Layered iron-based superconductors for SRF cavities

Akira Miyazaki

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Outline

- Iron-based SC and recent applications
- Iron-based SC for SRF?
- Surface resistance of Iron-based SC
- ML theory for Iron-based SC
- Remarks
- Conclusion

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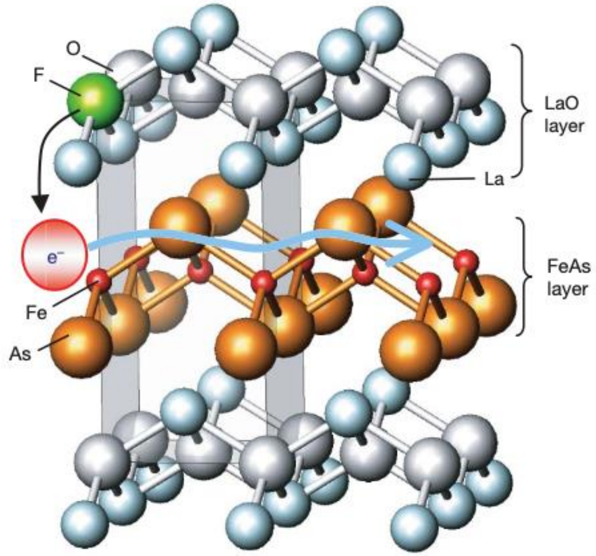
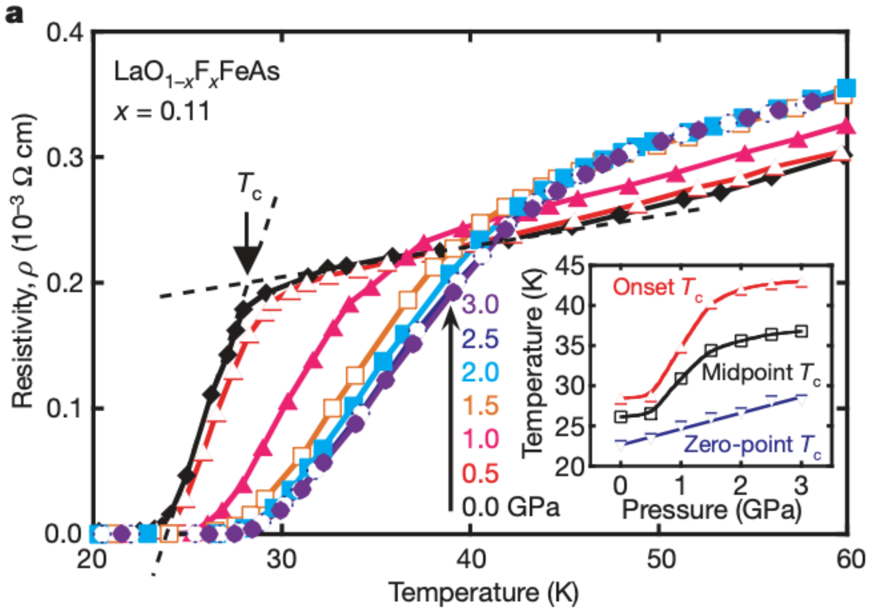
Iron-based superconductors

LaOFeAs





Y. Kamihira et al J. Am. Chem. Soc. 30, 3296-3297 (2008)
H. Takahashi et al, Nature 453, pages 376–378 (2008)

Hideo Hosono

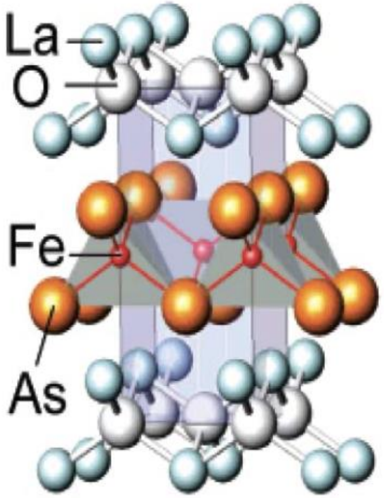
- Iron-based superconductors were discovered by the team in Tokyo Institute of Technology (currently: Institute of Science Tokyo) in 2008
- Surprising discovery: Iron is magnetic element → usually not good for SC
- Non-BCS (i.e. phonon mediation) mechanism for SC (spin / orbit??)
- Tc is higher than BCS but lower than cuprate (REBCO)

Main known Fe-based superconductors

Among them, the three phases most relevant for wire applications are 1111, 122, and 11 types with a T_c *of 55, 38 and 8 K, respectively.*

X. Zhang et al “Progress in the development of high performance pnictide wires” CEC/ICMC 2017

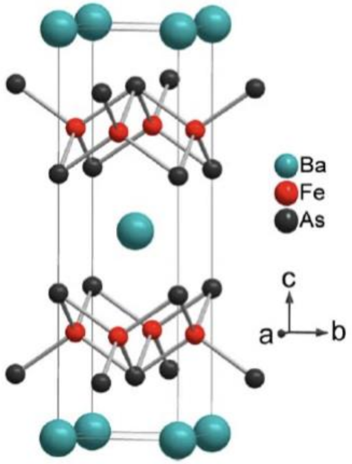
1111 Phase LnOFeAs



T_c ~55 K

Z. A. Ren et al., *Chin. Phys. Lett.* 25, 2215 (2008)

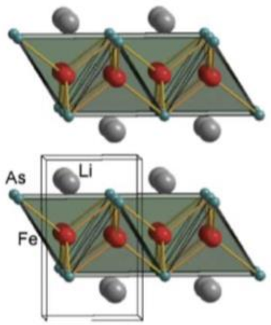
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

M. Rotter, et al., *Phys. Rev. Lett.* **101**, 107006 (2008)

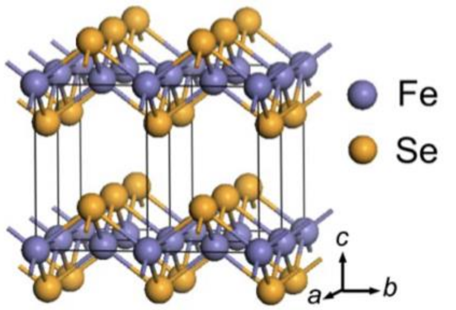
111 phase LiFeAs



T_c ~18 K

X. C. Wang, et al., *Solid State Commun*. **148**, 538 (2008).

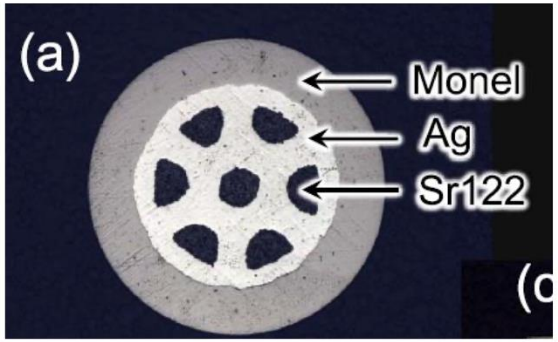
11 phase FeSe



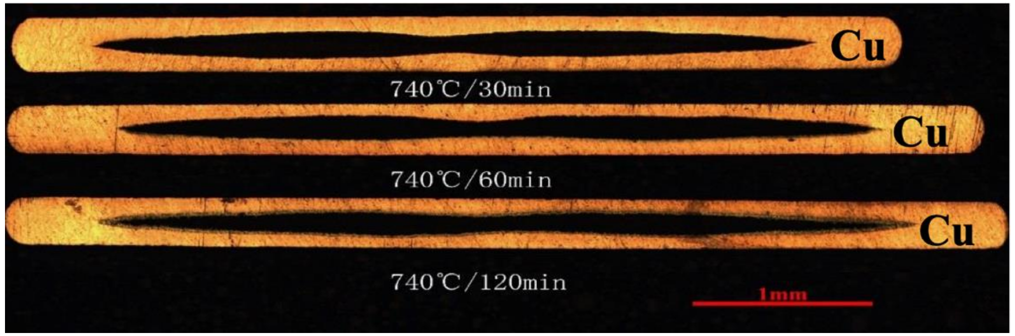
T_c ~8 K

F. C. Hsu, et al., *Proc. Natl. Acad. Sci. U.S.A.* **105**, 14262 (2008).

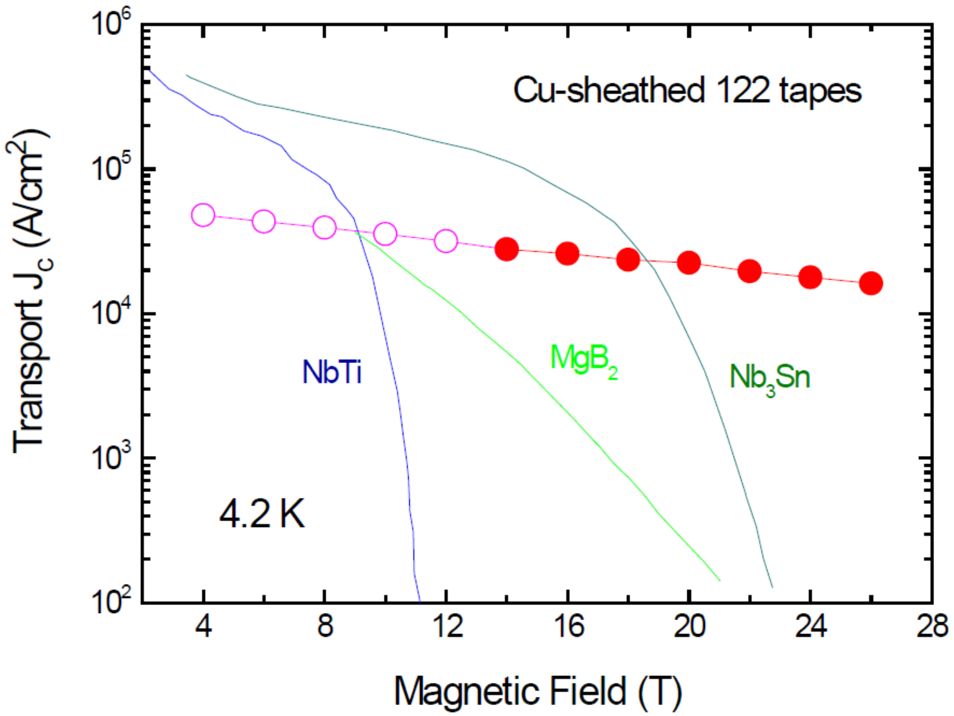
Application of Iron-based SC: Sr-122 wire

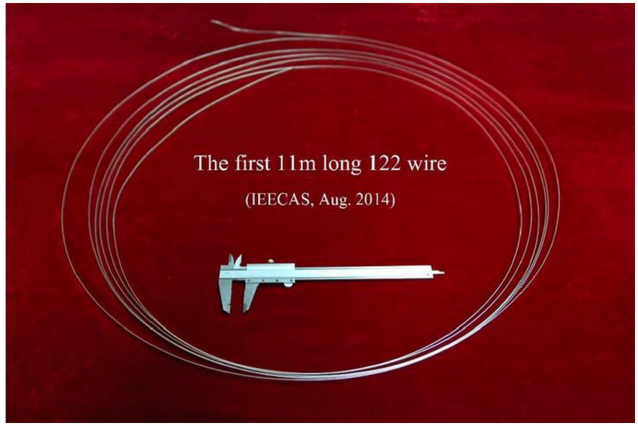


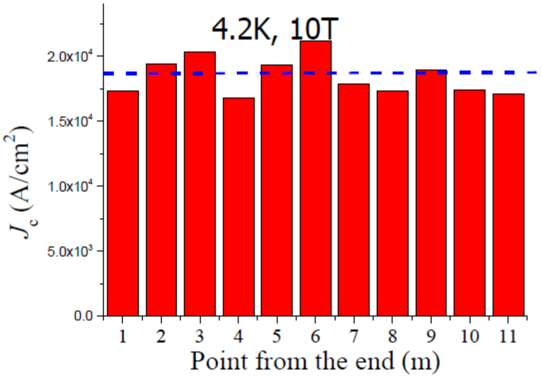
Monel/Ag, **IEECAS**



Y. Ma "Recent progress in Fe-based superconducting wires and tapes"





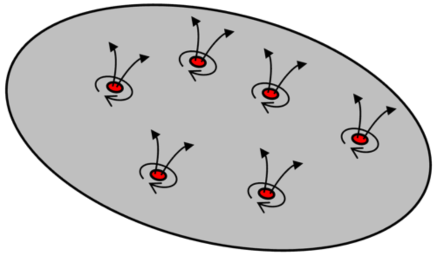


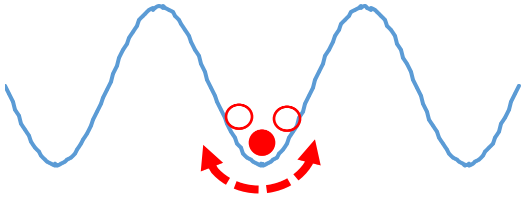
The minimum J_c ~1.7×10^{4}A/cm^2

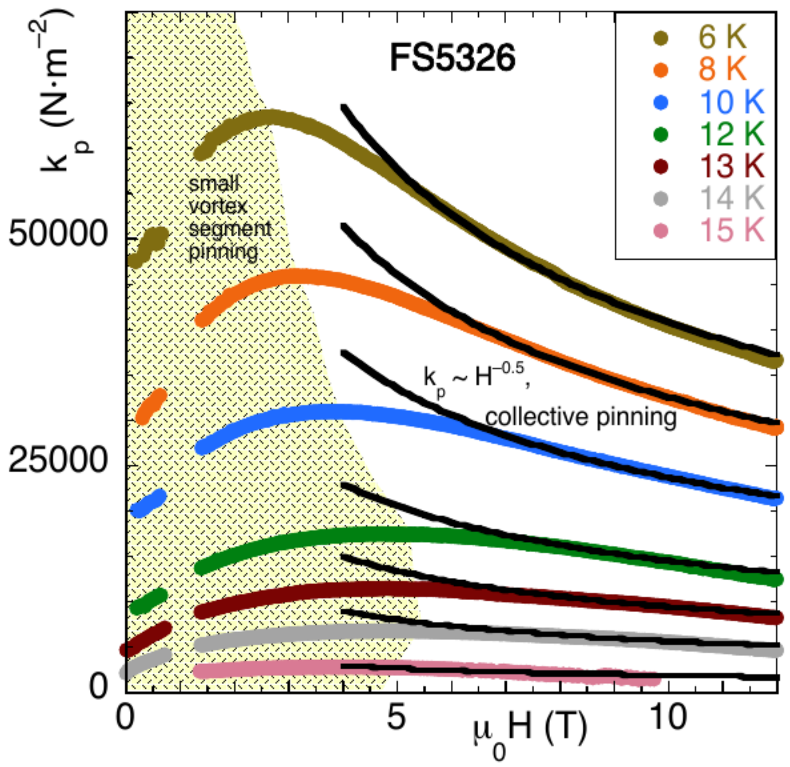
- Promising progress toward magnet applications
  - As handling in laboratory
- Market is growing → why not RF cavities as well?

Iron-based SC and RF: DM axion

$$\eta\dot{\mathbf{x}} + k_p\mathbf{x} = \mathbf{J}_{rf} \times \mathbf{\Phi}_0 + \mathbf{F}_{th}$$

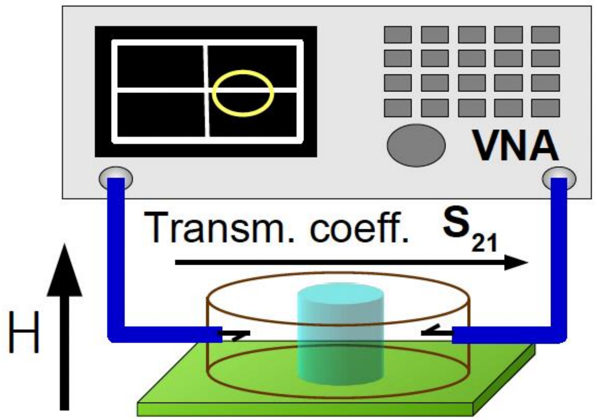




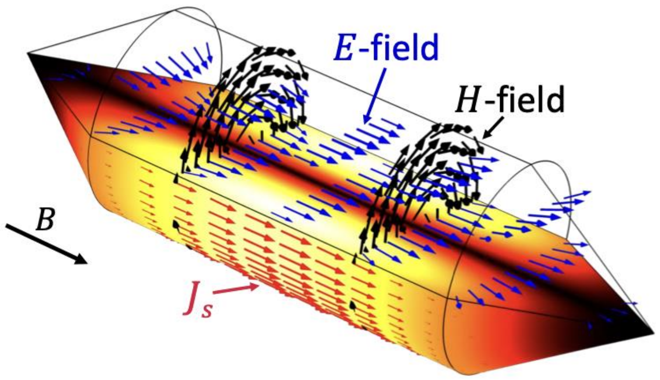


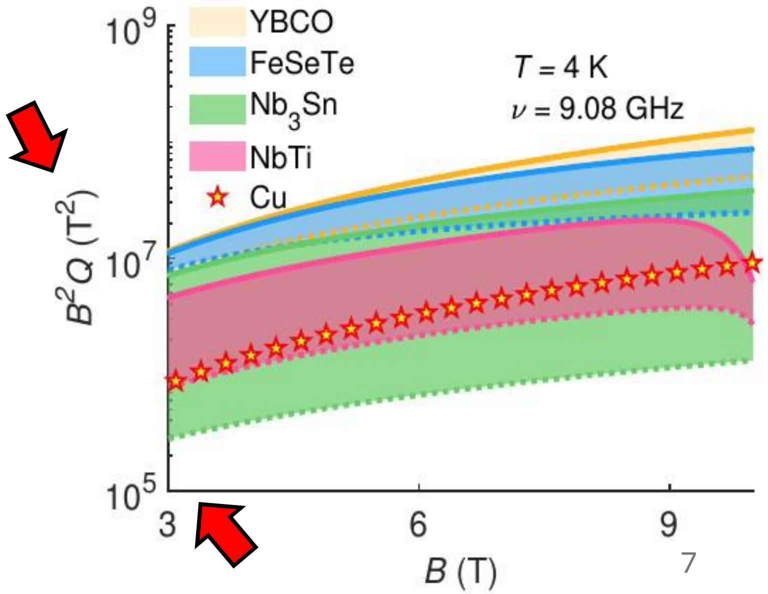
N. Pompeo TFSRF2022

Dielectric cavity for sample measurement



Sample < ϕ20 mm





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Iron-based SC for SRF cavities


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Superconductor Science and Technology

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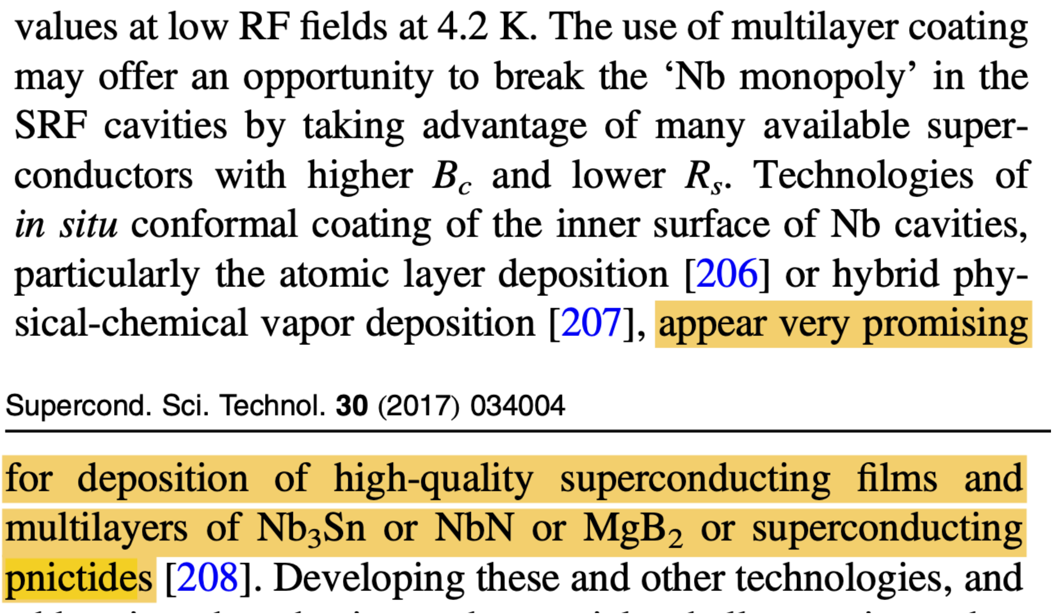
doi:10.1088/1361-6668/30/3/034004

Theory of RF superconductivity for resonant cavities

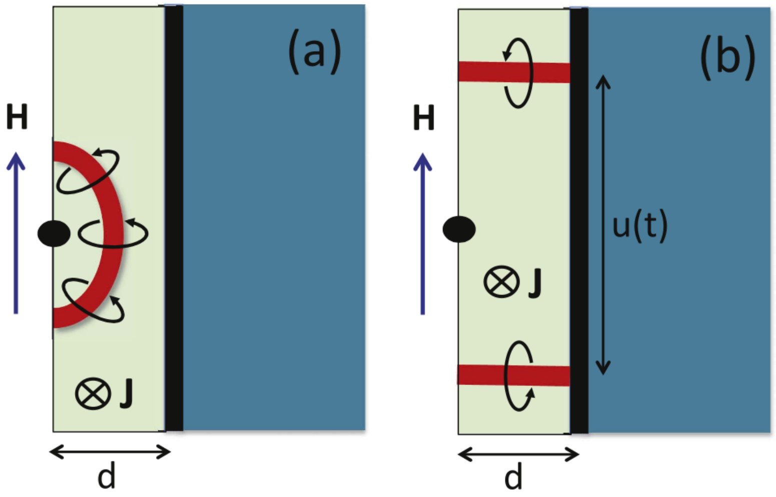
Alex Gurevich

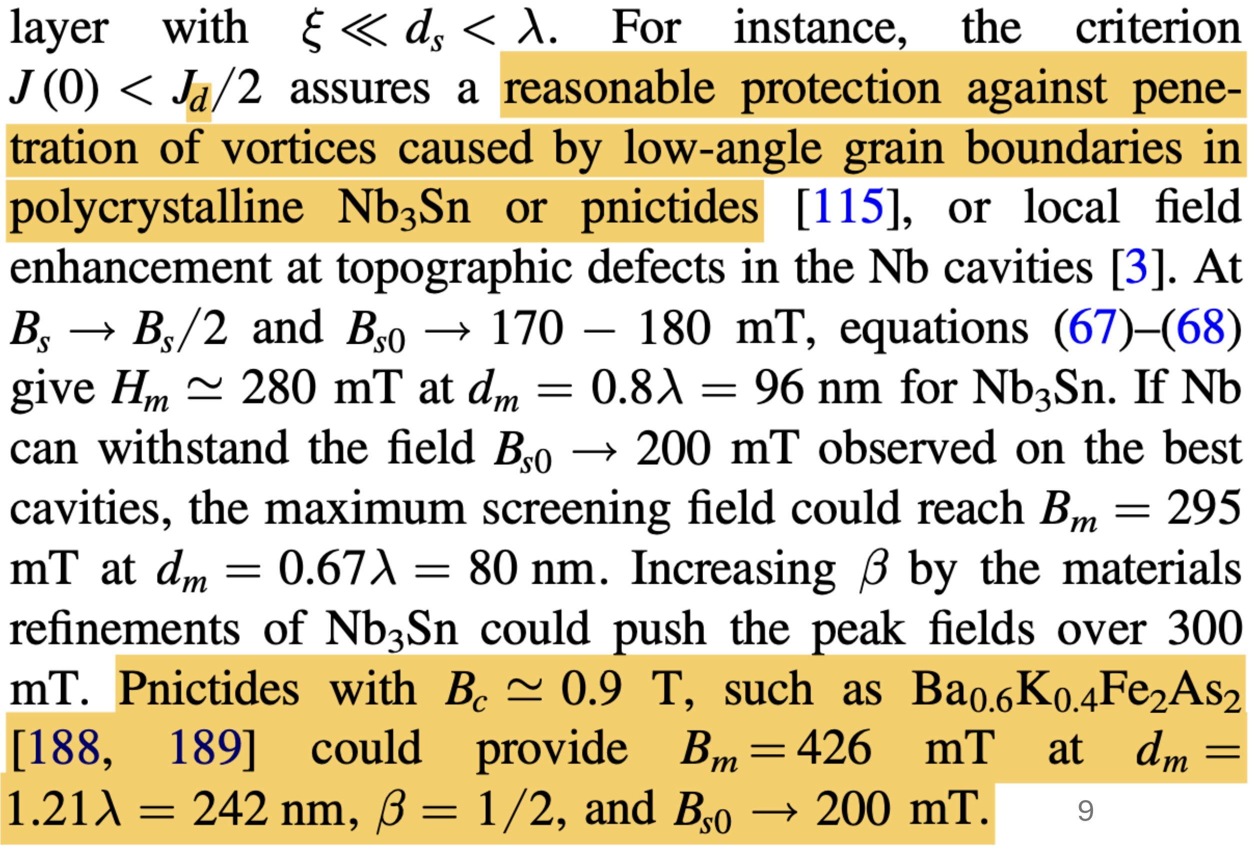
Department of Physics and Center for Accelerator Science, Old Dominion University, 4600 Elkhorn Avenue, Norfolk, VA 23529, USA


values at low RF fields at 4.2 K. The use of multilayer coating may offer an opportunity to break the 'Nb monopoly' in the SRF cavities by taking advantage of many available superconductors with higher B_c and lower R_s. Technologies of *in situ* conformal coating of the inner surface of Nb cavities, particularly the atomic layer deposition [206] or hybrid physical-chemical vapor deposition [207], appear very promising

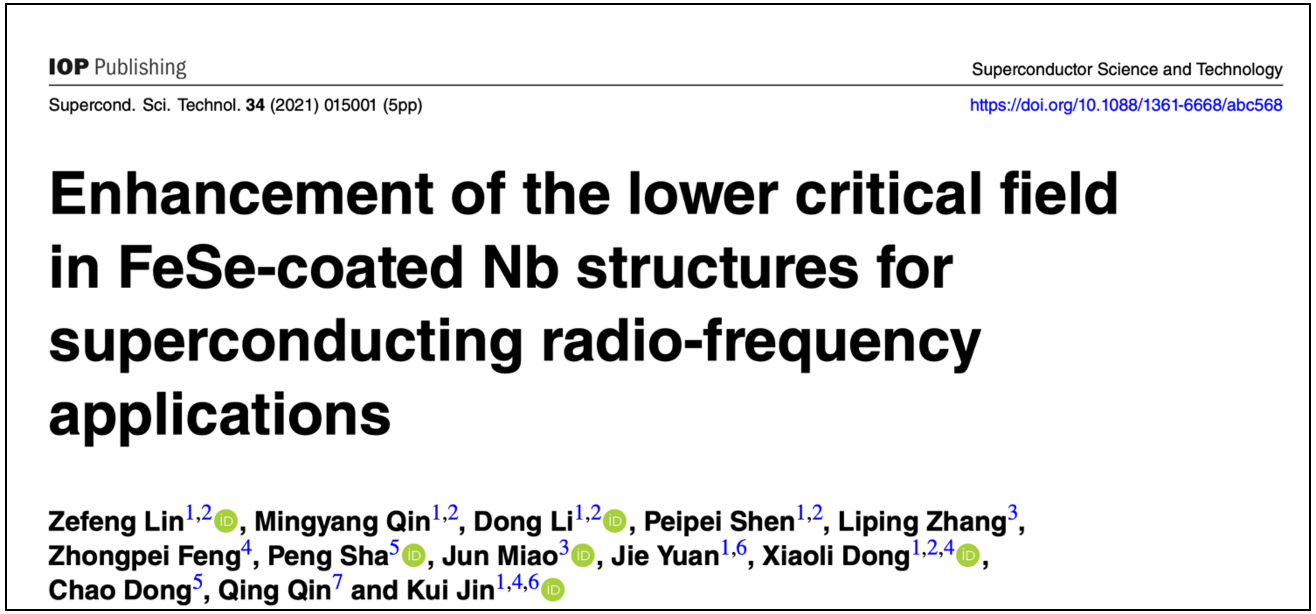
Supercond. Sci. Technol. **30** (2017) 034004

for deposition of high-quality superconducting films and multilayers of Nb_3Sn or NbN or MgB_2 or superconducting pnictides [208]. Developing these and other technologies, and




layer with $\xi \ll d_s < \lambda$. For instance, the criterion $J(0) < J_d/2$ assures a reasonable protection against penetration of vortices caused by low-angle grain boundaries in polycrystalline Nb_3Sn or pnictides [115], or local field enhancement at topographic defects in the Nb cavities [3]. At $B_s \to B_s/2$ and $B_{s0} \to 170 - 180$ mT, equations (67)–(68) give $H_m \simeq 280$ mT at $d_m = 0.8\lambda = 96$ nm for Nb_3Sn. If Nb can withstand the field $B_{s0} \to 200$ mT observed on the best cavities, the maximum screening field could reach $B_m = 295$ mT at $d_m = 0.67\lambda = 80$ nm. Increasing β by the materials refinements of Nb_3Sn could push the peak fields over 300 mT. Pnictides with $B_c \simeq 0.9$ T, such as $Ba_{0.6}K_{0.4}Fe_2As_2$ [188, 189] could provide $B_m = 426$ mT at $d_m = 1.21\lambda = 242$ nm, $\beta = 1/2$, and $B_{s0} \to 200$ mT.

Significant enhancement was observed in Hc1 and Hc2



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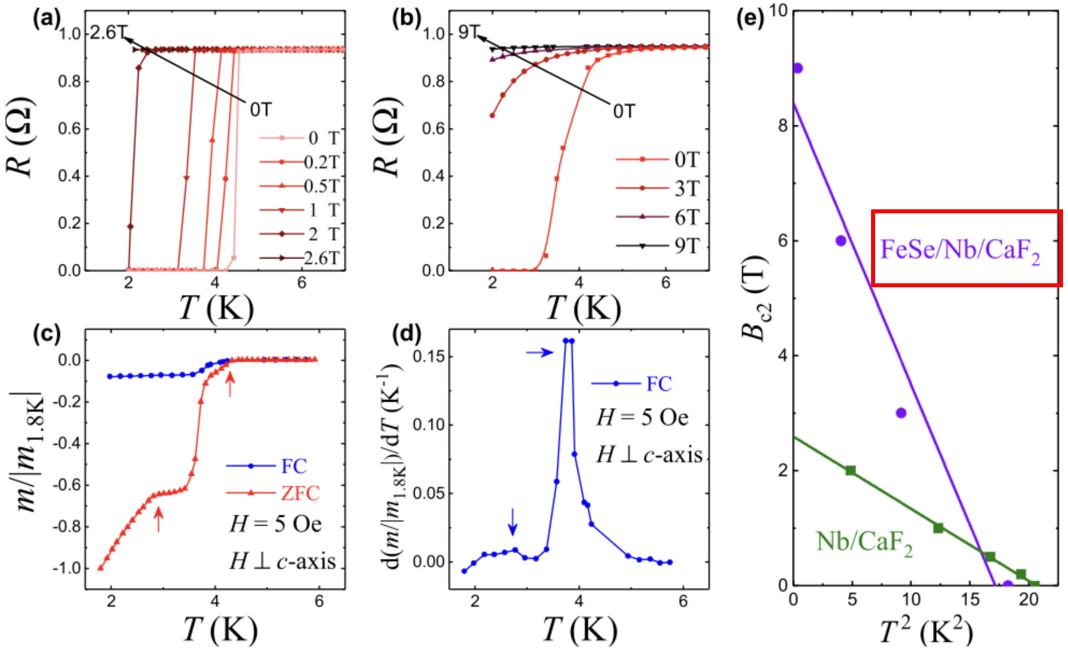
Supercond. Sci. Technol. **34** (2021) 015001 (5pp) | https://doi.org/10.1088/1361-6668/abc568

Enhancement of the lower critical field in FeSe-coated Nb structures for superconducting radio-frequency applications

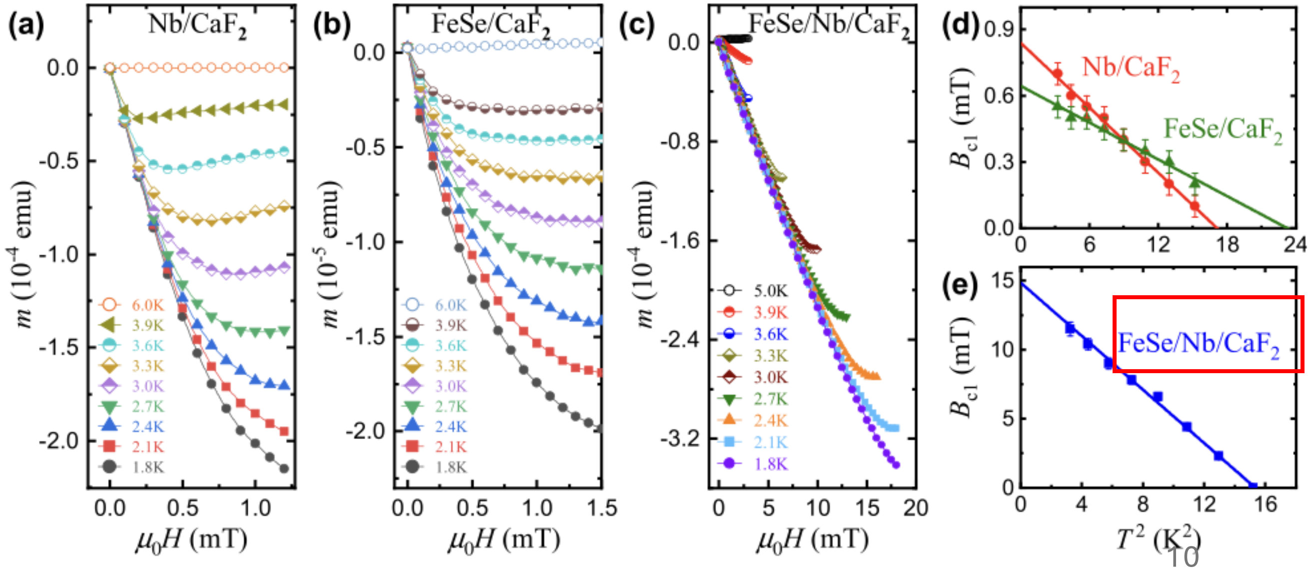
Zefeng Lin[1,2], Mingyang Qin[1,2], Dong Li[1,2], Peipei Shen[1,2], Liping Zhang[3], Zhongpei Feng[4], Peng Sha[5], Jun Miao[3], Jie Yuan[1,6], Xiaoli Dong[1,2,4], Chao Dong[5], Qing Qin[7] and Kui Jin[1,4,6]



- Not pnictide (FeSe): Tc is as low as Nb

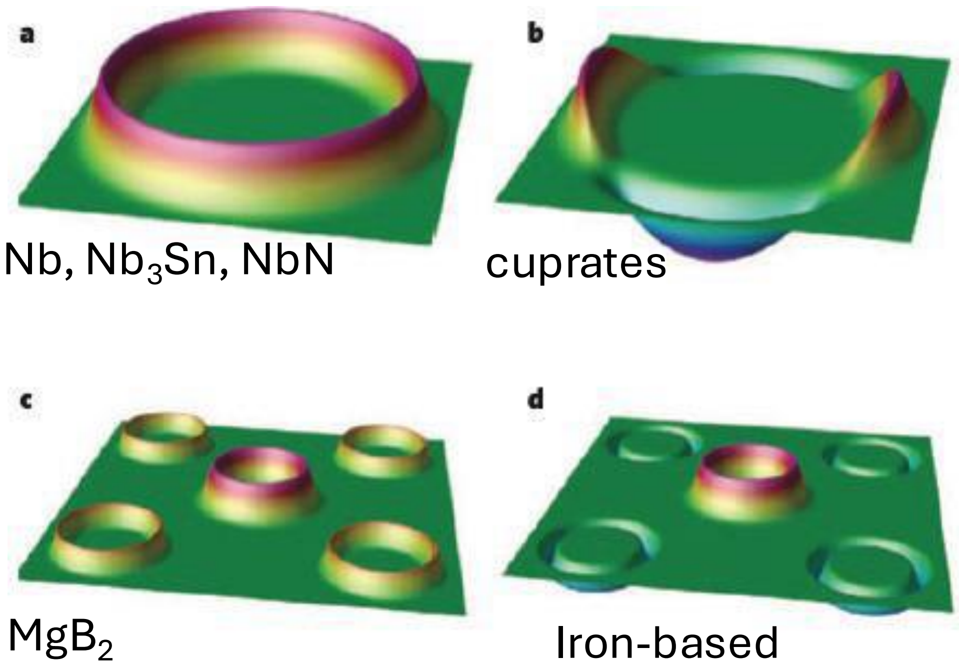
→ Not for high-T SRF but high-G at 2-4 K

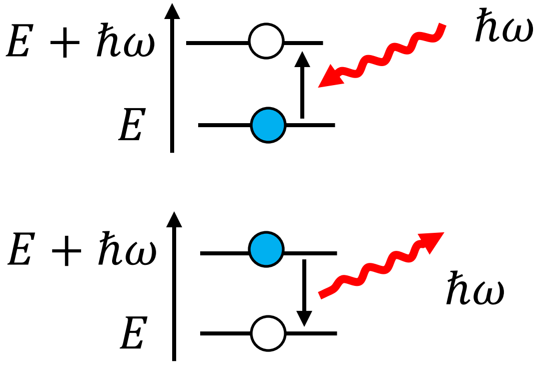
- Multilayer function was proven in DC
- FeSe/Nb structure showed factor 2-4 enhancement in H_{c2} and factor 16 enhancement in H_{c1} compared to Nb
- Absolute value in H_{c1} is very low

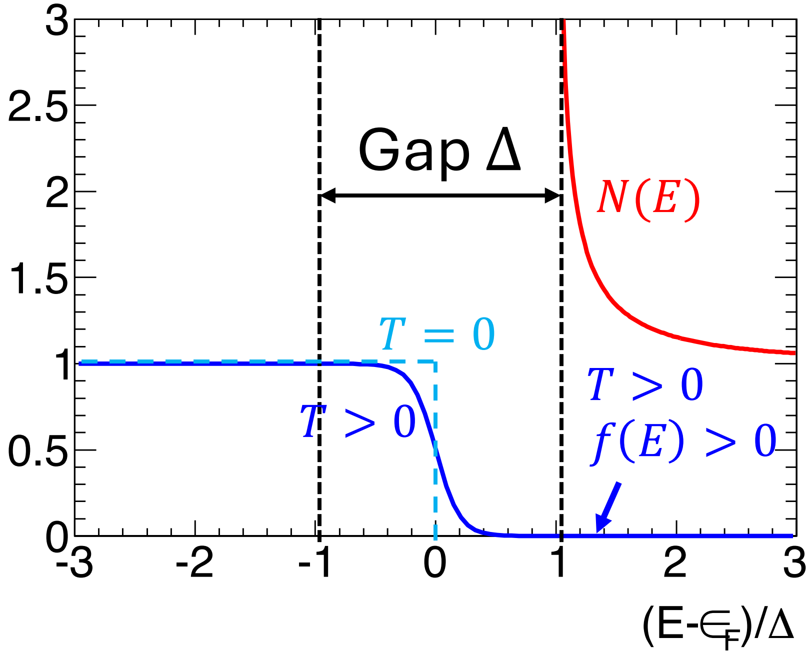


Surface resistance: naivest possible argument

$$R_s \propto \hbar\omega(n_+ - n_-) = \hbar\omega \int_{\Delta}^{\infty} dE\,[f(E) - f(E+\hbar\omega)] \times N(E)N(E+\hbar\omega)$$

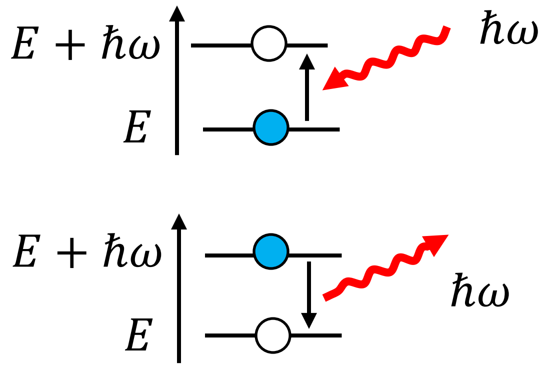






- Gapless SC may have too much thermal excitation of quasiparticles → low R_s
- Gap-full is the minimum requirement
- Iron-based SC often shows two gap structure
    - If MgB2 is OK, Iron-based SC would also be OK?

Optical conductivity in the Meissner state



$$\sigma_1 = \frac{2\sigma_n}{\hbar\omega}\int_0^\infty [f(\epsilon) - f(\epsilon+\hbar\omega)][\mathrm{Re}G^R(\epsilon)\mathrm{Re}G^R(\epsilon+\omega) + \mathrm{Re}F^R(\epsilon)\mathrm{Re}F^R(\epsilon+\omega)]d\epsilon$$

S. N. Nam, Phys Rev 156 470 (1967)

$$\sim \frac{2\sigma_n}{\hbar\omega}(1-e^{-\omega/T})\int_0^\infty e^{-\epsilon/kT}N(\epsilon)N(\epsilon+\hbar\omega)d\epsilon$$

J. Halbritter Z. Physik 266 p.209 (1974)

Quasi-classical Green functions

Conventional s-wave (Dynes)

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta_0^2}}\right)$$

$$\Delta_0(T) = \Delta_0[\cos(\pi T^2/2T_c^2)]^{1/2}$$

Cuprate d-wave

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\left\langle\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta^2(\theta)}}\right\rangle\right)$$

$$\Delta(\theta) = \Delta_0\cos 2\theta$$

P. Coleman ”Introduction to Many-Body Physics”

Pnictide s$_\pm$-wave

$$\frac{N(\epsilon)}{N_0} = \mathrm{Re}\left(\left\langle\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta^2_{\alpha_{1,2},\beta_{1,2}}(\phi_{1,2})}}\right\rangle\right)$$

$$\Delta_{\alpha_{1,2},\beta_{1,2}}(\phi_{1,2}) = \Delta_0\Phi_{\alpha_{1,2},\beta_{1,2}}$$

$$\Phi_{\alpha_{1,2}} = -\Phi_a$$

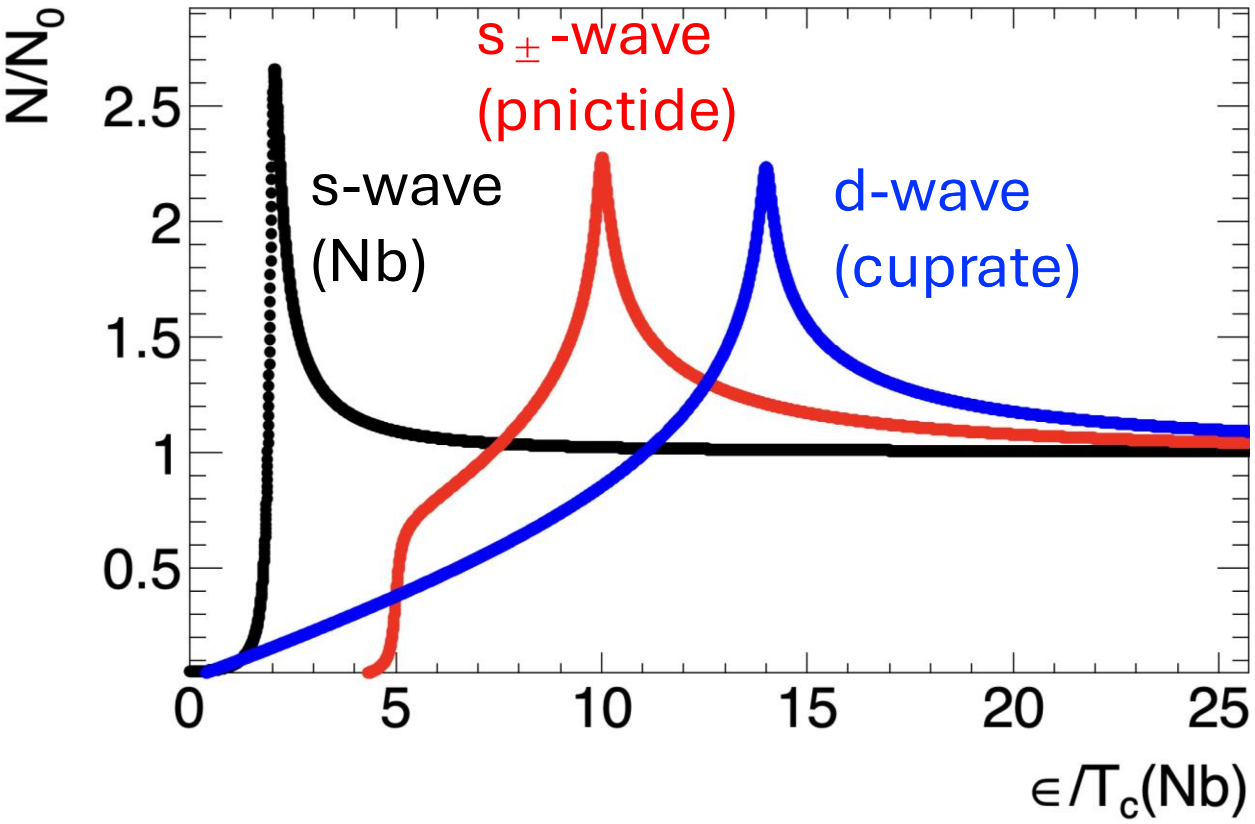
$$\Phi_{\beta_{1,2}} = \frac{1+\Phi_{\beta_{min}}}{2} \pm \frac{(1-\Phi_{\beta_{min}})}{2}\cos(2\phi_{1,2})$$

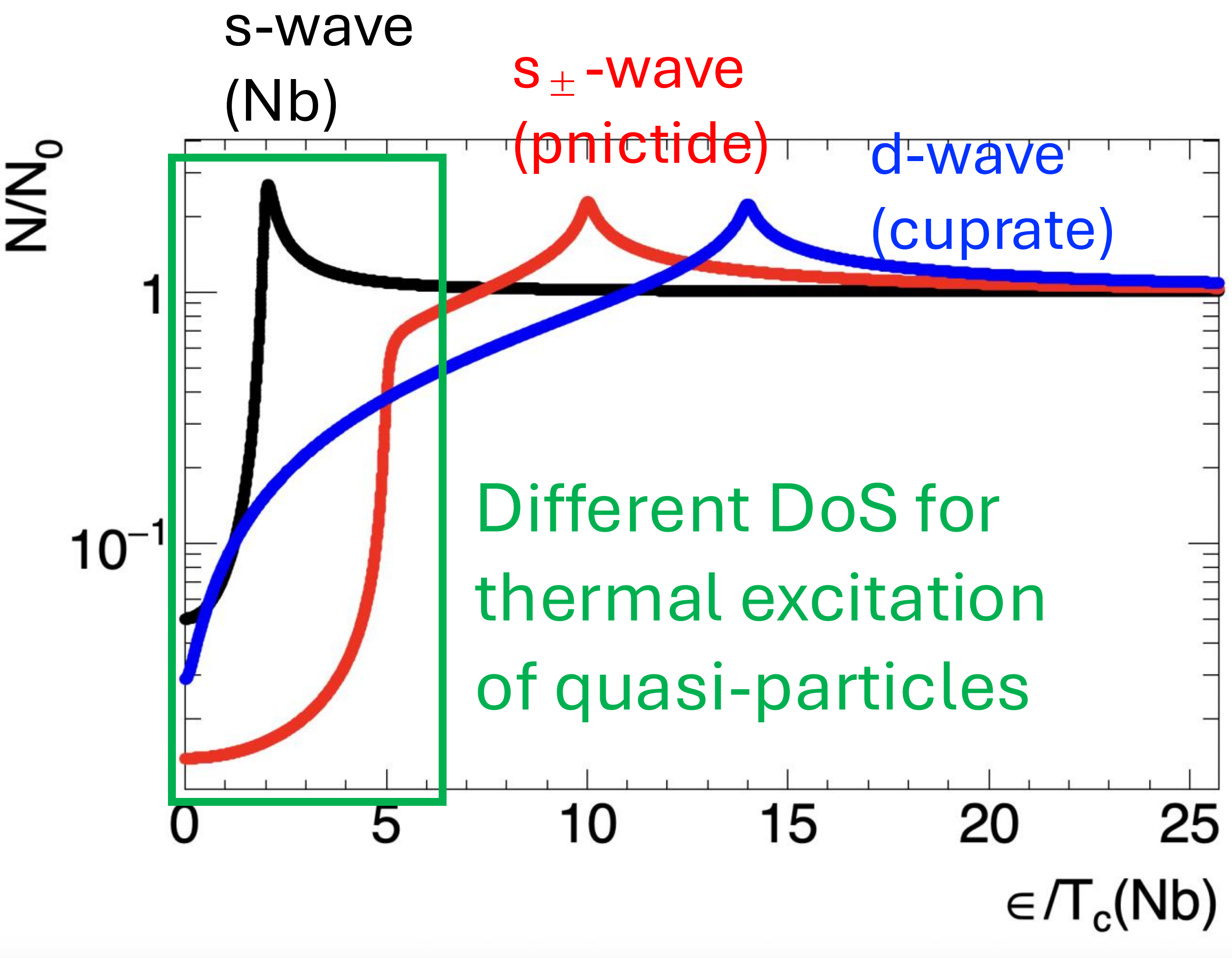
Y. Nagai et al New J. Phys. 10 103026 (2008)

Assumption

- Meissner state = thermodynamical state
- Optical conductivity formulae for BCS SC may be still valid in 1st order approximation

Density of states





Different DoS for thermal excitation of quasi-particles

The energy is normalized to $T_c(\mathrm{Nb}) = 9.25\ \mathrm{K}$

Assumed parameters:

$T_c(\mathrm{pnictide}) = 5 \times T_c(\mathrm{Nb})$

$T_c(\mathrm{cuprate}) = 7 \times T_c(\mathrm{Nb})$

$\Delta_0 = 2 \times T_c$

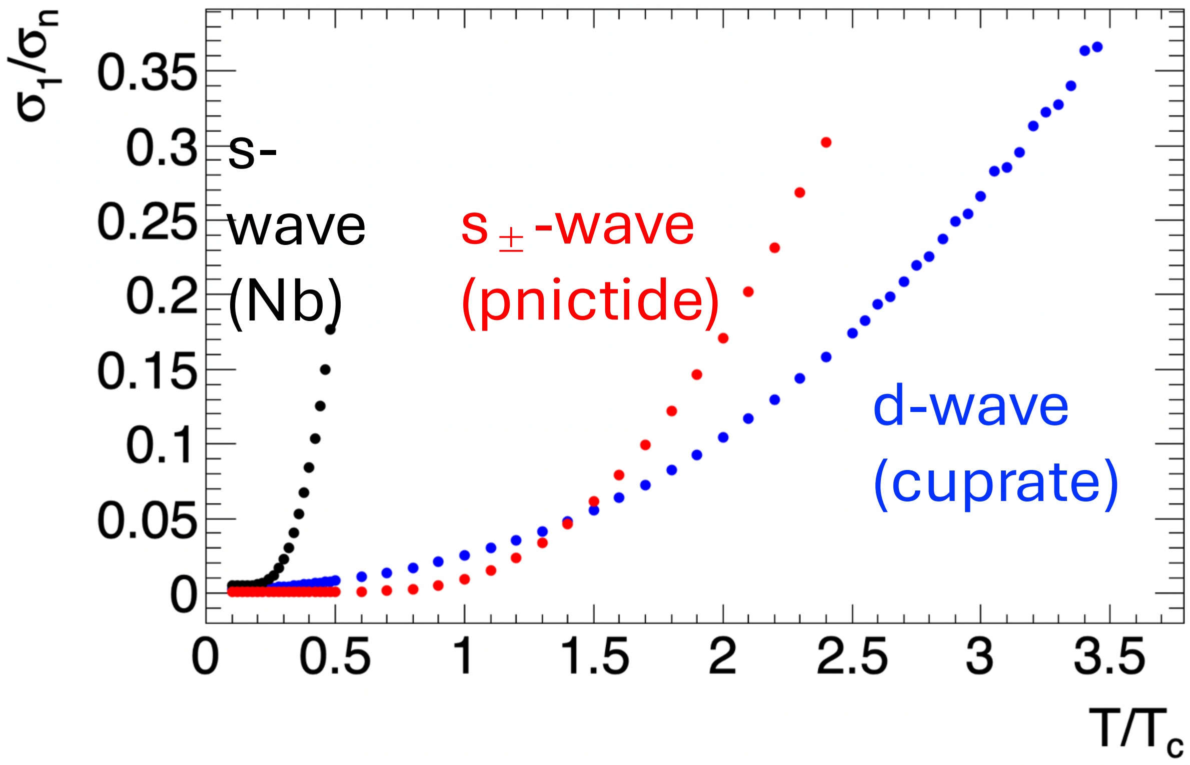
$\Phi_a = 1$

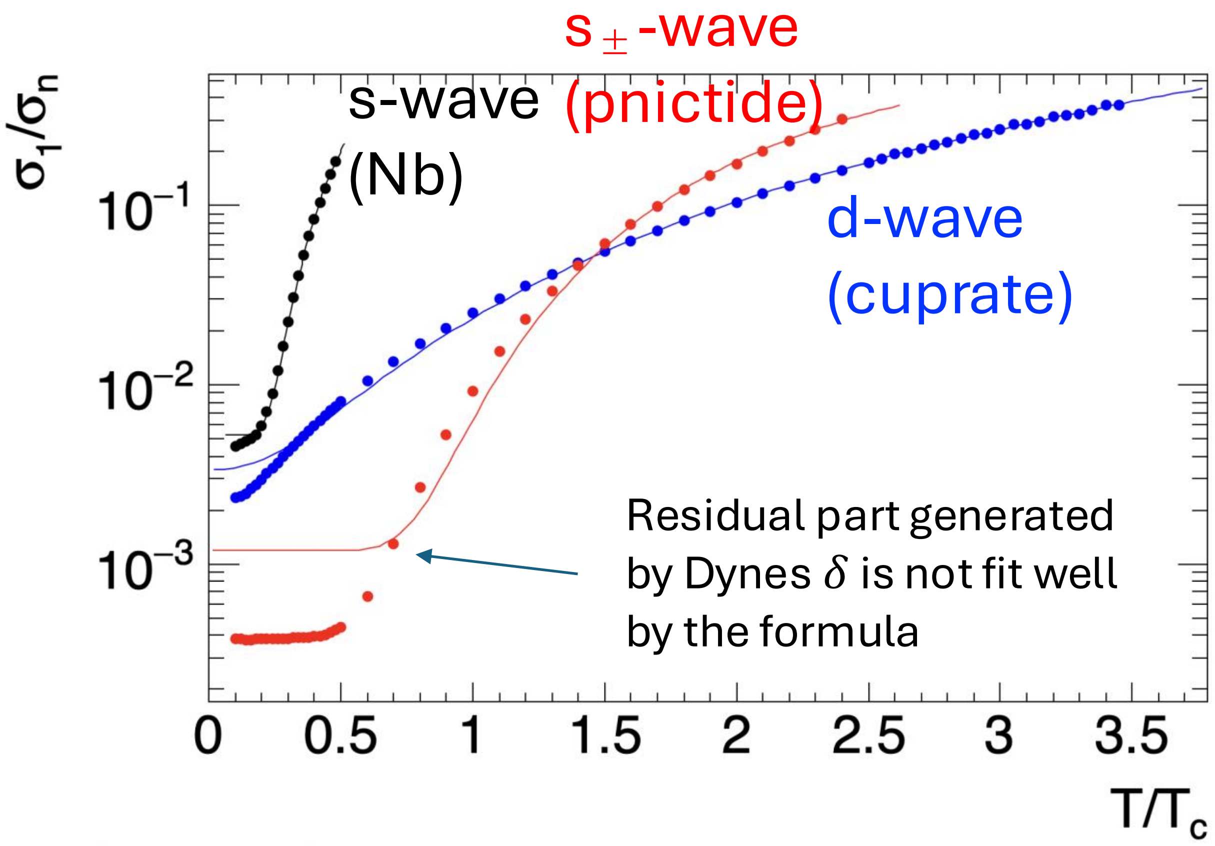
$\Phi_{\beta_{min}} = 0.5$

$\delta = 0.1$

$$\frac{\sigma_1}{\sigma_n} \sim \frac{2\sigma_n}{\hbar\omega}\left(1 - e^{-\omega/T}\right) \int_0^\infty e^{-\epsilon/kT} N(\epsilon) N(\epsilon + \hbar\omega) d\epsilon$$

σ_1 vs T: an example ($\omega = 0.02{\sim}600$ MHz)





Residual part generated by Dynes δ is not fit well by the formula

Best fitting functions

gap-full: $\frac{\sigma_1(T)}{\sigma_n} = \frac{A}{T}\exp\left(-\frac{\Delta}{T}\right) + B$

Gapless: $\frac{\sigma_1(T)}{\sigma_n} = CT^{\alpha} + B$

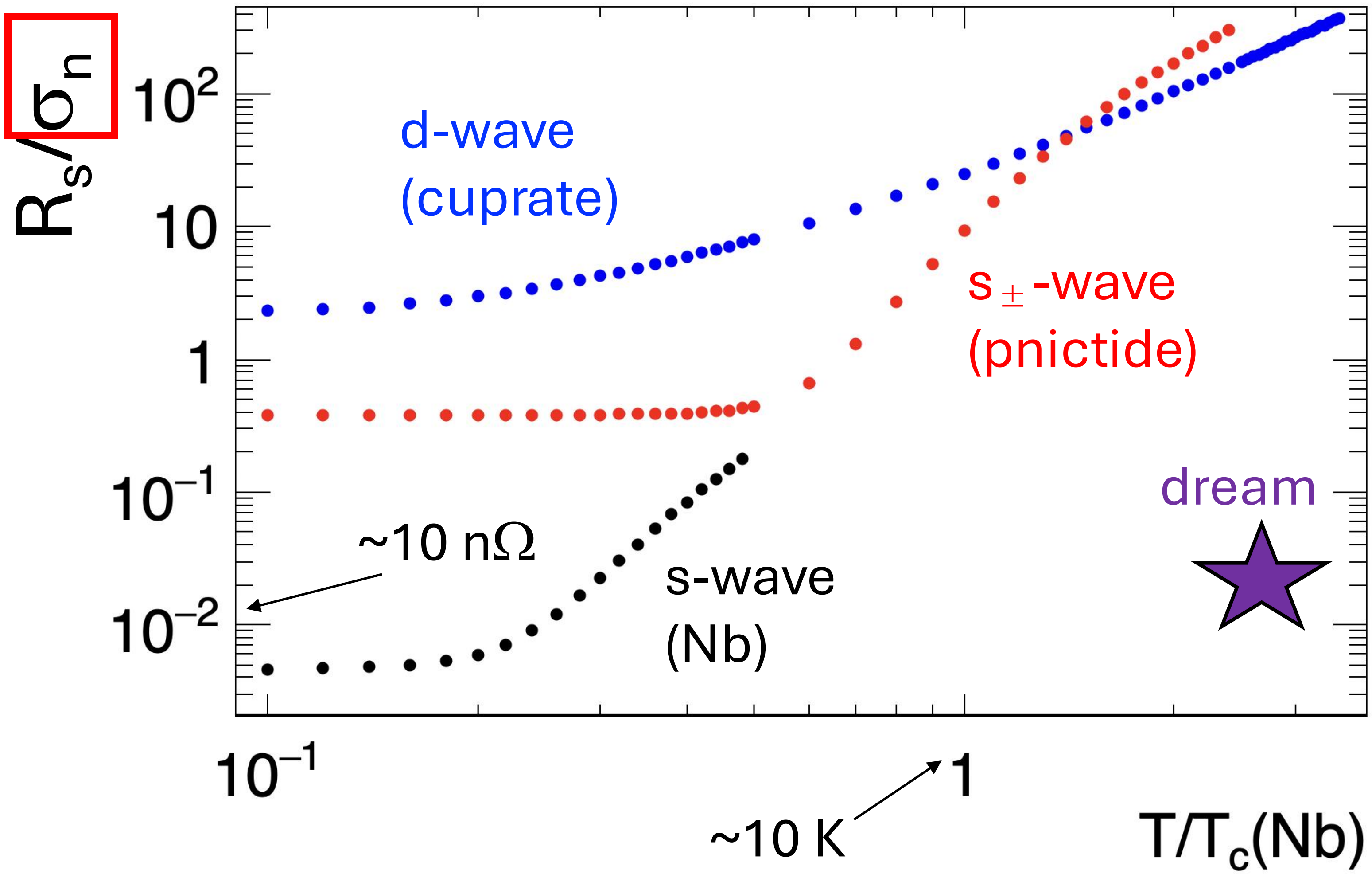
	Nb	pnictide
A	8.67 ± 0.23	23.8 ± 0.81
Δ	2.24 ± 0.01	8.43 ± 0.07
B	0.0052 ± 0.0003	0.0012 ± 0.0005

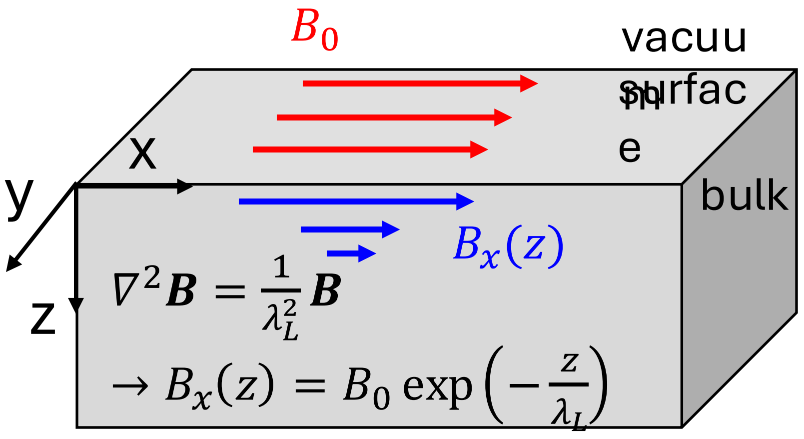
	cuprate
C	0.0201 ± 0.0003
α	2.341 ± 0.015
B	0.0034 ± 0.00044

Surface resistance

$$Z_s = \sqrt{\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2}} \xrightarrow{T\ll T_c,\,\sigma_1\ll\sigma_2} \sqrt{\frac{\mu_0}{\omega\sigma_2^3}}\left(\frac{1}{2}\sigma_1 + i\sigma_2\right) \to R_s = \mathrm{Re}(Z_s) = \frac{\mu_0\omega^2\lambda^3}{2}\sigma_1(T)$$

The penetration depth is factor 10 longer in HTS than Nb
→ RF field looks more materials → more loss





$$\nabla^2 \boldsymbol{B} = \frac{1}{\lambda_L^2}\boldsymbol{B}$$

$$\to B_x(z) = B_0 \exp\left(-\frac{z}{\lambda_L}\right)$$

	λ_L [nm]
Nb	>36
pnictide	200-400
cuprate	130-170 / 500-850

→ **Clearly, the chance is in multilayer $d \lesssim \lambda$**

Lesson learned from R_s calculation

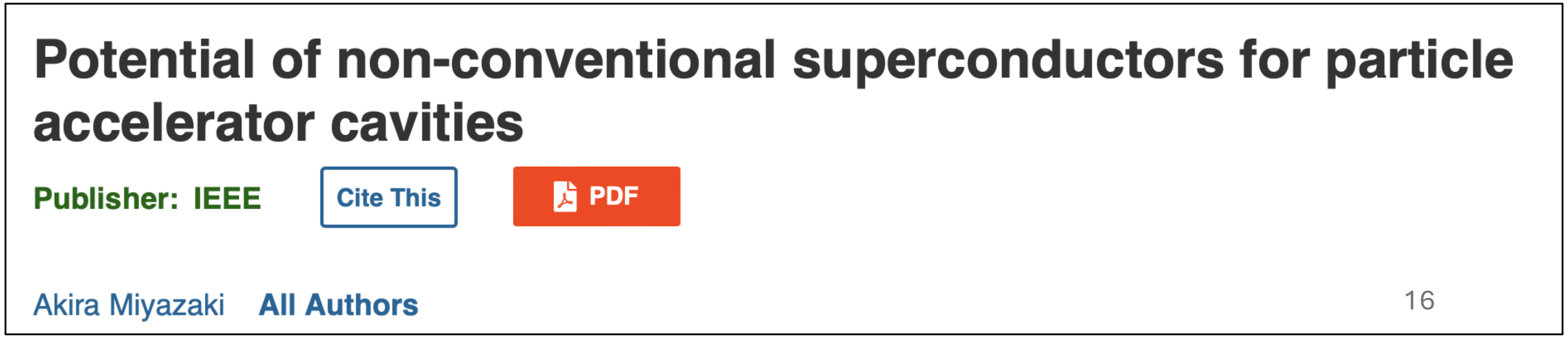
- $\frac{\sigma_1(T)}{\sigma_n} = \frac{A}{T}\exp\left(-\frac{\Delta}{T}\right) + B$ may be still valid (smaller Δ dominates) for iron-based superconductors
- REBCO could be useful in high-T pulsed operation (→ SLAC & CERN)
- Long penetration depth causes high loss

A. Dhar LCWS2024

- Multilayer may be an option!
- Experimental data of H_{c1} enhancement already exists

→ Let's apply multilayer theory for iron-based SC

The former discussion was recently published→



Potential of non-conventional superconductors for particle accelerator cavities

Akira Miyazaki All Authors

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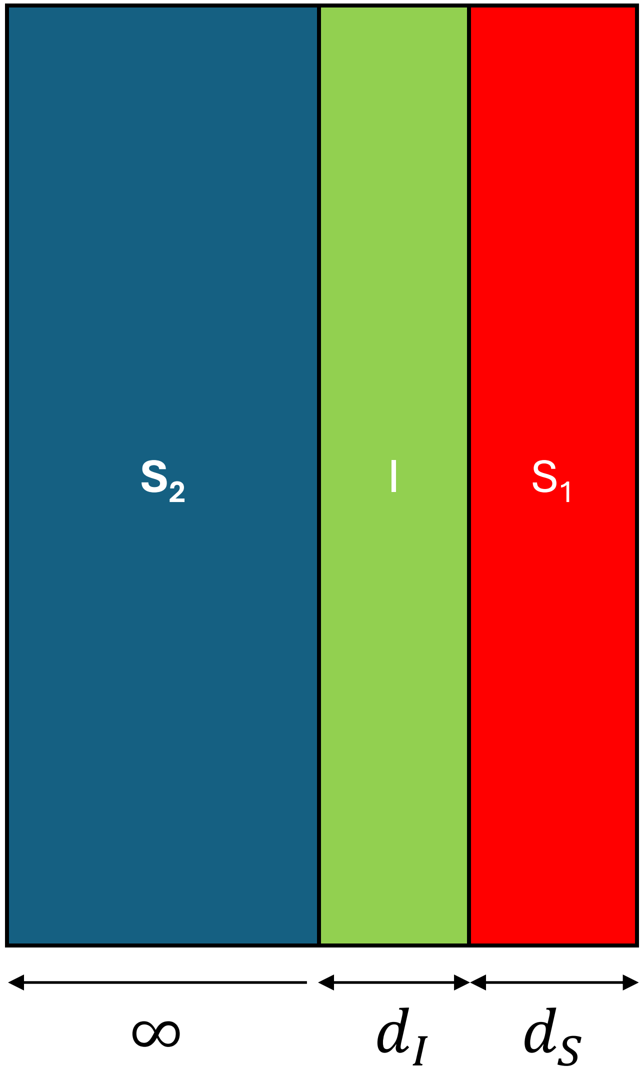
Multilayer theory by Kubo: London equation



T. Kubo et al arXiv:1304.6876

If $\frac{\phi_0}{4\pi\xi_1\lambda_1}\frac{1}{\sinh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\cosh\left(\frac{d_s}{\lambda_1}\right)} < B_{sh,2}$

$$B_v = \frac{\phi_0}{4\pi\xi_1\lambda_1}\frac{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}{\sinh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\cosh\left(\frac{d_s}{\lambda_1}\right)}$$

(attenuated B-field through S$_1$ is lower than that of S$_2$ → breakdown determined by S1)

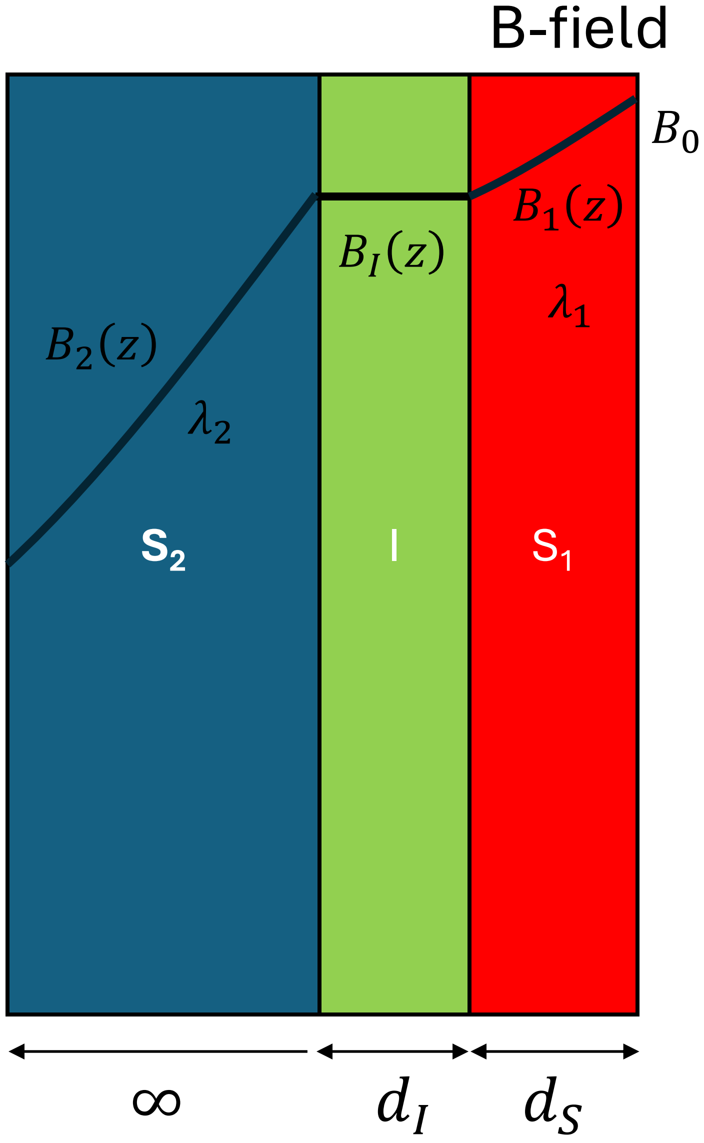
If $\frac{\phi_0}{4\pi\xi_1\lambda_1}\frac{1}{\sinh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\cosh\left(\frac{d_s}{\lambda_1}\right)} > B_{sh,2}$

$$B_v = \left[\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)\right]B_{sh,2}$$

(attenuated B-field through S$_1$ is still higher than that of S$_2$ → breakdown determined by S$_2$)

Assumption: London equation is valid for iron-based SC (probably OK)

field distribution inside a ML structure → RF loss calculation

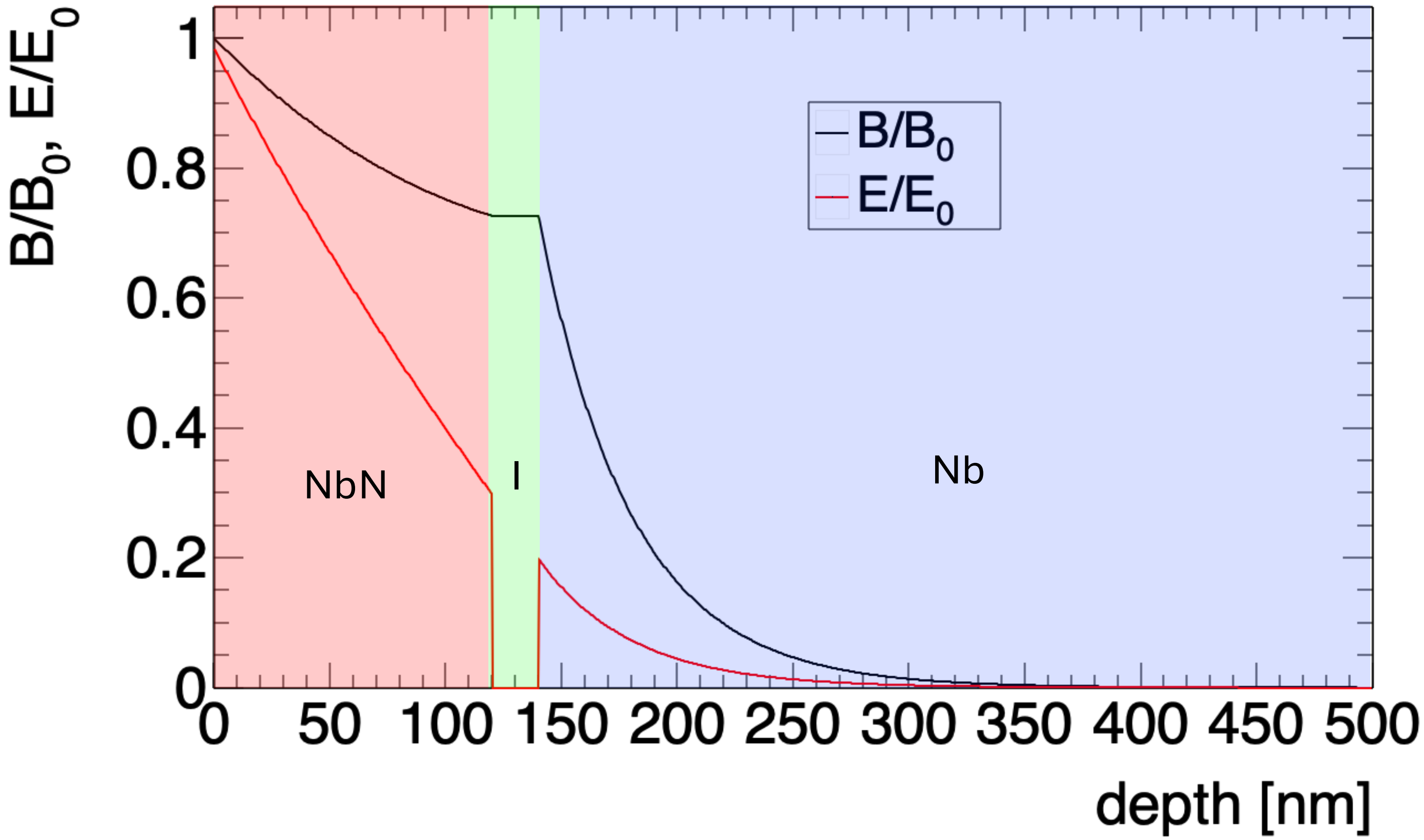


$$\left\{\begin{aligned}
B_1(z) &= B_0\frac{\cosh\left(\frac{d_s-z}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s-z}{\lambda_1}\right)}{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}\\
B_I(z) &= B_0\frac{1}{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}\\
B_2(z) &= B_0\frac{\exp\left(-\frac{z-d_s-d_I}{\lambda_2}\right)}{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}
\end{aligned}\right.$$

$$\left\{\begin{aligned}
E_1(z) &= \omega\lambda_1B_0\frac{\sinh\left(\frac{d_s-z}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\cosh\left(\frac{d_s-z}{\lambda_1}\right)}{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}\\
E_I(z) &= 0\\
E_2(z) &= \omega\lambda_2B_0\frac{\exp\left(-\frac{z-d_s-d_I}{\lambda_2}\right)}{\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)}
\end{aligned}\right.$$

$$\boxed{E(z) = -\omega\lambda^2\frac{dB}{dz}}$$

Field distribution → surface resistance (ex: NbN/I/Nb)



parameter	value
ξ_{NbN} [nm]	5
λ_{NbN} [nm]	200
λ_{Nb} [nm]	40
d_s [nm]	120
d_I [nm]	20

Quasi-particle conductivity
(real part of optical conductivity)

$$\sigma_{1,2} = \frac{e^2 n_N \tau}{m^*} \propto \exp\left(-\frac{\Delta_{1,2}}{k_B T}\right)$$

$$\rightarrow \sigma_{1,2} \equiv \sigma_{0,1,2} \exp\left(-\frac{\Delta_{1,2}}{k_B T}\right)$$

Surface resistance

$$\frac{1}{2}\boxed{R_s}H^2 = \frac{\sigma_1}{2}\int_0^{d_s} E_1^2(z)dz + q(d_I, \epsilon, \delta) + \frac{\sigma_2}{2}\int_{d_s+d_I}^{\infty} E_2^2(z)dz$$

(Dielectric loss)

A. Gurevich AIP Advances 5 017112 (2015)

Multilayer BCS resistance

Surface resistance

$$\frac{1}{2}R_sH^2=\frac{\sigma_1}{2}\int_0^{d_s}E_1^2(z)dz+q(d_I,\epsilon,\delta)+\frac{\sigma_2}{2}\int_{d_s+d_I}^{\infty}E_2^2(z)dz \qquad \to R_s=R_{s,1}+q+R_{s,2}$$

Surface resistance

$$R_{s,1}=\boxed{\mu_0^2\omega^2\sigma_{0,1}\exp\left(-\frac{\Delta_1}{k_BT}\right)\lambda_1^3}\boxed{\frac{\left[-2\lambda_1^2(d_I+\lambda_2)+2d_s(d_I-\lambda_1+\lambda_2)(d_I+\lambda_1+\lambda_2)+2\lambda_1^2(d_I+\lambda_2)\cosh\left(\frac{2d_s}{\lambda_1}\right)+\lambda_1(\lambda_1^2+(d_I+\lambda_2)^2)\sinh\left(\frac{2d_s}{\lambda_1}\right)\right]}{4\lambda_1^3\left[\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)\right]^2}}$$

Semi-infinite bulk surface resistance

$\equiv D_1(d_s,d_I)$

Reduction factor by the finite layer thick

$$R_{s,2}=\boxed{\mu_0^2\omega^2\sigma_{0,2}\exp\left(-\frac{\Delta_2}{k_BT}\right)\lambda_2^3}\boxed{\frac{1}{2\left[\cosh\left(\frac{d_s}{\lambda_1}\right)+\left(\frac{\lambda_2}{\lambda_1}+\frac{d_I}{\lambda_1}\right)\sinh\left(\frac{d_s}{\lambda_1}\right)\right]^2}}$$

Semi-infinite bulk surface resistance

$\equiv D_2(d_s,d_I)$

Reduction factor by screening of the top layer

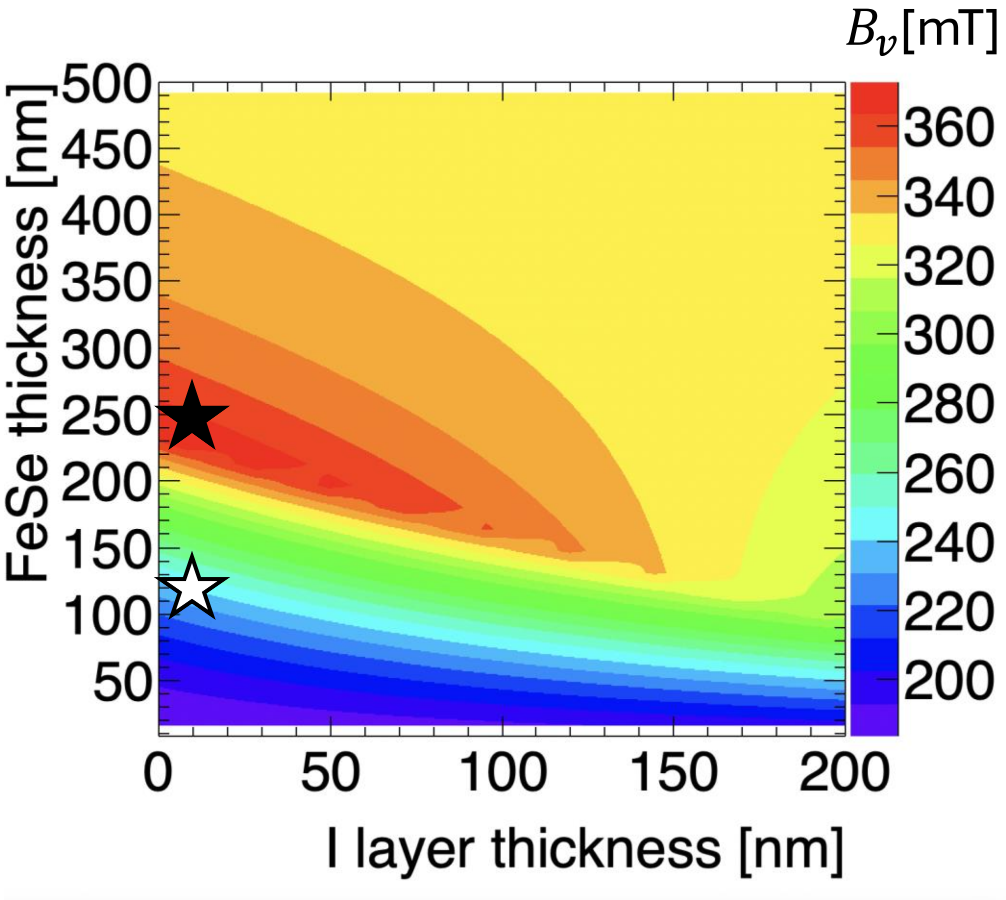
Assuming exponential formula validated from the former argument by using numerical integral of Green’s functions

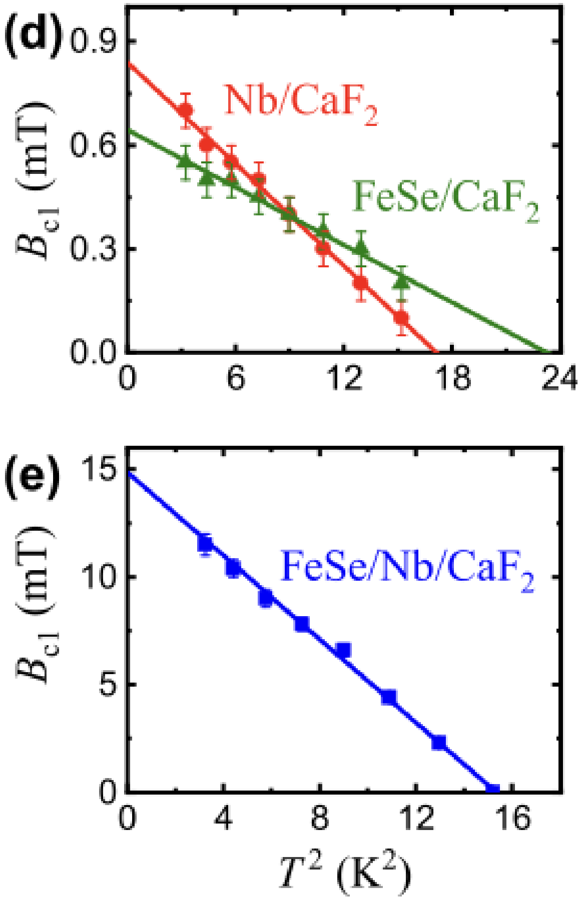
Breakdown field for FeSe/(I)/N multilayer structure

parameter	value
ξ_{FeSe} [nm]	2.5
λ_{FeSe} [nm]	200
λ_{Nb} [nm]	40
$B_{sh\,Nb}$ [mT]	180

$$\frac{280\text{ mT}}{180\text{mT}} = 1.6$$

Improvement with FeSe thick 130 nm



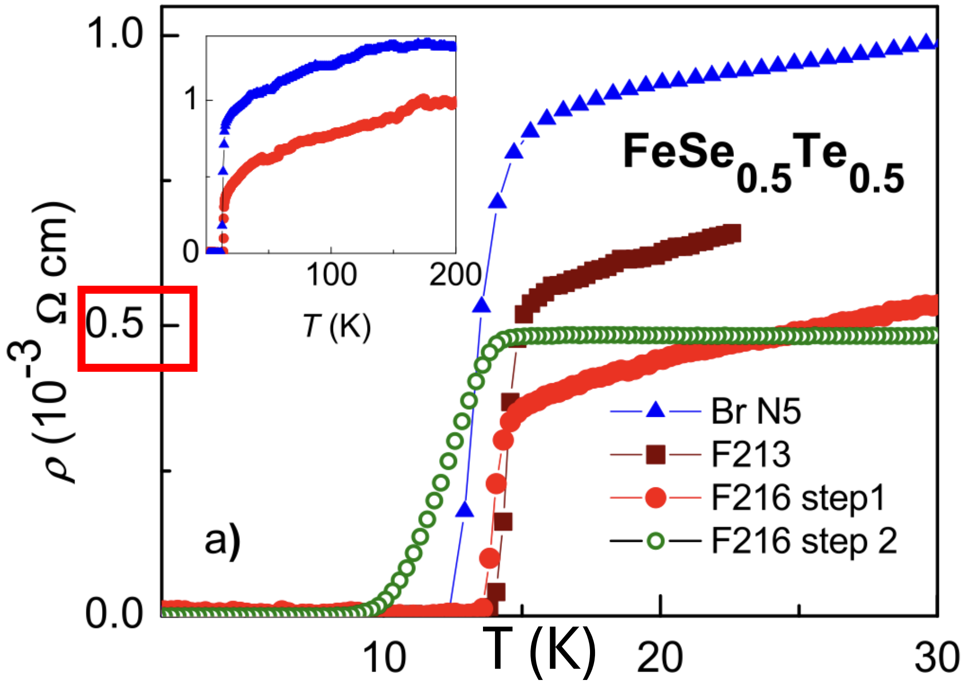


- ML enhancement of the breakdown field from 180 mT to 360 mT
  - FeSe thickness around 250 nm without insulator
- FeSe/Nb/CaF$_2$:FeSe 130 nm thick, no insulator, Nb 115 nm thick (Z. Lin et al SUST 34 015001)

Material parameters of FeSe

Eur. Phys. J. B 79, 289-299 (2011)

- Surface resistance of SRF cavities depend on normal conducting conductivity at cold $R_s \propto \sigma_n$
- But it becomes superconducting in the literature ☹
- Material dependence…
- Let's simply take $\rho = 500\ \mu\Omega\text{cm}$



- Superconducting gap $\Delta \sim 26\ \text{K}$
- In natural unit

$$\Delta_{\text{FeSe}} \sim 2.2\ \text{meV} > \Delta_{\text{Nb}} = 1.5\ \text{meV}$$

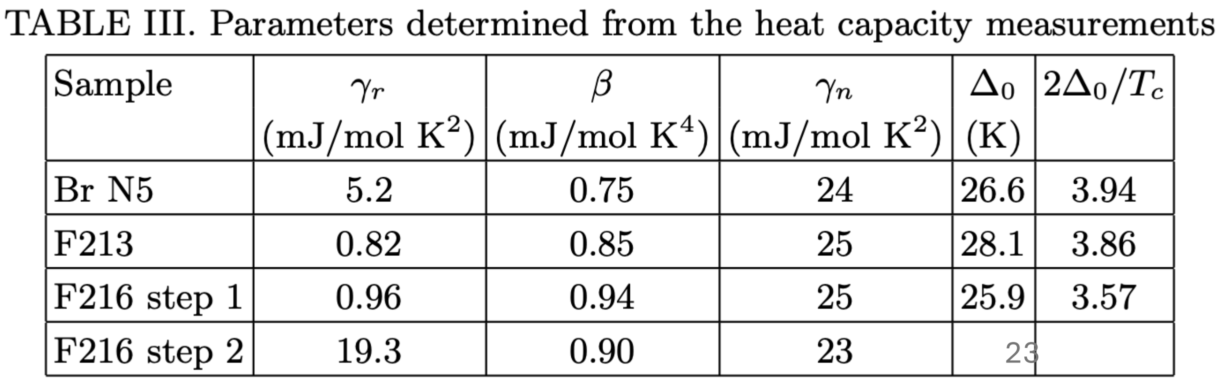
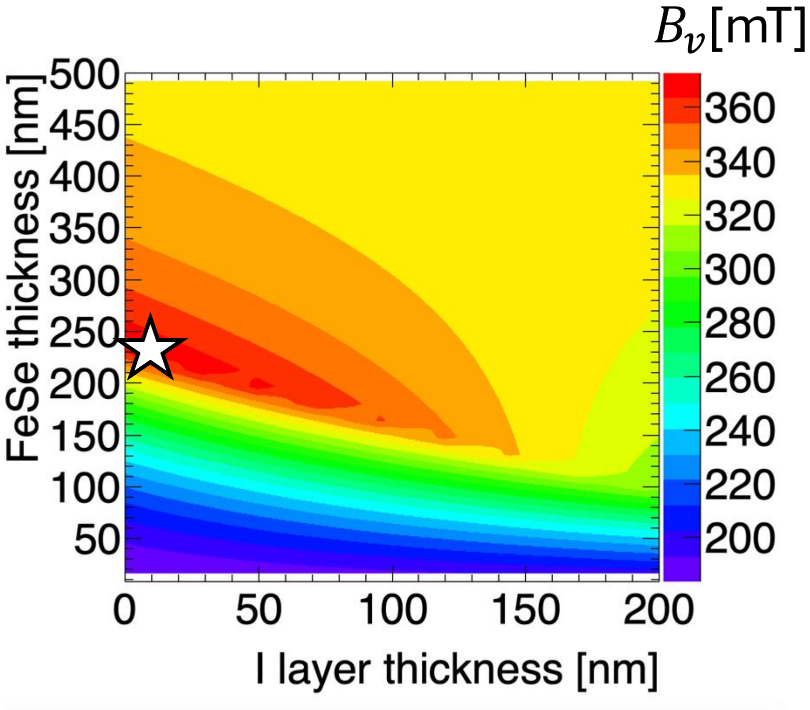
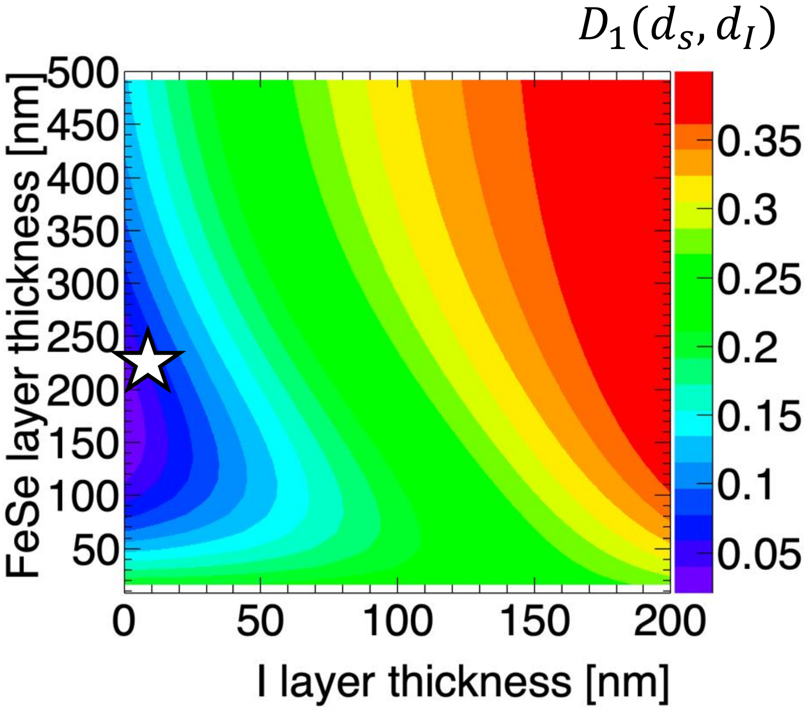


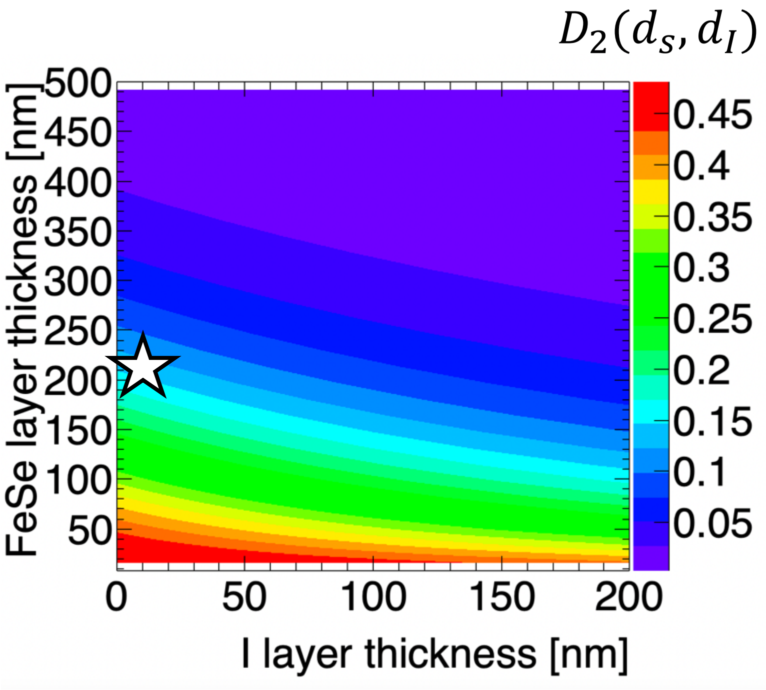
TABLE III. Parameters determined from the heat capacity measurements

Sample	γ_r (mJ/mol K^2)	β (mJ/mol K^4)	γ_n (mJ/mol K^2)	Δ_0 (K)	$2\Delta_0/T_c$
Br N5	5.2	0.75	24	26.6	3.94
F213	0.82	0.85	25	28.1	3.86
F216 step 1	0.96	0.94	25	25.9	3.57
F216 step 2	19.3	0.90	23		

Multilayer BCS resistance for FeSe/(I)/Nb







For $(d_I, d_s) = (0, 250\ \mathrm{nm})$, $D_1 \sim 0.1$, $D_2 \sim 0.1$

$$R_s \sim R_{s,1} + R_{s,2} = \mu_0^2\omega^2\sigma_{0,1}\exp\left(-\frac{\Delta_1}{k_BT}\right)\lambda_1^3 D_1(d_s,d_I) + \mu_0^2\omega^2\sigma_{0,2}\exp\left(-\frac{\Delta_2}{k_BT}\right)\lambda_2^3 D_2(d_s,d_I)$$

$$\underset{= R_{s,Nb}(T)}{\boxed{= \mu_0^2\omega^2\lambda_2^3\sigma_{0,Nb}\exp\left(-\frac{\Delta_{\mathrm{Nb}}}{k_BT}\right)}} \left[\underset{= 0.004}{\frac{\sigma_{0,FeSe}}{\sigma_{0,Nb}}} \underset{= 0.14\ \text{@4.2K}}{\underline{\left[\frac{\exp(-\Delta_{\mathrm{FeSe}}/k_BT)}{\exp(-\Delta_{\mathrm{Nb}}/k_BT)}\right]}} \underset{= 125}{\left(\frac{\lambda_{\mathrm{FeSe}}}{\lambda_{\mathrm{Nb}}}\right)^3} \underset{= 0.1}{D_1(d_s,d_I)} + \underset{= 0.1}{D_2(d_s,d_I)}\right]$$

$\sim 0.1 \times R_{s,Nb}(T = 4.2\ \mathrm{K})$

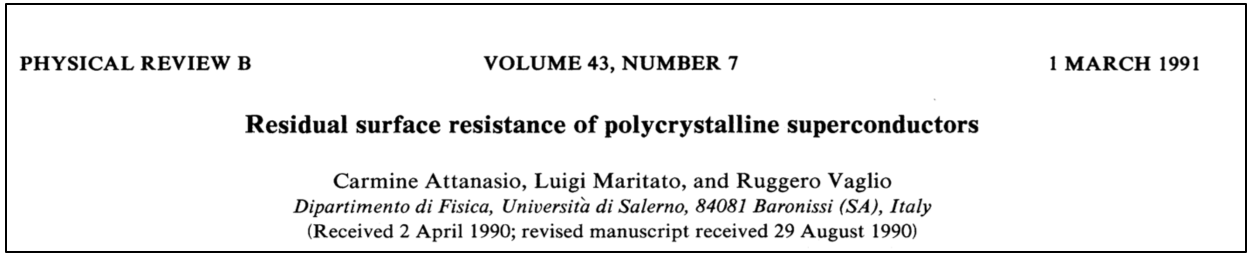
Large ρ_n → small σ_n → small R_s

parameter	value
λ_{FeSe} [nm]	200
λ_{Nb} [nm]	40
$\Delta_{FeSe,1}$ [meV]	2.2
Δ_{Nb} [meV]	1.5
ρ_{FeSe} [μΩcm]	500
ρ_{Nb} [μΩcm]	2

Outline

- Iron-based SC and recent applications
- Iron-based SC for SRF?
- Surface resistance of Iron-based SC
- ML theory for Iron-based SC
- Remarks
- Conclusion

Residual resistance caused by weak link


PHYSICAL REVIEW B VOLUME 43, NUMBER 7 1 MARCH 1991

Residual surface resistance of polycrystalline superconductors

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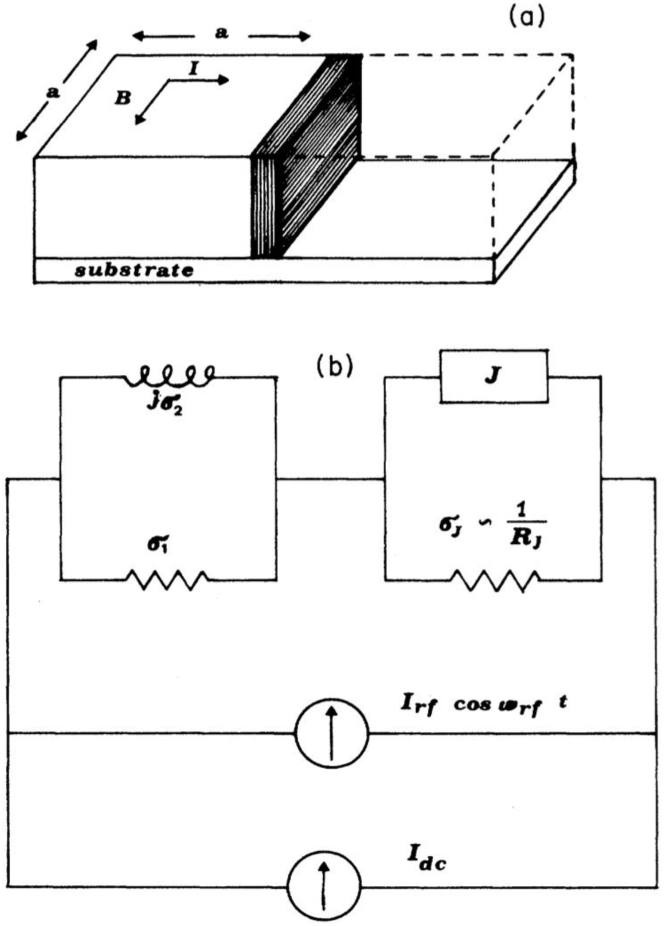
(Received 2 April 1990; revised manuscript received 29 August 1990)


Journal of Superconductivity, Vol. 8, No. 6, 1995

Nonlinear Surface Impedance of YBCO Thin Films: Measurements, Modeling, and Effects in Devices

Daniel E. Oates,[1] Paul P. Nguyen,[2] Gene Dresselhaus,[3] Mildred S. Dresselhaus,[4] Gad Koren,[5] and Emil Polturak[5]



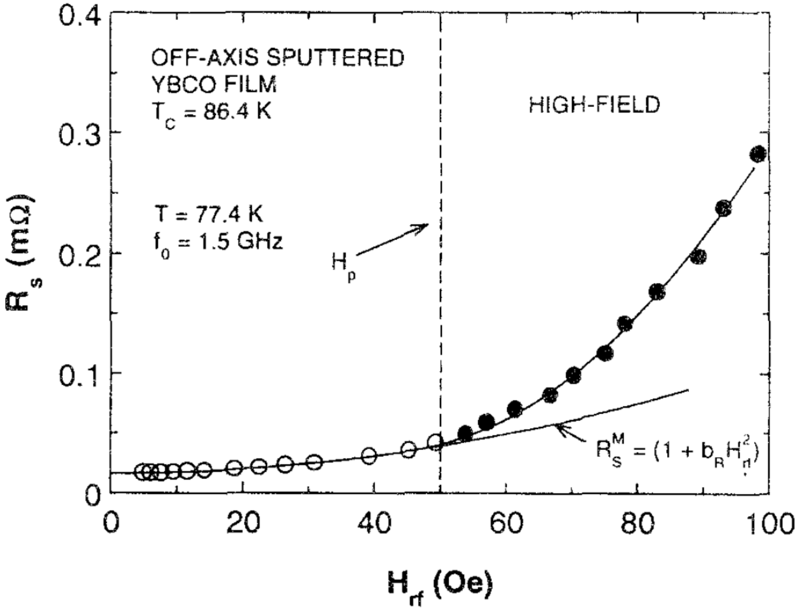


Fig. 7. R_S vs. H_{rf} showing the low- and intermediate-field region (○), which is fitted by the modified coupled-grain model as shown by R_S^M and the high-field region (●), which is fitted by the combination of the coupled-grain model and the Bean model.

- It is known that YBCO showed nonlinear residual resistance (Q-slope) well explained by the weak link model
- Iron-based superconductors also show weak-link structure (from wire studies)
- This term would appear on top of quasi-particle contributions discussed so far

Outlook: probably 30-year business

- More reliable material parameters (?)
    - Sample measurement on DC electric conductivity at cold
- Multi-layer sample
- Weak link calculation on multilayer
- Dielectric loss
- Find collaborators
    - Material science
    - Theorists
    - RF engineers

Outline

- Iron-based SC and recent applications
- Iron-based SC for SRF?
- Surface resistance of Iron-based SC
- ML theory for Iron-based SC
- Remarks
- Conclusion

Conclusion

- 16 years have passed since Iron-based SC was discovered in 2008
- Application of Iron-based SC for wire / tape / magnet is a hot topic
- RF application has been limited
  - Recent proposal for axion dark matter project
- Multilayer would be the way to go
  - Enhancement of critical fields has been experimentally shown
  - Enhancement of surface barrier was re-calculated (London equation)
- Gapless nature would also be excellent for surface resistance
  - The conventional BCS-like formula may sill be valid
  - Long penetration depth is problematic → layer thick thinner than λ
- Multilayer surface resistance was estimated
  - Small normal conducting DC electric conductivity helps (if the theory is valid)
- Residual resistance from weak link must be evaluated as well
- Looking for somebody who are willing to collaborate

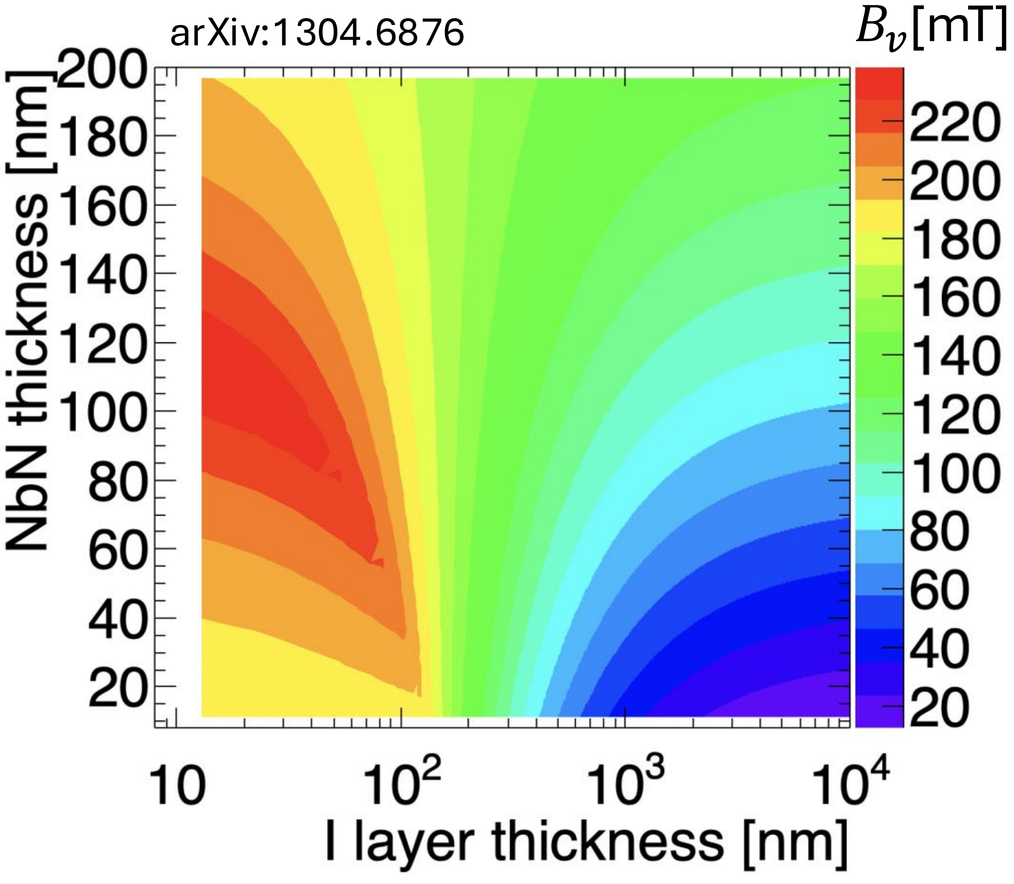
backup

Kubo’s calculation for NbN/I/N was reproduced

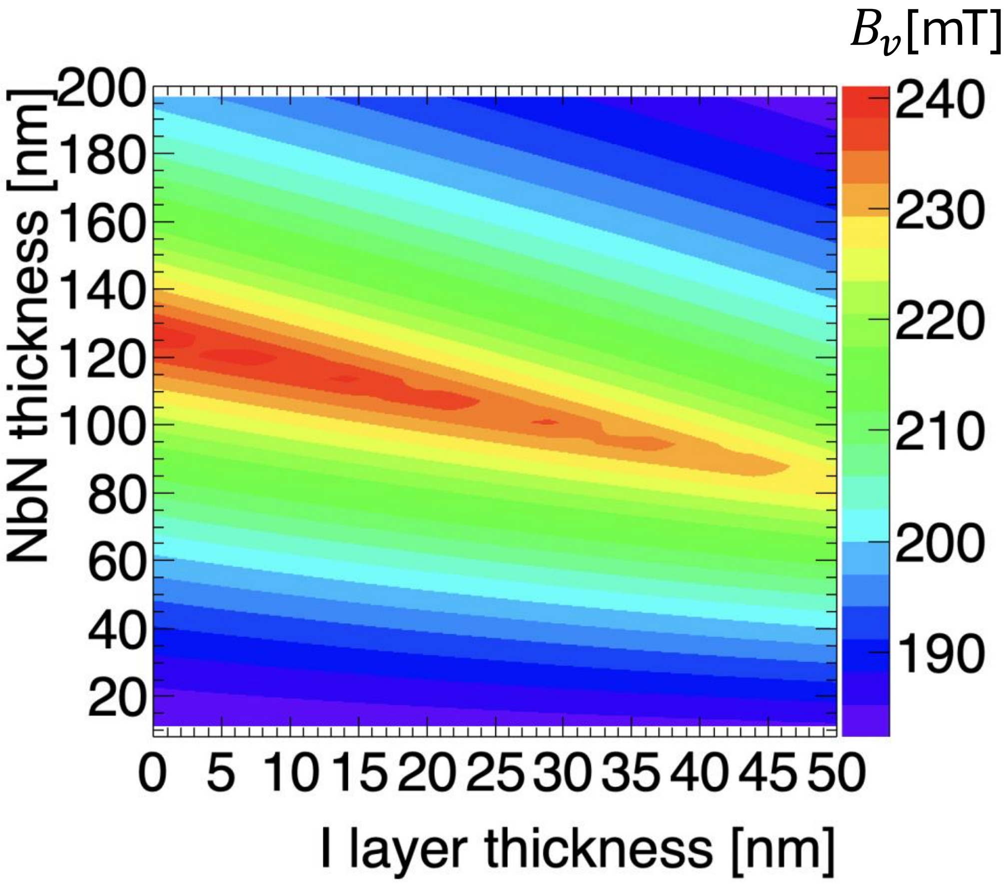
parameter	value
ξ_{NbN} [nm]	5
λ_{NbN} [nm]	200
λ_{Nb} [nm]	40
$B_{sh\,Nb}$ [mT]	180

Reproduced Fig.3 (a)

arXiv:1304.6876

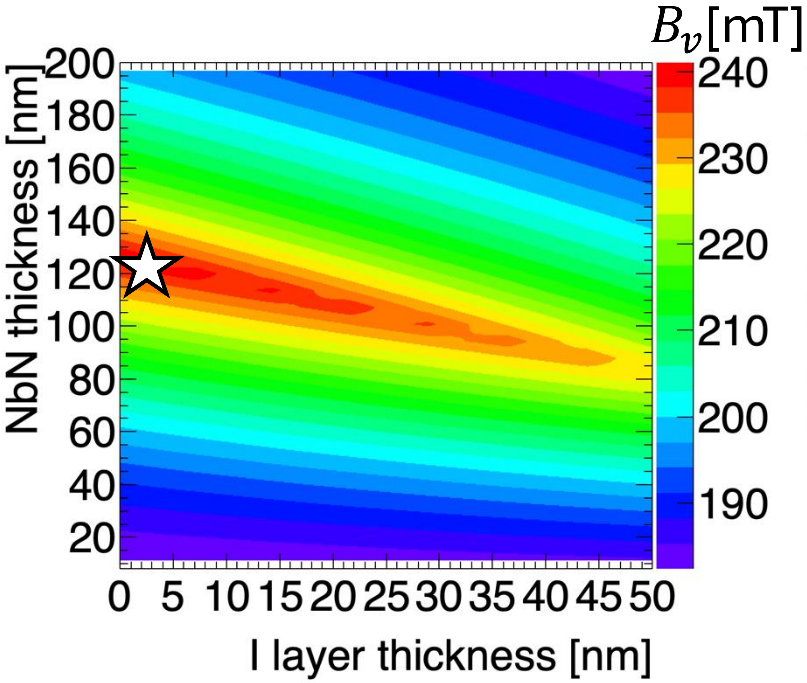


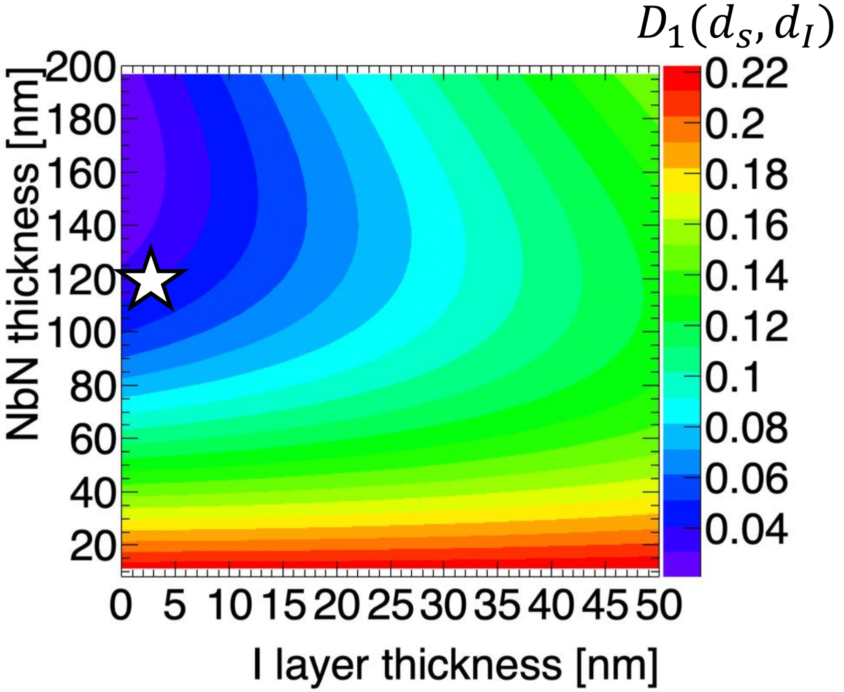
Enlarged around thinner I layer

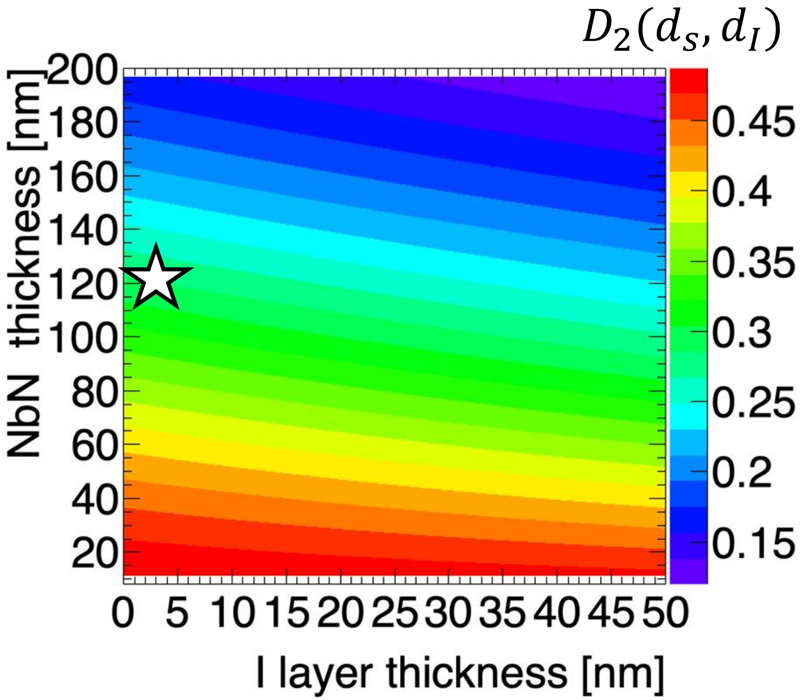


ML enhancement of the breakdown field from 180 mT to 240 mT is predicted with NbN thickness around 120 nm without an insulation layer

Multilayer BCS resistance for NbN/I/Nb







For $(d_I, d_s) = (0, 120\ \mathrm{nm})$, $D_1 \sim 0.05$, $D_2 \sim 0.3$

$$R_s \sim R_{s,1} + R_{s,2} = \mu_0^2 \omega^2 \sigma_{0,1} \exp\left(-\frac{\Delta_1}{k_B T}\right) \lambda_1^3 D_1(d_s, d_I) + \mu_0^2 \omega^2 \sigma_{0,2} \exp\left(-\frac{\Delta_2}{k_B T}\right) \lambda_2^3 D_2(d_s, d_I)$$

$$= \boxed{\mu_0^2 \omega^2 \lambda_2^3 \sigma_{0,Nb} \exp\left(-\frac{\Delta_{Nb}}{k_B T}\right)} \left[\underbrace{\frac{\sigma_{0,NbN}}{\sigma_{0,Nb}}}_{= 0.029} \underbrace{\left[\frac{\exp(-\Delta_{NbN}/k_B T)}{\exp(-\Delta_{Nb}/k_B T)}\right]}_{= 0.048\ @4.2\mathrm{K}} \underbrace{\left(\frac{\lambda_{NbN}}{\lambda_{Nb}}\right)^3}_{= 125} \underbrace{D_1(d_s, d_I)}_{= 0.05} \right.$$

$= R_{s,Nb}(T)$

$$\left. + \underbrace{D_2(d_s, d_I)}_{= 0.3} \right]$$

$$= 0.017 \times R_{s,Nb}(T = 4.2\ \mathrm{K})$$

ML is promising for higher Q not only high gradient

parameter	value
λ_{NbN} [nm]	200
λ_{Nb} [nm]	40
Δ_{NbN} [meV]	2.6
Δ_{Nb} [meV]	1.5
ρ_{NbN} [μΩcm]	70
ρ_{Nb} [μΩcm]	2