High Resolution Surface Resistance Studies

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The Quadrupole Resonator

- Sample:
  - 75 mm diameter
  - EBW to support tube
  - Massive sample (min 3mm thick) or film on Cu or Nb substrate
  - Equipped with a dc heater and 4 temperature sensors
Features

- Resonance Frequencies: 400, 800, 1200 MHz
- Almost identical magnetic field configuration
- Ratio of $B_{\text{peak}}$ to $E_{\text{peak}}$ is proportional to $f_{\text{res}}$
- $B_{\text{max}} \approx 60$ mT
- Temperatures 1.6 - 12 K
Calorimetric Measurement

Sample Temperature

RF switched on
Heater regulation

He bath
Heat

T-Diode
Heater
dc/RF Power

$P_{\text{dc1}}$
$P_{\text{dc2}}$
$P_{\text{rf}}$

Time

$T_{\text{interest}}$
$T_{\text{bath}}$
Calorimetric Measurement

\[ P_{RF} = P_{DC1} - P_{DC2} \approx \frac{1}{2} R_s \int H^2 dS \]

\[ R_s = \frac{2(P_{DC1} - P_{DC2})}{\int H^2 dS} \approx C_{P_t} \]

Measured directly

Sample Temperature

RF switched on

Heater regulation

Measurement directly

Simulation

\[ T_{interest} \]

\[ T_{bath} \]

dc/RF Power

\[ P_{dc1} \quad P_{dc2} \quad P_{rf} \]

Time

\[ P_{rf} \]

Time
**Errors & Resolution**

- **Temperature diodes:**
  - 12 mK absolute / 0.1 mK relative
- **Heater voltage:** 10 μV (relative)
- **Transmitted power:** $\Delta P = 3\%$ (absolute)
- **Pressure of helium bath:**
  - Changes the heat necessary for reaching $T_{\text{interest}}$
  - Pressure regulation system stabilizes ± 0.02 mbar
- **Minimal heating of 0.1 mK depends on the thermal conductivity:**
  - 2.5 μW at 2 K lead to smallest detectable $R_s$ change at 5 mT and 400 MHz

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- Pressure of helium bath:
  - Changes the heat necessary for reaching T_{\text{interest}}
  - Pressure regulation system stabilizes ± 0.02 mbar
- Minimal heating of 0.1 mK depends on the thermal conductivity:
  - 2.5 μW at 2 K leads to negligible stable R_s change at 5 mT and 400 MHz

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negligible
Relevant for low temperatures
dominant
No issue anymore
Resolution at 5mT: 0.44 nΩ
Reproducibility

Surface Resistance $R_s$ [nΩ] vs. RF Magnetic Field [mT]

Reactor grade Nb after 48 h mild baking 800 MHz, 2 K

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Reactor grade Nb after 48 h mild baking
800 MHz, 2 K
Samples

- Already measured:
  - Magnetron sputtered Nb/Cu
  - Bulk Nb + mild baking
  - MgB$_2$ (STI)

- To come:
  - Nb baked at 800 °C in N$_2$/Ar (FermiLab)
  - NbTiN (AASC)
  - HIPIMS Nb/Cu
MgB$_2$

- 500 nm MgB$_2$ on a Nb substrate (deposited by Chris Yung at STI)
- Strong multipacting on 1st RF test
- After new rinsing: even stronger multipacting + „burn marks“
- Continuous transition from sc to nc state
- XPS measurements show only 70% MgB$_2$ (rest MgB$_x$)

Cause for multipacting?
Influence of the Cooling Rate in Nb

- Reactor grade Nb + BCP + 48h mild baking
- 400 MHz, 2.5 K, 15 mT

Cooling speed was varied by regulating the heater power

![Diagram showing T-Diode, Heater, and Heat connections]

![Graph showing Surface Resistance vs. Cooling Rate]
Possible Explanations

• Dc Heater produces an additional B field
  • \( B_{\text{heater}} \) would compensate or sum up with residual field (2\( \mu \)T) due to imperfect shielding.
  • Inverting the heater current reproduced results.

• Temperature dependence of magnetic shielding
  • Shield is always at the same temperature
  • Not the case for cavities (Kugeler et al, THPO011, SRF2011 )

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Possible Explanations

- Nb hydride formation
  - Max T of the sample is 12 K → far away from Q-disease region

- Seebeck effect
  - Temperature gradient causes thermo voltage
  - Additional magnetic field is produced and trapped if thermal currents occur
    (Kugeler et al. THOBB201, IPAC13 Aull et al. PRSTAB 15(6):062001)
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Expulsion of Trapped flux

- Trapped flux studies on samples show already that the amount of trapped field can depend on the cooling conditions.

- The more flux is expelled the slower the sample is cooled down
  (Vogt et al, accepted for publication in PRSTAB 2013)
Conclusion & Outlook

• We found that the surface resistance decreases for lower cooling rates.

• The results are consistent with the expulsion of trapped flux while all other possible explanations could be ruled out due to the thermal decoupling of the sample from the host cavity.

• In a next step we continue to study this effect under the influence of external dc magnetic fields and transfer these studies to other materials and Nb films.