Comments on Niobium RRR and SRF cavity performance for ILC

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presented by A. Yamamoto (KEK & CERN)

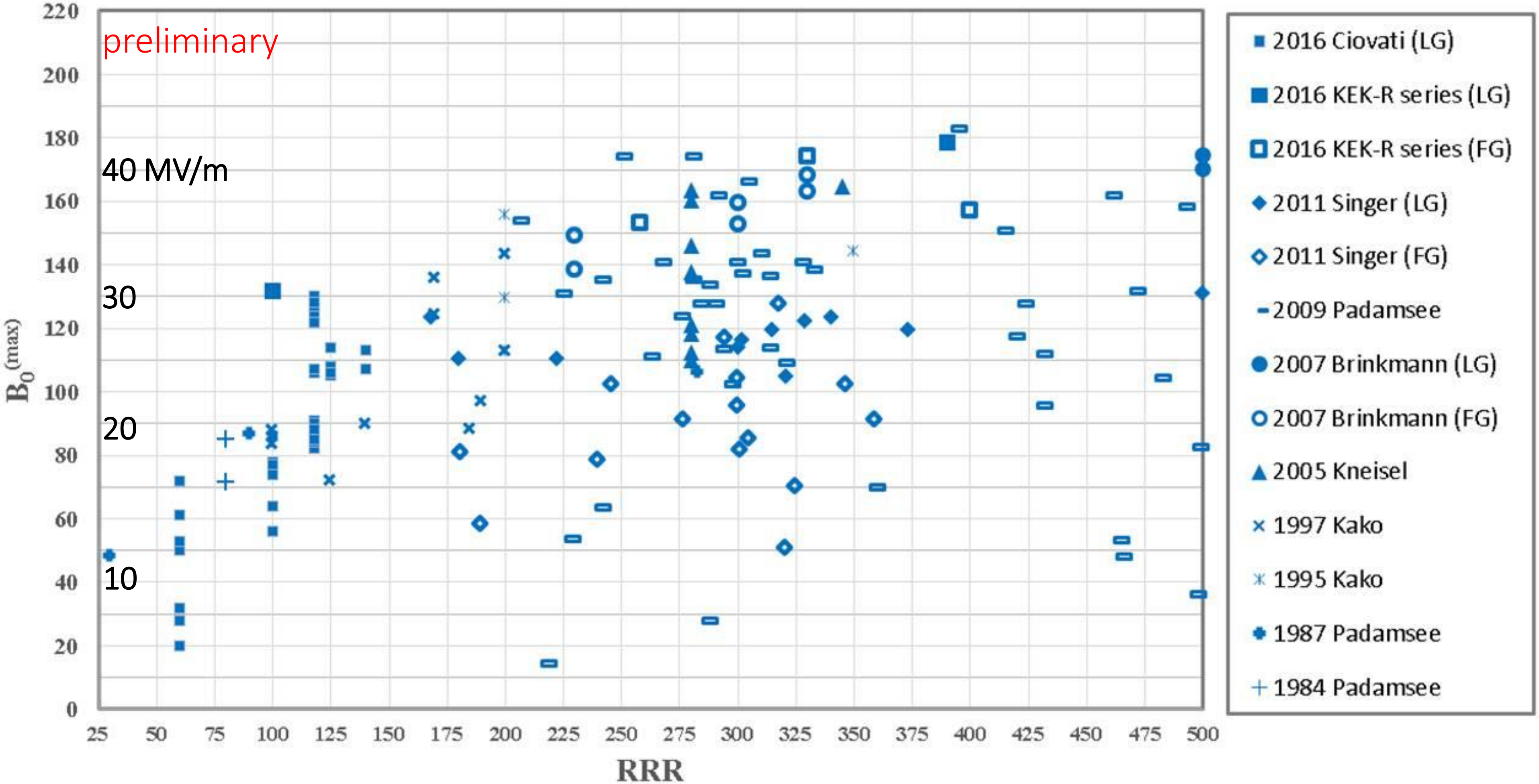
Picture from Interactions.org, Particle Physics News and Resources, http://www.interactions.org/cms/?pid=1900

- *We roughly estimates the quench fields as a function of RRR.*

- *The purpose is not to build a fundamental theory or to present quantitative simulations,*

- *but is to provide scientific basis to discuss specification of RRR in the context of cost reduction.*

Summary of experimental data



H. Padamsee, in *Proceedings of SRF1984, Geneva, Switzerland* (1984), p. 339, SRF84-21.

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E. Kako, M. Bolore, Y. Boudigou, J. P. Charrier, B. Coadou, E. Jacques, M. Juillard, J. P. Poupeau, H. Safa, S. Noguchi et al., in *Proceedings of SRF1997, Abano Terme Padova, Italy* (1997), p. 491, SRF97C10.

P. Kneisel, G. R. Myneni, G. Ciovati, J. Sekutowicz, and T. Carneiro, in *Proceedings of SRF2005, Cornell University, Ithaca, New York, USA* (2005), p. 134, MOP09.

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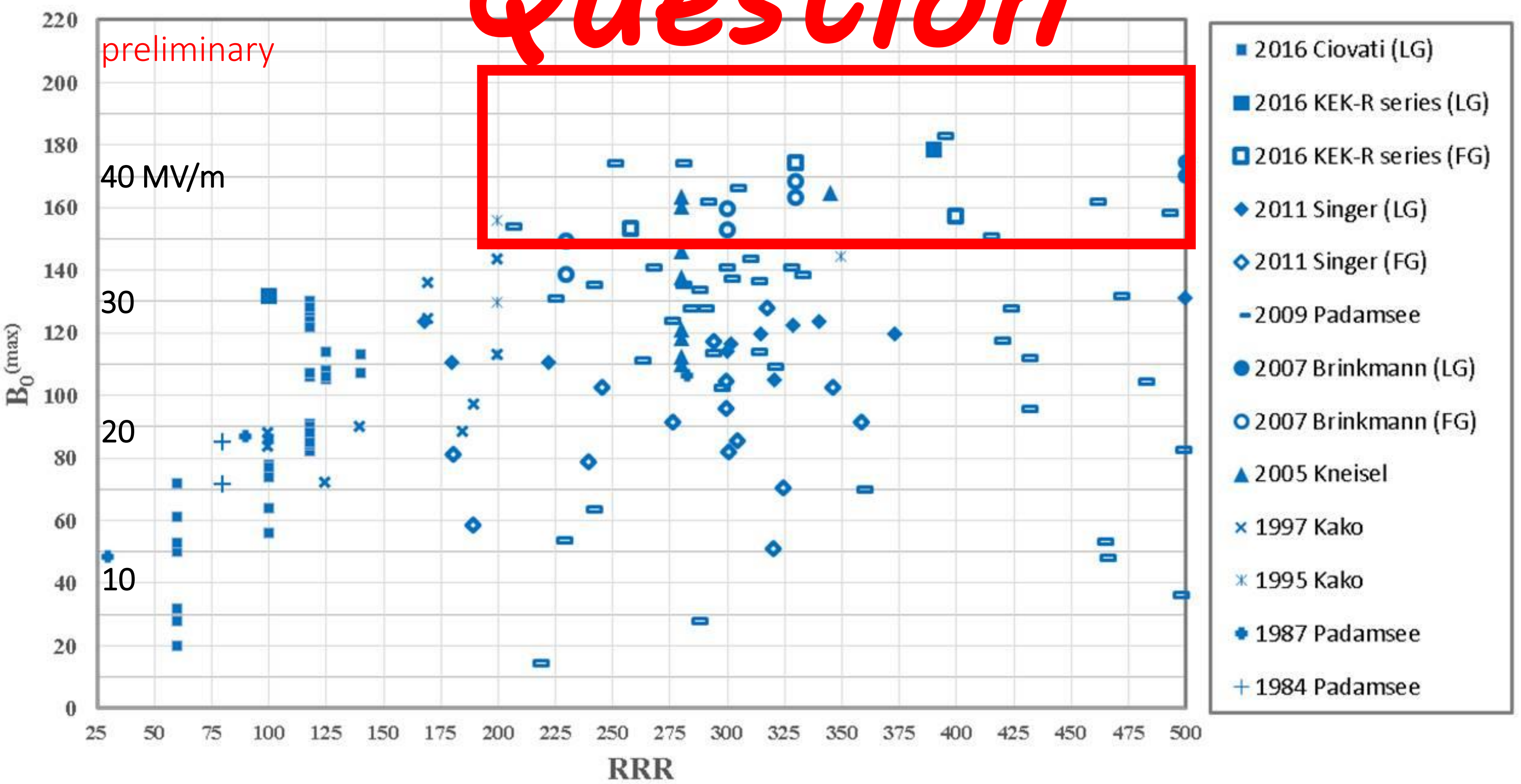
H. Shimizu, H. Inoue, E. Kako, T. Saeki, K. Umemori, Y. Watanabe, and M. Yamanaka, in *Proceedings of SRF2015, Whistler, BC, Canada* (2015), p. 1146, THPB030.

G. Ciovati, P. Dhakal, and G. R. Myneni, Supercond. Sci. Technol. **29**, 064002 (2016).

* The world record is around 200mT. However, I do not know its RRR value, and could not plot them here.

Question



RRR $\gtrsim$ 200 is enough for ILC?

Why do we use high purity Nb materials?

There are two reasons: we need

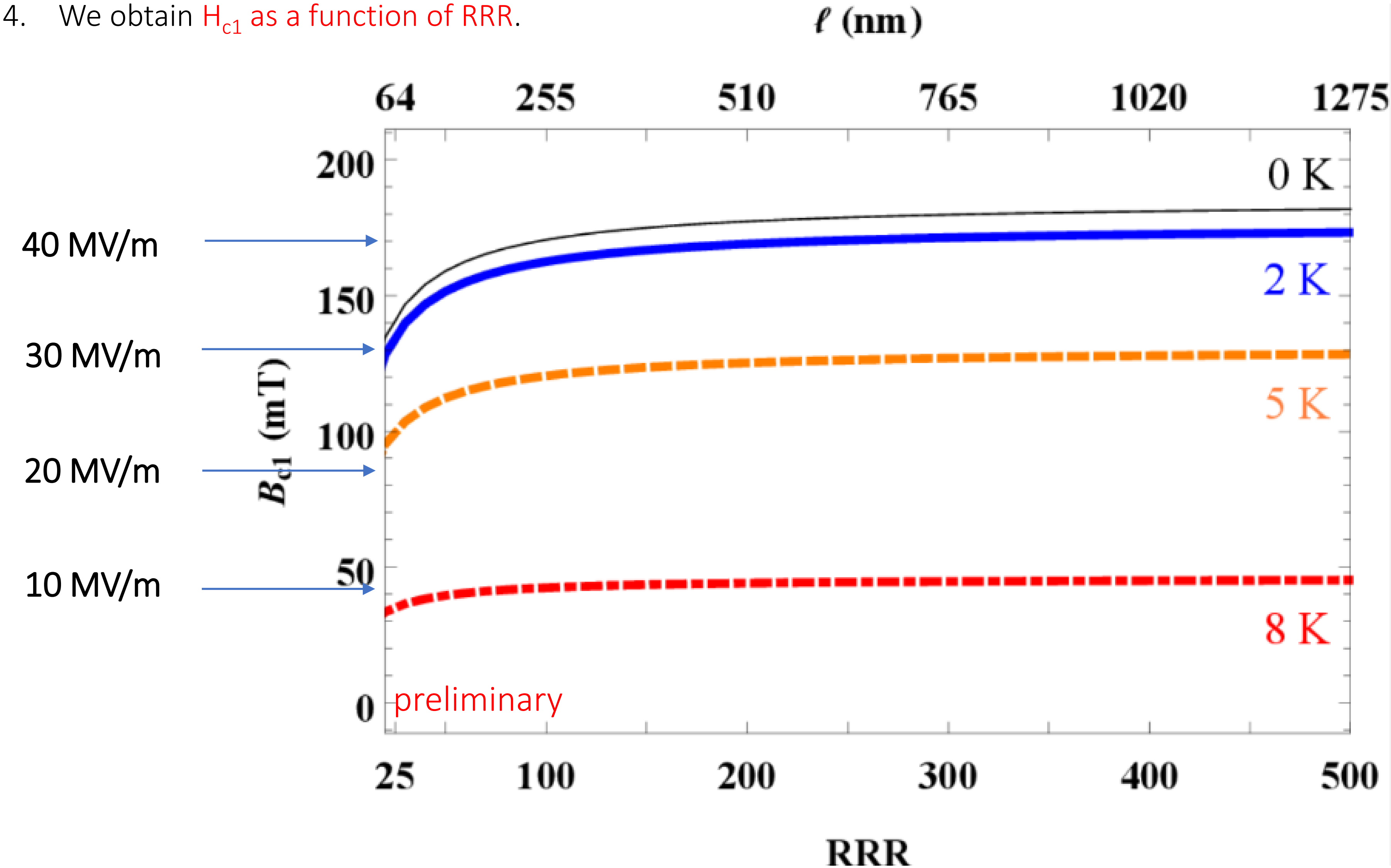
- Higher H_{c1} to prevent vortex penetration
- Higher thermal conductivity for thermal stabilization

These values can be expressed with RRR.

Screening Test #1

The lower critical field H_{c1}

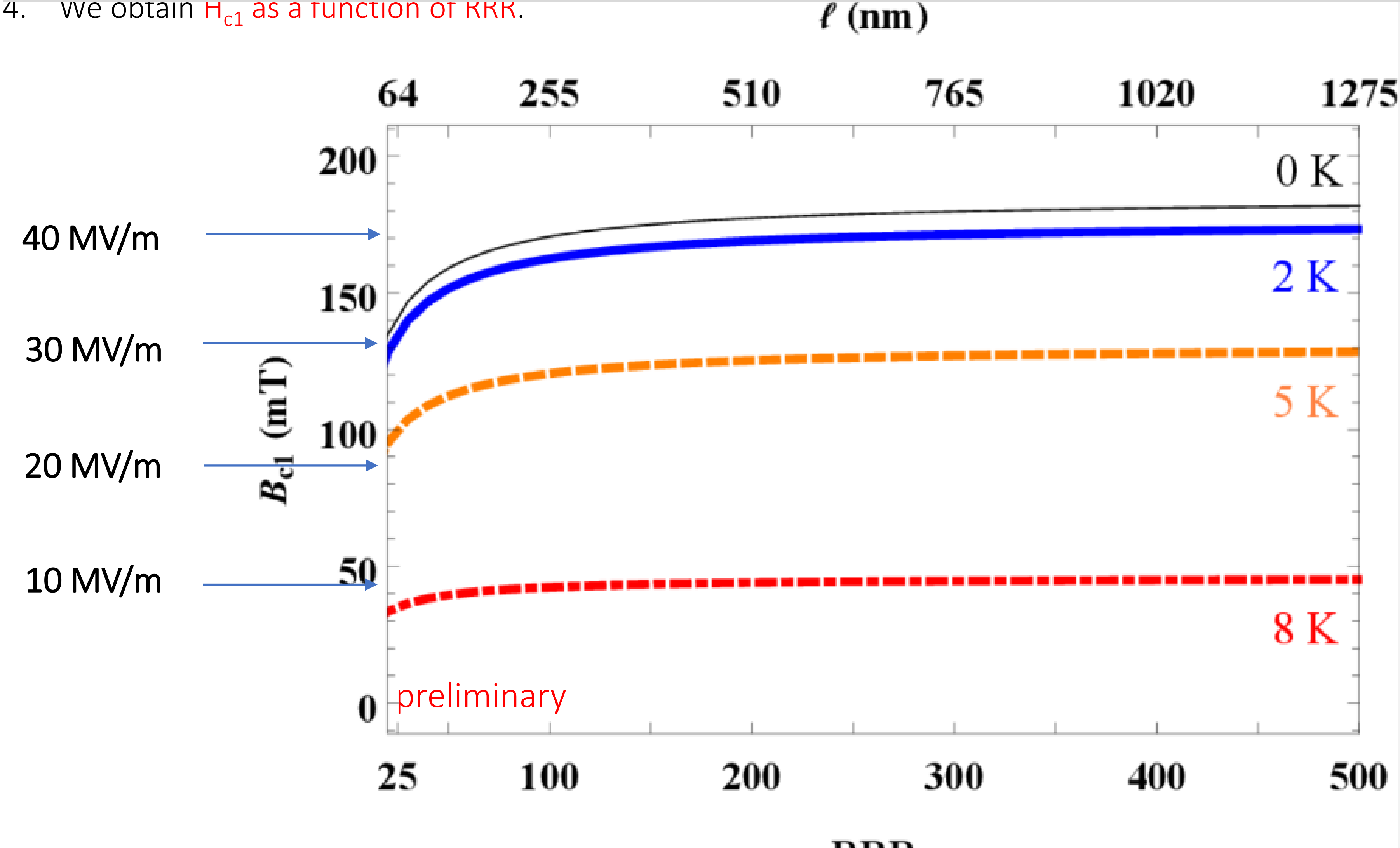
1. H_{c1} of Nb is obtained by GL formula at T~T_c [E. H. Brandt, Phys. Rev. B 68, 054506 (2003)].
2. Extrapolate it to T<<T_c, which agrees well with experimental data at T=0 if $\kappa_{GL} \lesssim 2$.
3. Based on the BCS theory, express κ_{GL} with microscopic parameters such as ξ_0 and mfp (l), and express mfp with RRR. (see Appendix)
4. We obtain H_{c1} as a function of RRR.



I know the world record is ~200mT, which is larger than B_{c1} by 20%. Thus, in the later analysis, we assume the maximum field is around B_{c1} – 1.2*B_{c1}

$RRR \gtrsim 50$ is necessary for ILC

4. We obtain H_{c1} as a function of RRR.



I know the world record is ~200mT, which is larger than B_{c1} by 20%. Thus, in the later analysis, we assume the maximum field is around $B_{c1} - 1.2{*}B_{c1}$

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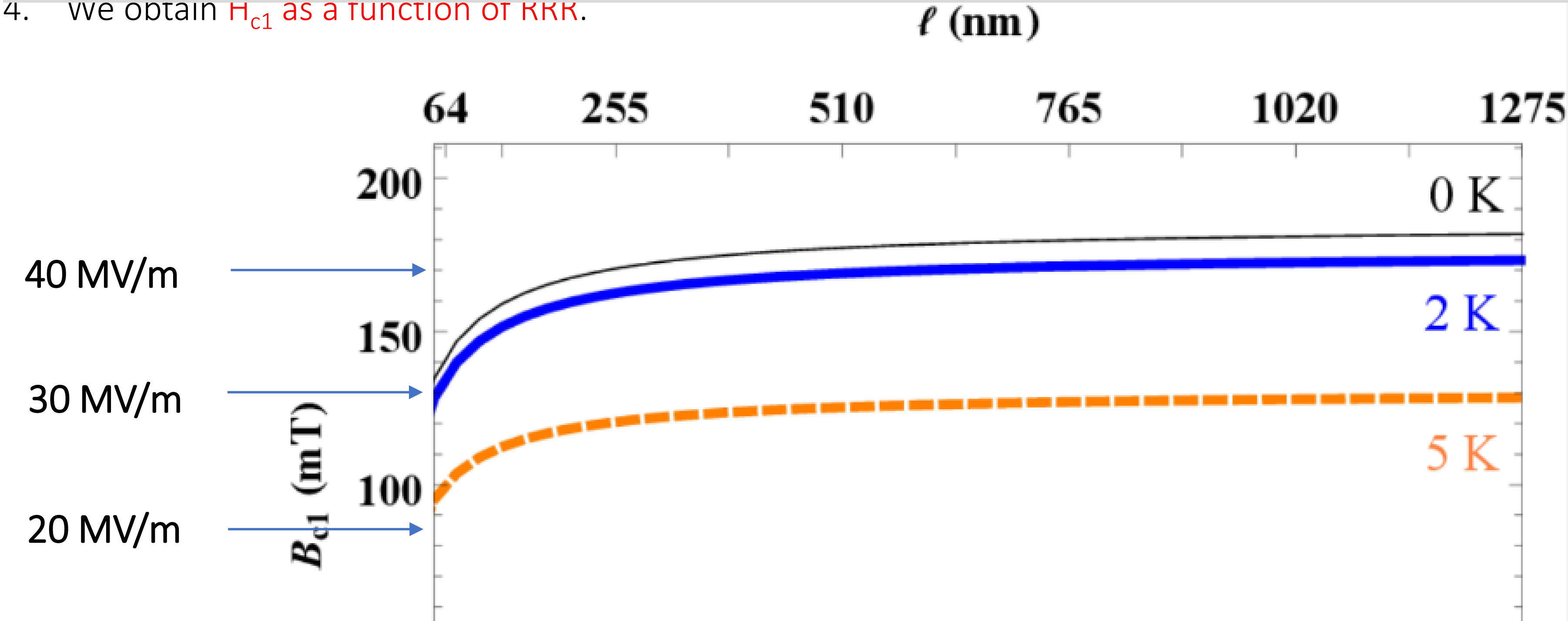
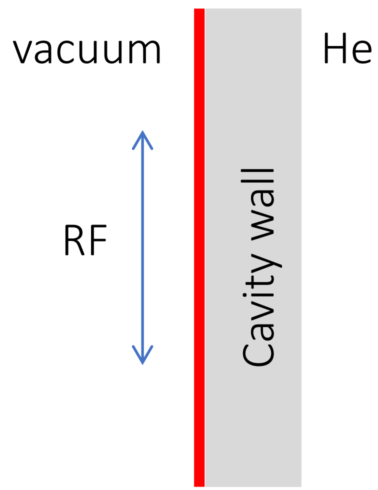


We can reconfirm that N-doped cavities corresponding to mfp~50nm yield B_{c1}~130mT and thus cannot pass this screening test.

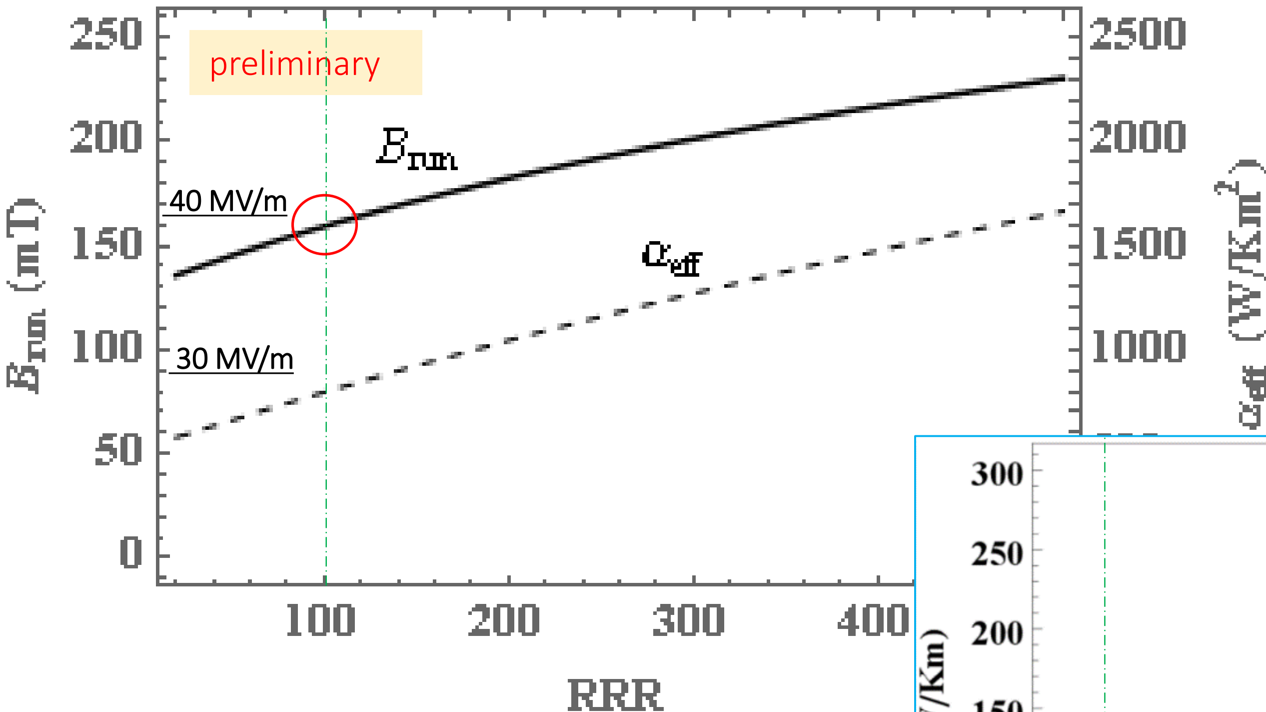
Screening Test #2
Thermal runaway for the defect-free case

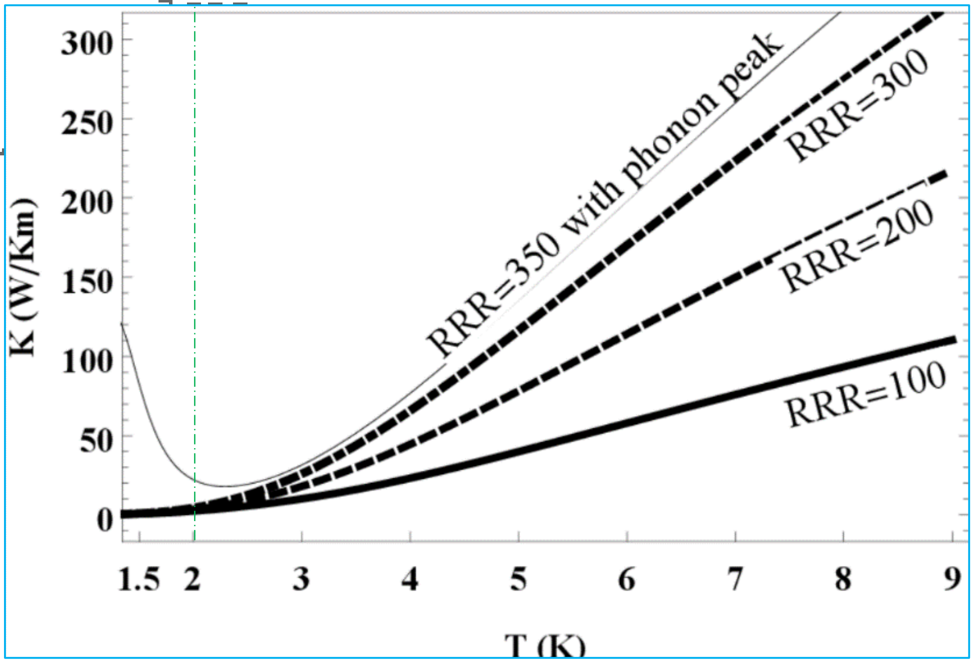


This is a well-studied effect.

- A small temperature rise at the inner surface due to BCS heating induces exponential increase of $R_s \propto e^{-\Delta/kT}$.
- It further increases the inner temperature.
- This positive feedback causes the **thermal runaway** even if any defect does not exist.

1. The thermal runaway field for defect-free case is obtained by solving the 1D thermal diffusion equation. [A. Gurevich and G. Ciovati, Phys. Rev. B 87, 054502 (2013)]
2. Express thermal conductivity with RRR by using [F. Koechlin and B. Bonin, Supercond. Sci. Technol. 9, 453 (1996)]
3. We obtain the thermal runaway field as a function of RRR.

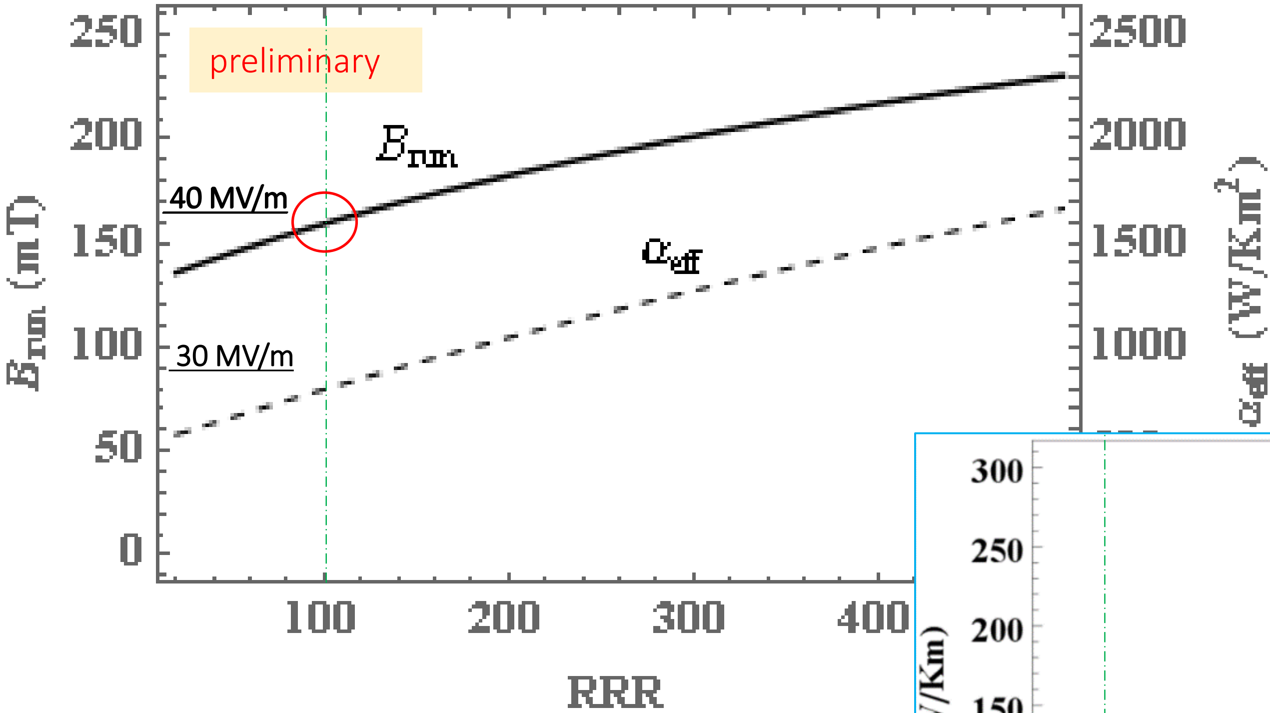


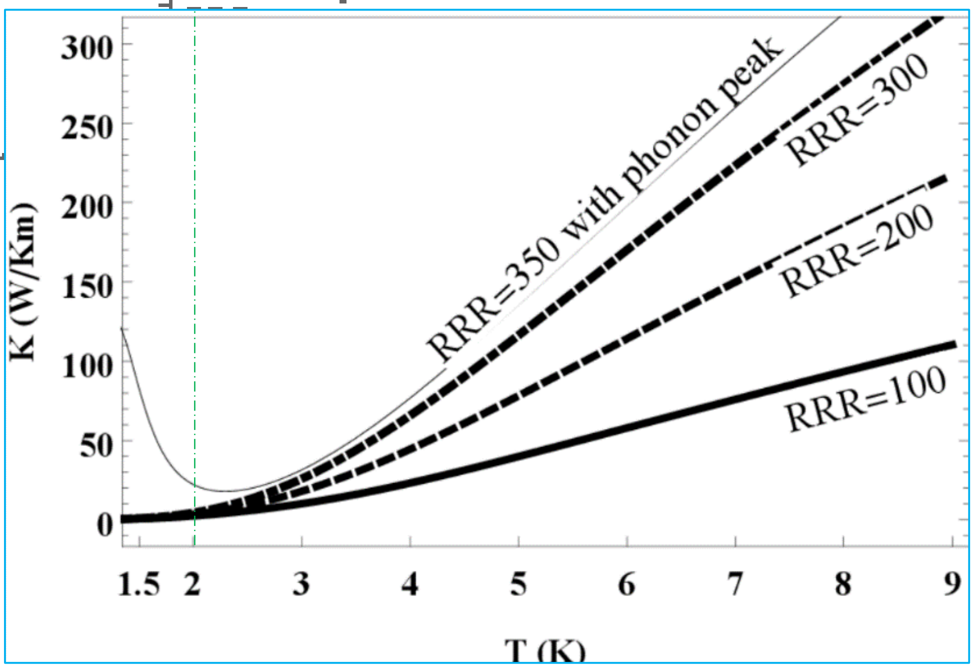


Assumptions:

- No phonon peak
- Wall thickness d=2.8mm
- Bath temperature T_b=2K
- Kapitza conductance a_K=10,000W/Km^2

$RRR \gtrsim 100$ is necessary when phonon peak is absent





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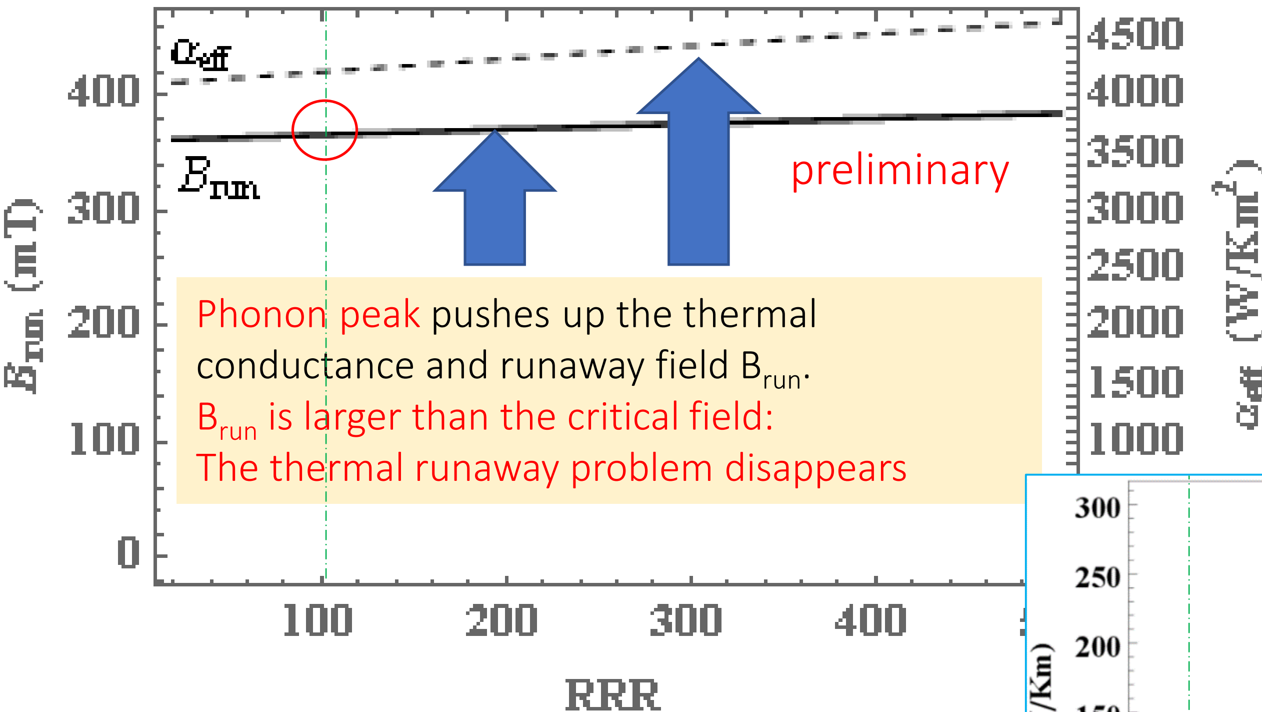
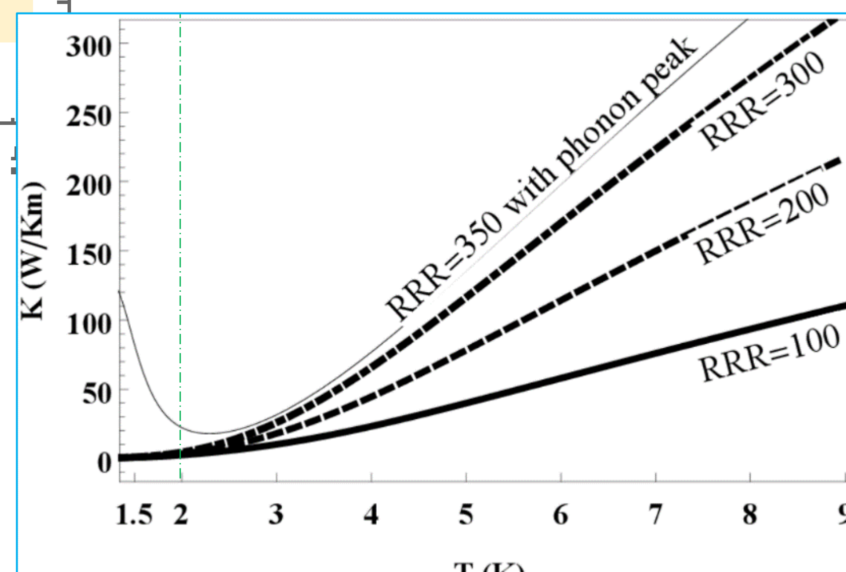
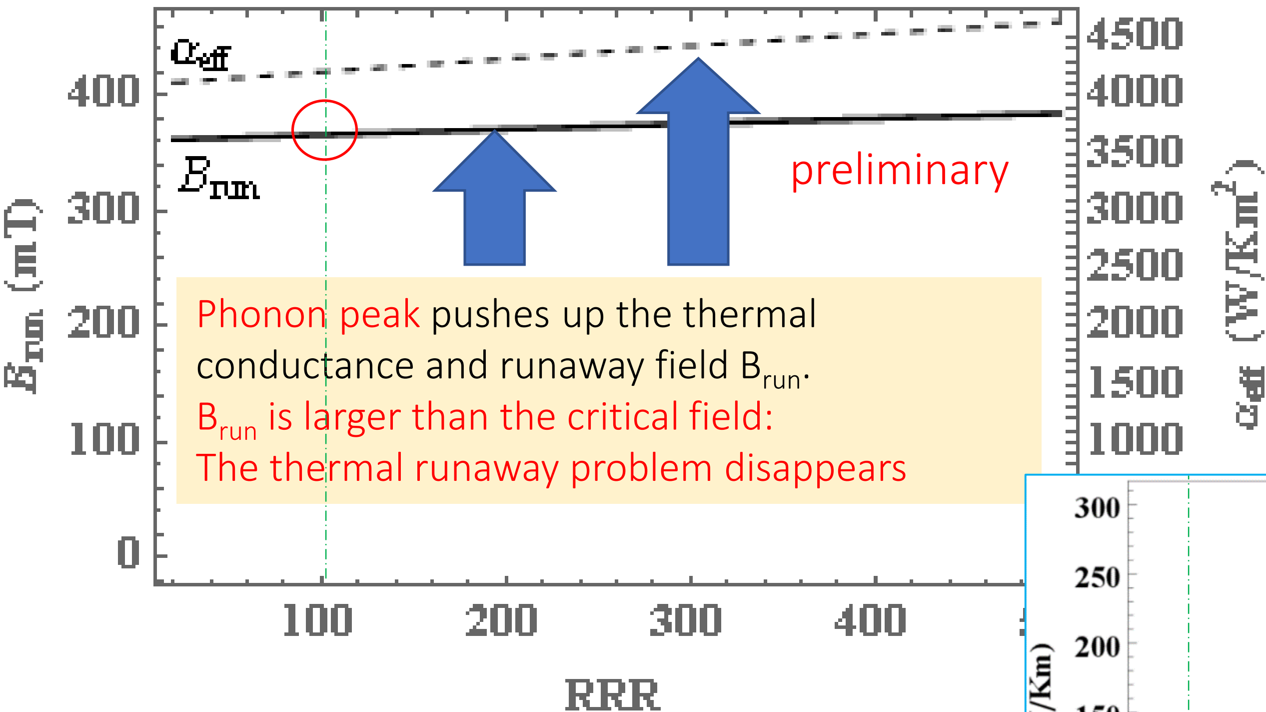


Phonon peak pushes up the thermal conductance and runaway field B_{run}.
B_{run} is larger than the critical field:
The thermal runaway problem disappears



Assumptions:
- Include phonon peak
- Wall thickness d=2.8mm
- Bath temperature T_b=2K
- Kapitza conductance a_K=10,000W/Km^2

Thermal runaway disappeared when phonon peak is available



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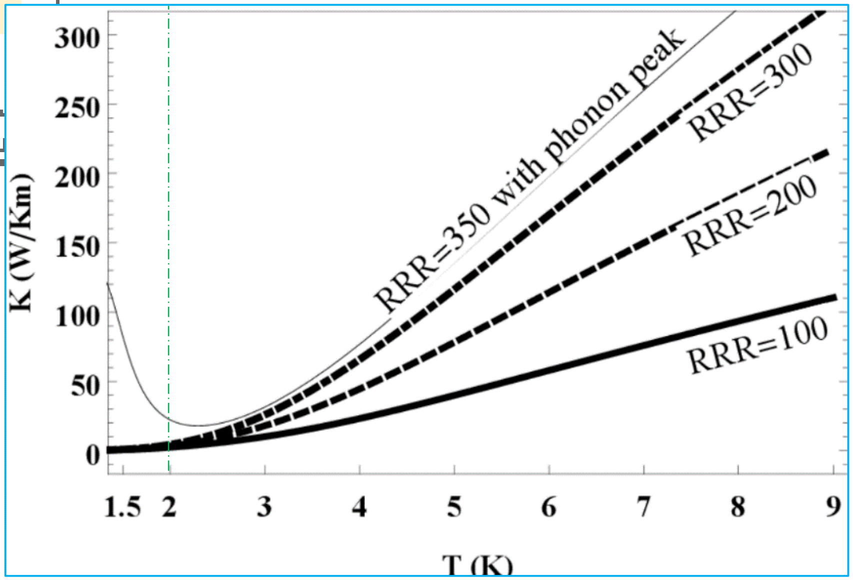


Assumptions:

- Include phonon peak
- Wall thickness d=2.8mm
- Bath temperature T_b=2K
- Kapitza conductance a_K=10,000W/Km^2

Summary of Screening Tests #1 and #2

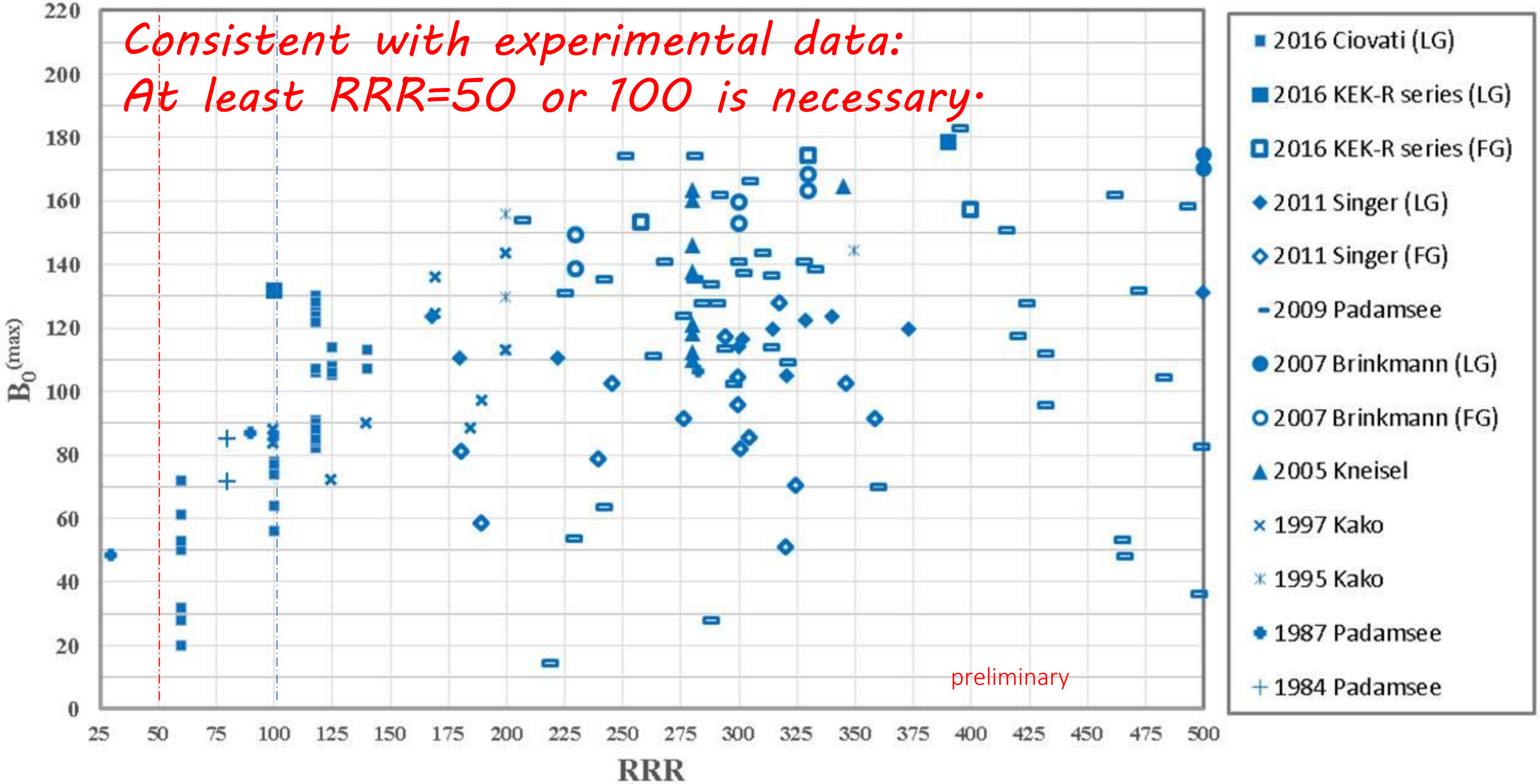
- In terms of H_{c1}, RRR>50 is necessary
- In terms of thermal runaway,
  - RRR>100 is necessary when the phonon peak is absent
  - Arbitrary RRR is OK, when the phonon peak is available.

- Large grain with phonon peak → RRR>50
- Fine grain → RRR>100

are necessary for ILC.

This is the minimum condition.

Summary of Screening Tests #1 and #2



- Large grain with phonon peak → RRR>50
- Fine grain → RRR>100

are necessary for ILC.

This is the <u>minimum</u> condition.

Then,

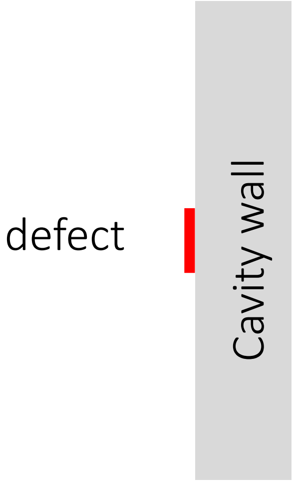
RRR~300 is too much?

No! Too early to conclude!

Screening Test #3

H_{c1} at a heating defect:

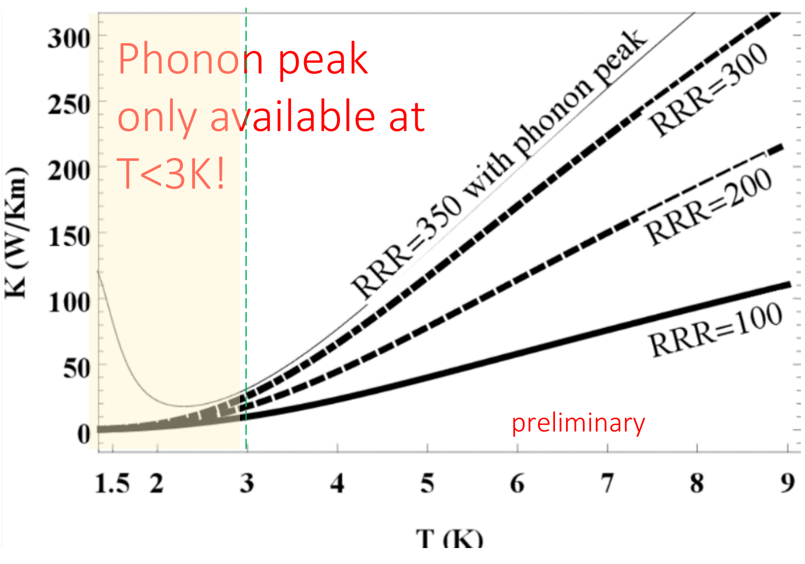
Simultaneous test for H_{c1} & thermal conductivity

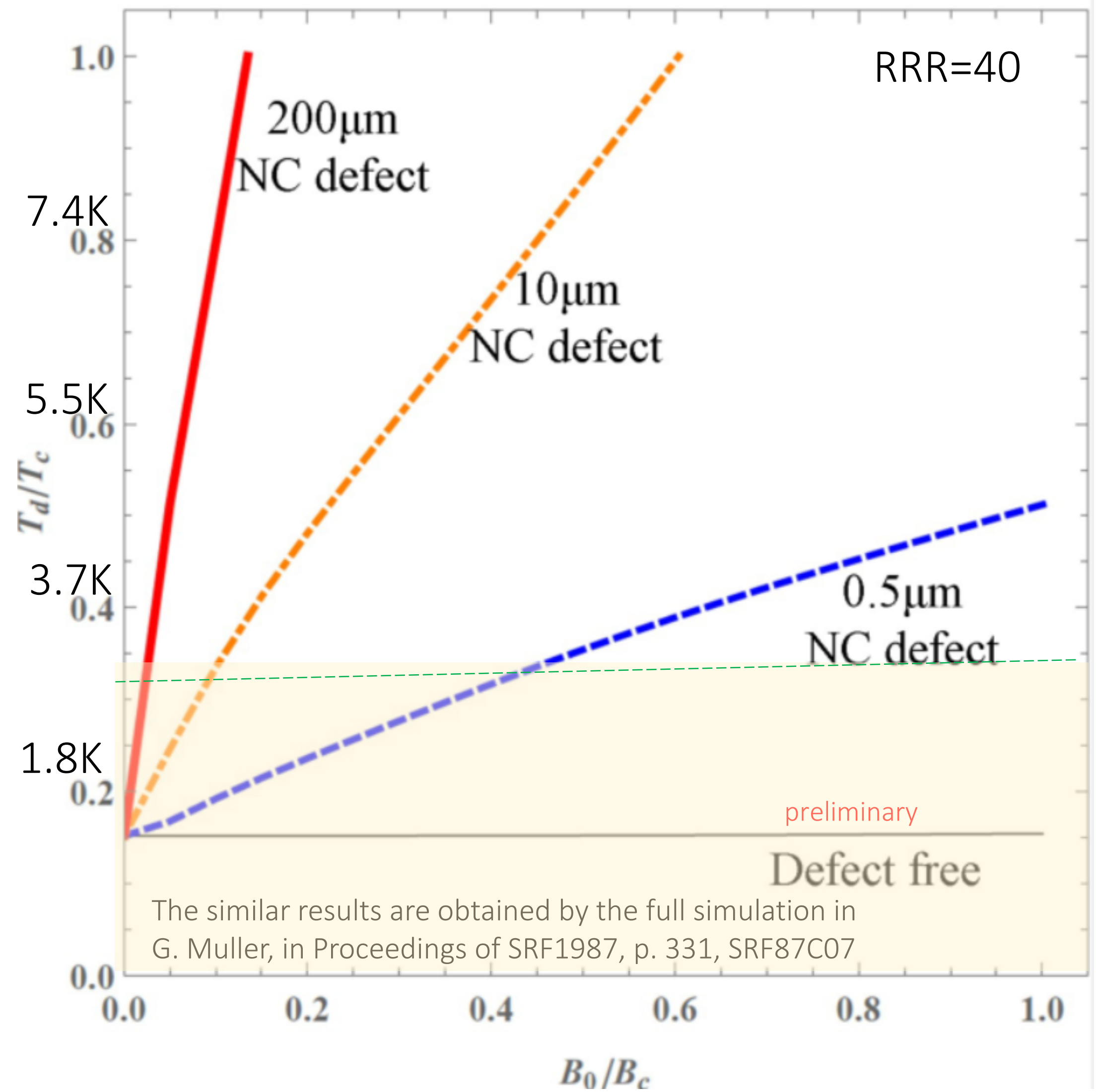


The temperature rise at a defect significantly suppresses H_{c1}.

1. Consider defects such as normal conducting contamination or weak superconducting precipitates.
2. Calculate the temperature rise around the defect, assuming Rs at defect is given by that of normal Nb. [G. Muller, in Proceedings of SRF1987, Argonne National Laboratory,Illinois, USA (1987), p. 331, SRF87C07. A. Gurevich and G. Ciovati, Phys. Rev. B 87, 054502 (2013)]

This is much different regime than the screening test#2. The temperature rise is local and huge. The phonon peak (T<3K) does not play an important role.





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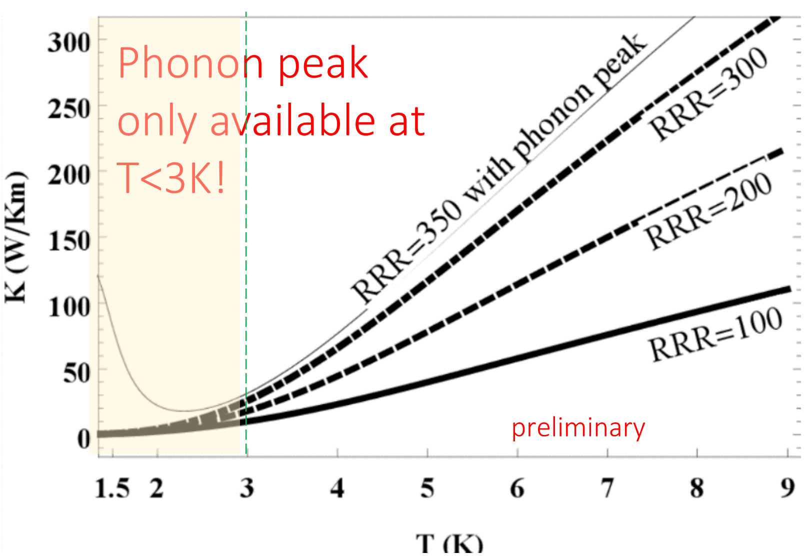
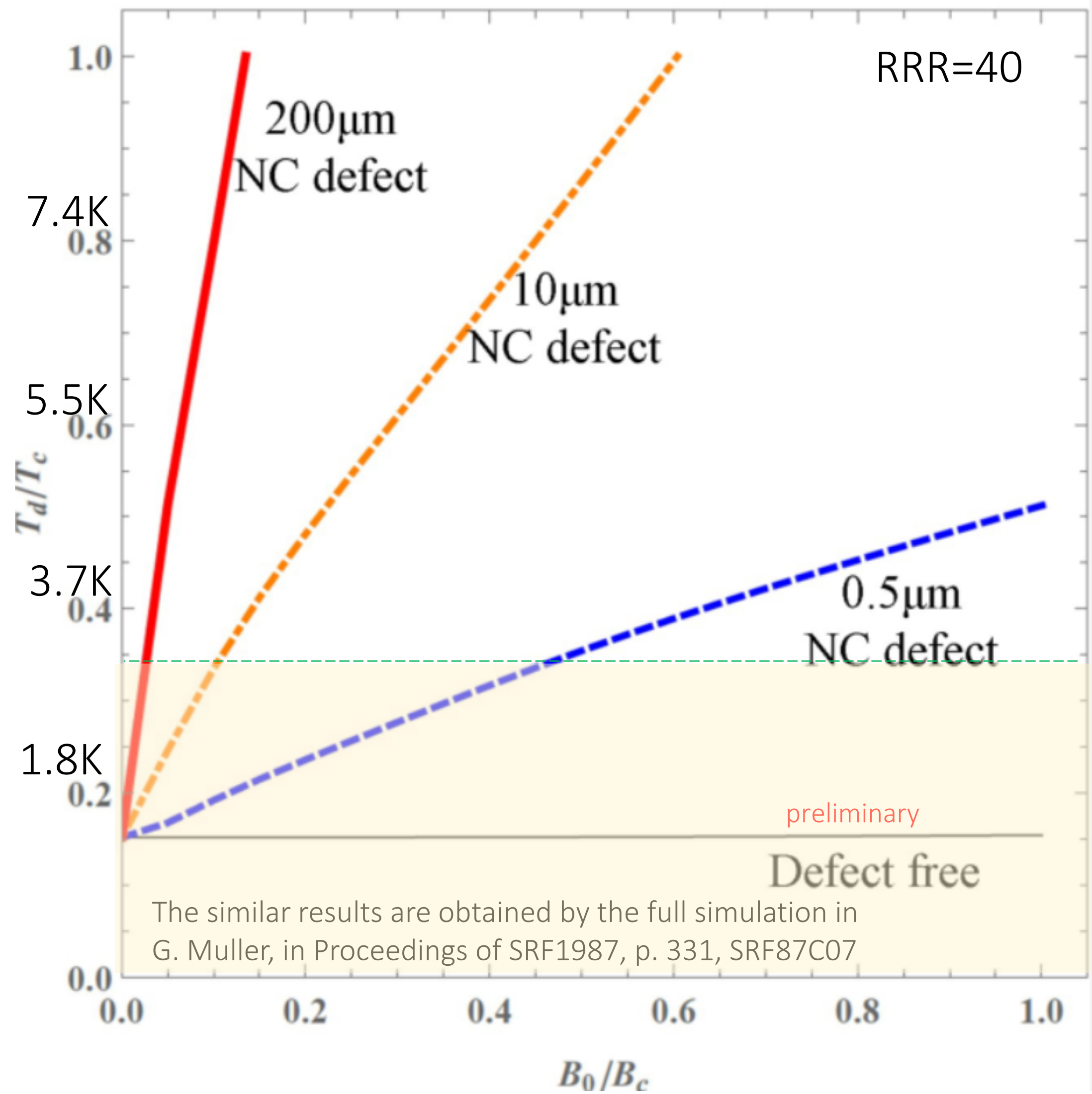
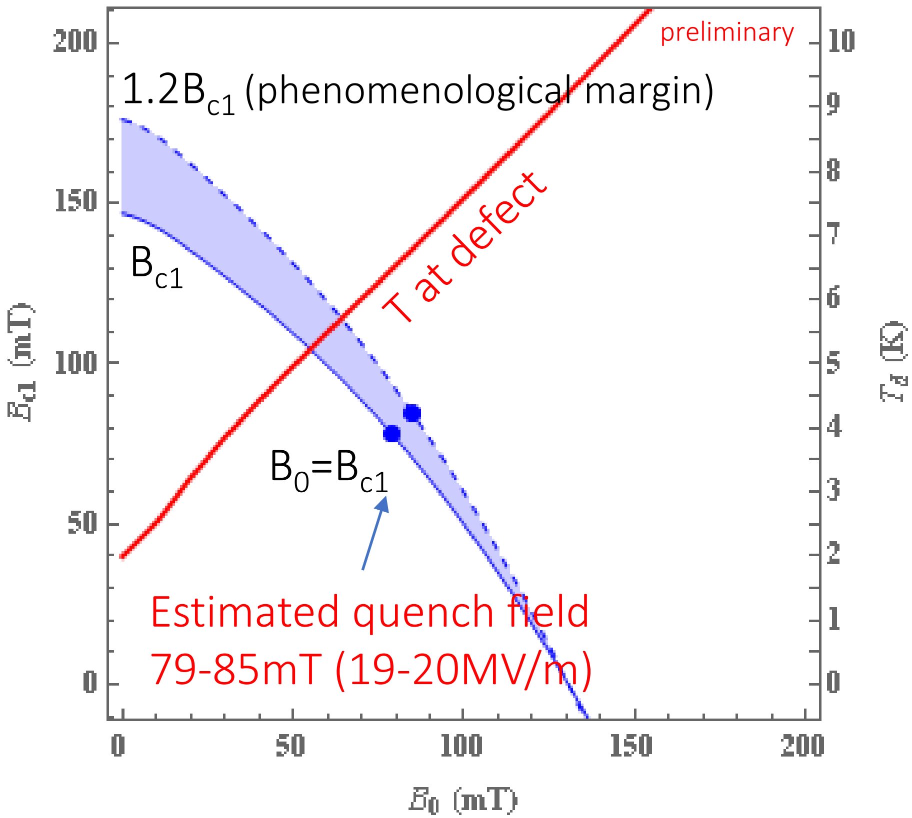
To fight against defects, thermal conductivity needs to be improved, too, resulting in
→ RRR to be as high as possible.





Here we should remind that H_{c1} decreases as the defect temperature increases.



RRR=40
with a normal defect (5µm)

At $B_0=B_{c1}(T)$, Nb material around the defect transitions from Meissner state to the vortex state. Thus dissipation would drastically increase and trigger a quench or at least a sudden Q drop at this field: rough estimate of quench field.
Here we call this field as "estimated quench field".

The results are insensitive to whether phonon peak exists or not.
[Phonon peak can change only the T behavior (red curve) at T<3K]

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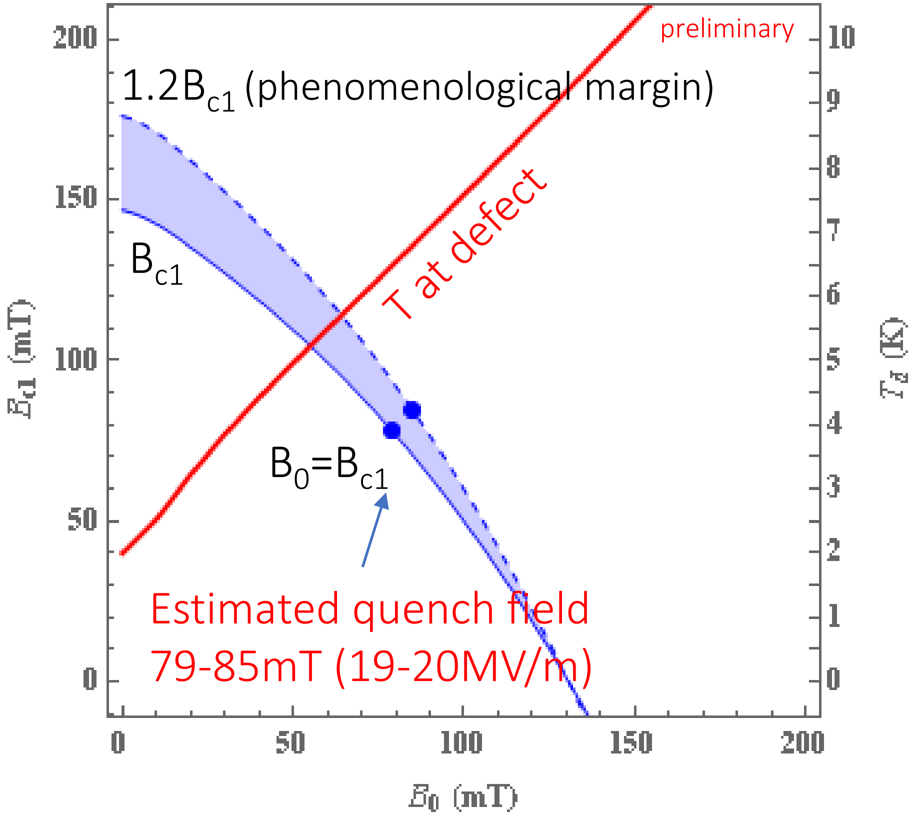

RRR=40
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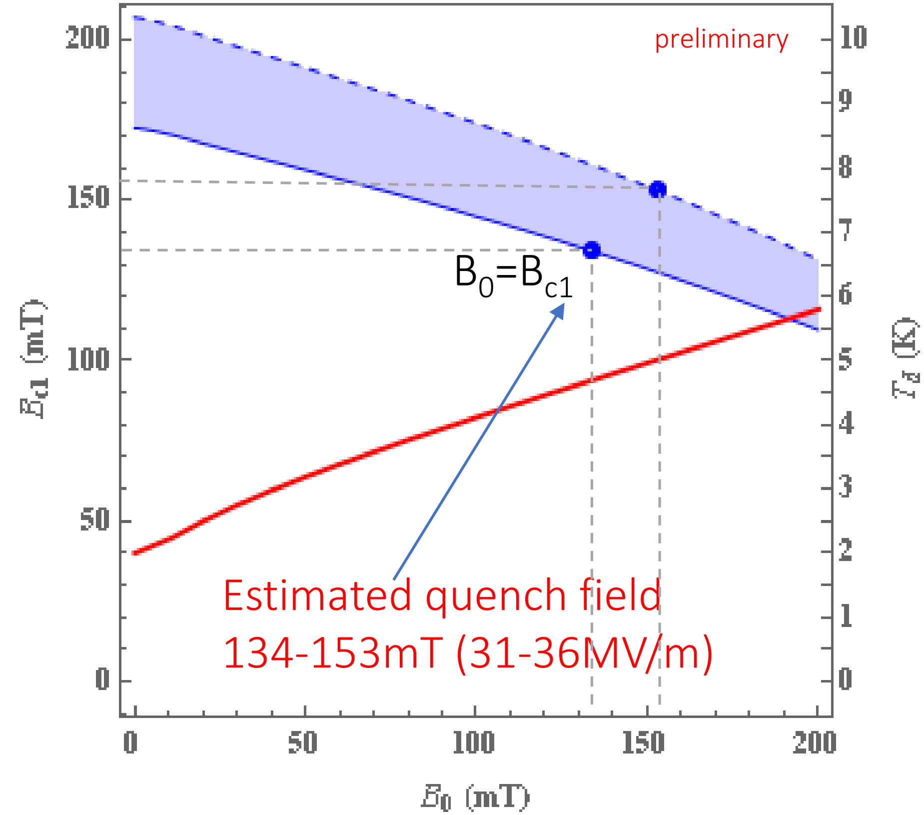
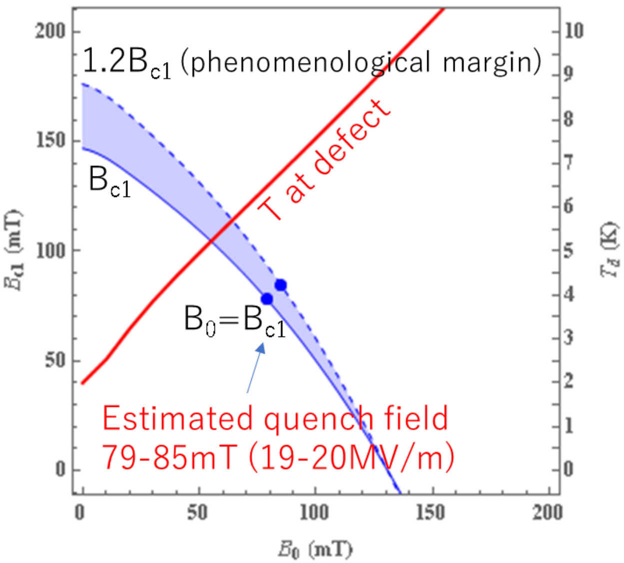


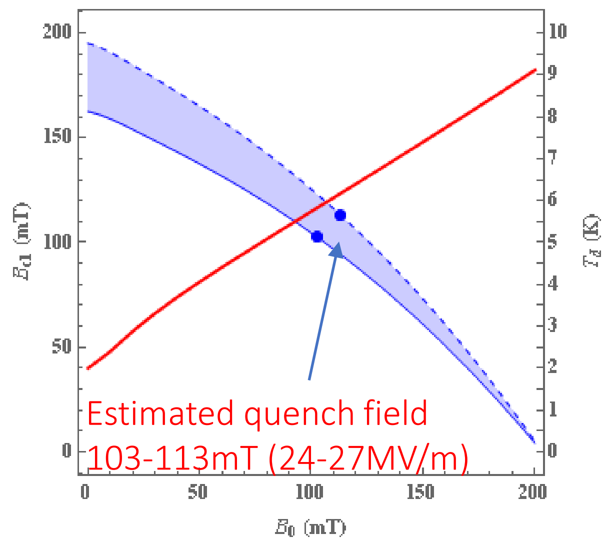
RRR=400
with a normal defect (5μm)

The results are insensitive to whether phonon peak exists or not.
[Phonon peak can change only the T behavior (red curve) at T<3K]

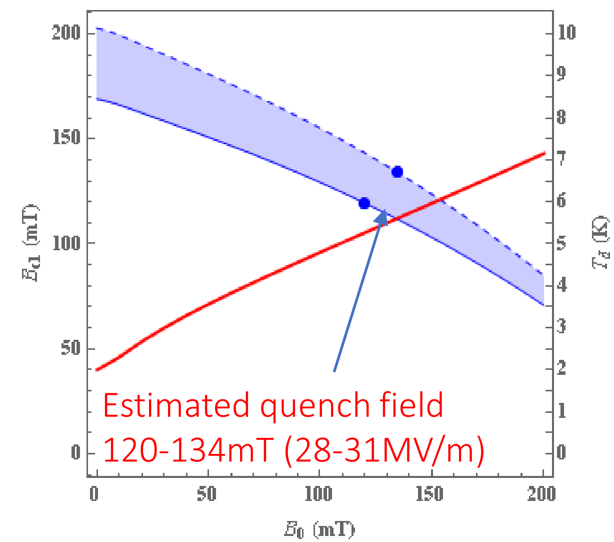
RRR=40



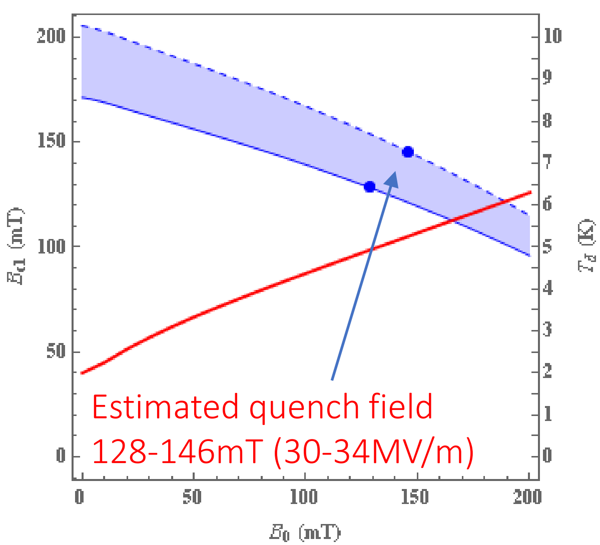
RRR=100



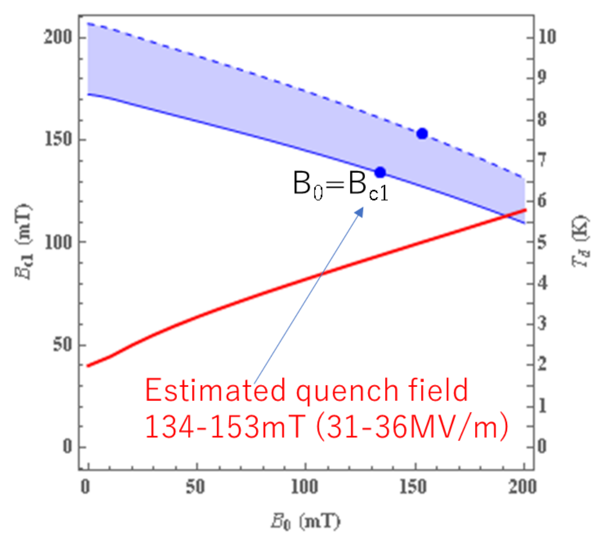
RRR=200



RRR=300



RRR=400



preliminary

RRR	Bq [mT]	Eq [MV/m]
40	79~85	19~20
100	103~113	24~27
200	120~134	28~31
300	128~146	30~34
400	134~153	32~36

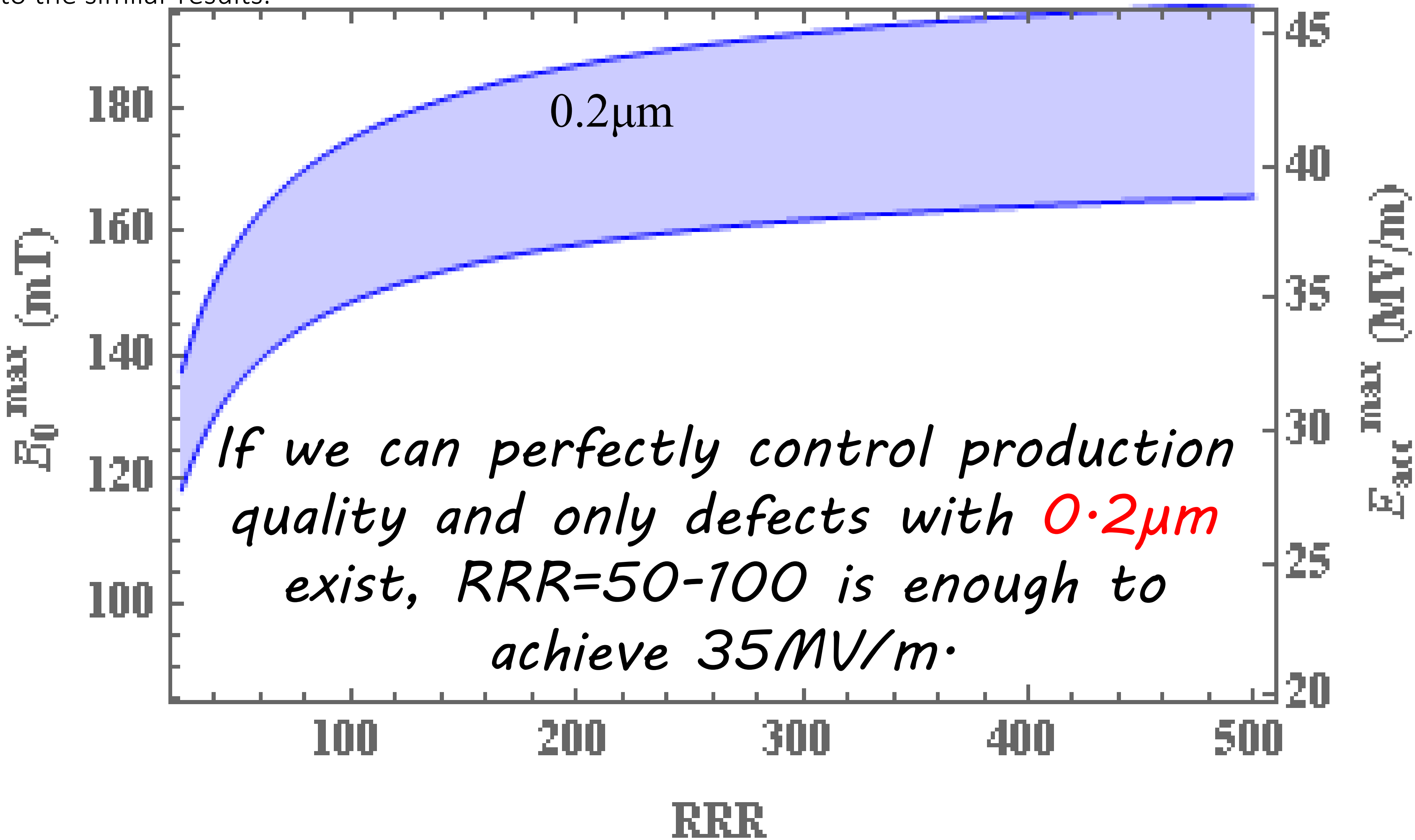
A normal defect size of 5 um is assumed

The results are insensitive to whether phonon peak exists or not.

[Phonon peak can change only the T behavior (red curve) at T<3K]

Estimated quench field as functions of RRR and normal defect size

Other heat sources with the same amount of dissipation as normal defect with the sizes shown here also lead to the similar results.



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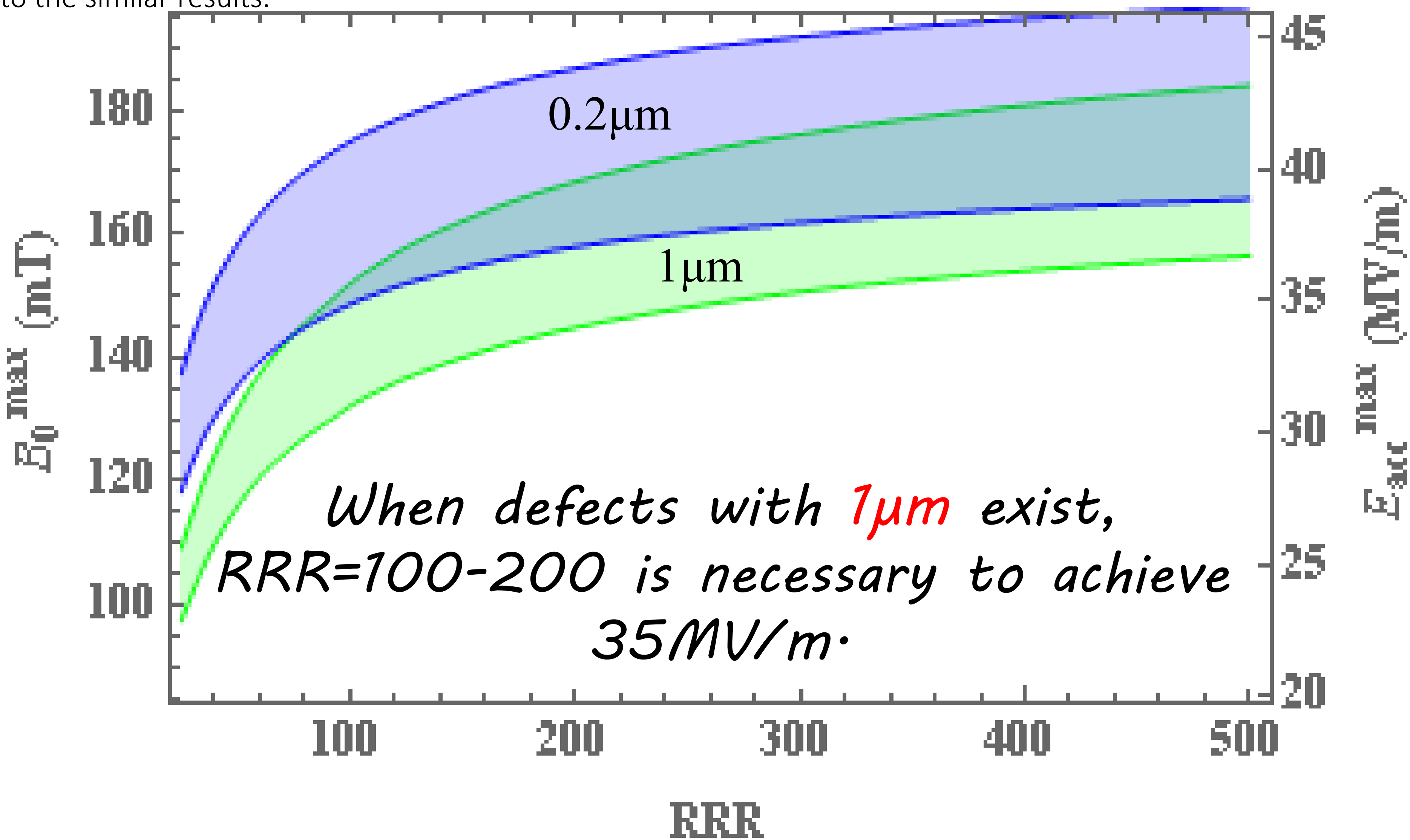

When defects with 1μm exist, RRR=100-200 is necessary to achieve 35MV/m.

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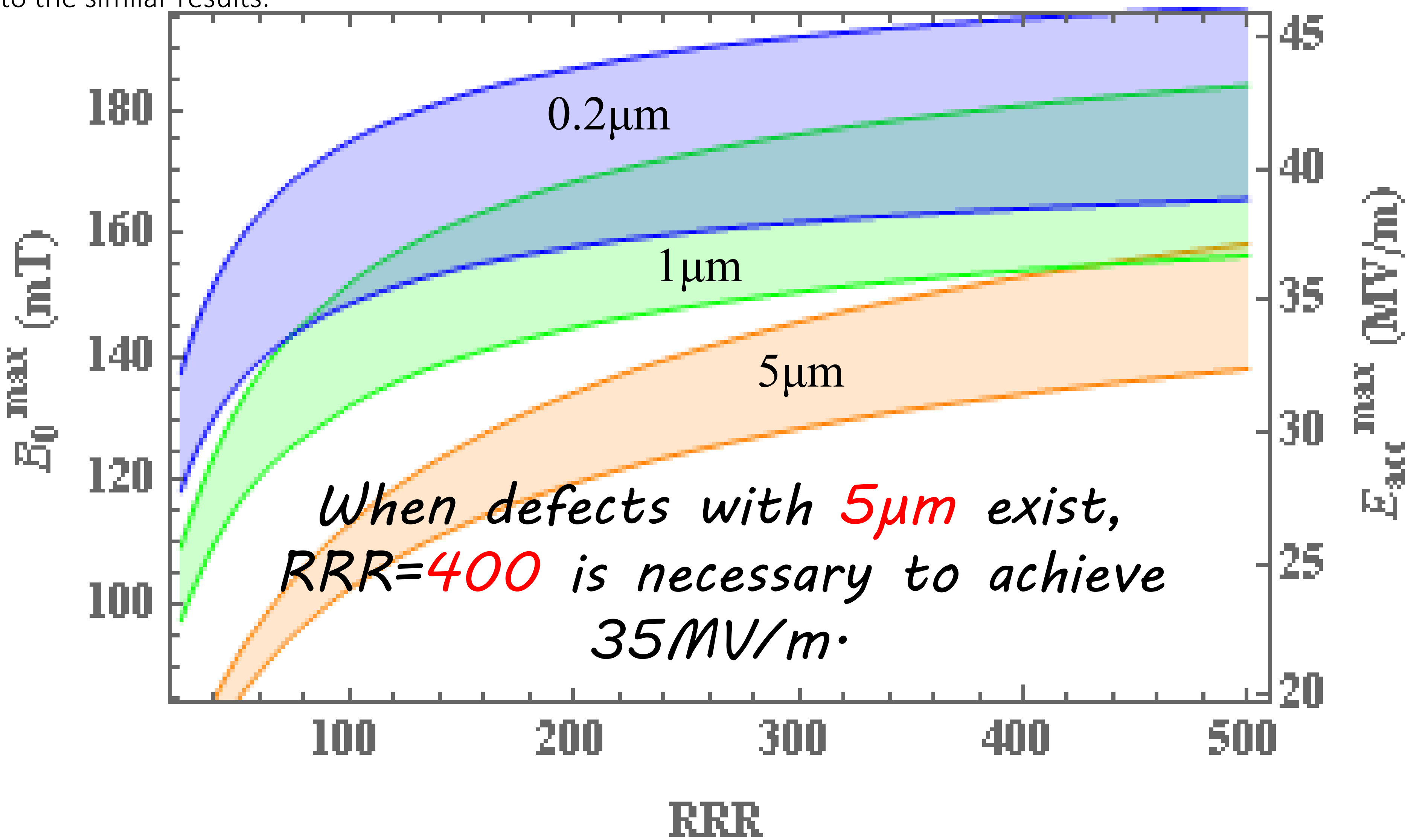

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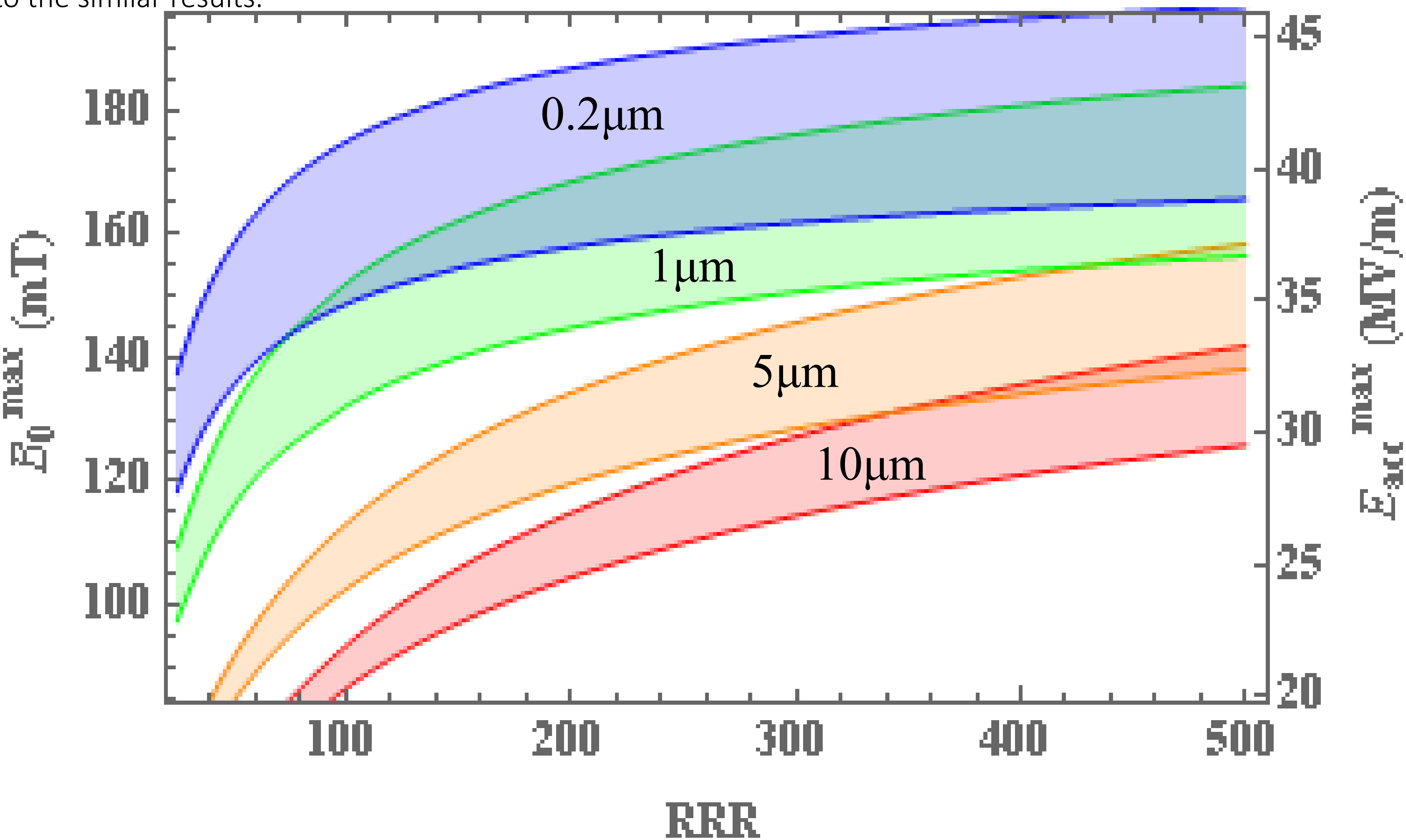


Summary

- As shown theoretically and experimentally, the ILC spec can be achieved by RRR>100-cavities, but a defect prevents achieving ILC spec, where the phonon peak does not play an important role.

- In general, there always exist defects that can be additional heat sources. For example, when a 5μm normal defect exists as shown in the last page, a RRR=300-cavity may achieve 30-34MV/m, but a RRR=200-cavity cannot: this defect is acceptable for RRR=300, but unacceptable for RRR=200.

- If we decrease RRR, a defect that we have not needed to care about so far newly becomes a cause of quench below the ILC spec, regardless of whether the phonon peak exists or not.

- Thus, naively, we can expect the probability of cavity exceeding ILC spec would deteriorate as we decrease RRR.

Yet you may need to reduce RRR for the project!
What is the necessary RRR?

- As shown in the final figure, it depends on the defect size, namely, our quality control! If you reduce RRR, you need improvement of cavity fabrication technologies to offset the increasing risk of quench due to RRR degradation.

- Comment: Remind phonon peak can suppress the T increase if T<3K. In a case that a defect is very small and always remains T<3K, LG with phonon peak would further suppress T increase and H_{c1} degradation than FG. Thus when we want to achieve a very high field >40MV/m, LG with phonon peak is superior to FG. This superiority will be discussed somewhere else.

Appendix

H_{c1} of Nb as functions of RRR

The GL formula for H_{c1} at <u>T~Tc</u> is given by

$$B_{c1} = h(\kappa_{\rm GL}) B_c \qquad h(\kappa_{\rm GL}) \equiv \frac{\ln \kappa_{\rm GL} + C(\kappa_{\rm GL})}{\sqrt{2}\kappa_{\rm GL}}, \qquad C(\kappa_{\rm GL}) = 0.5 + \frac{1+\ln 2}{2\kappa_{\rm GL} - \sqrt{2} + 2}.$$

E. H. Brandt, Phys. Rev. B 68, 054506 (2003)

This formula is not applicable at T<<Tc. So I introduce the following trick.
Since B_c does not vary with a density of nonmagnetic impurities, we can write

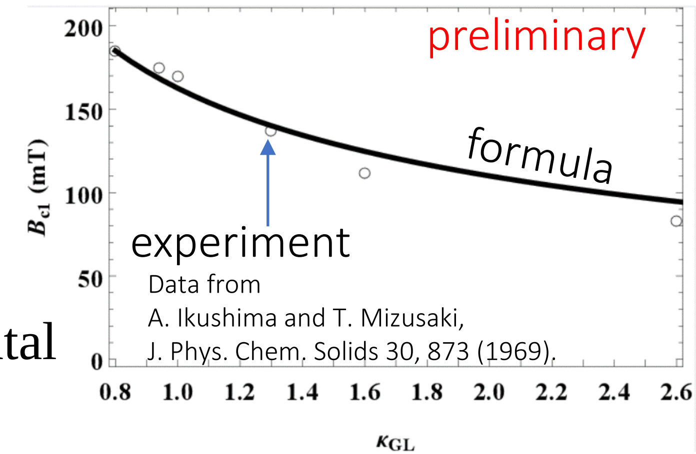
$$B_c = B_{c1}/h(\kappa_{\rm GL}) = B_{c1}^{\rm clean}/h(\kappa_{\rm GL}^{\rm clean})$$

Then we obtain the extrapolation formula

$$\boxed{B_{c1}(\kappa_{\rm GL}, 0) \simeq \frac{h(\kappa_{\rm GL})}{h(\kappa_{\rm GL}^{\rm clean})} B_{c1}^{\rm clean}(0)}$$

Temperature

This extrapolation formula agrees well with experimental data at the parameter region that we are interested in.



The next task is to express $\kappa_{\rm GL}$ with mfp. This is obtained long years ago by Gorkov: the relation between BCS and GL. We have

$$\boxed{\kappa_{\rm GL}(\ell) = \frac{7\zeta(3)}{\pi^2} \frac{a_{\rm imp}}{\Lambda(a_{\rm imp})} \kappa_{\rm GL}^{\rm clean},}$$

$$\Lambda(a_{\rm imp}) \equiv \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2[(2n+1)a_{\rm imp}^{-1} + 1]} = 1 - \frac{4}{\pi^2 a_{\rm imp}} \left[\gamma_E + \ln 4 + \psi\left(\frac{1+a_{\rm imp}}{2}\right)\right],$$

$$a_{\rm imp} \equiv \frac{\pi}{2e^{\gamma_E}} \frac{\xi_0}{\ell} \simeq 0.882 \frac{\xi_0}{\ell}, \qquad \kappa_{\rm GL}^{\rm clean} = \frac{2e^{\gamma_E}}{\pi} \sqrt{\frac{6}{7\zeta(3)}} \frac{\lambda_L^{\rm clean}(0)}{\xi_0} \simeq 0.957 \frac{\lambda_L^{\rm clean}(0)}{\xi_0},$$

The final task is to express mfp with RRR.

mfp= $(3.7 \times 10^{-16}\, \Omega \cdot {\rm m}^2)/\rho_n$
= RRR × 2.55nm

B. B. Goodman and G. Kuhn, J. Phys. Paris 29, 240 (1968)

Using $\rho_n \simeq {\rm RRR}^{-1} \times \rho_n(295\,{\rm K}) \simeq {\rm RRR}^{-1} \times 1.45 \times 10^{-7}\, \Omega \cdot {\rm m}$

preliminary