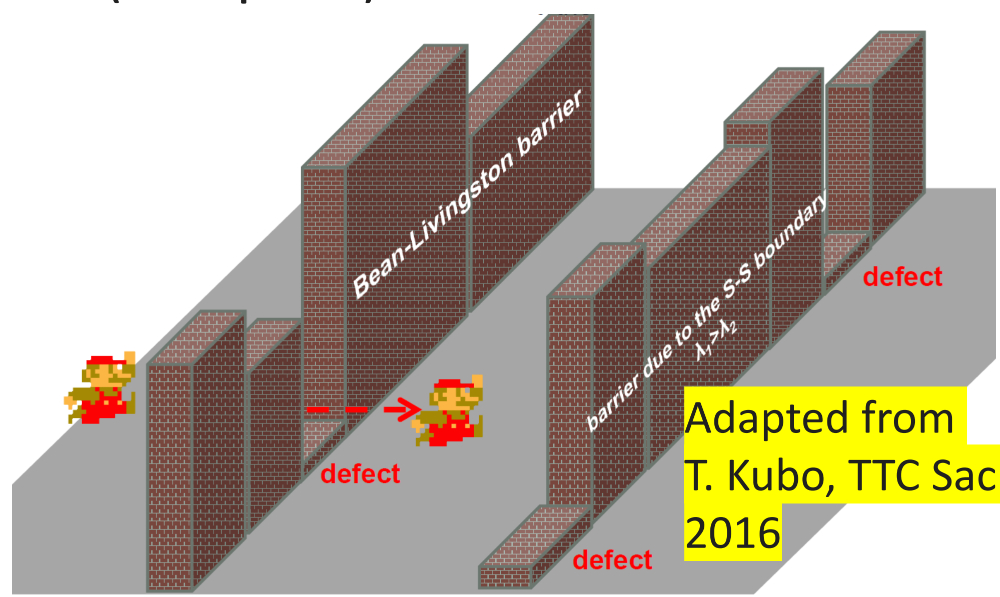
G. S. Mkrtchyan *et al.*, Zh. Eksp. Theor. Fiz. **63**, 667 (1972)

Layer thickness dependence



T. Kubo, LINAC 2014
M. Checchin et al LINAC 2016
T. Kubo, SUST (2017)

- Wide layer → two peaks in the force
- Thin layer → forces summation (one peak)

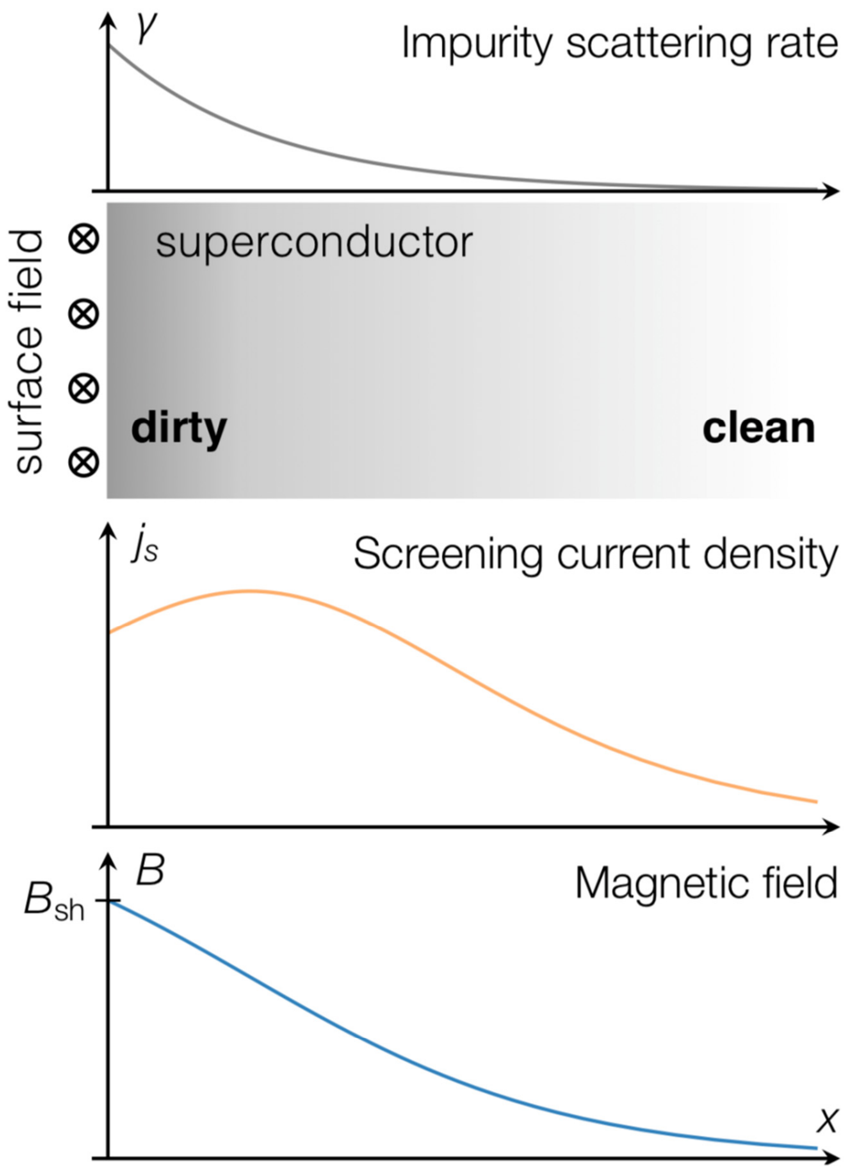


Adapted from T. Kubo, TTC Saclay 2016

SS layer structure:

Currents redistribution

Disorder heterogeneity can enhance B_{sh}



✔ Longer effective penetration depth due to dirty layer

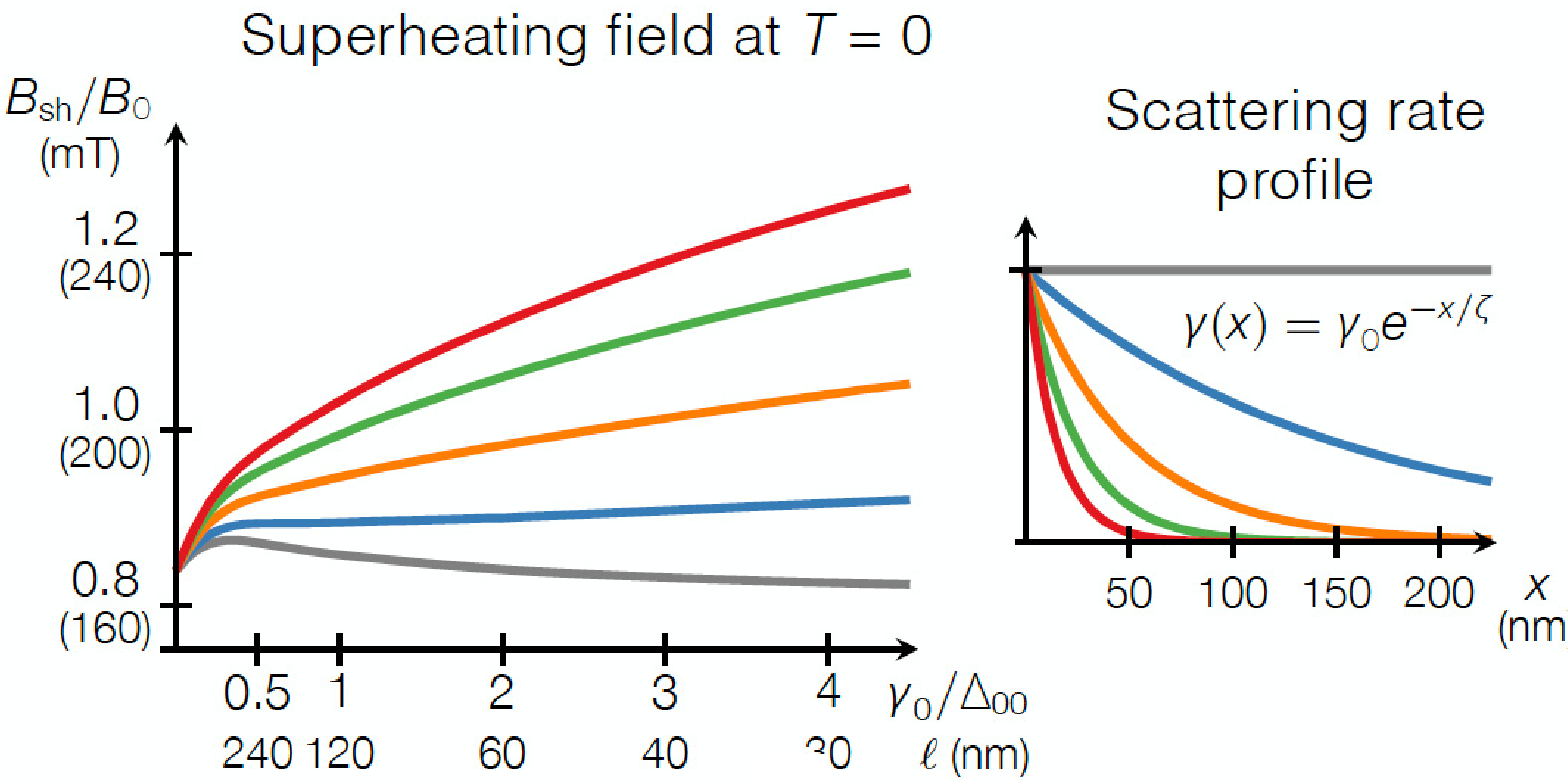
- Slowly varying B-field requires less screening current density

✔ Most screening current is in the clean region and is not suppressed by disorder

V. Ngampruetikorn, TTC RIKEN 2018

V. Ngampruetikorn and J. Sauls, arXiv:1809.04057v1

Results suggest *thin dirty layer* as design principle for optimal maximum gradient



V. Ngampruetikorn, TTC RIKEN 2018

V. Ngampruetikorn and J. Sauls, arXiv:1809.04057v1

Concluding…

Conclusions

- **Low T bake cavities** (120 C baked, N-infused, and 70-120 C baked) **show higher quench field** compared to N-doped and EP/BCP cavities for same value of mean-free-path at the surface
- **Low T baked cavities** are suspected (120 C bake and 120 C N-infused are confirmed) to **have low mean-free-path layer at the RF surface**, while N-doped and EP/BCP cavities do not
- Bulk μSR measurements show **higher T_c SC layers increase the field at which vortices penetrates into the SC**
- Theoretical calculations performed with different approaches suggest that **low mean-free-path layers at the RF surface can enhance the maximum peak magnetic field achievable** in SRF cavities
- **Low T baked cavities might represent the first working example of SS structures**