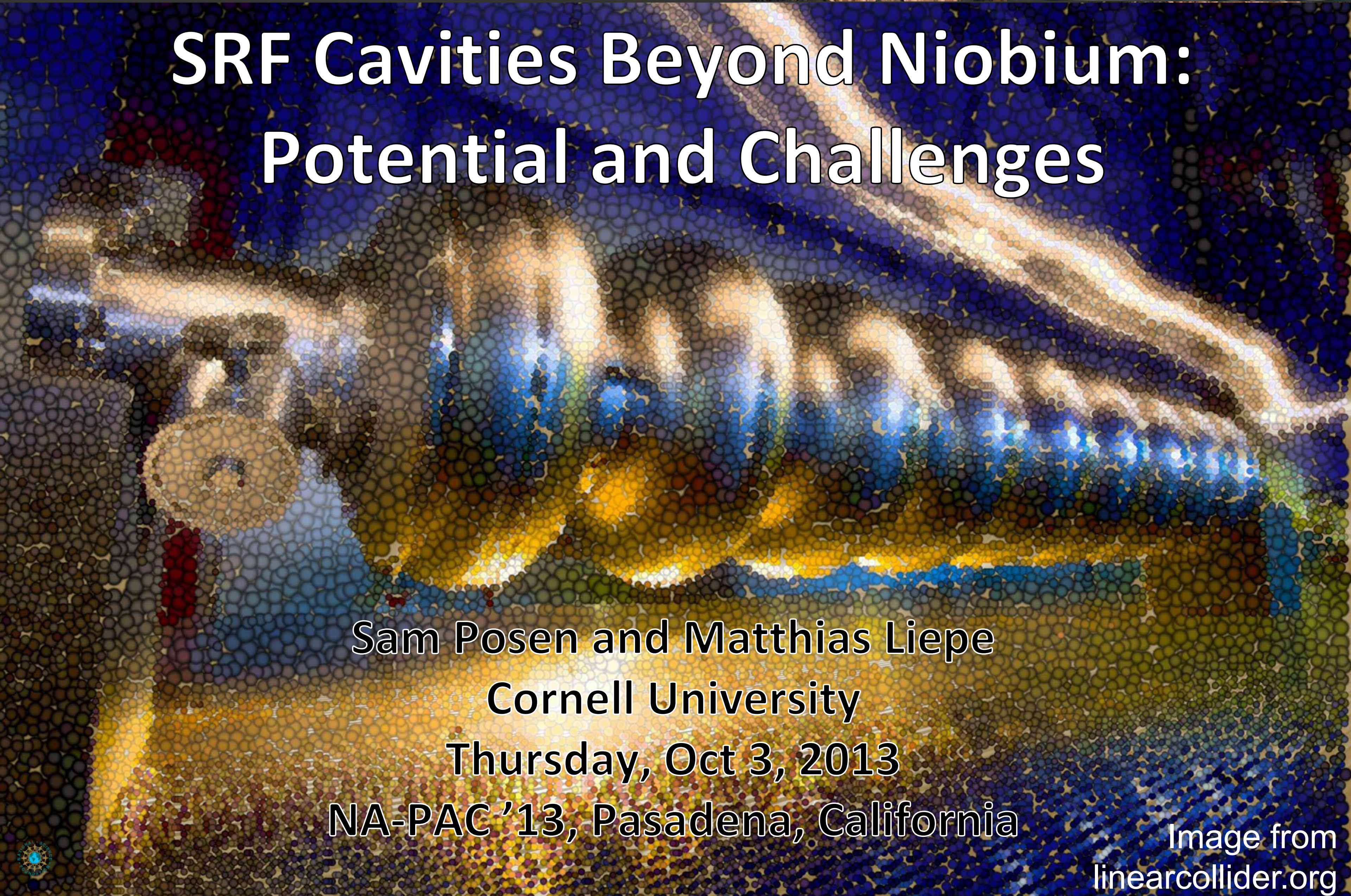
Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)

SRF Cavities Beyond Niobium: Potential and Challenges



Sam Posen and Matthias Liepe
Cornell University

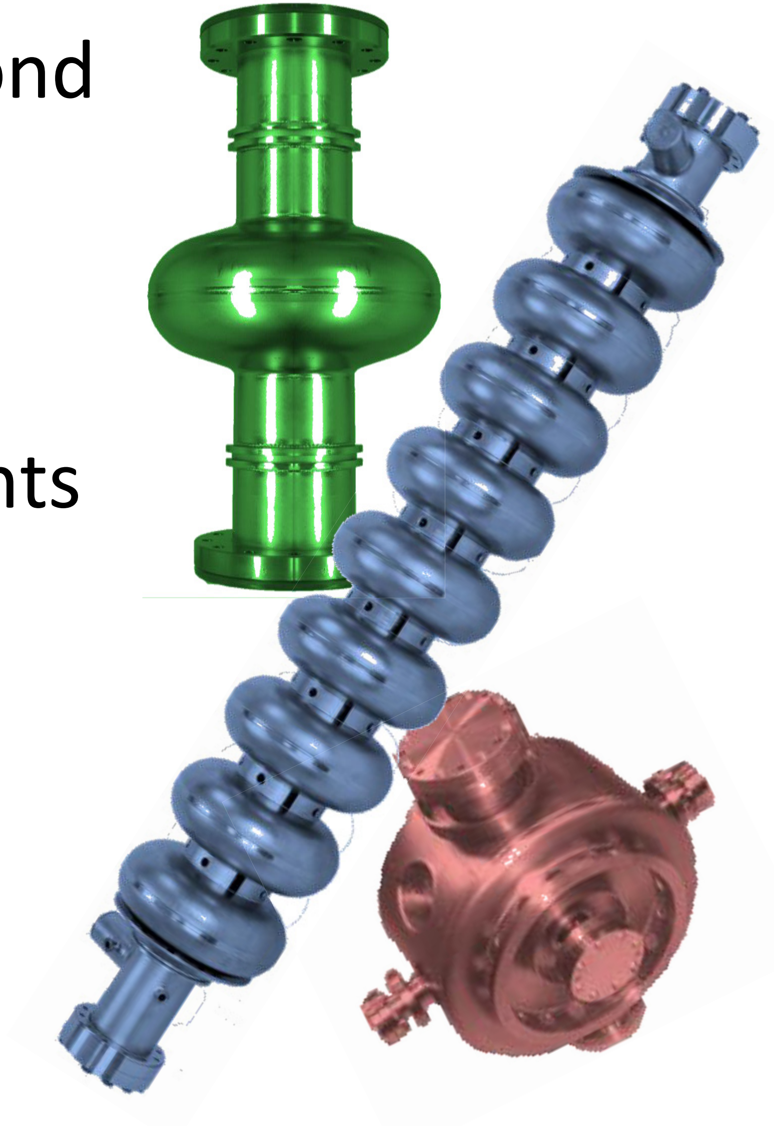
Thursday, Oct 3, 2013

NA-PAC '13, Pasadena, California

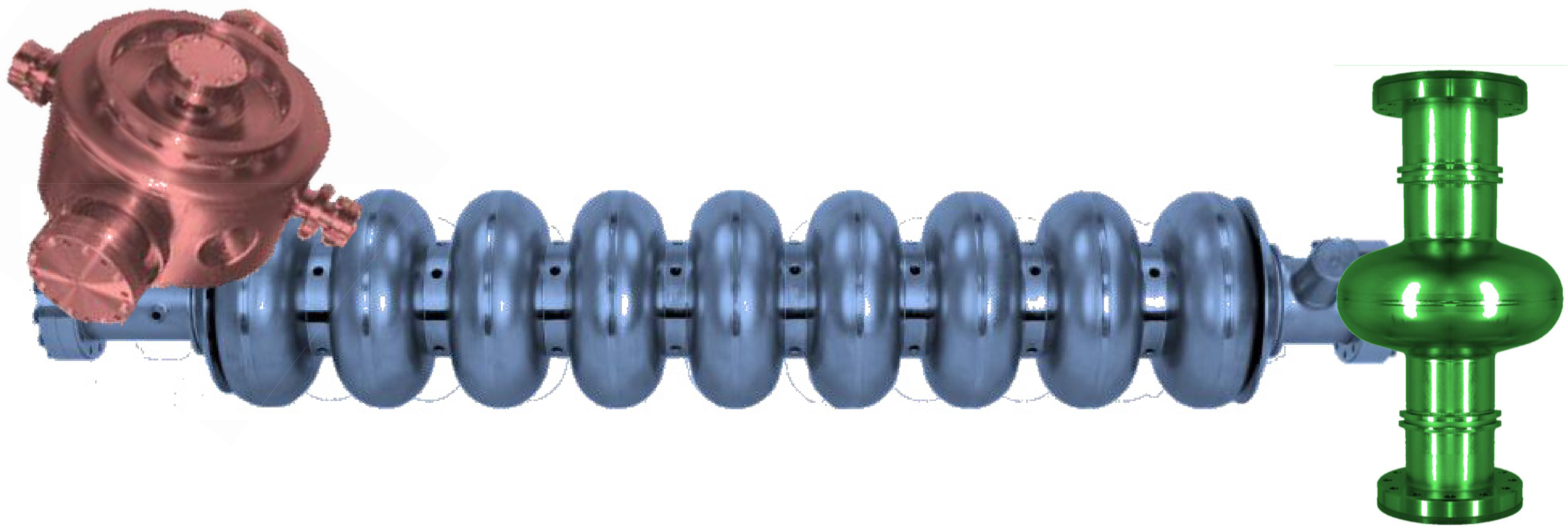
Image from linearcollider.org

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

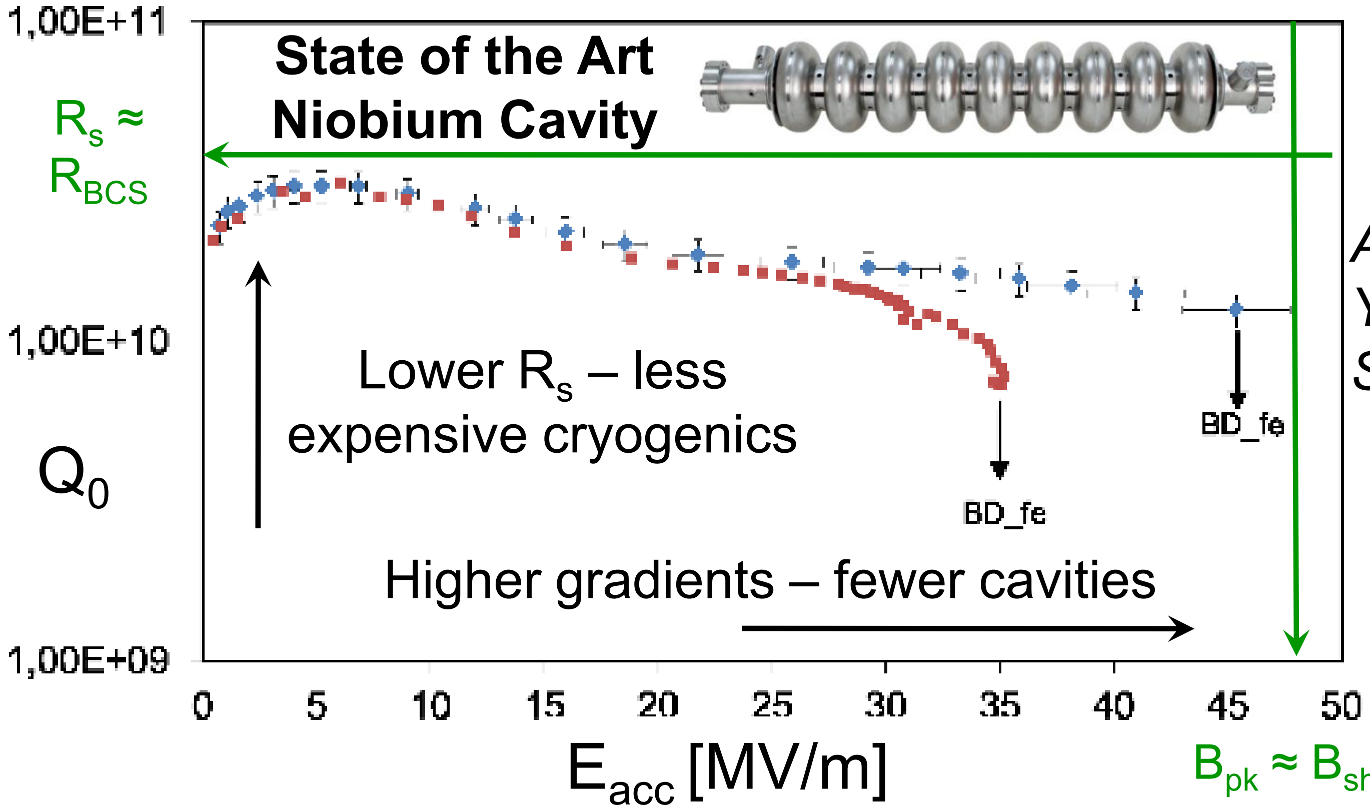


Why Look at Alternative SRF Materials?



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



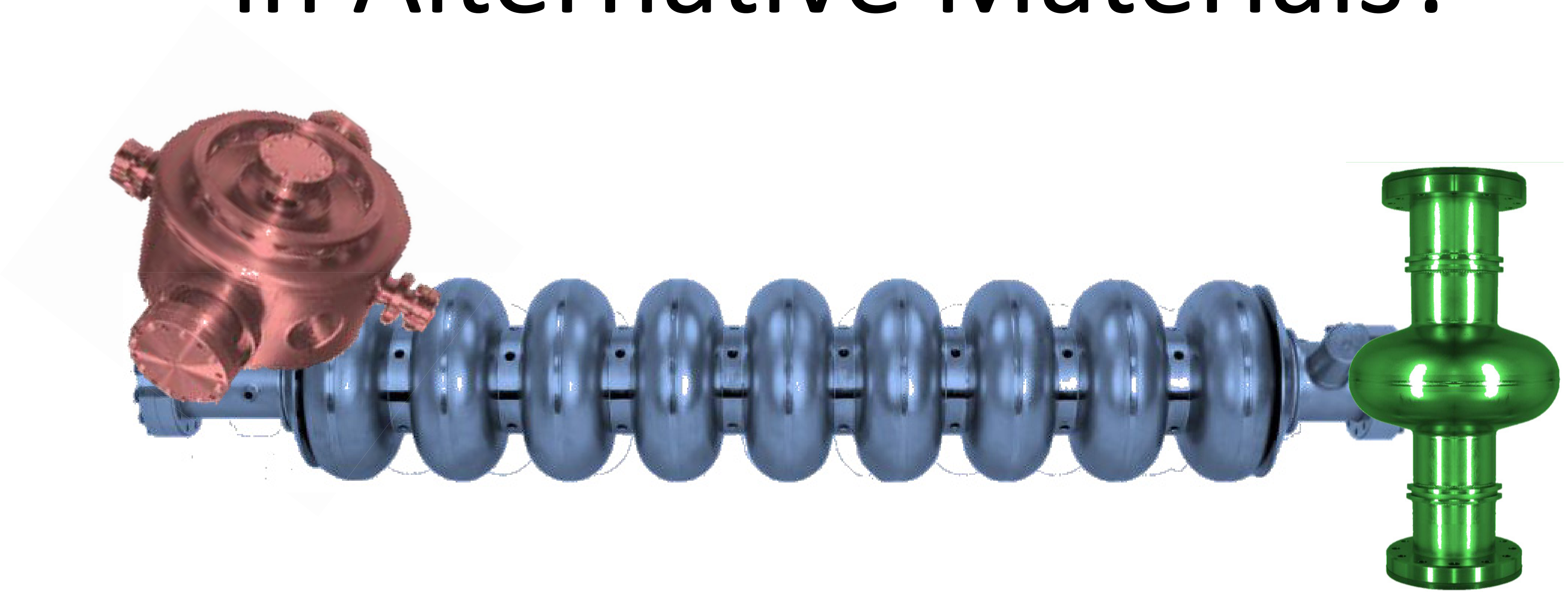
A. Yamamoto, SRF11

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 requied 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 Nb_3Sn 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 ~ξ can reduce barrier to vortex penetration—need "large enough" ξ
  - Nb has ξ ~ 20 nm and it gets very close to B_{sh}
  - New results on Nb_3Sn with ξ ~ 3 nm show barrier intact

Larger Max Field → Fewer Cavities Needed

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

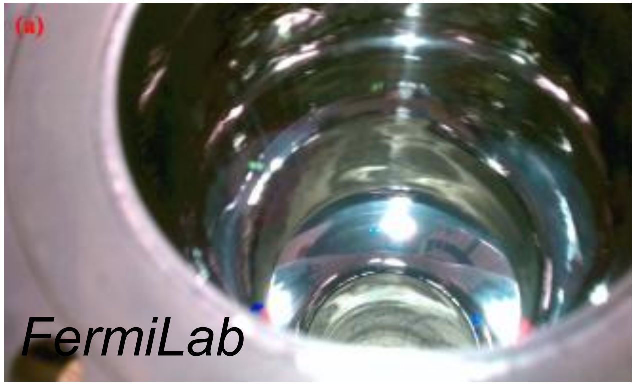
- Temperature dependent surface resistance from BCS theory: R_{BCS}
  - Need large T_c, small normal resistivity ρ_n ← *Vaglio, (1998)*
- Temp. independent "residual resistance": $R_s(T) = R_{BCS}(T) + R_{res}$ – not well understood
  - Strong connections between grains: it is known that weak links can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

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

Smaller R_s → 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

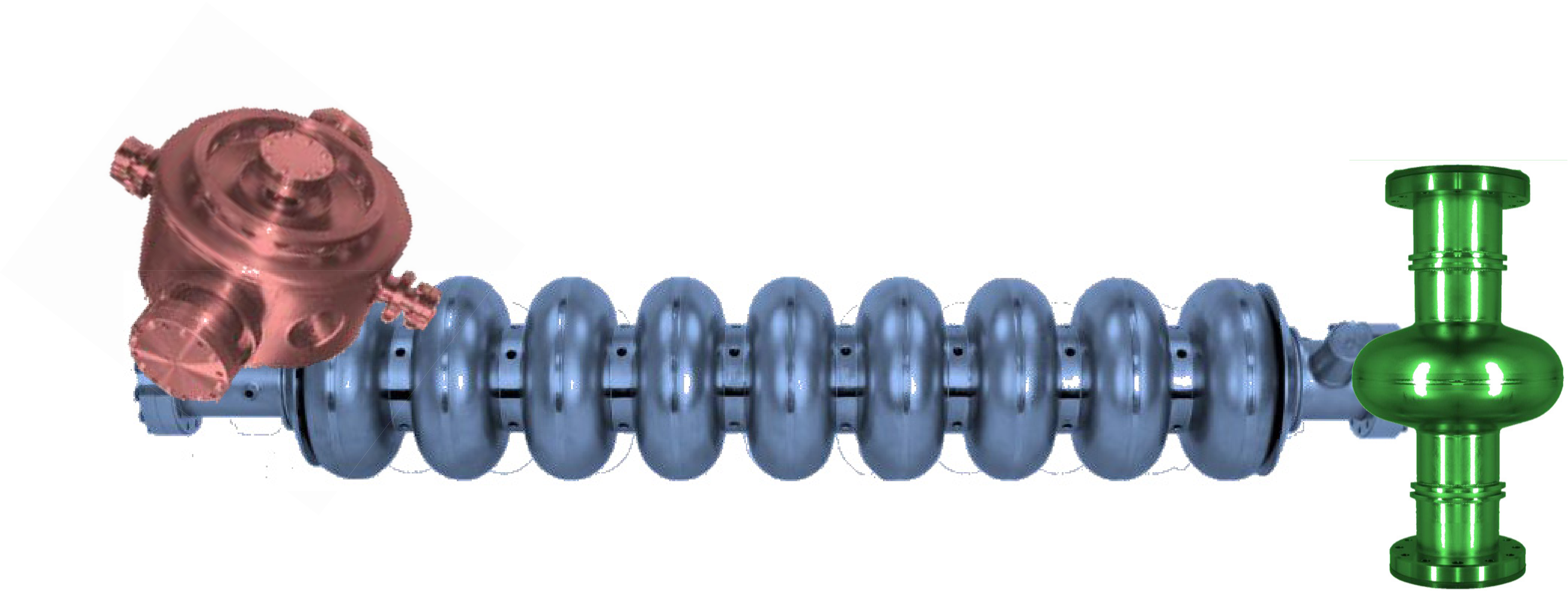
Material	$\lambda(0)$ [nm]	$\xi(0)$ [nm]	B_{sh} [mT]	T_c [K]	$\rho_n(0)$ [$\mu\Omega$cm]
Nb	50	22	210	9.2	2
Nb_3Sn	111	4.2	410	18	8
MgB_2	185	4.9	210	40	0.1
NbN	375	2.9	160	16	144

Parameters for: Nb from [1] assuming RRR = 10; Nb_3Sn from [2]; NbN from [3]; MgB_2 from [4] and [5]. B_{sh} for Nb found from equation in [6] and for others calculated from [7]. B_c used to calculated B_{sh} found from [8] eq. 4.20.

[1] B. Maxfield andW. 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.

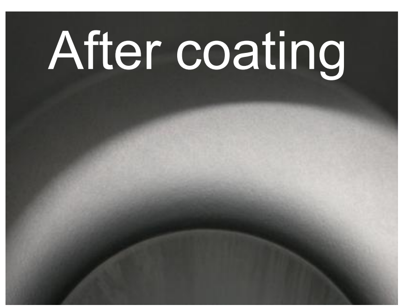
Nb_3Sn



Nb_3Sn

Potential

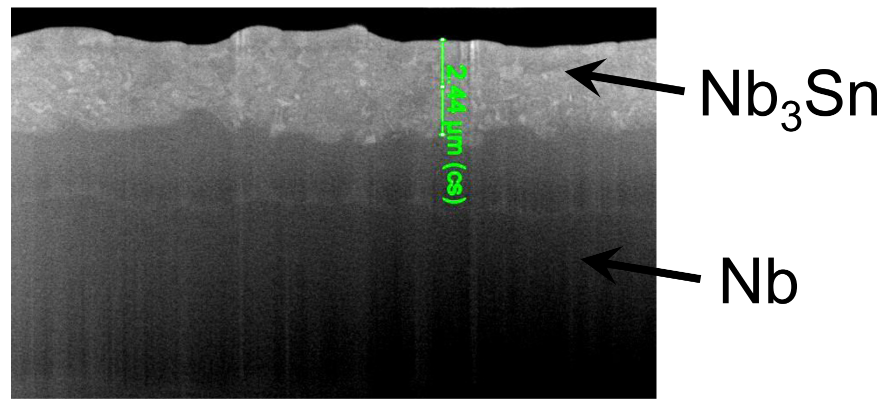
- Small R_s – Small ρ_n, high T_c ~ 18 K (twice Nb)
- Large B_{sh} ~ 400 mT (twice Nb)
- Decent ξ ~ 3-4 nm
- Can alloy existing Nb cavities
- Non-reactive

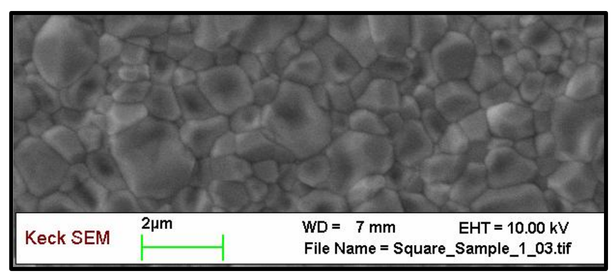


Challenges

- Material is brittle
- Low thermal conductivity

→ Films avoid these

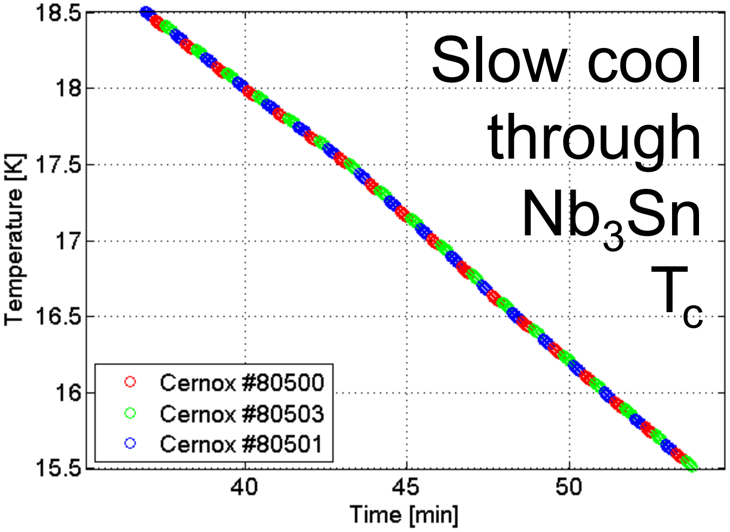




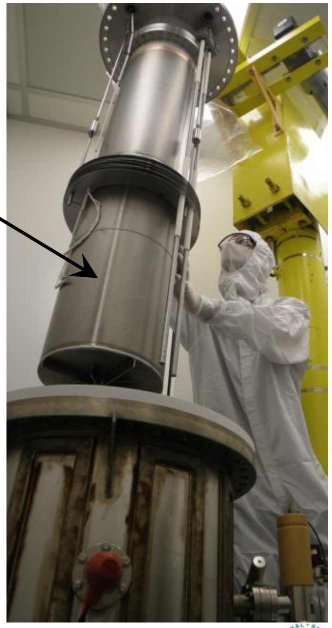
Images from Cornell

Challenges With Films (Any Material)

- 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



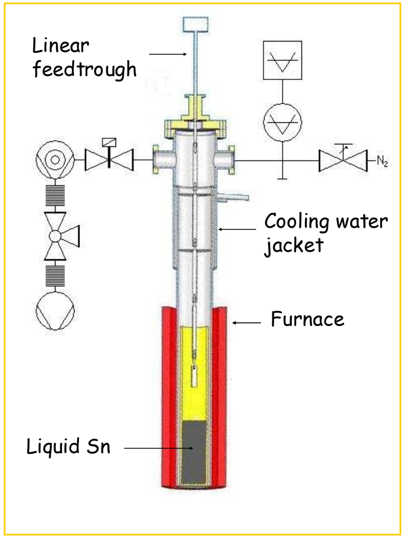
Cornell Nb_3Sn Coating Chamber



Preparation Methods

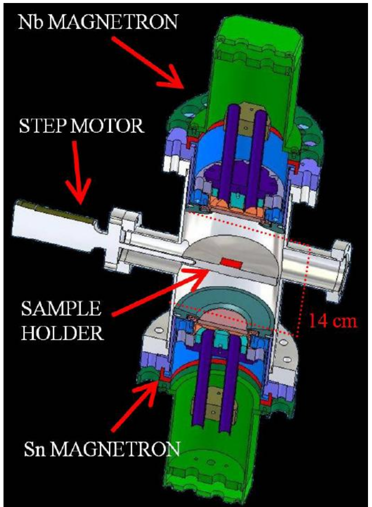
Liquid Tin Dipping – INFN

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



S. Deambrosis et al. (2009)

Multilayer Sputtering – INFN

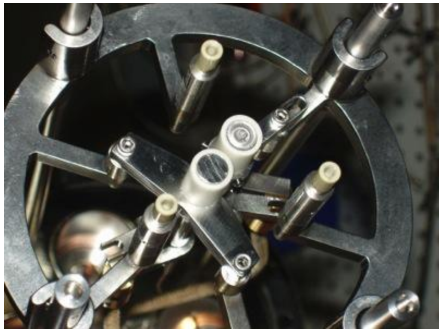


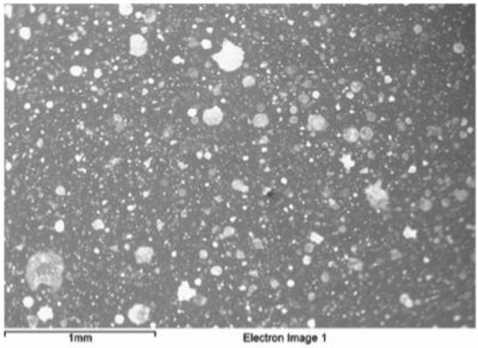
- Alternate coatings of Nb and Sn, then anneal
- No encouraging RF results so far

A. Rossi et al. (2009)

Cathodic Arc Deposition – Alameda Applied Sciences

- More energetic ions than sputtering
- Low T_c measured

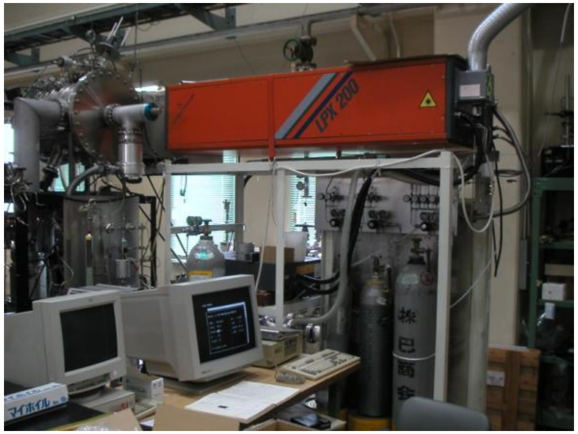


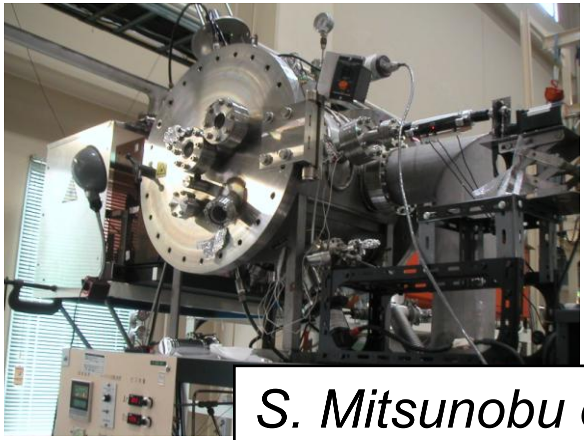


M. Krishnan et al. (2012)

Preparation Methods

Pulsed Laser Deposition - KEK



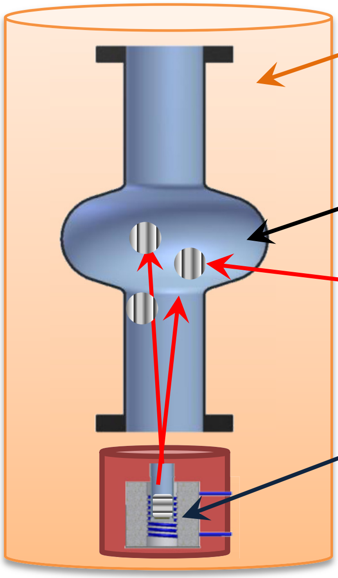


S. Mitsunobu et al.

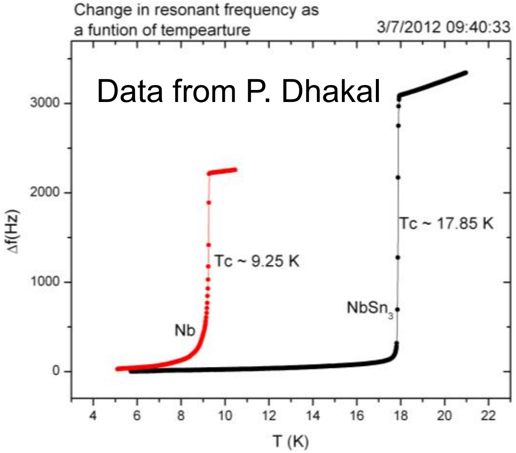
- Studies have started
- Also use PLD for MgB_2

Vapor Diffusion – Cornell and Jefferson Lab

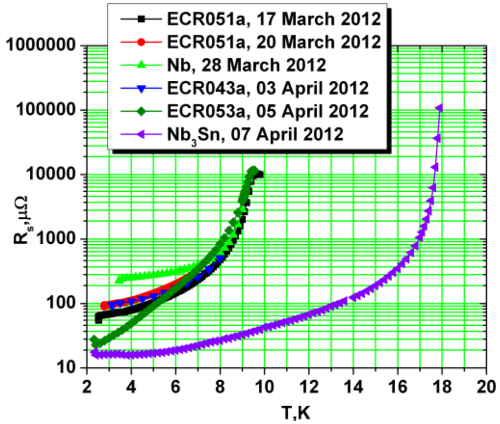
- Pioneering studies 80s-90s at Siemens AG and U. Wuppertal
- In UHV furnace, tin vapor alloys with Nb cavity
- Very promising RF results



Jefferson Lab, Courtesy of G. Eremeev



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

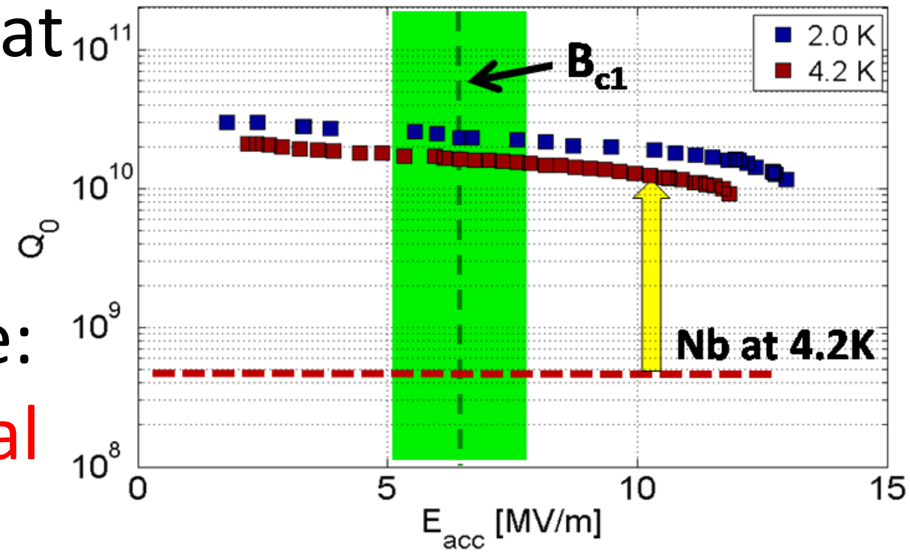


Recent measurements of surface resistance of several ECR films, bulk Nb sample, and Nb_3Sn sample as a function of temperature at 7.4 GHz.

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

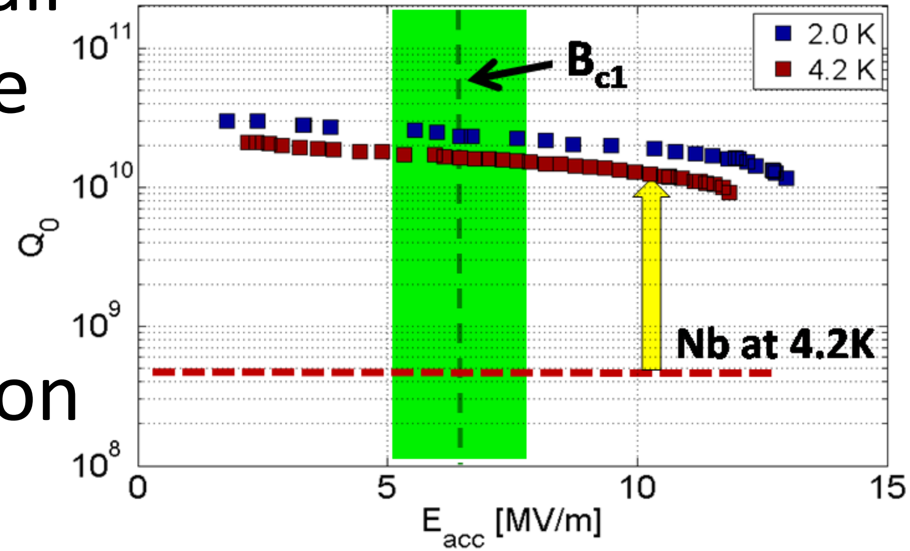
Cornell Nb_3Sn Cavity

- Achieved fields ~12 MV/m at 4.2 K with Q_0 $1x10^{10}$, 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



Cornell Nb_3Sn Cavity

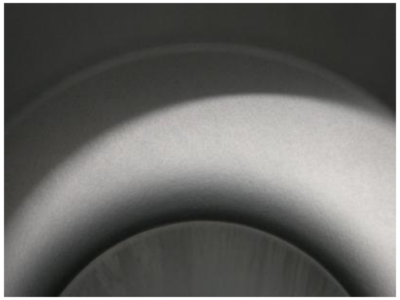
- Proves that even with small ξ of Nb_3Sn (making it more vulnerable to surface defects), energy barrier prevents vortex penetration
- Shows the potential of alternative SRF materials

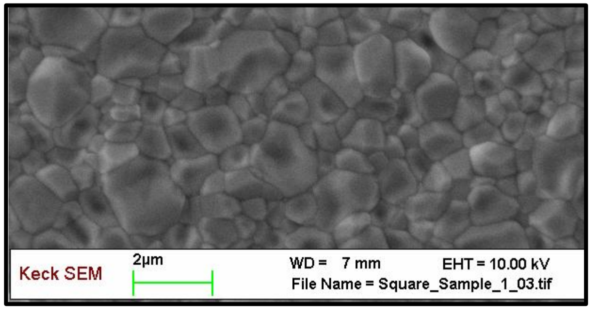


See details in talk tomorrow! (9:15 in Aud. A)

Current Status of Nb_3Sn

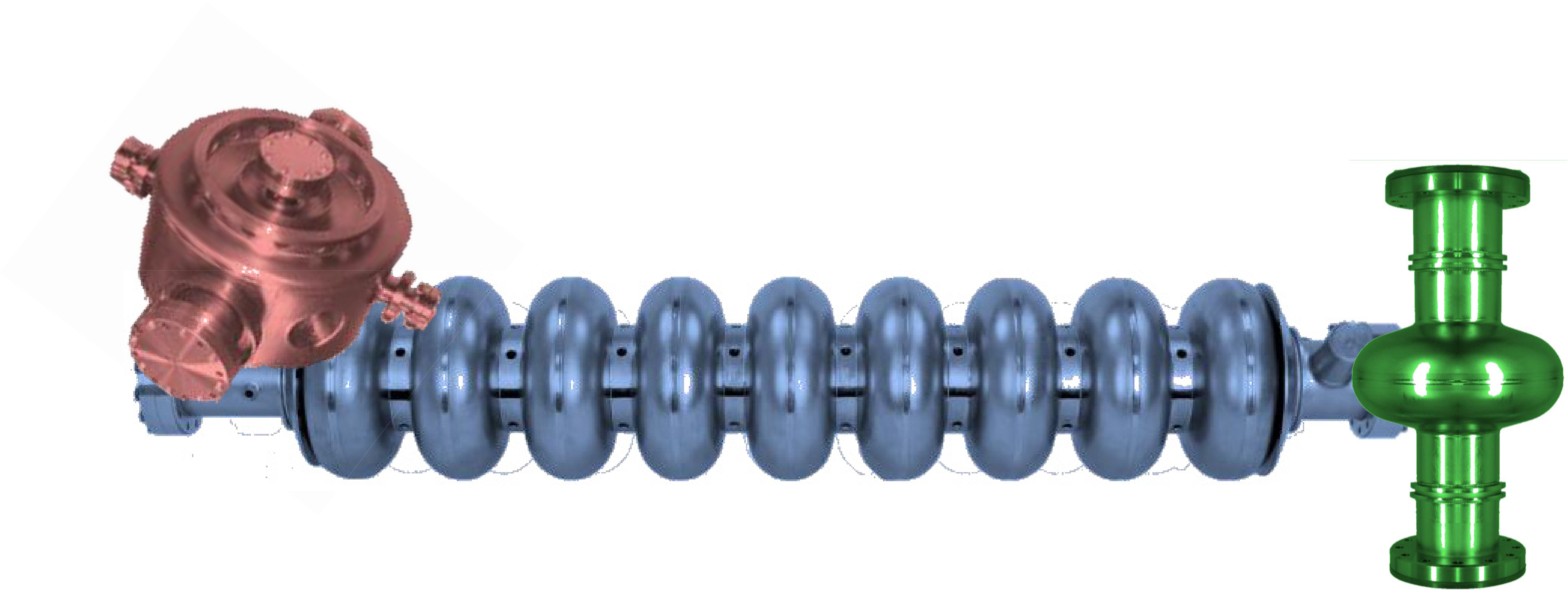
- Cavity fabrication is established – Nb_3Sn ready for first applications
- Far smaller R_s than Nb achieved down to 2 K
- Surface mag. fields up to ~55 mT with small R_s
  - Achieved E_{acc} is useful, but far below ultimate limit of material, superheating field
  - Nb: 200 mT, Nb_3Sn ~400 mT





Color Code
Goal Achieved
Goal in Progress
Fundamental Problem

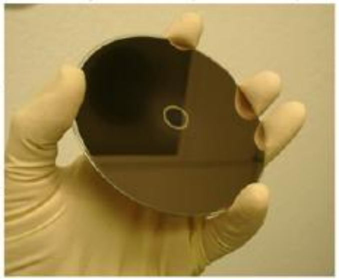
MgB_2



MgB_2

Potential

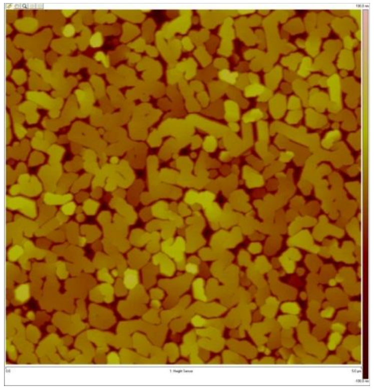
- Small R_s – small ρ_n, very high T_c ~ 40 K (smaller gap dominates R_s, but still good)
- B_{sh} not clear yet, but possible range ~200-600 mT. Need more development of SRF quality MgB_2 films
- Very high T_c raises possibility of operation at high T
- Decent ξ ~ 5 nm



T. Tajima, Los Alamos

Challenges

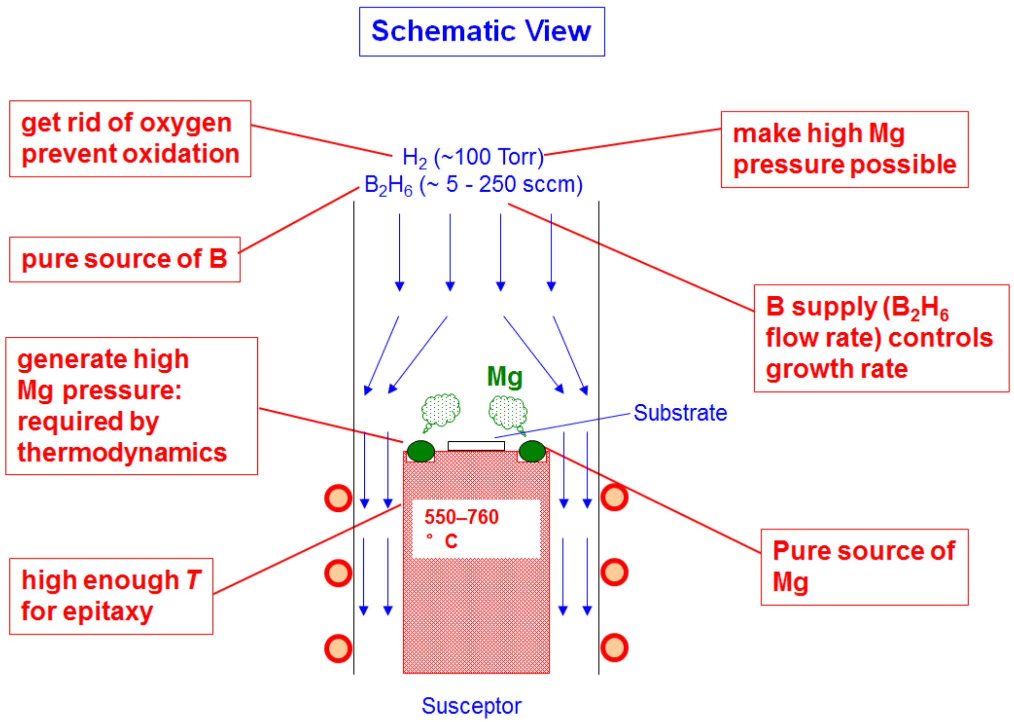
- Mg highly reactive with oxygen: must have very small background during coating
- R_s increase with field predicted for two gap materials, but might be possible to reduce it
- Reacts with water – "capping" layer may be required

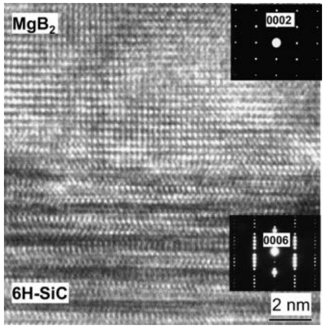


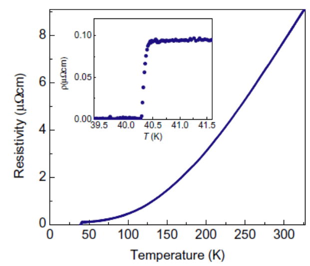
X. Xi, Temple U.

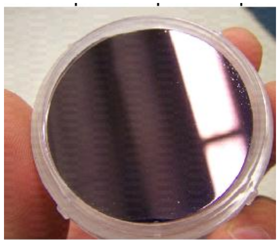
Temple University, Courtesy X. Xi

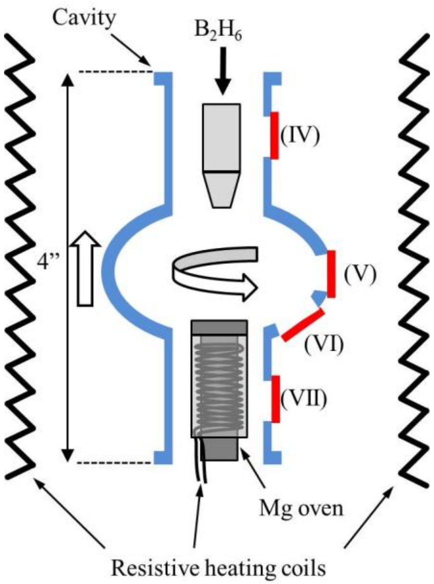
Hybrid Physical-Chemical Vapor Deposition











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

Los Alamos, Courtesy of T. Tajima

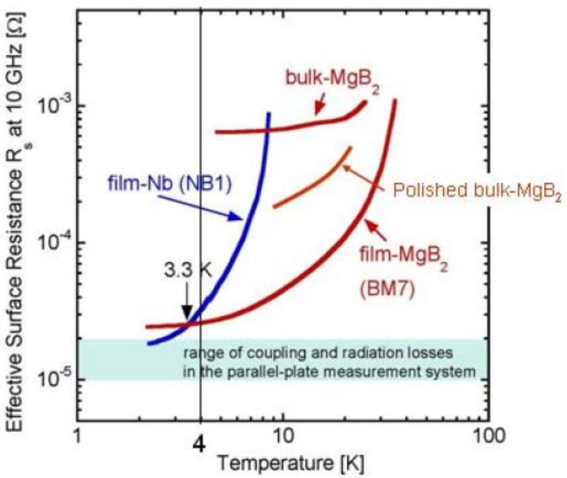


Figure 3: Surface resistance vs. temperature of a 400 nm MgB_2 film coated on a sapphire substrate. Bulk samples and Nb data are shown for comparison. [6]

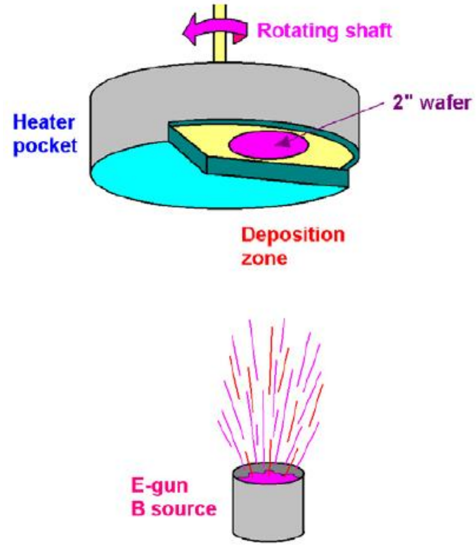


Figure 1: MgB_2 coating system at STI. [5]

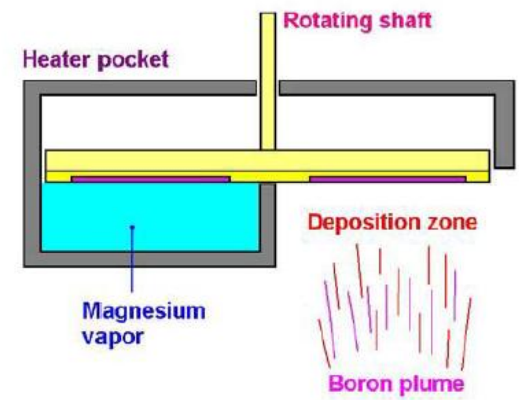


Figure 2: Cross section of the deposition chamber. [5]

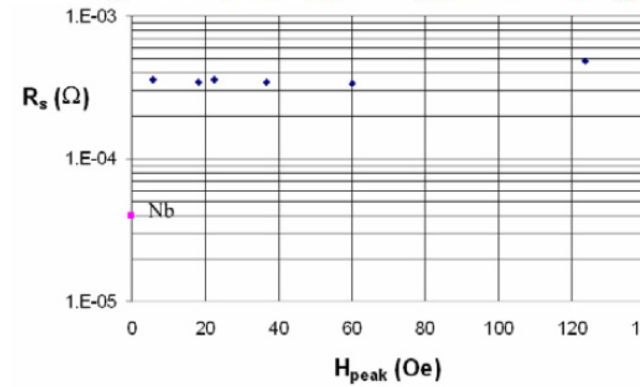


Figure 6: R_s of the Nb TE_{011} mode cavity with a MgB_2 sample at the center of the bottom plate, as a function of the peak magnetic field on the sample. The data was converted to 10 GHz using an f^2 law.

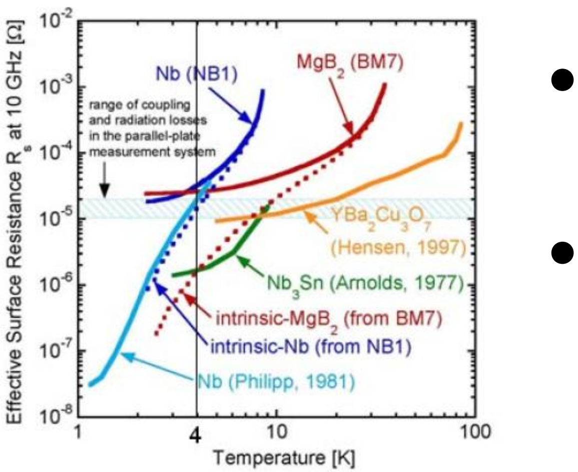


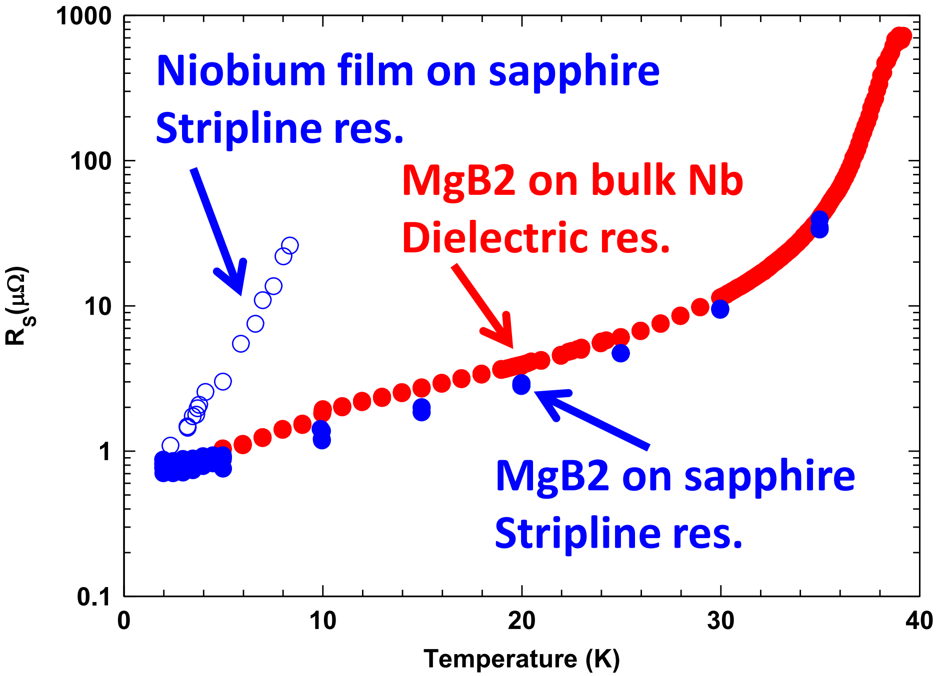
Figure 4: Prediction of intrinsic (BCS) surface resistance (dotted line) from experimental data. [6]

- R_s lower than Nb at 10 GHz for T > ~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

MIT Lincoln Labs, Courtesy of D. Oates

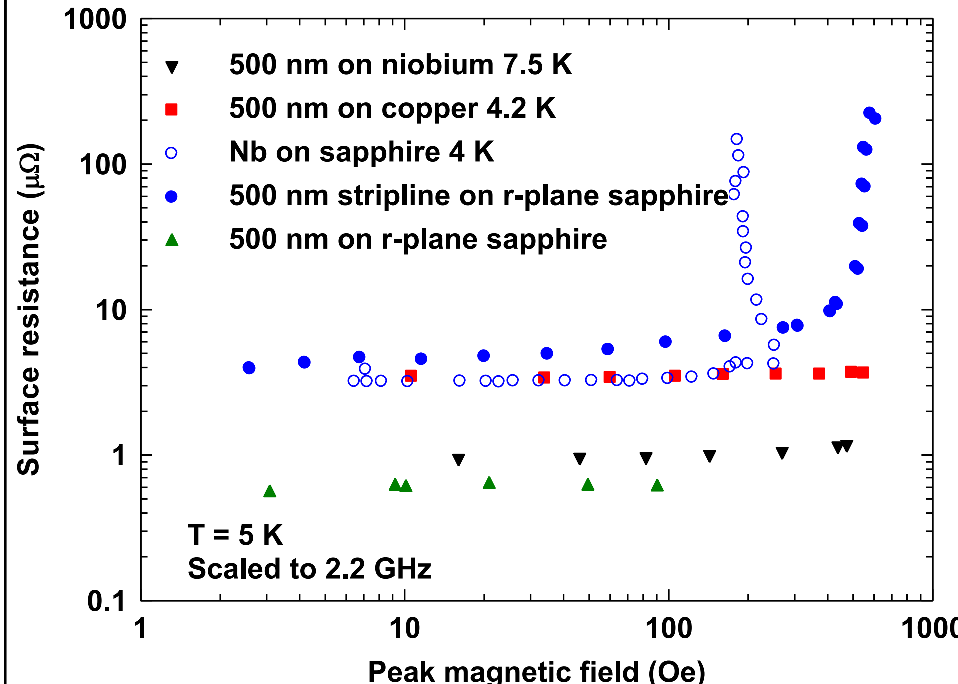
Low-Power $R_S(T)$: MgB_2 and Nb



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

R_S vs H_{RF}

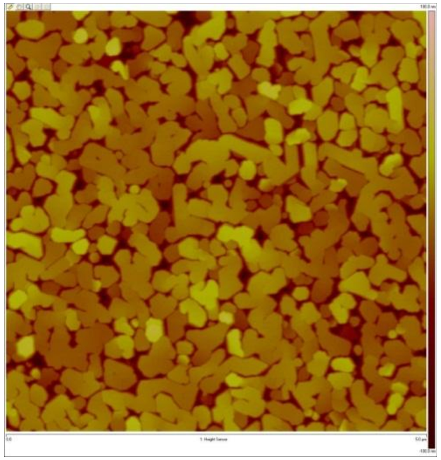
Dielectric and Metallic Substrates

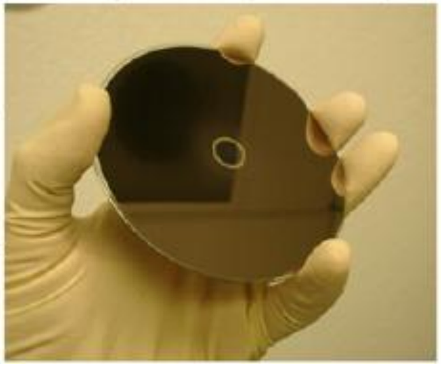


MgB_2 films produced by B. Moeckly at STI (Superconducting Technologies Inc.) by reactive co-evaporation

Current Status of MgB_2

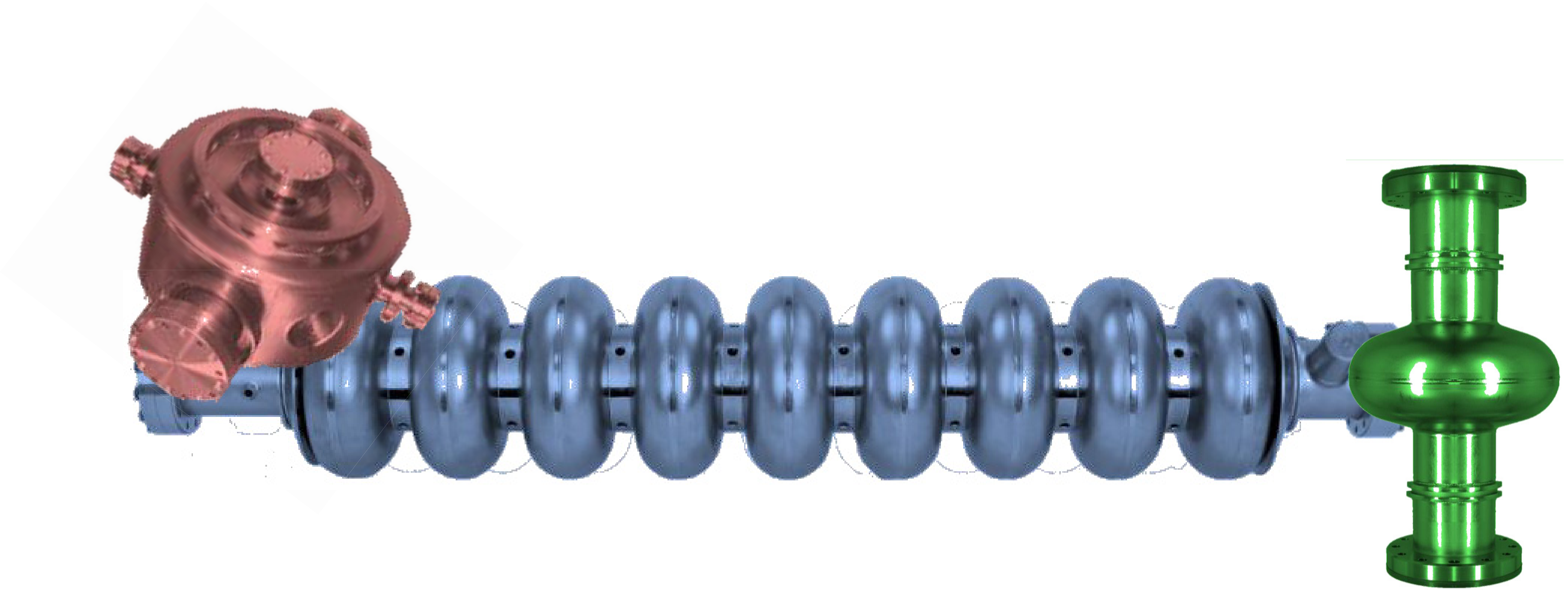
- Several sample studies; cavity fabrication is coming soon
- Smaller R_s than Nb achieved at high temperature and frequency
  - Need to show small R_{res} is possible
- Only relatively small gradients measured so far, as no cavities built yet
  - Need to see if two-gap nature increases R_s at high gradients





Color Code
Goal Achieved
Goal in Progress
Fundamental Problem

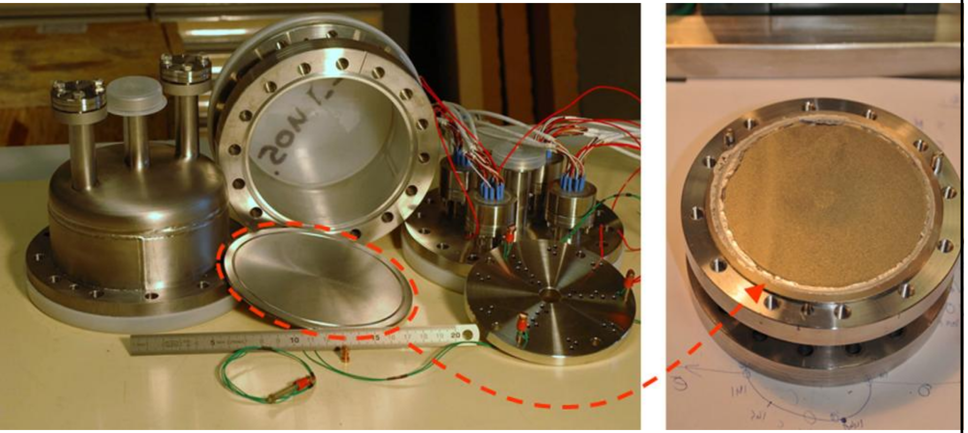
NbN



NbN

Potential

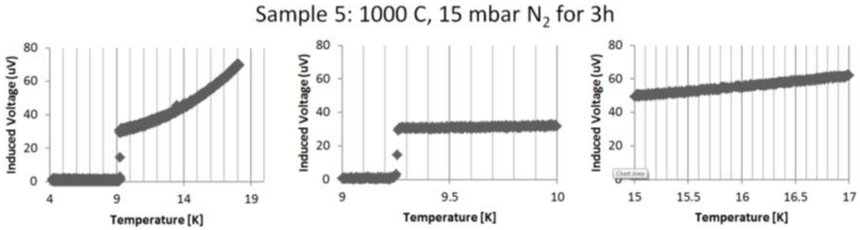
- Small R_s – high T_c ~ 15 -17 K
- B_{sh} okay ~ 150-200 mT
- Decent ξ ~ 3 nm
- Might be possible to treat large Nb cavities with N_2 in furnace



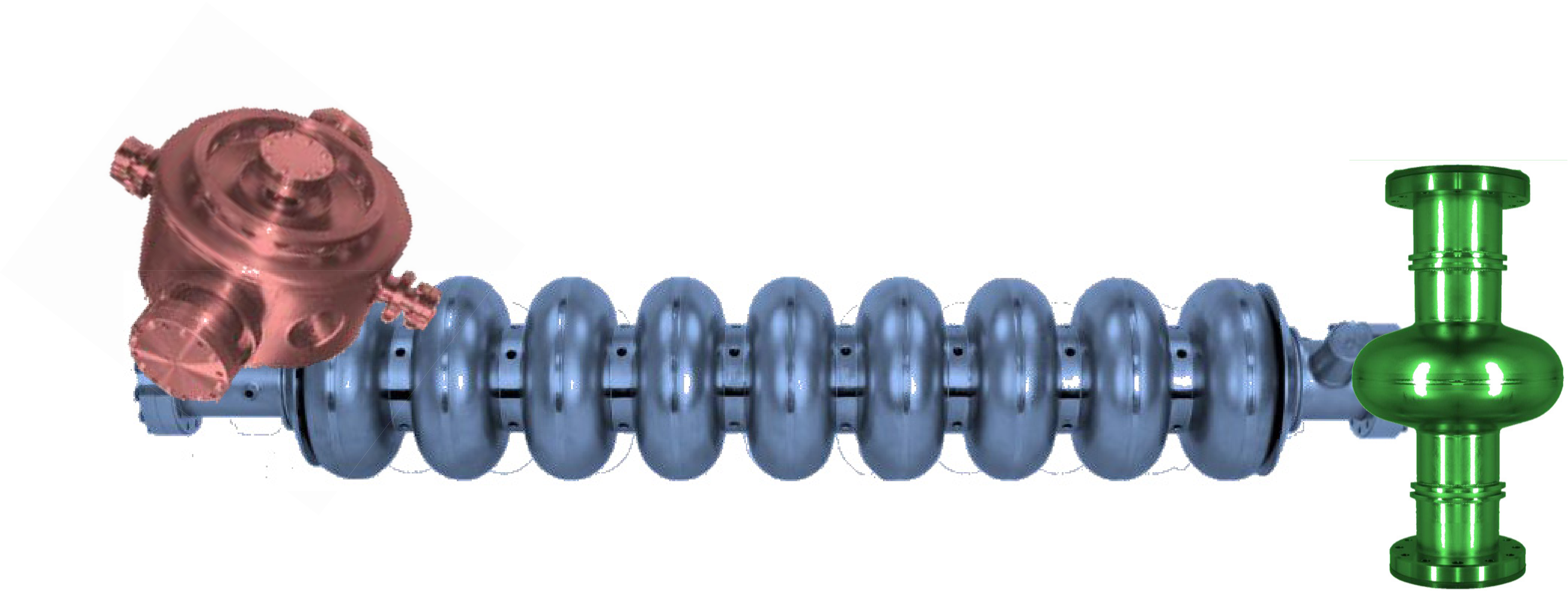
Sputtered NbN, *C. Anoine et al. (2013) APL* 102603

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



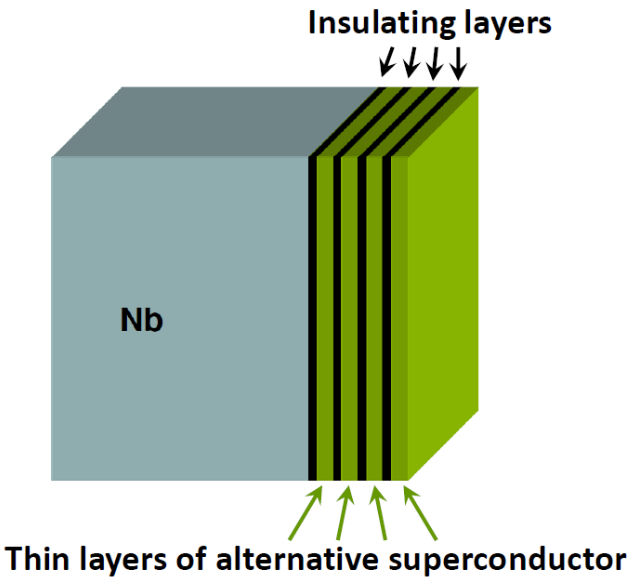
Multilayers

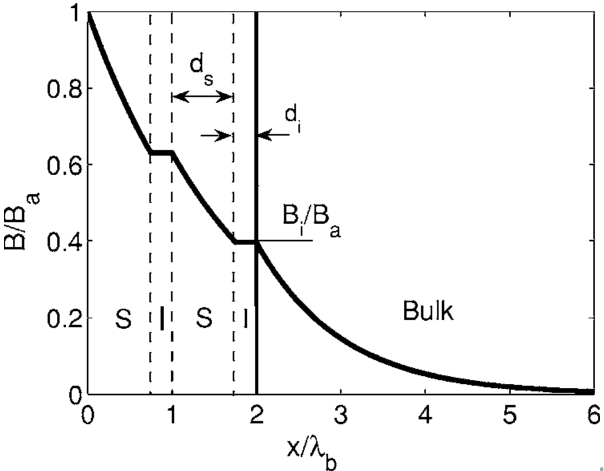


Multilayers

- 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)

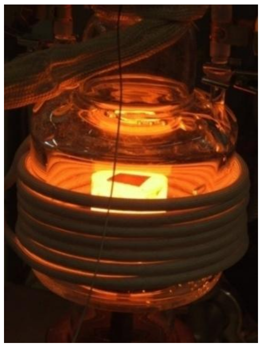


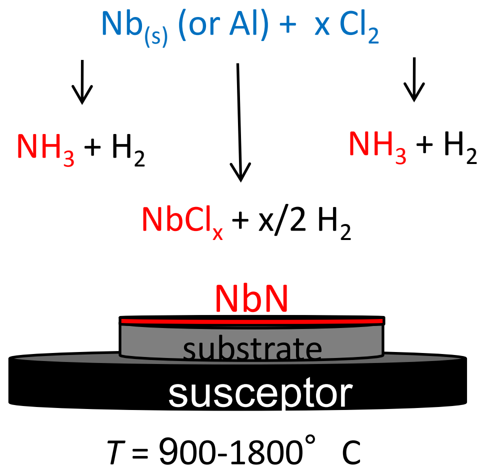


Fabrication

CVD of NbN (AlN) layers

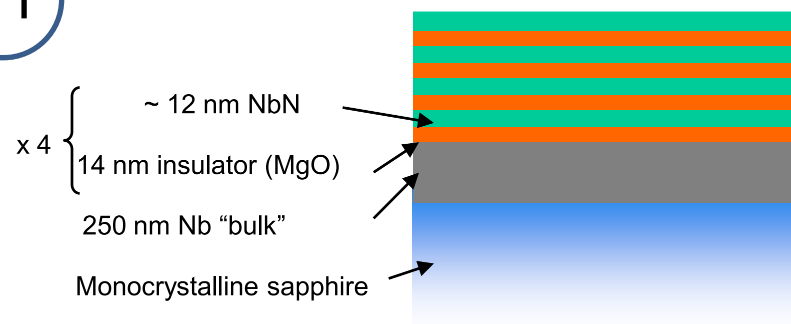
High Temperature CVD
using Nb (Al) Chloride and NH_3





F. Weiss et al., Grenoble IPT

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

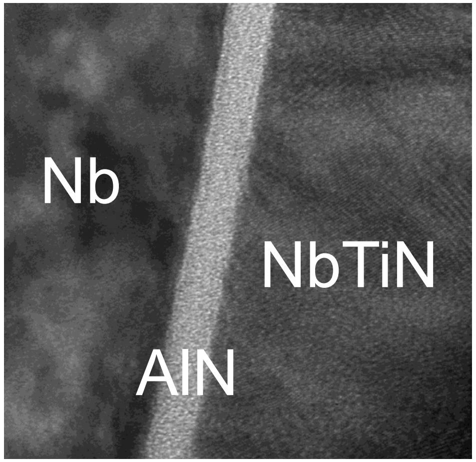


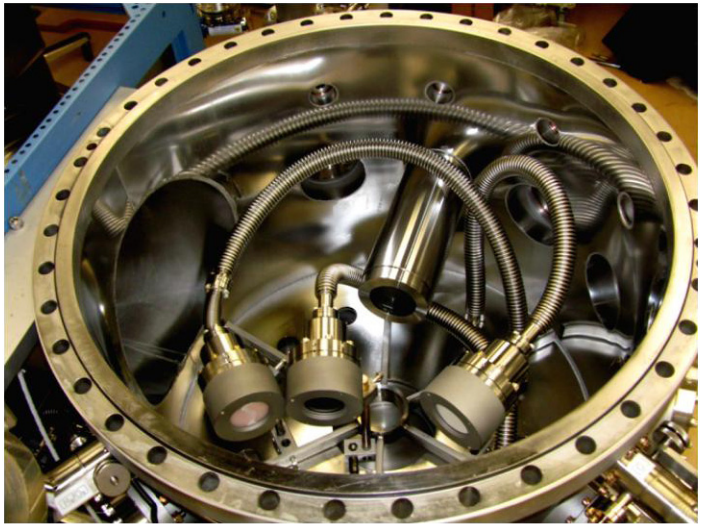
Test sample ML

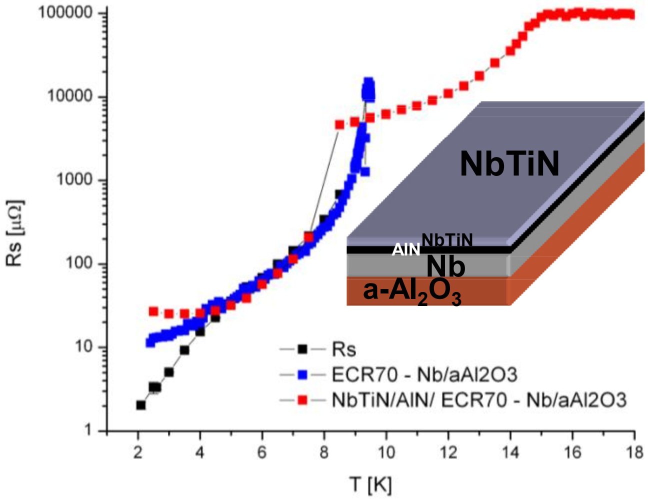
C. Antoine, CEA

NbTiN

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



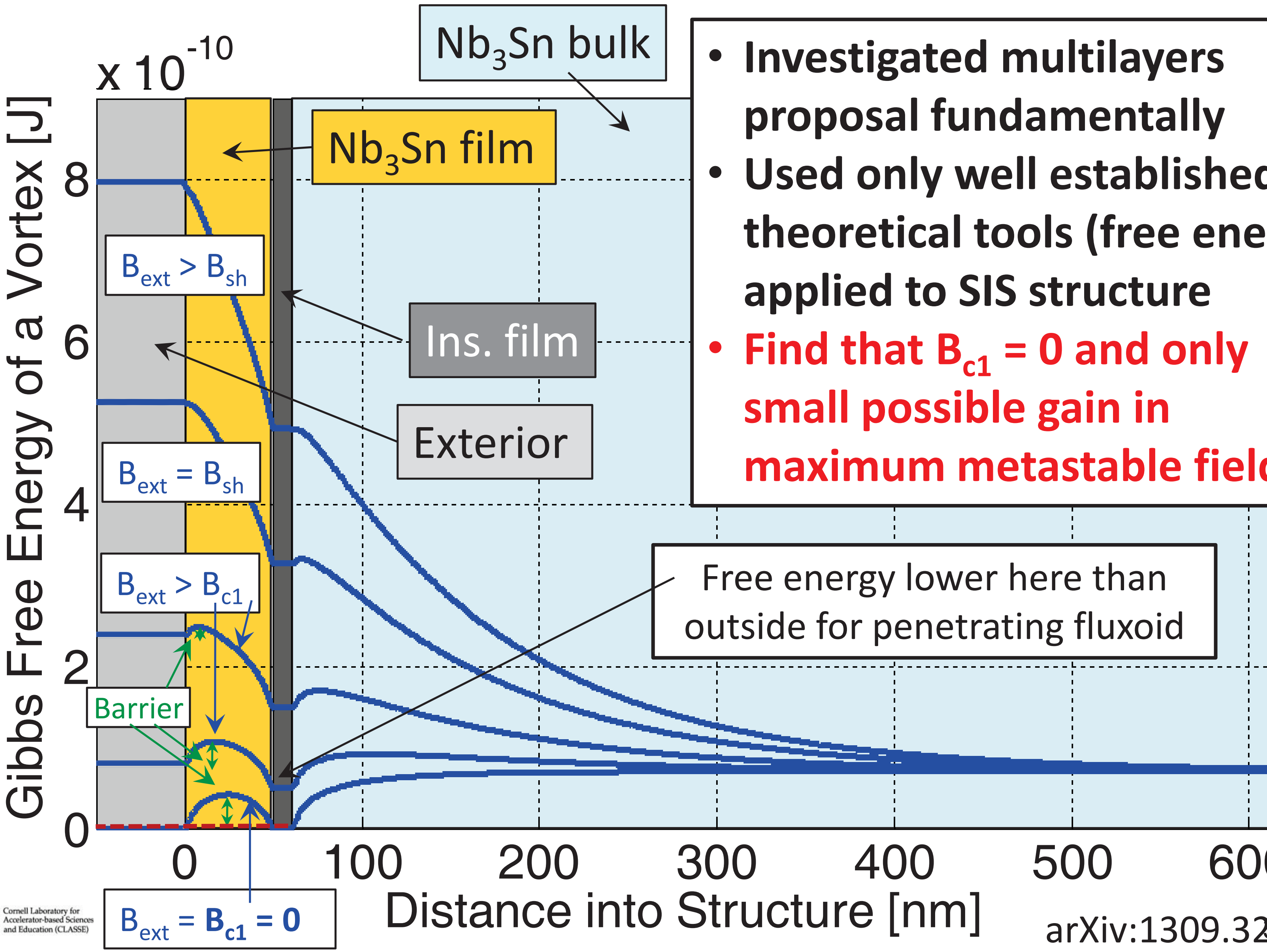




A.M. Valente-Feliciano, Jefferson Lab

New Theory from Cornell

NAPAC '13
NAPAC13.LBL.GOV



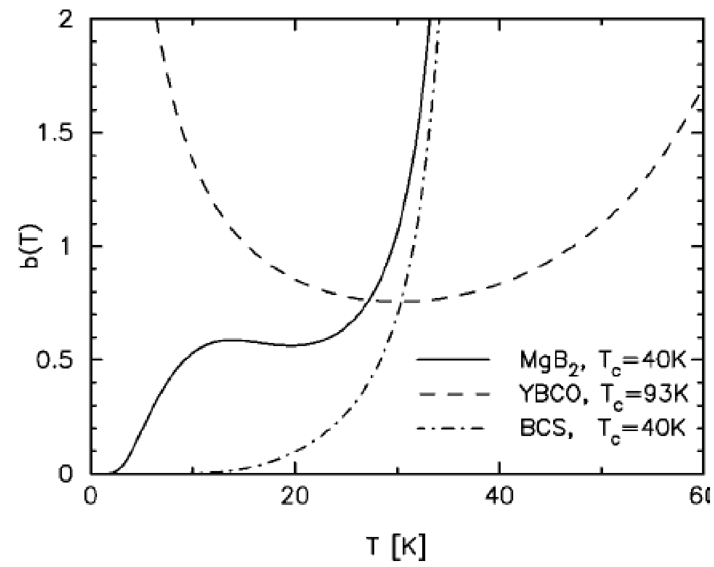
- **Investigated multilayers proposal fundamentally**
- **Used only well established theoretical tools (free energy) applied to SIS structure**
- **Find that B_{c1} = 0 and only small possible gain in maximum metastable field**

arXiv:1309.3239

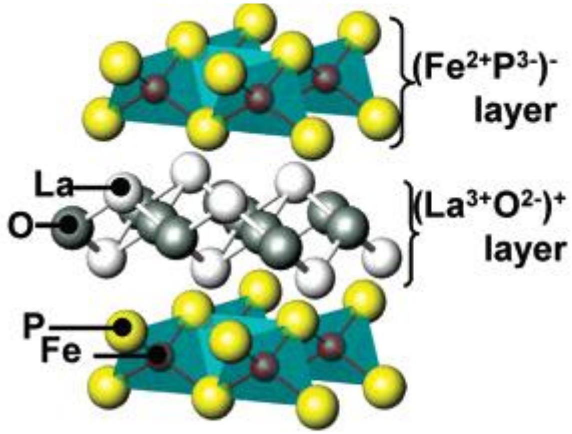
Other Possible Materials

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

Nonlinear Coefficient



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!

Acknowledgements

- I would like to extend sincere thanks to the following contributors:
  - Grigory Eremeev, JLab
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