Superconducting RF Activities at Los Alamos 2000 - 2005
- my 5 years of experience -

Tsuyoshi Tajima

Los Alamos Neutron Science Center (LANSCE)

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Los Alamos Neutron Science Center (LANSCE)

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

Future Materials Test Station

Proton Radiography

800-MeV Linear Accelerator

Isotope Production Facility

LANSCE Visitor's Center

Manuel Lujan Jr. Neutron Scattering Center

Proton Storage Ring

SC LAB

Weapons Neutron Research

Neutron Resonance Spectroscopy

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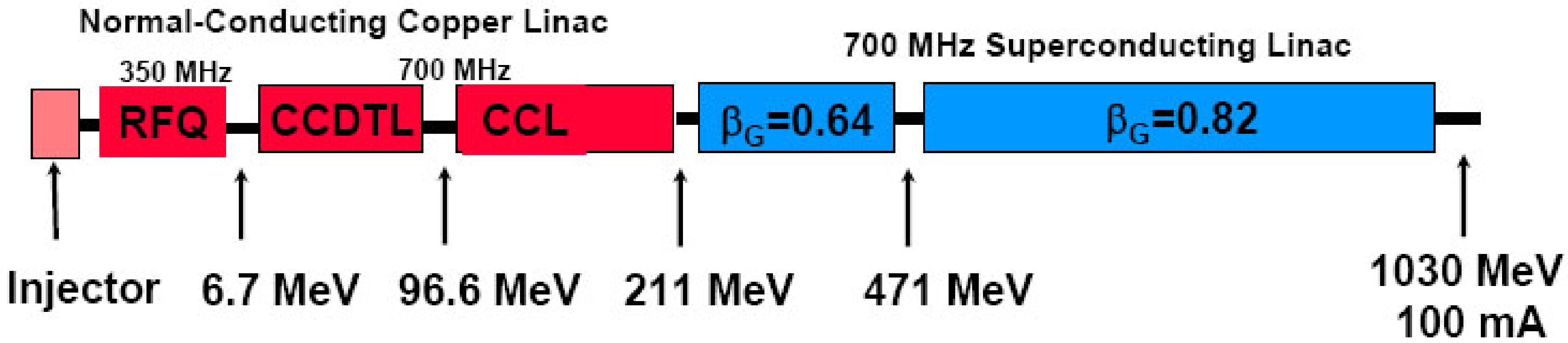
   – Measurements of MgB_2 RF surface resistance and its dependence on higher gradients

1. Accelerator Production of Tritium (APT) Project

- Purpose: Replenish Tritium Inventory for Nuclear Weapons (3 kg/year)
- Method: Using spallation neutrons made by proton accelerator, split Lithium into Tritium and Helium.



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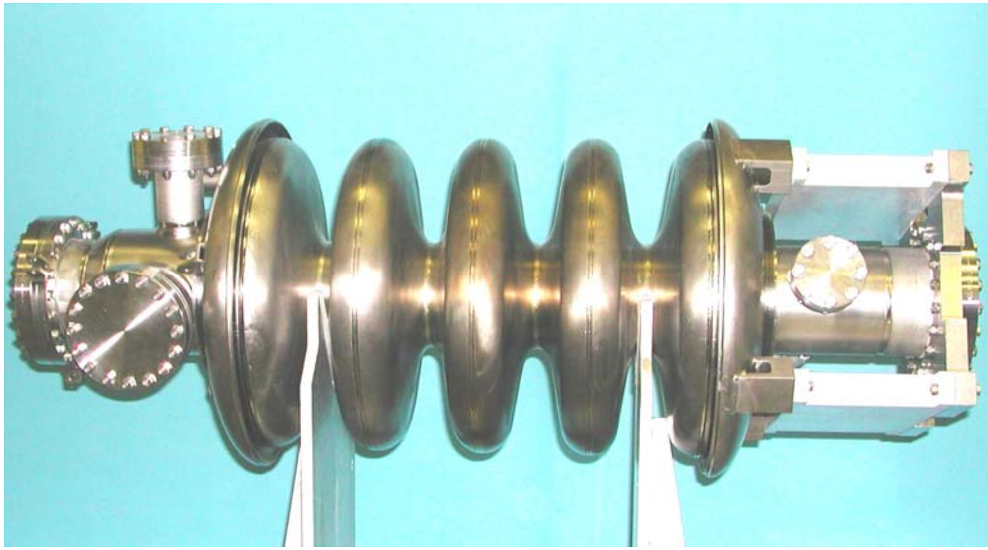
700 MHz SC Section Specs

β	0.64	0.82
E_{acc} (MV/m)	5.5	4.1 (6.4)
Real estate E_{acc}	1.54	1.26 (1.89)
E_{peak}	19.1	12.7 (19.1)
No. Cavities	90	312
Aperture (cm)	13	16
Aperture/(rms-beam size)	35	45
Thermal load @ 1.9 K (kW)	2.0	6.1 (9.2)

Numbers in parentheses are for 1.7 GeV case

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
H_p/E_{acc}= 69.6 Oe/(MV/m)

Facilities for SRF Activities at LANSCE

2600 ft^2 Class-100 Clean room

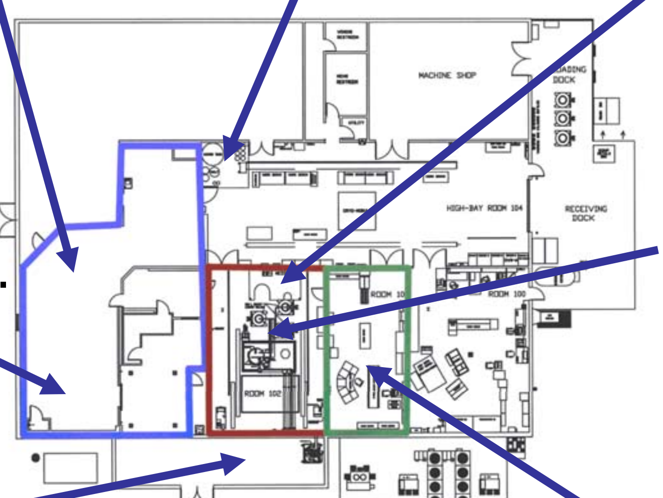
Ultra-pure water system with 1500 gallon storage tank

2 Inserts for 38-inch, 10 feet deep cryostat

High-pressure rinse in a clean room.

140 ft.

100 ft.



Cryostat with movable radiation shield

Pumps to pump down the cryostat to < 2 K

Control, tuning

This 2,600 ft^2 clean room is divided into class-1,000 and class-100 clean rooms for assembling SC cavities.

Behind the curtain is a 13 m x 7 m class 100 area with ceiling height of 10 feet.

The other areas are class 1000 and ceiling height of 8 feet.

High-pressure rinsing system. While the cavity is rotating on the turn table at ~ 30 rpm, water jets at 1,000-1500 psi move up and down automatically and rinse off the particles and chemical residues from the inner surface of the cavity.

Ultrasonic cleaning system to degrease, clean, and rinse the components for SC cavities and power couplers in the clean room. (three 90-gallon baths with 40-kHz oscillators)

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Ultra-pure water system that can produce 2,000 gallons per day of de-ionized water with a resistivity (purity) of ~18 MΩ·cm.

Shown in the center is a 1,500-gallon storage tank.

38-inch diameter, 10-ft deep cryostat with radiation shield

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Two 38-inch diameter cryostat inserts

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Cavity Performance Measurement

- Q_0 (Cavity unloaded Q) versus E_{acc} (accelerating gradient, MV/m)
- Basic parameters

$$Q_0 = G / R_s$$

G: Geometrical Factor, constant dependent on the cavity shape

$$R_s = R_{BCS} + R_{res}$$

R_s: RF Surface Resistance

$$R_{BCS} = A \cdot \frac{f^2}{T} \cdot \exp\left(- \frac{\Delta}{k_B T_c} \cdot \frac{T_c}{T} \right)$$

$$R_{res} = R_{res}(H_{rf}) + R_{fl}(H_{rf}, H_{ext}, T)$$

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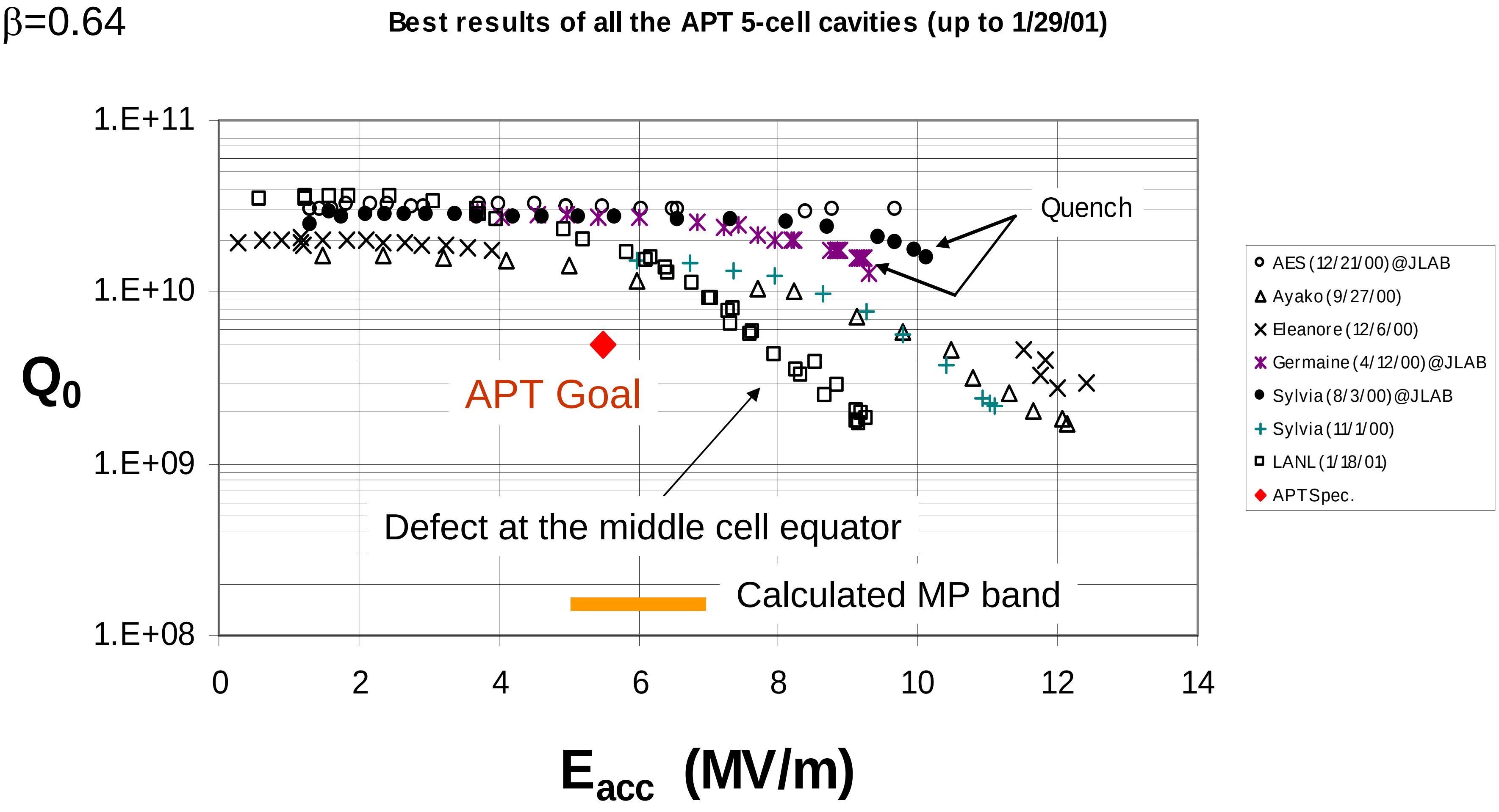
Results of 6 Prototype Cavities at 2 K. Defects, field emission and MP? limited performance.

$\beta=0.64$



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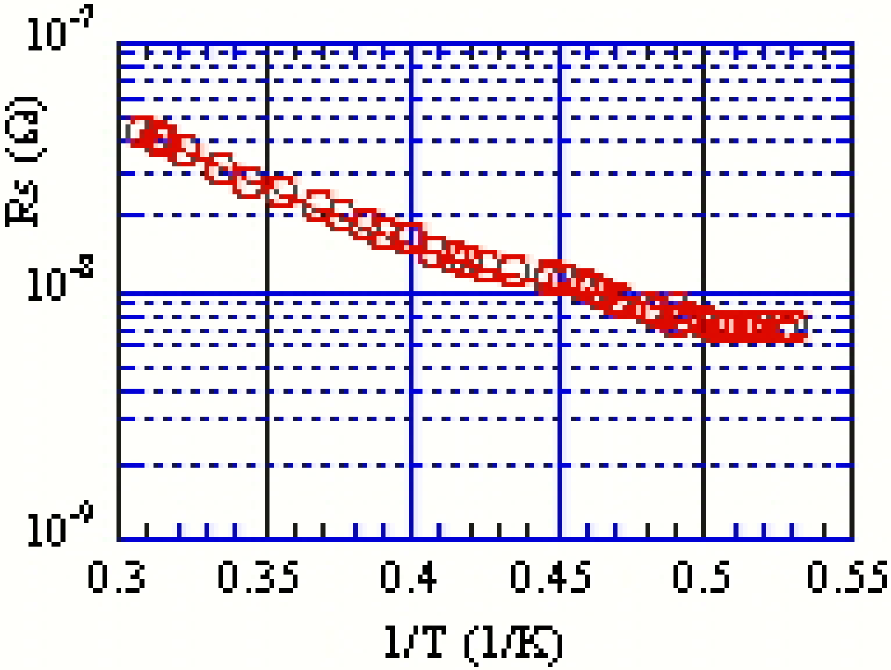
An example of the temperature dependence of R_s

Cavity: Sylvia

$Rs = a*1/T*exp(-b*1/T)+Rres$		
	Value	Error
a	3.9804e-05	4.4326e-06
b	18.734	0.35986
Rres	6.4452e-09	1.9664e-10
Chisq	1.5188e-17	NA
R	0.99857	NA



Comparison with TESLA Cavities

- Difference of E_p/E_{acc} and H_p/E_{acc}.

$$\frac{\left(E_p/E_{acc}\right)_{APT}}{\left(E_p/E_{acc}\right)_{TESLA}} = \frac{3.38}{2.0} = 1.69$$

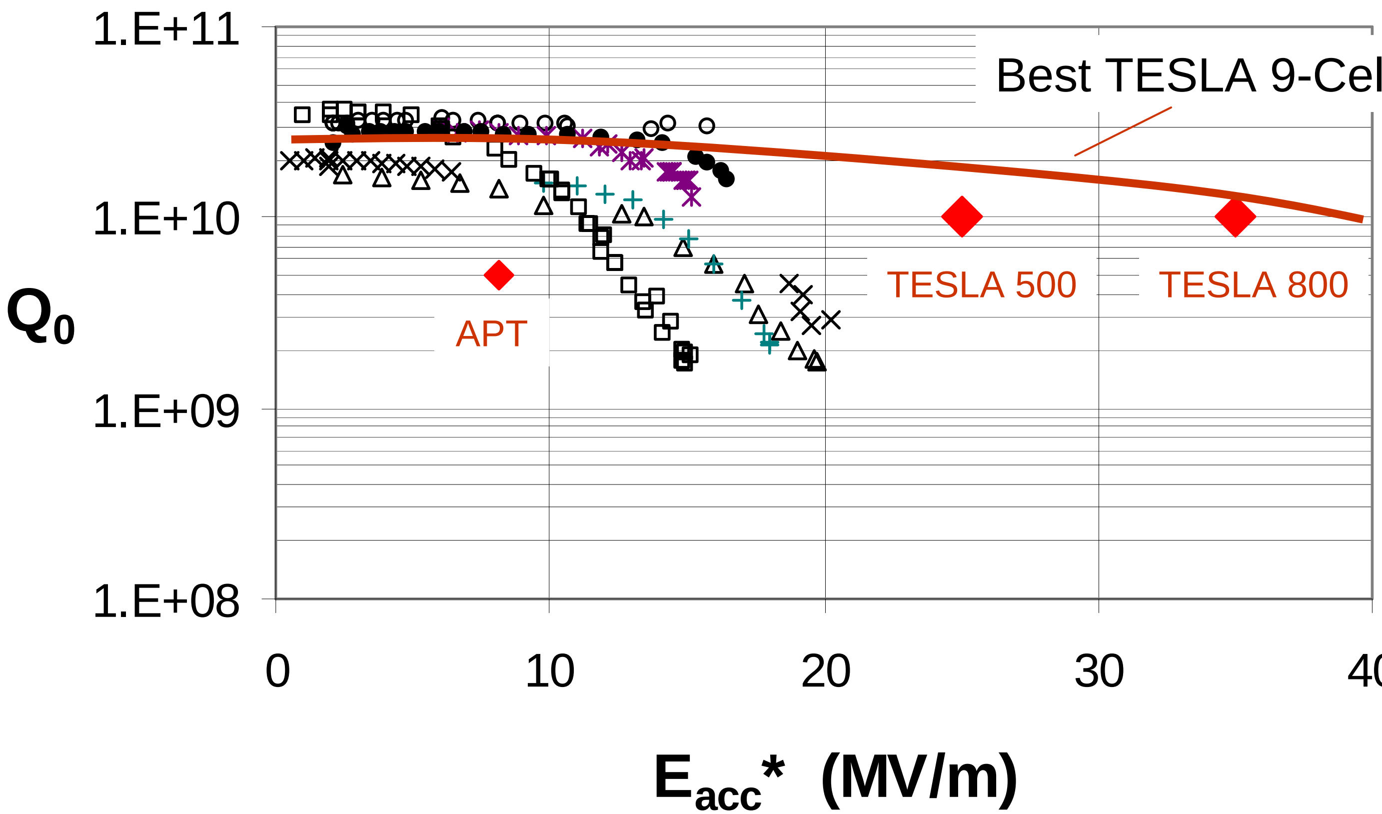
$$\frac{\left(H_p/E_{acc}\right)_{APT}}{\left(H_p/E_{acc}\right)_{TESLA}} = \frac{69.6}{42.6} = 1.63$$

APT cavity shape is not well optimized!

- Difference of β. APT(0.64) vs. TESLA (1).
  - It might be more susceptible to multipacting due to the squeezed shape

Comparison with TESLA Cavities

APT results were converted to TESLA equivalent numbers for comparison.



E_{acc}*: H_p/E_{acc}=42.6 was used.

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Issues that need to be addressed

- The APT Goal was achieved, but we need to achieve higher gradients for future machines to further reduce costs.
- Q_0 drops at medium and high gradient due to Multipacting and Field emission.
- Measures to take
  - MP free design of the cavity with MP codes.
  - Thermometry and other diagnostics for detecting heating spots to localize and identify the problem.
  - Improve contamination control during assembly to reduce field emission due to migrated particles.

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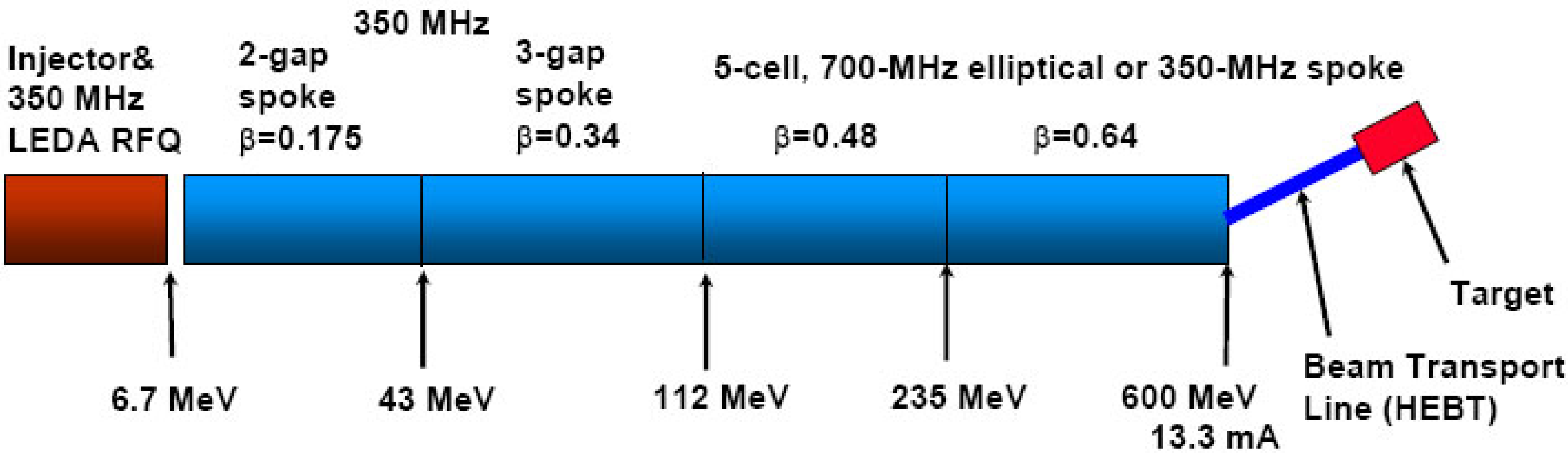
2. Advanced Accelerator Applications (AAA) Project

- Purpose: Transmutation of Nuclear Waste, i.e., reduce life of nuclear waste by about 2 orders of magnitude to <500 years.
- Method: Accelerator-Driven System.



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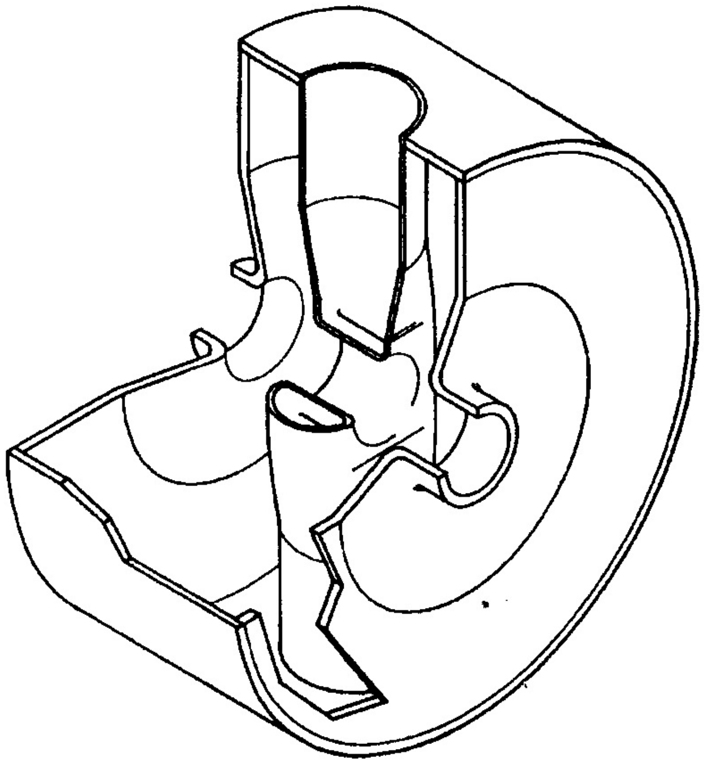
Spoke Cavity Development for Low-Energy Sections of Proton Linacs

- Studies have been carried out at ANL since late '80s (Jean Delayen, Ken Shepard)
- Advantages over elliptical cavities
  - Compact (~1/2 of elliptical)
  - Can be operated at 4 K
  - Mechanically stable
- One spoke cavity loaned from ANL was evaluated at LANL and the result was promising



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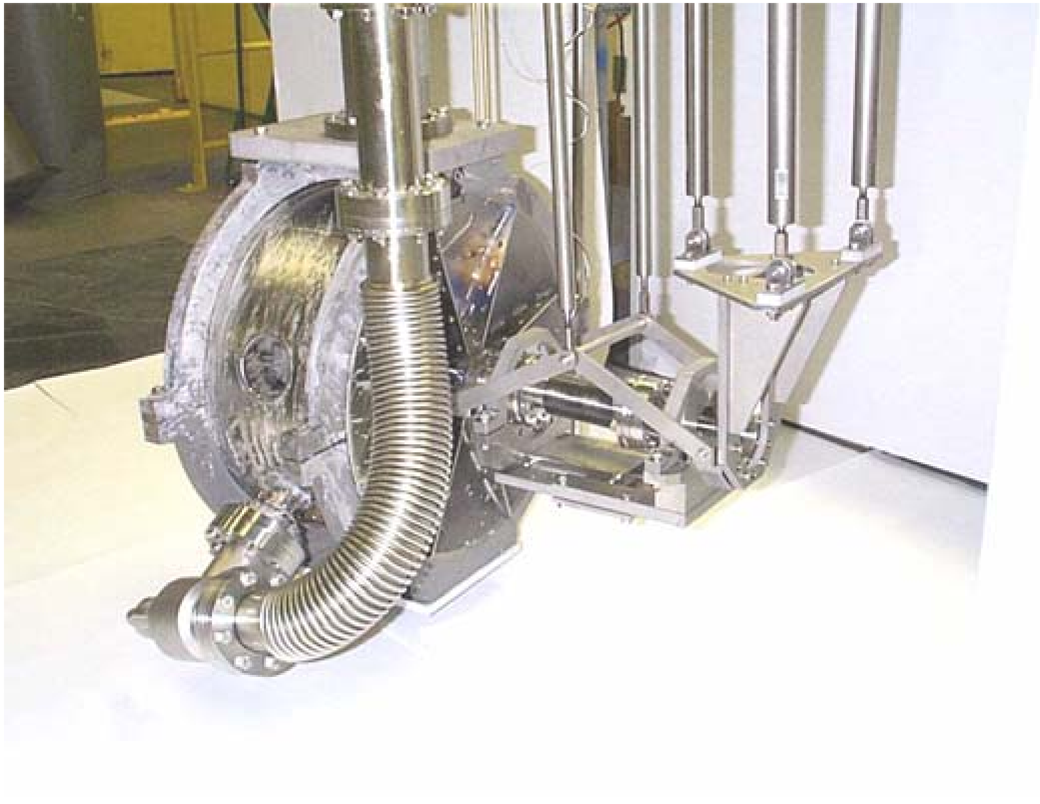
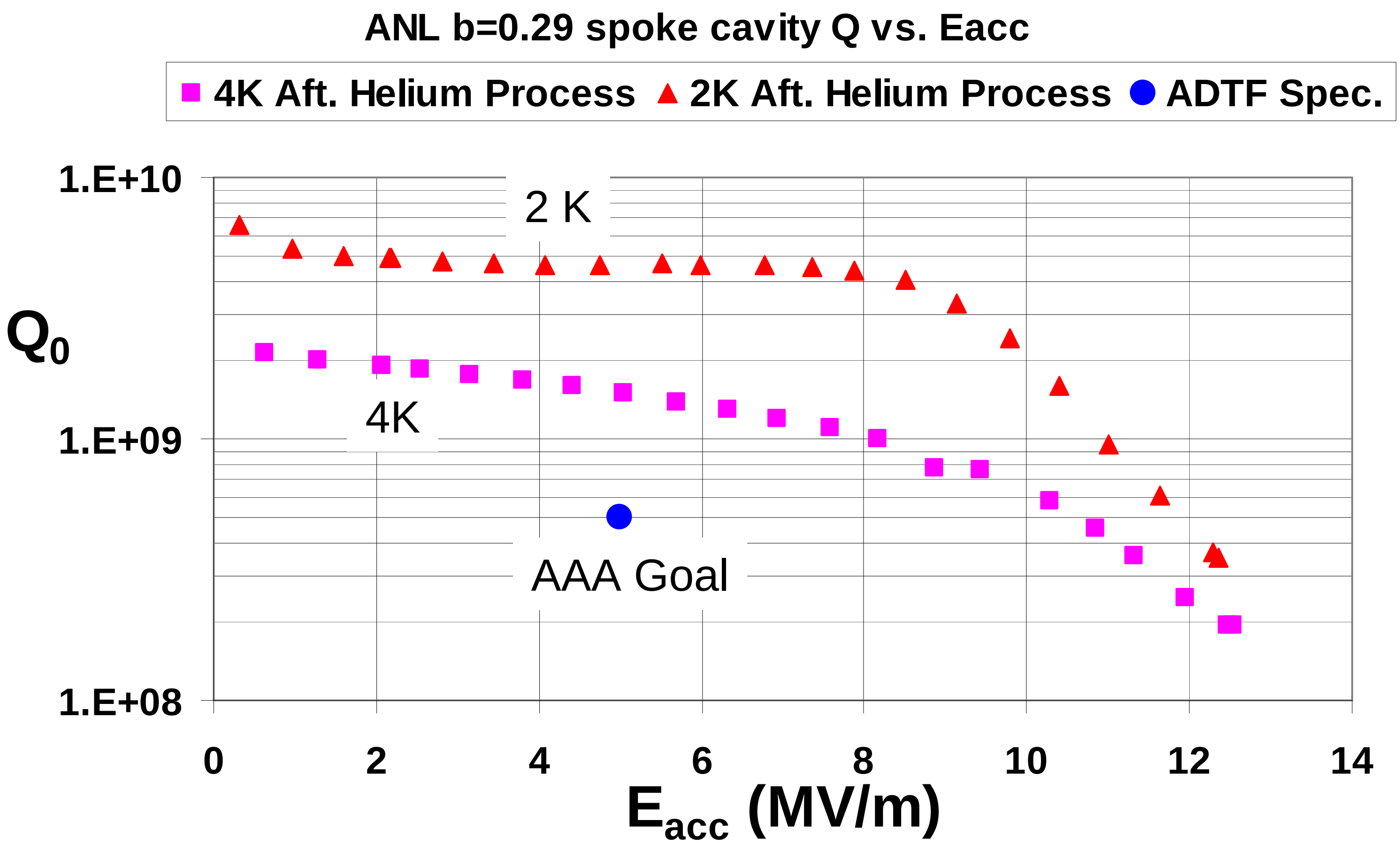
Tests on ANL $\beta = 0.29$, 340 MHz, 2-gap Spoke Cavity



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

E_p/E_{acc} : 3.18
H_p/E_{acc} : 85 Oe/MV/m

Vertical Test Results of ANL β=0.29, 340 MHz, 2-Gap Spoke Cavity



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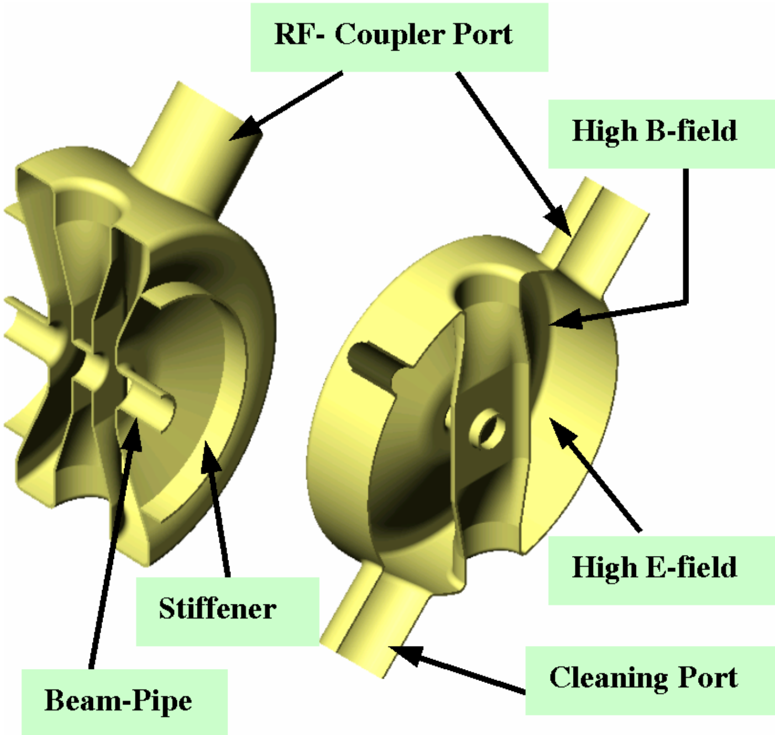
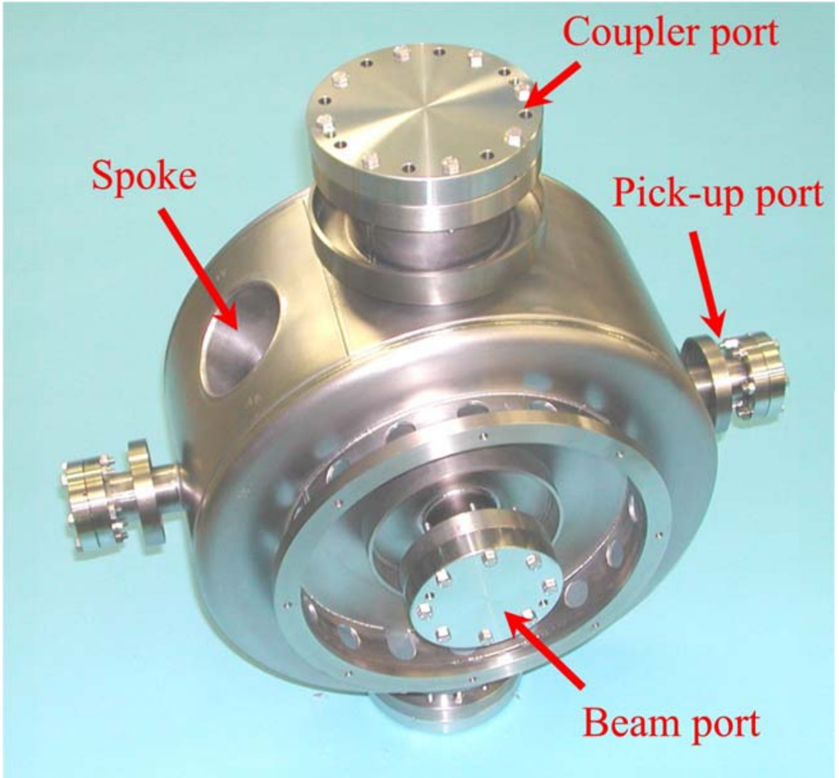
AAA β=0.175, 350-MHz, 2-Gap, Spoke Cavity

Two cavities were fabricated at ZANON, Italy.





Cell diameter : 39.2 cm
Cavity length : 20 cm
Beam aperture : 5 cm

E_p/E_{acc} : 2.82
H_p/E_{acc} : 69 Oe/MV/m

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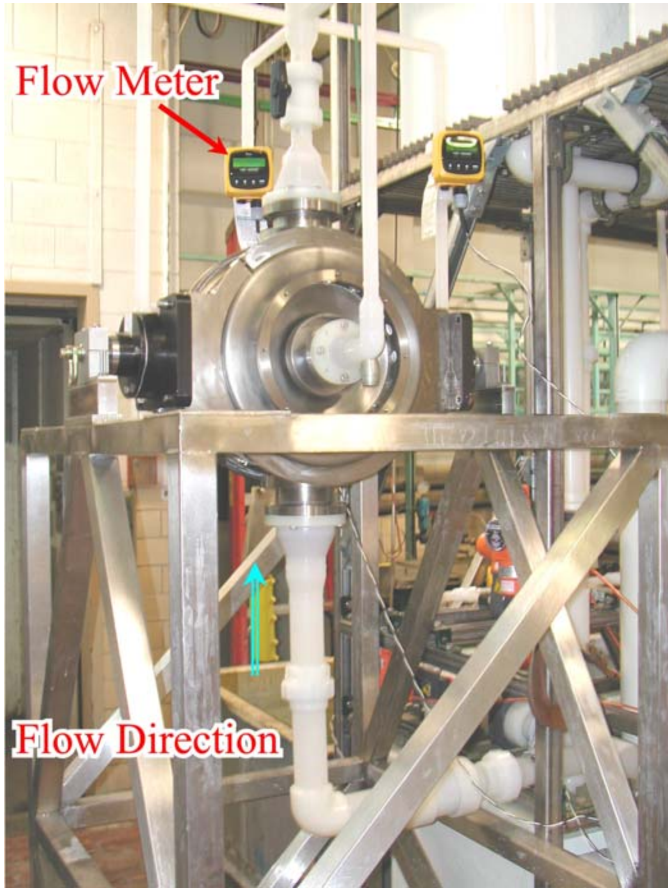
Buffered Chemical Polishing (BCP) Improvement $HF:HNO_3:H_3PO_4$=1:1:2 by volume at < 15 ºC

EZ02

EZ01



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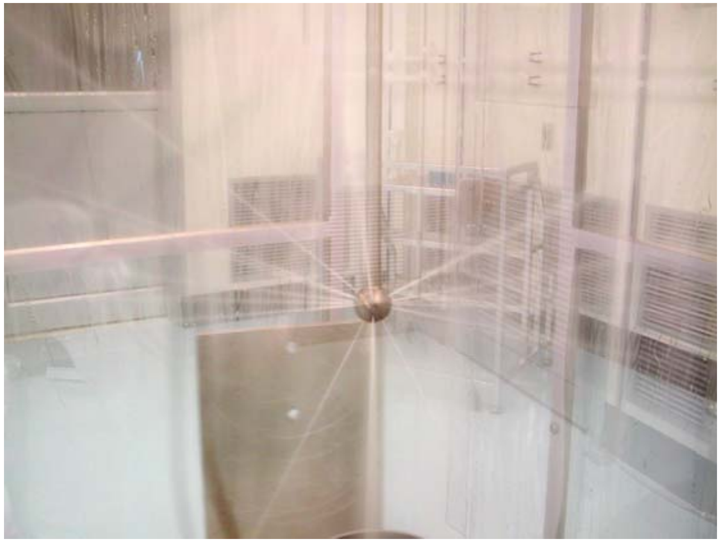
High Pressure Rinsing (HPR) Procedure

- 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



Nozzle made by SST

Outer diameter: 31.75 mm

Holes: 457 μm-diam., 3.81 mm long

No. of holes: 21

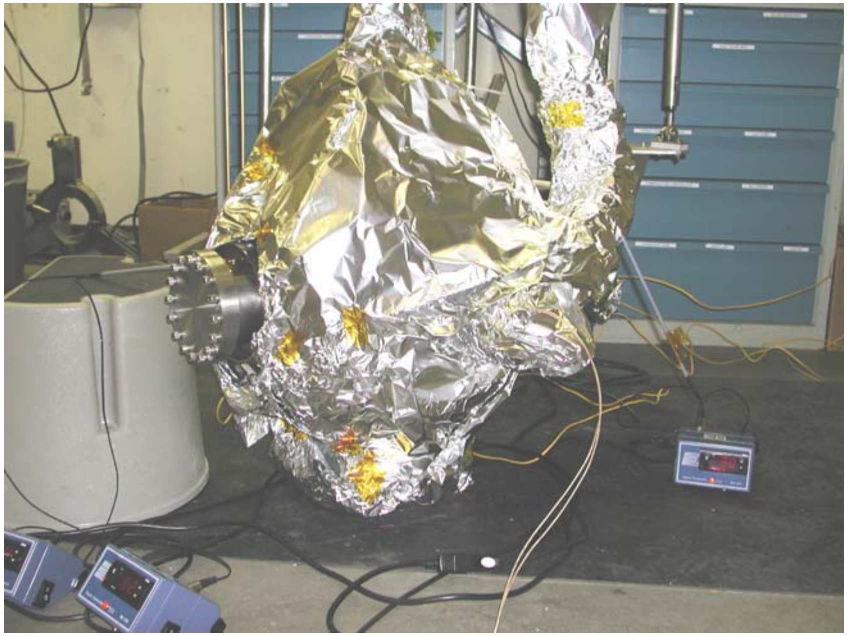
11 different angles to cover all the surfaces

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.
- Nominally, all the flanges are Conflat, but indium seals were used to attach Nb blank flanges on the large radial ports for the vertical tests.
- Special polyethylene cover was made to attach indium on the flat surface inside of Conflat knife edge.

Set Up on the Insert and Baking

Baking at ~ 110 ºC for ~ 2 days
Indium < 80 ºC



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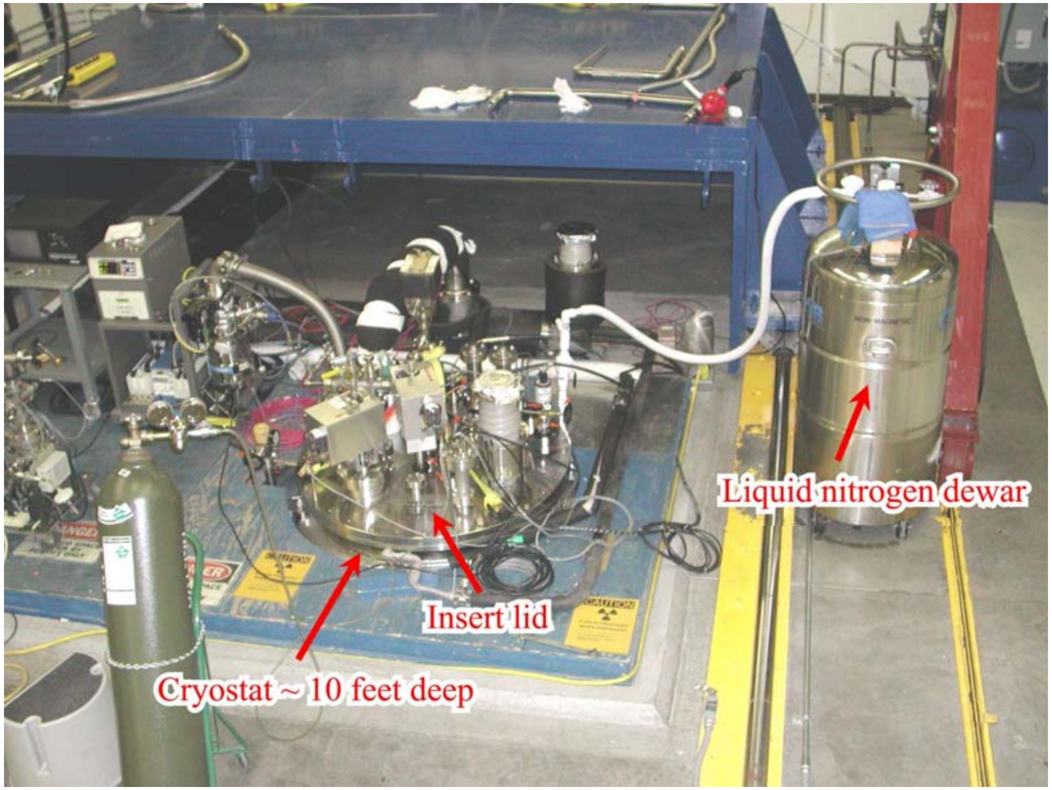
Indirect Pre-Cooling with Liquid Nitrogen



- 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

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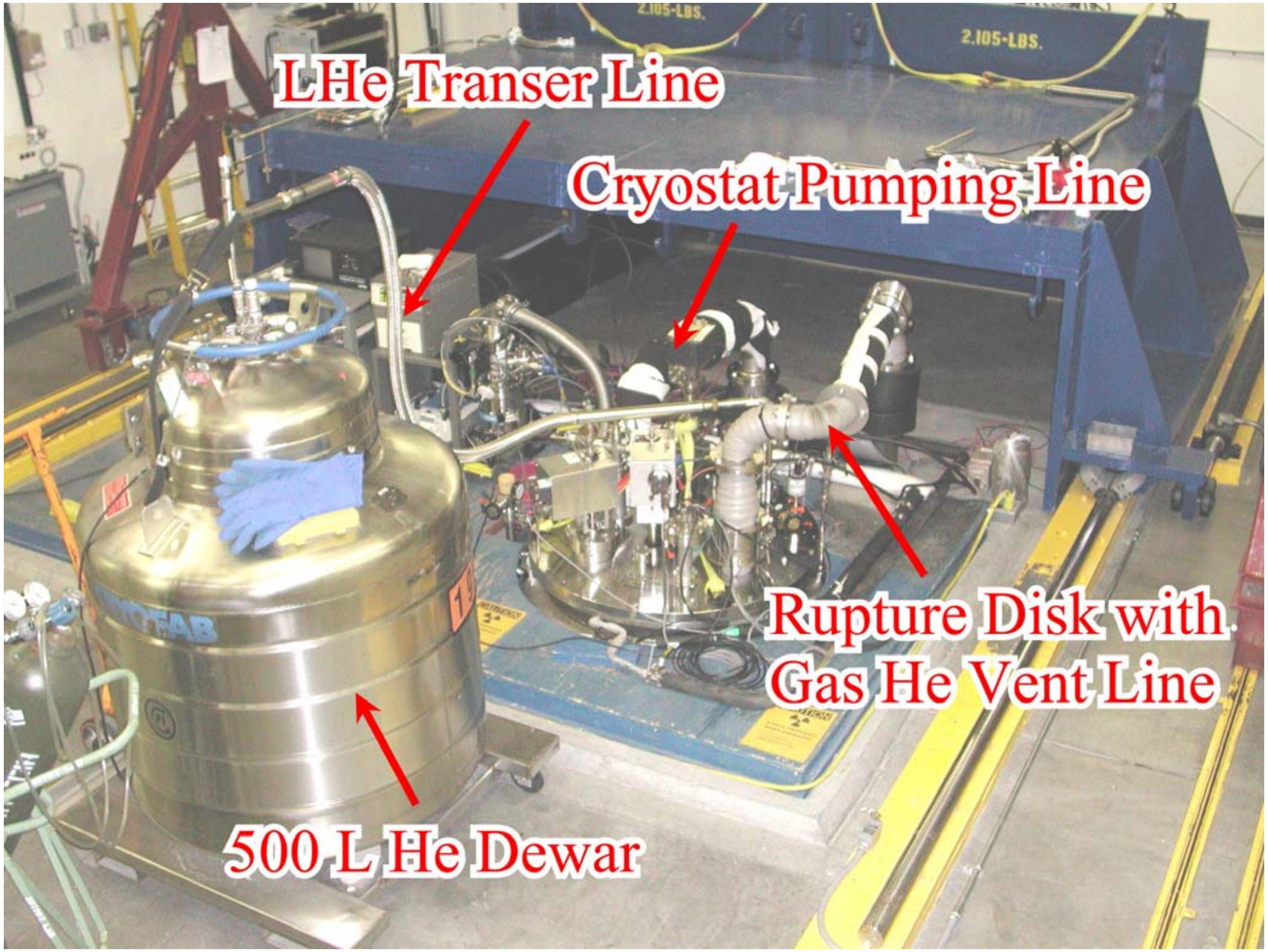
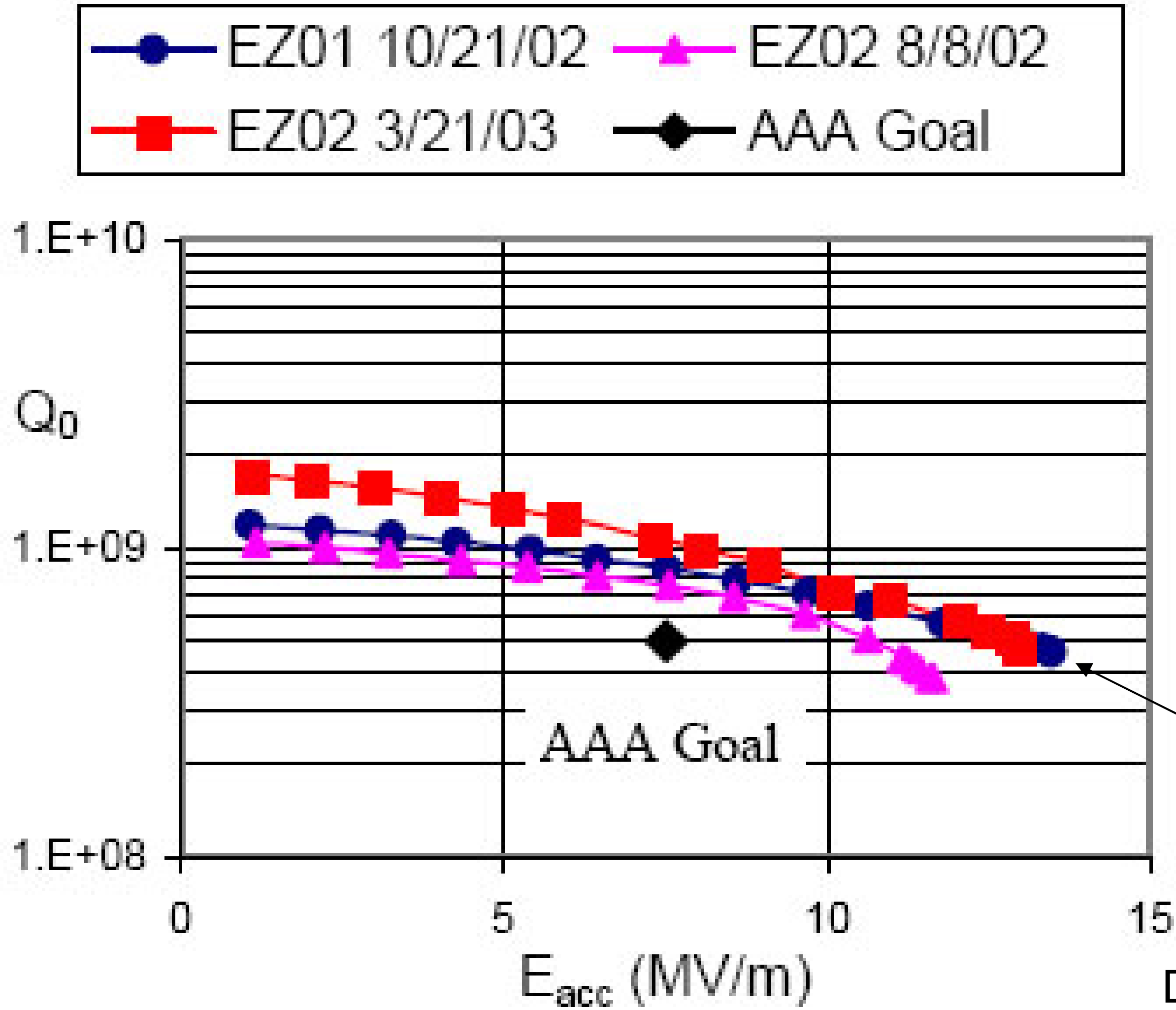
Helium Transfer and Testing



Vertical Test Results of LANL β=0.175, 350-MHz, Spoke Cavities



With Nb blank flanges on large radial ports

The second EZ02 test was done after disassembly and high-pressure rinse.

$E_{acc,\ max}$ = 13.5 MV/m
$E_{p,\ max}$= 38.0 MV/m
$H_{p,\ max}$ = 994 Oe

Details in PAC03 Proceedings.

Some questions that need to be answered.

- What is the experimentally achievable H_p at 4 K? It has been ~1800 Oe at 2 K with TESLA cavities. (Due to the better thermal conductivity of liquid He at T<2.17 K (Lamda point), it is expected that the achievable field is higher at 2 K.)
- Are there any difference between elliptical and spoke cavities in terms of the field limitations? It has been shown for spoke cavities that the maximum fields are almost the same at 4 K and 2 K, whereas some elliptical cavities have shown difference as much as a factor of 2.

Q_0 disease tests

- Q_0 disease is a degradation of Q_0 due to niobium hydrides (T_c~1.2 K?) caused by holding the cavity at medium temperatures (~100 K). It had been said before our tests that low frequency cavities (<500 MHz) do not show it.
- A systematic Q disease tests have been carried out with our 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

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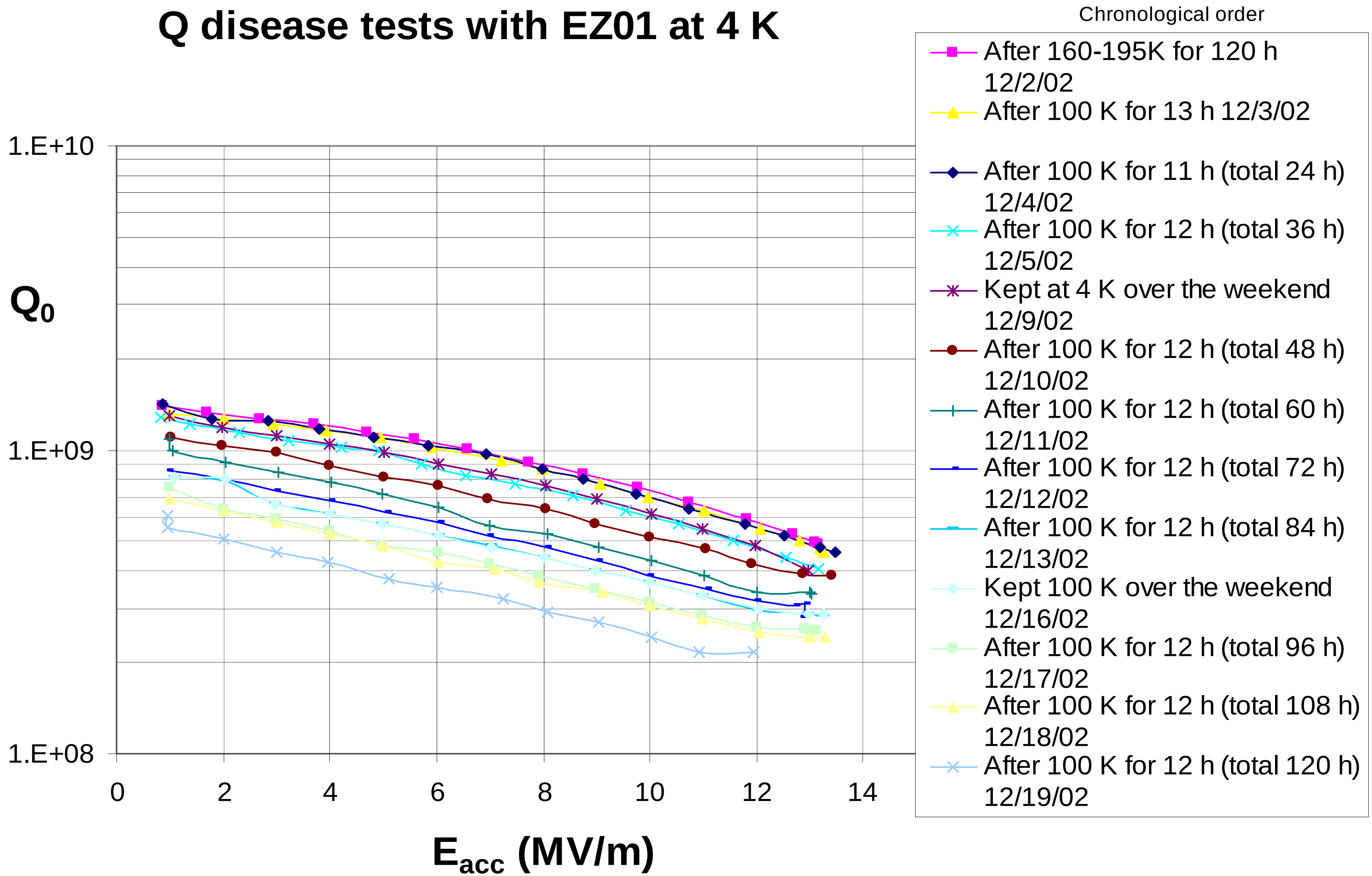
Q_0 – E_{acc} Curves During the Tests



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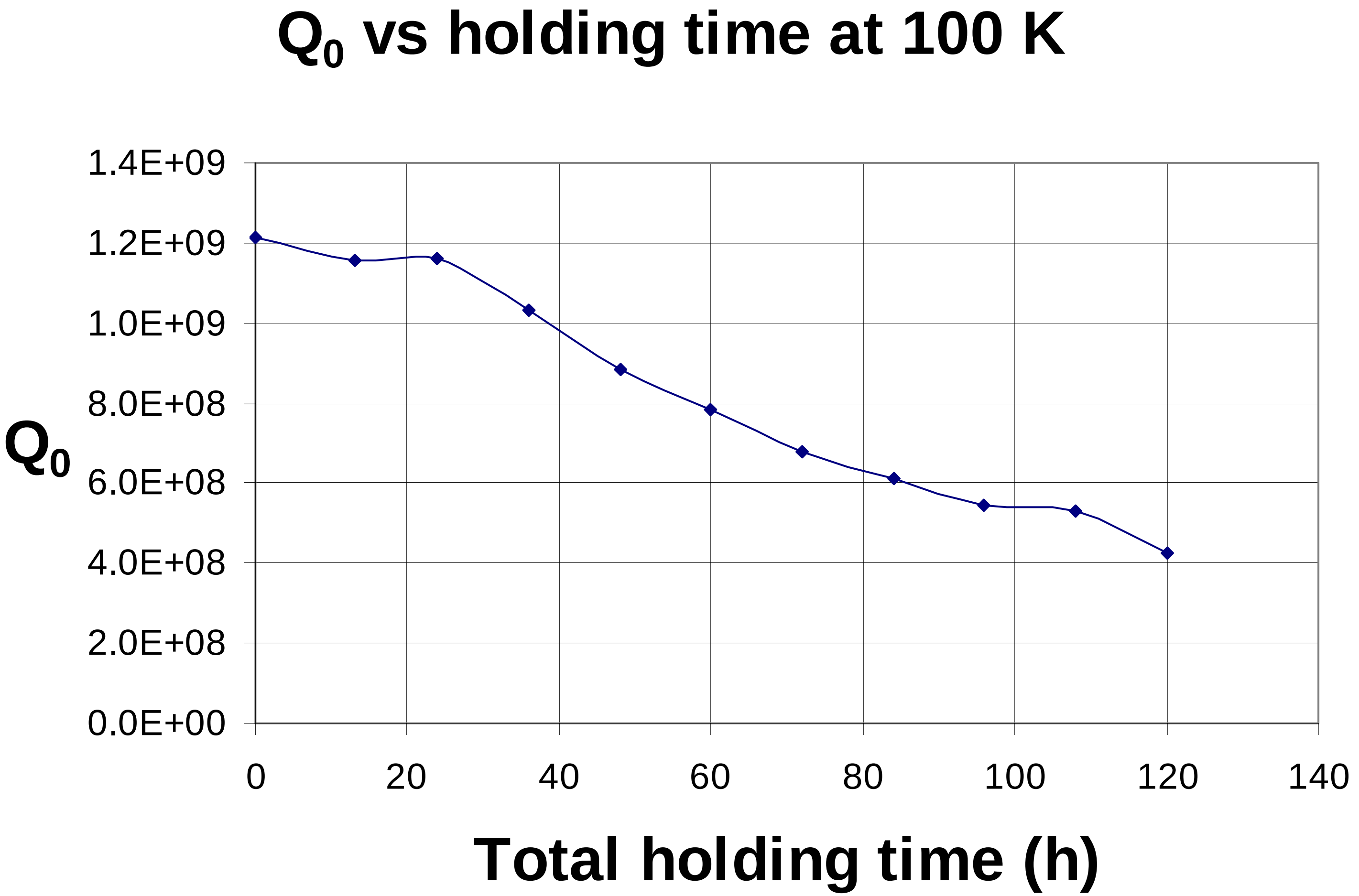
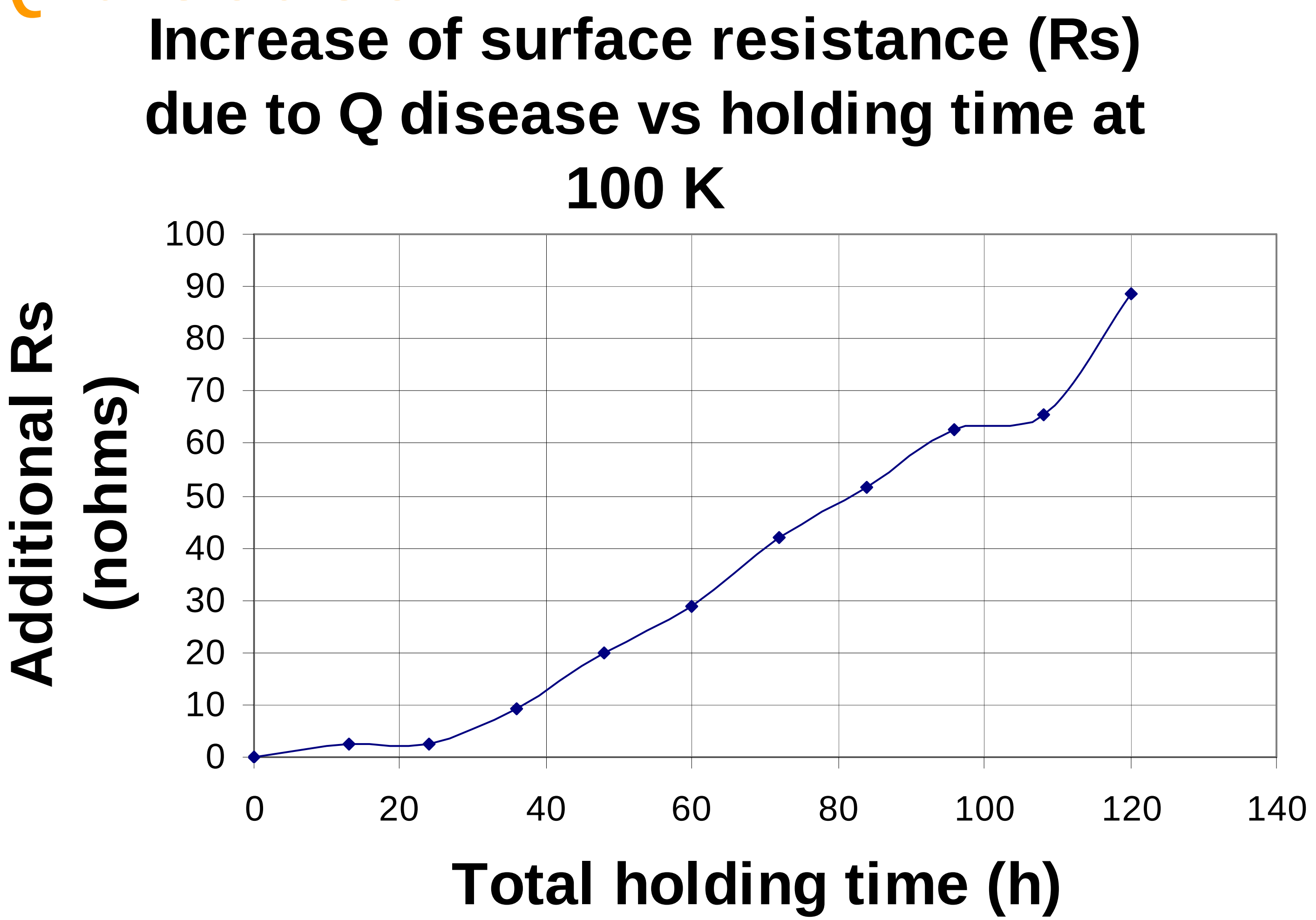
Q_0 Dependence on the Holding Time at 100 K



Additional Surface Resistance Due to Q disease



Summary of the Q disease tests

- With our 350-MHz spoke cavities, little Q disease occurs after 150-μm BCP, up to ~24 hours of holding time at ~100 K.
- Holding the cavity for longer time causes Q disease.
- The additional surface resistance due to the Q disease increases linearly after the increase starts.
- Q disease disappears if the cavity is warmed up to 180 K. From what temperature this effect occurs needs to be determined.

3. High-T_c Materials Study for RF Cavities

- Motivation
  - Reduction of construction and operation cost of particle accelerators is unavoidable for future projects !!
  - Although Nb cavities have reduced costs significantly, present accelerator costs are still too high to be easily funded.
  - High-T_c materials could further reduce the costs.

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Problems with Bulk-Nb cavities

- **Expensive material (price similar to Silver).**
- **Fabrication cost is much higher than copper cavities.**
- **Predicted theoretical limit of accelerating gradient (E_{acc}) is ~50 MV/m based on the theoretical critical magnetic field (H_c) of ~2000 Oe and the ratio of H_c/E_{acc}~40 Oe/(MV/m).**
- **Experimentally, ~1750±100 Oe has been shown to limit the performance.**
- **State-of-the-art cavities have already shown the performance close to the limit, i.e., no further improvement of E_{acc}. (Lowering the H_c/E_{acc} can improve the E_{acc}, but ~35 Oe/MV/m seems to be the limit.)**
- **Need to use expensive liquid helium (4K at atmospheric pressure) to cool the cavities since the Nb transition temperature (T_c) is 9.2 K.**
- **Need to even lower the liquid helium temperature from 4K to ~2K for cavities at frequencies of >500 MHz to reduce the BCS surface loss to be within the refrigerator's manageable level. This leads to a much more complicated and expensive refrigeration system.**
- **Need to shield ambient magnetic field to <10 mG (<2 mG for ILC) level to keep the RF surface loss sufficiently low.**

It is a breakthrough if one can find a solution to these problems !!

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How can we solve these problems?

- Most of the problems can be solved by coating a high-T_c material on a cheap metal such as copper. (Achievable E_{acc} is unknown.)
- But, unfortunately, it has been shown that the so-called high-T_c materials that has T_c> 77K (liquid nitrogen) such as YBCO cannot be used since the RF surface resistance increases rapidly with higher magnetic field or E_{acc}.

Present Candidates

•Nb_3Sn (T_c=18K)

This has been studied until ~1996 for many years and has demonstrated some success with a few single-cell cavities, but experimental studies have shown lower critical magnetic field compared to Nb and difficulty in making uniform high-quality film. We have not studied this material yet. It might be just engineering of how to coat the cavity.

•MgB_2 (T_c=39K)

We started evaluating this material in 2003. See below.

Theoretical Limit Based on Superheating Critical Field. (These do not match experimental results, although experiments are difficult at high fields.)

H_p/E_{acc}=40 (Oe/MV/m)

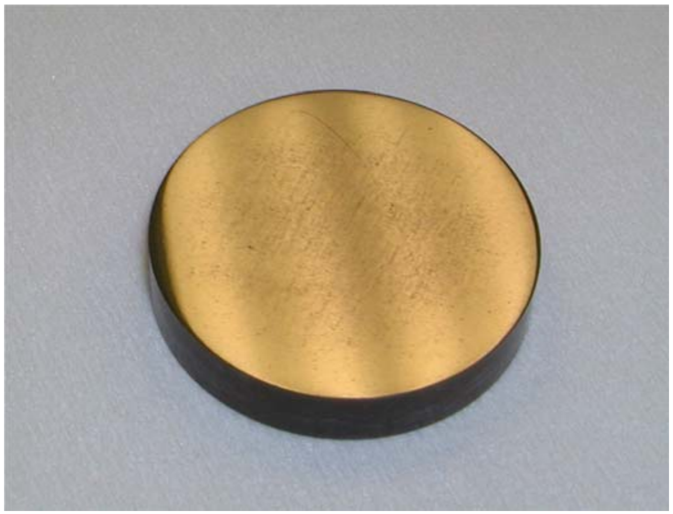
Material	**Operation Temp. [K]**	**Theoretical Limit E_{acc} [MV/m]**
Nb	4	49
Nb_3Sn	4	95
MgB_2	4	80
MgB_2	20	52

Magnesium Diboride (MgB_2)

- This material is readily available, but its superconductivity at 39K was found relatively recently (2001).
- A number of studies on this material has been done since then and it was found that the loss at higher magnetic field is much less than other high-T_c materials.
- Measurements at LANL have shown that the BCS resistance at 4 K is about one order of magnitude lower than Nb.
- It has also been shown that this can be coated in much simpler fashion compared to other high-T_c materials such as YBCO, which would lead to less cost.
- Coating on various substrates seems possible without degrading the quality.

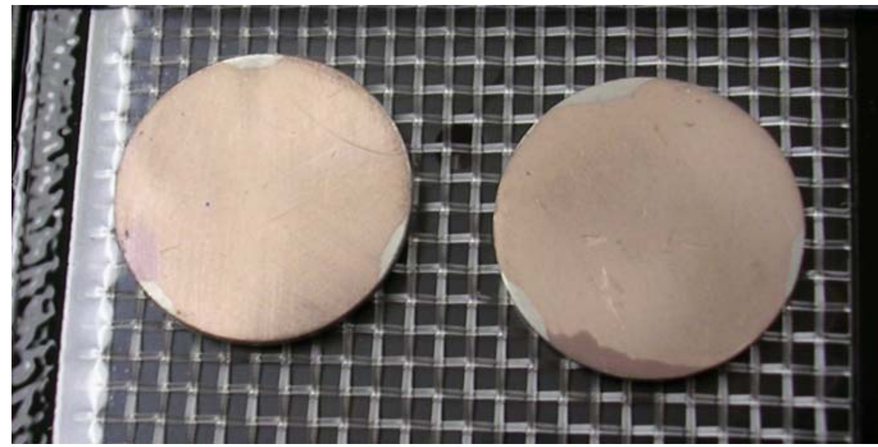
Bulk and Film Samples We Tested

Bulk sample made by HIP at UCSD



25.0 mm in diameter and 4.60 mm in thickness after polishing the surface with a $0.1\text{–}\mu m$ diamond lapping film. A reflection of 3 fluorescent lights is seen on the surface.

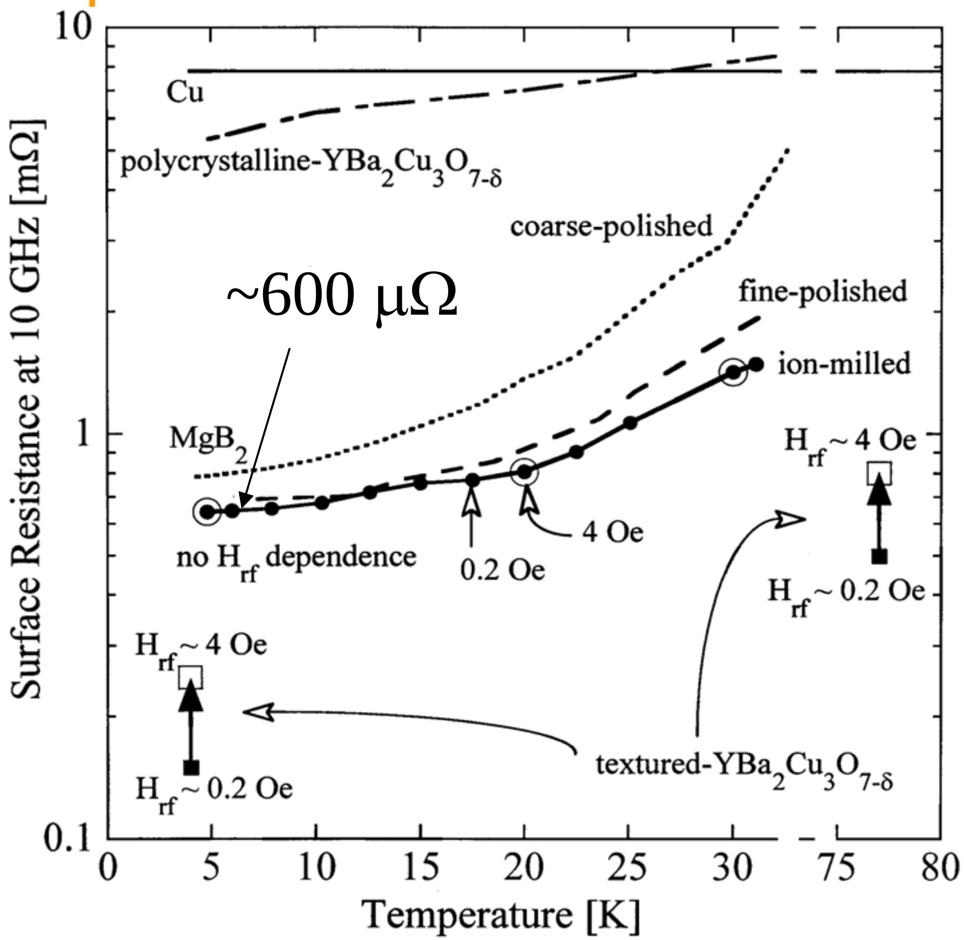
400 nm film on Nb coated at STI



Diameter: 14.6 mm
Substrate: 1 mm Nb

Films coated on 1 cm^2 sapphire are not shown here.

First RF Surface Resistance Measurement of HIP Bulk Sample at STC of LANL

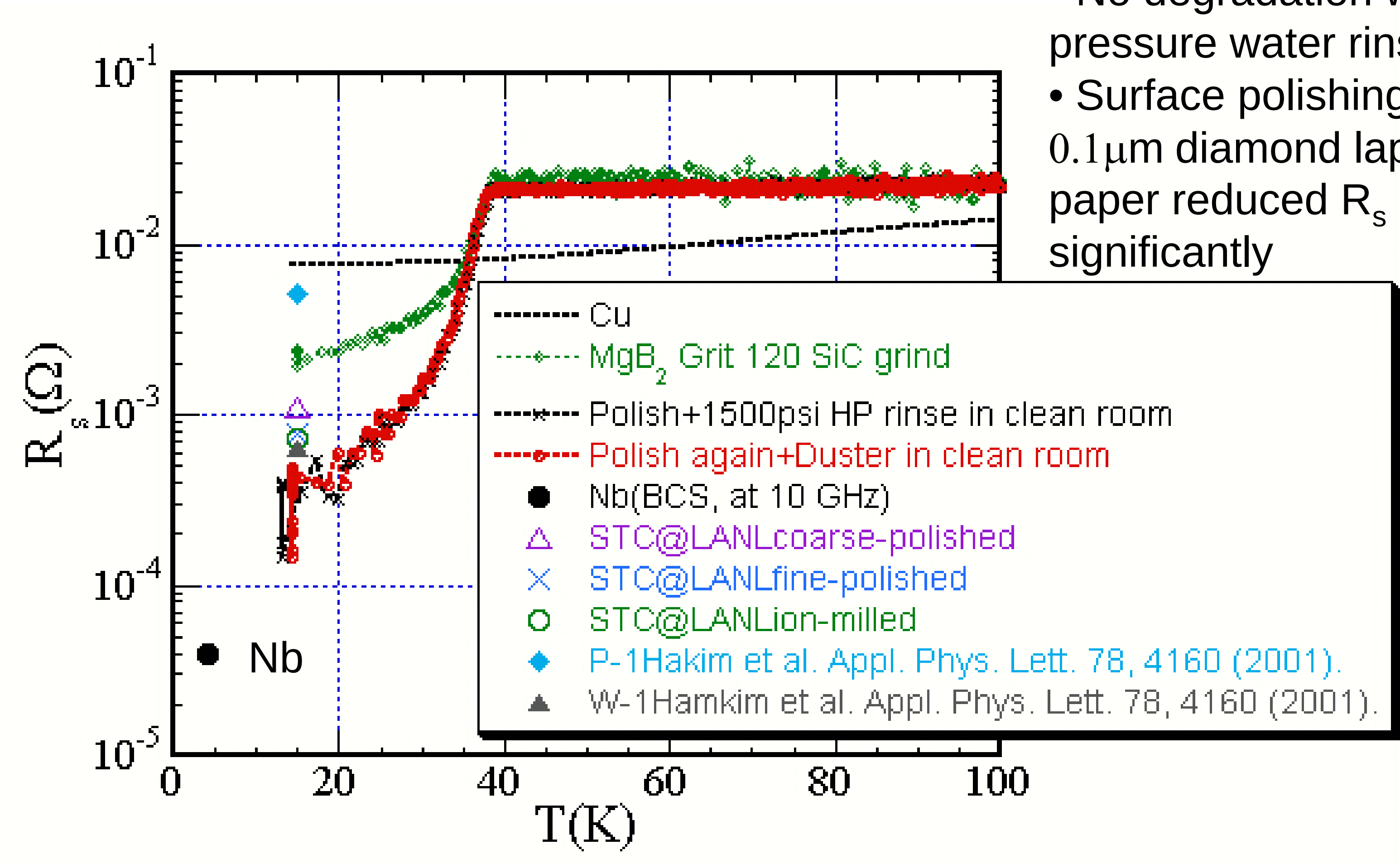


- No increase of R_s from 0.2 to 4 Oe as compared to significant increase with YBCO.
- This material is not optimized for low R_s, i.e., there is room for improvement

- R_s (BCS) of Nb (4K, 10 GHz) ~ 40 μΩ

Alp Findikoglu et al. (Superconductivity Technology Center at LANL), Applied Physics Letters 83 108 (2003).

RF Surface Resistance Measurement of HIP Bulk MgB_2 at LANSCE of LANL: Results Converted to 10 GHz



- No degradation with high-pressure water rinse
- Surface polishing with 0.1μm diamond lapping paper reduced R_s significantly

T. Tajima, J. Liu et al., 6th European Conference of Applied Superconductivity, Sorrento, September 14-18

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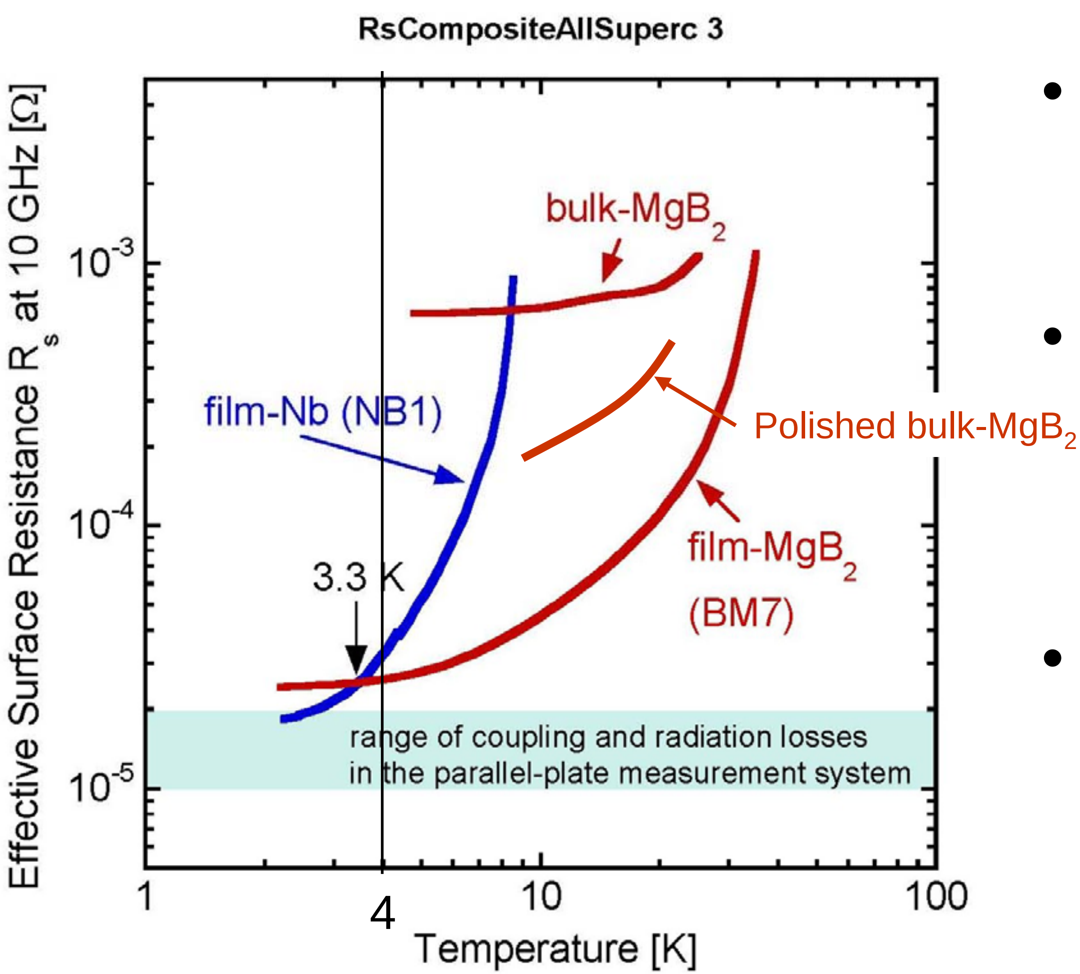
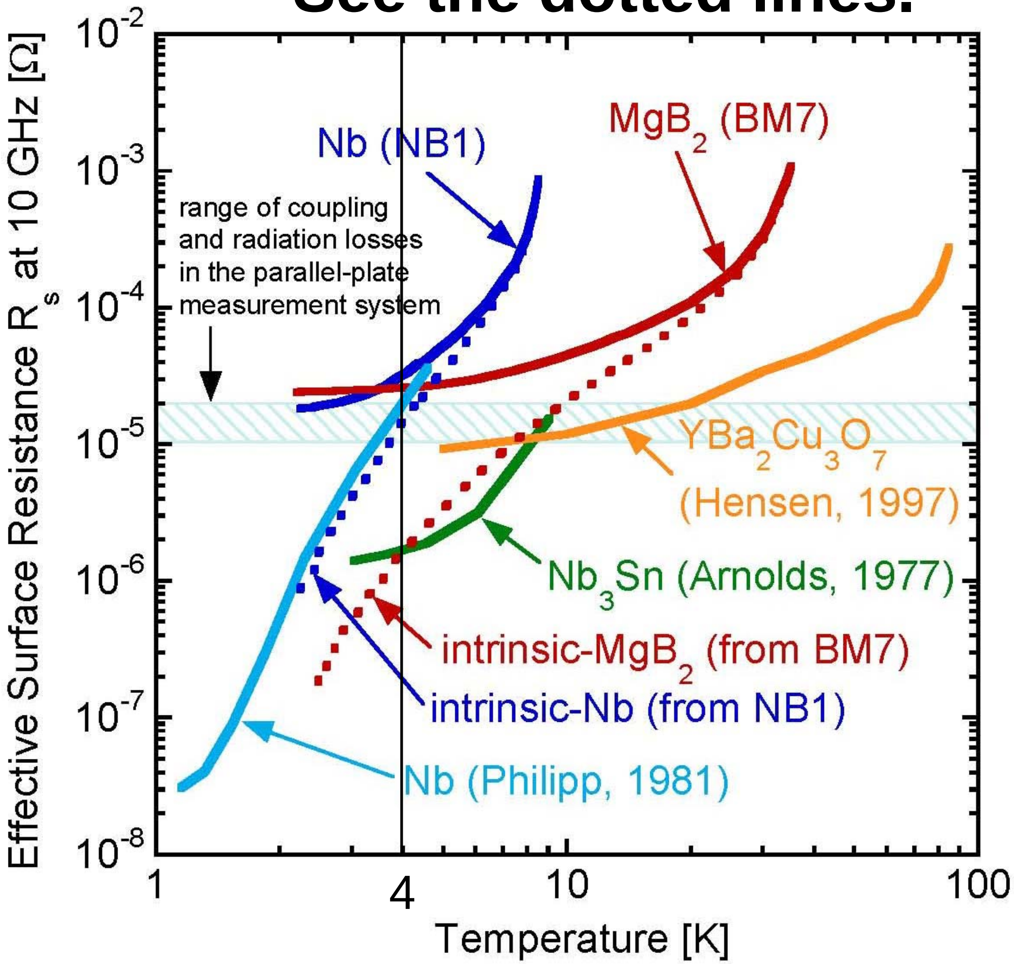
400 nm film on 1 cm^2 sapphire substrate showed further R_s reduction, lower than Nb at 4 K!!



- Data taken by Alp Findikoglu of STC at LANL, unpublished
- Film prepared by Brian Moeckly of Superconductor Technologies, Inc.
- Polycrystal, non-epitaxial film

Intrinsic (BCS) Resistance could be about one order of magnitude lower than Nb at 4 K!!

See the dotted lines.



Alp Findikoglu of STC at LANL, unpublished

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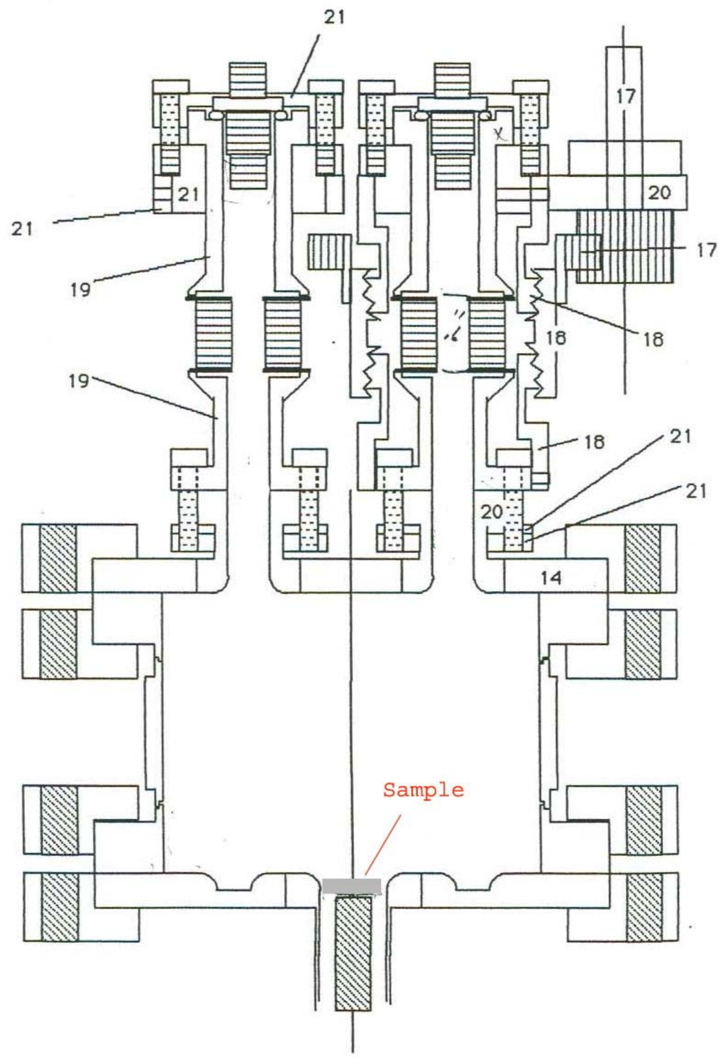
R_s Dependence on Magnetic Field was measured in collaboration with Cornell

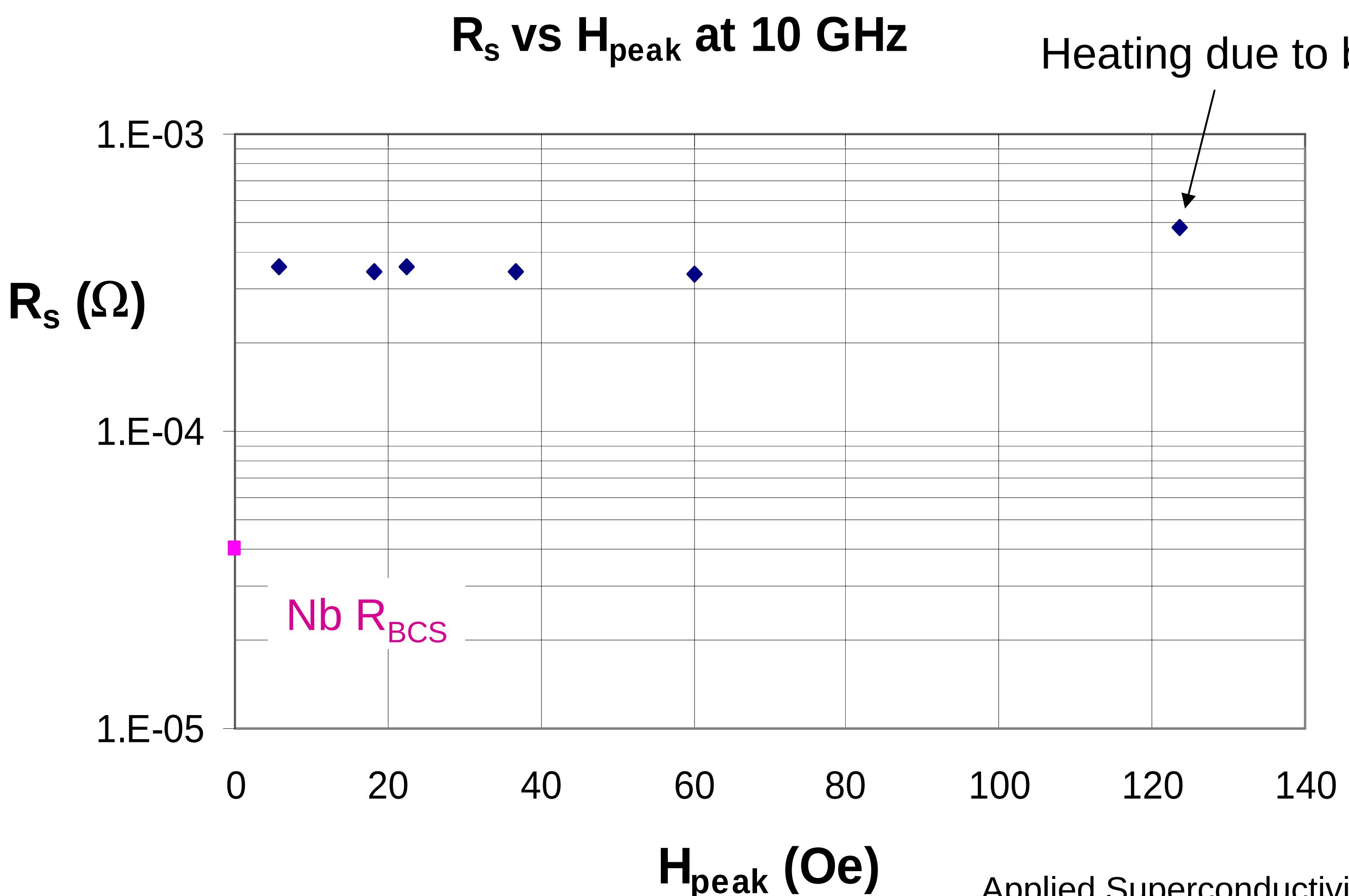
- This measurement is critical to determine the feasibility of materials for accelerator applications.
- We placed a MgB_2 coated Nb disk in a TE_{011} mode cavity and measured cavity Q_0 which is inversely proportional to R_s.
- We increased the magnetic field up to available limit and measured the change of Q_0.
- Measured at 4K so that Nb is superconducting, which makes the measurement more sensitive to the R_s change of MgB_2 than using Cu cavity.

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



Measurements in collaboration with Cornell personnel Alexander Romanenko, Hasan Padamsee

Results showed little increase of R_s up to ~120 Oe, available power !



As you can see, the film quality is not good.

It may be due to the surface roughness. (The substrate Nb was not polished.)

Applied Superconductivity Conf., Oct., 2004

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Future Plans for MgB_2 Study

- Continue power dependence tests with better films and coating on copper at higher magnetic fields.
- Develop methods for coating on inner surfaces of elliptical cavities and other shapes.
- Evaluate the quality of the films and try to coat existing small (~3 GHz) elliptical single-cell cavities and take Q_0 - E_{acc} curves.
- In parallel, test the critical magnetic field with short pulses (< 1 μs) at SLAC to avoid heating effect at high magnetic fields.