LANL Facilities and Activities for Radio-Frequency (RF) Superconductivity R&D

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Accelerator Operations and Technology (AOT) Division

Talk at NSCL, MSU, on 31 July 2007

Los Alamos Neutron Science Center (LANSCE)

800-MeV (~1 MW) LANSCE (formerly LAMPF) linac is the heart of the facility -first beam in 1972.

Proton Radiography

800-MeV Linear Accelerator

Isotope Production Facility

LANSCE Visitor's Center

Manuel Lujan Jr.Neutron Scattering Center

Proton Storage Ring

SRF LAB

Weapons Neutron Research

Neutron Resonance Spectroscopy

Superconducting RF (SRF) Laboratory

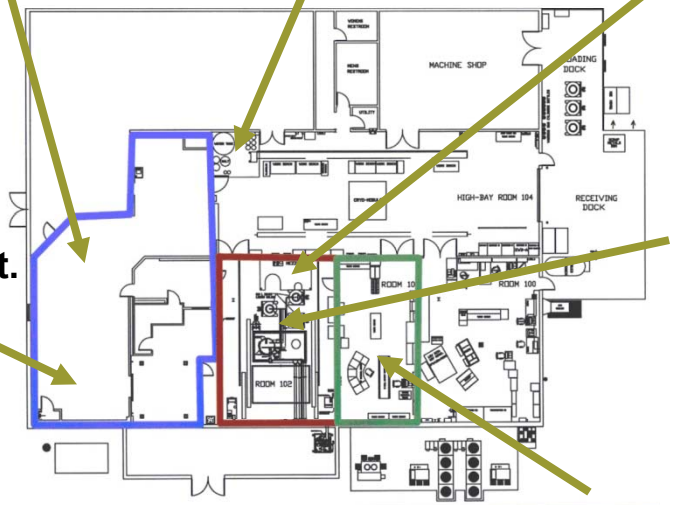
Superconducting cavities are assembled in a 2600 ft^2 Clean room

2000 gallons/day ultra-pure water system for high-pressure rinse

Two cryostat inserts

140 ft.

100 ft.



38-inch diameter 10-ft deep cryostat

High-pressure rinse in a clean room.

Control, tuning

Building MPF-17

Operated by Los Alamos National Security, LLC for NNSA

R&D on RF superconductivity started at LANL around 1990. The SRF team was led by Brian Rusnak till 1999.

- **1990 – 1992: Funded by LDRD tech development at around ~1M$/yr.**

  Major accomplishments: set up lab, performed ~100 tests on nine 3 GHz cavities to test the effect of cleanliness, cleaner chemistry, etc.

- **1992 – 1994: Funded by LDRD for PILAC (pion linac) at ~1 M$/yr**

  Major accomplishments: built 1st double-side Ti heat (before iris welding) treated 4 cell beta=0.85 niobium cavity at 805 MHz for high gradient pion acceleration

- **1994 – 2001: Funded by DOE APT/AAA funds at ~70 M$ over 7 years**

  Major accomplishments: built first reduced beta elliptical cavities at 700 MHz at beta = 0.48, 0.64, and 0.82, built multi-cell elliptical cavities at 700 MHz, demonstrated the effects of proton irradiation on an operating SRF cavity, rebuilt and upgraded the SRF laboratory space, built and tested a 1 MW cw power coupler.

LANL SRF R&D history (cont.)

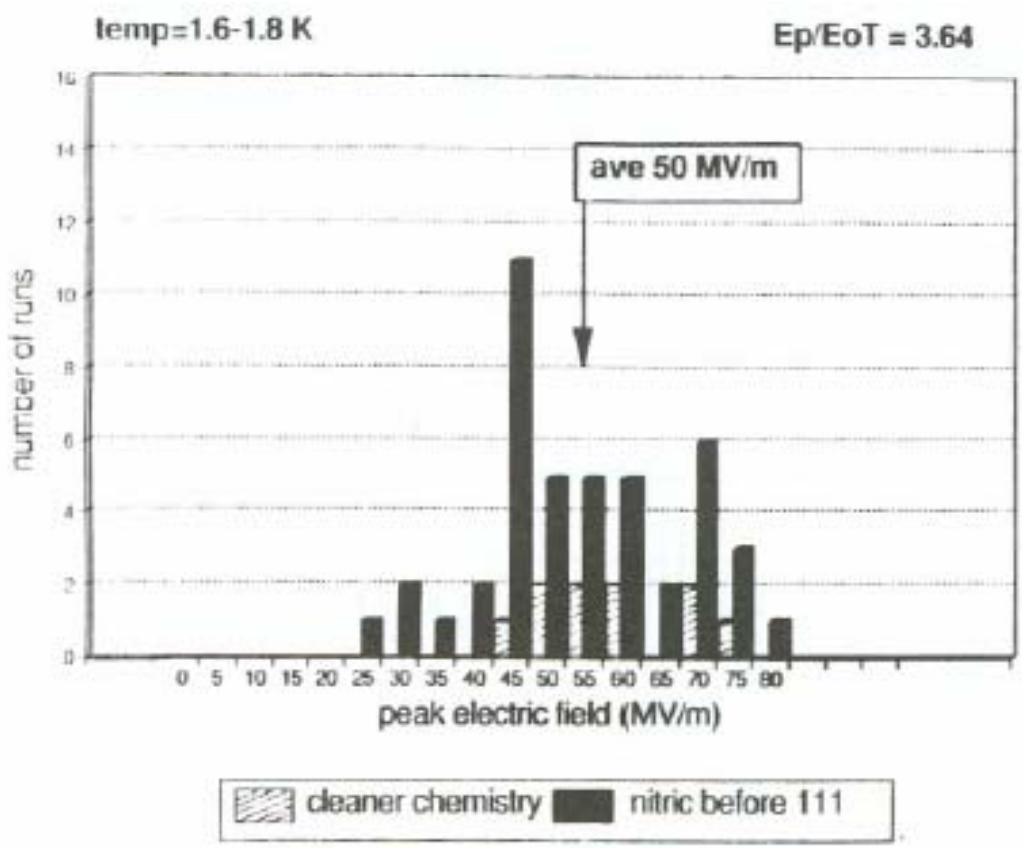
- **2001 – 2005: a total of ~400 K$ for high-T_c material research for SRF cavity application.**

  Major accomplishments: demonstrated surface resistance of MgB_2 lower than niobium at 4 K and its dependence on magnetic fields much less than YBCO and other high-T_c materials.

- **2007 – present: Funded by the SC/HEP for the ILC, 371 K$ in FY07**

  Ongoing work: re-starting the facilities for SRF cavity tests, developing 9-cell cavity temperature mapping system, pre-conceptual design of automated clean inspection and assembly, high pulsed power tests to determine RF critical temperature of superconductors such as Nb and MgB_2 in collaboration with SLAC.

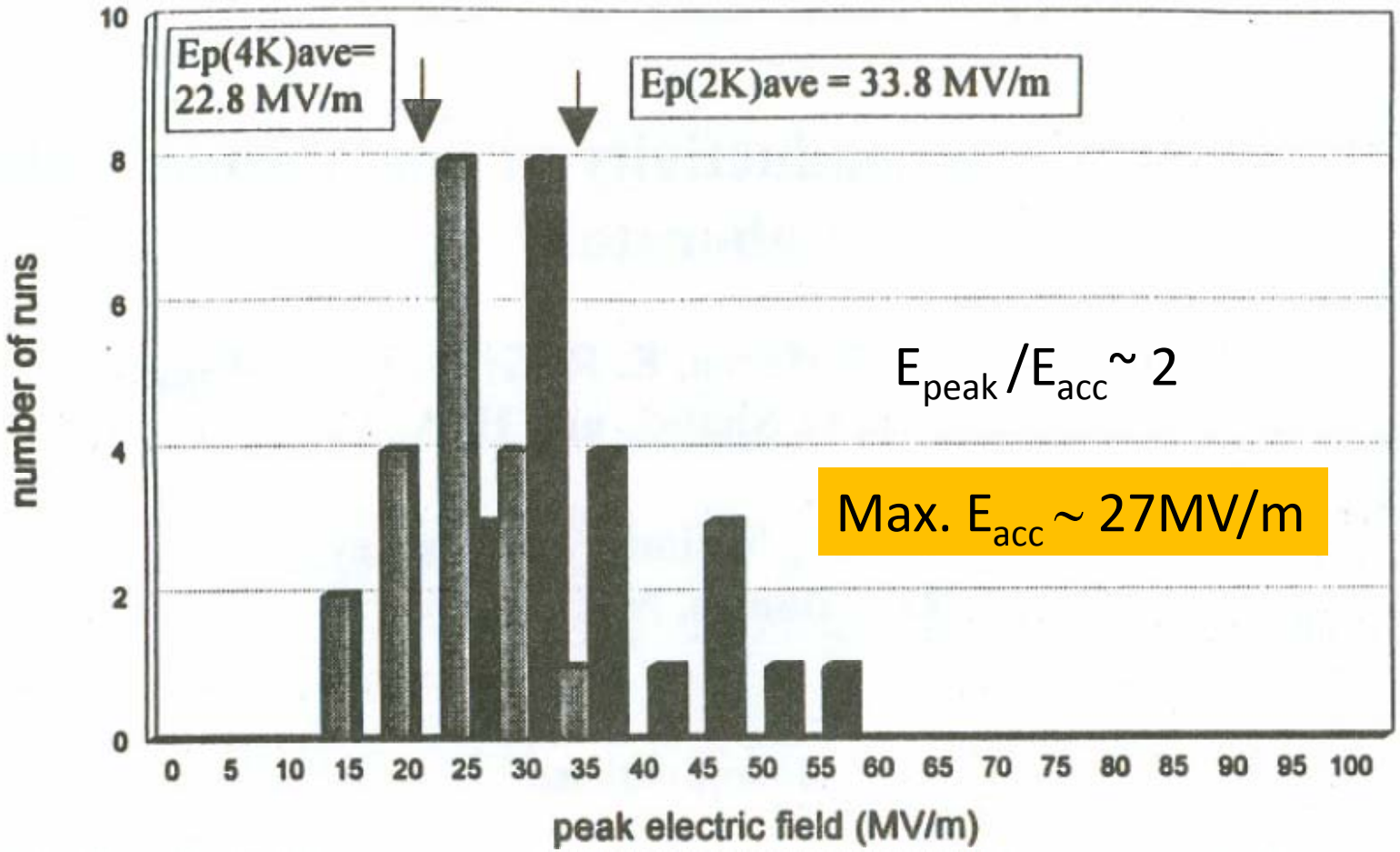
Highlights of early work: 3 GHz cavity tests results. Comparison with and without cleaner chemistry in 1992



B. Rusnak et al., Proc. LINAC1992, p. 728.

- 82 runs with 9 cavities
- "cleaner chemistry" means under HEPA filtered air and using analytical grade chemicals
- did not show a drastic change with cleaner chemistry

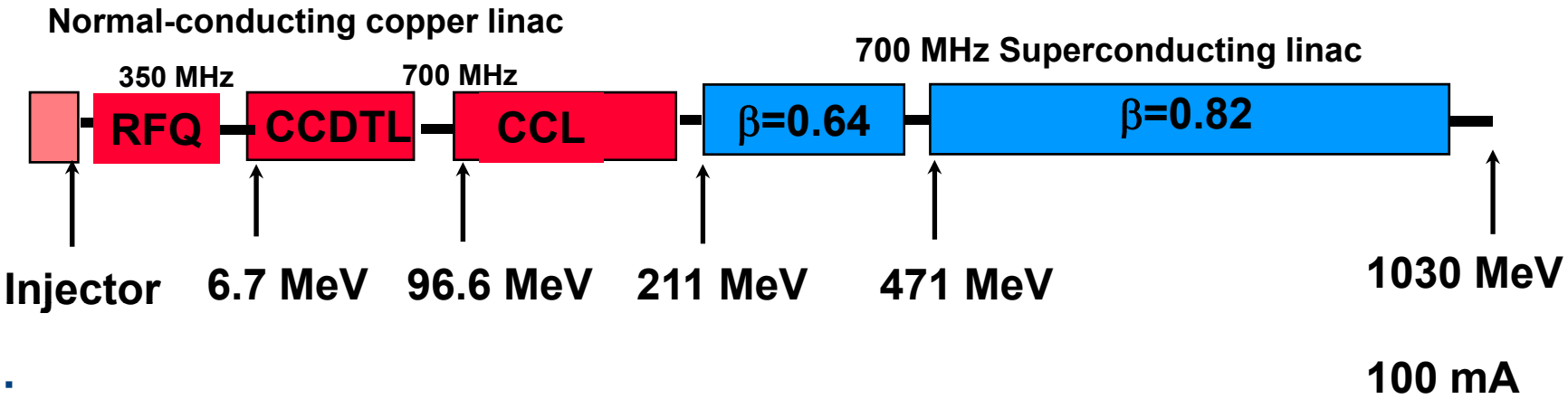
805 MHz single-cell tests results (B. Rusnak et al., Proc. SRF1993 workshop)



$E_{peak}/E_{acc} \sim 2$

Max. $E_{acc} \sim 27$MV/m

Accelerator Production of Tritium (APT) project boosted our SRF work, although APT was not down selected



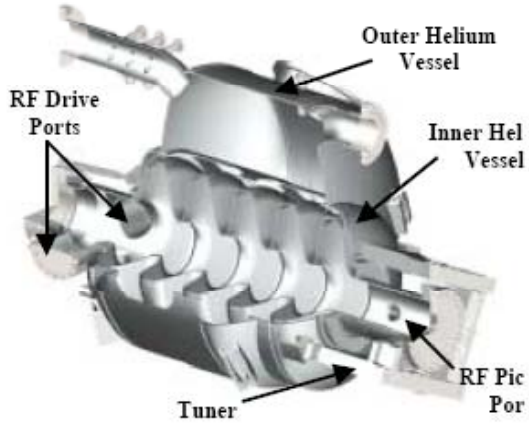


Figure 3: The β=0.64, 5-cell cavity with titanium helium vessels and some piping.

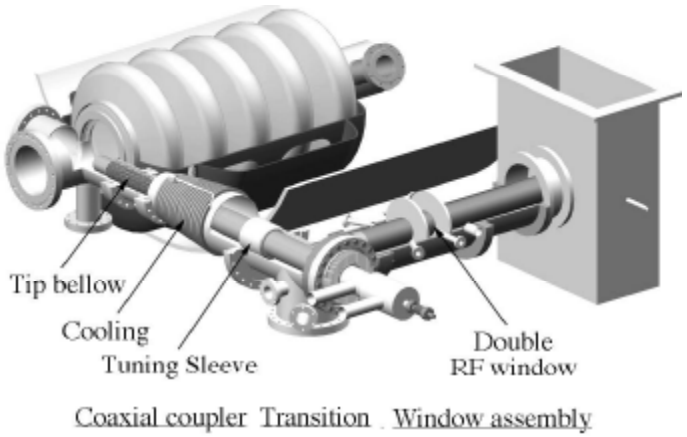
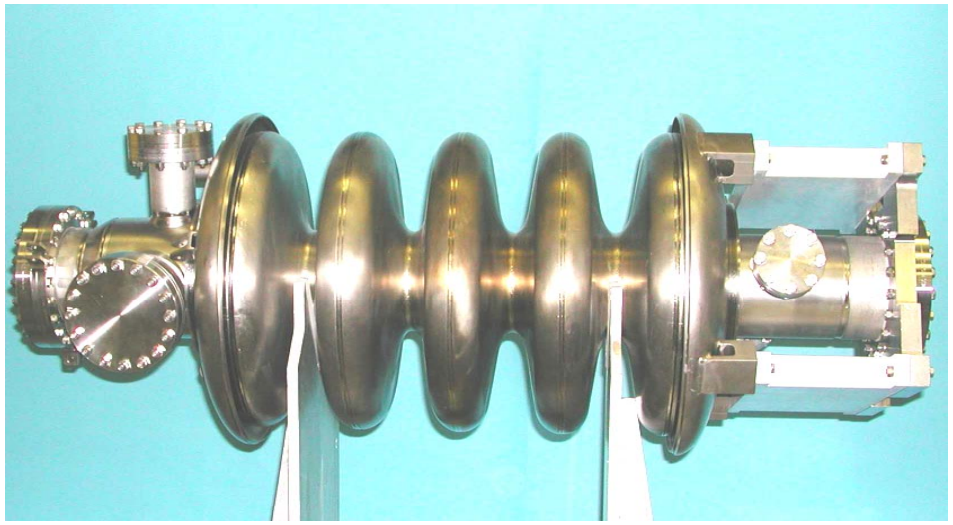


Figure 3: Illustration of the APT power coupler.

Chan et al., LINAC98

APT β = 0.64, 700 MHz, 5-Cell Cavity



Cavity length : 116 cm

Cell diameter : 40 cm

Beam aperture : 13 cm

E_p/E_{acc} = 3.38

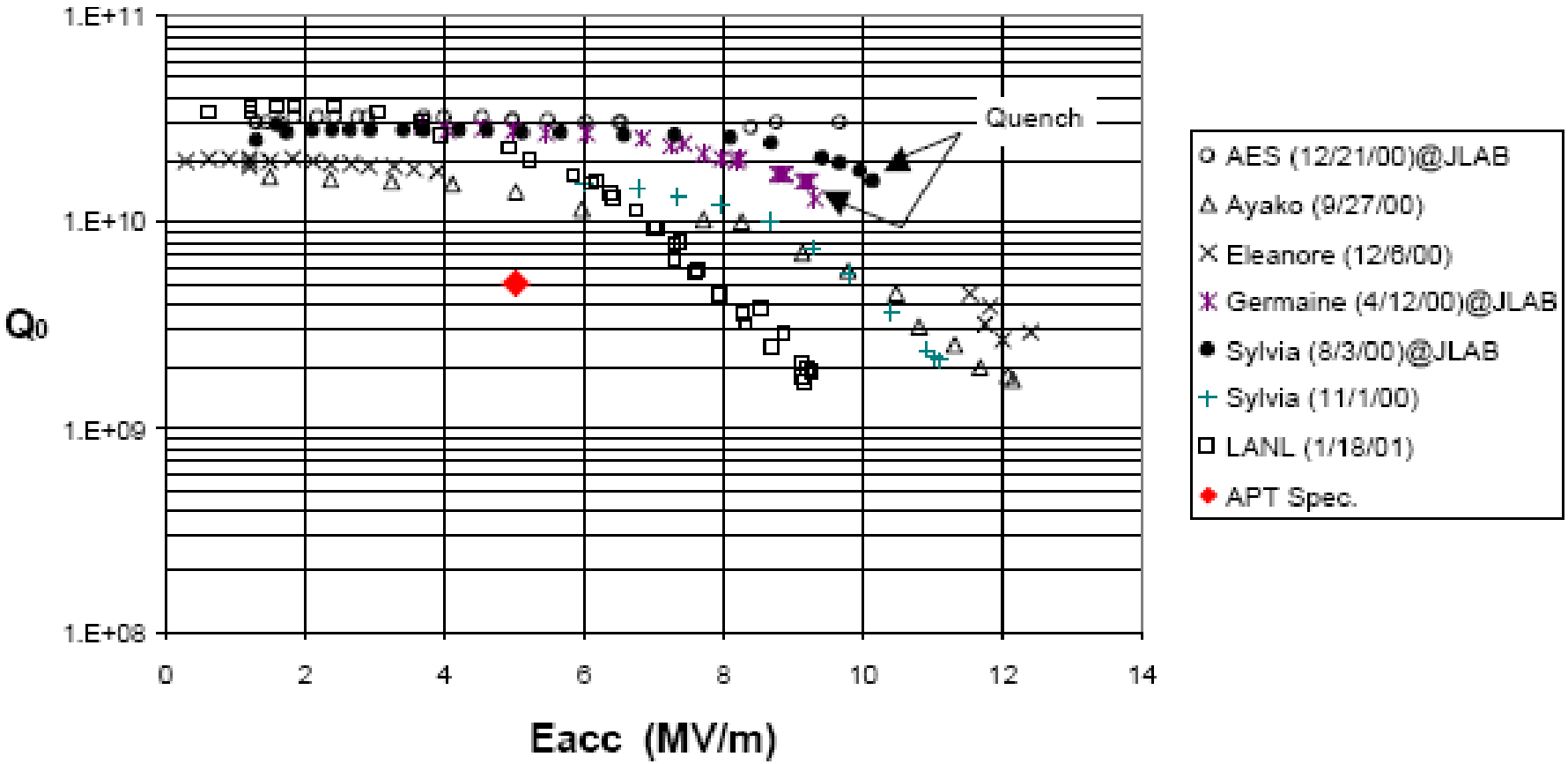
B_p/E_{acc} = 6.96 mT/MV/m

Our Typical Cavity Test Procedure

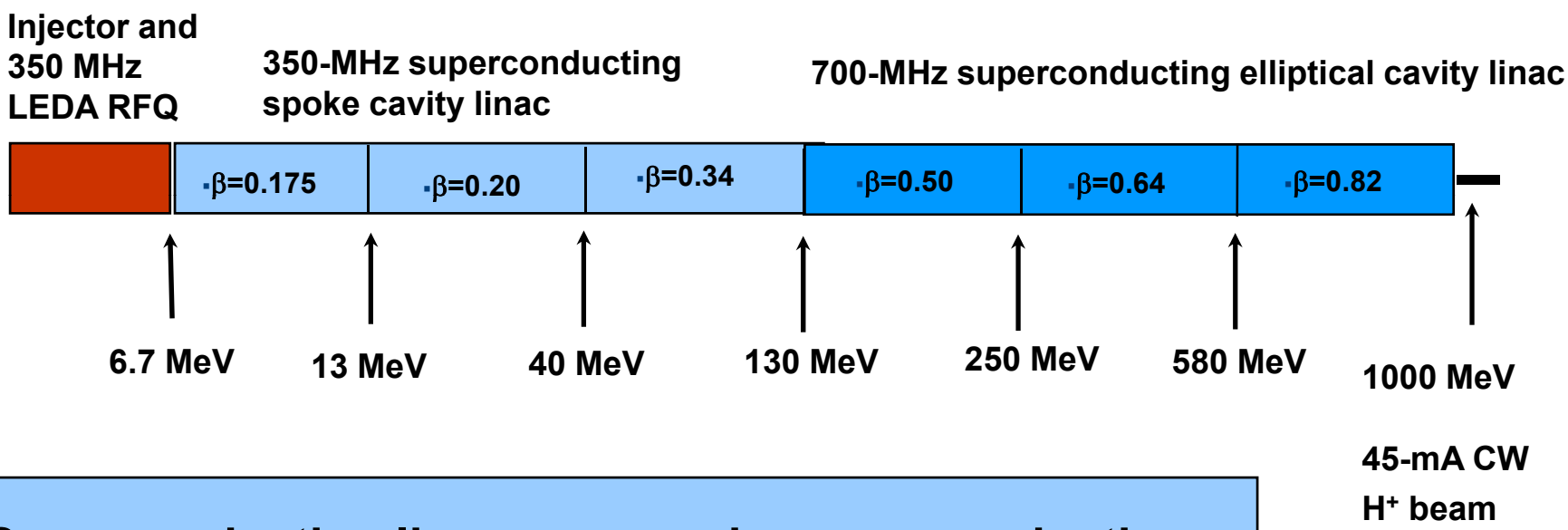
- Chemically polish the inner surface (~150 μm) and rinse off chemicals with pure water at MST-6 (Materials Science Div.)
- Ultra-pure water rinse (1000-1200 psi) in the clean room
- Dry and assemble with flanges and a vacuum valve in the clean room
- Set on the cryostat insert and pump down, bake at ~110 C
- Move into the cryostat, pre-cool by liquid nitrogen and fill the cryostat with liquid helium
- Put radiation shield on and feed RF power

Vertical tests have been carried out for 6 APT cavities

Six β=0.64, 5-cell, 700 MHz cavities were fabricated at CERCA (4), AES (1) and LANL (1)



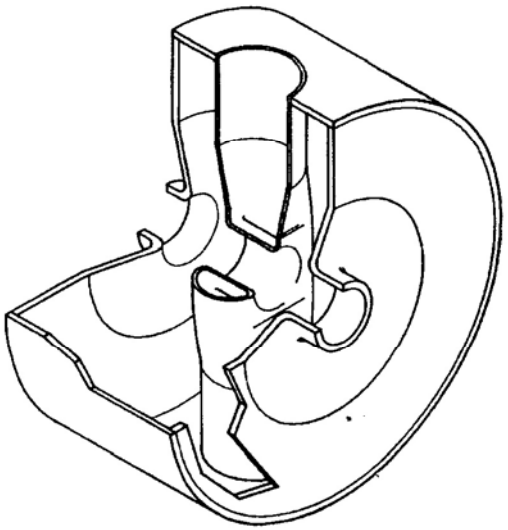
Accelerator Transmutation Waste (ATW) 1-GeV superconducting linac design extends superconducting cavities down to the RFQ. Unfortunately not funded.



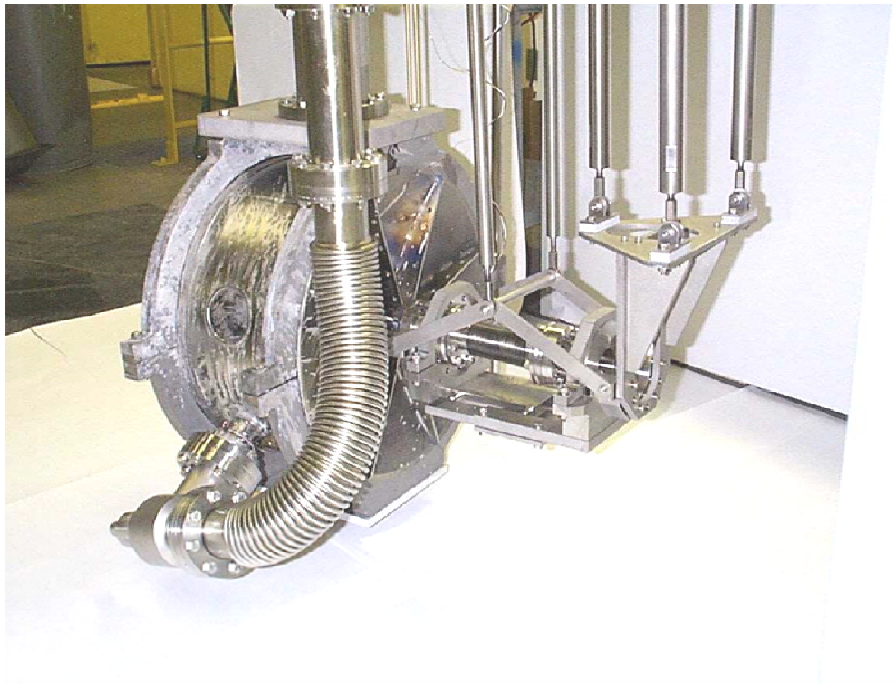
Superconducting linac uses spoke-superconducting structures for the lower velocities.

Spoke Cavity Development for Low-Energy Sections of Proton Linacs

- **Studies have been carried out at ANL since late ’80s**
- **Advantages over elliptical cavities**
  - Compact (diameter ~1/2 of elliptical for the same freq.)
  - Mechanically stable
- **One spoke cavity loaned from ANL was evaluated at LANL and the result was promising**



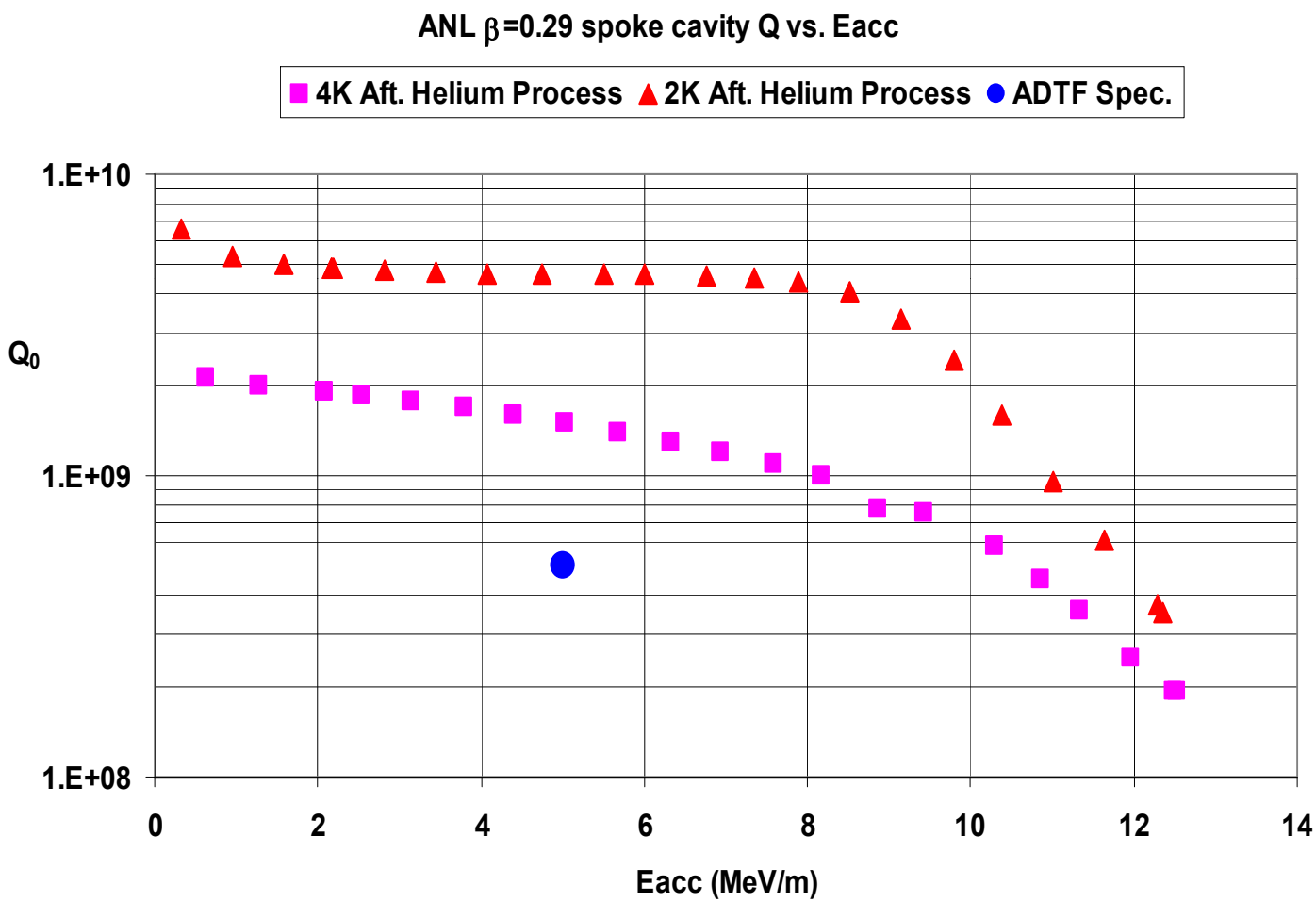
β = 0.29, 340 MHz, 2-gap Spoke Cavity on Loan from ANL



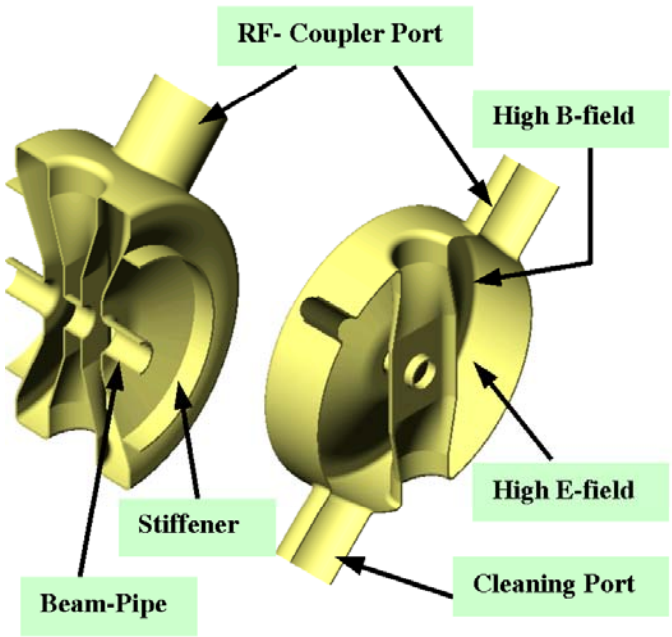
- Cell diameter : 44.2 cm
- Cavity length : 30 cm
- Beam aperture : 3.2 cm

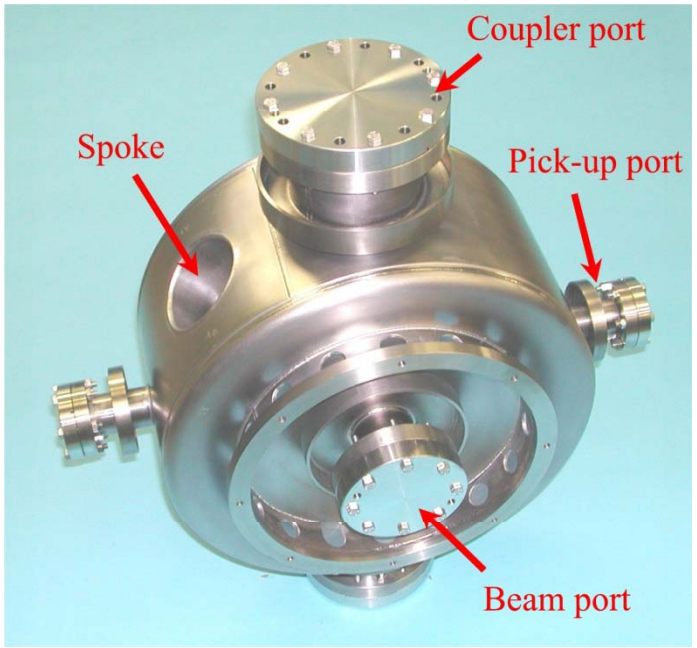
- E_{pk}/E_{acc} : 3.18
- B_{pk}/E_{acc} : 8.5 mT/MV/m

BCP and HPR improved the performance of ANL spoke cavity from ~5 MV/m to >12 MV/m



Two LANL β=0.175, 350-MHz, 2-Gap Spoke Cavity were fabricated





Cell diameter : 39.2 cm

Cavity length : 20 cm

Beam aperture : 5 cm

Manufactured by Zanon

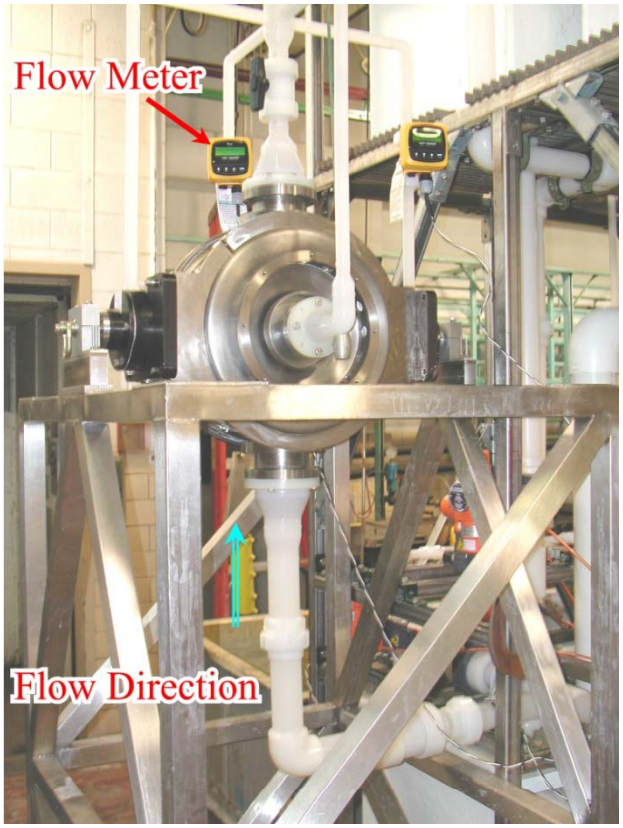
E_{pk}/E_{acc} : 2.82

B_{pk}/E_{acc} : 7.4 mT/MV/m

Improved Buffered Chemical Polishing (BCP) set up $HF:HNO_3:H_3PO_4$=1:1:2 by volume at < 15 ºC

EZ02

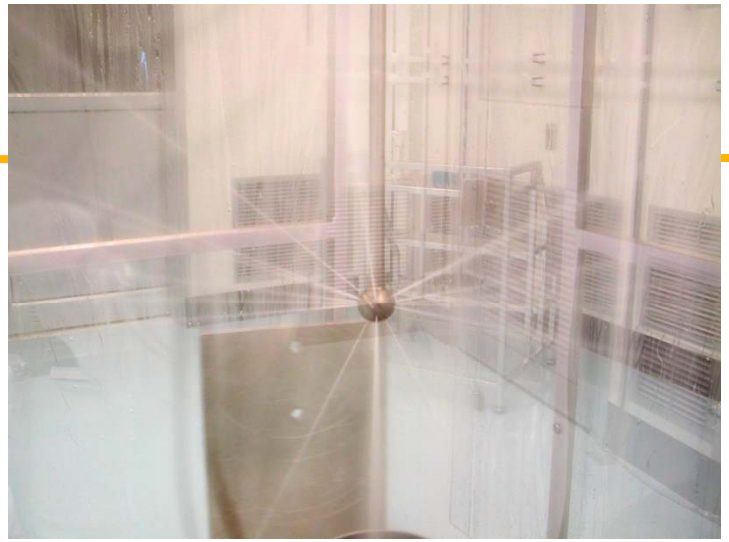
EZ01

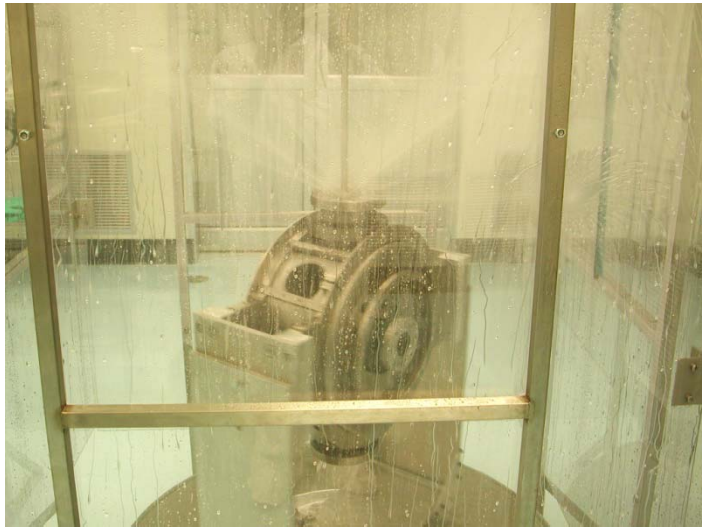


High Pressure Rinsing (HPR)

- **Ultra-pure water**
- **Pressure 1000-1200 psi (69 – 83 bar)**
- **At 4 positions**
  - beam port 1 (10 min.)
  - radial port 1 (10 min.)
  - beam port 2 (10 min.)
  - radial port 2 (20 min.)
- **Sweep speed**
  - Up ~ 4 mm/s
  - Down ~ 7.5 mm/s
- **Table rotation ~ 23 rpm**

Spoke cavity HPR

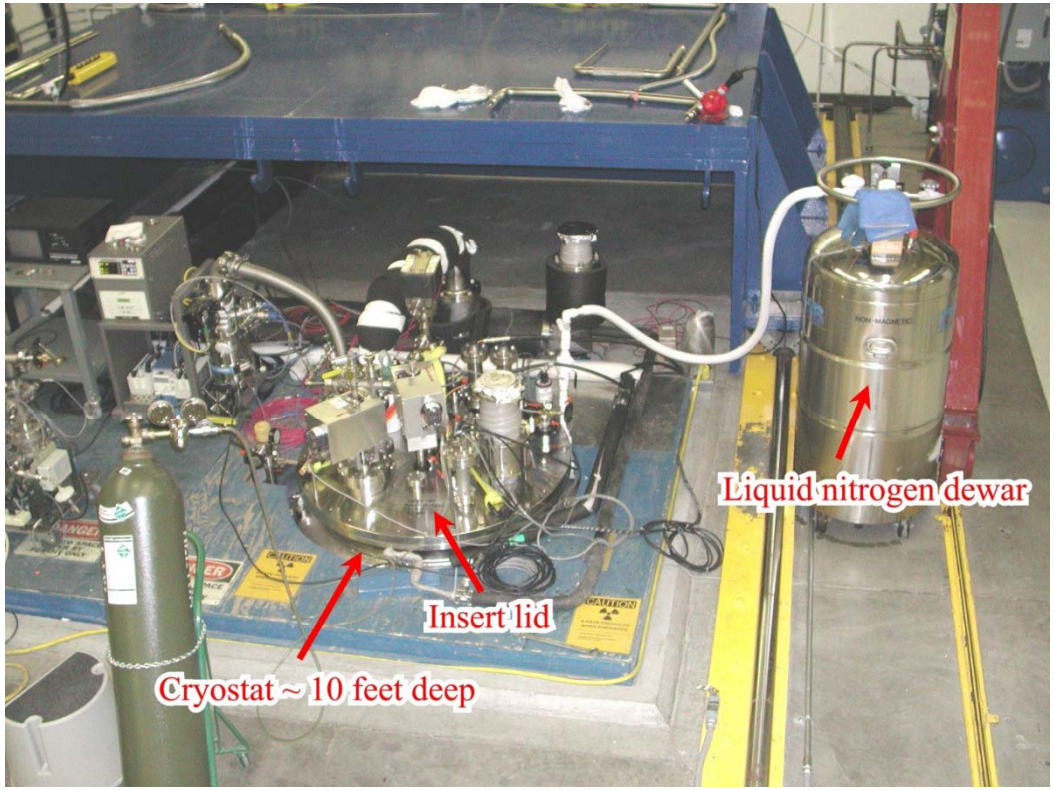




Assembly in the Clean Room

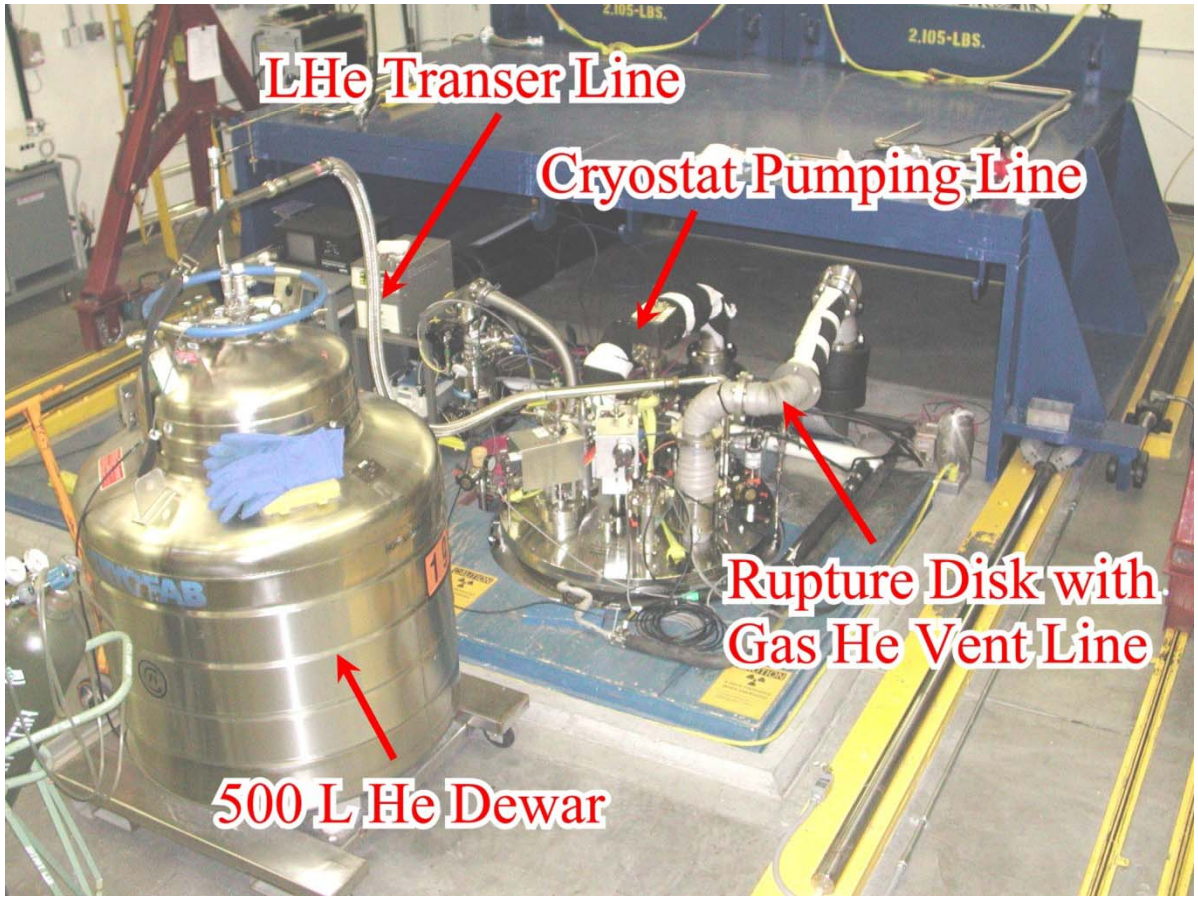
- Clean room class 100
- For tapped holes, anti-seize grease is used
- For through holes, SS bolts and silicon-bronze nuts are used.
- Special polyethylene cover was made to attach indium on the flat surface inside of Conflat knife edge.

Indirect Pre-Cooling with LN



- Fill the vacuum-insulated layer between inner and outer vessel with LN
- This operation is carried out one day before LHe transfer
- When LHe transfer starts, the cavity temperature is ~ 250 K

Helium Transfer and Testing



LANL spoke cavity results and effect of He processing

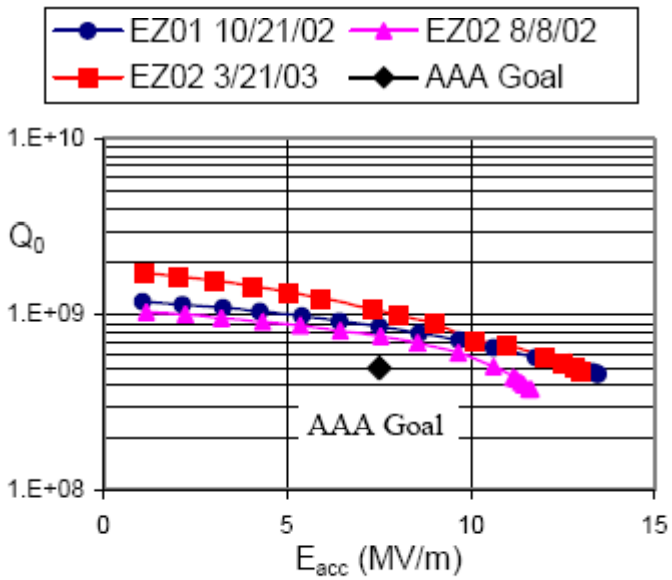


Figure 2: Q_0-E_{acc} curves of the two LANL/AAA cavities at 4 K. Test dates are written in the legend. Repeated high-pressure rinse and helium processing improved the EZ02 result in the second test.

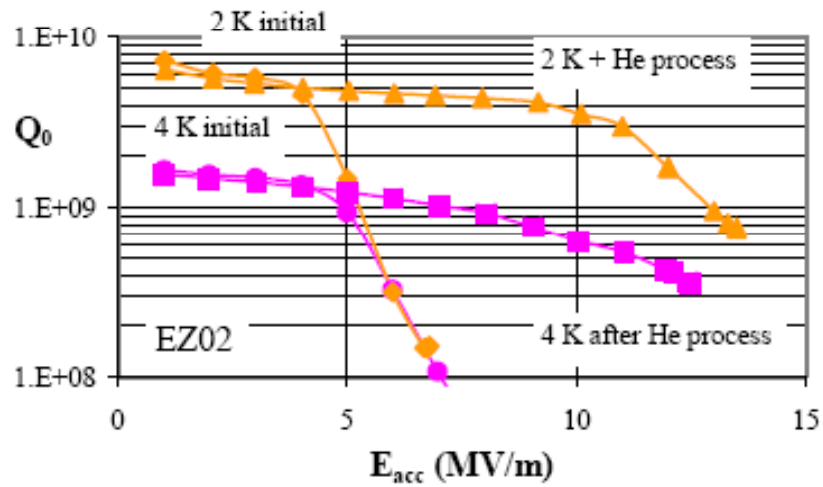


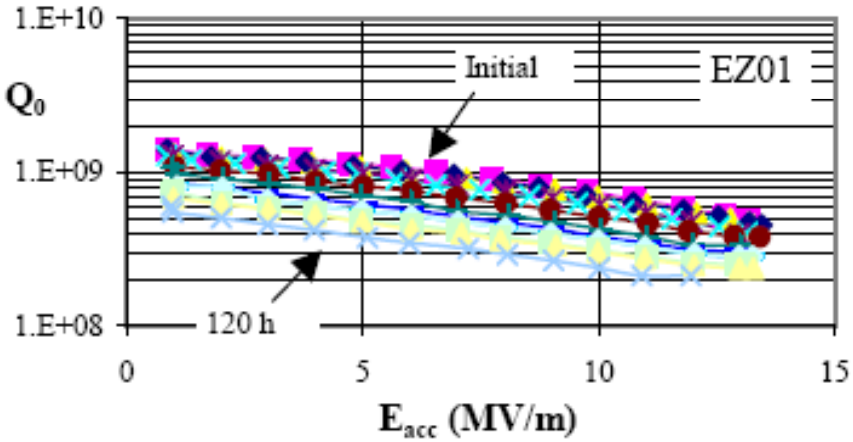
Figure 3: Q_0-E_{acc} curves at 2 K together with 4 K data. The EZ02 data also include the curves before helium processing. After ~12 minutes of helium processing the performance improved drastically.

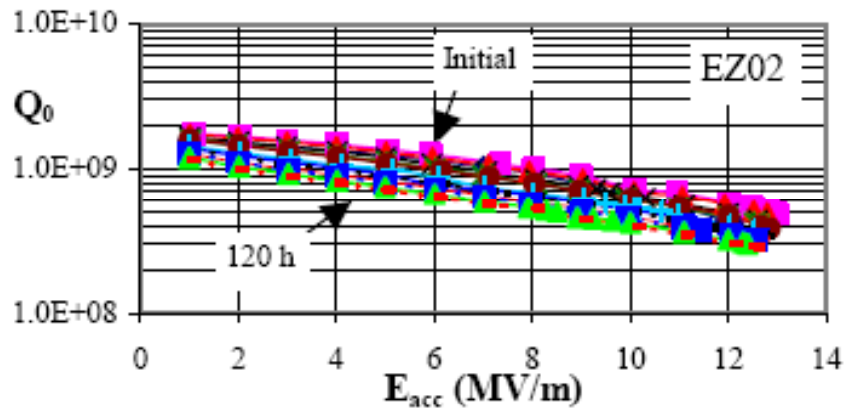
T. Tajima et al., PAC03, Portland, OR

Q_0 disease tests were carried out to check if it occurs with 350 MHz cavities

- Q_0 disease has been tested with 350 MHz spoke cavities
- Spoke cavities made of RRR~250 Nb.
- No high temperature heat treatment. (<150 °C)
- Standard BCP ($HF:HNO_3:H_3PO_4$=1:1:2) ~150 μm at <15°C

Cavities were held at 100 K for up to 120h. A linear increase in additional R_s was observed after 24 hours.





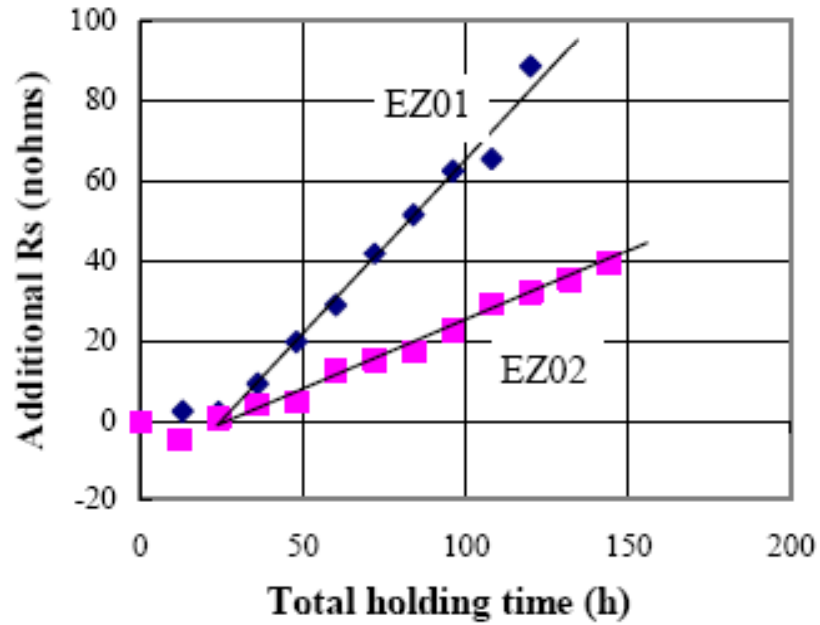


Figure 2: Additional surface resistance due to Q disease as a function of accumulated holding time at 100 K. The data was taken at E_{acc}=4 MV/m.

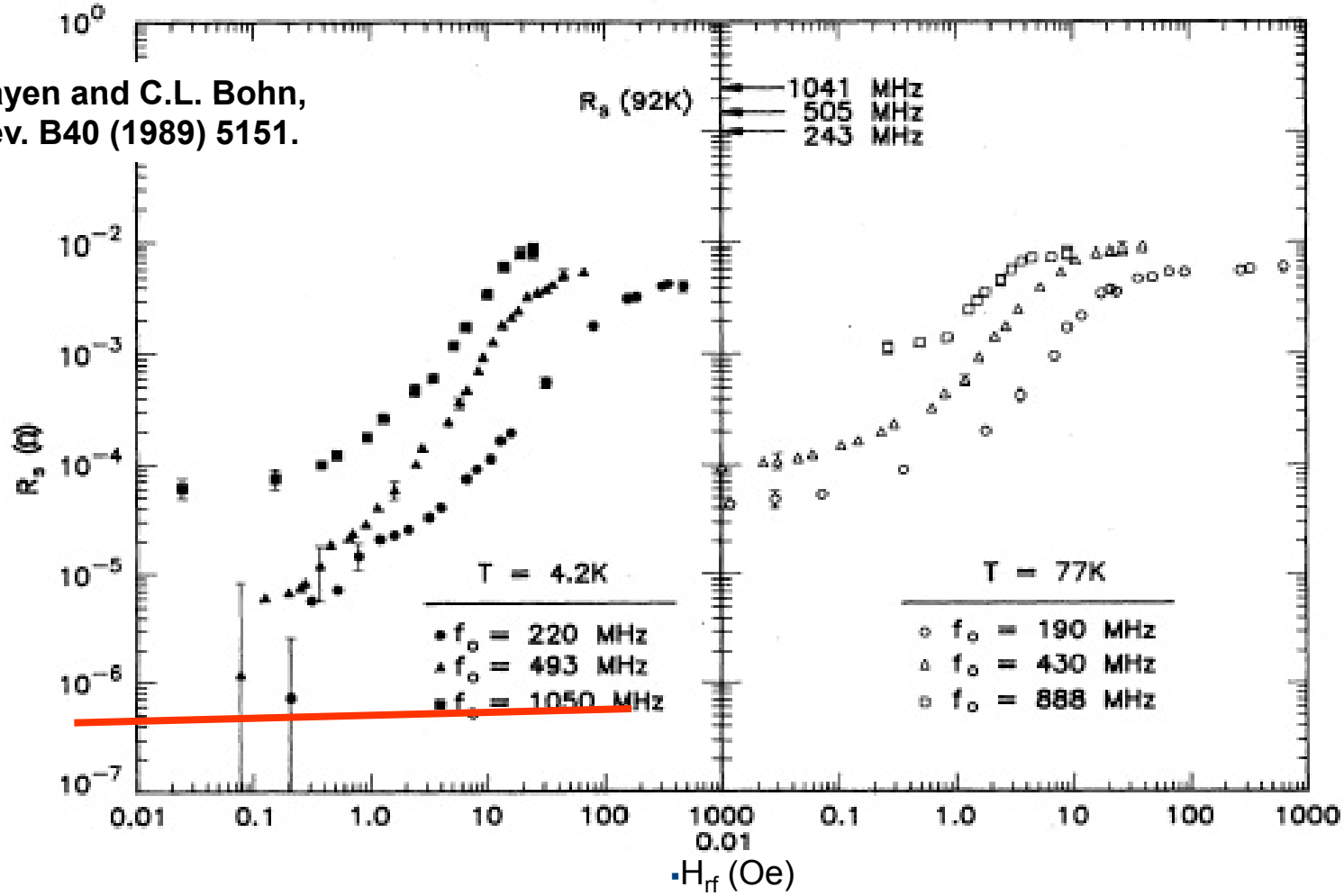
T. Tajima et al, SRF2003, Travemunde, Germany, 2003

Studies on MgB_2 to check its feasibility for accelerator applications

MgB_2 was discovered to be superconductive at 39K in 2001

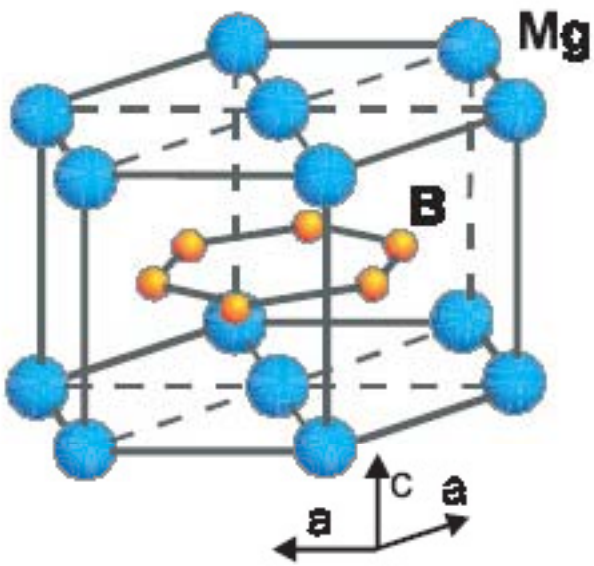
R_s of YBCO: Rapid increase with magnetic field prevented us from using high-T_c materials

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



▪Nb at 1GHz

Magnesium Diboride (MgB_2) : Features

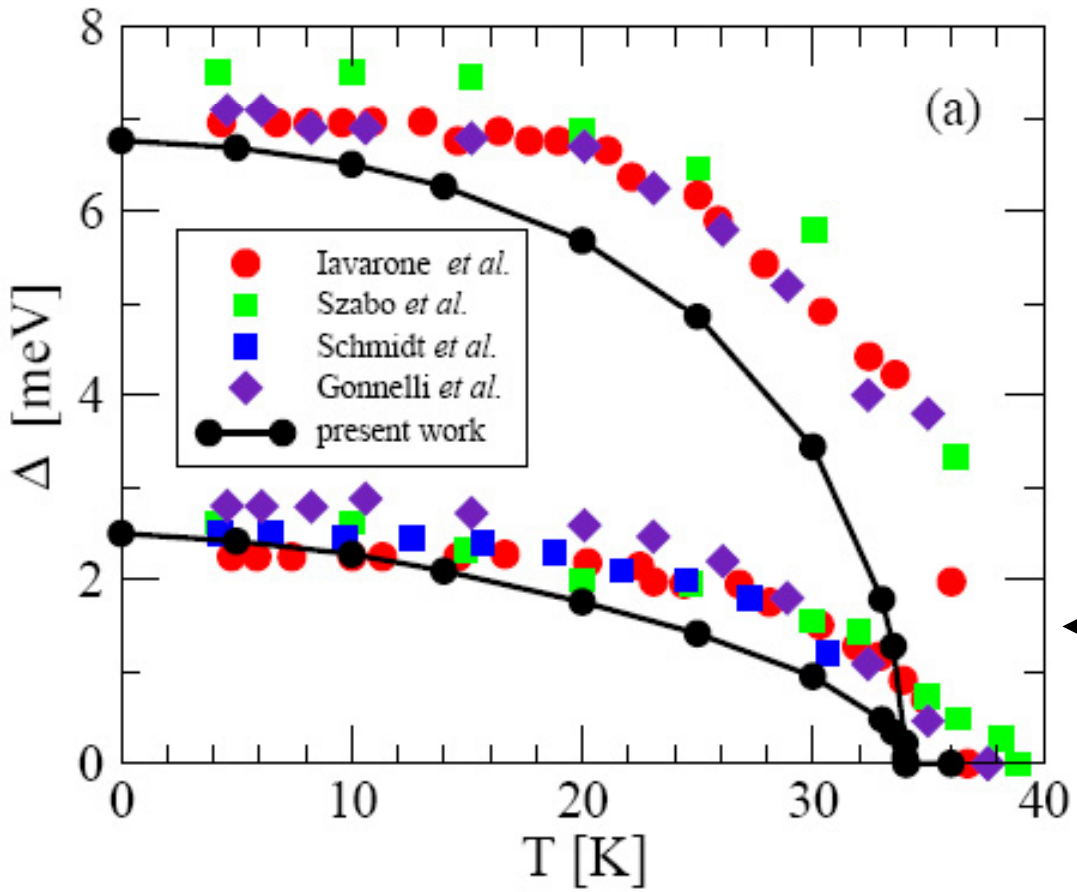


Graphite-type boron layers separated by hexagonal close-packed layers of magnesium

- 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 RF applications.

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

MgB_2 has two energy gaps. Unfortunately, the lower energy gap has been indicated for RF applications.

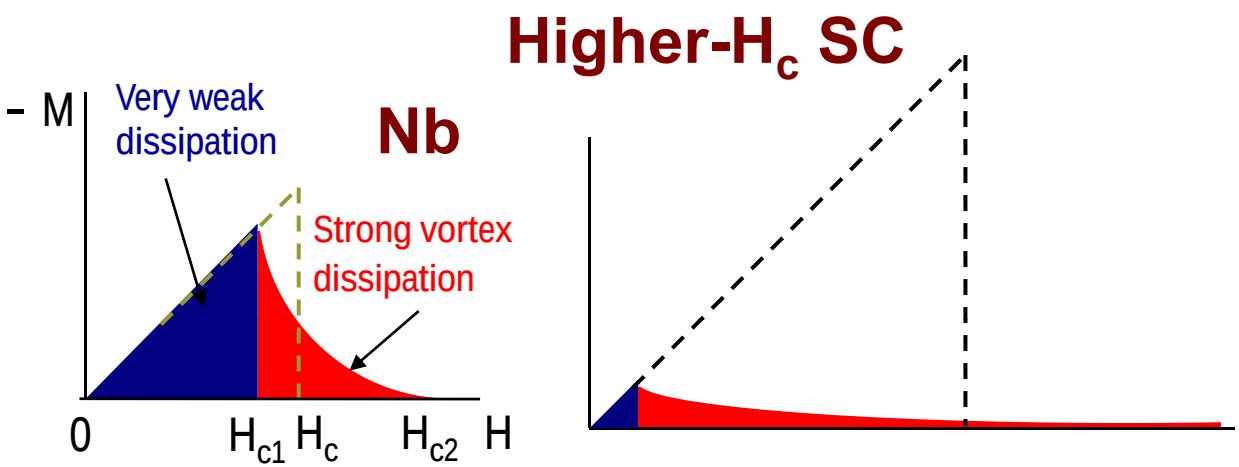


RF response has shown lower energy gap behavior.

Nb

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

What is the characteristics of MgB_2 compared to other materials?



Very weak dissipation at $H < H_{c1}$ ($Q = 10^{10}$-10^{11})
Q drop due to vortex dissipation at $H > H_{c1}$

Nb has the highest lower critical field H_{c1}

Material	T_c (K)	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
Pb	7.2	0.08	na	na	48
Nb	9.2	0.2	0.17	0.4	40
Nb_3Sn	18	0.54	0.05	30	85
NbN	16.2	0.23	0.02	15	200
MgB_2	40	0.43	0.03	3.5	140
YBCO	93	1.4	0.01	100	150

$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

Thermodynamic critical field H_c (surface barrier for vortices disappears)

$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda\xi}$$

A. Gurevich,Thin film Workshop, Padova, Italy, October 2006

Thin film superconductor and its benefit

- **For thin films:**

Enhanced lower critical field and surface barrier in films

Use thin films with d < λ to enhance the lower critical field

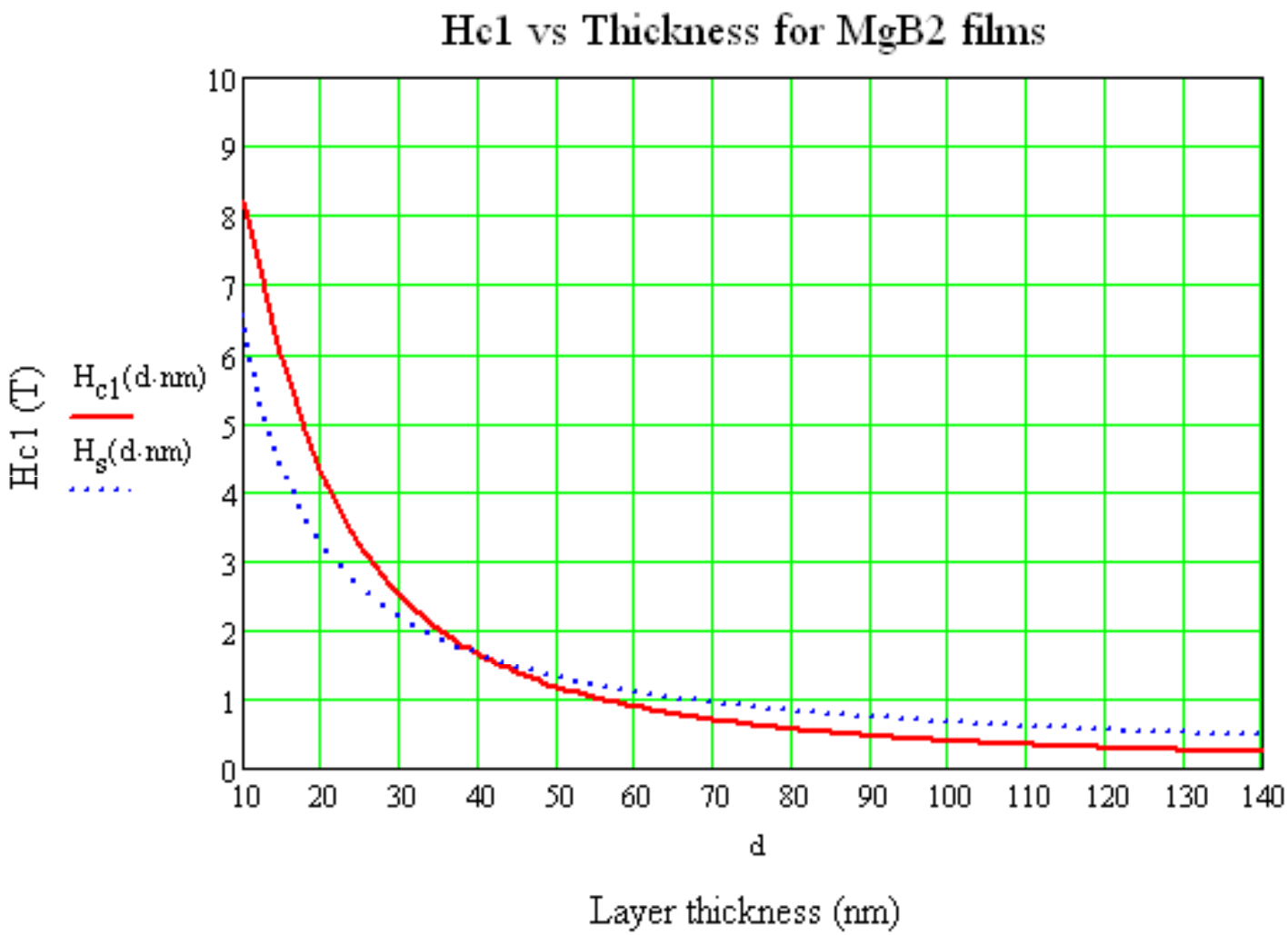
$$H_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} - 0.07\right)$$

where Φ_0, ξ are the fluxon and coherence length, respectively.

Field at which the surface barrier disappears

$$H_s = \frac{\phi_0}{2\pi d\,\xi}$$

MgB_2 : enhancement of H_{c1} with very thin film



What gradient can we get theoretically?

Simple example

- **Assumptions**

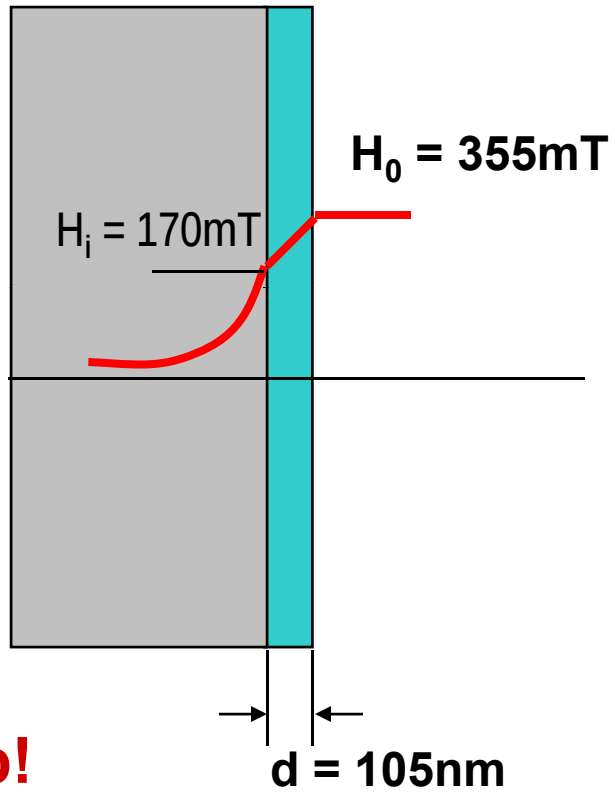
  Hc1(Nb) = 0.17T

  $\lambda(MgB_2)$ = 140nm

  $\xi(MgB_2)$ = 5nm

  What is the optimum [d,Hc1(MgB_2)] ?

- Hc1(MgB_2) = 355mT
- d=105nm



2x greater than Nb!
No vortex penetration
Eacc ≈ 100MV/m

What we can observe during the tests of MgB_2

- **$d < d_{opt}$**
  - Quench due to Nb substrate
- **$d > d_{opt}$**
  - Quench due to MgB_2 layer
- **Therefore, the key is to determine d_{opt}**

  Given a MgB_2 coating method:
  - Accurate determination of λ and ξ
  - Calculation of d_{opt} using previous formulas

MgB_2 Coating methods

- **What is the most suitable coating method for SRF cavities?**

Ongoing research:

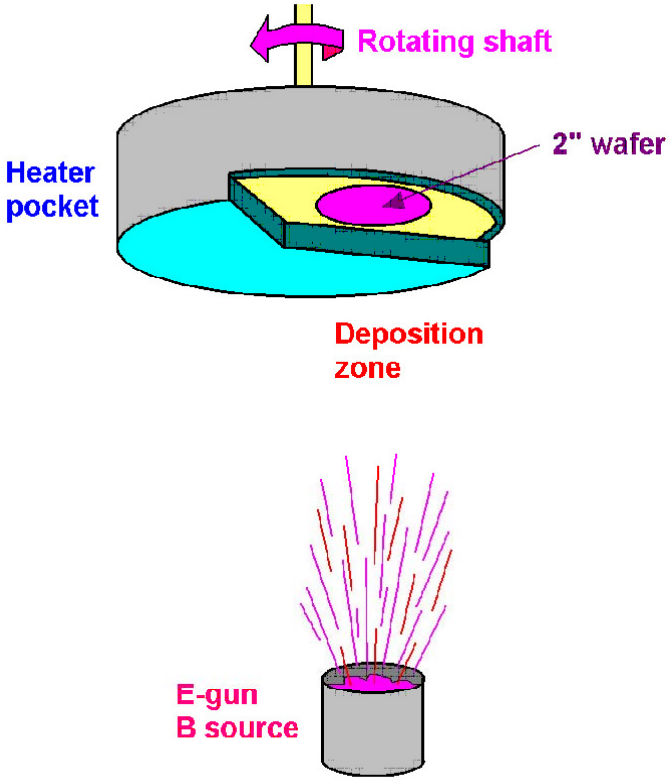
- **RE – Reactive Evaporation**

  Superconductor Technologies, Inc. (STI)
- **PAD – Polymer-Assisted Deposition**

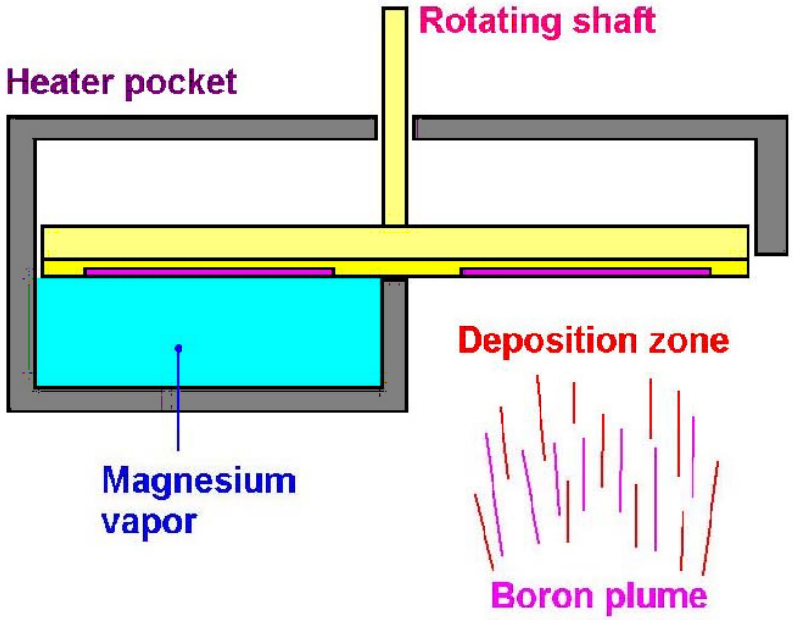
  Superconductivity Technology Center at LANL
- **HPCVD – Hybrid Physical-Chemical Vapor Deposition**

  Pennsylvania State University

RE at STI (B. Moecly et al.)



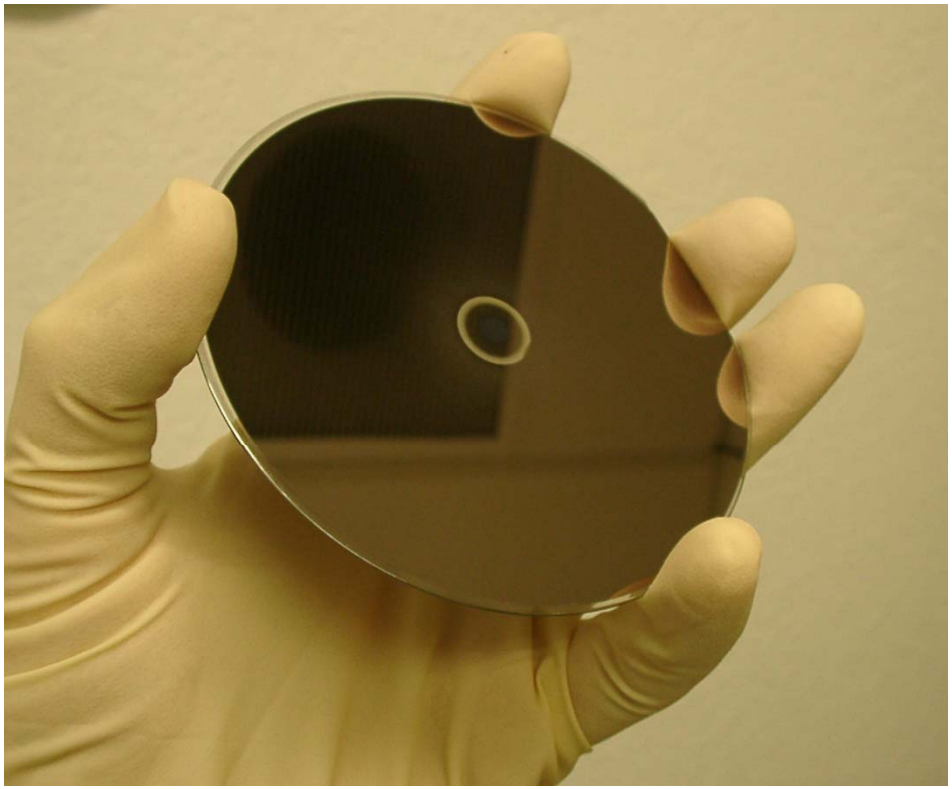
In-situ reactive evaporation



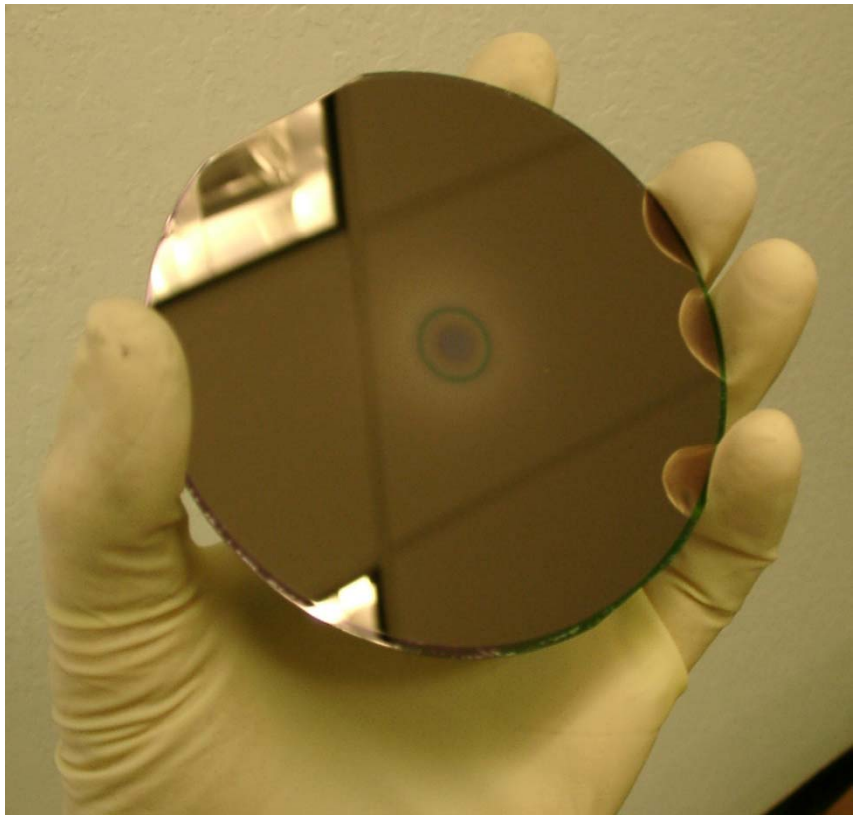
More details are found in
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al, Proc. PAC05.

RE at STI (B. Moecly et al.)

R-plane sapphire



Si_3N_4 / Si

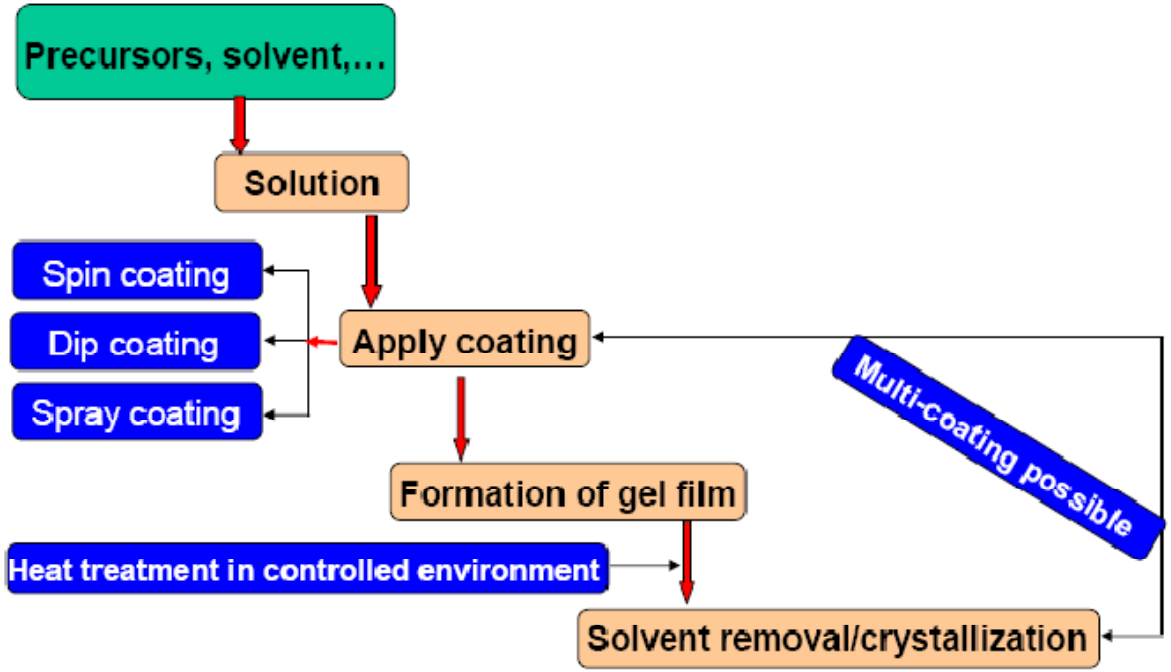


B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

PAD at LANL (Q. Jia et al.)

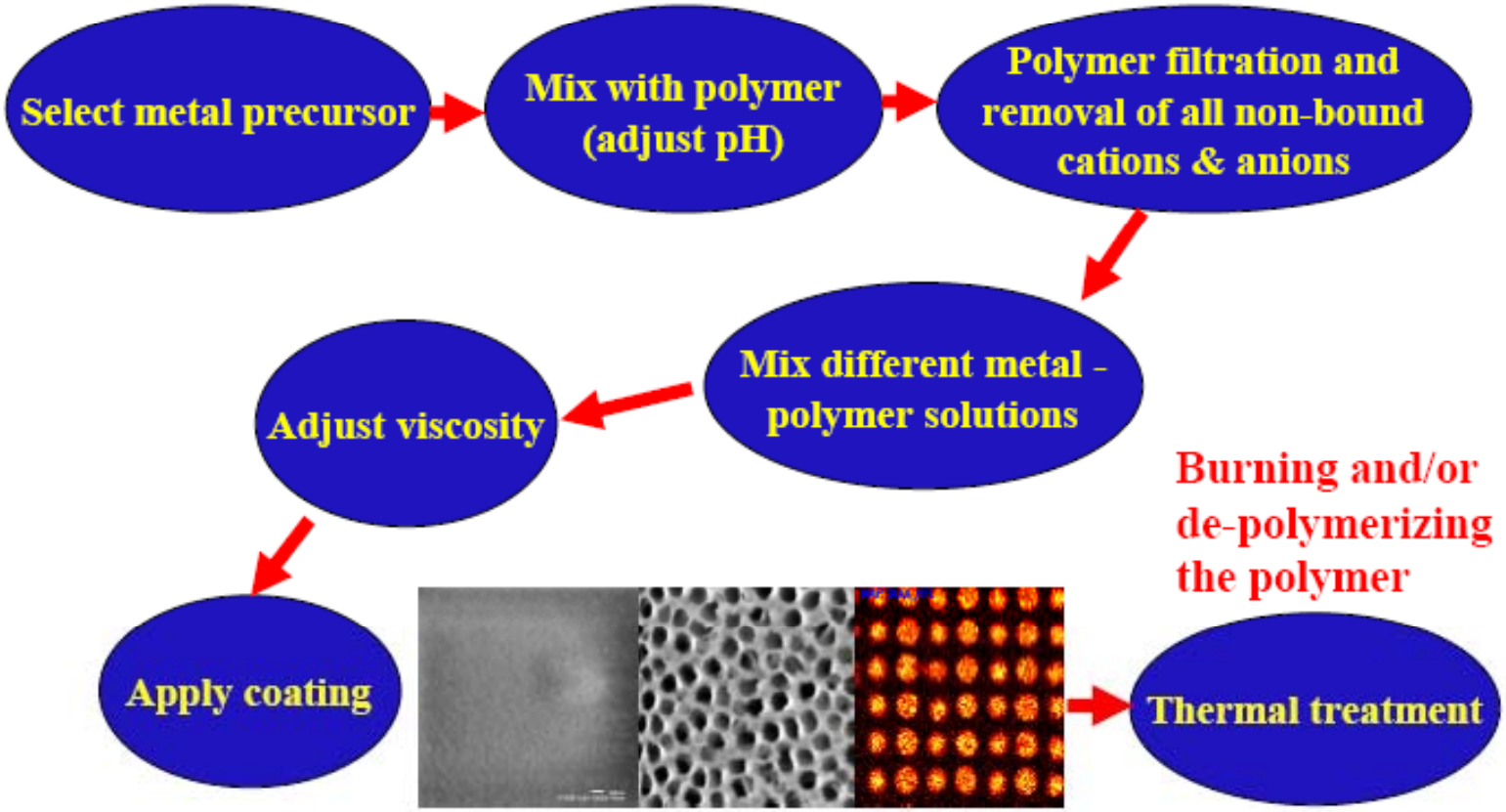
- A chemical solution technique to deposit films of nearly any metal-oxide using aqueous solution by mixing metal precursors with water-soluble polymers
- Polymer plays a critical role in metal-oxide films

Typical chemical solution deposition process flowchart



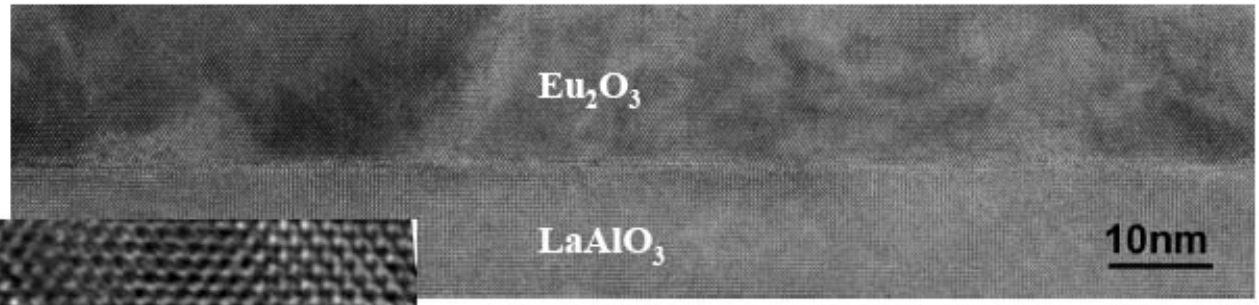
PAD at LANL (Q. Jia et al.)

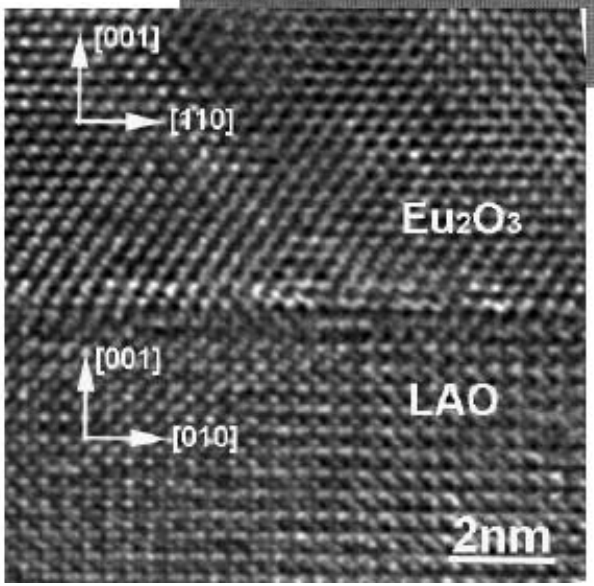
- **Process**

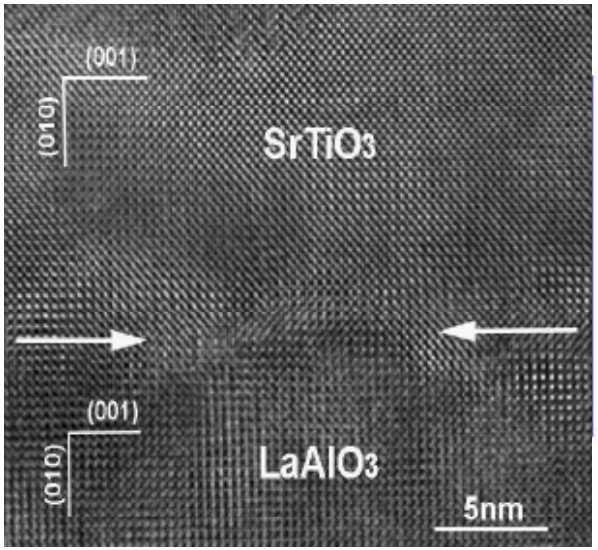


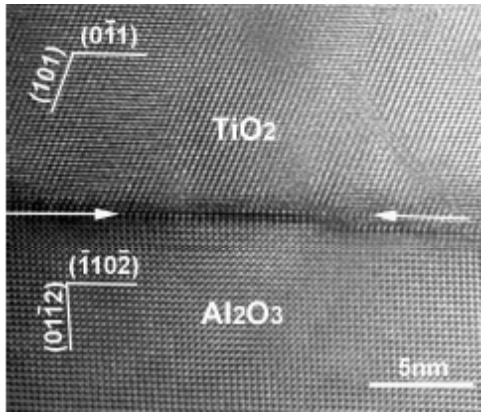
PAD at LANL (Q. Jia et al.)

- **Examples**



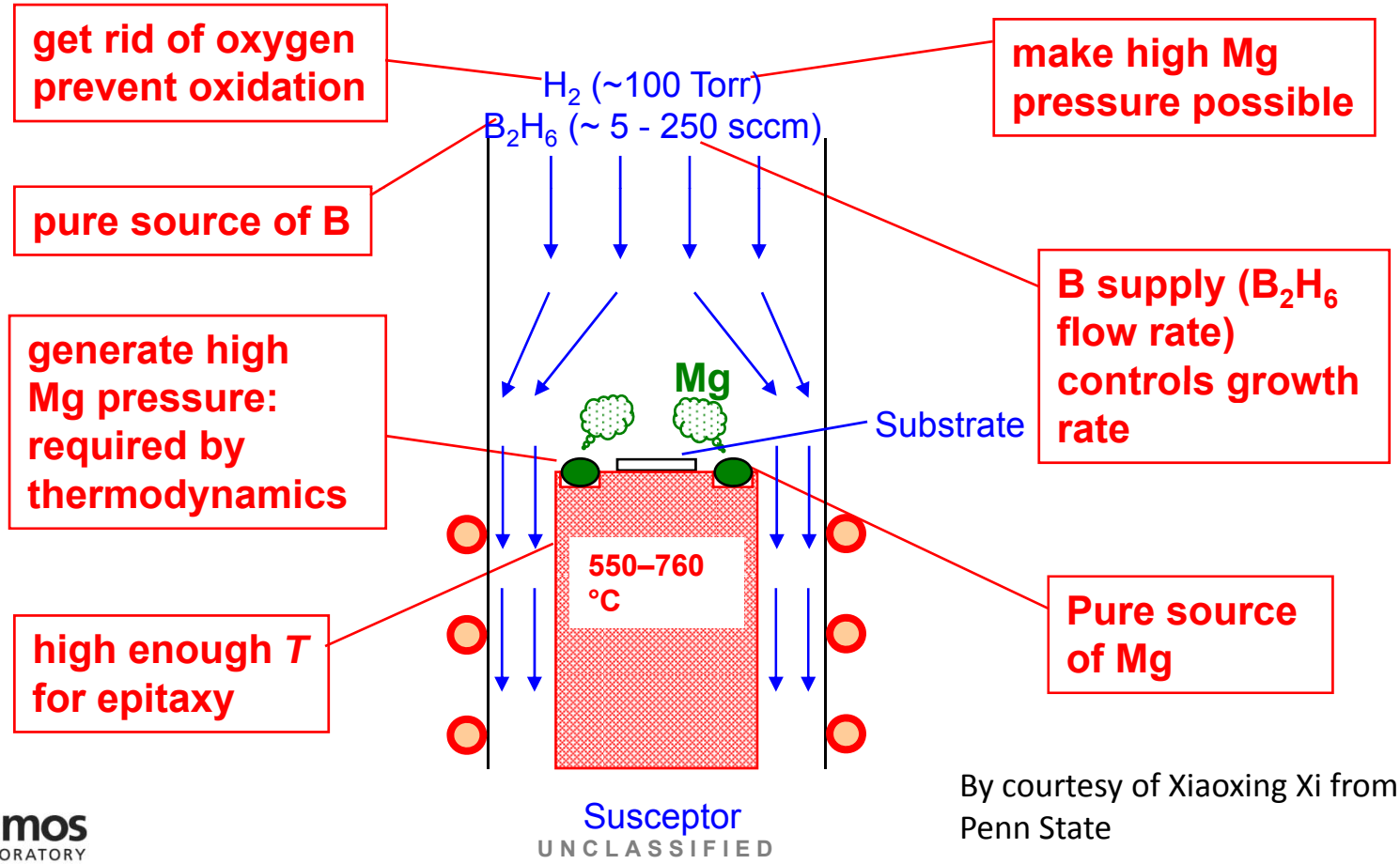






HPCVD at PSU (X. Xi et al.)

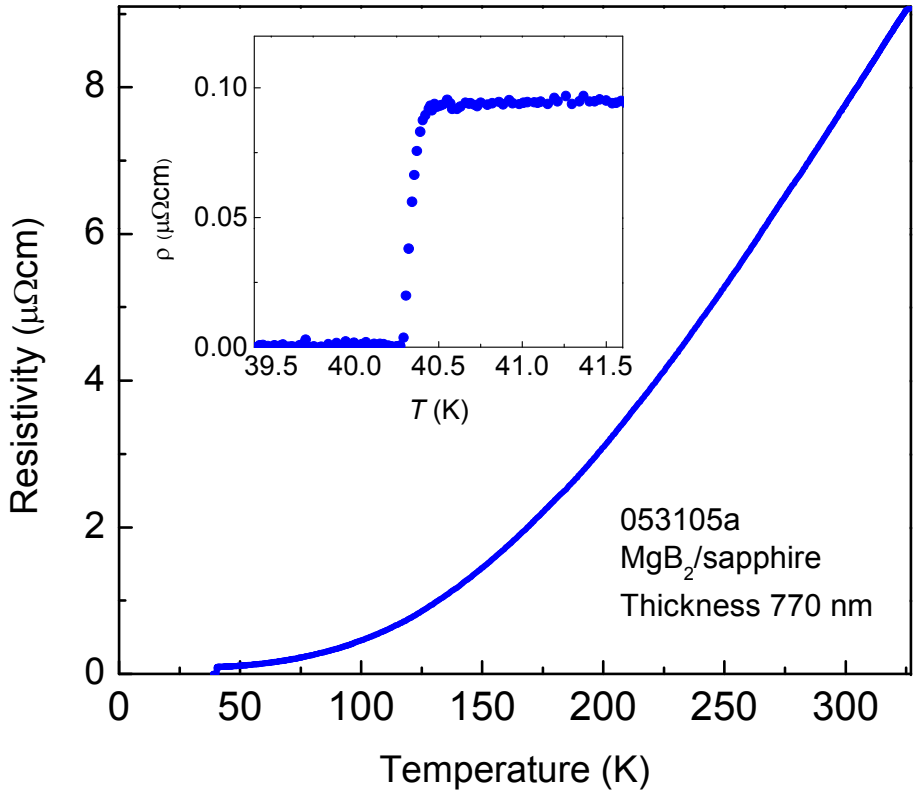
Schematic View



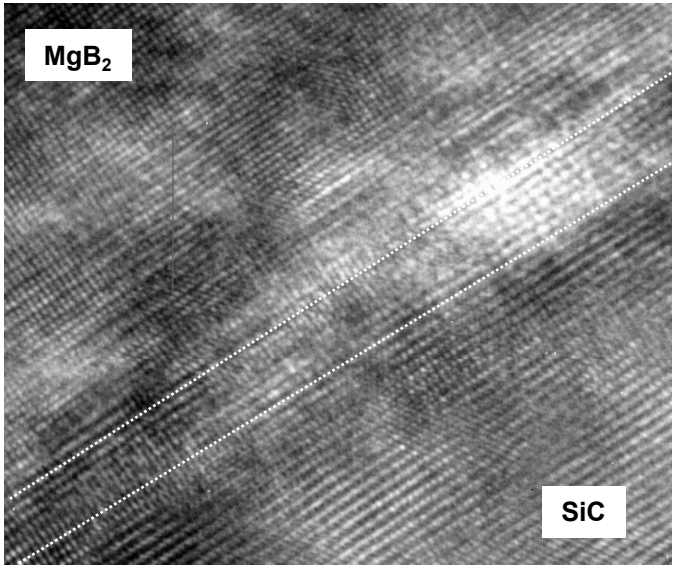
By courtesy of Xiaoxing Xi from Penn State

HPCVD at PSU (X. Xi et al.)

- **Example of epitaxial MgB2 Films by HPCVD: *RRR* > 80**

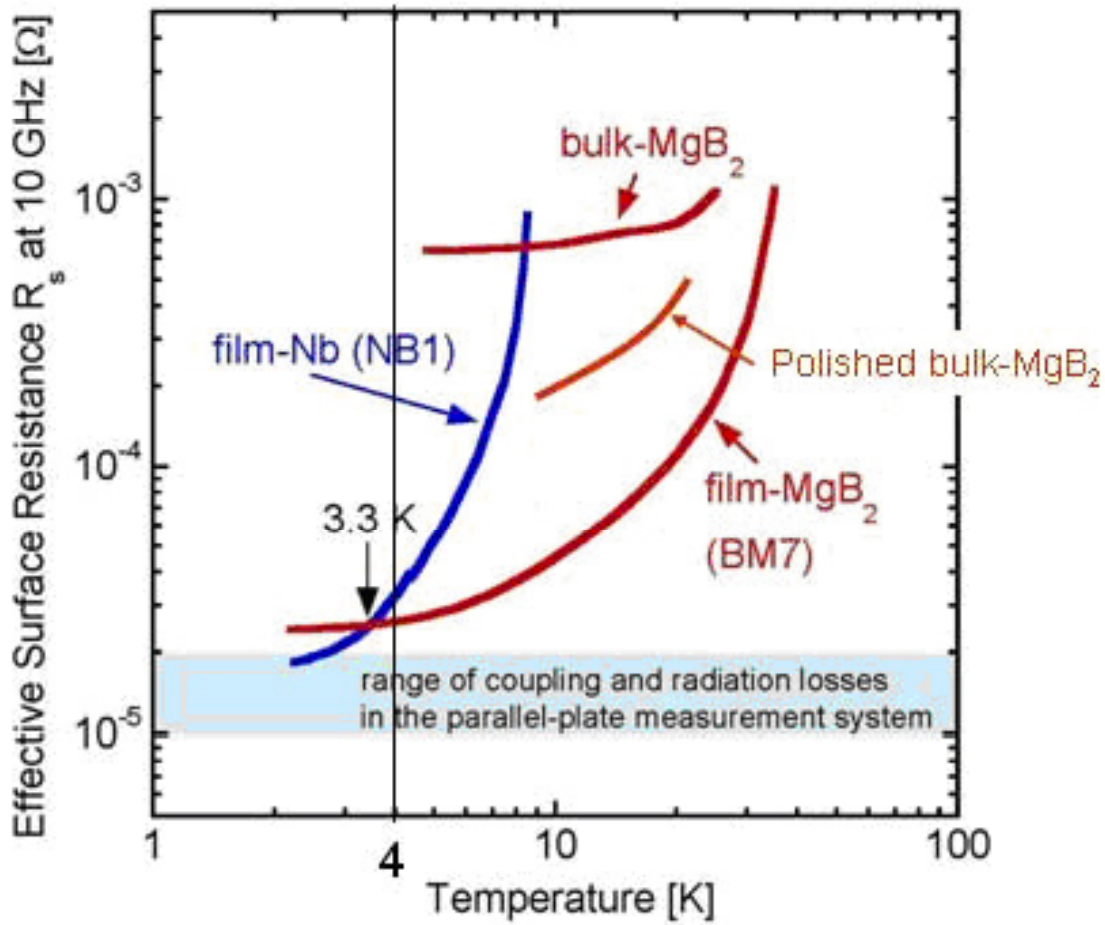


interface



RF Surface Resistance (R_s) at 10 GHz: LANL results with samples from STI (film) and UCSD (bulk)

- **R_s lower than Nb at 4K**
- **Still residual resistance dominates at low temperatures**

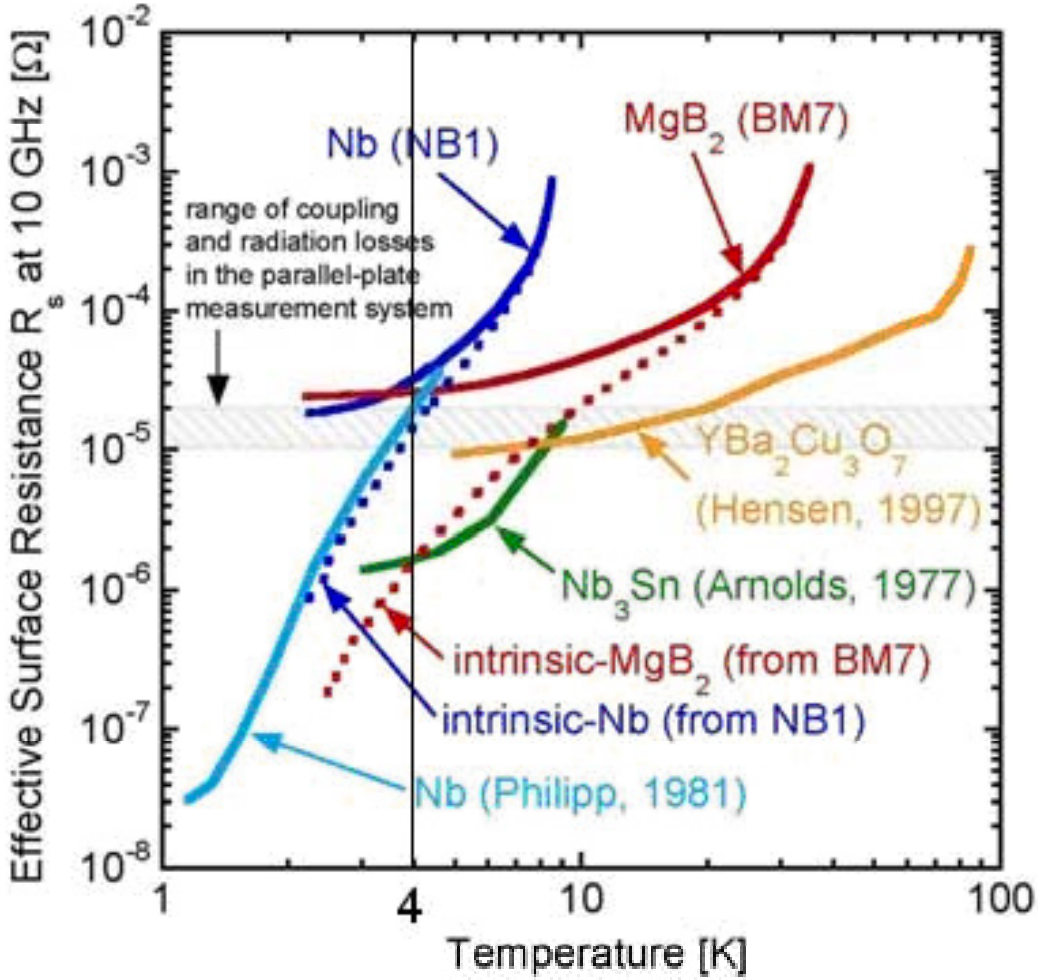


- A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.
- B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
- T. Tajima et al., Proc. PAC05.

- Generally, $R_s \propto f^2$ at $T<T_c/2$

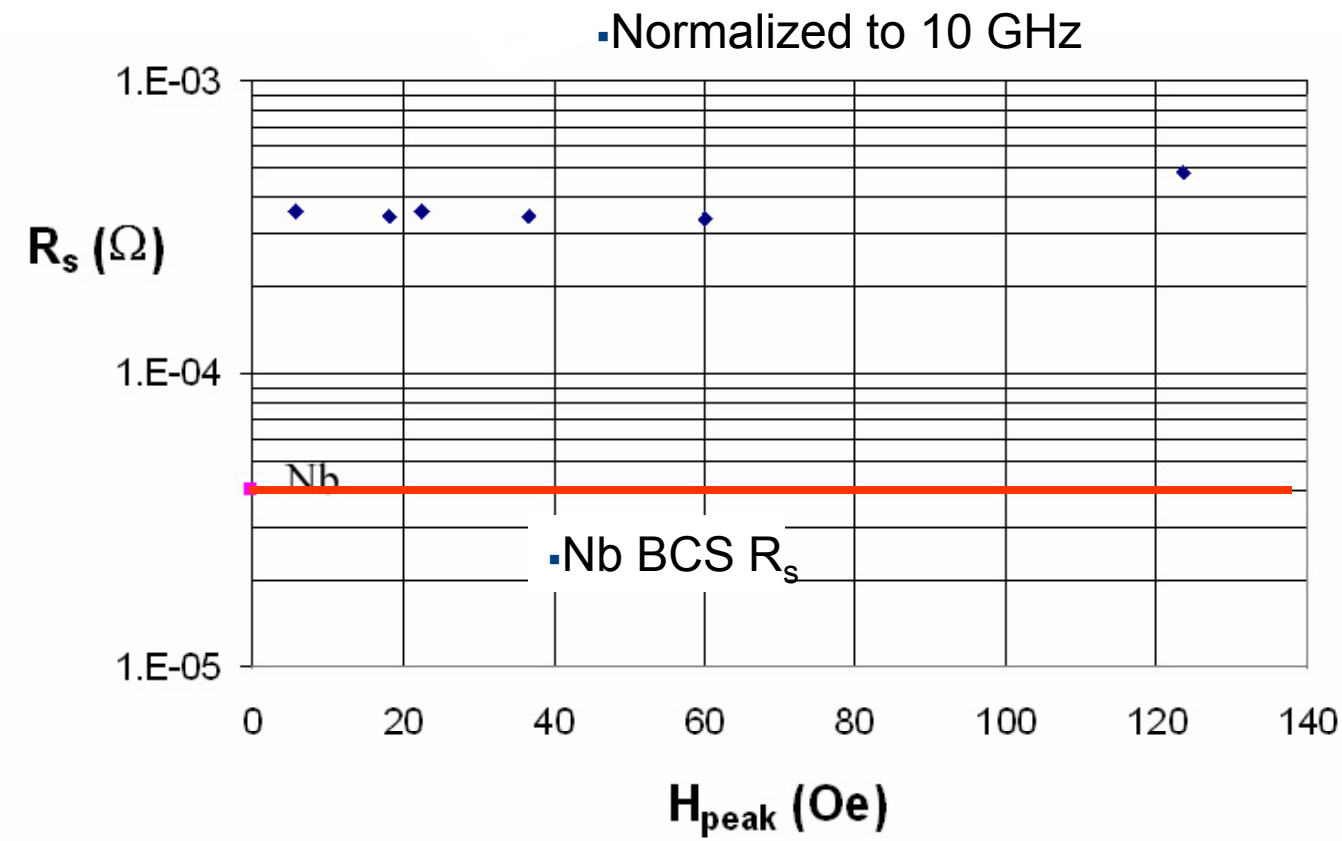
RF Surface Resistance (R_s) at 10 GHz: LANL measurements compared to the data from other references, and prediction

- **Dotted line is the predicted BCS resistance by subtracting the residual resistance (temperature independent)**



- 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 Power Dependence Test of the sample coated on a rough Nb disk at STI with reactive evaporation method



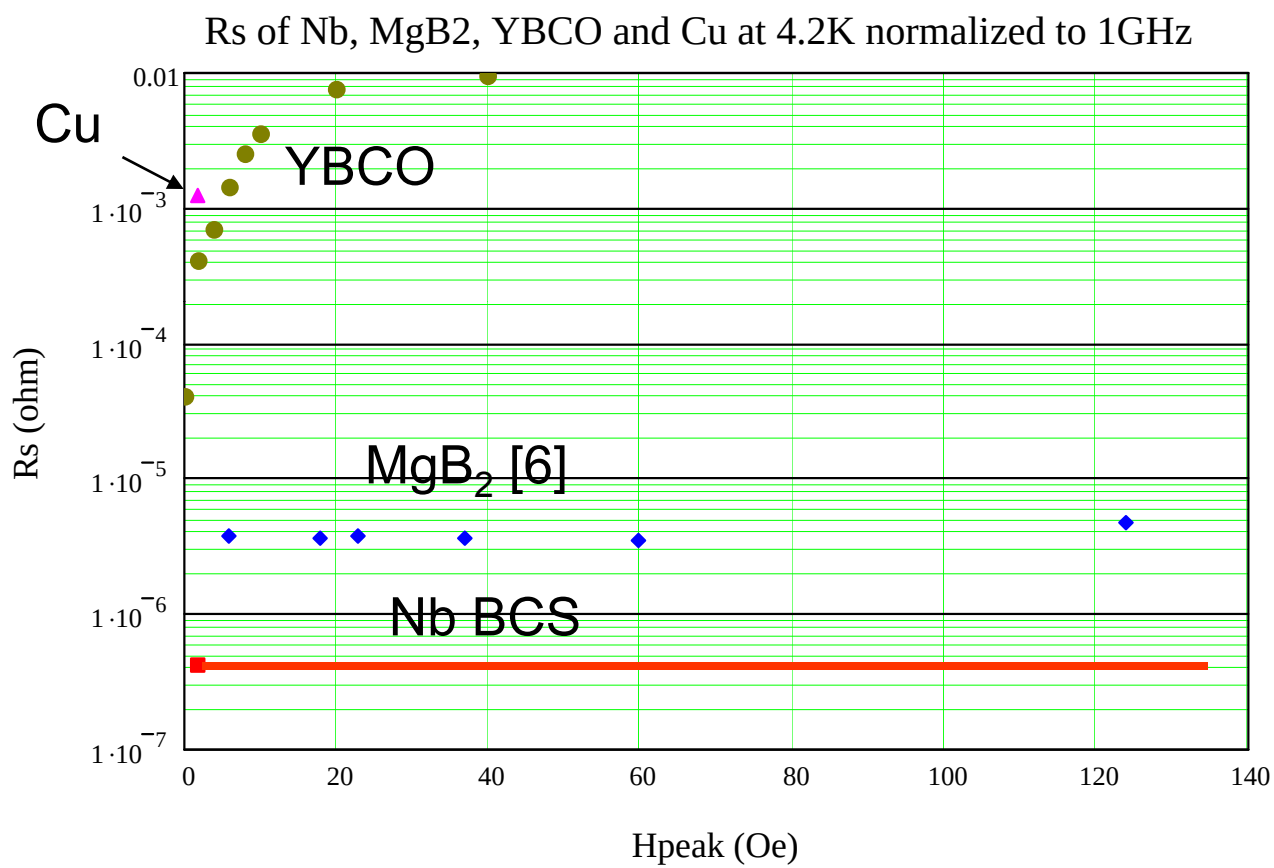
- First attempt to coat on a Nb substrate (1.5 cm disk).

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

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

- T. Tajima et al., Proc. PAC2005, p. 4215

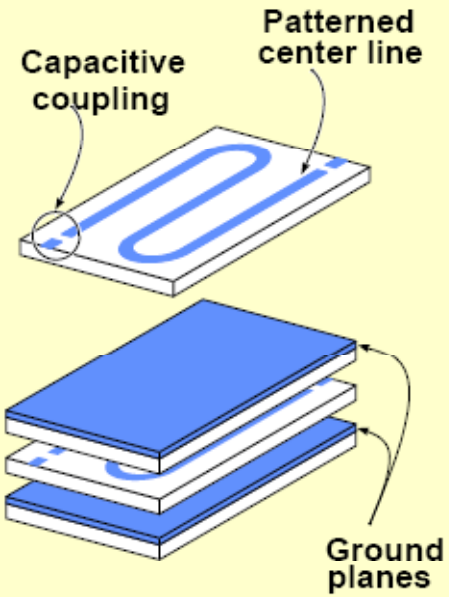
R_s Power Dependence Test at Cornell, compared to the R_s of YBCO and Cu, results normalized to 1 GHz



Recent results from MIT with STI films are very encouraging!! [D. Oates et al., ASC2006]

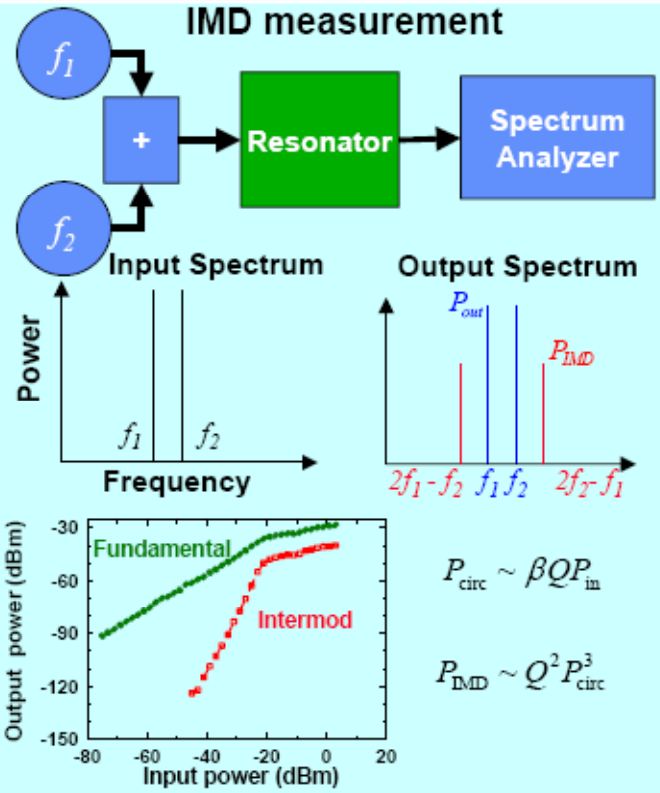
Measurement Methods

Stripline resonator



Used for measurement of $Z_S(I_{rf}, T, f)$, intermodulation distortion, and 3rd harmonic generation.

IMD measurement



$$P_{circ} \sim \beta Q P_{in}$$

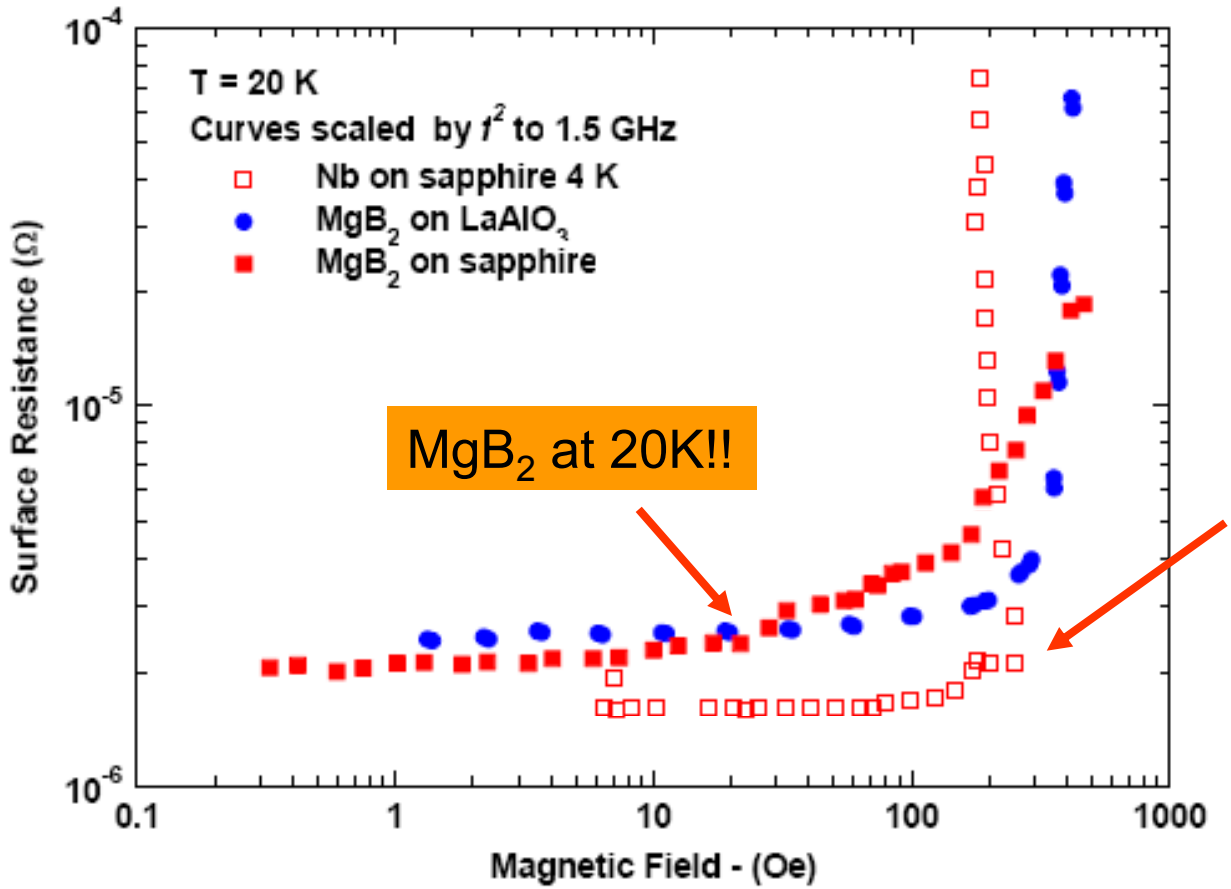
$$P_{IMD} \sim Q^2 P_{circ}^3$$

SUPERCONDUCTOR TECHNOLOGIES

MIT Lincoln Laboratory

ASC MgB2-7
D.E.Oates 10/4/2006

Recent results at MIT shows an R_s comparable to Nb even at 20 K! and does not show significant increase until ~400 Oe, equivalent of ~10 MV/m SRF cavity!!



- Coated at STI with reactive evaporation
- Thickness: 500 nm

Nb at 4.2 K, enhanced field at the edges may have caused this low take off.

[D. Oates et al., ASC2006]

R_s Power dependence tests at various temperatures at MIT: The R_s at 5K is lower than that of Nb at 4.2K!, although it seems to increase faster at higher fields

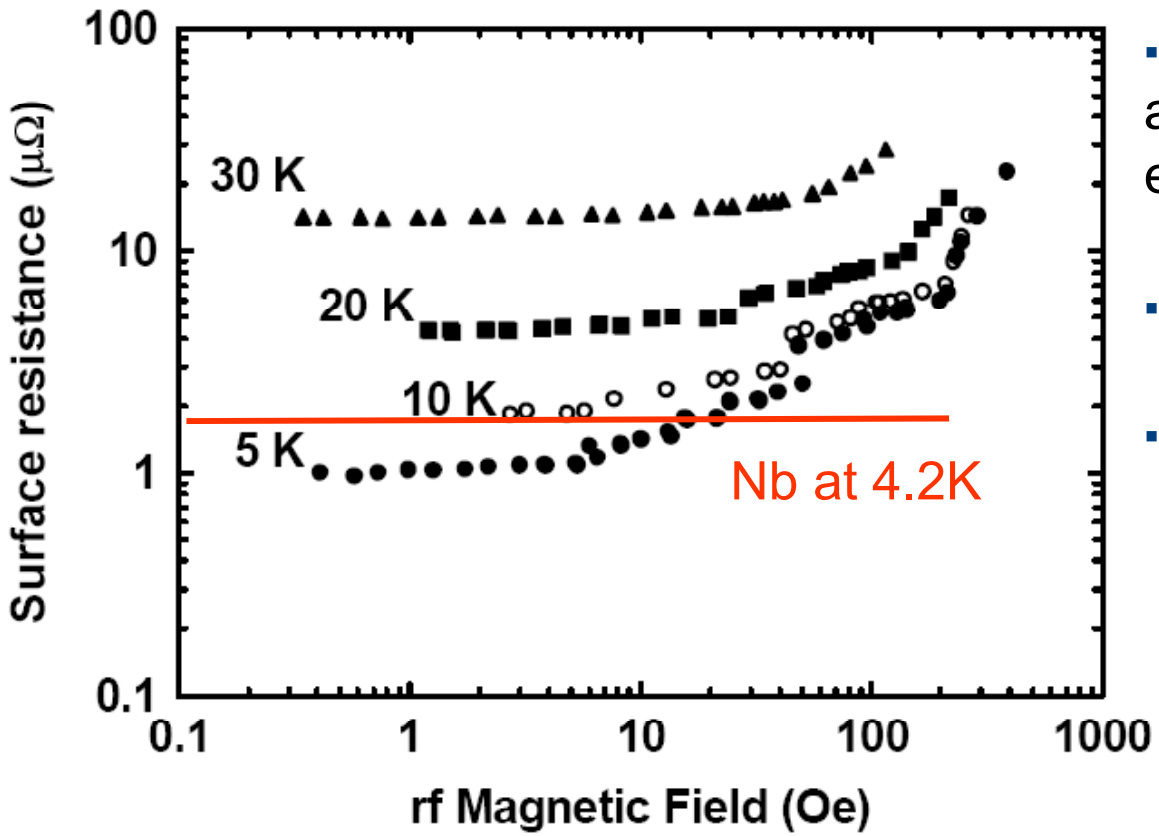


Fig. 3. R_S vs H_{rf} at several temperatures as indicated on the graph.

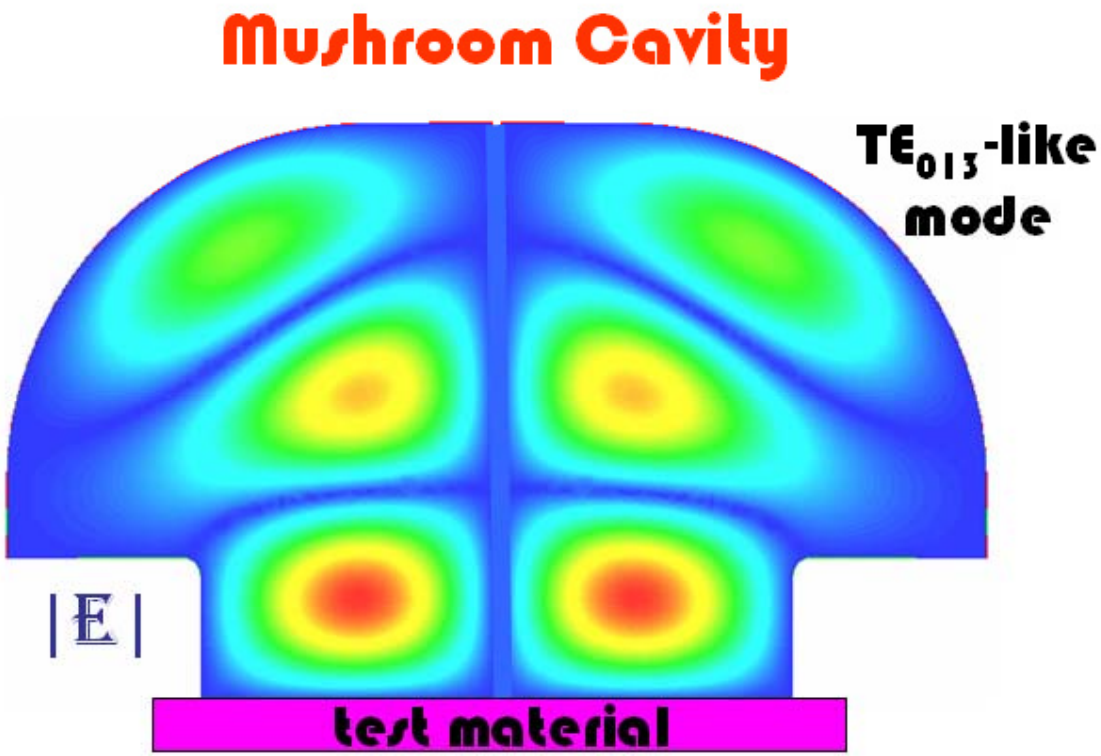
- Coated on Sapphire at STI with reactive evaporation
- Thickness: 500 nm
- Scaled to 1.5 GHz

[D. Oates et al., ASC2006]

RF Critical Magnetic Field Measurement in collaboration with SLAC [Sami Tantawi et al.]

- **Superconducting materials test cavity**
  - No surface electric fields (no multipacting)
  - Magnetic field concentrated on bottom (sample) face
- **<u>X-band</u> (~11.424 GHz):**
  - high power available
  - fits in cryogenic Dewar
  - Relatively large (2-3”) samples required

RF Critical Magnetic Field Measurement at SLAC [Sami Tantawi et al.]

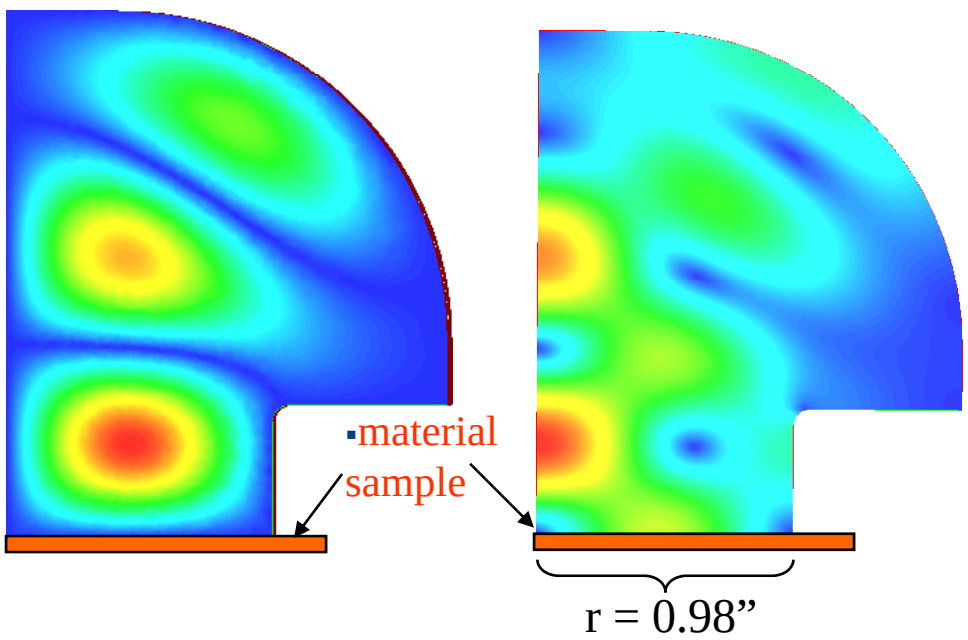


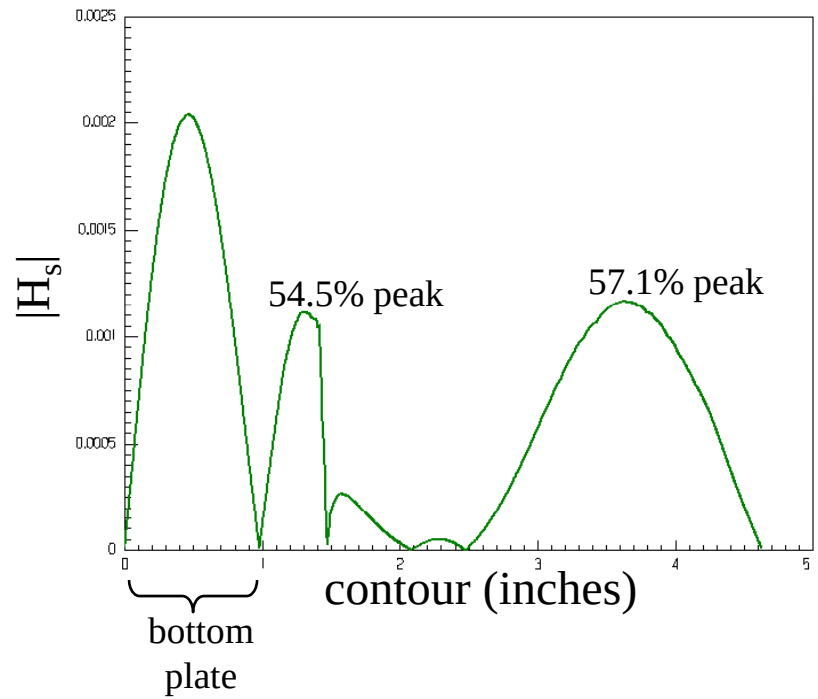
Quench is detected by the change of cavity Q_0

RF Critical Magnetic Field Measurement at SLAC [Sami Tantawi et al.]

TE_{013}-like mode

|E| Q_0=~45,000 (Cu) |H|





RF Critical Magnetic Field Measurement at SLAC

Issues and plans

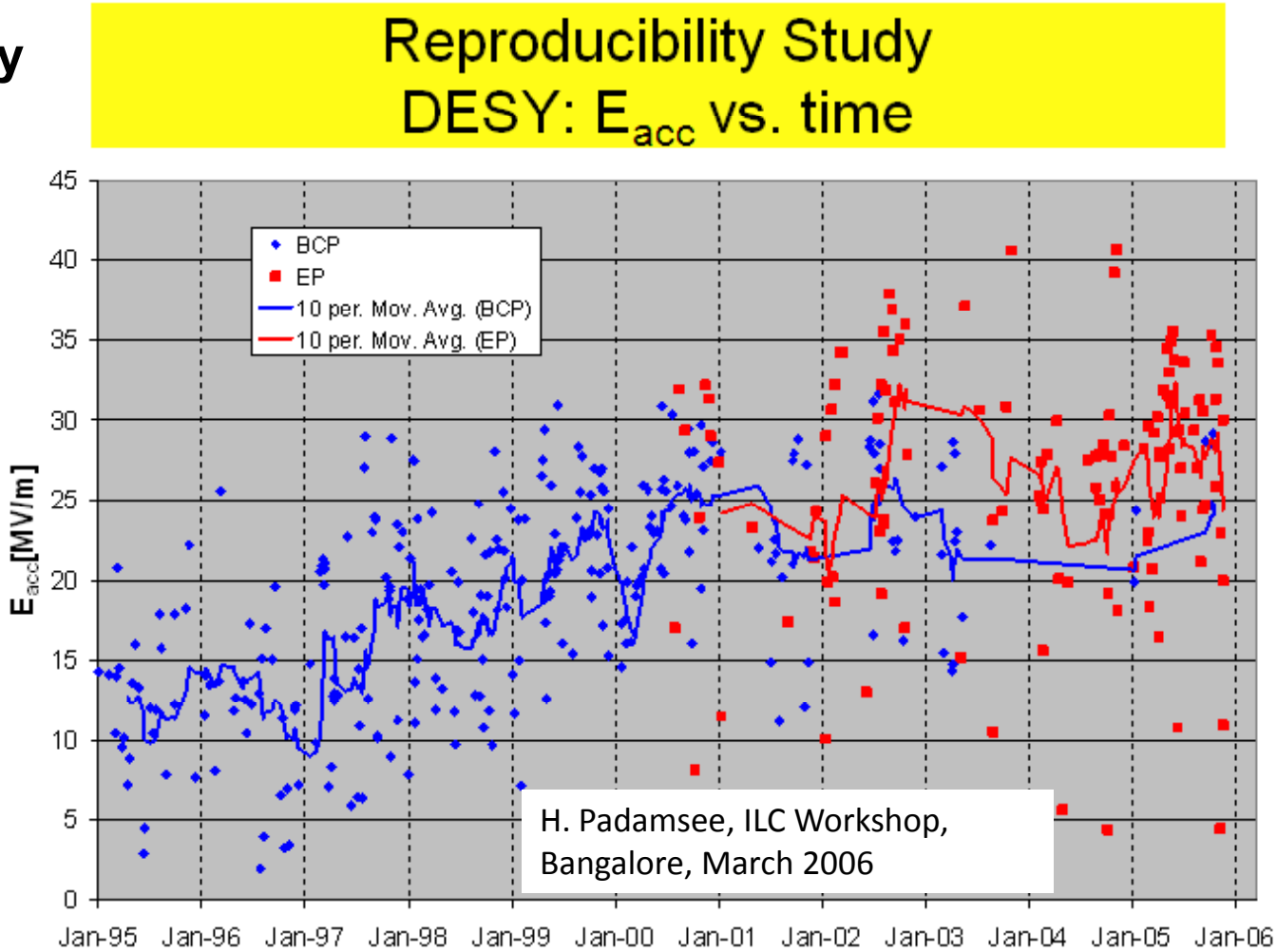
- Calibration of the system for absolute measurements seems not easy
- However, it is still valid when compared to Nb as a relative measurement
- Measurement of Nb, done once, to be done again with new configuration
- Measurement of thin film MgB_2… to be tested in August or September 2007
- Single crystal Nb will also be tested soon.

ILC work started from June 2007

We plan to help understand the scatter of cavity performance and propose some ideas for better yield and methods of improving bad cavities

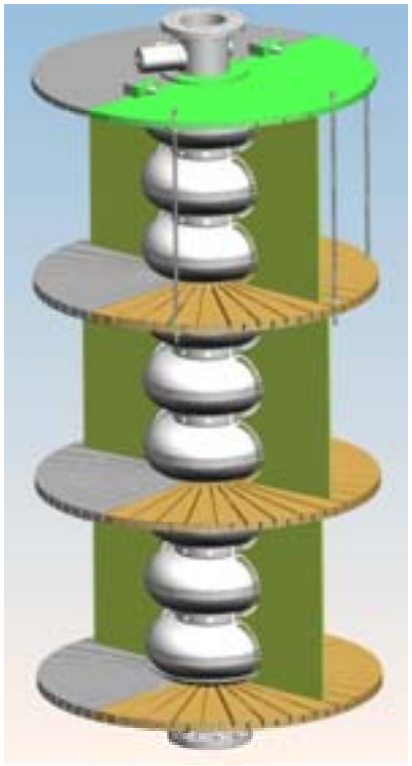
1.3 GHz, 9-cell SRF cavities performance has been widely scattered

TESLA type cavity



H. Padamsee, ILC Workshop, Bangalore, March 2006

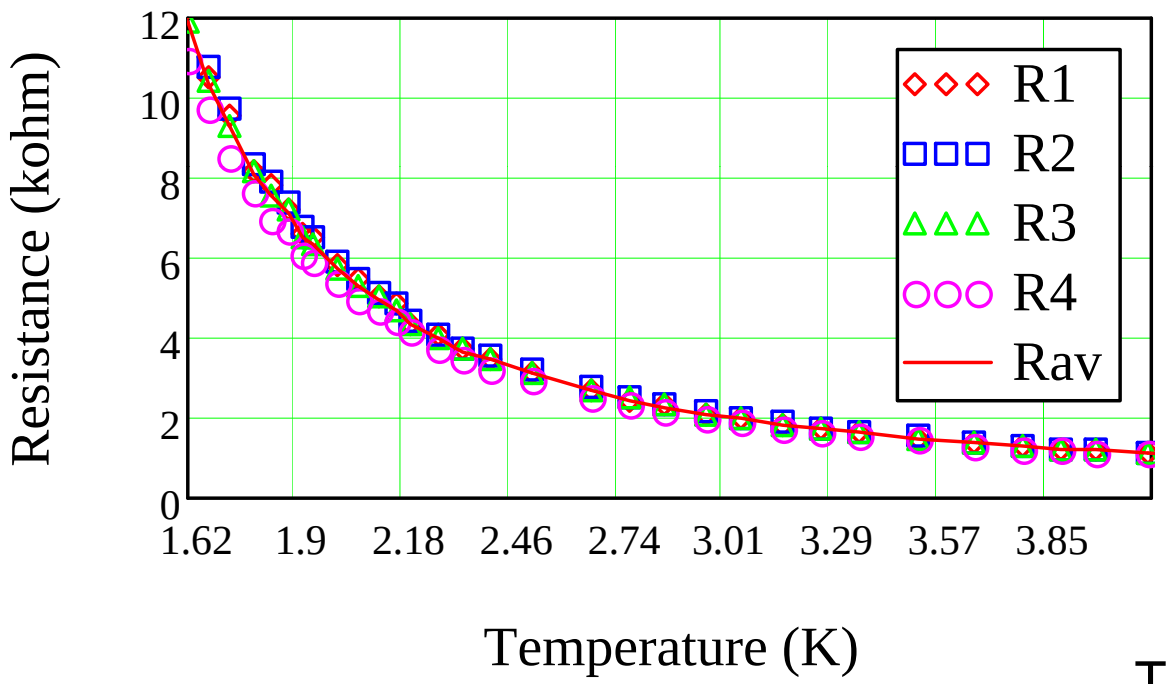
Recent work for the ILC: Temperature mapping system for 9-cell ILC cavities



Only 6 boards are shown out of 108 boards.

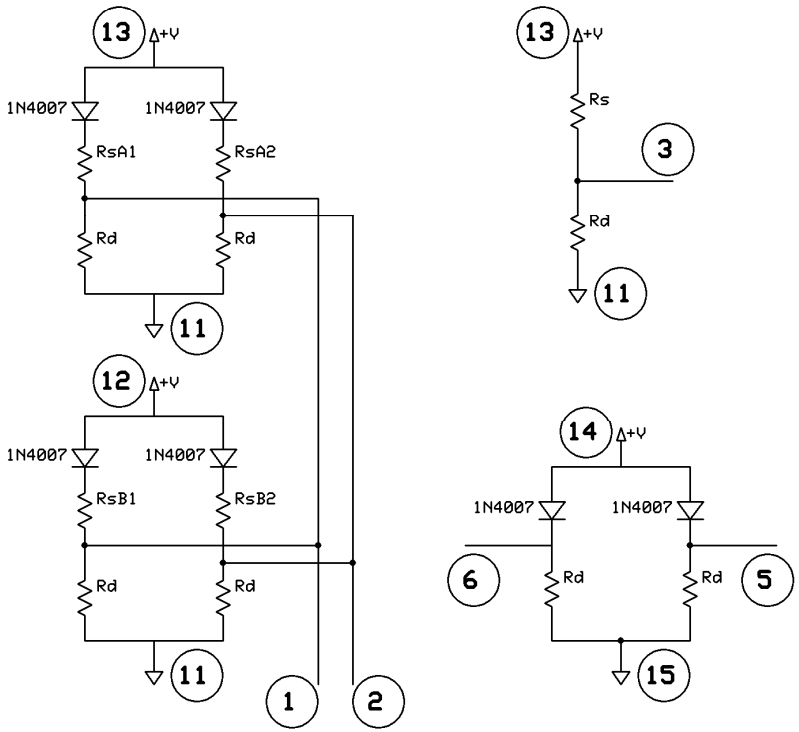
- **Use of ~5500 Allen-Bradley 100-ohm resistors as sensors**
- **~17 sensors per meridian per cell and every 10 degrees.**
- **36 G-10 board covers 3 cells and there will be 108 boards in total.**
- **We will power only 12 boards at a time to reduce the number of cables that come out of the cryostat to ~720.**
- **The power switching will be done in the cryostat.**
- **Expected time for one mapping is ~2s.**

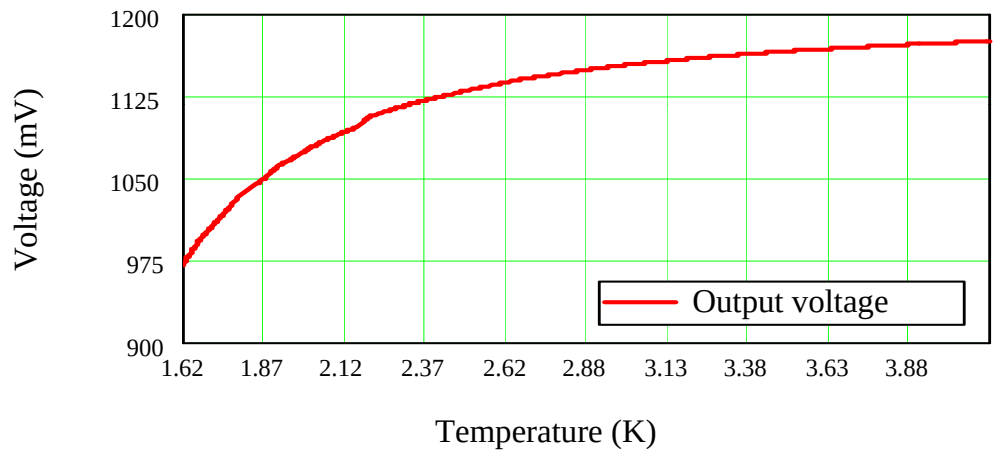
7000 Allen-Bradley sensors were purchased and some were tested and showed good sensitivity



This test was done by G. Ciovati at Jlab.

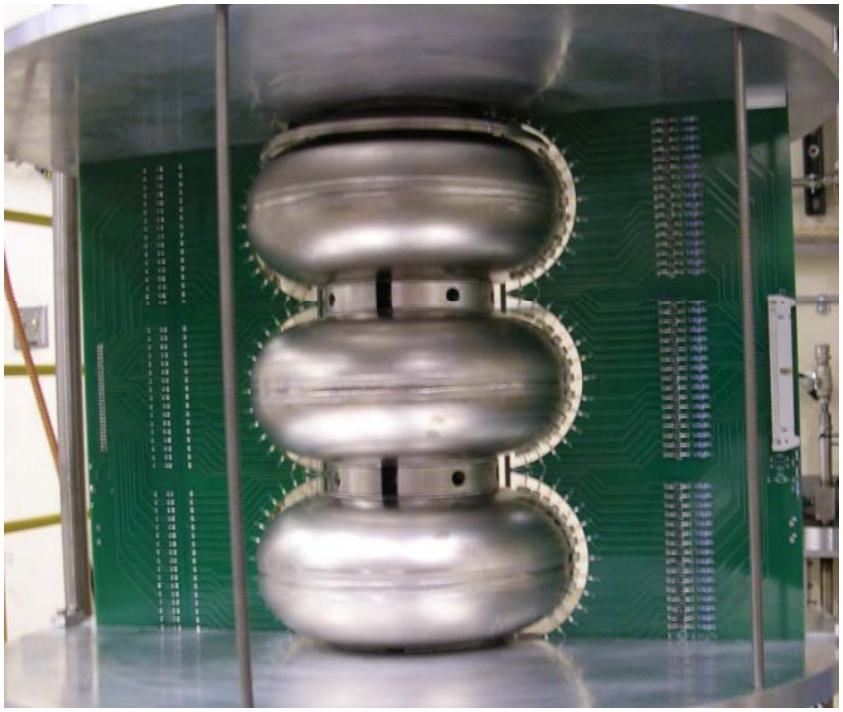
For the switching of sensors in the cryostat, temperature insensitive diodes and resistors were selected after testing them





A. Canabal et al., PAC07

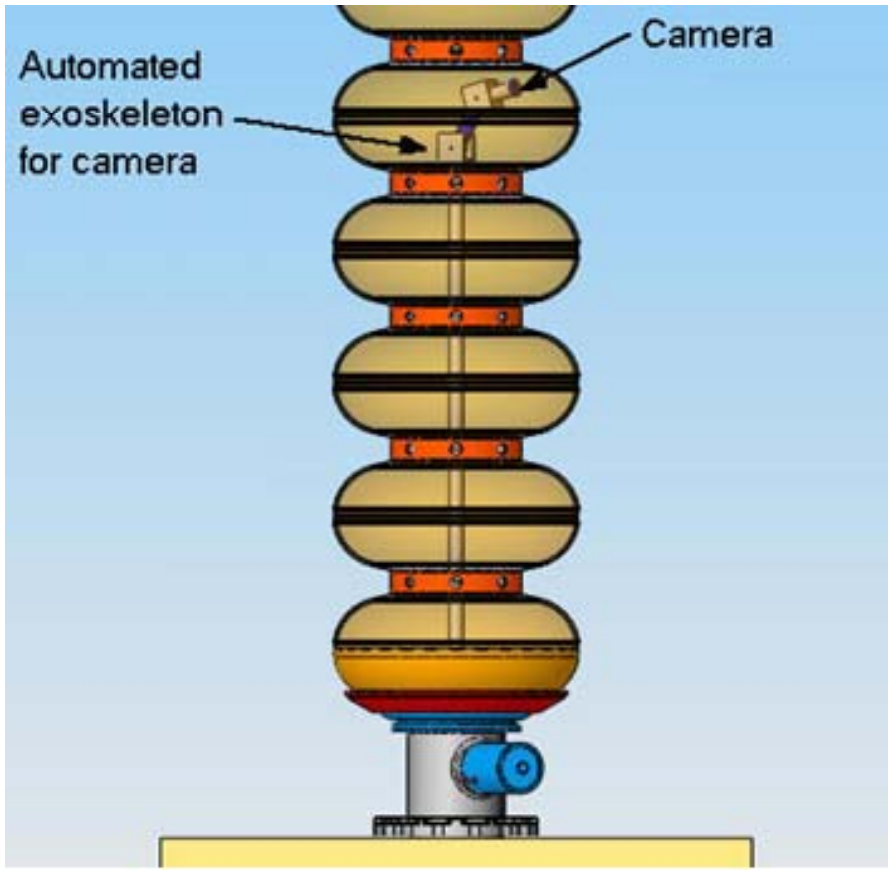
Two prototype boards with complete circuits were fabricated and attached on a 9-cell cavity



Shown at the PAC07 tour

Plan to complete the first system and show first results at SRF2007 workshop.

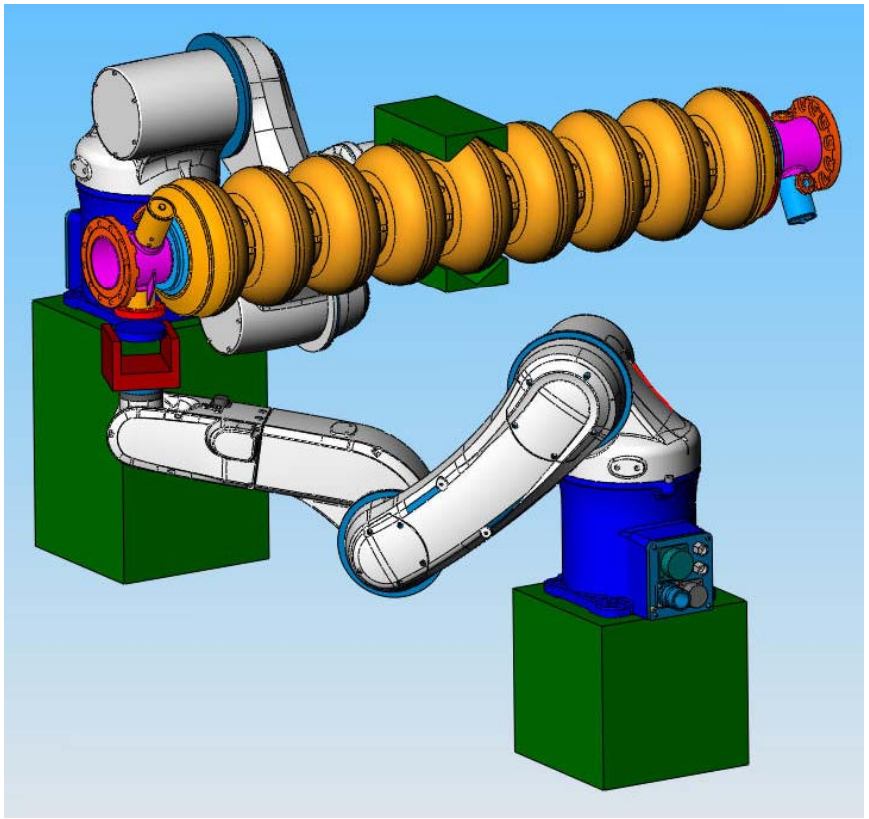
Automated inspection system will be built in FY08



- **Pre-conceptual design started in June 2007.**
- **A clean camera will be used in a clean room.**
- **A camera with ~10 um resolution will go to the coordinates identified by the T-map system and look at the heating areas.**

T. Harden et al., PAC07

Automated sealing of flanges with cleanroom compatible robot arms could increase the reliability and productivity



- Starting with high pressure rinsing
- Up to the point where all the ports are sealed with flanges
- 24/7 operation could be possible

T. Harden et al., PAC07

Summary

- LANL has a relatively long history of RF superconductivity R&D
- However, little work has been done in the last ~4 years due to funding shortage
- With the new ILC funding from June 2007, we have restarted our activities to contribute to the improvement of cavity performance, which, we hope, could lead to a high yield of >35MV/m cavities