High T_c : New Developments & Progress on Understanding the Mechanisms and Hope for the Future

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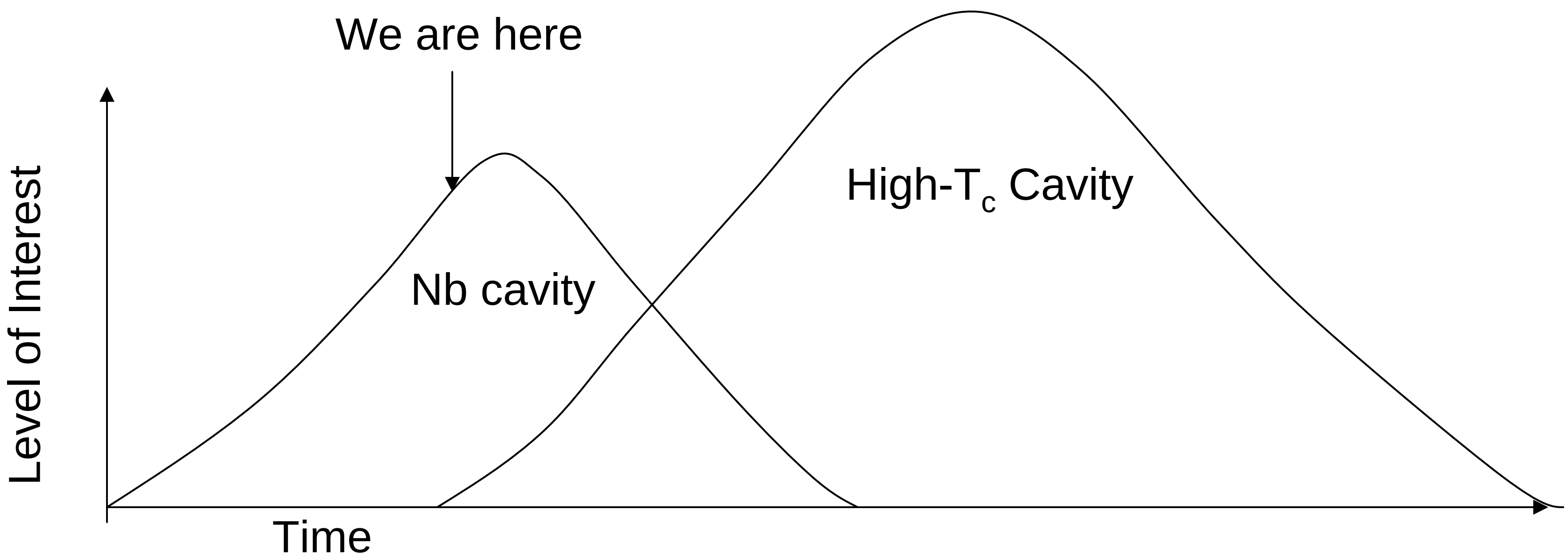
Why do we need high-T_c materials study for RF cavities?

- High-purity Nb and cavities are still expensive.
- Refrigeration to get to 4 K or lower is expensive
- Nb cavities have reached close to its theoretical limit and the recipe to get good results such as E_{acc} >35 MV/m repeatedly will be established within ~5 years.



Outline

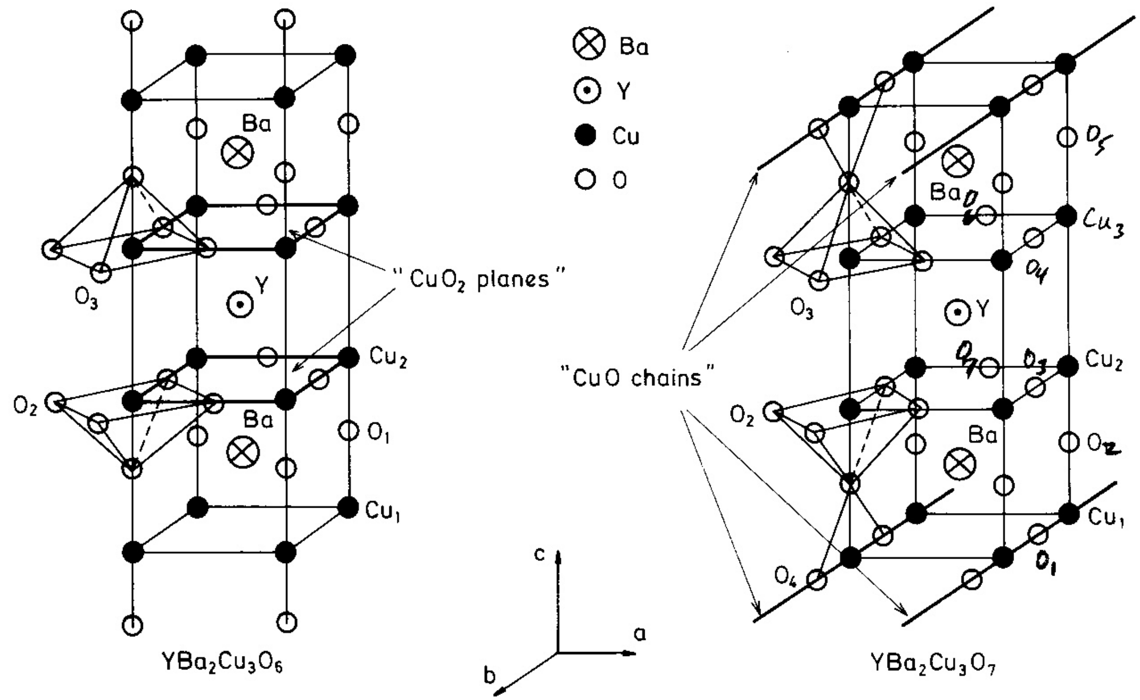
1. What are high-T_c materials
2. Mechanisms of Superconductivity in High-T_c materials (Cu oxide and MgB_2)
3. Properties of High-T_c materials that are related to the application to SRF cavities
4. Developments in the past 2 years

What are high-T_c materials

- In 1986, Georg Bednorz and Alex Müller discovered a superconductivity at **~38 K** in $La_{2-x}Sr_xCuO_4$ ceramics.
- In 1987, research groups in Alabama and Houston, coordinated by K. Wu and Paul Chu discovered $Y_1Ba_2Cu_3O_7$ ceramics with **T_c= 92 K**. For the first time above LN2 temperature.
- The highest T_c so far is **138 K** with $(Hg_{0.8}Tl_{0.2})Ba_2Ca_2Cu_3O_{8.33}$
- Is room temperature superconductor possible??
- MgB_2 was discovered to be superconductive at ~**40 K** in early 2001. It was a surprise since it is a simple binary intermetallic compound.

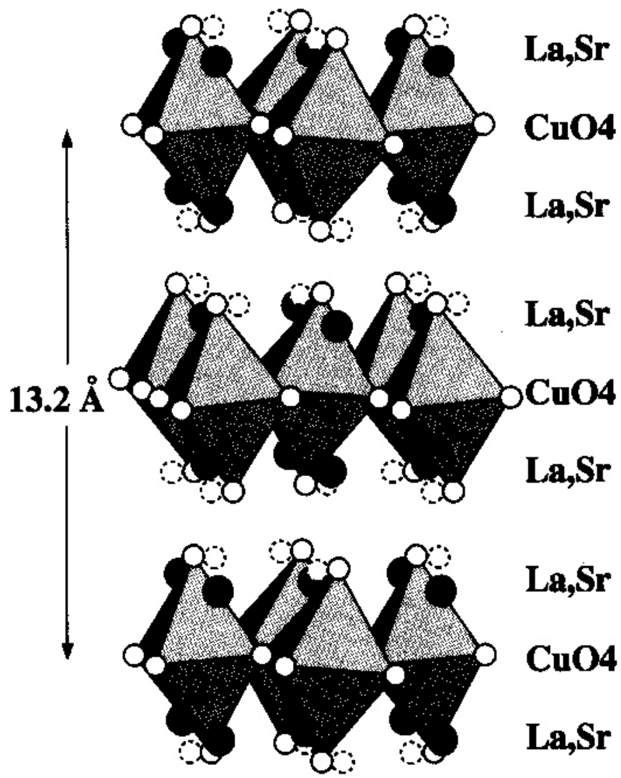
2. Mechanisms of Superconductivity in High-T_c materials - Cuprates (..Cu_xO_y)

- In general, superconductivity results from the interaction between electrons (holes) and phonons, the quantized lattice vibration
- The superconductivity occurs when additional oxygen is doped into $YBa_2Cu_3O_6$ which forms CuO "chains."
- These oxygen ions attract electrons from CuO_2 plane, which produces holes that become Cooper pairs.

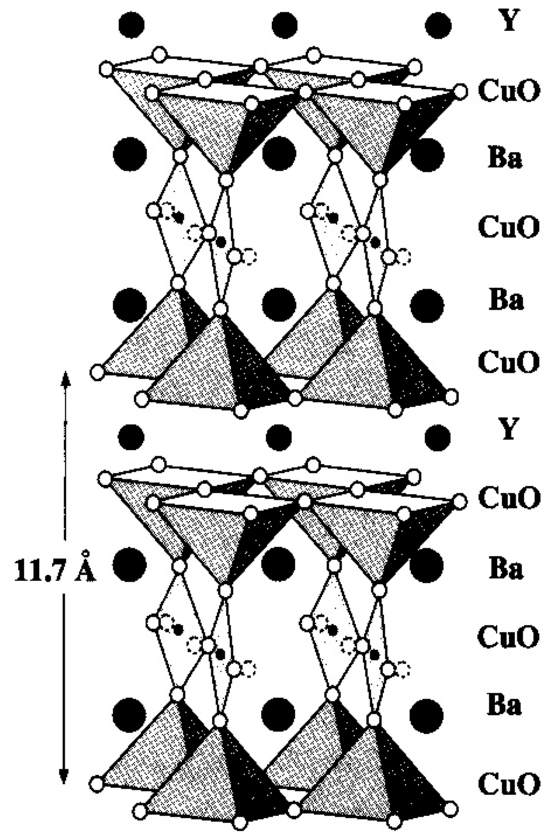


M. Cyrot and D. Pavuna, "Introduction to Superconductivity and High-T_c Materials," World Scientific Publishing Co, Ltd. (1992)

$(La,Sr)_2CuO_4$ and $YBa_2Cu_3O_7$



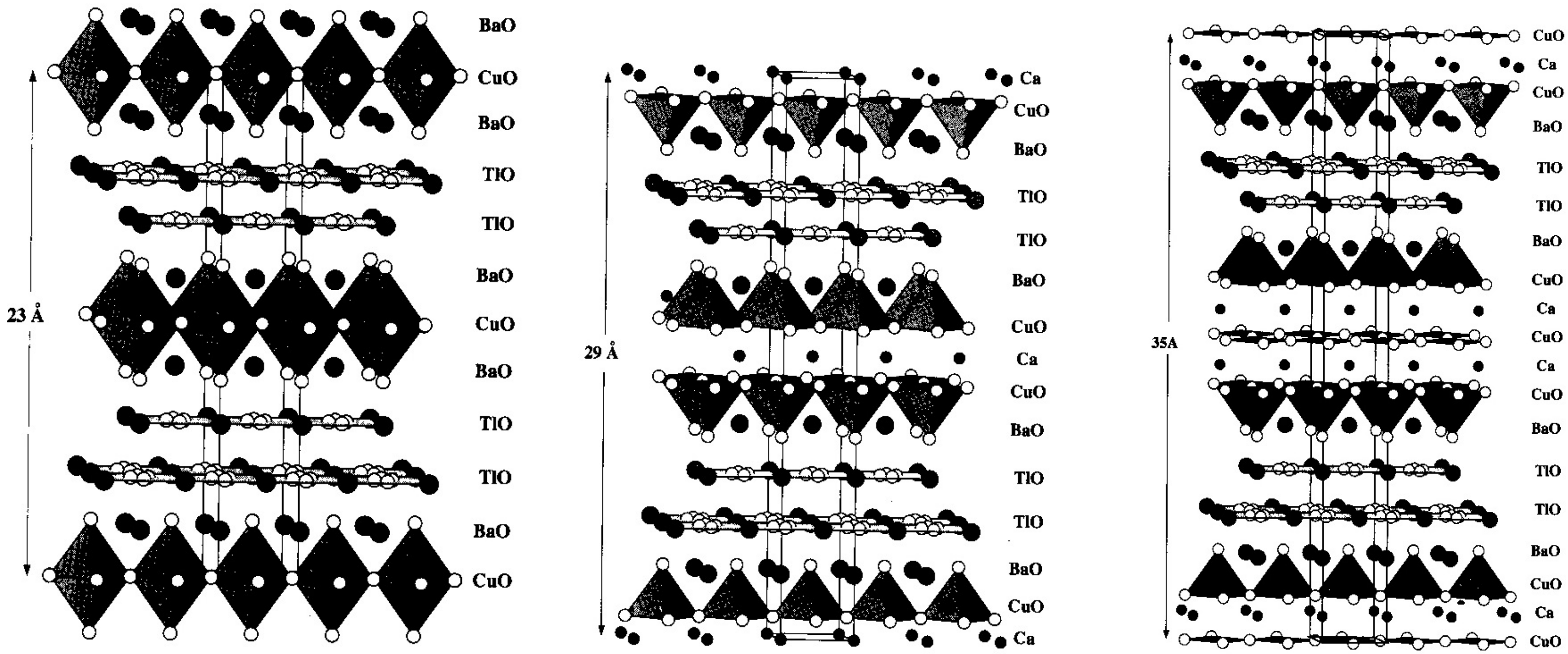
a) $(La,Sr)_2CuO_4$ T_c=38 K



b) $YBa_2Cu_3O_7$ T_c=92 K

M. Cyrot and D. Pavuna, "Introduction to Superconductivity and High-T_c Materials," World Scientific Publishing Co, Ltd. (1992)

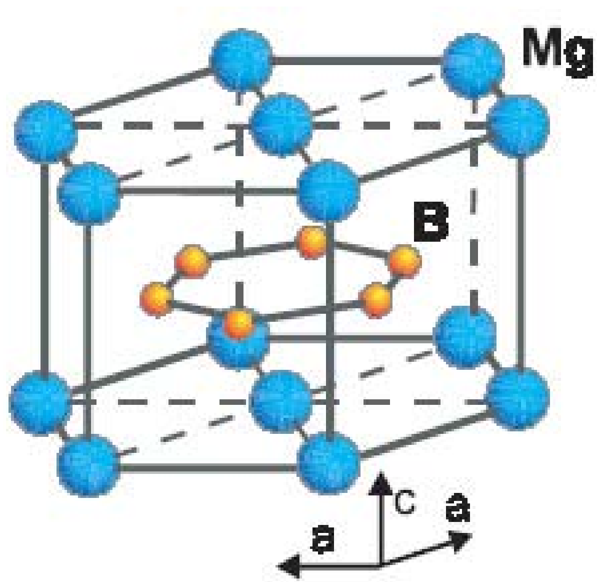
$Tl_2Ba_2Cu_1O_6$ (85K), $Tl_2Ca_1Ba_2Cu_2O_8$ (105K) and $Tl_2Ca_2Ba_2Cu_3O_{10}$ (125K)



c) $Tl_2Ba_2Cu_1O_6$ T_c=85 K   d) $Tl_2Ca_1Ba_2Cu_2O_8$ T_c=105 K   e) $Tl_2Ca_2Ba_2Cu_3O_{10}$ T_c=125 K

M. Cyrot and D. Pavuna, “Introduction to Superconductivity and High-T_c Materials,” World Scientific Publishing Co, Ltd. (1992)

Magnesium Diboride (MgB_2)



Graphite-type boron layers separated by hexagonal close-packed layers of magnesium

Superconductivity comes from the phonon-mediated Cooper pair production similar to the low-temperature superconductors except for the two-gap nature.

Compared to cuprates:

- Cheaper
- Lower anisotropy
- Larger coherence length
- Transparency of grain boundaries to current flows

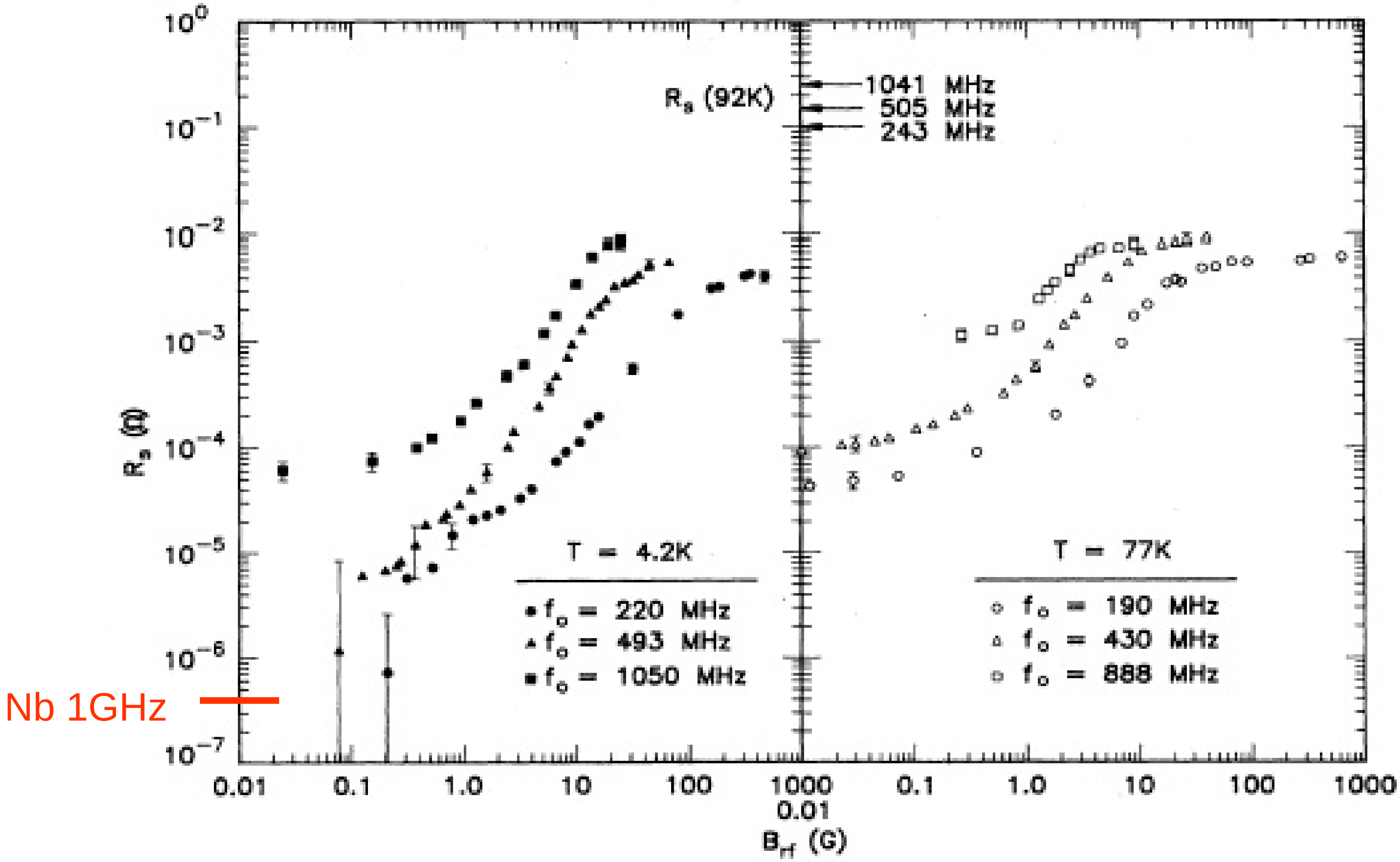
These makes MgB_2 attractive for applications.

C. Buzea and T. Yamashita, Superconductor Sci. Technol. 14 (2001) R115.

2. Properties of High-T_c materials that are related to the application to SRF cavities

- The RF surface resistance (R_s), which is proportional of $1/Q_0$, is the most important property for RF cavities.
- The other critical property is RF critical magnetic field ($H_{c, RF}$)
- Here, we focus on the R_s and its power dependence and will not discuss $H_{c, RF}$ since there is no data yet, to my knowledge.

R_s of YBCO shows rapid increase with H_{RF}

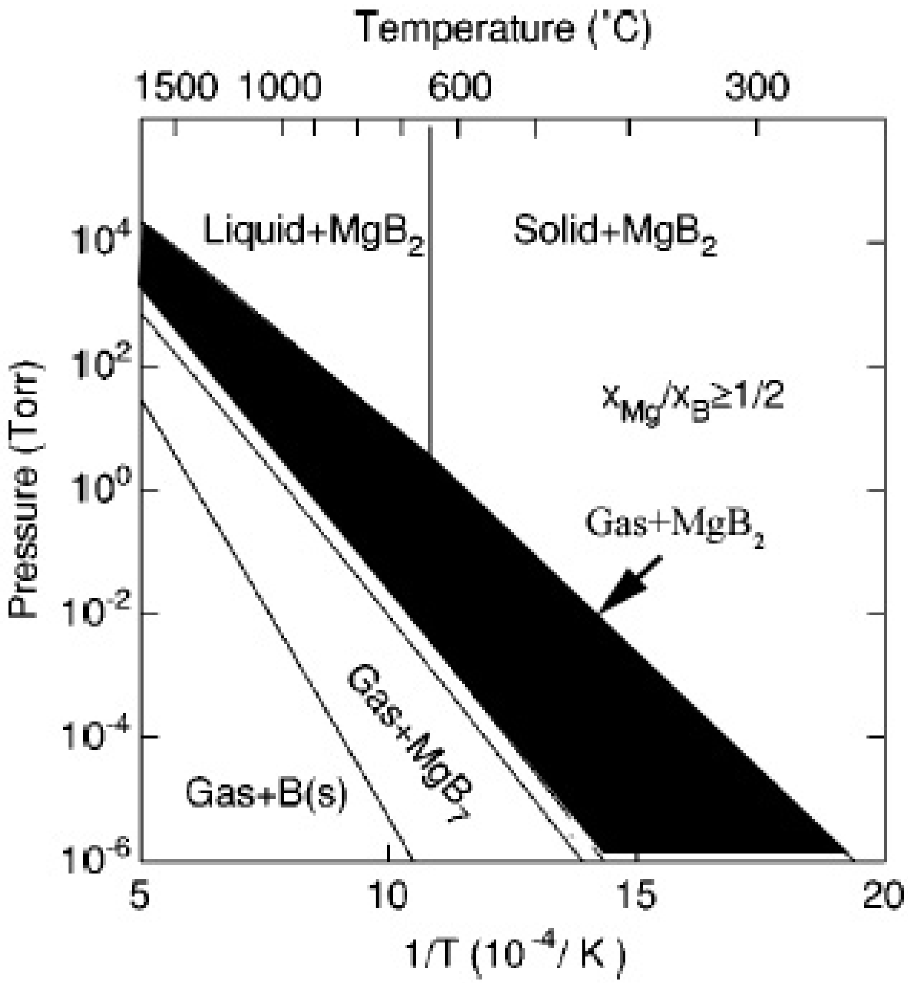


J.R. Delayen and C.L. Bohn, Phys. Rev. B40 (1989) 5151.

3. Developments in the past 2 years

- To my knowledge, no efforts to use YBCO or other cuprates for SRF cavities have been made.
- MgB_2 has shown in 2003 lower R_s than Nb at 4 K and about 10x lower predicted BCS R_s.
- A MgB_2 sample was tested up to H_{RF}~120 Oe, i.e. equivalent of E_{acc}~3 MV/m, with little increase in the R_s. (late 2004)
- Here, we focus on the development of MgB_2.

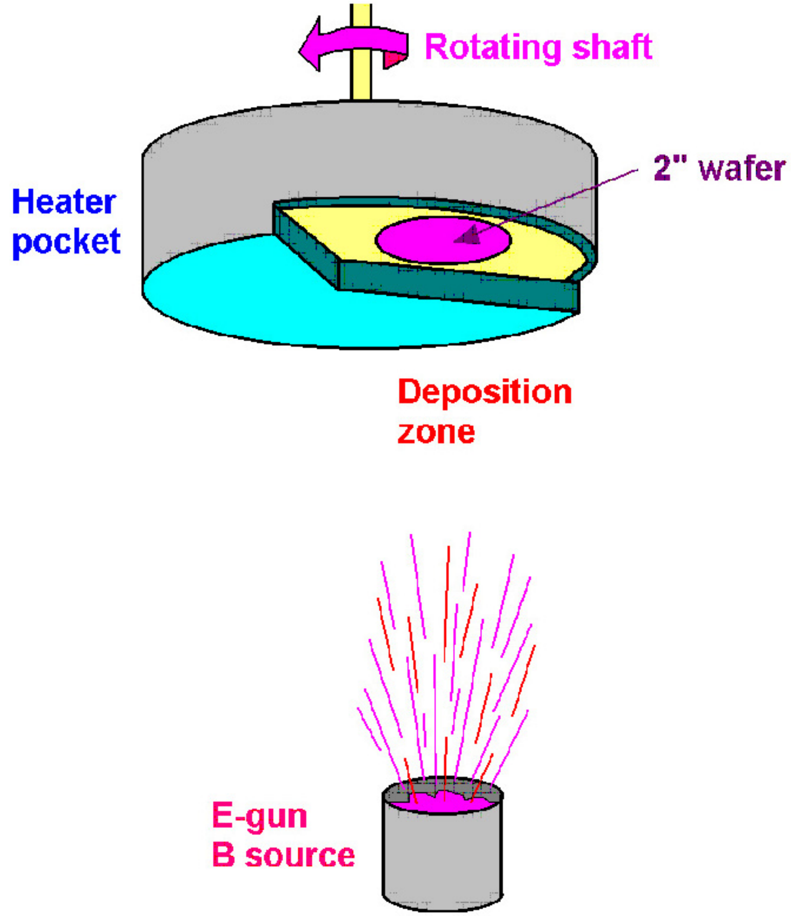
Simple binary compound, but needs high Mg pressure to form MgB_2 phase



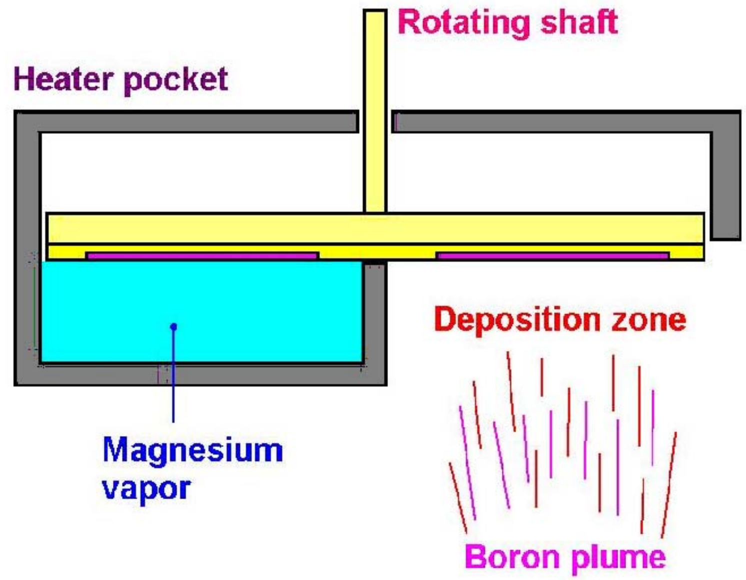
Pressure-temperature phase diagram for the Mg:B

Zi-Kui Liu et al., Appl. Phys. Lett. 78 3678 (2001).

MgB_2 Film Growth, an example at the Superconductor Technologies, Inc. (STI)



In-situ reactive evaporation

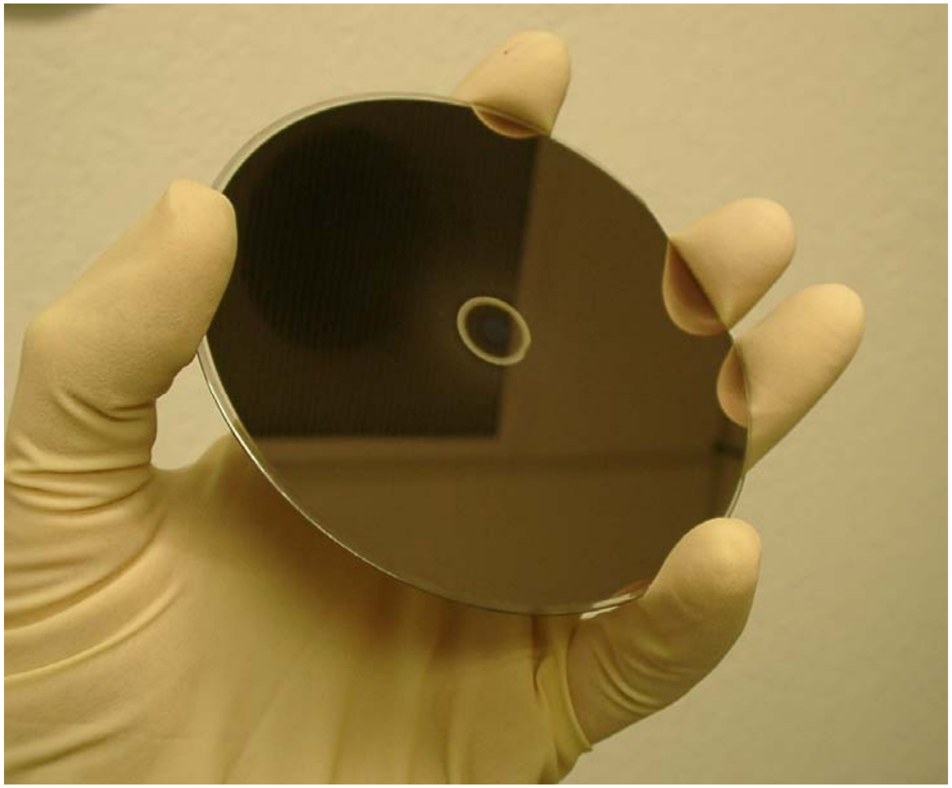


More details are found in
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al, Proc. PAC05.

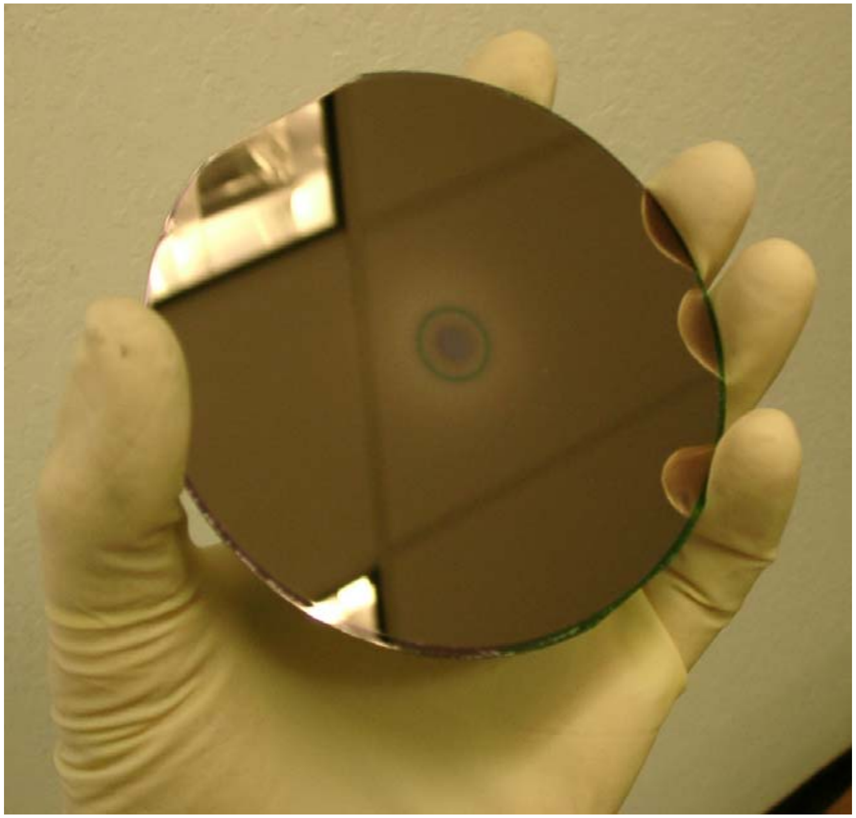
B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

MgB_2 on 4" substrates

R-plane sapphire



Si_3N_4 / Si



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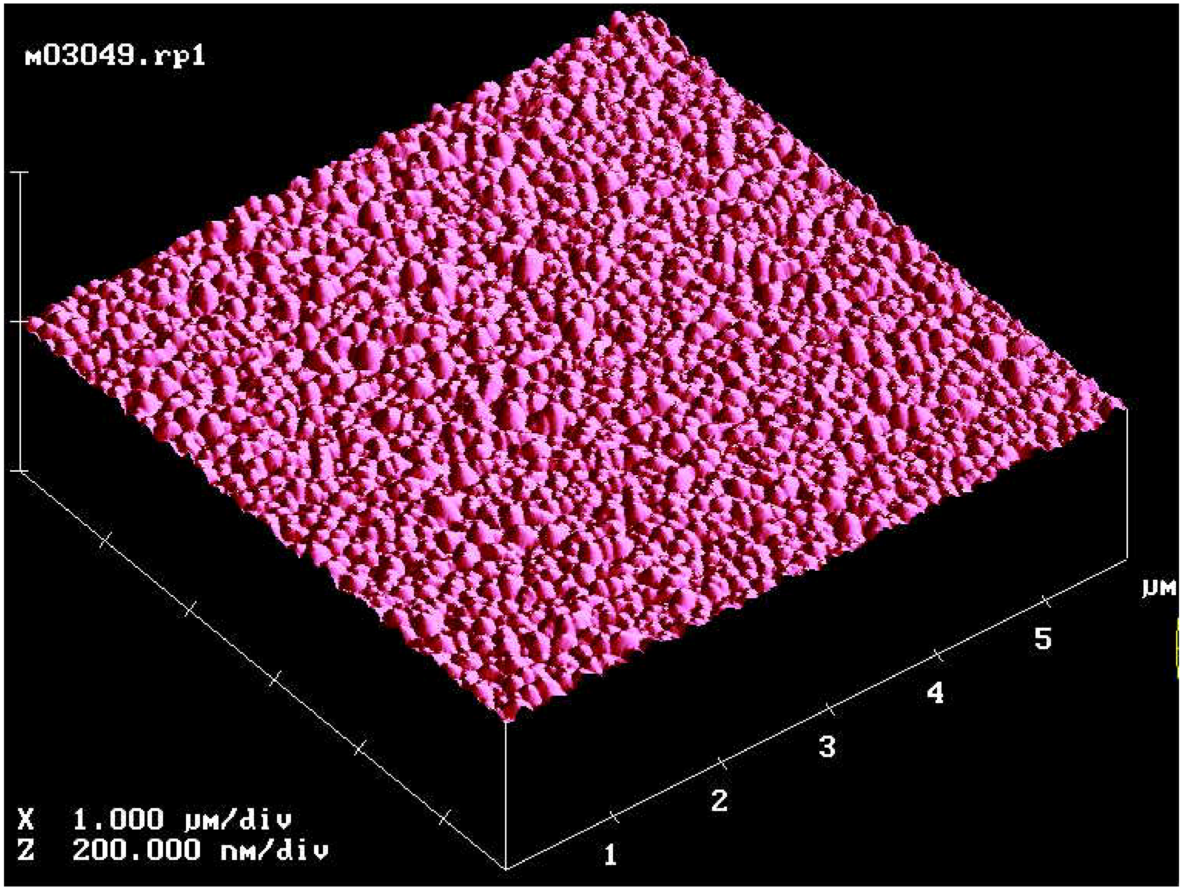
Surface morphology – MgB_2 on *r*-plane sapphire



- Typical surface on *r*-plane sapphire
- Growth T = 550 °C
- t = 5500 Å
- Small, conical grains
- ~1000 – 2000 Å diameter
- RMS roughness = 44 Å

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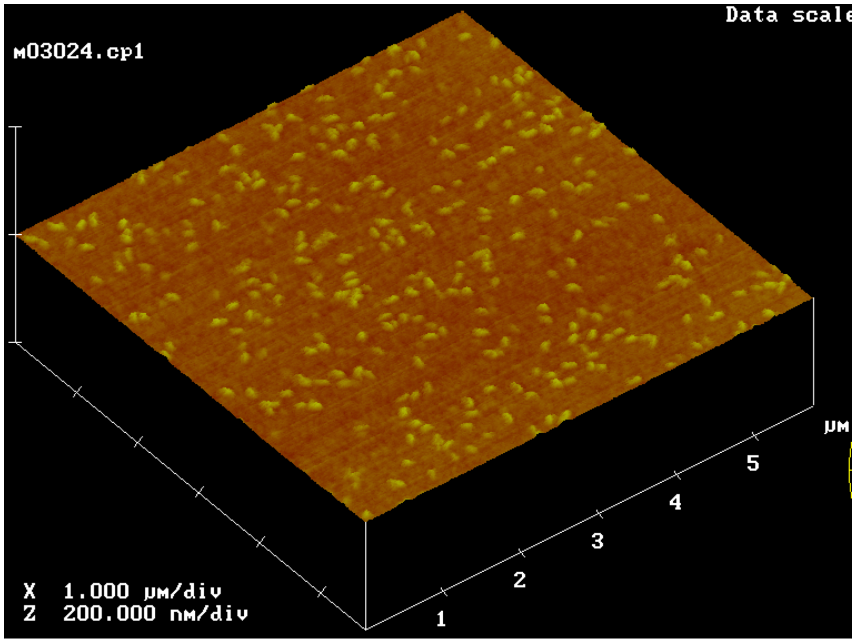
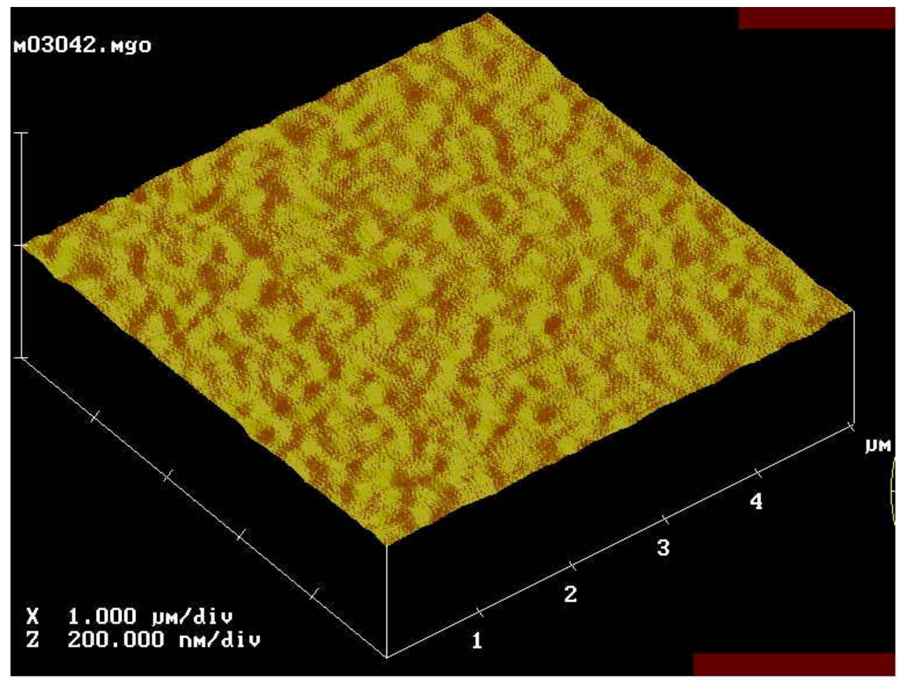
Surface morphology – smoother films



- MgB2 on sapphire
- Low *T* growth: 450 °C
- *t* = 1500 Å
- RMS roughness = 12 Å



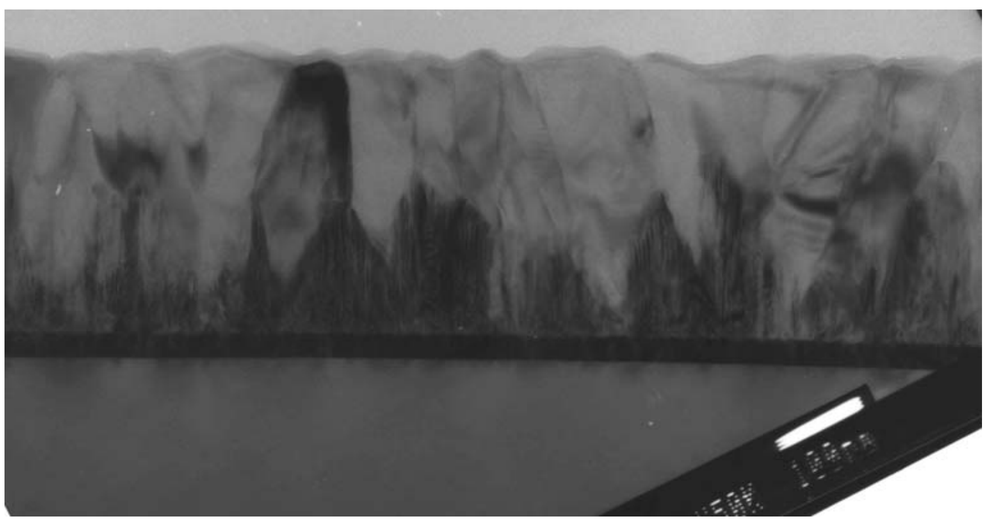
B.H. Moeckly, ONR Superconducting Electronics Program Review Red Bank, NJ, February 8, 2005

- MgB_2 on MgO
- Growth *T* = 550 °C
- *t* = 3000 Å
- RMS roughness = 22 Å

Microstructure – MgB_2 on *c*-plane sapphire

- Columnar growth
- Clear layer at interface
- Layer looks grown, not reacted

- Grain size ~100 nm
- Numerous threading defects in lower half
- Defects decrease with thickness



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Dave Smith

Stability – DI water soak

- Films etch very slowly in water
- Films also seem stable with time

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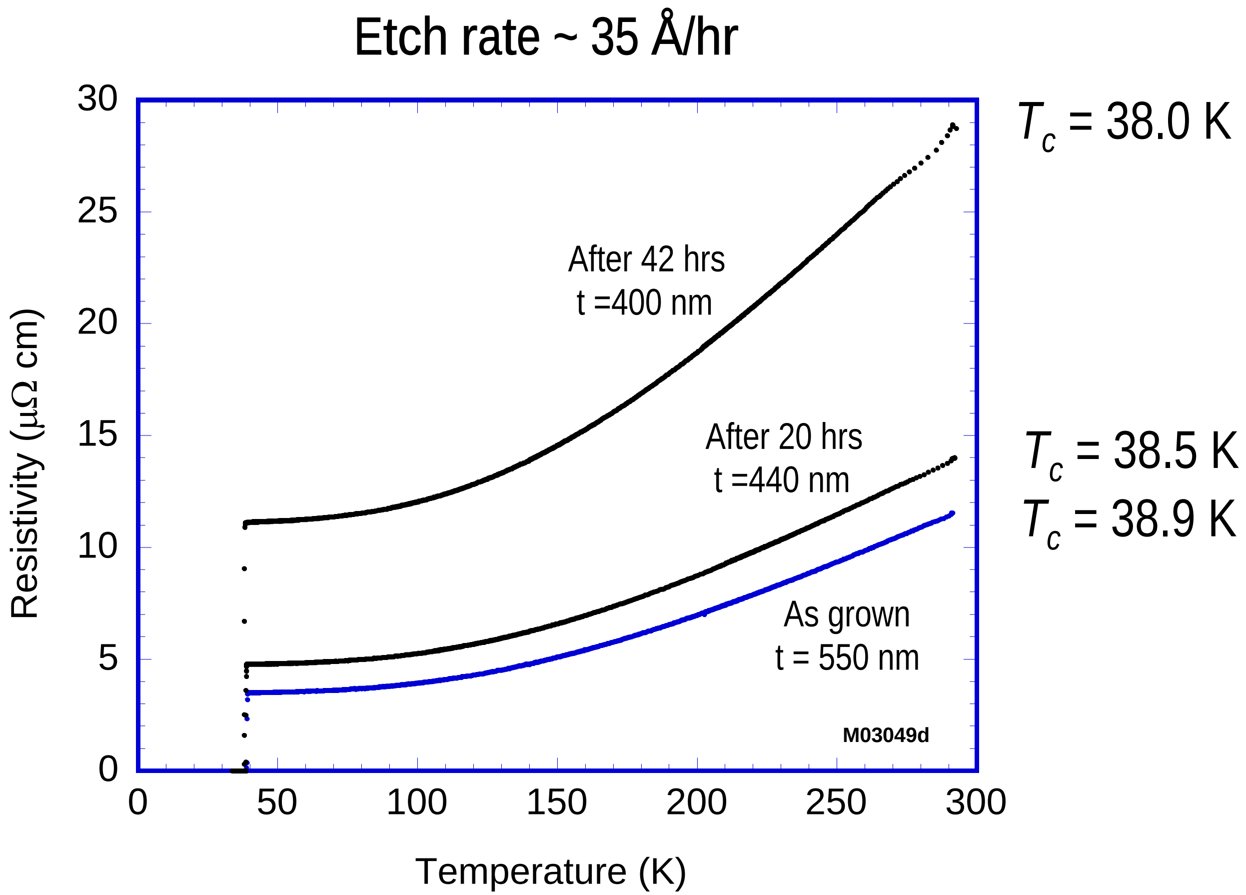
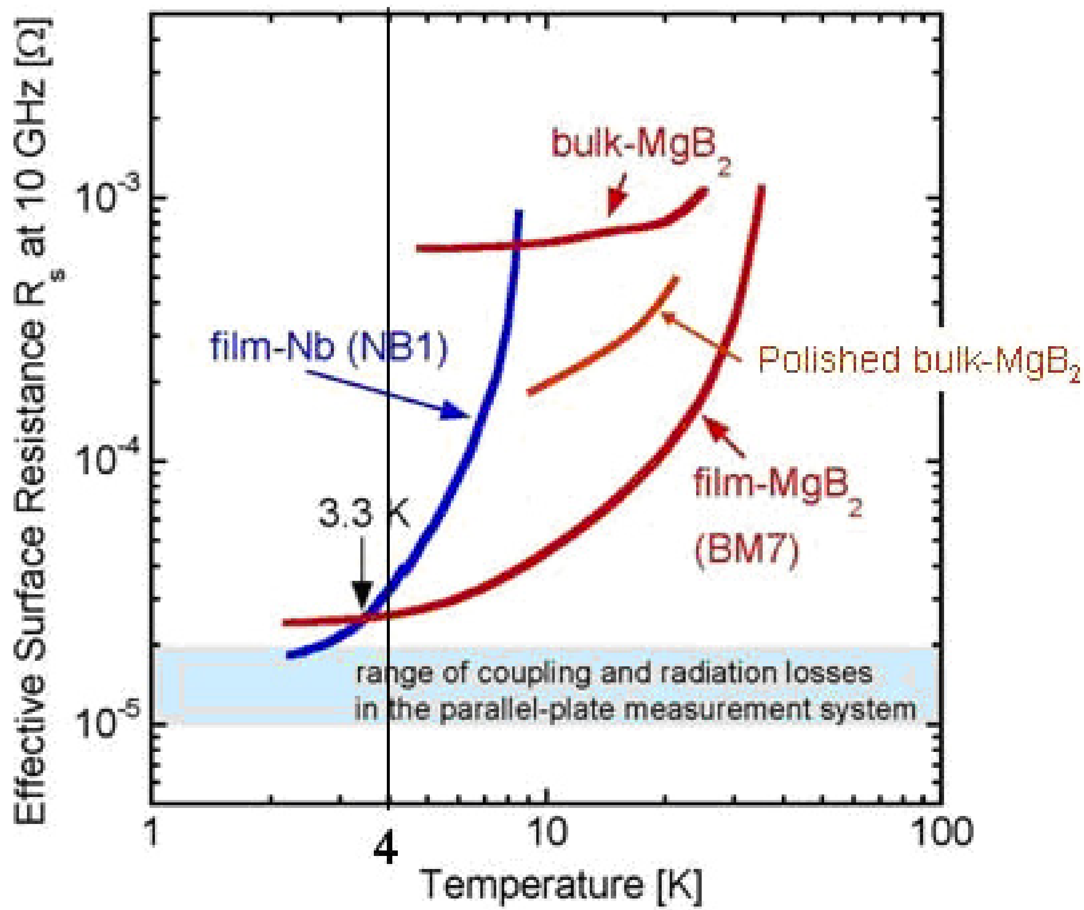


Latest films have shown R_s lower then Nb at 4 K.

Residual resistance still dominates at lower temperatures.

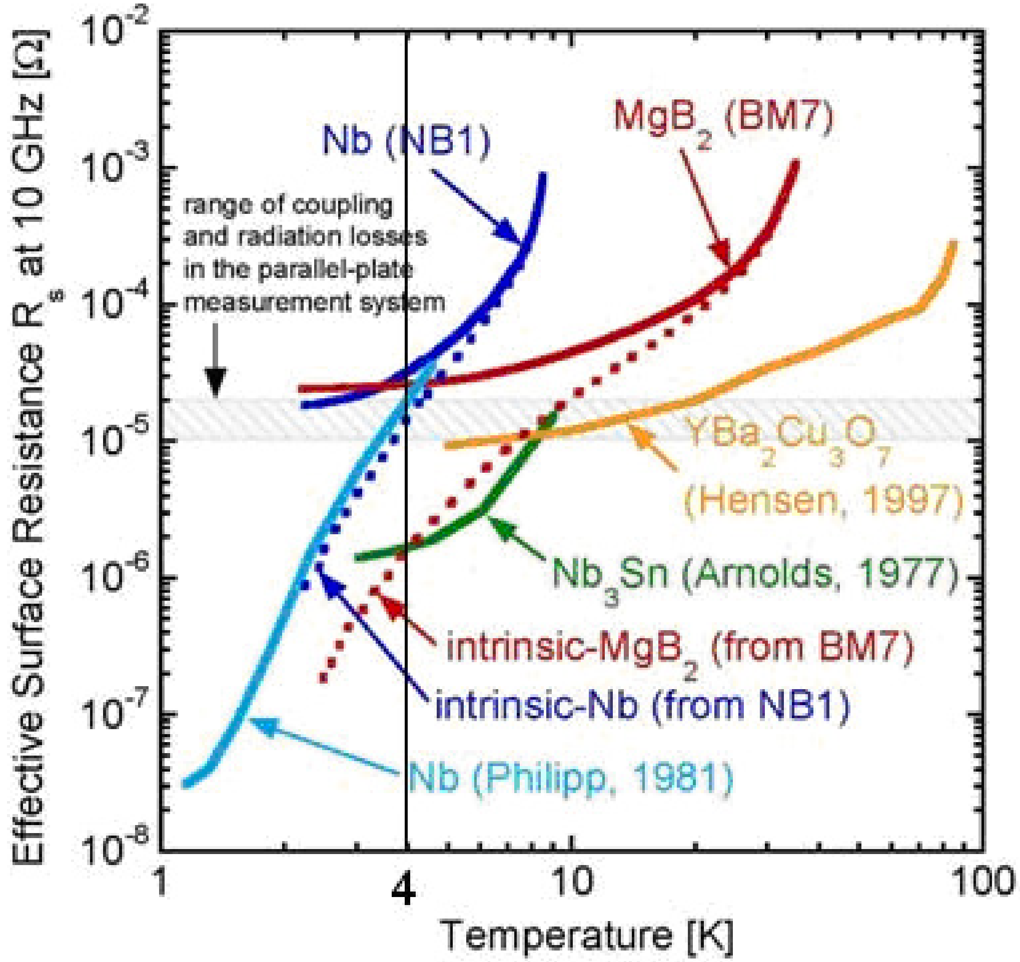
1 cm^2 sample on r-cut sapphire



A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al., Proc. PAC05.

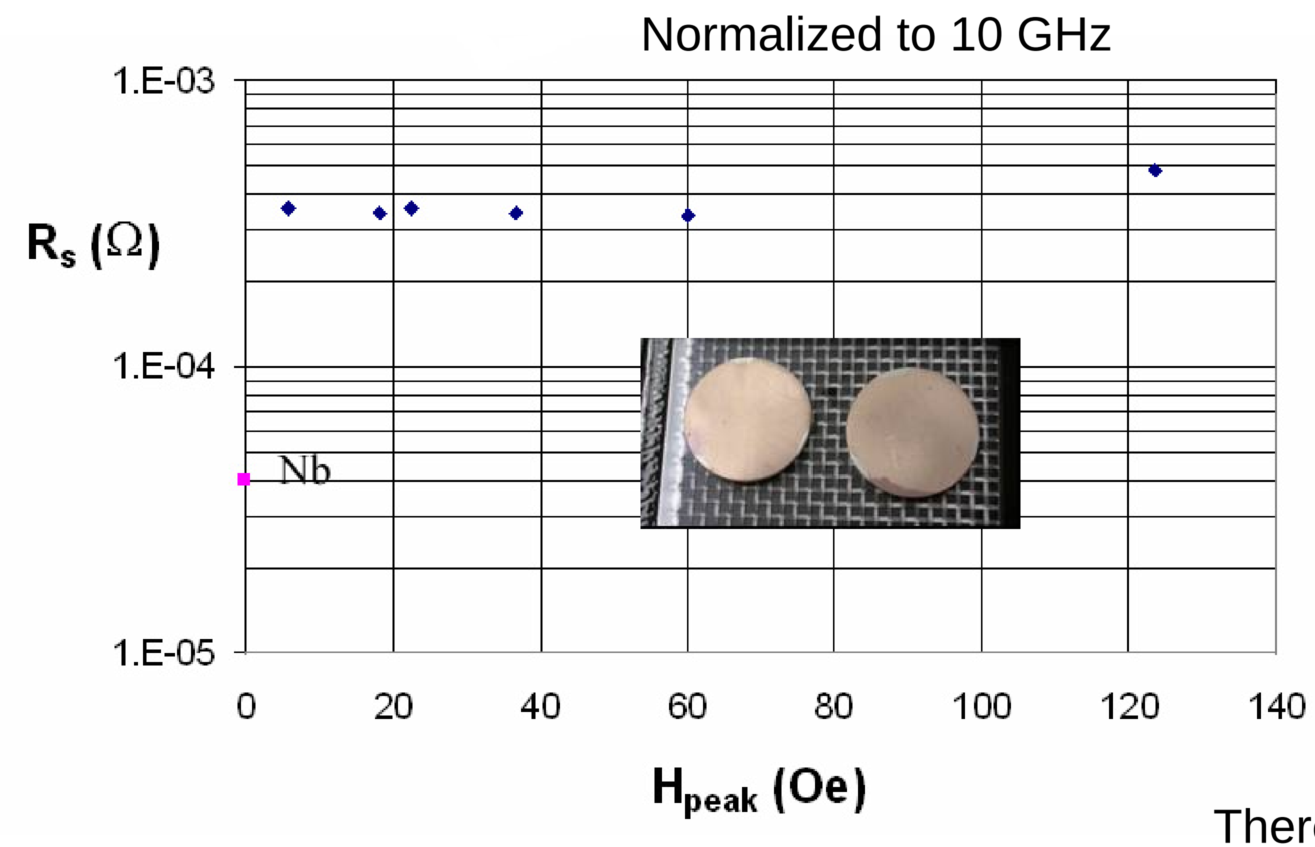
Predicted BCS R_s is ~1/10 of Nb

Dotted lines are predicted BCS resistance.



A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.

R_s does not change much with H_{RF}.



Measurement at Cornell with TE_{011} Nb cavity at 4.2 K.

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

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

The highest H was limited by available power.

There was only one test and the result needs to be confirmed with others.

Summary

- It is important for the SRF community to continue looking for high-T_c materials that can be applied to SRF cavities.
- YBCO and other cuprates show rapid increase of R_s with H_{RF}, preventing the use of cuprates for SRF cavities.
- MgB_2 is more complicated than Nb but less complicated and cheaper than YBCO and other higher-T_c materials and could potentially lead to significant cost reduction.
- Critical parameters such as R_s power dependence and critical H_{RF} need to be determined.
- Making a MgB_2-coated cavity might be easier than you think. Let's try to coat/make a cavity with MgB_2 and measure the performance.

Thanks for the data and/or discussions and collaborations!

A. Findikoglu, A. Jason, F. Krawczyk, F. Mueller, A. Shapiro (LANL)

H. Padamsee, A. Romanenko, R. Geng (Cornell)

J. Delayen, G. Wu, L. Phillips, A-M, Valente (JLab)

B. Moeckly (STI)

J. Price (NSWCCD)

H. Abe (NIMS, Japan)

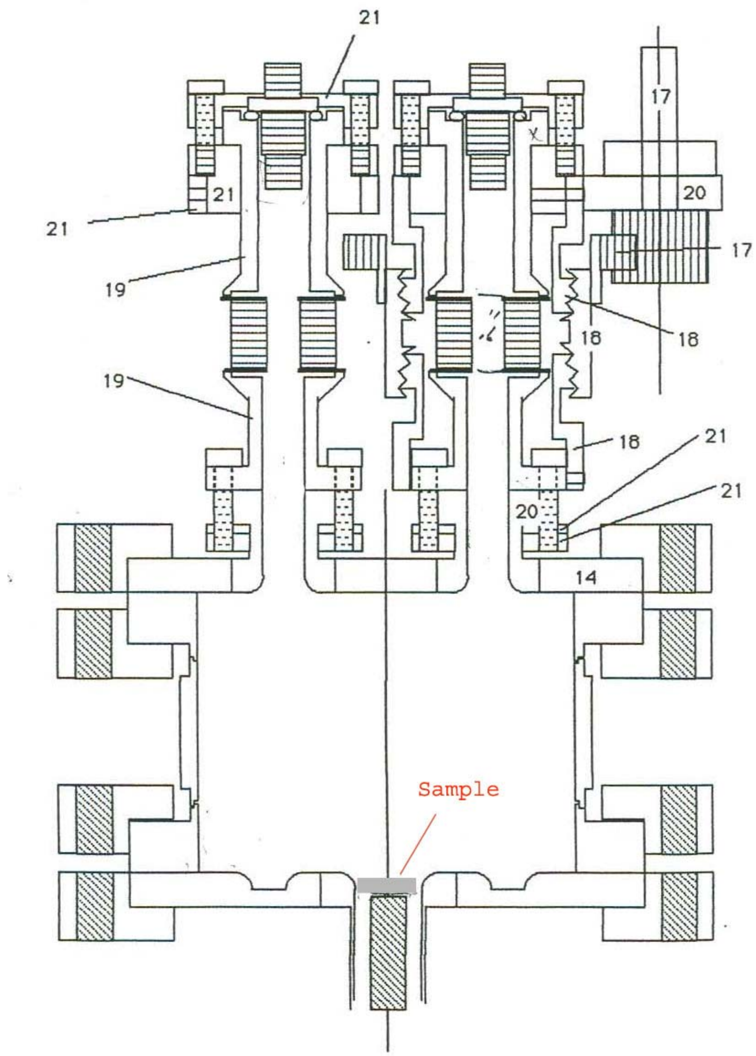
Y. Zhao (Univ. Wollongong, Australia)

J. Liu (SINAP, China, formerly at LANL)

D. Oates (MIT, Lincoln Lab.)

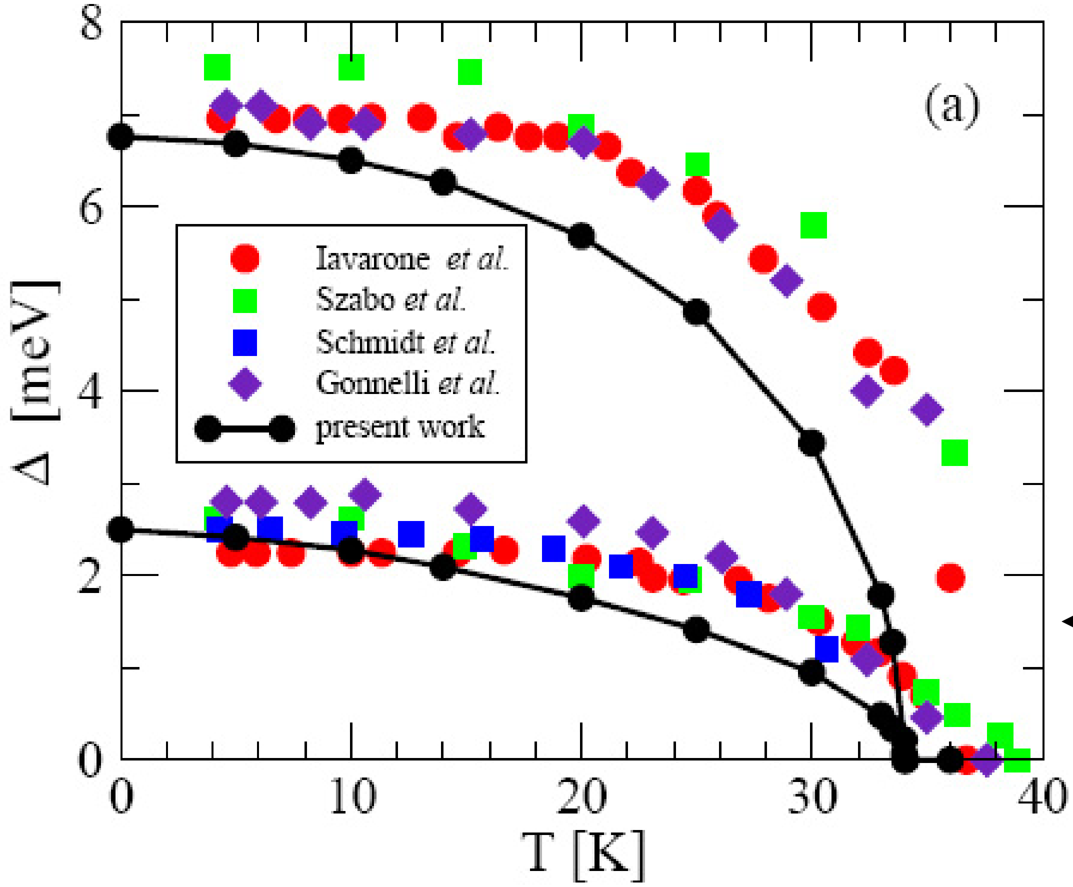
Backup Slides

Tests at Cornell with 6-GHz Nb TE_{011} Cavity



Measurement by Alexander Romanenko, Hasan Padamsee

MgB_2 has two energy gaps



RF response has shown lower energy gap behavior.

← Nb

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