Poster WEPFDV004

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A New Model for Q-slope in SRF Cavities: RF Heating at Multiple Josephson Junctions at Weakly Linked Grain Boundaries or Dislocations

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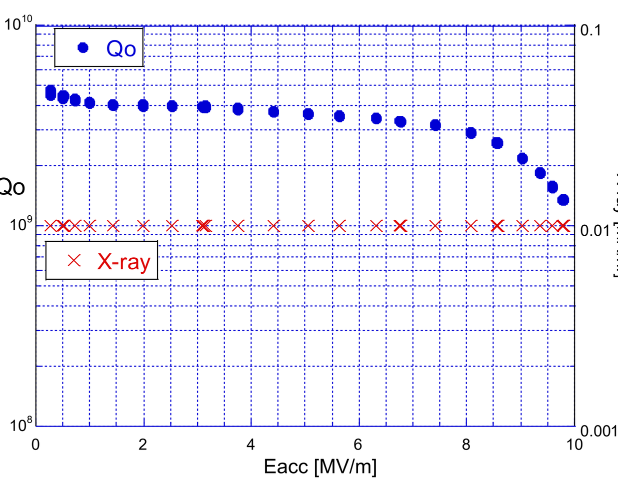
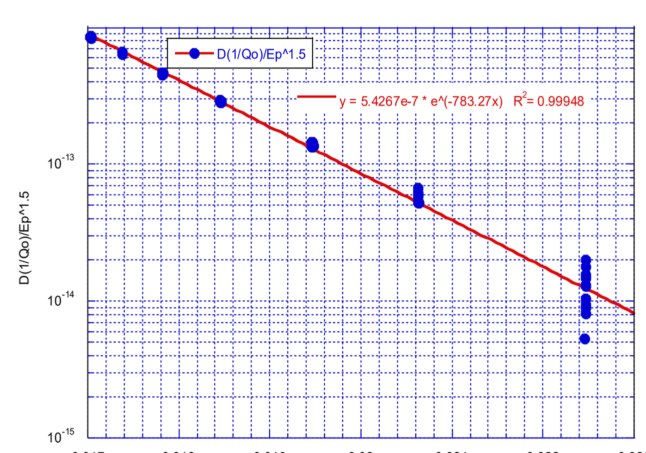
Abstract

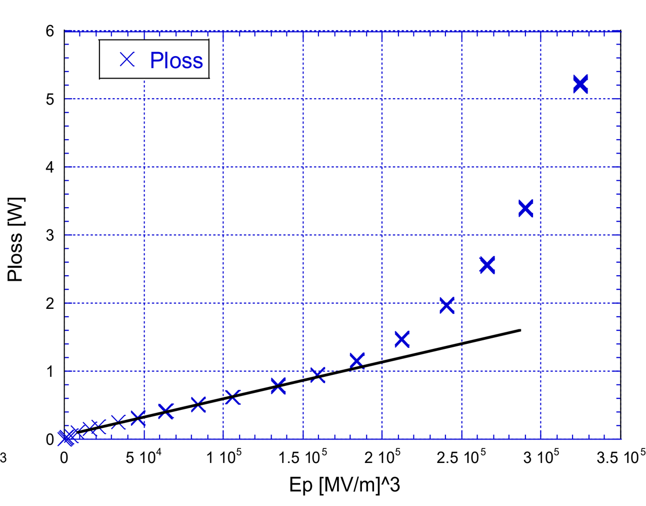
Several models are already proposed for Q-slopes in SRF cavity performance, medium field Q-slope (MFQS), high field Q-slope (HFQS). However, these does not explain both in a way unified. Here, a new model by multiple Josephson junctions at weakly linked grain boundaries or dislocations is proposed for the unified explanation. This model suggests two kind of junctions: ceramic like one and weak superconductor one. If plotted the field vs. RF power dissipation, an increase of RF loss is remarkably observed in proportional to the cube of fields, on both BCP'ed and EP'ed cavity (MFQS). An exponential RF dissipation is often observed at high fields for BCP'ed cavity (HFQS). If supposed the number of J-junctions linearly increases with the fields (this is explained by the flux quantum penetration condition), these behaviors are easily explained. In addition, this model has a potential to explain the anti-Q slope behavior observed in Nitrogen doped or mid-temperature baked cavity. In this paper, this model will be explained, then several data analysis results will be presented.

Motivation: FRIB cavity data analysis

- HFQS is well fitted by FN (Flower Nordheim)-plot (FE), which suggests ***a tunneling mechanism*** as behind physics.
- Ep^3 dependence commonly observed in Ploss vs Ep
- Example: 85-029 0.085QWR



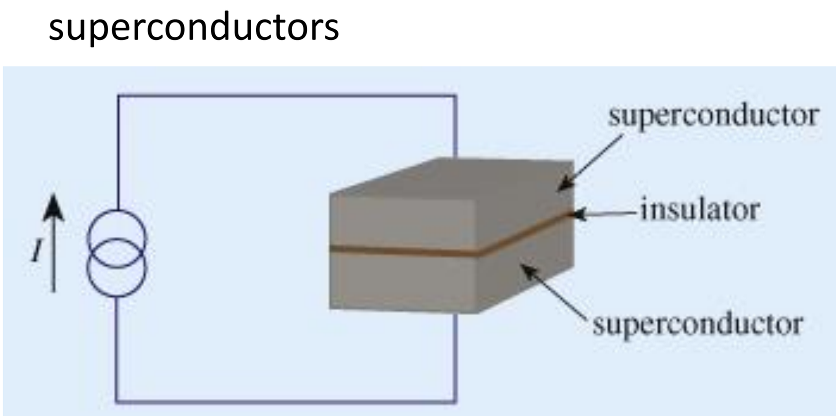


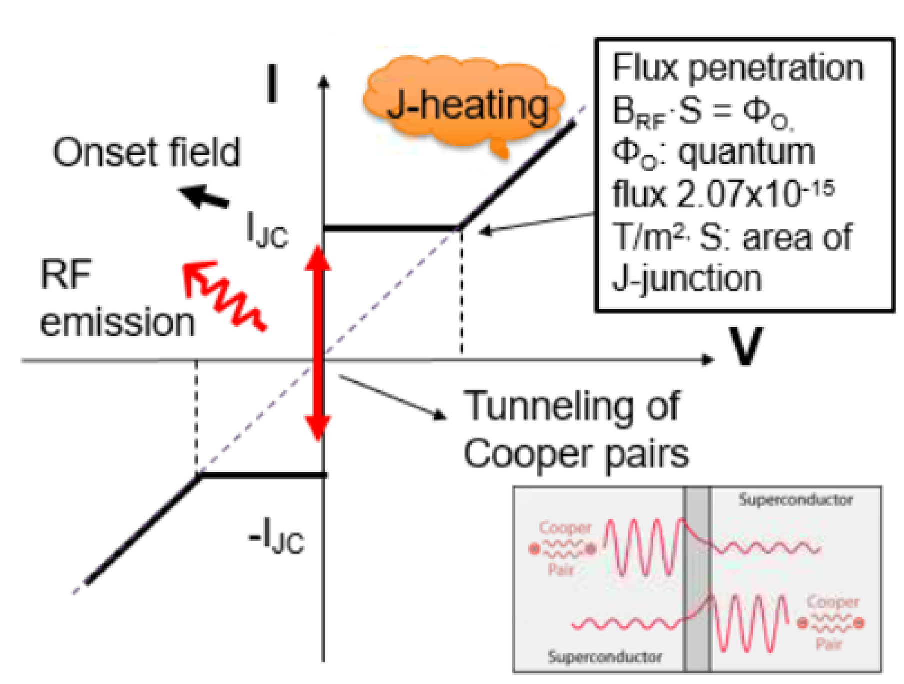


Josephson mechanism

B. D. Josephson (1962). "Possible new effects in superconductive tunneling". Phys. Lett. ***1*** *(7): 251–253*

- Tunneling effect of Cooper pairs or Quasi-electrons through an insulator sandwiched by superconductors





$I < I_C$, Zero voltage due to tunneling of Cooper pairs, no electric resistance (RF emission)

Josephson equations

1) $I = I_C \sin(\varphi)$, 2) $V(t) = \frac{\hbar}{2e}\frac{\partial\varphi}{\partial t}$

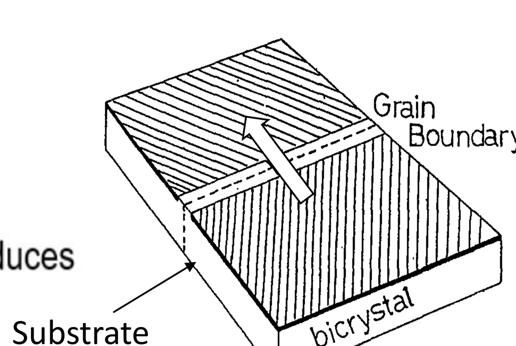
When applied V(t): $V(t) = V_0 \sin(\omega t)$ to Cooper pair chage,

$I(t) = I_C \sin(V_0 \int_0^t \sin(\omega t)dt)$

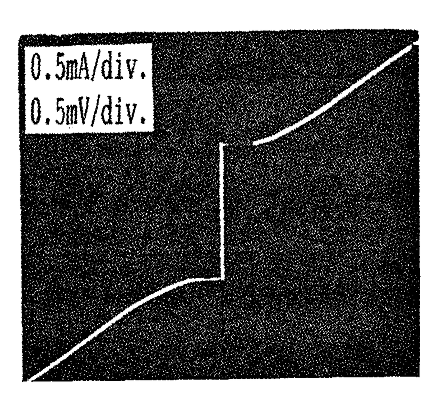
is generated without any loss.

RF emission will happen, which has been already observed.

$I > I_C$, Quasi-electron makes tunneling the insulator, and produces voltage with electric resistance (RF dissipation)



Bicrystal grain boundary Josephson element



Characteristics of current vs voltage at 4.2 K with Bicrystal grain boundary Josephson element at h= 24⁰ (elevation angle).
Width 3 μm, thickness 200 nm, ***Tomoya Ogawa, PhD thesis, 1994, Tohoku University, Japan.***
http://hdl.handle.net/10097/6949

- **B. Bonin and H. Safa, Sacly, France, in 1991 proposed Josephson array model with RF dissipation by the analogy of HTC.** "Power dissipation and Technology for high field in granular RF Superconductivity", 1991, 4 257, Superconducting Science

RF dissipation at weakly linked grain boundaries by Josephson mechanism

Multiple J-junctions (N) exist on the SRF surface,

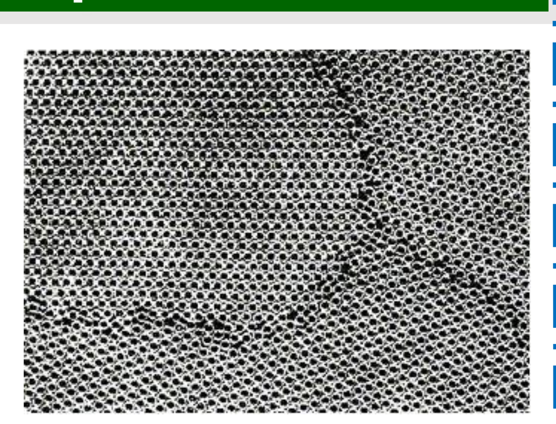
At $B_{RF}\cdot S = \Phi_O$, Φ_O: quantum flux 2.07×10^{-15} T/m^2, S: area of J-junction

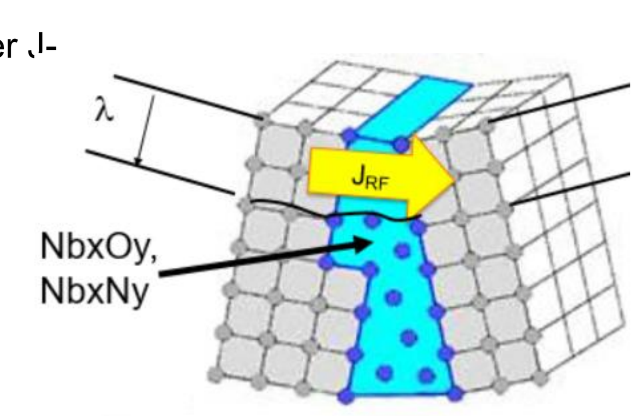
1) RF current penetrates the junction, and Voltage V_J happens
2) The RF current J_{RF} feels this voltage
3) As the result, Josephson heating happens at one core

$p_J = V_J \cdot J_{RF}$, $V_J \propto B_{RF}$

$p_J \propto B_{RF}^2$

4) Total J-heating $P_{J-T} = p_J \times N$
5) N (number of J-junctions) increase lineally with B_{RF}: $S = \Phi_O/B_{RF}$, opens smaller J-junction with increased B_{RF}
6) As the result, Field dependence of RF dissipation : $B_{RF}^2 \times N(B_{RF}) \sim B_{RF}^3$
   - Insulator case, $N(B_{RF}) \sim B_{RF}$, Medium Q-Slope $\sim B_{RF}^3$ or E_P^3
   - Weak superconductor case, $N(B_{RF}) \sim B_{RF} \times \exp[\alpha\cdot(B_{RF} - B_{onset})]$, breaking of SC at B_{onset} by B_{RF}, Exponential behavior with HFQS





Big picture of this model

- By a simple calculation, the Ep^3 dependence of P_{loss} at medium fields concludes:

  Measured Qo* is expressed, as **Qo* = Qo/(1+α·Eacc),**

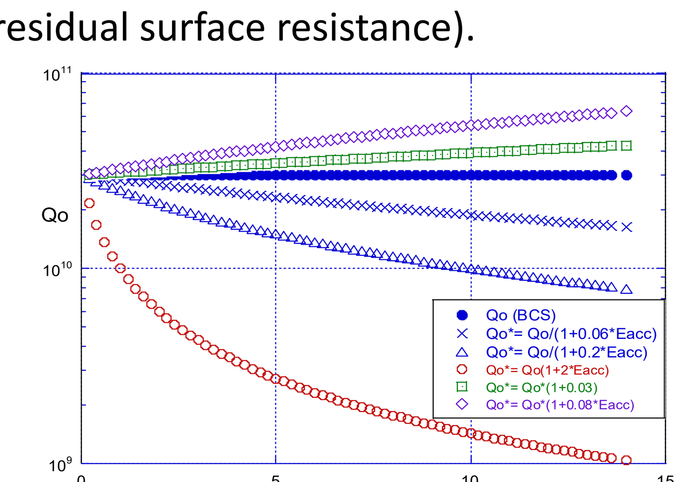
  Qo (constant with fields) is the one from just BCS heating, includes residual surface resistance).

- The model includes the RF emission: U*= U +ΔU (emission).
  - Remember $\Delta U \propto N\cdot Ep^2 \propto Ep^3$

  By a simple calculation, the Ep^3 dependence of emission leads as:

  Q* = Qo·(1+α·Eacc)

- This model has potentials to explain many medium Q-slopes, HFQS, and Anti-Q slope behavior.



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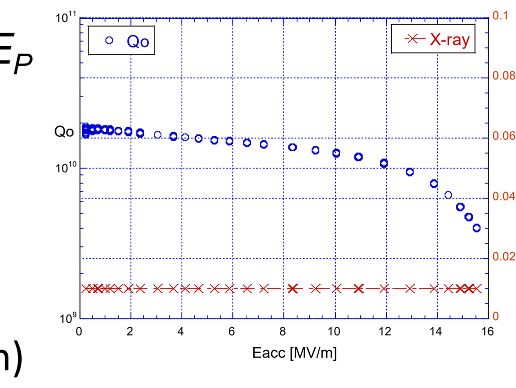
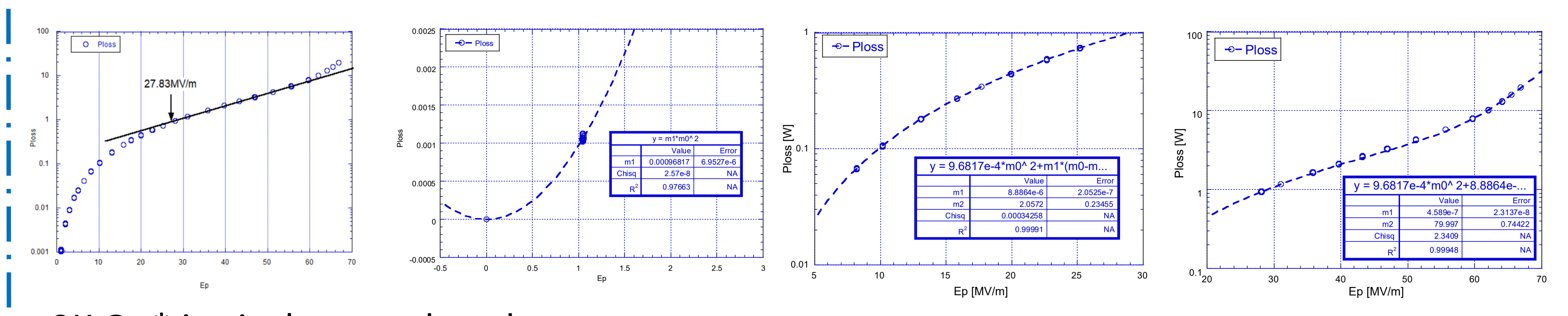
Data analysis example by this model

0) Assume ***NO thermal feedback for 2K data***, because L-He has no bubbling below λ-point (2.17K)
1) Plotting Ep vs Ploss is easy to data analysis, linear combination of RF dissipation mechanisms
2) ***BCS heating (due to BCS + residual surface resistance)*** is data fitted by ***α x Ep²***
   - α is obtained by a couple of lowest field data, and Ploss = 0 at Ep=0
3) Medium field region (C_2 < Ep < C_4) is data fitted by:
   - BCS heating + ***J-heating*** (Ep^3 term) = α x Ep^2 ***+ C_1 x (Ep - C_2)² x E_P***
   - ***C_2 : onset of the J-heating***
4) High field region (Ep > C_4) is data fitted by BCS heating + J-heating +HFQS heating
5) HFQS heating = ***C_3 x (Ep – C_4)² x Ep x exp[C_5 x (Ep-C_4) x β]***
   - ***C_4 is the HFQS onset***, which is estimated by the Ploss vs Ep plot (right graph)
   - β= [Bp/Ep] [T/(MV/m)]

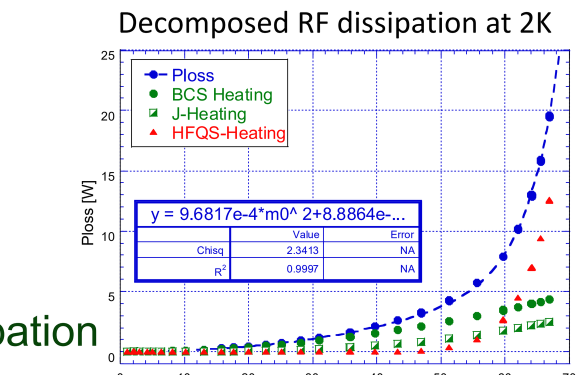




- 2K Qo* is nicely reproduced.

Ploss = 9.6817E-4 x Ep² + 8.8864E-6 x (Ep – 2.0572)² x Ep + 4.589E-7 x (Ep - 27.83)² x Ep x exp [79.997 (Ep - 27.83) x1.7907E-3]

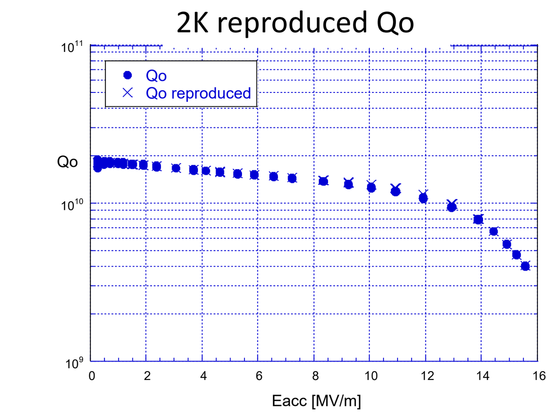
Decomposed RF dissipation at 2K



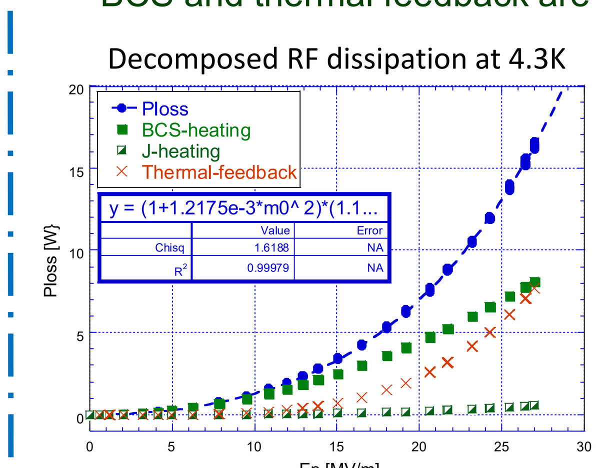
- **4.3 K Data analysis**
- ***Thermal Feedback*** has a rather big impact on the Ploss
- This effect is estimated as: multiply C_6 x Ep^2 x P_{loss} on the RF dissipation
- Ploss = (1+ C_6 x Ep^2) x (BCS heating + J-Heating)

  =(1+ 1.2175E-3 x Ep²) x (1.11538E-2 x Ep² + 3.2124E-5 x (Ep - 1.250)² x Ep)
- BCS and thermal feedback are dominant, J-heating is hindered.

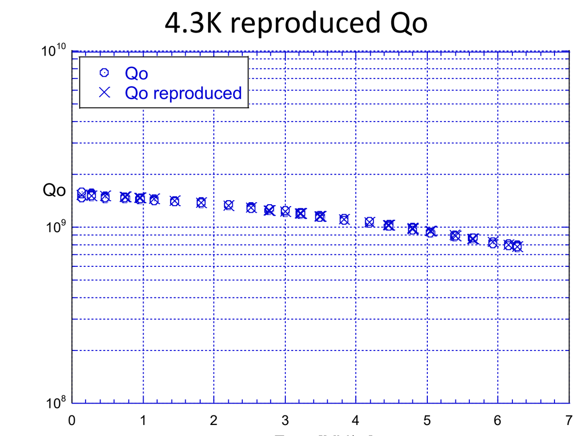
2K reproduced Qo



Decomposed RF dissipation at 4.3K



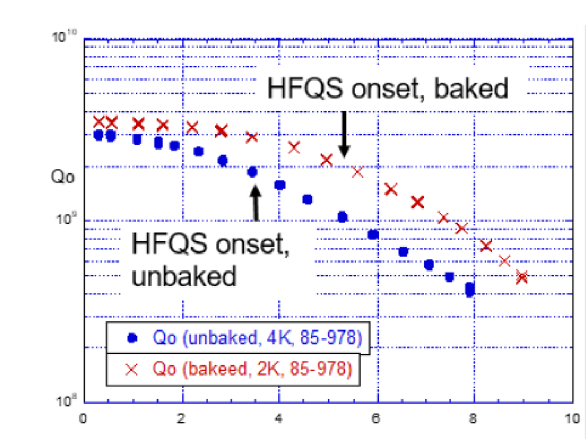
4.3K reproduced Qo

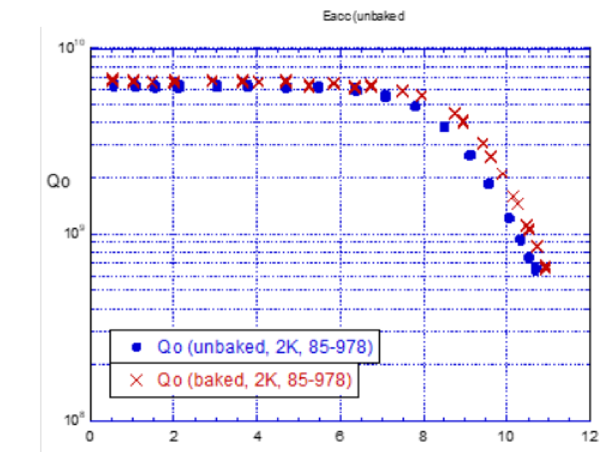


Analysis of BCP'ed baked cavity

- LTB pushes up the J-heating/HFQS onsets, makes a smaller element size, and reduces both contribution ***at 4.3K.***
- The smaller size can be produced by Oxygen diffusion during LTB.
- On the other hand, ***at 2K***, both heating have a already small contribution by one order of magnitude, and the impact is not so remarkable as 4.3 K case.

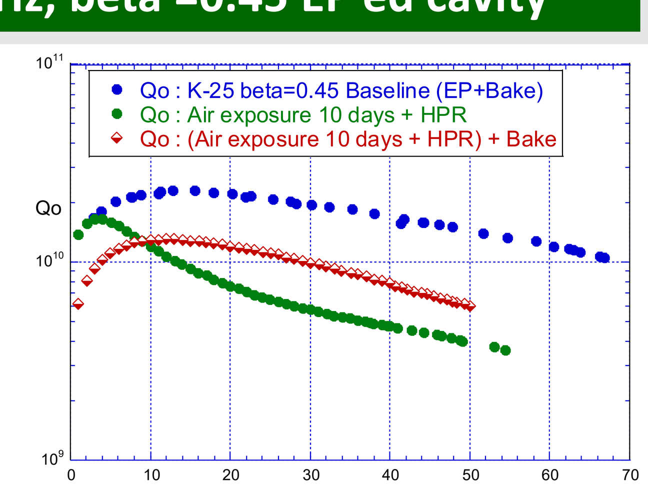
Insulator size	Temp	Unbaked	Baked
W [μm]	4.3 K	7.7	1.6
	2 K	8.2	1.7
J-Heating Strength [W/(MV/m)3	4.3 K	3.7E-5	1.4E-6
	2 K	1.7E-6	1.9E-6

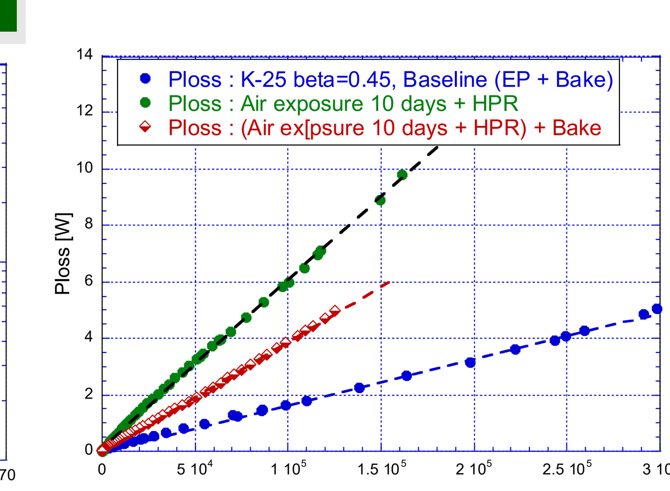




Air exposure impact on 1.3GHz, beta =0.45 EP'ed cavity

- Air exposure enhances the J-heating
- Baking after air exposure mitigates the J-heating





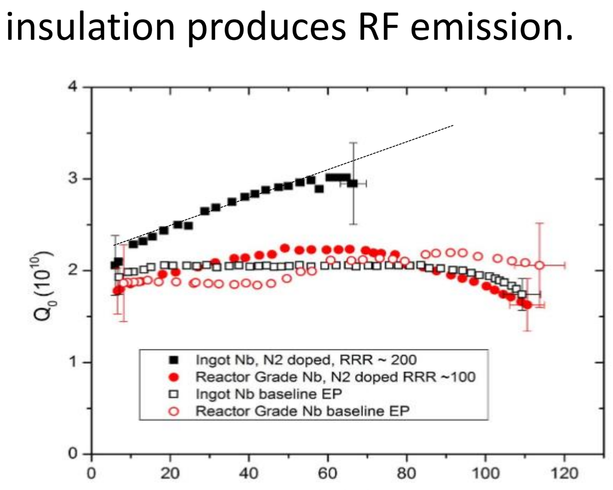
Anti-Q slope

- J_{RF} < Ic, Cooper pair oscillation at the insulation produces RF emission.
- One junction produce ΔU ∝ Ep^2
- The total emission power is :

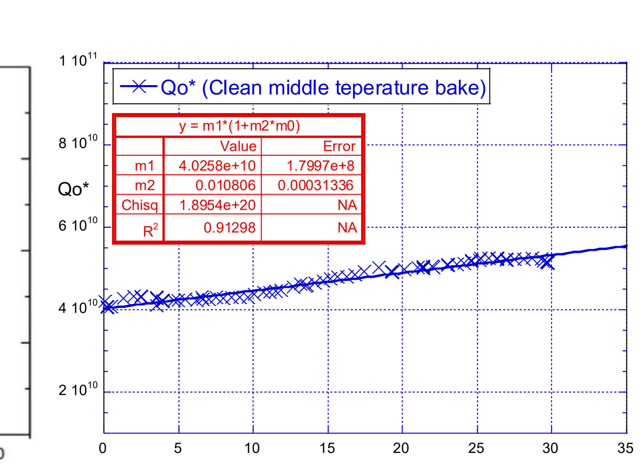
  ΔU = N x ΔU ∝ Ep^3

- $Q^* = \frac{\omega(U+\Delta U)}{P_{loss}}$ = Qo x (1+ α x Ep))

Measured Qo increases linearly propanol to Ep.



P. Dhakal et al., IEEE Transaction on Applied Superconductivity, Vol. 25. No.3, June 2015



S. Posen et al., Phys. Rev. Appl. 13, 014024 (2020)

Summary

- Josephson array model with RF dissipation was proposed by B. Bonin and H. Safa, Sacly, France, in 1991.
- The presented model here has been advanced it by introducing the number of Josephson junction increases linileary proportional to the field.
- The medium Q-slope proportional to Ep^3 is easily explained by this model.
- The HFQS is interpreted as the insulator made of weak superconductor. This mode has many potential to explain various Q-slope behaviors, very much intuitively.
- The Anti-Q slope behavior is explained by the RF emission at J_{RF} < I_C.