
# SURFACE RESISTANCE STUDY ON LOW FREQUENCY (LOW BETA) CAVITIES

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# OUTLINE

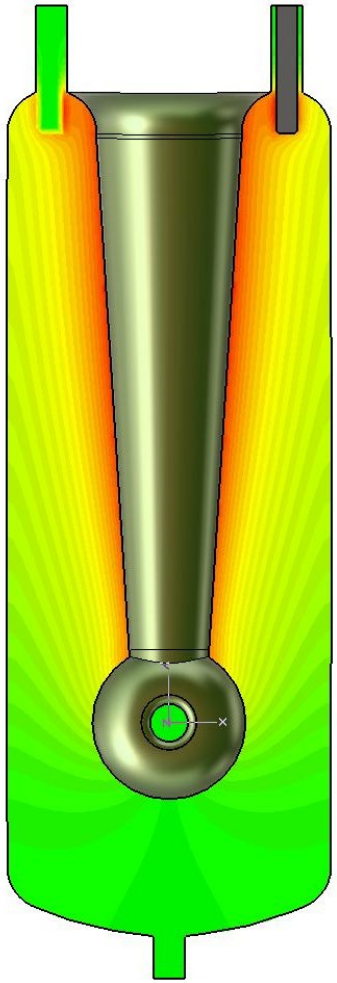
⇒ **Presentation of cavities studied**
- Spiral2 Quarter-Wave Resonator (QWR)
- ESS Double-Spoke Resonator (DSR)

⇒ **Surface resistance model**

⇒ **Test results and model comparison**

⇒ **Flux trapping study**
- Spiral2 Quarter-Wave Resonator (QWR)
- ESS Double-Spoke Resonator (DSR)

# LOW FREQUENCY CAVITIES STUDIED

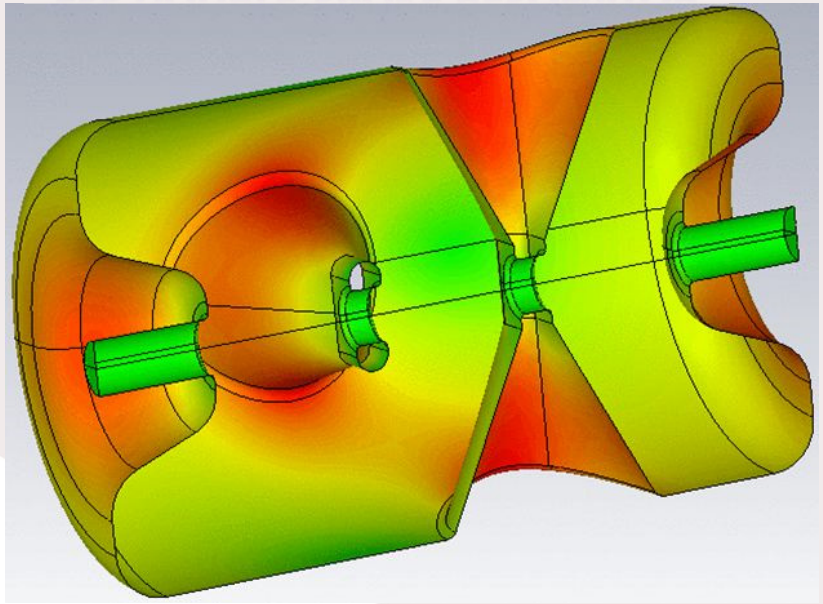


## SPIRAL2 QUARTER-WAVE RESONATOR

- ✓ Bulk Niobium
- ✓ 88 MHz
- ✓ 4.2K
- ✓ 6.5 MV/m
- ✓ Bpk/Eacc = 10.5 mT/MV/m

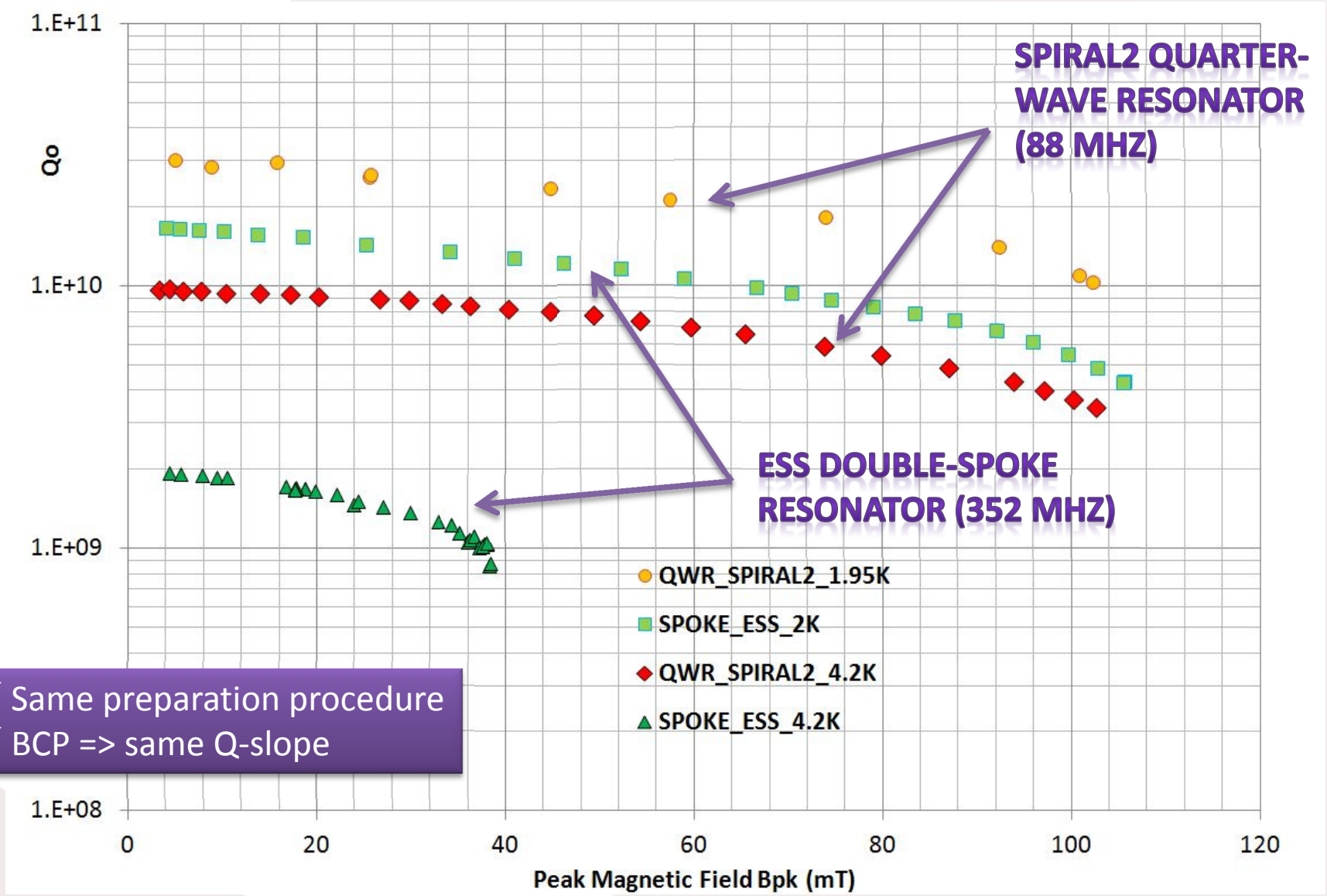
| $R_{BCS}$ (nΩ) | 4.2K | 2K | 1.5K |
|---|---|---|---|
| 1300 MHz | 600 | 15 | 1.2 |
| 700 MHz | 174 | 4.3 | 0.35 |
| 352 MHz | 44 | 1 | 9E-2 |
| 88 MHz | 3 | 7E-2 | 6E-3 |

## ESS DOUBLE-SPOKE RESONATOR



- ✓ Bulk Niobium
- ✓ 352 MHz
- ✓ 2K
- ✓ 9 MV/m
- ✓ Bpk/Eacc = 6.9 mT/MV/m

# LOW FREQUENCY CAVITY STUDIED




- ✓ Same preparation procedure
- ✓ BCP => same Q-slope

# PRESENTATION OF RS MODEL

- **Standard expression :** $Q_0 = \frac{G}{R_s}$

$$G = 2 \cdot \pi \cdot F \cdot \frac{\iiint_V \frac{1}{2 \cdot \mu_0} \cdot B^2 \cdot dV}{\iint_S \frac{1}{2} \cdot \left( \frac{B}{\mu_0} \right)^2 \cdot dS}$$

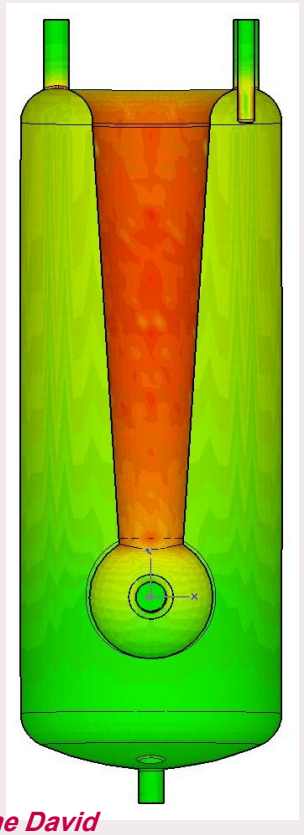
- **True if Rs does not depend on B !!**
- **Not valid once we implement Rs(B) to model the Q-slope**

⇒ Need to discretize

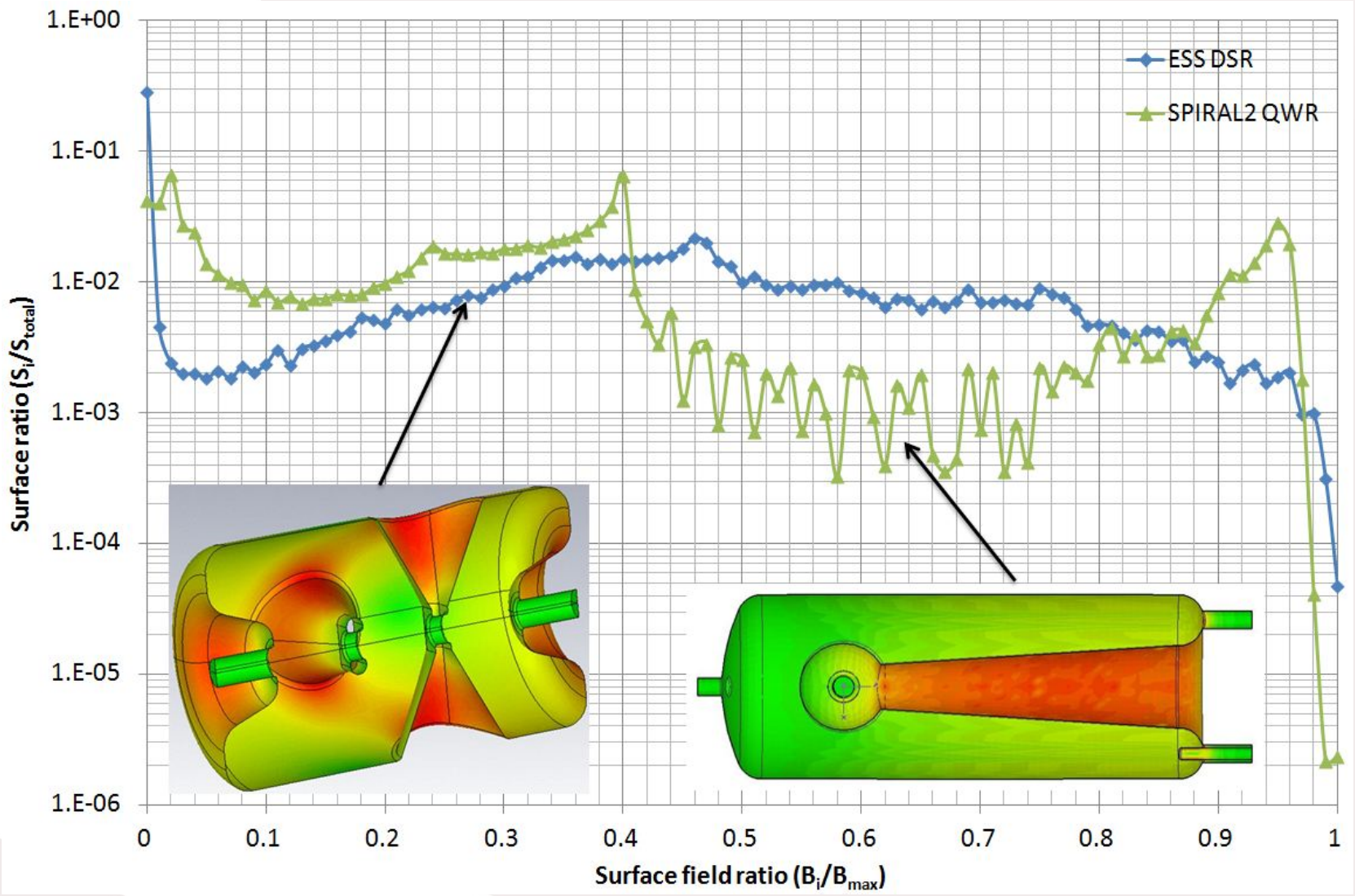
$$\iint_S Rs(B) \cdot B^2 \approx \sum_i Rs_i(B_i) \cdot B_i^2 \cdot S_i$$

⇒ Evaluate $B_i$ and $S_i$ all over the surface with CST Microwave Studio

$S_i$ = total surface area where $B_{i-1} < B < B_i$



# PRESENTATION OF RS MODEL



# A GOOD MODEL TO FIT SPIRAL2 QWR Q-CURVES

- Qo can be expressed :

$$Q_0 = G \cdot \frac{\sum_i B_i^2 \cdot X_i}{\sum_i Rs_i(B_i) \cdot B_i^2 \cdot X_i}$$

With $$R_{Si} = R_{BCS}(T, Bi) + R_{res}(T, Bi)$$

- Second order phase transition :

$$\Delta(T, B) = \Delta(T, B = 0) \cdot \left(1 - \left(\frac{B}{Bc(T)}\right)^2\right)$$

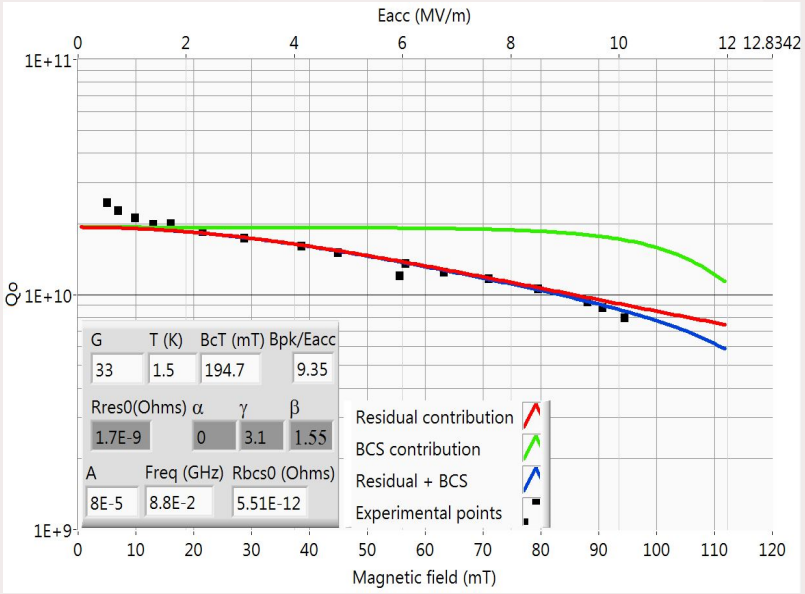
$$R_{BCS} = \frac{A(\lambda, \xi, l, \ldots) \cdot \omega^2}{T} \cdot \exp\left(\frac{-\Delta(T = 0, B = 0)}{k_B \cdot T} \cdot \left(1 - \left(\beta \frac{B}{Bc(T)}\right)^2\right)\right)$$

$$R_{res}(T, B) = R_{res\,0}\left(1 + \alpha \frac{B}{Bc(T)} + \left(\gamma \cdot \frac{B}{Bc(T)}\right)^2\right)$$

- 5 fitting parameters A, β, $R_{res0}$, γ and α.
- α and γ contribute to residual resistance because dominating at low temperature (T< 2K).

# ALPHA AND GAMMA PARAMETERS

$$R_{res}(T,B) = R_{res0} \cdot \left(1 + \alpha \cdot \frac{B}{Bc(T)} + \left(\gamma \cdot \frac{B}{Bc(T)}\right)^2\right)$$




⇒ α and γ are attributed to residual resistance because their contribution is dominating at low temperature (< 2K). $R_{BCS}$ is negligeable.

⇒ α : linear dependence : zero for good cavities, not zero when Q-disease or bad etching

- something to do with hydrogen

⇒ γ : quadratic dependence : never zero, dominating below 2K.

- something to do with material pollution ? Or temperature instabilities ?

# BETA PARAMETER

$$R_{BCS} \propto \exp\left(\left(1-\left(\beta \cdot \frac{B}{Bc(T)}\right)^2\right)\right)$$

Over 3 Spiral2 QWR, none have the same β factor.

⇒ β could be either : a magnetic field enhancement (geometrical or roughness?)

OR

a degradation of Bc

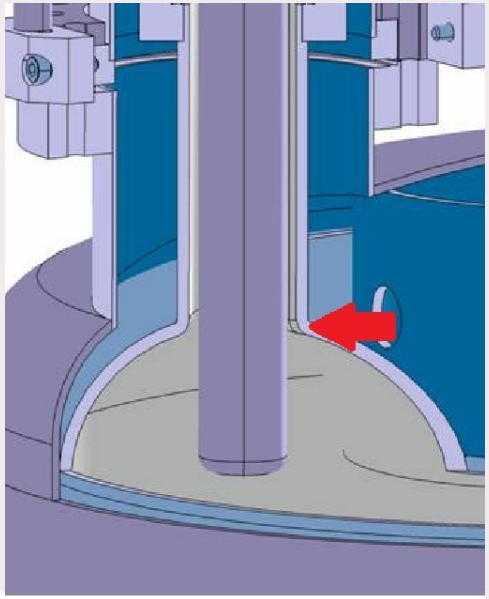
⇒ Quench detection campaign showed quench is occuring around plunger port (not maximum surface magnetic field if radius of curvature is 5 mm !!)

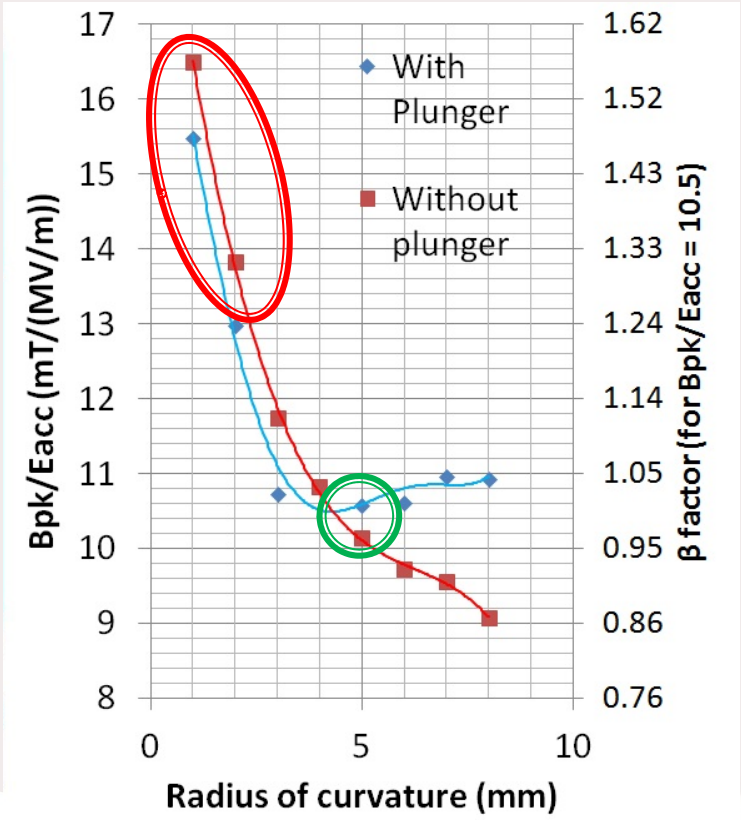
⇒ Difficult welding

⇒ Radius of curvature is lower than expected and not controlled

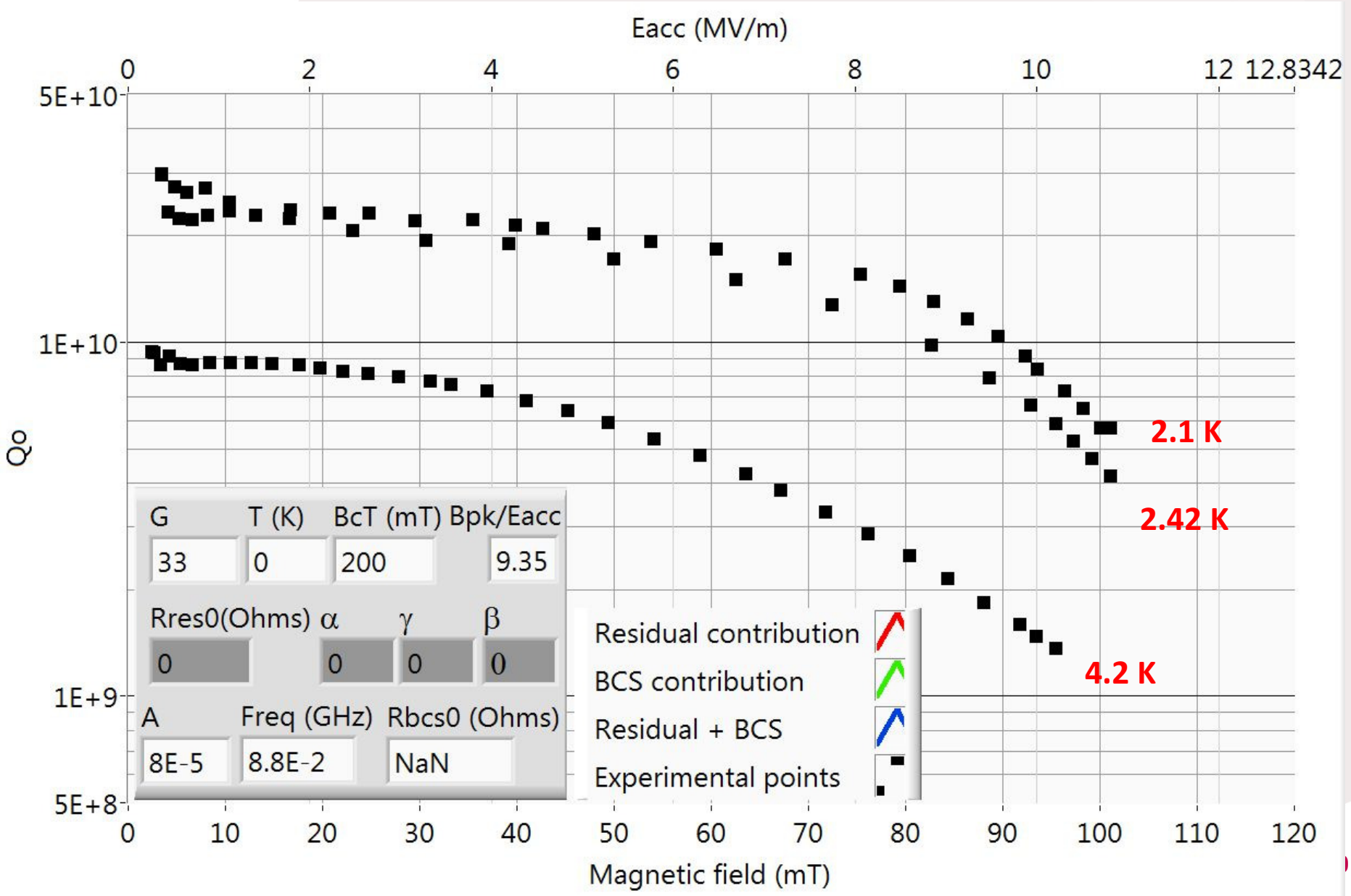
⇒ Bpk/Eacc is not 10.5 mT/MV/m but between 13 and 17

⇒ Explains why none of cavities could go above 160 mT





# TEST RESULTS (MB09-BAKED)



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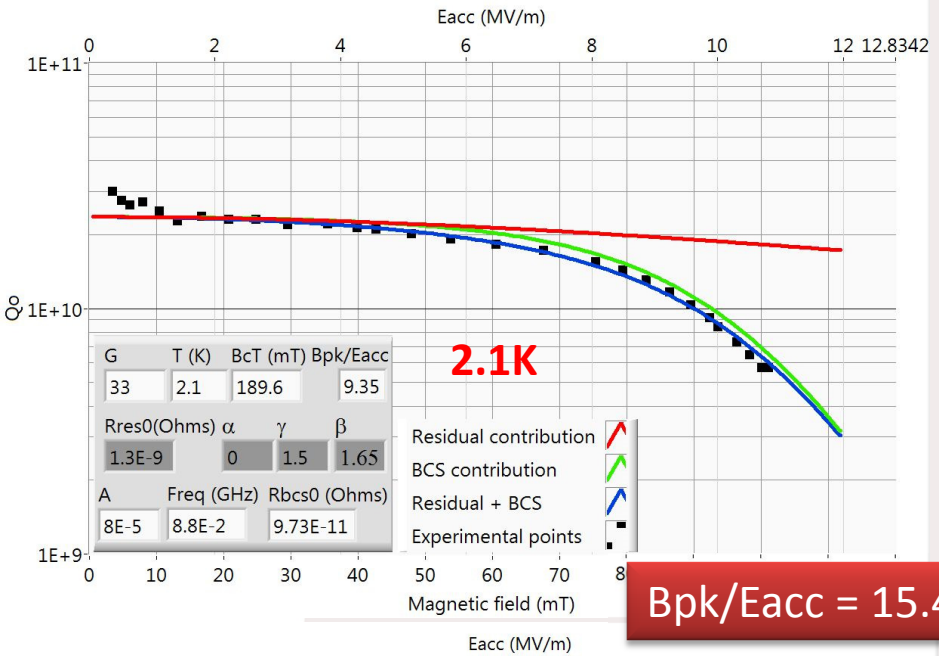
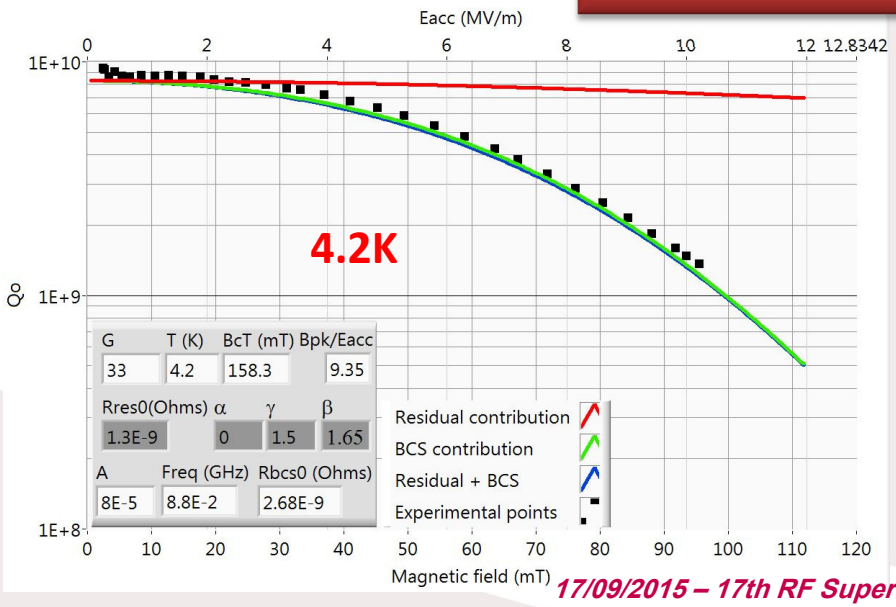




Bpk/Eacc = 15.4 mT/MV/m




**Red curve : Residual contribution**

**Green curve : BCS contribution**

**Blue curve : Residual + BCS contributions**

**Black dots : Experimental points**

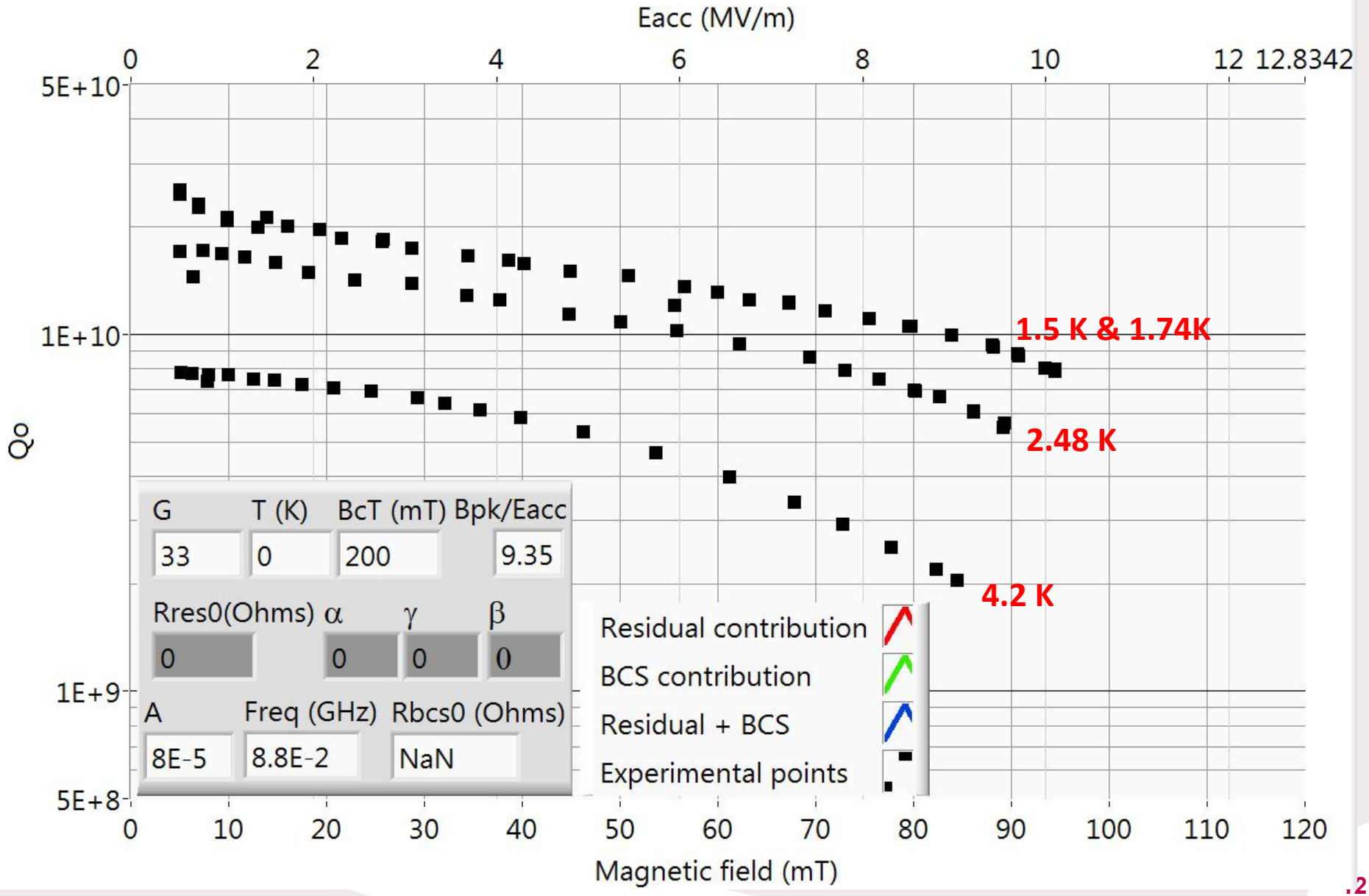
**None of fitting parameters changed**

**Just temperature is changing :**

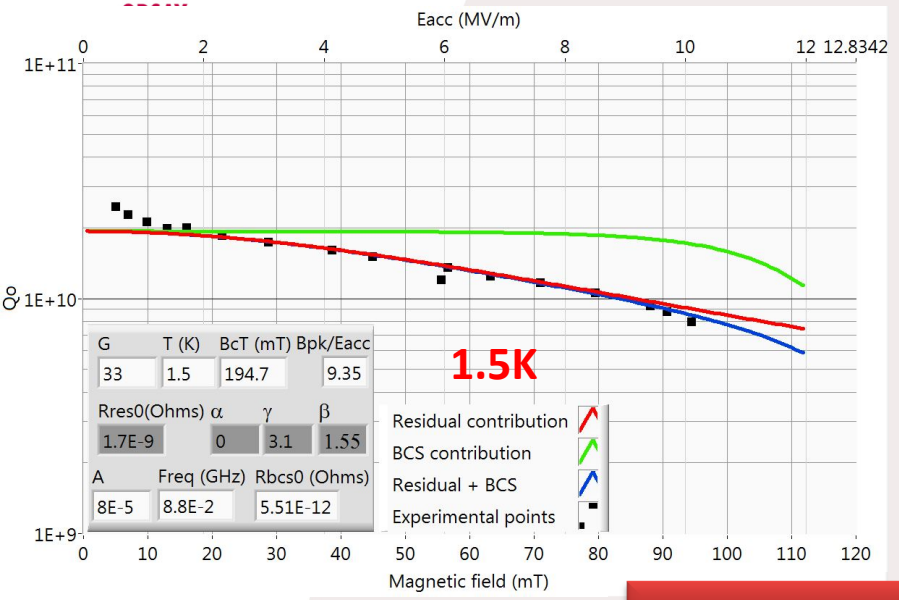
**=> Rbcs(T)**

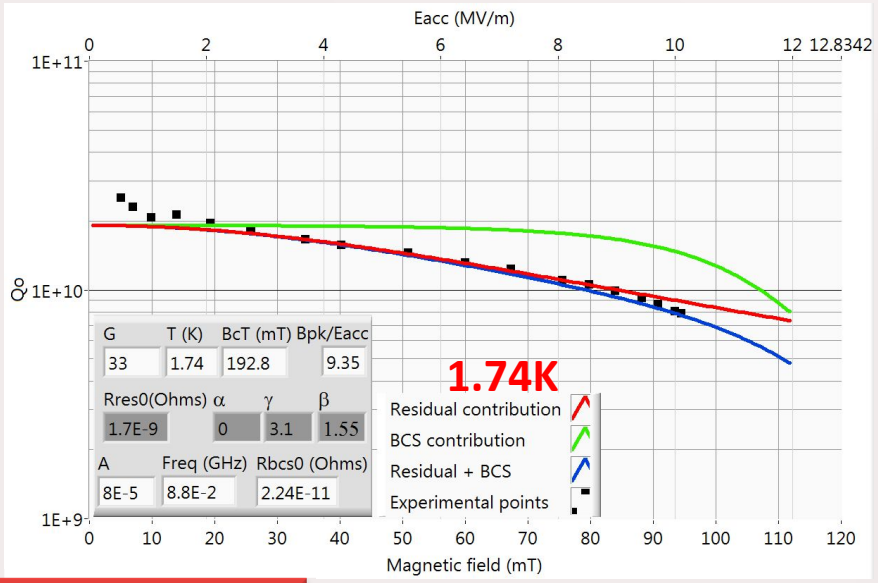
**=> Bc(T)**

# TEST RESULTS (MB05)

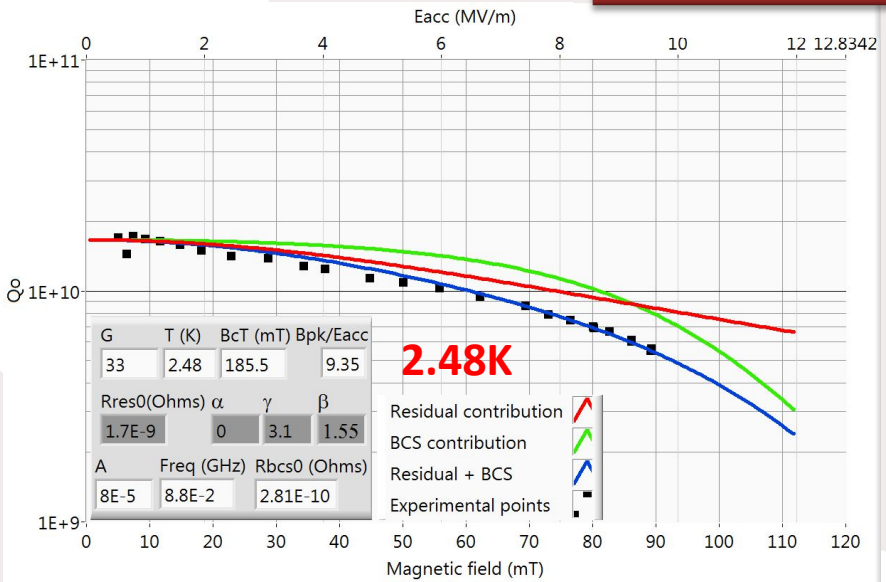


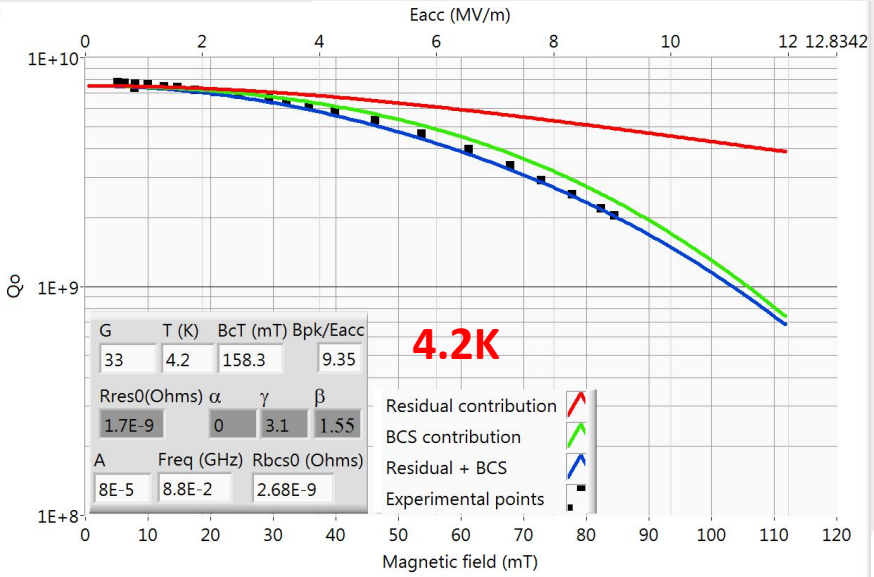
# TEST RESULTS (MB05 - BAKED)



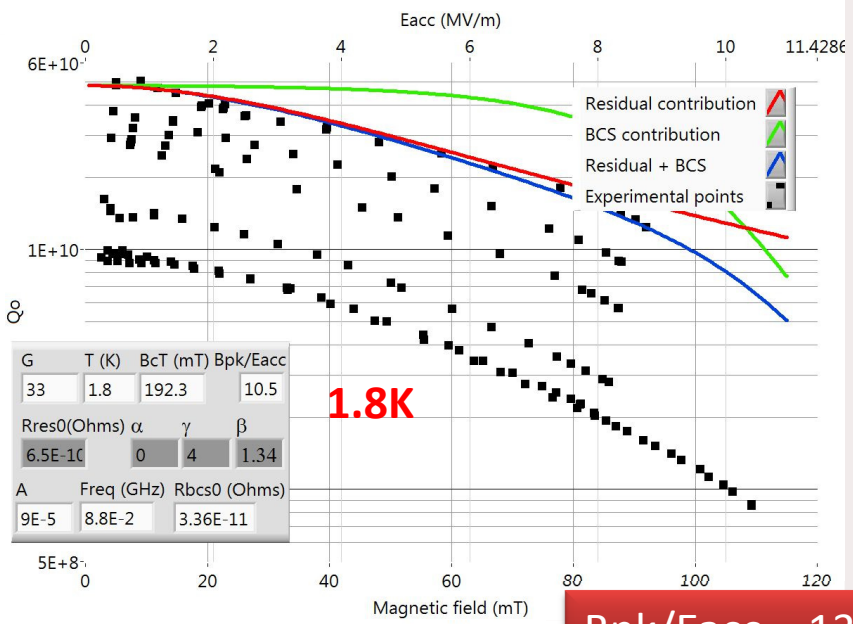



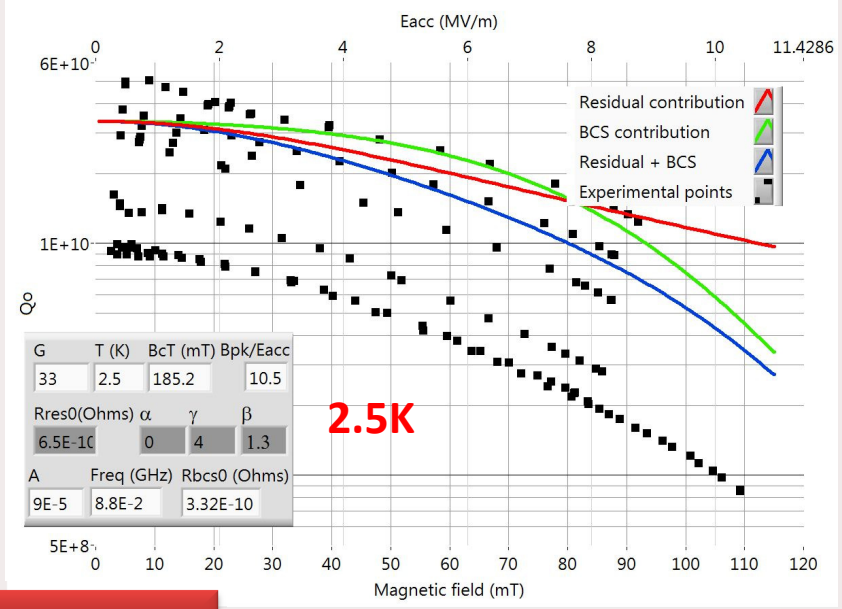

Bpk/Eacc = 14.5 mT/MV/m



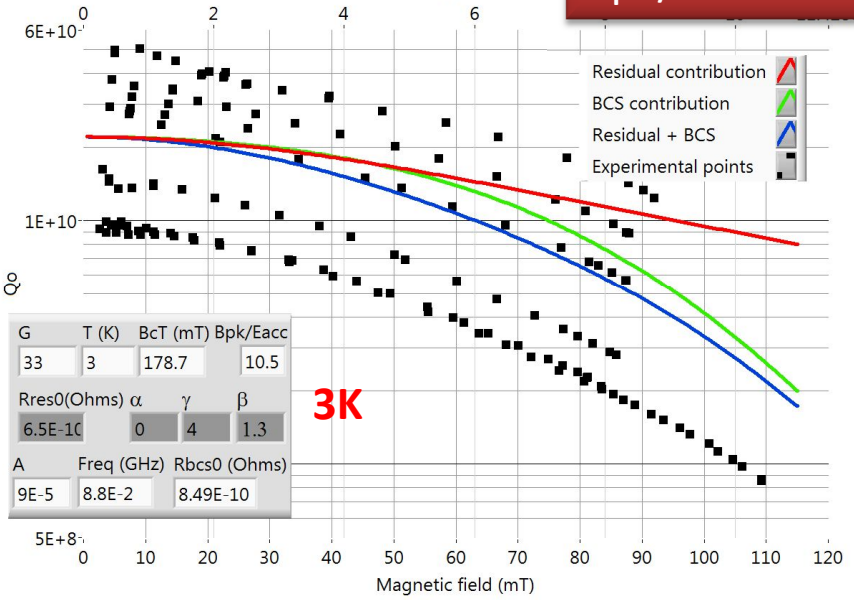



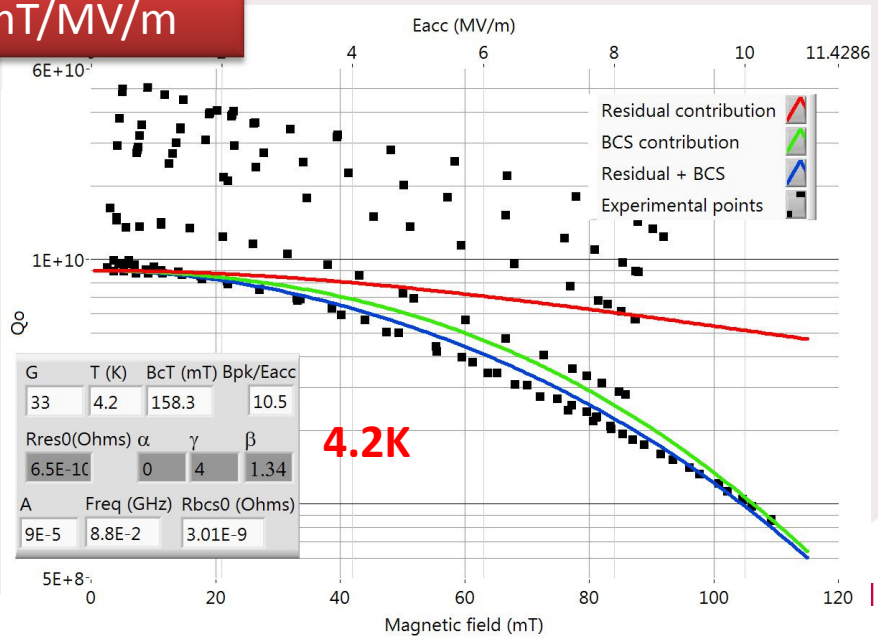
# TEST RESULTS (TOKYO - UNBAKED)



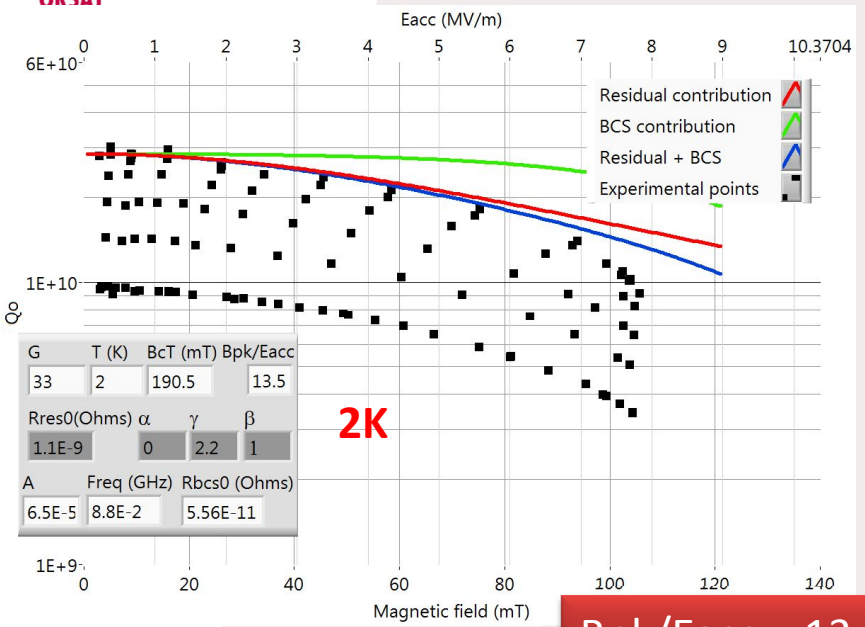



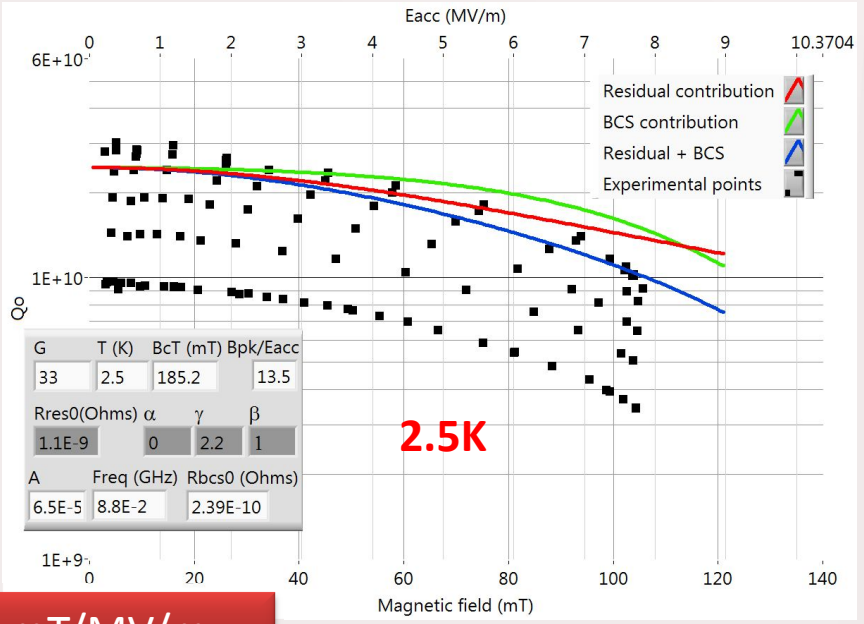

Bpk/Eacc = 13.5 mT/MV/m



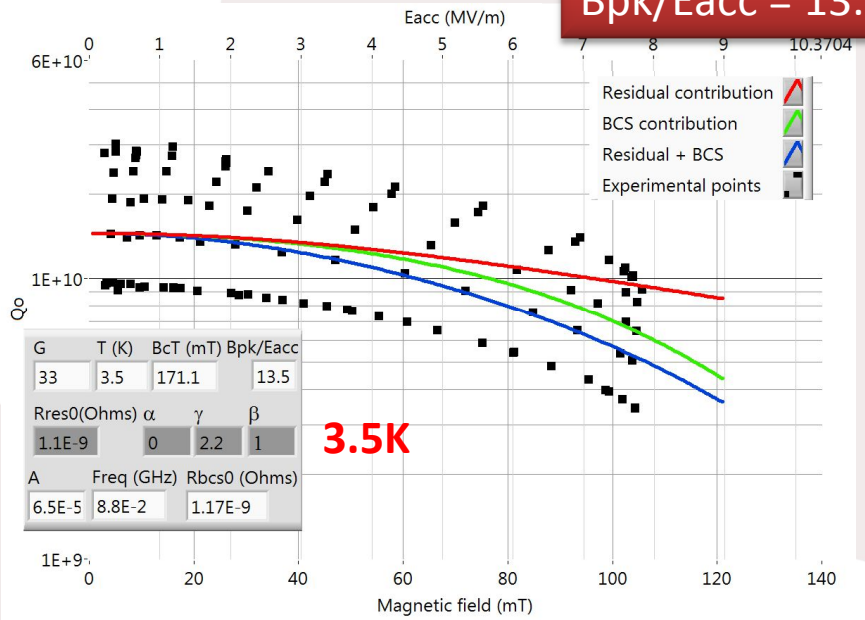



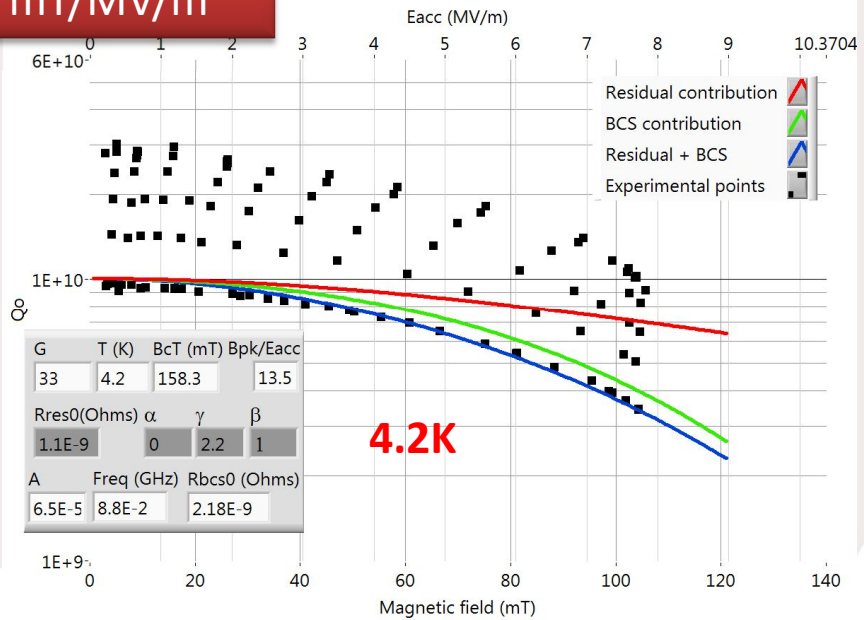
# TEST RESULTS (TOKYO - BAKED)




Bpk/Eacc = 13.5 mT/MV/m



# TEST RESULTS (TOKYO - COMPARISON)

| | Unbaked cavity | Baked cavity | |
|---|---|---|---|
| $R_{BCS}$ at B=0 at 4.2K | 3.01 nΩ | 2.2 nΩ | - 27 % |
| $R_{BCS}$ at B=0 below 2K | < 0.1 nΩ | < 0.1 nΩ | / |
| A | 9E-5 | 6.5E-5 | -27 % |
| β | 1.34 | 1.34 | = |
| Rres at B=0 | 0.65 nΩ | 1.1 nΩ | +70% |
| α | 0 | 0 | |
| γ | 4 | 2.8 | |
| Rres*$\gamma^2$ (nΩ) | 10.4 | 8.6 | -17% |

**Baking a cavity leads to :**

⇒ **A decrease of Rbcs (decrease of electron mean free path)**

⇒ **An increase of Rres (diffusion of impurities)**

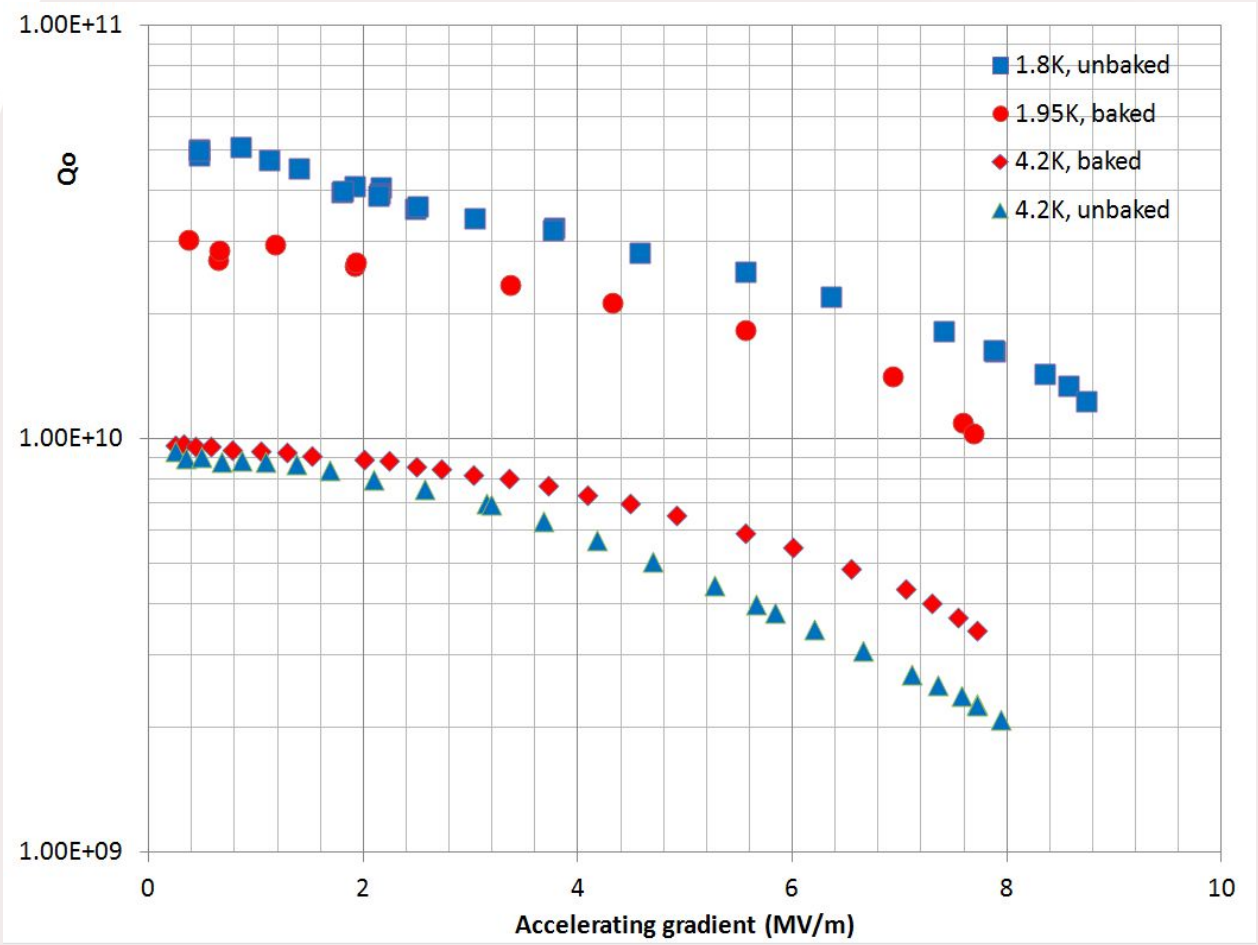
⇒ **β is not changing**

⇒ **Rres*$\gamma^2$ is slightly changing**

⇒ **α is still zero**

$$R_{res}(T,B) = R_{res0} \cdot \left( 1 + \alpha \cdot \frac{B}{Bc(T)} + \left( \gamma \cdot \frac{B}{Bc(T)} \right)^2 \right)$$

# TEST RESULTS (TOKYO - COMPARISON)

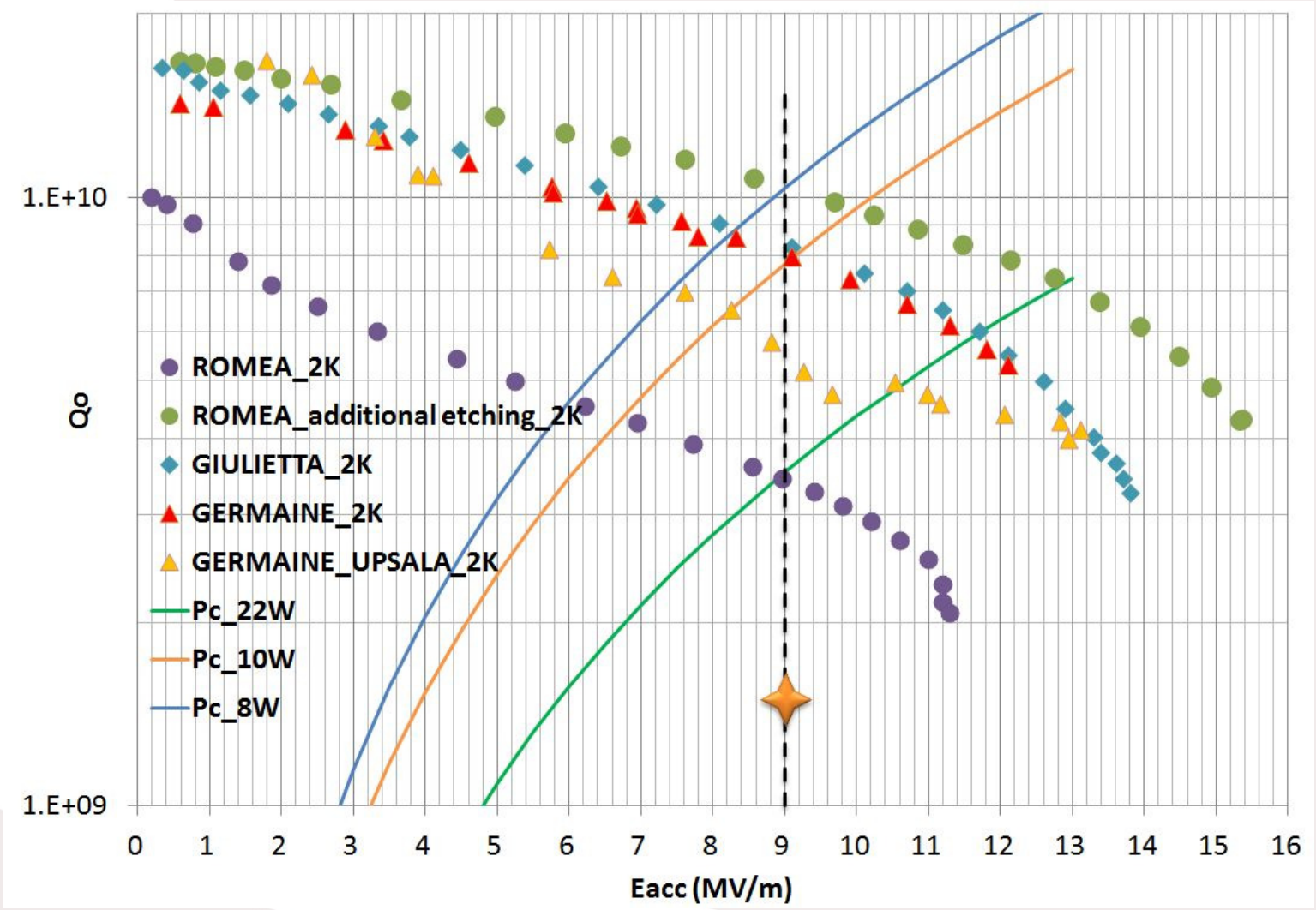



**At low frequency, 120°C baking is justified if operated at 4.2K.**

**At 2K, baking is not improving Qo but could be required to decrease multipacting strength**

# WHAT ABOUT SPOKE RESONATOR (ESS)

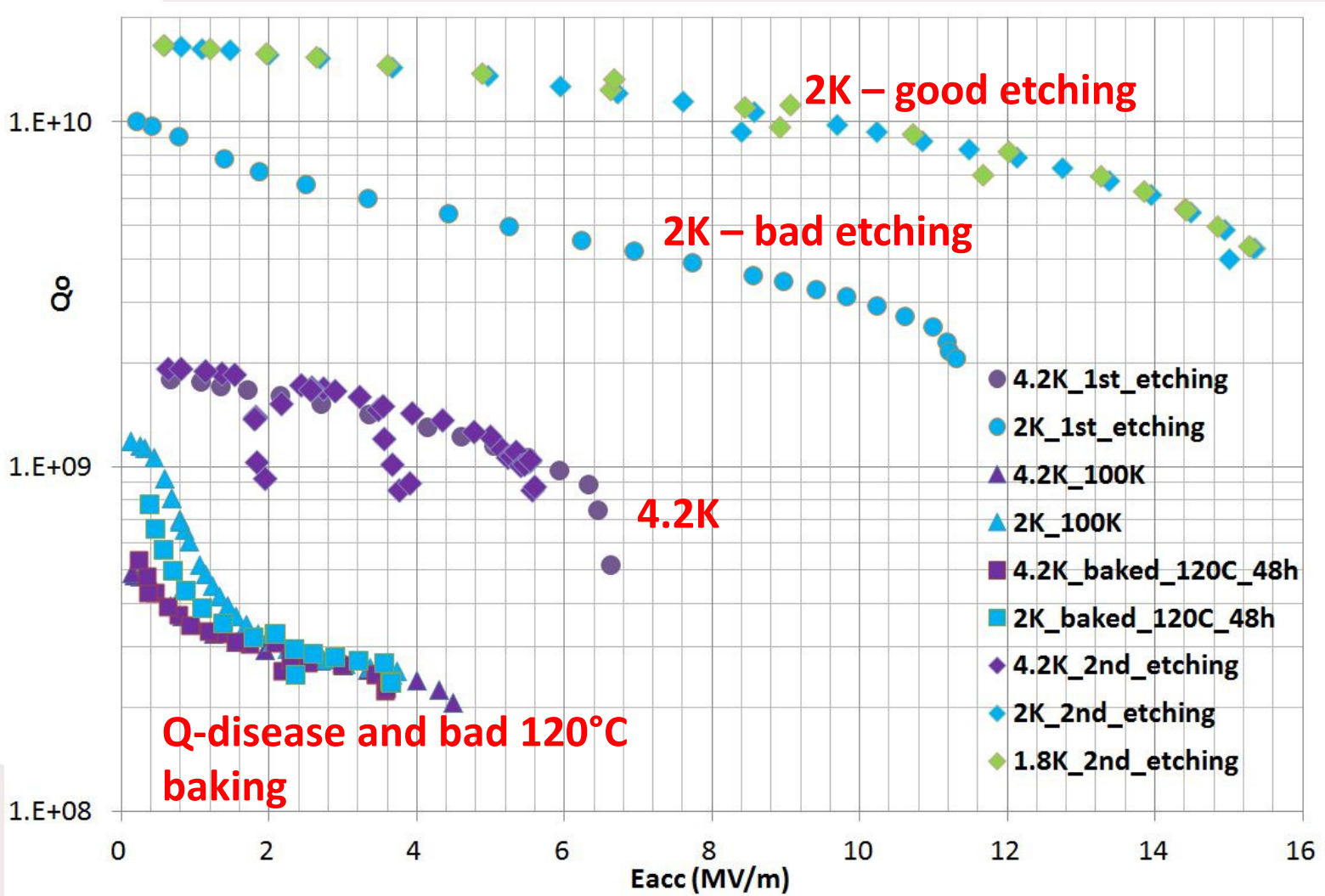
⇒ 3 prototypes (ROMEA, GIULIETTA, GERMAINE)



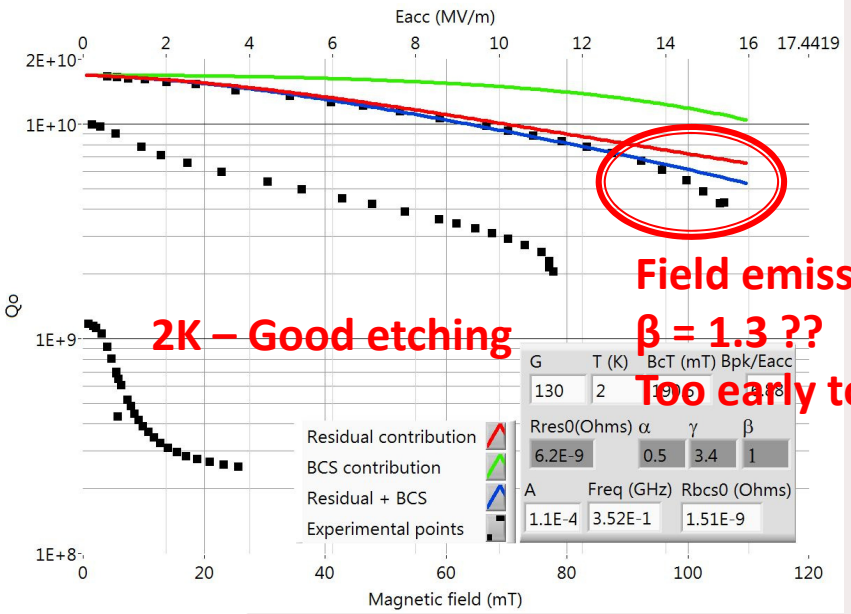
# WHAT ABOUT SPOKE RESONATOR (ESS)

⇒ The model is fitting nicely Qo curves for Spiral2 QWR (88 MHz)

⇒ What about at a higher frequency (352 MHz) ?

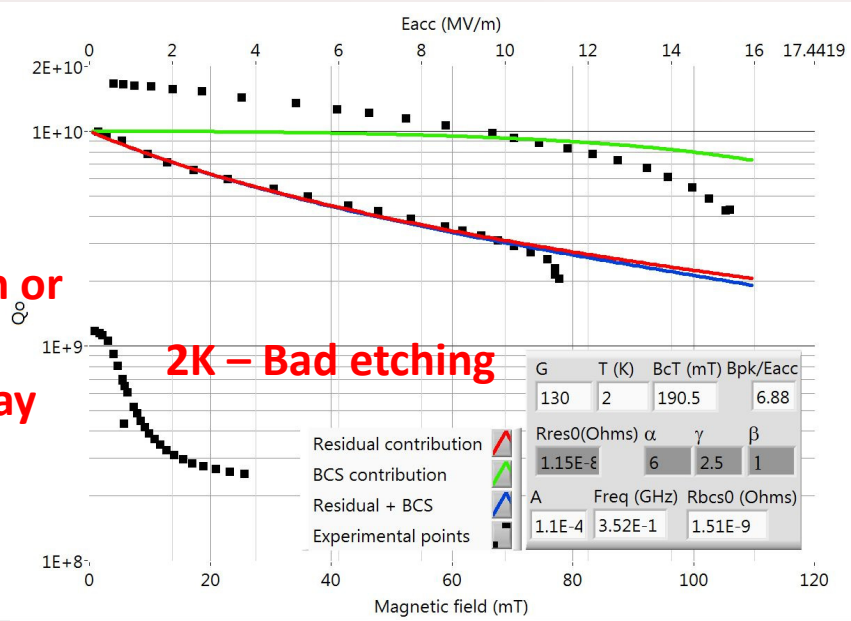


# WHAT ABOUT SPOKE RESONATOR

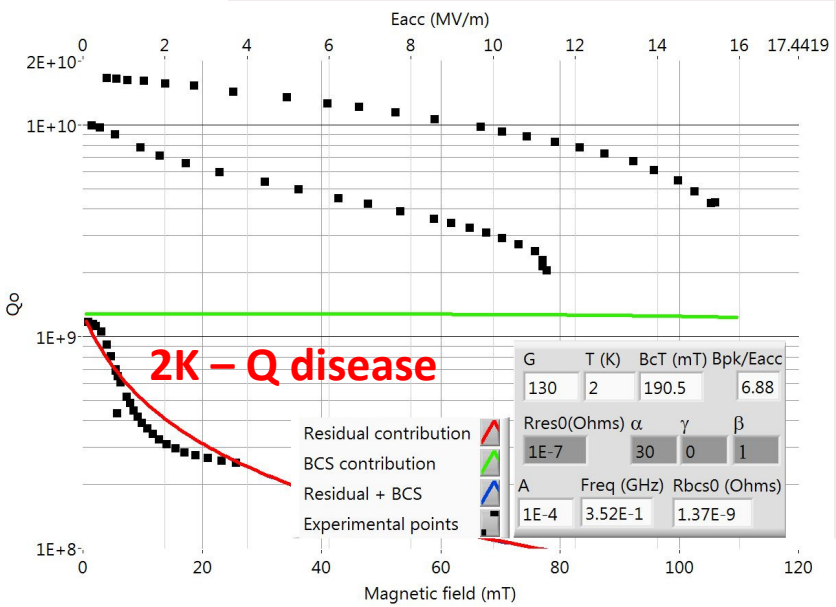



2K – Good etching

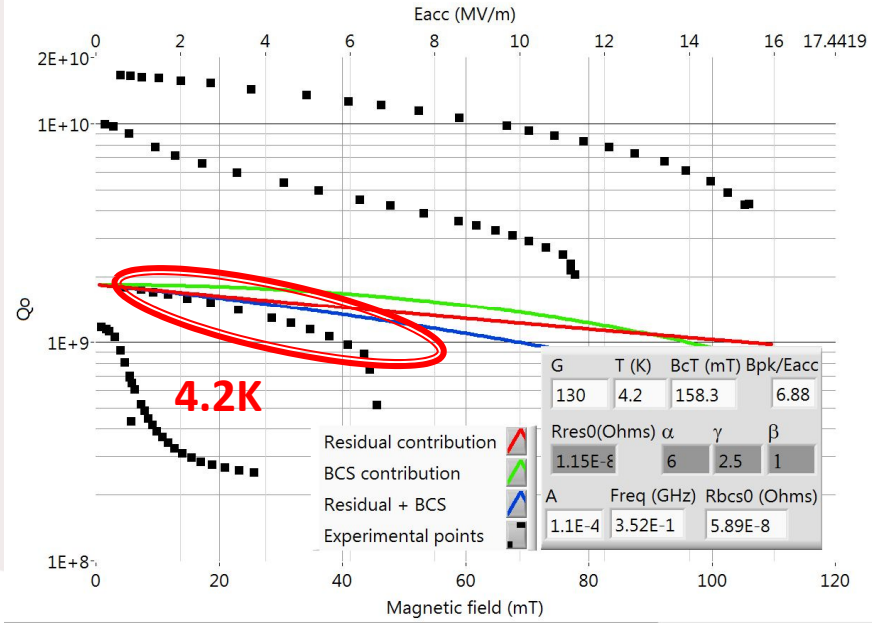
Field emission or
β = 1.3 ??
Too early to say




2K – Bad etching




2K – Q disease




4.2K

# WHAT ABOUT SPOKE RESONATOR

| | Bad etching | Good etching | Q-disease |
|---|---|---|---|
| **Comments** | 200 µm with T<30°C | Additional 60 µm with T<18°C | 6h at 90K |
| **$R_{BCS}$ at B=0 below 2K** | 1.5 nΩ | 1.5 nΩ | 1.5 nΩ |
| **Rres at B=0** | 11.5 nΩ | 6.2 nΩ | 100 nΩ |
| **$\alpha$** | 6 | 0.5 | >25 |
| **$\gamma$** | 2.5 | 3.4 | ? |
| **Rres*$\alpha$ (nΩ)** | 69 | 3.1 | >2500 |
| **Rres*$\gamma^2$ (nΩ)** | 71.9 | 71.7 | ? |

A better etching leads to :

$\Rightarrow$ A decrease of Rres

$\Rightarrow$ A decrease of Rres*$\alpha$
(less hydrogen)

$\Rightarrow$ At 4.2K, Qo slope more important than predicted (thermal instabilities).

# IN CONCLUSION FOR THE MODEL

⇒ Very nice predictions for Spiral2 QWR.

⇒ Good predictions at 2K for Spoke resonator but not for Q-slope at 4.2K

- problems of thermal instabilities because of Rs > 50 nΩ (power density too high)

⇒ Helped us through β factor to explain why all cavities where limited at 100-120 mT at 4.2K

⇒ Need more work to understand the residual parameters $\alpha$ and $\gamma$

- $\alpha$ : linear factor linked to hydrogen (Q-disease, bad etching)
- $\gamma$ : quadratic factor is changed with a baking (thermal instabilities ?, material pollution?)

# FLUX TRAPPING STUDY ON SPIRAL2 QWR

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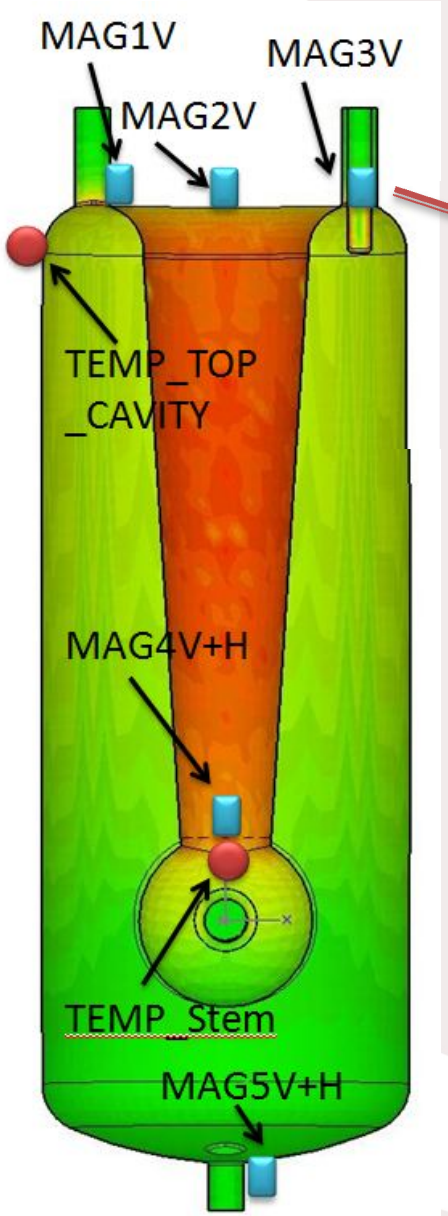


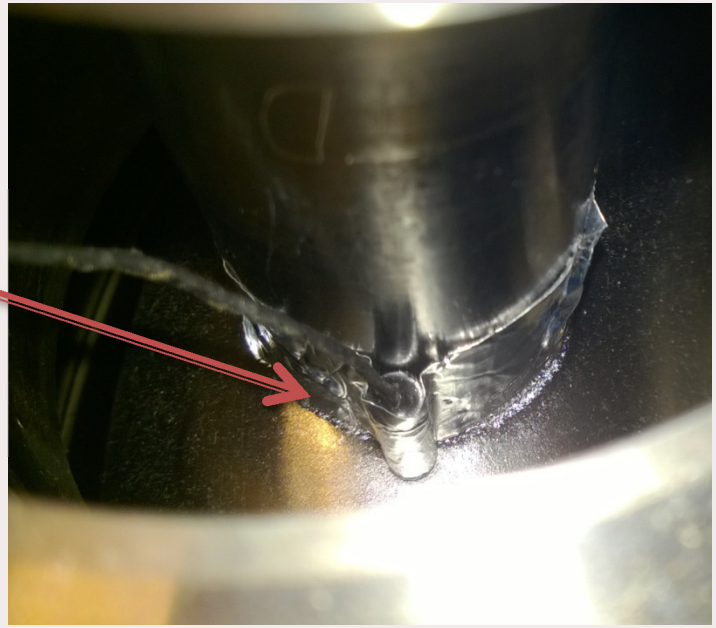

⇒ 9 magnetic sensors (fluxgate) available (mounted as triaxial sensor or alone)

⇒ Monitoring of residual magnetic field during cooling down

⇒ Measurement of magnetic sensitivity of cavity

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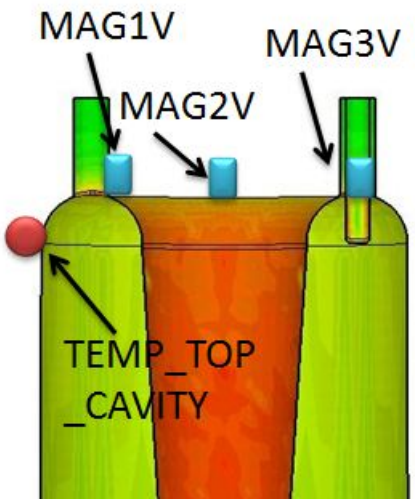

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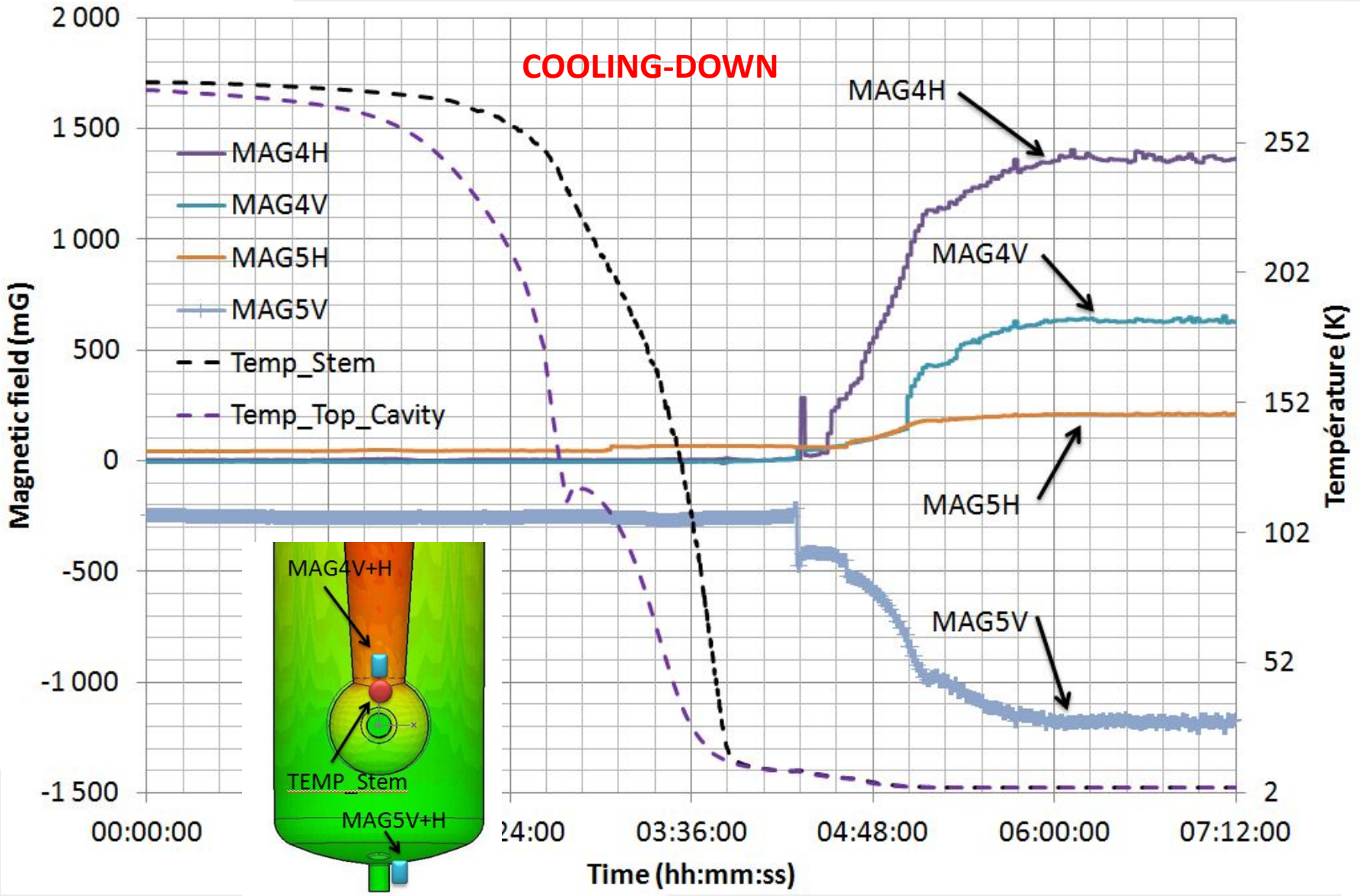

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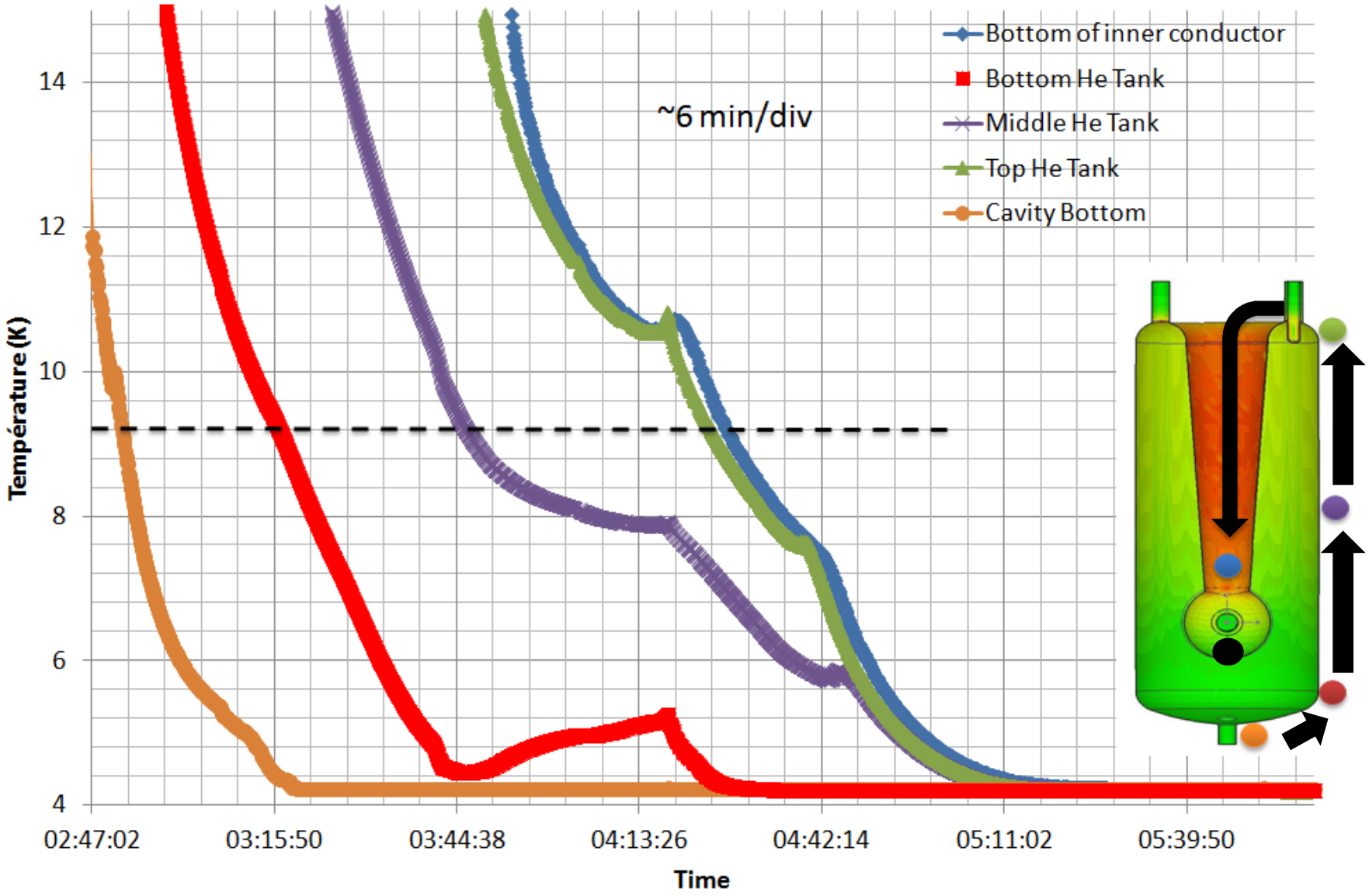

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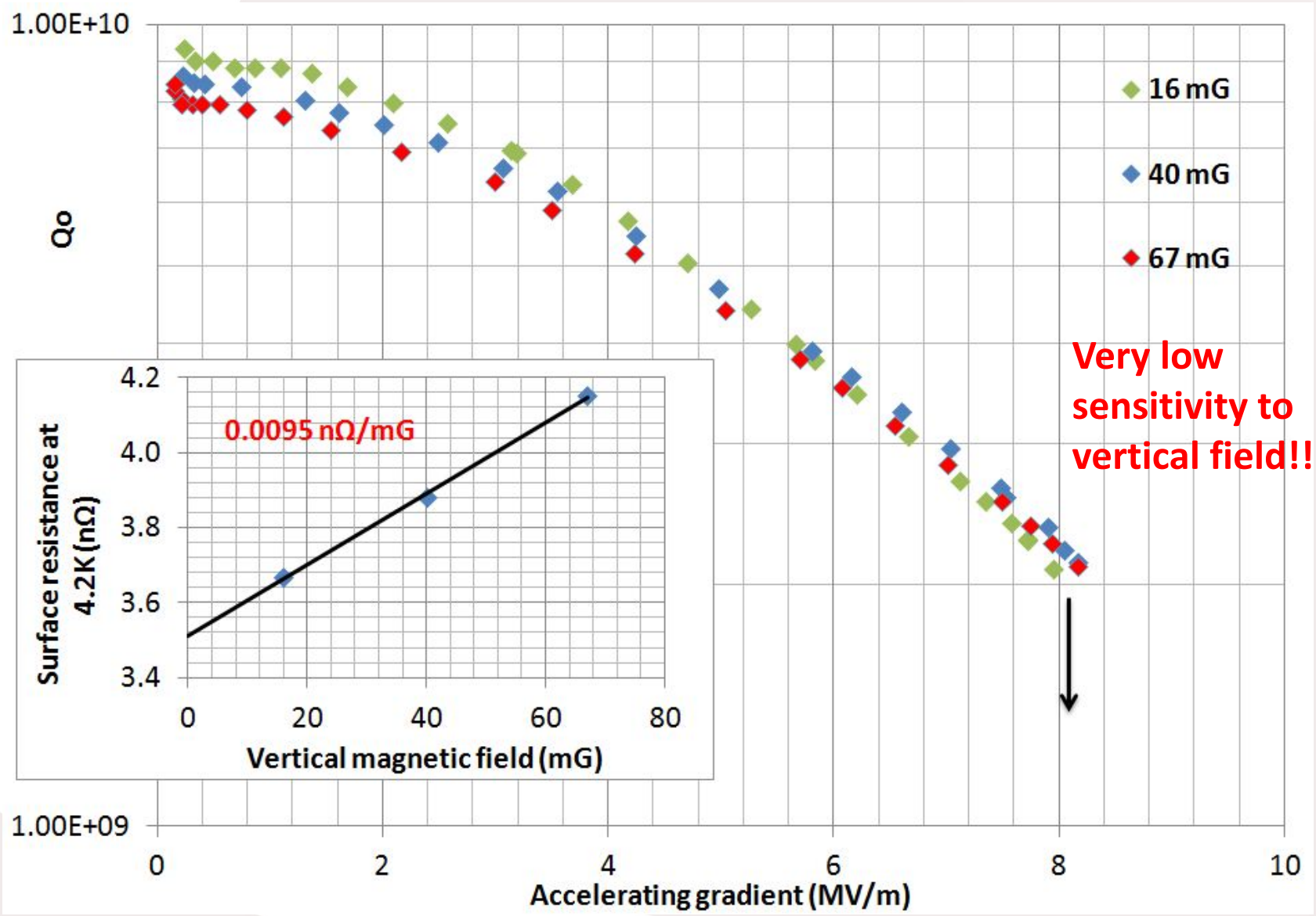
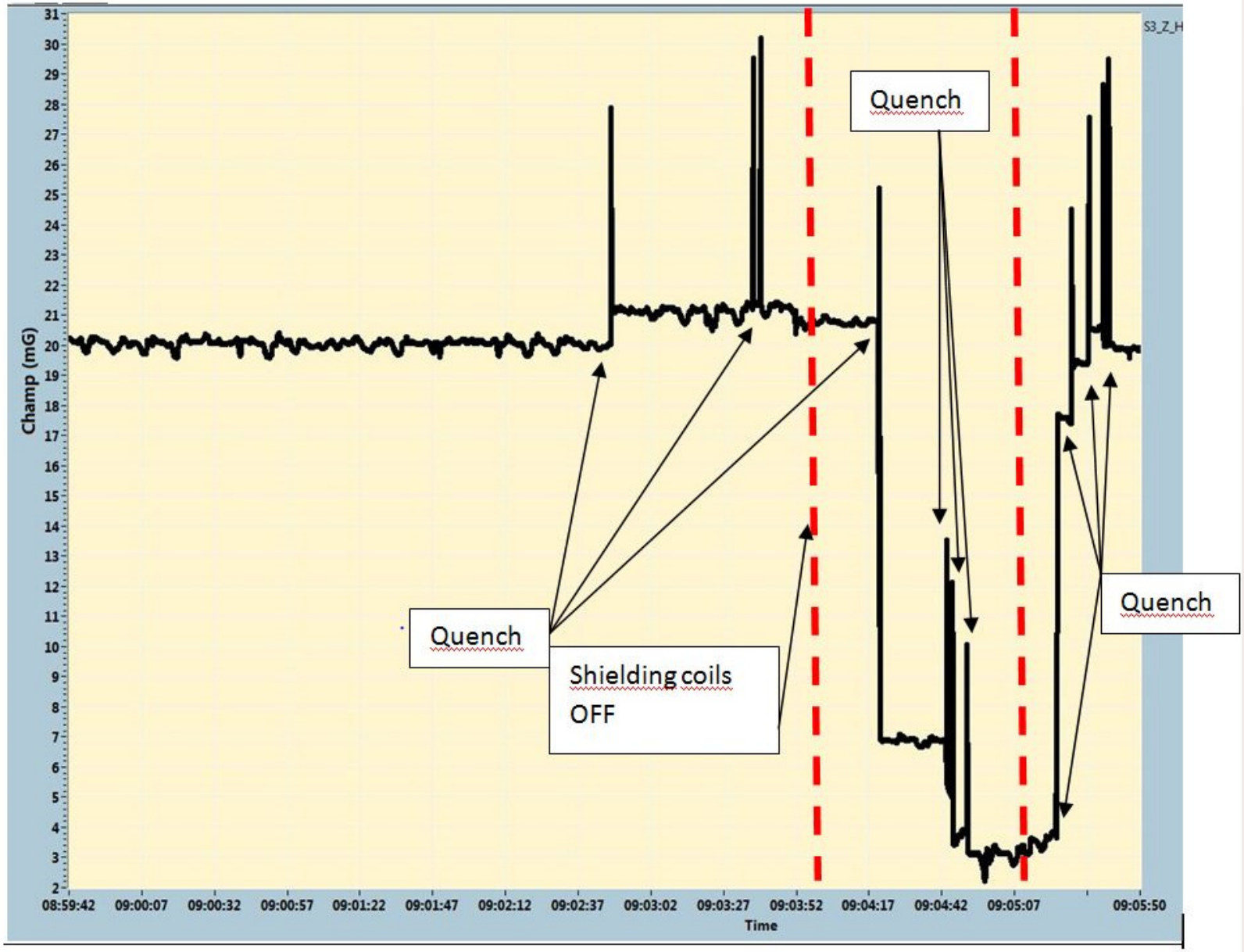
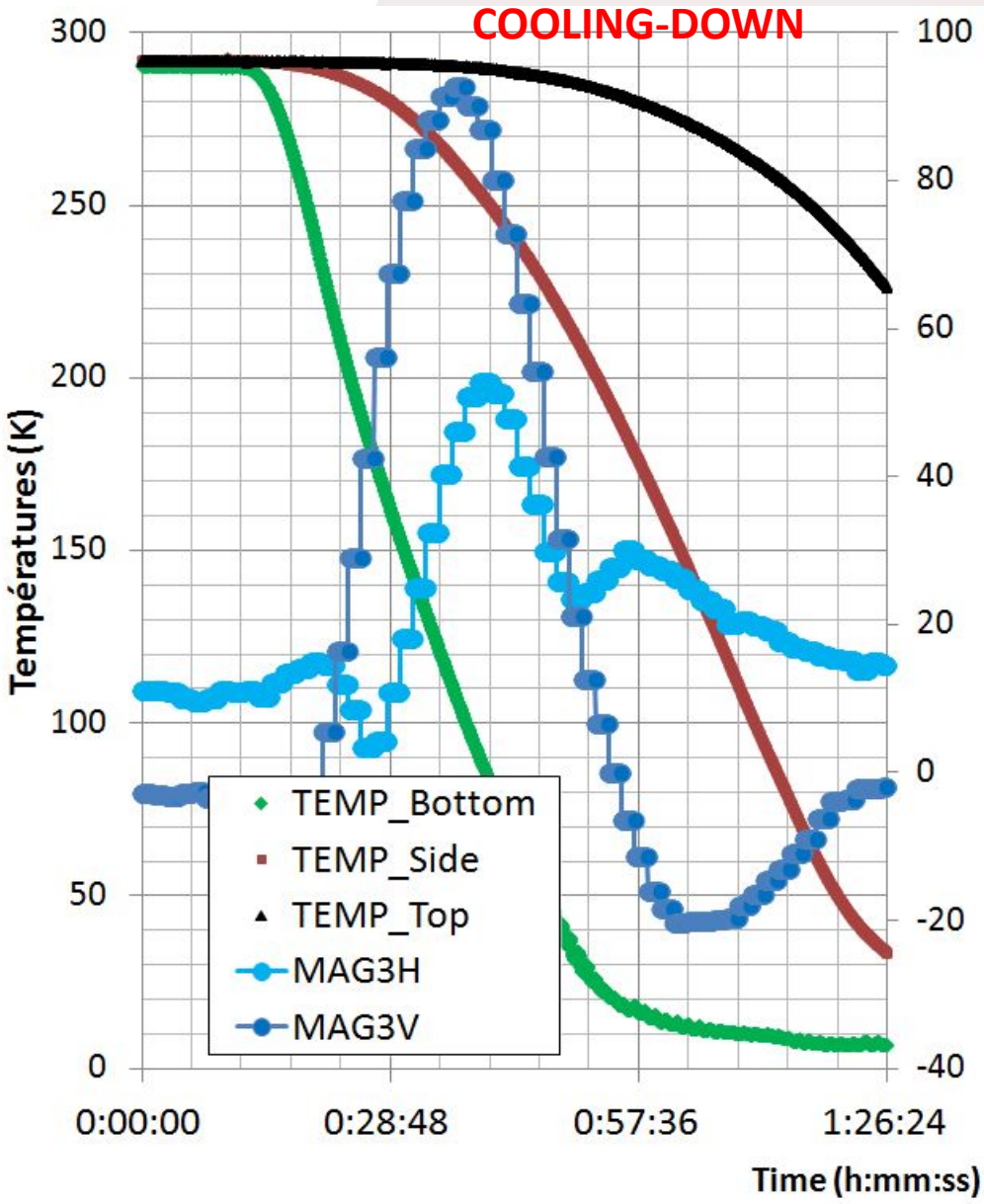
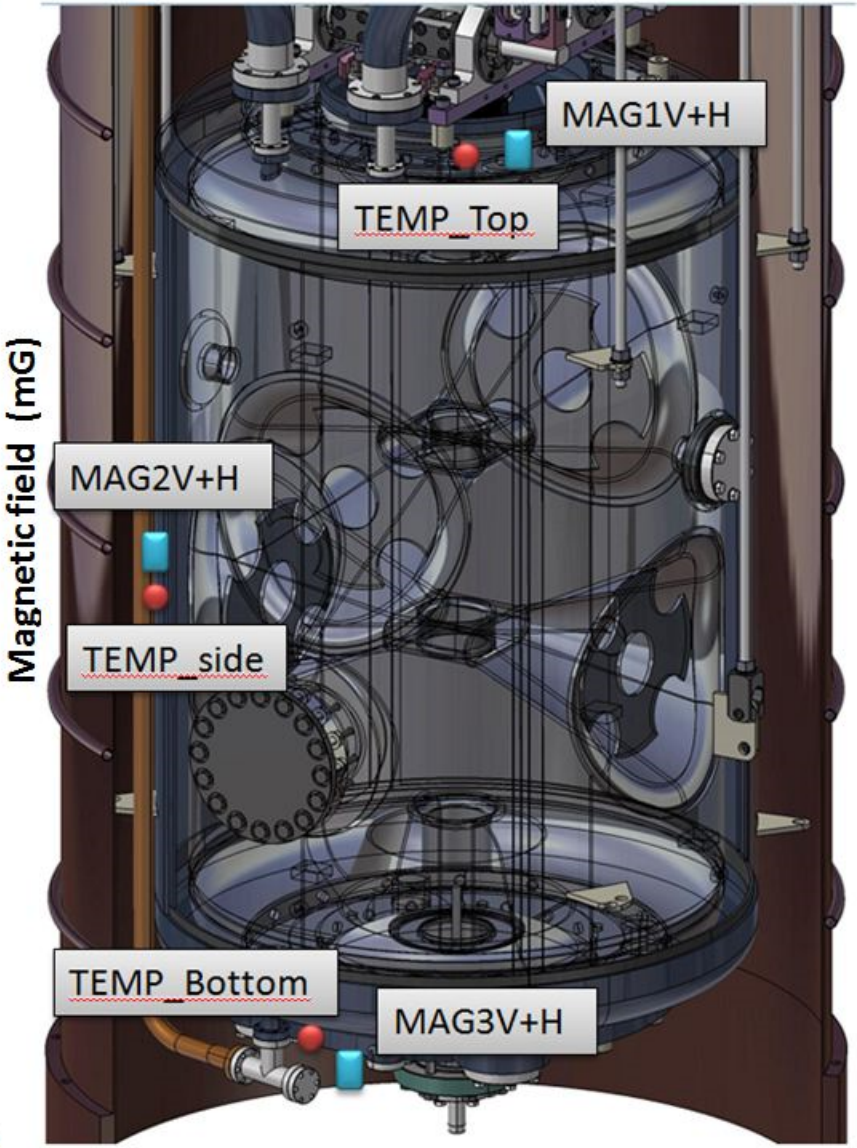


# FLUX TRAPPING STUDY ON SPIRAL2 QWR (QUENCH)

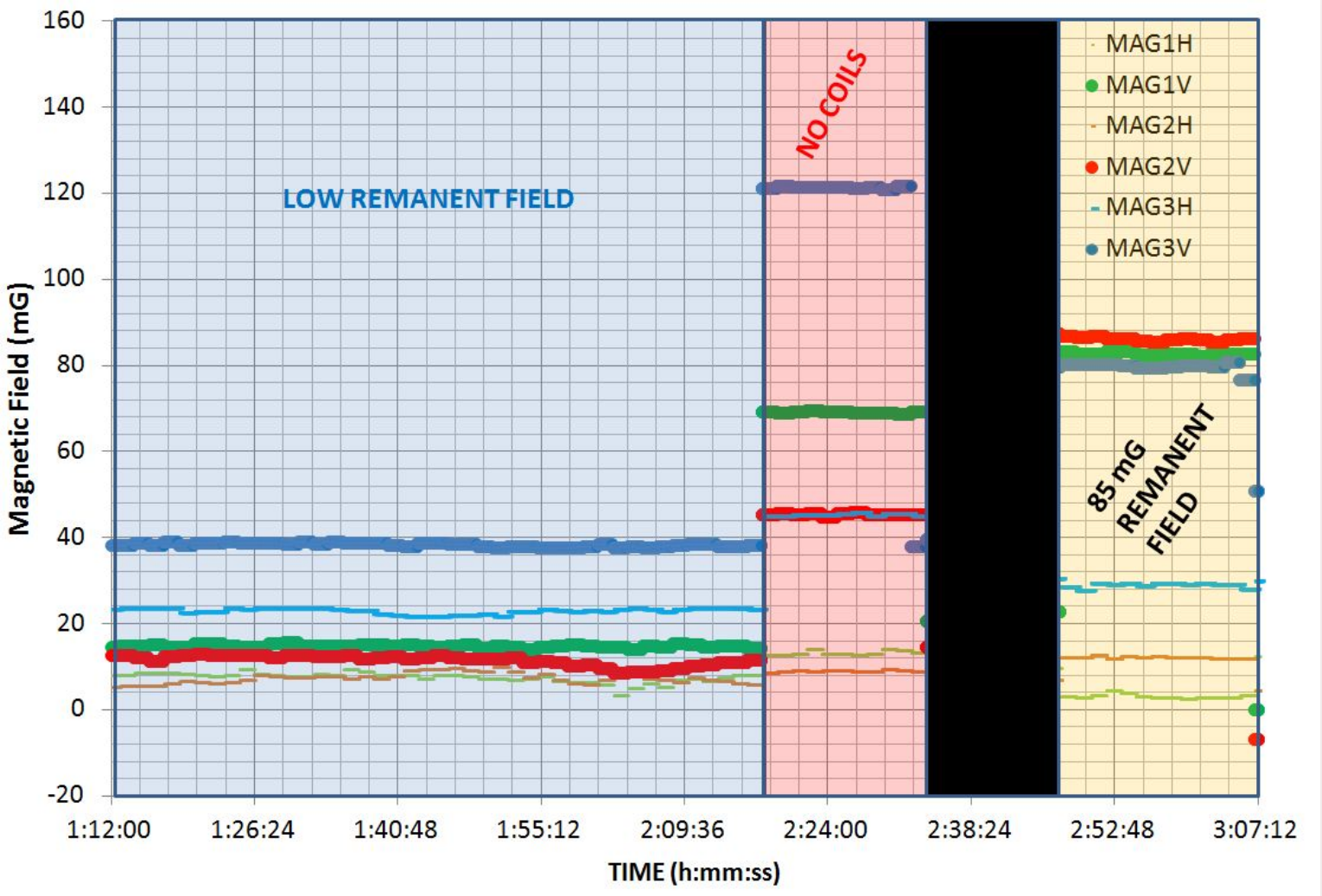


# FLUX TRAPPING STUDY ON ESS DSR



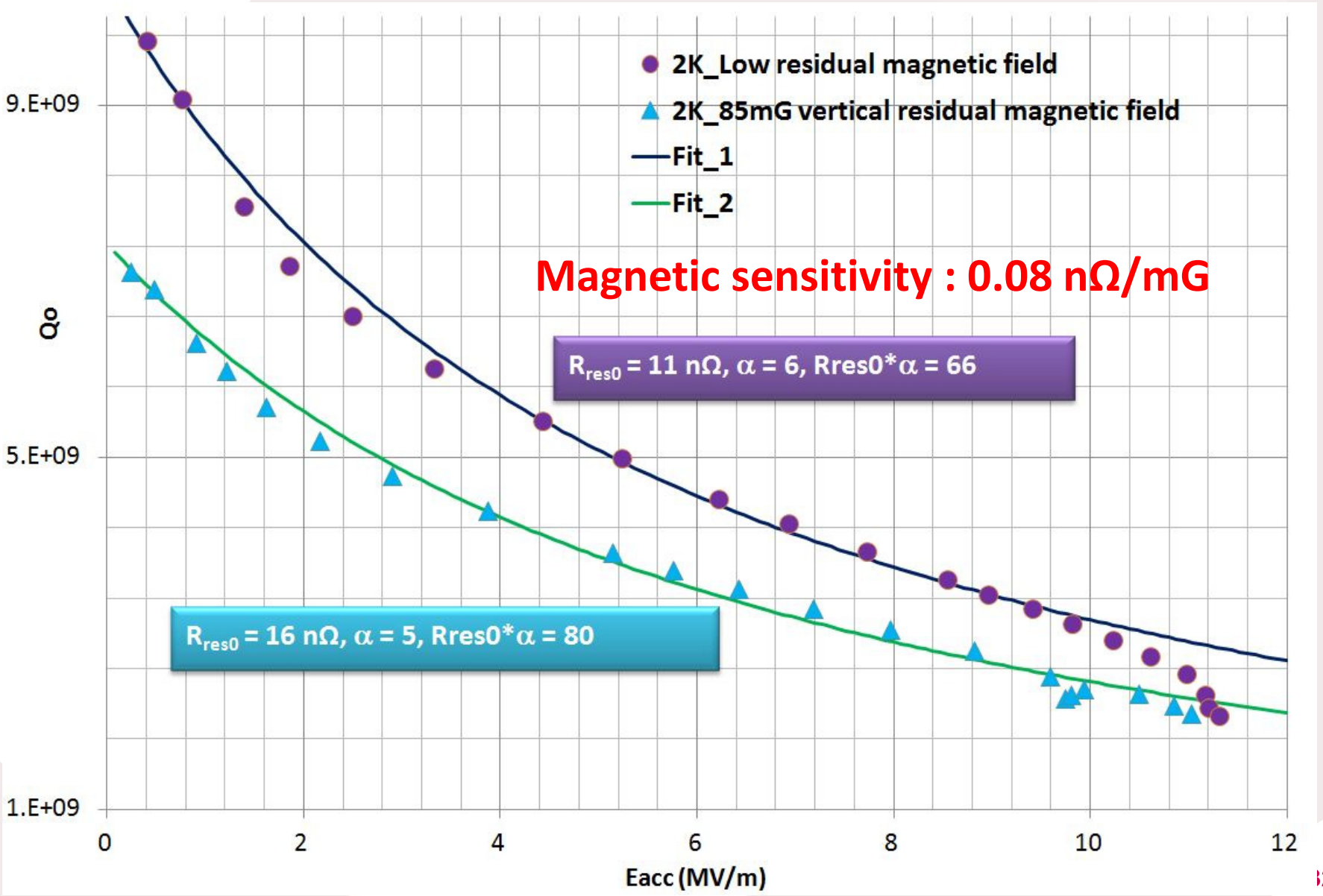



# FLUX TRAPPING STUDY ON ESS DSR




Magnetic configurations to study magnetic sensitivity of cavity

# FLUX TRAPPING STUDY ON ESS DSR



# IN CONCLUSION FOR FLUX TRAPPING STUDY

⇒ 9 magnetic sensors (multiplexed) give very precise measurement of the magnetic field during cooling down.

⇒ SPIRAL2 QWR :

- No thermal current
- Huge magnetic field is appearing close to transition on SPIRAL2 QWR
- No degradation of the Qo despite more than 1500 mG close to magnetic area (field not trapped along inner conductor but at the very bottom)
- Very low magnetic sensitivity 0.01 nΩ/mG

⇒ ESS Spoke Resonator

- Magnetic sensors difficult to install (spoke bars not accessible)
- Important thermal current created during cooling down (90 mG)
- Magnetic sensitivity in beam tube direction evaluated at 0.08 nΩ/mG

# THANKS FOR YOUR ATTENTION

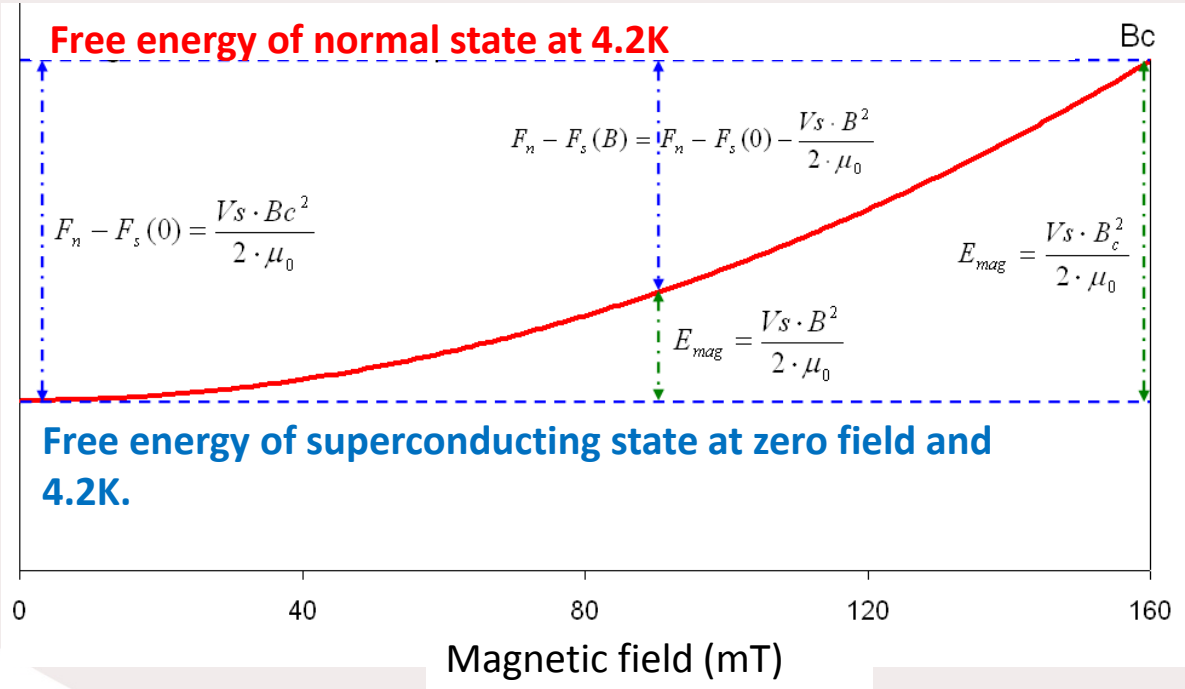
# A GOOD MODEL TO FIT SPIRAL2 QWR Q-CURVES

- **$R_{BCS}$ model :**

$$R_{BCS} = \frac{A(\lambda, \xi, l, \ldots) \cdot \omega^2}{T} \cdot \exp\left(\frac{-\Delta(T)}{k_B \cdot T}\right)$$

**=> Transition of first order in field : Δ(B) = cste for B<Bc, Δ(B) = 0 for B>Bc**

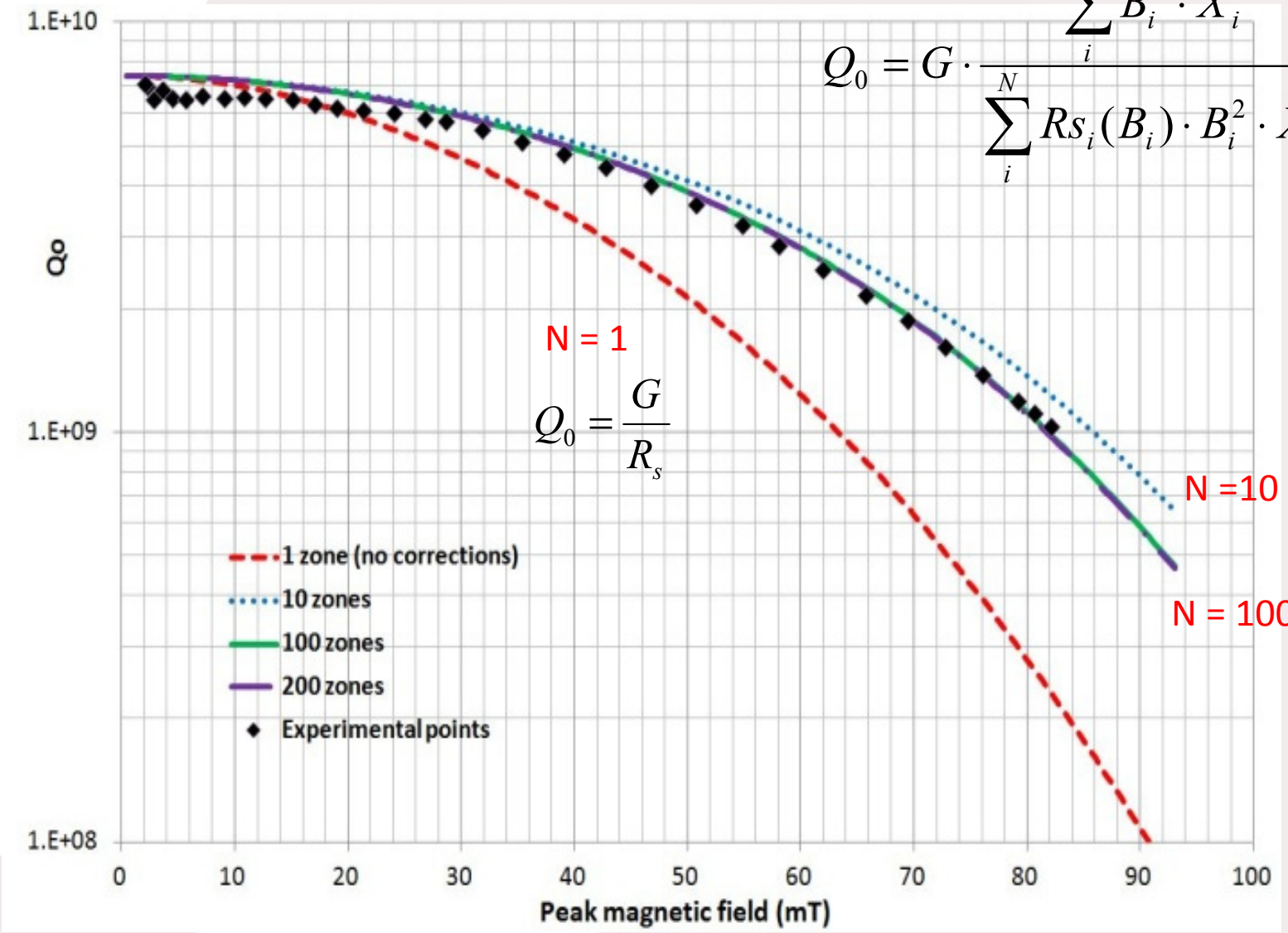
**=> Transition of second order in field :**



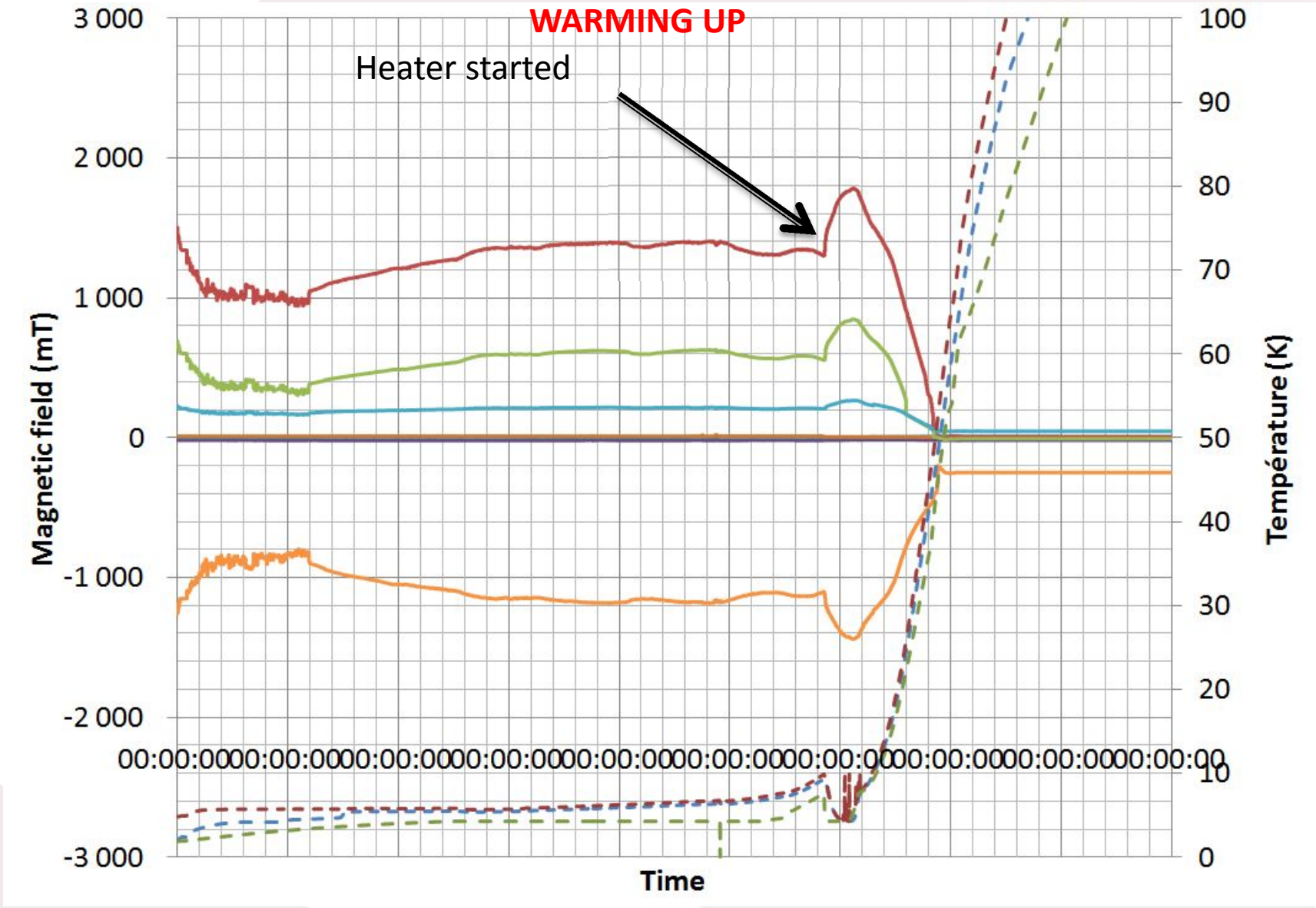

$$\Delta(T, B) = \Delta(T, B = 0) \cdot \left(1 - \left(\frac{B}{Bc(T)}\right)^2\right) \qquad Bc(T) = Bc(0) \cdot \left(1 - \left(\frac{T}{Tc}\right)^2\right)$$

# EFFECT OF NUMBER OF DIVISONS IN MODEL

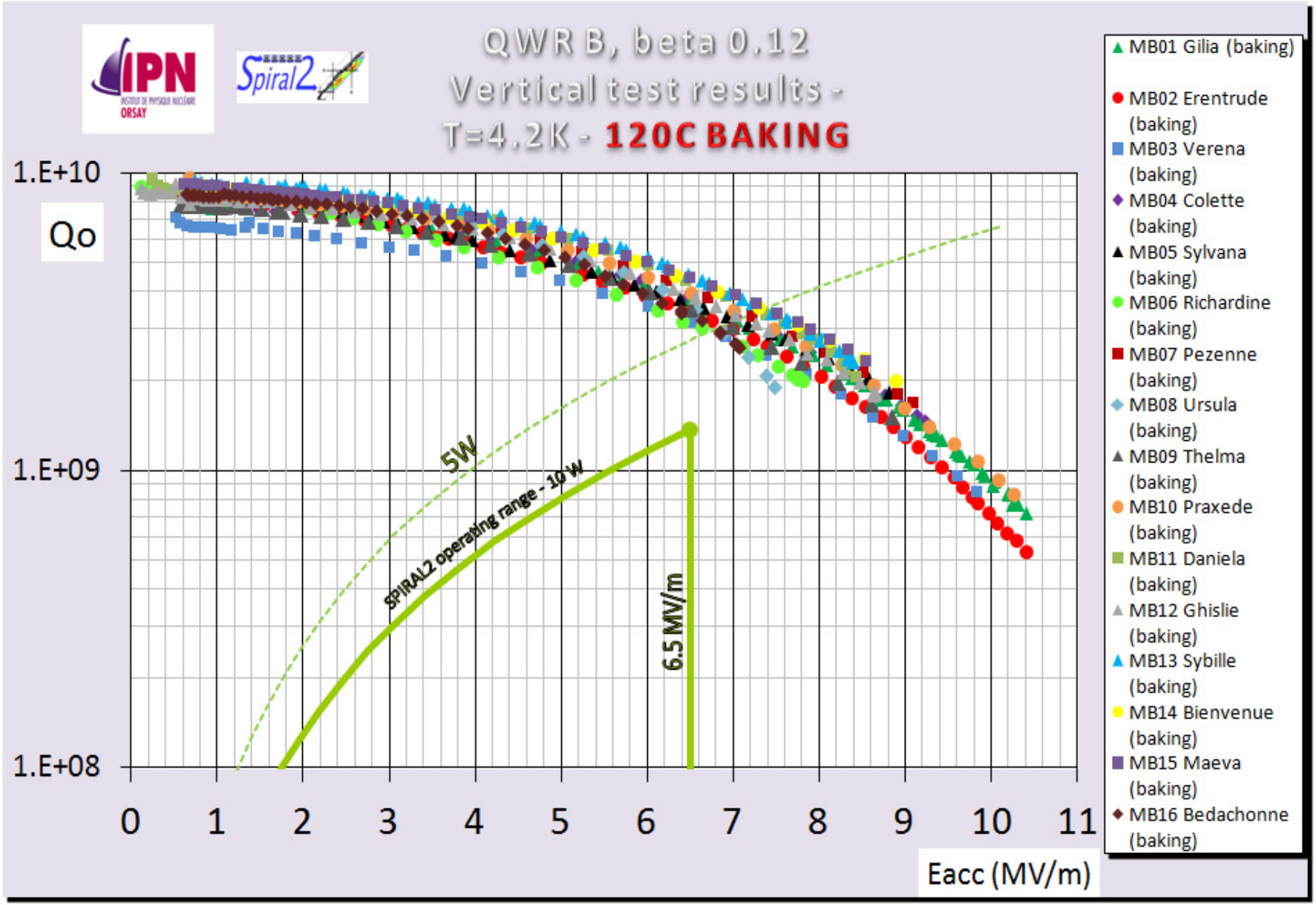
$$Q_0 = G \cdot \frac{\sum_i B_i^2 \cdot X_i}{\sum_i^N Rs_i(B_i) \cdot B_i^2 \cdot X_i}$$



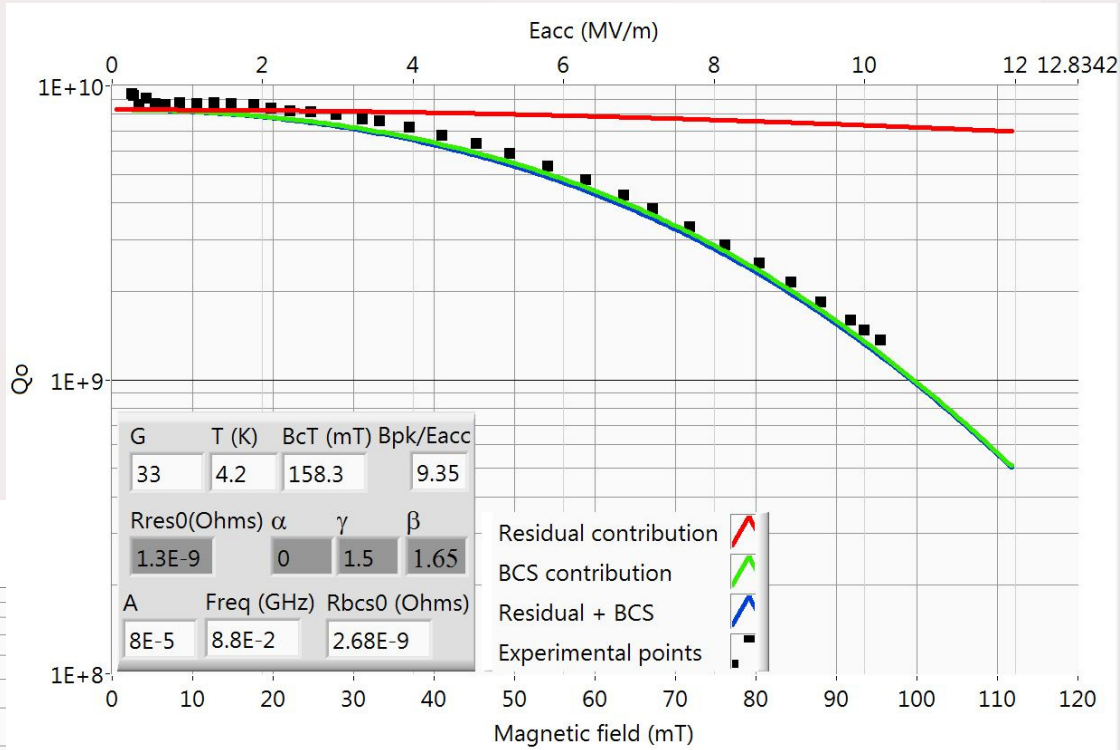
# FLUX TRAPPING STUDY ON SPIRAL2 QWR

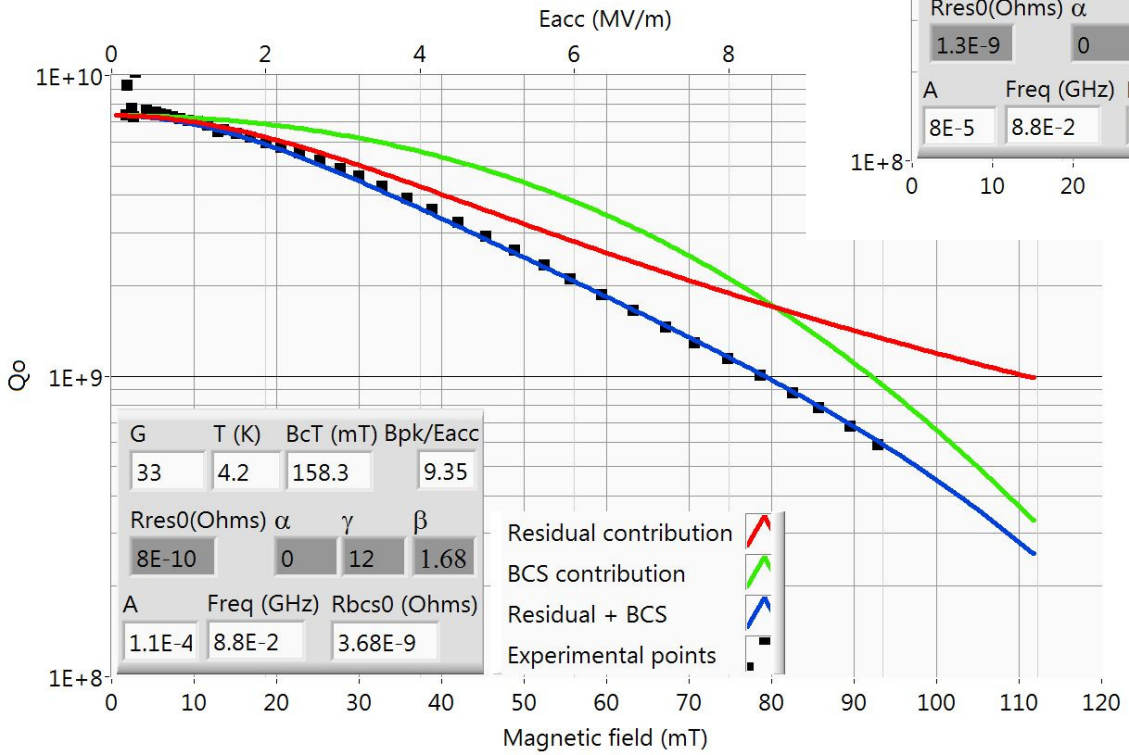


# A GOOD MODEL TO FIT SPIRAL2 QWR Q-CURVES



# BEFORE/ AFTER BAKING AT 120°C (MB09) AT 4.2K




## Baking at 120°C :

- Rres0 increased of 38%.
- $R_{BCS0}$ decreased of 37%
- β is constant
- γ decreased at lot (from 1.5 to 12)

# WITH/WITHOUT MAGNETIC FIELD (MB05)