Revising of Knobloch-Model

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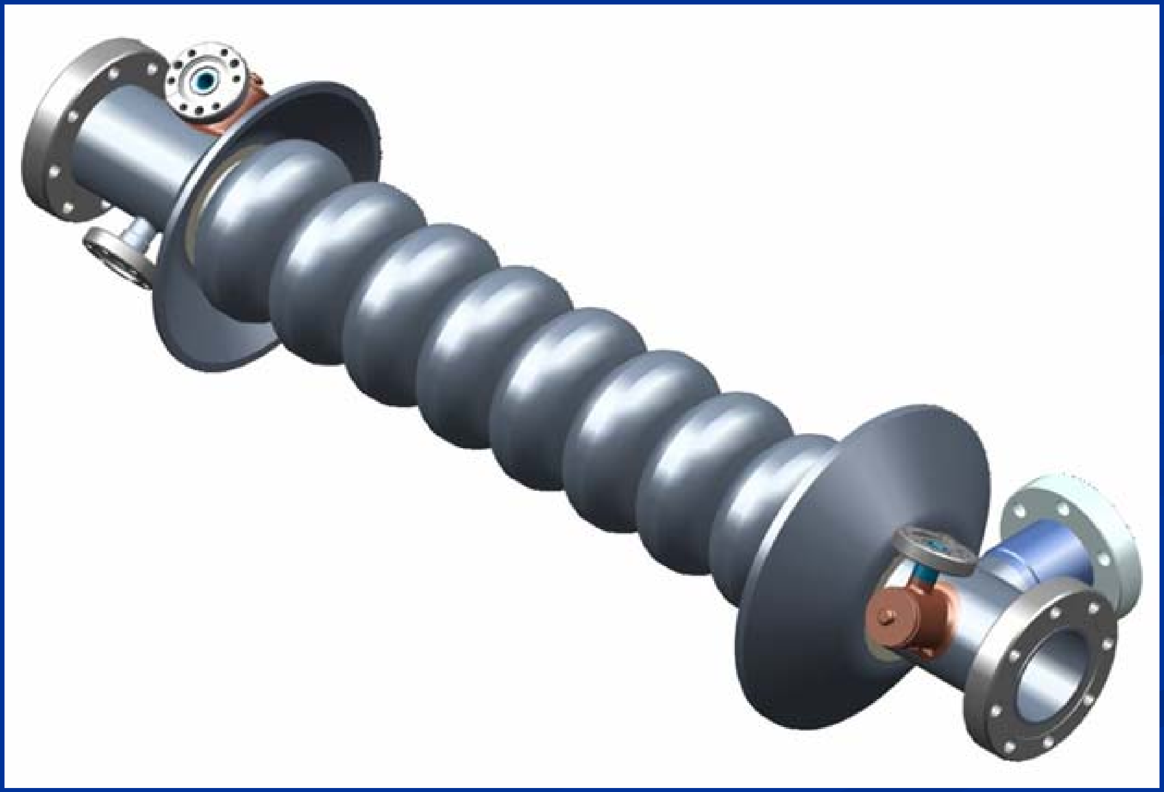
Structure of the presentation

- Basics of RF cavities and RF Superconductivity
- Knobloch model
- Discussion of Knobloch model
- Thermal model
- The Equivalent Ellipsis Approach
- Improving of Knobloch model and conclusion
- What was not done?

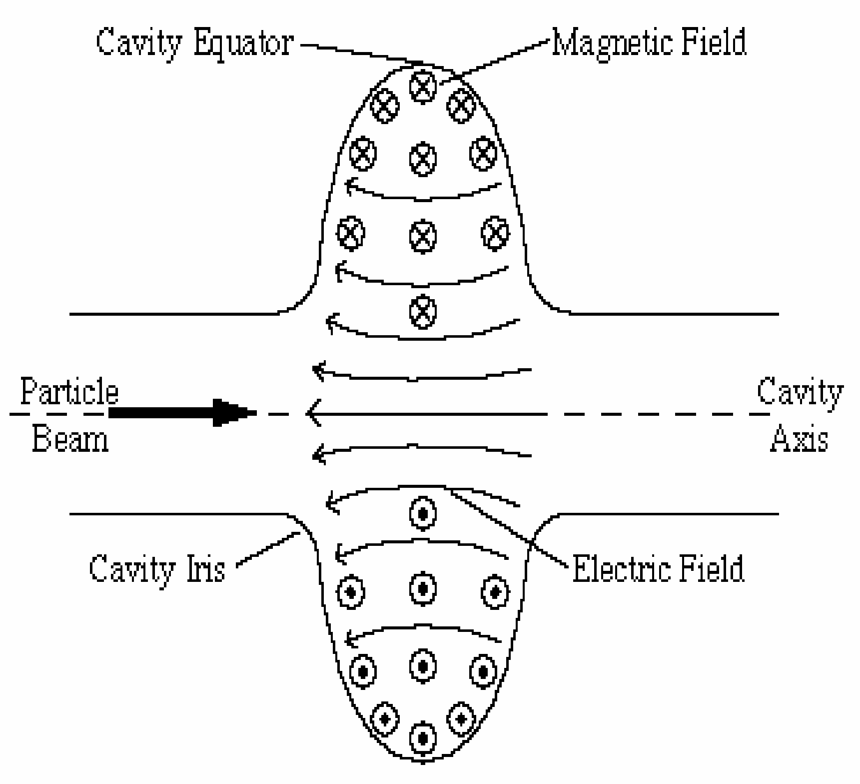
RF Cavity

RF accelerating cavities are microwave resonators with connecting tubes to allow particle beams to pass through for acceleration



The fundamental or lowest RF frequency mode (TM 010)

- The electric field is roughly parallel to the beam axis, and decays to zero radially upon approach to the cavity walls.
- The magnetic field is azimuthal, with the highest magnetic field located near the cavity equator. The magnetic field is zero on the cavity axis.



Q-factor

- The Q of an accelerating cavity is the RF angular frequency (ω) times the ratio of the stored energy in the electromagnetic fields (U) to the dissipated power (P_{diss}):

$$Q = \frac{\omega U}{P_{diss}}$$

- In the situation where all cavity losses are due to surface currents, the Q can alternately be defined as the ratio of the geometry factor G to the microwave surface resistance R_{surf}.

$$P_{diss} = \iint_A \frac{1}{2} H^2 R_{surf} \, dA \qquad Q = \frac{G}{R_{surf}}$$

Basics of RF Superconductivity

- It is well known that superconductors has zero DC electrical resistance when the temperature is below the critical temperature T_C According to BCS theory, below T_C the electrons of a conductor gain a small net attraction through their interaction with the surrounding lattice. The electrons then condense into "Cooper pairs," which move without resistance through the conductor. The Cooper pairs have binding energy Δ, which is dependent on temperature.
- Unlike DC resistance, RF surface resistance is zero only at $T = 0$ K. At temperatures above absolute zero, but below the critical temperature, the surface resistance is greatly reduced, but non-zero.

Two fluid model

- Non zero RF surface resistance can be understood through the "London two-fluid model." The two fluids are paired (superconducting) and unpaired (normal conducting) electrons. The binding energy of the Cooper pairs is comparable to thermal energies, therefore we can express the fraction of unpaired electrons by a Boltzmann distribution:

$$\frac{n_{NC}}{n_{SC}} = \exp\left(-\frac{\Delta(T)}{k_B T}\right)$$

- Cooper pairs move without resistance, and thus dissipate no power. The electromagnetic fields must extend into the surface of the conductor in order to provide the forces to accelerate the pairs back and forth to sustain the RF surface currents. The EM fields will act on the unpaired electrons as well, therefore causing power dissipation.

BCS Resistance

For temperatures less than $T_C/2$, the superconducting surface resistance can be well represented as:

$$P_{surf} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta(0)}{k_B T}\right) + P_0$$

- The first term is the BCS resistance. The coefficient A is a complex function of material parameters such as the superconducting coherence length, the penetration depth, the electron mean free path, and the Fermi velocity.
- The second term is the residual, or temperature independent, resistance R_0. Mechanisms for R_0 are not well understood.

Theoretical Potential of SRF Cavities

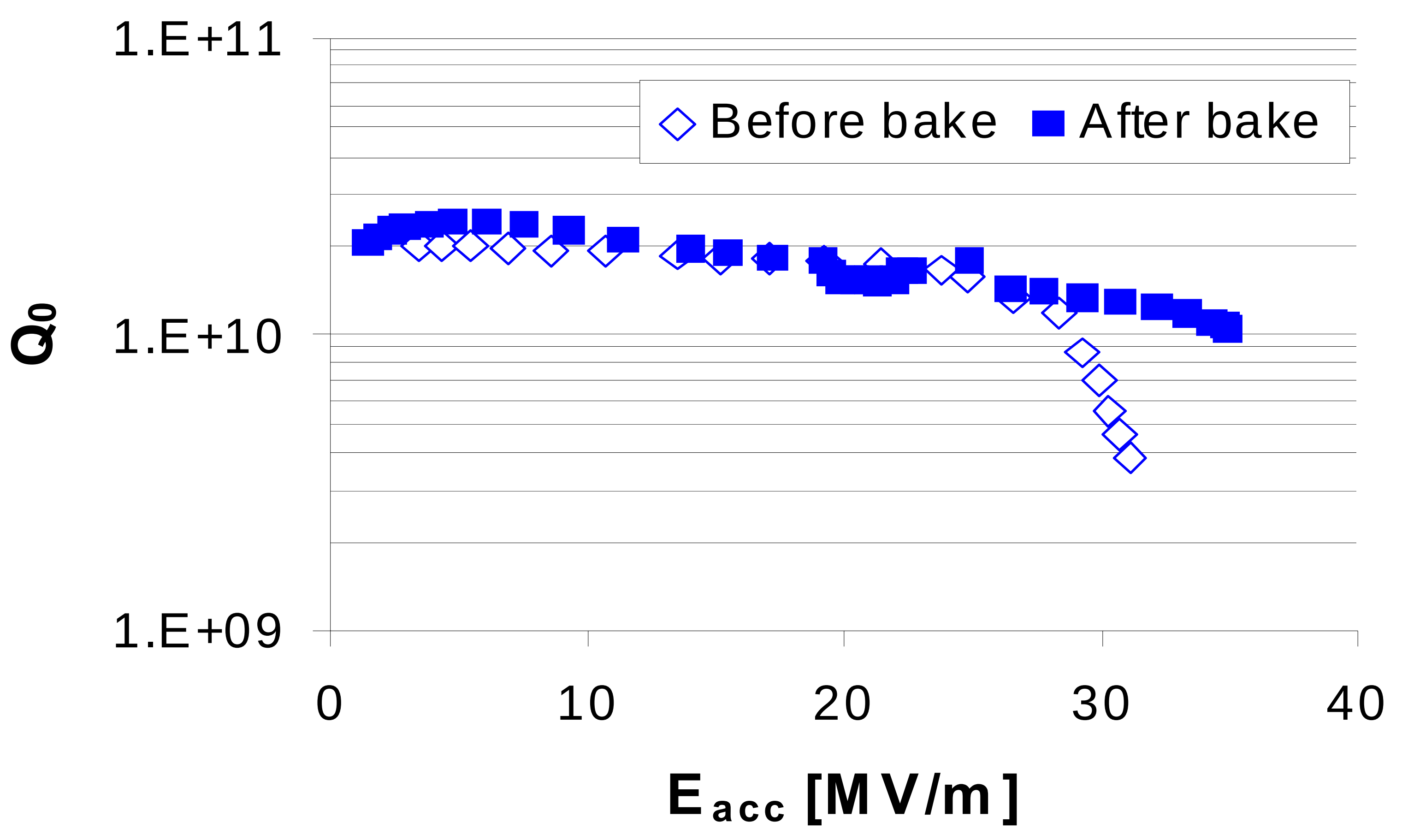
- In Type II superconductors, the magnetic field is completely expelled up to a first critical field, H_{C1}. Above H_{C1}, the magnetic field penetrates partially. This behavior persists up to a second critical field, *Hc2*. Above *Hc2*, the field penetrates completely, destroying the superconductivity.
- In RF conditions situation is slightly different. The penetration of the magnetic field into the RF surface requires nucleation of a flux line, which requires a finite amount of time. So the complete shielding of magnetic fields can persist to fields higher than the critical field, up to a limit called the superheating critical field, H_{SH}.

H_C	1993 Oe(*)
H_{C1}	1735 Oe(*)
H_{C2}	~4000 Oe(*)
H_{SH}	2300 Oe(**)

In typical SRF accelerating cavities, *Hpeak* = 2300 Oe corresponds to accelerating gradients of **50 to 60 MV/m !!!**

(*) Superconducting Properties of High-Purity **Niobium (**DK Finnemore, TF Stromberg, CA Swenson - Physical Review, 1966 – APS)
(**) http://www.lns.cornell.edu/public/CESR/SRF/

But what do we see in experiment?!



Q-drop and its removal by baking in a 9-cell DESY cavity

Q-drop

The Q-drop limits the acceleration gradient of Nb cavities to gradients below the 35 MV/m specified for ILC.

Performance of Nb cavity can be improved by baking but cause of this phenomena is not investigated well.

Knobloch model

One of the models trying to explain Q-drop was presented by J. Knobloch. It explains the Q-drop as the result of localized quenching of sharp edges of some grains in the equator region due to geometric enhancement of the magnetic field.

Geometric enhancement of the magnetic field

Knobloch model implies that the sharp edges of grains can produce magnetic field enhancement of up to a factor 2 and typical value is about 1.4.

Details of Knobloch model

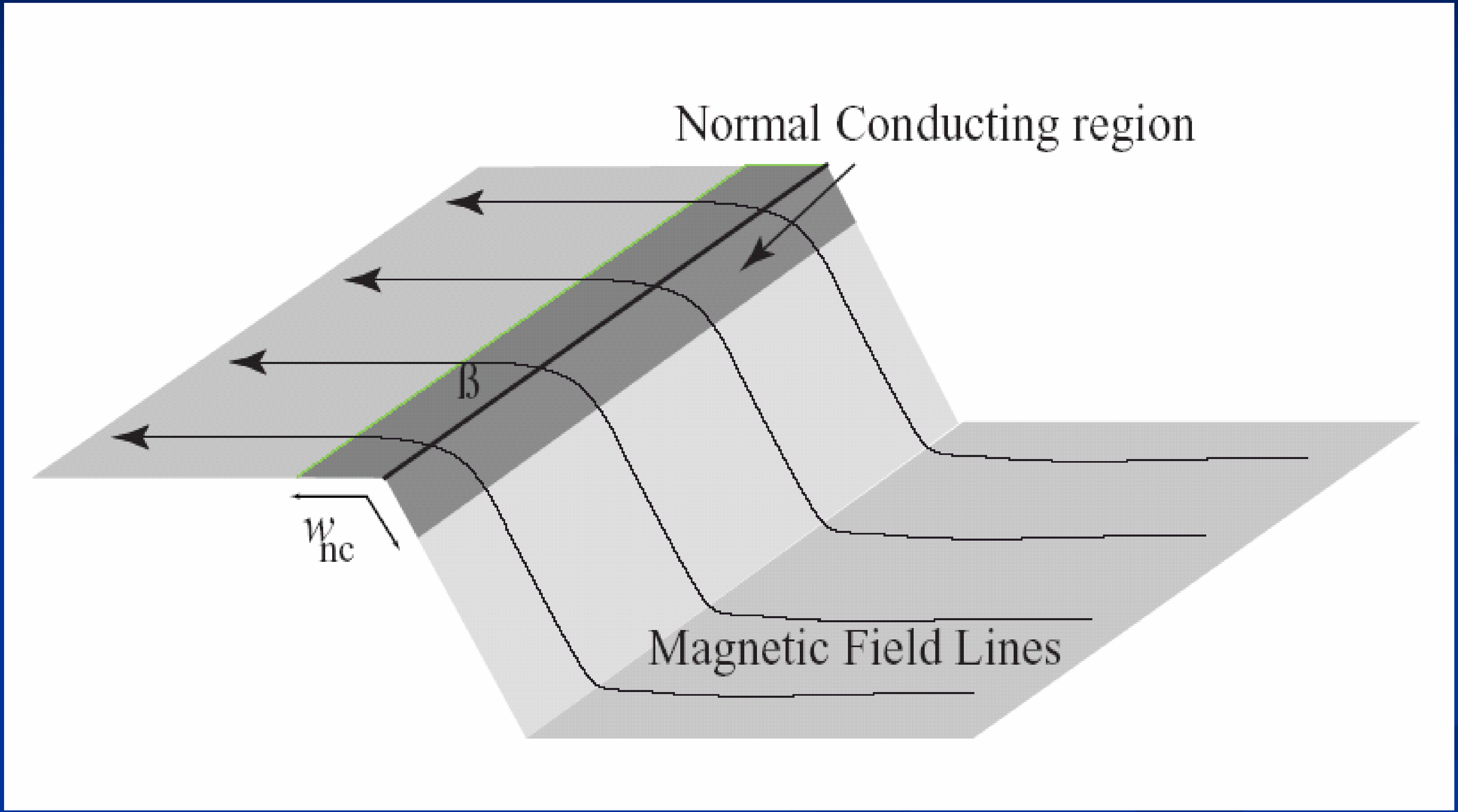
Step #1

- The number of grains and then grain edges at the inner surface of cavity can be estimated from "effective cavity area", *Aeff*, and the average grain size *l*.
- The effective cavity area at peak magnetic field produces the same heat dissipation as cavity of real shape with real field distribution.

Assumptions

- only one of two opposite grain edges can have field enhancement
- field enhancement only increases field component that is perpendicular to grain edge (and grain edges are randomly oriented to the field).
  So $\beta_{eff} = \sqrt{\left(\beta \sin(\alpha)\right)^2 + \cos^2(\alpha)}$
- quenched regions around grain edges are ~ 1mm wide

Quenched grain edge

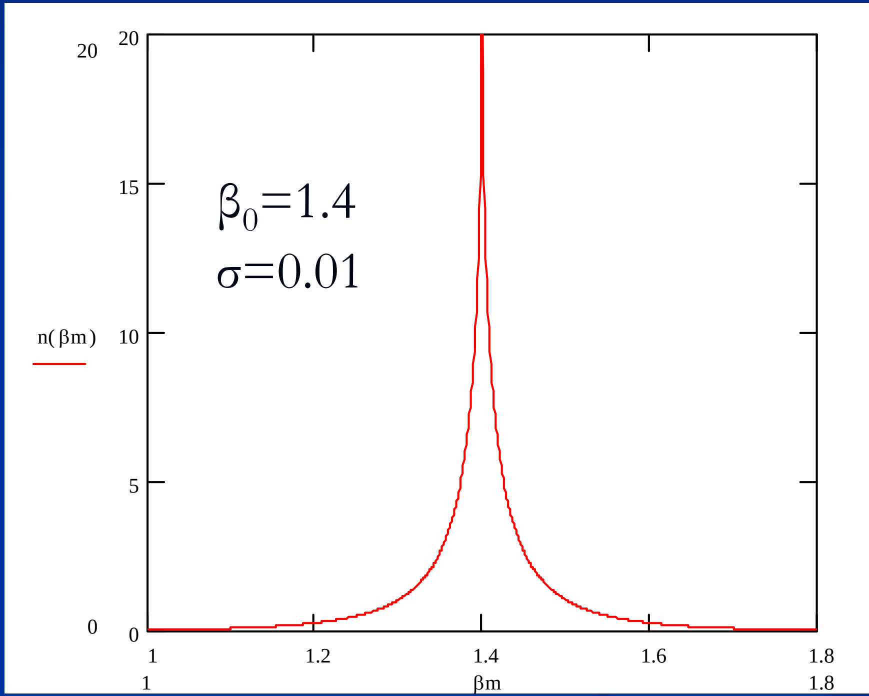


Step #2

Then we need Knobloch distribution of field enhancement factors:

$$n(\beta) = e^{-\sqrt{\frac{\beta-\beta_0}{\sigma}}} \Bigg/ \int_0^{\infty} e^{-\sqrt{\frac{\beta'-\beta_0}{\sigma}}} d\beta'$$

where $\beta = \dfrac{H_{crit}}{H_{peak}}$



Doesn't this distribution look strange?

Step #3

The power dissipation in the quenched grain edges, *Pq(H)*, is then given by the product of the number of quenched grain edges times the power dissipated in each of them:

$$P_q(H) = lw\frac{1}{2}R_n\beta_0^2 H^2 f\frac{2}{\pi}N\int_0^{\pi/2}\int_{\beta_{\min}}^{\infty} n(\beta)\,d\beta\,d\alpha\left(\frac{\beta_e H}{H_{crit}}\right)^{2.03}$$

where $\beta_{\min}(H,\alpha) = \sqrt{\left(\frac{H_{crit}}{H}\right)^2 - \cos^2\alpha \Big/ \sin^2\alpha}$

End the last step:

$$R_{tot}\left(H\right)=\frac{2\left(P_q\left(H\right)+P_0\left(H\right)\right)}{H^2}\quad\left(\Omega\right)$$

where P_0 is the uniform dissipation in "regular" areas obtained from the BCS resistance

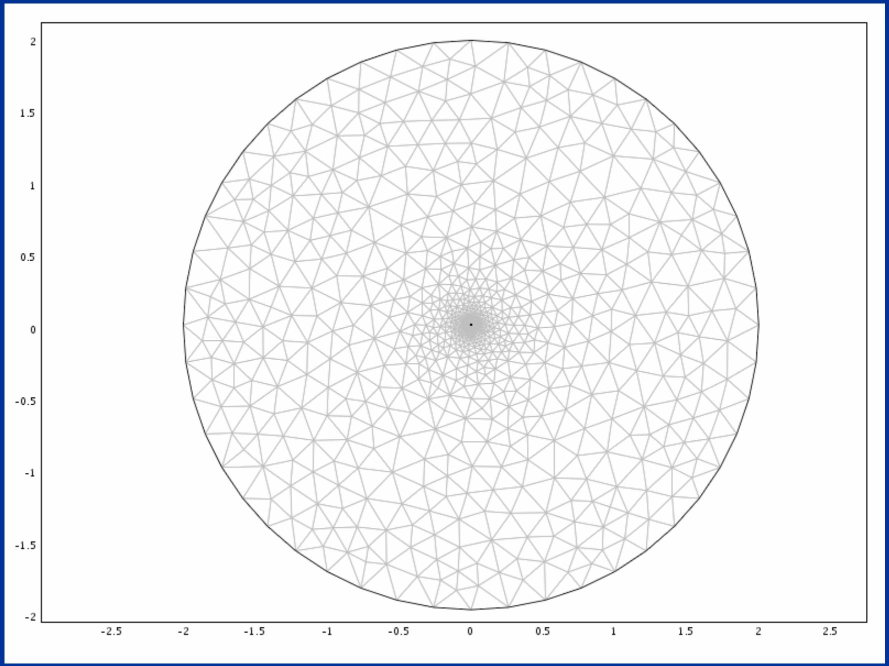
This model has enough parameters for us to fit results to experiment. So it can successfully "explain" Q-drop.

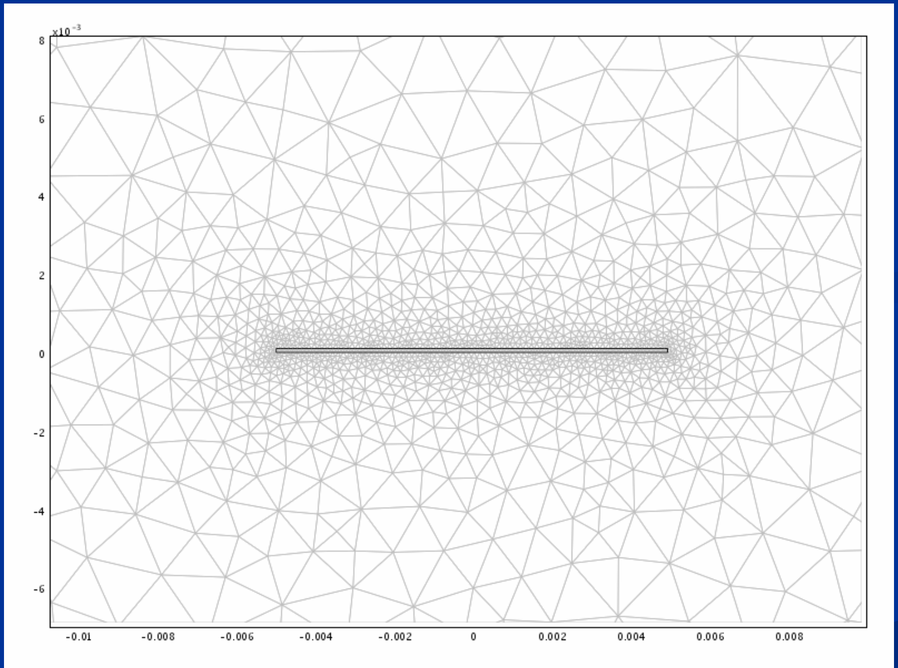
But…

- Knobloch model fails to explain curing of Q-drop by baking.
- Knobloch model predicts ~6000 hotspots (or quenched edges) when Q start to drop.

Thermal model

We developed a Comsol™ model to simulate the stationary temperature distribution in the Nb walls of the SRF cavity.





Description of the model

- The RF field causes heating of inner surface, with $P(H)=\frac{1}{2}RH^2 \quad \left(\frac{W}{m^2}\right)$ where *R* is the real part of the surface impedance.
- We assume that if magnetic field is lower than critical one for a given temperature (i.e. $H<Hcrit(T)$) then $R=R_{BCS}$ can be described by the usual fit from Padamsee,

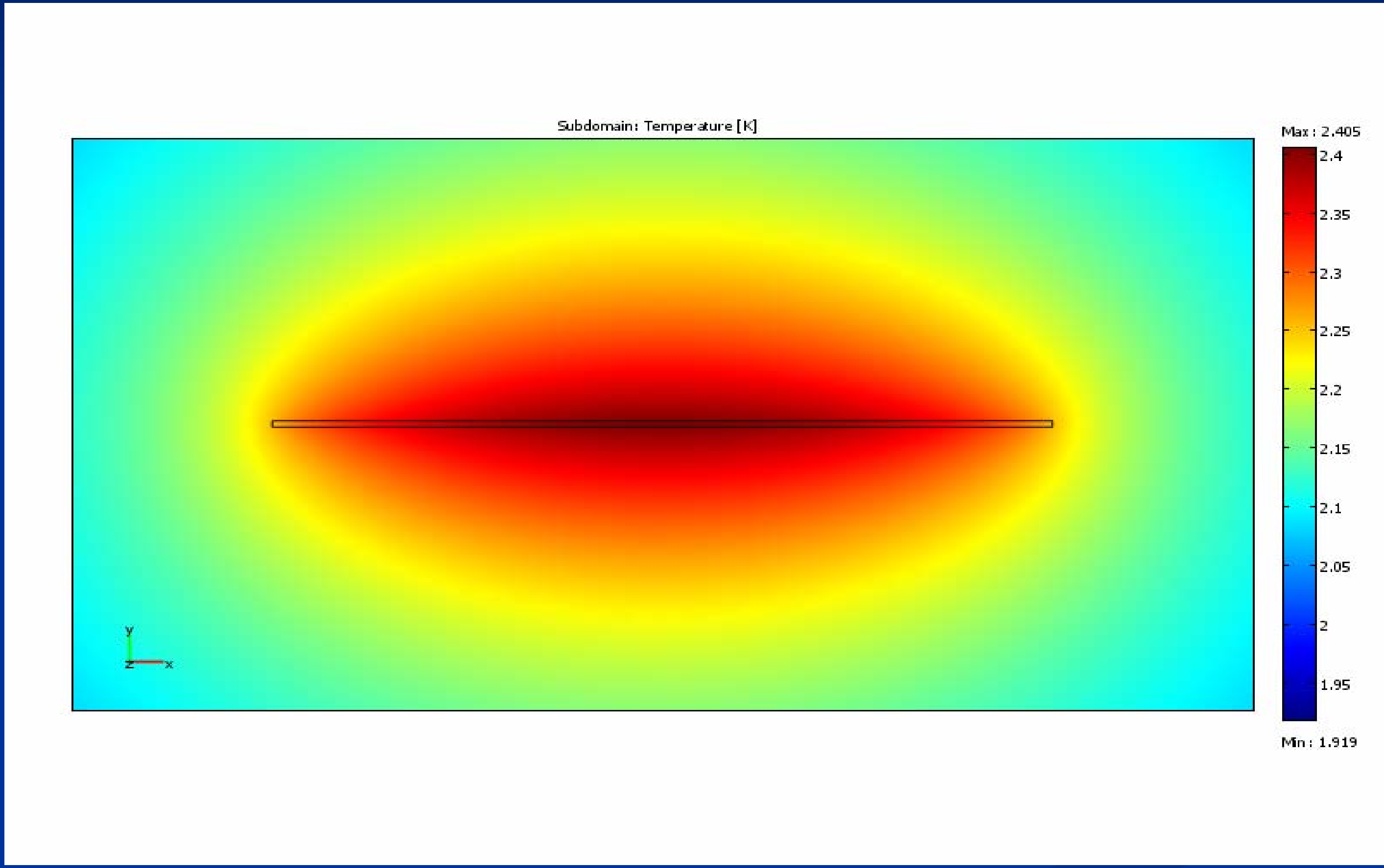
$$R_{s,BCS}(T,f)=1.7\cdot 2\cdot 10^{-4}\frac{1}{T}\left(\frac{f\,(GHz)}{1.5GHz}\right)^2 e^{\left(\frac{-17.67K}{T}\right)} \quad (\Omega)$$

  as function of temperature *T* and frequency *f*, else Nb is assumed to be normal conducting and $R=Rn=1.35$ mΩ.
- The external surface of the cavity is cooled by liquid helium. The Kapitza interface impedance for the calculation of the heat flux to the helium is described by the following expression from Mittag:

$$a_{Kap}(T)=200\cdot\left(T_b^{4.65}\right)\left[1+1.5\left(\frac{T-T_b}{T_b}\right)+\left(\frac{T-T_b}{T_b}\right)^2+0.25\left(\frac{T-T_b}{T_b}\right)^3\right] \quad \left(\frac{W}{Km^2}\right)$$

  where T_0 is the temperature of the helium bath.
- The thermal conductivity of the Nb is considered to be constant, $k=20$ W/m/K.

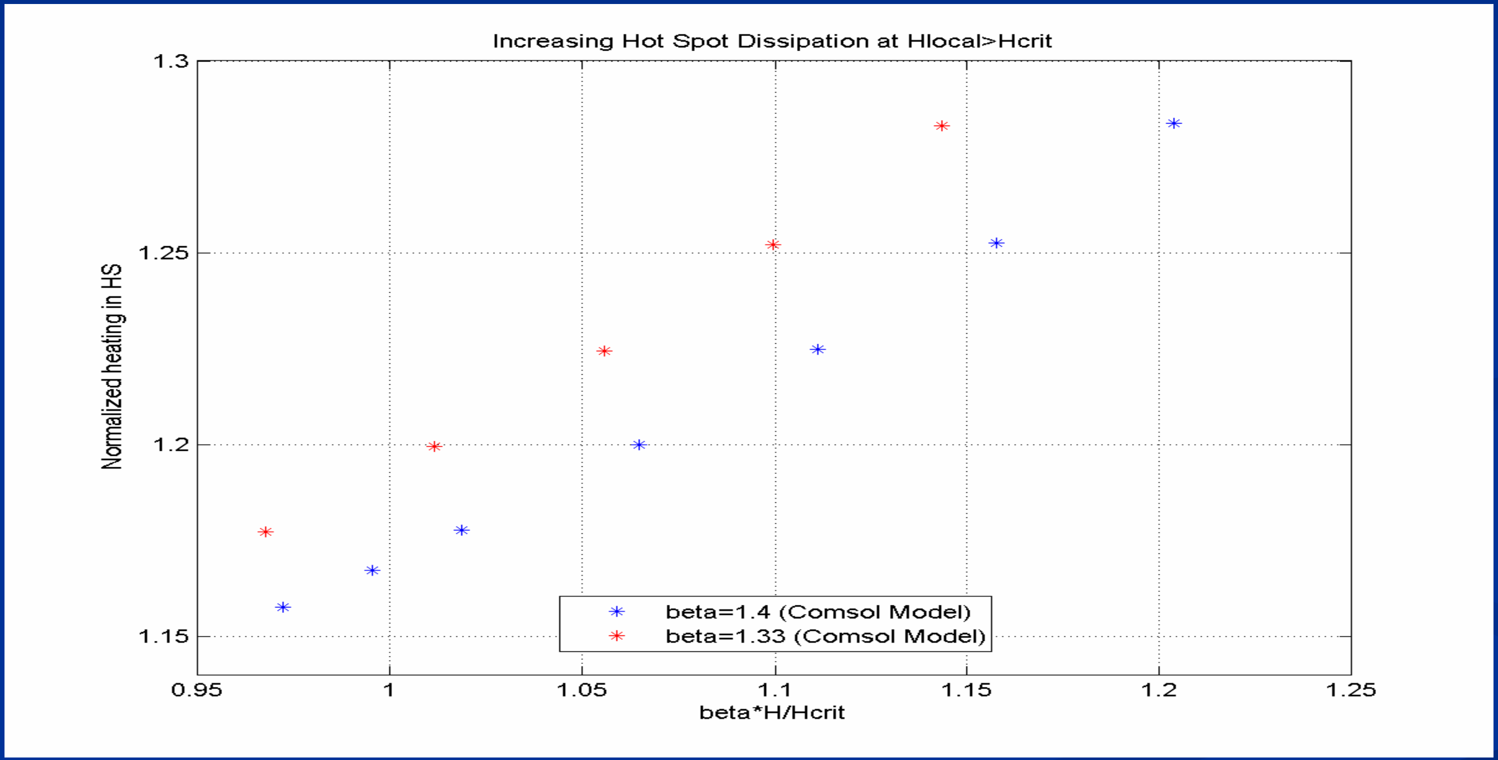
Result of a finite element thermal model of a 100 mm x 1.5 mm normal region on a 3 mm thick Nb plate.



It is thermally stable with a peak temperature of 2.4 K (T_0=1.9 K) !

Adjacent region effect

According to Knobloch the additional losses due to this effect is not more than 20% of the loss generated in the normal core of the hot spot (or the quenched grain edge).



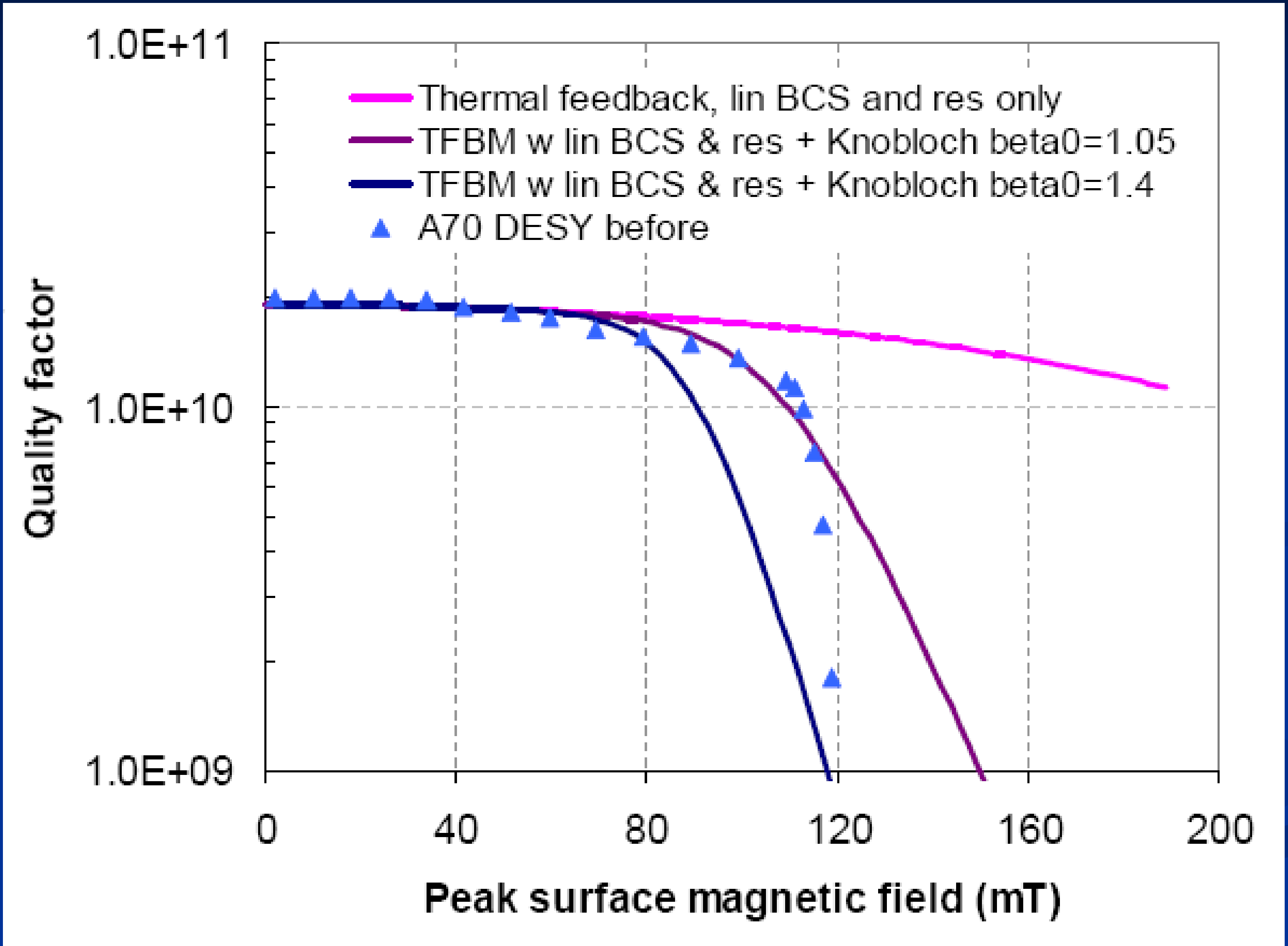
Results of thermal simulation in Comsol

The Equivalent Ellipsis Approach

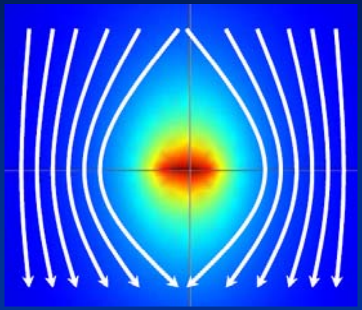
Profilometric surface topology measurements can be mathematically transformed into an “equivalent” 3D ellipsoid and the mean FE factor calculated analytically!

surf. treat.	BCP	EP	BCP	EP
heat treat.	annealed	annealed	not ann.	not ann.
σRMS (um)	6.5	1.2	2.6	0.95
Dev. Surf. (%)	100.1	100.05	100.64	100.1
a (um)	4566	3693	3706	3907
b (um)	2954	3653	3640	3452
c (um)	98	63.2	313	78.5
β	1.0283	1.0135	1.0651	1.0182

Equivalent ellipsis approach shows much lower average FE-factors (~1.05) than those suggested by Jens (~1.6)!


1.0E+11
1.0E+10
1.0E+09
Quality factor
Thermal feedback, lin BCS and res only
TFBM w lin BCS & res + Knobloch beta0=1.05
TFBM w lin BCS & res + Knobloch beta0=1.4
A70 DESY before
0
40
80
120
160
200
Peak surface magnetic field (mT)

Improving of Knobloch model



- May be current bypasses hot region?
- We propose the following improvements to the Kobloch model:
  - shift the FE factor distribution to a smaller β_0=1.05 or even replace FE factor distribution function with one found from an experiment.
  - reduce the dissipation in the hot spot taking into account the results of the electromagnetic simulations.

And then…

Those two effects together would resulte in a reduction of the magnitude of the Q-drop predicted by the model. The reduced strength of the effect would indicate that the FE effect is not responsible for the Q-drop and thus would resolve the issue of why baking would modify the FE factor distribution.

What was not done? or Future work to do…

- Electro-magnetic simulation in order to verify current diffusion idea.
- Find real FE distribution function from experiment
- Understand that Knobloch model can't describe Q-slope phenomenon well. Isolated hot spots do exist, but significant is something else! For example niobium hydride. So we need more physical and chemical studies of niobium surface!

Questions?

Additional slides (from earlier drafts)

Average accelerating gradient

The particle beam traverses the cavity experiencing an accelerating force along the axis of the cavity due to the electric field. In addition, since the particles take a finite time to cross the cavity, the accelerating field is the time average of the electric field along the particles flight. So the average gradient is:

$$< E_{acc} > = \frac{2}{T_{RF}} \int_0^{\frac{1}{2}T_{RF}} E_{acc}(z,t)\,dt$$

RF cavity operation

- Since the RF fields alternate in time, the particle beam must, of course, be in the proper phase with respect to the fields in order that the force be accelerating rather than decelerating.