In Situ Resistivity Measurement of Metal Surfaces to Track Down Dislocations Caused by High Field Conditioning

UPPSALA UNIVERSITET

M. Coman, M. Jacewicz, D. Dancila

FREIA, Department of Physics and Astronomy, Uppsala University, Sweden

Introduction

- **Surface Conditioning:** Progressive development of resistance to vacuum arcing over the operational life of a high gradient system
- **Hypothesis:** Sharp features form on the surface due to the collective activity of the dislocations within the surface layer of the sample [1]. During conditioning, new dislocations are created → increase in resistivity near the surface (**we can measure this!**)
- **Cryogenic Measurements:** At temperatures of a few kelvin, the resistivity is given only by the scattering of the electrons off the lattice defects
- **Sensitivity to a thin layer near the surface:** At GHz frequencies, the current penetrates only a few um in the copper sample at room temperature (skin effect) → we can measure the resistivity only near the surface by using RF methods

Aim: test the hypothesis by measuring the surface resistivity during the conditioning process using RF methods in cryogenic conditions.

Method

- Information about the resistivity from the **quality factor** of the resonant system, obtained by fitting the Q-circle (Fig. 1) [2]

$$Q_0 = \frac{G}{R_S} \qquad R_S = \sqrt{\frac{\omega \mu \rho}{2}}$$

- **But, at cryogenic temperatures, we have the anomalous skin effect** [3]
- At cryogenic temperatures, the skin depth (0.1 um) is much smaller than the mean free path (4.2 um)
- Most conduction band electrons will not suffer any collisions in the skin depth and they will penetrate deeper into the material. We are sensitive to changes in resistivity ~1 um underneath the surface
- Calculation for Rs is more complicated: we have small changes in Rs even for a big change in ρ (Fig. 2)

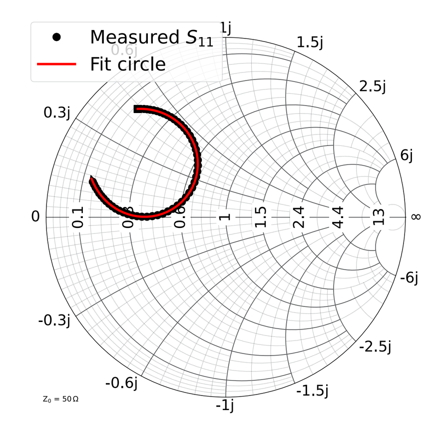


Fig. 1. Fitted Q-circle

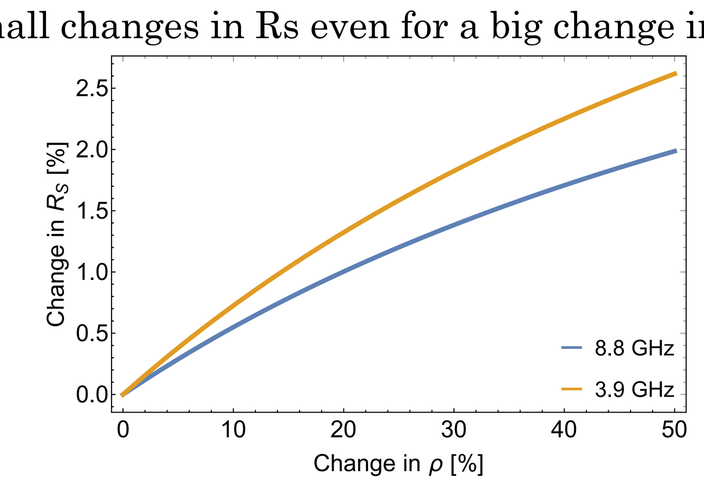


Fig. 2. Change in Rs in anomalous conditions

Experimental Set-Up

- Our usual experimental set-up consists of two large electrodes, separated by an alumina spacer (~60um gap) [4]
- For more information about the set-up - "Cryogenic high-gradient discharge system at Uppsala University" on Thursday
- The conditioning is done using DC pulses, reaching fields of around 100-150 MV/m
- In between cycles of DC pulses, we disconnect the DC generator and connect a VNA to obtain the Q-circle
- But we need to modify the electrode system to contain a resonant mode between the electrodes
- Modify the anode by making a groove (choke [5])
- We propose two designs based on this idea

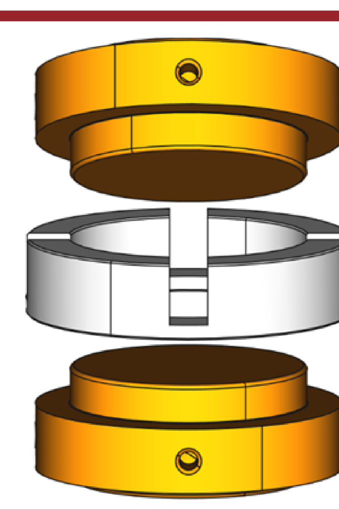


Fig. 3. Electrode system

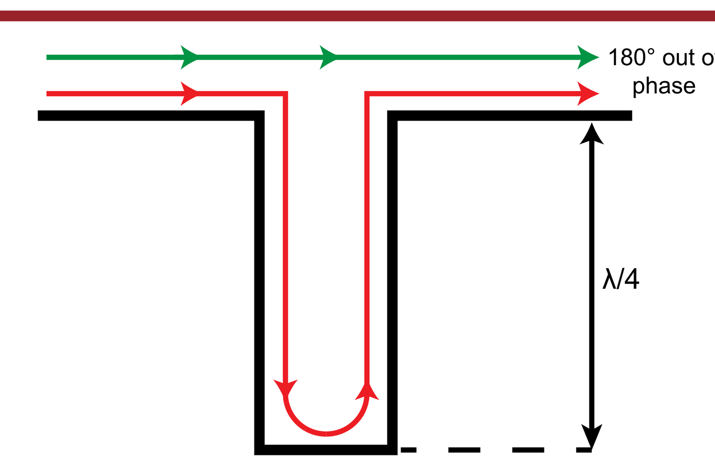


Fig. 4. Working principle of a choke cavity

First Design

- Modify only the anode ✓
- Antenna is introduced horizontally

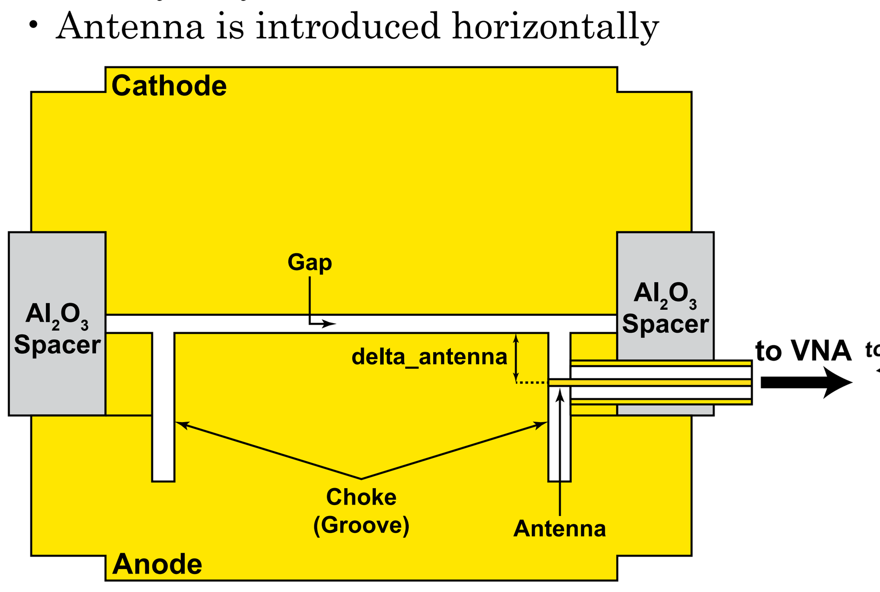


Fig. 4. Cross-section through the electrode system

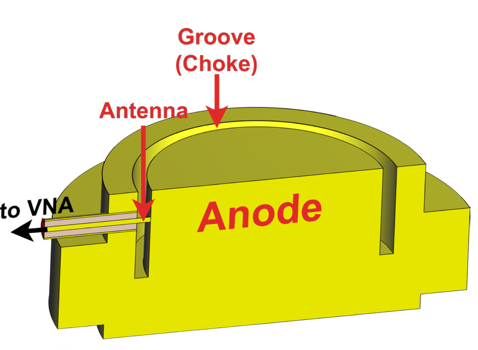


Fig. 5. Anode with groove

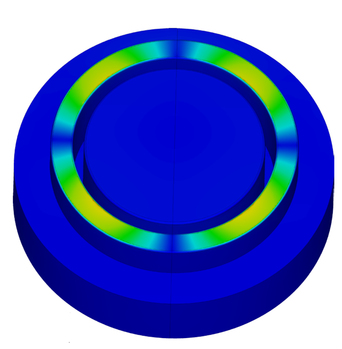


Fig. 6. Parasitic Mode

- Coupling in this way introduces parasitic modes (Fig. 6)
- Make notches ×
- Electrical contact is important! ×
- Use fundamental mode, f = 3.9 GHz
- Room temperature, gap = 75 um, Q_0= 74
- Cryogenic temperatures, gap = 60 um, Q_0= 580

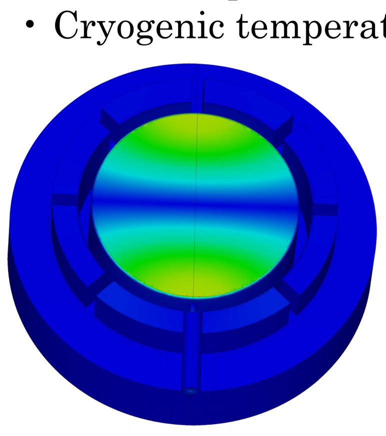


Fig. 7. E-field

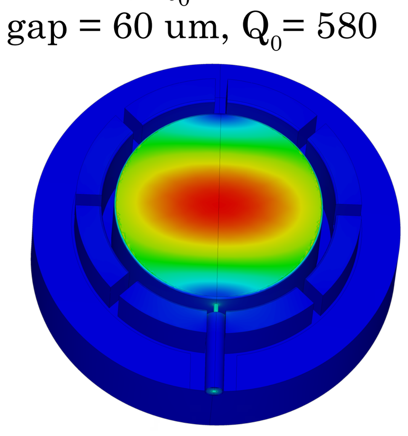


Fig. 8. H-field

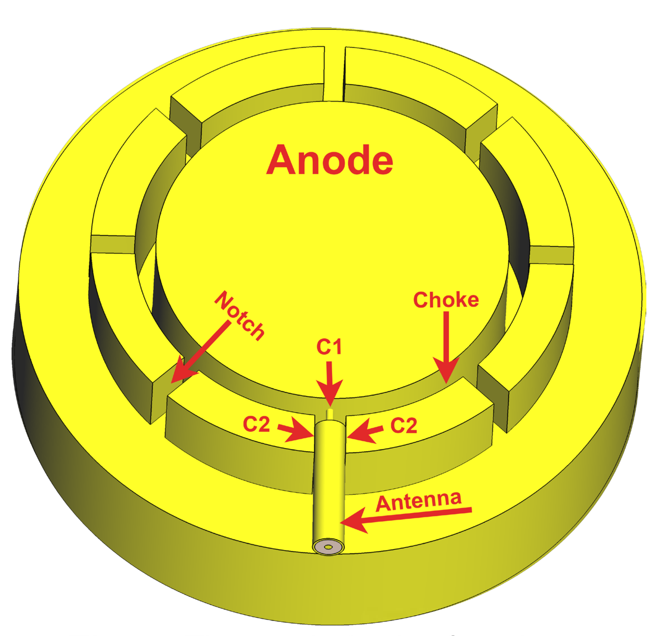


Fig. 9. The anode in the first design

Second Design

- Modify both the anode and the cathode ×
- Antenna in the center

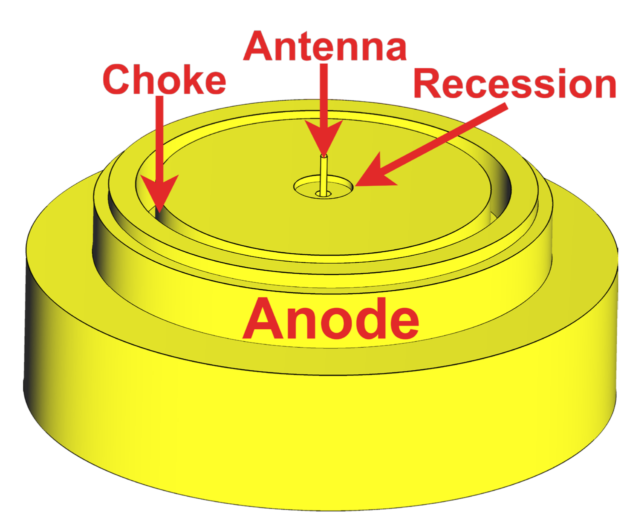


Fig. 9. The anode in the second design

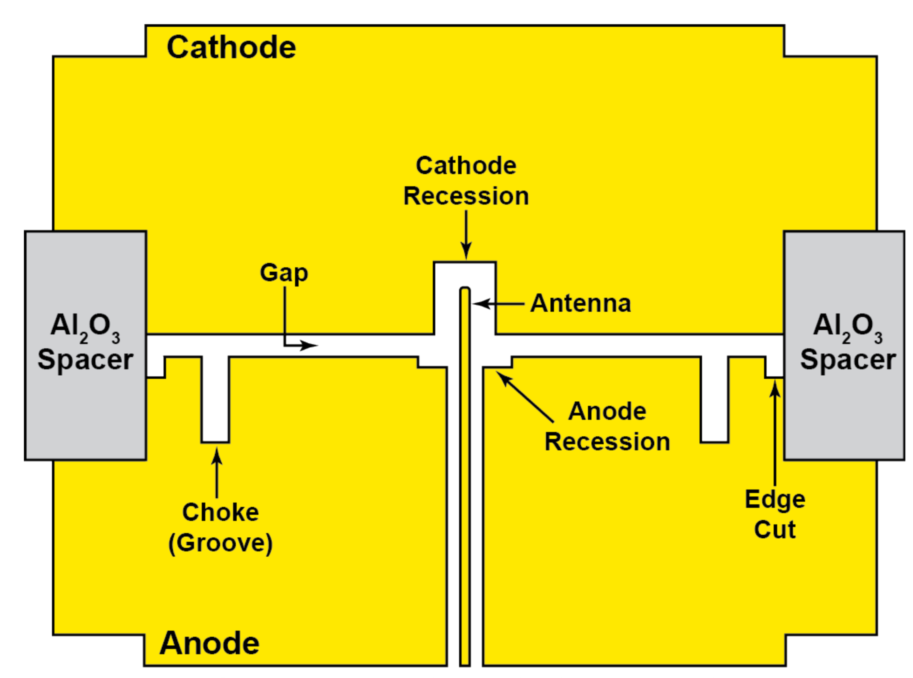


Fig. 10. Cross-section through the electrode system

- No need for notches, simpler design ✓
- No issues with electrical contact ✓
- Use higher order mode, f = 8.8 GHz
- Cryogenic temperatures, g = 60 um, Q_0= 880

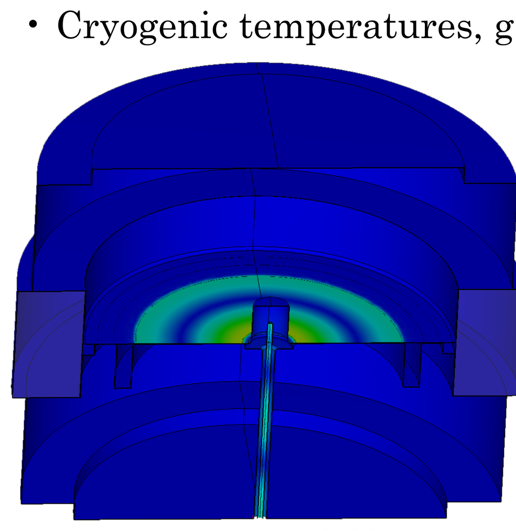


Fig. 11. E-field

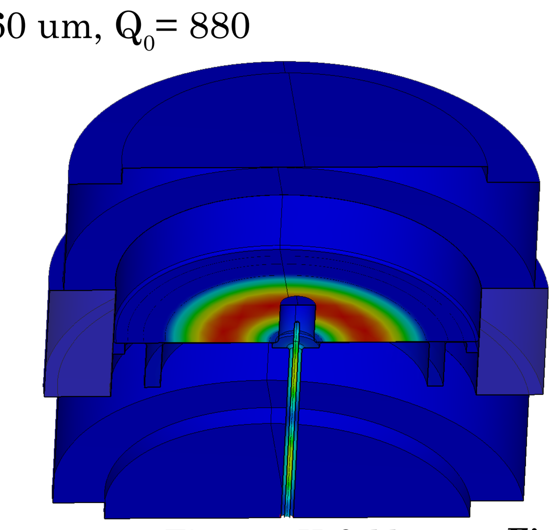


Fig. 12. H-field

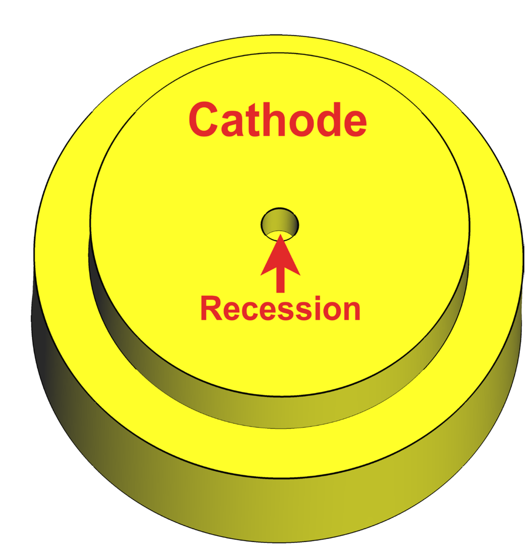
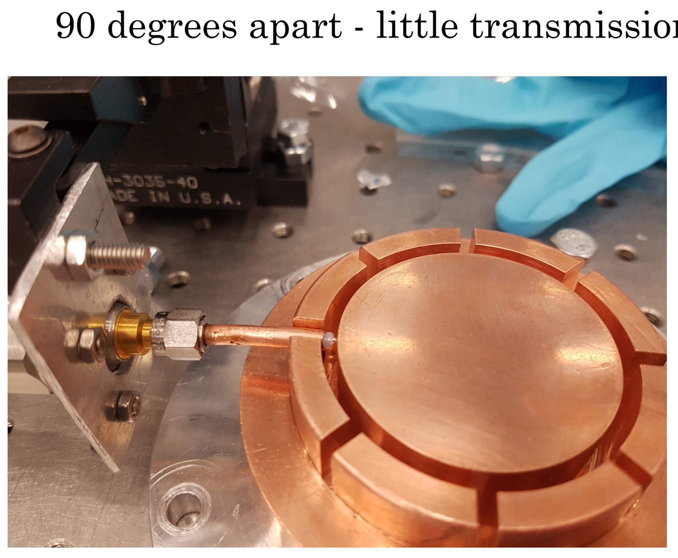
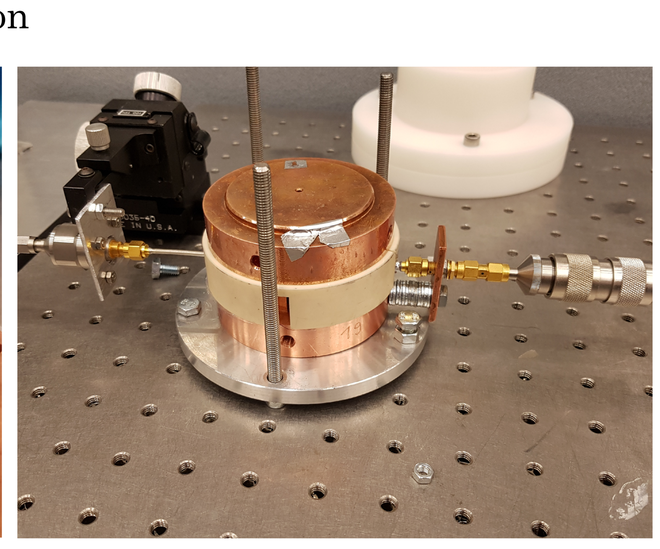


Fig. 13. The cathode in the second design

Testing the first design

- The first design was manufactured in Uppsala University's workshop
- The design was tested at room temperature
- Measured frequency: 3.7 GHz
- Gap Size: 75 um, Q_0= 75, very close to the values obtained from simulations
- How can we be sure that we coupled to the correct mode and not to the parasitic mode? Make transmission measurements: antennas 180 degrees apart - significant transmission, antennas 90 degrees apart - little transmission





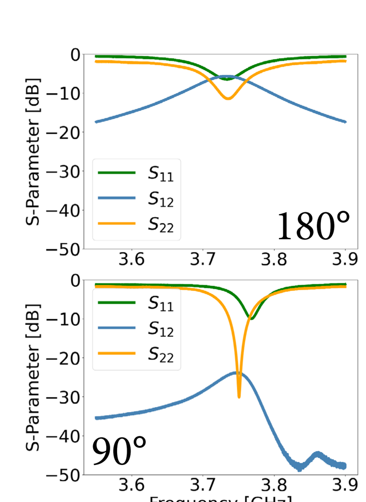


Fig. 13. The modified anode (1st design), with the antennas used for testing the design (left and center) and the S-parameters measured in transmission configuration (right)

Conclusions

- We propose making surface resistivity measurements during high-field conditioning to test the dislocation hypothesis
- Cryogenic conditions, DC conditioning, RF resistivity measurement
- Slight issue: the anomalous skin effect
- The current electrode system needs to be modified in order to contain a resonant mode between electrodes
- We have proposed two designs
- First design:
  - Only the anode is modified
  - Notches, more complicated design
  - Electrical contact issues
- Second Design:
  - Both electrodes are modified
  - Simpler design
  - No issues with electrical contact
- We have tested the first design at room temperature: **it works as expected!**
- Next steps: test the second design, make RF resistivity measurements in cryogenic conditions during conditioning
- These designs might also be used for novel methods of investigating RF breakdowns.

References

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[2] A P Gregory. Q-factor measurement by using a vector network analyser. NPL Report 10.47120/npl.MAT58, December 2021.
[3] G. E. H. Reuter and E. H. Sondheimer. The theory of the anomalous skin effect in metals. Canadian Journal of Physics 1982-may 01 vol. 60 iss. 5, 60, may 1948.
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[6] CST Studio Suite, "CST Microwave Studio," 2008. http:// www.cst.com