Breakdown position measurement in the DC spark system

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Preface

- What?
  - Localize breakdowns in the Fixed Gap System (FGS)
- Why?
  - Information on position of correlated breakdowns
    - How frequently do successive BDs happen in the same spot?
  - Complement SEM studies
- How?
  - Four antennas located around a spark gap

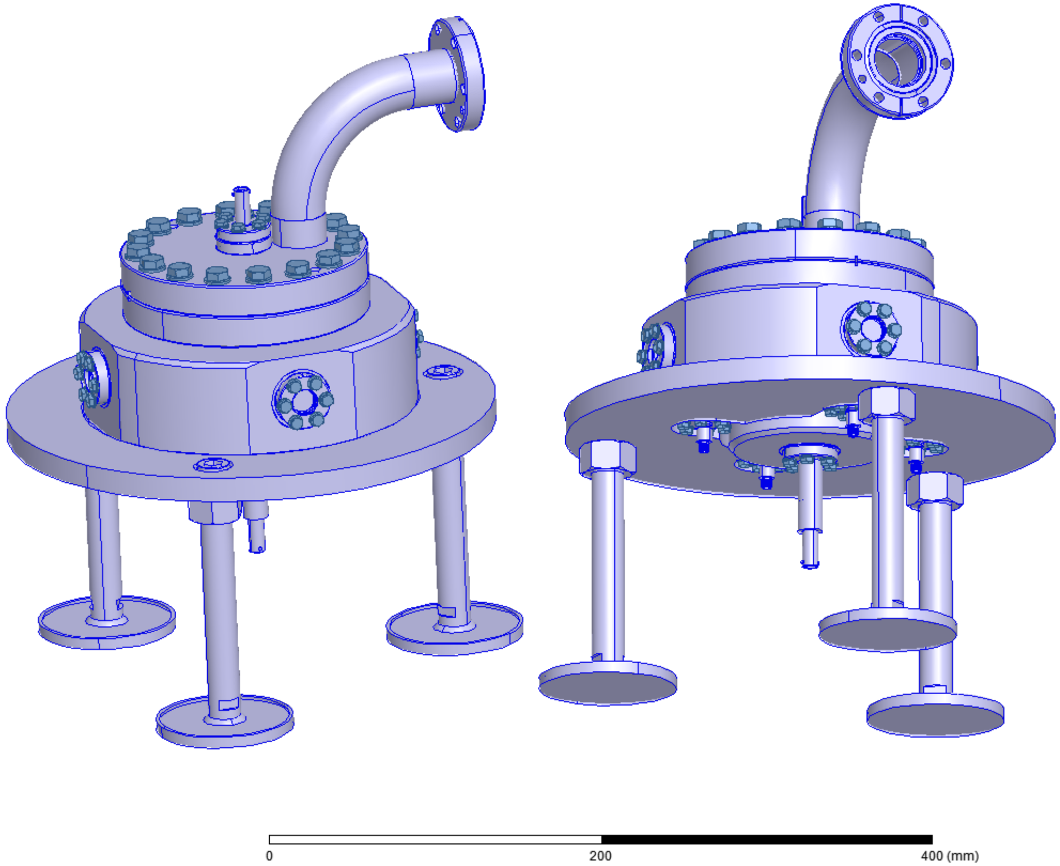
Outline

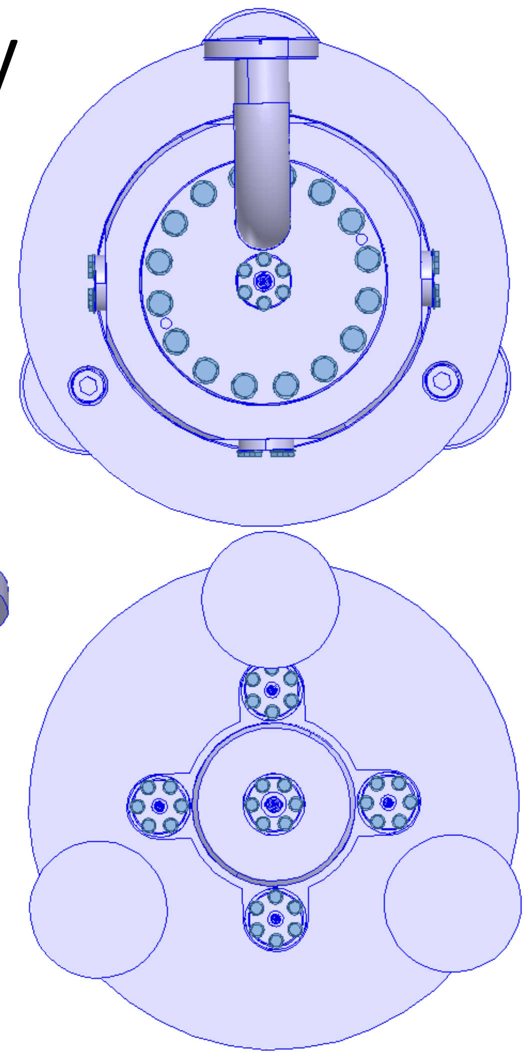
- Introduction to the Fixed Gap System
- Modal analysis of the gap
- Measurement of S-parameters
- Breakdown signal measurement with the current setup
- Going beyond cut-off
- Conclusions and future work

Introduction to the Fixed Gap System

The Fixed Gap System - Outer view

Stainless steel body

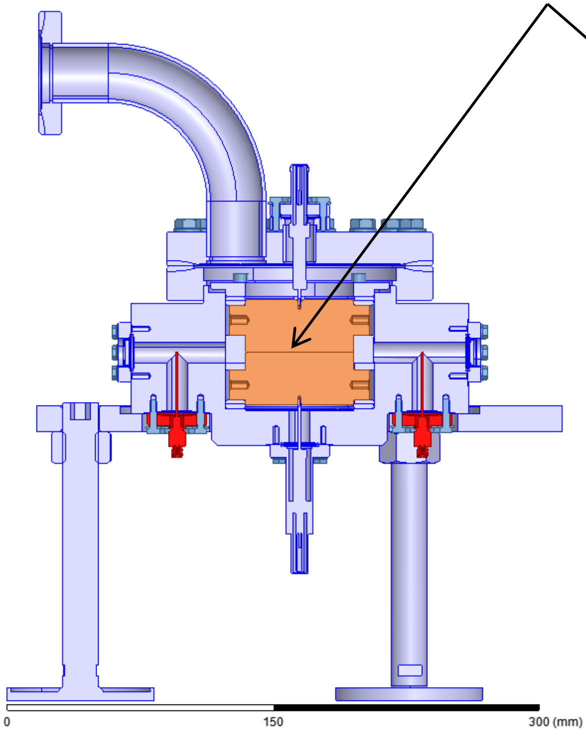




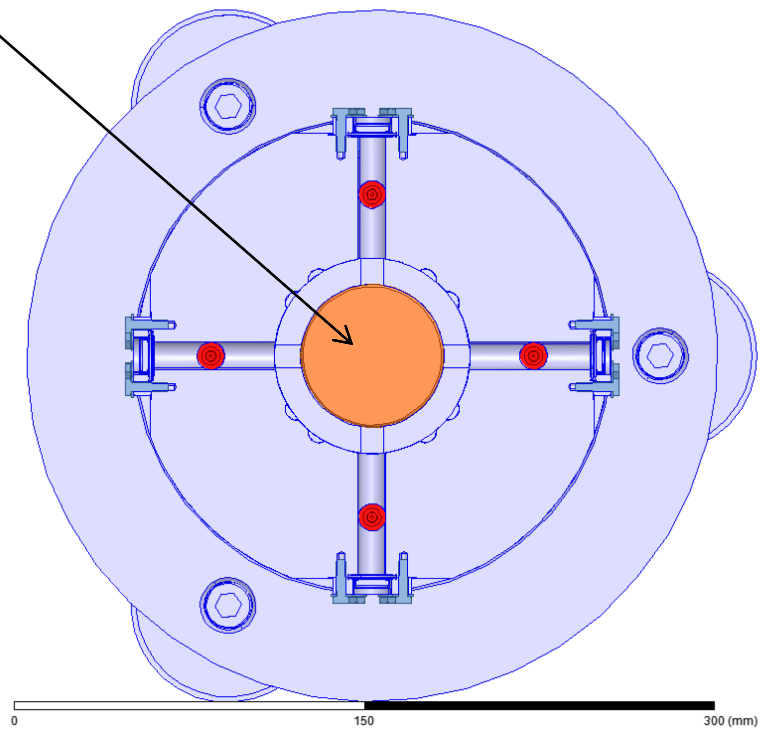
The Fixed Gap System – Section views and antennas

Copper electrodes (orange) and coax antennas (red)

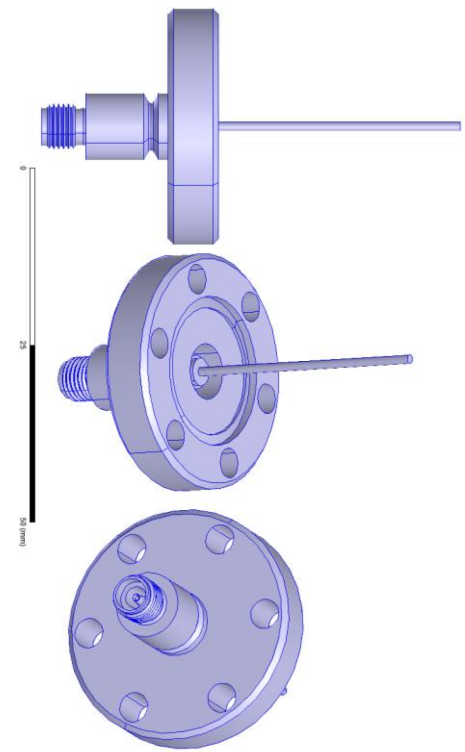
Breakdowns happen in this 60 µm gap



Side cross-section

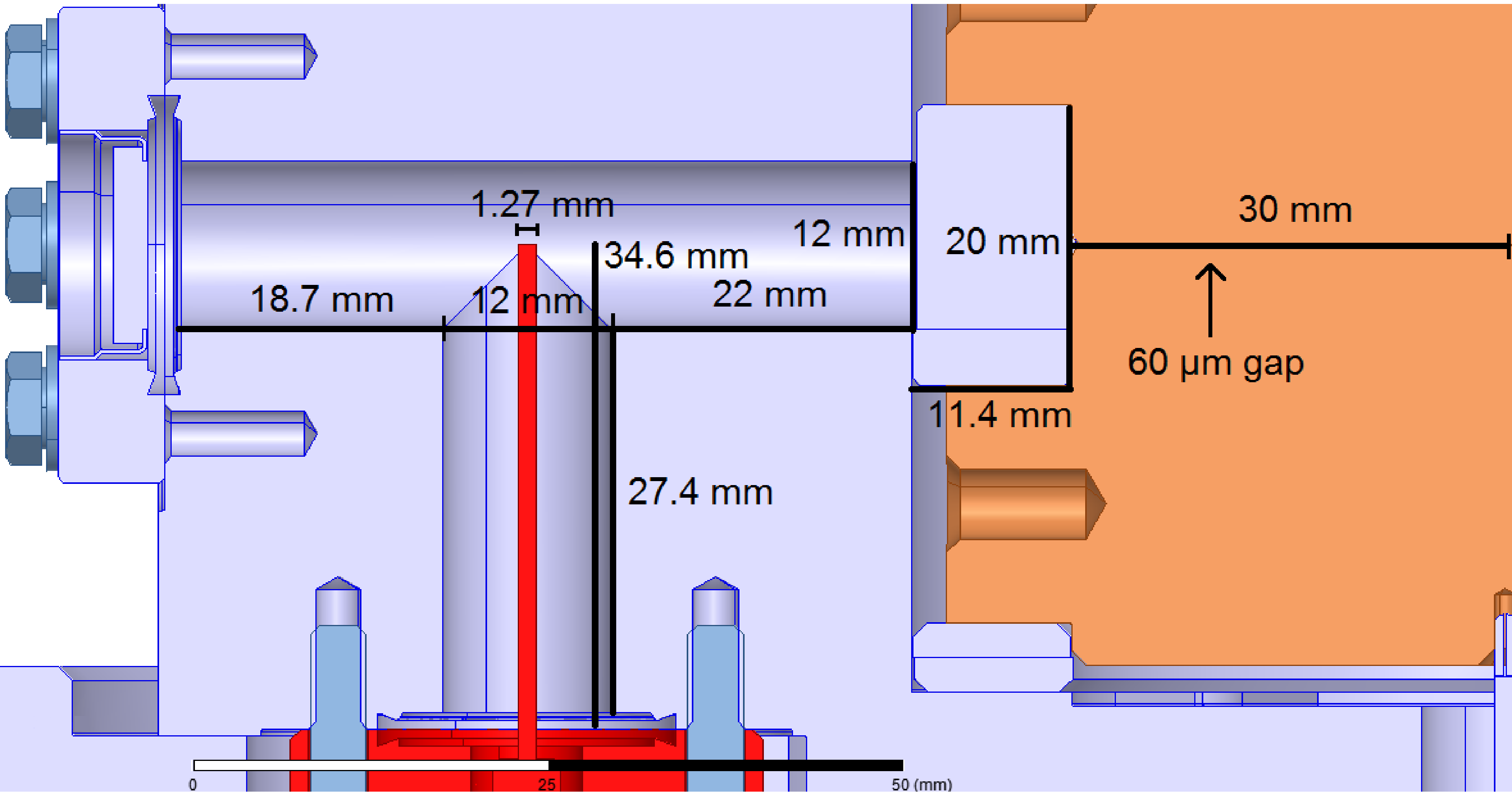


Top cross-section

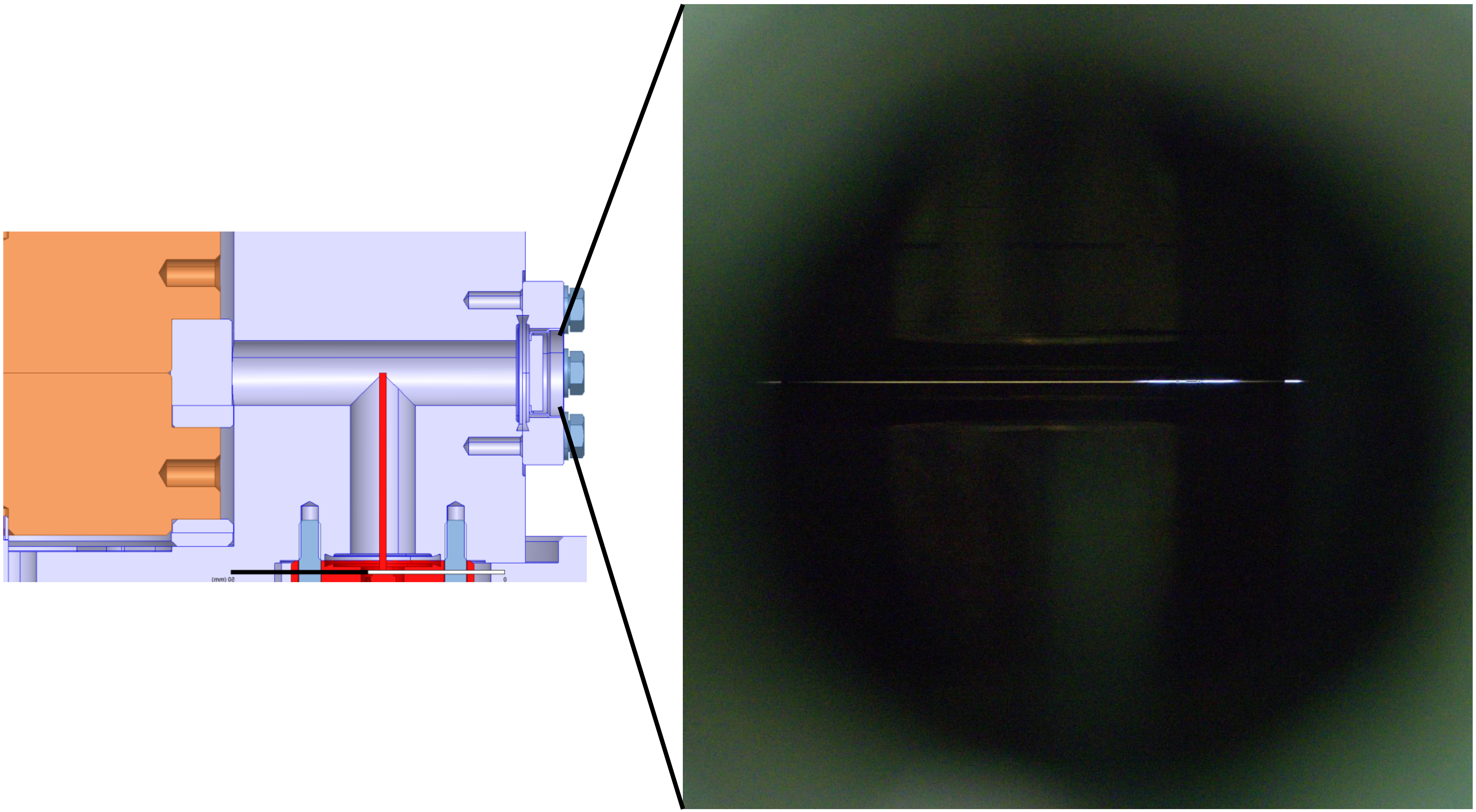


DN16CF SMA antenna

The Fixed Gap System – Detailed section view

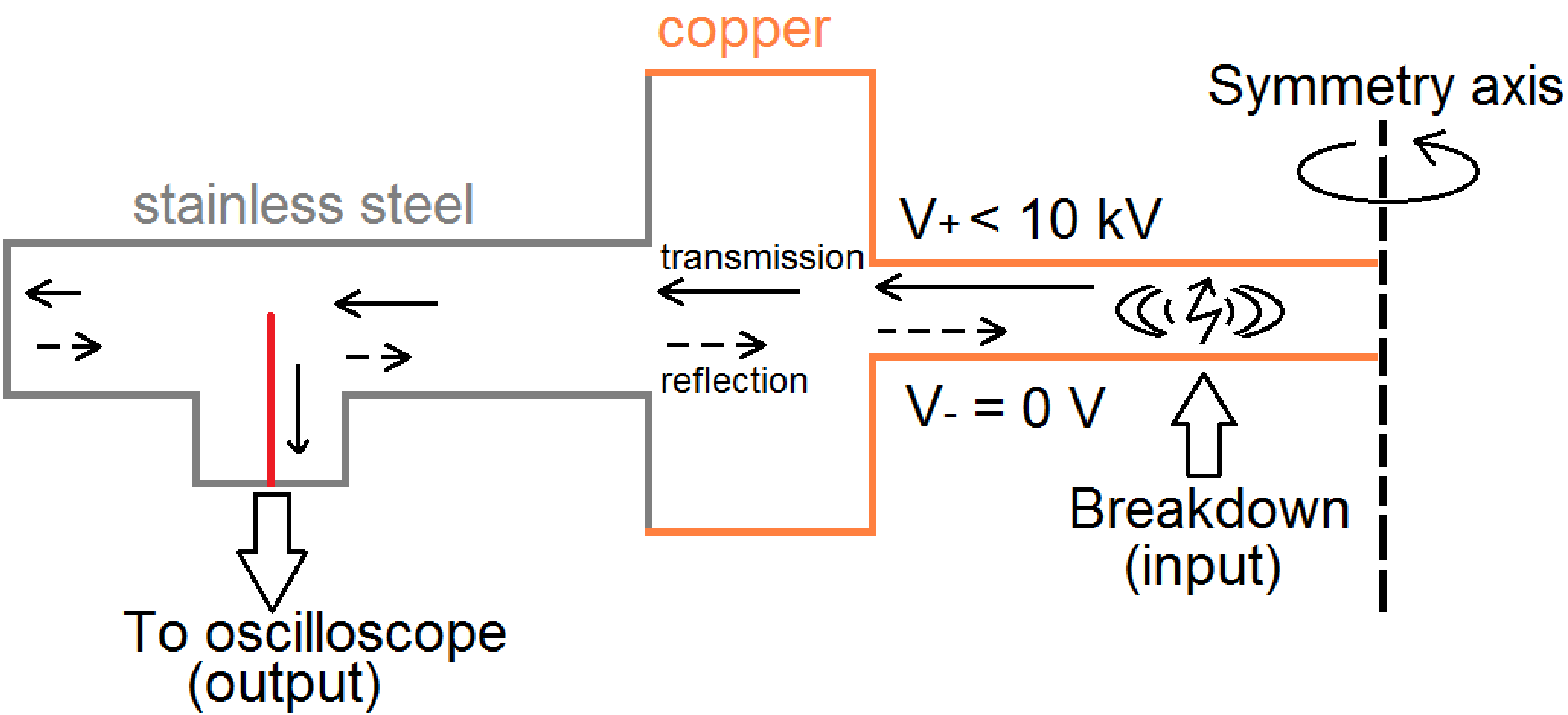


The Fixed Gap System – A closer look at a breakdown



An actual breakdown in the spark gap. Picture taken by Kyrre Sjobak.

The Fixed Gap System – Signal path

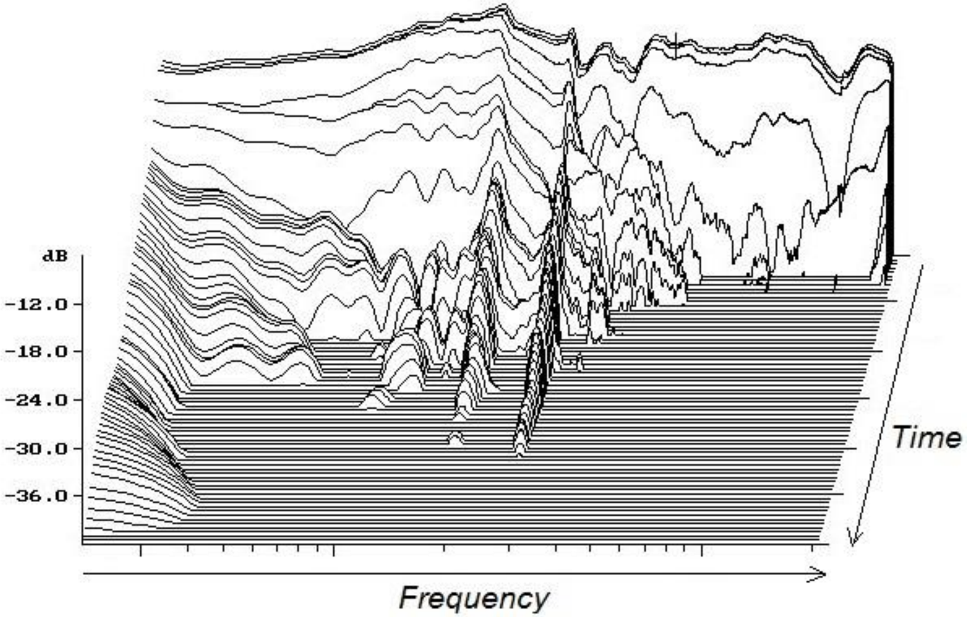


The breakdown signal propagates from the gap to the antennas, being attenuated and reflected from the boundaries of changing cross-section (=changing impedance) on its way.

Propagation and steady-state behavior

- Two aspects of the system are of specific interest:
  1. Propagation (*transmission*)
     - How well are the different parts of the system coupled to each other? = *"What frequencies reach the antenna?"*
  2. Steady-state behavior (*standing waves*)
     - What are the eigenmodes of the gap? = *"Which frequencies are useful for localization purposes?"*

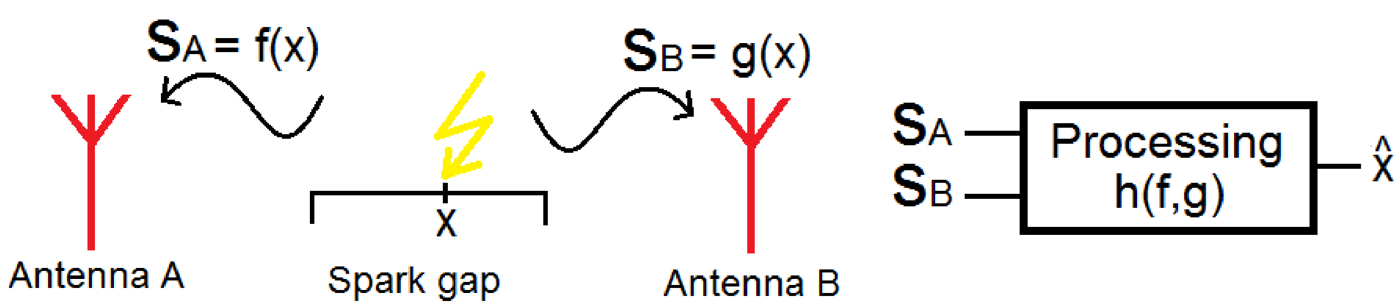
Ideally: "1. and 2. match" = frequencies of interest propagate to the antennas



A waterfall diagram [1].
(Not measured in the FGS)

Breakdown localization strategies – a short overview

- Task: decode position information from received signals = estimate



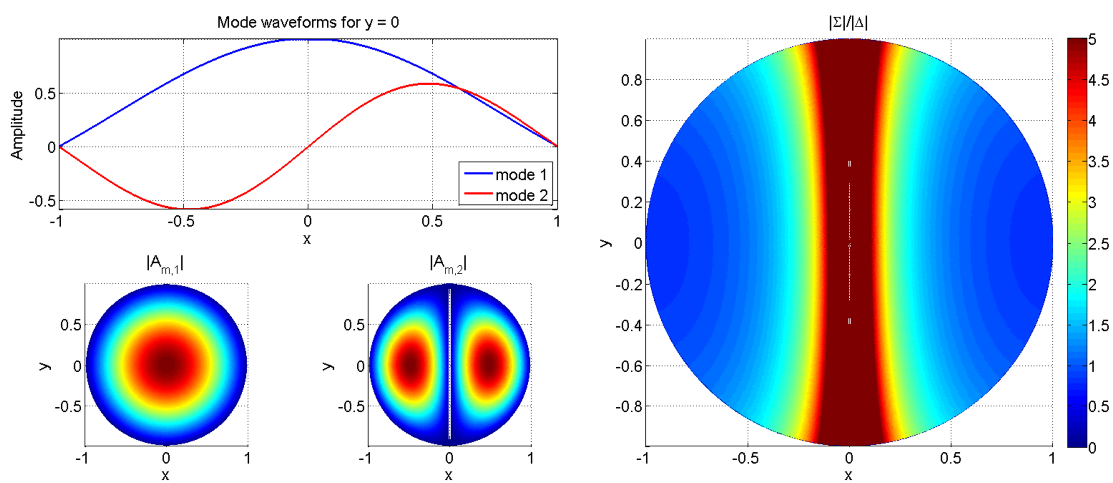
- Challenges: attenuation, multipath, reflection, non-controllable input, no direct way of verifying estimate correctness

Breakdown localization strategies – some considered techniques

Method	Description	pros	cons
Time difference of arrival (TDOA)	Triangulate BD position by time delay between antennas	Simple, widely used (LORAN C)	Limited BW, (1 sample delay: fs ≥ 30 GHz for 10 mm resolution)
Modal mapping	Mode amplitude is a function of excitation coordinates (cf. BPM)	Can be made independent of excitation signal	No control over transmitted signal -> difficult calibration, mode coupling
Difference signal between opposite antennas	Power of difference signal prop. to time delay	Not limited by BW issues, simple	loss/shadowing, coupling of radiation to antennas, power normalization
Phase difference between opposite antennas	Phase difference through downmixing (single freq.) or slope of difference (multiple freq.)	Not limited by BW issues	Is phase info. preserved in a usable form?, sensitive to multipath and noise
Optical	Camera + image processing	Simple, robust	New sensors needed, limited FOV, lighting?
Acoustical waves	Sensing of mechanical vibrations on the chassis	TDOA feasible	New sensors needed, may not be robust
Received signal strength (RSS) techniques	Amplitude differences in signals received at antennas correlated to BD position	widely used (in-/outdoor localization)	Limited BW, not very robust, no control over transmitted signal, complicated loss/shadowing effects

Breakdown localization strategies – Modal mapping

- Can a similar method to BPM be used for BD localization in the FGS?
  - Use monopole for intensity
    - eliminate unknown and varying excitation = reference/calibration
  - Use dipole for position
    - phase and magnitude carry information about x and y
    - 2 pairs of antenna necessary for knowing both x and y

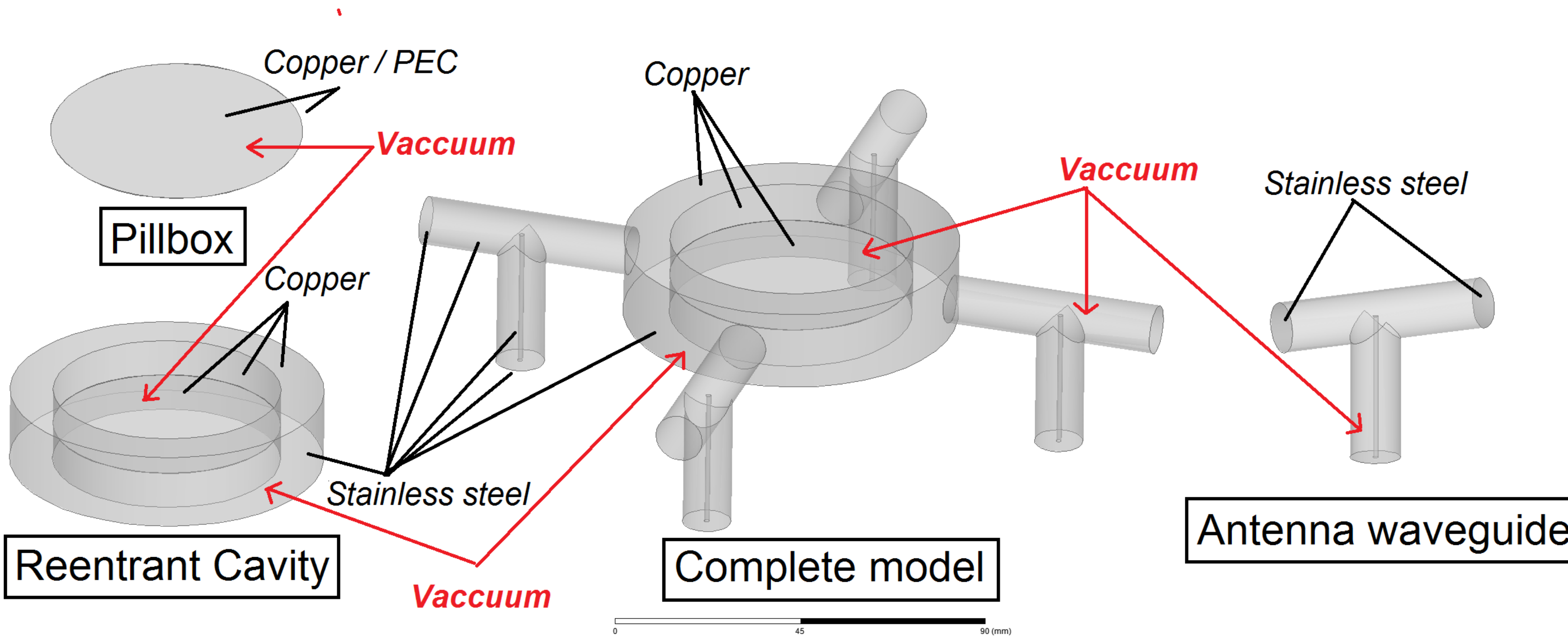


Need to do a modal analysis of the gap/system in order to understand its steady-state beahavior

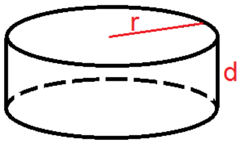
Modal analysis of the gap

Modal analysis – Used models

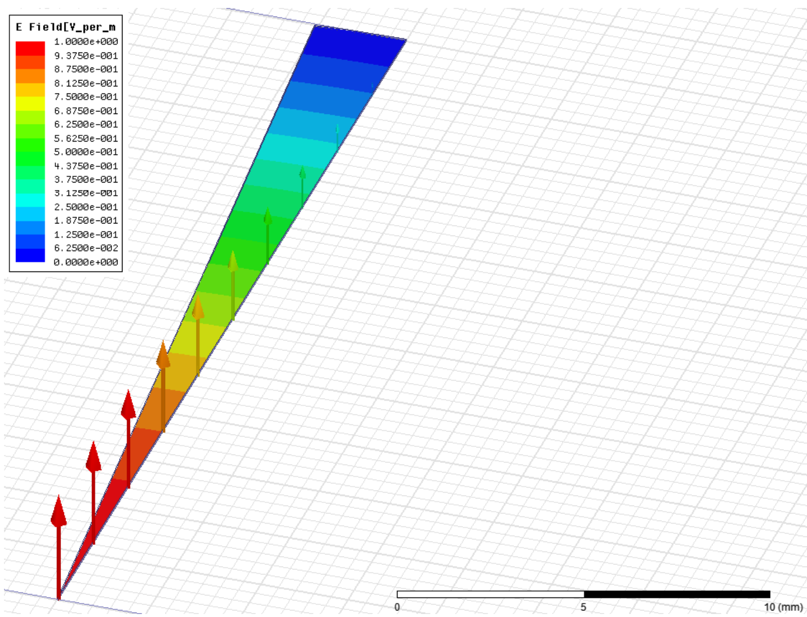
- HFSS simulation of the inner geometry
  - Symmetry can be exploited and the models simplified for faster computation



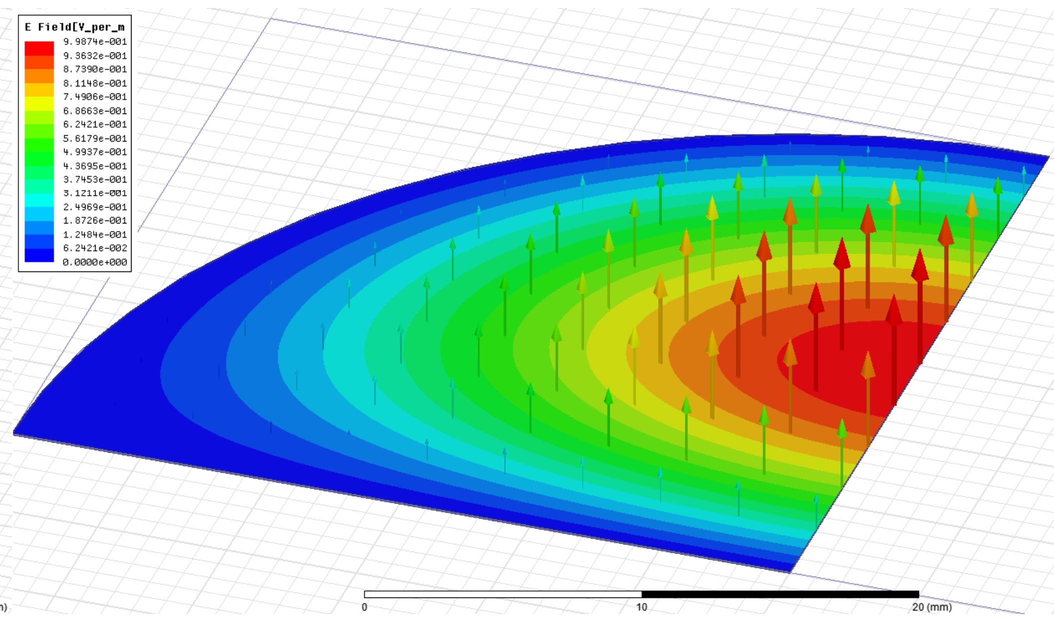
Modal analysis – Pillbox



r = 30mm, d = 60 µm



TM010



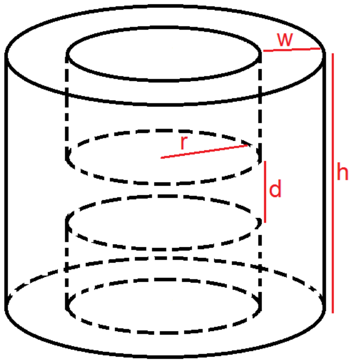
TM110

f = 3.8 GHz

Q = 56

f = 6.1 GHz

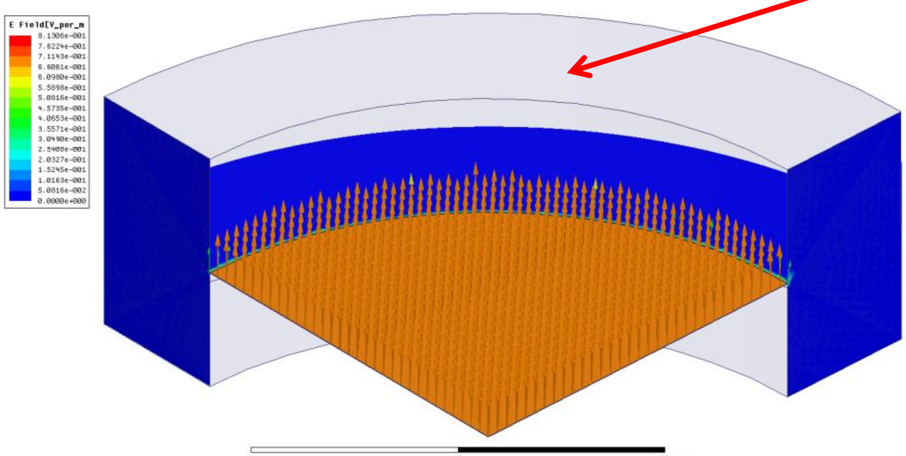
Q = 71

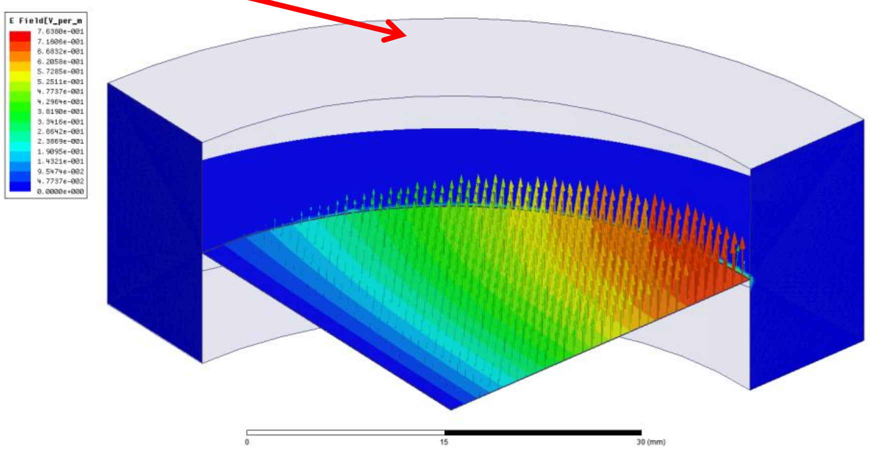


Modal analysis – Cavity

r = 30mm, d = 60 µm, w = 11.4 mm, h = 20 mm

Cavity filled with vacuum, instead of actual dielectric spacer (Al_2O_3)





First monopole

f = 0.21 GHz

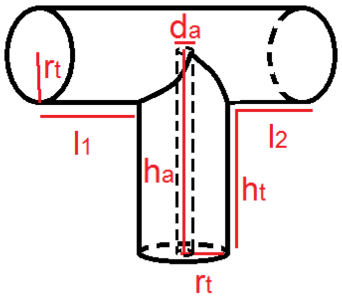
Q = 308

First dipole

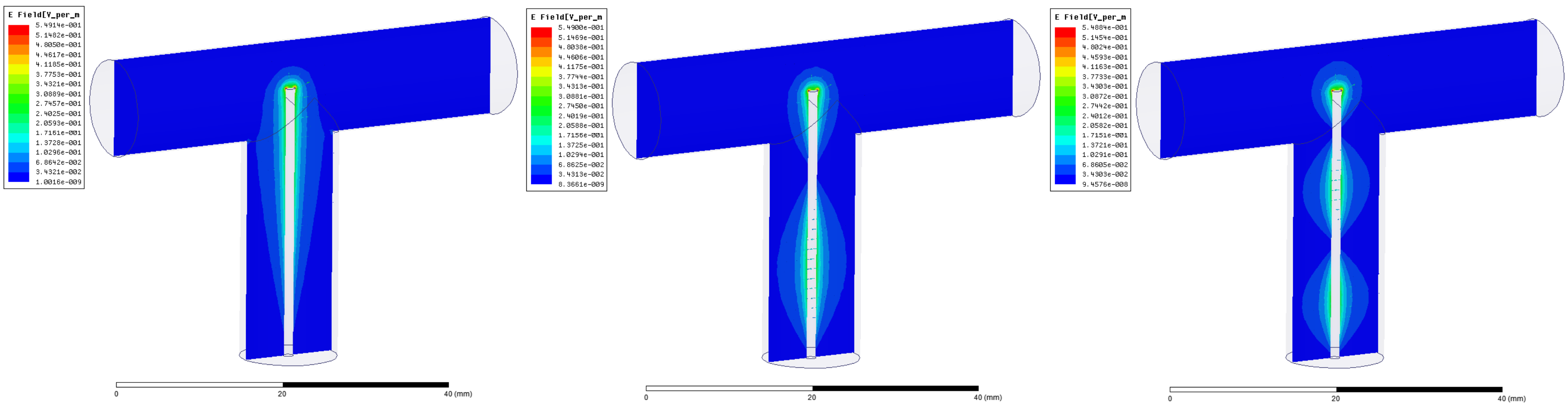
f = 2.9 GHz

Q = 50

Modal analysis – Antenna waveguide



r_t = 6mm, h_t = 27.4 mm, h_a = 34.6 mm, d_a = 1.27 mm , l_1 = 18.7 mm, l_2 = 22 mm



f = 2.1 GHz
Q = 233

f = 6.4 GHz
Q = 407

f = 10.6 GHz
Q = 540

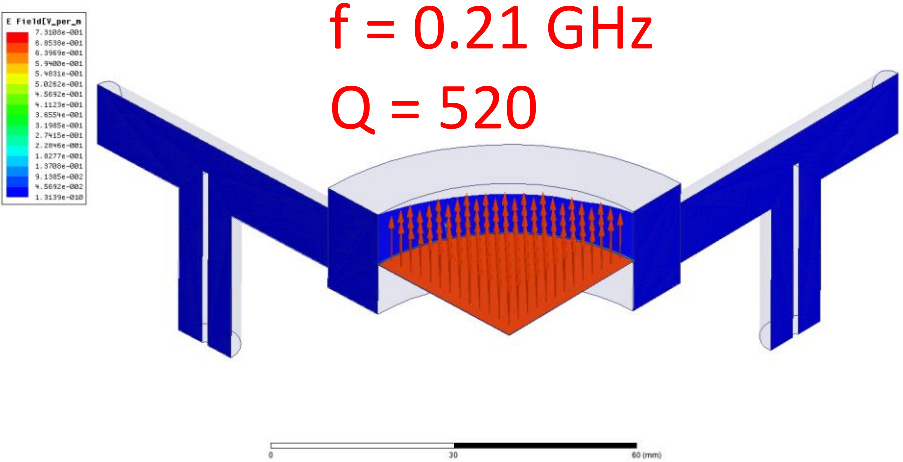
Cylindrical waveguide lowest cut-off: f_c = 14.6 GHz (TE_{01})

Modal analysis – Complete model

- Agreement with previous simulations
  - Modes couple weakly to the antennas

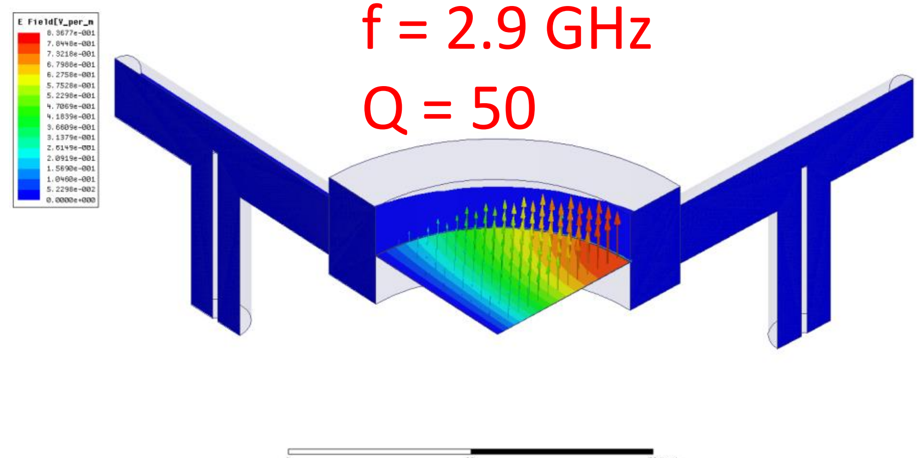
f = 0.21 GHz

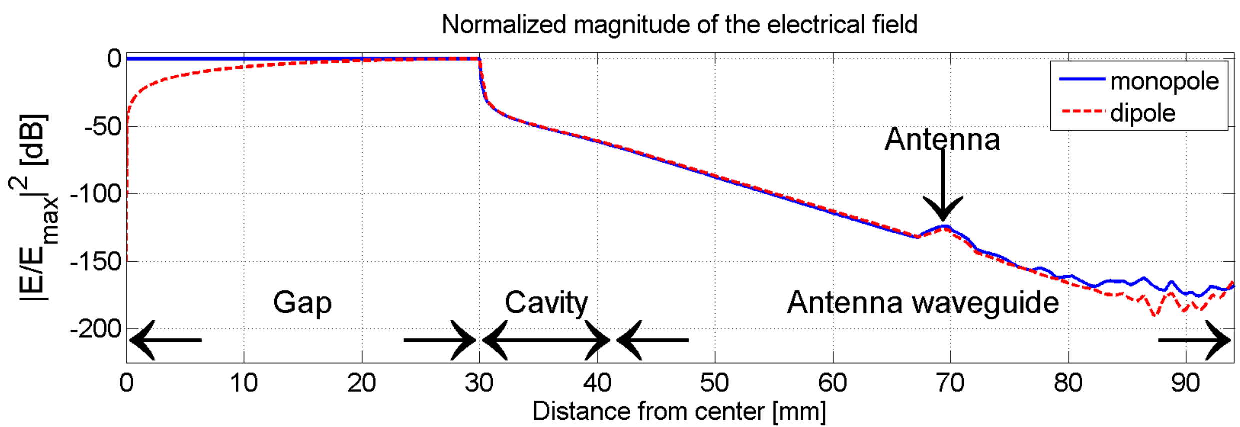
Q = 520



f = 2.9 GHz

Q = 50

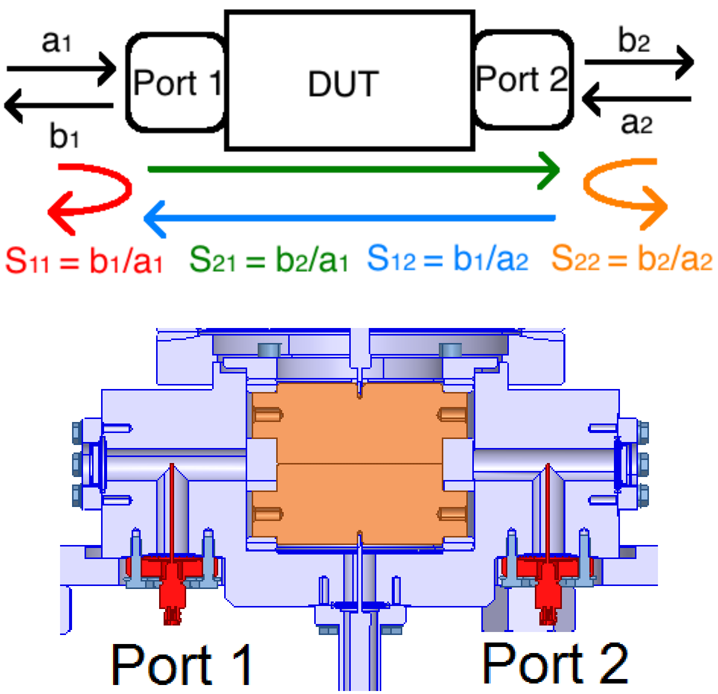




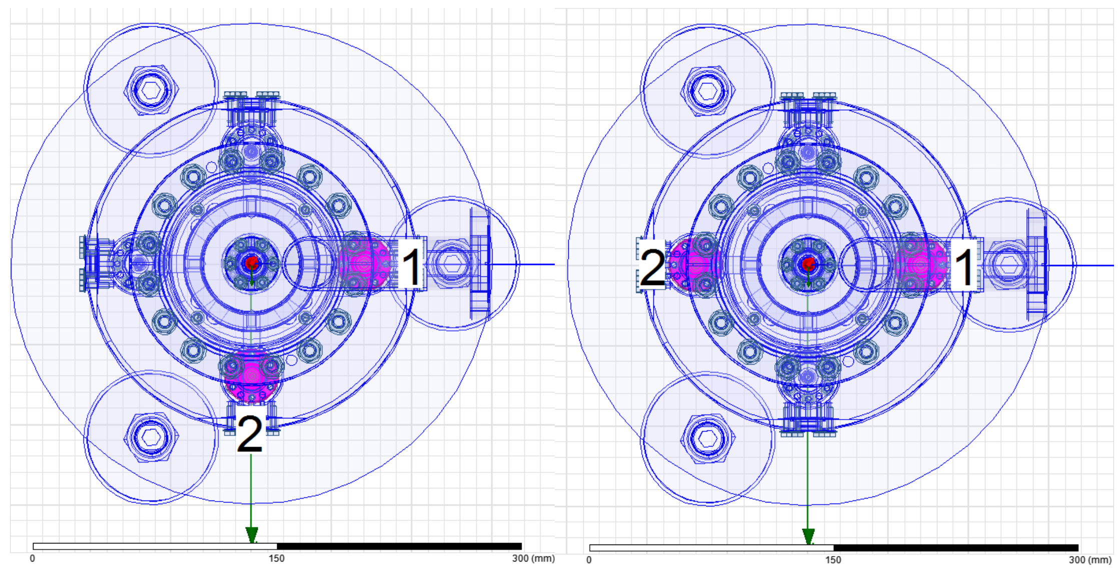
Measurement of S-parameters

Vector Network Analyzer (VNA) - Setup

- Measure S-parameters of neighboring and opposite antennas



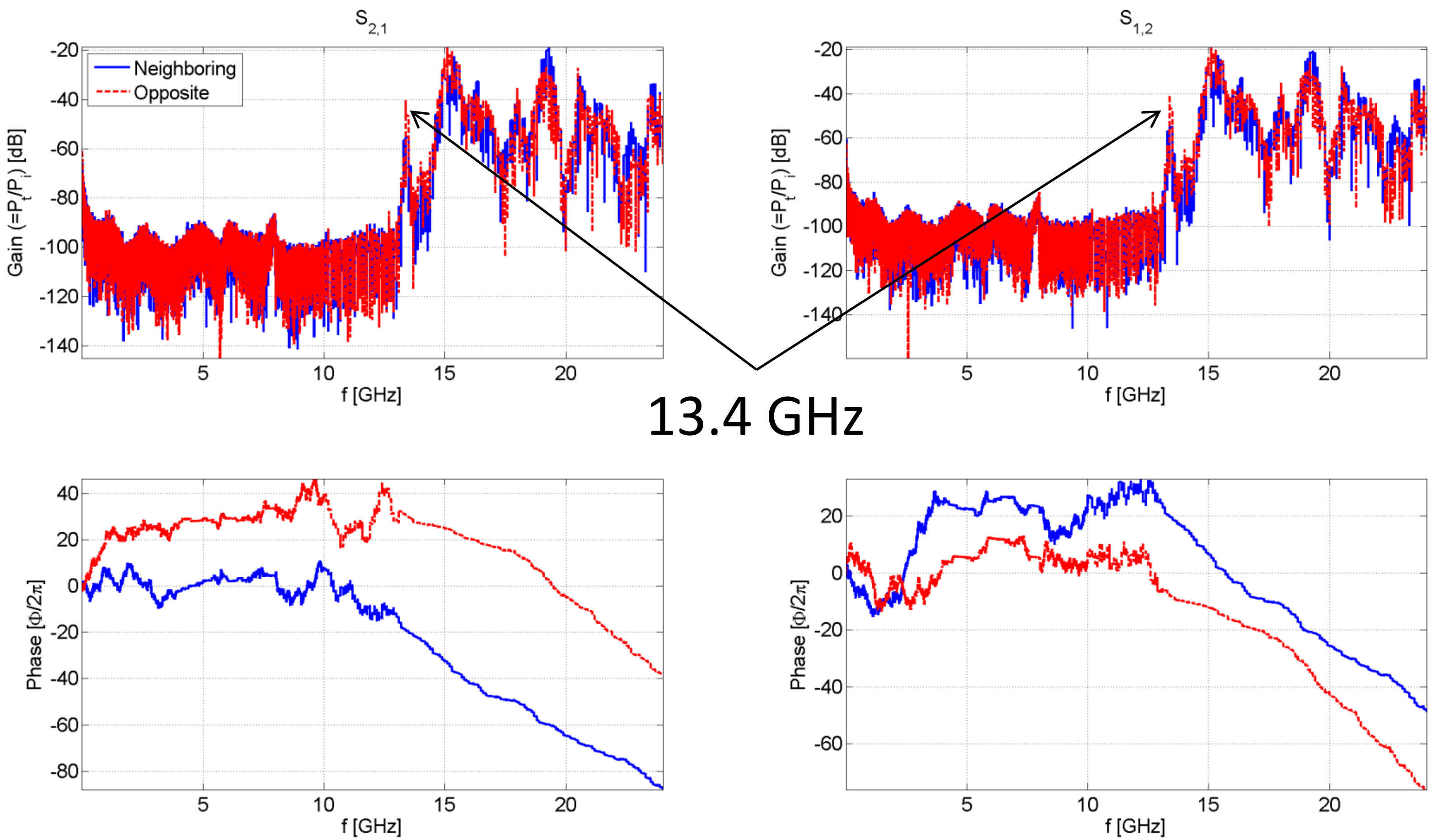
Concept of S-parameters and VNA setup



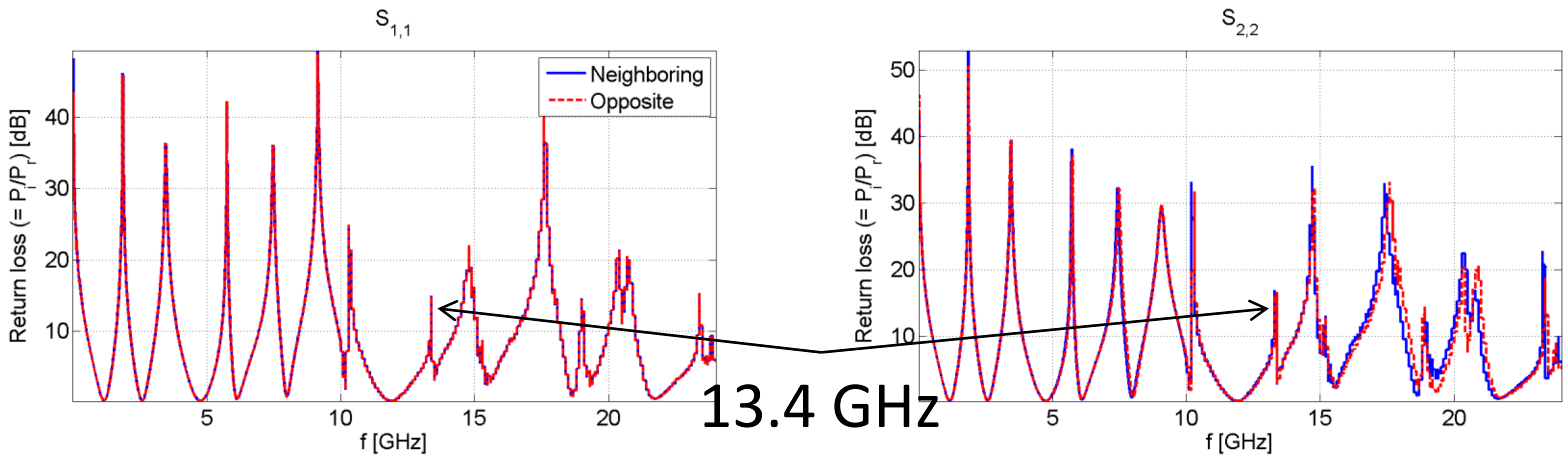
Top view of ports analyzed with the VNA

VNA – Transmission results

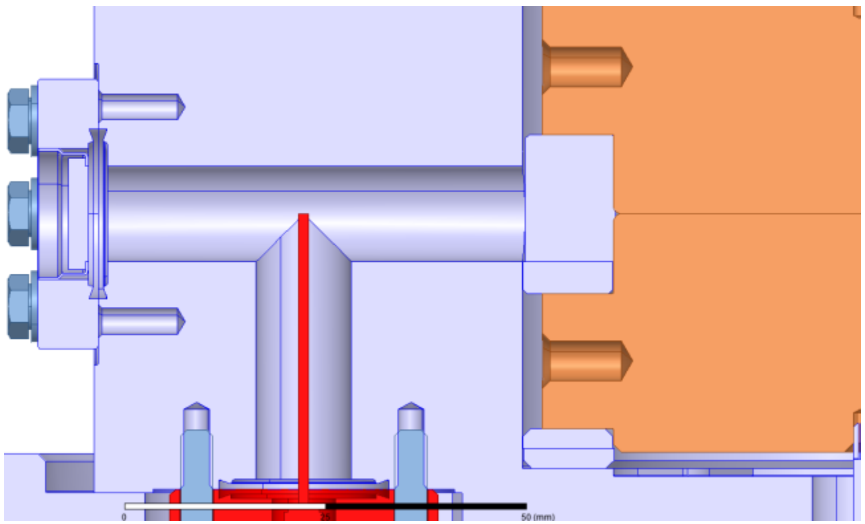
- Cut-off agrees with simulations



VNA – Reflection results

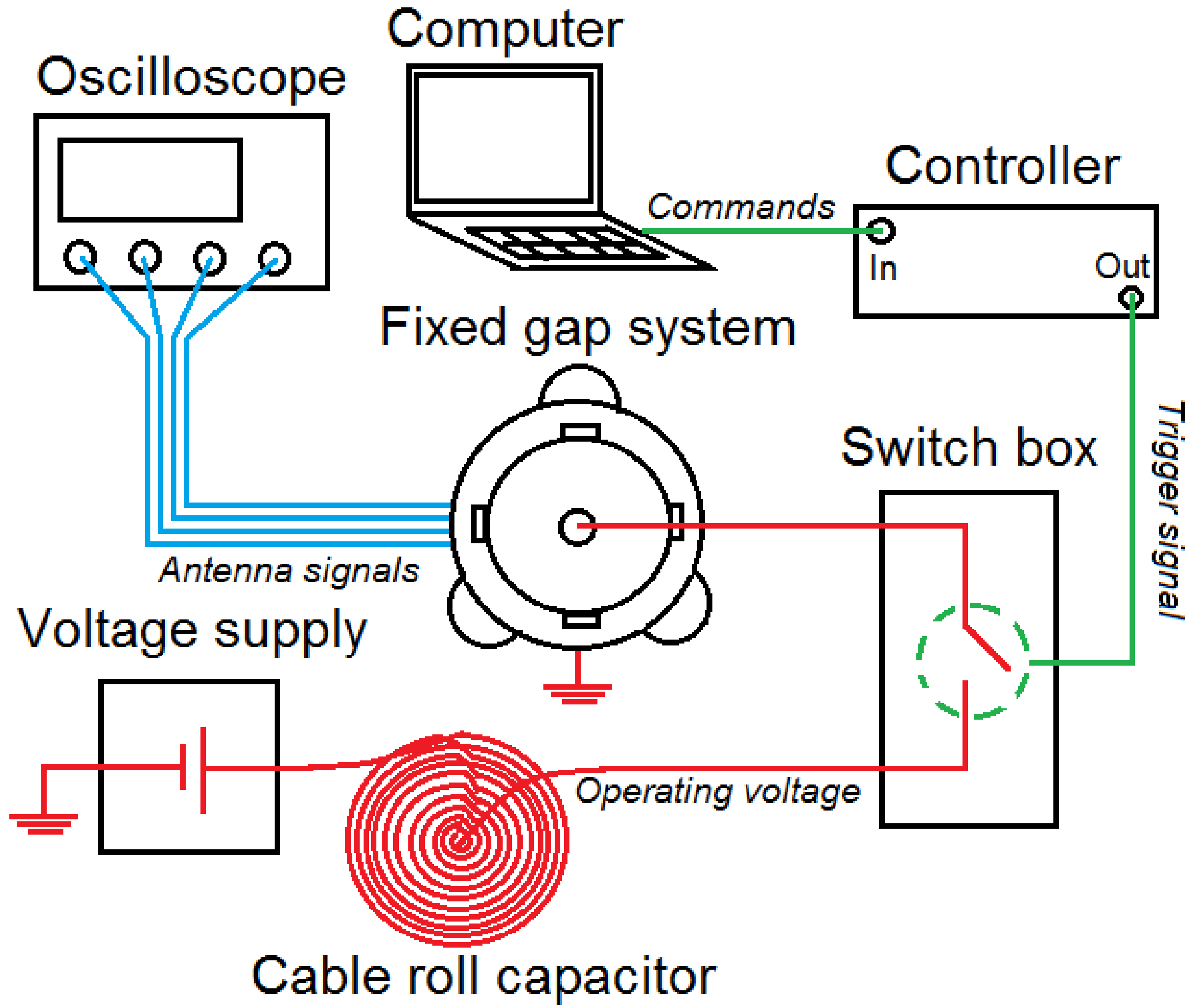


- A possible explanation:
  - Below cut-off:
    - well defined peaks determined by the antenna and its immediate surroundings
  - Above cut-off:
    - reflections get more complicated as the rest of the system's geometry influences the results



Breakdown signal measurement with the current setup

Antenna signal measurement – setup



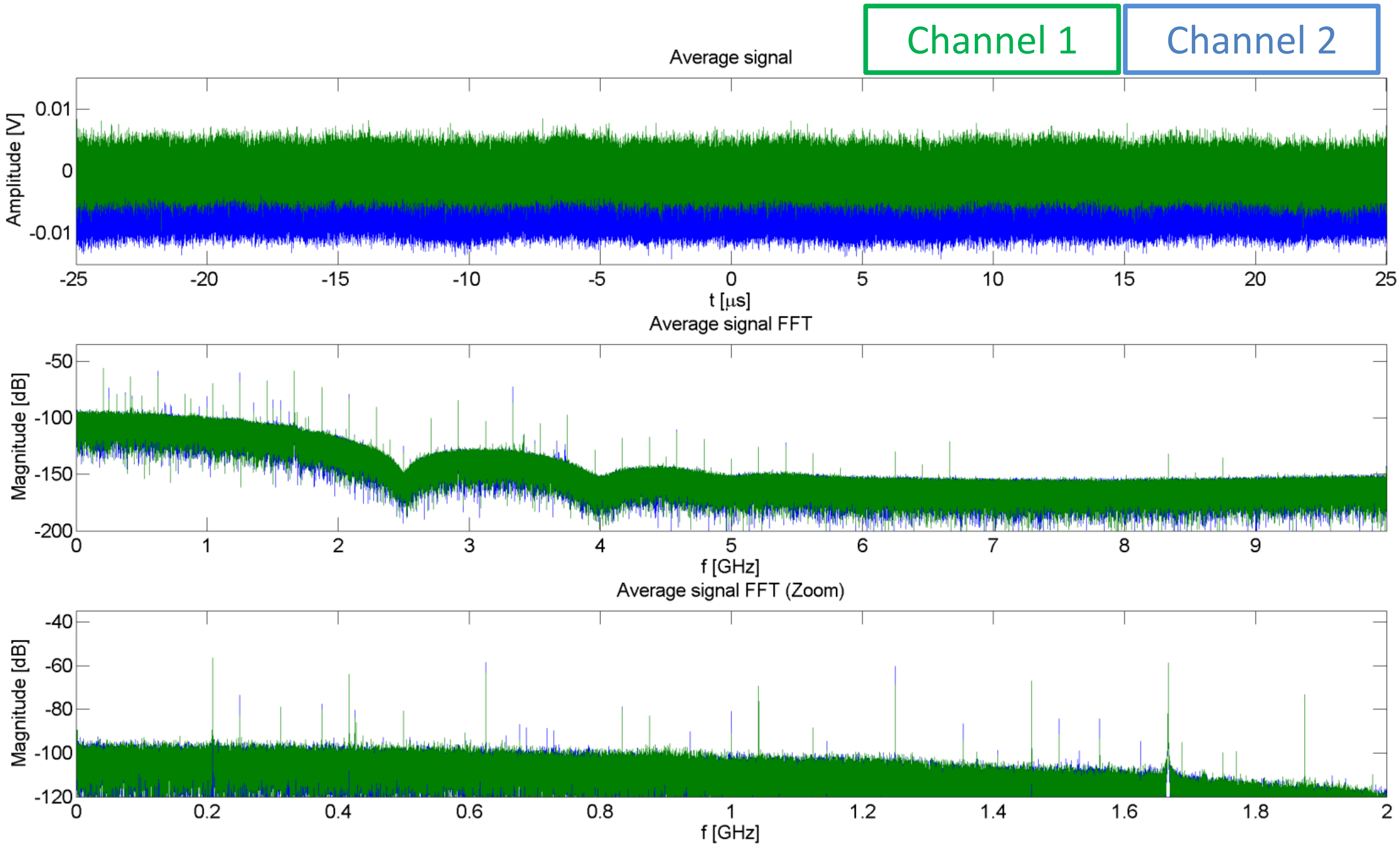
Next: What does the current setup actually pick up?

Measurement 1 – background noise

- Goal: understand the limitations of the oscilloscope
- Two setups:
  a. External loop antenna
  b. FGS antennas

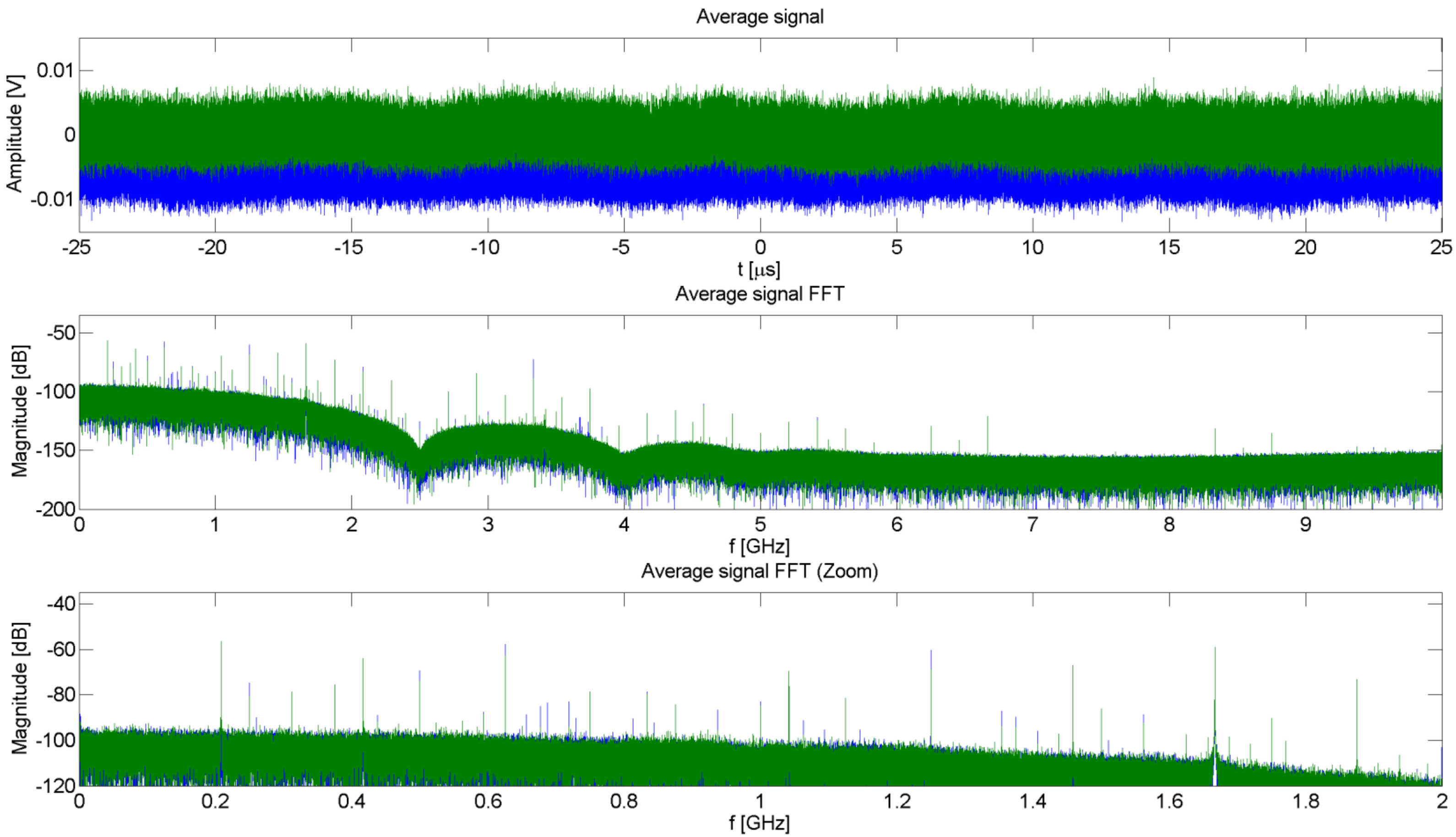
The makeshift loop antenna for system-external measurements

Measurement 1 – background noise, external loop antenna



500 snapshot average, Oscilloscope with external loop antenna (<u>not</u> FGS antennas!), 20 GS/s

Measurement 1 – background noise with FGS antennas



500 snapshot average, Oscilloscope with opposite FGS antennas, 20 Gs/s

Background noise measurement - conclusions

- Oscilloscope (Lecroy WavePro 7100A)
  1. Limited bandwidth (1 GHz analog BW)
  2. Harmonic noise (multiples of 208 MHz)
  3. Channel DC-offset

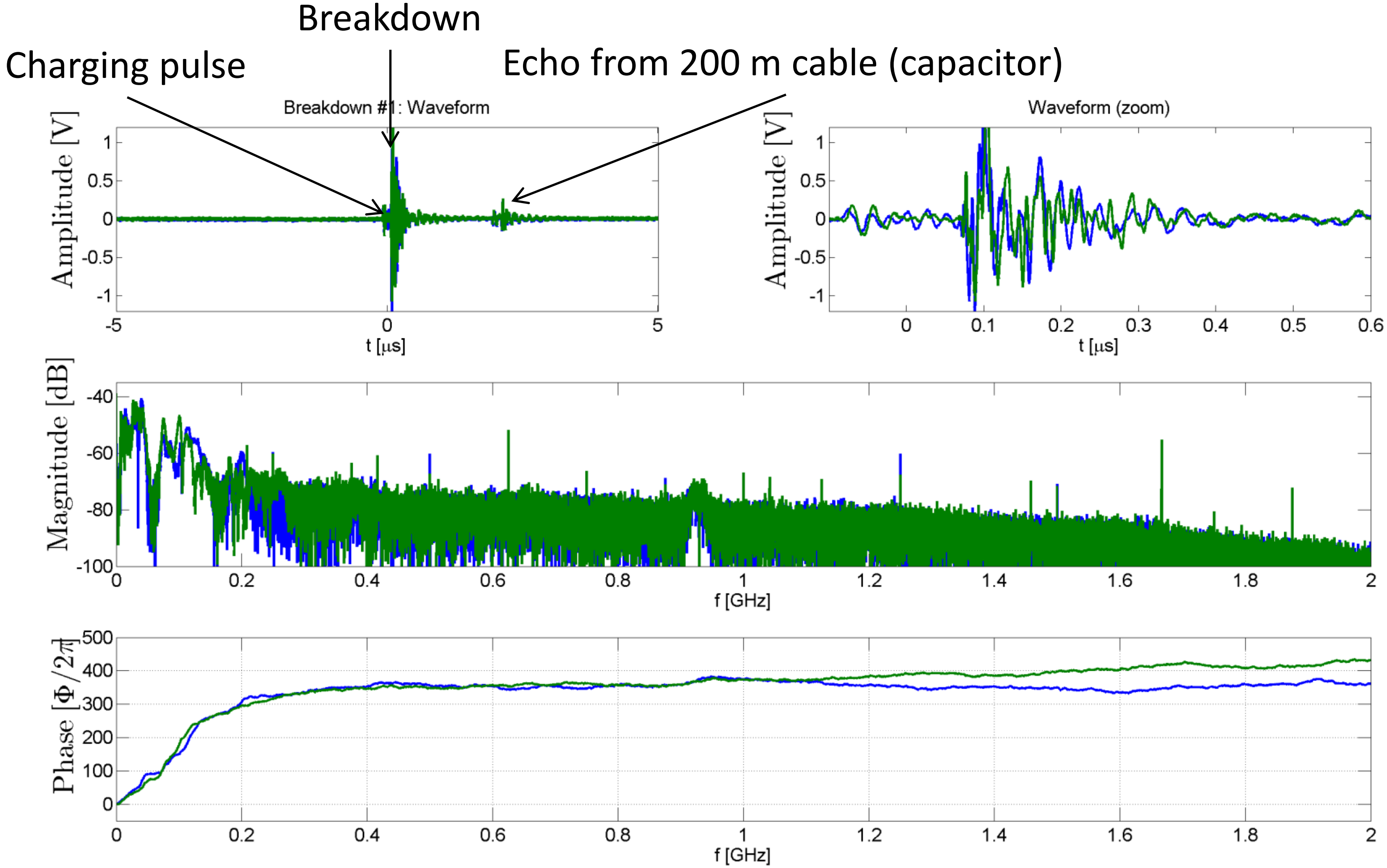
Cannot say much about anything above 1-2 GHz (without downmixing)

Measurement 2 – Breakdown signal

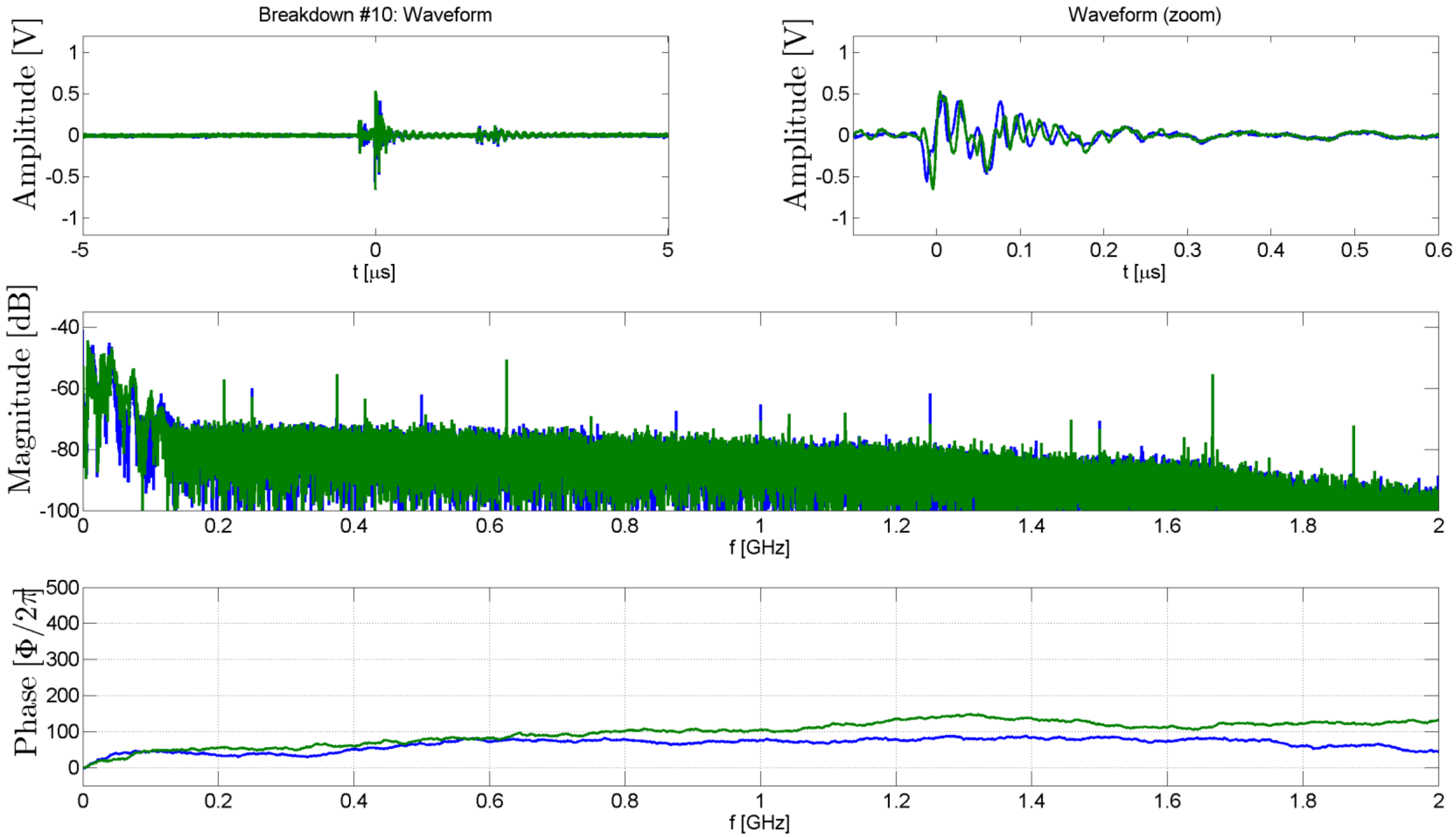
- Goal: see if anything useful is picked up by the antennas
- 3 setups:
  a. Cables attached to opposite FGS antennas
  b. Cables detached from FGS antennas
  c. External loop antenna

Antenna T-connectors and the terminations (50 Ohm, < 18 GHz) at the unused ports

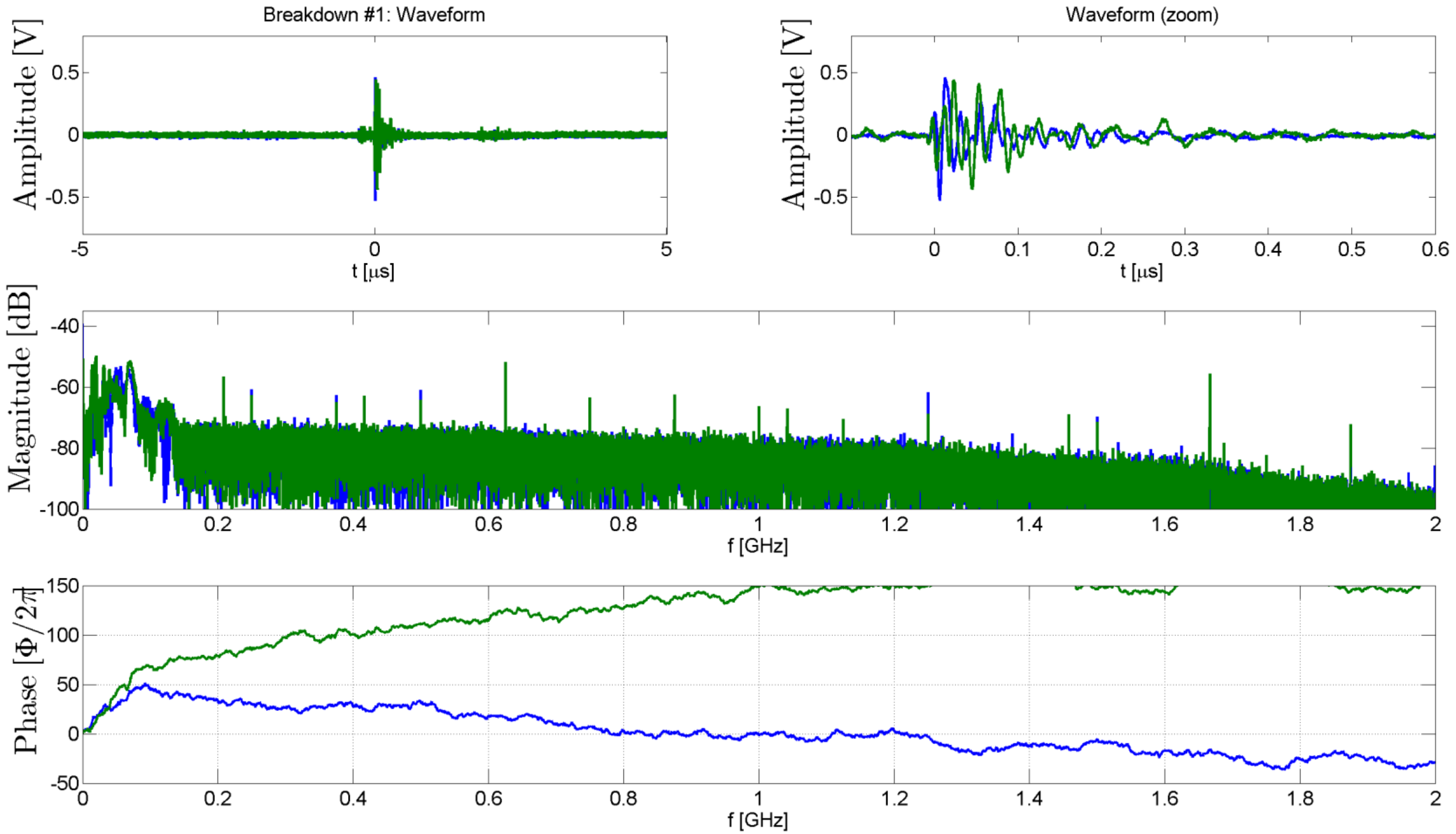
Measurement 2 - Breakdown signal, FGS antennas



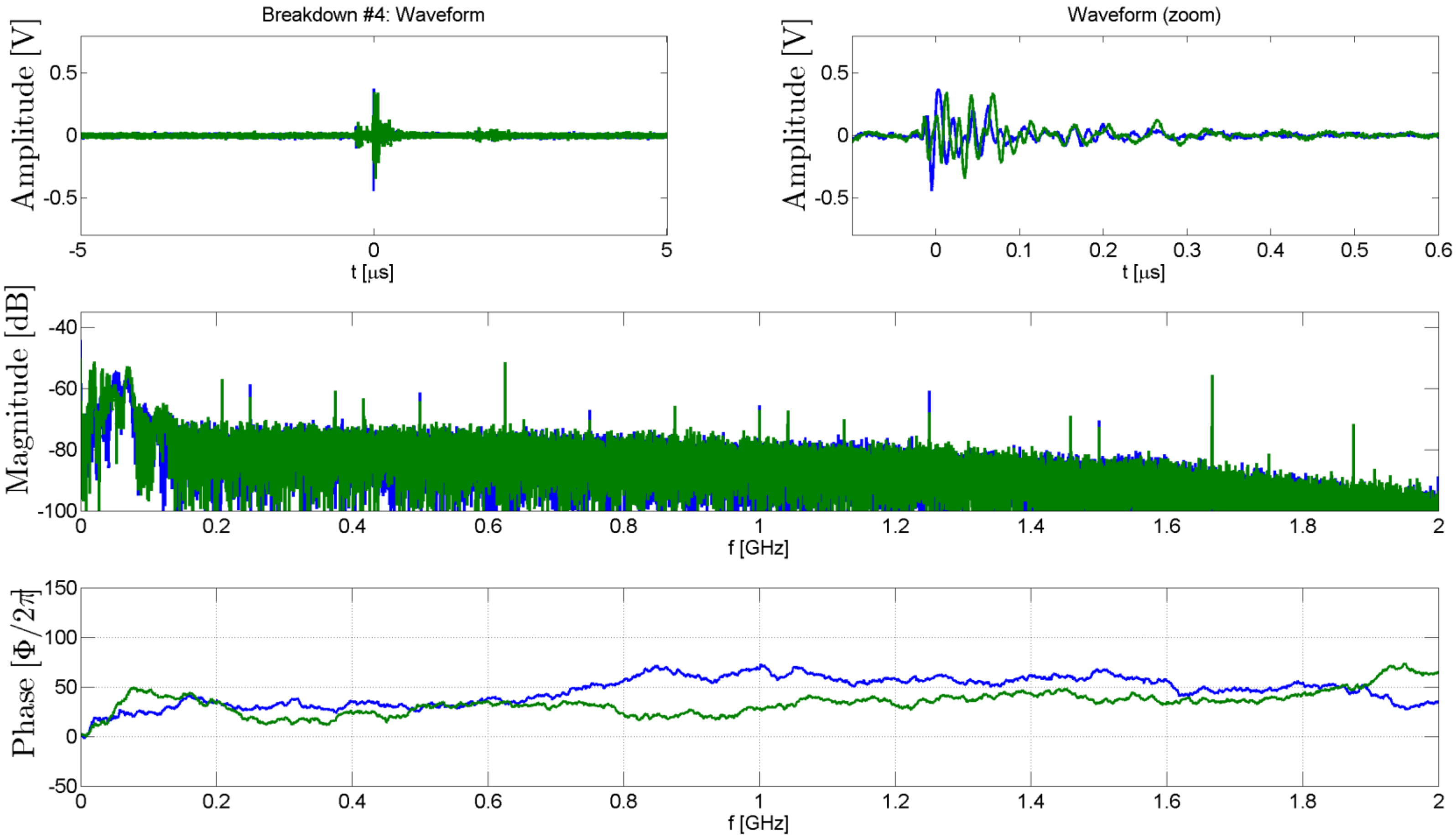
Measurement 2 - Breakdown signal, FGS antennas



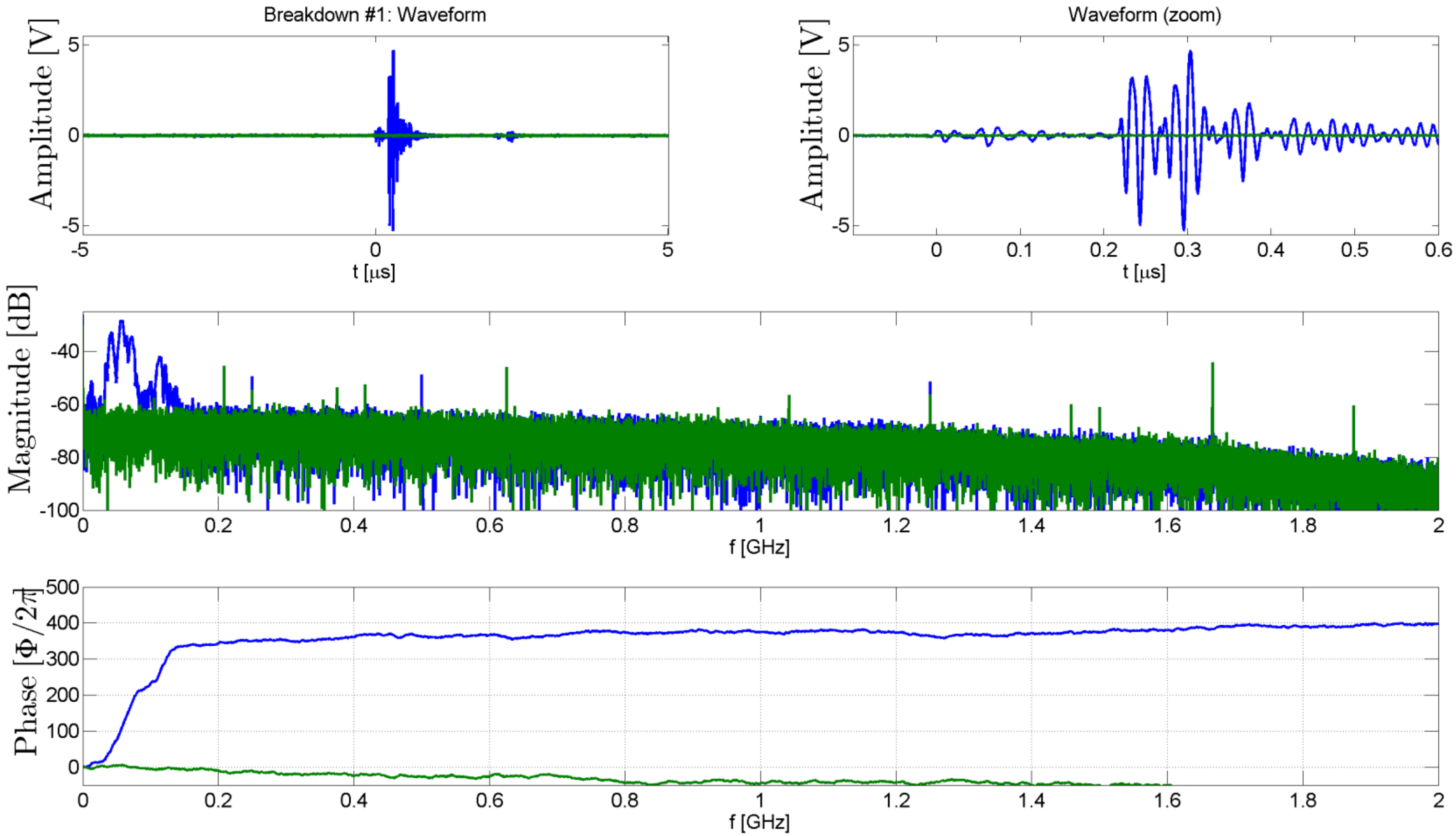
Measurement 2 - Breakdown signal, cables detached



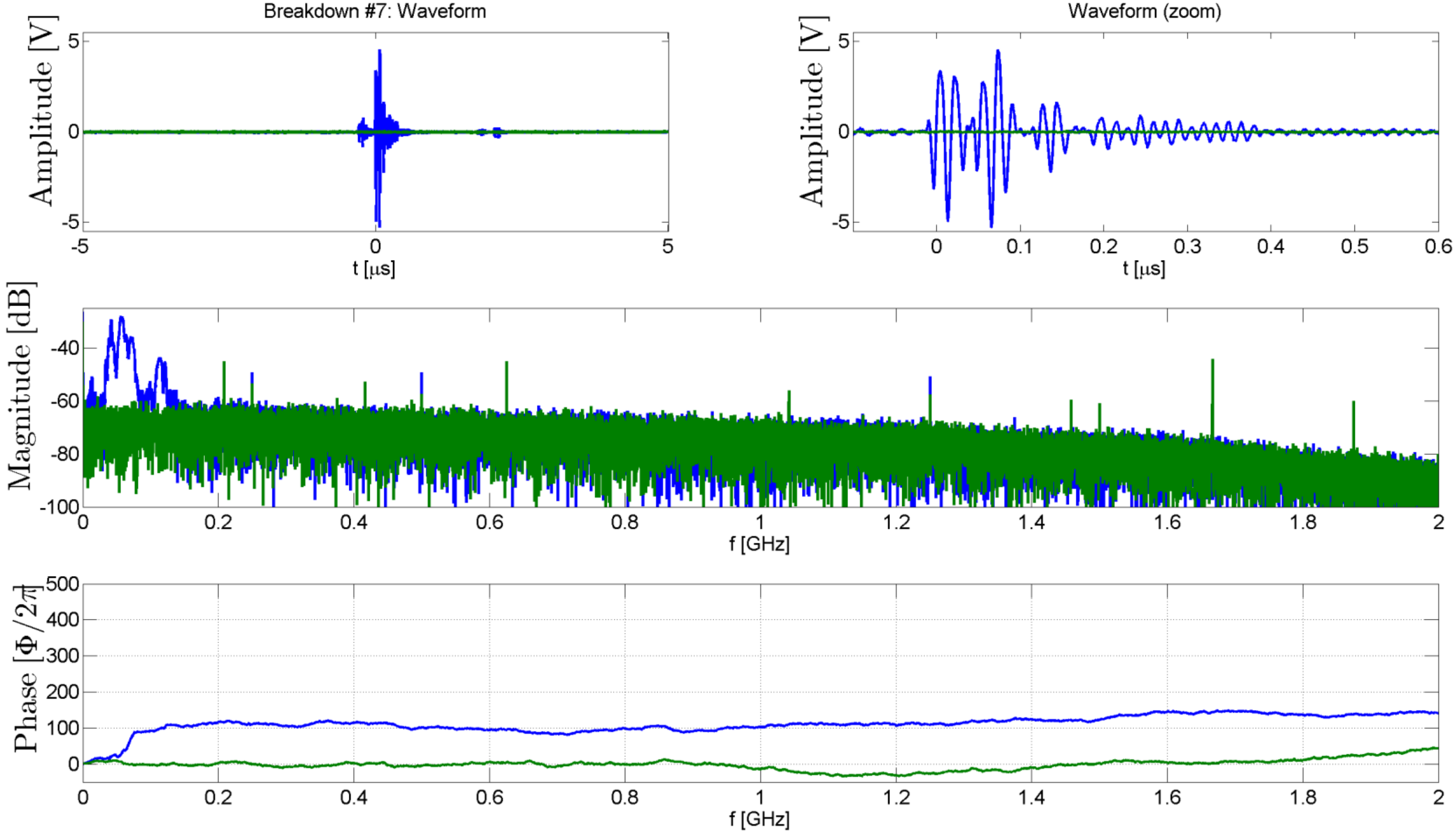
Measurement 2 - Breakdown signal, cables detached



Measurement 2 - Breakdown signal, external loop antenna



Measurement 2 - Breakdown signal, external loop antenna



Breakdown signal measurement - Conclusions

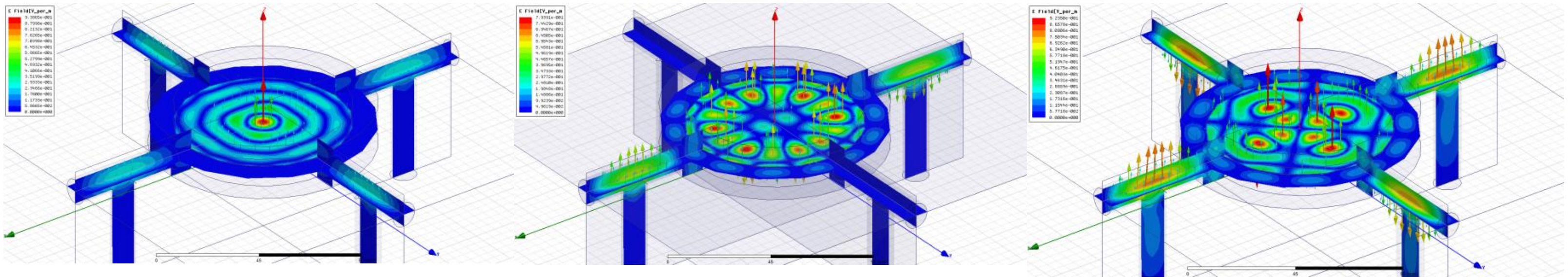
1. No significant signal above 200 MHz (as seen on the oscilloscope)
2. Low frequency content largely picked up/ created outside of the system
   – Ground oscillations (?) and propagation through air

No useful signal within oscilloscope bandwidth. What about above 13 GHz?

Going beyond cut-off

13 GHz and beyond - challenges

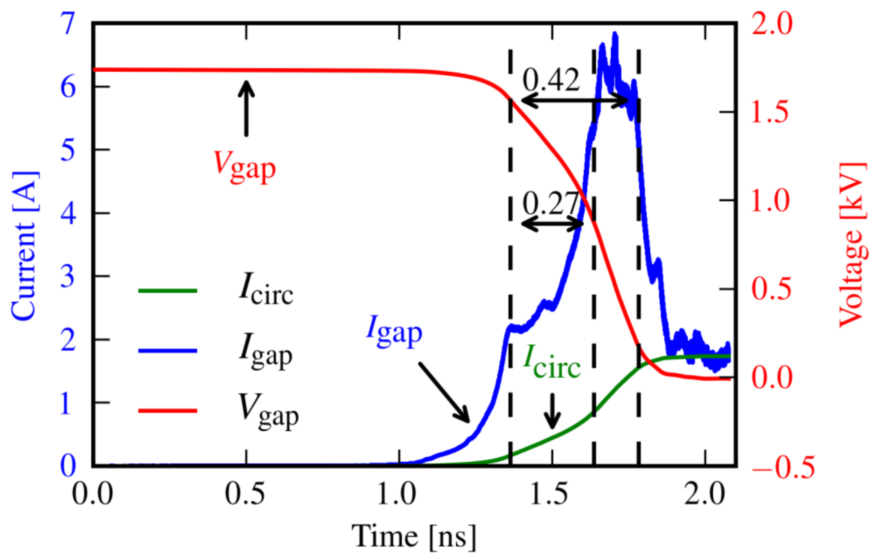
- Downmixing of high frequencies that actually couple well to the antenna is possible...
- ... but faces two challenges:
  1. High order standing wave patterns complicate breakdown localization
  2. The breakdown signal may not excite these frequencies

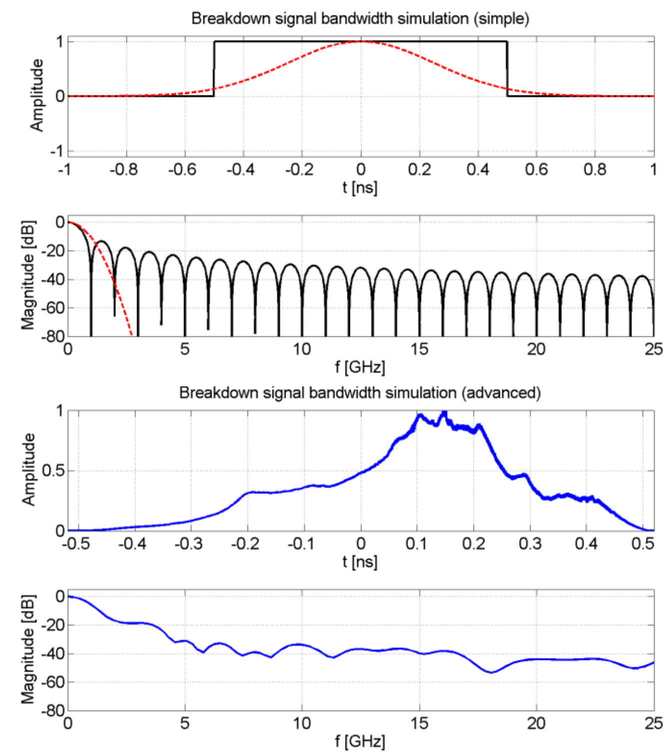


Some gap eigenmodes that couple to the antennas around 15 GHz.

Breakdown gap current bandwidth estimation

- What about the bandwidth of the breakdown signal?





Left: Arc current simulation [1]. Right: FFT of simple waveforms and arc current simulation

- Nothing conclusive, but may give some idea of what to expect

Conclusions and future work

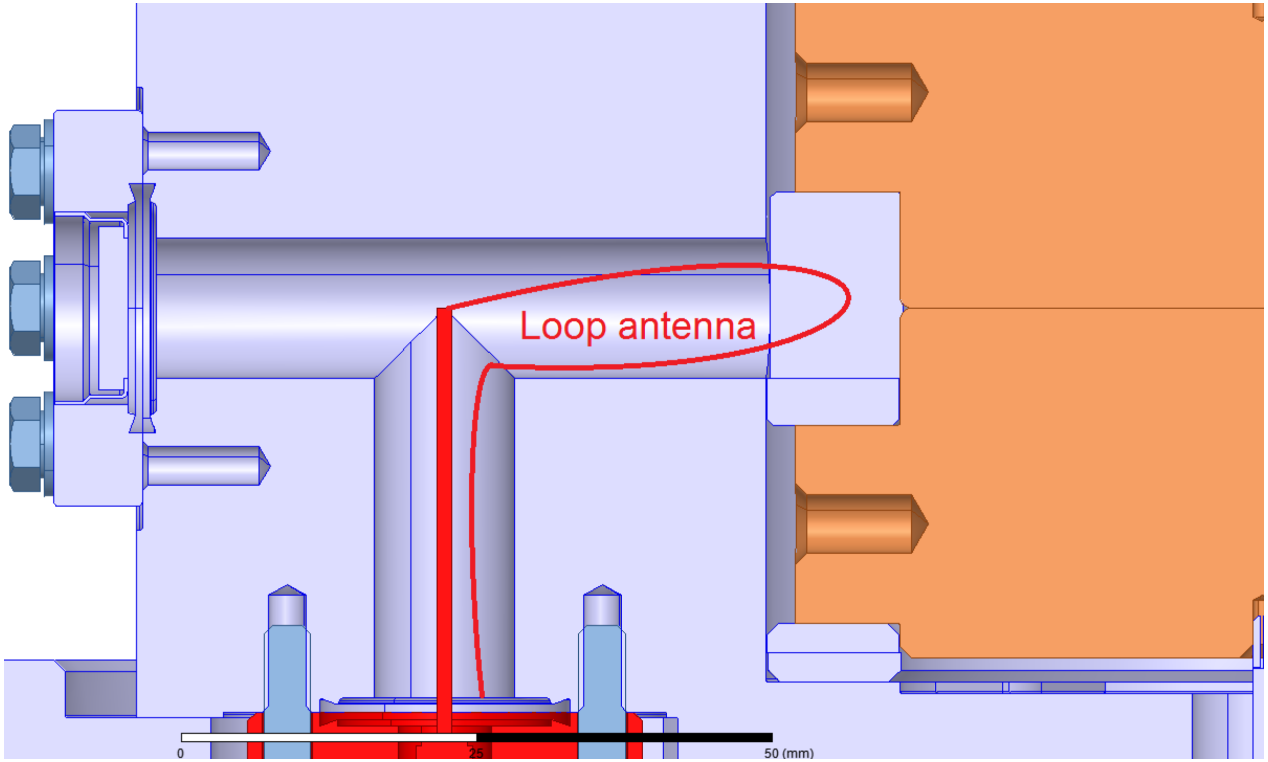
Conclusions

1. Interesting frequency band 3-6 GHz (gap monopole and dipole modes)
2. Unable to work below 13 GHz, due to antenna waveguide cut-off
3. Frequencies above 13 GHz may be poorly excited by a breakdown and complicated to analyze

Modifications to the current setup/system necessary!

Modification idea 1 – Avoid waveguide cut-off

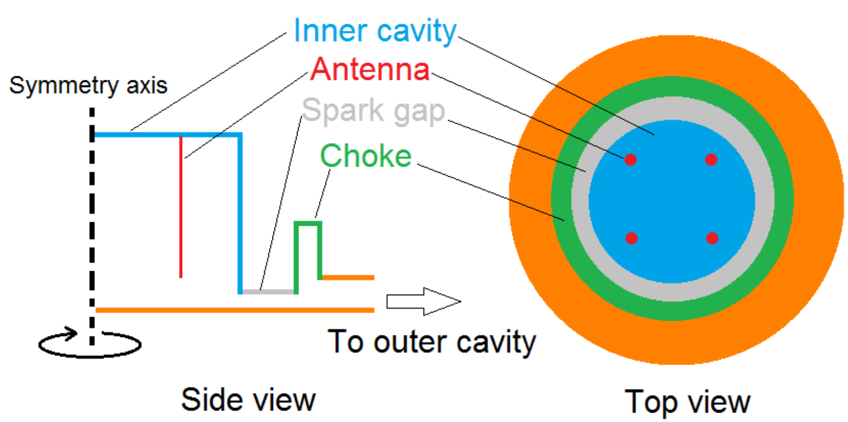
- Extend the antenna closer to the gap, beyond the waveguide that it's currently in

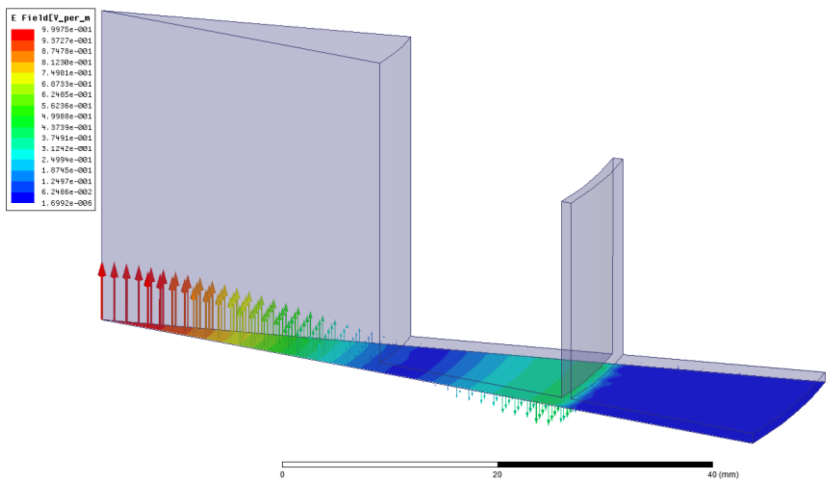


Loop antenna, which avoids the high cut-off frequency of the waveguide.

Modification idea 2 – Place antennas within a controlled cavity

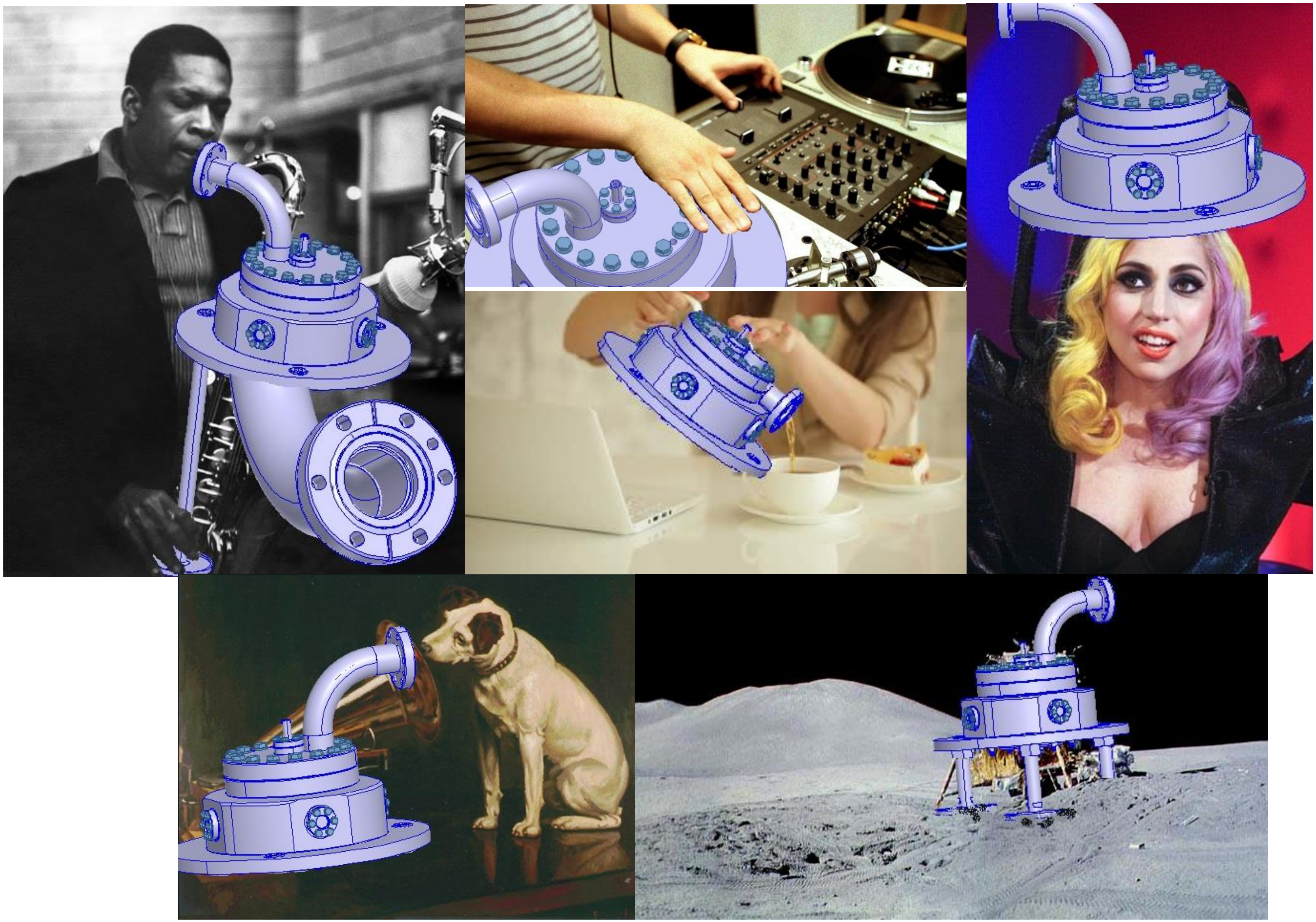
- Modify one electrode and confine brakedowns to a circle (reduces problem from 2D to 1D)
- Control mode frequency and Q with a choke
  - Acts as a high impedance barrier for a specific frequency -> confines the mode within the cavity
- Choke dipole (and monopole?), dampen rest



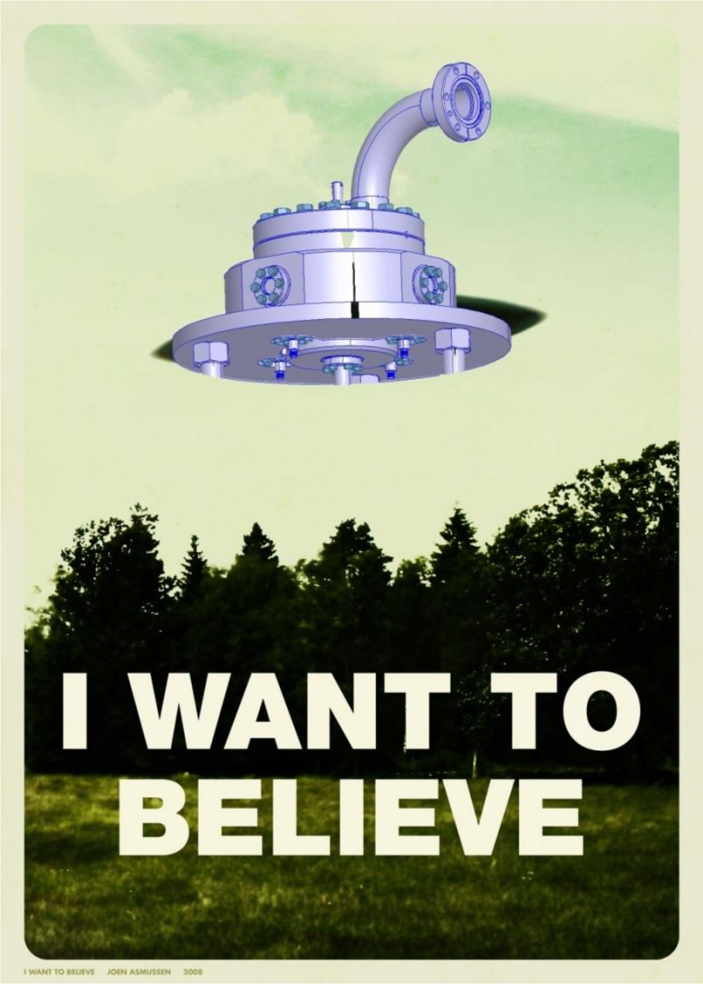


Left: conceptual drawing of new geometry. Right: simulation of choked TM010.

Other modification ideas



Thanks!



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