New Materials for SRF Cavities (here “new” means “alternative”)

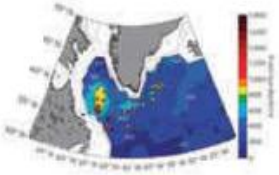
Tsuyoshi Tajima

KEK

On leave from LANL

E. Hand, *Nature* 456 (2008) 555.

NATURE|Vol 456|4 December 2008 NEWS



OCEAN MIXING
North Atlantic overturning restarts after stagnant decade.
www.nature.com/news

Can triniobium tin shrink accelerators?

The superconducting cavities that drive most of the world's particle accelerators are running out of room for improvement. But

A theoretical prediction of E_{acc} at 2 K is mentioned.

Nb_3Sn 120 MV/m

MgB_2 200 MV/m

to improve the performance of superconducting cavities. When stacked in a row and pumped with microwave pulses, they build up large electromagnetic fields that accelerate the charged particles used in particle-physics experiments, or in

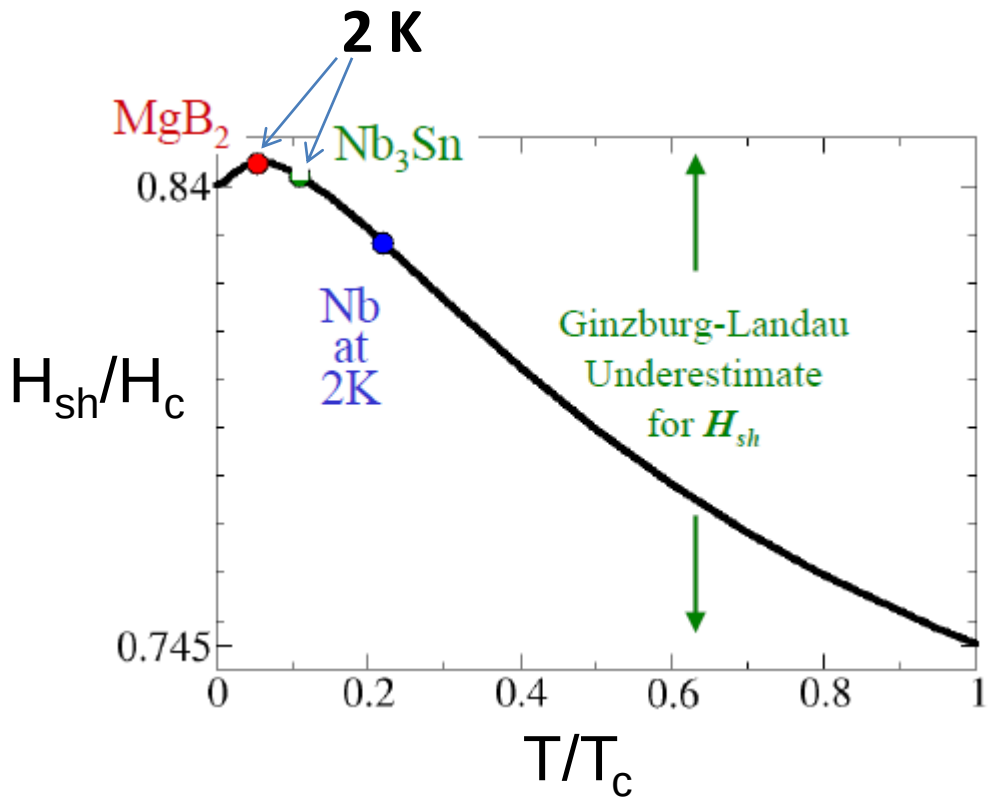
C. SCHMID/DESY

need thousands of cavities, stretching along a tunnel 31 kilometres long, to help it produce energies of 500 gigaelectron-volts. And that's if its niobium cavities can reach ambitious target gradients of a bit more than 30 MeV per metre (see graph). Ramping up the gradients to a theoretically possible peak of 200 MeV per metre could significantly reduce the length of the ILC, therefore also reducing costs of most of its physical parts such as tunnels and beamlines.

Breaking the limits

According to Sethna, old theories describing the limits of superconducting materials didn't correctly account for ultracold operating temperatures or vortices in the superconductors, which,

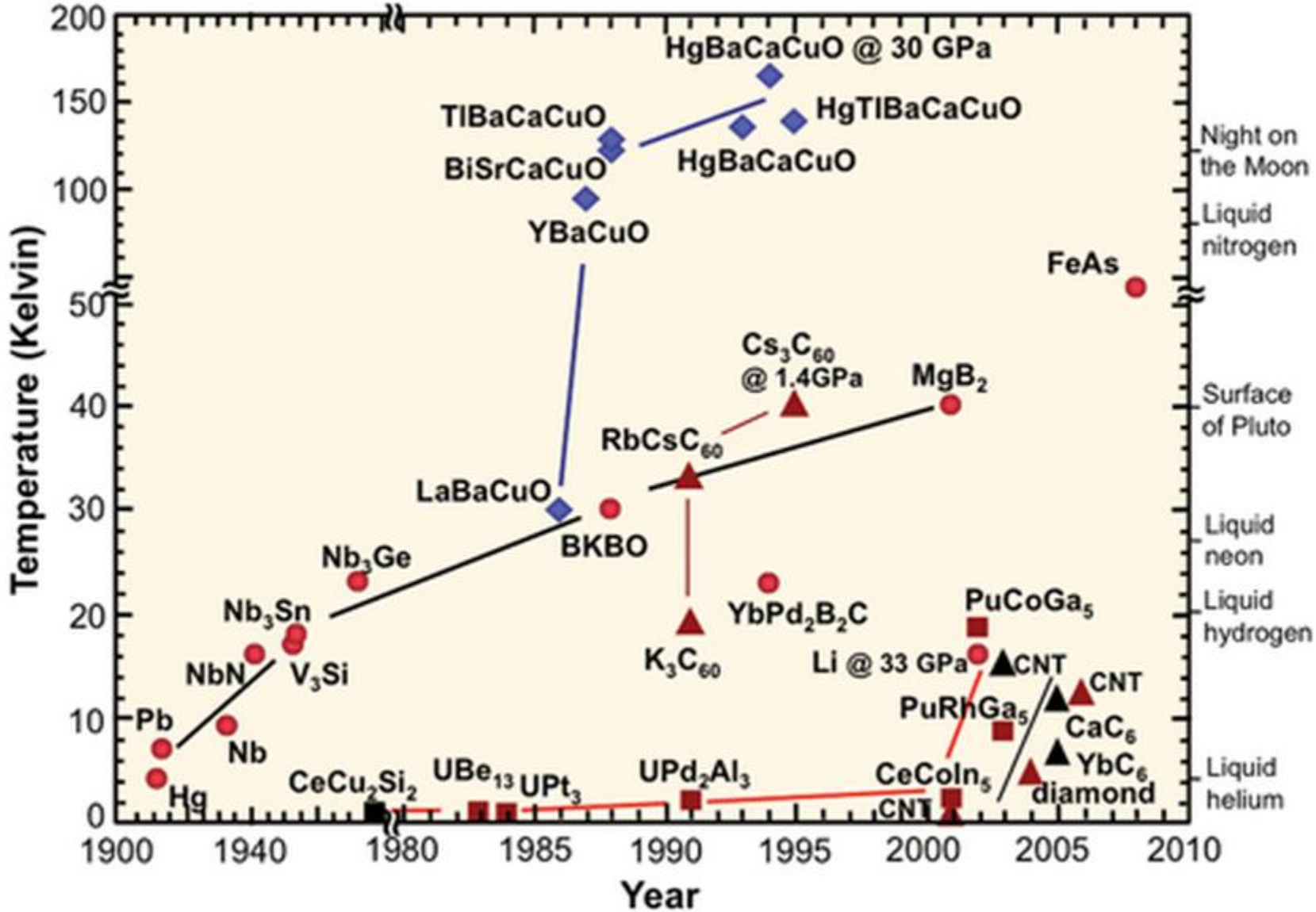
G-L theory is only valid in the vicinity of T_c .
At $T << T_c$, $H_{sh} \neq 0.75\ H_c$ (this was obtained from G-L equations)
Solving Eilenberger's equation which is applicable to any T gives
Max. $H_{sh} = 0.845\ H_c$ @ $T/T_c = 0.06$ [1]



[1] G. Catelani, J. Sethna, PRB **78** (2008) 224509.

Discoveries of Superconductors

http://en.wikipedia.org/wiki/File:Sc_history.gif



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Clicking this leads you to a list of past SRF workshop proceedings

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DIPAC'03	ICALEPCS'03	SRF'03	Cyclotrons'04
APAC'04	LINAC'04	RuPAC'04	PAC'05
ICALEPCS'05	SRF'05	EPAC'06	LINAC'06

What have been discussed in the past SRF Conference/Workshop Tutorials

- SRF2009 (Berlin)
  - Ruben Hühne, "High Temperature Superconductors: Properties and Applications."
- SRF2007 (Beijing)
  - A-M Valente-Feliciano, "SRF Materials Other Than Nb."
  - V. Palmieri, "Thin Film Review."
  - X. Xi, "Prospects for Higher T_c Superconductors for SRF Application" (Talk)

What I will talk about today

- First 40 minutes
  - Important factors for the material to be used for SRF cavities
  - Brief overview of some materials
  - Nb_3Sn
- Break (10 minutes)
- Second 40 minutes
  - MgB_2
  - Multilayer SC thin films concept to enhance the breakdown field (proposed by Alex Gurevich in 2005)

Important factors for the material to be used for SRF cavities

- Low RF surface resistance for high Q_0 to reduce the consumption of liquid helium
- High H_{c1} and H_{sh} for high gradient (vortices cause RF losses)
- Good thermal conductivity (in the case of bulk material)
- Practically,
  - Should not degrade over time
  - Can be cleaned with high-pressure water rinse
  - Can have a smooth surface

RF surface resistance (R_s)

$$R = R_{BCS} + R_{residual}$$

Intrinsic resistance derived from BCS theory

Note that Weingarten [1] includes the following contributions to analyze Q_0 - E_{acc} curves

- the non-linear surface resistance, R_{nl} (B, f, T)
- the surface resistance describing dielectric losses, $R_{diel}(f)$
- the surface resistance describing the low-field Q increase, $R_{Q\text{-}inc}$ (B, f, T).

[1] W. Weingarten, Proc. SRF2009, p. 347.

Low normal-state resistivity at ~T_c (ρ_n) and larger energy gap (Δ) are important to have low BCS resistance

At $T<T_c/2$

$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\eta\omega}{\pi\Delta}\right)^{\frac{3}{2}}\frac{\sigma_1}{\sigma_n} = A\sqrt{\rho_n}\, e^{-\frac{\Delta}{K_B T}}\left(1+O(\Delta,\omega,T)\right)$$

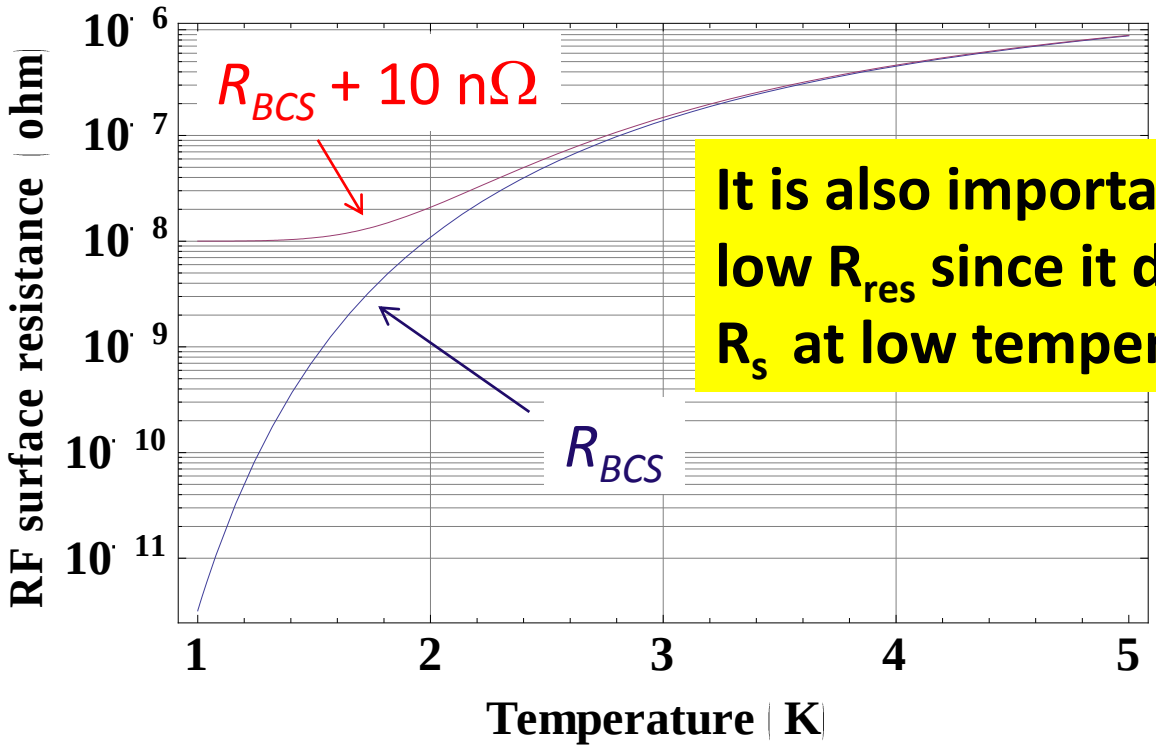
A & B constants weakly dependent on material
ω = RF frequency
ρn = Normal State conductivity
Λ = Penetration depth
Tc = Transition Temperature

[1] A-M Valente-Feliciano, SRF 2007 Tutorial
[2] V. Palmieri,

A convenient expression and a good fit of BCS resistance [1]

$$R_{BCS} = 2\times10^{-4}\,\frac{1}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

f : RF frequency in GHz

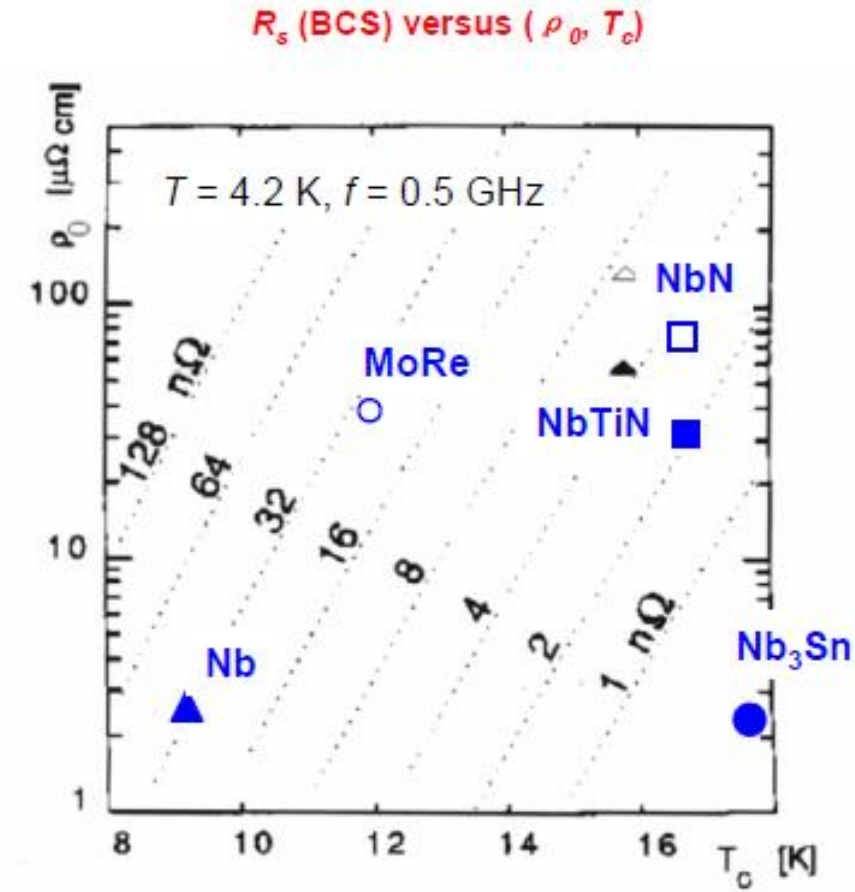


It is also important to have low R_{res} since it dominates R_s at low temperatures

[1] H. Padamsee, J. Knobloch and T. Hays, *RF Superconductivity for* Accelerators, John Wiley & Sons, Inc. ©1998, p. 88.

Overview of some materials that have been studied (excluding MgB_2)

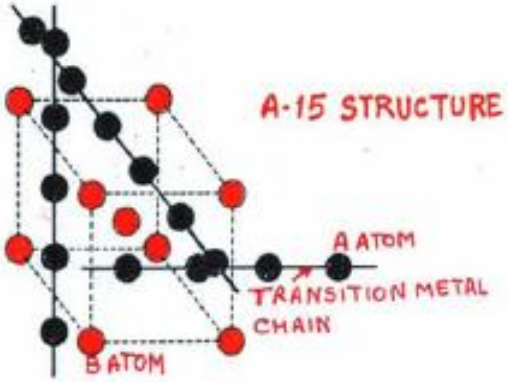
X. Xi, SRF2007



R. Vaglio, *Particle Accelerators* **61** (1998) 391

— B1 compounds: NbN, NbTiN, etc. High resistivity.

— A15 compounds: Nb_3Sn, V_3Si, Mo_3Re, etc.



Some Candidate Materials

Material	Nb	Nb_3Sn	MgB_2	NbN	NbTiN	Mo_3Re
T_c [K]	9.2	18.3	39	16.2	17.5	15
ρ_n [$\mu\Omega$·cm]	2	20	0.3-5 [2]	70	35	
λ (0) [nm]	40	85	140	200	151	140
ξ [nm]						
$\kappa = \lambda_L/\xi$						
H_c (0) [mT]	200	540	430	230		430
H_{c1} (0) [mT]	170	50	30	20	30	30
H_{c2} (0) [T]	0.4	30	3.5	15		3.5
H_{sh} (0) [mT]						
Ref.						

[1] most data are from A-M. Valente-Feliciano, SRF2007 tutorial
[2] C. Zhuang et al., SUST 22 (2009) 025002.

Iron-based superconductors

- In February 2008, a superconductivity based on iron (Fe) and a “pnictide” (e.g., arsenic) was discovered [1, 2].

[1]http://www.ncnr.nist.gov/news/FeAsSuperconductors.html

[2] Y. Kamihara et al. *J. Am. Chem. Soc.* 130 (2008) 3296

Various types of iron-based superconductors and their T_c's [http://en.wikipedia.org/wiki/Iron-based_superconductor]

oxypnictide	T_c (K)	non−oxypnictide	T_c (K)
$LaO_{0.89}F_{0.11}FeAs$	26[8]	$Ba_{0.6}K_{0.4}Fe_2As_2$	38[9]
$LaO_{0.9}F_{0.2}FeAs$	28.5[10]	$Ca_{0.6}Na_{0.4}Fe_2As_2$	26[11]
$CeFeAsO_{0.84}F_{0.16}$	41[8]	$CaFe_{0.9}Co_{0.1}AsF$	22[12]
$SmFeAsO_{0.9}F_{0.1}$	43[8]	$Sr_{0.5}Sm_{0.5}FeAsF$	56[13]
$La_{0.5}Y_{0.5}FeAsO_{0.6}$	43.1[14]	LiFeAs	<18[15][16]
$NdFeAsO_{0.89}F_{0.11}$	52[8]	NaFeAs	9−25[17][18]
$PrFeAsO_{0.89}F_{0.11}$	52[19]	FeSe*	<27[20][21]
$GdFeAsO_{0.85}$	53.5[22]	$BaFe_{1.8}Co_{0.2}As_2$ +	25.3[23]
$SmFeAsO_{\sim 0.85}$	55[24]		

Applicability to SRF is unknown.

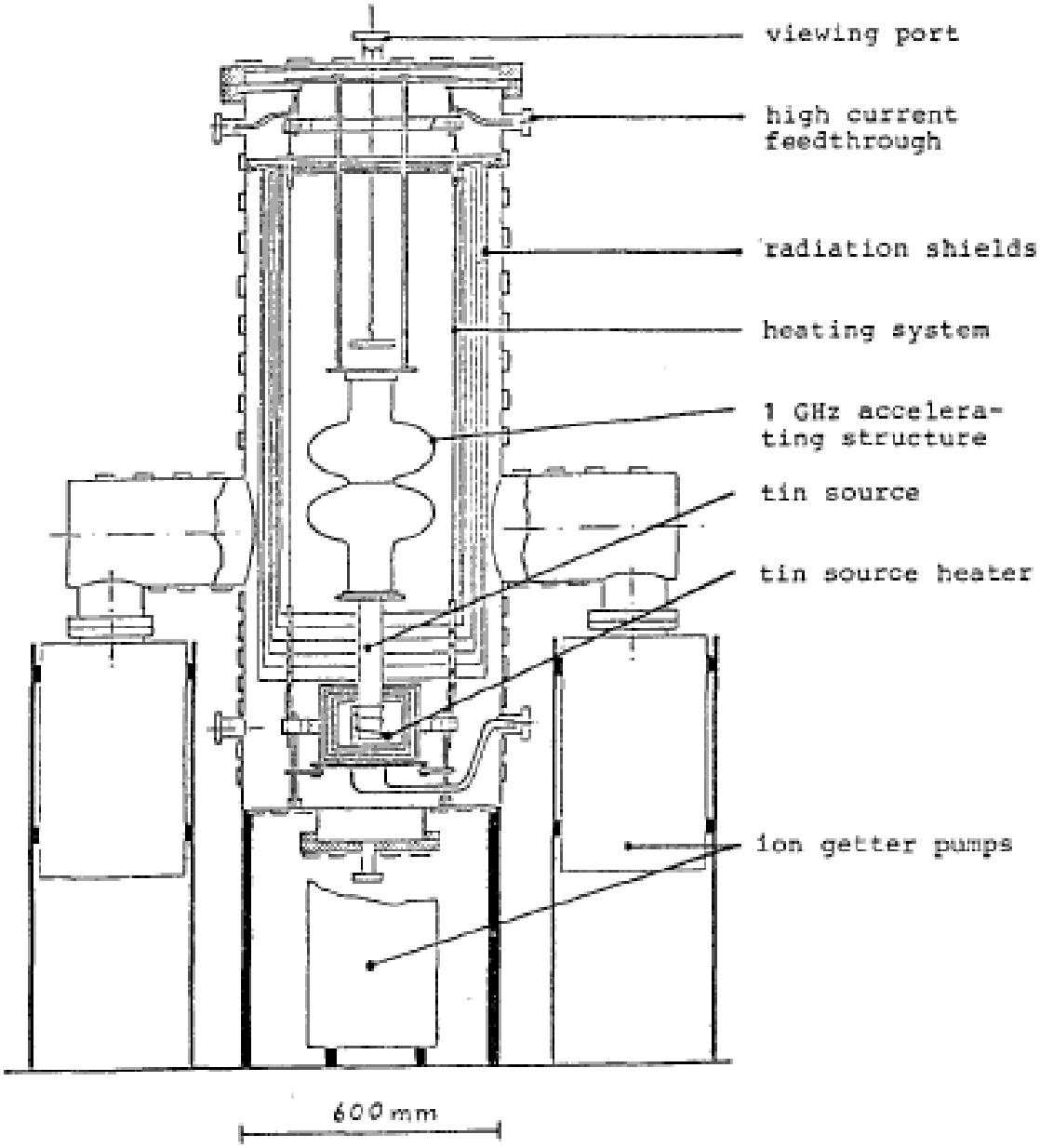
Nb_3Sn

- The only material with some success up to cavity shape 1.5 GHz [1]
- Sn vapor diffusion method developed at Wuppertal Univ. in the '80s and '90s [2]

[1] G. Mueller et al. EPAC1996.

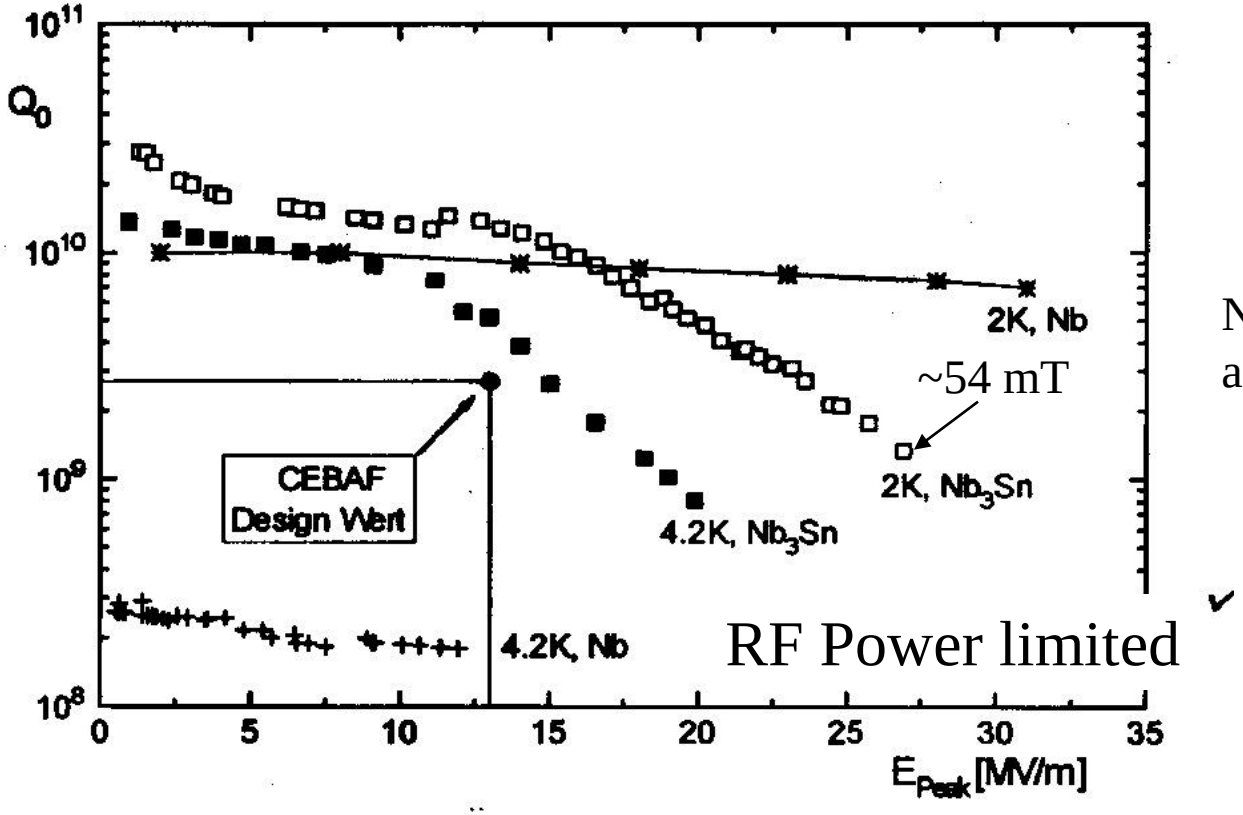
[2] M. Peiniger et al. SRF1987.

Coating system for 1 GHz cavities [2]



Nb_3Sn

One 1.5 GHz single-cell cavity result has shown that CEBAF accelerator could be operated at 4.2 K with Nb_3Sn cavities instead of using Nb cavities at 2 K



Cavity Q_0 was ~50x Nb at low field at 4.2 K!!

Best R_{res} = 2.2 nΩ!

Nb_3Sn coating at Wuppertal and measurement at JLAB

G. Mueller et al. EPAC1996

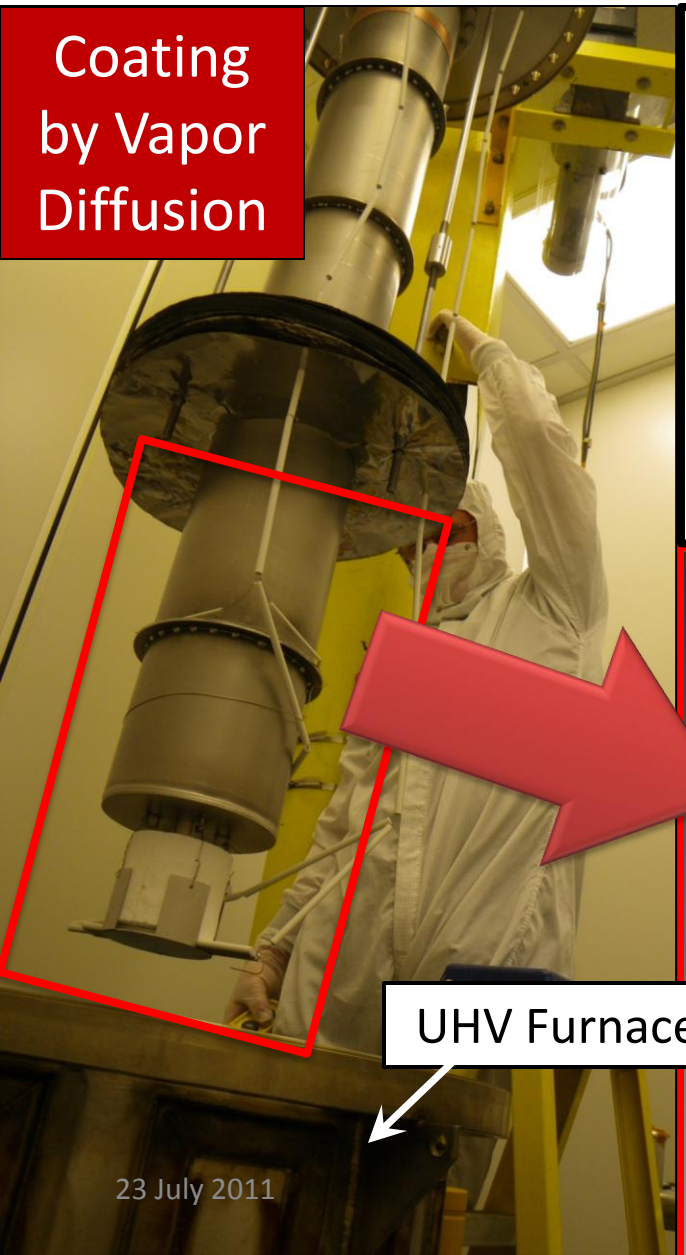
Recent activities at Cornell using Sn vapor diffusion method

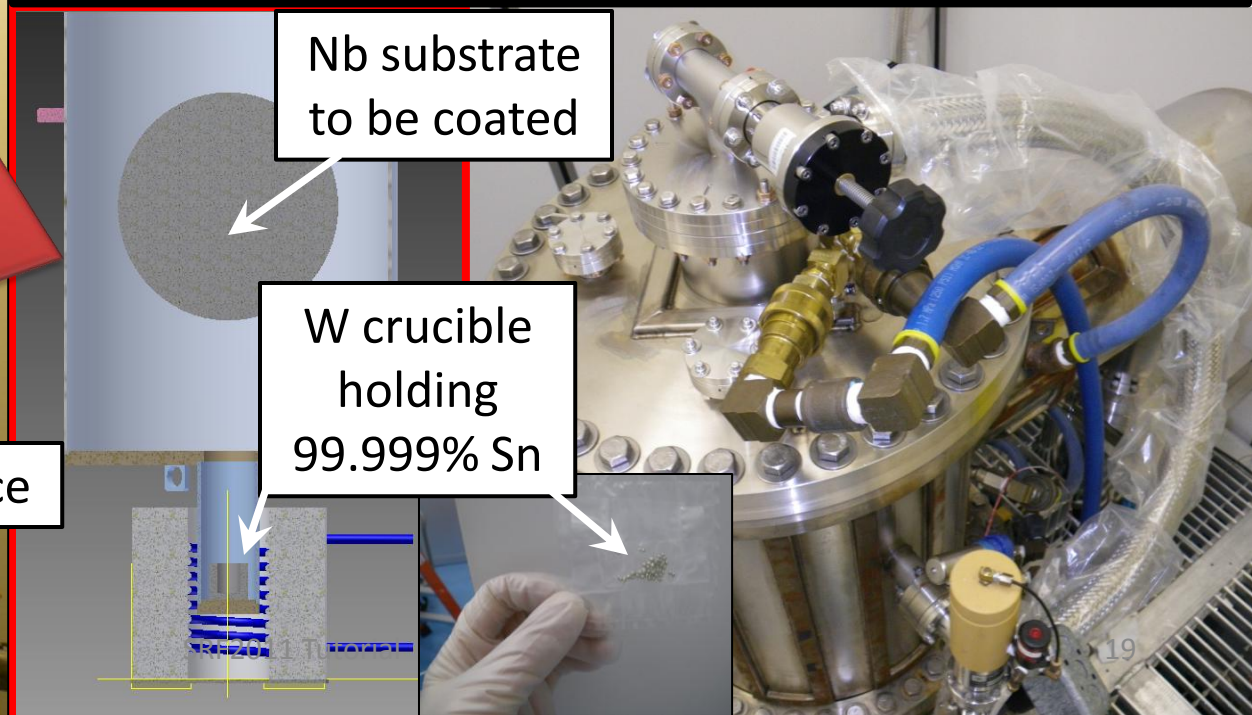
The following slides were provided by Yi Xie, Sam Posen and Matthias Liepe

Nb_3Sn Fabrication at Cornell

Coating by Vapor Diffusion

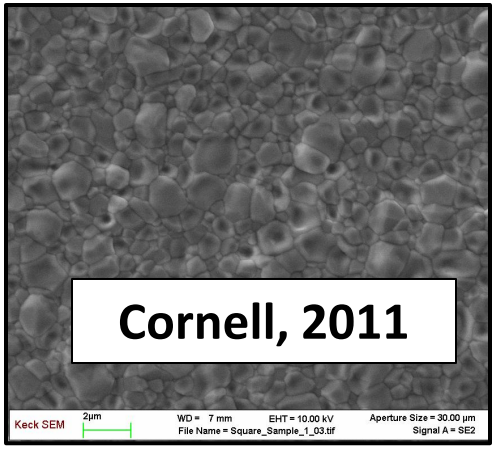
Coating procedure follows work of Müller et al., Wuppertal in 80s and 90s, but with addition of HPR, EP, full cavity T-mapping, cavity dissection at bad spots…

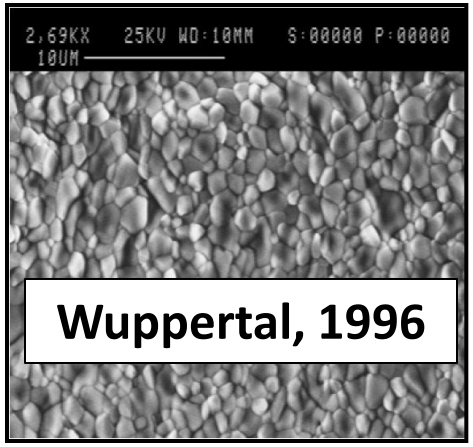


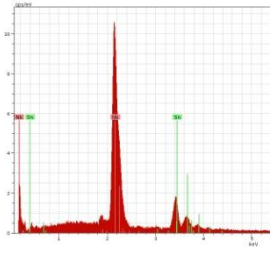


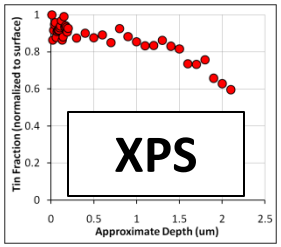
Nb_3Sn Fabrication at Cornell

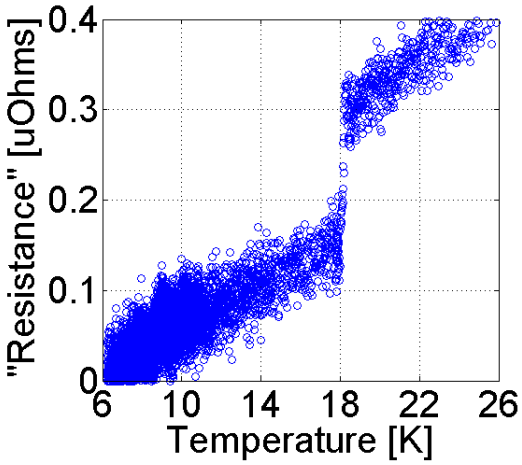
Tests for Nb_3Sn: SEM images of new micron-sized grains, anodization color, EDX measurements, XPS measurements, T_c measurements. Measurements confirm stoichiometric Nb_3Sn.

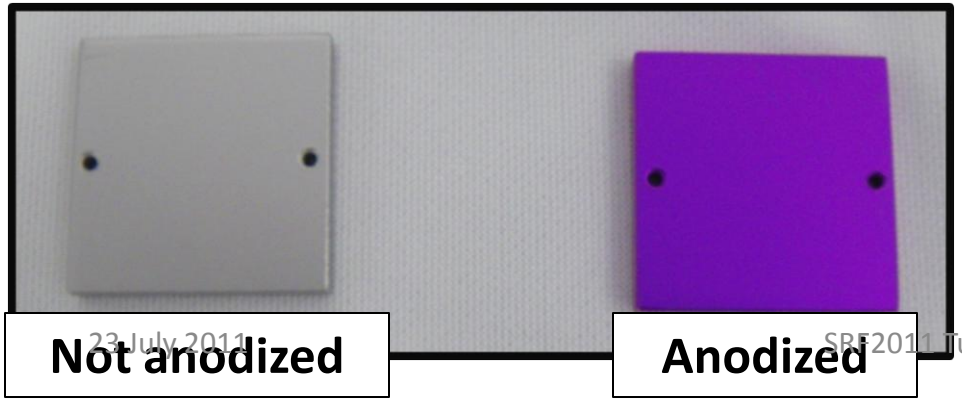








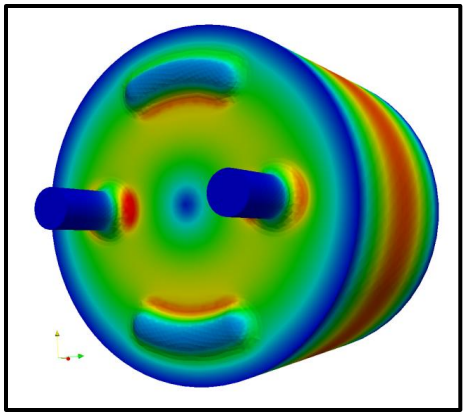


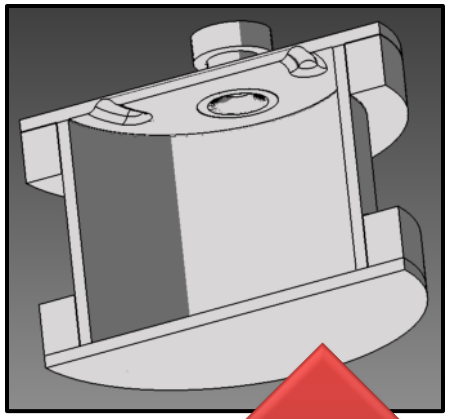


See Sam Posen's poster THPO066

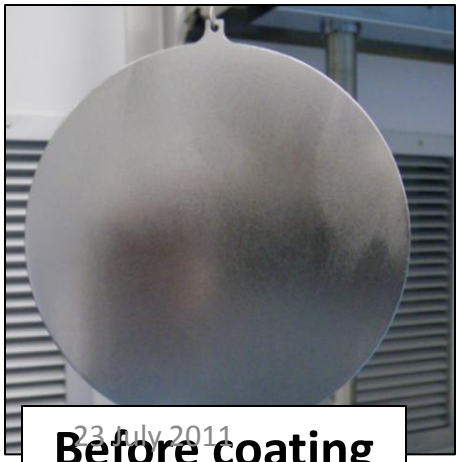
RF Tests of Samples at Cornell

Generate sample with size of 3.75”, 3mm thick bottom plate of Pillbox TE cavity. Surface fields up to 400 Oe already demonstrated! Nb_3Sn plate already made and will be tested very soon!



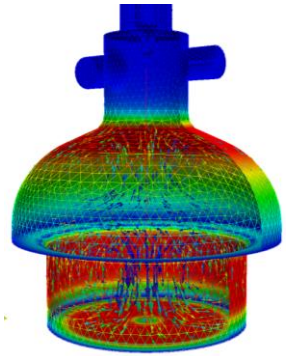


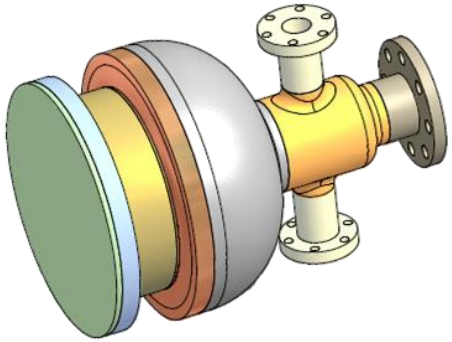
Next step: Mushroom TE cavity. Designed to reach >200 mT on sample! Then full cavities!



Before coating

With Nb_3Sn coating





See Yi Xie’s poster THPO050

Acknowledgements

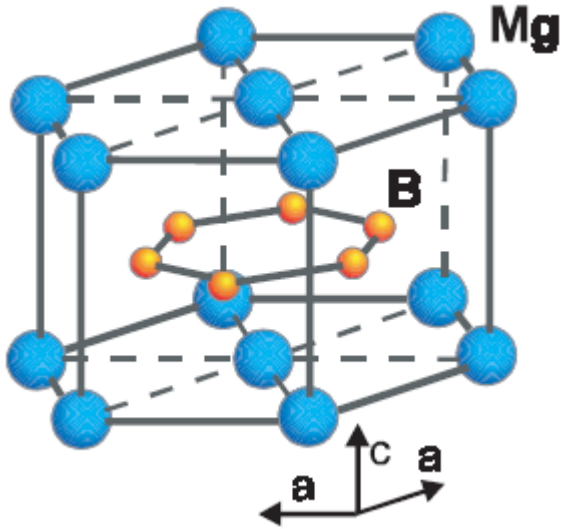
- I would like to thank the following people who have provided me with the slides for this presentation.

M. Liepe, S. Posen, Yi Xie,

- Also, I would like to thank the following people whose data were used in this presentation.

G. Catelani, S. Deambrosis, E. Hand, T. Hays, P. Kneisel, G. Mueller, J. Knobloch, H. Padamsee, V. Palmieri, M. Peiniger, J. Sethna, R. Vaglio, A-M. Valente Feliciano, W. Weingartin, X. Xi

Break (10 minutes)



- Relatively easy to deposit compared to other higher-TC SC.
- Absence of weak links ⇒ Less Q_0 drop as H (equiv. of E) goes up.
- Similar behavior to other low-temperature superconductors except for 2-gap nature

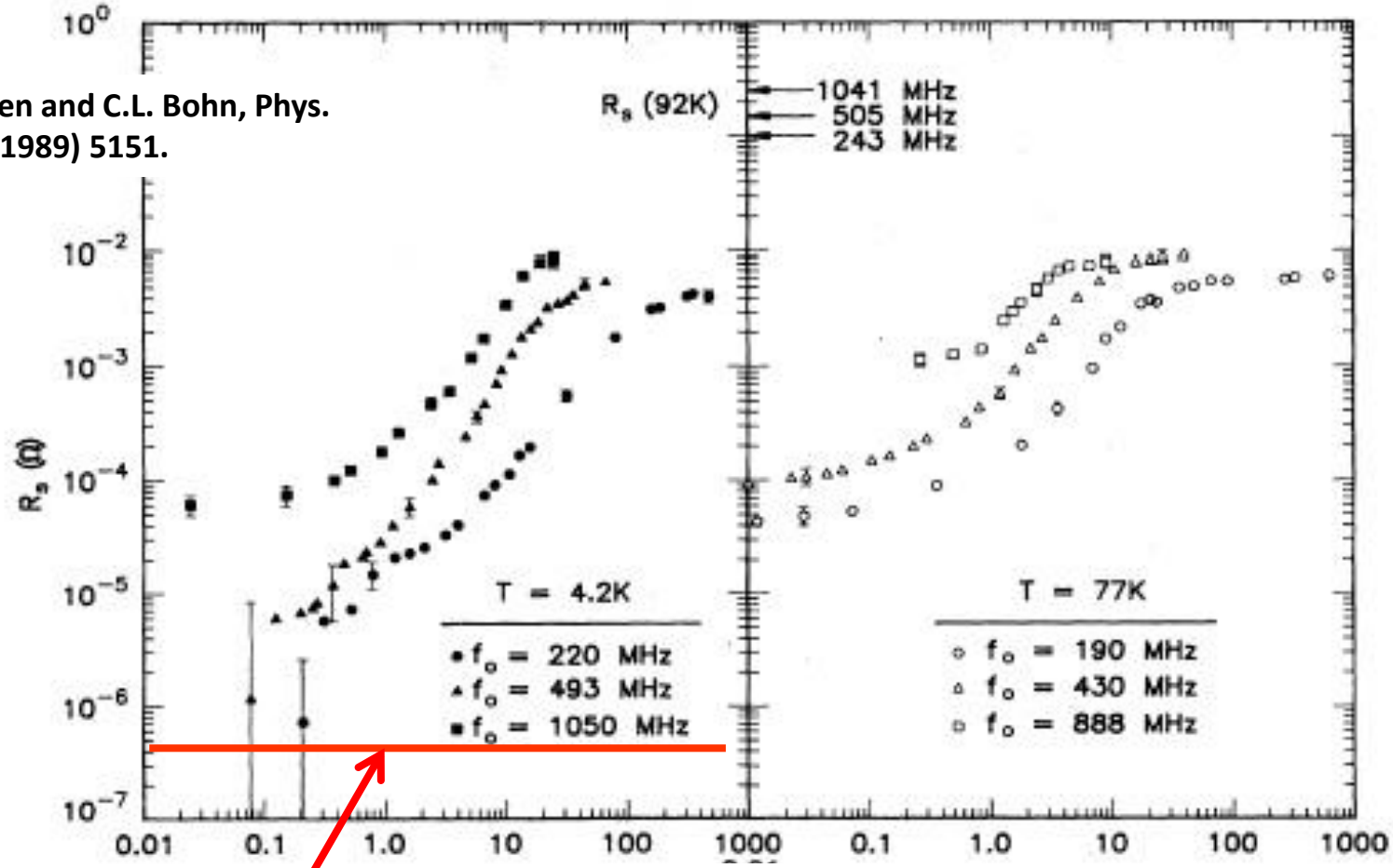
[**Cristina Buzea and Tsutomu Yamashita**, Supercond. Sci. Technol. **14** (2001) R115–R146]

Magnesium Diboride (MgB_2)

Discovered by Jun Akimitsu et al. of Aoyama Gakuin Univ., Japan, in 2001 (Announced in January) [J. Nagamatsu et al., *Nature* 410 (2001) 63.]

R_s of YBCO: Rapid increase with magnetic field prevented us from using high-T_c materials

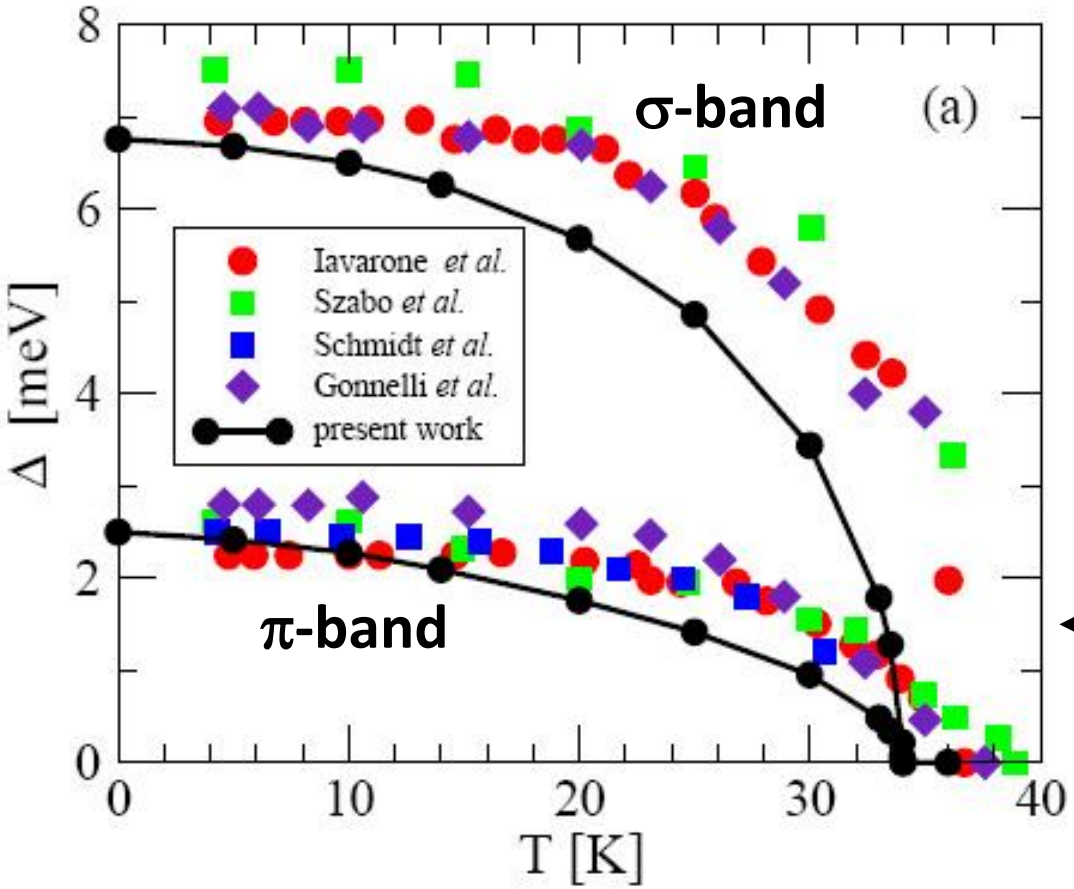
J.R. Delayen and C.L. Bohn, Phys. Rev. B40 (1989) 5151.



BCS R_s of Nb @ 1 GHz 4.4×10^{-7} Ω

RF Magnetic field (Oe)

MgB_2 has two energy gaps. Unfortunately, the lower energy gap seems to dominate for RF.

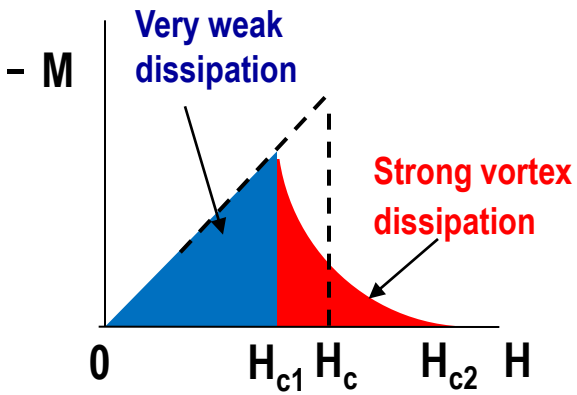


RF response has shown lower energy gap behavior.

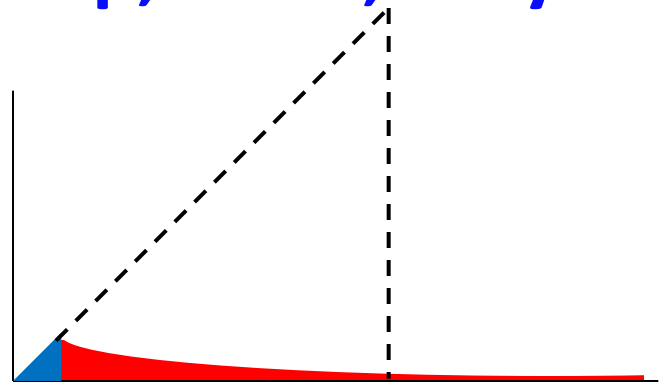
Nb energy gap ~1.5 meV

A. Floris et al., cond-mat/0408688v1 31 Aug 2004

Superconducting Materials [A. Gurevich, SRF Materials Workshop, FNAL, May 2007]



Nb



Higher-H_c SC

Very weak dissipation at $H < H_{c1}$ ($Q = 10^{10}$-10^{11})
Q drop due to vortex dissipation at $H > H_{c1}$

Nb has the highest lower critical field H_{c1}

Material	T_c (K)	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
Pb	7.2	0.08	na	na	48
Nb	9.2	0.2	0.17	0.4	40
Nb_3Sn	18	0.54	0.05	30	85
NbN	16.2	0.23	0.02	15	200
MgB_2	40	0.43	0.03	3.5	140
YBCO	93	1.4	0.01	100	150

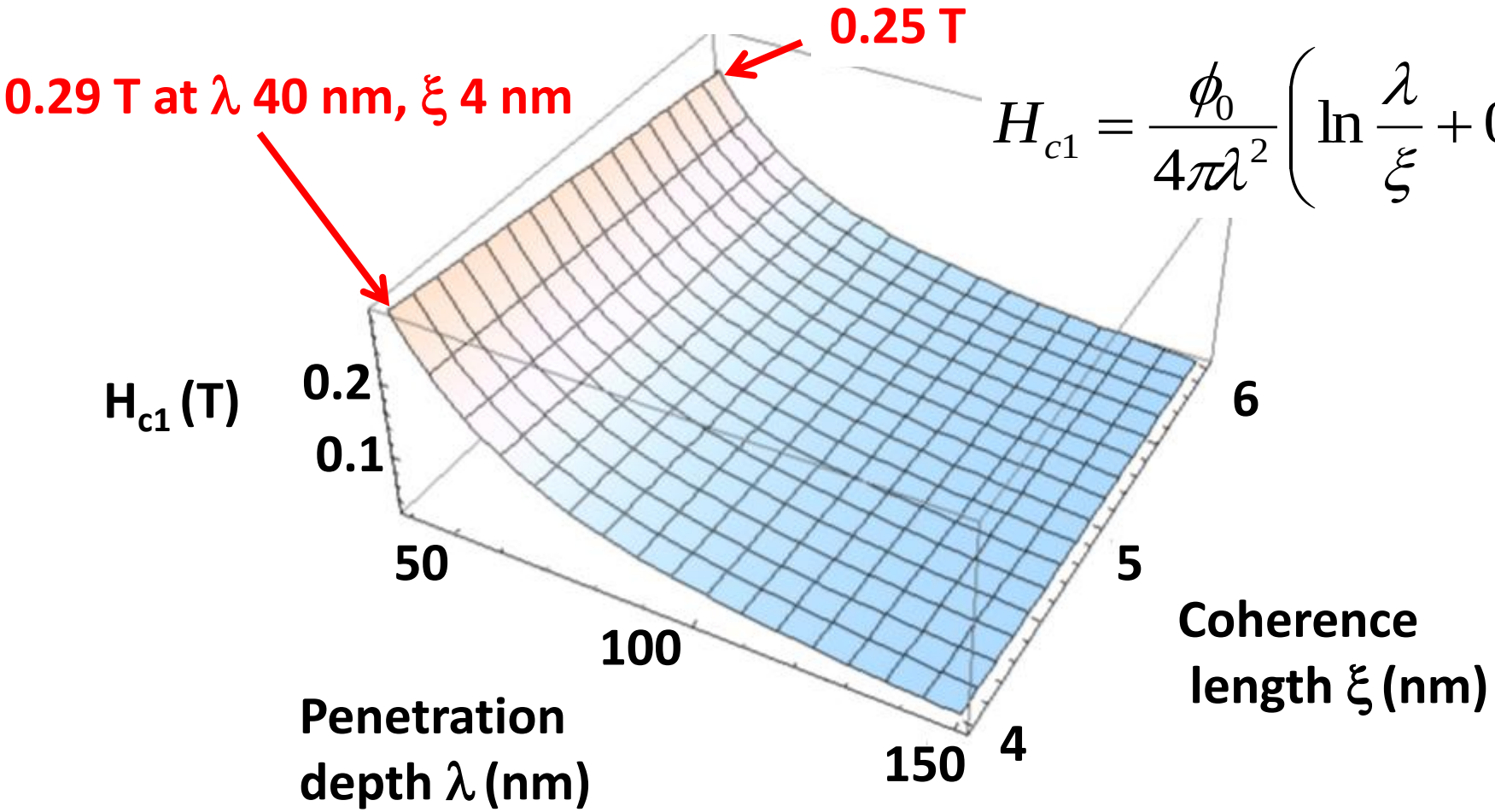
$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

Thermodynamic critical field H_c (surface barrier for vortices disappears)

$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}$$

Theoretical H_{c1} value for MgB_2

- Significantly changes with penetration depth
- Changes less with coherent length



$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

Theoretical H_c value for MgB_2

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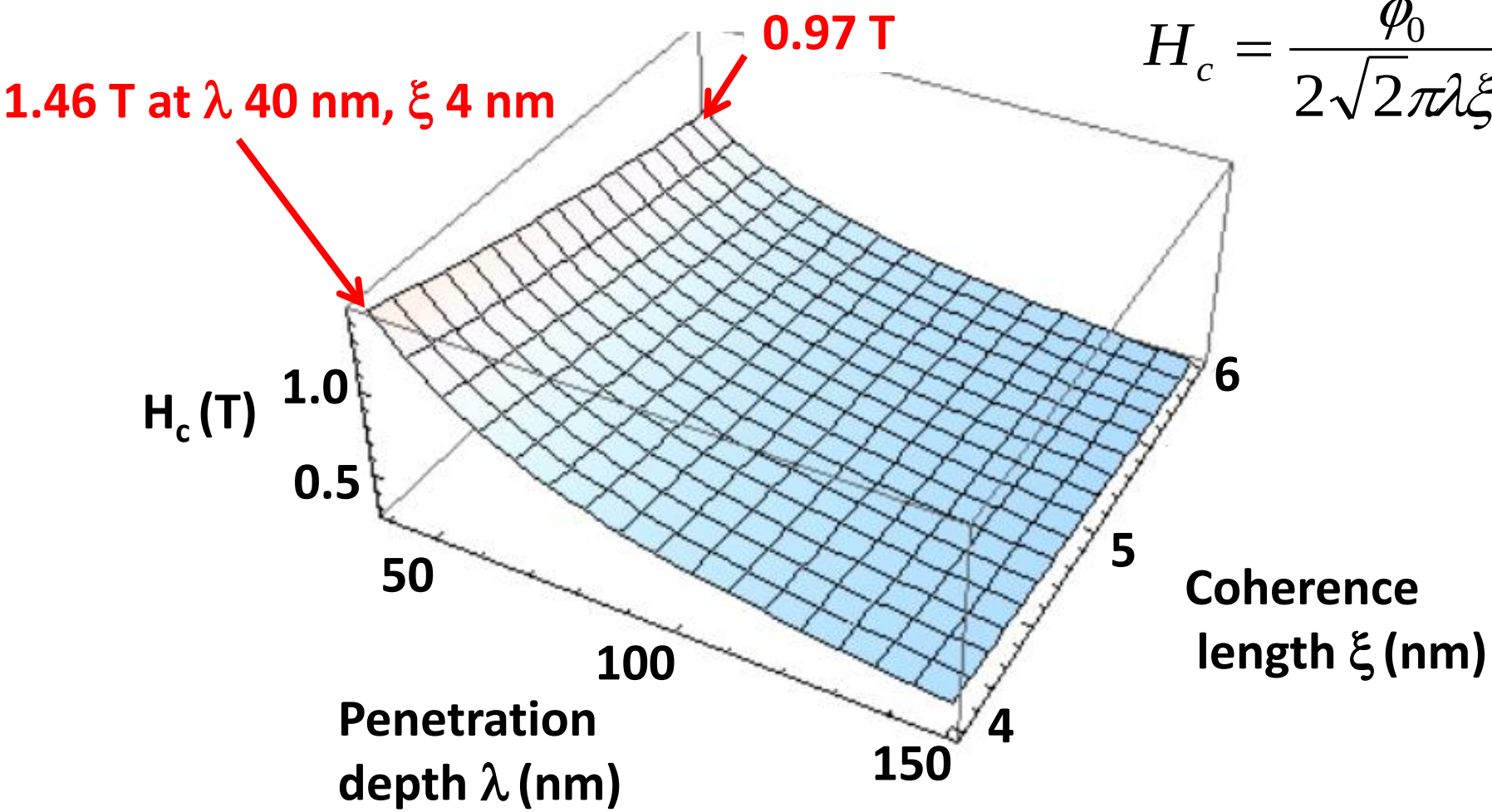
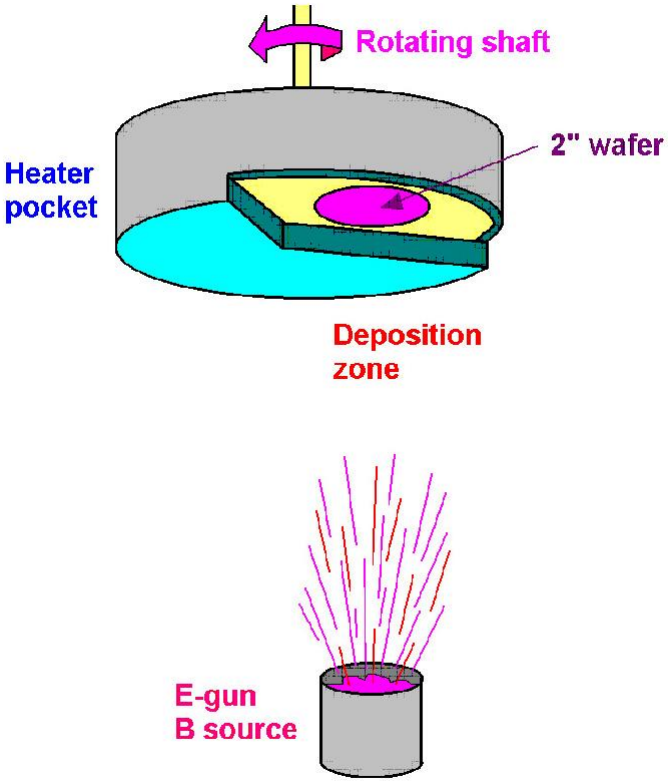
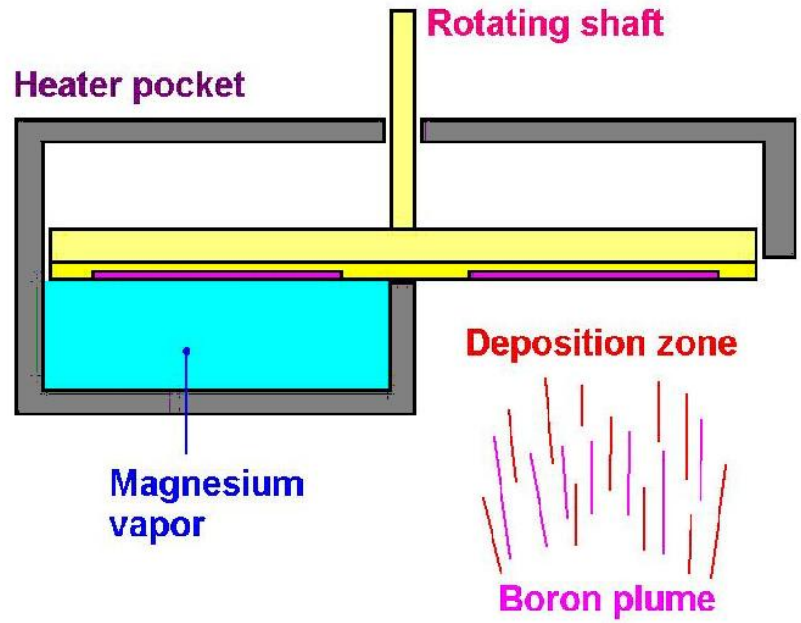
$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}$$



Early studies (2004-2005) using thin films prepared by Superconducting Technologies, Inc. (STI), Santa Barbara, CA.



In-situ reactive evaporation

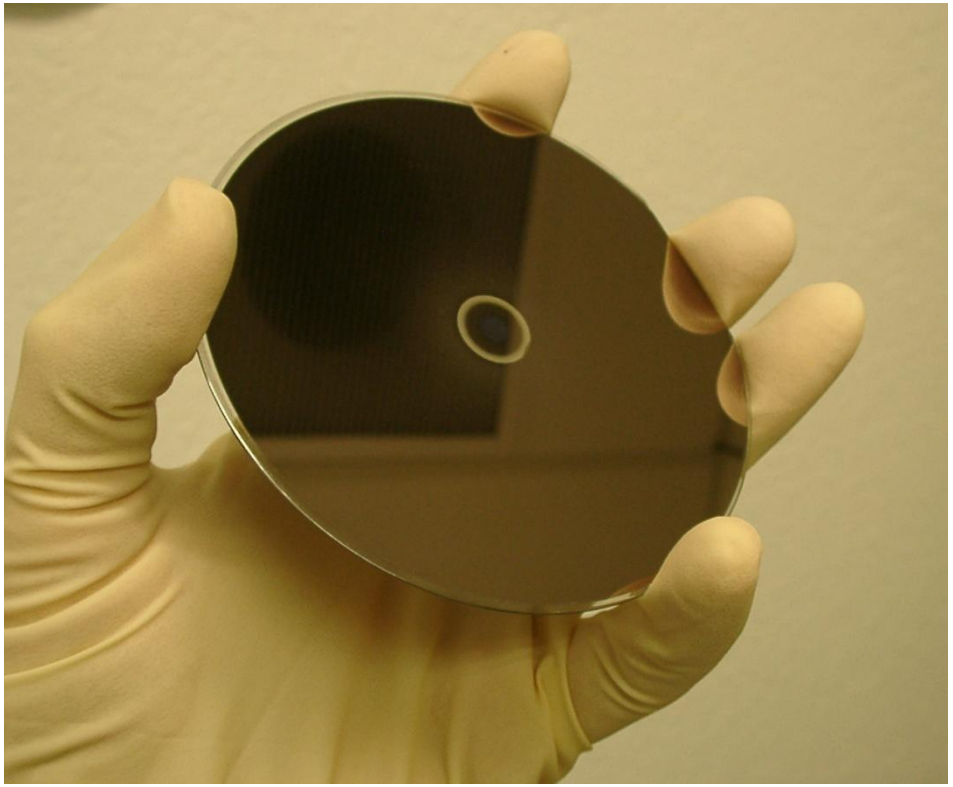


More details are found in
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al, Proc. PAC05.

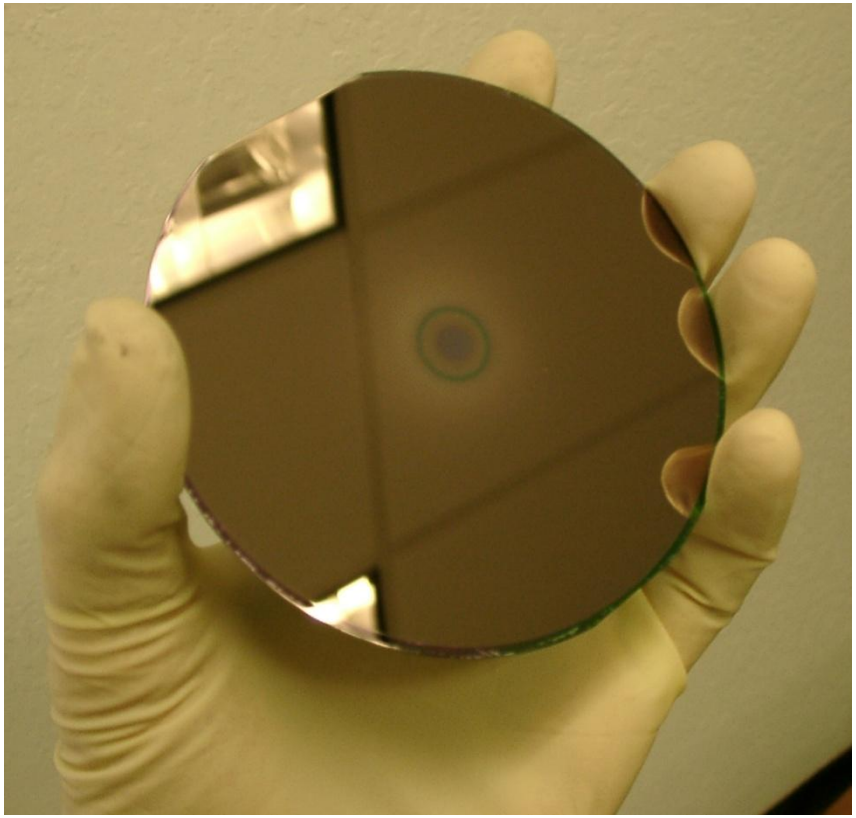
B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

Reactive evaporation at STI (B. Moeckly et al.)

R-plane sapphire



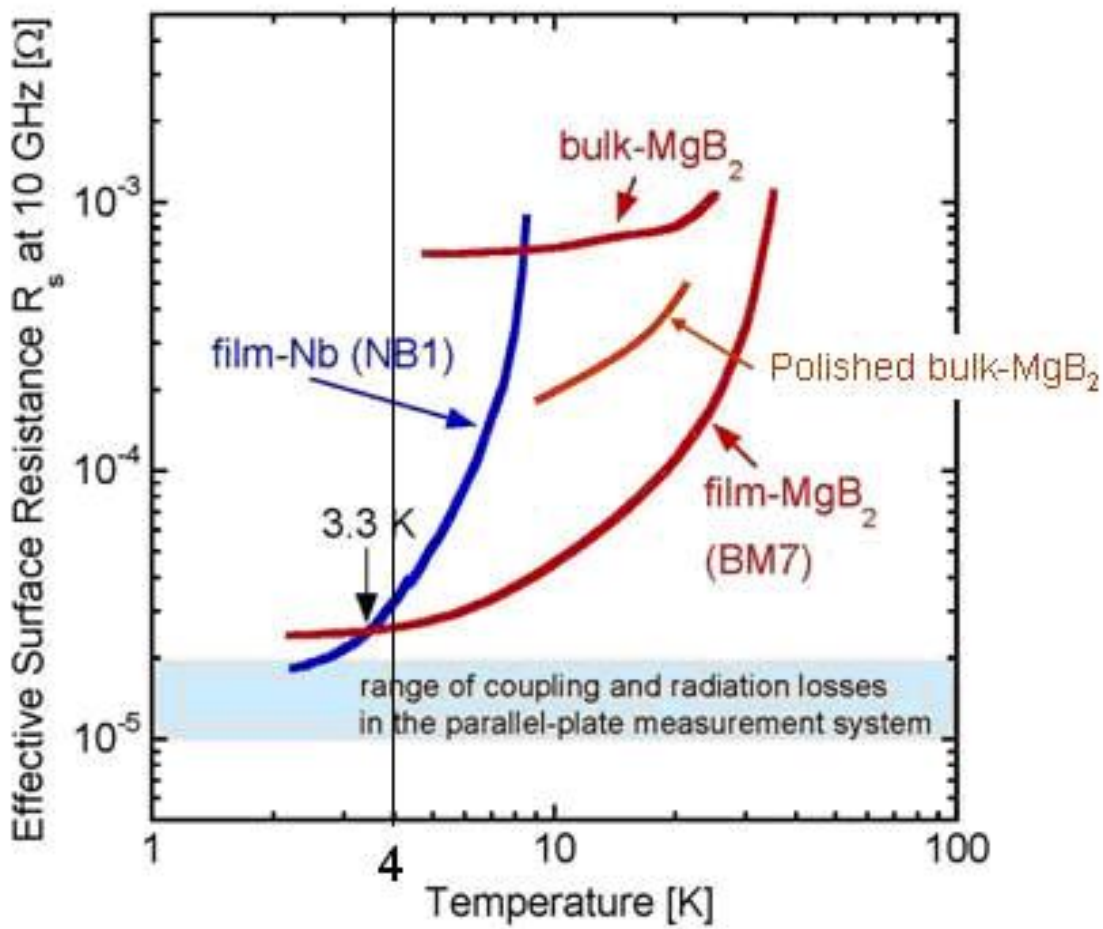
Si_3N_4 / Si



B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

RF Surface Resistance (R_s) at 10 GHz: LANL results with samples from STI (film) and UCSD (bulk) [1-3]

- R_s lower than Nb at 4K
- Still residual resistance seems to dominates at low temperatures



[1] A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.

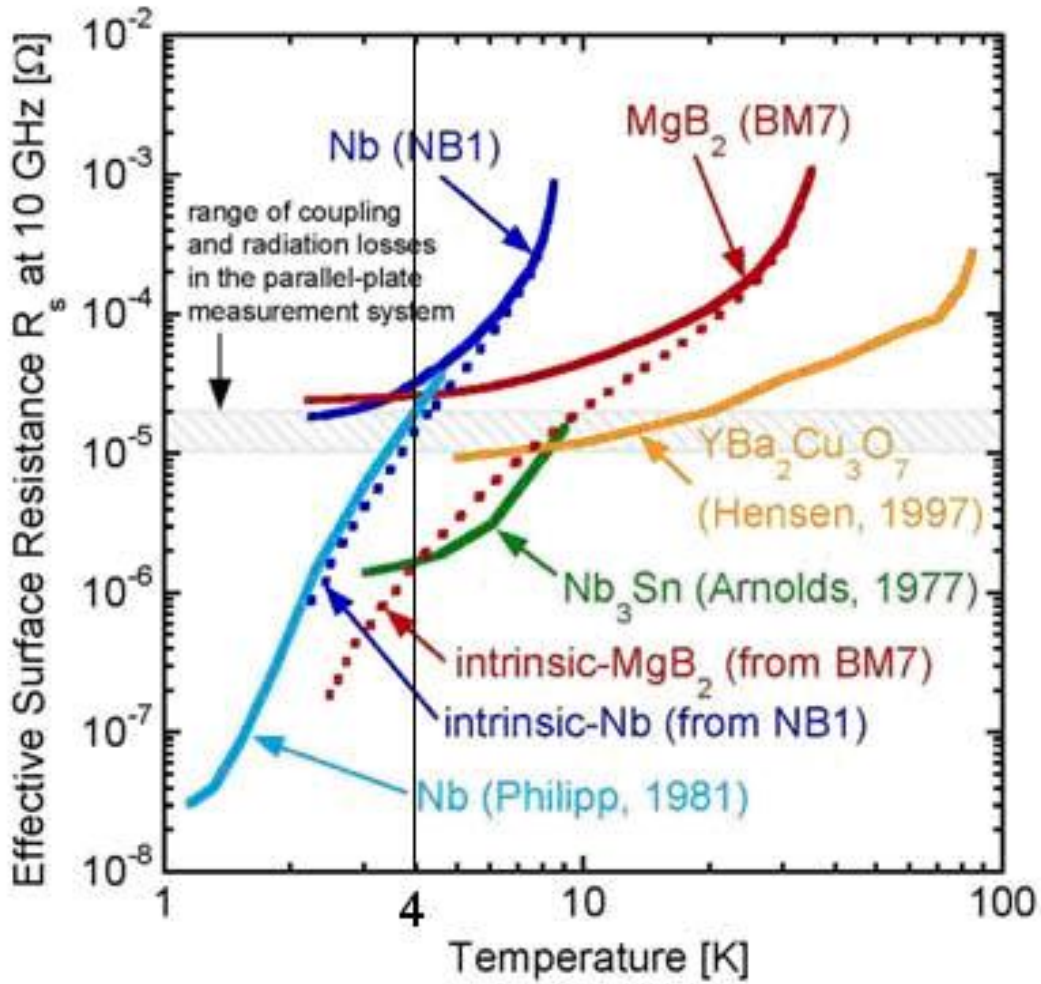
[2] B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.

[3] T. Tajima et al., Proc. PAC05.

Generally, $R_s \propto f^2$ at $T<T_c/2$

High-pressure rinsing of bulk MgB_2 with water did not degrade the R_s [3]

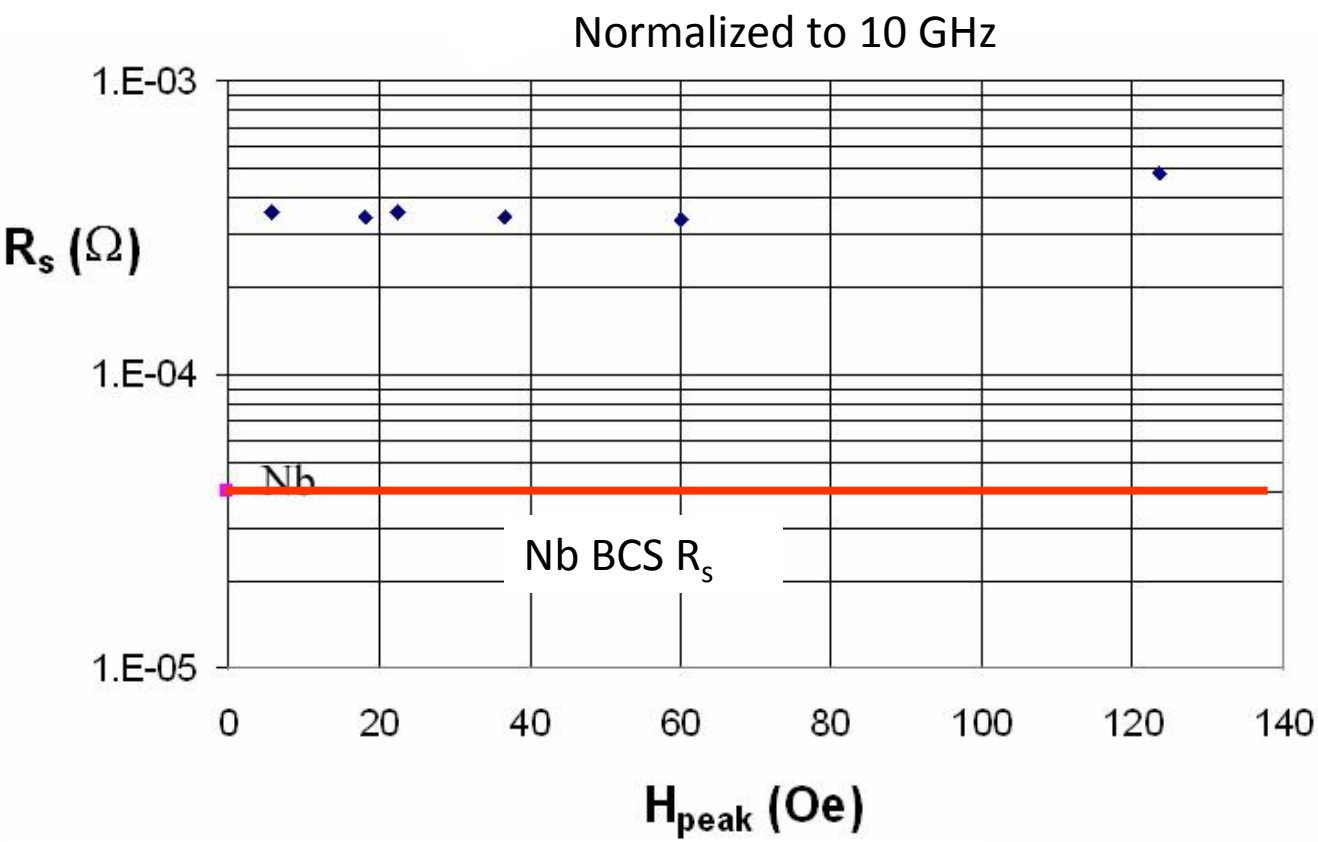
The BCS resistance of MgB_2 films prepared at STI was about one order of magnitude lower than that of Nb at 4 K (dotted lines) [1, 2]

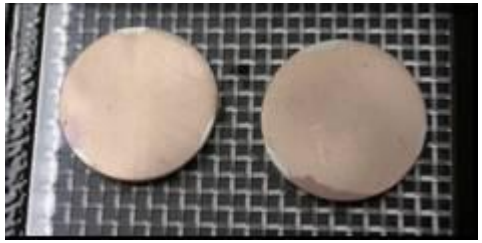


[1] A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.

[2] B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.

500 nm MgB_2 coated on a rough Nb was tested with Cornell TE cavity. R_s showed little increase up to a power limit (H_{peak} ~ 123 Oe). Consistent with the absence of weak links





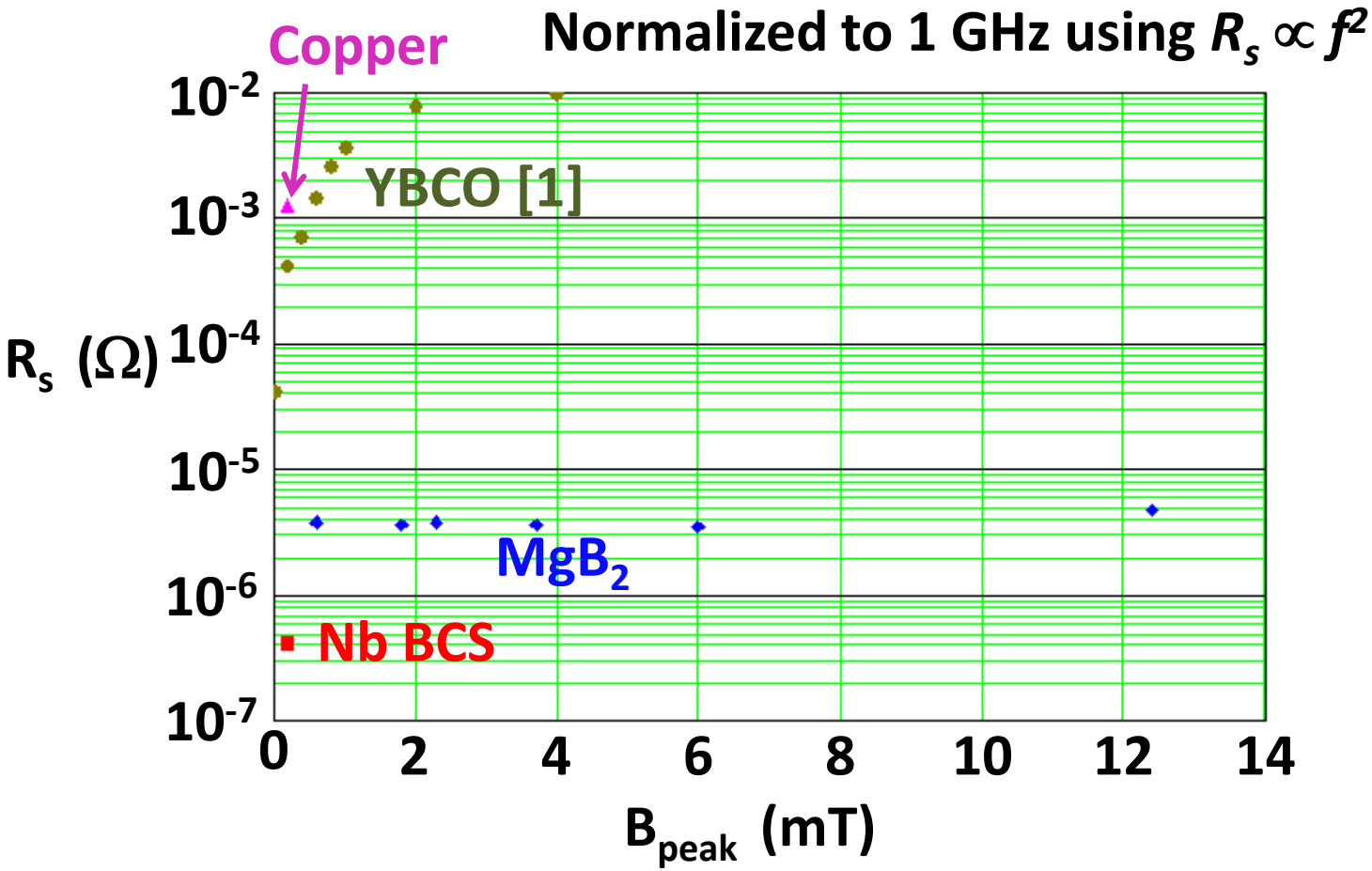
First attempt to coat on a Nb substrate (1.5 cm diameter disk).

R_s was higher than Nb due to the rough (R_a~400nm) substrate.

Test at Cornell (A. Romanenko) with TE_{011} Nb cavity at 4.2 K.

T. Tajima et al., Proc. PAC2005, p. 4215

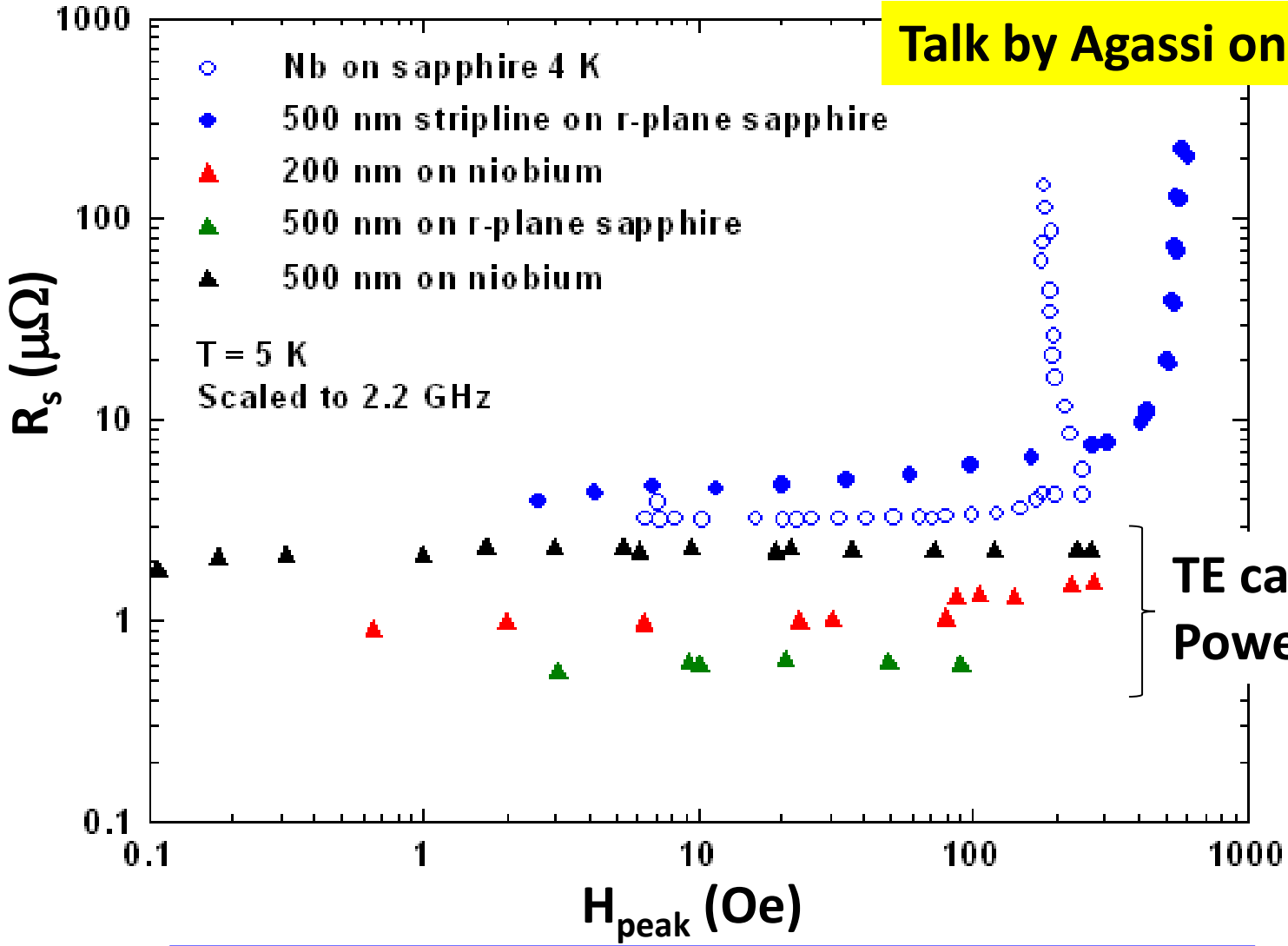
500 nm thick MgB_2 film power dependence (2005): While R_s of MgB_2 was higher than Nb BCS R_s due to rough Nb substrate, the flat H_{peak} dependence was very encouraging.



[1] J.R. Delayen and C.L. Bohn, Phys. Rev. B40 (1989) 5151.

Recent results at MIT with stripline and TE cavity measurements show R_s without significant increase up to at least ~30 mT [1]

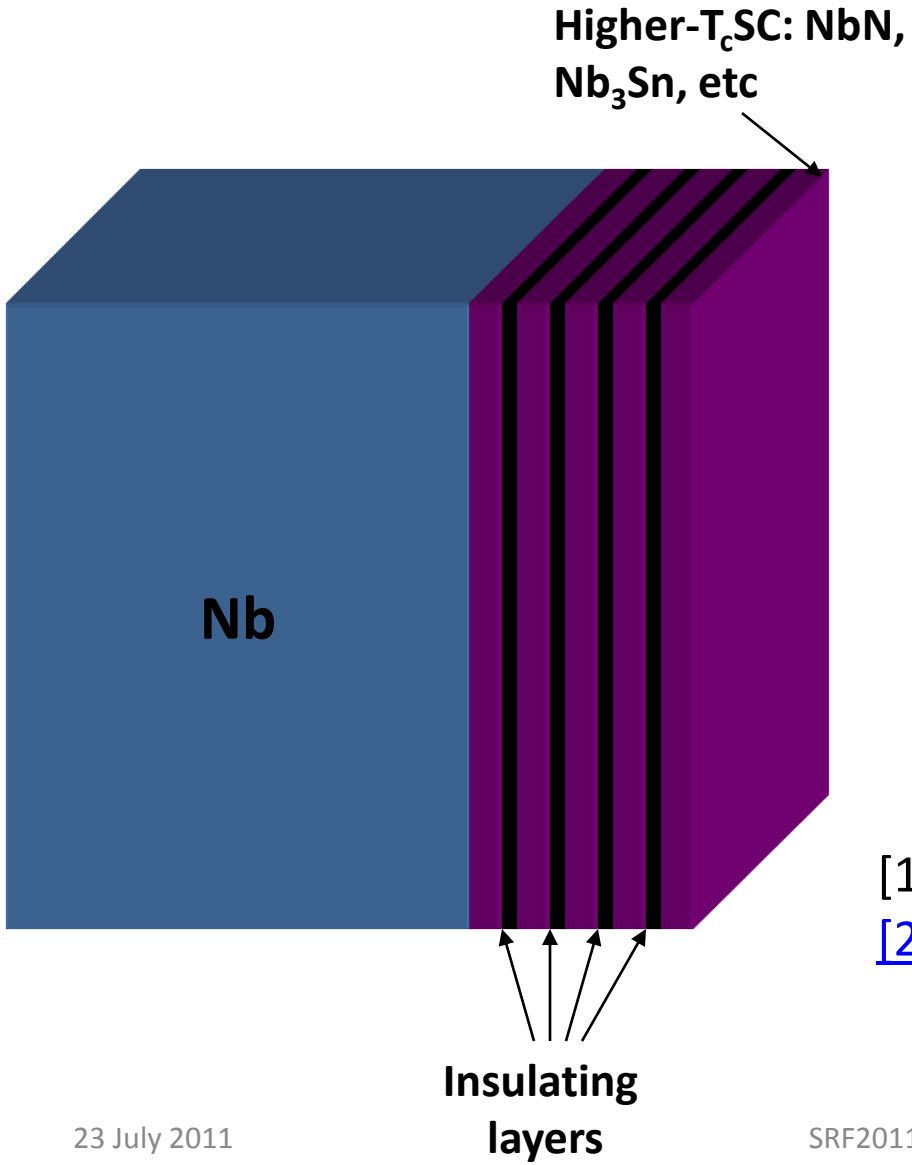
Talk by Agassi on Tuesday

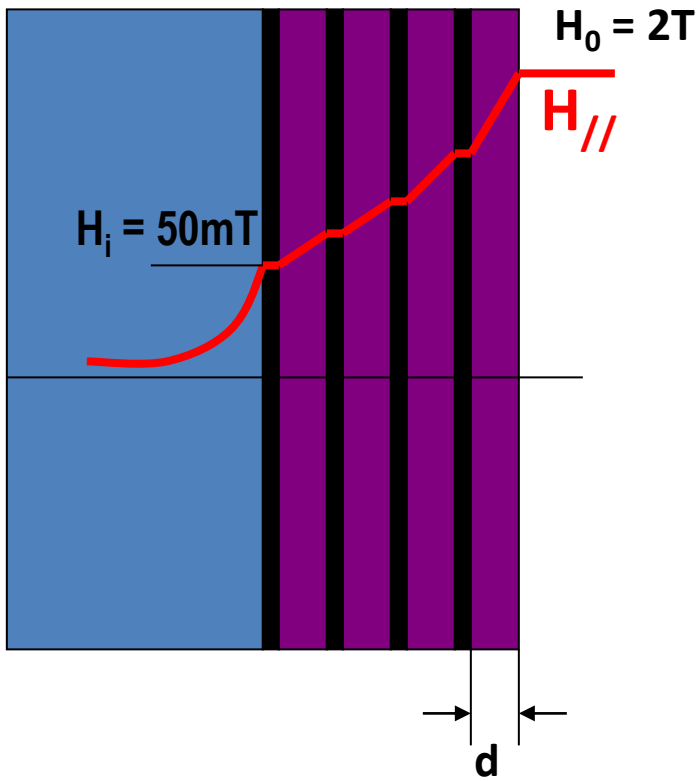


TE cavity meas.
Power limited

[1] D. E. Oates, Y. D. Agassi and B. H. Moeckly, Supercond. Sci. Tech. **23**, 03401 (2010)

Multilayer thin film superconductors concept proposed by Alex Gurevich [1, 2]

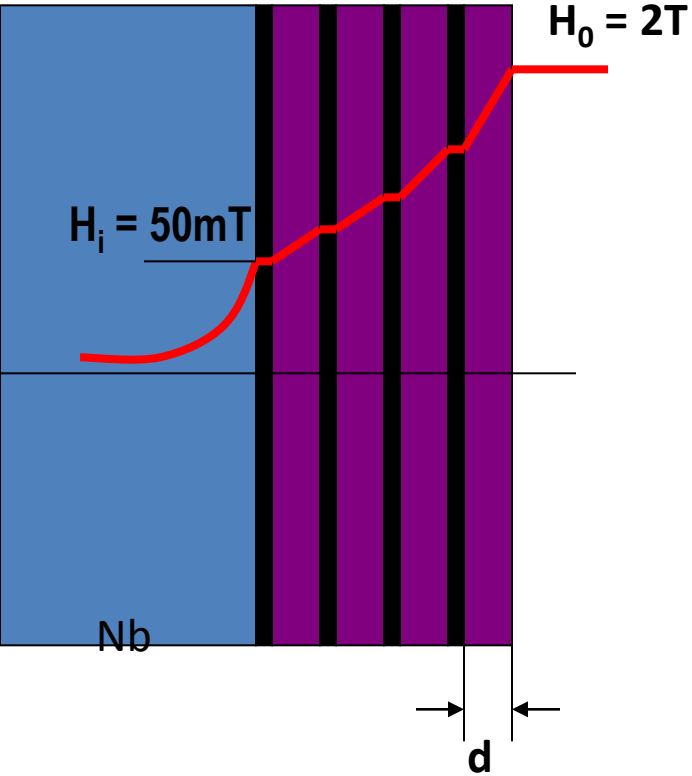




[1] A. Gurevich, APL **88** (2006) 012511

[2] A. Gurevich, SRF Materials Workshop, FNAL, 23-24 May 2007

An example [Gurevich, SRF Materials Workshop, FNAL, May 2007]



Example: Nb_3Sn layers with d = 30nm
λ_0 = 65 nm and H_{c1} = 2.4T

Peak rf field H_0 = 2T < H_{c1}

Internal rf field H_i = 50 mT (high-Q regime)

$$H_0 \exp\left(-\frac{dN}{\lambda_0}\right) = H_i \qquad \Rightarrow \qquad N = \frac{\lambda_0}{d} \ln \frac{H_0}{H_i}$$

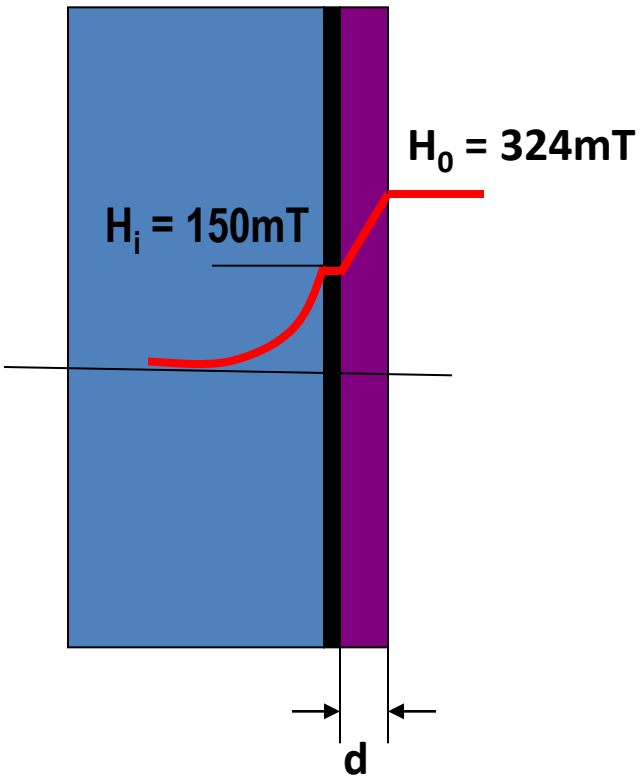
N = (65/30)ln(40) = 8 layers

Strong reduction of the BCS resistance by Nb_3Sn layers due to larger Δ and shorter λ:

$$R_s \propto \frac{\mu_0^2 \omega^2 \lambda^4 \Delta n_0}{k_B T p_F} \ln \frac{\Delta}{\hbar\omega} \exp\left(-\frac{\Delta}{k_B T}\right)$$

Clean limit

Another example with only 1 layer Nb_3Sn [Gurevich, SRF Materials Workshop, FNAL, May 2007]



A Nb cavity coated by a single Nb_3Sn layer of thickness d = 50nm and a dielectric layer in between

If the Nb cavity can withstand H_i = 150mT, then the external field can be as high as

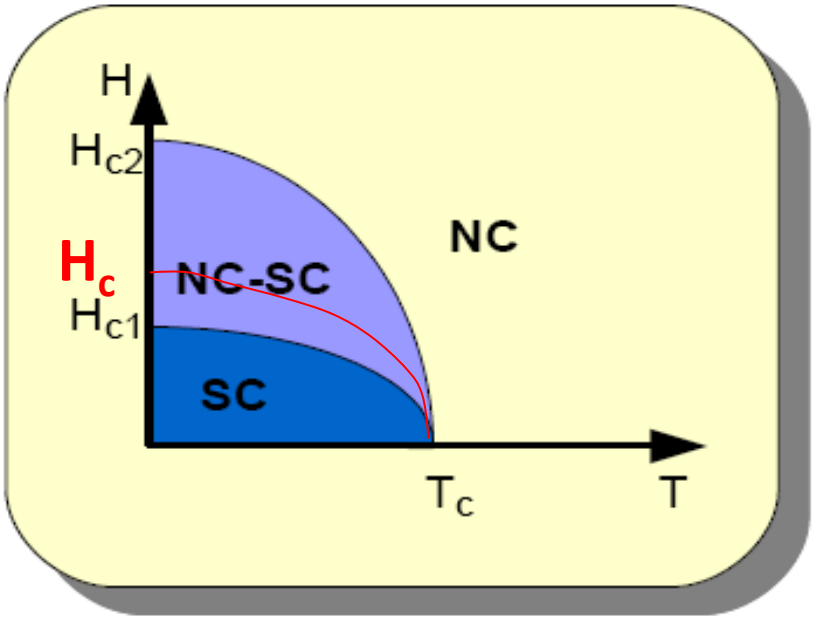
$$H_0 = H_i \exp(d/\lambda_0) = 150\exp(50/65) = 324\,mT$$

Lower critical field for the Nb_3Sn layer with d = 50 nm and ξ = 3nm: H_{c1} = 1.4T is much higher than H_0

A single layer coating more than doubles the breakdown field with no vortex penetration, enabling E_{acc}~ 100 MV/m

The key idea of using multilayer thin film superconductors is the fact that $B_{c1//}$ (= $\mu_0 H_{c1//}$) increases when the film thickness d gets close to λ (magnetic penetration depth)

- The RF critical magnetic field H_{RF} in a type-II superconductor is somewhere between H_{c1} and H_{c2}
- The higher the $H_{c1//}$, the better to prevent vortex penetration

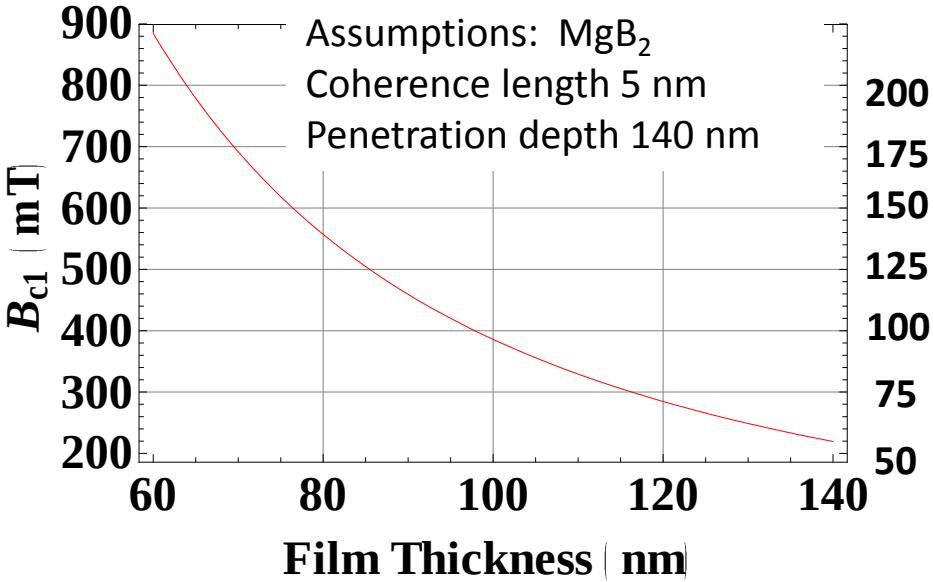


- Use thin films with thickness d < λ_L to enhance the lower critical field

$$B_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}, \quad d < \lambda$$

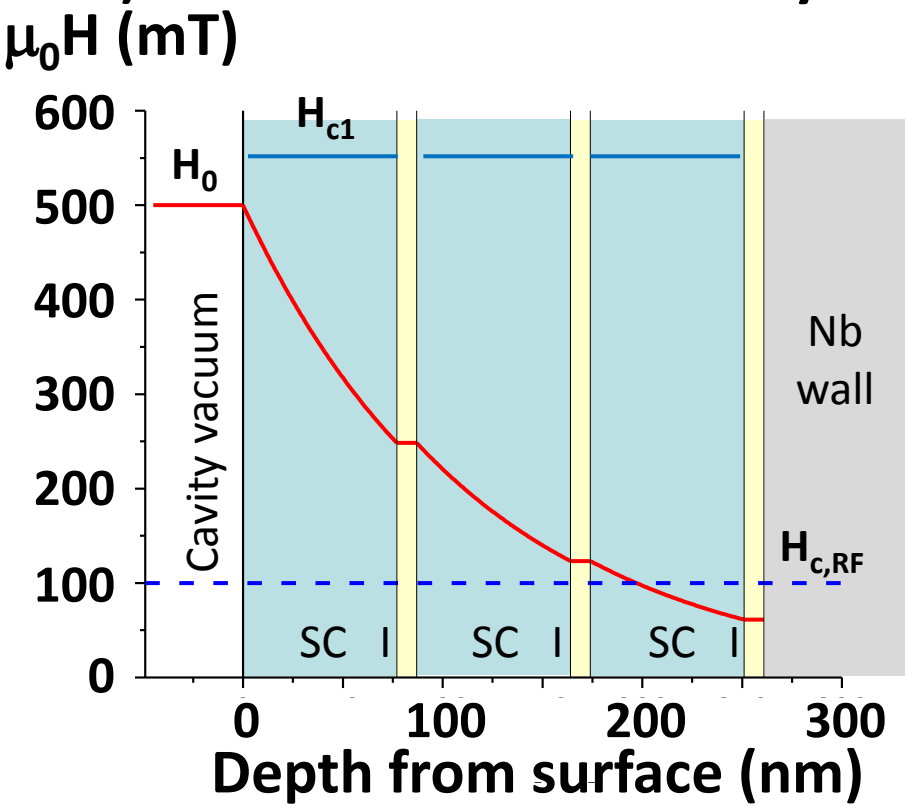
[Gurevich, APL 88 (2006) 012511]

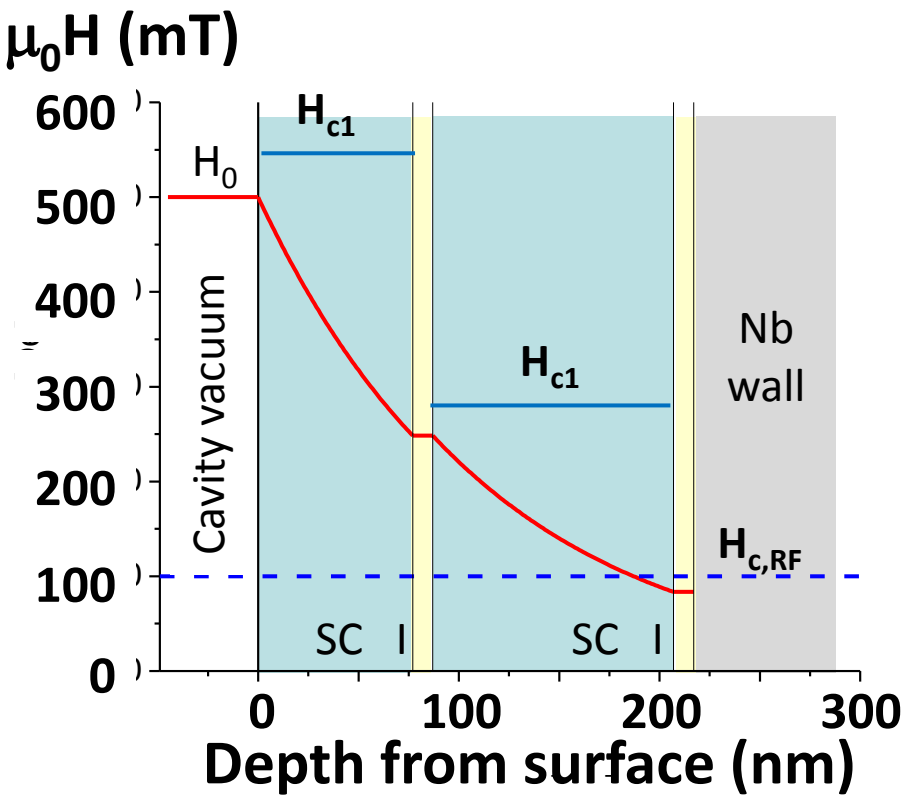
Predicted H_{c1} as a function of film thickness



Variable thickness films could reduce the number of layers

An example of achieving ~125 MV/m using MgB_2 layers (λ = 110 nm) with 10 nm insulation layers





Fixed thickness multilayers:

- $d \leq$ 77nm for $H_{c1} \geq$ 5500 Oe
- 3 layers needed
- coating curved walls with very thin uniform of layers is challenging

Variable thickness multilayers:

- $d_1 \leq$ 77nm for $H_{c1} \geq$ 5500 Oe
- only 2 layers needed
- 2nd layer is thicker: 100nm $\leq d_2 \leq$ 120nm

DC Magnetization measurements:

A Quantum Design Magnetic Property Measurement System (MPMS) SQUID is used to measure T_c and H_{c1}

In the Meissner State

(total expulsion of magnetic flux):

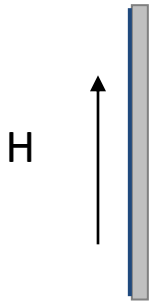
$$-4\pi * \frac{dm}{dH} = \frac{V}{1-D}$$

m: total magnetic moment
H: magnetic field
V: volume of the sample
D: demagnetization factor

The Meissner slopes are different for each orientation because each one has a different demagnetization factor

In a superconducting thin films:

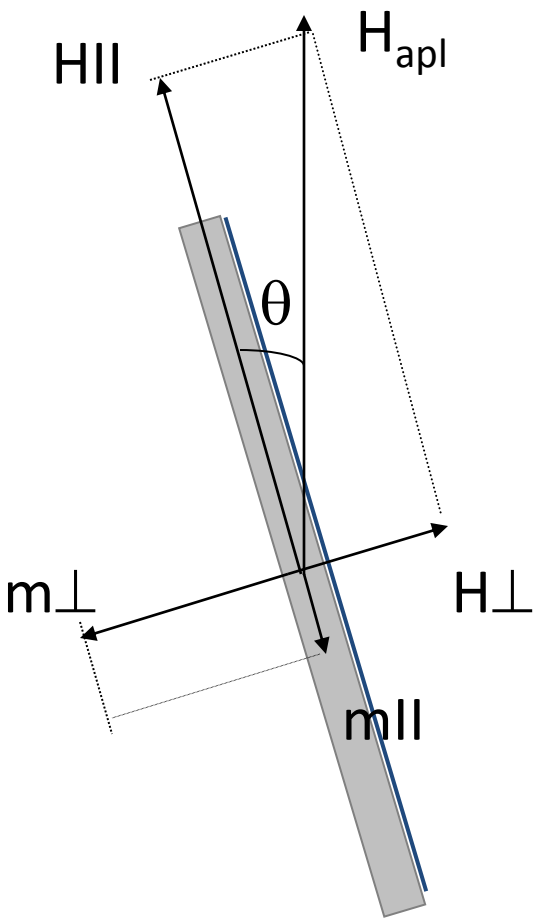
If
then 1 – D ~ 0



And if

then 1 – D ~ 1

Magnetic field and magnetization alignment in thin films

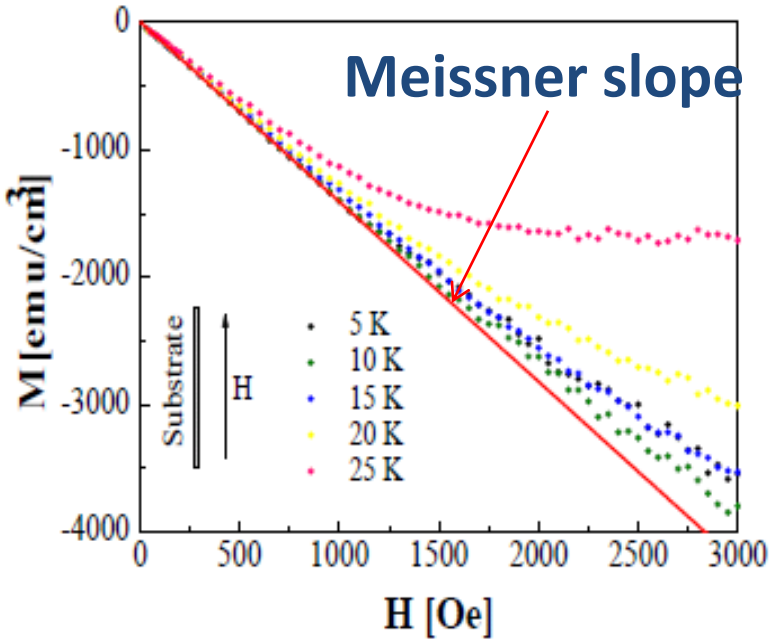


$$m_{\perp} = -\frac{H_{\perp}}{4\pi}\frac{V}{1-D}; \qquad m_{II} = -\frac{H_{II}}{4\pi}V$$

$$m_z = -\frac{VH}{4\pi}(\cos^2\theta + \tfrac{1}{1-D}\sin^2\theta)$$

If the film is exactly aligned with H (Θ=0) the Meissner slope *dm/dH* gives the film volume.
A calculated volume larger than the real one indicates misalignment.
Alignment ~ 0.1° or better is needed.

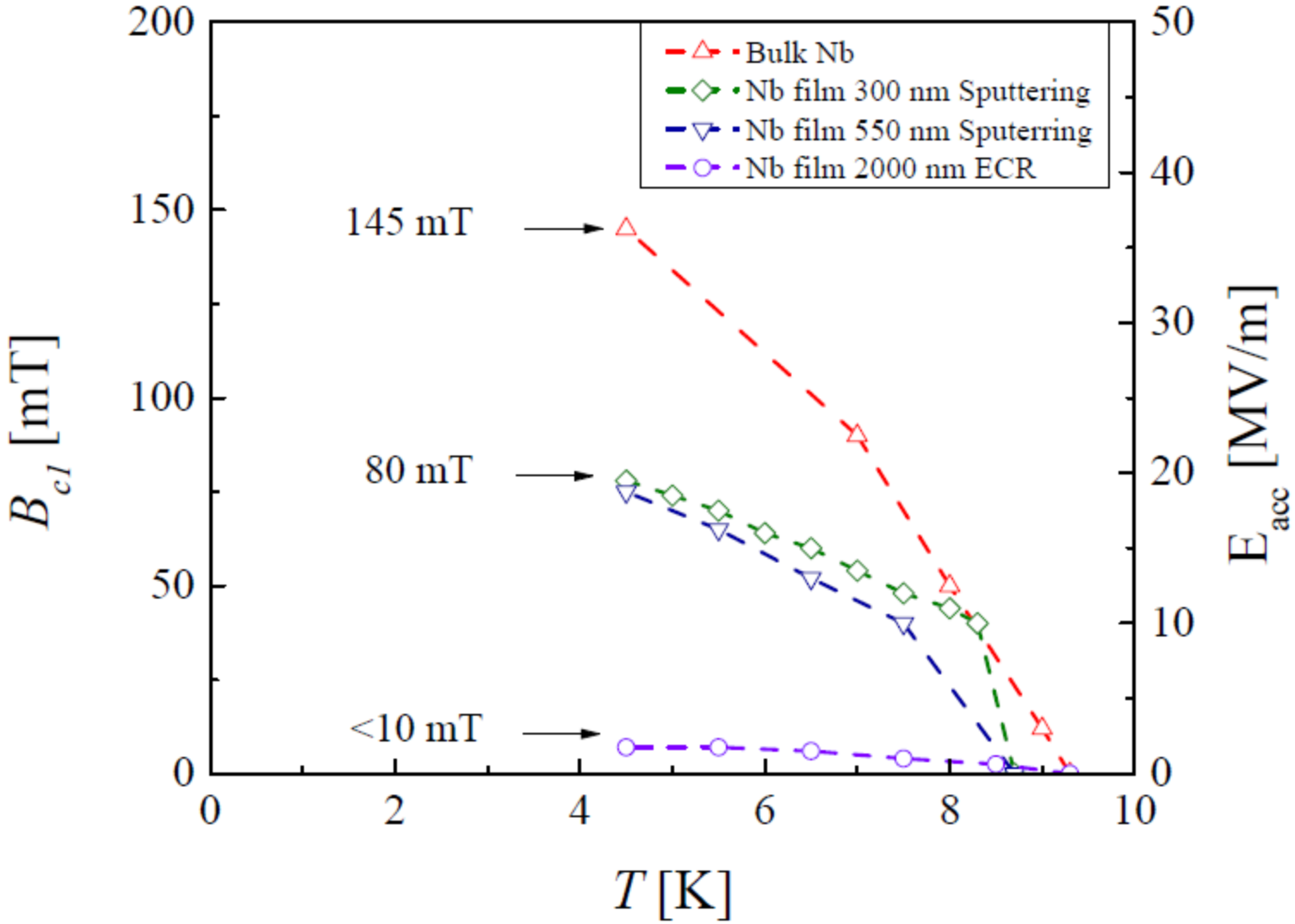
An example of H_{c1} measurements at different temperatures



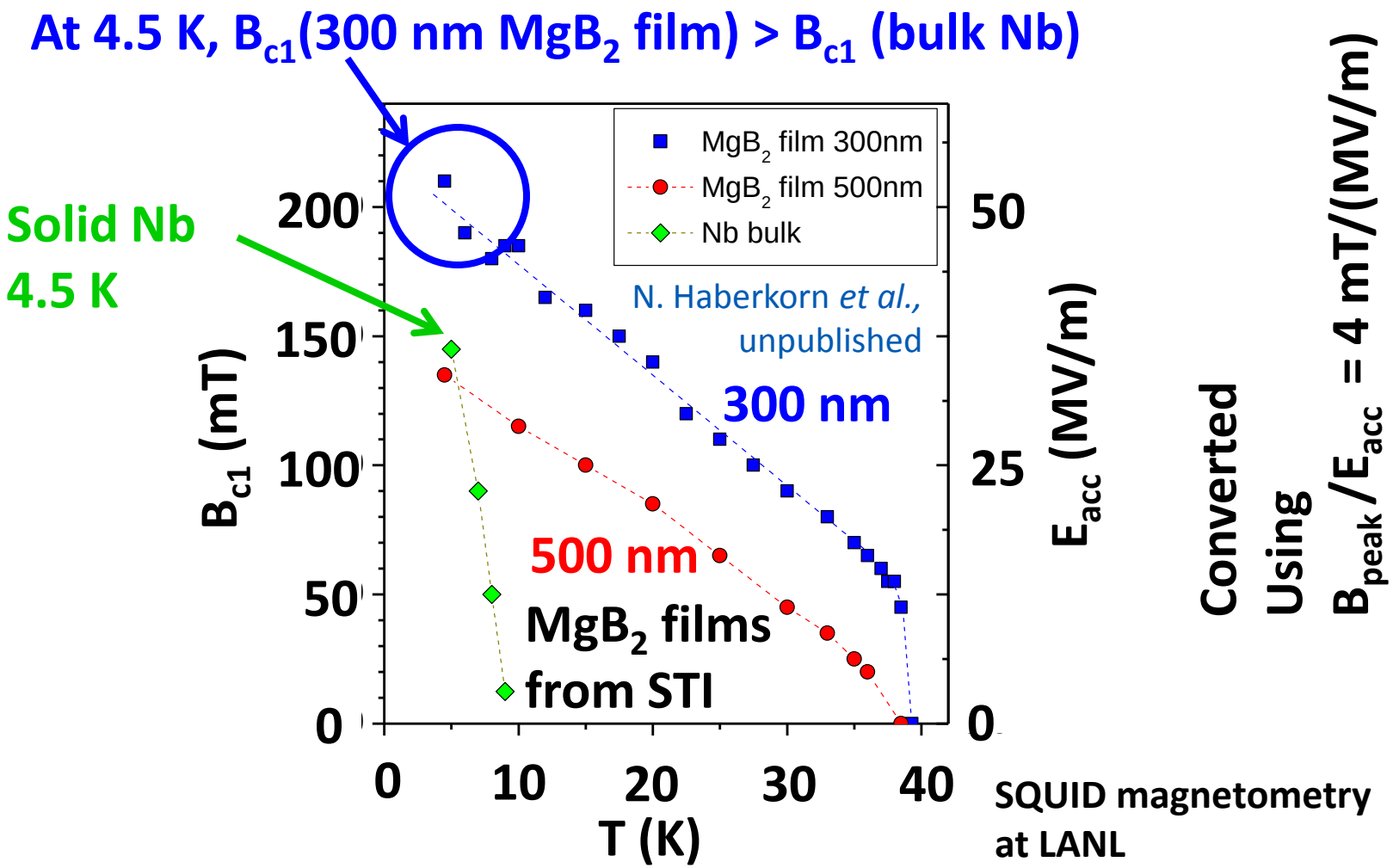
In this presentation, H_{c1} is defined as the H where the data starts to deviate from the Meissner slope, indicating vortex entrance into the film.
This may be an overestimate of H_{c1} due to surface barriers, but it is the relevant field for cavities.

Figure: Magnetization curves as a function of applied magnetic field at various temperatures for ~360 nm thick MgB_2 film (T_c ~ 31.8 K) deposited on a Si substrate at Kagoshima Univ. , Japan.

In the case of Nb



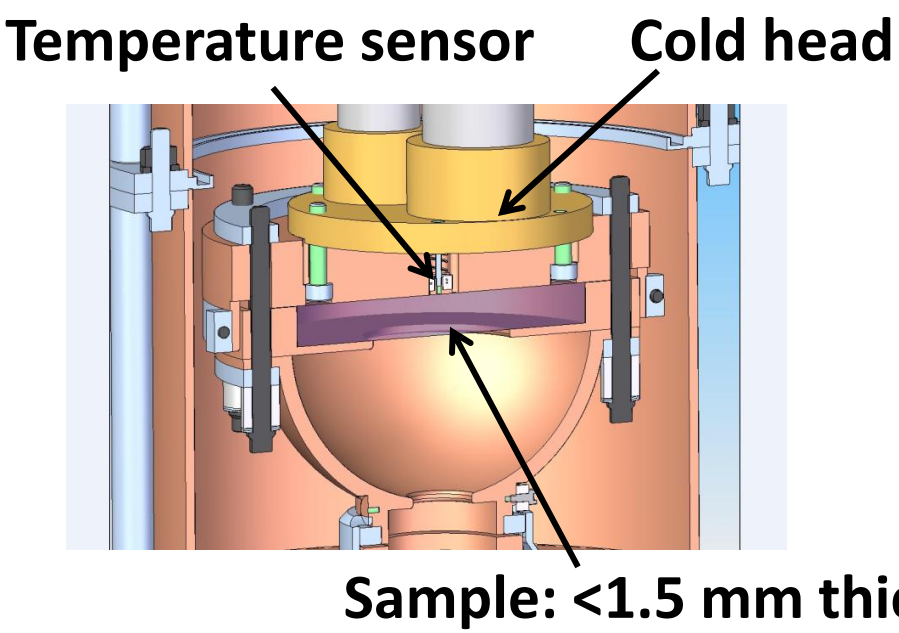
B_{c1} of 300 nm MgB_2 film showed higher than that of Nb by ~25 % at 4.5 K, the lowest measured temperature, B_{c1} > 200 mT.

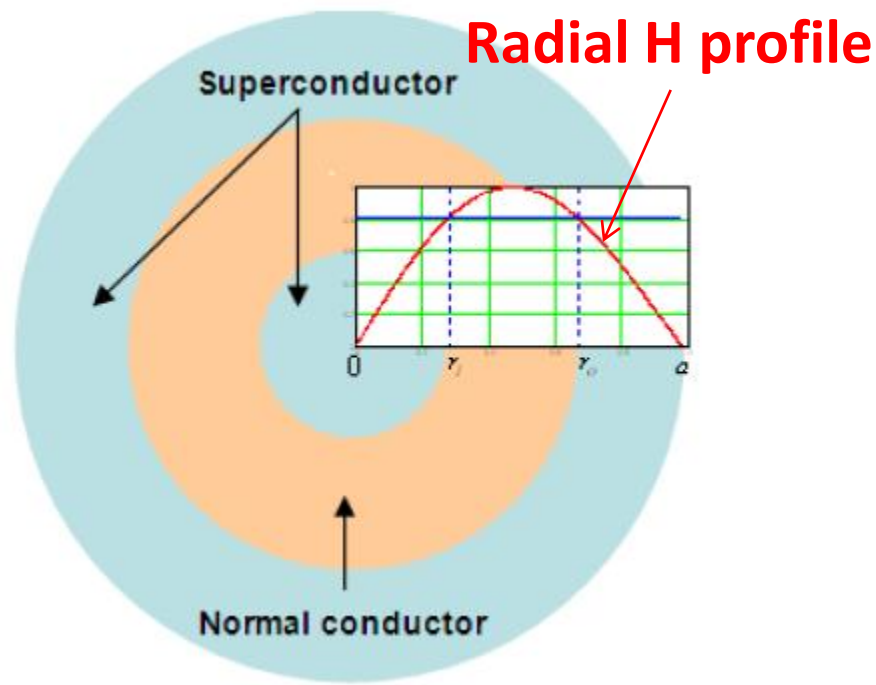


RF measurements of 2-inch (50.8 mm) diameter wafers (~1 mm thick) have been carried out at SLAC using 11.4 GHz system [S. Tantawi, J. Guo et al.]

Hemi-spherical TE_{013}–mode cavity with magnetic fields in parallel with the sample surface

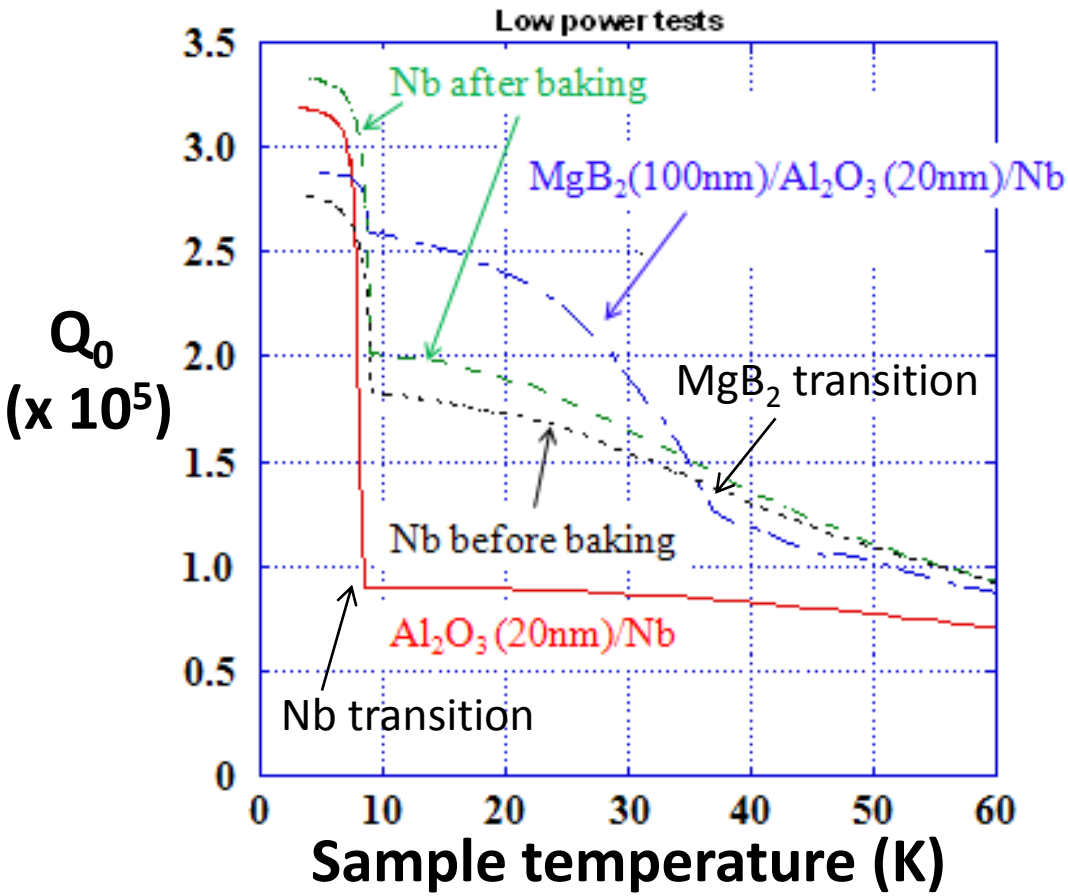
Typical distribution of superconducting and normal-conducting regions after quench





Low-power test results on Nb, Al_2O_3(20nm)/Nb and MgB_2(100nm)/Alumina(20nm)/Nb

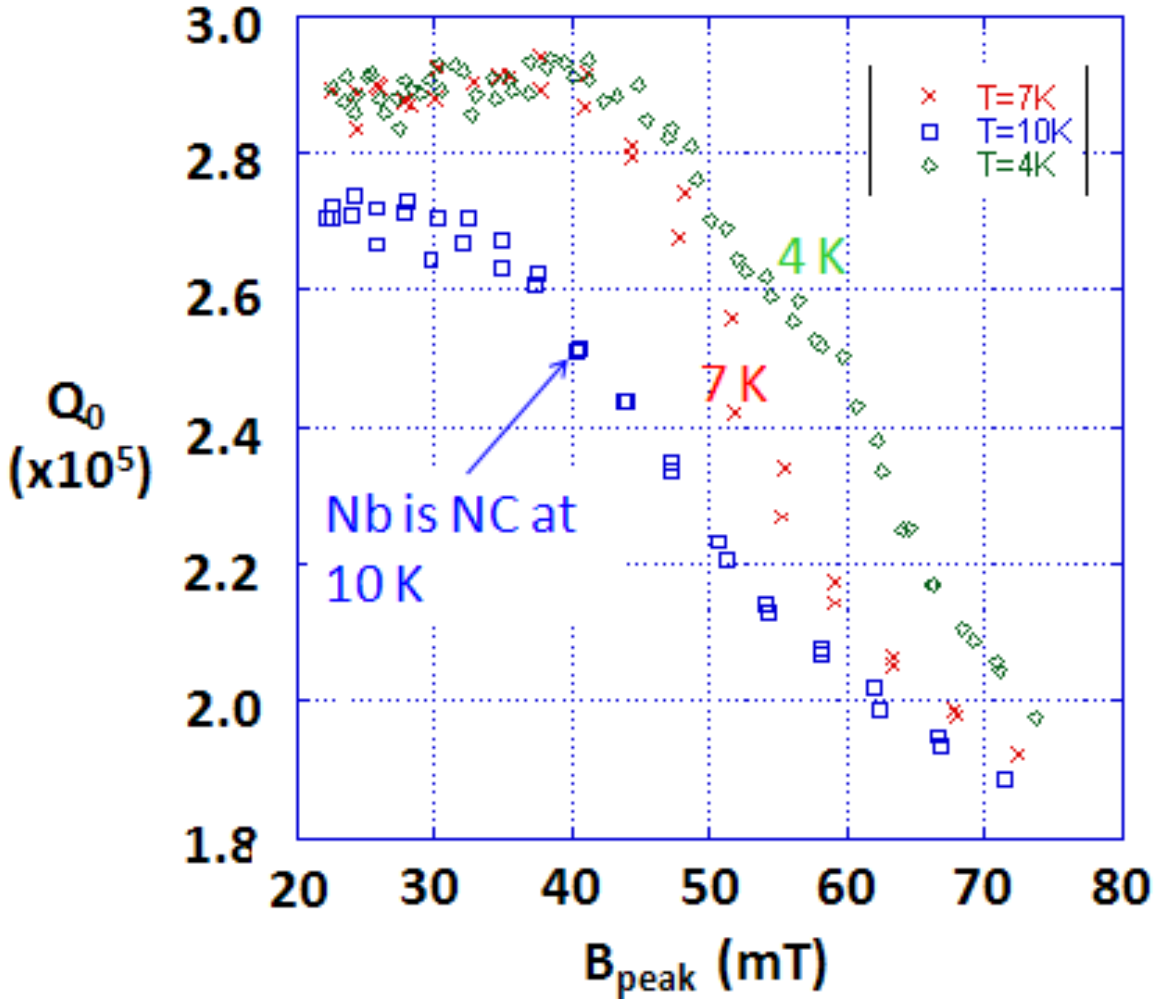
Max. Q_0 ~ 3.5 x 10^5 due to Cu host cavity



11.4 GHz

- **UHV baking at 800 °C for 4 hours cleaned the Nb surface**
- **Alumina coating with ALD at 300 °C increased RF resistance in both NC and SC states**
- **Subsequent MgB_2 coating with reactive co-evaporation at 550 °C reduced NC resistance down to Nb transition, but increased SC resistance at <9 K.**

High-power test results of $MgB_2(100nm)/Al_2O_3(20nm)/Nb$



The power density that causes thermal quench has been determined using experimental data

With the SLAC system, the following relationship between Q_0 and B_{peak} holds

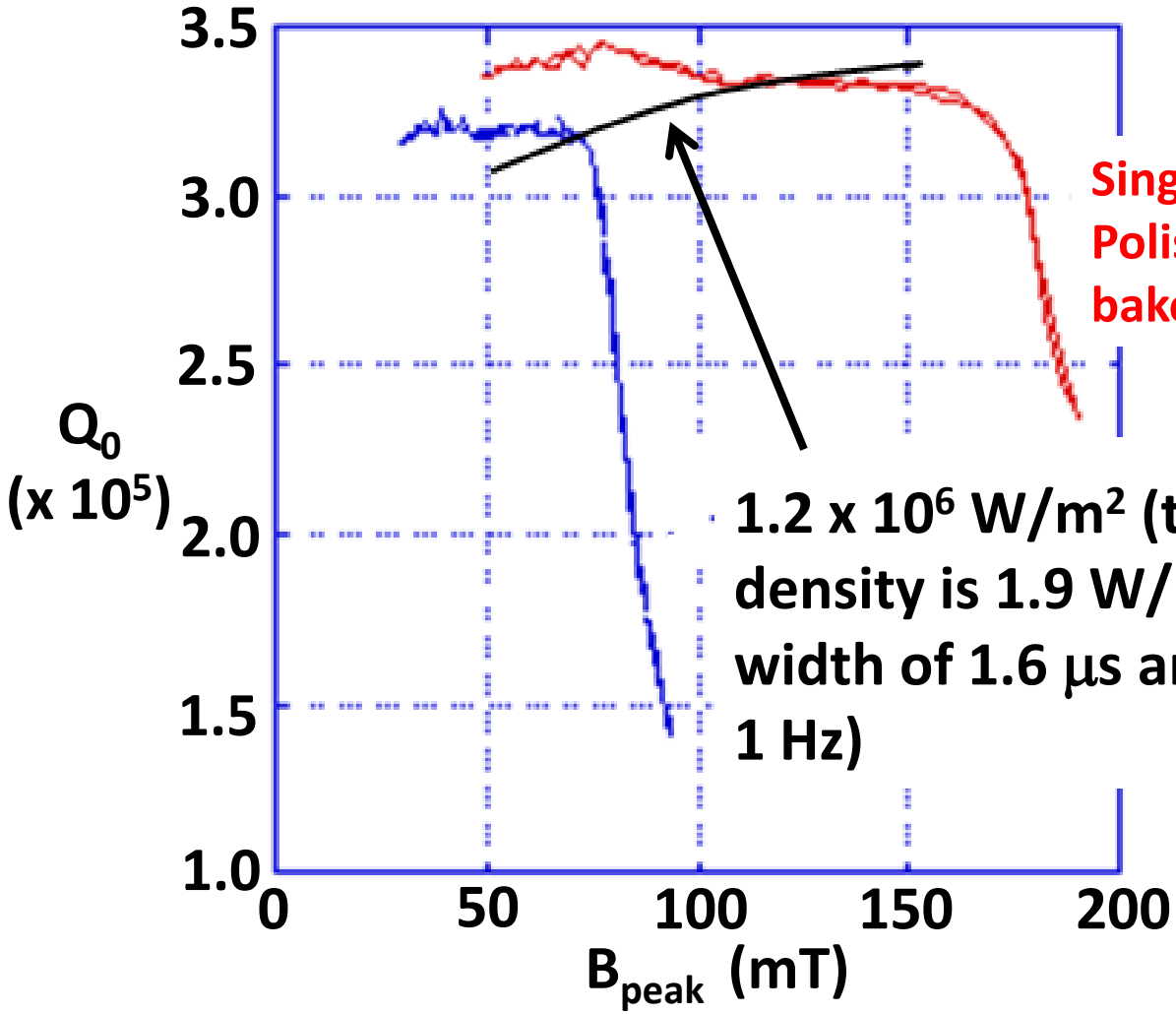
$$Q_0 = \left[8.08\times10^{-10} \times \frac{P_{diss}[W/m^2]}{\{B_{peak}[mT]\}^2} + 2.87\times10^{-6} \right]^{-1}$$

P_{diss} : peak power density

From Nb quench data, a power density needed to thermally quench was determined

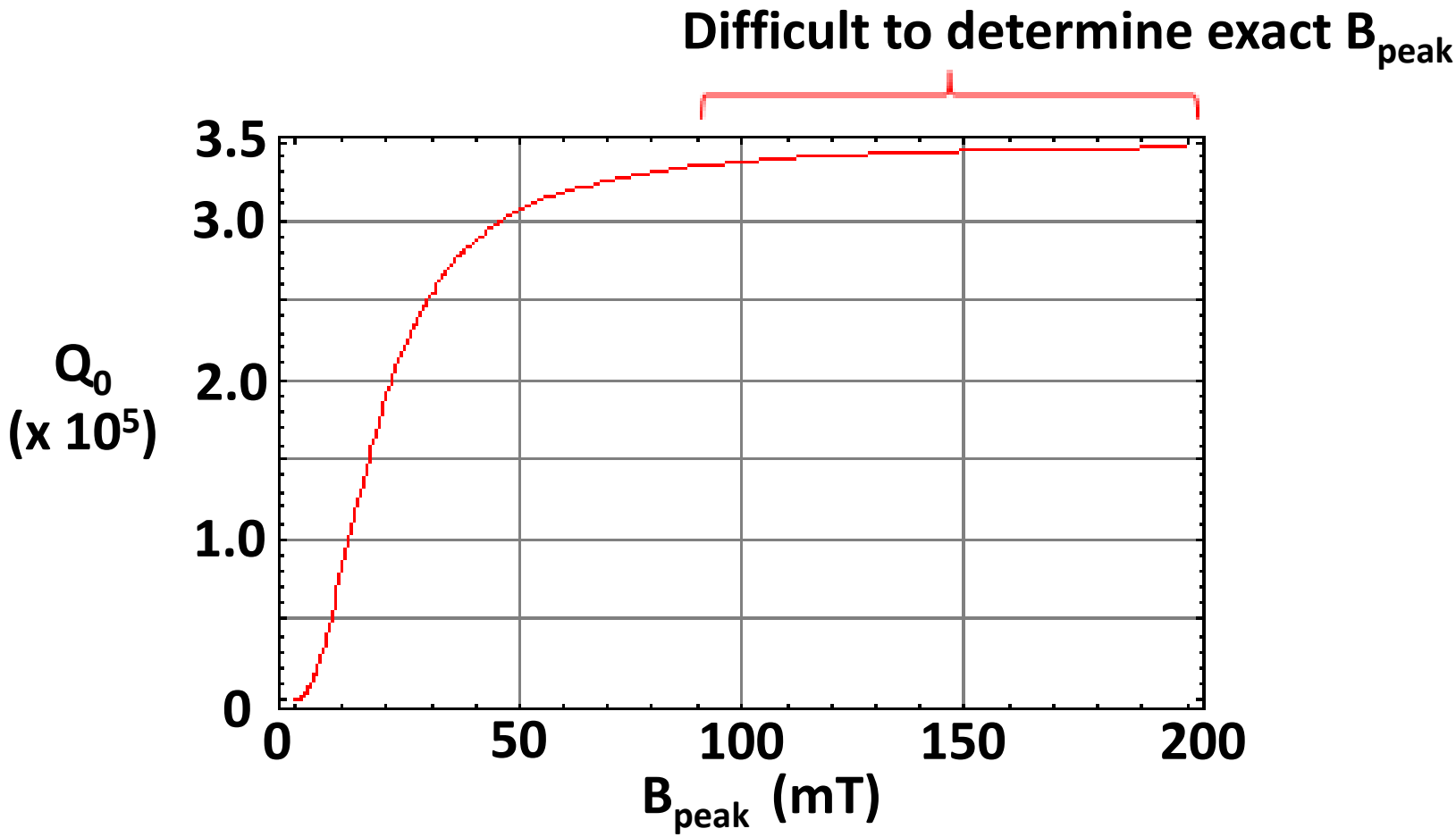
Talk of Guo on Tuesday

Max. Q_0 ~ 3.5 x 10^5 due to Cu host cavity

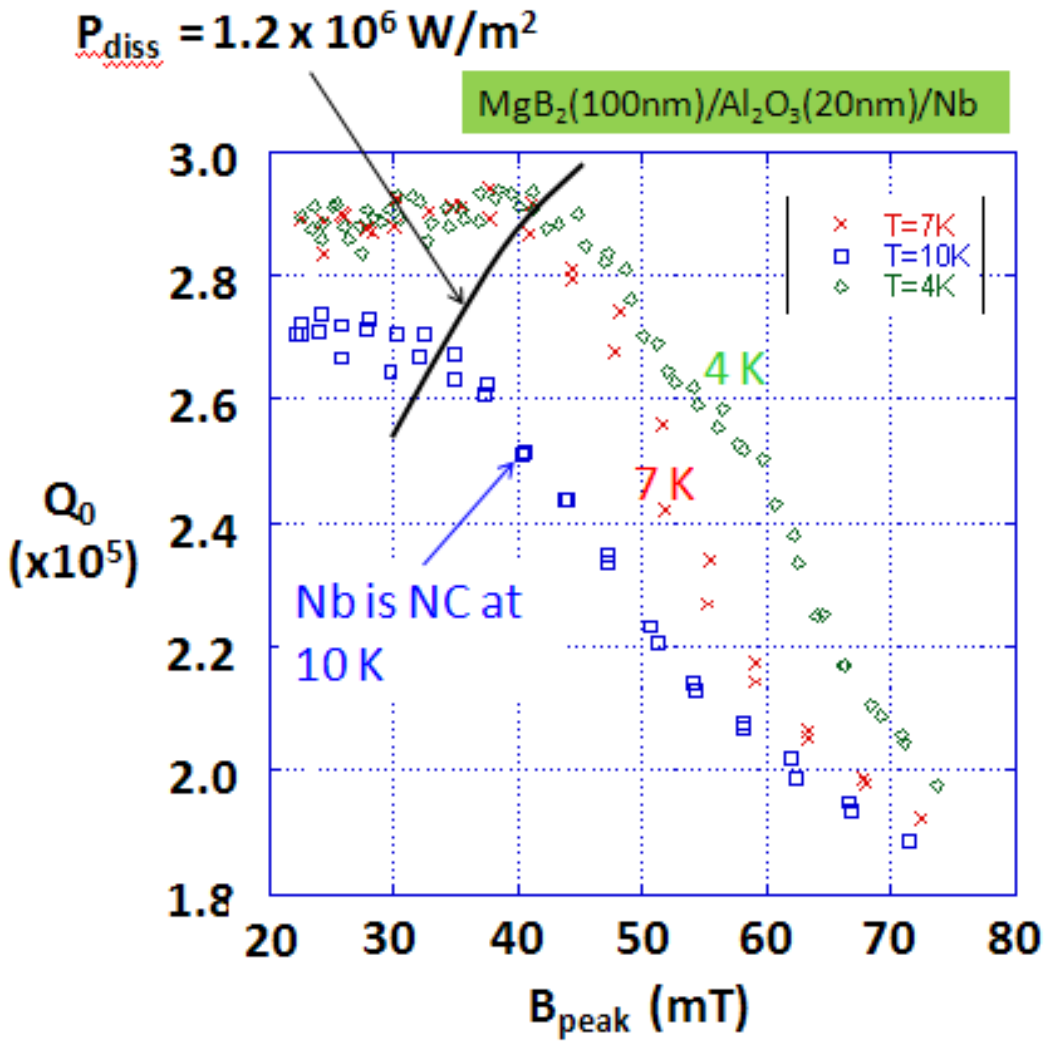


1.2 x 10^6 W/m^2 (time averaged density is 1.9 W/m^2 from pulse width of 1.6 μs and rep rate of 1 Hz)

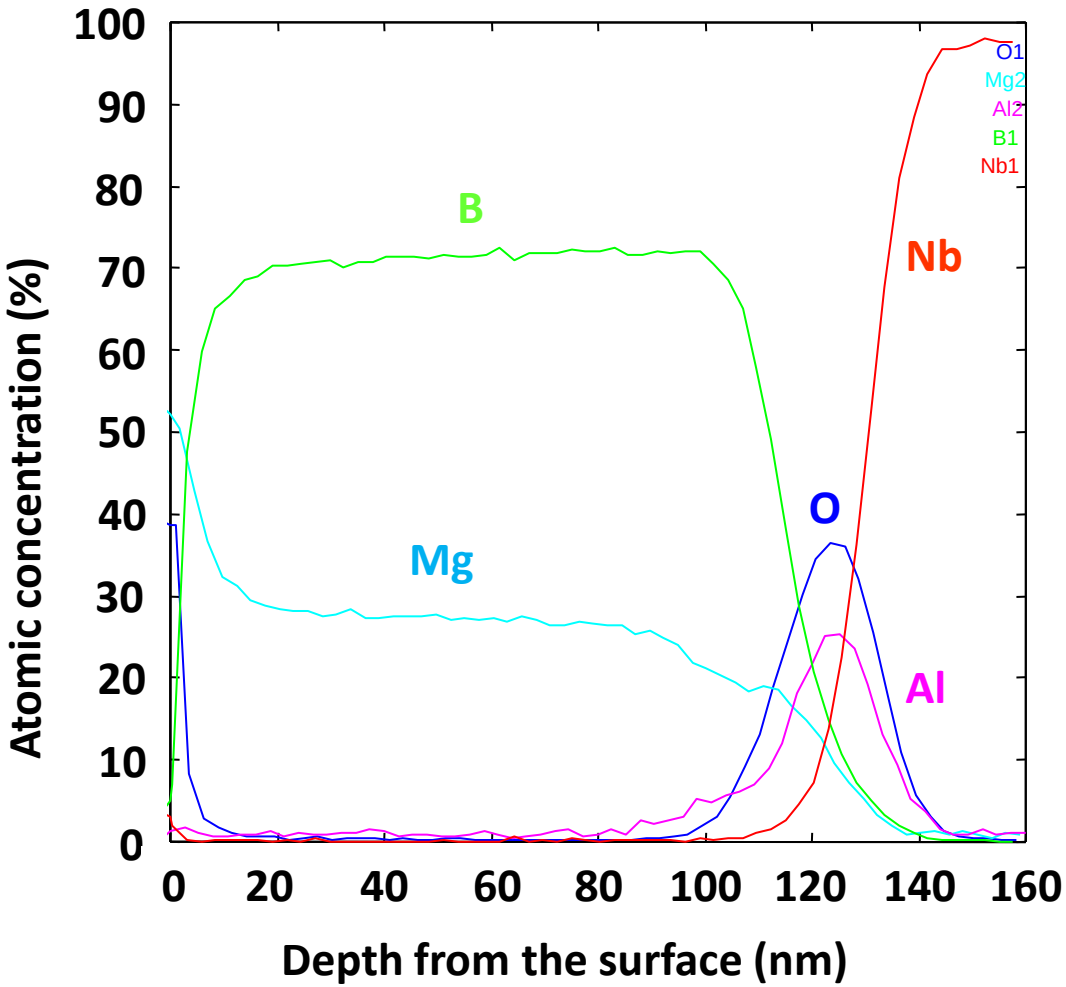
Q_0 as a function of magnetic field when the peak power density is 1.2 x 10^6 W/m^2 in the case of 2-inch single-grain Nb (thickness approx. 1.06 ± 0.06 mm) RRR > 300.



High-power tests of MgB_2(100nm)/Al_2O_3(20nm)/Nb : sample at various temperatures indicate the quenches due to thermal heating



Auger depth profile shows inter-diffusion of all the elements at the interface of MgB_2(100nm)/Al_2O_3(20nm)/Nb system



- Both ALD Alumina coating at 300 °C and MgB_2 coating at 550 °C have contributed to this inter-diffusion
- This interface layer is probably responsible for high RF resistance
- Developing a technique to prevent this inter-diffusion will be the key to success

Conclusion from MgB_2 studies

- H_{sh} can be increased by multilayer thin superconductor films. A >25 % higher H_{sh} (>200 mT) than bulk Nb with ≤300 nm MgB_2 films at 4.5 K was demonstrated.
- High-power RF tests at SLAC have shown quench fields significantly lower than the values predicted with DC magnetization measurements. Detailed analyses indicate that these quenches are mostly thermal, not magnetic.
- Developing a coating technique to reduce the inter-diffusion responsible for the increase in R_s is the key to success

Acknowledgements

- I would like to thank the following people who have provided me with the slides for this presentation.

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- Also, I would like to thank the following people whose data were used in this presentation.

D. Agassi, T. Doi, V. Dolgashev, A. Findikoglu, A. Floris, J. Guo, A. Gurevich, H. Inoue, D. Martin, A. Matsumoto, B. Moeckly, D. Oates, H. Ohsato, M. Pellin, T. Proslier, A. Romanenko, R. Schulze, S. Tantawi, D. Tsuya, A-M. Valente Feliciano, E. Watanabe, C. Yoneda, C. Yung

Conclusion

- **Promising materials for SRF applications require low normal conducting resistance at T_c, high T_c, large energy gap, high thermal conductivity (in the case of bulk), smoothness, stable and cleanable surfaces.**
- **So far, Nb_3Sn and MgB_2 look the best. To the best of my knowledge, pnictides such as FeAs have not been studied in terms of RF application.**
- **Hope that at least one SRF cavity using an alternative material can show a world record of E_{acc} (>59 MV/m) with a reasonable Q_0 within 3 years.**