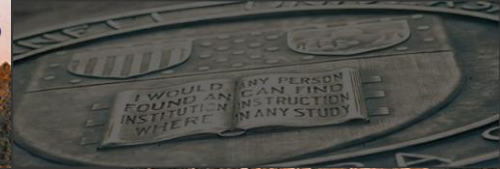




Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)



SRF Cavities Beyond Niobium: Potential and Challenges

Sam Posen and Matthias Liepe
Cornell University

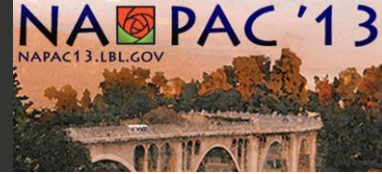
Wednesday, Oct 2, 2013

NA-PAC '13, Pasadena, California

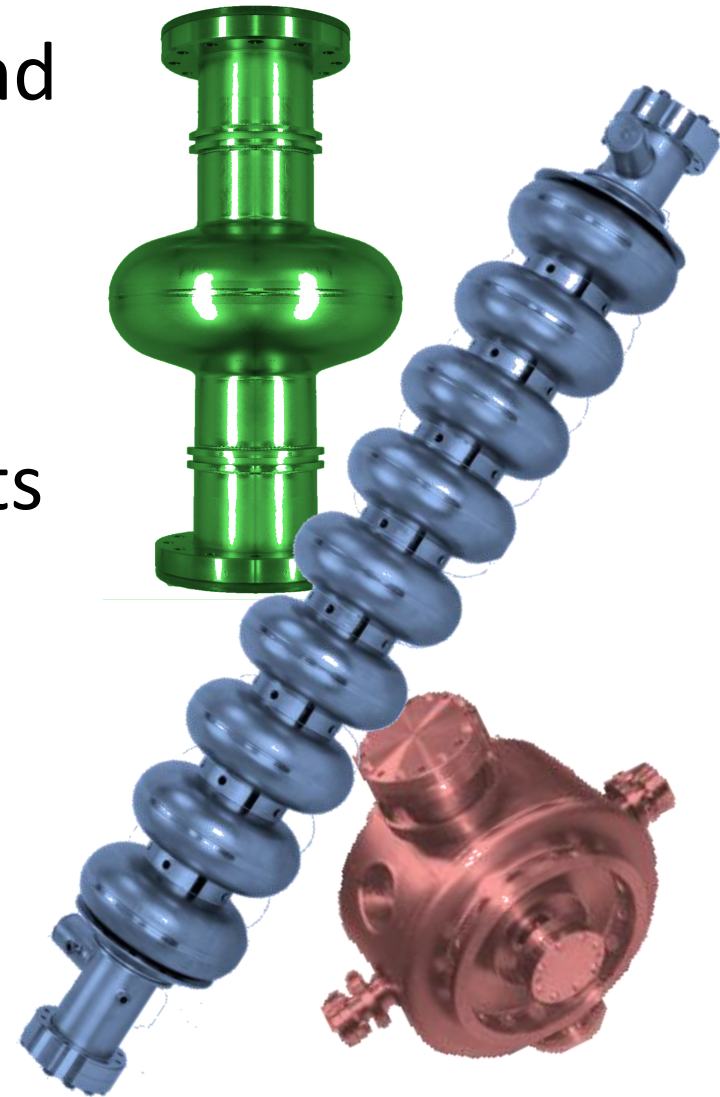
Image from
linearcollider.org



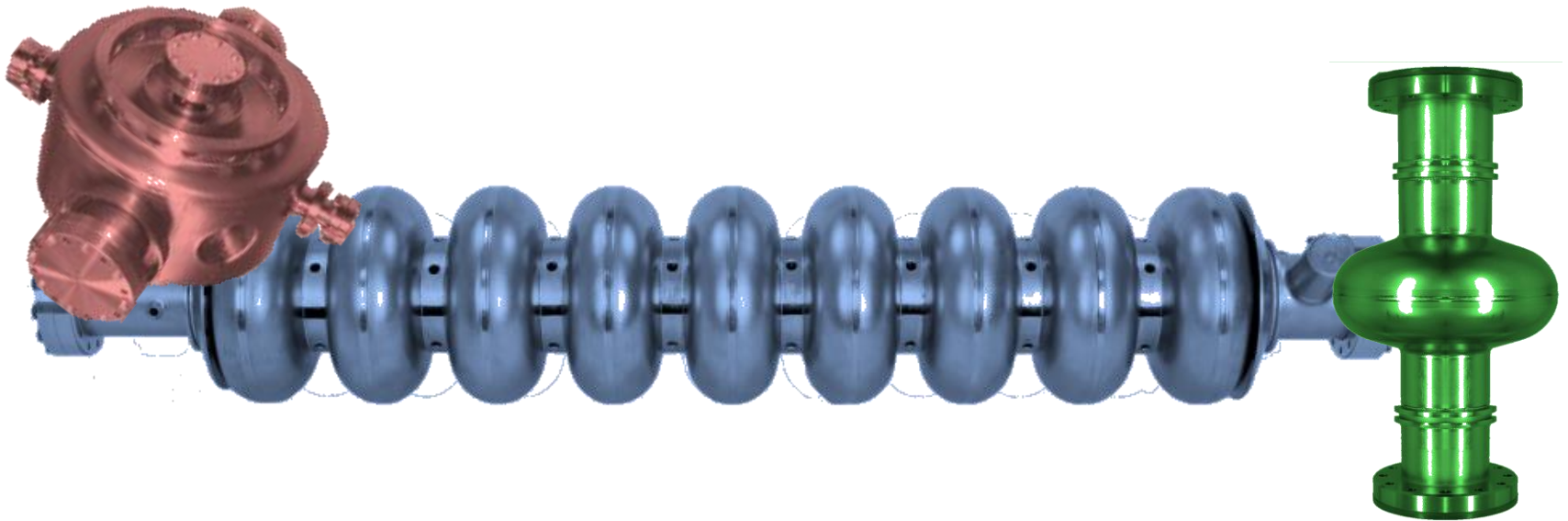
Outline



- Motivation – Why Look Beyond Niobium?
- Properties to look for in alternative SRF materials
- 3 materials with large amounts of recent development:
1) Nb_3Sn , 2) MgB_2 , 3) NbN
- SIS multilayer films
- Other materials, briefly
- Summary



Why Look at Alternative SRF Materials?

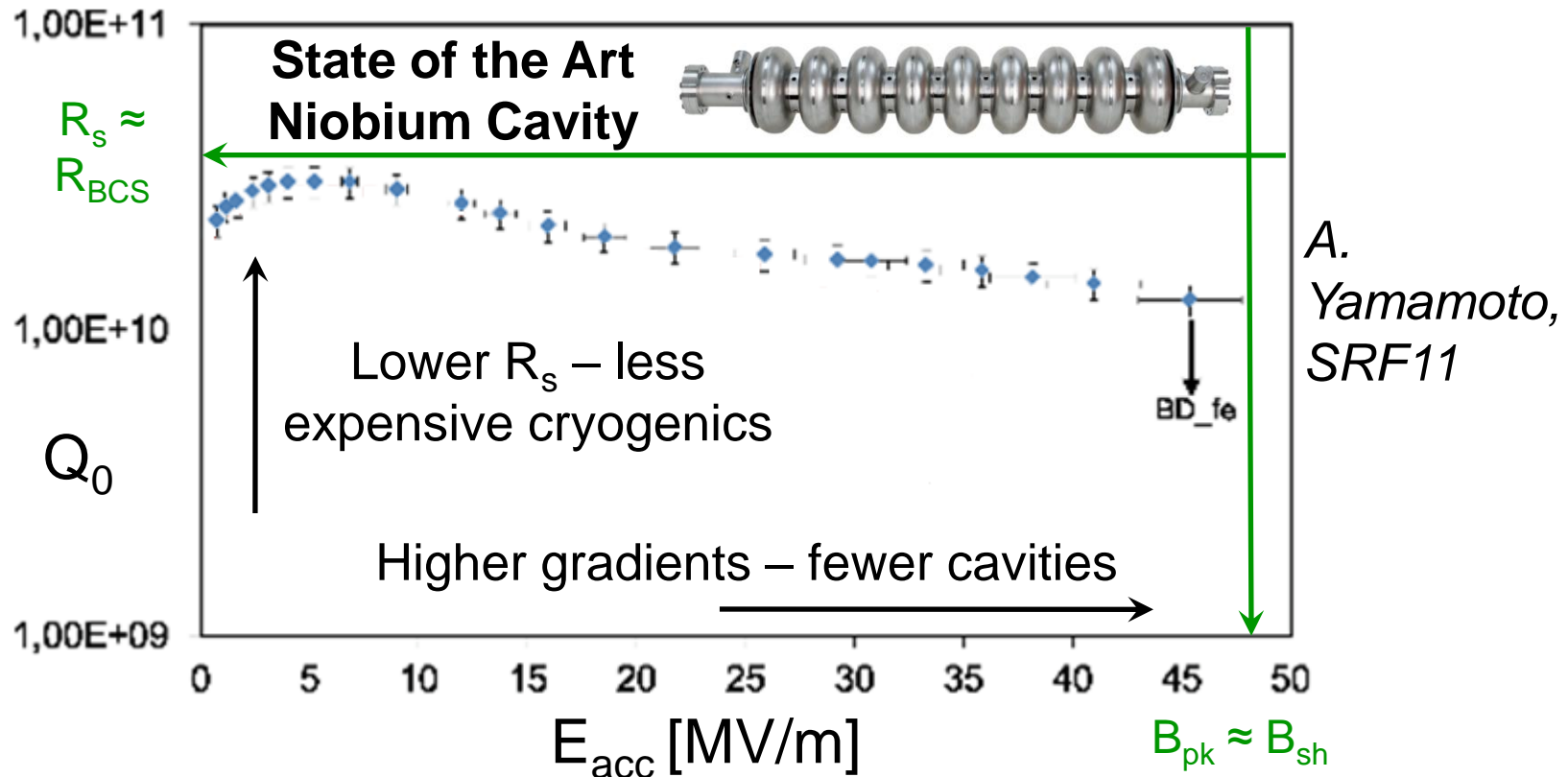




Why Look Beyond Niobium?



- Two figures of merit: E_{acc} and Q_0 ($\sim R_s^{-1}$)
- After years of development, Nb cavities are starting to reach fundamental limits of the material





Why Look Beyond Niobium?

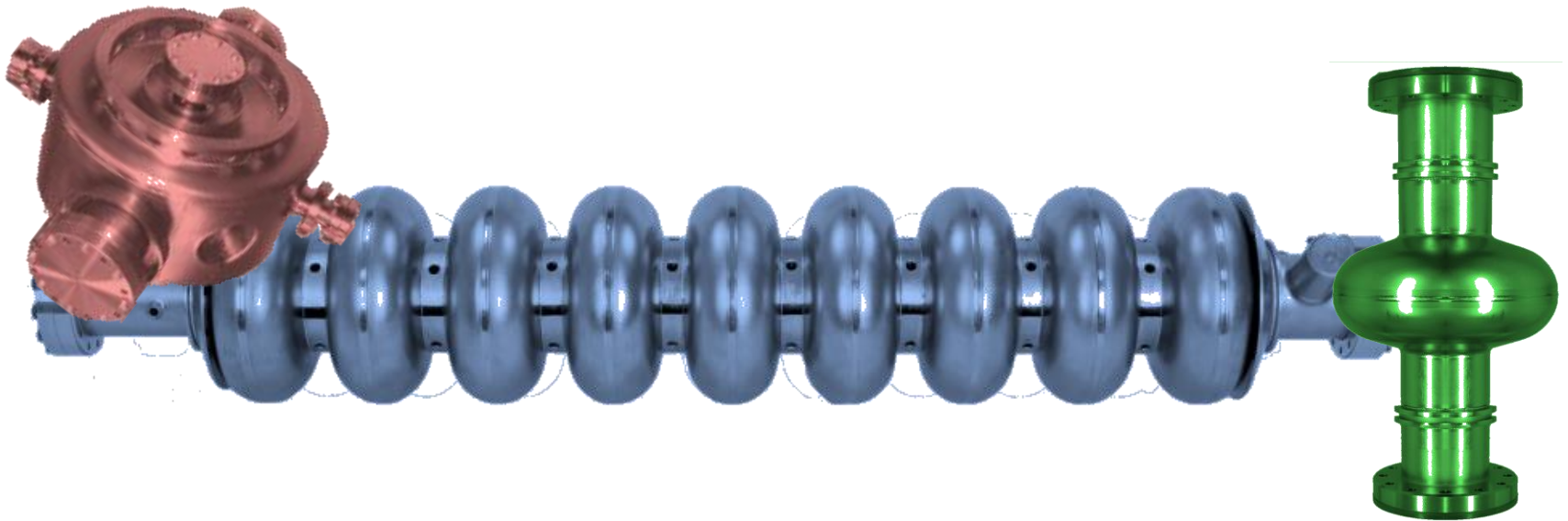


- CW SRF linacs – Cost driver: **cryogenics**
 - Cost optimum for Nb: operate ~ 2 K, where R_s is small
 - Alternative materials can have much smaller R_s at ~ 2 K: smaller cryo plant and less grid power
 - Materials with higher T_c may allow operation at higher T: LHe at atmospheric pressure or even cold gas
- High energy SRF linacs – Cost driver: **number of cavities**
 - RF critical field fundamentally limits E_{acc} , and therefore sets minimum number of cavities required to reach a given energy
 - Alternative material with higher critical magnetic field: fewer cavities required to reach same energy

Need **long term** R&D to realize full potential of new materials, but already a Cornell Nb₃Sn cavity is superior to Nb cavities for some applications. Fast growth over the next years can be expected with **continuous R&D**.

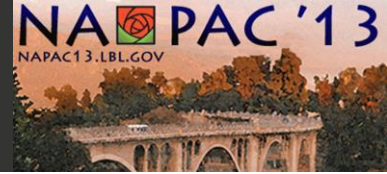


What Properties to Look for in Alternative Materials?





Properties to Look for in Materials: What Gives Large Maximum Field?



- RF limit is superheating field B_{sh} , NOT B_{irr}
 - EXCLUDE vortices, not pin them inside superconductor!
Normal conducting vortex cores = huge RF dissipation
- Surface defects with size $\sim \xi$ can reduce barrier to vortex penetration—need “large enough” ξ
 - Nb has $\xi \sim 20$ nm and it gets very close to B_{sh}
 - New results on Nb_3Sn with $\xi \sim 3$ nm show barrier intact

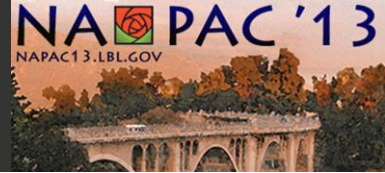


Larger Max Field  **Fewer Cavities Needed**





Properties to Look for in Materials: What Gives Small Surface Resistance?



- Temperature dependent surface resistance from BCS theory: R_{BCS} Vaglio, (1998)
 - Need large T_c , small normal resistivity ρ_n
- Temp. independent “residual resistance”: $R_s(T) = R_{BCS}(T) + R_{res}$ – not well understood
 - Strong connections between grains: it is known that weak links can contribute to R_{res}



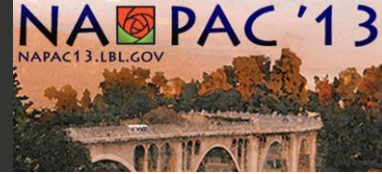
LHC & SNS cryo equipment. Images from USPAS lectures by Tom Peterson and John Weisend

Smaller R_s \longrightarrow Smaller Cryogenic Costs





Properties to Look for in Materials: Requirements for Cavity Operation

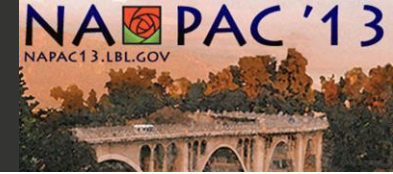


- Ability to conform to complex geometry over large area
- Decent thermal conductivity for cooling to avoid breakdown
- Minimal surface roughness—avoid field enhancement
- Cleanliness: Potential field emitting dust? Is there a method to clean surface contaminants?





Experimental Properties of Promising Materials



Material	$\lambda(0)$ [nm]	$\xi(0)$ [nm]	B_{sh} [mT]	T_c [K]	$\rho_n(0)$ [$\mu\Omega\text{cm}$]
Nb	50	22	210	9.2	2
Nb ₃ Sn	111	4.2	410	18	8
MgB ₂	185	4.9	210	40	0.1
NbN	375	2.9	160	16	144

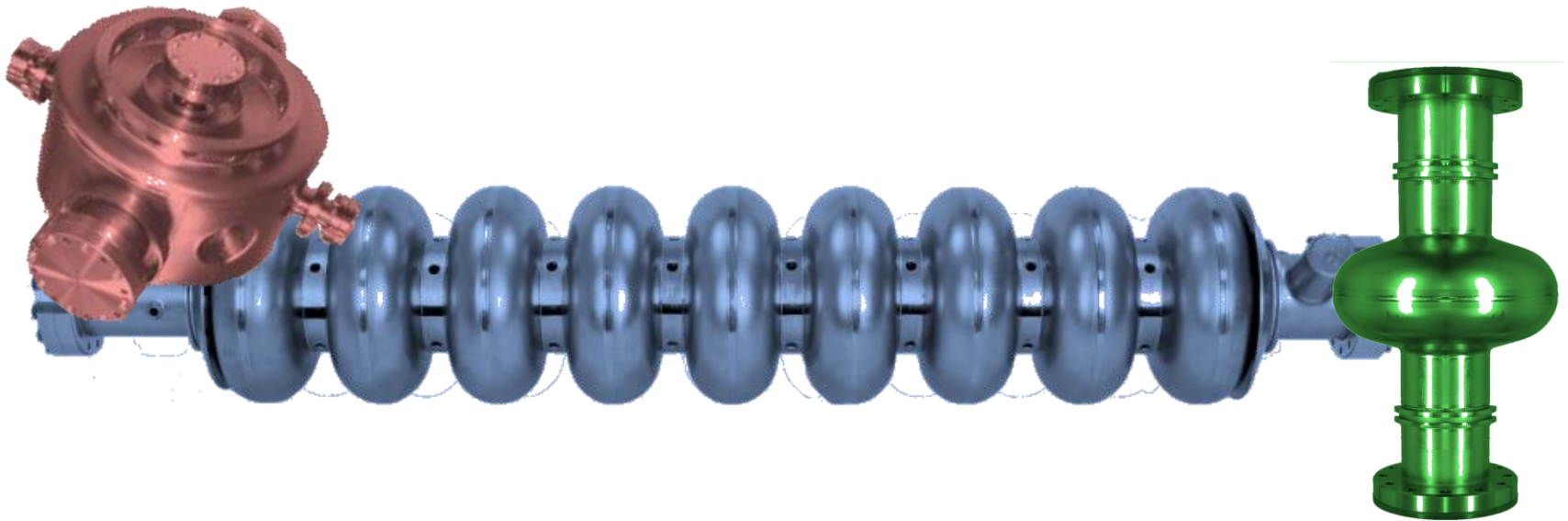
Parameters for: Nb from [1] assuming RRR = 10; Nb₃Sn from [2]; NbN from [3]; MgB₂ from [4] and [5]. B_{sh} for Nb found from equation in [6] and for others calculated from [7]. B_c used to calculate B_{sh} found from [8] eq. 4.20.

- [1] B. Maxfield and W. McLean, Phys. Rev. 139, A1515 (1965).
- [2] M. Hein, *High-Temperature Superconductor Thin Films at Microwave Frequencies* (Berlin: Springer, 1999).
- [3] D. Oates, et al., Phys. Rev. B 43, 7655 (1991).
- [4] Y. Wang, T. Plackowski, and A. Junod, Physica C 355, 179 (2001).
- [5] X.X. Xi et al., Physica C, 456, 22-37 (2007).
- [6] A. Dolgert, S. Bartolo, and A. Dorsey, Erratum [Phys. Rev. B 53, 5650 (1996)], Phys. Rev. B 56, 2883 (1997).
- [7] M. Transtrum, G. Catelani, and J. Sethna, Phys. Rev. B 83, 094505 (2011).
- [8] M. Tinkham, Introduction to Superconductivity (New York: Dover, 1996).

Material parameters vary with fabrication. References were chosen to try to display realistic properties for polycrystalline films.

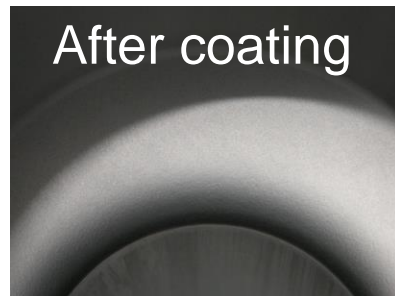


Nb_3Sn



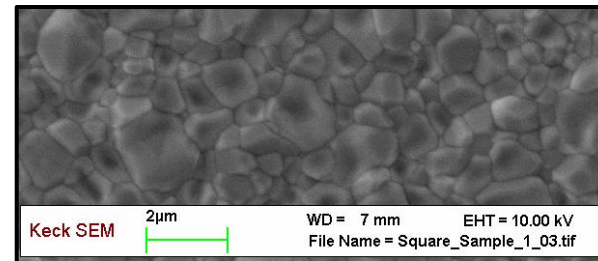
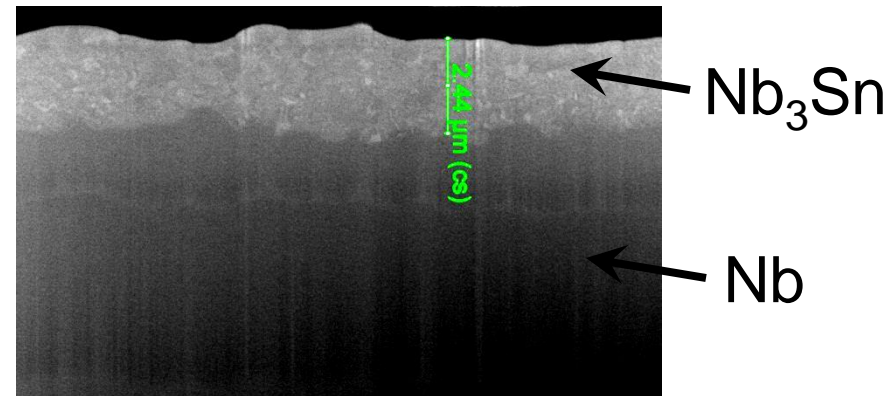
Potential

- Small R_s – Small ρ_n , high $T_c \sim 18$ K (twice Nb)
- Large $B_{sh} \sim 400$ mT (twice Nb)
- Decent $\xi \sim 3-4$ nm
- Can alloy existing Nb cavities
- Non-reactive



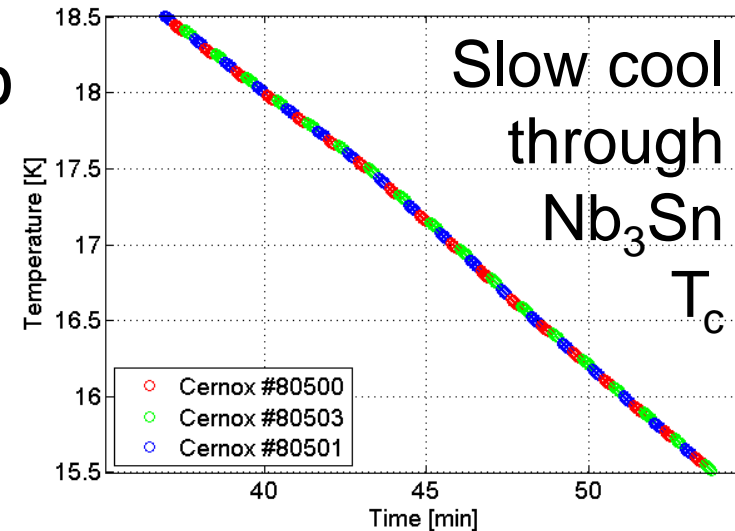
Challenges

- Material is brittle
- Low thermal conductivity
→ Films avoid these

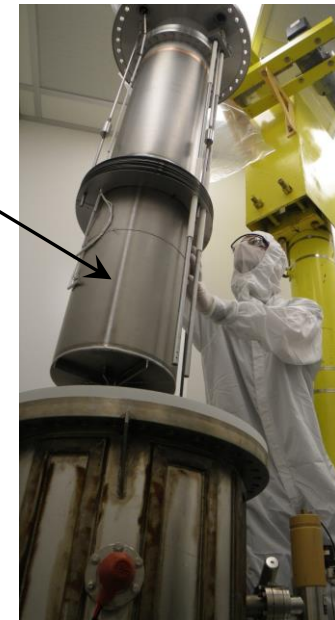


Images
from
Cornell

- Film/substrate interface can trap flux from thermocurrents if cooled quickly or non-uniformly
 - Require new cooldown after quench to regain small R_s
- Coating only a few μm thick: to clean surface, only light chemistry available
- Large structures: welding coated pieces together difficult, coating entire structure also difficult



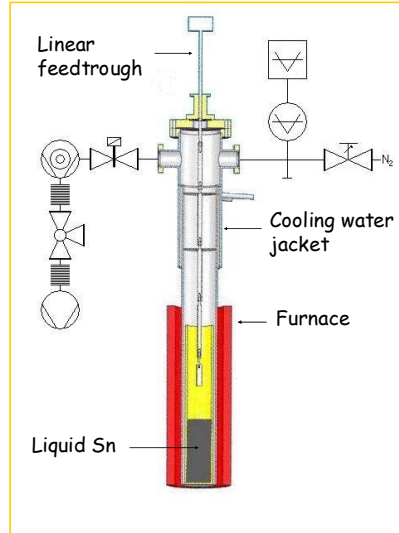
Cornell Nb_3Sn Coating Chamber



Liquid Tin Dipping – INFN

Problems with tin droplets on surface and spurious tin-rich phases

S. Deambrosis et al. (2009)



Cathodic Arc Deposition – Alameda Applied Sciences

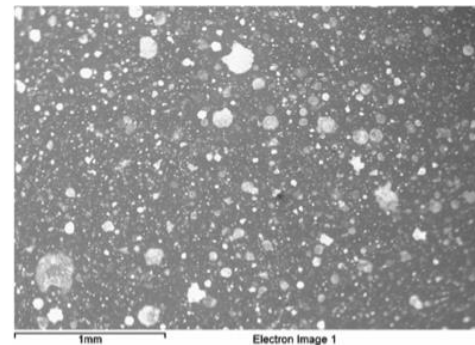
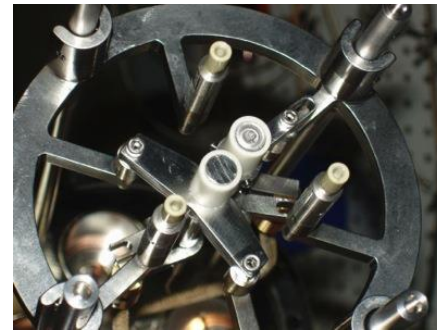
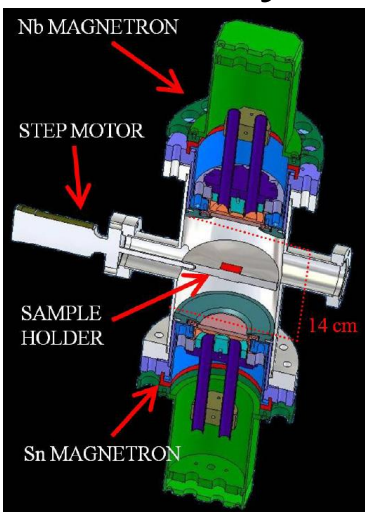


- More energetic ions than sputtering
- Low T_c measured

Multilayer Sputtering – INFN

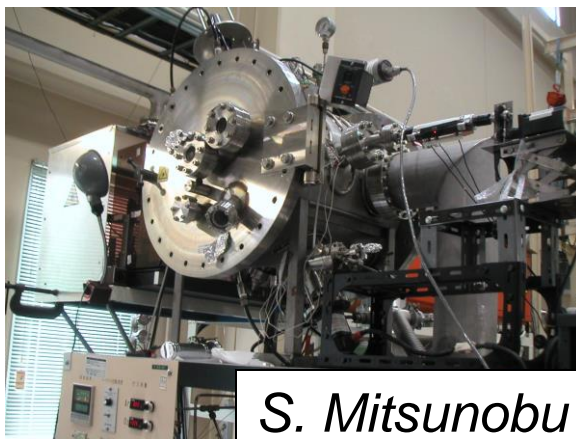
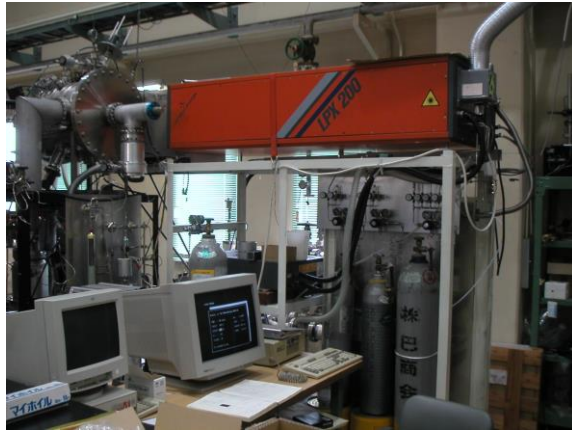
- Alternate coatings of Nb and Sn, then anneal
- No encouraging RF results so far

A. Rossi et al. (2009)



M. Krishnan et al. (2012)

Pulsed Laser Deposition - KEK

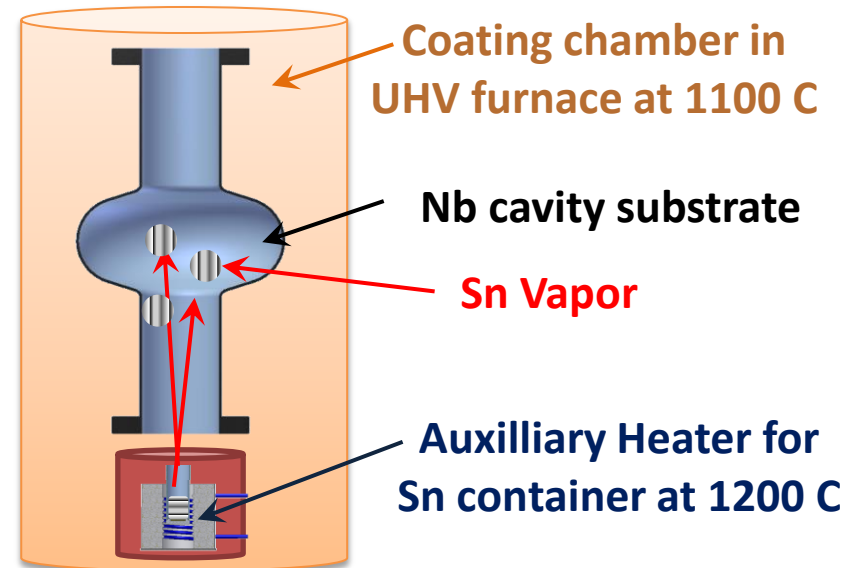


S. Mitsunobu et al.

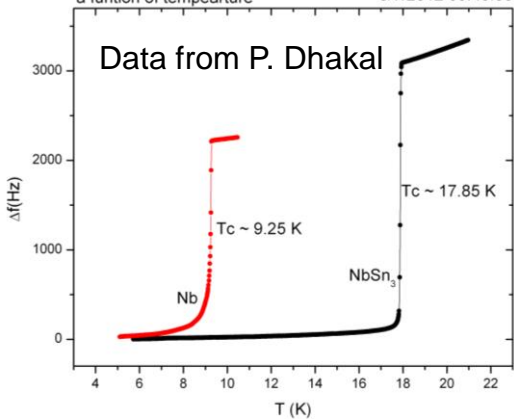
- Studies have started
- Also use PLD for MgB_2

Vapor Diffusion – Cornell and Jefferson Lab

- Pioneering studies 80s-90s at Siemens AG and U. Wuppertal
- In UHV furnace, tin vapor alloys with Nb cavity
- Very promising RF results



Change in resonant frequency as a function of temperature 3/7/2012 09:40:33

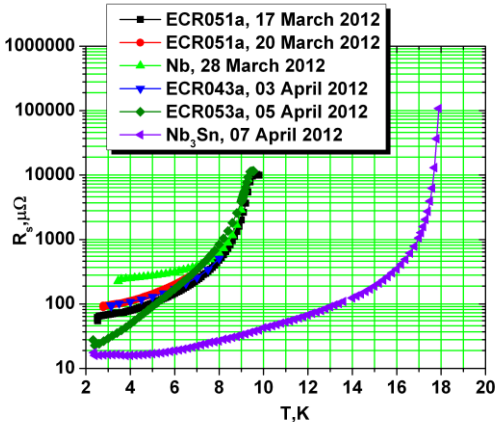


- Preliminary studies with **samples** have been done. RF measurements on a sample indicated the **transition temperature of 17.9 K** and RF surface resistance of about $30 \mu\Omega$ at 9 K and 7.4 GHz.

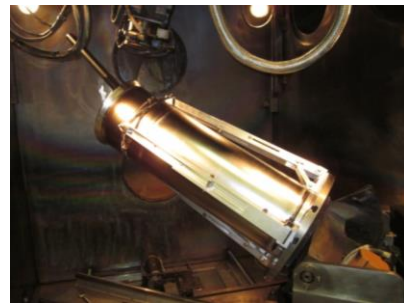
- The **horizontal insert** has been built and inserted in the furnace. The first furnace run has been done at 1200°C for 2 hours.

Transition temperature is ~ 17.85 K. The best of three samples shows very smooth surface with no residual tin contamination

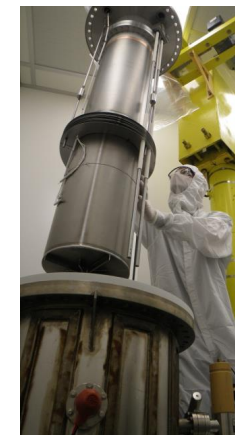
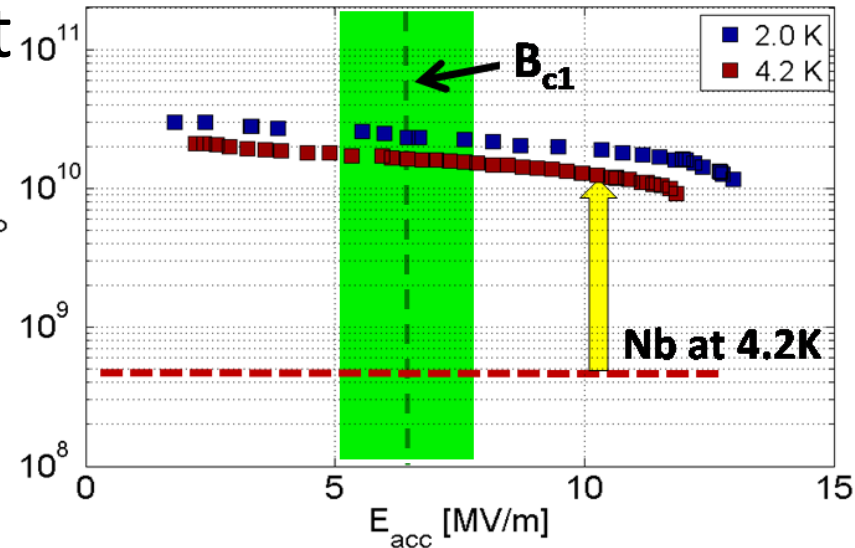
- **R&D furnace for Nb_3Sn** development was ordered in October 2012, delivered in August 2013, and is being commissioned.



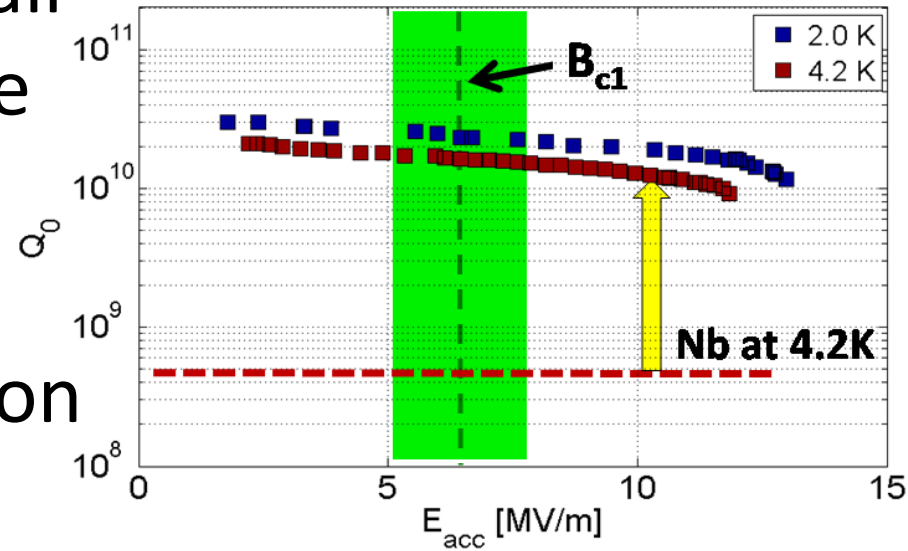
Recent measurements of surface resistance of several ECR films, bulk Nb sample, and Nb_3Sn sample as a function of temperature at 7.4 GHz.



- Achieved fields ~ 12 MV/m at 4.2 K with Q_0 1×10^{10} , **20 times higher than niobium**
- Breakthrough performance: **the first alternative material accelerator cavity with significantly smaller R_s than niobium at useful gradients and temperatures**
- Performance level already useful for some applications



- Proves that even with small ξ of Nb₃Sn (making it more vulnerable to surface defects), energy barrier prevents vortex penetration
- Shows the potential of alternative SRF materials



**See details in
talk tomorrow!
(9:15 in Aud. A)**

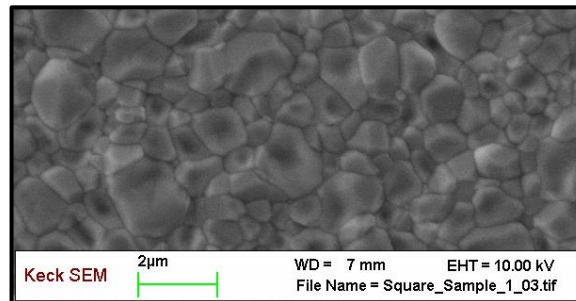
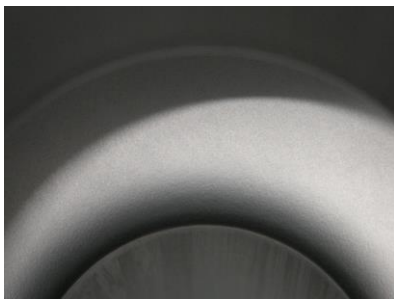




Current Status of Nb₃Sn



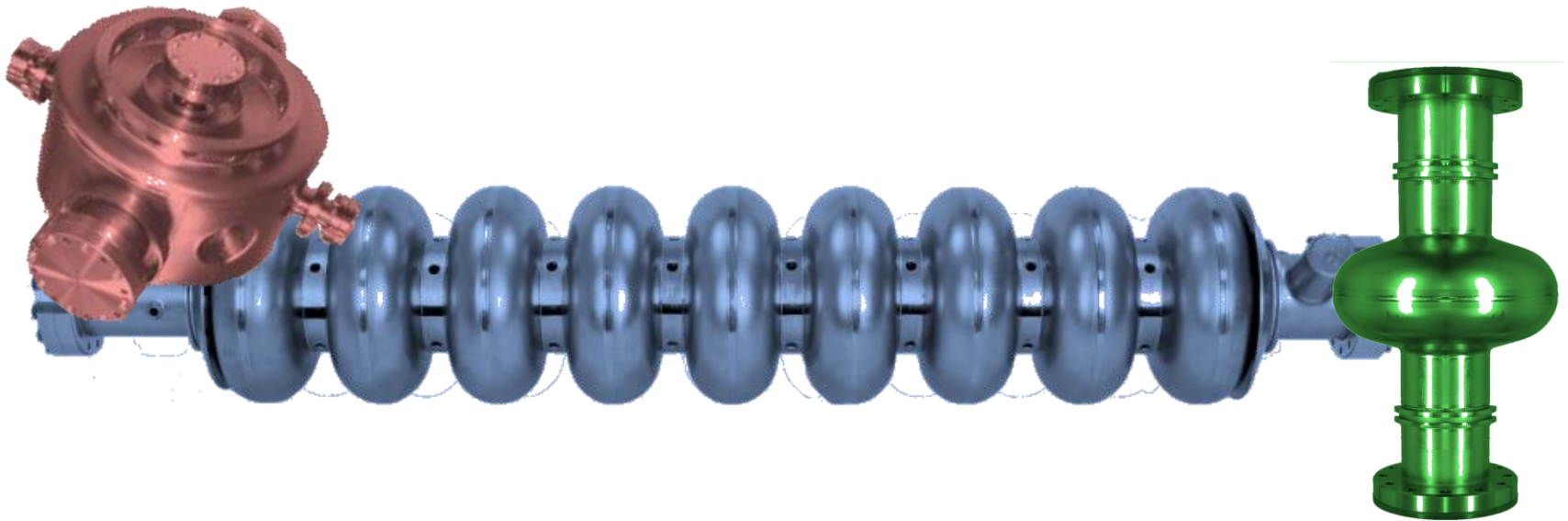
- Cavity fabrication is established – Nb₃Sn ready for first applications
- Far smaller R_s than Nb achieved down to 2 K
- Surface mag. fields up to ~55 mT with small R_s
 - Achieved E_{acc} is useful, but far below ultimate limit of material, superheating field
 - Nb: 200 mT, Nb₃Sn ~400 mT



Color Code
Goal Achieved
Goal in Progress
Fundamental Problem

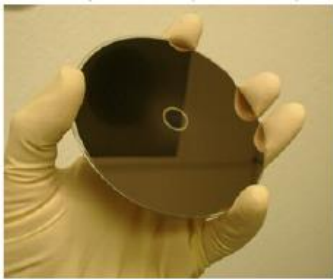


MgB₂



Potential

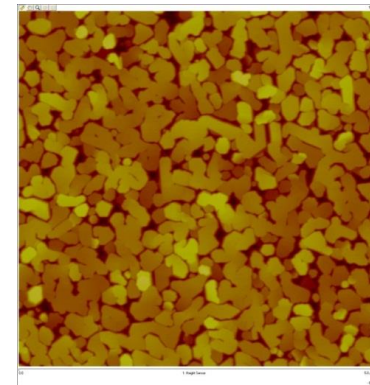
- Small R_s – small ρ_n , very high $T_c \sim 40$ K (smaller gap dominates R_s , but still good)
- B_{sh} not clear yet, but possible range ~ 200 - 600 mT. Need more development of SRF quality MgB₂ films
- Very high T_c raises possibility of operation at high T
- Decent $\xi \sim 5$ nm



*T. Tajima,
Los Alamos*

Challenges

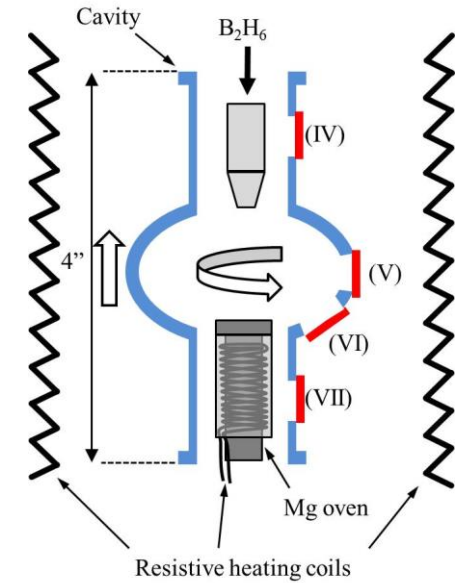
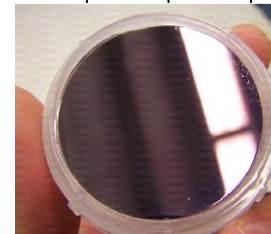
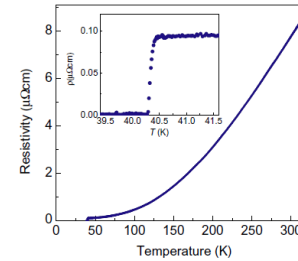
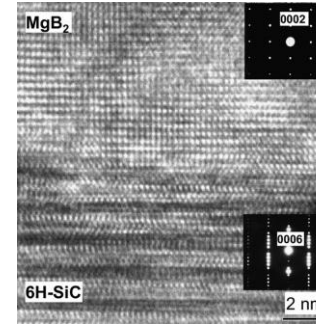
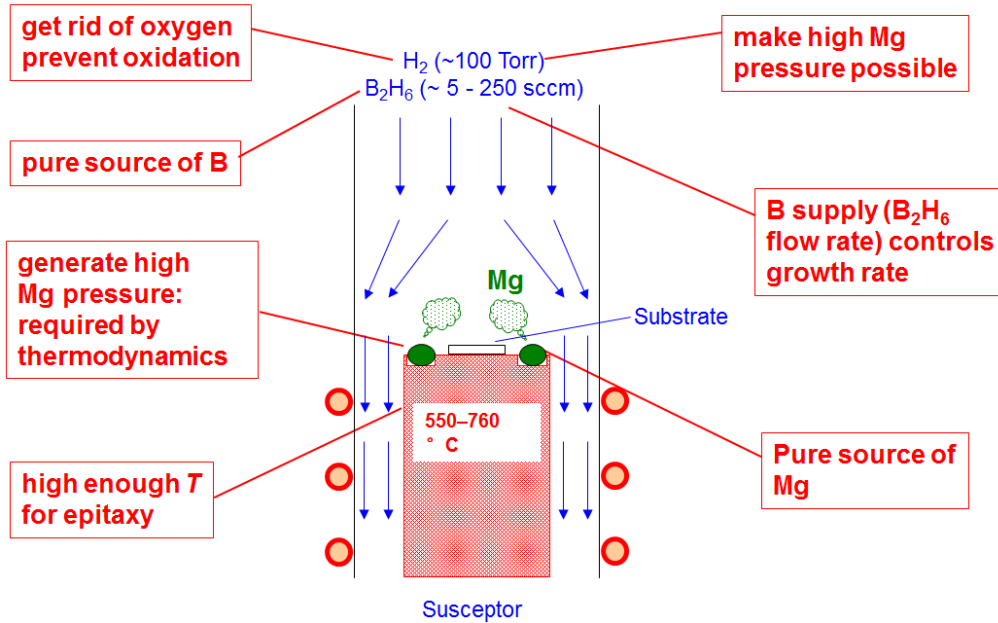
- Mg highly reactive with oxygen: must have very small background during coating
- R_s increase with field predicted for two gap materials, but might be possible to reduce it
- Reacts with water – “capping” layer may be required



*X. Xi,
Temple U.*

Hybrid Physical-Chemical Vapor Deposition

Schematic View



- HPCVD Process gives excellent T_c
- Working towards cavity coating capability

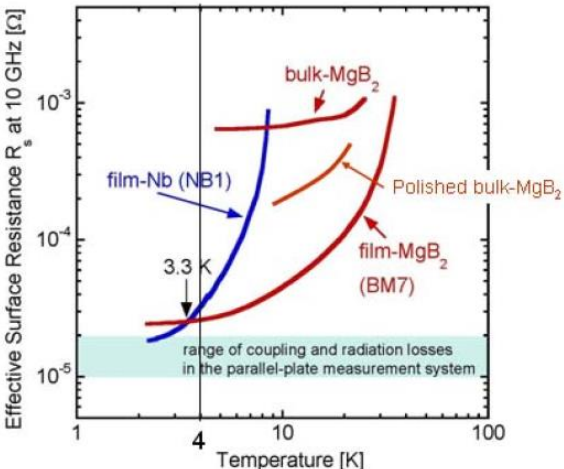


Figure 3: Surface resistance vs. temperature of a 400 nm MgB_2 film coated on a sapphire substrate. Bulk samples and Nb data are shown for comparison. [6]

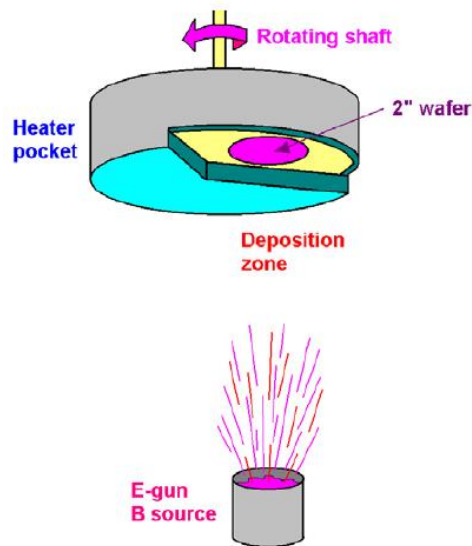


Figure 1: MgB_2 coating system at STI. [5]

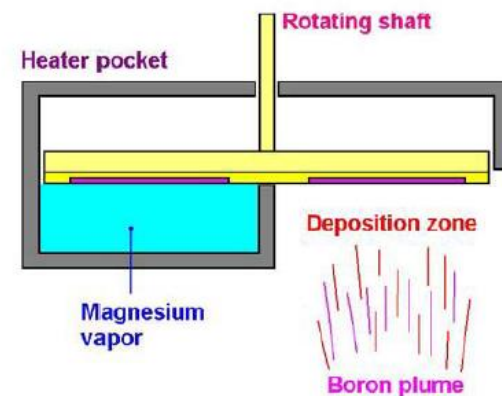


Figure 2: Cross section of the deposition chamber. [5]

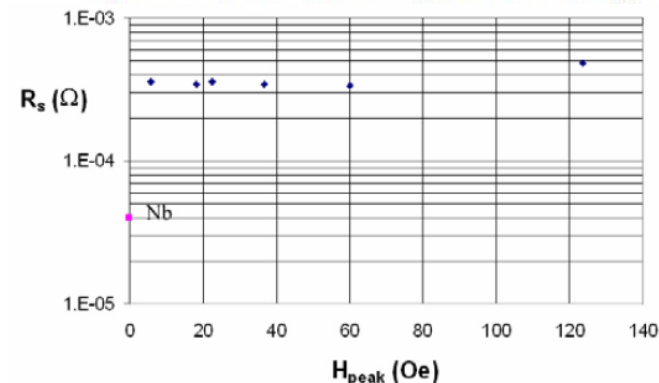


Figure 6: R_s of the Nb TE_{011} mode cavity with a MgB_2 sample at the center of the bottom plate, as a function of the peak magnetic field on the sample. The data was converted to 10 GHz using an f^2 law.

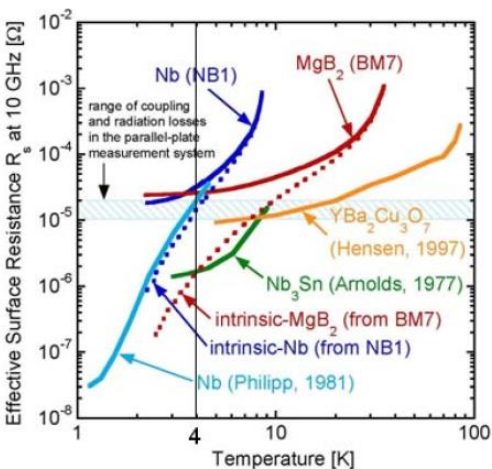


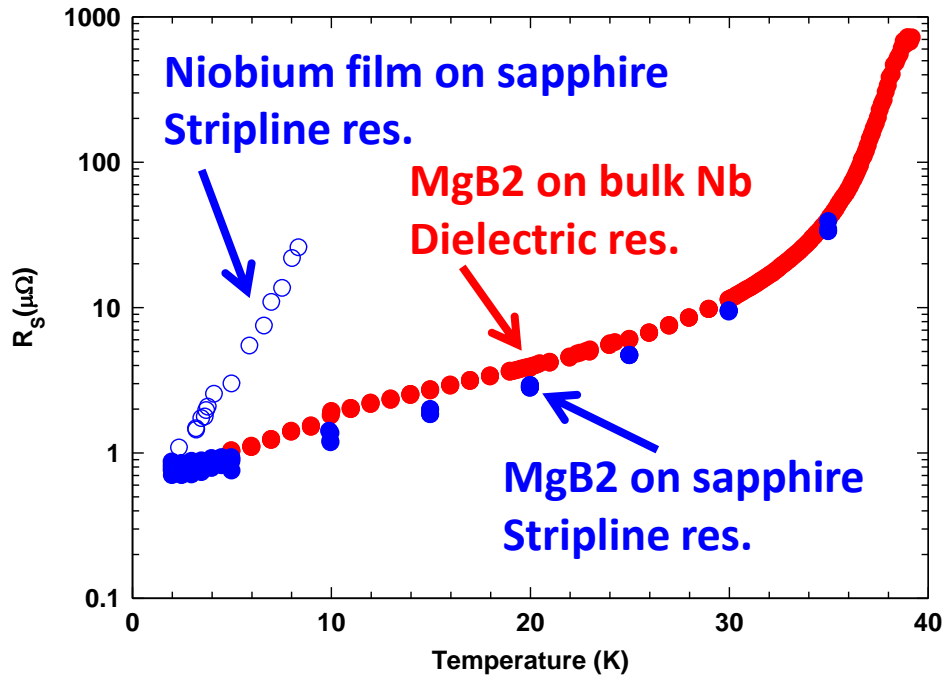
Figure 4: Prediction of intrinsic (BCS) surface resistance (dotted line) from experimental data. [6]

- R_s lower than Nb at 10 GHz for $T > \sim 4$ K
- Little increase in R_s with B up to 12 mT

MgB_2 films produced at STI (Superconducting Technologies Inc. – B. Moeckly et al) by reactive co-evaporation



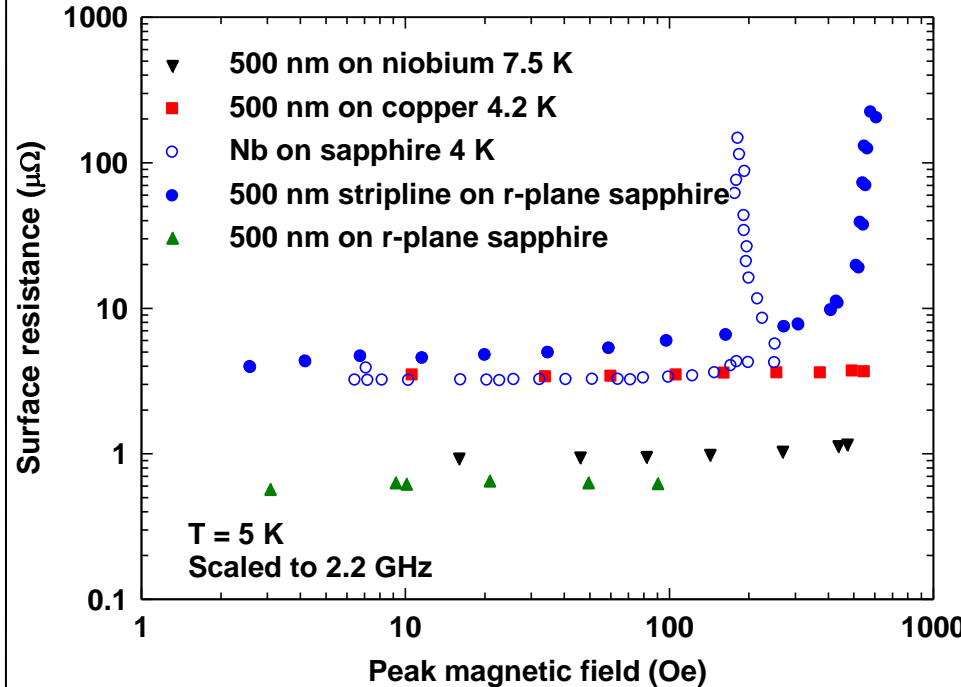
Low-Power $R_S(T)$: MgB₂ and Nb



R_S extrapolated to 2.2 GHz by f^2 for the dielectric-resonator data

R_S vs H_{RF}

Dielectric and Metallic Substrates

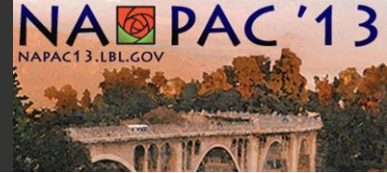


MgB₂ films produced by B. Moeckly at STI (Superconducting Technologies Inc.) by reactive co-evaporation

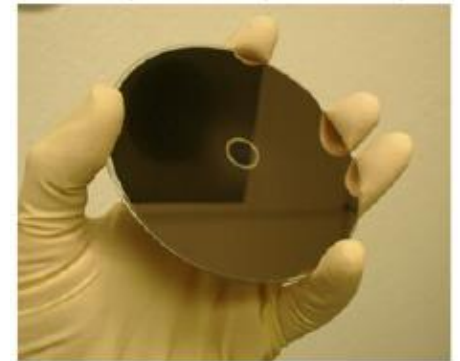
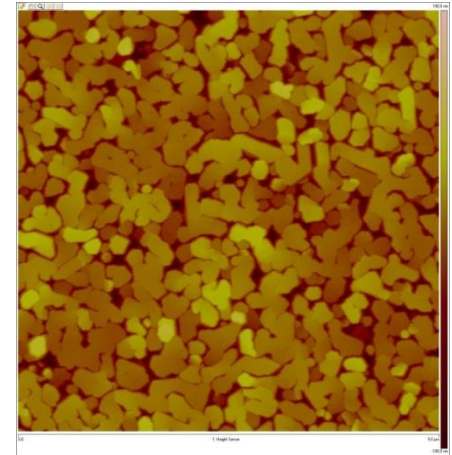




Current Status of MgB_2



- Several sample studies; cavity fabrication is coming soon
- Smaller R_s than Nb achieved at high temperature and frequency
 - Need to show small R_{res} is possible
- Only relatively small gradients measured so far, as no cavities built yet
 - Need to see if two-gap nature increases R_s at high gradients



Color Code

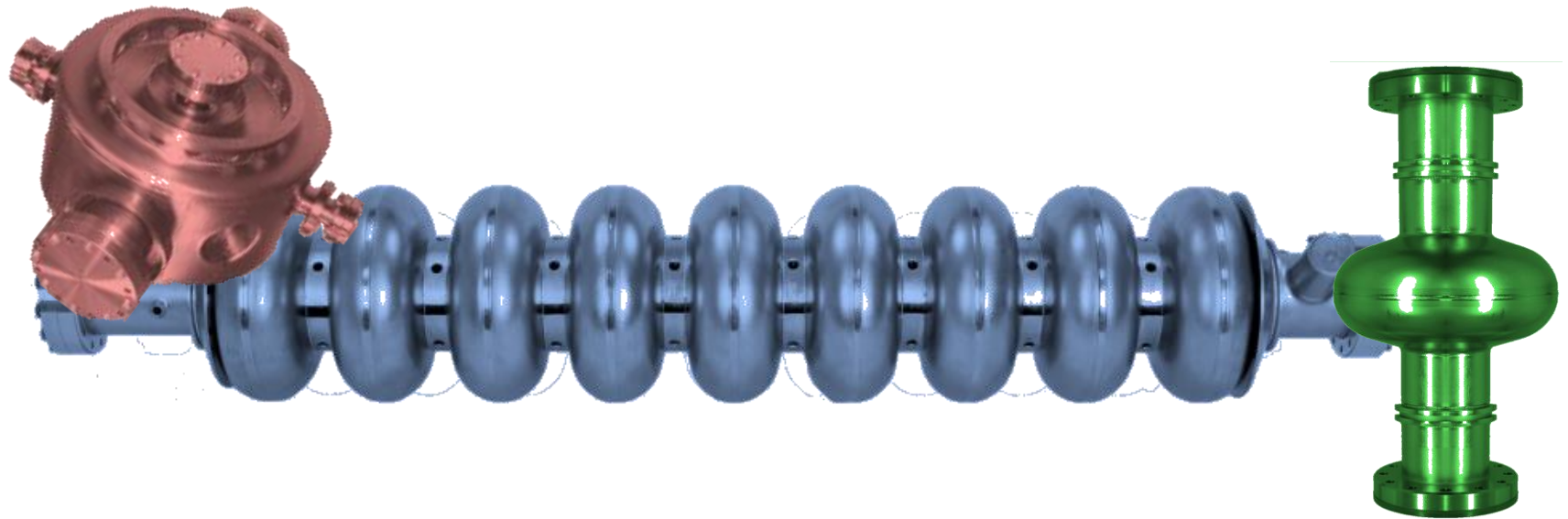
Goal Achieved

Goal in Progress

Fundamental Problem

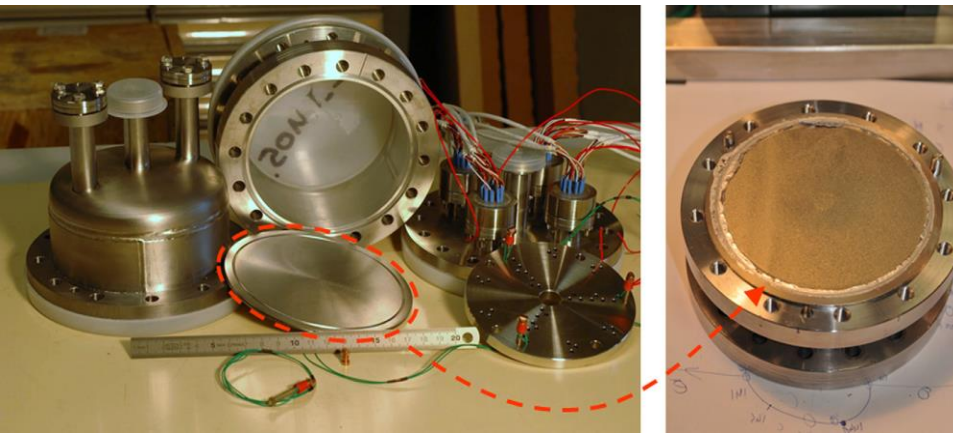


NbN



Potential

- Small R_s – high $T_c \sim 15 - 17$ K
- B_{sh} okay $\sim 150-200$ mT
- Decent $\xi \sim 3$ nm
- Might be possible to treat large Nb cavities with N_2 in furnace

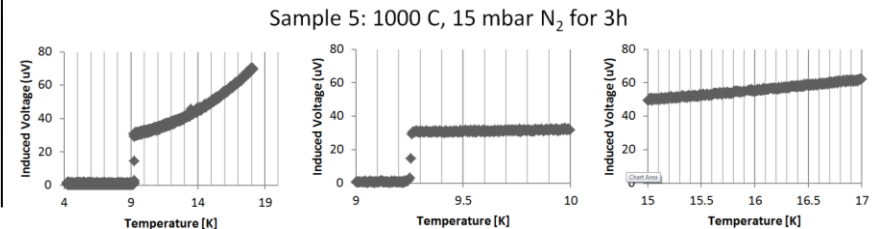


Sputtered NbN, *C. Anoine et al. (2013)*

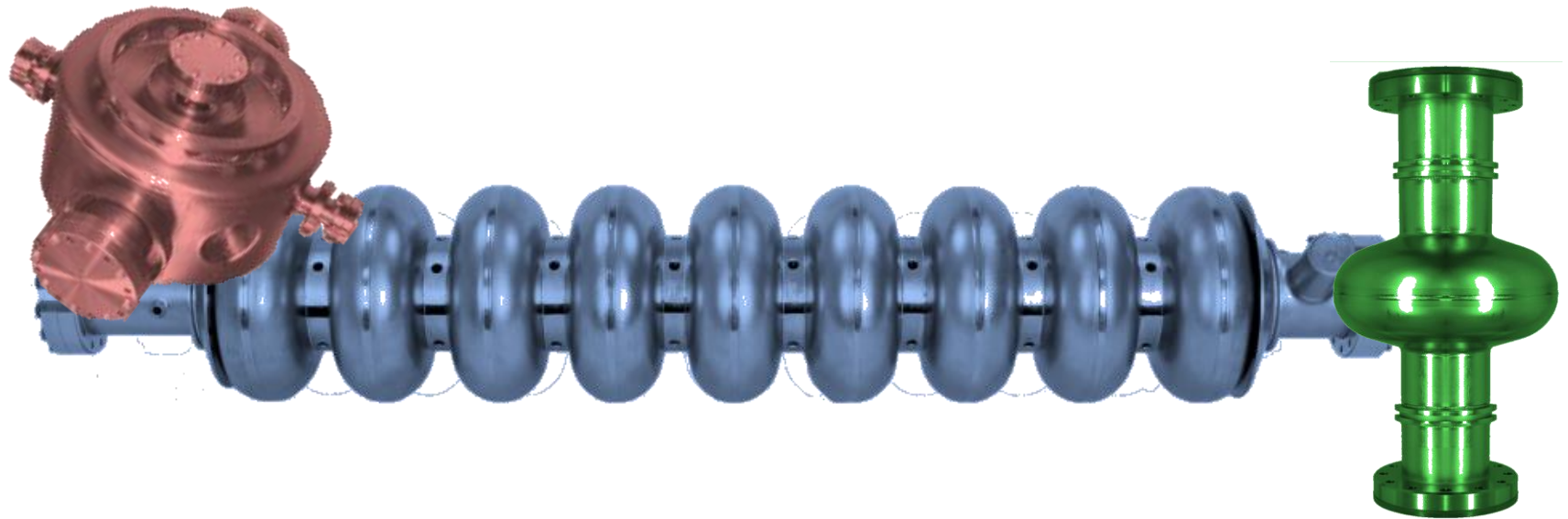
APL 102603

Challenges

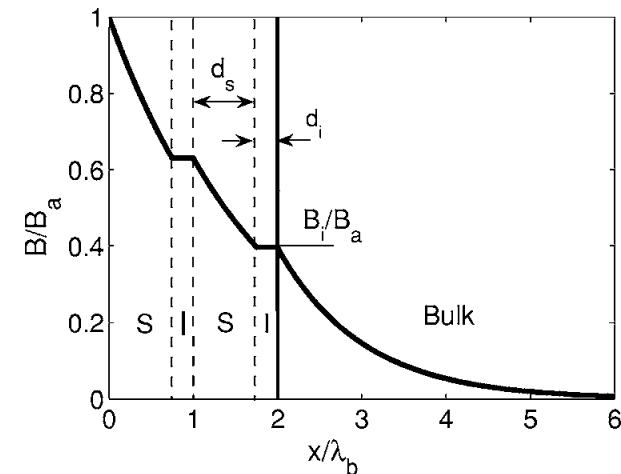
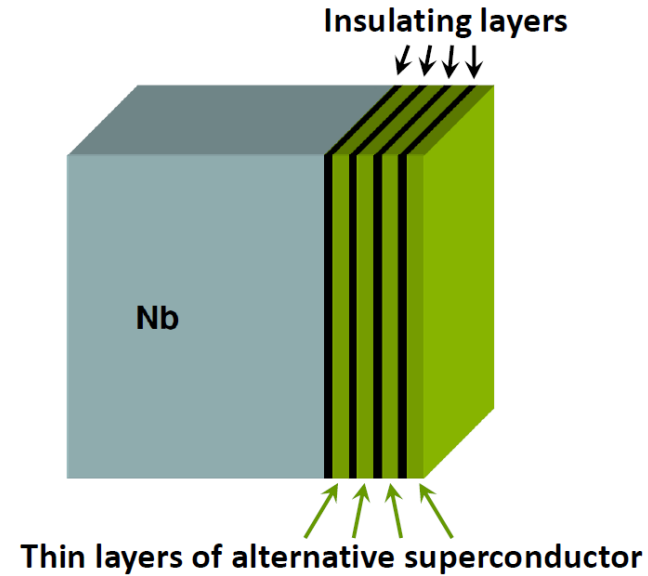
- Complex phase diagram – very difficult to achieve correct phase for furnace treatment
- Tests show large R_{res}
- Recently R_s reduction in Nb measured after N_2 furnace treatment—speculated cause was superconducting NbN growth, but sample T_c revealed that another mechanism must have been responsible



Multilayers



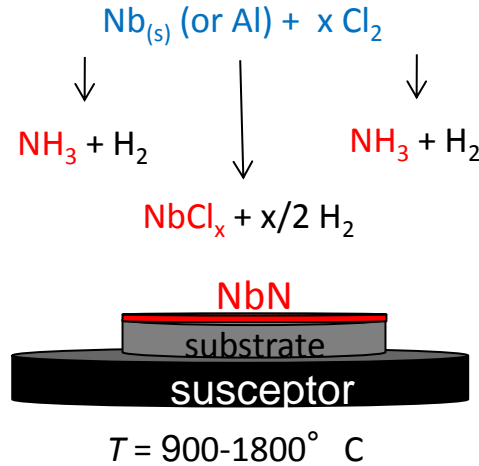
- A. Gurevich proposal: don't use bulk films—use alternating layers of thin superconductor and insulator on top of bulk superconductor, “SIS multilayers”
- Enhancement of B_{c1} (onset of metastable state) in thin films avoids problem of vortex penetration at small defects



A. Gurevich, APL 012511 (2006)

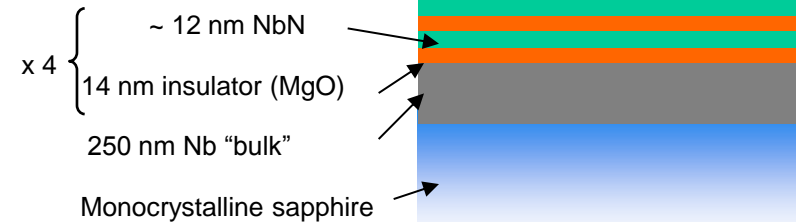
CVD of NbN (AlN) layers

High Temperature CVD
using Nb (Al) Chloride and NH_3



F. Weiss et al., Grenoble IPT

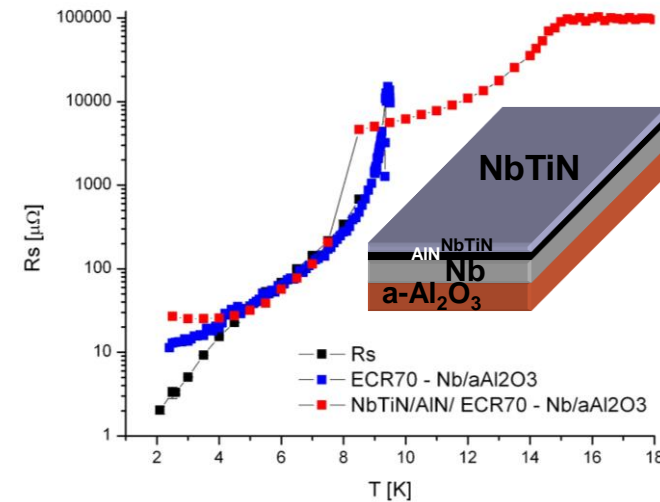
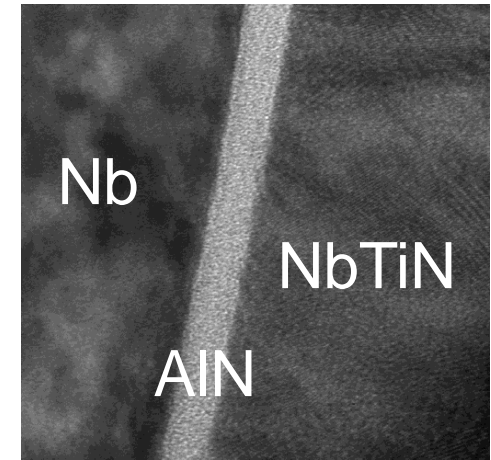
- CVD, HPCVD, ALD, sputtering, HiPIMS
- S: NbN, NbTiN, MgB_2
- I: MgO, AlN, Al_2O_3



Test sample ML

C. Antoine, CEA

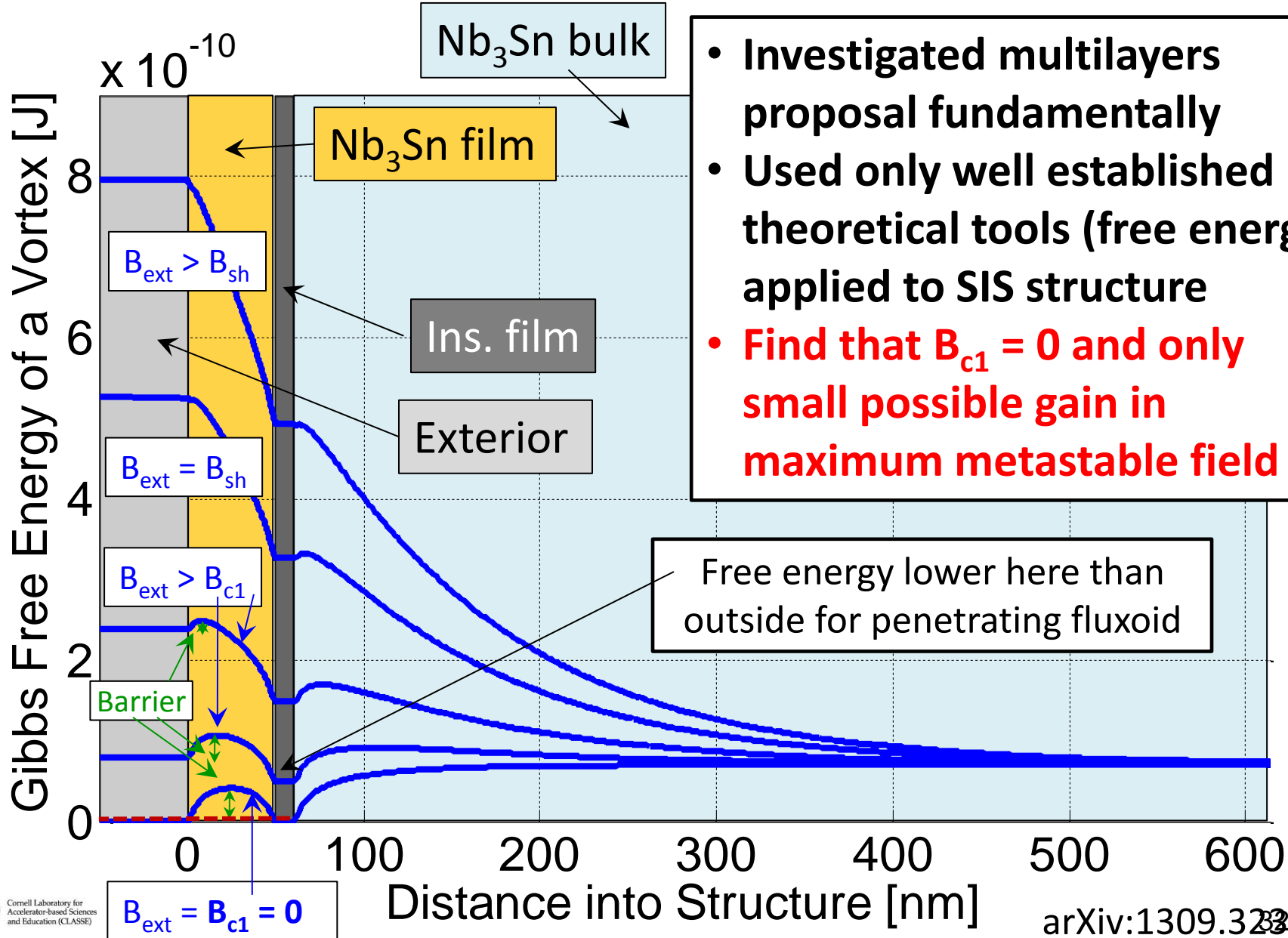
- Addition of Ti can increase NbN resistivity, thermodynamic stability
- JLab starting to use this material for multilayers: T_c and R_s measured



A.M. Valente-Feliciano, Jefferson Lab



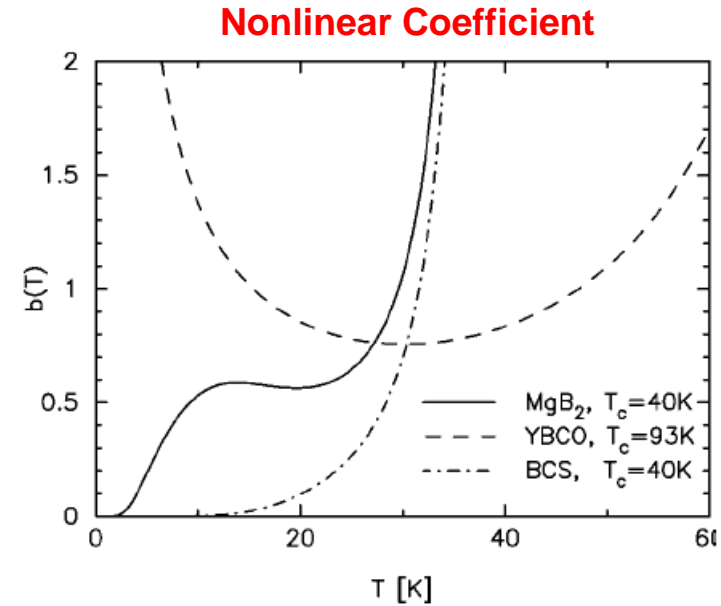
New Theory from Cornell



- Investigated multilayers proposal fundamentally
- Used only well established theoretical tools (free energy) applied to SIS structure
- **Find that $B_{c1} = 0$ and only small possible gain in maximum metastable field**

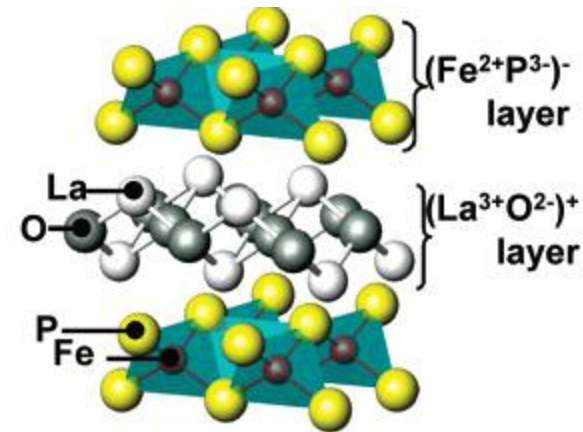


- YBCO ($T_c \sim 95$ K) – nonlinear increase in R_s with field, Large R_{res}
- **Oxypnictides** ($T_c \sim 20-60$ K) – difficult structure, but exciting possibility: more research needed
- **V_3Si , Mo_3Re , Nb_3GaAl** ($T_c \sim 10-20$ K) – further investigation needed



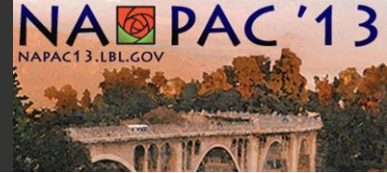
Dahm & Scalapino, APL 85, 4436 (2004)

Y. Kamihara et al. (2006).





Summary



- Alternative SRF materials offer lower R_s , higher T_c , higher B_{sh} than niobium → **more efficient cavities (factor of 10-100?), higher gradients (factor of 2?)**
- Breakthrough **Nb_3Sn** cavity: at 4.2 K and usable gradients, Q_0 is 20 times higher than Nb (details tomorrow morning)
- **MgB_2** looks very promising—first cavities soon!





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