Review of RF properties of NbN and MgB_2 thin coating on Nb samples and cavities

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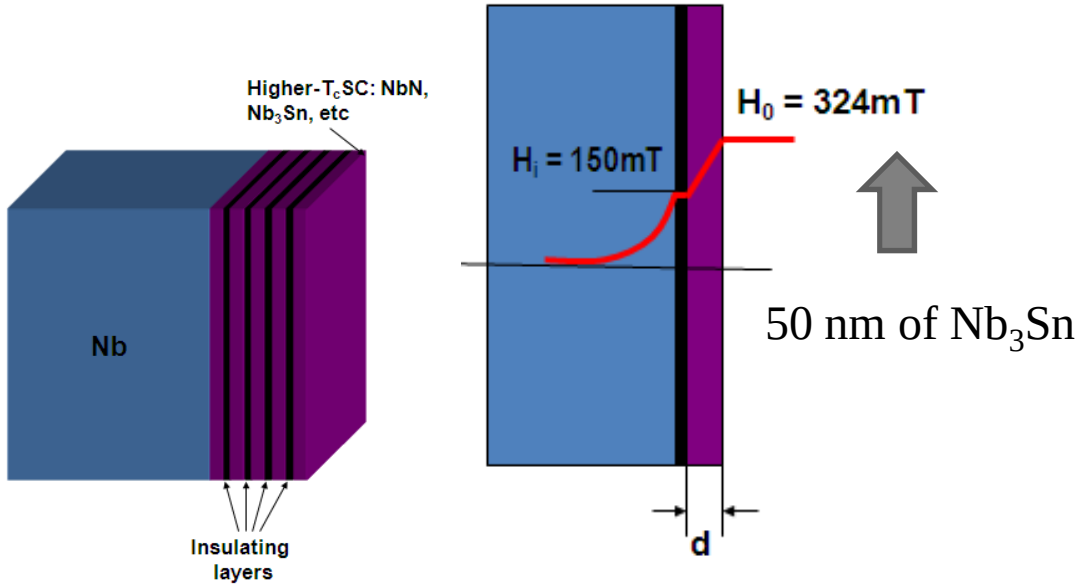
Motivation: Gurevich's idea of enhancing RF breakdown field by coating thin (d < λ_L) superconductor layers in 2005

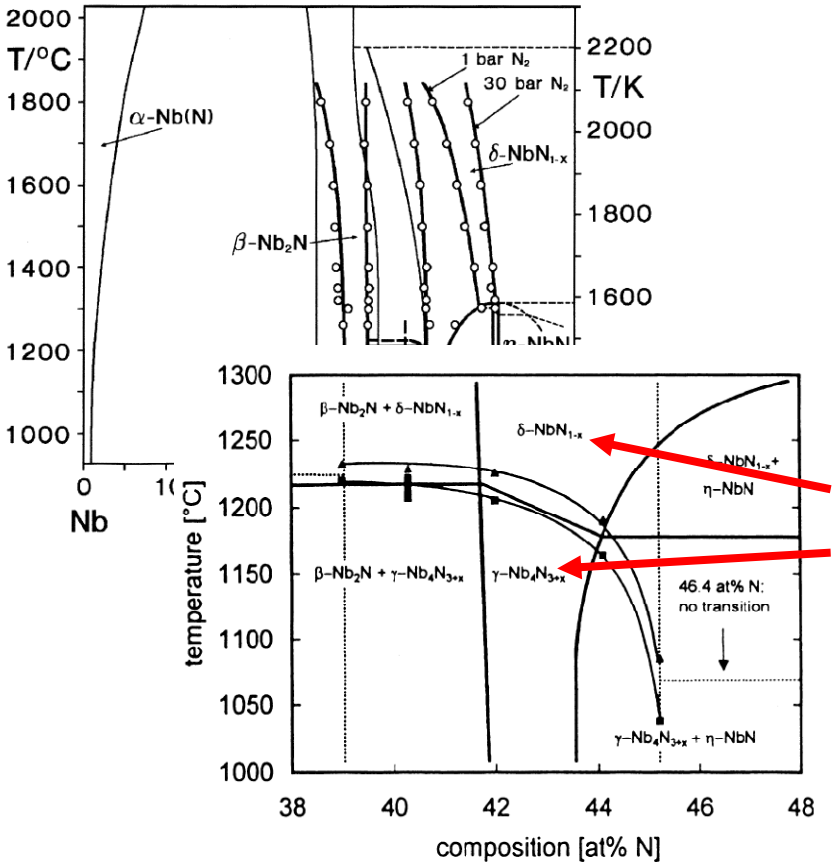
Increase of B_{c1} in parallel with the magnetic field like in the cavity

$$\mu_0 H_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\xi}, \qquad d < \lambda$$



A. Gurevich, Appl. Phys. Lett. **88 (2006) 012511.**

Niobium nitride (NbN) phases



Different nitrides are present in the Nb–N system: β-Nb_2N (hexagonal), γ-$Nb_4N_{3\pm x}$ (tetragonal), δ-NbN_{1-x} (fcc), η-NbN (hexagonal), δ'-NbN (hexagonal) and other N-rich phases (Nb_5N_6, Nb_4N_5). In addition, nitrogen dissolves in the metal forming α-Nb(N) solid solution (bcc).

δ – NbN → T_c ~ 15 – 17.3 K

γ – NbN → T_c ~ 12 – 15 K

RF cavity studies mostly focus on δ phase.

Two ways of deposition:

Sputtering of Nb in Ar/N_2 atmosphere;

Annealing in N rich enviroment(N_2 or NH_3)

W. Lengauer et al., *Acta*

V. Buscaglia et al., *J. Alloys Compd.* ***266 (1998), p. 201.***

R_s of NbN

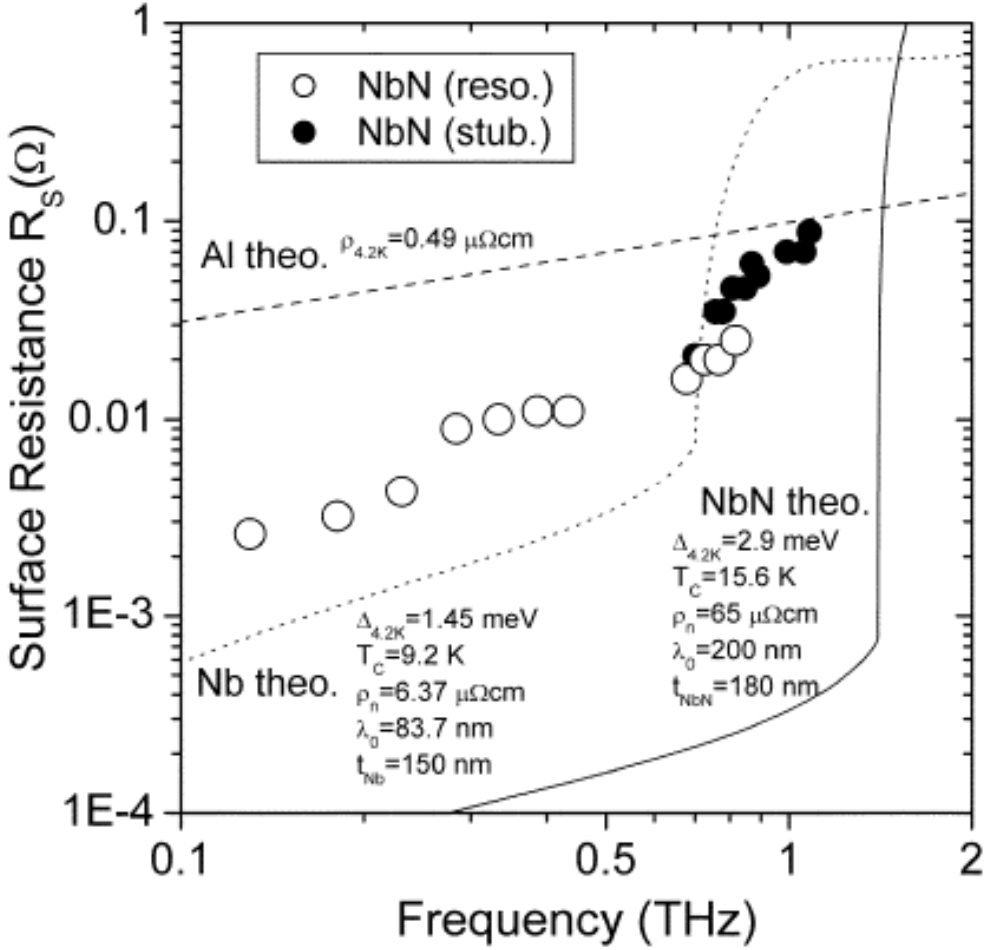
Thin films coatings are typically done either by sputtering Nb or by annealing niobium in N_2 rich atmosphere.

Main focus on higher-T_c δ phase NbN.

Typically, thin films have a relatively high normal-conducting resistivity and low RRR.

60 μΩ cm and RRR ~ 1 is reported for single-crystal niobium nitride film.

Theoretically, an order of magnitude lower resistance than Nb.



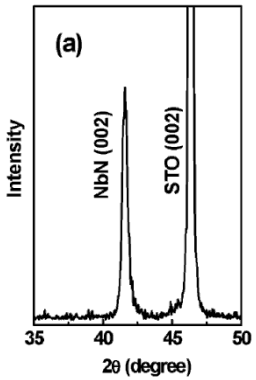
A. Kawakami et al., *IEEE Trans. Appl. Supercond.,Vol.13, pp. 1147-1150, (2003)*

Z. Wang et al., J. Appl. Phys. **79, 7837 (1996)**

LANL's effort of coating NbN using Polymer Assisted Deposition (PAD) technique

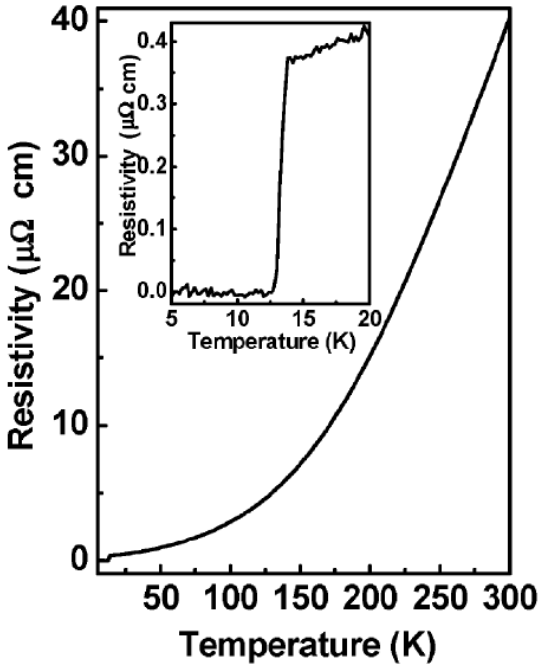
High-quality epitaxial films grown by PAD: an aqueous solution of niobium ion bound to polymer spin coated on substrate, and then annealed at 900 °C for 5 hours in gaseous ammonium.

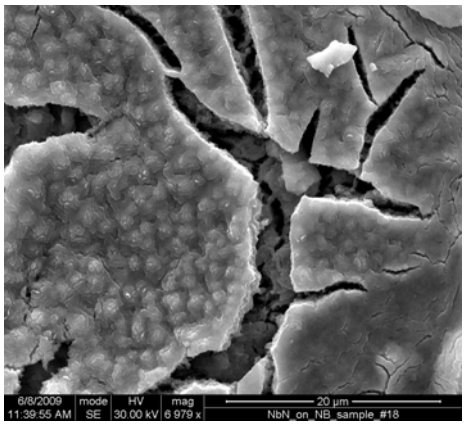
LANL: First attempts to deposit on polycrystalline niobium – unsuccessful, working with single-crystal Nb now

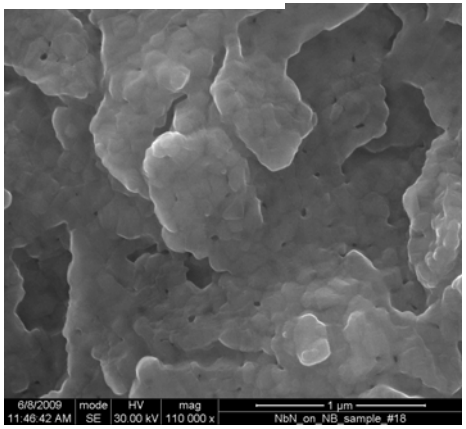


Unusually high RRR = 98.4 and low $\rho_{20} \approx 0.4\ \mu\Omega$ cm

$T_c \approx 14$ K (γ – NbN)

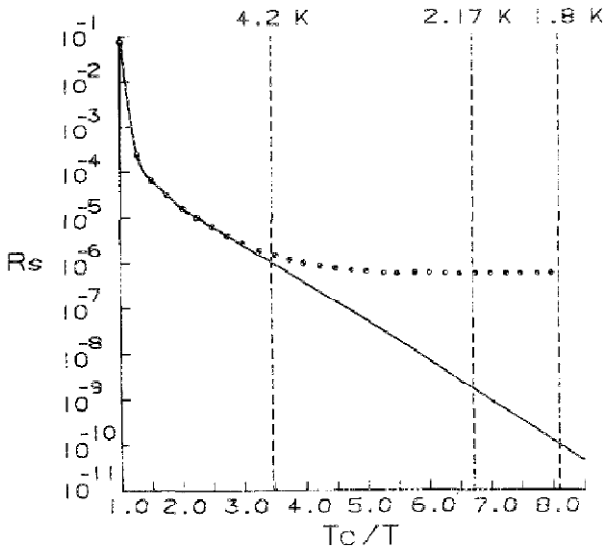






Guifu Zou et al., Chem. Commun., 2008, 6022–6024

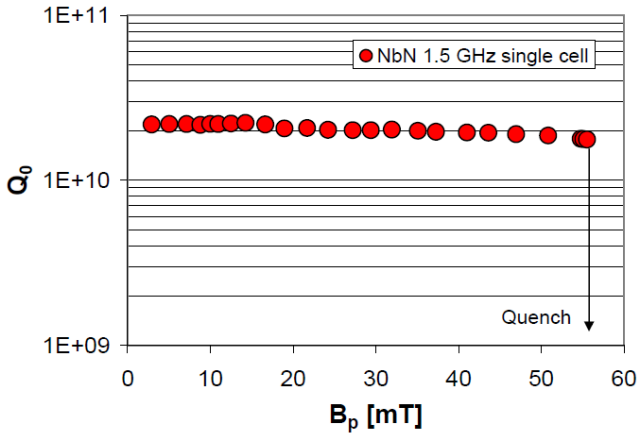
NbN work at other labs



At 4.2 K, R_s^{NbN} lower than R_s^{Nb} has been reported in 4.5 GHz cavity. But the coating had high residual resistance.

NbN work also is being done:

- at JLab on developing a superconducting connection between adjacent niobium cavities with the capability to carry up to 30 mT of the magnetic flux;
- at IHEP to improve Nb sputtered films;
- ideas at different labs to use ALD…



J. Hao et al., *Physica C* ***450 (2006), p. 101***

P. Kneisel et al., in Proc. of PAC 2007, (2007)

P. Fabbricatore et al., J. Appl. Phys. **66, 5944 (1989)**

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Nb compounds investigation studies at JLab and surrounding Universities (W&M, ODU, NSU)

NbTiN, NbN coatings with Reactive DC sputtering and High Power Pulse Magnetron Sputtering in self-sputtering mode & MgO coating with RF sputtering

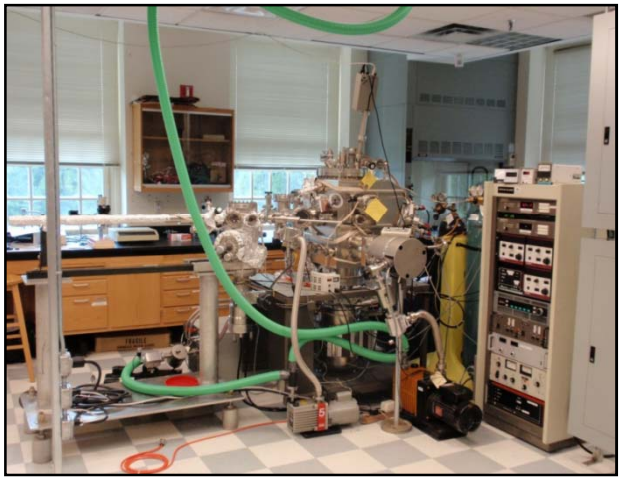
New UHV Multi-technique deposition system under commissioning @ JLab

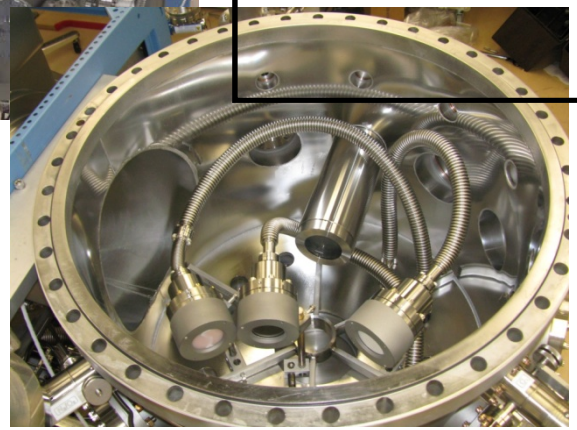
Nucleation studies in collaboration with Prof. A. Lukaszew (College William & Mary)

In-situ observation of the nucleation and subsequent growth with coating parameters, annealing… in homo-epitaxy and hetero-epitaxy on single crystal and polycrystalline substrates.

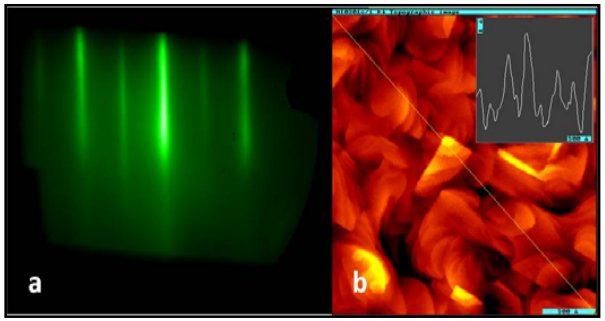
Film growth approach in 3 sequential phases:

- ✓ Film nucleation on the substrate (NbN, NbTiN/MgO and MgO/NbN, NbTiN
- ✓ Growth of an appropriate template for subsequent deposition of the final rf surface
- ✓ Deposition of the final surface optimized for minimum defect density.





UHV system with in-situ RHEED & STM

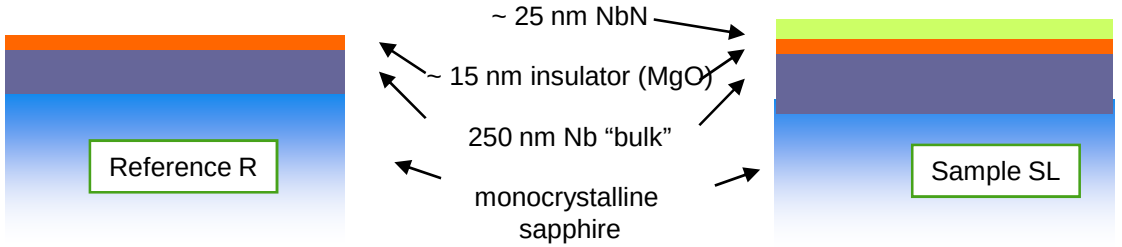


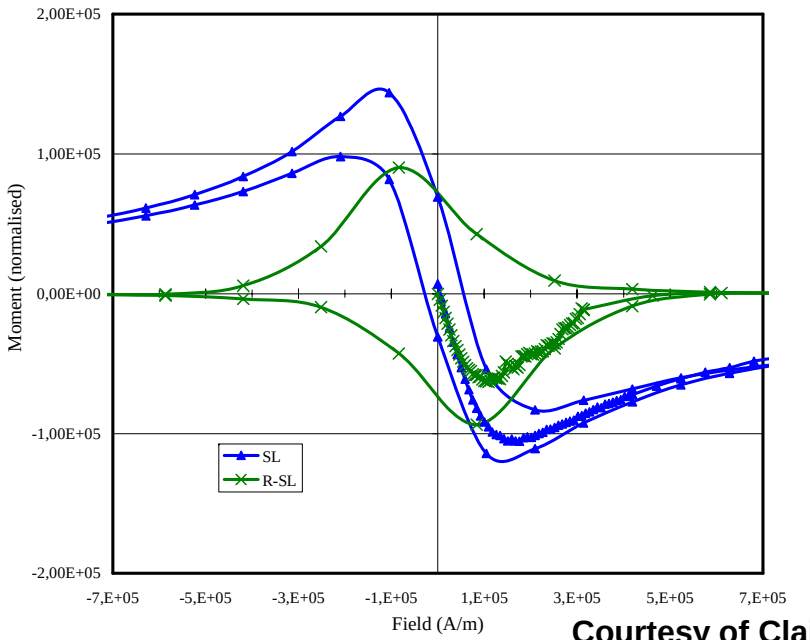
Old Dominion University

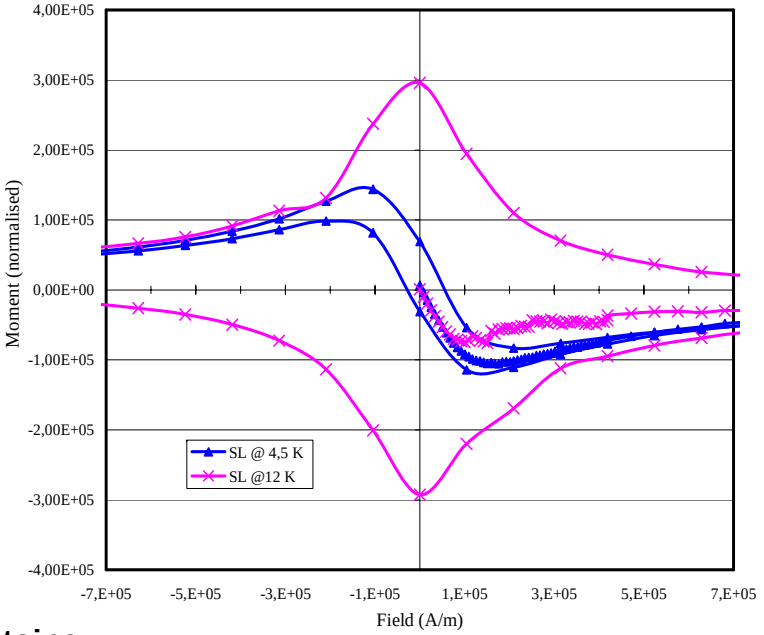
NSU Norfolk State University

Nanometric layers I/S/I/ on Nb

- Screening effect experimentally demonstrated for the **1st time** on a model sample
- Collaboration with J.C. Villégier, CEA-Inac / Grenoble
  - Asserted techniques used for superconducting electronics (Josephson Junctions)
- *(H // sample surface.; longitudinal moment)*
- Area of the hysteresis is proportional to the vortices' number trapped inside the material
- Dramatic change in behavior : vortice penetration is prevented in the composite structure NbN / Nb compare to Nb or NbN alones !







Courtesy of Claire Antoine

For more details see the poster TUPPO 070

Magnesium Diboride (MgB_2)

A variety of thin film process have been tried to grow MgB_2 thin films, e.g., hybrid physical–chemical vapor deposition (HPCVD), molecular beam epitaxy (MBE), reactive evaporation, ultra high vacuum–molecular beam epitaxy (UHV–MBE), electron beam evaporation (EBE), ultra high vacuum–electron beam evaporation (UHV–EBE) and pulsed laser deposition (PLD).

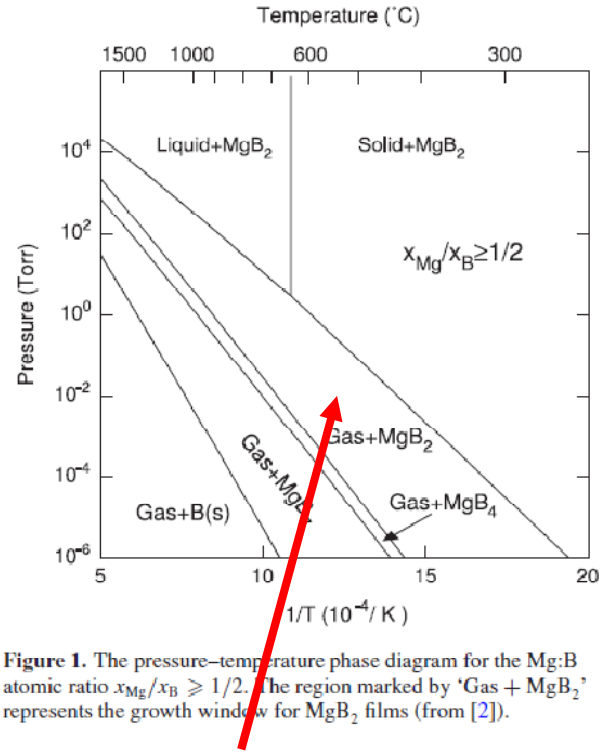


Figure 1. The pressure–temperature phase diagram for the Mg:B atomic ratio $x_{Mg}/x_B \geqslant 1/2$. The region marked by 'Gas + MgB_2' represents the growth window for MgB_2 films (from [2]).

RRR ~ 8 – 100

ρ_{40} ~ 0.1 – 2 μΩ cm

X.X.Xi, Supercond. Sci. Technol. **22 (2009) 043001.**
S.C.Park et al., **Physica C 469, Issues 15-20 (2009) pp. 1574-1577**
X.X. Xi et al., *Physica C* ***456 (2007), p. 22.***
Y. Harada et al., *Physica C* ***426–431 (2005), p. 1453.***
B.H. Moeckly and W.S. Ruby, *Supercond. Sci. Technol.* ***19 (2006), p. L21.***
Y. Harada et al., *Physica C* ***412–414 (2004), p. 1383.***
S. Yata et al., *Physica C* ***388–389 (2003), p. 155.***
H.M. Zhu et al., *Physica C* ***452 (2007), p. 11.***
W.N. Kang et al., *Science* ***292 (2001), p. 1521.***
Y.S. Wu et al., *Physica C* ***468 (2008), p. 218.***

MgB_2 deposition with reactive evaporation

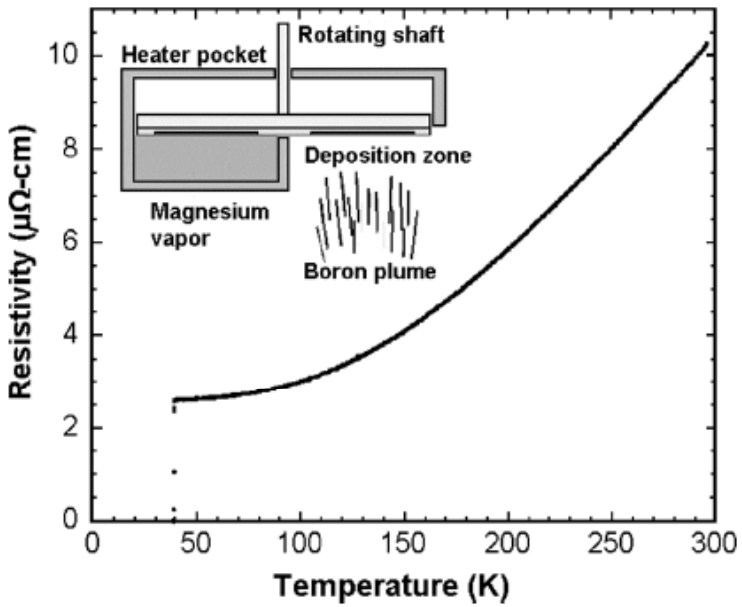


Fig. 1. $R - T$ curve of a 500-nm-thick MgB_2 thin film deposited onto r-plane sapphire. The T_c is 39.1 K. Note the low room-temperature resistivity and residual resistivity. The pocket heater used for the reactive evaporation process is shown in the inset.

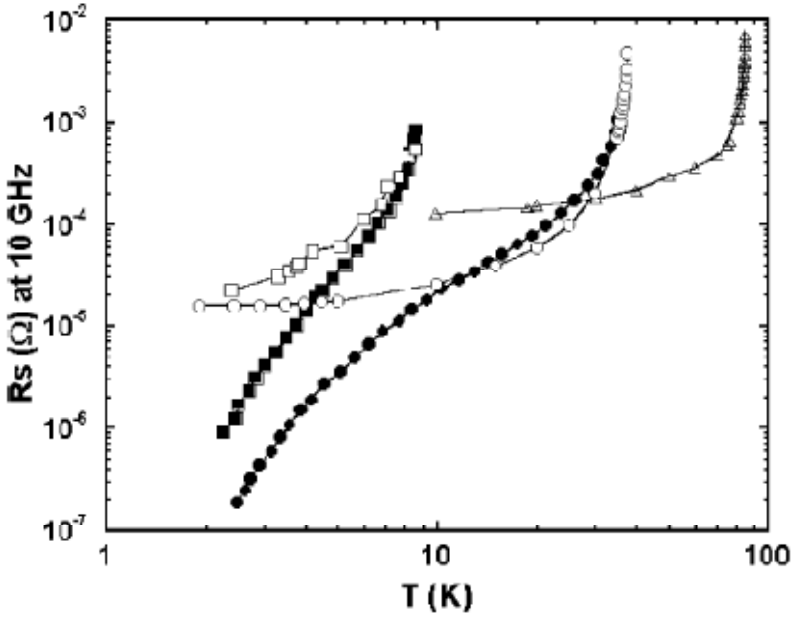


Fig. 3. R_s vs. T scaled to 10 GHz for our MgB_2 films on sapphire (○), a YBCO film on LAO (△), and for Nb thin films (□). Filled symbols indicate parallel plate measurements with external losses subtracted, and open symbols indicate stripline resonator measurements including external losses.

Brian H. Moeckly et al., IEEE Tran. Appl. Supercond., Vol. 15, No. 2, (2005) pp. 3308-3312

MgB_2 deposition with Hybrid Physical Chemical Vapor Deposition (HPCVD)

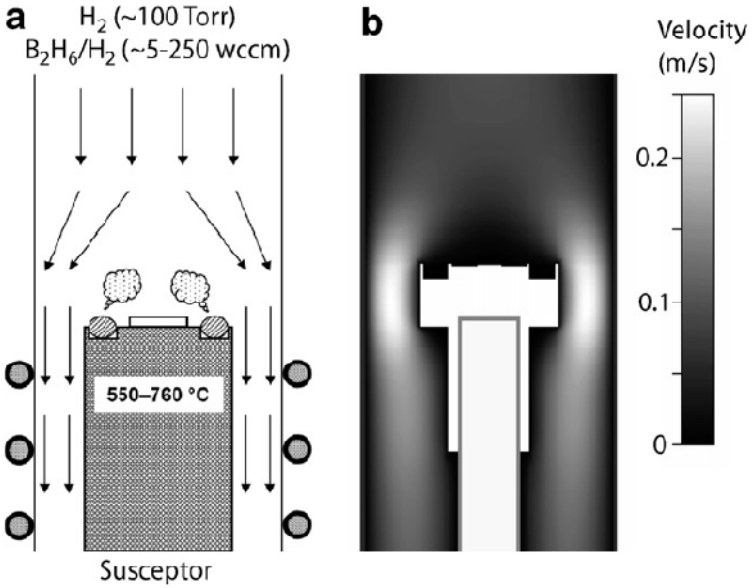


Fig. 2. (a) Schematic of the HPCVD system. (b) Calculated gas velocity profile in the reactor near the susceptor (from Ref. [54]).

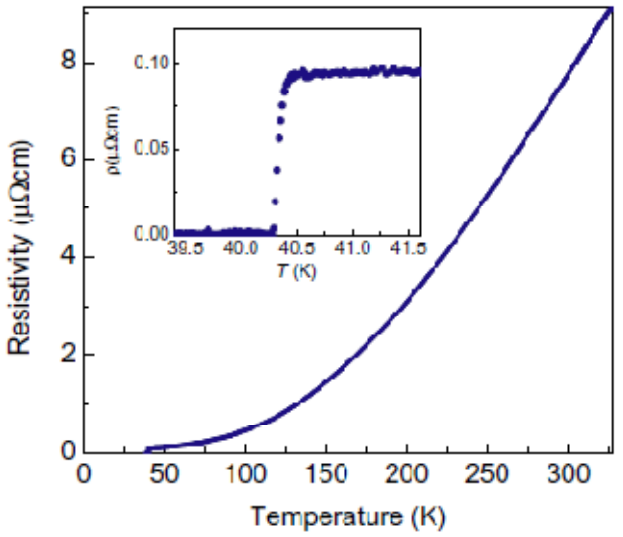


Fig. 4. Resistivity vs temperature curve for a 7700 Å MgB_2 thin film on sapphire substrate. The inset shows details near the superconducting transition.

X.X.Xi, Physica C 456 (2007) 22–37.

MgB_2: R_s vs. magnetic field

RF measurement @ Cornell University

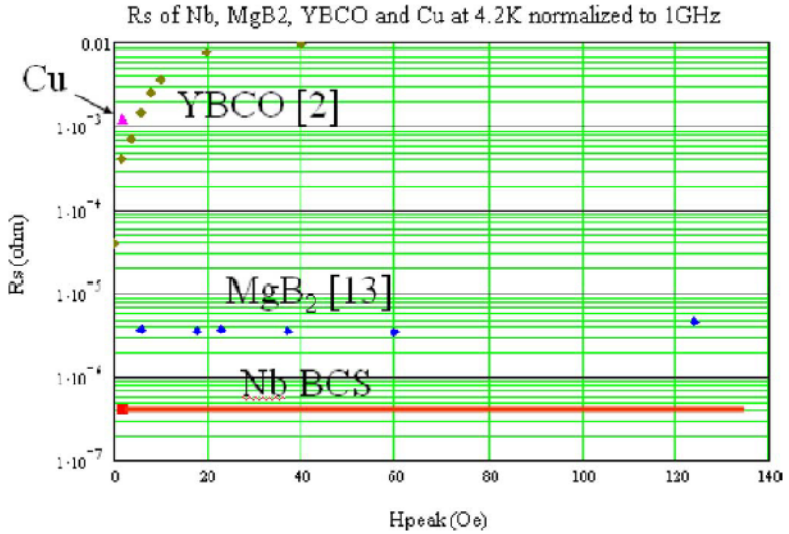
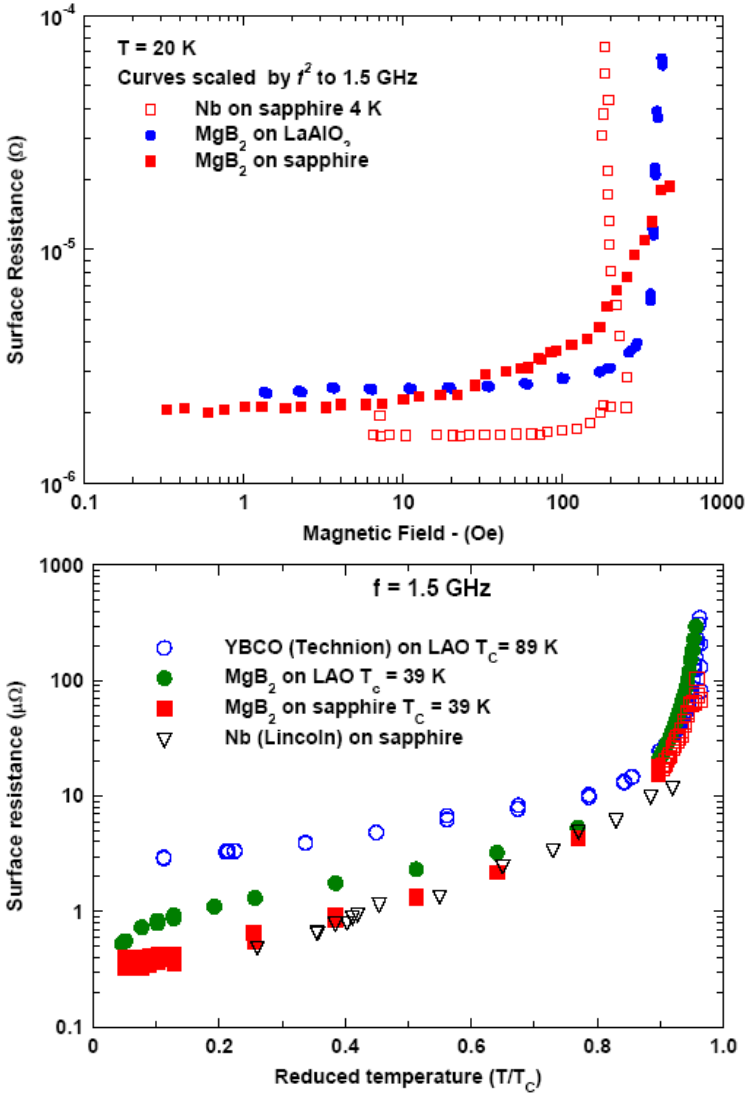


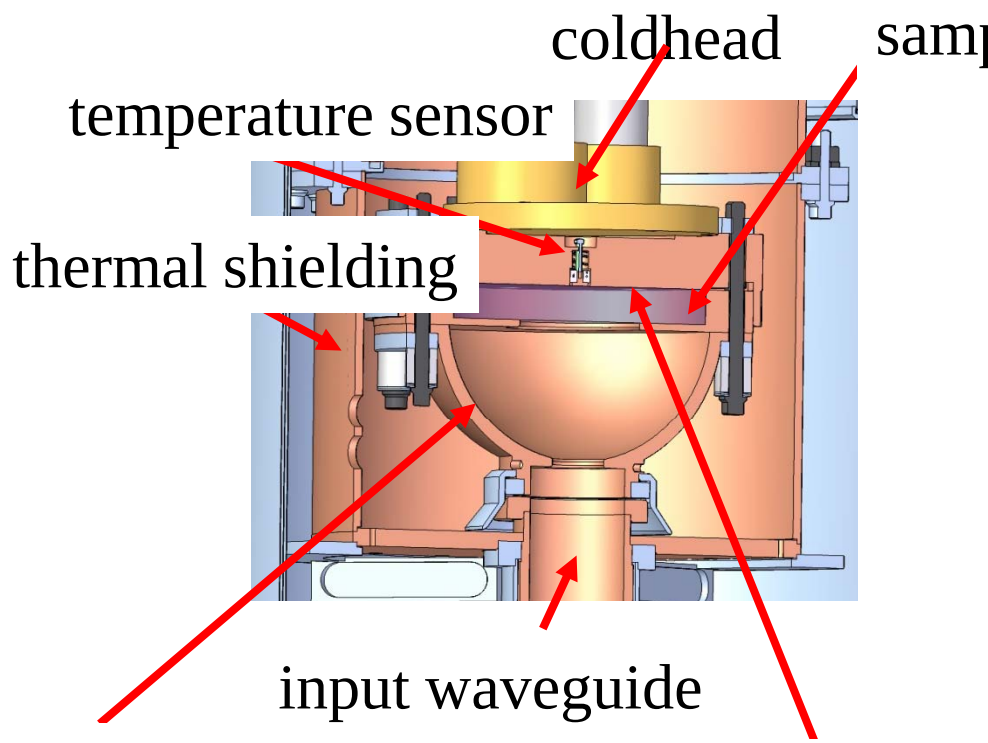
Fig. 10. Surface resistance at 1 GHz as a function of surface magnetic field. The data were scaled from 6 GHz data using f^2 law.

RF measurement @ MIT/Lincoln Lab



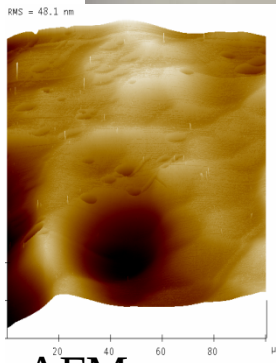
D. Oates et al., Journal of Physics: Conference Series **97 (2008) 012204.**
T. Tajima et al, IEEE Trans. Appl. Supercond., 17, 2, (2007)

MgB_2 tests at Stanford Linear Accelerator Center (SLAC) in collaboration with LANL

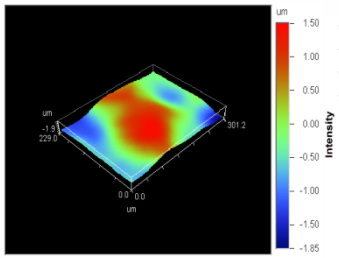


First few depositions were done on fine-grain niobium samples – no SC transition, so we switched to single-crystal niobium

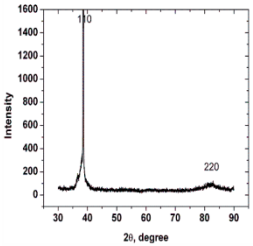
Single-crystal Nb after 150 µm BCP



AFM



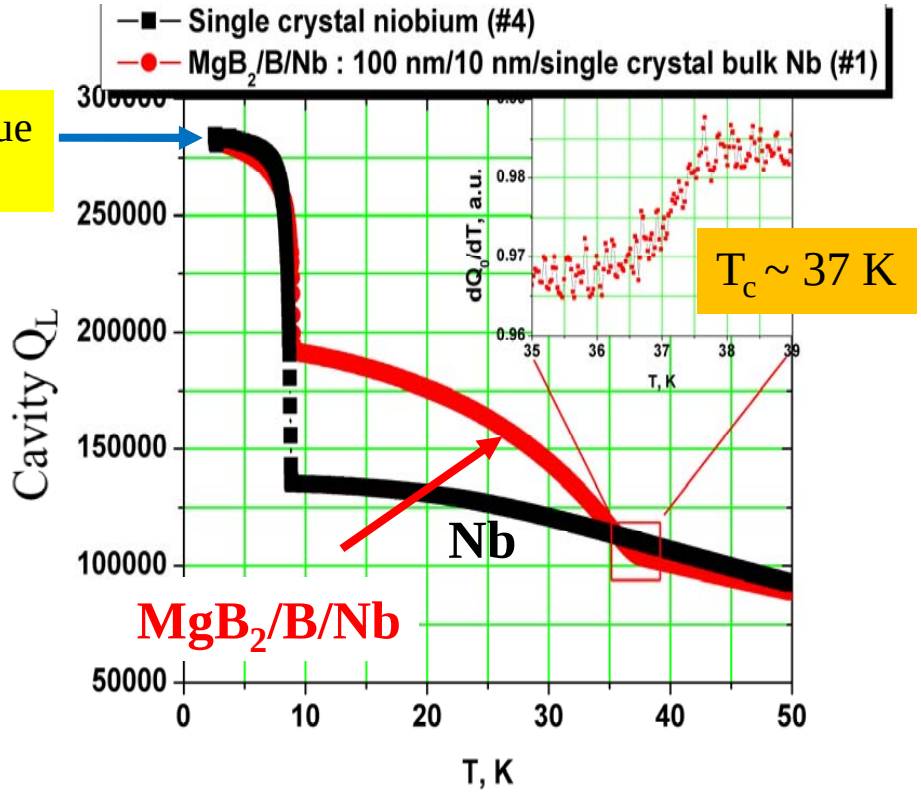
Optical profilometry

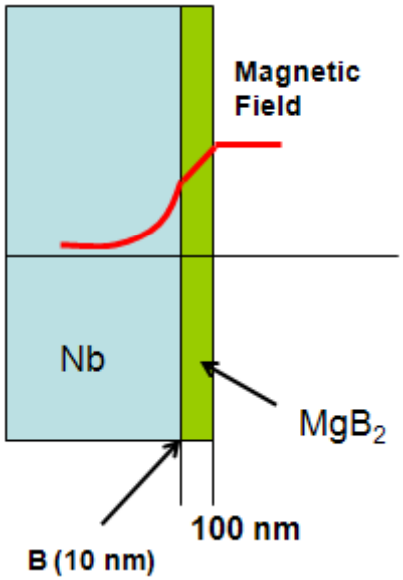


XRD

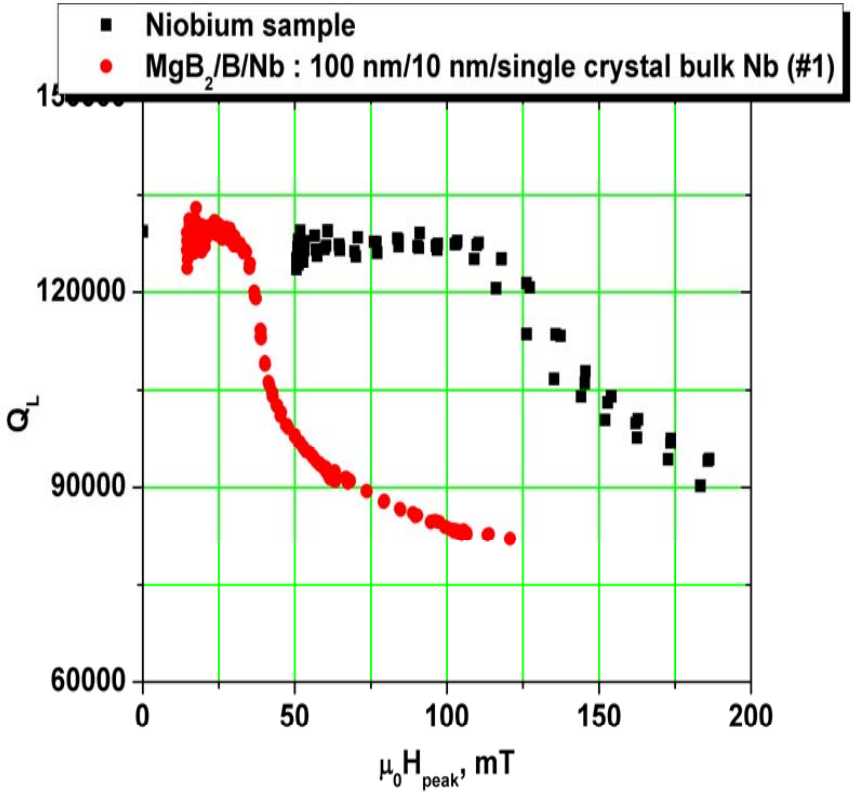
MgB_2 (100 nm) coated Nb was tested at low power and compared to Nb without coating

Saturation due to Cu loss?

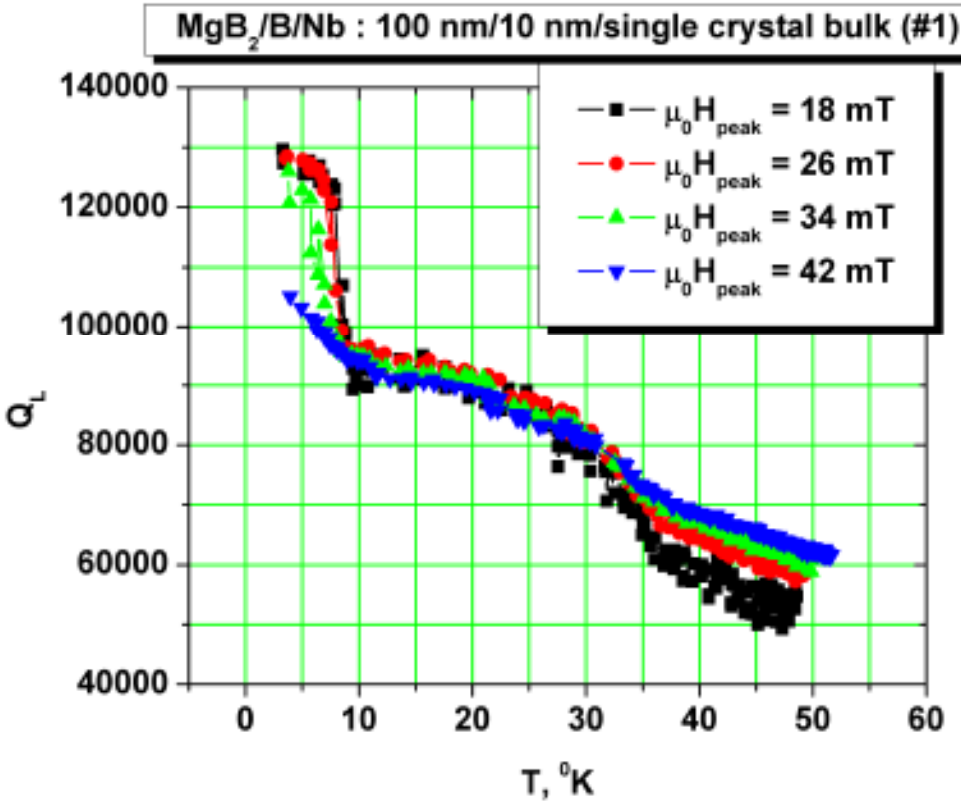




High-power test results showed a breakdown at ~40 mT in Nb not in MgB_2



Cavity Q vs. magnetic field



Cavity Q vs. T at 18-42 mT

Conclusion

- Both NbN and MgB_2 promise a reduction in the surface resistance by a factor of 10 and an increase in the critical field by a factor of 2 over niobium at low temperatures because of larger energy gaps
- Studies on thin film flat samples show results comparable to those of Nb samples
- We should develop methods to coat cavities to make direct comparison to practical Nb cavities
- LANL plans to optimize NbN and MgB_2 deposition parameters and develop methods to coat cavity surfaces
- A lot of posters on characterization and coating development this afternoon; Please, visit:

TUPPO034 by Y.Xi et al.,
TUPPO039 by G. Martinet et al.,
TUPPO042 by B. Xiao et al.,
TUPPO043 by D.L. Bowring et al.,
TUPPO068 by M. Krishnan et al.,
TUPPO070 by C.Z. Antoine.,
TUPPO077 by S. Mitsunobu et al.,
ET ALIA…

Acknowledgments

I would like to thank:

- **Peter Kneisel of JLab for providing single-crystal Nb disks**
- **Brian Moeckly of Superconductor Technologies, Inc. (STI) for coating MgB_2 thin films**
- **Sami Tantawi, Valery Dolgashev, Chris Nantista, Charles Yoneda, David Martin and Jiquan Guo of SLAC for helping us conduct testing at SLAC**
- **Ricky Campisi of ORNL/SNS and Xiaoxing Xi of Temple University for useful discussions**
- **Claire Antoine and her colleagues for providing some new NbN results**
- **Anne-Marie Valente-Felicano for information on JLab NbN work**
- **And Tsuyoshi Tajima for useful suggestions in preparation for this talk**

Thank you!