200MHz SCRF cavity development

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CERN

Contents

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- Performance: Eacc and Q
- Q-slope
- Performance when $H_{ext} \neq 0$
- Future work plan and status
- Conclusion

Requirements to acceleration

- The highest possible Eacc to minimize muon decay
- Large transverse and longitudinal acceptances

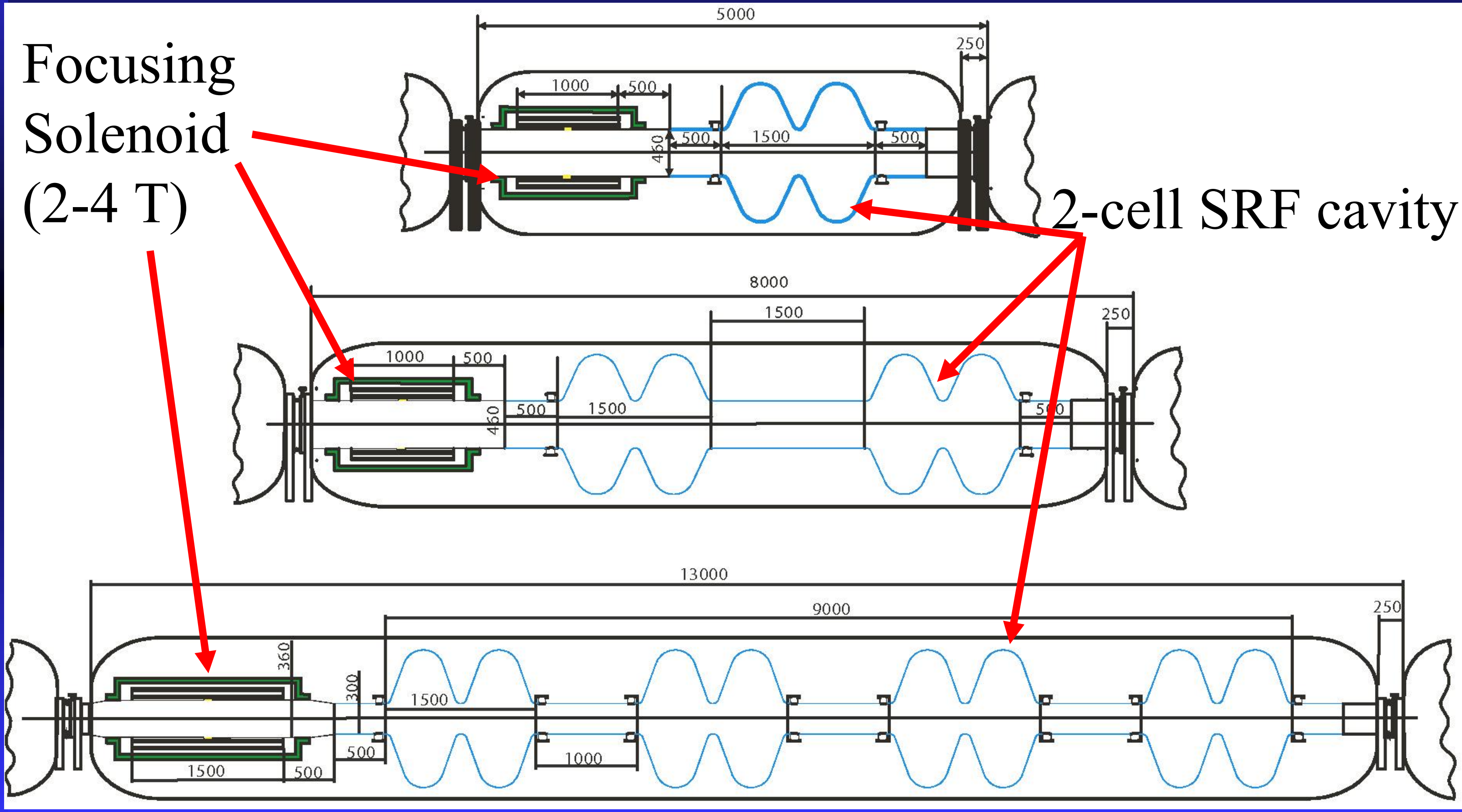
Both requirements favor the choice of SRF

- SRF cavities have a high Q_0

$$P_d = \frac{Eacc^2}{(R/Q)Q_0}$$

- SRF can achieve high gradients with modest RF power
- SRF cavities accommodate a larger aperture without a large penalty for the low R/Q

200MHz SRF layout for Linac



200MHz SRF parameter list

2-cell, 460 mm-aperture cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	43
aperture diameter (mm)	460
E_{acc} (MV/m)	15
Energy gain per cavity (MV)	22.5
Stored energy per cavity (J)	1932
R/Q (Ω/cavity)	208
E_p/E_{acc}	1.54
H_p/E_{acc} (Oe/MV/m)	44
E_{pk} at 10 MV/m (MV/m)	23.1
H_{pk} at 10 MV/m (Oe)	660
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	980
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (watt)	18.3
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40

2-cell, 300 mm-diameter cavity parameters.

RF freq (MHz)	201.25
No. of cells per cavity	2
Active cavity length (m)	1.5
No. of cavities	256
Linac	76
RLA	180
Aperture diameter (mm)	300
E_{acc} (MV/m)	17
Energy gain per cavity (MV)	25.5
Stored energy per cavity (J)	2008
R/Q (Ω/cavity)	258
E_p/E_{acc}	1.43
H_p/E_{acc} (Oe/MV/m)	38
E_{pk} at 15 MV/m (MV/m)	24.3
H_{pk} at 15 MV/m (Oe)	646
Q_0	6×10^9
Bandwidth (Hz)	200
Input power per cavity (kW)	1016
RF on-time (ms)	3
RF duty factor (%)	4.5
Dynamic heat load per cavity (W)	18.9
Operating temperature (K)	2.5
Q_L	10^6
Microphonics detuning tolerable (Hz)	40
Wall thickness (mm)	8
Lorentz force detuning at 15 MV/m (Hz)	128

300 high gradient 200MHz cavities needed

Why Nb-Cu cavities?

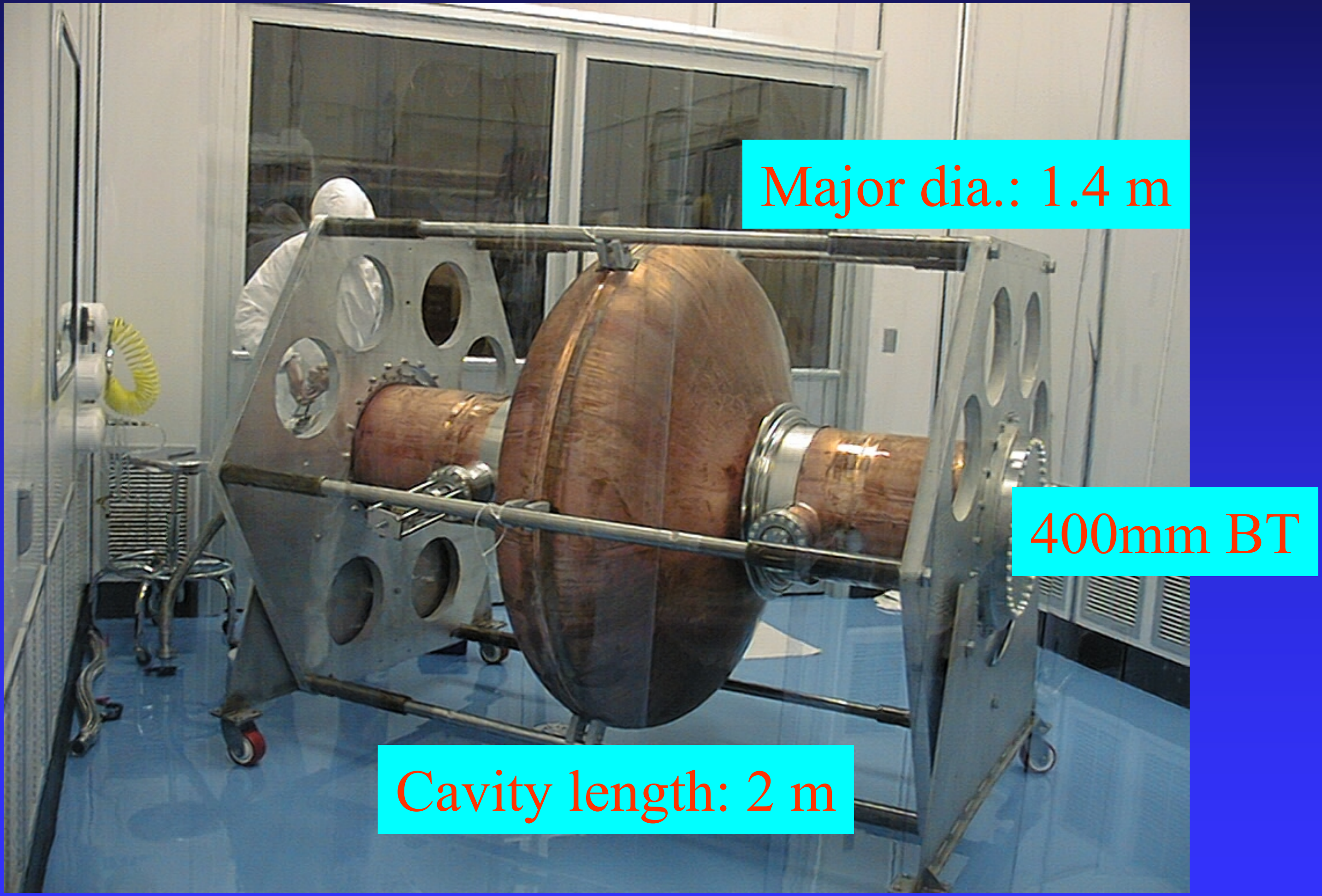
- Save material cost
- Save cost on magnetic field shielding (Rs of Nb-Cu less sensitive to residual mag. field)
- Save cost on LHe inventory by pipe cooling (Brazing Cu pipe to Cu cavity)

1.5GHz bulk Nb cavity (3mm) material cost: ~ $ 2k/cell
200MHz: X $(1500/200)^2 = 56 \rightarrow$ $ 112k/cell
Thicker material (8mm) needed: X 2.7 → $300k/cell

Nb Material cost for 600 cells: 180M$

Cu (OF) is X 40 cheaper: 5M$

First 200MHz Nb-Cu cavity



Fabrication at CERN

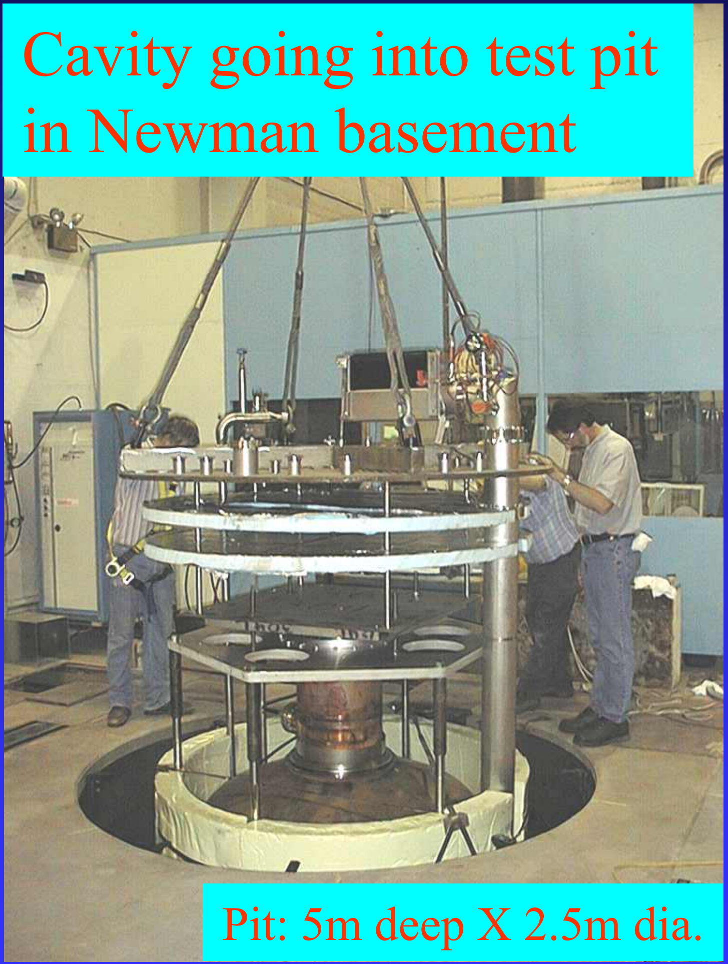
Electro-polished half cell

Magnetron Nb film (1-2 μm) sputtering

- DC voltage: 400-650 V
- Gas pressure: 2 mTorr
- Substrate T: 100 °C
- RRR = 11
- Tc = 9.5 K

RF test at Cornell

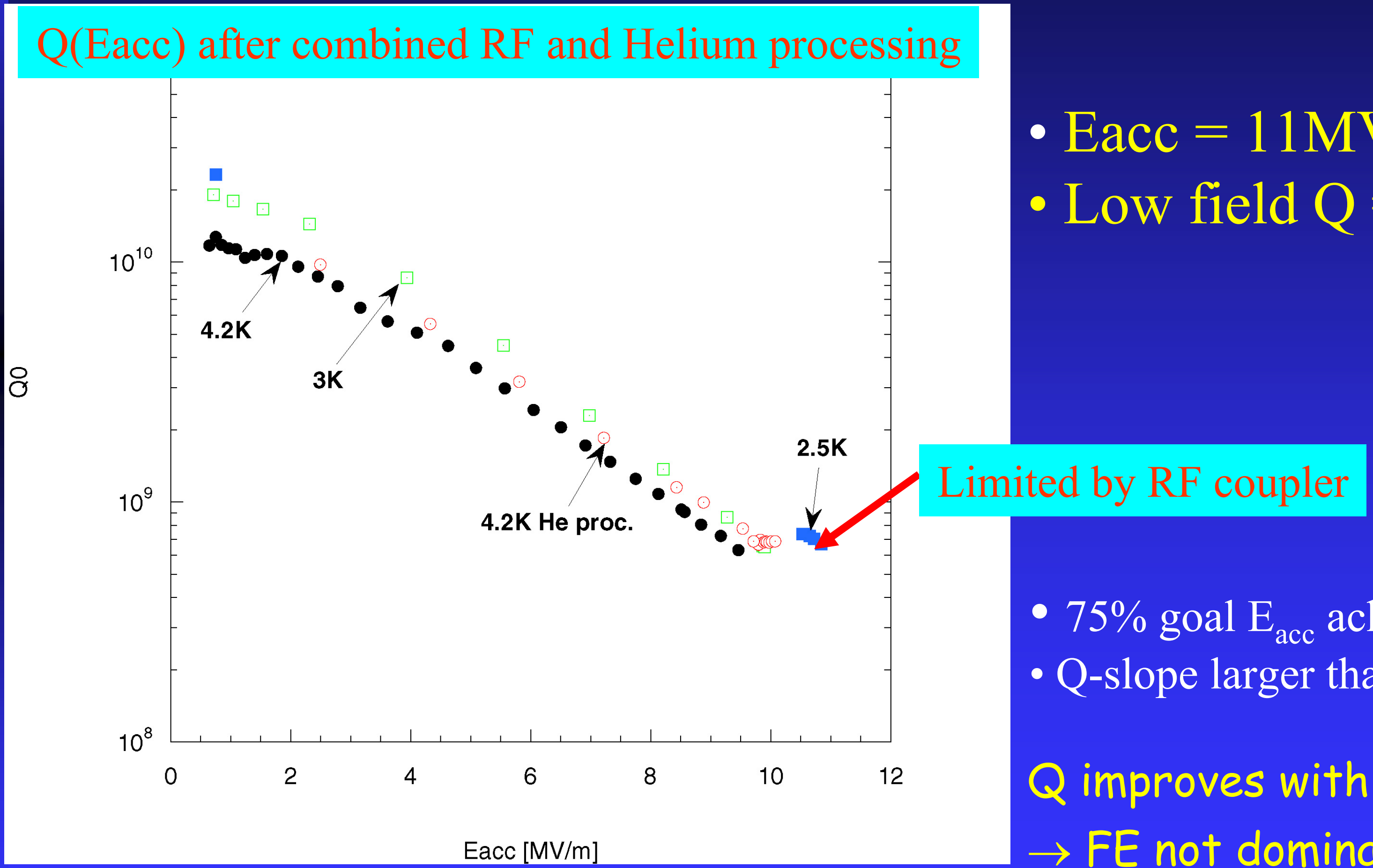
Cavity on test stand



Cavity going into test pit in Newman basement

Pit: 5m deep X 2.5m dia.

Performance of the cavity

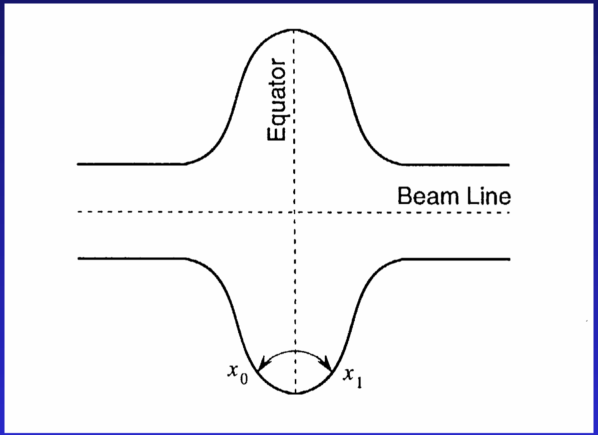


- Eacc = 11MV/m
- Low field Q = 2E10

- 75% goal E_{acc} achieved
- Q-slope larger than expected

Q improves with lower T
→ FE not dominant

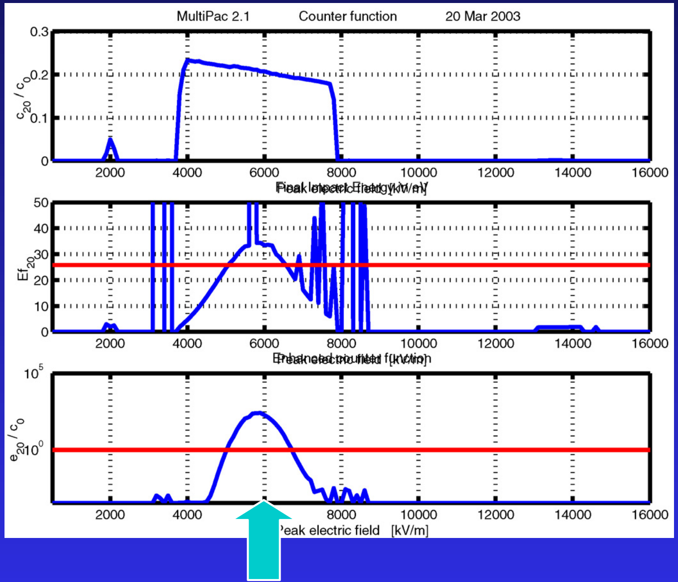
Two-point Multipacting



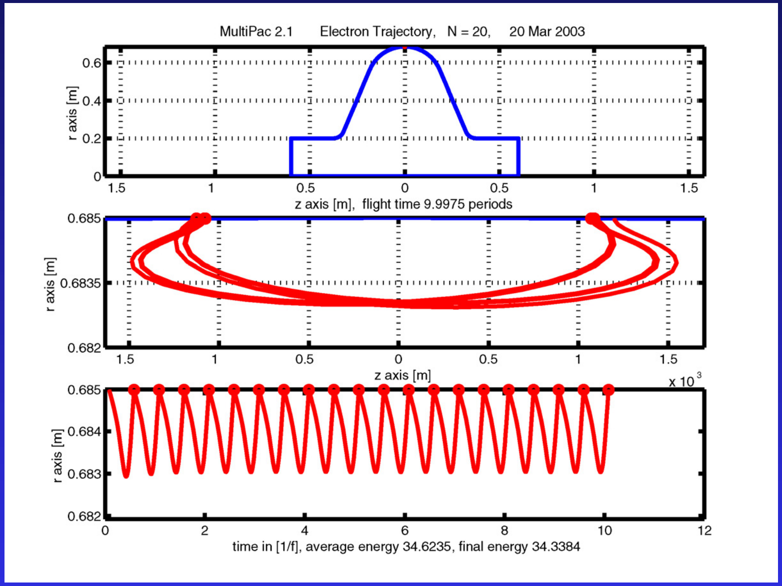
- Two points symmetric about equator are involved
- Spontaneously emitted electrons arrive at opposite point after T/2
- Accelerated electrons impact surface and release secondary electrons
- Secondary electrons are in turn accelerated by RF field and impact again
- The process will go on until the number of electrons are saturated

MP electrons drain RF power → A sharp Q drop

Two-point MP at 3 MV/m



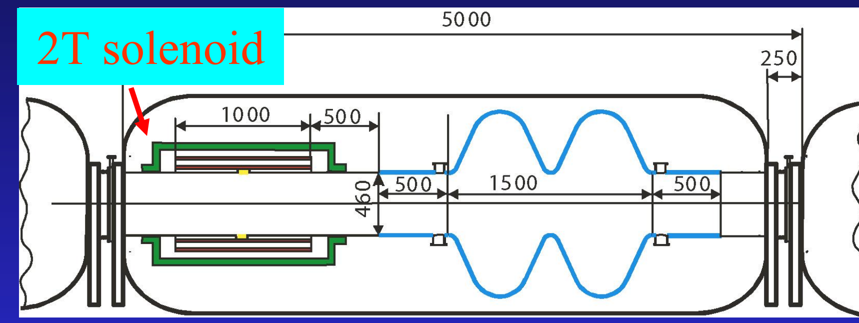
MULTIPAC simulation confirmed exp. observation



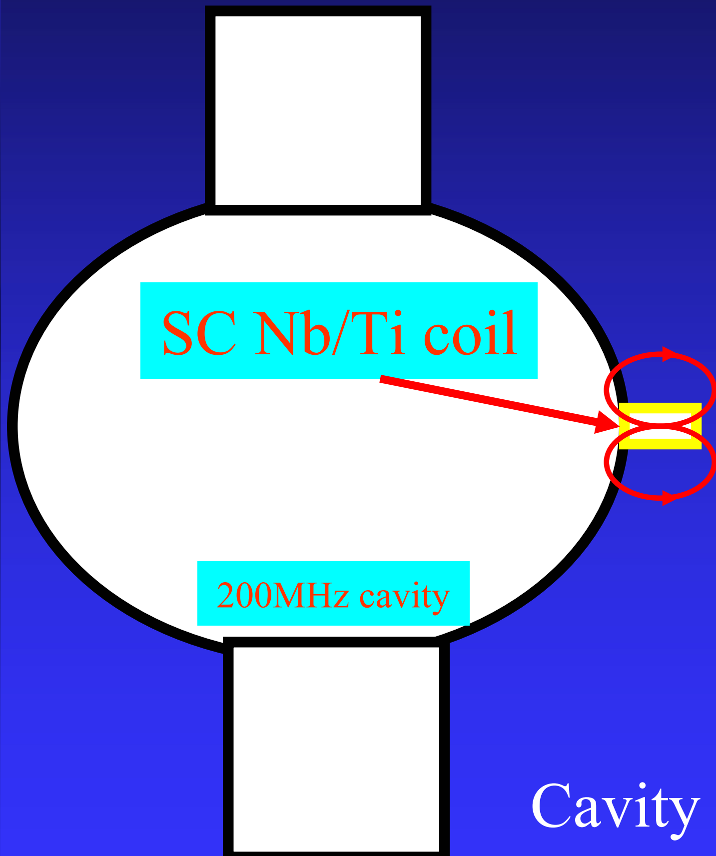
Resonant trajectory of MP electrons

It was possible to process through MP barrier

H_{ext} effect on cavity



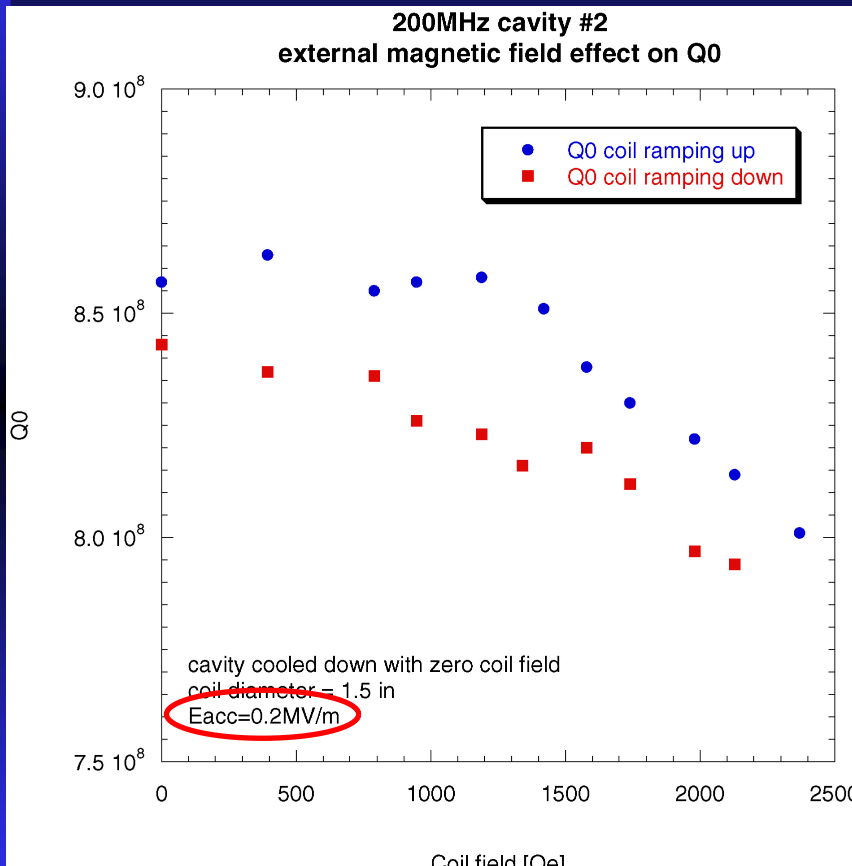
Layout of Linear Accelerator for ν source

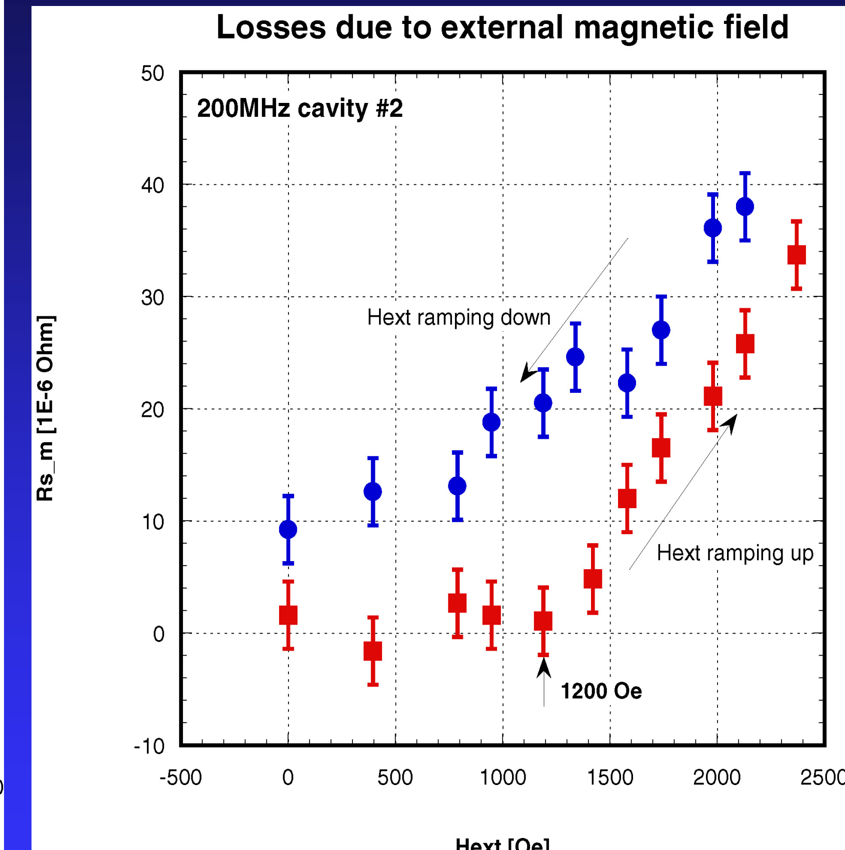


- 2T solenoid needed for tight focusing
- Solenoid and cavity fitted in one cryostat
- Large aperture (460 mm)
- Q: Will cavity still work $H_{ext} > 0$?

Cavity test in the presence of an H_{ext}

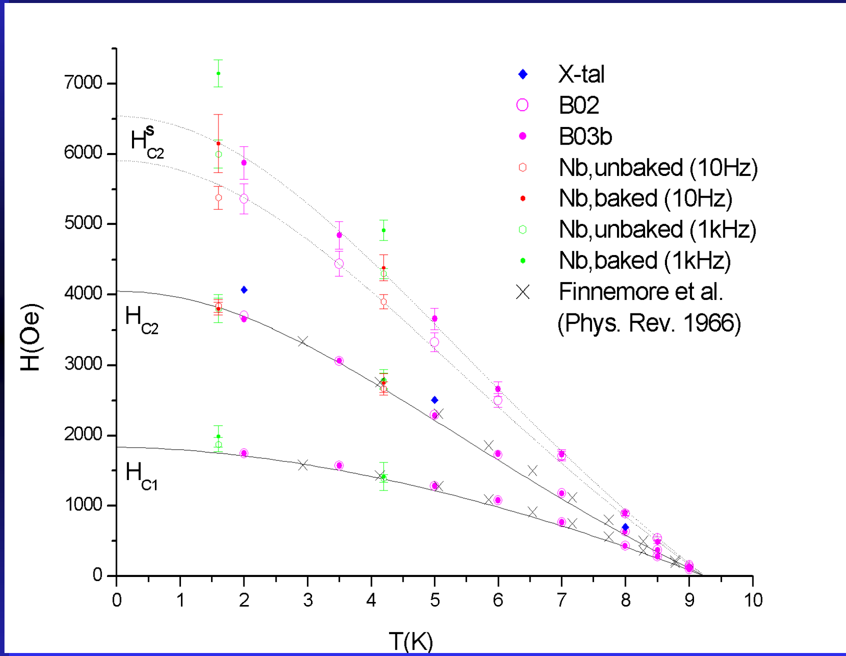
H_{ext} effect on cavity





Cavity stays intact up to Hext = 1200 Oe

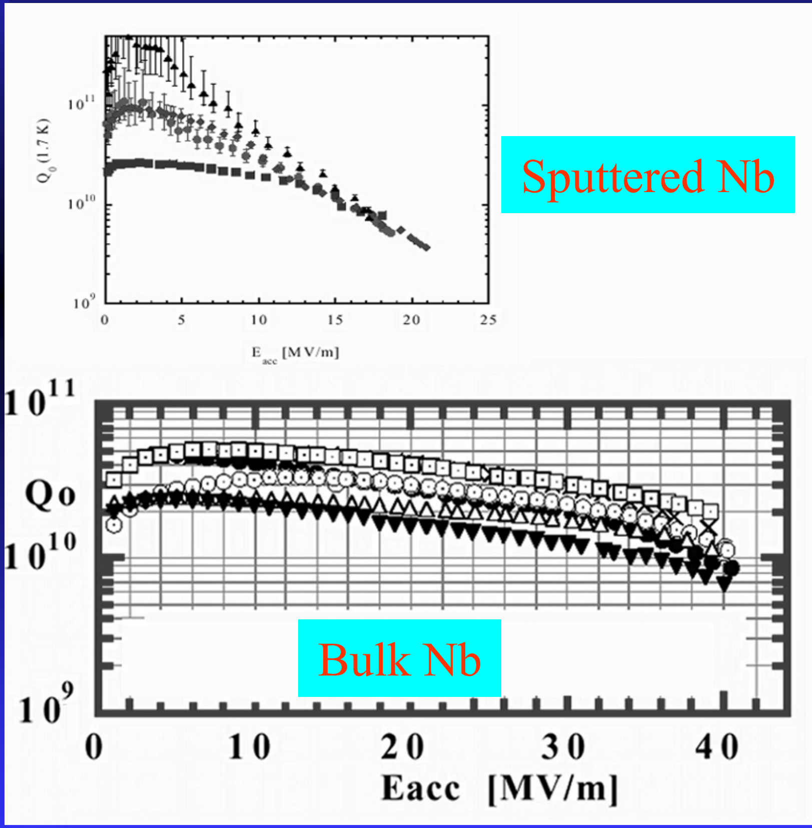
Hext effect on cavity



- Nb is a type-II SC
- Mixed state above Hc1
- Magnetic flux penetration
- Normal cores cause Rs ↑

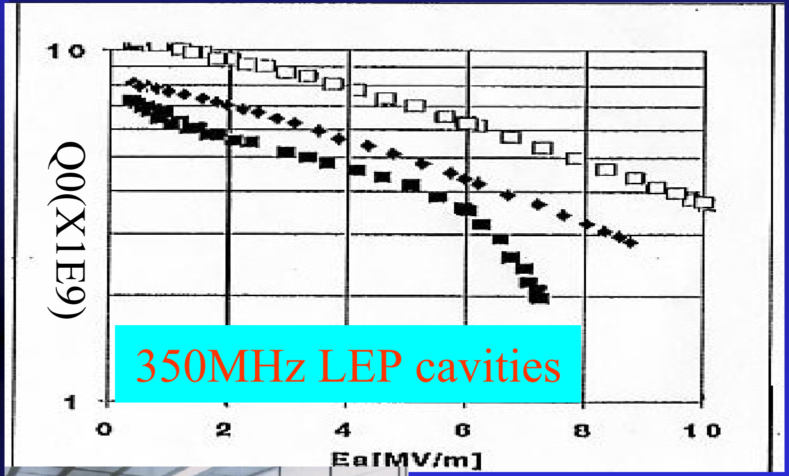
- Onset H_{ext} for loss increase consistent with Hc1 of Nb
- Msmts at higher Eacc needed: $H_{ext} + H_{RF}$; resistive flux flow

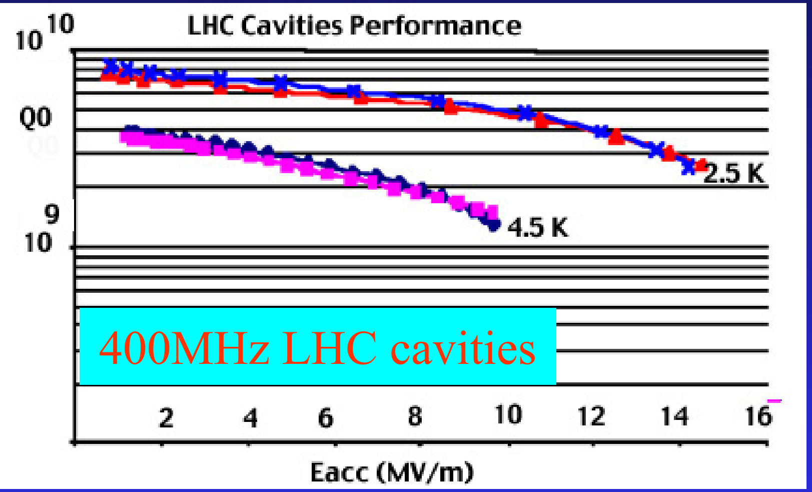
Q-slope of sputtered film Nb cavities



- Q-slope is a result of material properties of film Nb
- The Cu substrate (surface) has some influence
- The exact Q-slope mechanism is not fully understood

Nb-Cu cavities

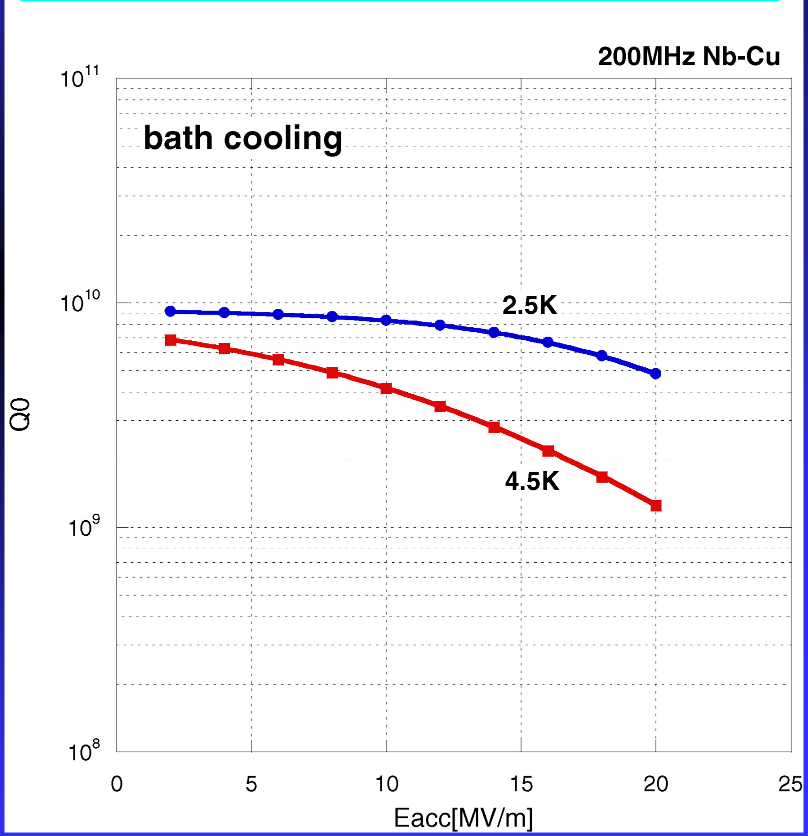


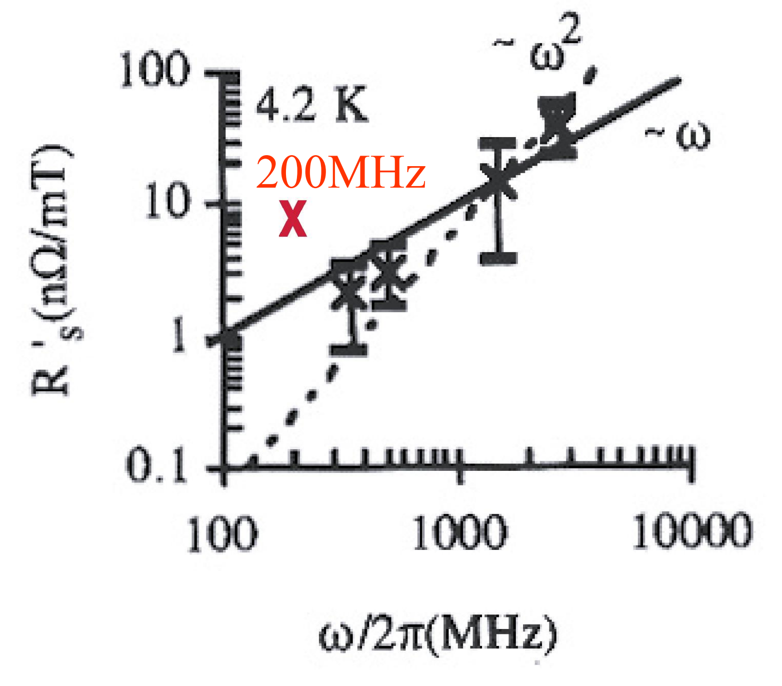


Despite Q-slope, sputtered Nb-Cu cavities have achieved a 15MV/m Eacc at 400MHz

Expected performance

Projecting LHC 400MHz to 200MHz

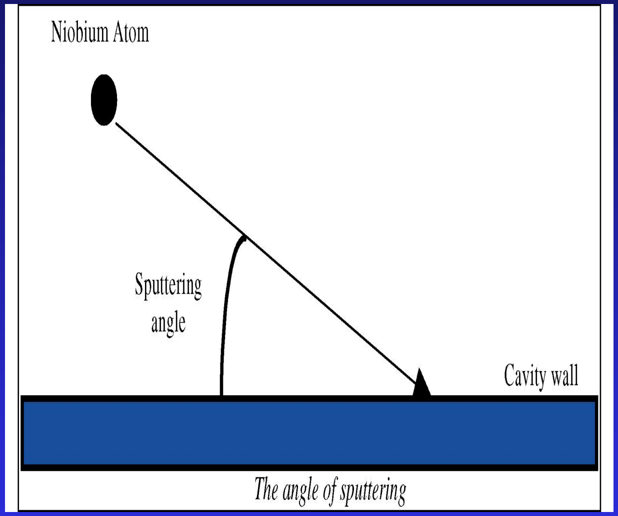




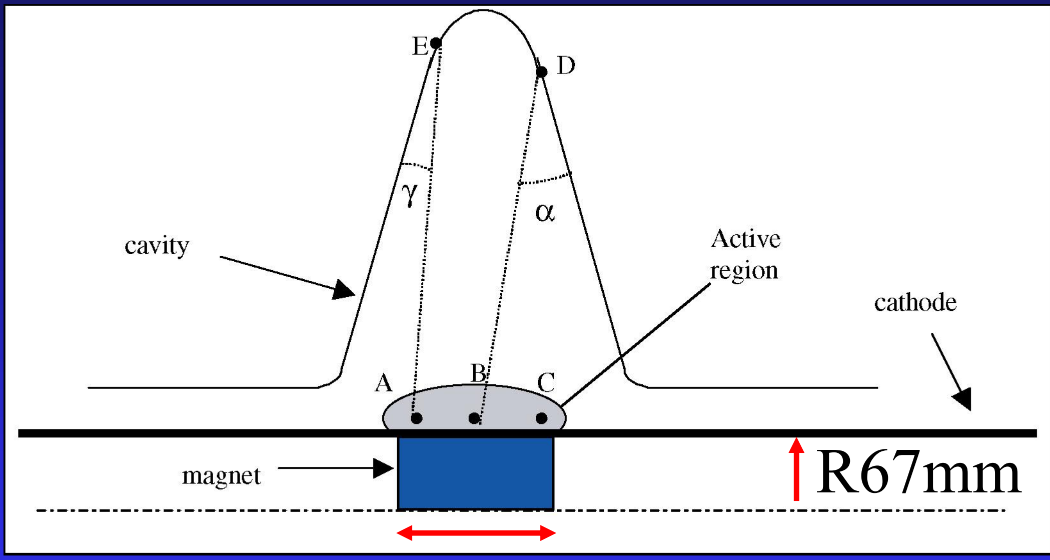
Empirical frequency dependence of Q-slope

Measured Q-slope of 200MHz cavity is 10 times too steep than projected

Q-slope: impact angle effect



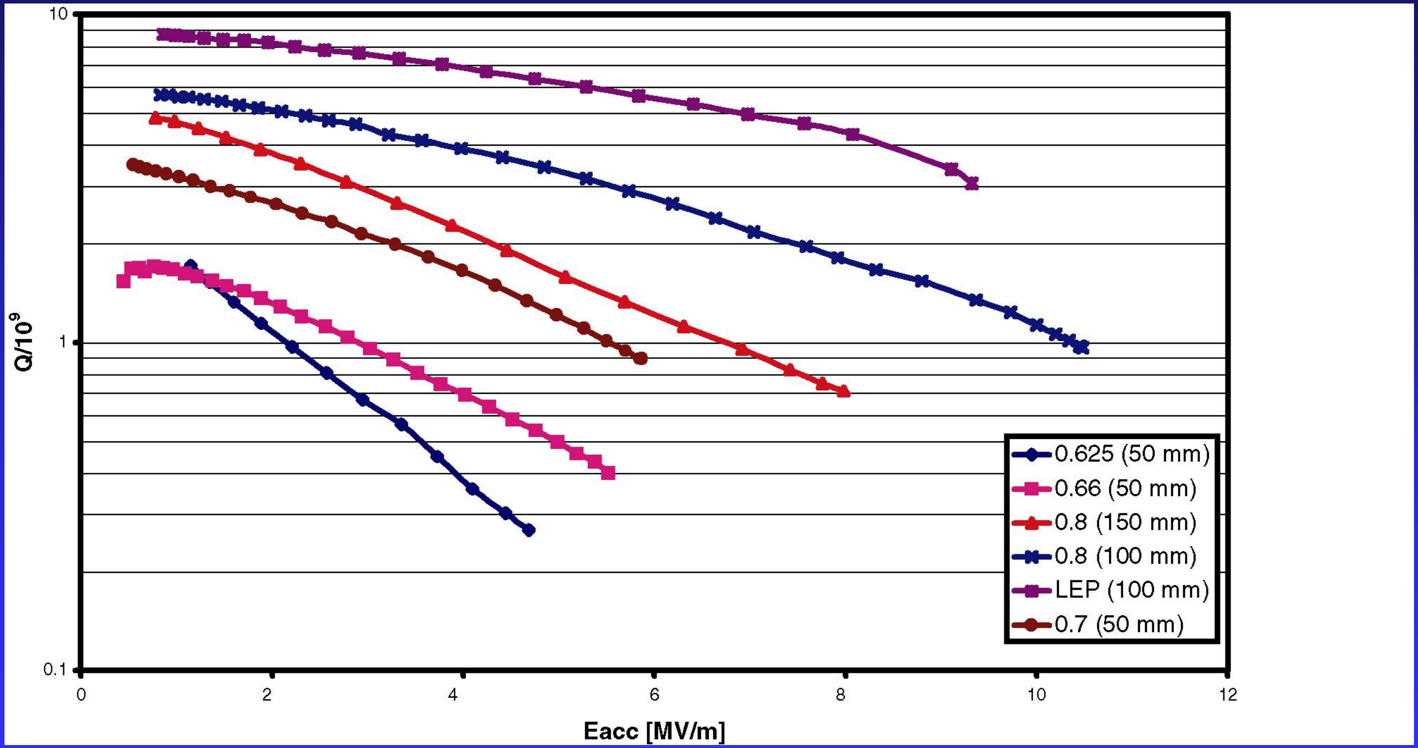
Impact angle of Nb atom: γ



100mm

- CERN explored low β 350MHz cavities
- With the same cathode geometry, lower β → low γ

Q-slope: impact angle effect



Correlation: lower β → lower γ → steeper Q-slope

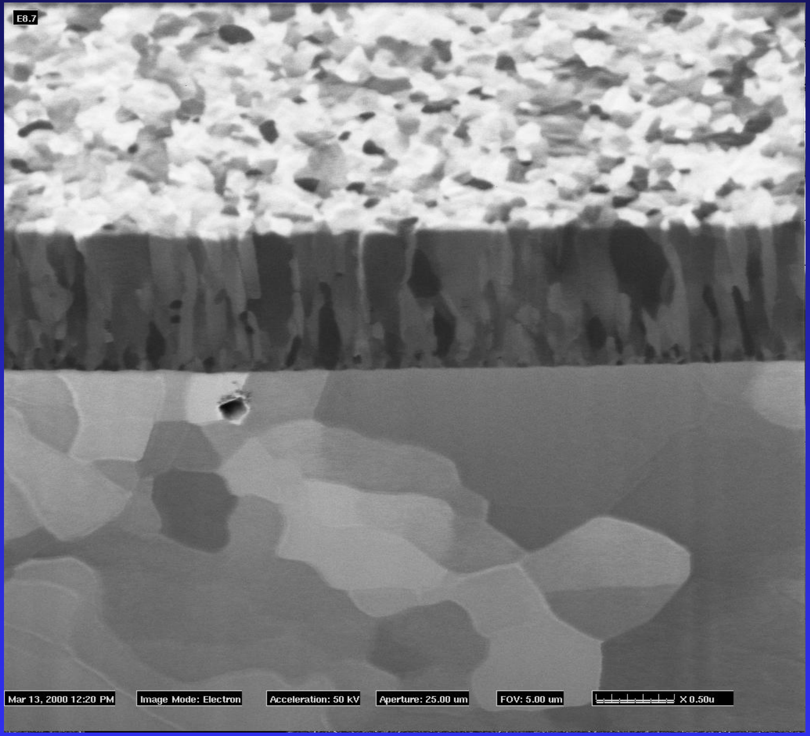
Q-slope: impact angle effect

- A smaller impact angle results in pronounced shadowing effect and poor film quality (open boundaries, voids, dislocations)
- The cathode used to sputter 200MHz cavity was recycled from sputtering system for LEP2 cavities
- Due to an increase in equator radius, a smaller impact angle is evident for 200MHz cavity
- Cavity returned to CERN for recoating with improved geometry - expect completion in March - retest 6/05

Other techniques for Nb film deposition

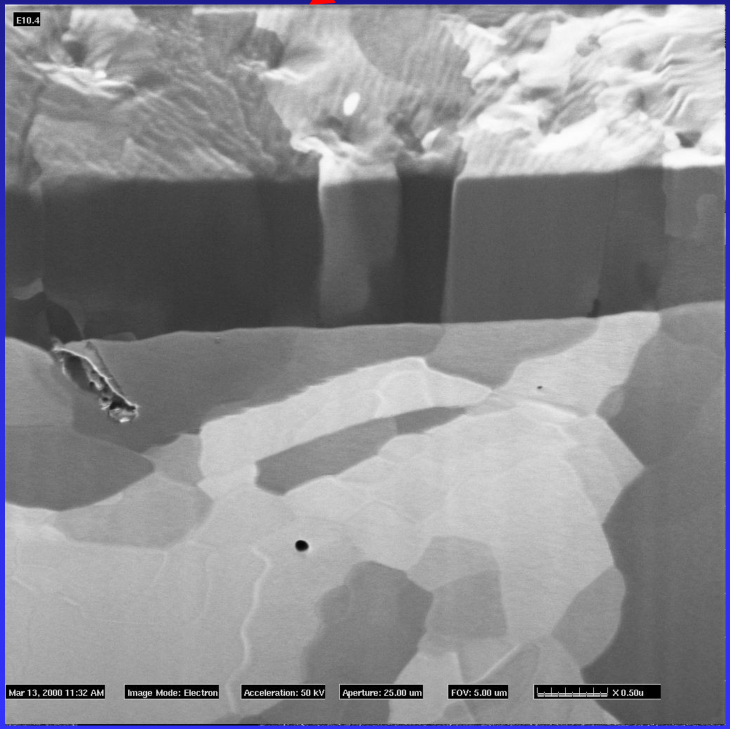
- Bias sputtering
- Energetic deposition in vacuum
- Vacuum arc deposition
- Electron cyclotron resonance sputtering

Nb Sputtering Variation



Standard Films

Oxide-free



- Standard films have rod like form
- Avoid oxide formation
- More uniform and larger grains

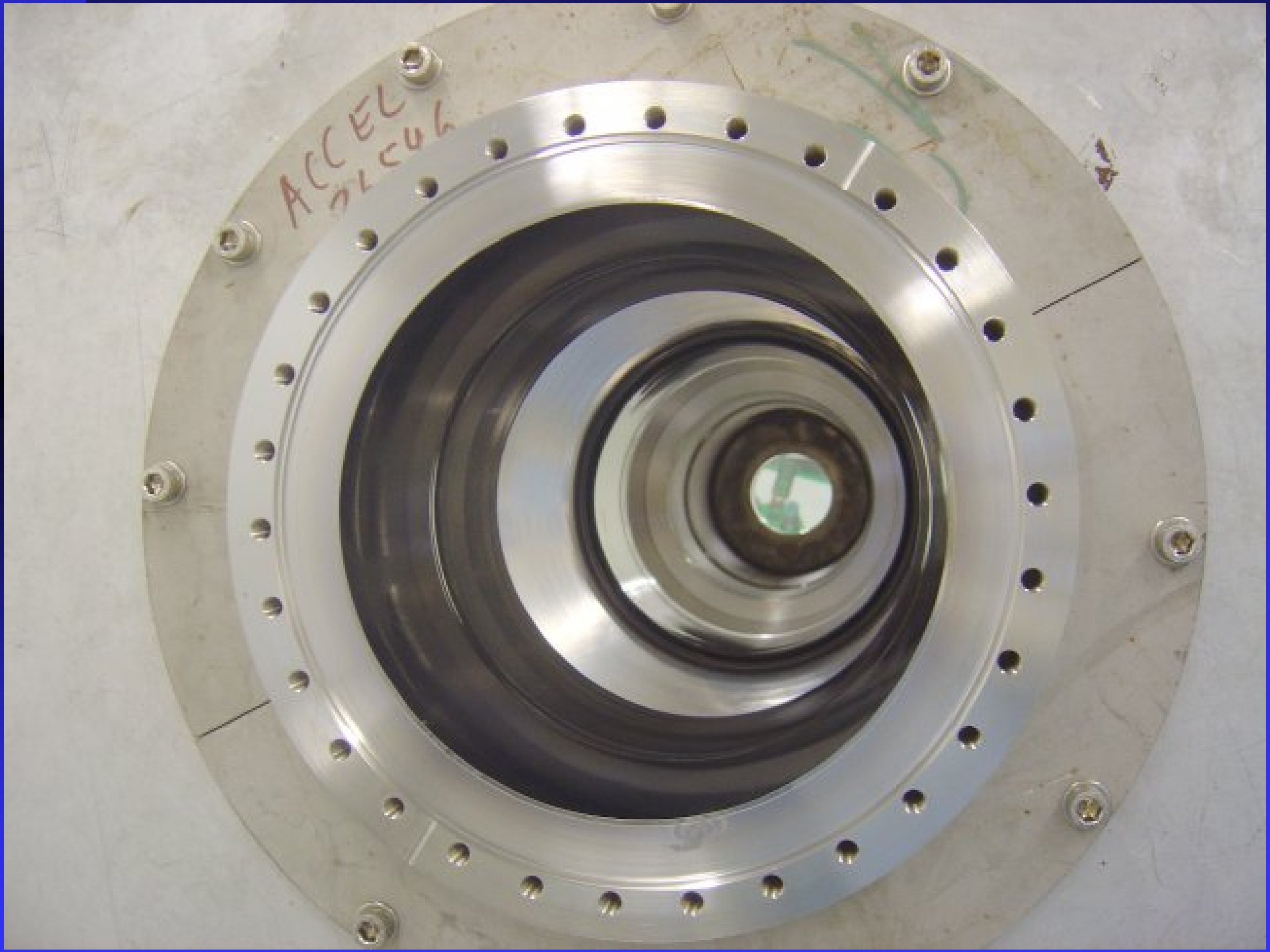
Reducing Q-Slope

- Study Nb film with 500MHz cavities (less LHe) with existing LEPP infrastructure developed for CESR SRF
- Seamless Cu cavities to simplify fabrication (Italy)

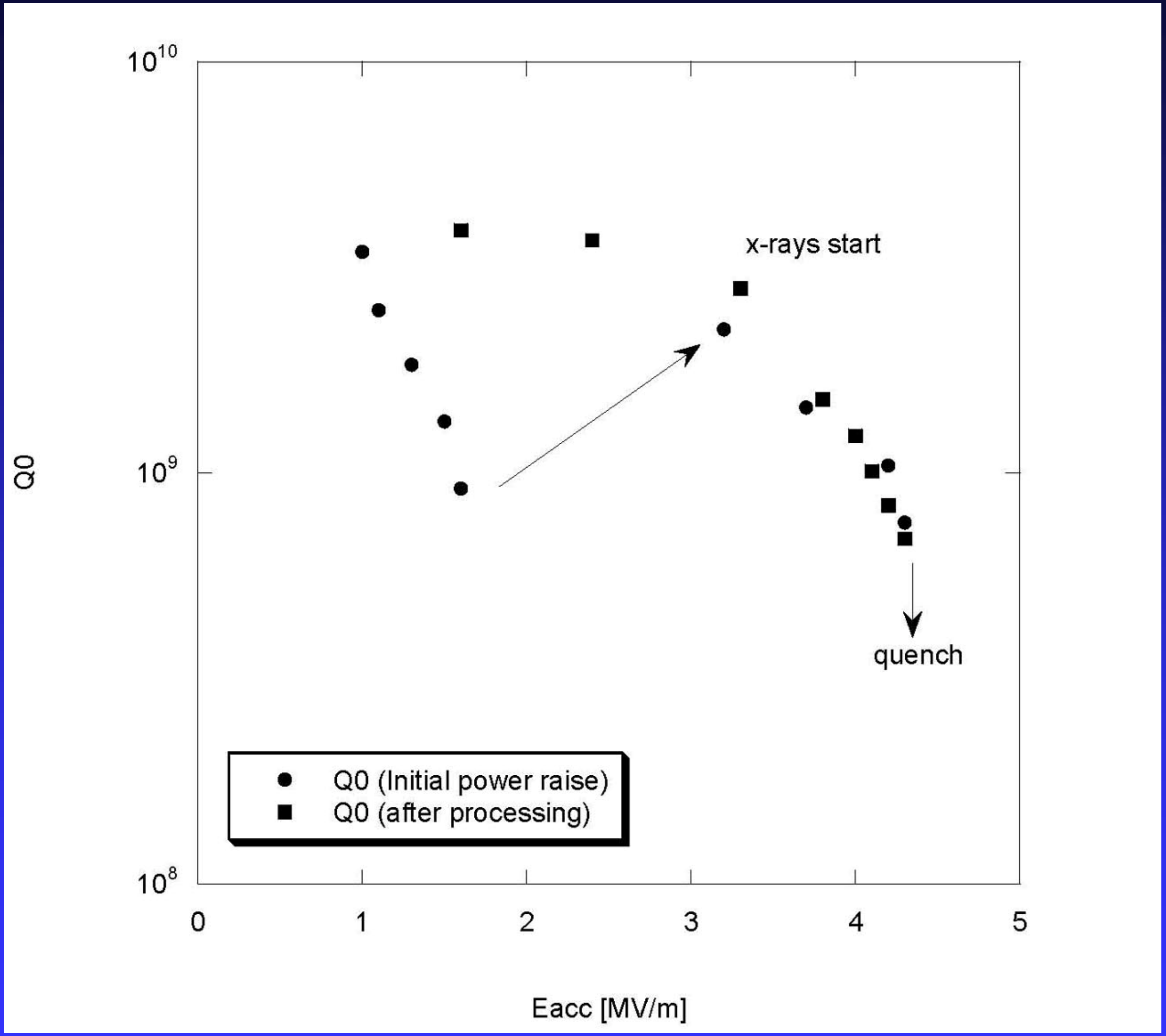
500 MHz

ACCEL Sputtering Setup

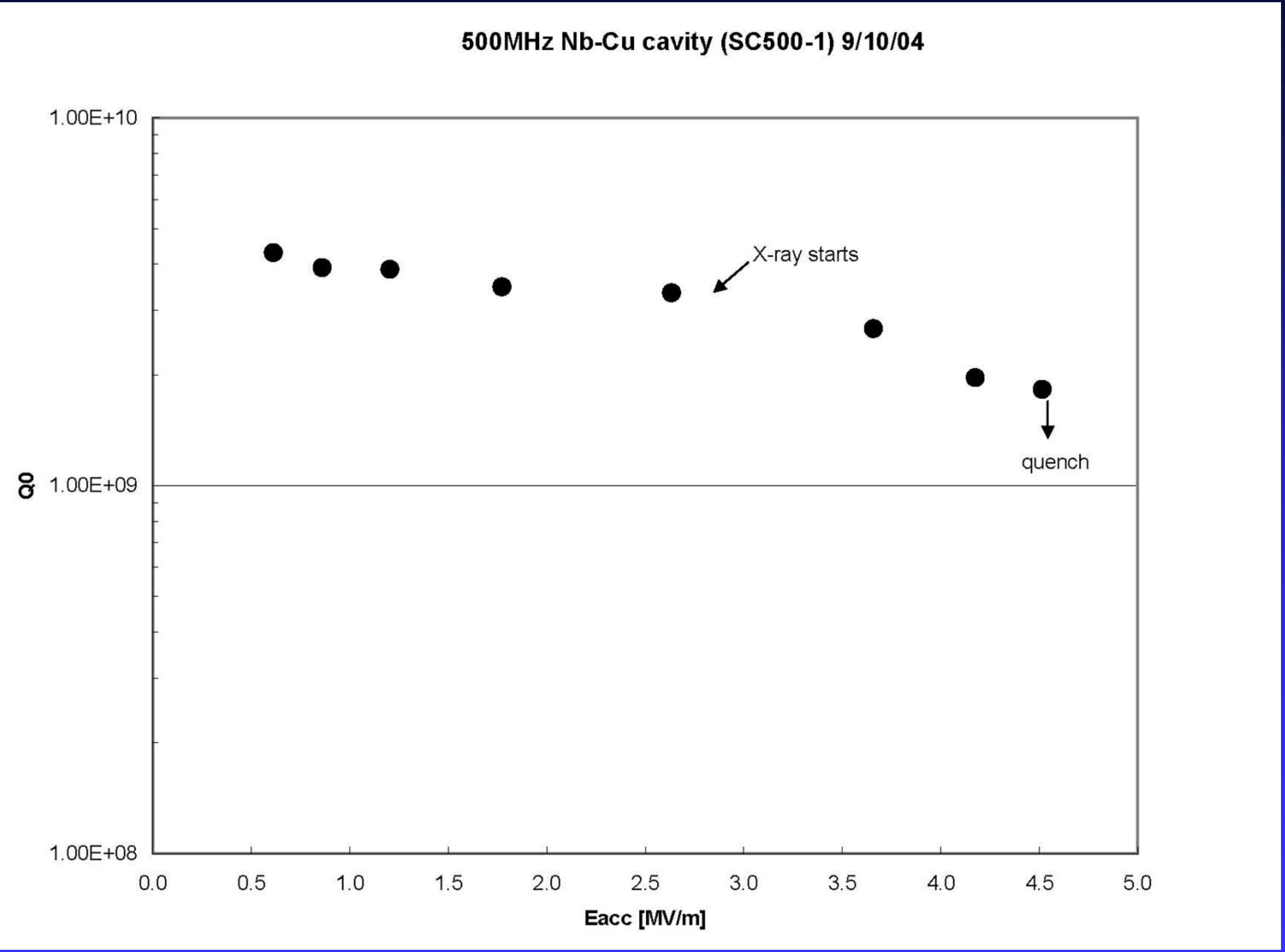
500 MHz Progress

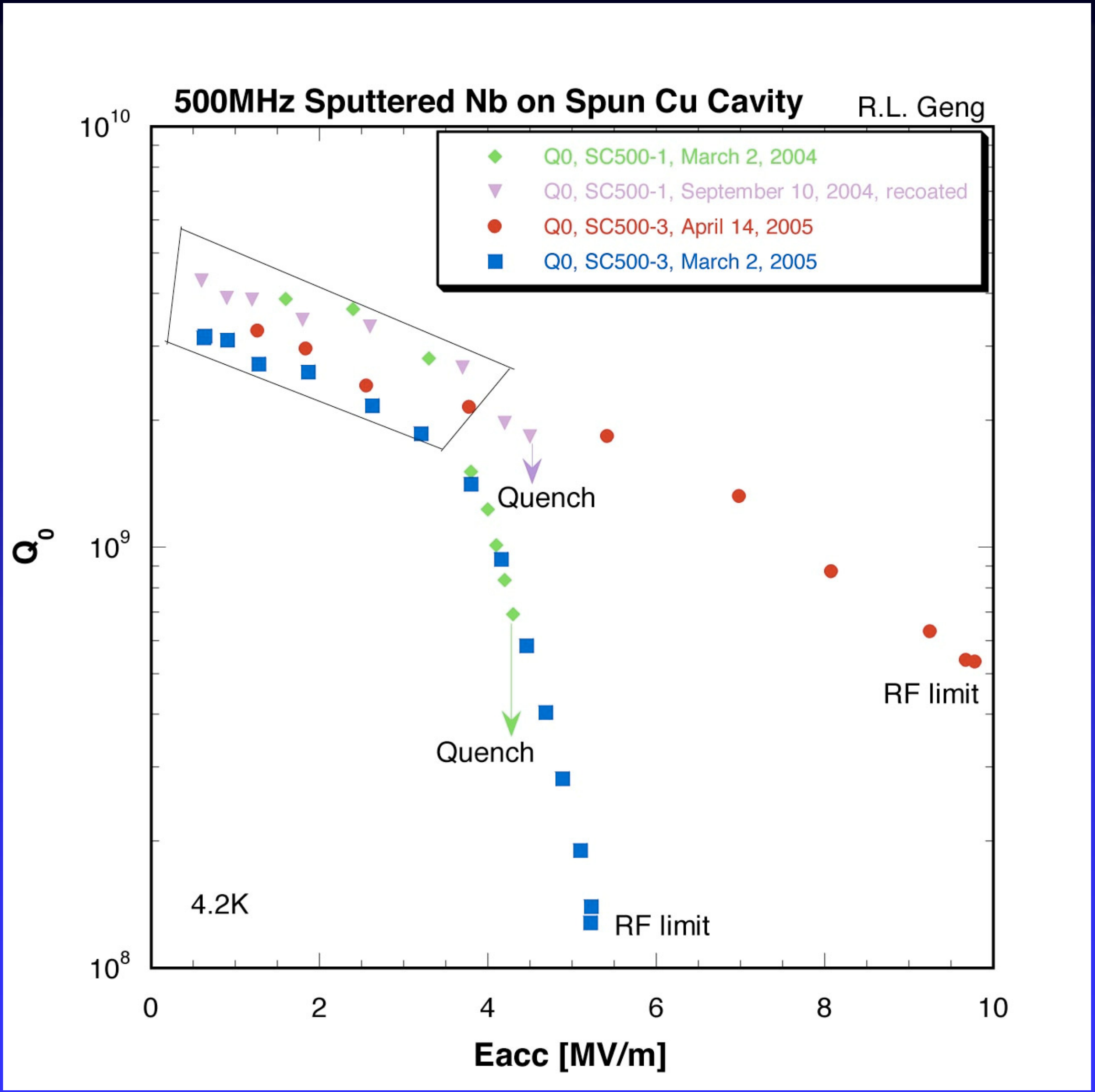


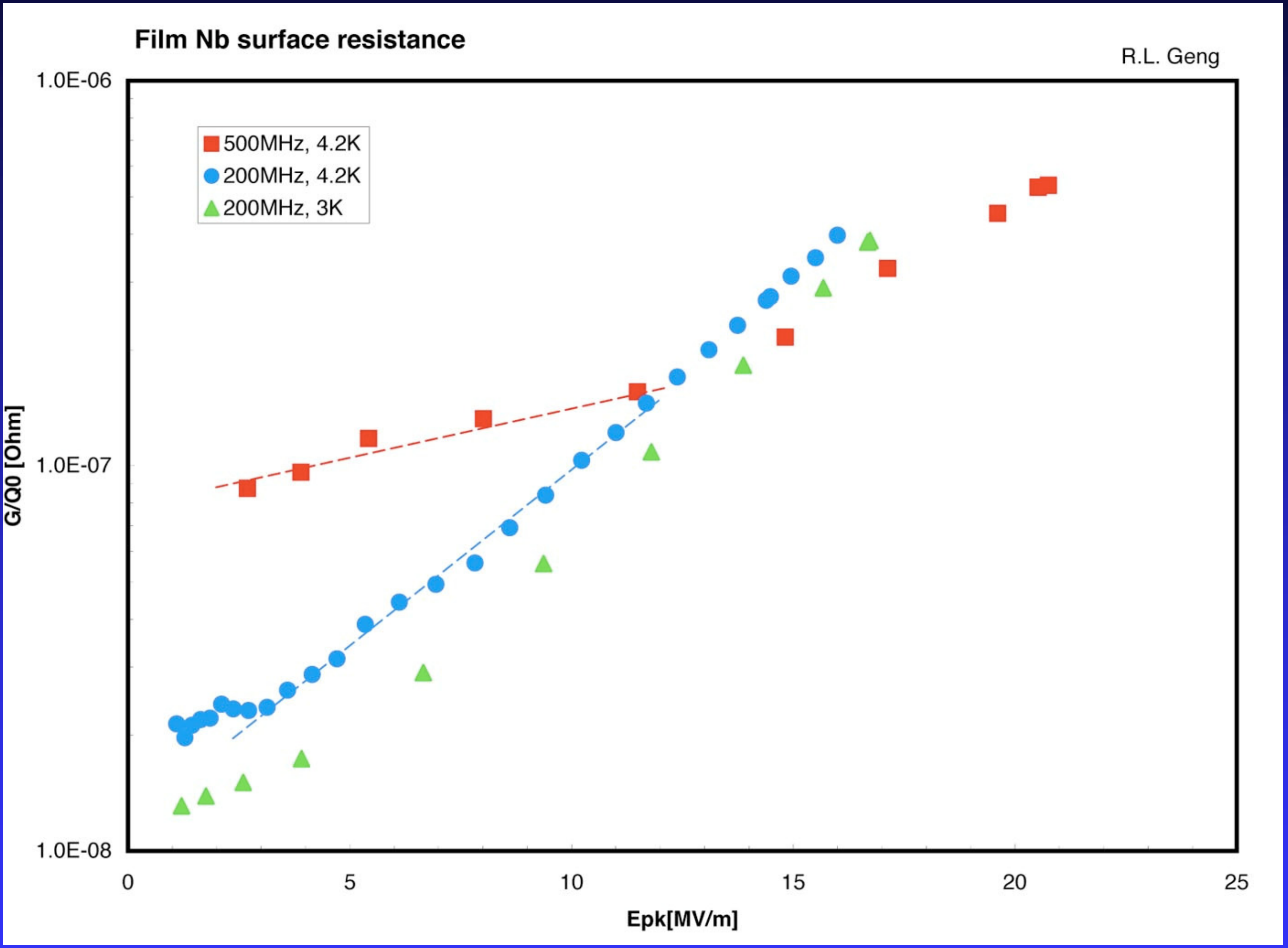
ACCEL Nb Coated Cavity before Final Water Rinse

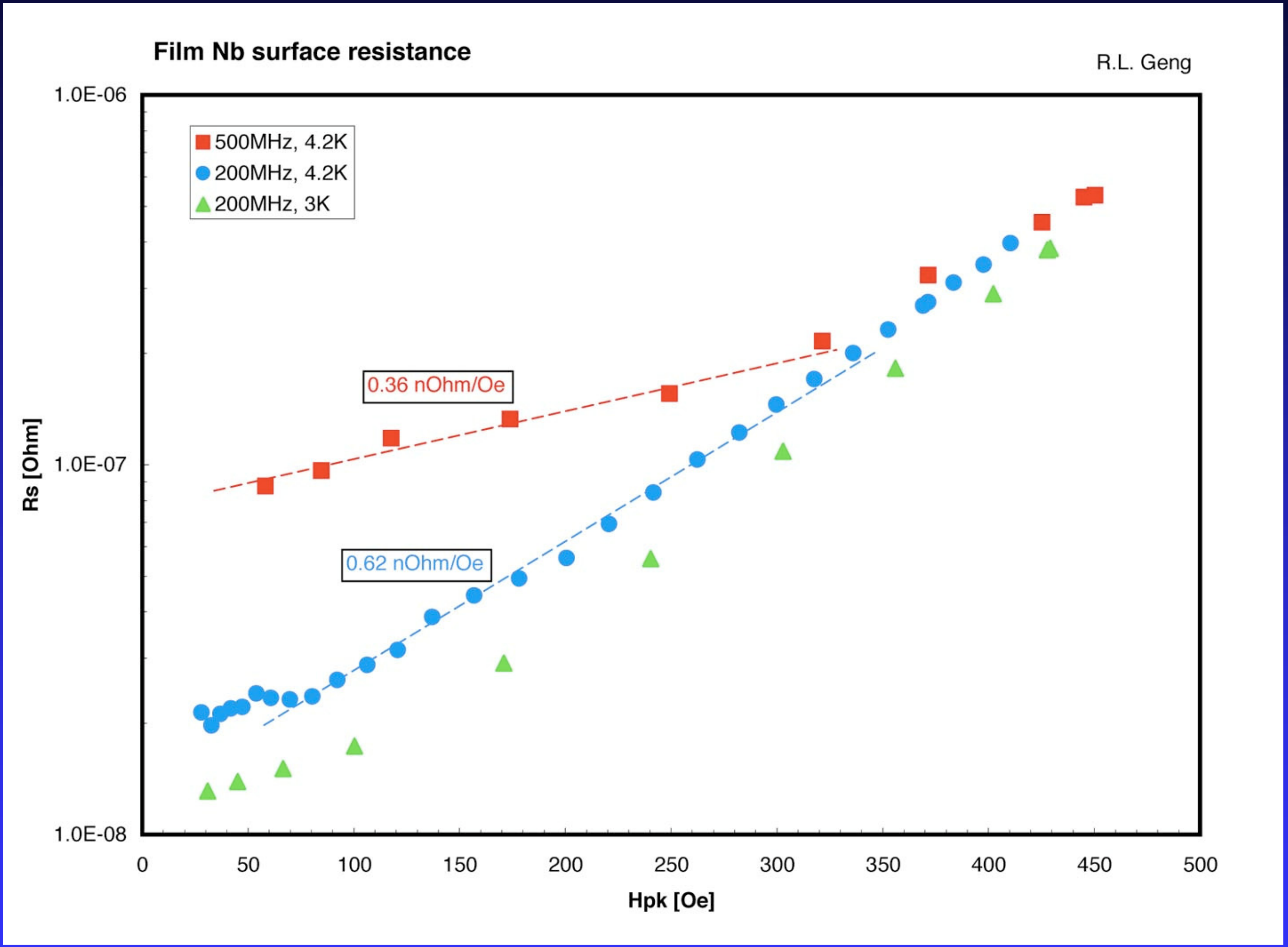


10^{10}
10^{9}
10^{8}
Q0
x-rays start
quench
Q0 (Initial power raise)
Q0 (after processing)
0
1
2
3
4
5
Eacc [MV/m]

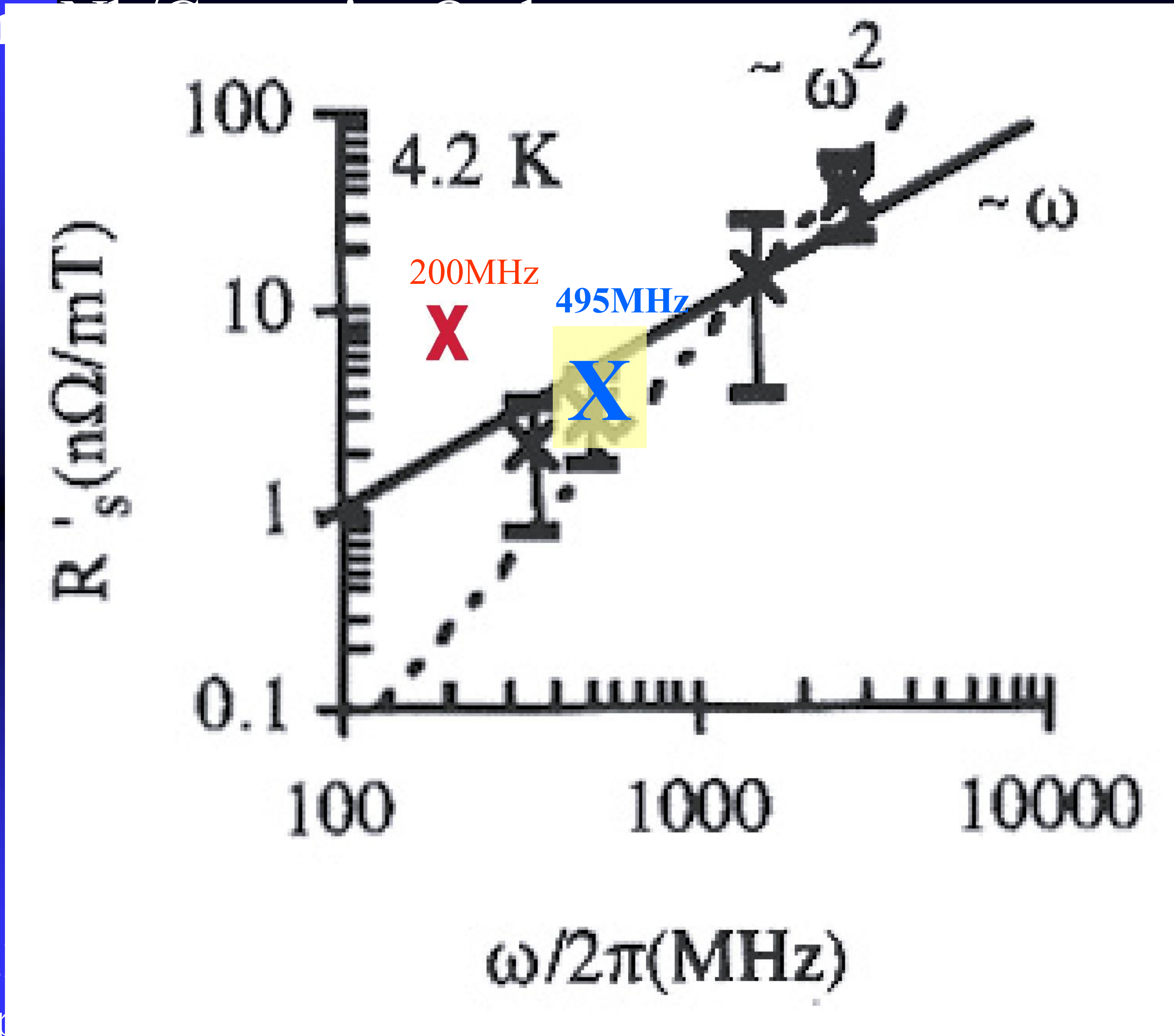

500MHz Nb-Cu cavity (SC500-1) 9/10/04
1.00E+10
1.00E+09
1.00E+08
Q0
X-ray starts
quench
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Eacc [MV/m]


500MHz Sputtered Nb on Spun Cu Cavity
R.L. Geng
Q0, SC500-1, March 2, 2004
Q0, SC500-1, September 10, 2004, recoated
Q0, SC500-3, April 14, 2005
Q0, SC500-3, March 2, 2005
10^{10}
10^{9}
10^{8}
Q_0
Quench
Quench
RF limit
RF limit
4.2K
0
2
4
6
8
10
Eacc [MV/m]


Film Nb surface resistance
R.L. Geng
500MHz, 4.2K
200MHz, 4.2K
200MHz, 3K
1.0E-06
1.0E-07
1.0E-08
G/Q0 [Ohm]
0
5
10
15
20
25
Epk[MV/m]


Film Nb surface resistance
R.L. Geng
500MHz, 4.2K
200MHz, 4.2K
200MHz, 3K
0.36 nOhm/Oe
0.62 nOhm/Oe
Rs [Ohm]
1.0E-06
1.0E-07
1.0E-08
0
50
100
150
200
250
300
350
400
450
500
Hpk [Oe]

Fil



100
10
1
0.1
4.2 K
~ ω²
~ ω
200MHz
495MHz
R's(nΩ/mT)
100
1000
10000
ω/2π(MHz)

R.
Ap

Recent Program

- 500 MHz cavity from ACCEL, assembled and tested twice to 4MV/m with heavy field emission and quench.
- Recoat 200 MHz cavity #1 at CERN in 3/04 - peeling observed - recoated again still bad - recoat again and hope to have by early spring.
- Use Auger surface analysis system and SIMS to further characterize Nb sputtered surfaces.
- Explore effectiveness of Atomic Force Microscopy in characterizing good Nb RF surfaces.

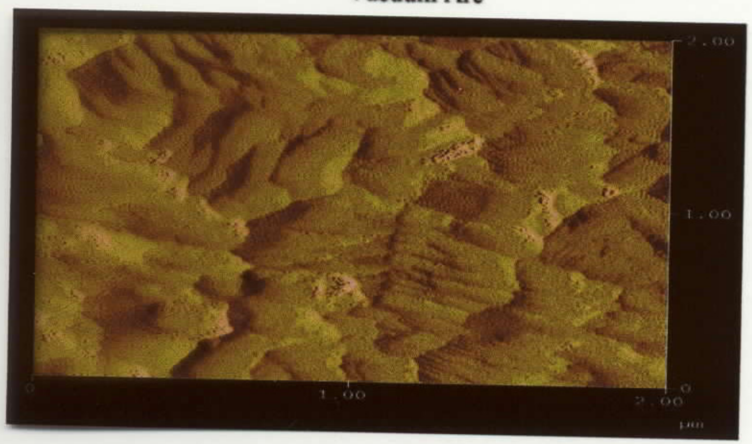
Near term Program

- Electron Cyclotron Resonance Coating R&D work at JLAB under way.
- Incorporate the results from these studies into the 500 MHz cavity program.
- Spin two 500 MHz cavities from explosion bonded Nb-Cu sheet. Single cell 1300 MHz cavity spun from this material has achieved 40 MV/m accelerating gradient.
- Spin two 500 MHz cavities from hot isostatic bonded Nb-Cu sheet.
- Bias Sputter coat a spun Cu single cell 500 MHz cavity at ACCEL.

PKU Bias Sputter

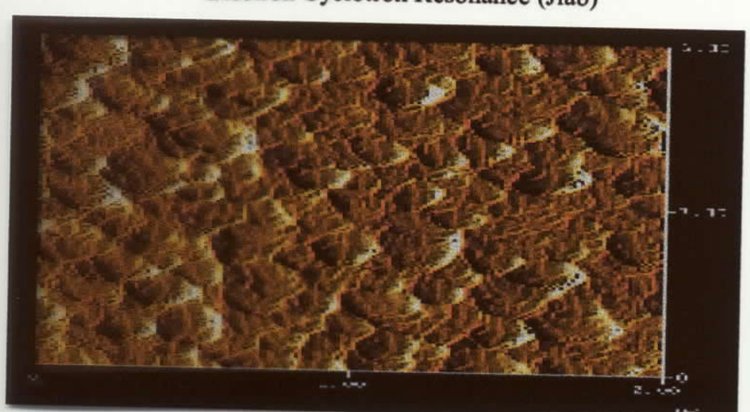
Accel Magnetron Sputter

Vacuum Arc

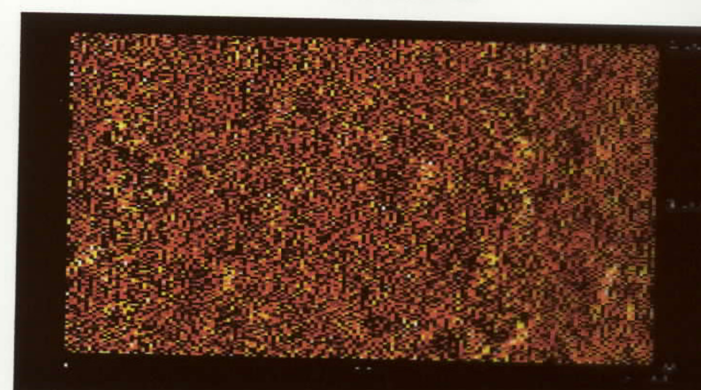


Solid Nb Electro Polished

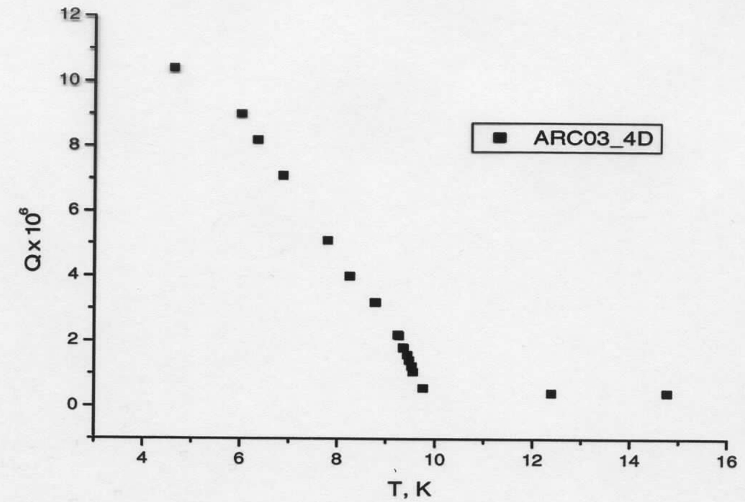
Electron Cyclotron Resonance (Jlab)



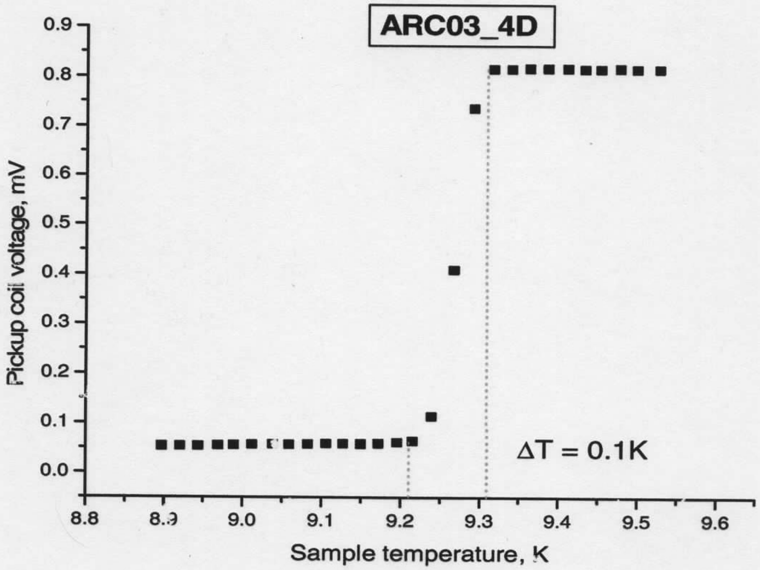
Pku Nb on Cu



ARC03_4D

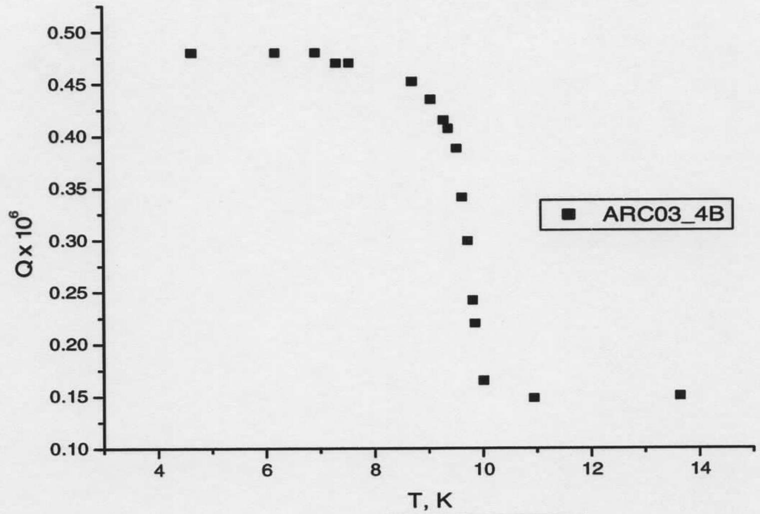


12
10
8
6
4
2
0
Q x 10⁸
4
6
8
10
12
14
16
T, K
ARC03_4D

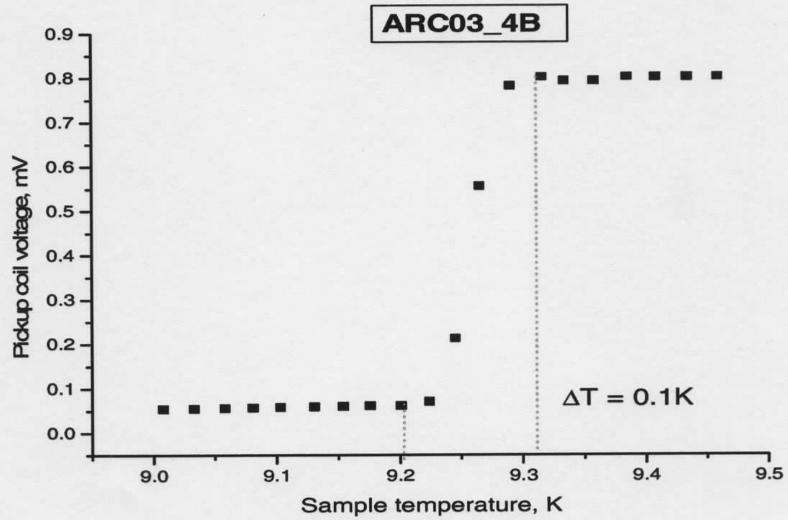


ARC03_4D
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Pickup coil voltage, mV
ΔT = 0.1K
8.8
8.9
9.0
9.1
9.2
9.3
9.4
9.5
9.6
Sample temperature, K

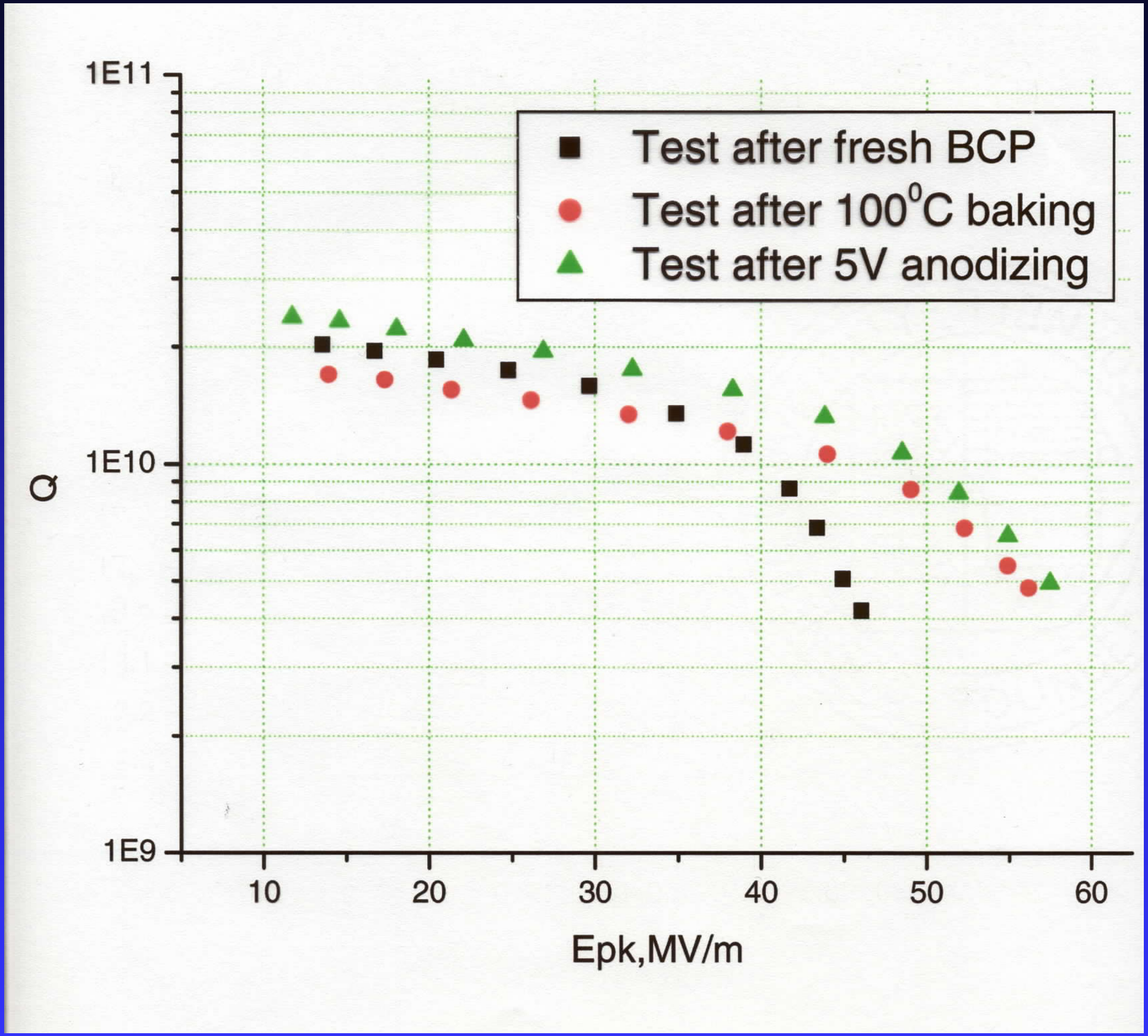
ARC03_4B



Q x 10^6
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
4
6
8
10
12
14
T, K
ARC03_4B



ARC03_4B
Pickup coil voltage, mV
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
9.0
9.1
9.2
9.3
9.4
9.5
Sample temperature, K
ΔT = 0.1K



1E11
1E10
1E9
Q
10
20
30
40
50
60
Epk,MV/m
Test after fresh BCP
Test after 100^{0}C baking
Test after 5V anodizing

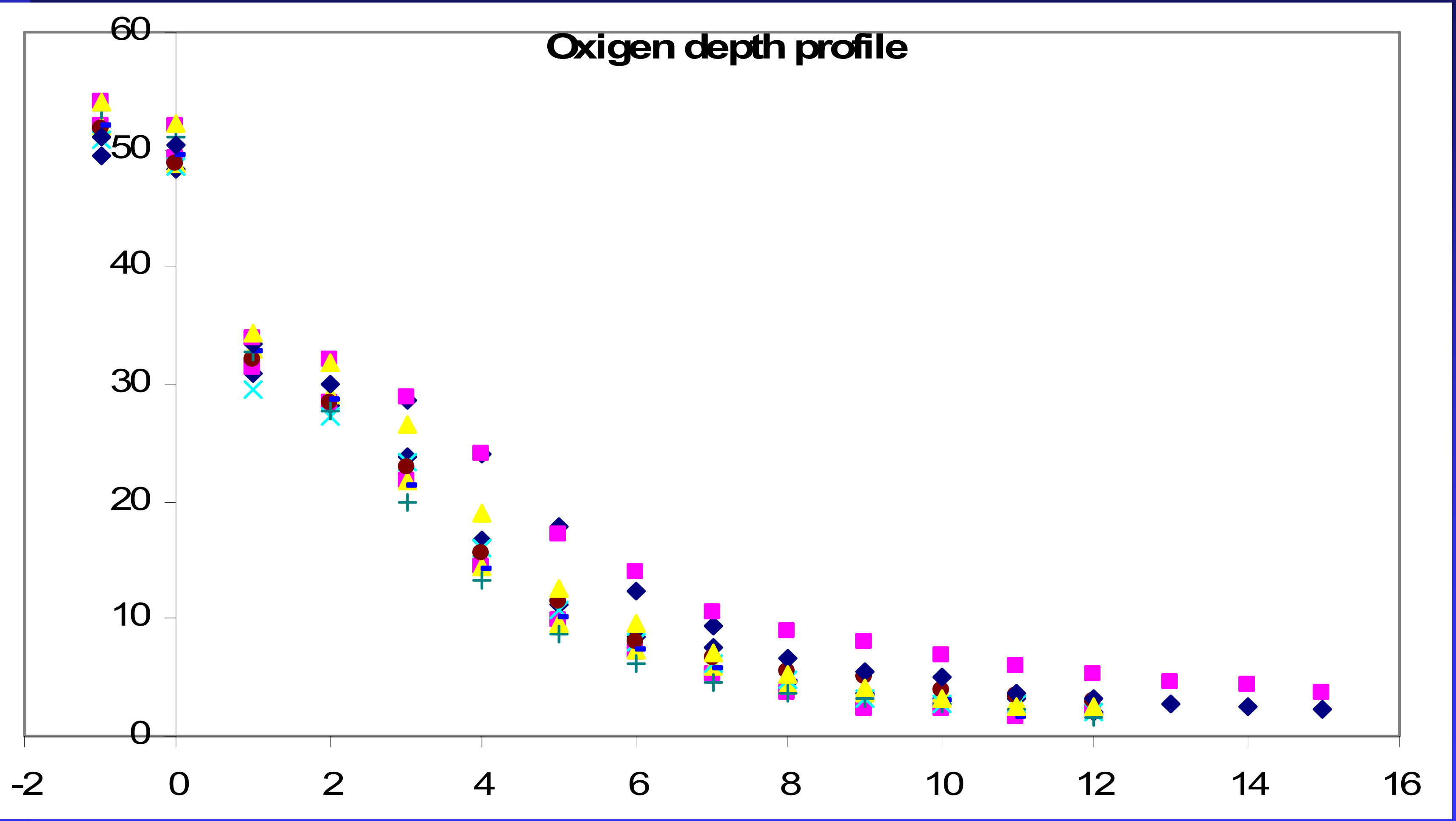
PHI 660 Scanning Auger Micrcoscope (SAM + SIMS)

Sensitive to first
10 - 100 nm

SIMS results
For NbO/Nb

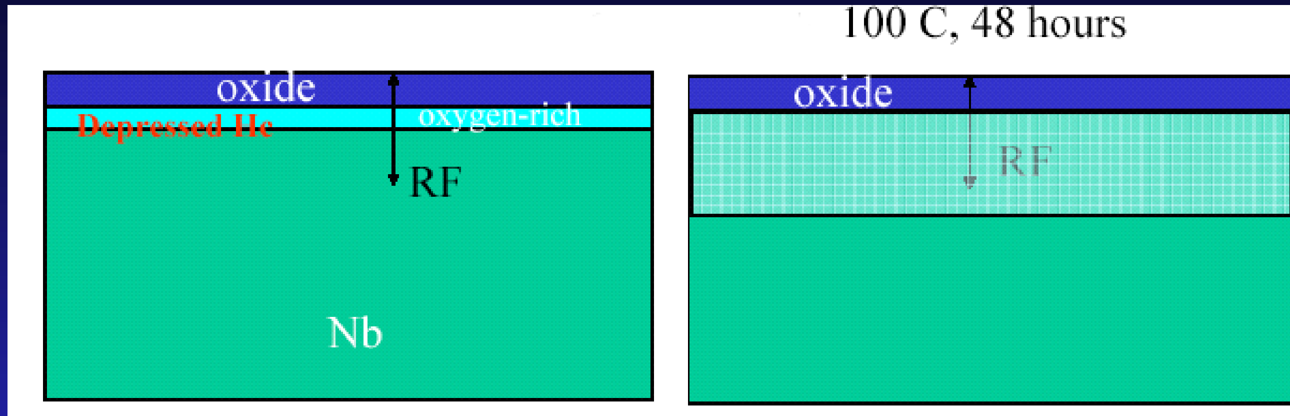
Auger O-depth profile: no distinguishable difference for baked vs. unbaked Nb

Oxygen concentration [%] in large grain samples vs. depth [nm]



Oxygen Pollution Model

BCP leaves natural oxide + oxygen rich layer

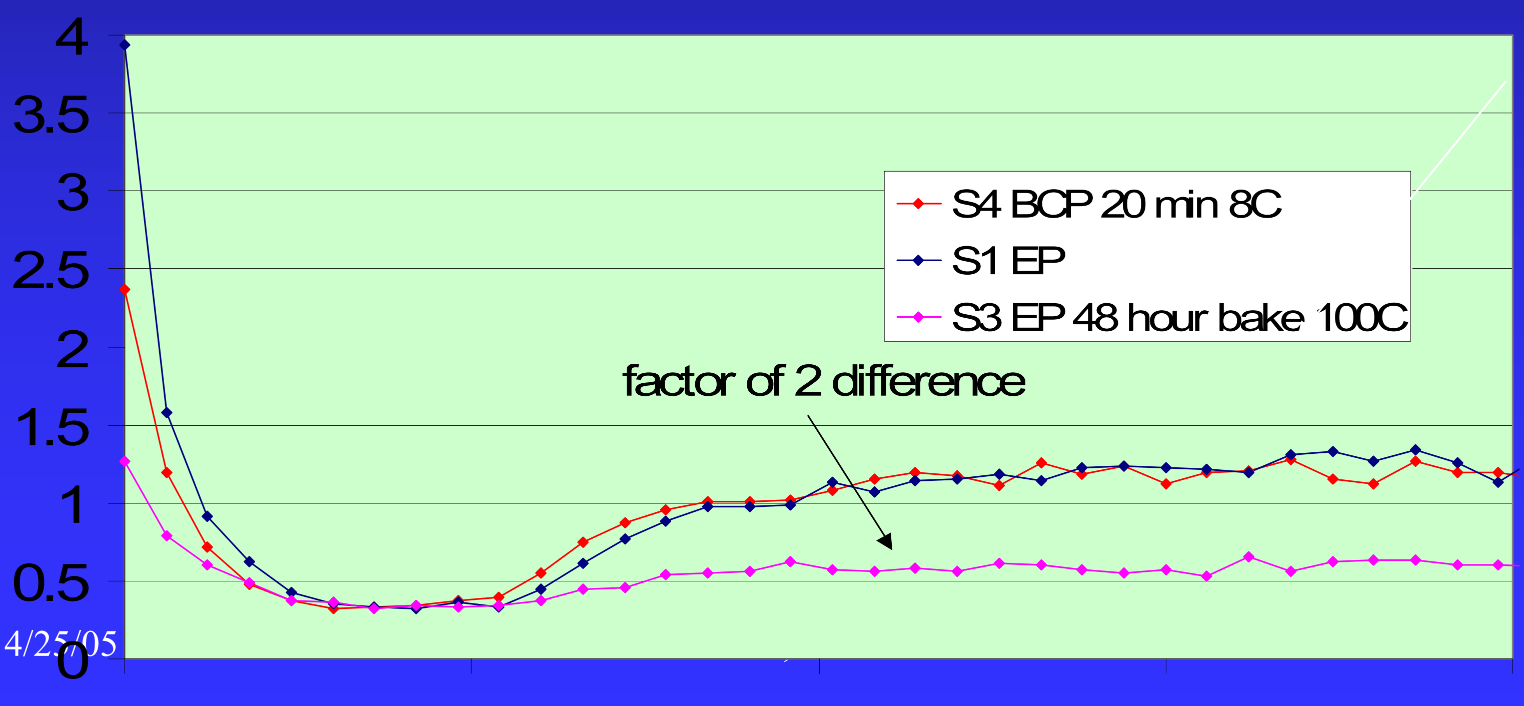


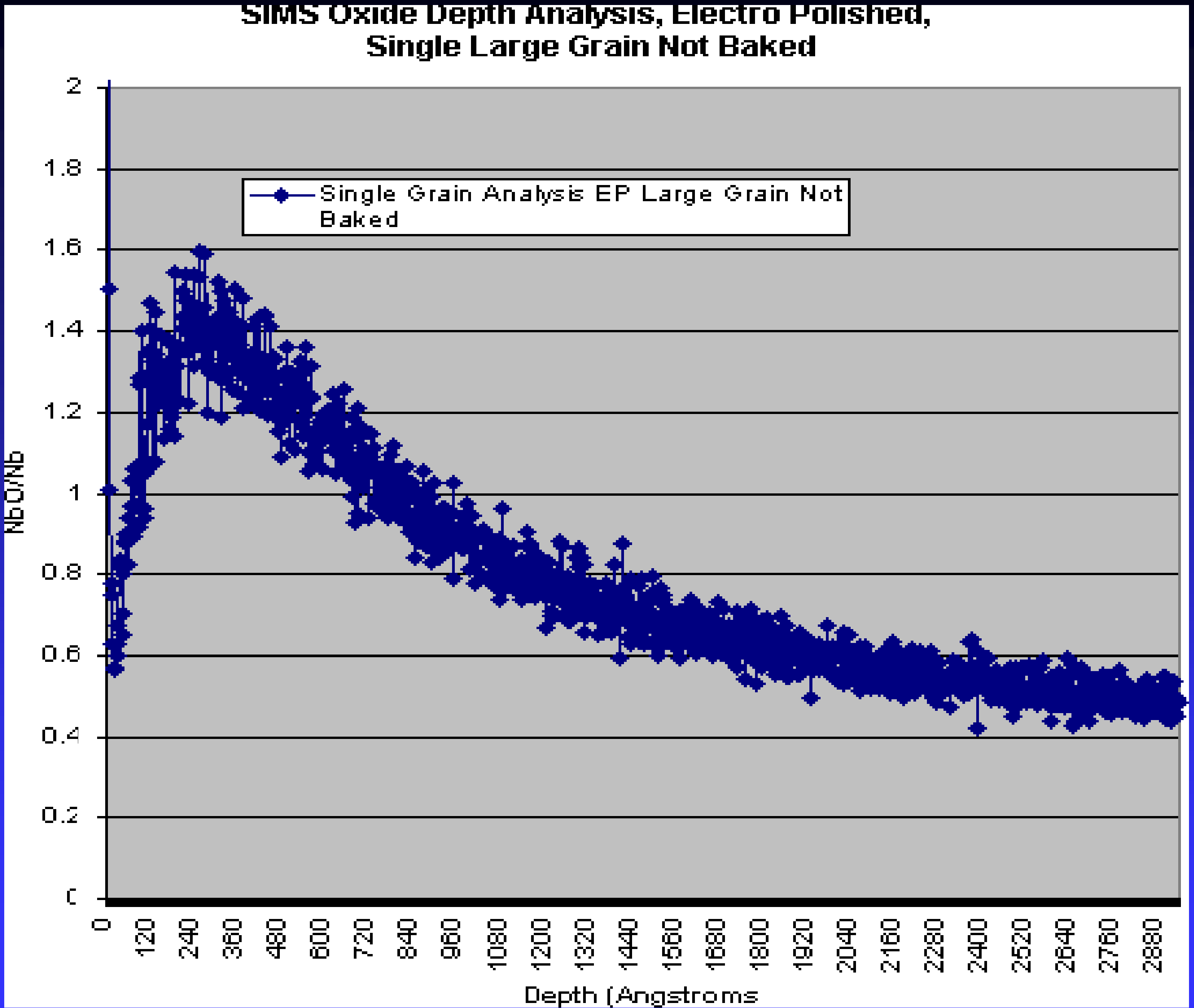
Baking dilutes oxygen rich layer

Go deeper !

SIMS Analysis

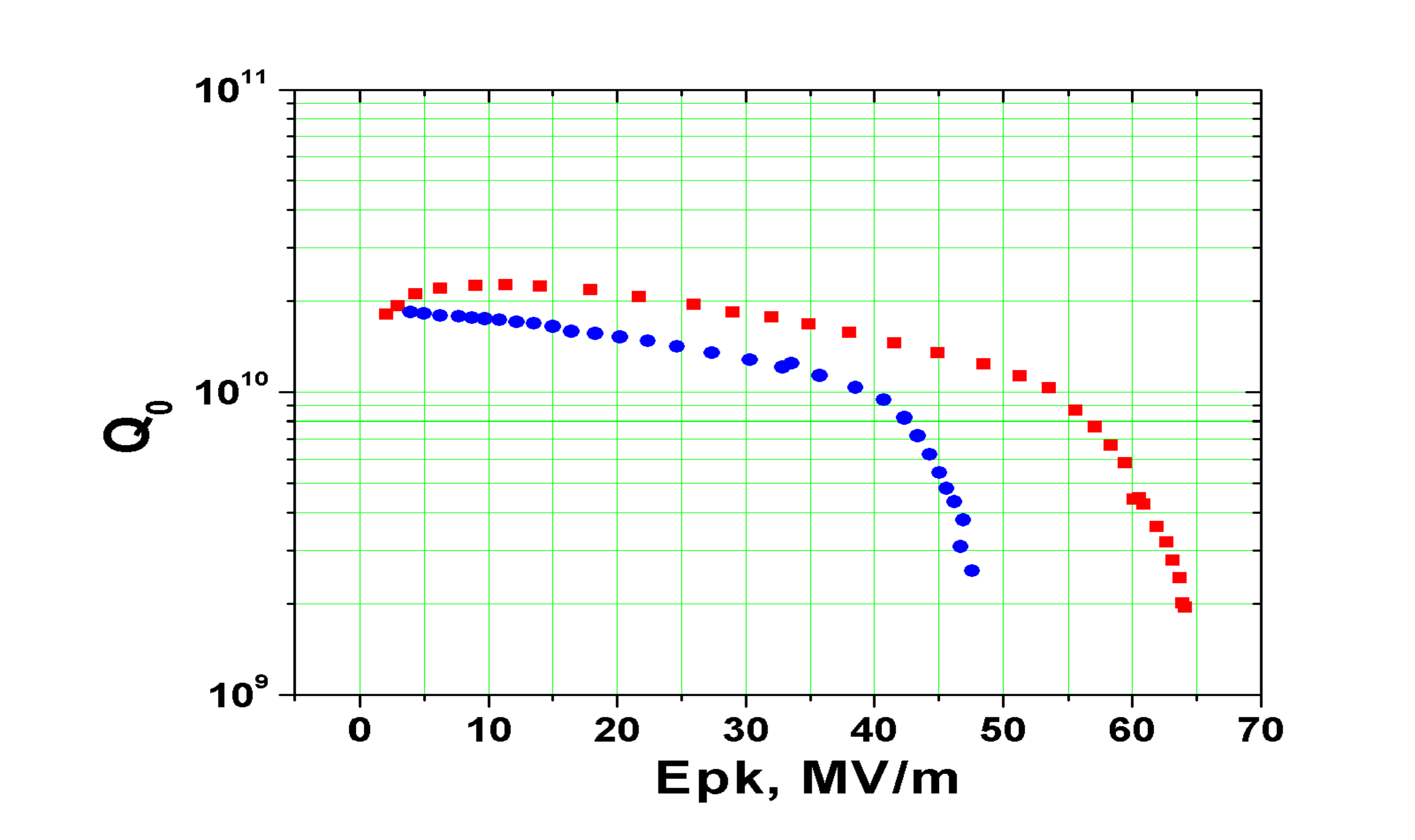
ratio of NbO/Nb signals (SIMS)



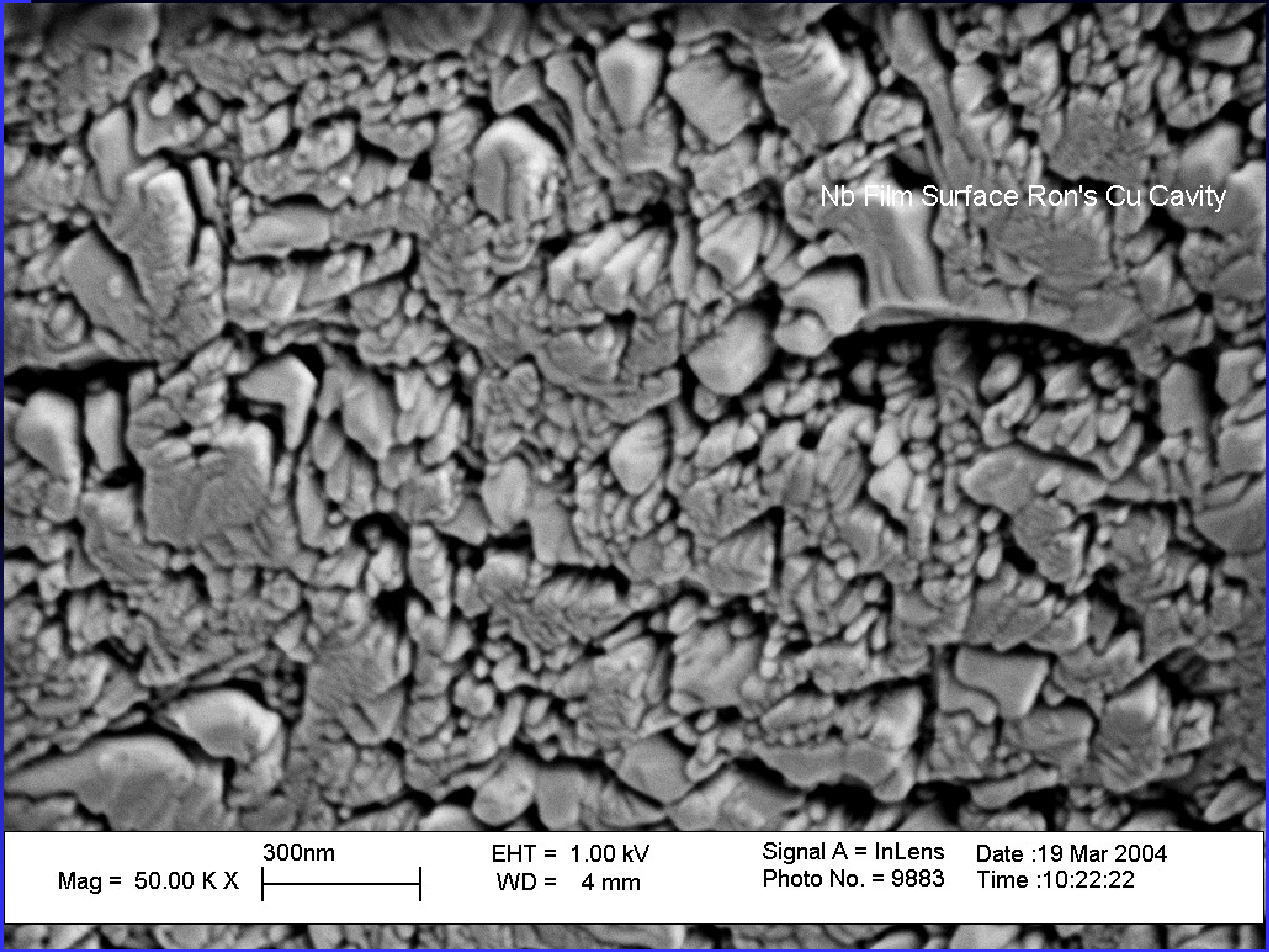

SIMS Oxide Depth Analysis, Electro Polished,
Single Large Grain Not Baked
Single Grain Analysis EP Large Grain Not Baked
NbO/Nb
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
2760
2880
Depth (Angstroms

Q-Slope Improvement with 100 C bake on a BCP Cavity

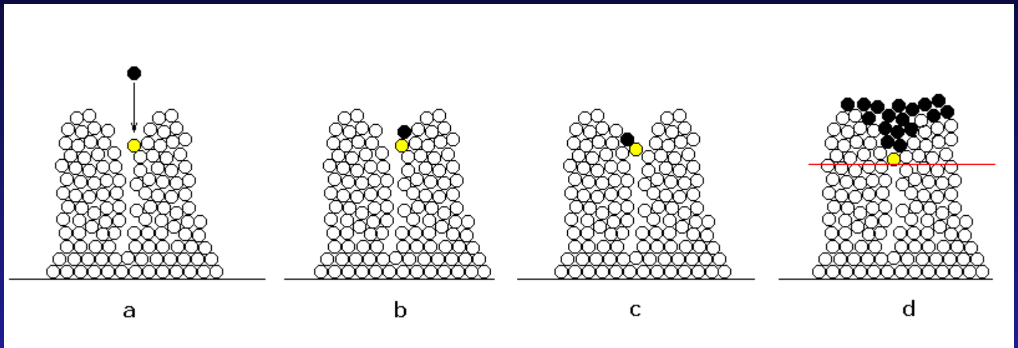
Russian Nb - 500 RRR, no HT, "smoother"

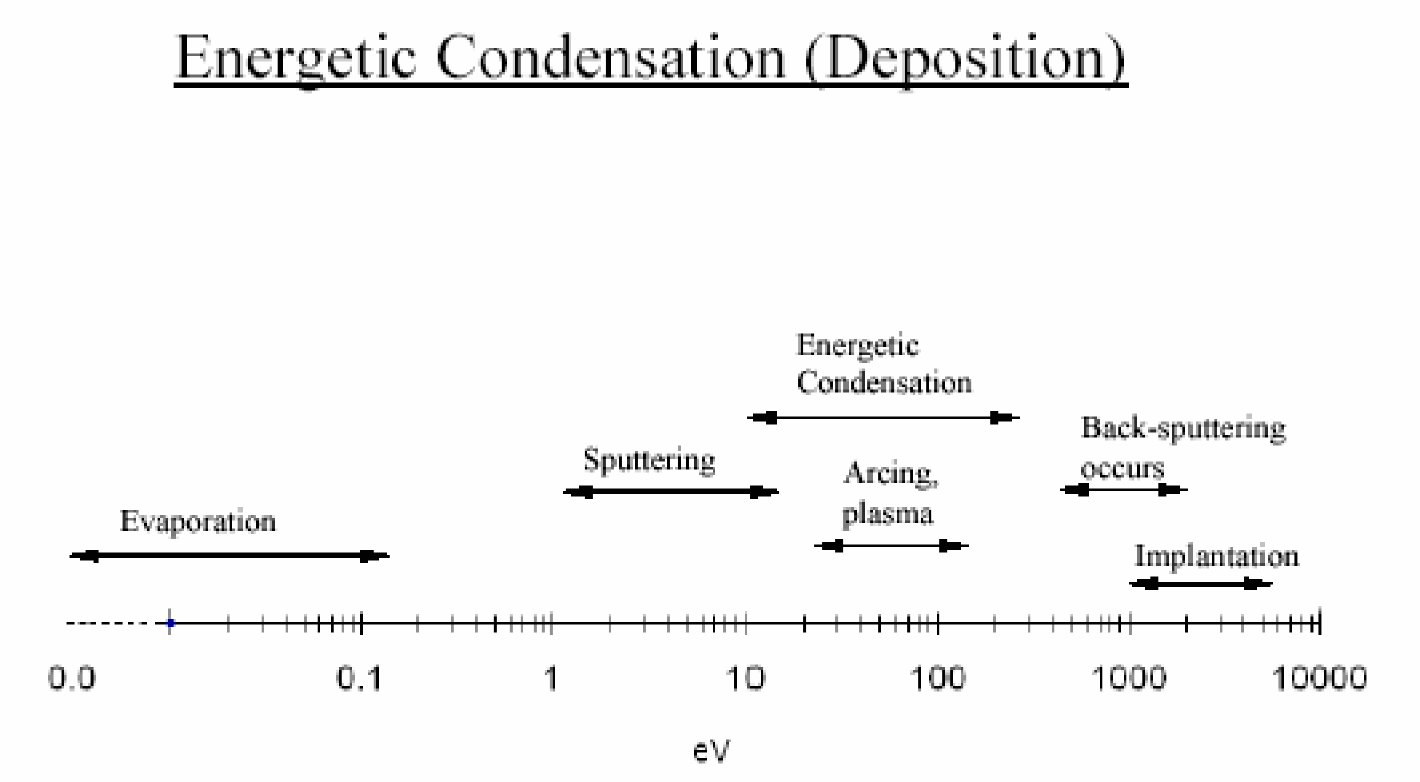


Blue circles – fresh BCP
Red squares – after additional 100 C baking


Nb Film Surface Ron's Cu Cavity
300nm
Mag = 50.00 K X
EHT = 1.00 kV
WD = 4 mm
Signal A = InLens
Photo No. = 9883
Date :19 Mar 2004
Time :10:22:22

Improve Films with Energetic Deposition

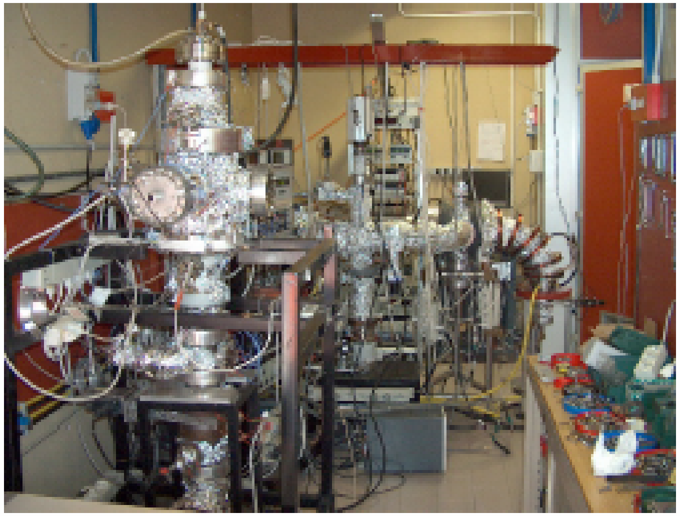




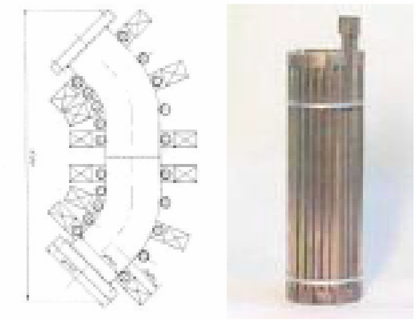
INFN/Roma and Andrzej Soltan Institute

Cathodic Arc Deposition

- No working gas (UHV)
- Ionized niobium (up to 95%)
- High ion energy (10-100eV)
- Excellent adhesion
- High purity
- Possible to apply bias and magnetic field
- Chemical process capable (i.e. NbN)



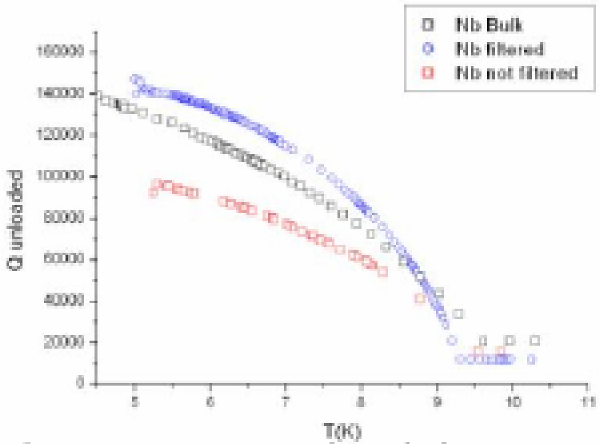
Linear, Planar arc systems



Macro particle filters

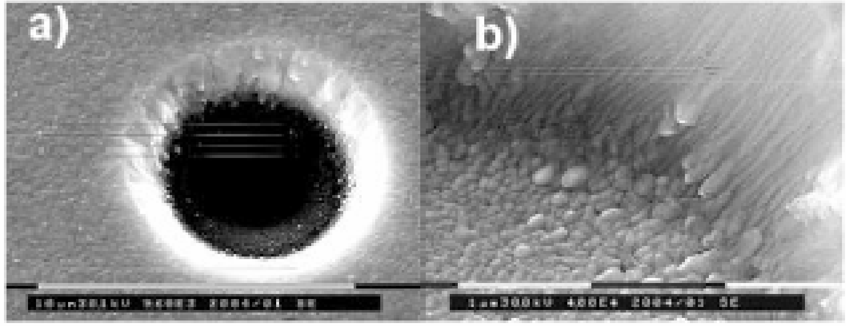
INFN/Roma and Andrzej Soltan Institute (cont.)

- RRR 20-100
- SC transition width comparable to bulk
- Low field Rs no worse than bulk
- Columnar growth but densely packed.



Q measurement implying Rs.

SEM pictures of film surface
with/without macro particle filter

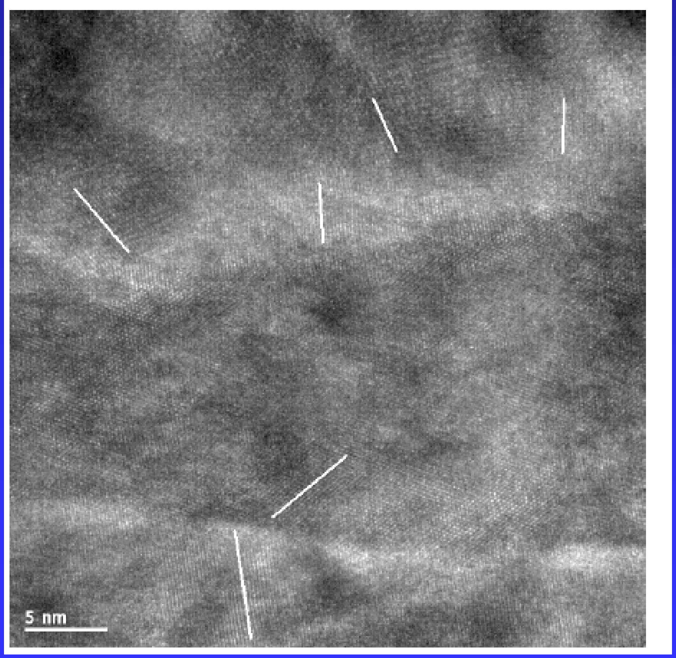


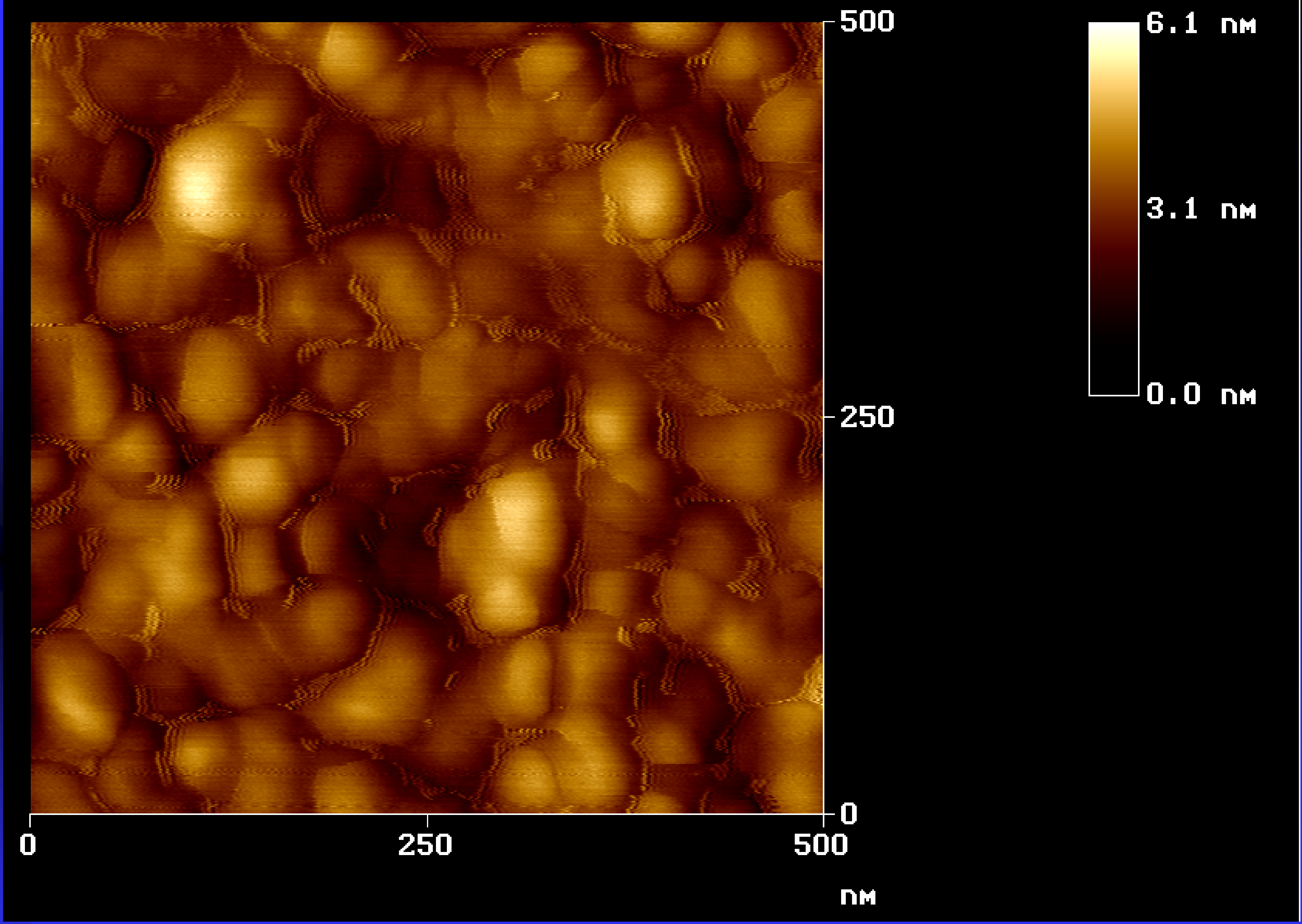
SEM pictures of film structure

Jefferson Lab

Energy-Controlled ECR Plasma

- Niobium Ion Energy is around 63 eV, and controllable.
- Deposition Energy of 114 eV yields better film quality for sapphire substrate.
- Epitaxial growth of niobium on sapphire
- Bias voltage affects Nb film crystal orientation



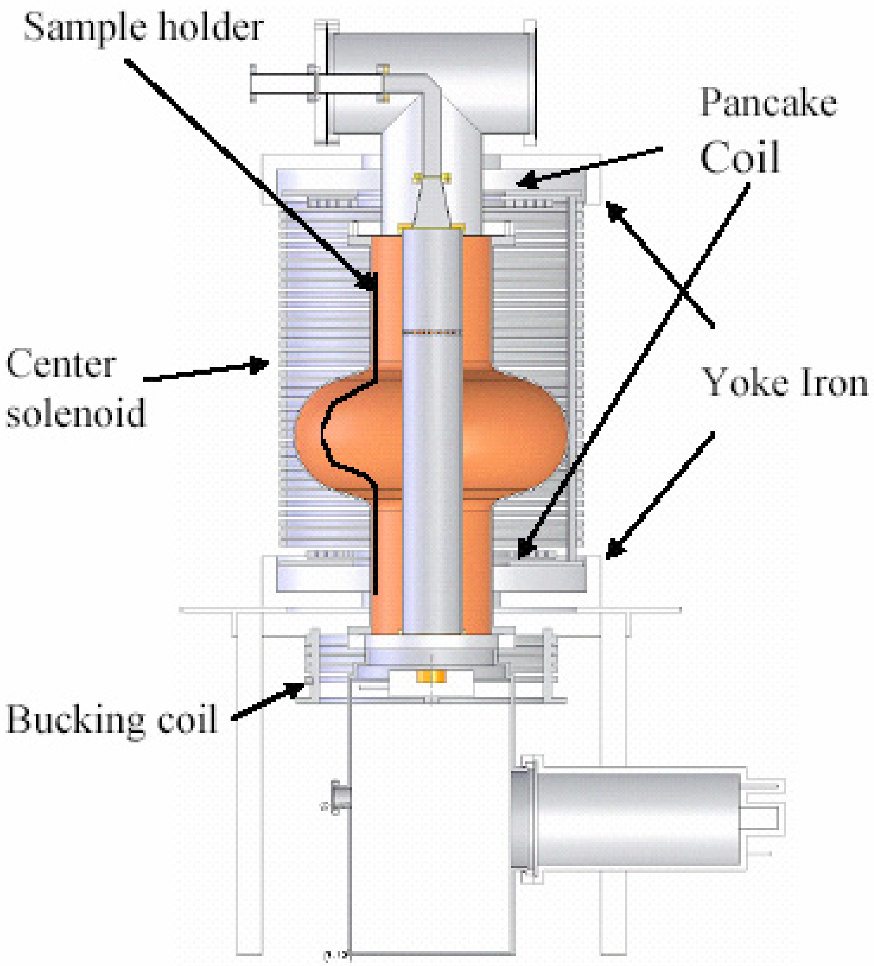


The AFM picture shows a flat, densely packed, niobium thin film on a sapphire substrate with 80 nm grain sizes

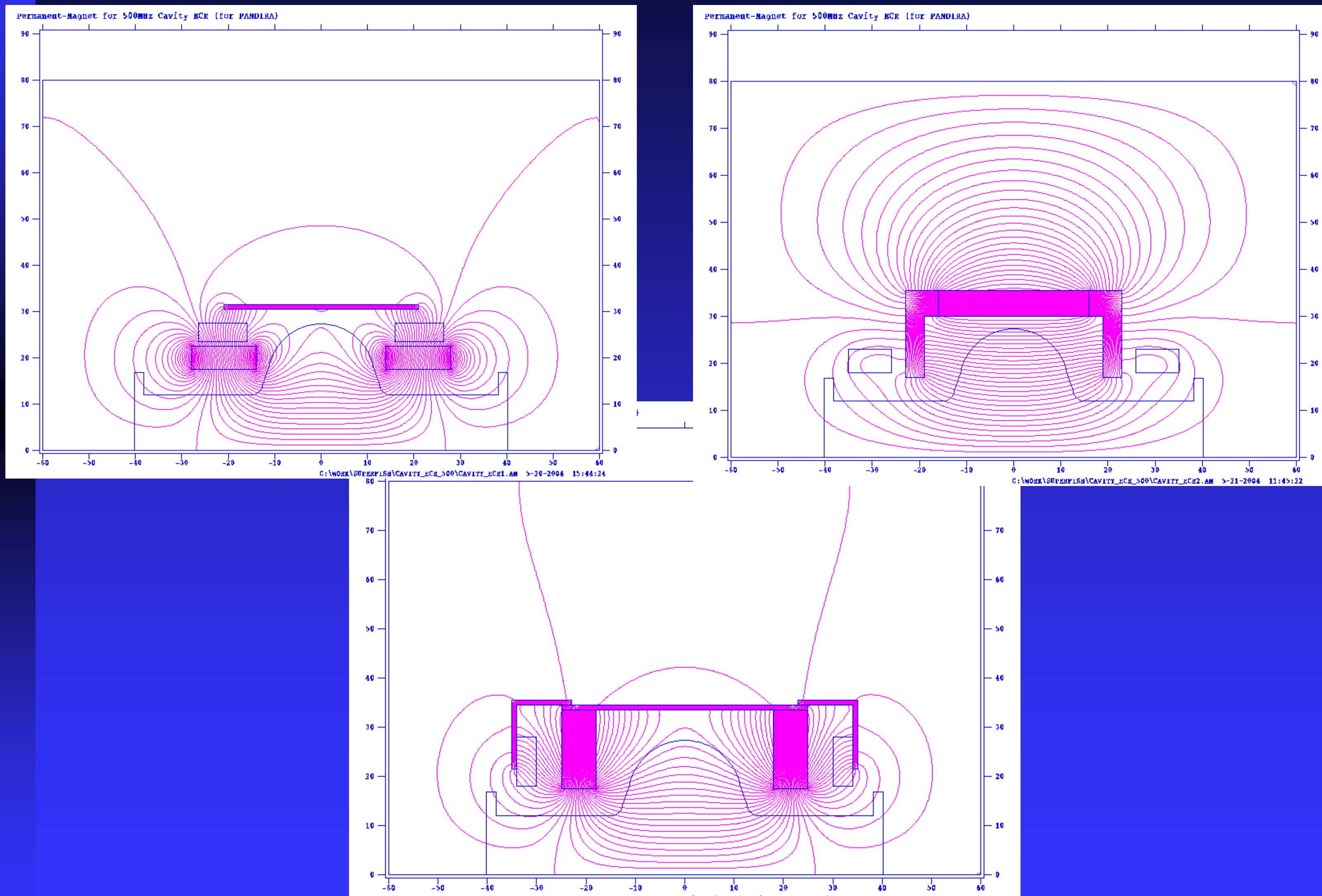
Jefferson Lab/Cornell

- No working gas like argon
- High vacuum means reduced impurities
- Controllable "single" deposition energy,
- Near 90-degree deposition angle
- Excellent bonding
- No macro particles
- Faster rate (Conditional)
- Smooth surface (also shown in Cu hyperthermal deposition)

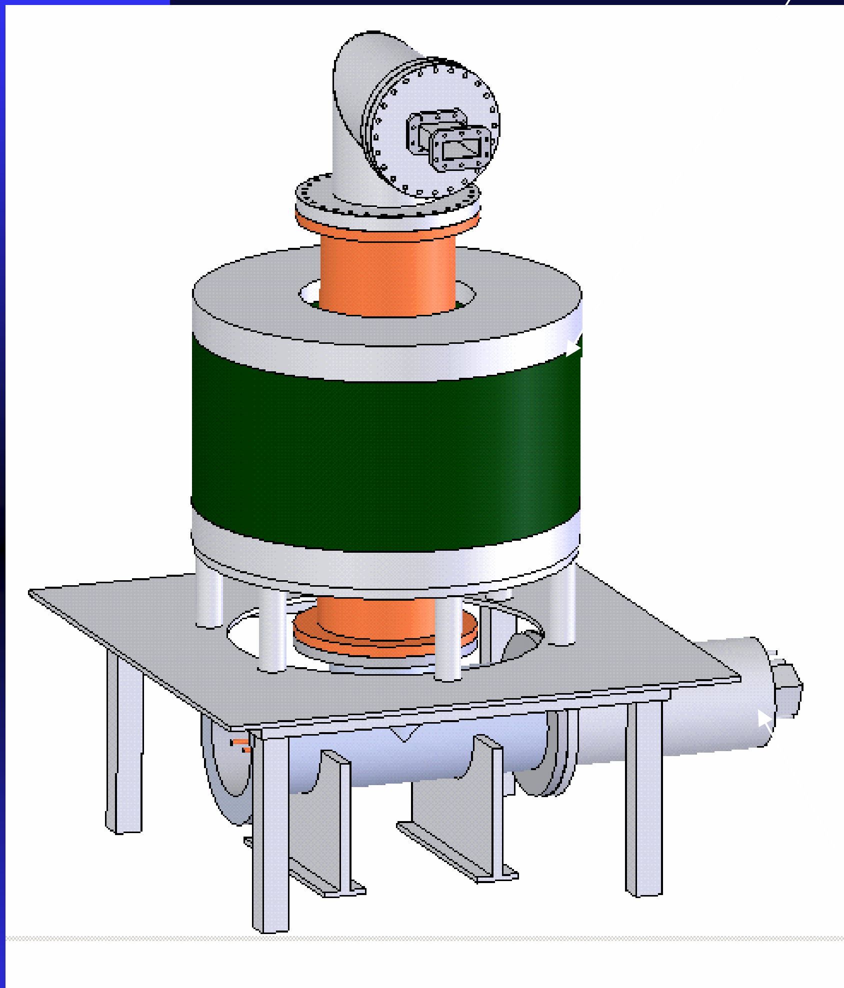
500MHz Deposition System



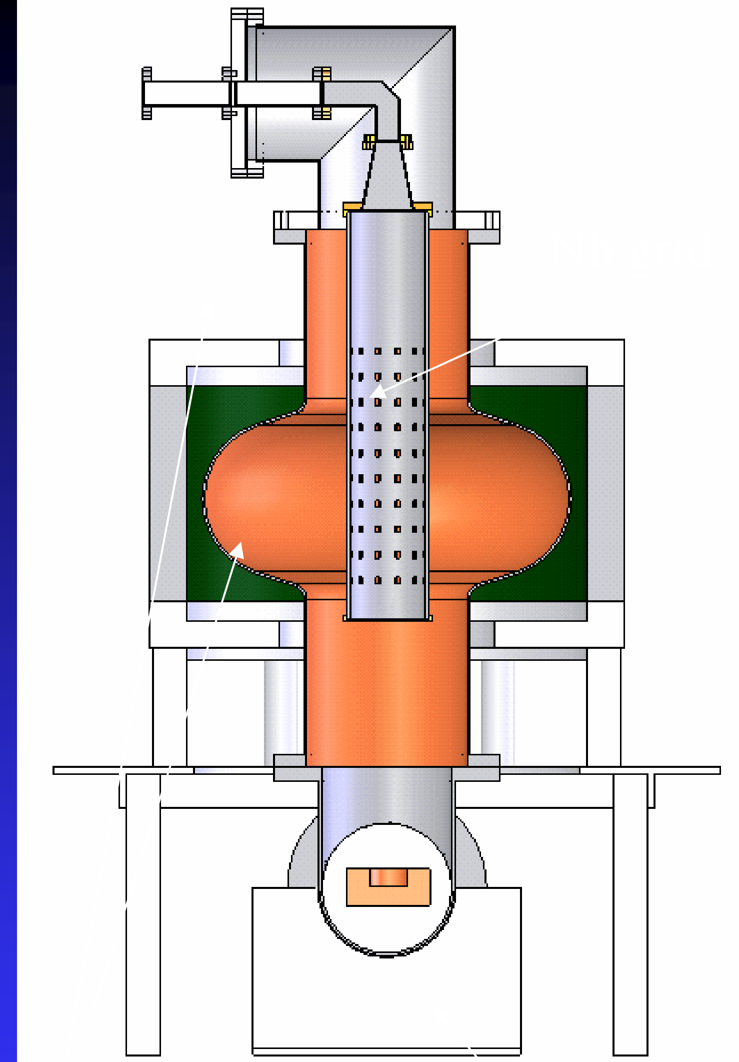
Optimize magnetic field for ECR inside an elliptical cavity



magnet



Cryopump



Yoke

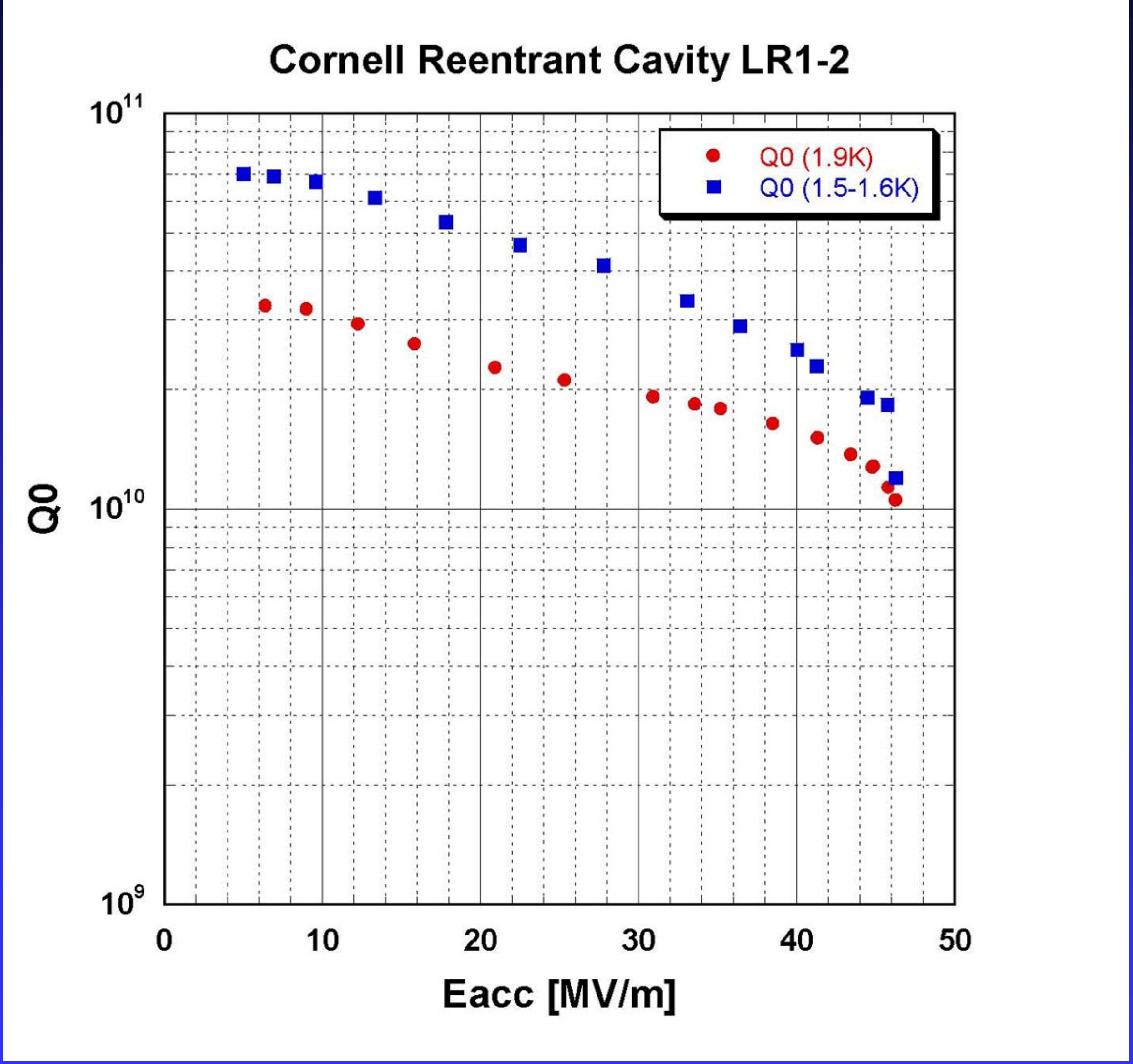
E-gun

Conclusion

- First 200MHz SC cavities have been constructed.
- Test results for first cavity -> Eacc = 11 MV/m with Q_0 = 2E10 at low field.
- MP barriers are present and can be processed through.
- Cavity performance not affected by Hext < 1200 Oe.
- Next 200 MHz test will include measurements on Hext effect at higher Eacc.
- Making good progess on understanding Q-slope.
- Confident that we can build 200 MHz SCRF cavities with Eacc > 17 MV/m.

Conclusion

- Because of diffusion of Cu into Nb, if it is essential to have low temperature bake to delute the oxygen rich layer then bonded Nb sheet to Copper is an attactive solution.
- Cost of 1 mm Nb bonded to 4 mm of Cu is 1/3 that of 5 mm RRR 300 Nb sheet in small quantities.
- Plan continued effort in developing sputter coated cavities after the end of the current NSF muon contract (9/1/05).


Cornell Reentrant Cavity LR1-2
Q0 (1.9K)
Q0 (1.5-1.6K)
Q0
10^{11}
10^{10}
10^{9}
0
10
20
30
40
50
Eacc [MV/m]