Comparison of Nb, Nb_3Sn, MgB_2, cuprate, and pnictide for future SRF cavities

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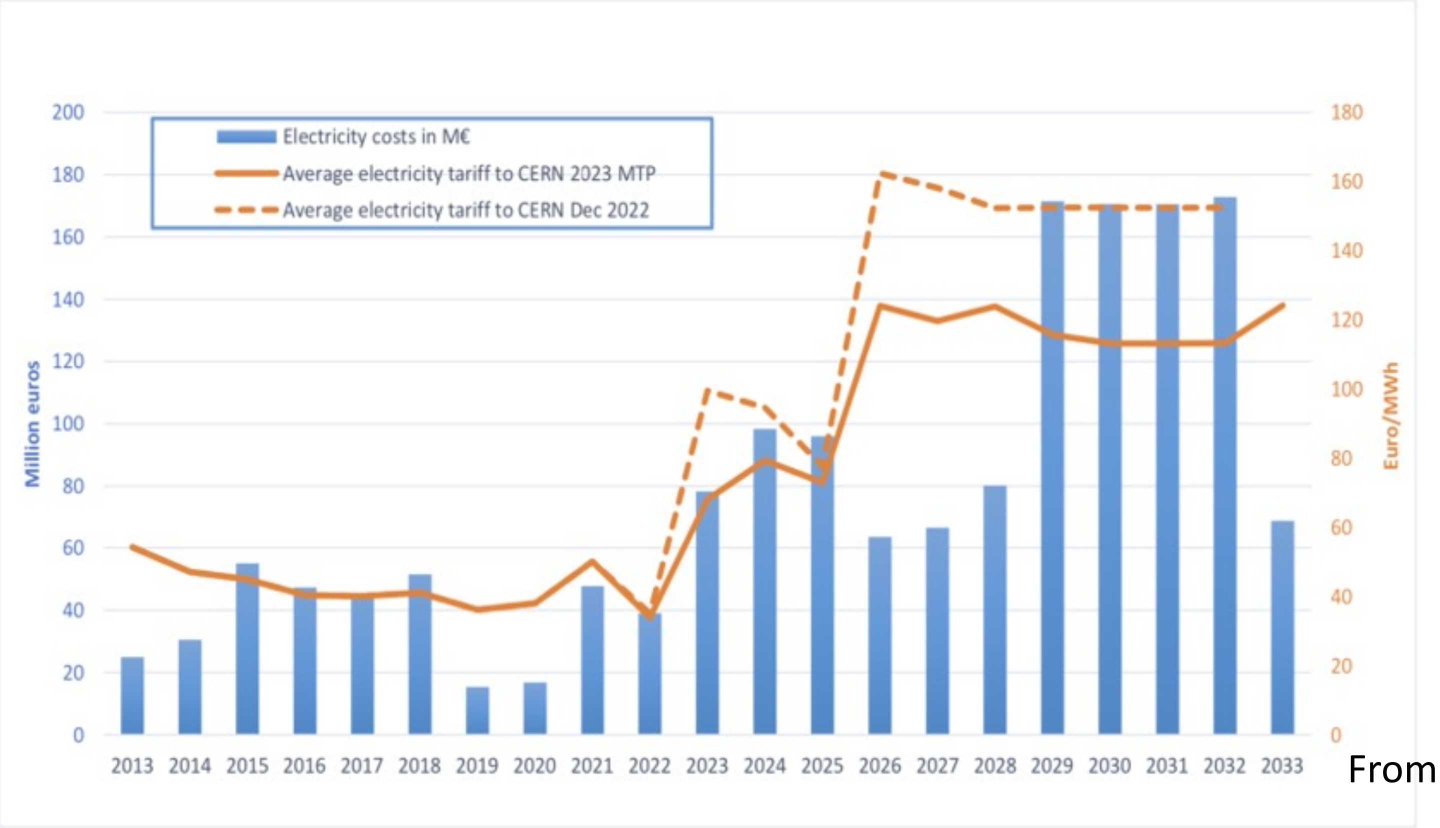
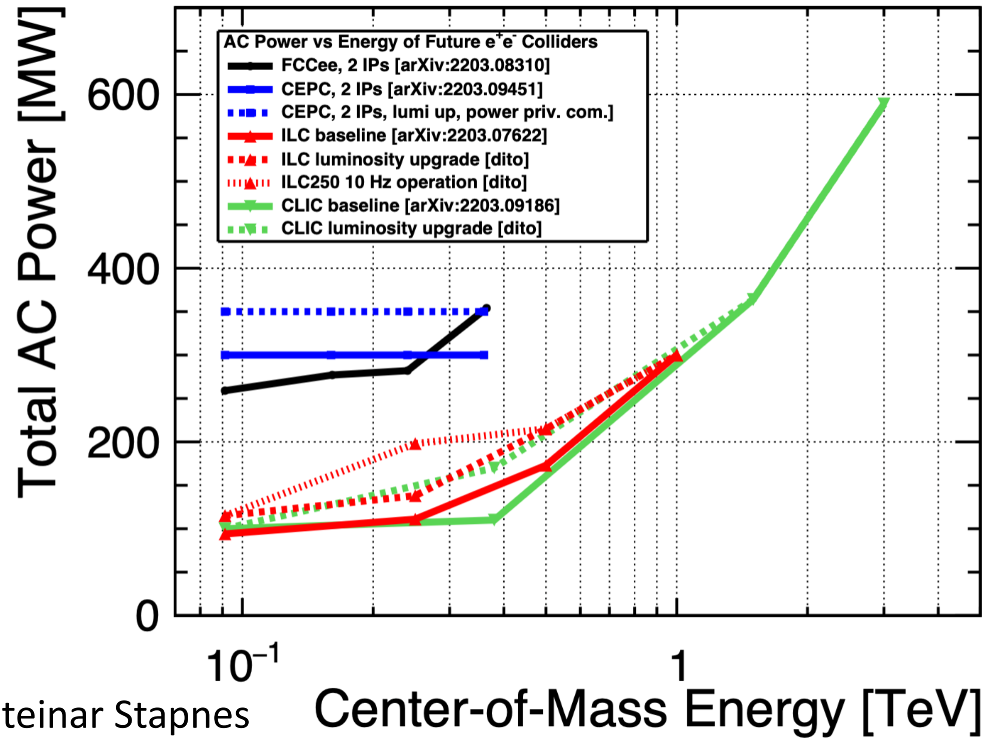
Issues: beyond Nb for sustainability and higher performance

- Niobium material is getting more and more expensive
- Cryogenic costs: infrastructure, helium, and electricity

Cryocooler
2.7 W (→ 10 W) at 4.2 K
Eg ESS@2K
spoke 7W
high-β elliptical 30 W

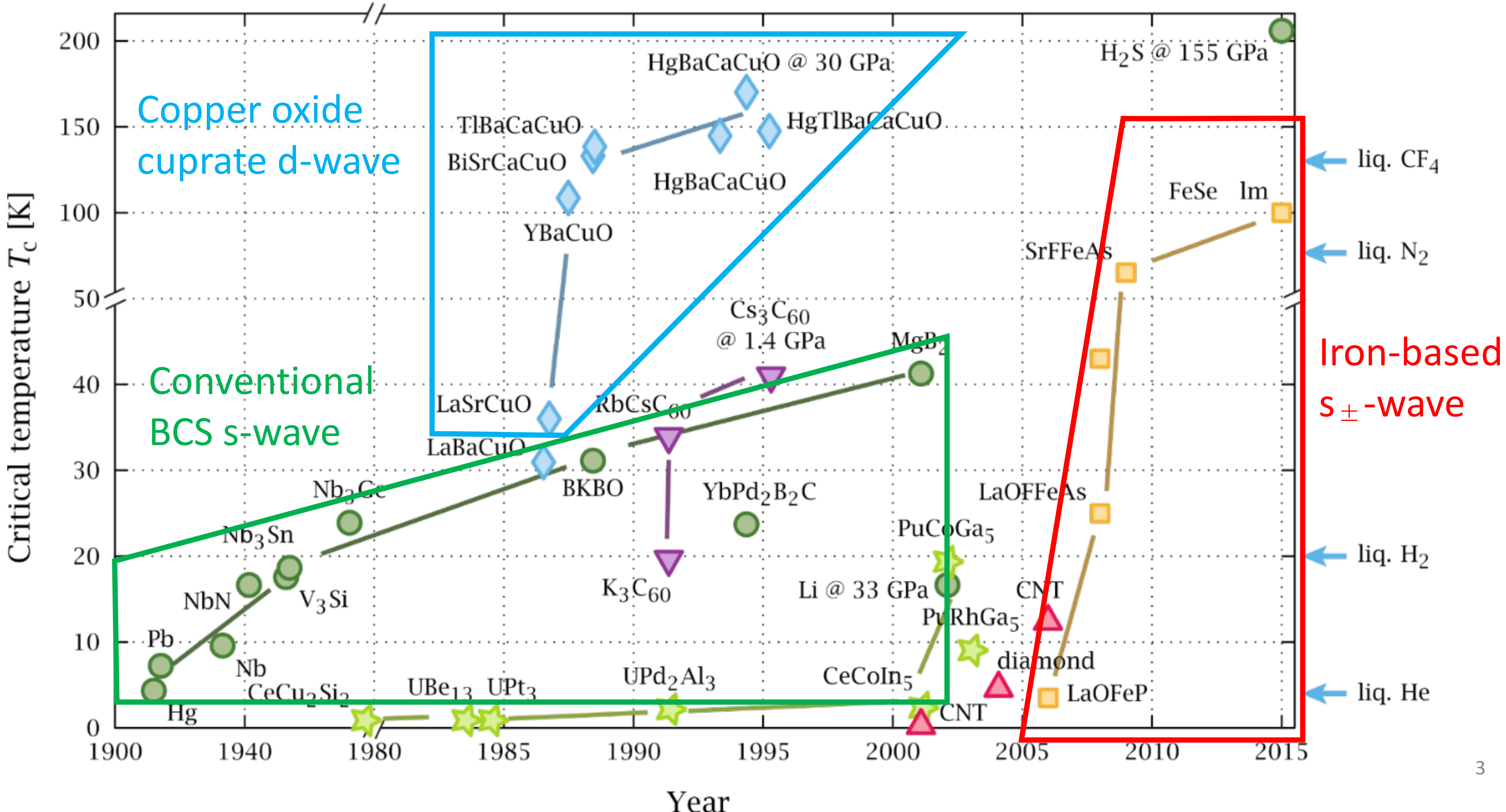




From: Steinar Stapnes

Another point: HTS market is growing

Three different families of superconductors



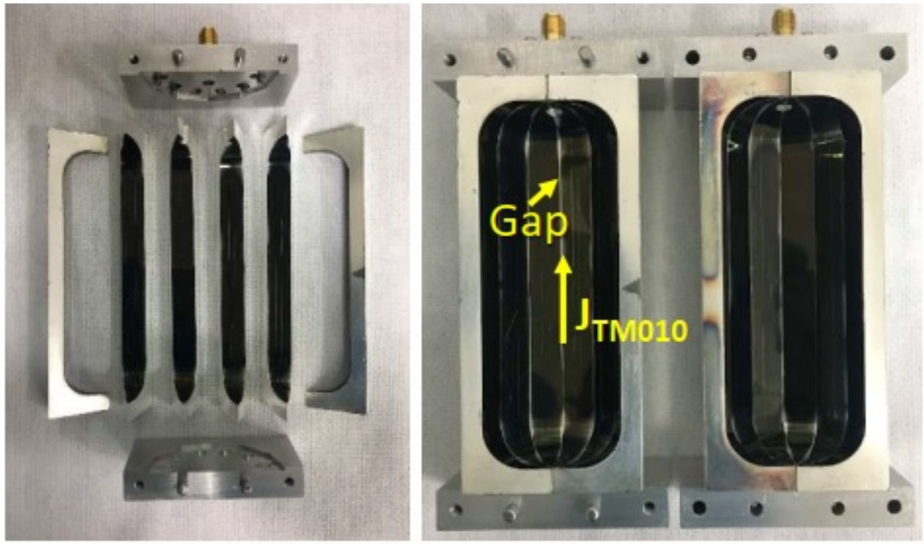
Copper oxide
cuprate d-wave

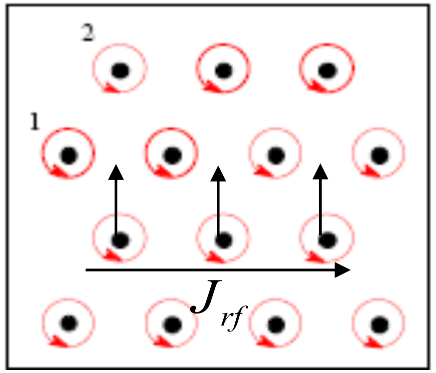
Conventional
BCS s-wave

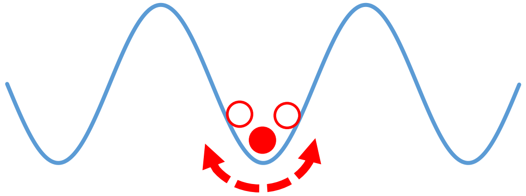
Iron-based
$s_{\pm}$-wave

HTS SRF cavities under B reaching 10^7

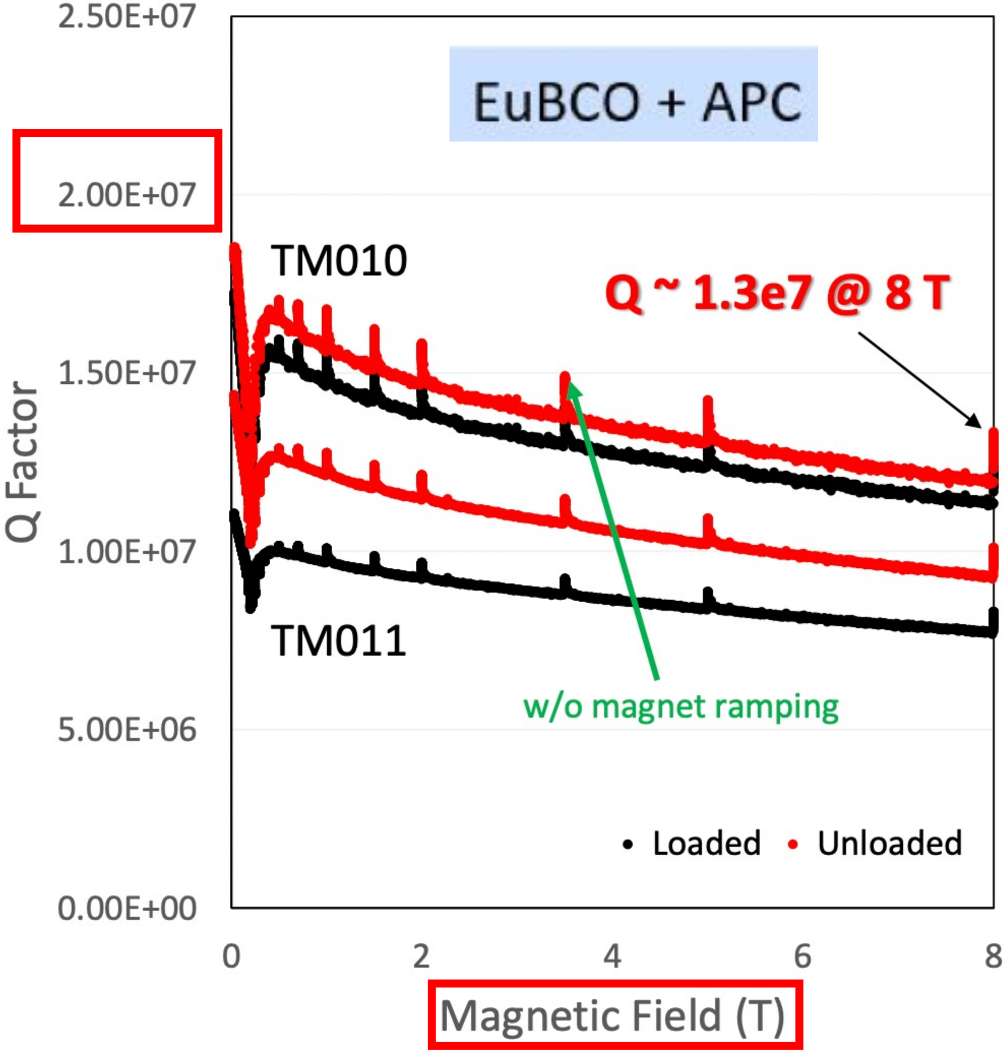
cuprate tapes on copper cavities







Danho Ahn PATRAS2022



→ How to estimate surface resistance at low B-field and lower RF frequency?

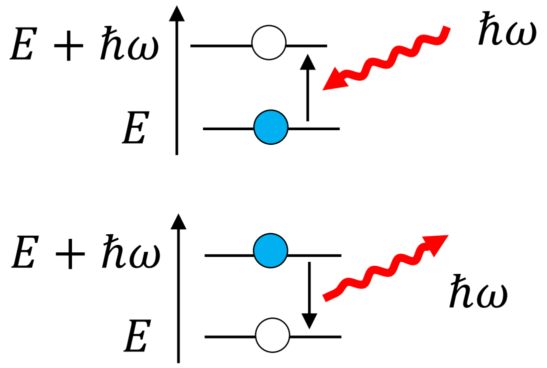
Optical conductivity in the Meissner state

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

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

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

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



Conventional s-wave (Nb, Nb_3Sn)

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

Clean MgB_2

$$\frac{N(\epsilon)}{N_0} = \sum_{\alpha=\sigma,\pi} N_\alpha \mathrm{Re}\left(\frac{\epsilon+i\delta}{\sqrt{(\epsilon+i\delta)^2 - \Delta_\alpha^2}}\right)$$

K. Watanabe and T. Kita, JPSJ 73 2239 (2004)

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

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

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

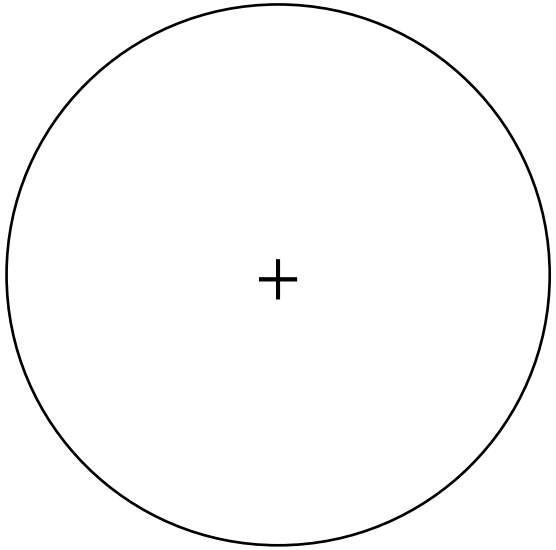
$$\Phi_{\alpha_{1,2}} = -\Phi_a$$

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

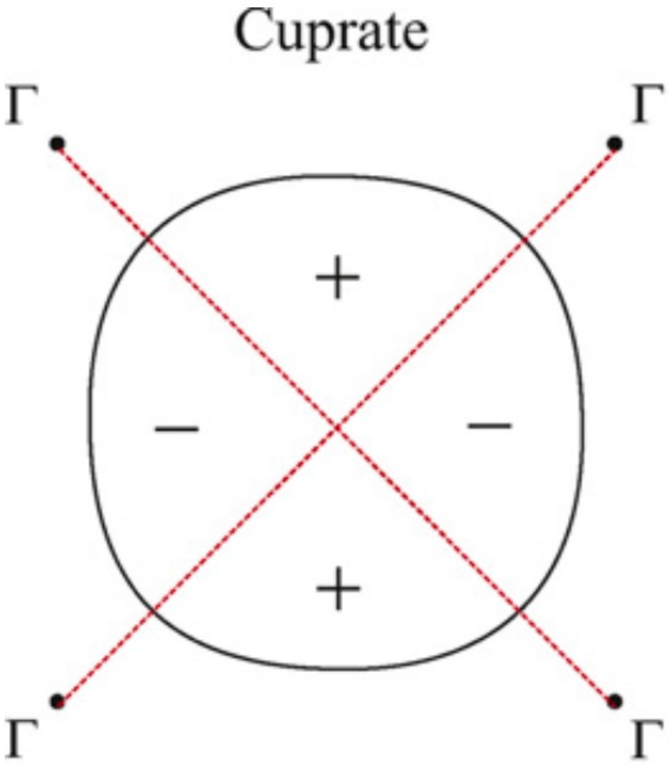
Y. Nagai et al New J. Phys. 10 103026 (2008)

Fermi surface and gap structure

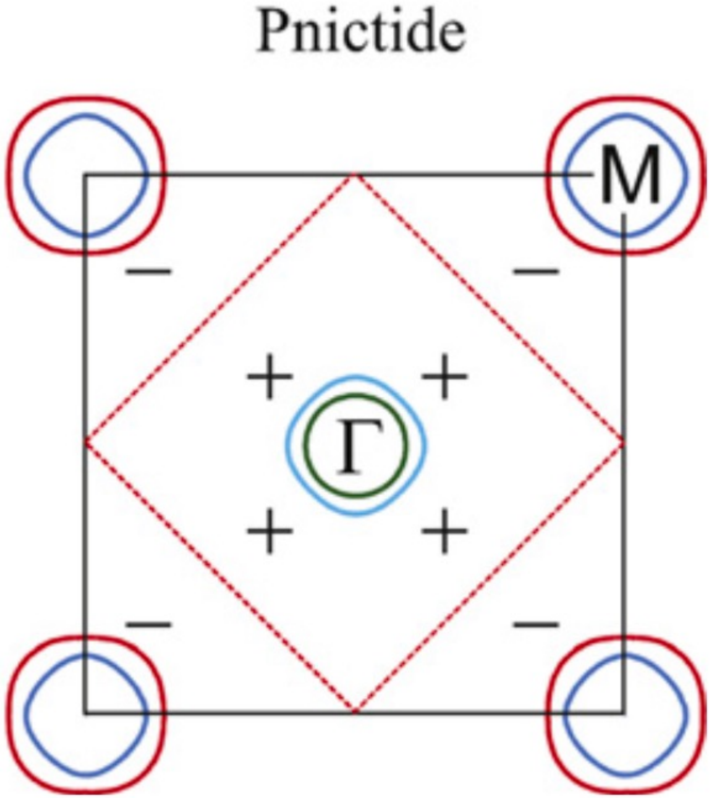
BCS



Gap-full



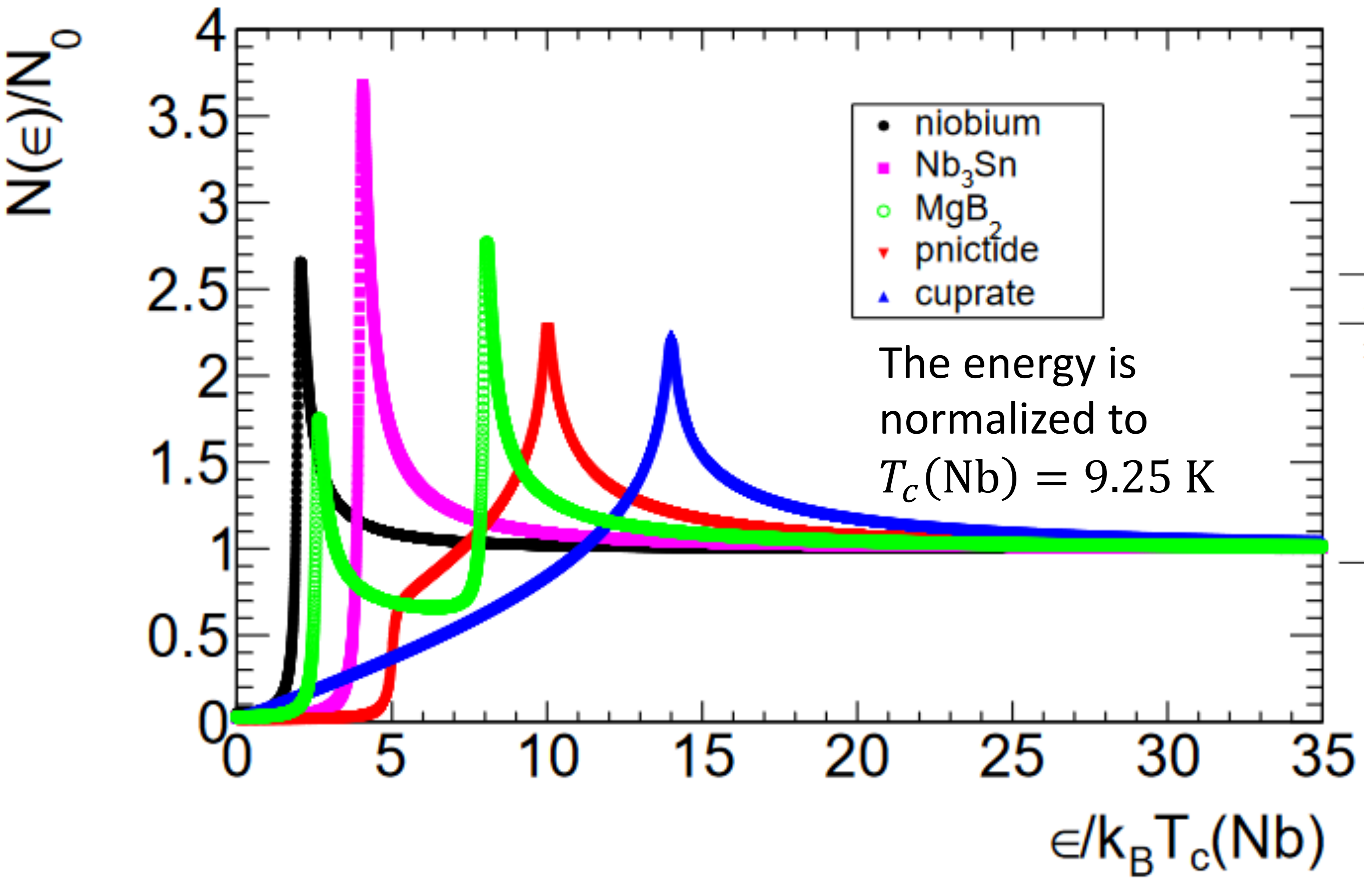
Gapless nodes



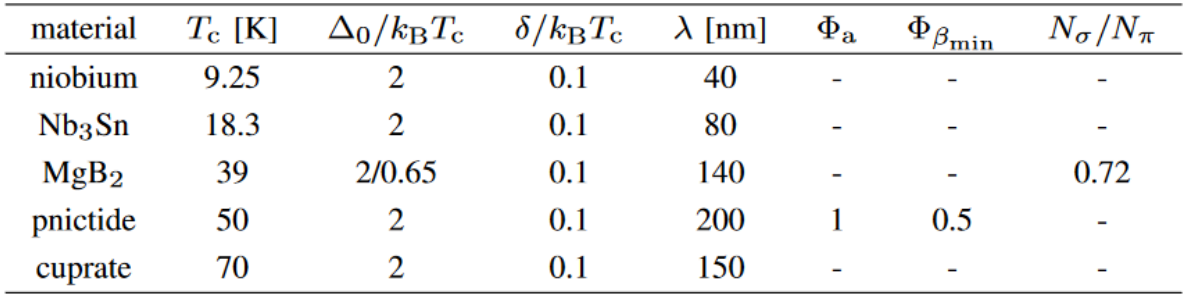
Double gap but gap-full

A. Carrington, Physique 12 (2011) 502–514

Summary of density of states



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



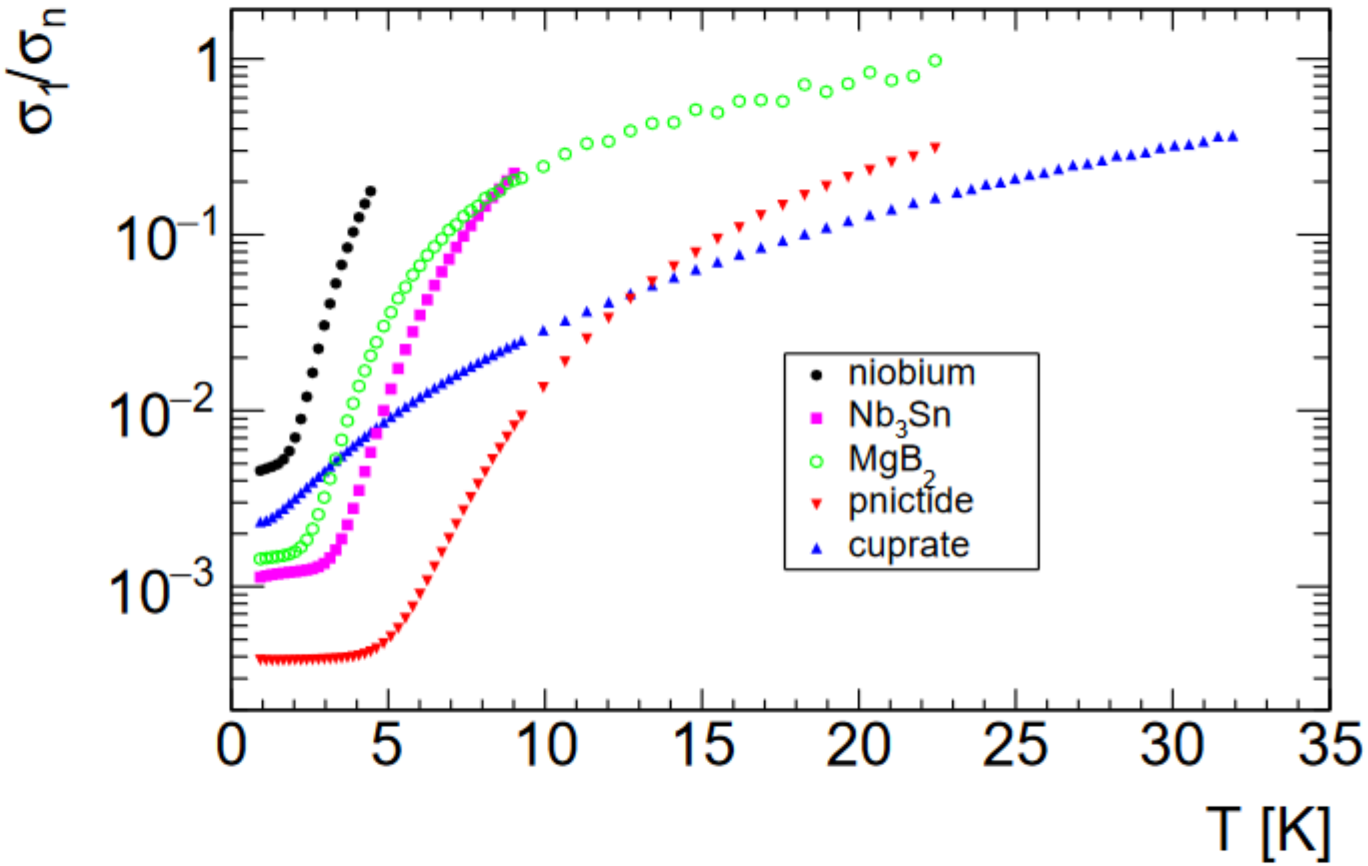
material	T_c [K]	$\Delta_0/k_\mathrm{B}T_\mathrm{c}$	$\delta/k_\mathrm{B}T_\mathrm{c}$	λ [nm]	Φ_a	$\Phi_{\beta_\mathrm{min}}$	N_σ/N_π
niobium	9.25	2	0.1	40	-	-	-
$\mathrm{Nb_3Sn}$	18.3	2	0.1	80	-	-	-
$\mathrm{MgB_2}$	39	2/0.65	0.1	140	-	-	0.72
pnictide	50	2	0.1	200	1	0.5	-
cuprate	70	2	0.1	150	-	-	-

Substitute $N(\epsilon)$ to

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

And perform numerical integral

σ_1 vs T: an example ($\omega = 0.02\sim600$ MHz)



<u>Best fitting functions</u>

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

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

$$\frac{\sigma_1(T)}{\sigma_n} = \frac{2}{3}\left(\frac{T}{\Delta_0}\right)^2 \ln^2\frac{4\Delta_0}{T}$$

PRL 71 3705 (1993)

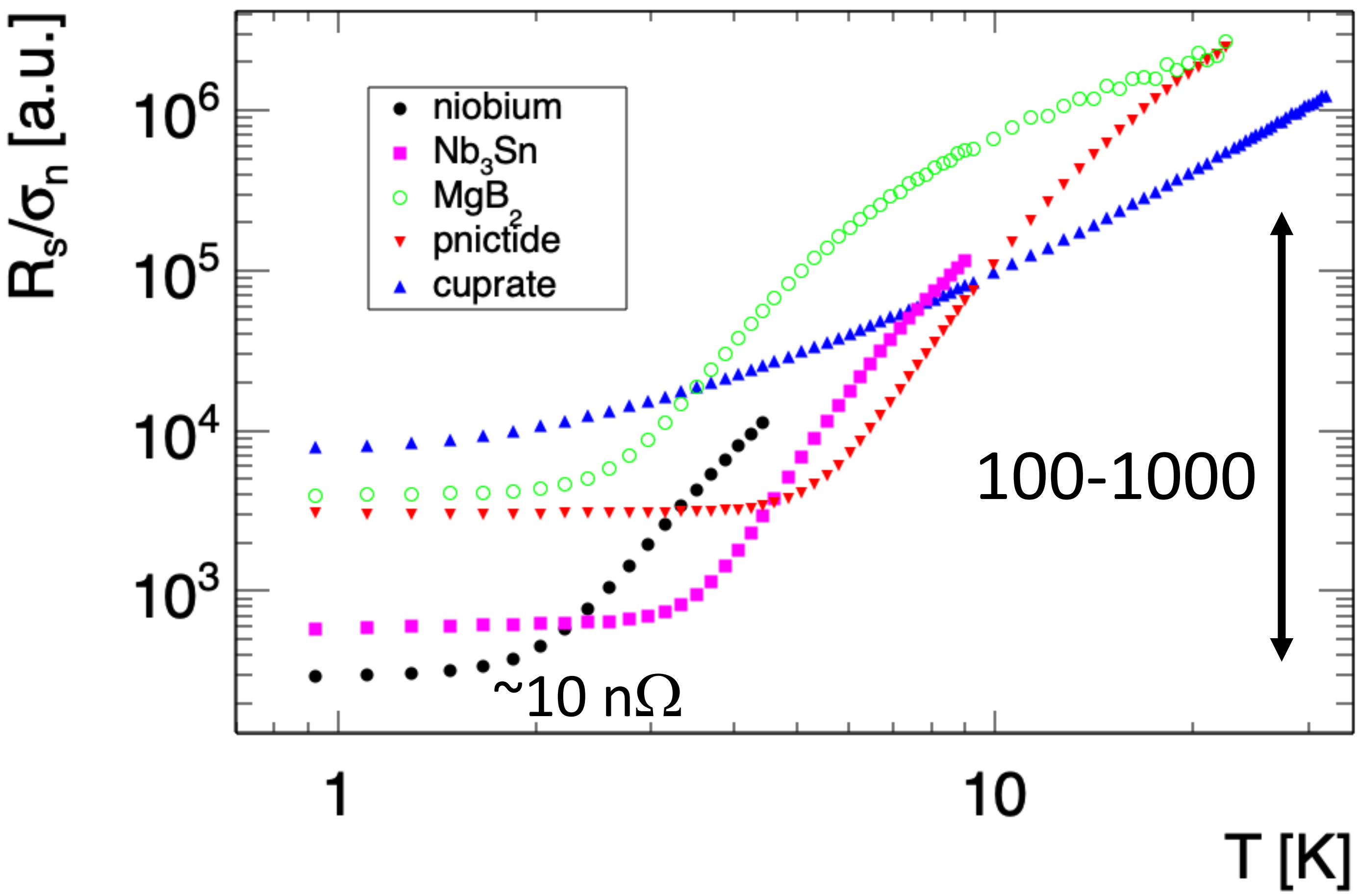
	Nb	Nb_3Sn	MgB_2	pnictide
A	81.8 ± 2.1	204.8 ± 2.9	34.0 ± 0.6	106.3 ± 2.3
Δ	20.8 ± 0.11	41.8 ± 0.11	26.8 ± 0.1	67.0 ± 0.11
B	0.0053 ± 0.0002	0.0015 ± 0.0001	0.0018 ± 0.0001	0.0006 ± 0.00006

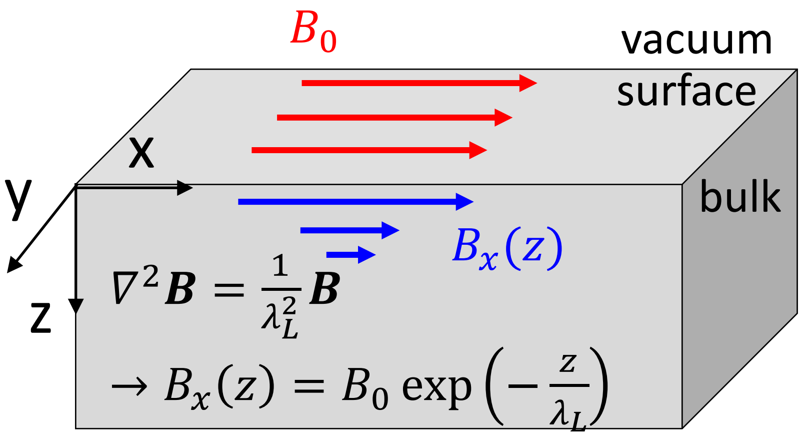
	cuprate
C	0.0001 ± 0.00005
α	2.341 ± 0.013
B	0.0038 ± 0.00036

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





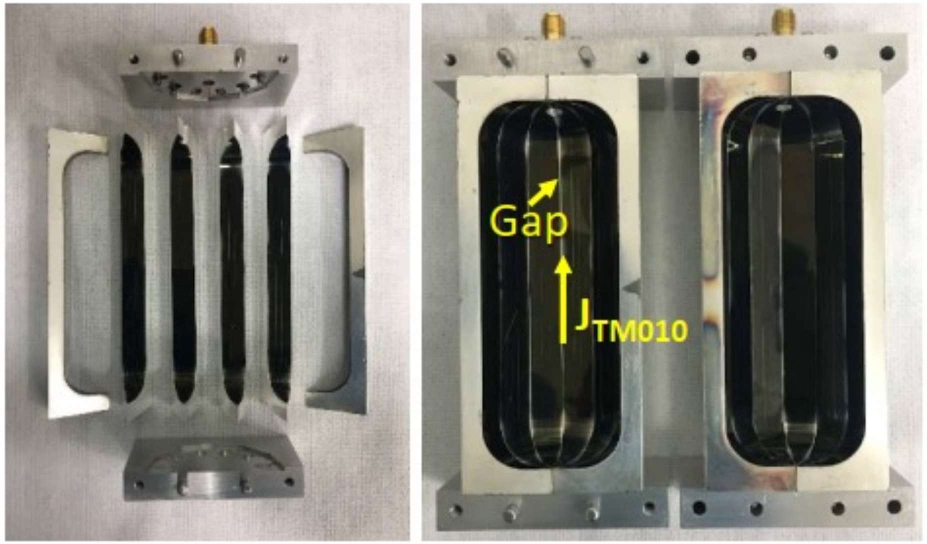
$$\nabla^2\boldsymbol{B} = \frac{1}{\lambda_L^2}\boldsymbol{B}$$

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

Thin film, multilayer

HTS: between SC and NC → pulse operation (?)

Nb $Q_0 \approx 10^{10}$, ms-CW



HTS $Q_0 \approx 10^{5\text{-}8}$, 10-100 μs

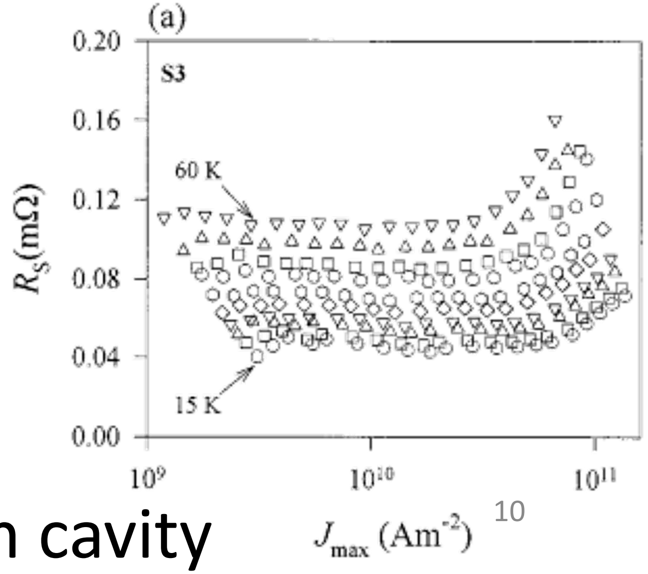
Cu $Q_0 \approx 10^4$, 1 μs

Lack of experimental data at high RF field

Microstrip resonator (200 μm, t350 nm, 8 GHz)~10^{11} A/m^2

Journal of Applied Physics 86, 2137 (1999)

→ t1 μm 10^5 A/m ~ 0.1T ~ 25 MV/m (?)



→ High gradient test at SLAC (I.FAST IIF) with the mushroom cavity

Summary

- Current SRF technology is at the risk of sustainability for the future
- Materials beyond Nb or even beyond Nb_3Sn could be useful to
    - Operate cavities at higher temperature
    - Ultimately high performance at low temperature
- A phenomenological model calculation was developed to compare s-wave, d-wave, and $s_\pm$-wave superconductors' RF performance in the Meissner state
    - High resistance due to long penetration depth → multilayer
    - Pulse operation
- More measurements are necessary!

Discussions

- More realistic modeling of the material
    - residual resistance, influence of grain boundaries, band-structure, e-ph counting, etc
- FeSe is also studied for higher gradient → H_{sh} calculation
    - Z. Lin et al SUST 34 015001 (2021)
- Deposition process: CVD, PVD (?)

Summary

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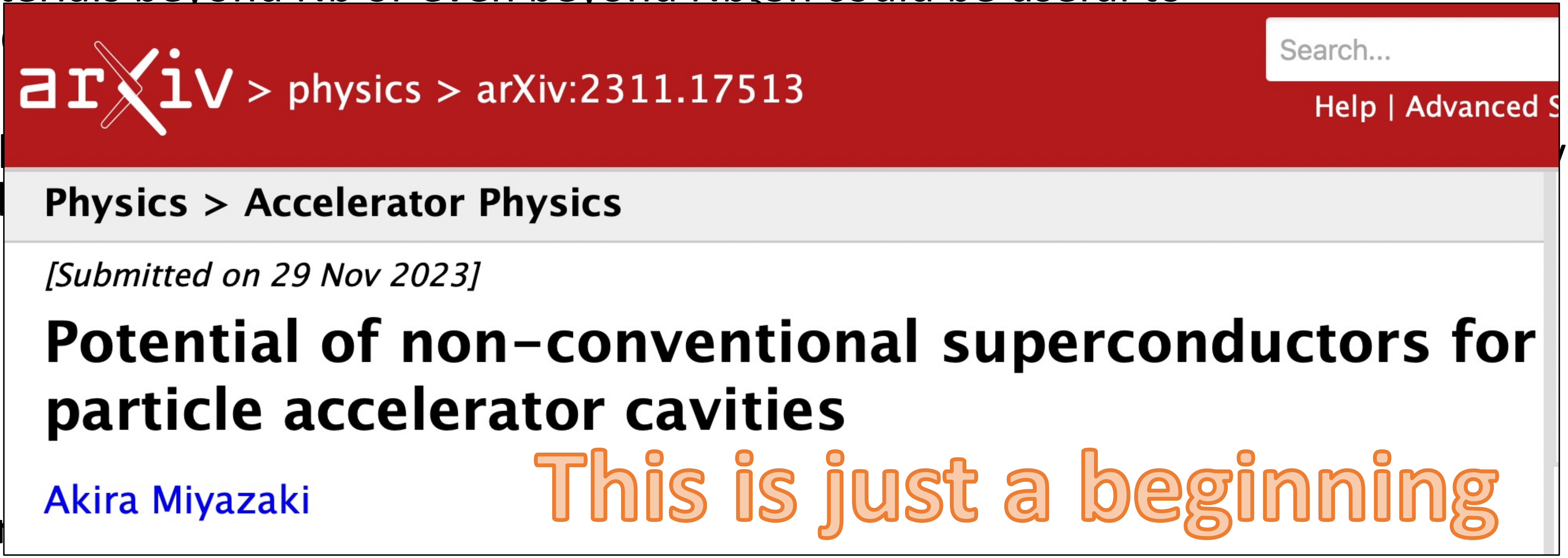

arXiv > physics > arXiv:2311.17513

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Physics > Accelerator Physics

[Submitted on 29 Nov 2023]

Potential of non-conventional superconductors for particle accelerator cavities

Akira Miyazaki

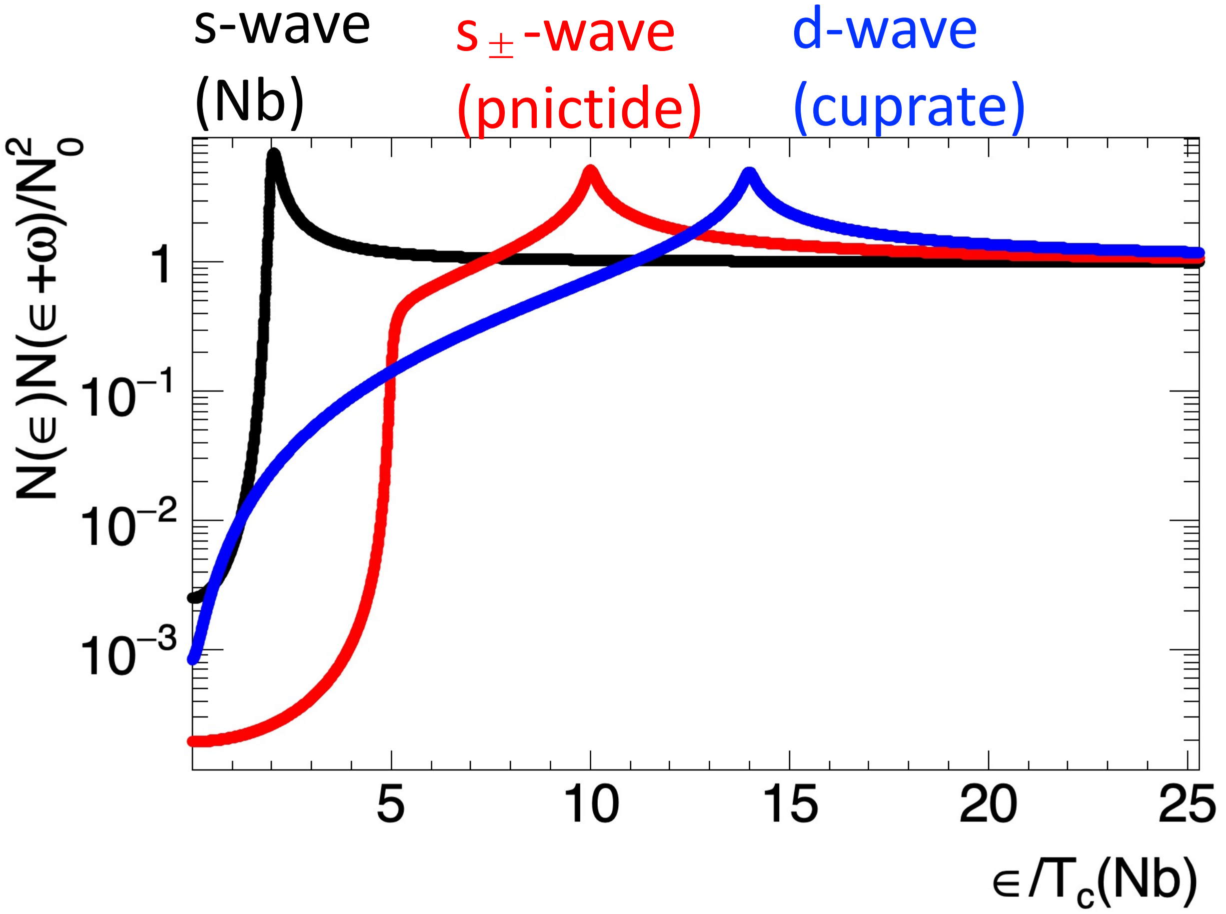
This is just a beginning

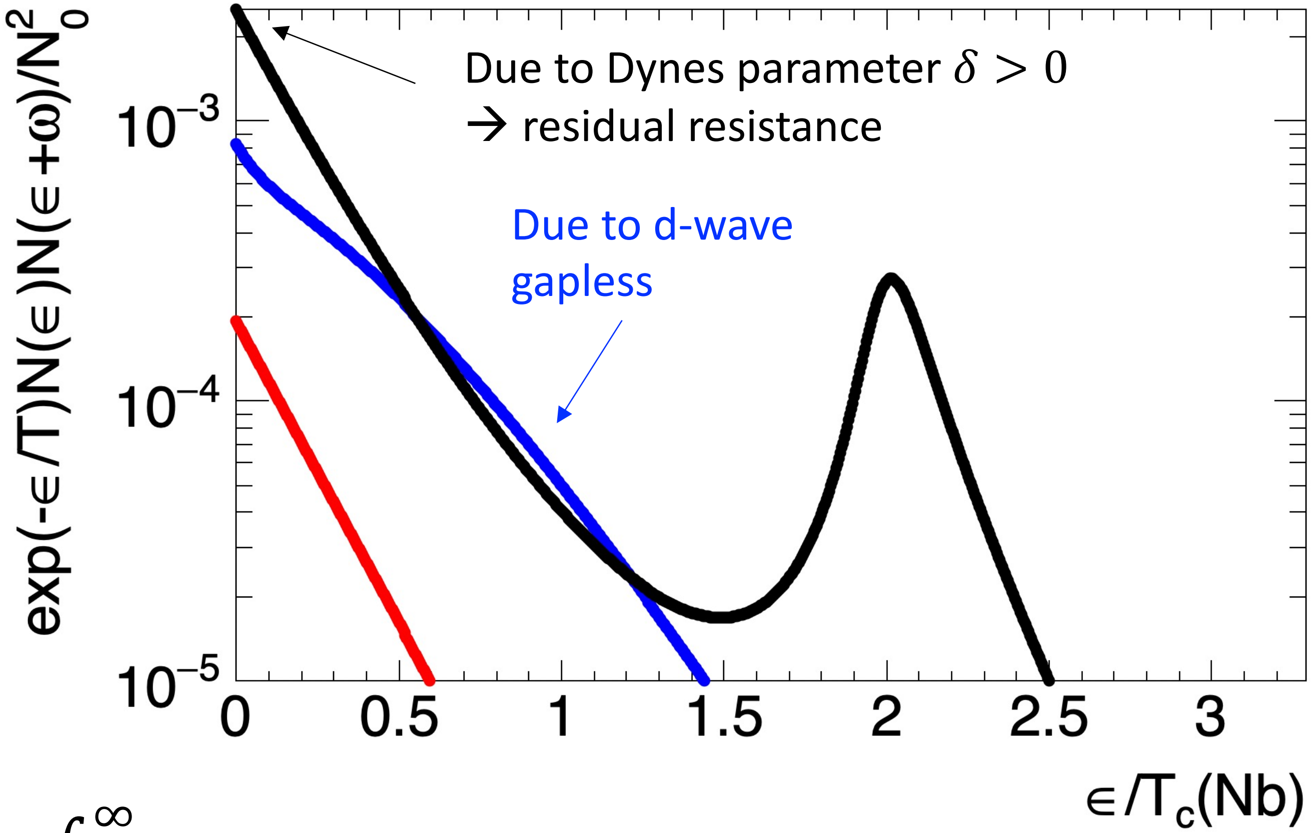
backup

Material table

Material	T_C (K)	ρ_n (μΩcm)	μ_0H_{C1} (mT)*	μ_0H_{C2} (mT)*	μ_0H_C (mT)*	μ_0H_{SH} (mT)*	λ (nm)*	ξ (nm)*	Δ (meV)	Type
Pb	7,1		n.a.	n.a.	80		48			I
Nb	**9,22**	**2**	**170**	**400**	**200**	**219**	**40**	**28**	**1.5**	**II**
NbN	**17,1**	**70**	**20**	**15 000**	**230**	**214**	**200-350**	**<5**	**2.6**	**II**
NbTi			4-13	>11 000	100-200	80-160	210-420	5,4		
NbTiN	17,3	35	30	15 000?			150-200	<5	2.8	II
Nb_3Sn	**18,3**	**20**	**50**	**30 000**	**540**	**425**	**80-100**	**<5**	**<5**	**II**
Mo_3Re	15	10-30	30	3 500	430	170	140			II
MgB_2	**39**	**0.1-10**	**30**	**3 500**	**430**	**170**	**140**	**5**	**2.3/7.2**	**II- 2gaps****
2H-$NbSe_2$	7,1	68	13	2680-15000	120	95	100-160	8-10		II- 2gaps**
YBCO/Cuprates	**93**		**10**	**100 000**	**1400**	**1050**	**150**	**0,03/2**		**d-wave****
Pnictides $Ba_{0.6}K_{0.4}Fe_2As_2$	**38**		**30**	**>50000**	**900**	**756**	**200**	**2**	**10-20**	**s/d wave****

$N(\epsilon)N(\epsilon+\hbar\omega)$ and $\boldsymbol{e^{-\epsilon/kT}}N(\epsilon)N(\epsilon+\hbar\omega)$ $(T=0.2,\, \omega=0.02)$





Due to Dynes parameter $\delta > 0$
→ residual resistance

Due to d-wave gapless

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