# Thin Film Applications for SRF

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# Why Thin Films?

- Thermal conductivity of, e.g., Cu is much larger than Nb - helps prevent hot spot quenches.
- Cheaper to use less Nb
- Possibility of other materials ($MgB_2$, NbN)
- Improved shielding from Earth's **B**-field
- Improved BCS surface resistance

R. Russo. *Meas. Sci. Technol.* **18** (2007) 2299-2313
S. Calatroni. *Proc. PAC 2005.*
H. Wang, et al. *Proc. PAC 2005.*

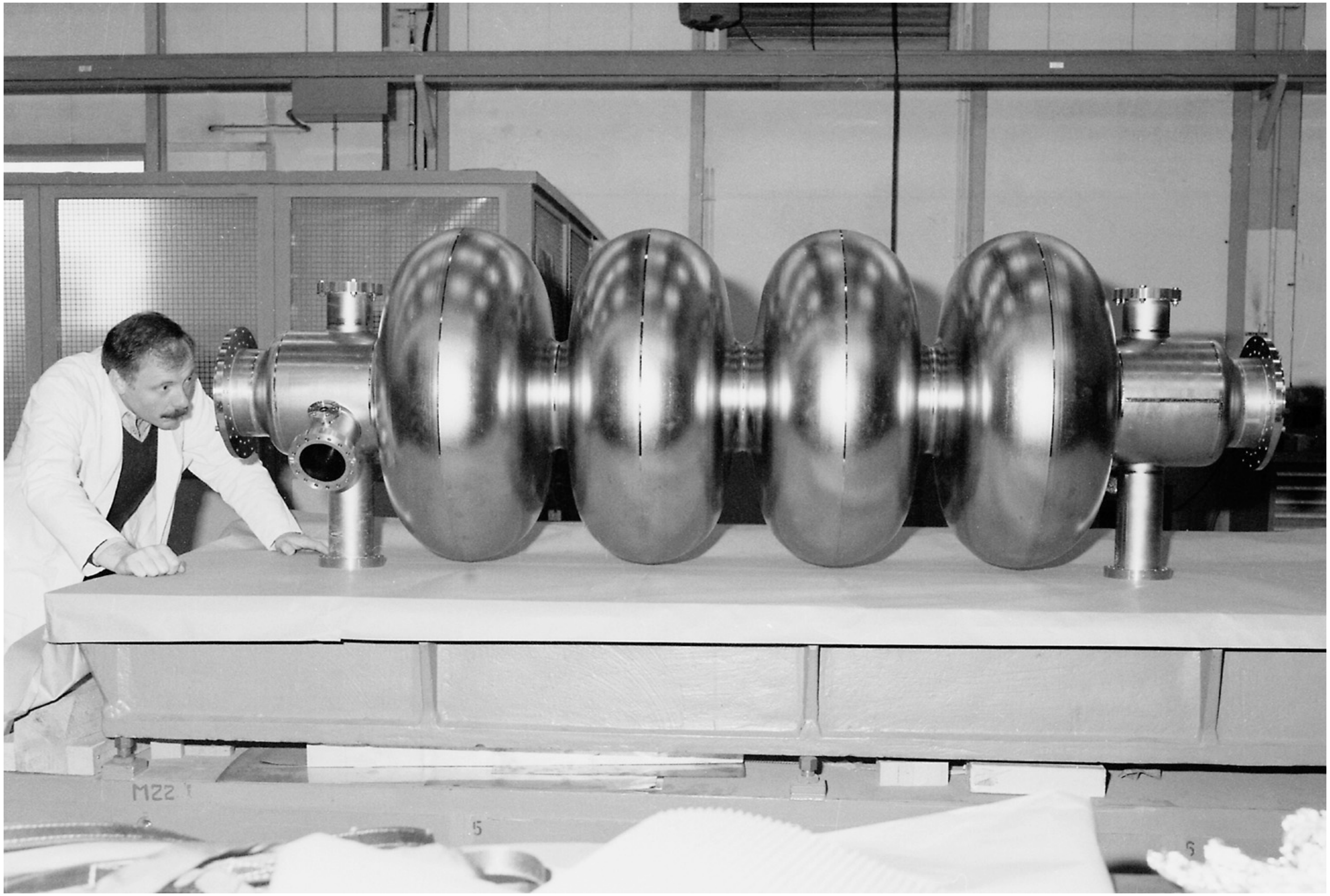
# Overview

- Some history
- Where is thin film SRF now?
- How thin/thick is too thin/thick?
- *Q*-slope and possible sources

# LEP II: 1998-2000

- industry produced 272 Nb/Cu cavities
- 352 MHz (big!) for 200 GeV (CM)
- avg. gradient 6-10 MV/m, depending
- magnetron sputtering

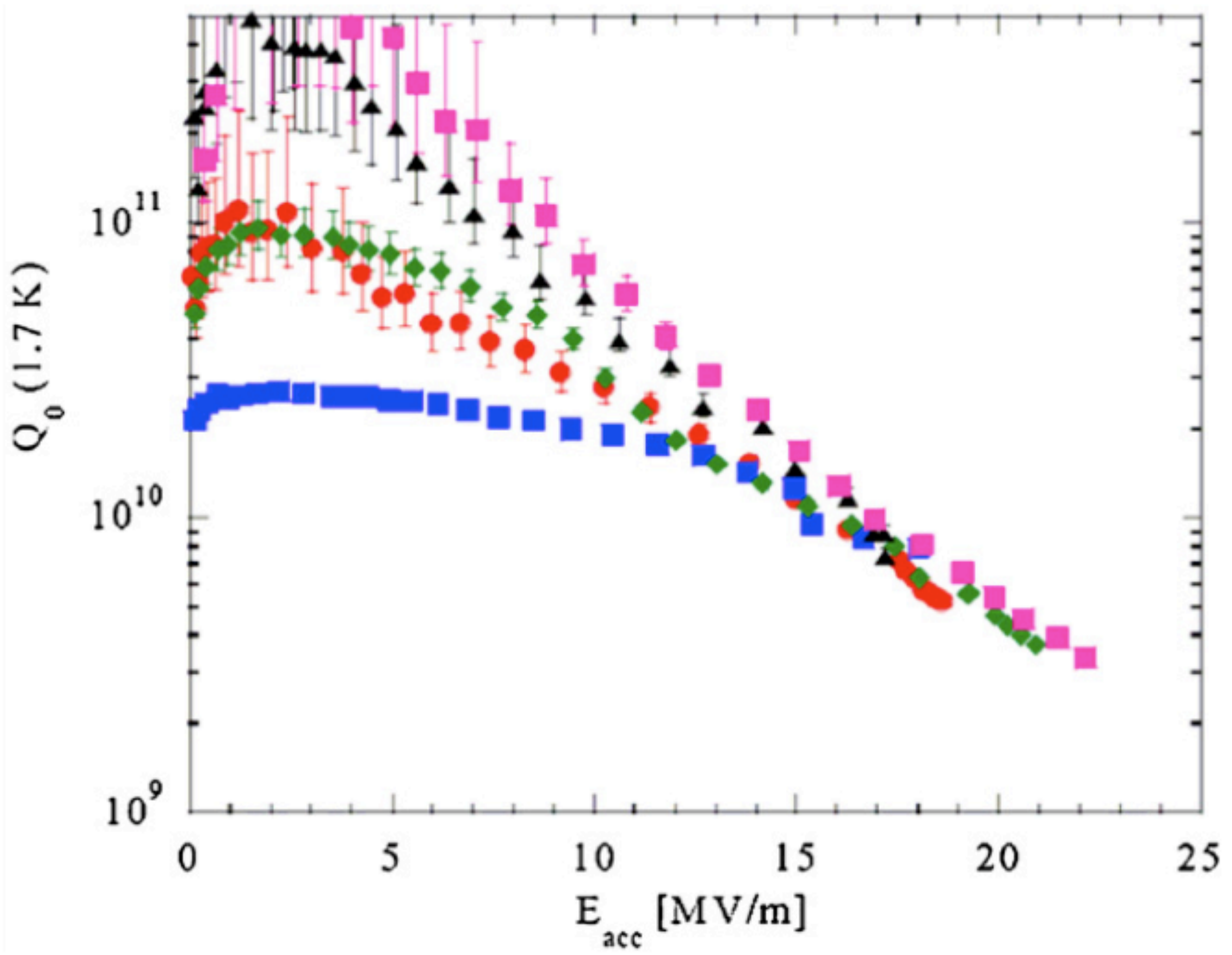
H. Padamsee. *Proc. PAC 2001*.
R. Russo. *Meas. Sci. Techol.* **18** (2007) 2299-2313.




D. Bloess. *Proc. Intl. Workshop on Thin Films 2006.*

# “High field” $Q$-Slope

Measured $Q_0$ of LEP 2 Nb/Cu Cavities




R. Russo. *Meas. Sci. Technol.* **18** (2007) 2299-2313.

# A quote from Enzo

"... experimentalists will never benefit simultaneously [from] extremely high Q values and high fields. ... Niobium sputtered cavities will never be usable at high accelerating gradients, unless Residual Resistivity Ratio values of at least 100 [are] achieved in the niobium film growth."

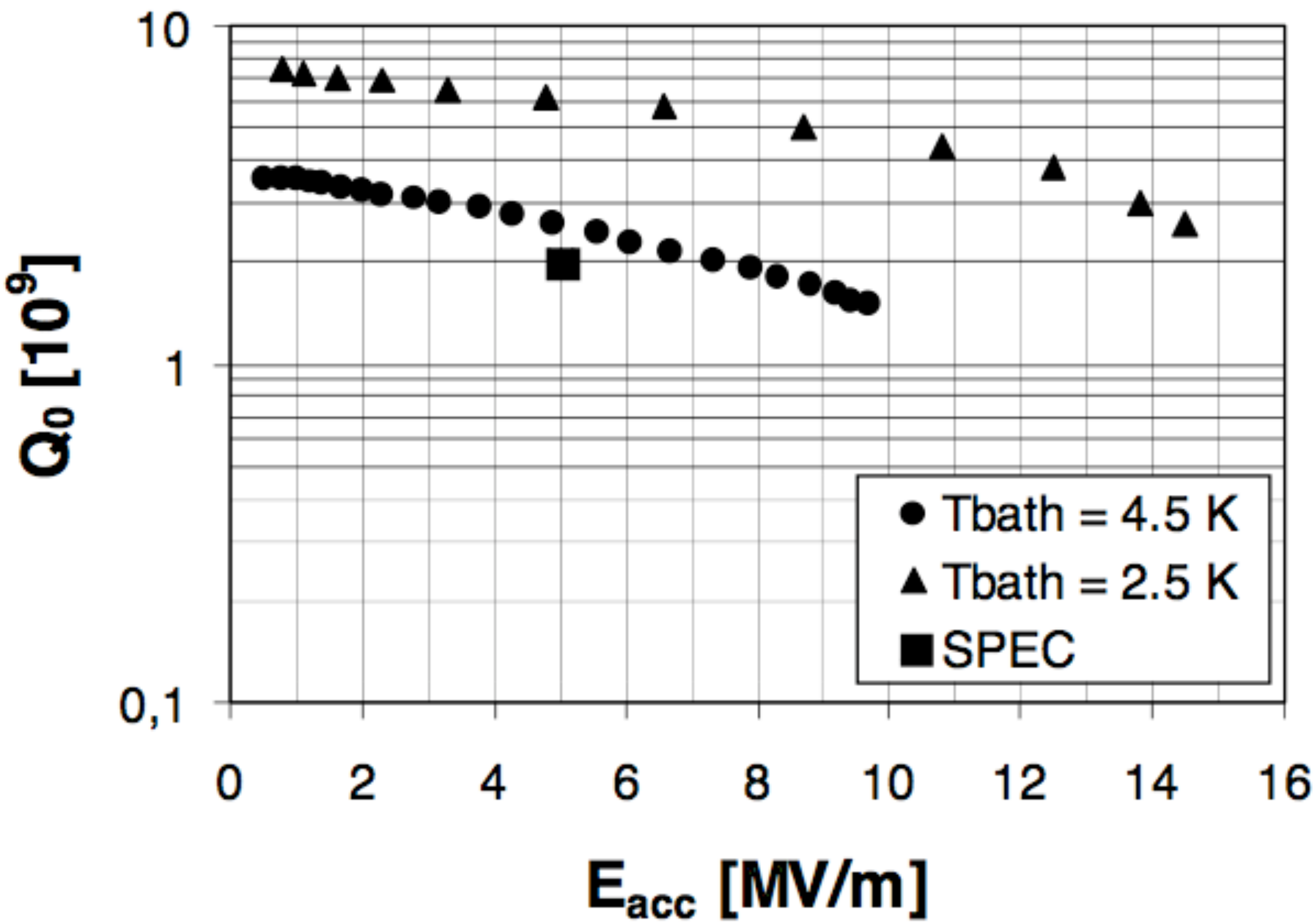
V. Palmieri. *Proc. of SRF 2005.*

# Thin Film SRF Today

| **Machine** | **What/ Where** | **Approx. Gradient** | **Frequency** |
|---|---|---|---|
| LHC | CERN | 5 MV/m | 400 MHz |
| SOLEIL | St.-Aubin, France | 5 MV/m | 352.2 MHz |
| ALPI | Legnaro, Italy | 4-6 MV/m | 80 MHz |


S. Bauer et al. *Proc SRF 1999.*
J. Jacob et al. *Proc. EPAC 2002.*
G. Bisoffi et al. *Proc. SRF 2007.*

# $Q_0$ vs. Gradient, LHC



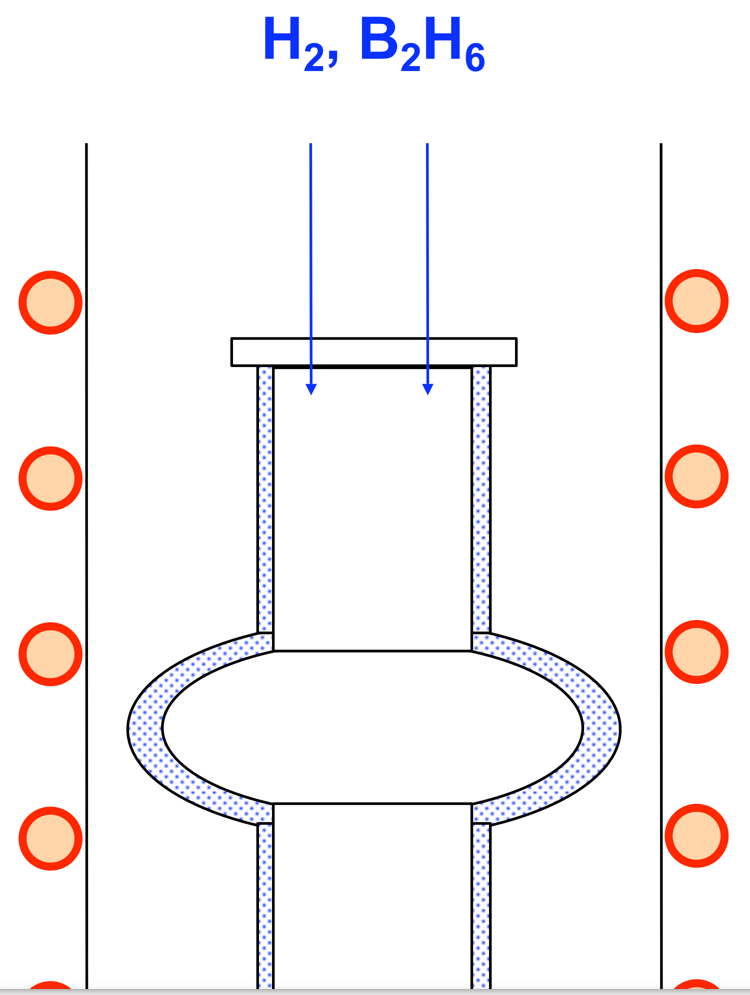

S. Bauer et al. *Proc SRF 1999.*

# $MgB_2$

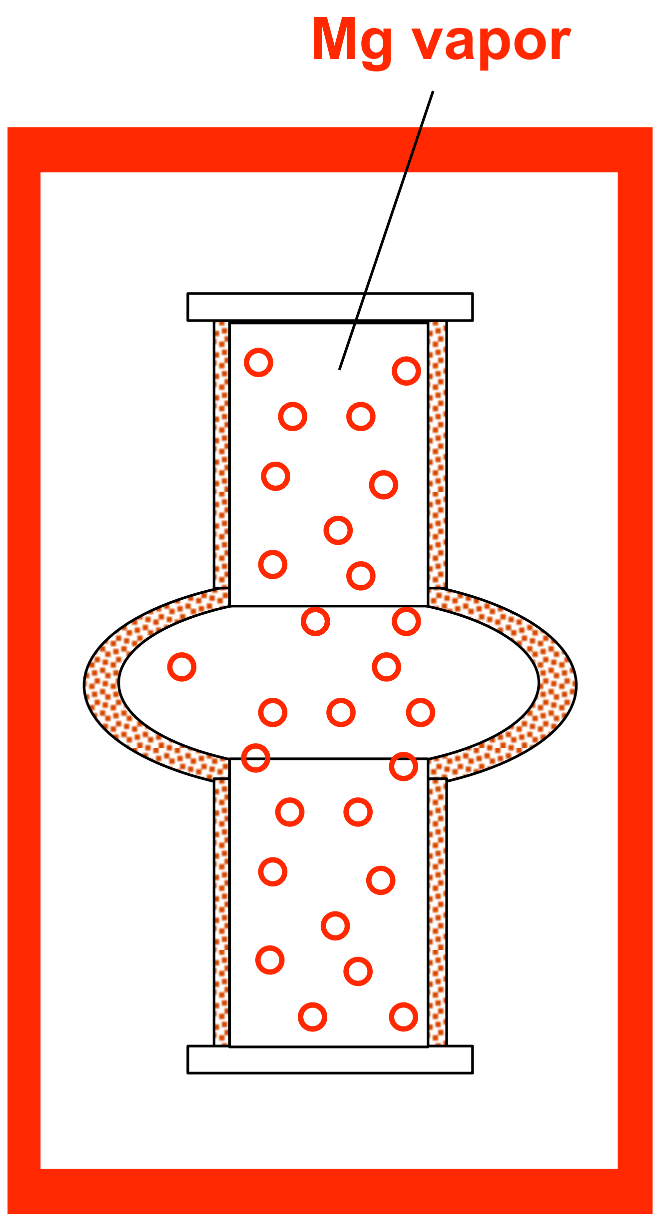
- First published in 2001
- $T_c$ = 39 K
- Theoretical max. gradient ~ 77 MV/m
- $R_{BCS}$(4 K, 500 MHz) = 2.5 nΩ

E.W. Collings, et al. *Supercond. Sci. Technol.* **17** (2004) S595-S601.

# Coating SRF Cavity with a Two-Step Process




X. Xi. *Proc. Workshop on SRF Materials, 2007.*

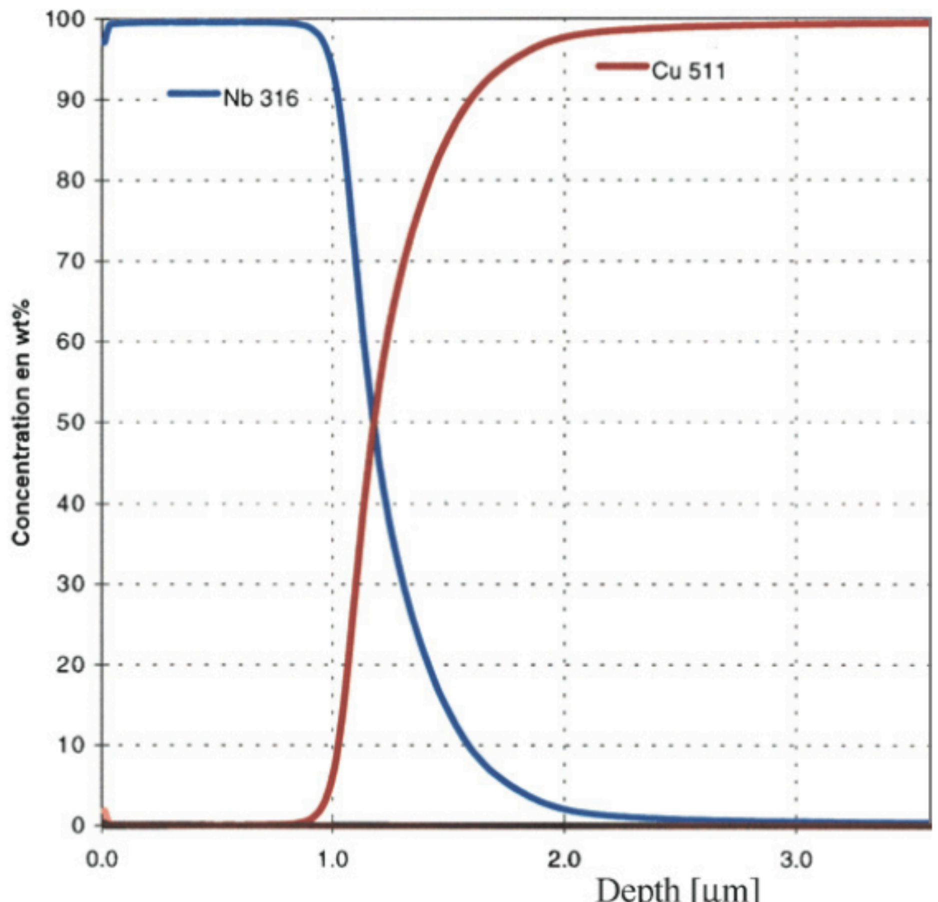



**Coating cavity with B layer at ~400-500°C using CVD**

**Reacting with Mg to form $MgB_2$ at ~ 850-900 °C in Mg vapor**

# How thin is too thin?

- Absolute lower limit is set by the London penetration depth. For Nb, this is ~36 nm.
- Practical lower limit set by substrate avg. surface roughness + concentration gradient.
- fcc to bcc transition



(b)

R.Russo. *Meas. Sci. Technol.* **18** (2007) 2299-2313.

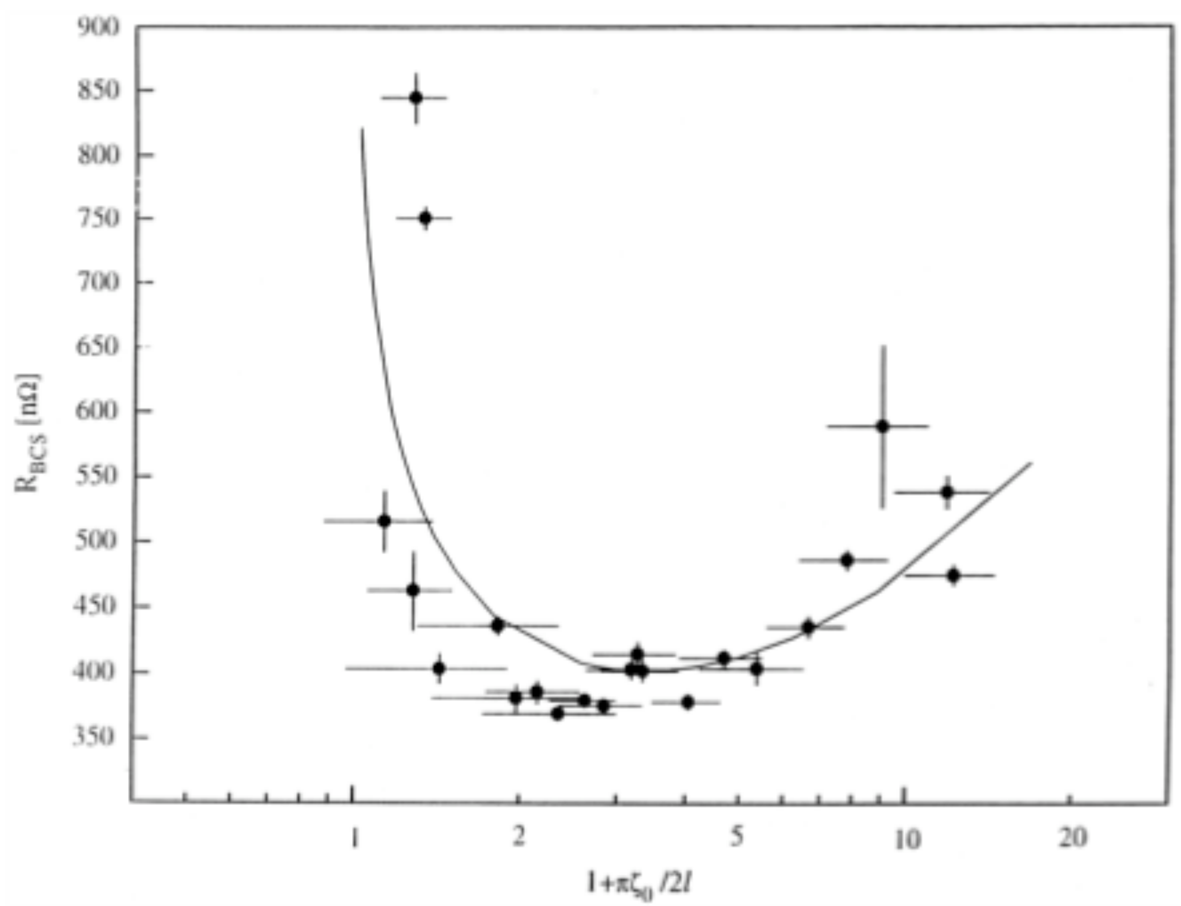
# How thin is thin enough?

- LEP 2 experience suggests excessive film stresses at >10μm, causing problems during HPR.
- These limits likely dependent on deposition technique. YMMV.
- **Useful range: 2 < *d* <10 μm.**

# Possible Sources of *Q*-drop

- *DISCLAIMER*: Strong disagreement about role of grain boundaries in film quality.
- I will discuss (not endorse!) the findings/ theories of various groups.
- Evidently lots of interesting work to be done here.

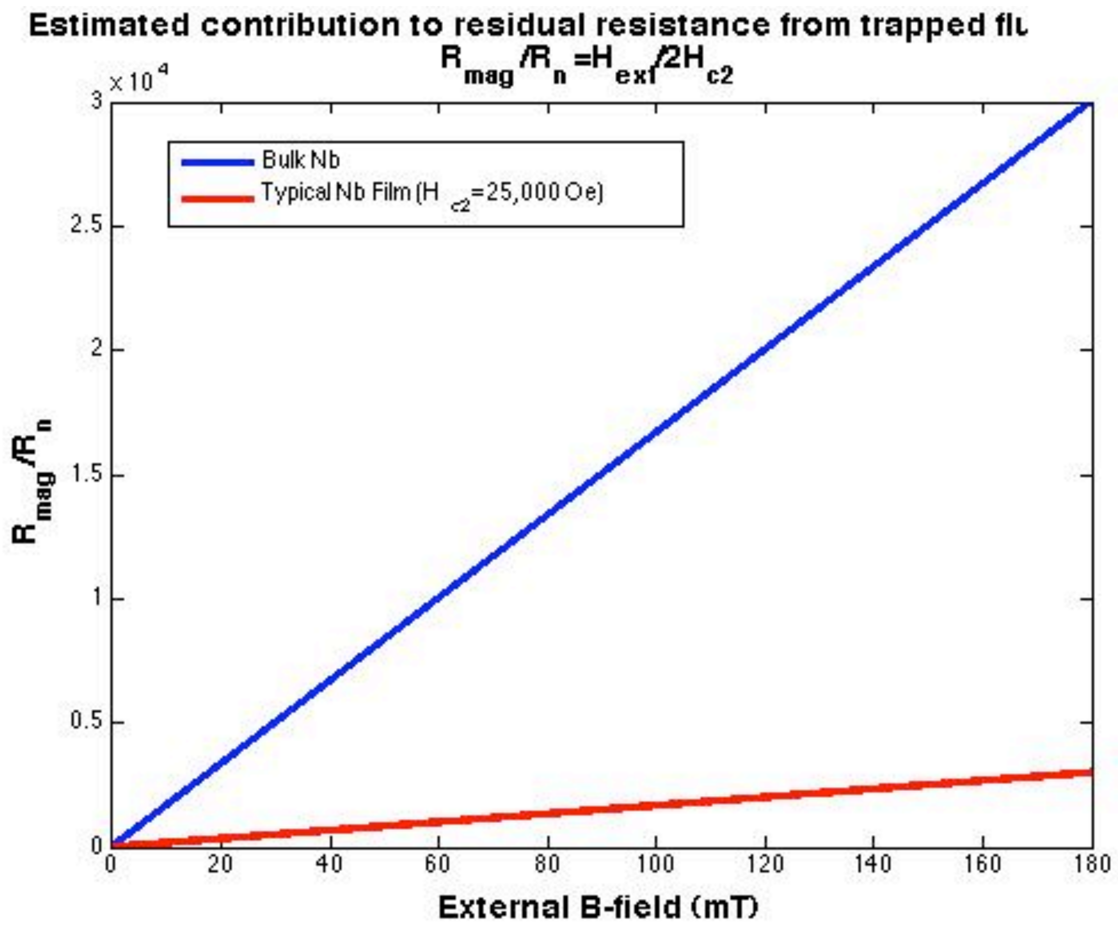
# Role of Mean Free Path




Dependence of $R_{BCS}$ on mean free path

C. Benvenuti et al. *Physica C* **316** (1999) 153-188.

# Trapped Magnetic Flux




$$R_{\rm mag} = \frac{H_{\rm DC,ext}}{2H_{\rm c2}} R_{\rm n}$$

- Flux vortices "pinned" by lattice defects.
- As $T$ drops below $T_c$ this pinned flux is trapped.
- Simple model for DC fields assumes all flux trapped.

# Trapped Flux, cont'd.

- G. Ciovati et al. *Proc. SRF 2005*.
- Thermometry measurements map "hot spots" in cavity due to trapped flux.
- Flux oscillates at pinning site, gives resistive losses.
- Authors: *Q*-drop might come from vortex penetration due to "reduced surface barrier" (lattice defects)

# Trapped Flux, cont'd.

- A. Romanenko et al. *Proc. SRF 2007*.
- Comparative thermometry studies of large and small grain cavities suggest crystal defects play a role in flux pinning.
- This experiment discounts role of field enhancement at grain boundaries, suboxide layer.
- *But...*

# Theories / Experiments Co[mparison]

B. Visentin. *Proc. Int'l Workshop on Thin Films.* 2006.

*B. Visentin - SRF (2003) – updated at Argonne Work*

| | Q-Slope Fit | Q-Slope before baking (EP = BCP) | Q-Slope Improvem$^{t}$ after baking | Q-Slope after baking (EP < BCP) | No change after 4 y. air exposure | Exceptional Results (BCP) | Q-Slope unchanged after HF chemistry | $TE_{011}$ Q-slope after baking | Quench EP > BCP | BCP Quench unchanged after baking | Argum$^{t}$ Validity | Fund$^{al}$ Disagreem$^{t}$ Exper. ≠ Theory |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Magnetic Field Enhancem$^{t}$** | Y simulat. code | N / $\beta_m \neq B_{C2}^S \neq$ | Y $B_{C2}^S \uparrow$ | Y lower $\beta_m$ | - | N high $\beta_m$ | - | - | Y lower $\beta_m$ | N $B_{C2}^S \uparrow$ | Y | $D_1$ |
| **Interface Tunnel Exchange** | Y $E^8$ | N $\beta^* \neq$ | Y $Nb_2O_{5-y} \downarrow$ | Y lower $\beta^*$ | N $Nb_2O_{5-y} \uparrow$ | N high $\beta^*$ | N / new $Nb_2O_{5-y}$ | N / improv$^{t}$ | - | - | Y | $D_2$ |
| **Thermal Feedback** | Y parabolic | Y ≅ thermal properties | Y $R_{BCS}\downarrow$ $R_{res}\uparrow$ | N ≅ therm. propties | - | - | - | - | - | - | N C coeff.$^{t}$ | - |
| **Magnetic Field Dependence of Δ** | Y expon$^{tial}$ | N $B_{C2}^S \neq$ | Y $B_{C2}^S \uparrow$ | Y higher $B_{C2}^S$ | - | - | - | - | - | - | N / thin film | $D_1$ |
| **Segregation of Impurities** | ? | N segregation ≠ | N only O diffusion | Y surface ≠ | - | Y good cleaning | N chemistry | - | - | - | Y | - |
| **Bad S.C. Layer Interstitial Oxygen $Nb_{4-6}O$** | ? | Y NC layer | Y O diffusion | N | N interstitial re-appears | - | N / new bad layer | - | Y higher $B_{C2}^S$ | N $B_{C2}\downarrow$ | Y | $D_1$ |

**Y** / **N** = theory in **agreement** / **contradiction** with experimental observation N+

/ = undisputable disagreement with experiment

# V. Palmieri. *Proc. SRF 2005*

- Paper *unique:* presents close approximation of an outright theory.
- $R_{\mathrm{BCS}} \propto \exp - \left[ \left( \Delta - p_{\mathrm{F}} v_{\mathrm{s}} \right) / kT \right] \qquad \text{where} \qquad p_{\mathrm{F}} v_{\mathrm{s}} / kT \propto \sqrt{\coth(\ell / \xi_0)}$
- $\ell \approx \left( 24 \ \mathring{A} \right) \times (\beta - 1)$
- As RRR drops below ~100, "parasitic" term starts to wreck $R_{\mathrm{BCS}}$.
- This theory describes *medium-field Q*-slope.

# Conclusions

- Parameter space of SRF thin film development is huge.
- Clearly lots of interesting work still to be done in this field.
- Thank you for your attention.