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Pathway to High Gradients in Superconducting RF Cavities by Avoiding Flux Dissipation

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Outline

- Current belief -> superheating field is the limit of SRF cavity gradients and that's why best cavities can go beyond Hc1 (surface barrier helps)
  - Can there be another interpretation?

- Potential alternative I suggest -> vortex nucleation/dissipation time is longer than the rf period -> cavities go above Hc1 because of that
  - Gives an exciting possible direction for advancing gradients

Some key experimental facts

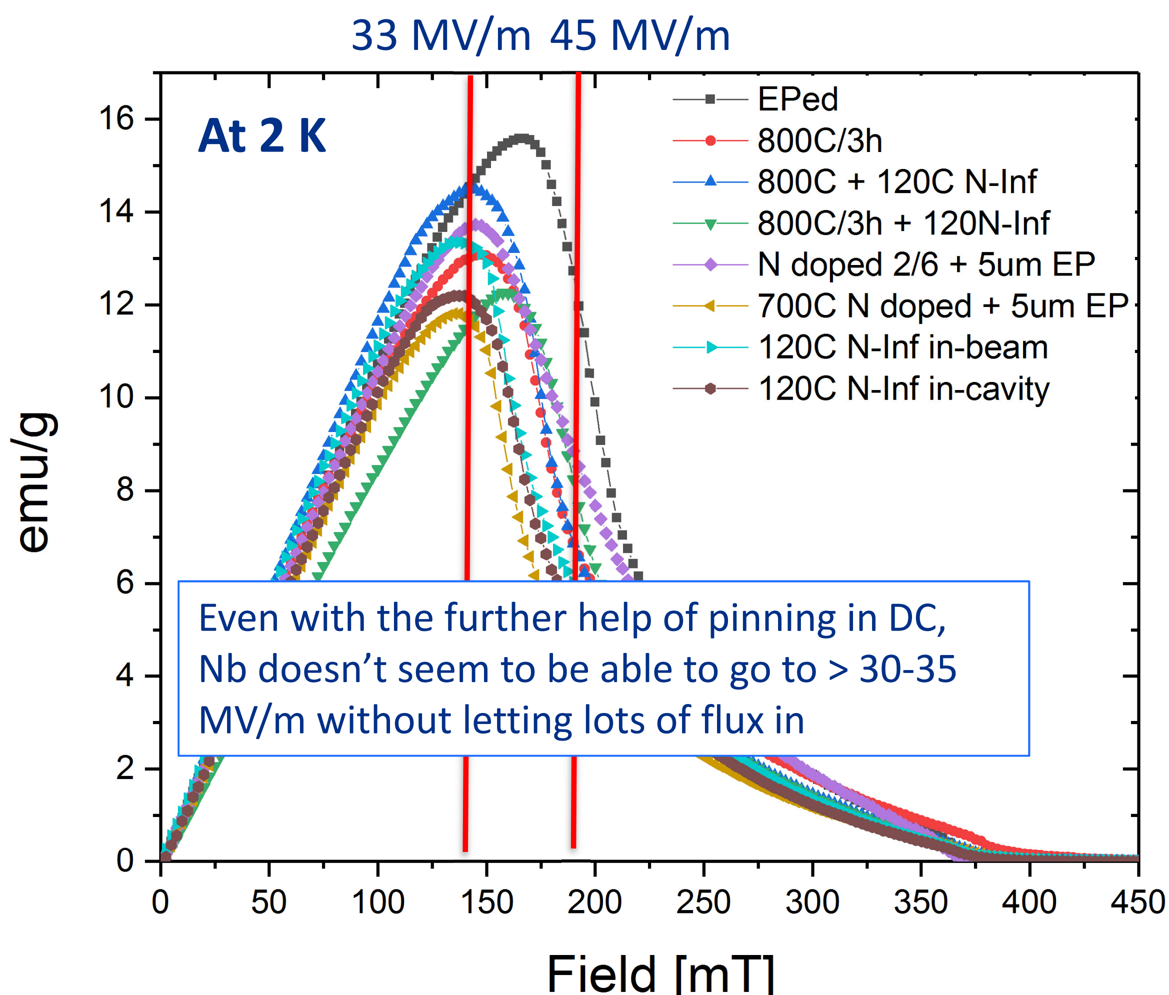
- All state-of-the-art cavities are limited by the localized quench
- Some klystron studies on BCP and EP cavities suggested a possible “global” transition
  - However, the cavities studied were HFQS limited -> observation of all hydrides going normal?
- DC fields of the first flux penetration measured on niobium samples are lower than maximum RF fields in cavities
  - More on this later

Current view of the "fundamental" gradient limit

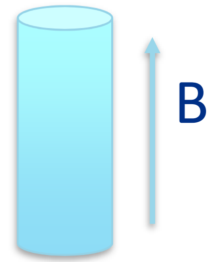
- DC superheating field is the "fundamental" limit
  - NB: has no direct proof
- Lots of recent theoretical calculations of DC superheating fields
- Exploring materials with higher Hsh than Nb (Nb3Sn, MgB2 etc)
- Various suggestions to improve DC Hsh
  - Multi (or single layers) of higher Hsh superconductor on top of Nb
  - Dirty layer on top of clean
- **However – is it the only promising way for pushing the gradients?**
  - **My answer is NO**

PPMS Magnetization Studies

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



H_p & $H_{c,\,peak}$ from the curve

Treatment	H_p, onset [mT]*	Hc, peak [mT]**
TD bulk EPed	120	170
800C/3hrs	100	150
800C + 120C N infusion	110	145
800C/3h + 120C/48h N infusion	115	160
N-doped 2/6, 800C/6h+N2/2m 25mT + 5um EP	105	145
800C/3h+700C/10m+700C/2m N2 + 700C/6m HV	105	135
Nb 120C Infusion, in beam tube	105	140
Nb 120C Infusion, in cavity	110	140

** Onset of Flux Penetration (Hp), defined as the first deviation point from the linearity from H = 0 mT, at 2K.*

*** $H_{c,\,peak}$: the peak value after H_p, at 2K*

Data by Z. Sung

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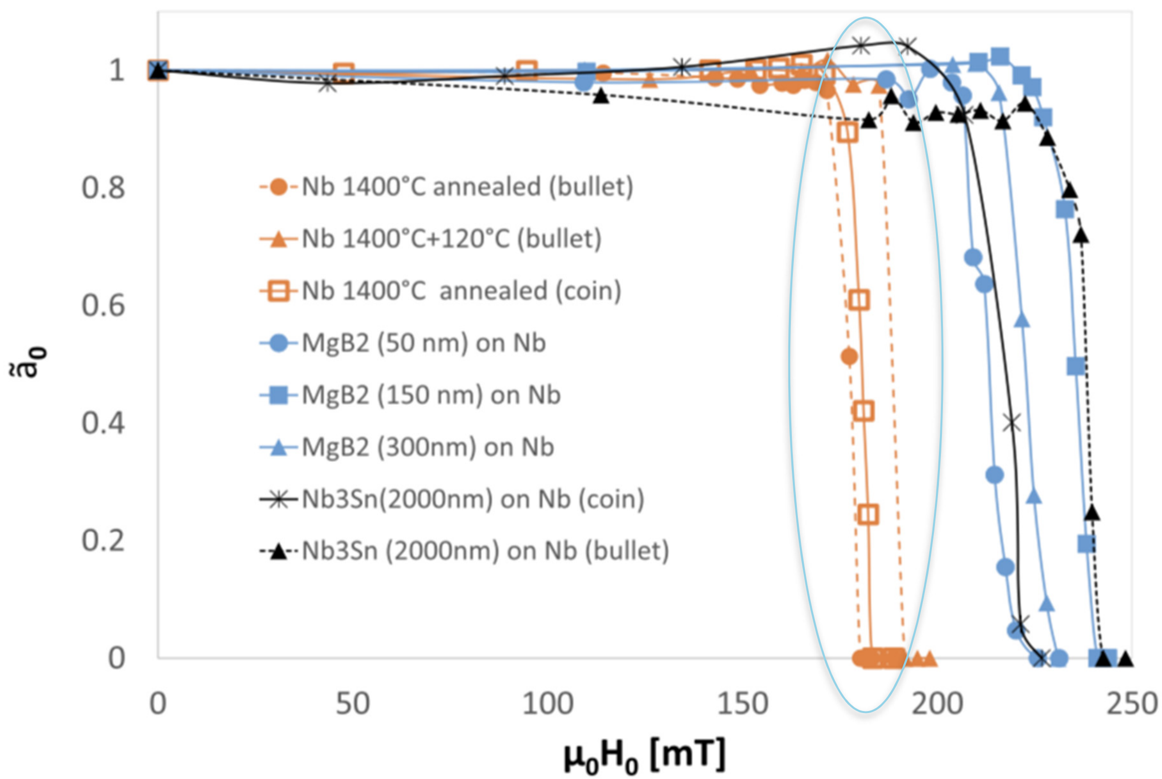
muSR studies



With the minimized pinning contribution: Maximum fields of first penetration are <~170 mT (2K) -> <~39 MV/m

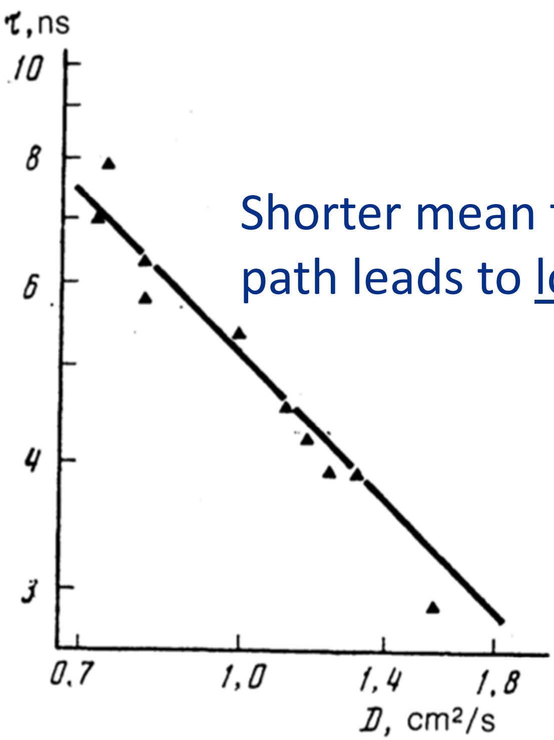
T. Junginger *et al*, 2017 *Supercond. Sci. Technol.* **30** 125012
T. Junginger et al, Phys. Rev. Accel. Beams, **21**, 032002 (2018)

- So how are current cavities reaching Eacc = 45 MV/m then?

I suggest another key mechanism is at play

- In addition to surface barrier (superheating) there is a "time barrier"
  - There should be enough time for vortices to nucleate/dissipate
- 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 <u>gapless</u> 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**

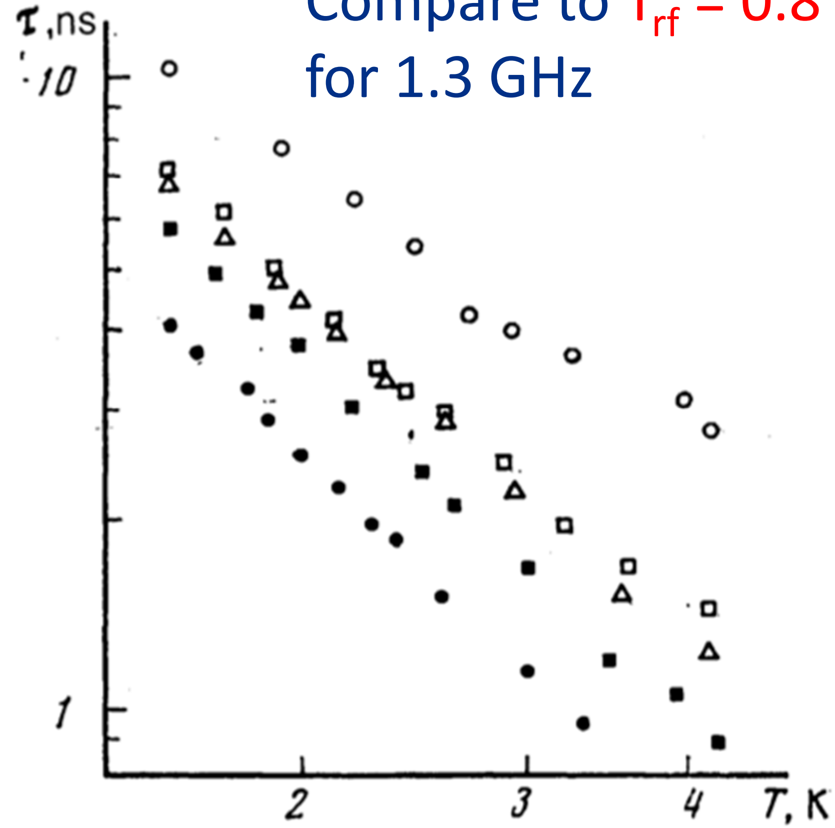
Experimental observations of gap relaxation time in Nb



Shorter mean free path leads to <u>longer</u> 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



If it is true, how else can we push the gradients then?

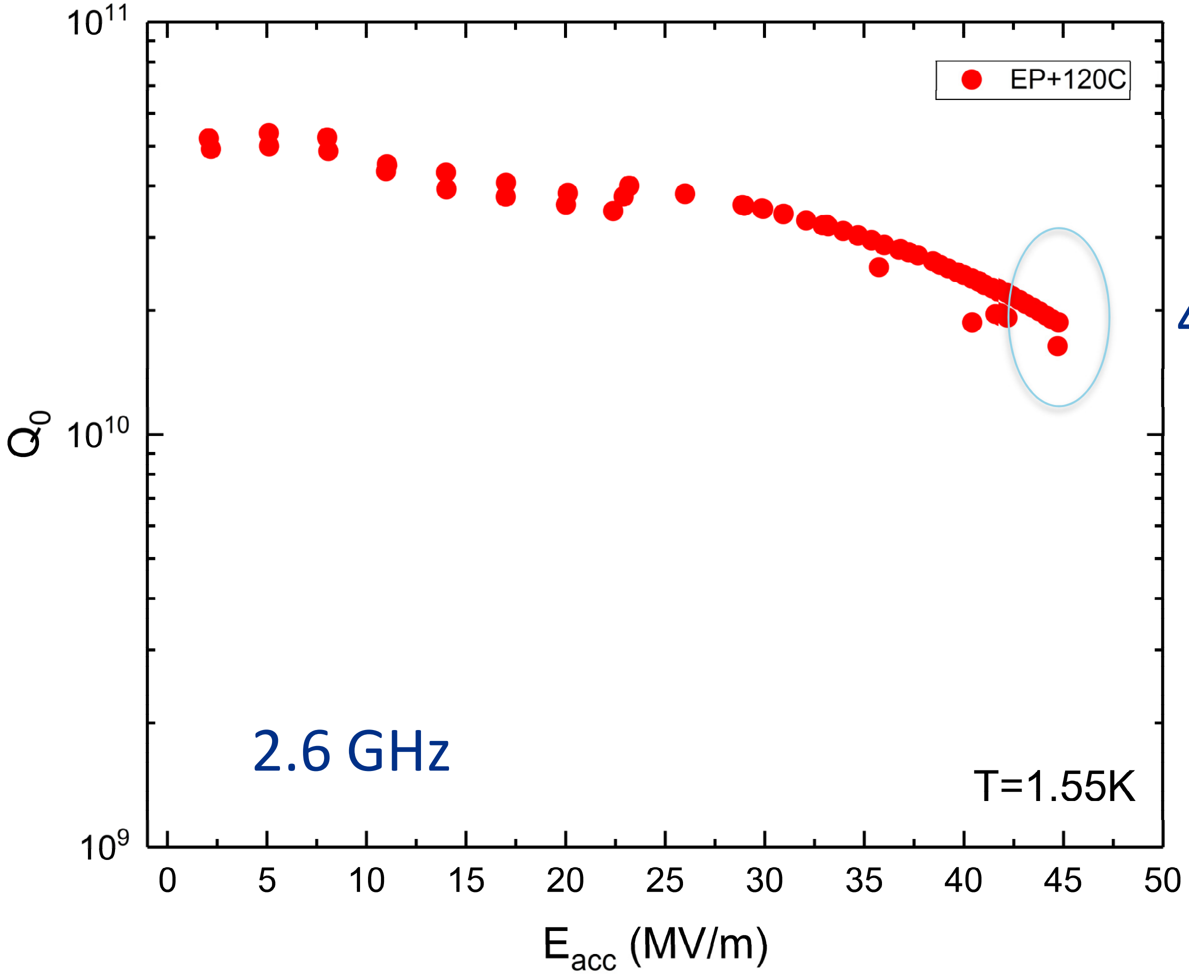
- Plenty of new opportunities!
  - Clean Nb Hc2 is ~100 MV/m, dirty is higher

- Increase frequency

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

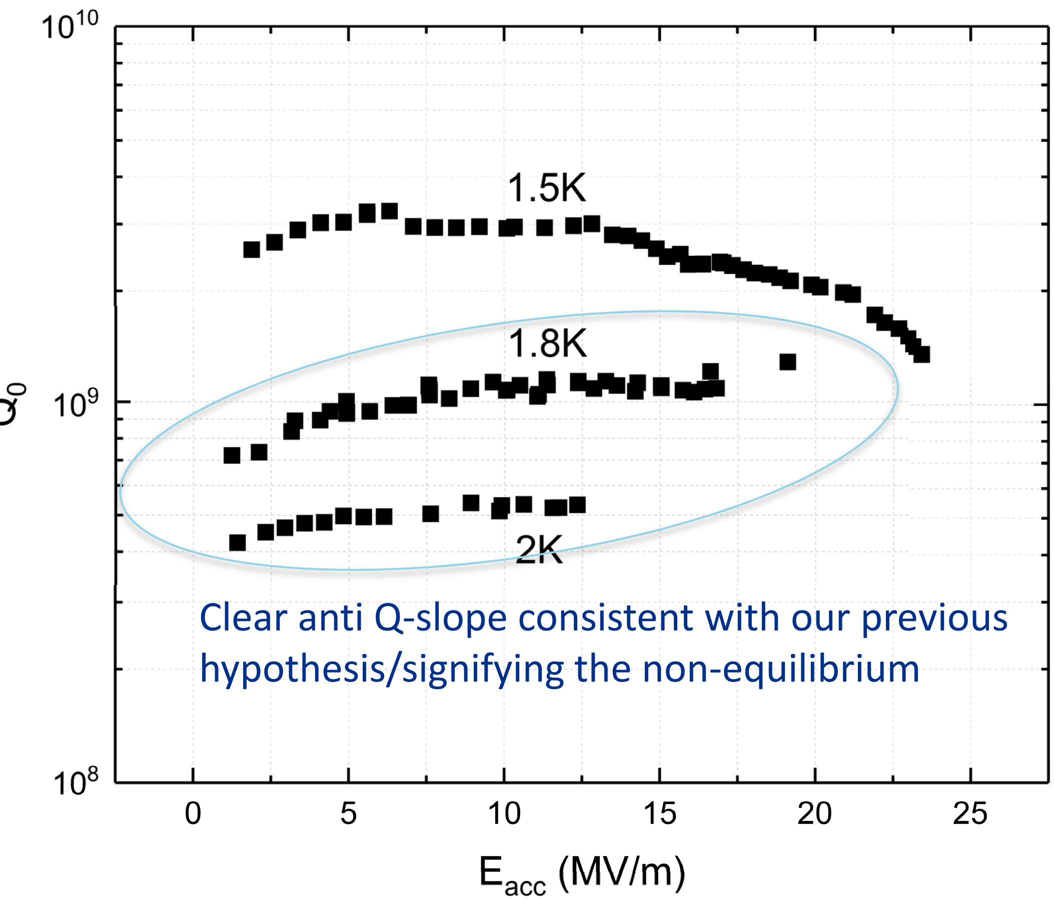
- Use “slower” (longer $\tau_{e\text{-}ph}$ scattering times) superconductors

Increasing frequency + state-of-the-art gradient treatment



46 MV/m!

9 GHz EP cavity – first measurements



No quench limit reached yet, all curves power-limited by the 1W amplifier available for this frequency range

A. Romanenko, LINAC’14, TUIOC02
M. Martinello et al, https://arxiv.org/pdf/1707.07582.pdf

M. Martinello, IPAC’18, THZGB4 – come see the latest

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So 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

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

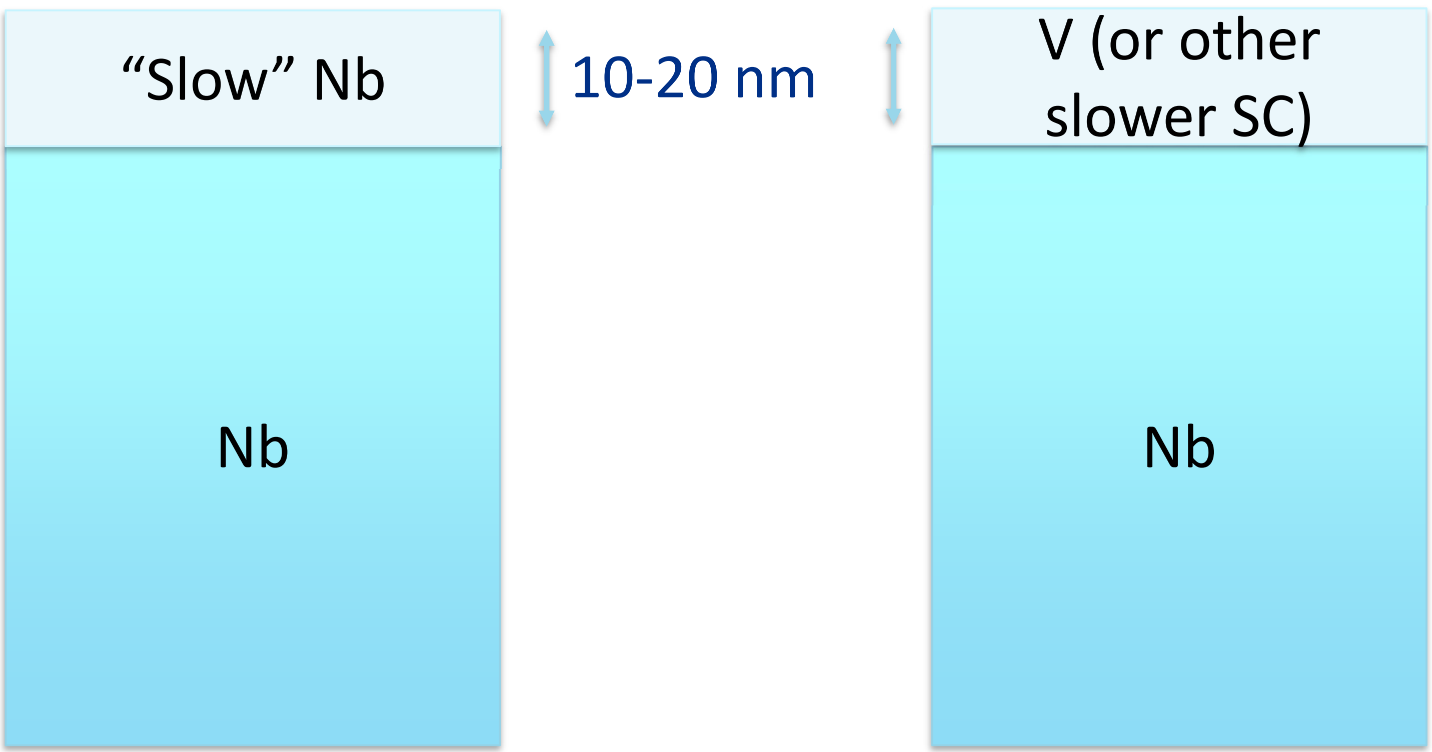
A15 are not good –too "fast"

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 slow superconductor should help too!

Option 1 | Option 2



Is it how 120C baking enables Hrf >> Hc1?

Explore techniques for lower Tc SC deposition

Summary

- Superheating due to surface barrier is one side of the coin, but not having enough time for vortices to form/dissipate is another promising direction
- Correct theory for a gapped superconductor suggests “time barrier” role in achieved fields may be a dominant factor
- 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