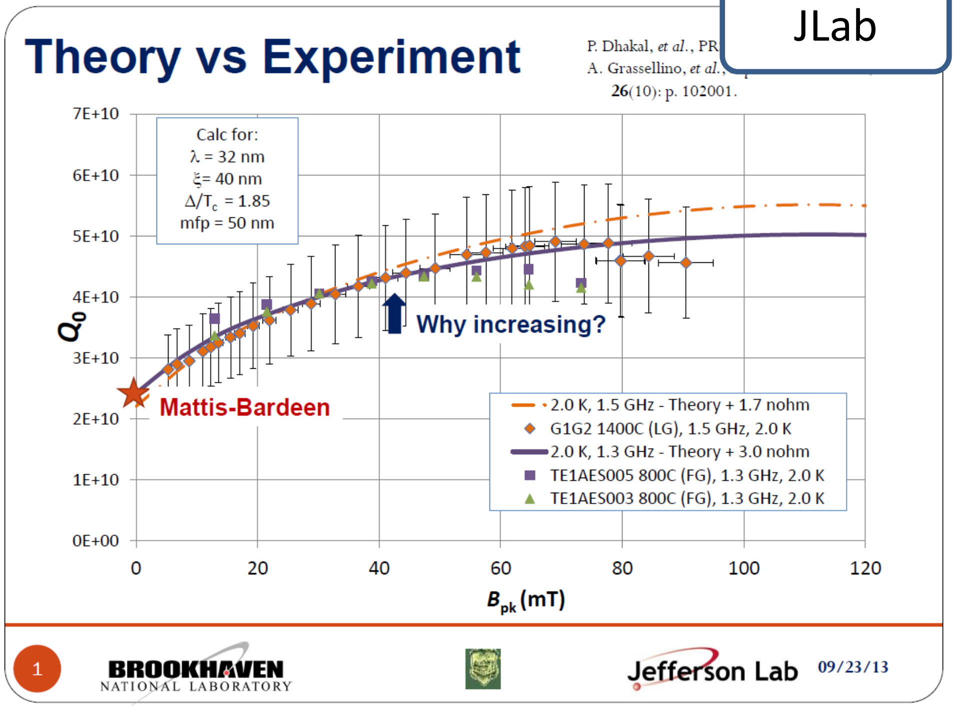

# Q- Increase or Q- slope ?

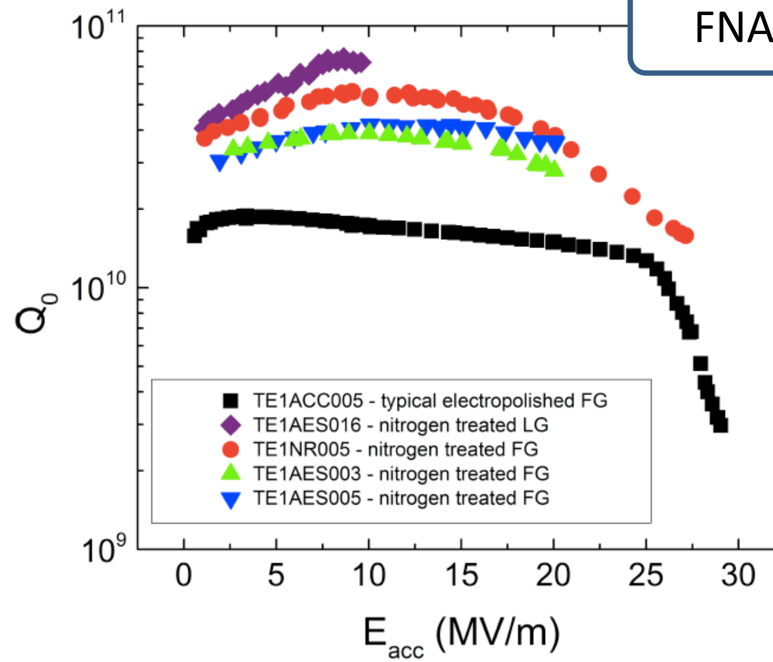
(medium field)

## Origin of dissipations

JLab

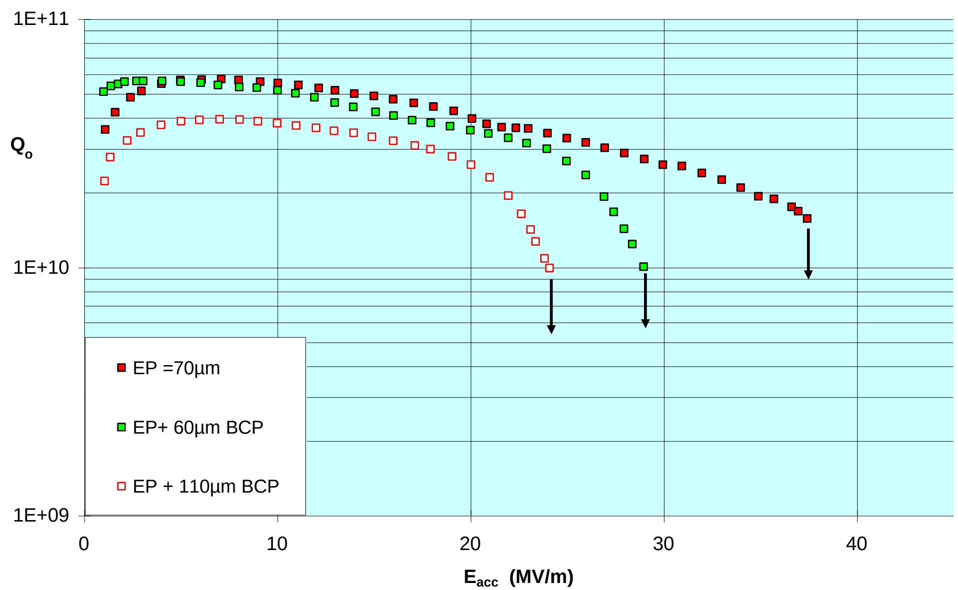



FNAL



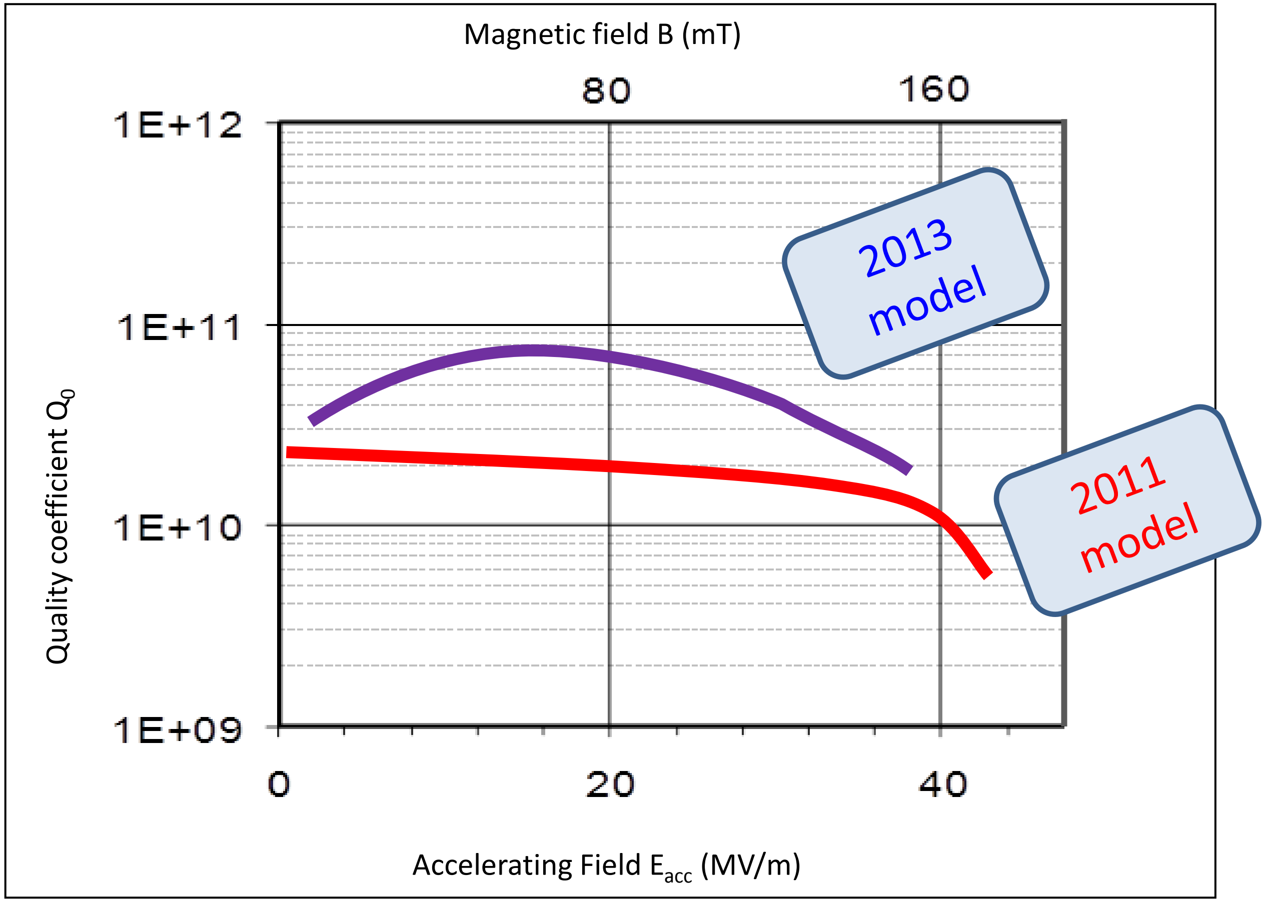

Curtesy C. Reece/ B.P. Xiao

Curtesy A. Grasselino




Saclay
1999
$Q_0 \sim 6.10^{11}$

# *Fashion week*… New 2013 model

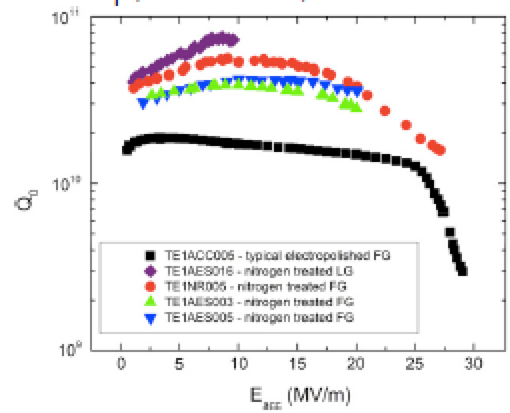


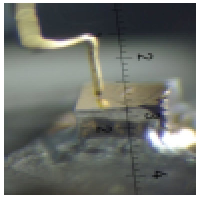
# Point Contact Tunneling

FNAL Cavity Samples:
1) 205A Nitrogen treated
2) C8 Cold Spot High Field Q slope

Similar Results - Near Ideal BCS

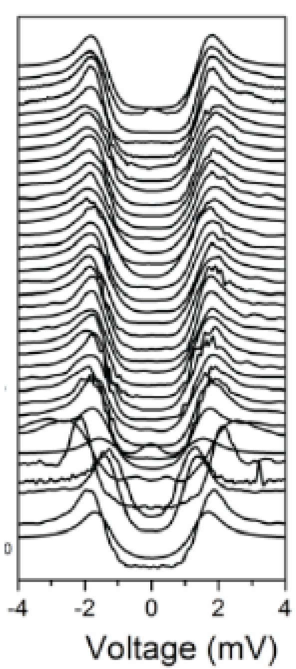
Grassellino et al, 2013
Supercond. Sci. Technol. 26 102001

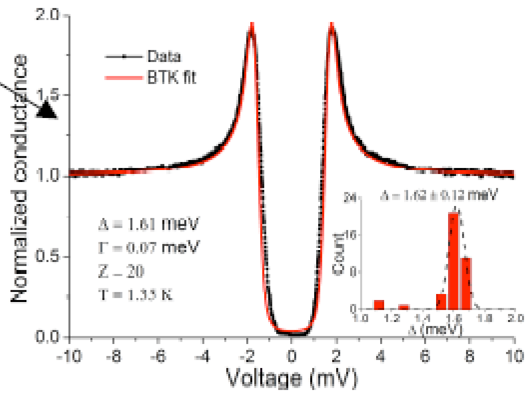


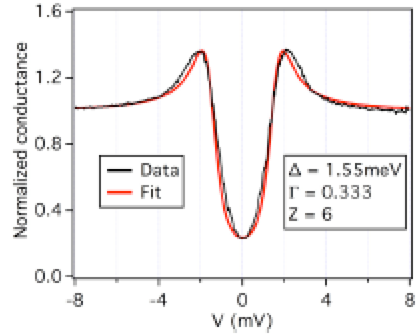
- $\Delta$ Sup. Gap
- $\Gamma$ DOS Broadening
- Z Barrier Strength
- Tunneling to Ohmic

Nb Single Crystal (110) Processed:
Standard EP, de-ionized water
Air dry (C. Antoine)

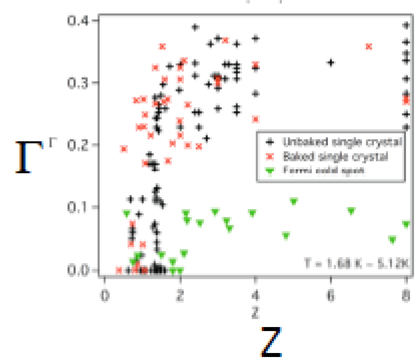



Contrast




$\Gamma/\Delta > 20\%$

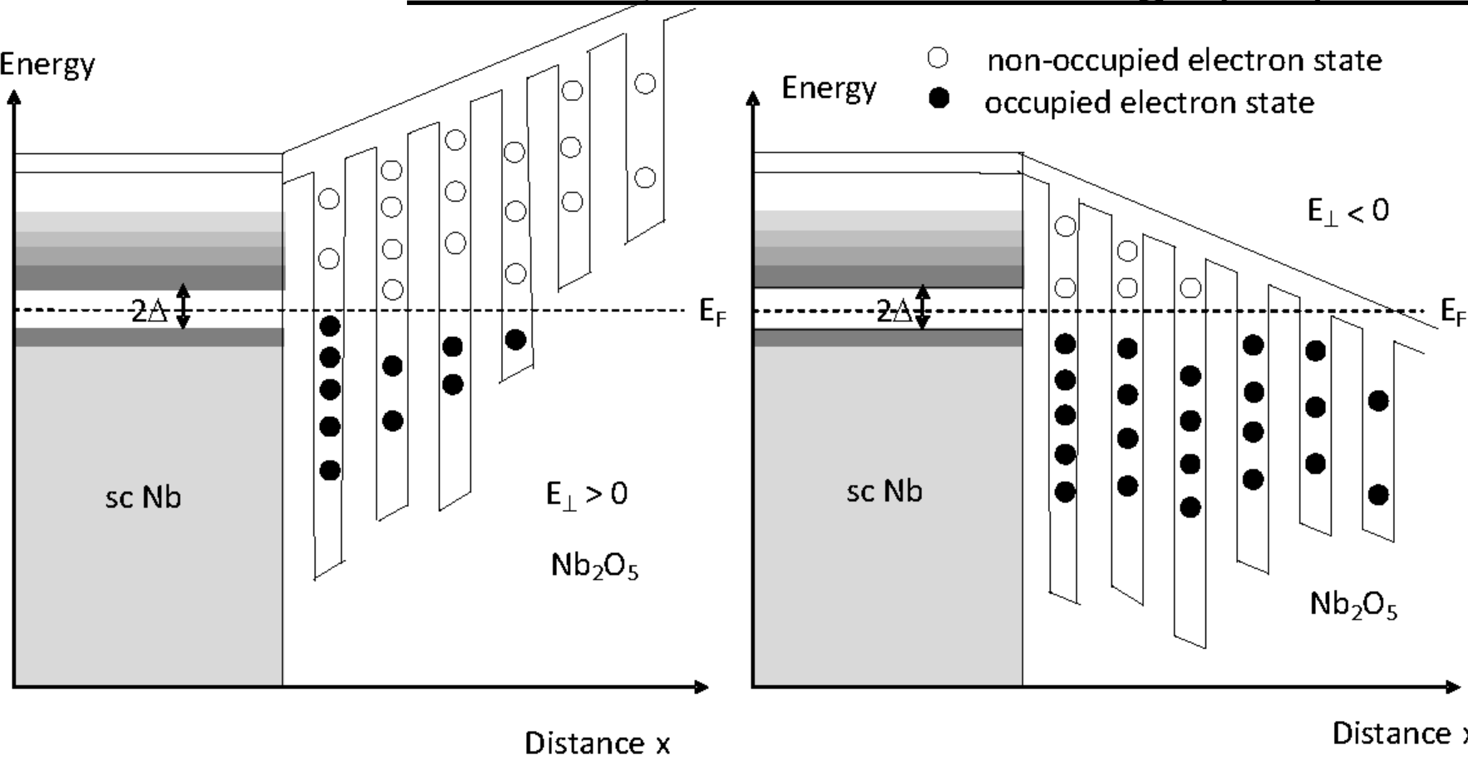



High Q consistent with:
- Near ideal BCS Gap, $\Gamma/\Delta < 5\%$
- High Z oxide barrier
- No de-pairing

Depairing $\Gamma$ coming from oxide/interface

# Temperature dependent medium field Q-slope

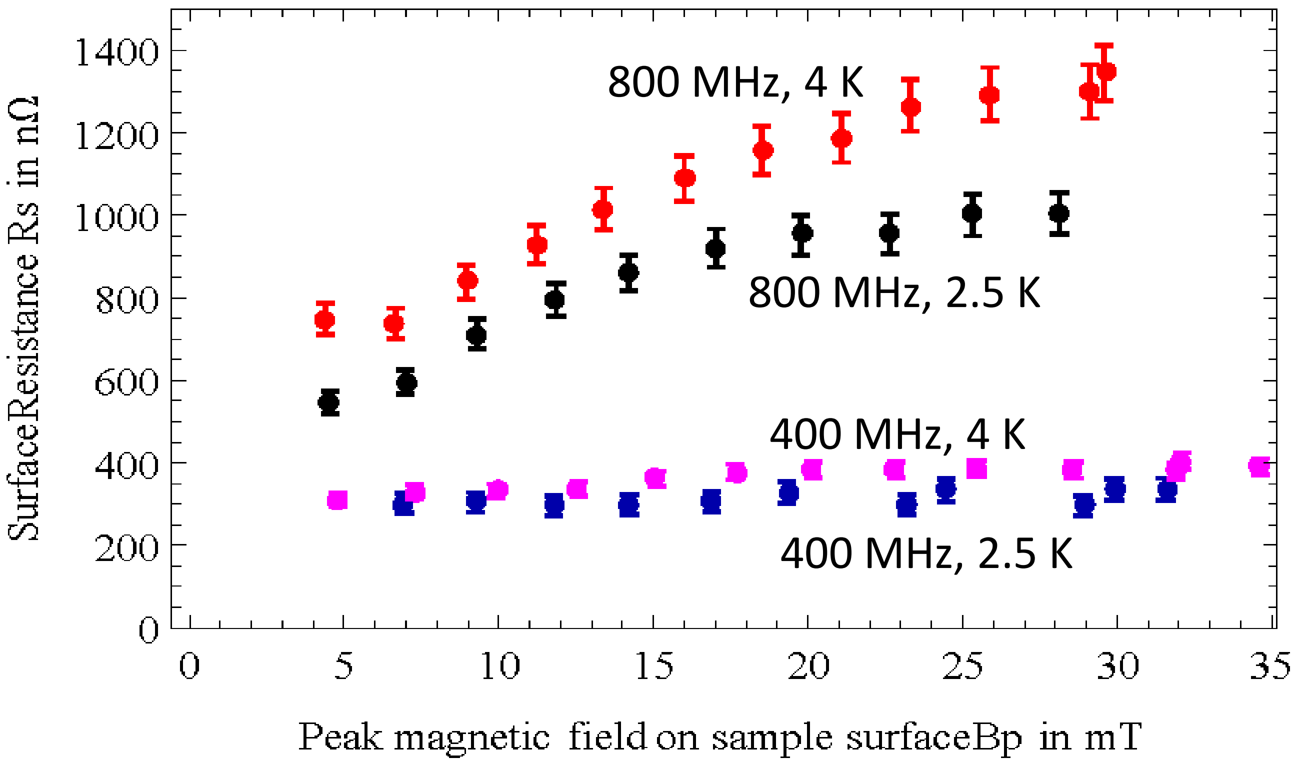
The Interface Tunnel Exchange (ITE) Model




Energy states at interface between superconductor and dielectric after exposure to positve (left) and negative (right) electric field

- Surface electric field only penetrates the oxides not  the superconductor
- Exchange of electrons within one RF period yields an electric surface resistance proportional to *f*
- Within the energy gap 2Δ there are no states available → Threshold effect

# Temperature independent medium field Q-slope




To explain this data set with magnetic losses one would need a model, which assumes *Rs*(*B*) prop. to $f^3$.

In the Quadrupole Resonator the ratio between *E/B* is proportional to f. Therefore the data can be explained by a model assuming *Rs*(*E*) prop to *f* after subtracting low field losses

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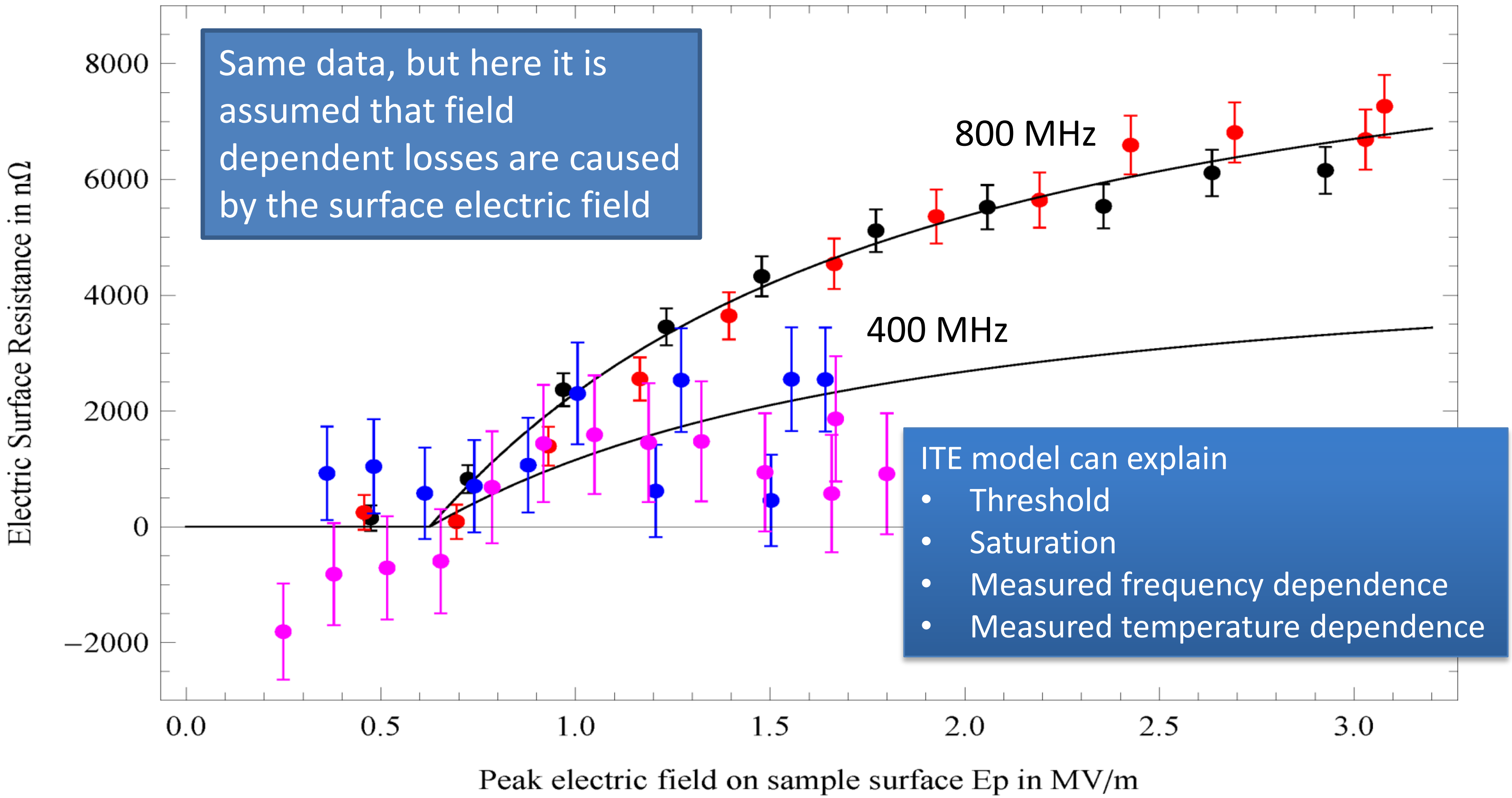
# Temperature independent medium field Q-slope




In the Quadrupole Resonator the ratio between *E/B* is proportional to f. Therefore the data can be explained by a model assuming *Rs*(*E*) prop to *f* after subtracting low field losses

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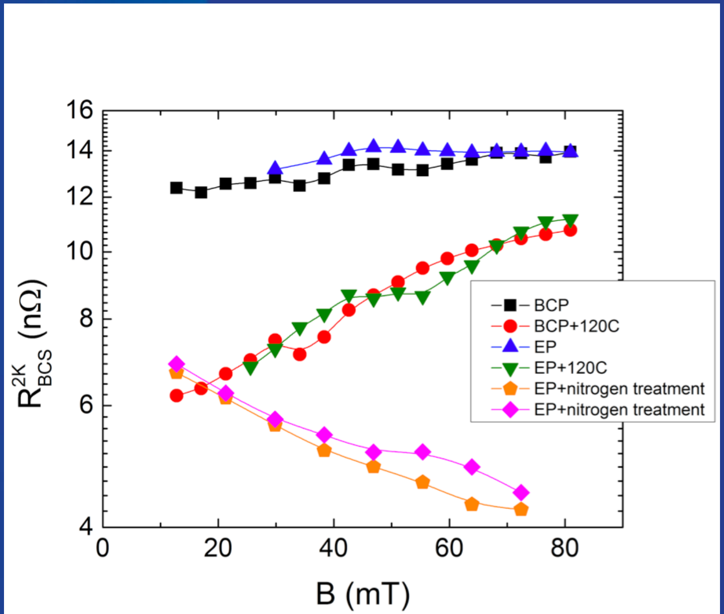
# Origin of medium field losses

The new study leading to the deconvolution in Rbcs(B) and R0(B) [1] allows to draw some important new conclusions on the origin of the low and medium field RF losses:

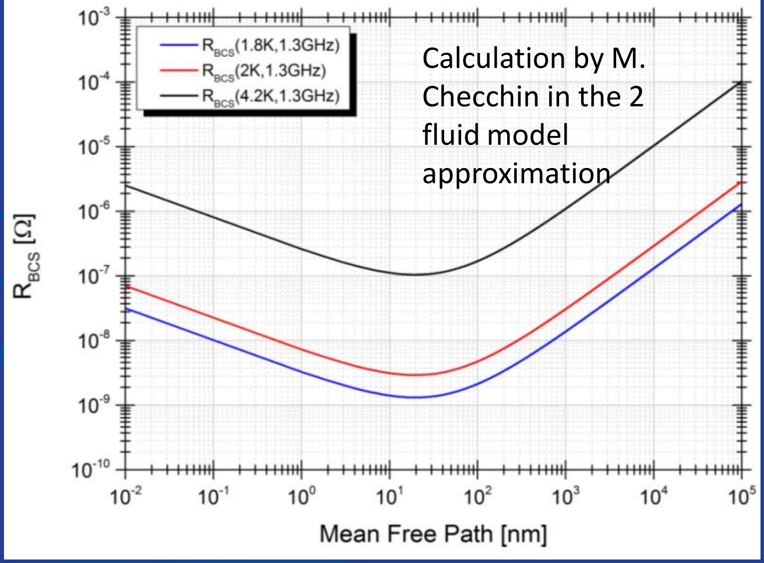
1. Both residual resistance and BCS resistance contribute to MFQS
2. Thermal feedback plays almost no role in avg performing 1.3 GHz cavities (below lambda point)
3. Roughness plays a role: BCP causes more MFQS than EP (manifests as residual)
4. 120C bake enhances the MFQS by making the BCS component strongly field dependent
5. Reverse field dependence is possible! Impurity doping leads to a BCS resistance decreasing with field, reaching BCS values previously unseen in our niobium

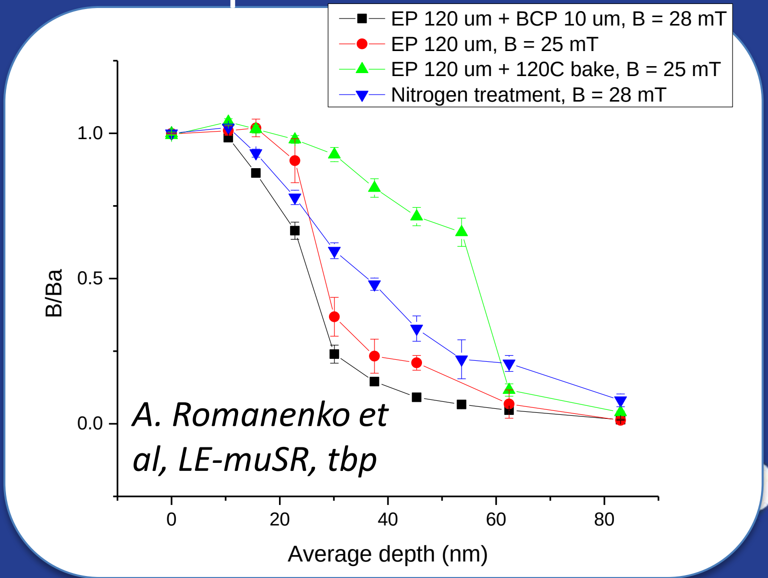
[1] A. Romanenko and A.Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

# Origin of low and medium field losses – BCS component

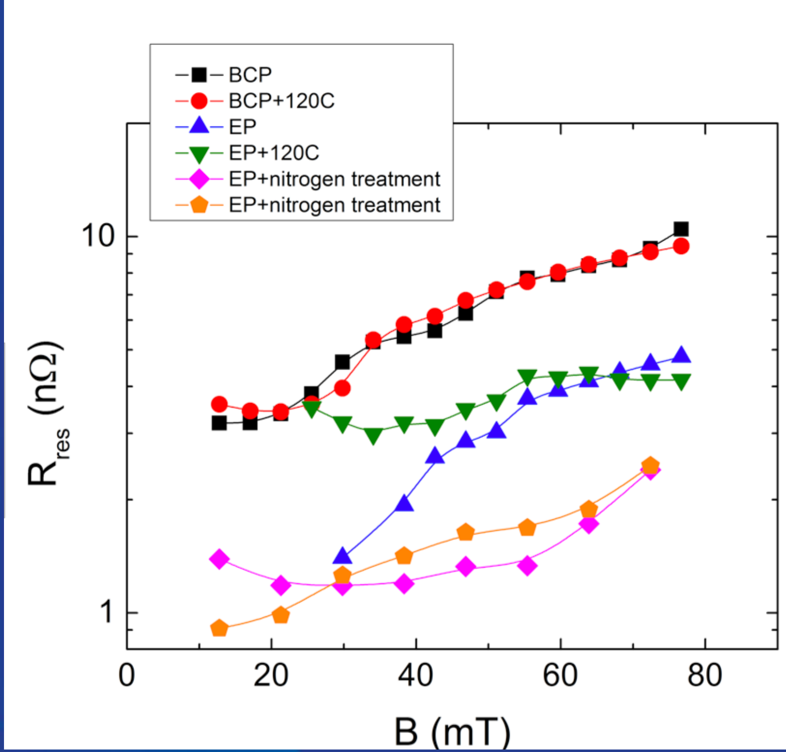


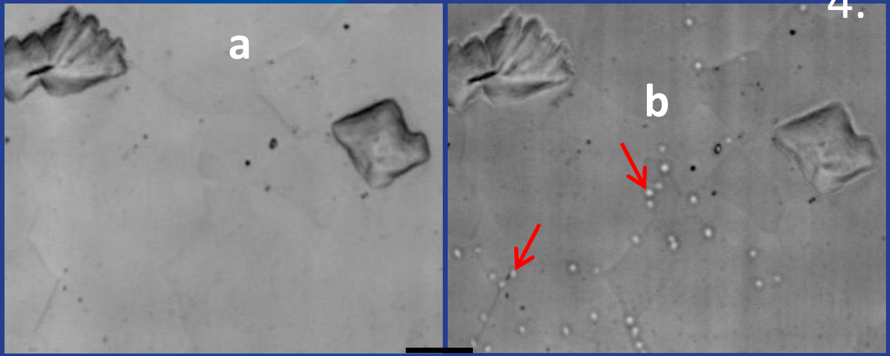

1. EP, BCP: clean limit →
   - High low field value bc of large mfp
   - No Q-slope bc of no Δ(H)
2. 120C bake: dirty limit →
   - Lower low field value bc of low mfp
   - Strong field dependence bc of Δ(H) (bc of dirty limit)
3. Nitrogen baked: Intermediate purity →
   - Lower low field value bc of low mfp
   - Decrease bc of λ(B)? Or is nitrogen a better dopant?



# Origin of low and medium field losses – residual part

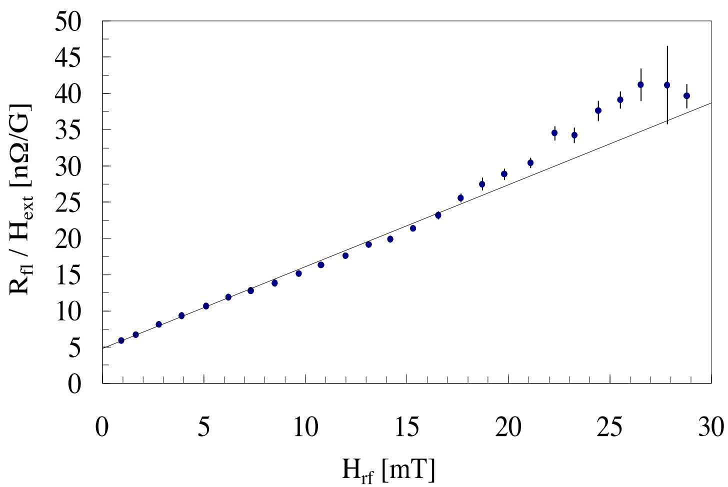


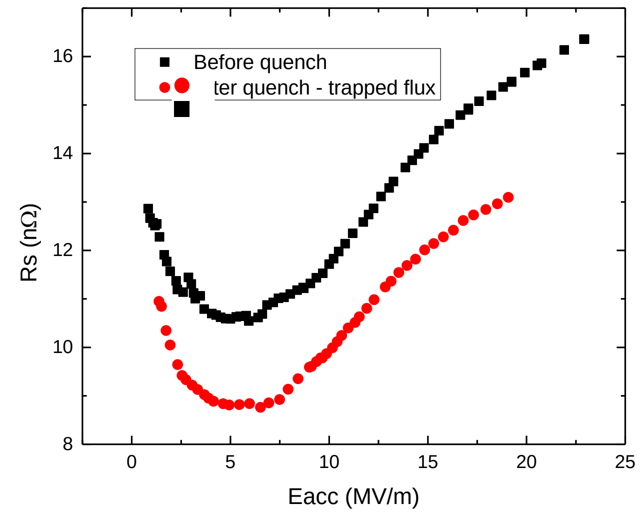

1. Hydrides:
   - Low field: yes (hydrides always present as shown via cryogenic TEM by Trenikhina and Romanenko, residual consistently <1 nΩ in annealed as last step cavities demostrated at FNAL)
   - Field dependence: yes (see second cooldown Rs(B))
2. (Macro)Roughness (BCP vs EP):
   - Low field: no
   - Field dependence: yes
3. Trapped flux:
   - Low field: yes
   - Field dependence: yes, linear
4. Oxide and suboxides:
   - Low field: maybe (increase in 120C localized in first ~ 3 nm)
   - Field dependence: not clear

Fermilab

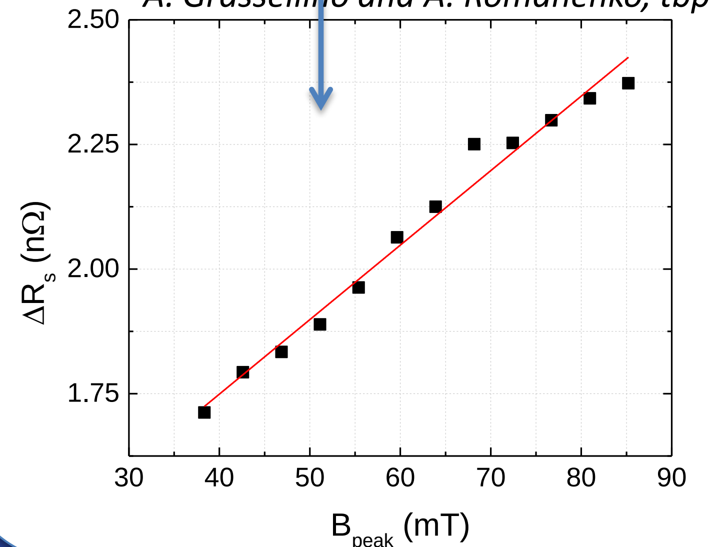
# Trapped flux produces a linear field dependence [$R_0(B)$]



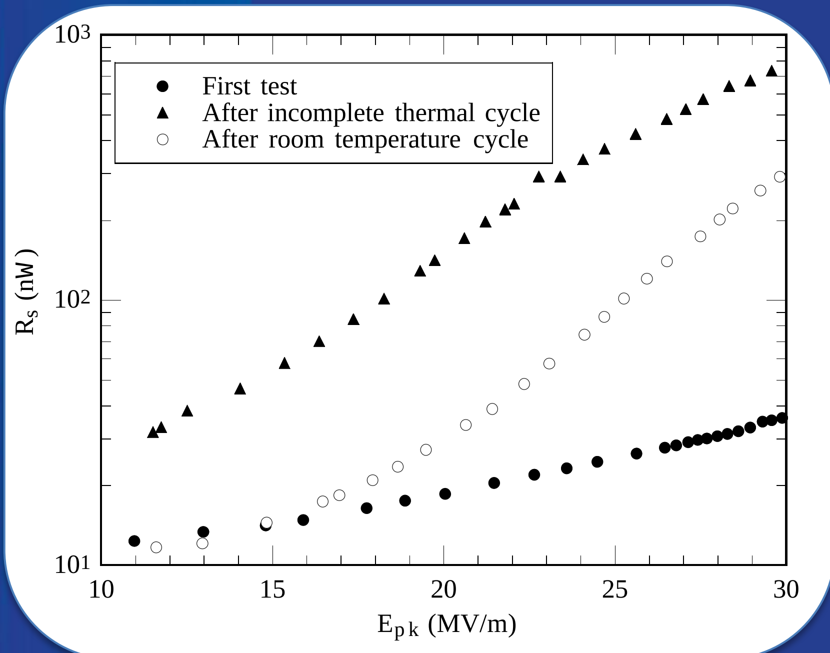

Benvenuti, Calatroni et al, Proceedings of the 1997 Workshop on RF Superconductivity, Abano Terme (Padova), Italy




*A. Grassellino and A. Romanenko, tbp*

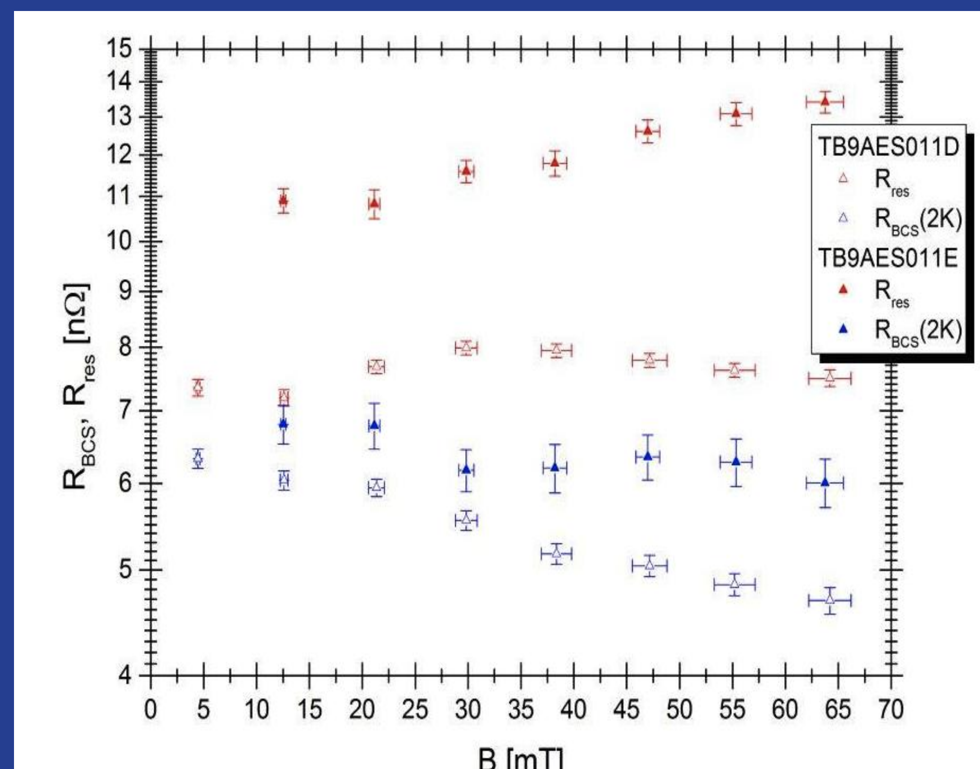


# Hydrogen affects the field dependence of residual resistance: example second cooldown

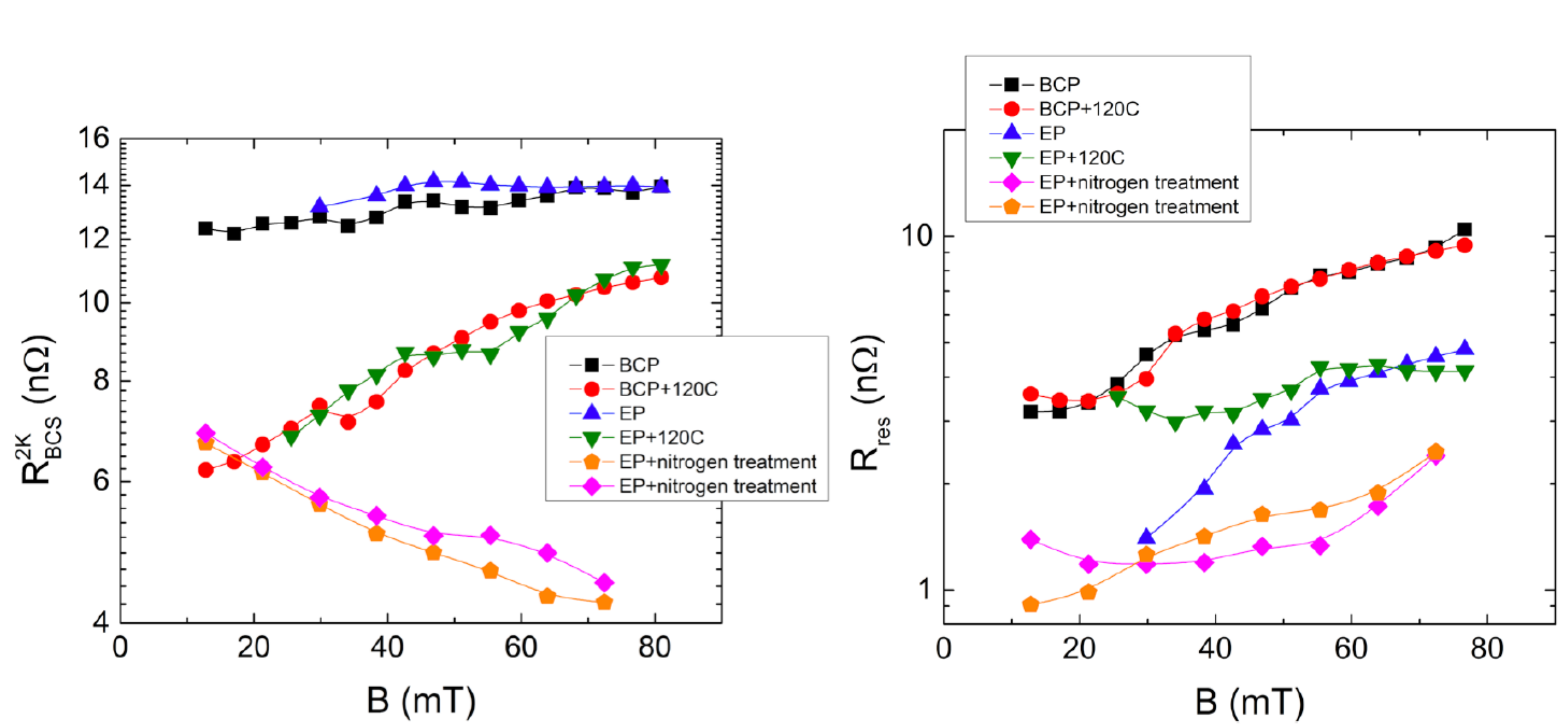



Knobloch and Padamsee, 8th Workshop on RF Superconductivity, Padova, Italy. SRF 981012-12

M. Checchin and A. Grassellino, to be published



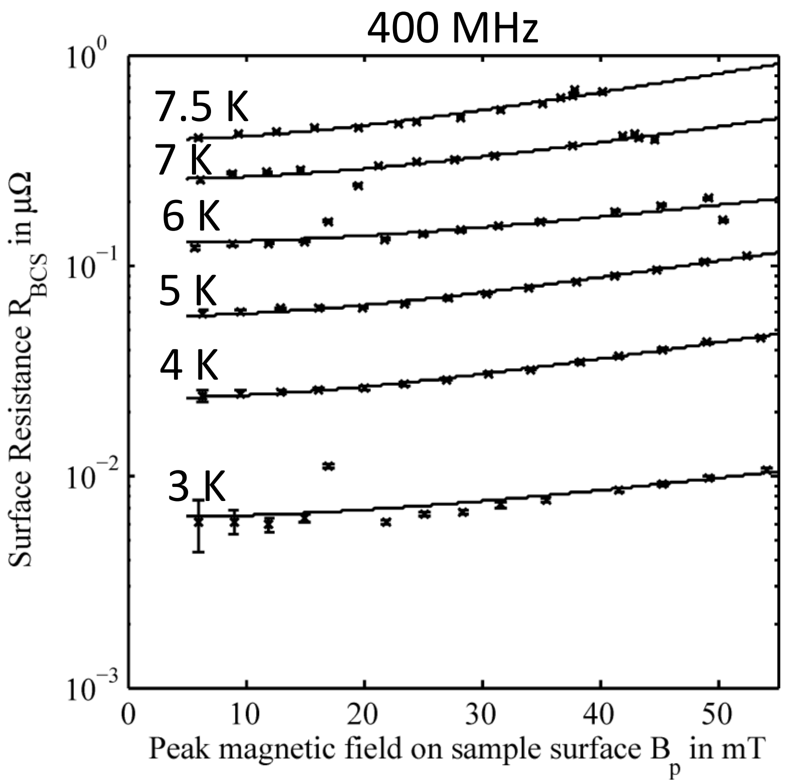

U.S. DEPARTMENT OF ENERGY

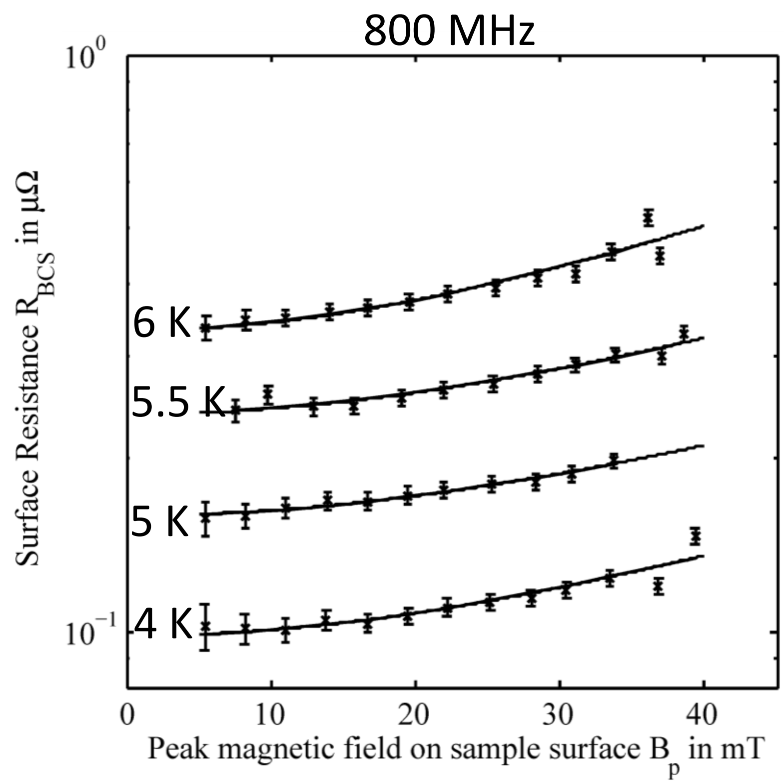


16
14
12
10
8
6
4
0
20
40
60
80
$R^{2K}_{BCS}$ (nΩ)
B (mT)
BCP
BCP+120C
EP
EP+120C
EP+nitrogen treatment
EP+nitrogen treatment
10
1
0
20
40
60
80
$R_{res}$ (nΩ)
B (mT)
BCP
BCP+120C
EP
EP+120C
EP+nitrogen treatment
EP+nitrogen treatment

# Temperature dependent medium field Q-slope

Quadrupole Resonator measurements on one bulk niobium sample




All curves can be fitted by $Rs(T,B)=Rs(T)\cdot c \cdot (B/Bc)^2$ with $c$=10.2+/-2.5 independent on T and f

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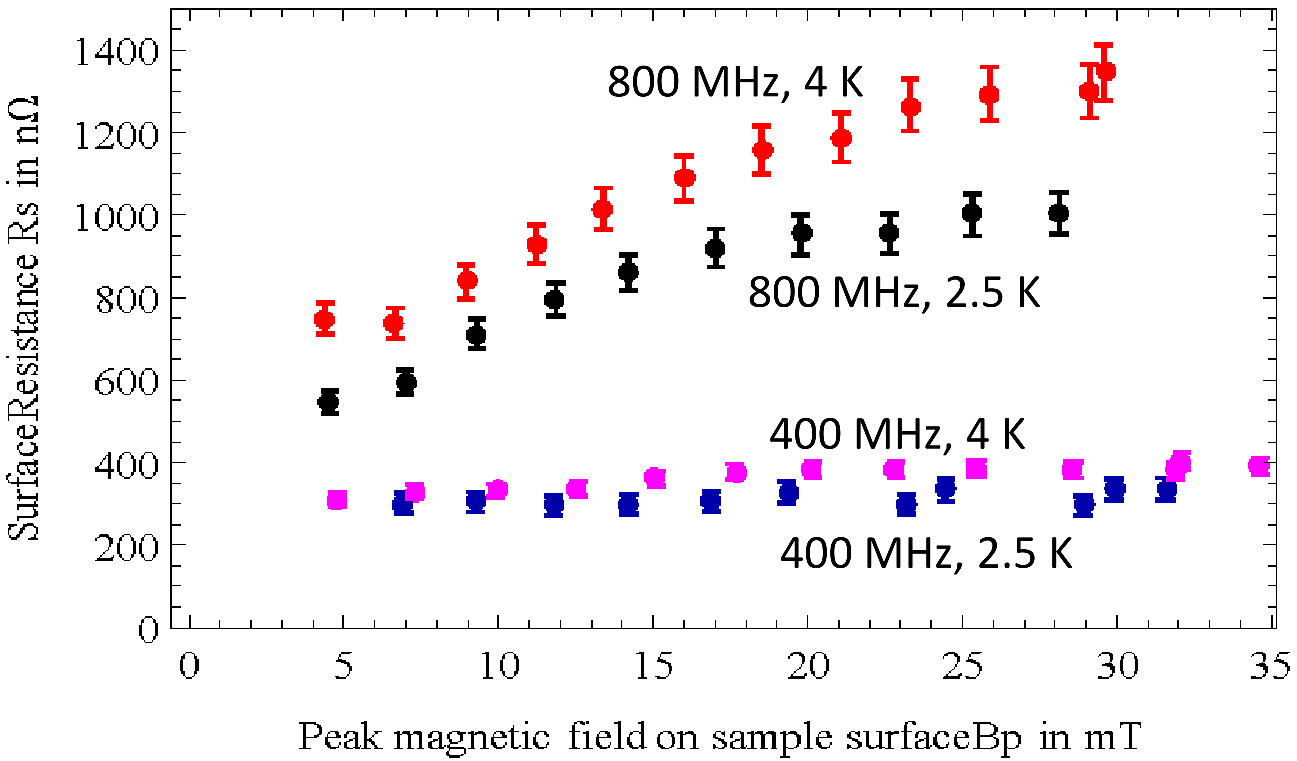
# Temperature independent medium field Q-slope




To explain this data set with magnetic losses one would need a model, which assumes *R*s(*B*) prop. to $f^3$.

In the Quadrupole Resonator the ratio between *E*/*B* is proportional to f. Therefore the data can be explained by a model assuming *R*s(*E*) prop to *f* after subtracting low field losses

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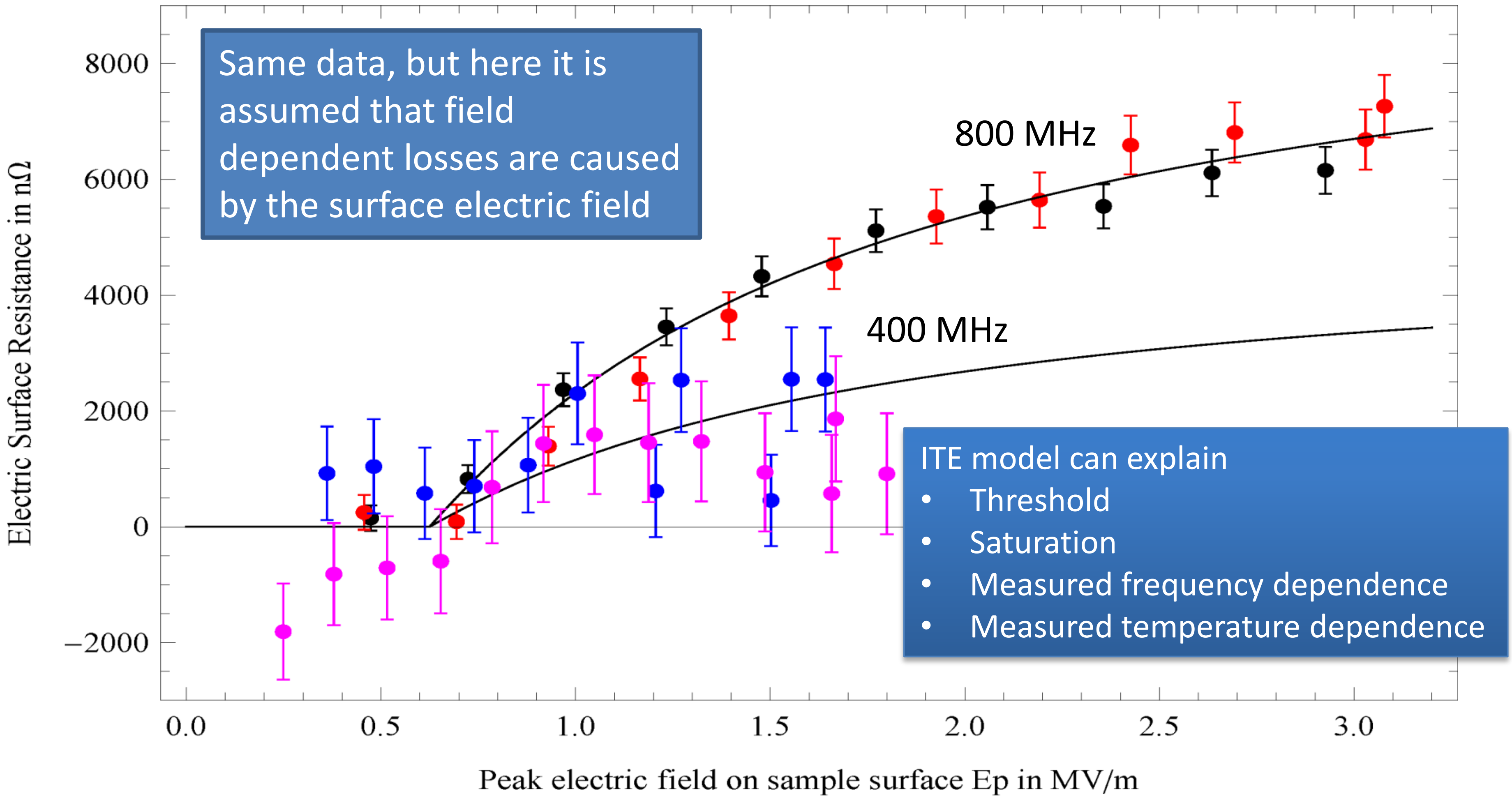
# Temperature independent medium field Q-slope

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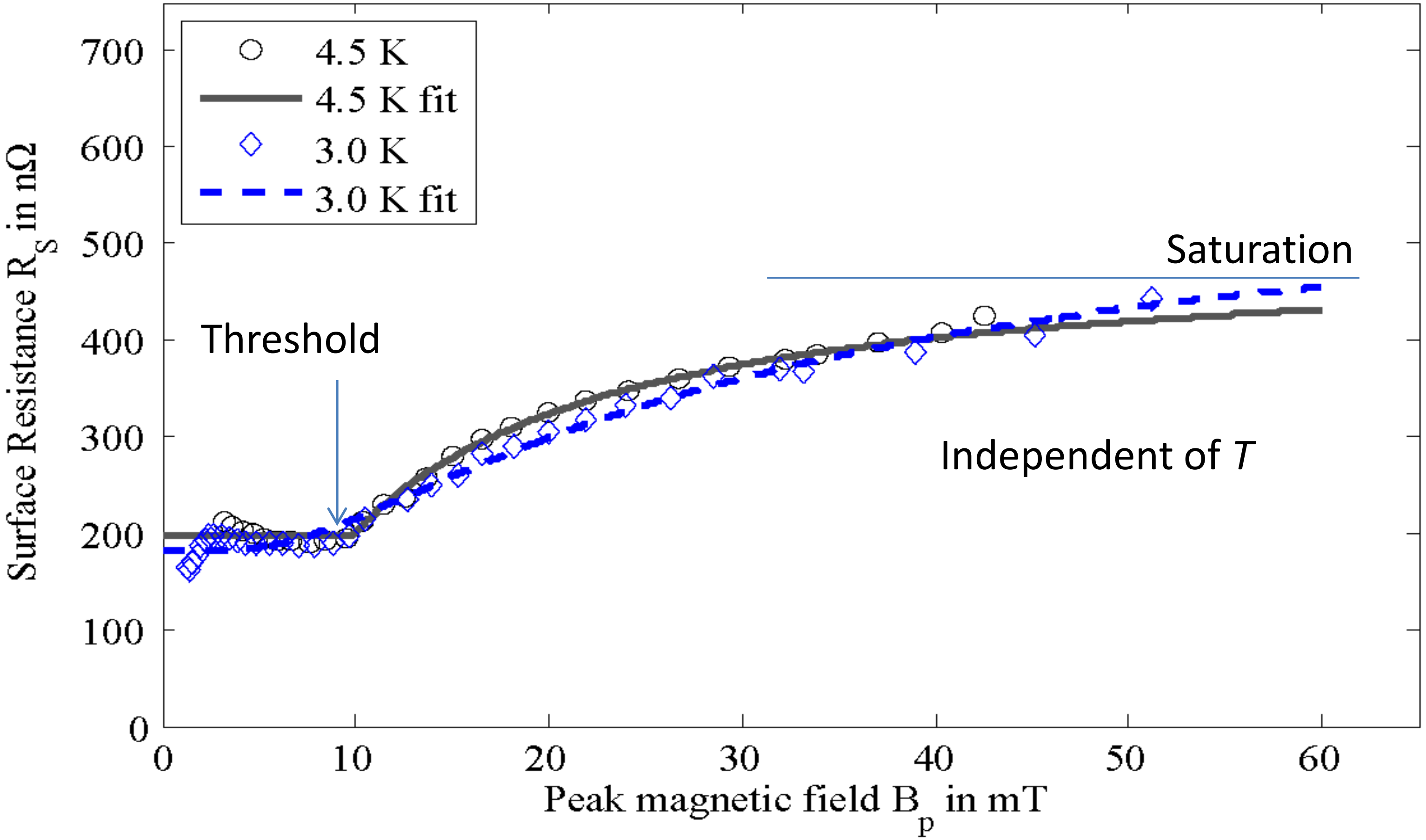
# Temperature independent medium field Q-slope

ITE fit can explain cavity data

Example: Early HIE Isolde QWR measurement (100 MHz)

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# Summary on medium field Q-slope

Combined results of surface resistance measurements on samples and cavities allow to conclude:

1. There are temperature dependent and independent contributors to the medium field *Q*-slope.
2. The temperature dependent surface resistance factorizes in a temperature and a field dependent part like $Rs(T,B)=Rs(T)\cdot c \cdot (B/Bc)^2$, where *c* is a constant independent of *T* and *f*. These losses can be correlated to the surface magnetic field.
3. Often a surface resistance increasing above a threshold field, saturating at higher field is observed. Quadrupole Resonator measurements give evidence that these losses are caused by the surface electric field and the interface tunnel exchange model can provide a good fit to the data with physically meaningful parameters.

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# Dissipation Mechanisms in SRF Cavities from Tunneling and Raman Spectroscopies

J. Zasadzinski

*Illinois Institute of Technology/ Argonne Lab*

**Principal Collaborators:**

IIT: C. Cao, M. Warren. A. Korczakowski
Argonne: T. Proslier, N. Groll, D. Ford
UIC: R. Tao, R. Klie (TEM/EELS)

**Nb Samples: SRF (Hot Spot, Cold Spot), Processed Nb Coupons**

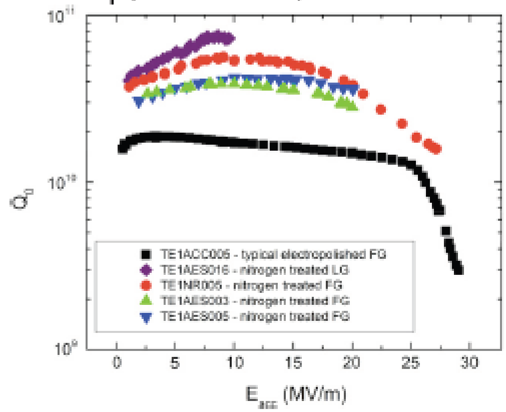
FNAL: L. Cooley, A. Romanenko, A. Grassellino
Jlab: G. Ciovati
CEA: C. Antoine

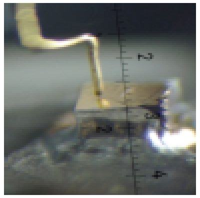
## No Singular Theme: Multimodal Processes

- Nb Oxide is NOT a benign dielectric (defective, variable conductivity, variable barrier strength, locally magnetic, source of De-Pairing)
- Hot Spots/ Cold Spots differ in the area density of macroscopic surface blemishes (etch pits, rough pits, patches of excess C, O, H)
- Very Best regions show ideal Nb gap, ideal oxide/interface, no depairing
- Surprises: NbC inclusions (50 nm - 1 μm) (Raman/TEM/EELS)

# Point Contact Tunneling

Grassellino et al, 2013
Supercond. Sci. Technol. 26 102001



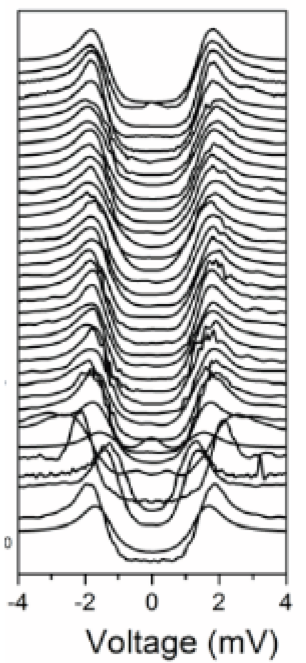



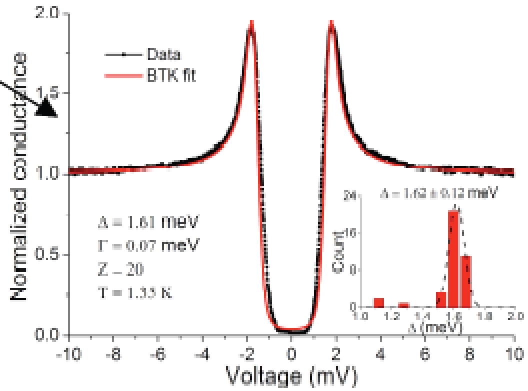
Δ Sup. Gap
Γ DOS Broadening
Z Barrier Strength
Tunneling to Ohmic

FNAL Cavity Samples:
1) 205A Nitrogen treated
2) C8 Cold Spot High Field Q slope

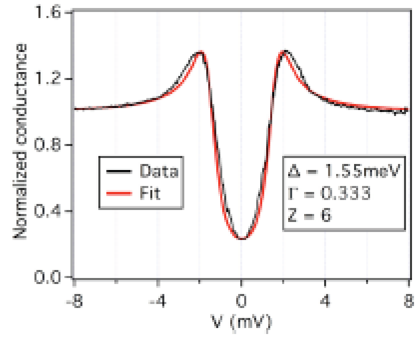
Similar Results - Near Ideal BCS

Nb Single Crystal (110) Processed
Standard EP, de-ionized water
Air dry (C. Antoine)

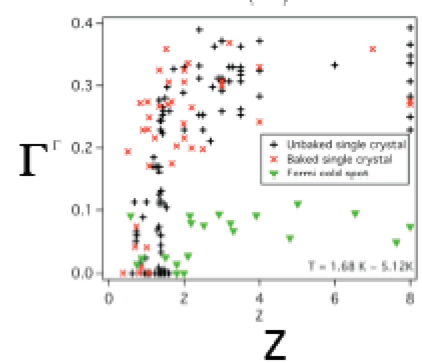



Contrast




Γ/Δ > 20%



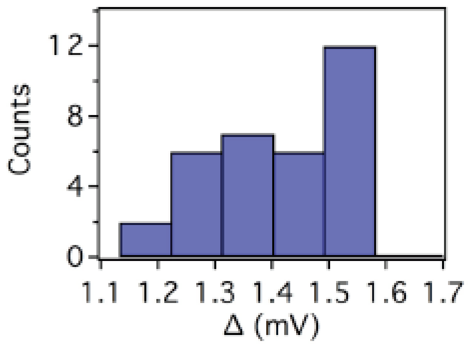

High Q consistent with:
- Near ideal BCS Gap, Γ/Δ < 5%
- High Z oxide barrier
- No de-pairing

Depairing Γ coming from oxide/interface

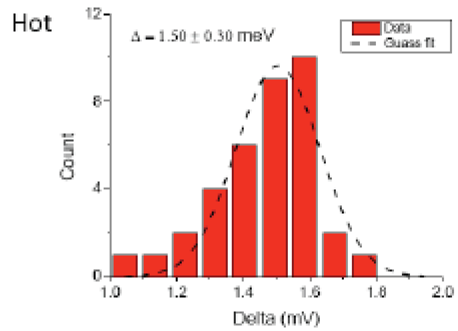
Δ Gap
Γ DOS Broadening
Z Barrier Strength

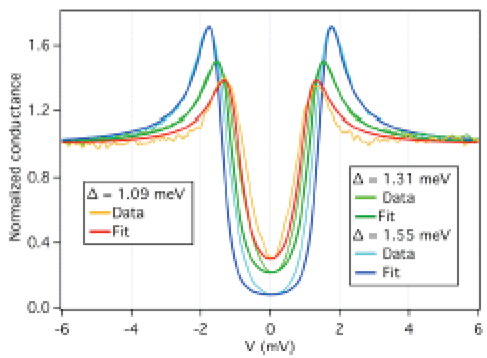
# Tunneling in Cavity Hot Spots

JLab

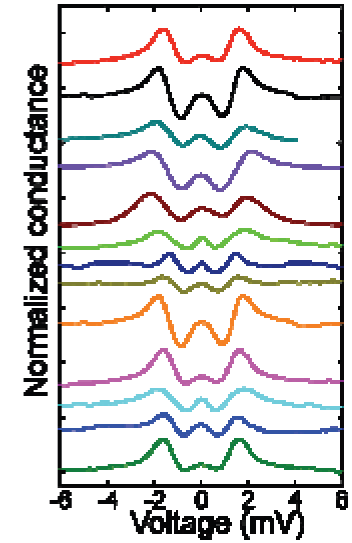



FNAL




Spin flip tunneling
(zero bias peak)




Hot Spots show distribution of Gaps as low as 1.0 meV.

Important $R_S \sim e^{-\Delta/kT}$

Areas of reduced $T_C$

Origin? $NbH_x$, $NbC_x$, Proximity Effects, magnetism?

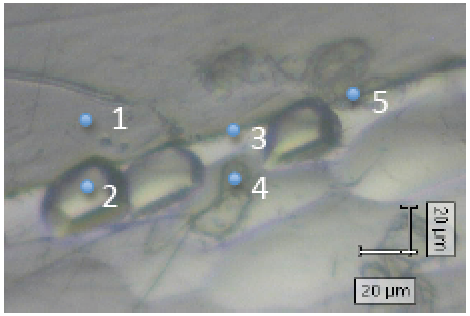
Need new probes! Measure local gap, composition, structure

Hot spots show regions of Kondo tunneling - magnetic moments in the oxide!

Is the origin of Pairbreaking Γ Magnetic moments in oxide?

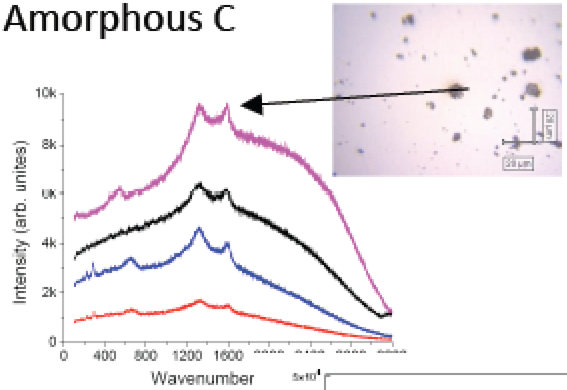
# Raman/SEM Mapping of Surface Blemishes

## Jlab Hot Spot

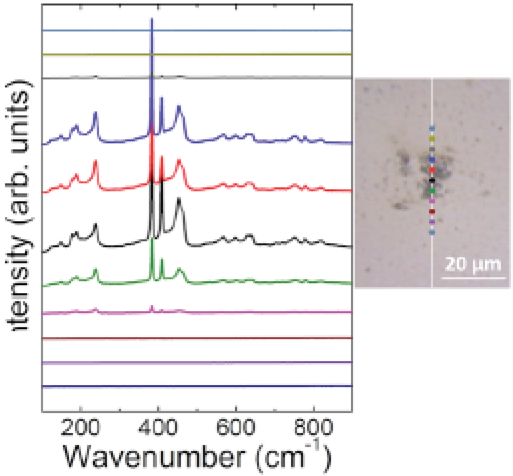



## FNAL 205A

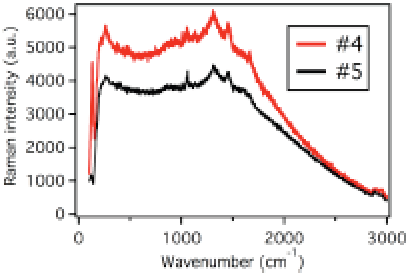
Amorphous C



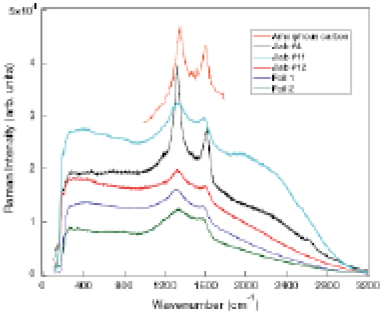

## NbC




## Chain Hydrocarbons $CH_2$



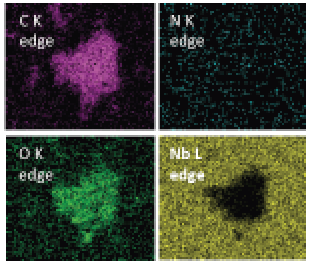

C. Cao et al, PhysRevSTAB.16.064701




SEM probes 1 µm

Thick excess C

Excess O also




Summary of Surface Blemish Studies:

- Higher density of blemishes on Hot Spots
- Raman shows a-C, $CH_2$ chains, NbC (inclusions in TEM)
- SEM shows excess carbon can be thick
- Raman not sensitive to $NbH_x$ need FTIR?
- Is excess C tied to reduced gaps in hot spots?