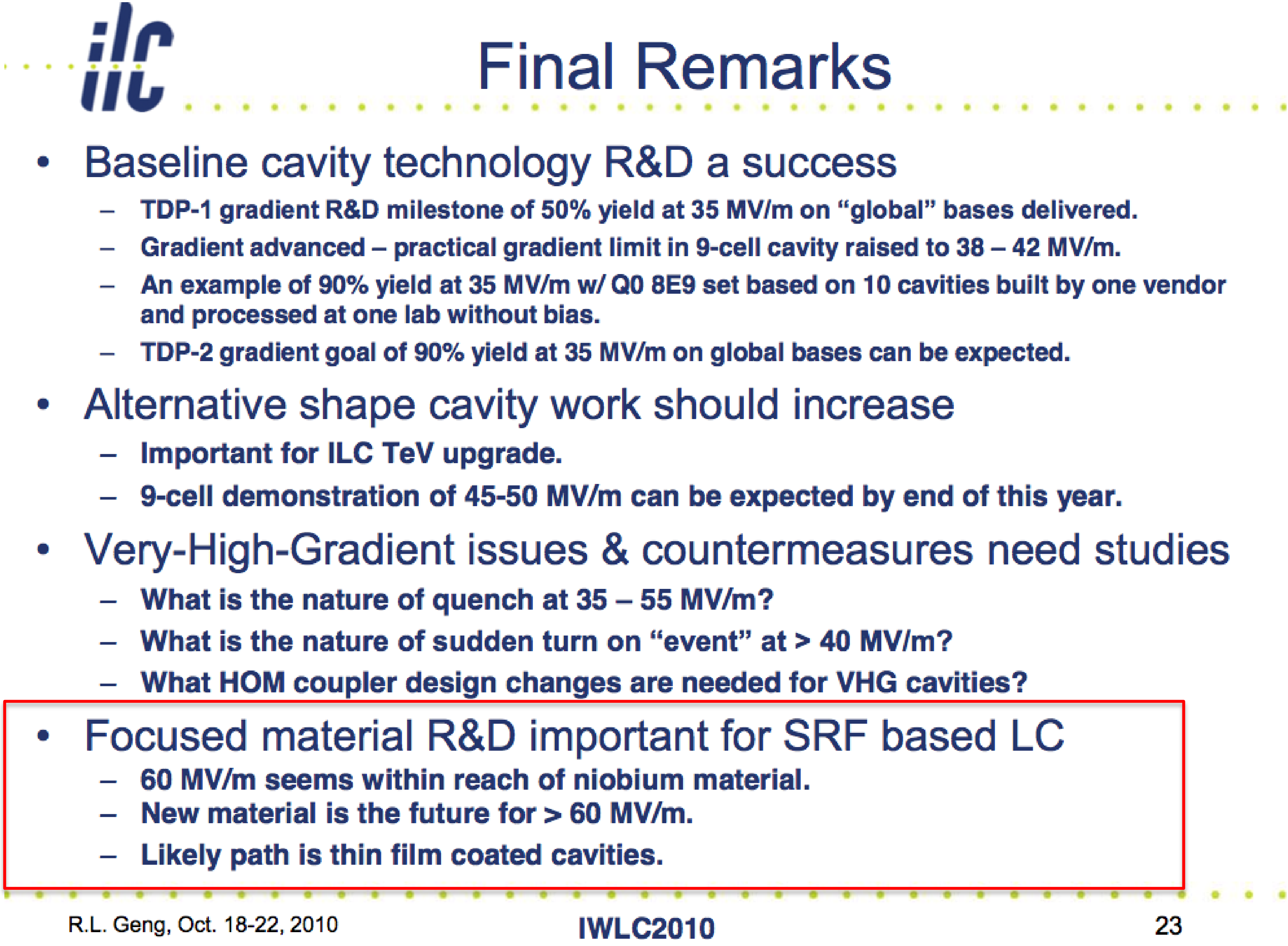
Tohoku Forum for Creativity 2013

Prospect of High Gradient Cavity

H. Hayano, 10222013

Remarks of Rongli Geng at IWLC2010



Final Remarks

- Baseline cavity technology R&D a success
  - TDP-1 gradient R&D milestone of 50% yield at 35 MV/m on "global" bases delivered.
  - Gradient advanced – practical gradient limit in 9-cell cavity raised to 38 – 42 MV/m.
  - An example of 90% yield at 35 MV/m w/ Q0 8E9 set based on 10 cavities built by one vendor and processed at one lab without bias.
  - TDP-2 gradient goal of 90% yield at 35 MV/m on global bases can be expected.
- Alternative shape cavity work should increase
  - Important for ILC TeV upgrade.
  - 9-cell demonstration of 45-50 MV/m can be expected by end of this year.
- Very-High-Gradient issues & countermeasures need studies
  - What is the nature of quench at 35 – 55 MV/m?
  - What is the nature of sudden turn on "event" at > 40 MV/m?
  - What HOM coupler design changes are needed for VHG cavities?
- Focused material R&D important for SRF based LC
  - 60 MV/m seems within reach of niobium material.
  - New material is the future for > 60 MV/m.
  - Likely path is thin film coated cavities.

R.L. Geng, Oct. 18-22, 2010

IWLC2010

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>60MV/m by Thin-Film coated Cavity

Look review lecture by T. Tajima(LANL)
for
“Thin Film coated Cavity”

Nb_3Sn : tri-niobium tin

MgB_2 : magnesium di-boride

Multi-layer thin film concept

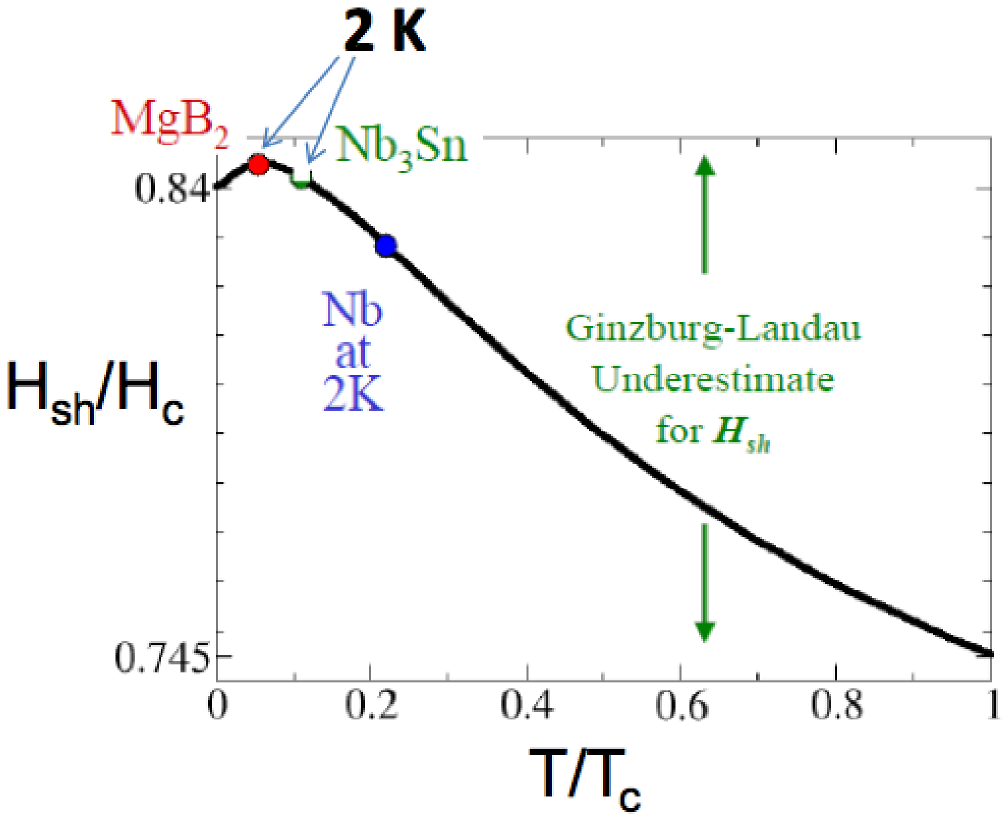
T. Tajima

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]

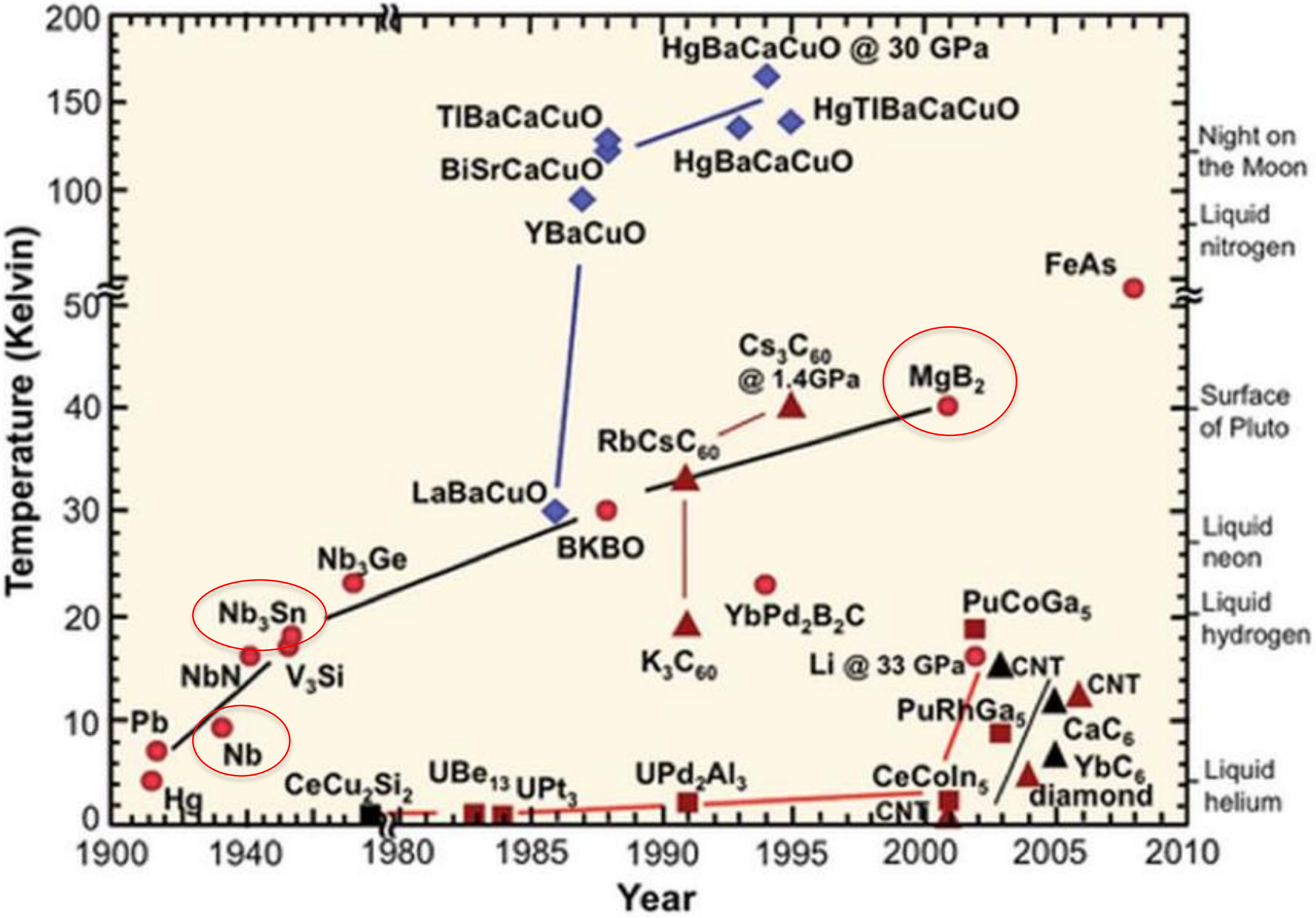


[1] G. Catelani, J. Sethna, PRB **78** (2008) 224509.

T. Tajima

Discoveries of Superconductors

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



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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

T. Tajima

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 [$\mu\Omega\cdot$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.

T. Tajima

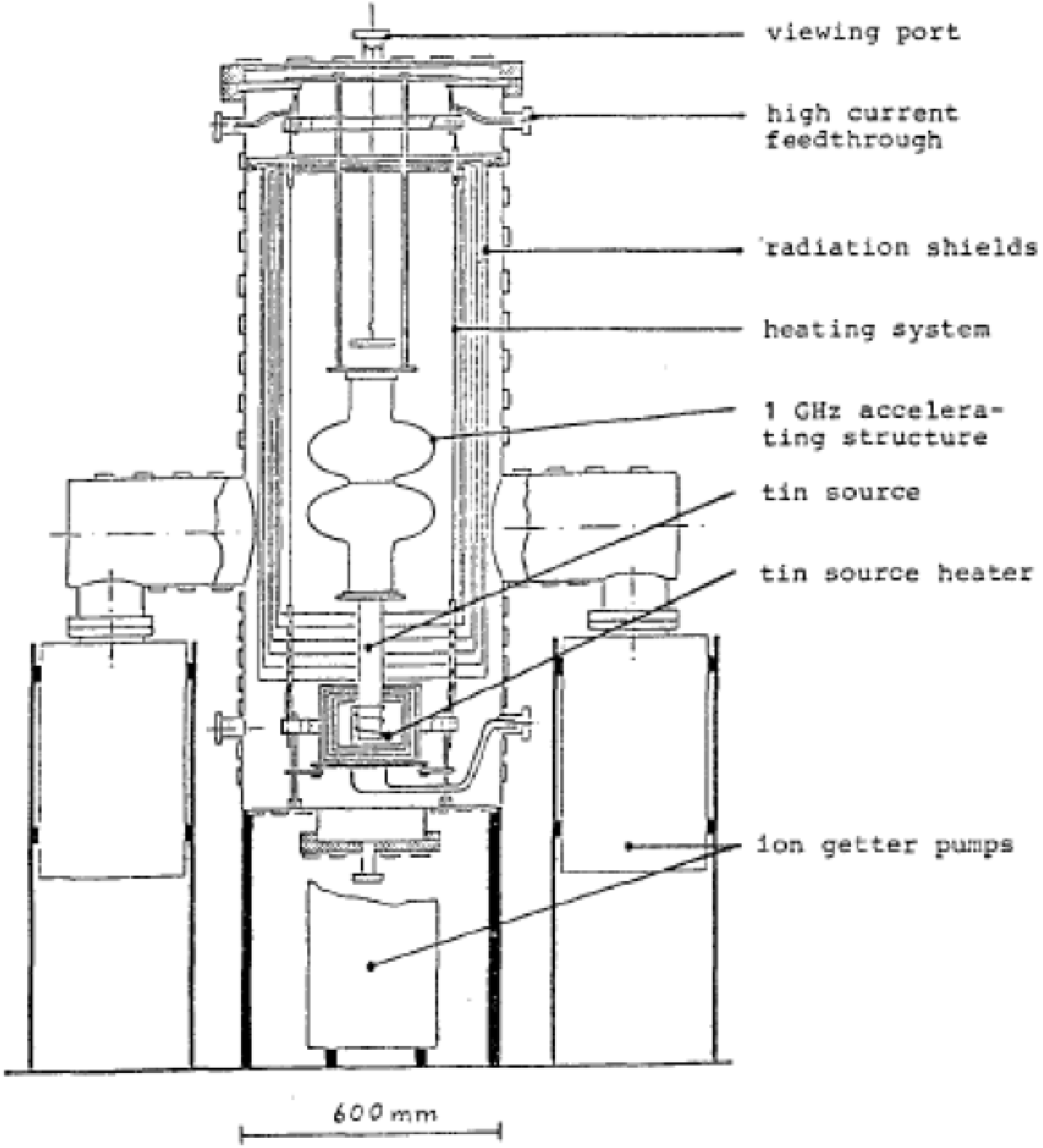
Nb_3Sn

- 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.

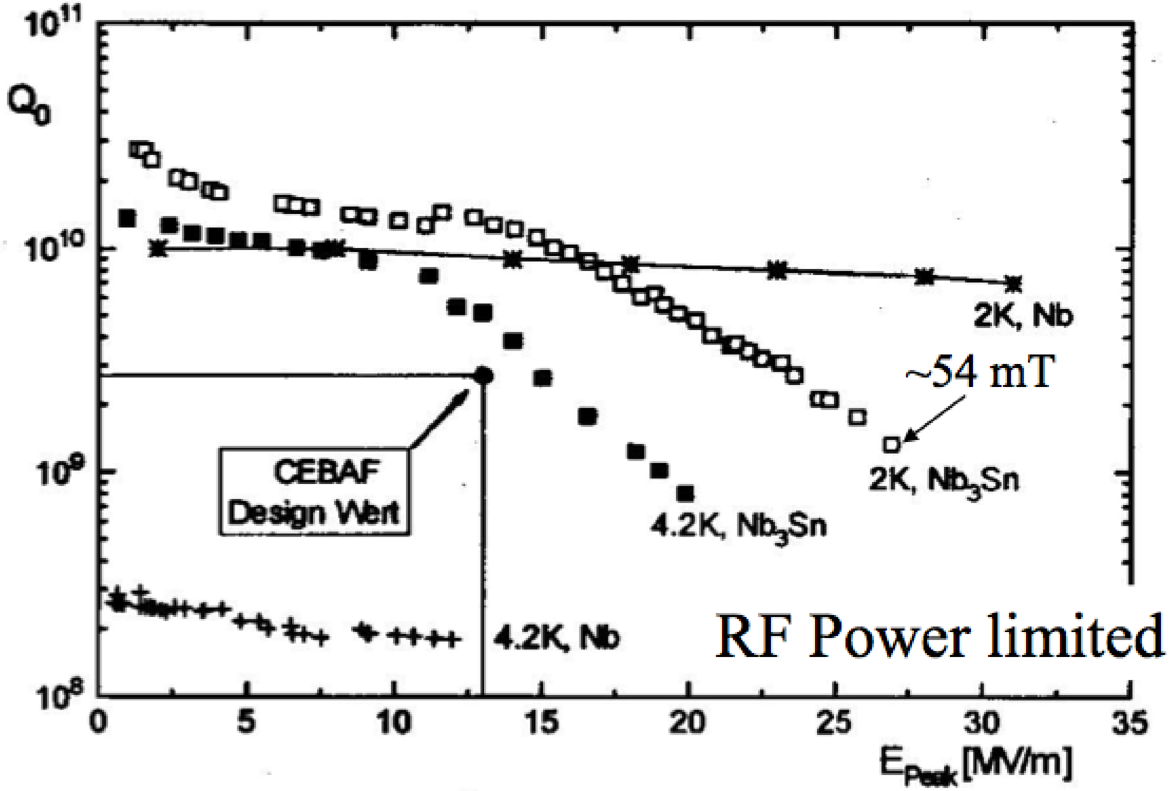
[2] M. Peiniger et al. SRF1987.

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



~54 mT

RF Power limited

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

Best R_{res} = 2.2 nΩ!

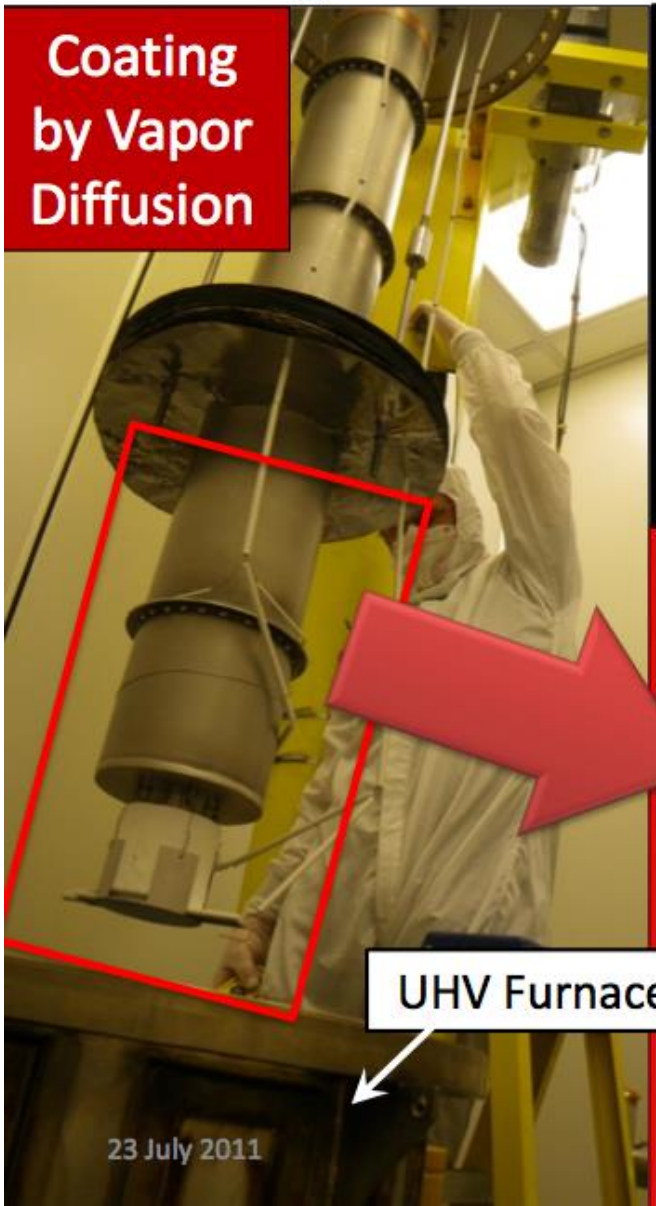
Nb_3Sn coating at Wuppertal and measurement at JLAB

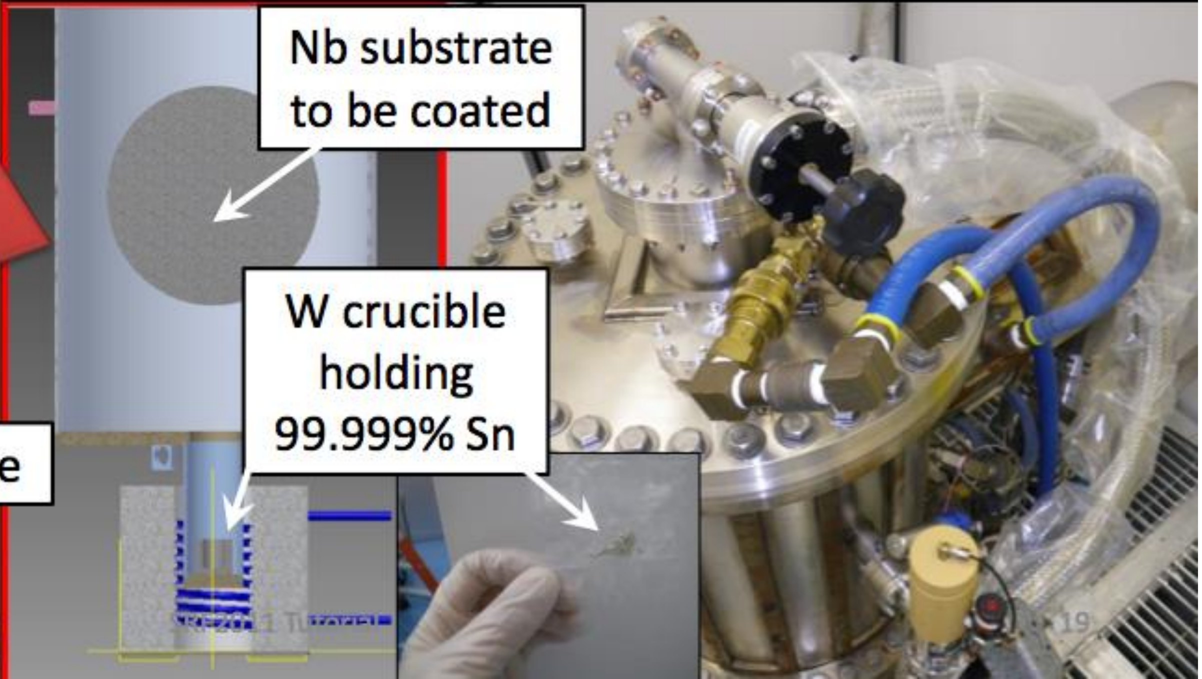
G. Mueller et al. EPAC1996

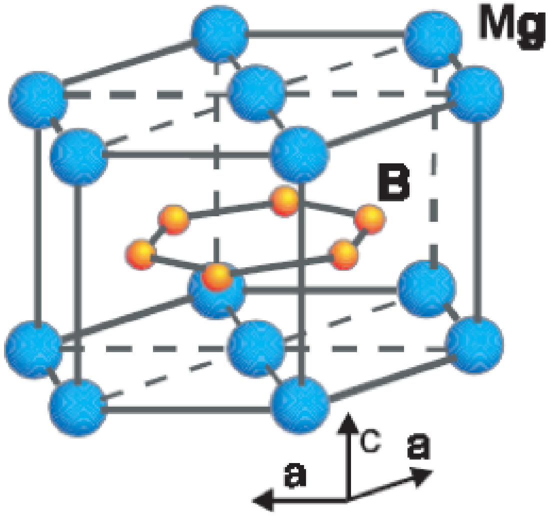
Nb_3Sn Fabrication at Cornell

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…







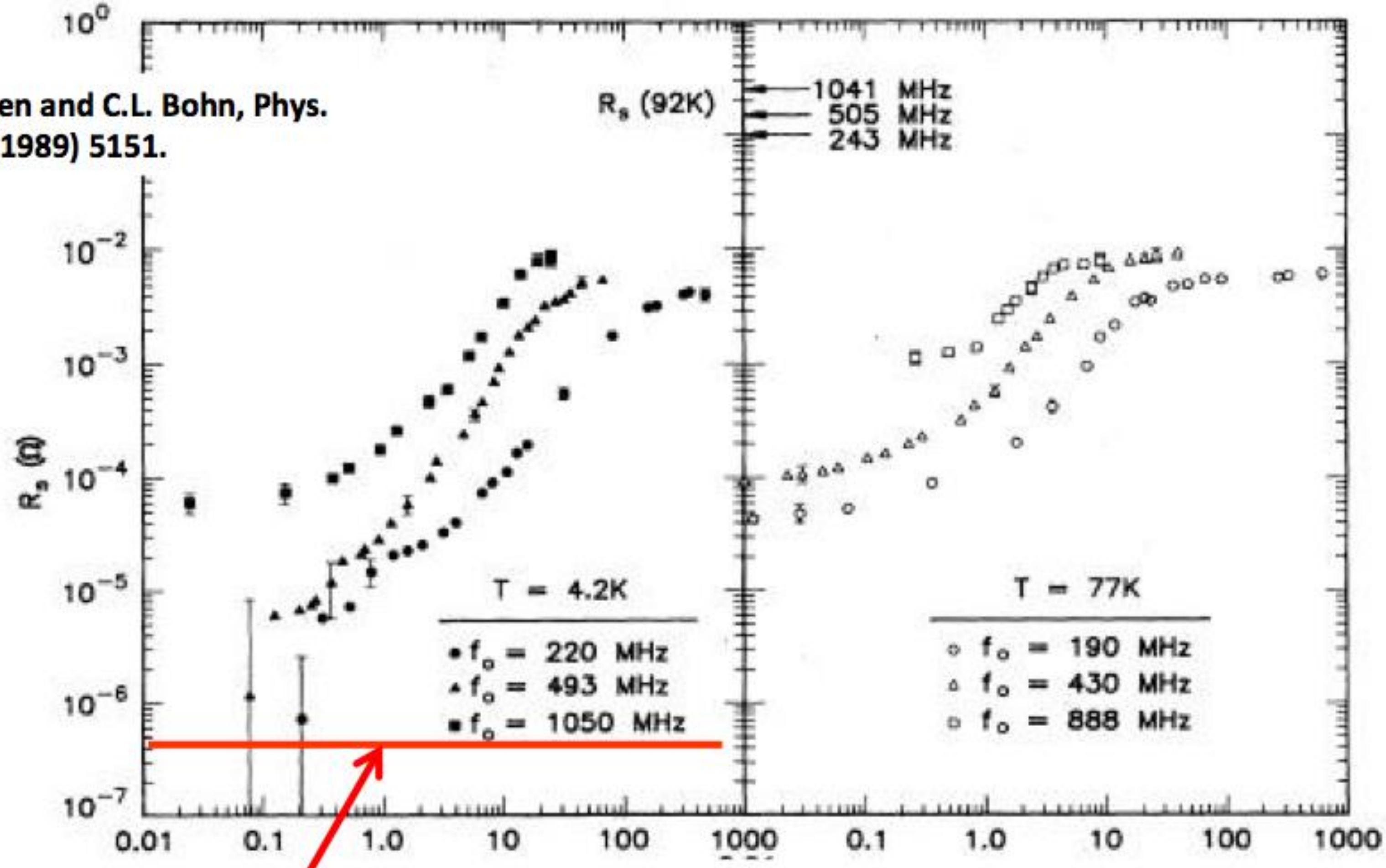
- Relatively easy to deposit compared to other higher-TC SC.
- Absence of weak links ⇒ Less Q_0 drop as H (equiv. of E) goes up.
- Similar behavior to other low-temperature superconductors except for 2-gap nature

[**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



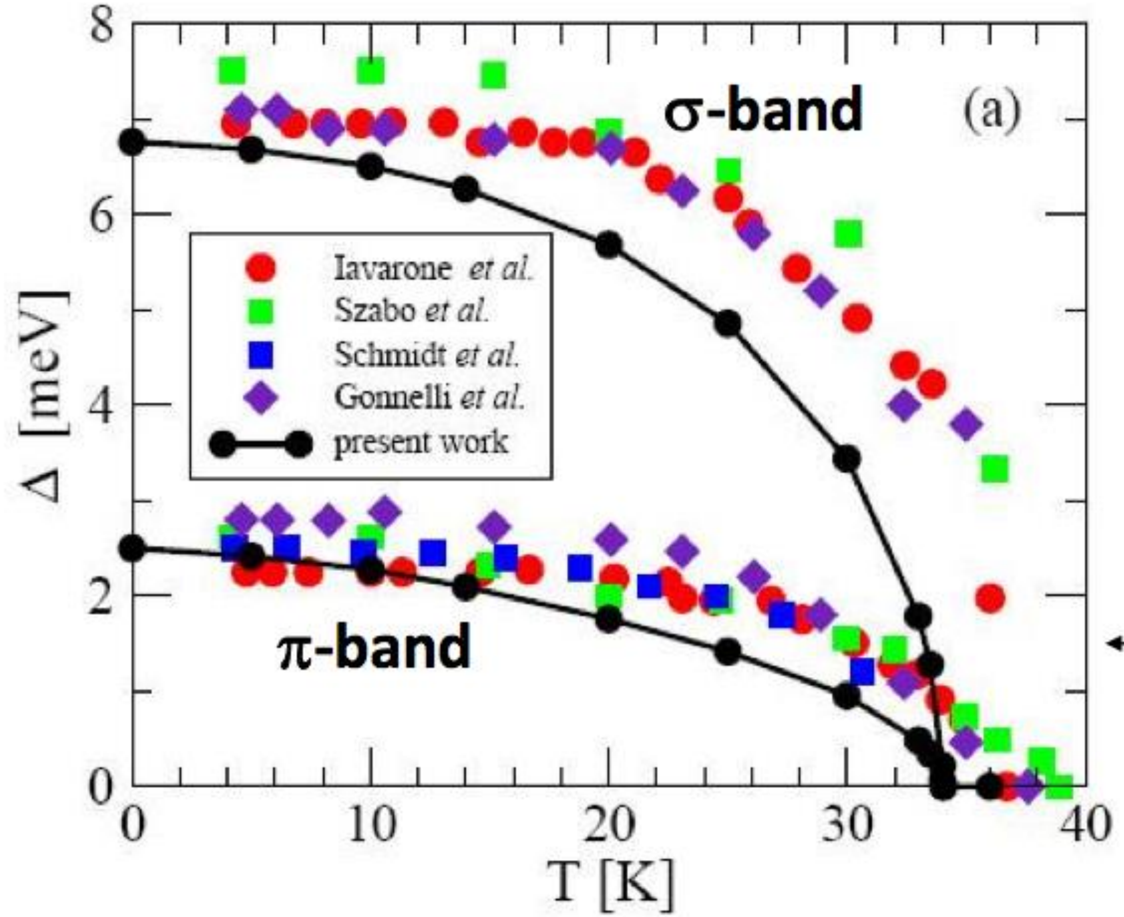
J.R. Delayen and C.L. Bohn, Phys. Rev. B40 (1989) 5151.

BCS R_s of Nb @ 1 GHz 4.4×10^{-7} Ω

RF Magnetic field (Oe)

T. Tajima

MgB$_2$ has two energy gaps. Unfortunately, the lower energy gap seems to dominate for RF.

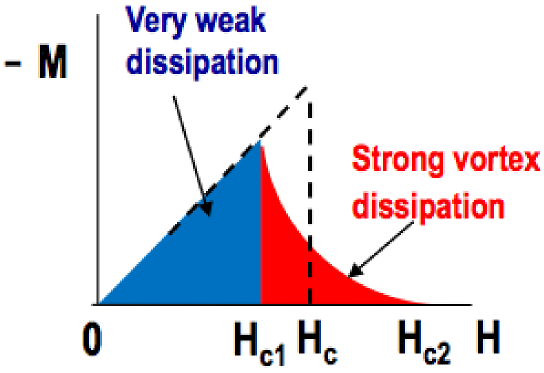


RF response has shown lower energy gap behavior.

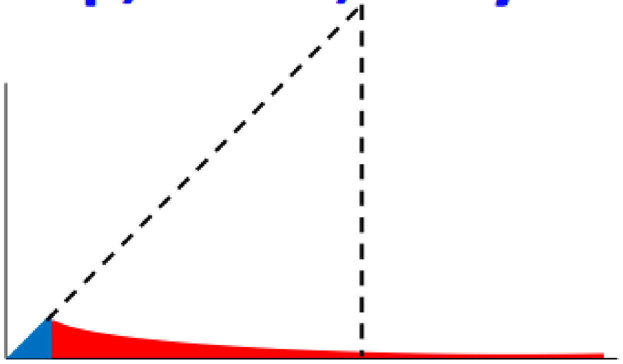
← **Nb energy gap ~1.5 meV**

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}

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

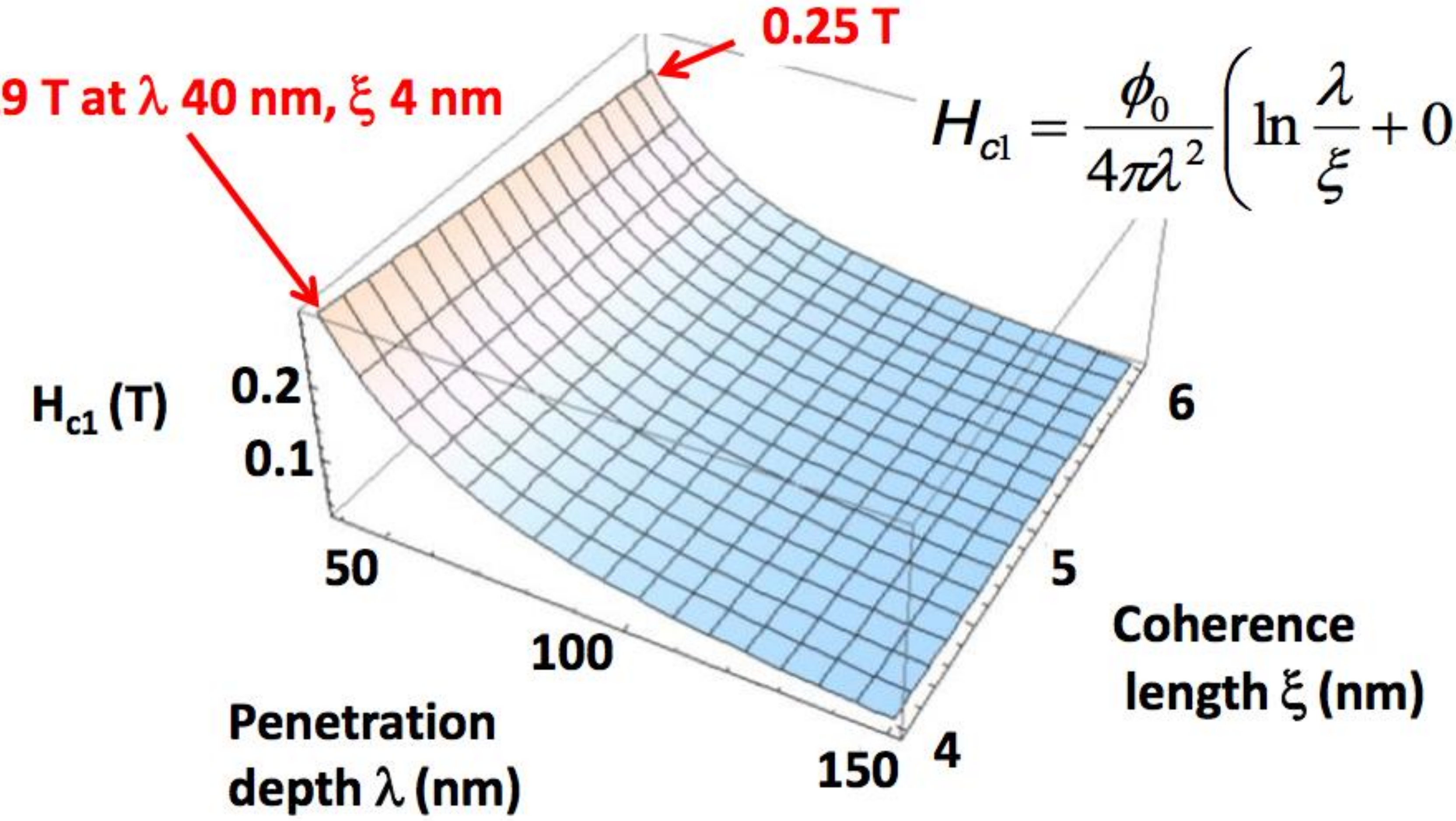
Thermodynamic critical field H_c (surface barrier for vortices disappears)

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

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

Theoretical H_{c1} value for MgB_2

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

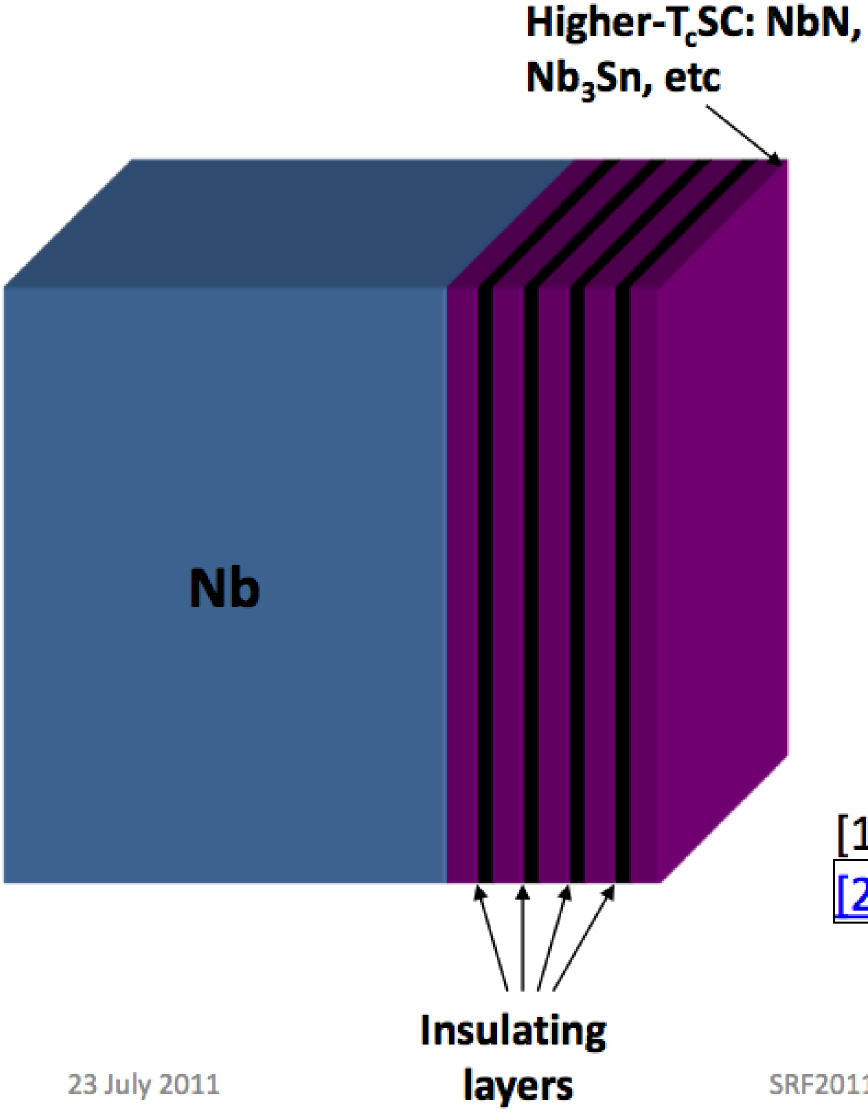


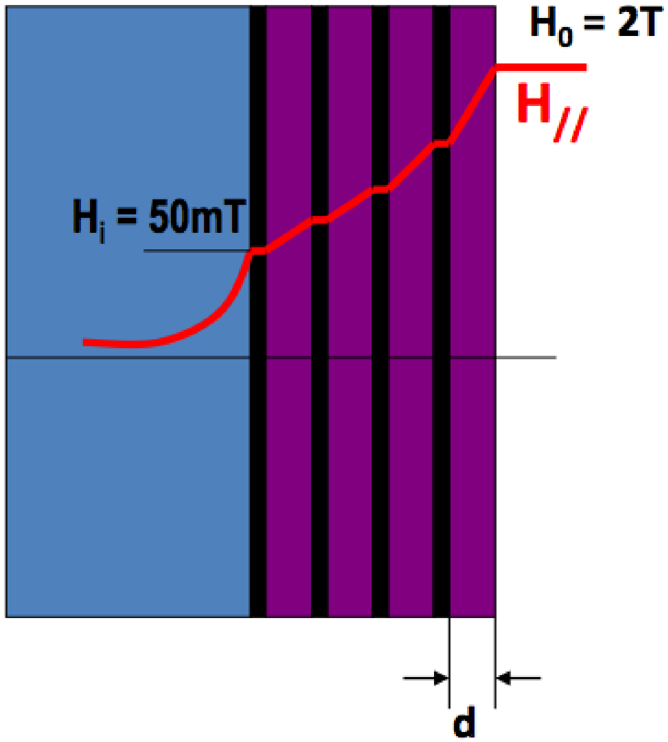
0.25 T

0.29 T at λ 40 nm, ξ 4 nm

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

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

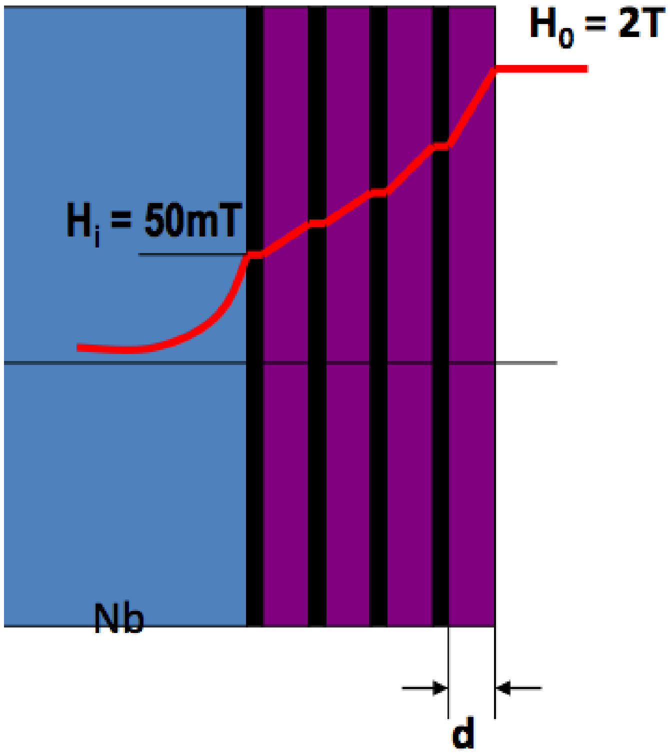




[1] A. Gurevich, APL **88** (2006) 012511

[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)

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

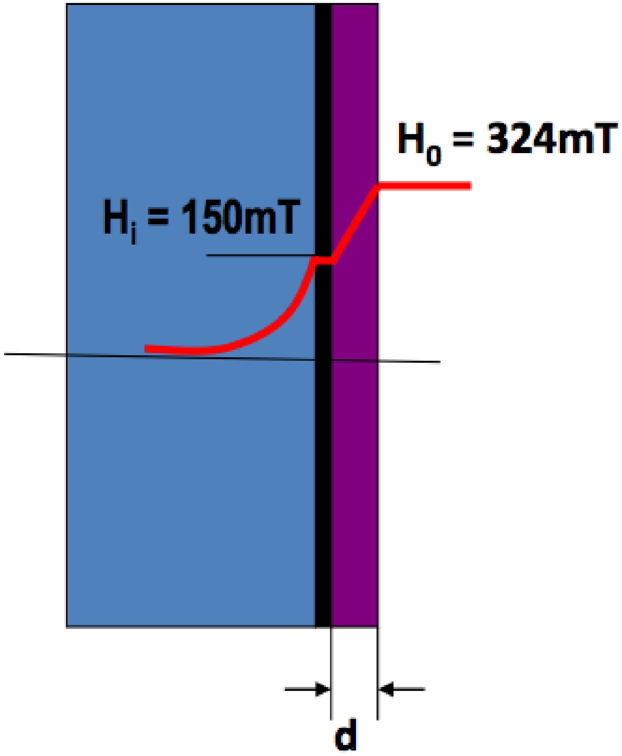
N = (65/30)ln(40) = 8 layers

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

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

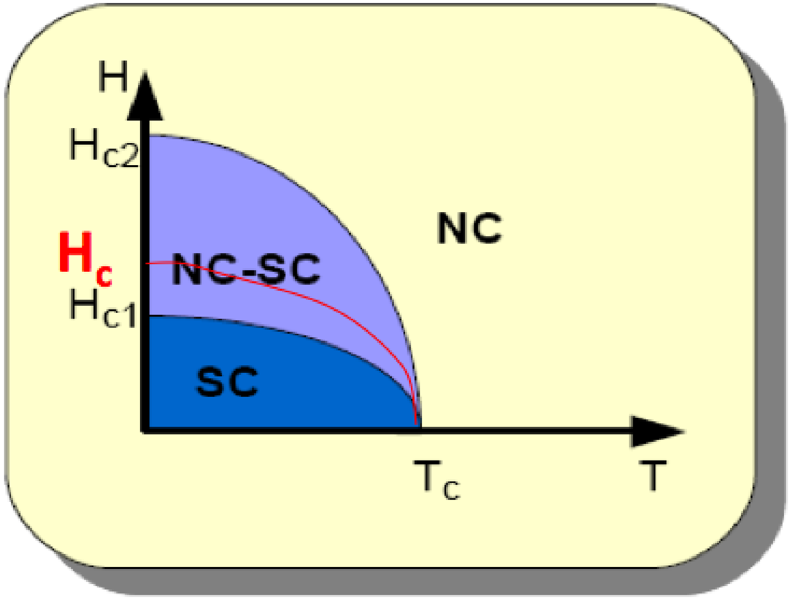
Lower critical field for the Nb_3Sn layer with d = 50 nm and ξ = 3nm: H_{c1} = 1.4T is much higher than H_0

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

T. Tajima

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

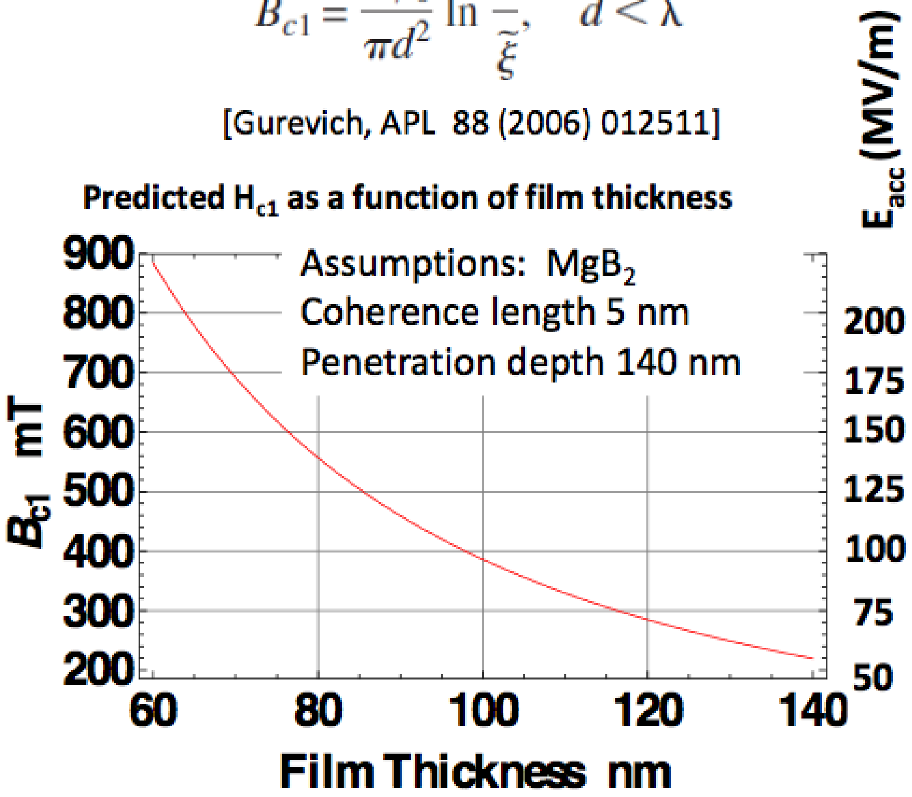


- Use thin films with thickness $d < \lambda_L$ to enhance the lower critical field

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

[Gurevich, APL 88 (2006) 012511]

Predicted H_{c1} as a function of film thickness



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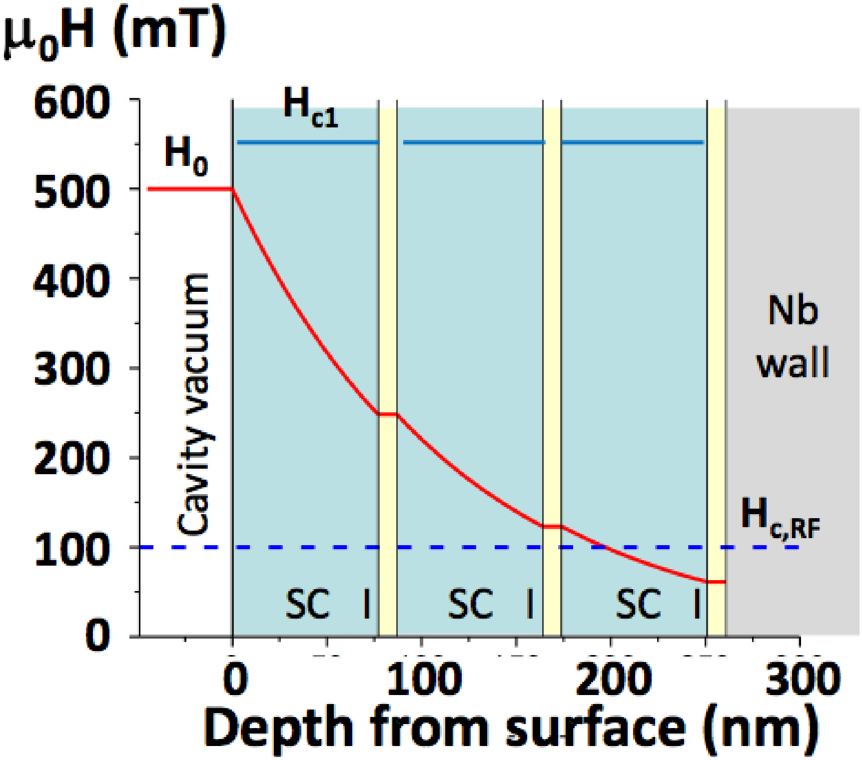
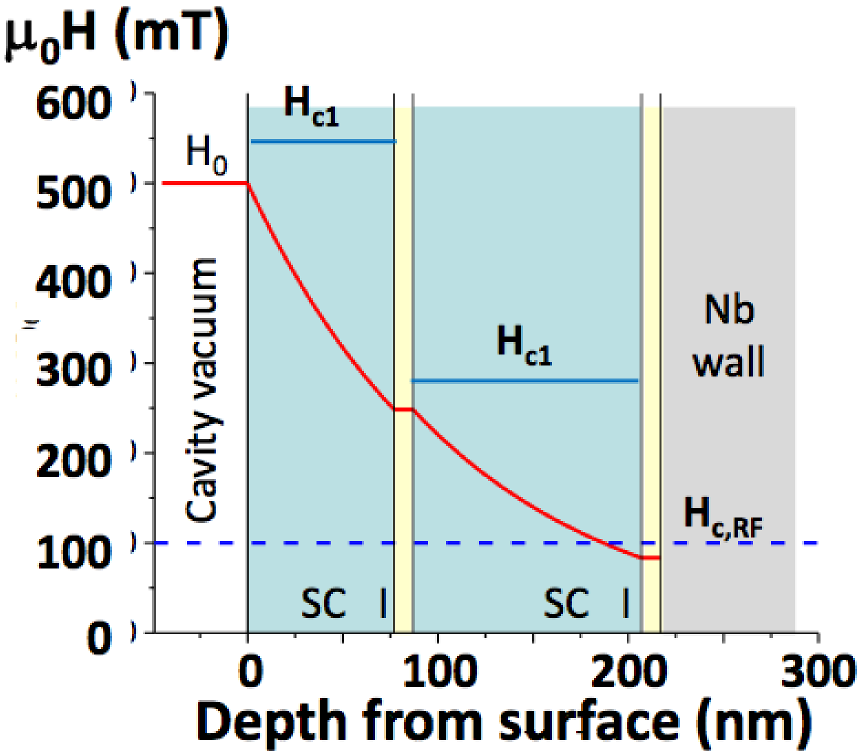
Variable thickness films could reduce the number of layers

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





Fixed thickness multilayers:

- *d* ≤ 77nm for H_{c1} ≥ 5500 Oe
- 3 layers needed
- coating curved walls with very thin uniform of layers is challenging

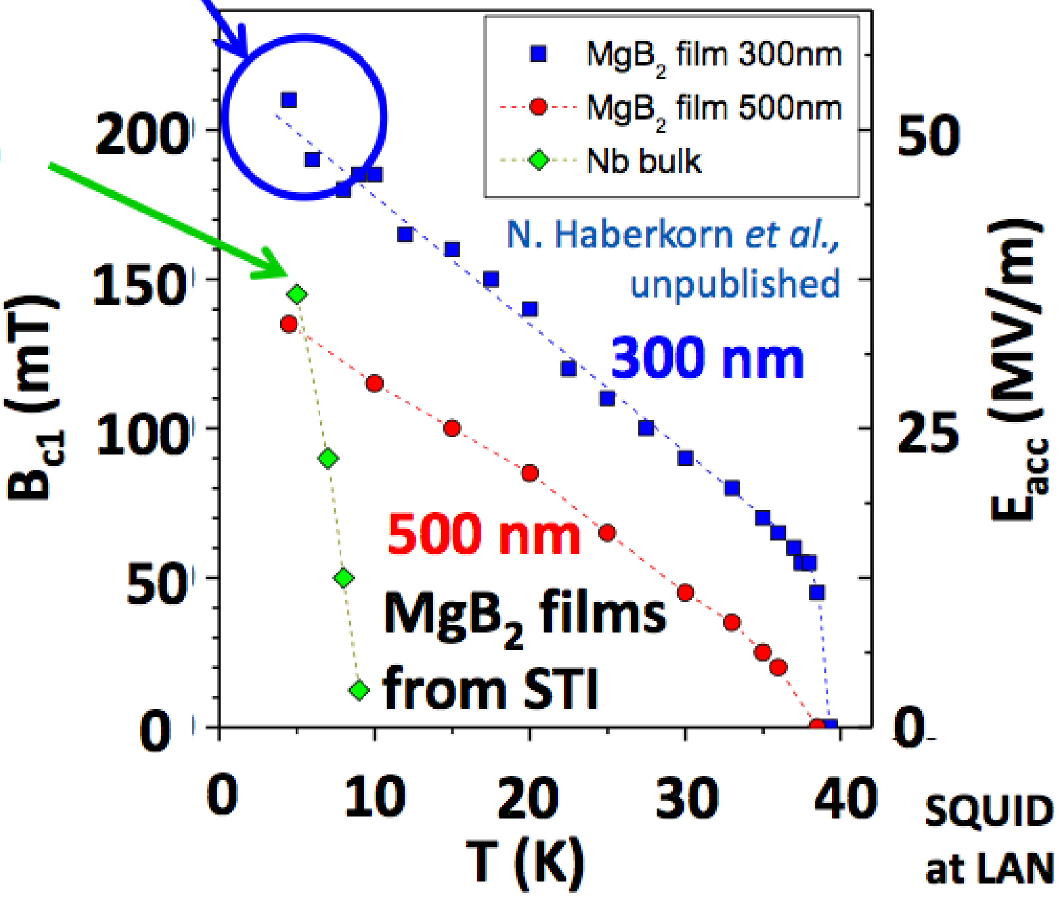
Variable thickness multilayers:

- d_1 ≤ 77nm for H_{c1} ≥ 5500 Oe
- only 2 layers needed
- 2nd layer is thicker: 100nm ≤ d_2 ≤ 120nm

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.

At 4.5 K, B_{c1}(300 nm MgB_2 film) > B_{c1} (bulk Nb)

Solid Nb
4.5 K



N. Haberkorn *et al.*, unpublished

300 nm

500 nm

MgB_2 films
from STI

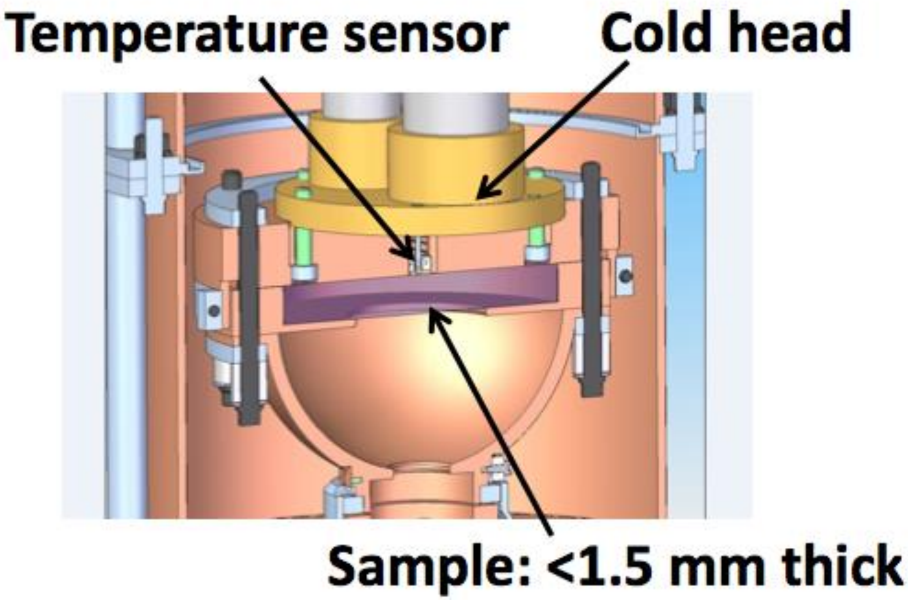
SQUID magnetometry
at LANL

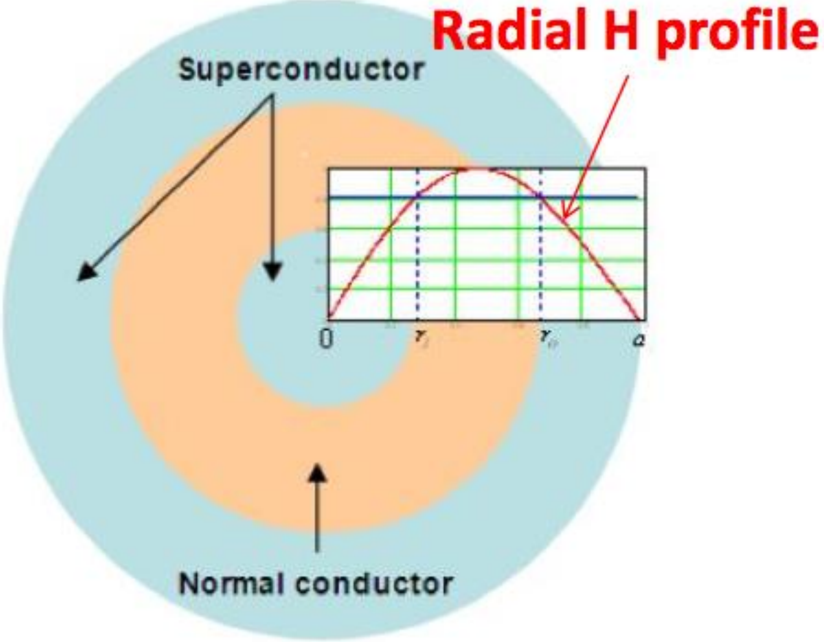
Converted
Using
B_{peak}/E_{acc} = 4 mT/(MV/m)

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

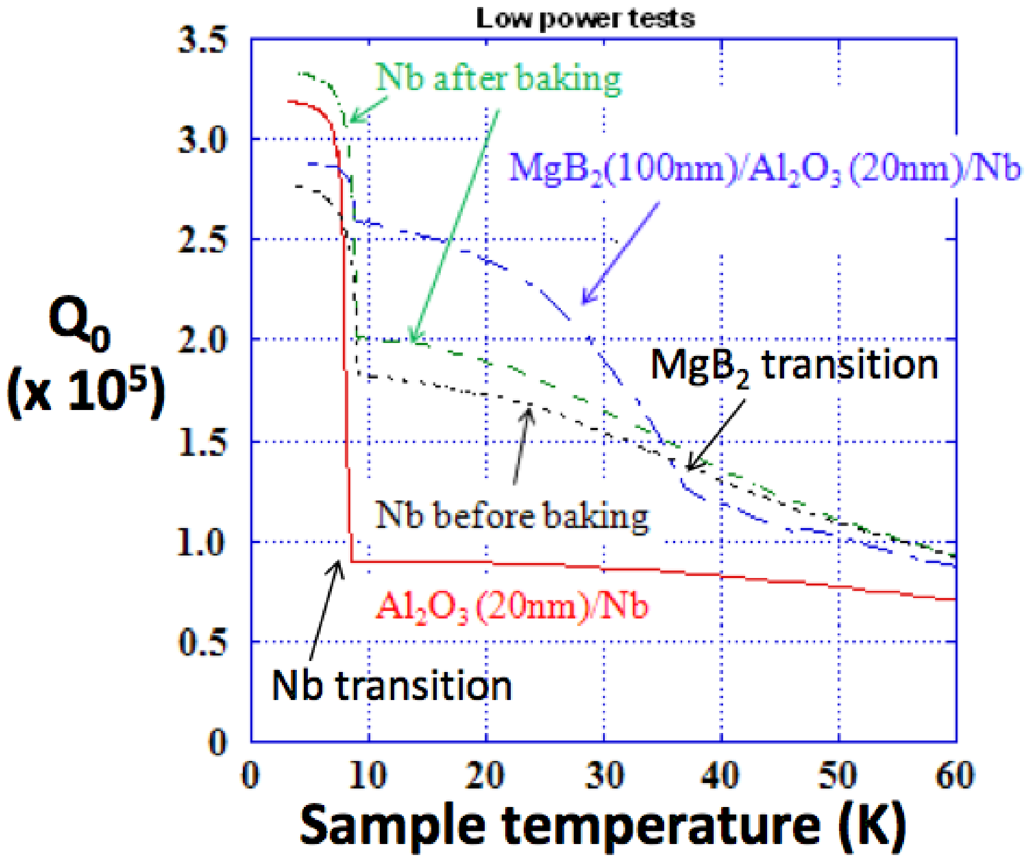




T. Tajima

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

Max. $Q_0 \sim 3.5 \times 10^5$ due to Cu host cavity

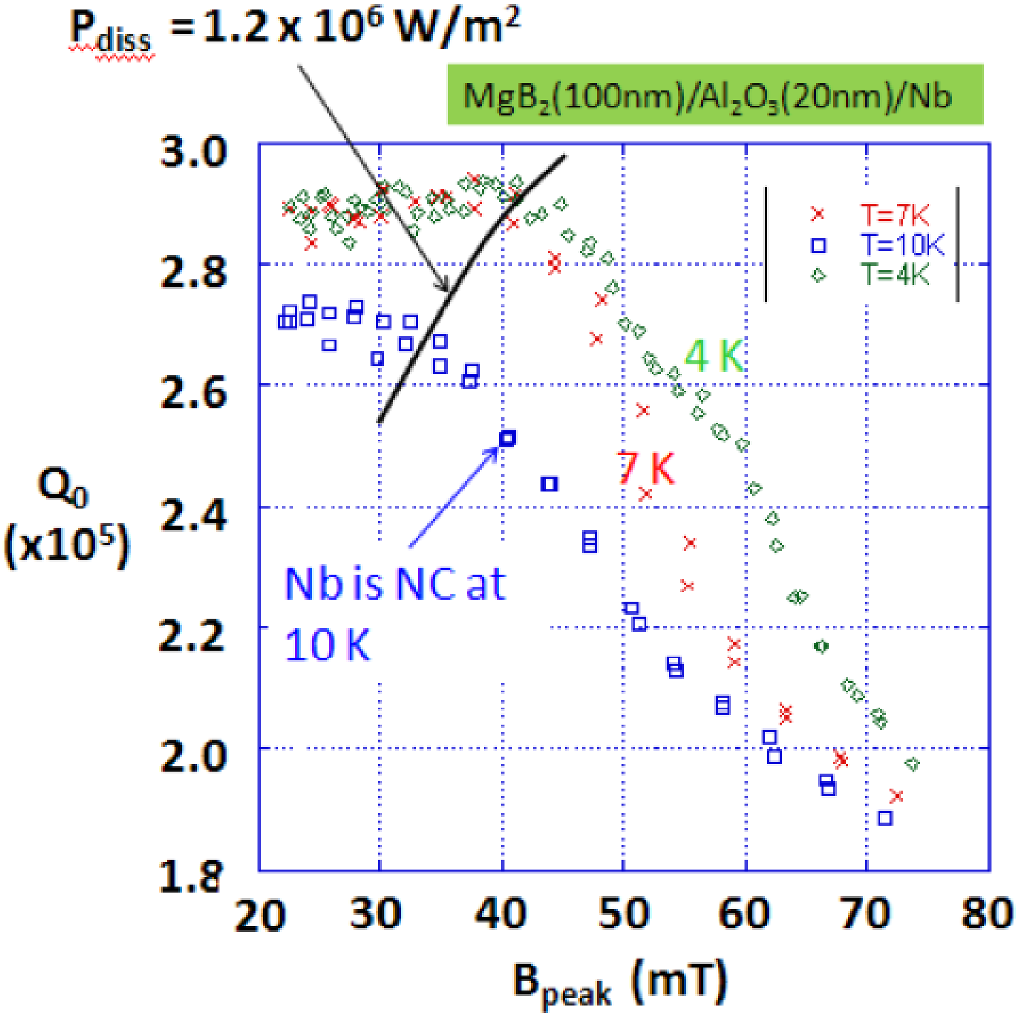


11.4 GHz

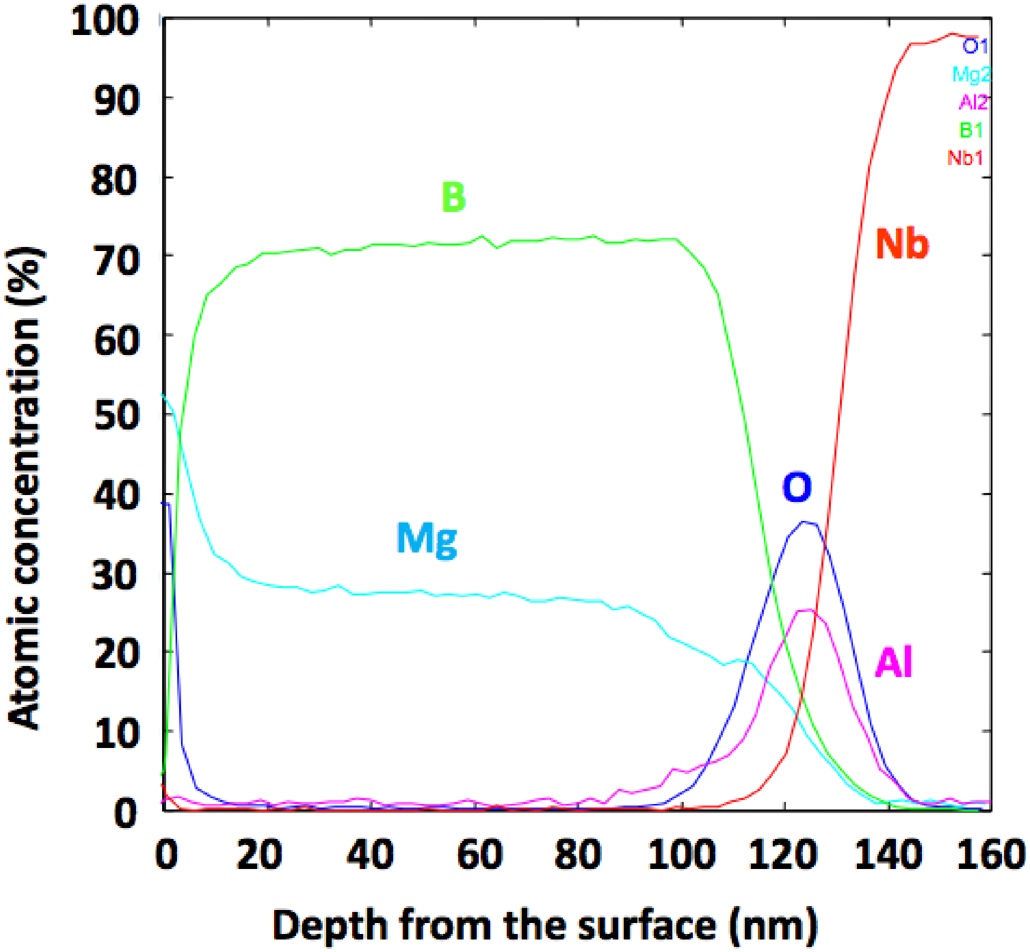
- UHV baking at 800 °C for 4 hours cleaned the Nb surface
- Alumina coating with ALD at 300 °C increased RF resistance in both NC and SC states
- Subsequent MgB_2 coating with reactive co-evaporation at 550 °C reduced NC resistance down to Nb transition, but increased SC resistance at <9 K.

T. Tajima

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

How to make thin-film on Nb?

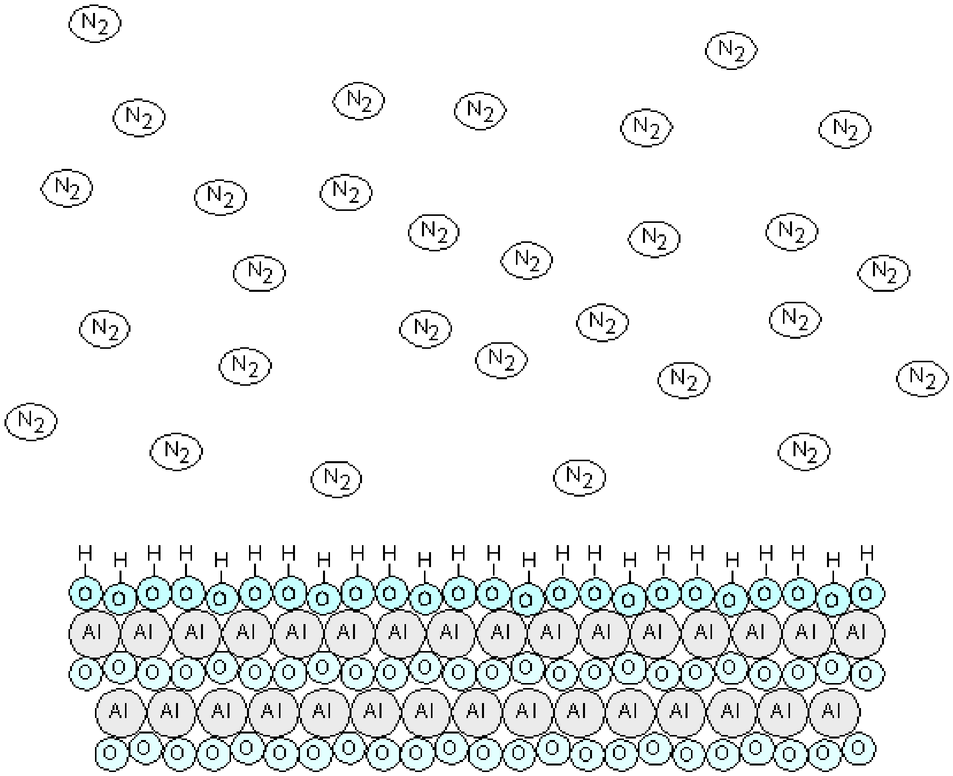
Look presentation by Chaoyue Cao (IIT)
for

“Point Contact Tunneling as a Surface Superconductivity Probe of bulk Nb and ($Nb_{1-x}Ti_x$)N Thin Films”

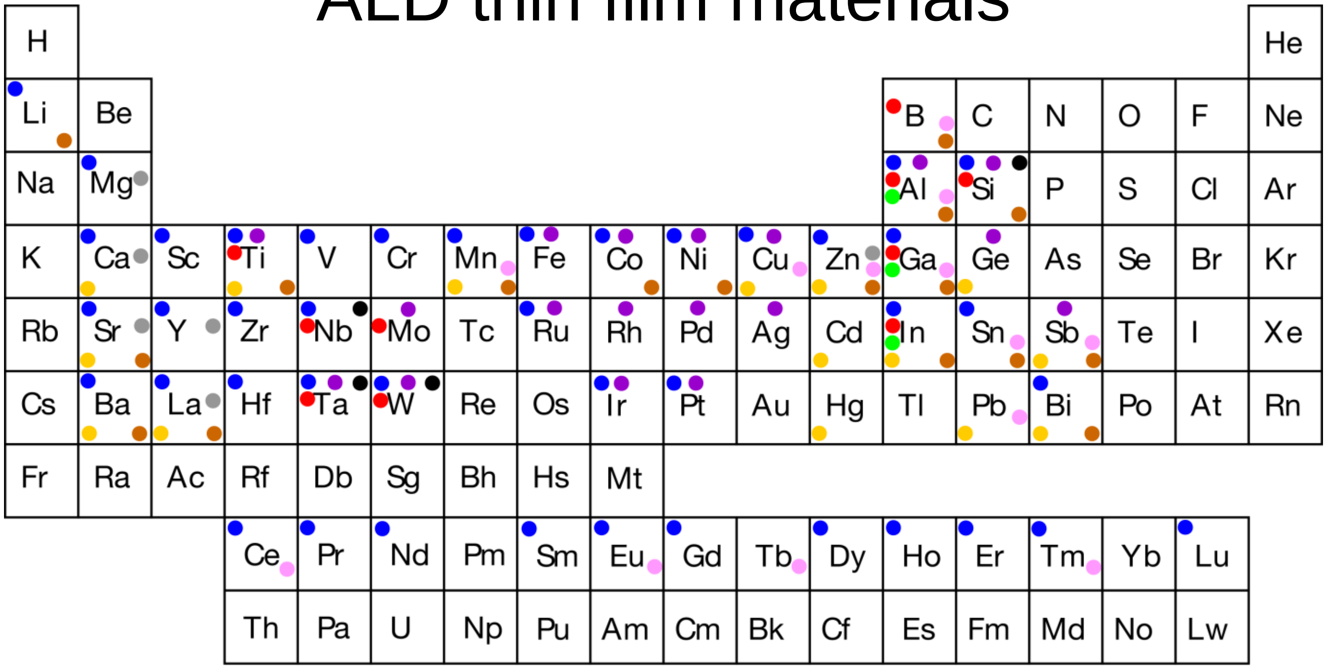
@ 5th Thin Film workshop 2012(Jlab)

Atomic layer deposition (ALD)

- A thin film synthesis process based on sequential, self-limiting surface reactions between vapors of chemical precursors and a solid surface to deposit films in an atomic layer-by-layer manner.



ALD thin film materials



- Oxide
- Nitride
- Phosphide/Arsenide
- Sulphide/Selenide/Telluride

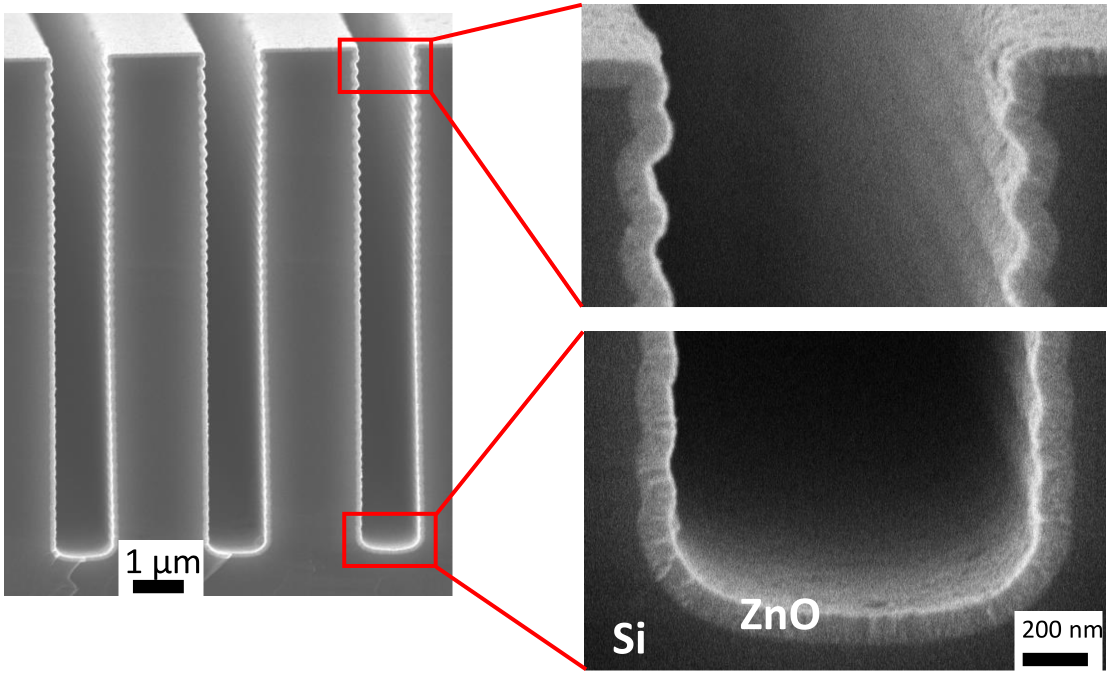
- Element

- Carbide
- Fluoride
- Dopant
- Mixed Oxide

Advantages:

- Atomic-level control of thickness and composition
- Smooth, continuous, pinhole-free coatings on large area substrates
- No line-of-sight limits → excellent conformality over complex shaped surfaces

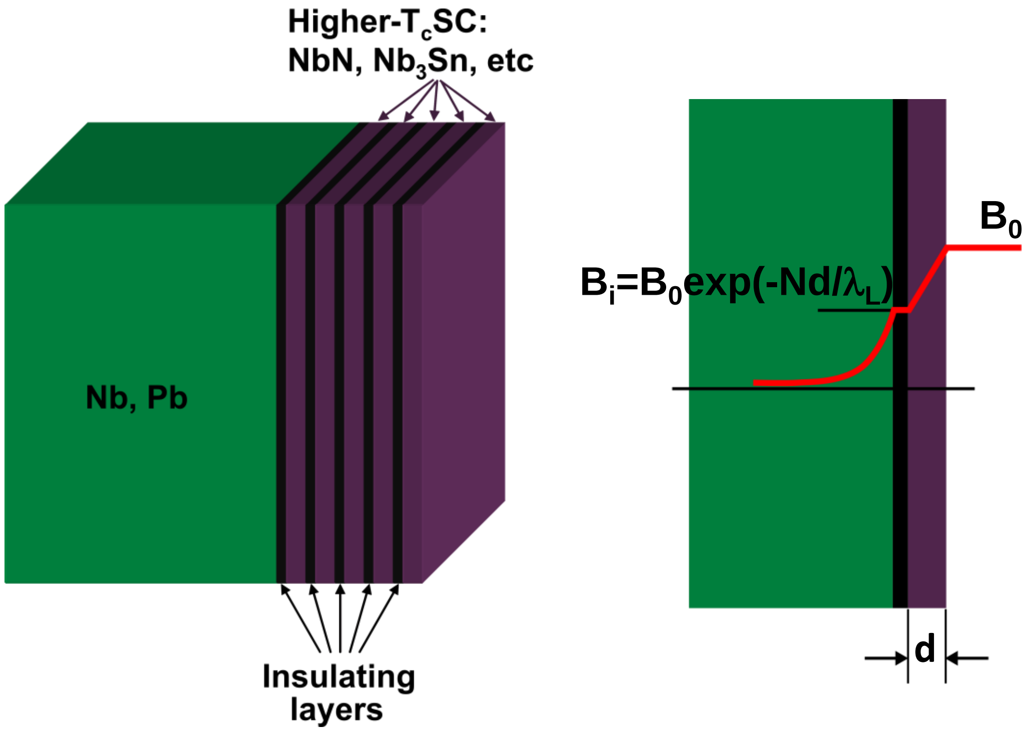
Coat inside Nb SRF cavity with precise, layered structure → ALD



- ALD is *very* good at coating non-planar surfaces

Multilayer thin films for SRF

- Superconductor-Insulator multilayer [Gurevich, *Appl. Phys. Lett.* **88**, 012511 (2006)]

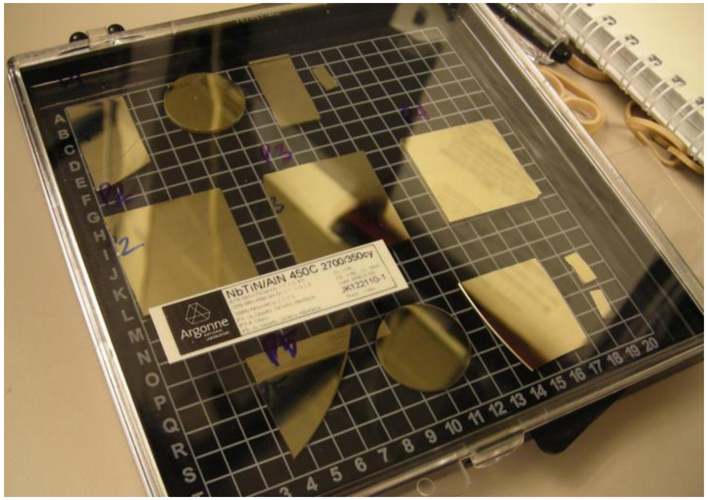


- Potential path to high E_{acc} and high Q_0

C. Cao

$Nb_{1-x}Ti_xN$ Thin Films made by ALD

- Chemistry: $(NbCl_5:TiCl_4)$ + Zn + NH_3 at 450°C, 500°C
- Can vary Ti content with $NbCl_5:TiCl_4$ ratio (1:2 ~ 20% TiN)
- Impurity content: 0.05 atom % Cl
- 21 sec/cycle
  2-7-1-5-1-5 ("NH3 dose"-"purge"-"MCl_x dose"-"purge"-"Zn dose"-"purge ")



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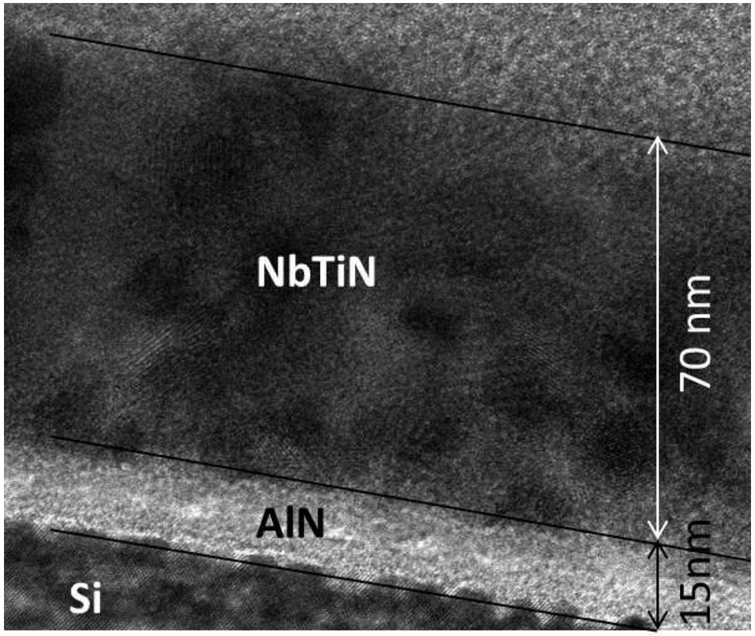
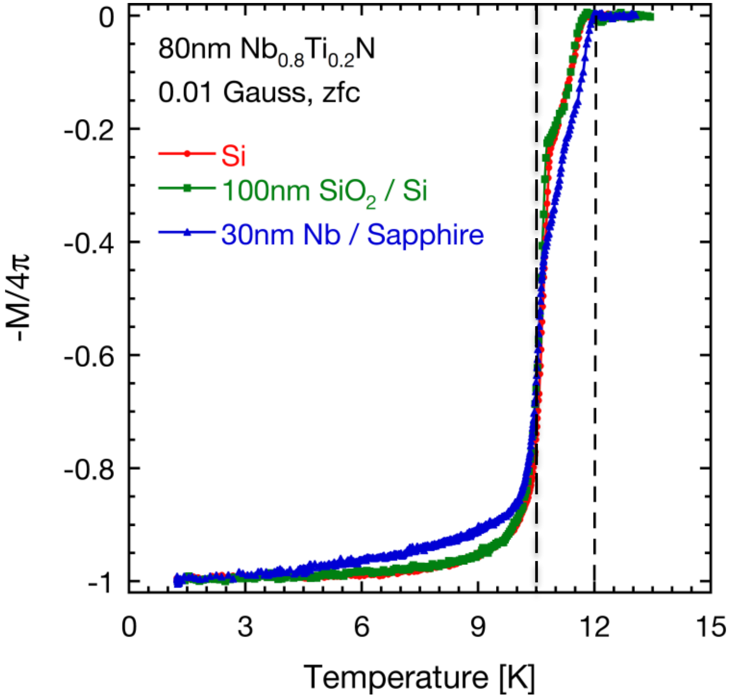


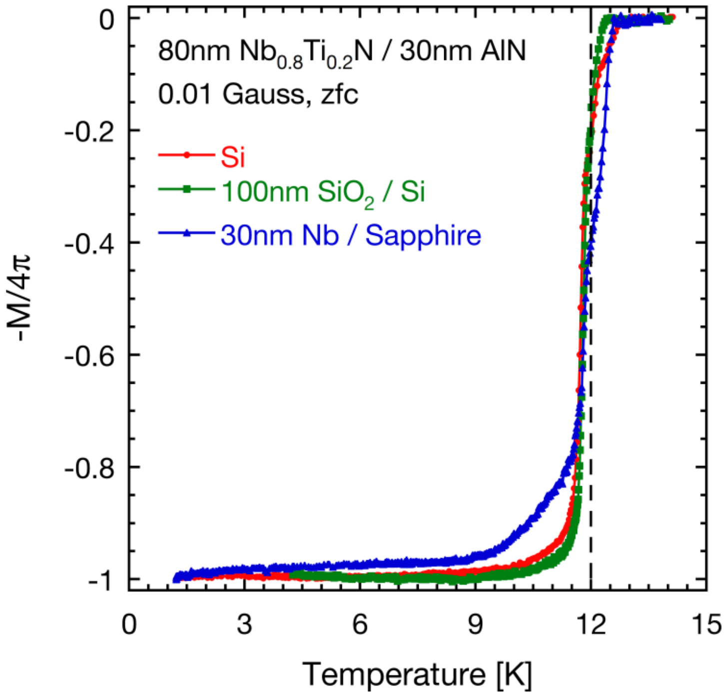
C. Cao

$Nb_{1-x}Ti_xN$-based superconductor-insulator structures

Aluminum nitride: AlN

- Oxygen-free insulator, stable interface with Nb(Ti)N
- Good thermal conductivity (285 W/m-K)
- Similar structure to Nb(Ti)N
  - 0.27% mismatch between in-plane spacing of (001)-oriented AlN and (111)-oriented NbN
- Can be grown with $AlCl_3$ and NH_3 at same temperature as Nb(Ti)N





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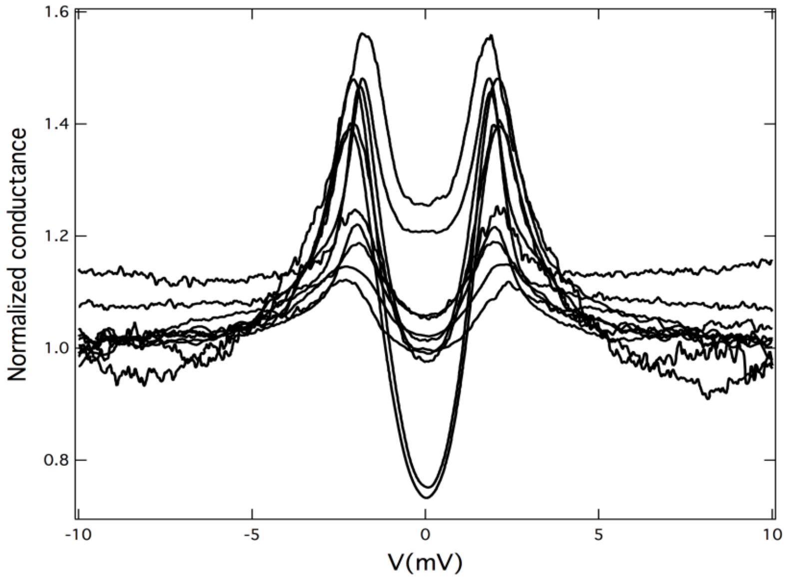
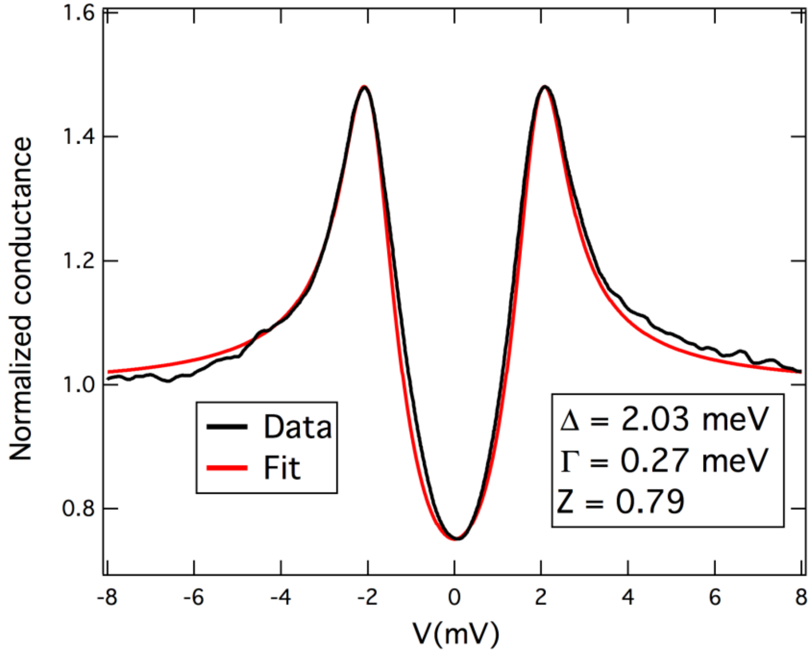
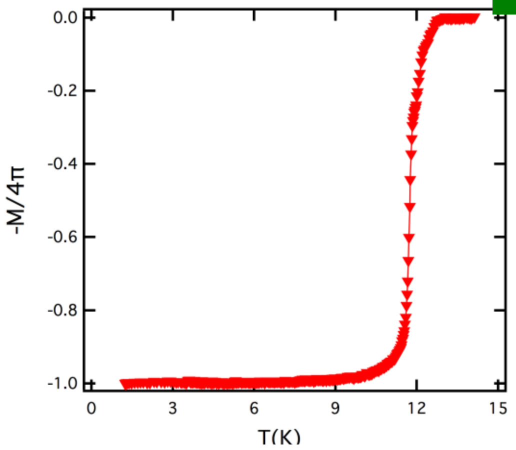
49nm $Nb_{0.8}Ti_{0.2}N$ on AlN

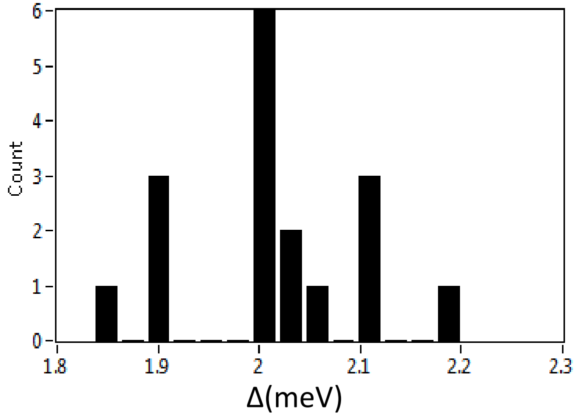


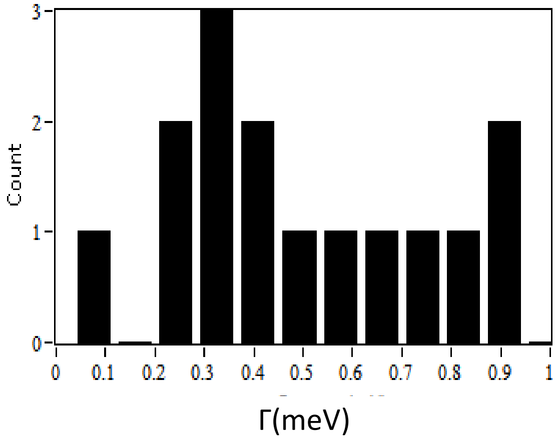


T_c= 12.8K by SQUID



$2\Delta/kT_c$ = 3.4 - 3.6 (BCS limit)

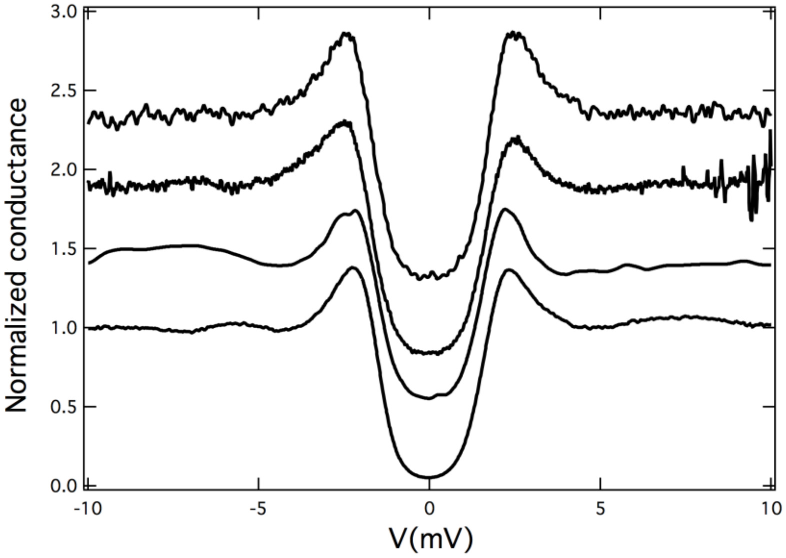


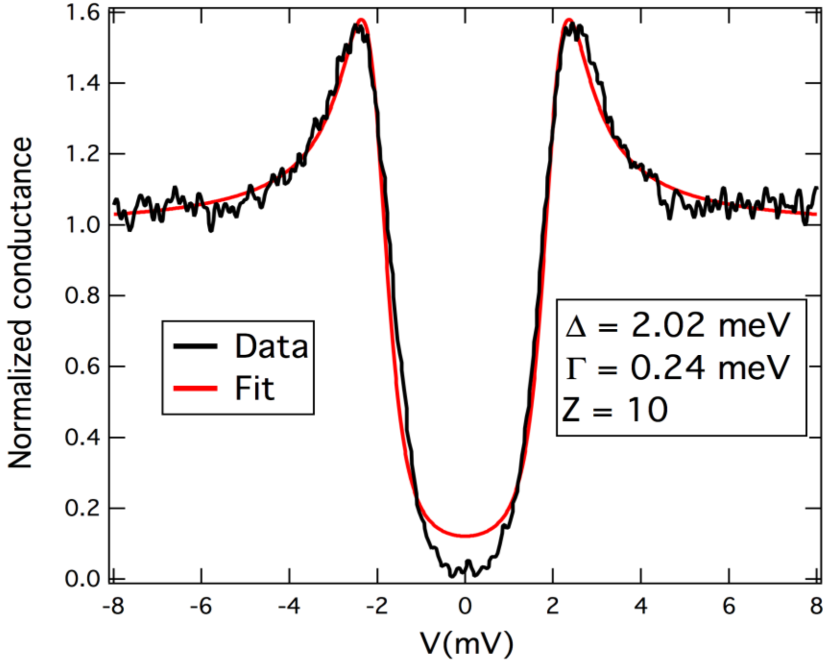


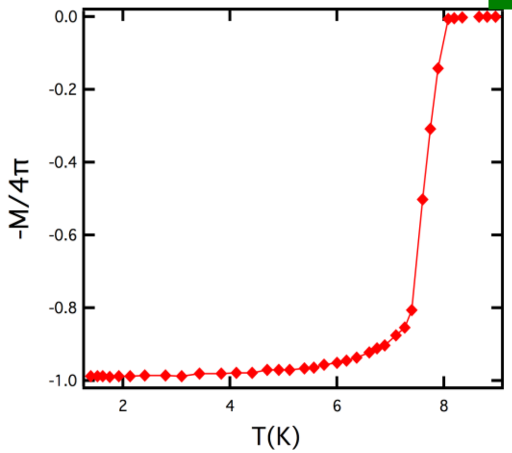
C. Cao

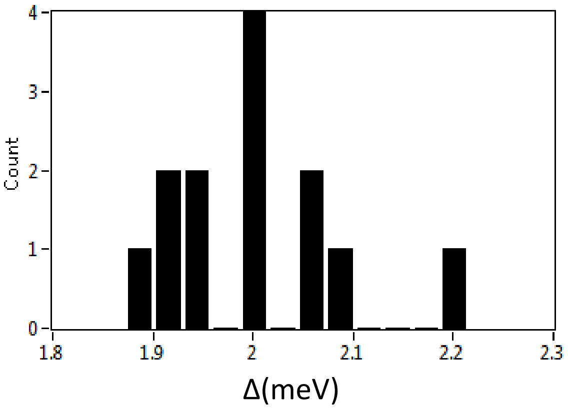
28nm $Nb_{0.8}Ti_{0.2}N$ (without AlN layer)

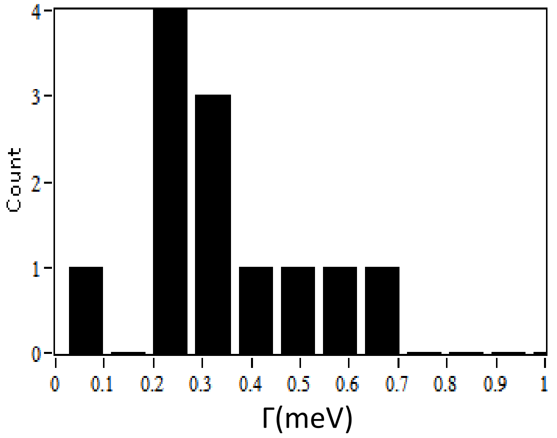
T_c= 8.3K
by SQUID









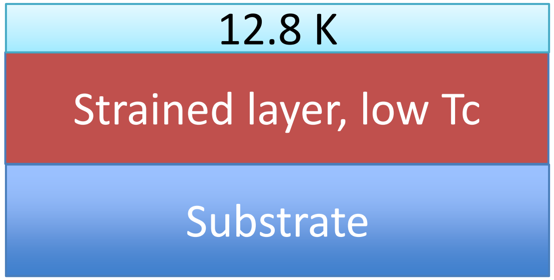


Conclusion

- Point contact tunneling (PCT) technique is ideal for measuring the local surface superconducting energy gap and density of states (DOS) of samples with a natural barrier.

- $Nb_{1-x}Ti_xN$ on AlN gives Tc = 12.8K, Δ = 1.8-2.2 meV, $2\Delta/kTc$ = 3.4-3.6(BCS limit).

- $Nb_{1-x}Ti_xN$ (without AlN) Tc = 8.3K. High quality gap region DOS, low zero bias conductance. Δ = 1.8-2.2 meV.



12.8 K

Strained layer, low Tc

Substrate

Application of “thin-film on Nb” to ILC?

Technology of;

(1) nm-level Smooth Nb cavity surface,

Tumbling, electro-polish, etc.

Hydroforming without welding.

(2) Well controlled thin-film formation on Nb cavity,

Atomic Layer Deposition (ALD)

will be required.

Then, we can reach >100MV/m with TESLA cavity shape.

End of slide