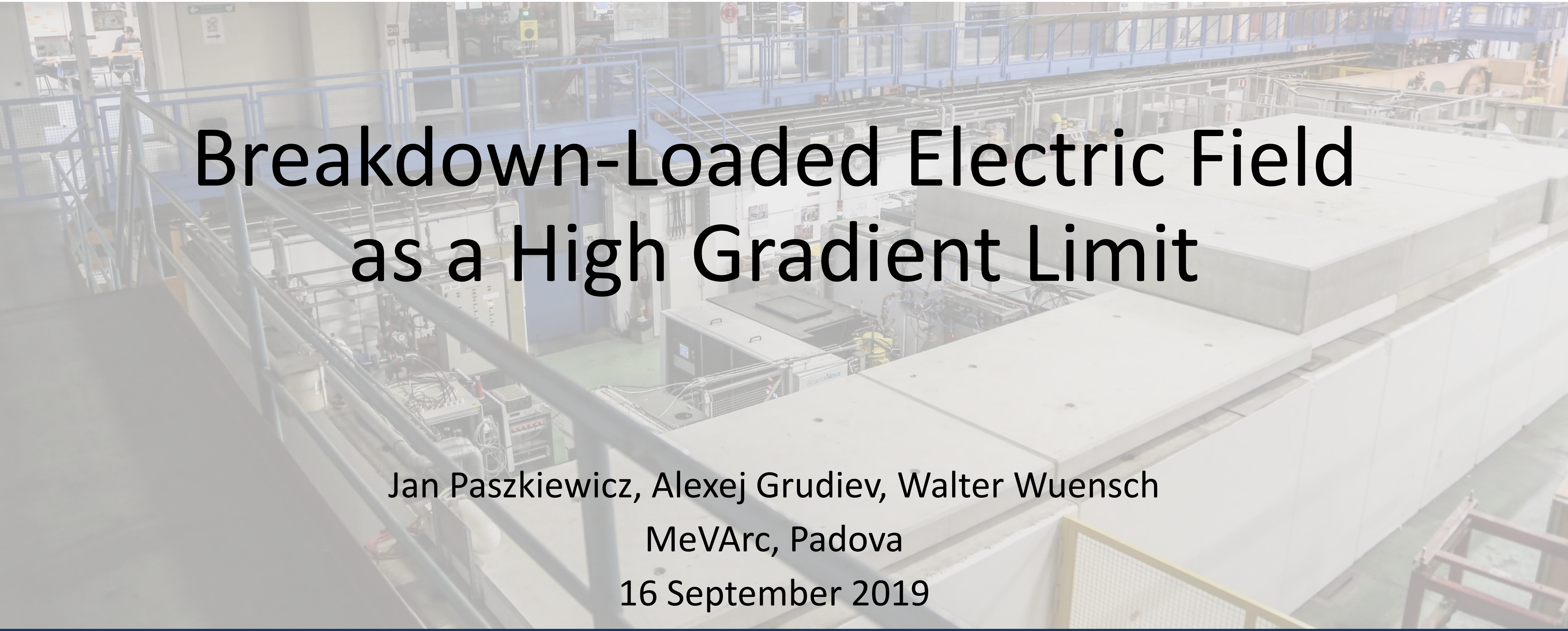
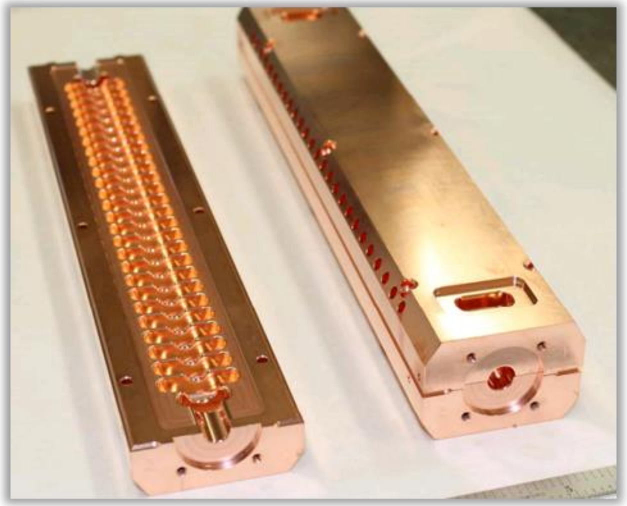


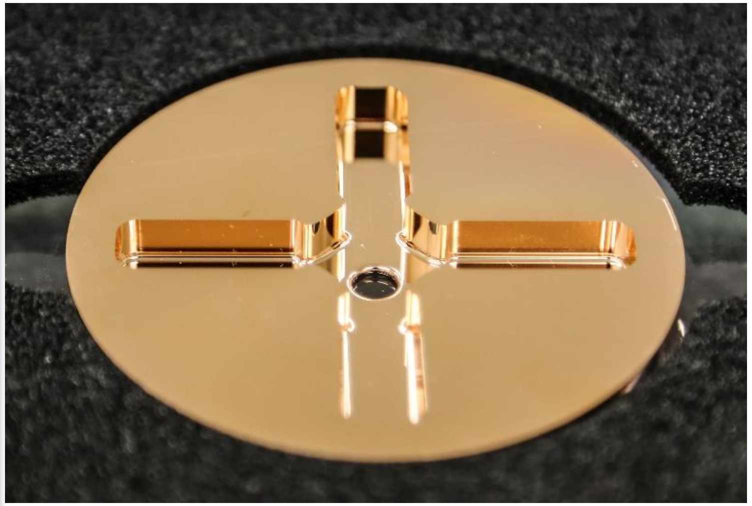
Breakdown-Loaded Electric Field as a High Gradient Limit

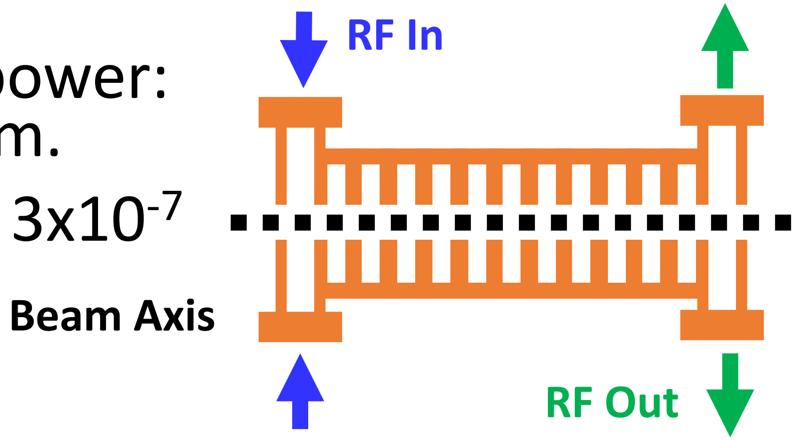
Jan Paszkiewicz, Alexej Grudiev, Walter Wuensch
MeVArc, Padova
16 September 2019

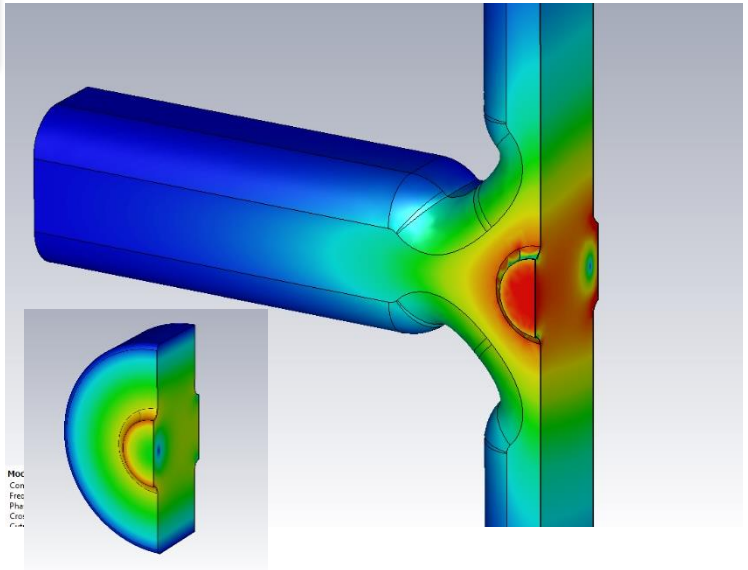
RF Accelerating Structures for CLIC

- X-band (11.994 GHz RF)
- Traveling wave: RF pulse passes through the structure, consist of a series of coupled resonant cells.
- Accelerating gradient (energy gain of particles) = 100 MV/m
- Peak surface field ≥ 200 MV/m, depends on design.
- High fields require high power: 40 - 50 MW without beam.
- CLIC BDR requirement: ≤ 3×10^{-7} bpp/m to limit losses of luminosity.





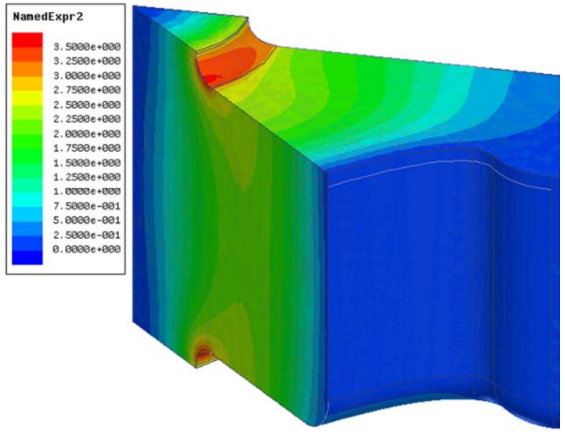




High-Gradient Limits

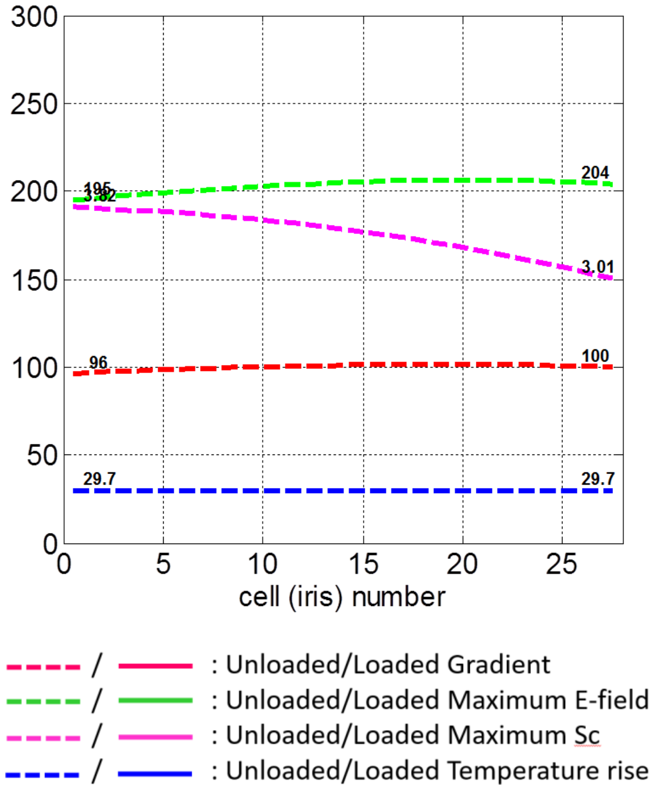
- Different structure designs can reach different peak accelerating gradients and surface fields.
- Experimental data suggests ultimate limit depends on power flow, not E field.
  - Global power flow: P/C
  - Local power flow: modified Poynting vector, S_c – used to optimise geometries

Example of surface S_c calculation in 1/8th of a damped cell (A. Grudiev):



$$S_c = Re\{E \times H^*\} + \frac{1}{6} Im\{E \times H^*\}$$

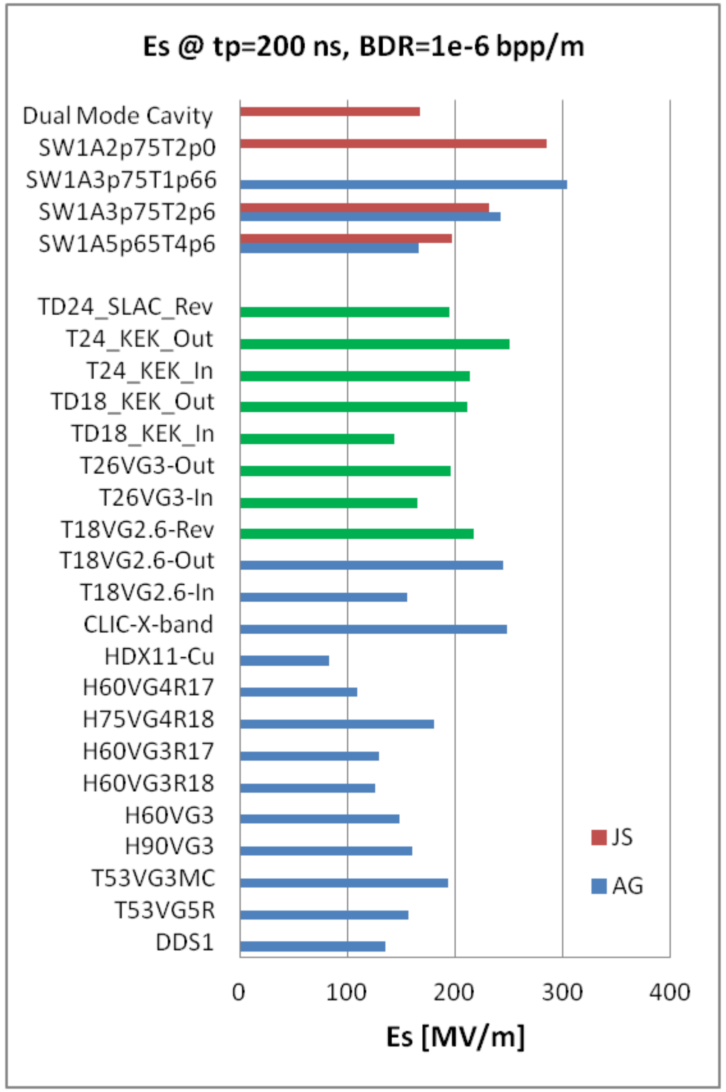
Example of structure tapering profile (A. Grudiev):

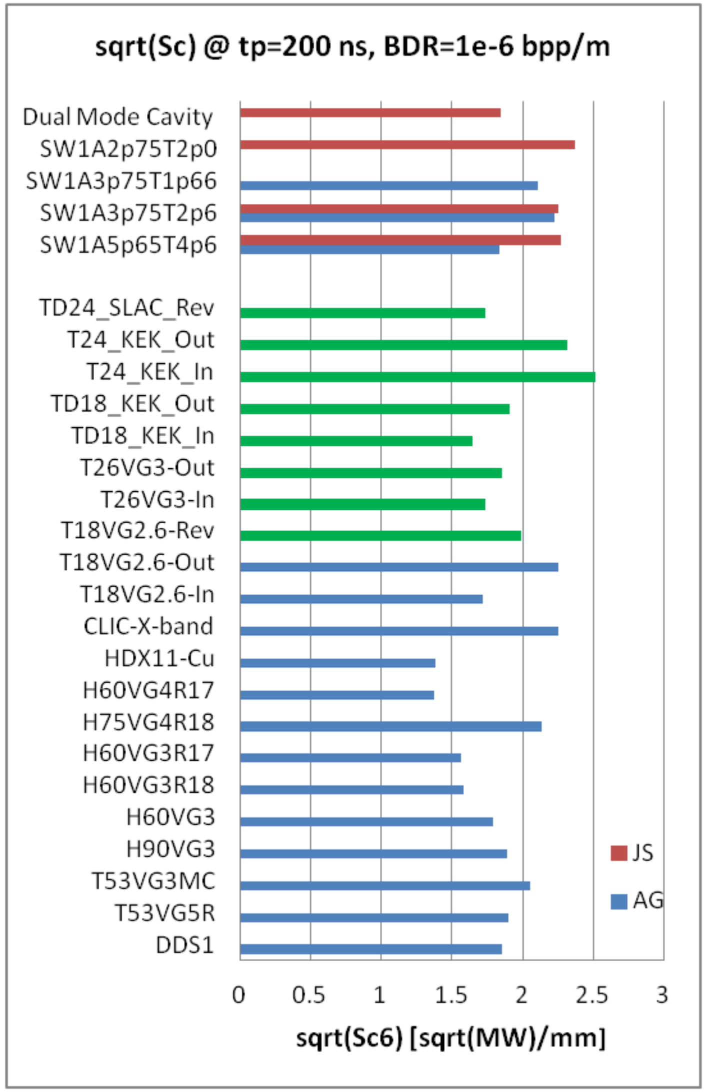


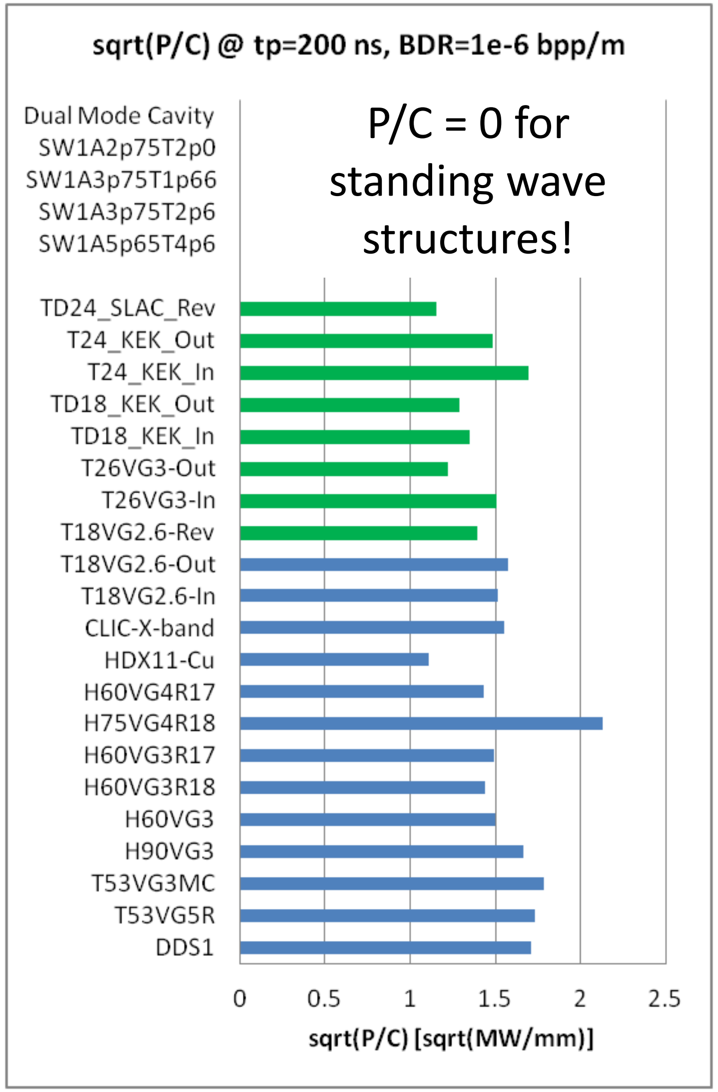
High-Gradient Limits

Standing wave

Traveling wave





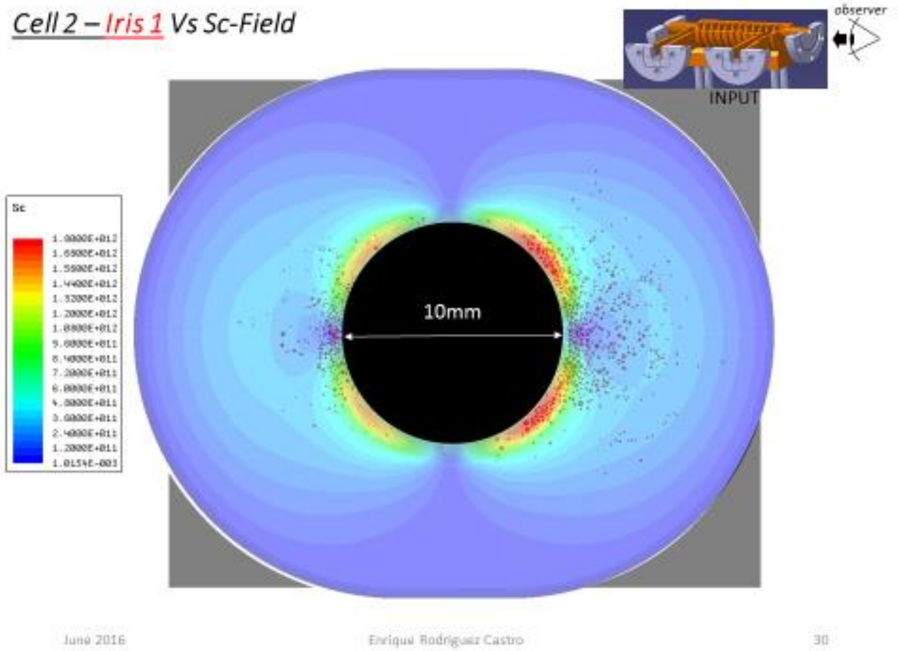


P/C = 0 for standing wave structures!

Plots from W. Wuensch’s slides for LCS

Limitations of S_c

- Breakdown locations:
  - Many structures tend to have most breakdowns close to the input despite tapering.
  - Post-mortem results of crab cavity do not match S_c prediction.
- Compatibility with DC experiments:
  - No (real or imaginary) power flow at f = 0.
- S_c uses unperturbed RF fields – what if we consider how local fields change during a breakdown?



Breakdown locations vs. Sc field distribution, E. R. Castro

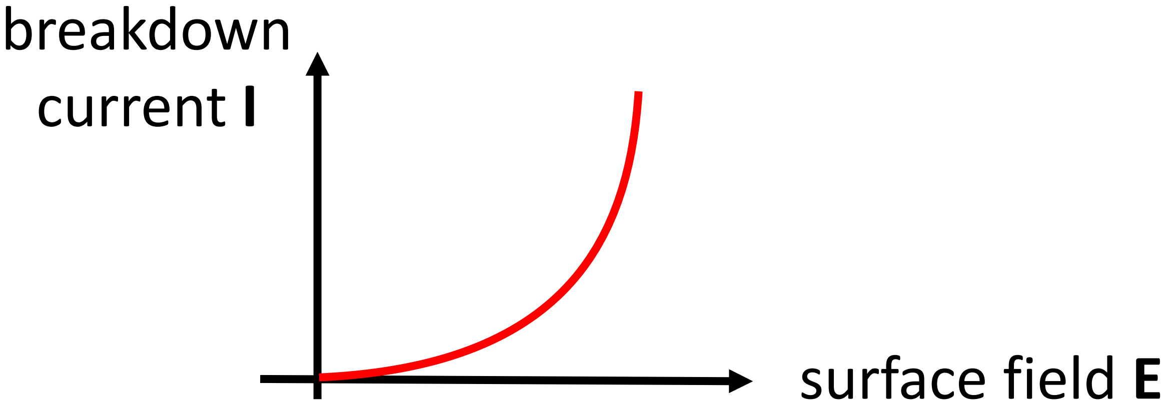
Hypothesis

- Ultimate BD limit is a function of available power, like with S_c.
- Nascent breakdown extracts power from RF by acceleration of charged particles (electrons). Interaction through E field only.
- Emitted current is a function of surface E field.
- Local surface E field decreases under BD loading. (In this case, we approximate the effect of complex plasma dynamics by a simple antenna on the surface.)
- Higher sustained E field under loading = higher BDR.

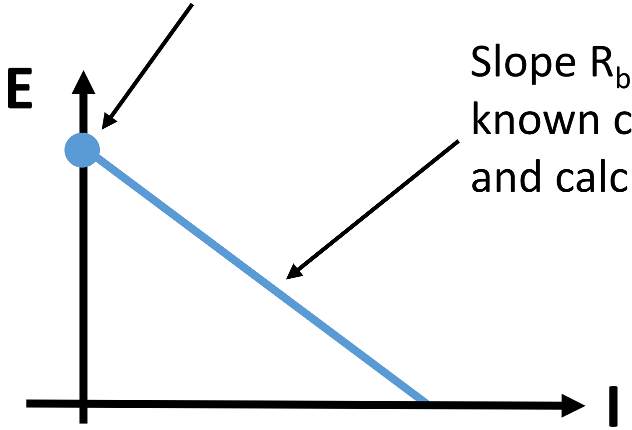
Outline of Procedure

Assume that any breakdown site will emit current as this function of surface field: (material property, to be fitted)

For every point in the structure, calculate a dependence of local field on antenna current:

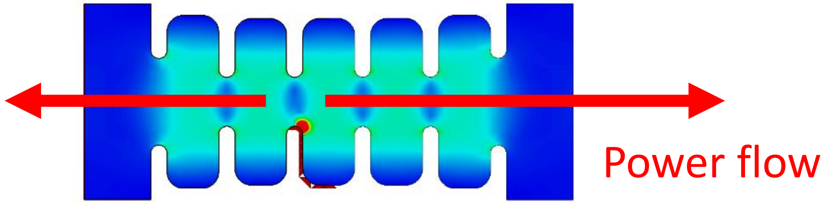


Unperturbed field, as determined by usual RF simulations.



Slope R_{bd} determined by forcing known current through antenna and calculating change in local field.

Example of field magnitudes with antenna as power source:

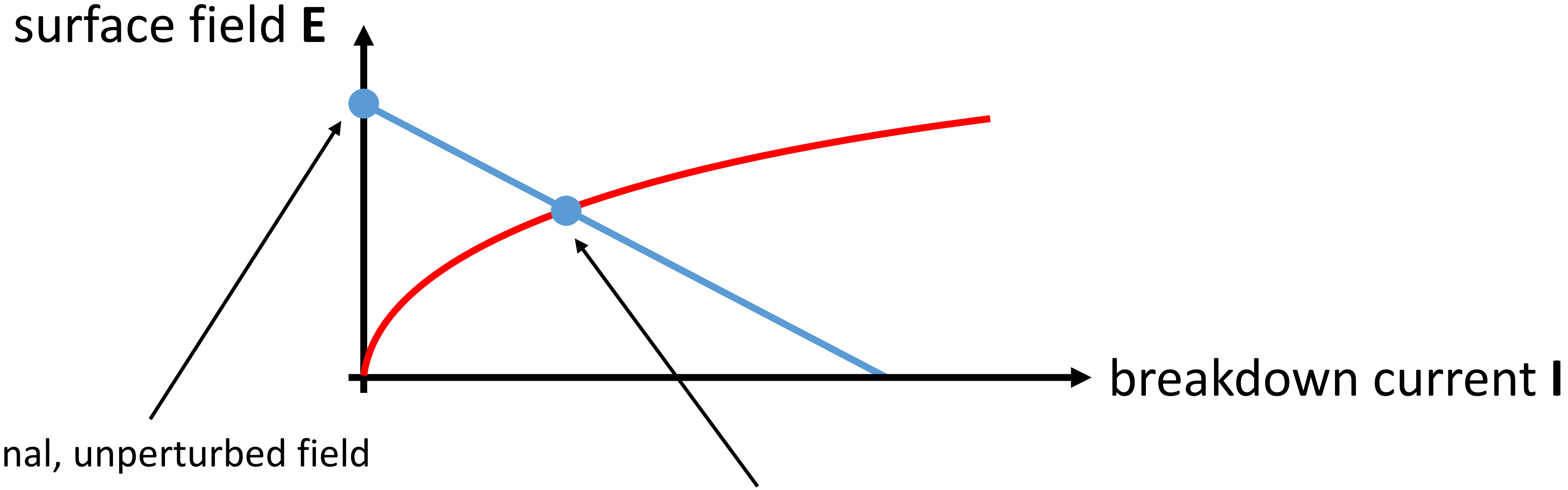


Define breakdown impedance as:

$$R_{bd} = Re\left\{\frac{V_{antenna}}{I_{antenna}}\right\}$$

Outline of Procedure

Combine the two plots to find the equilibrium solution:

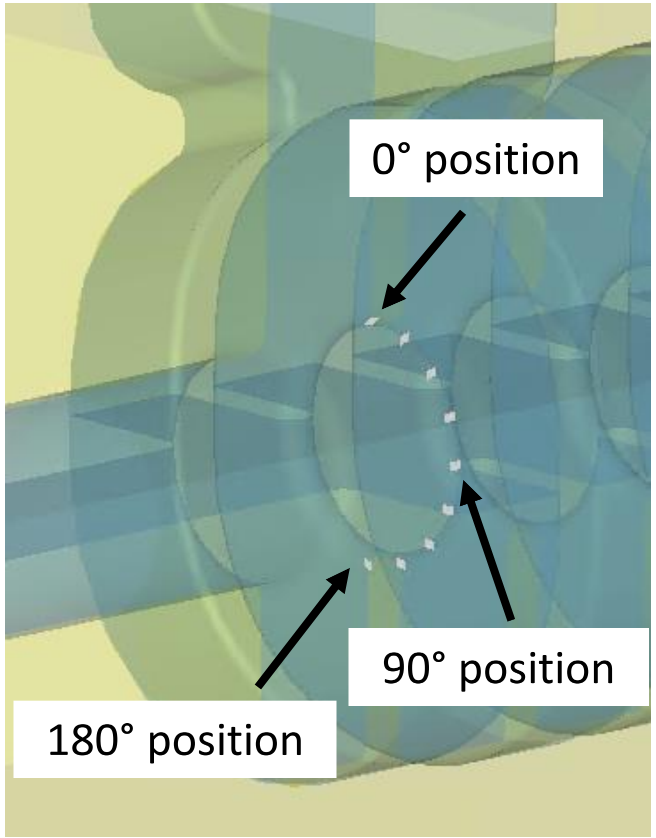


Original, unperturbed field

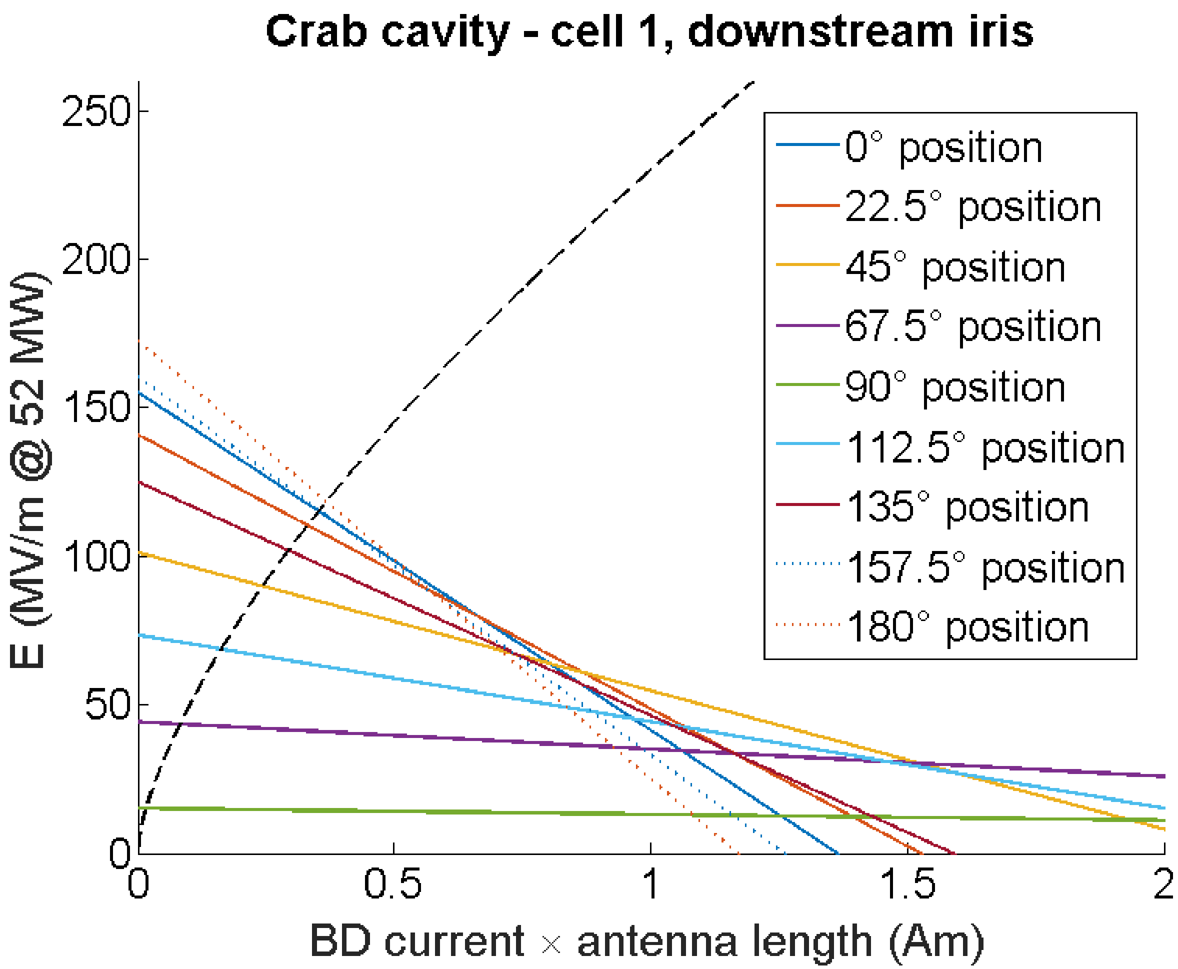
Field when loaded by a breakdown.
This is our new quantity.

Implications: No BD without E field, but power flow plays an important role.
Now repeat the calculation for every point in the structure!

Application to the CLIC Crab Cavity

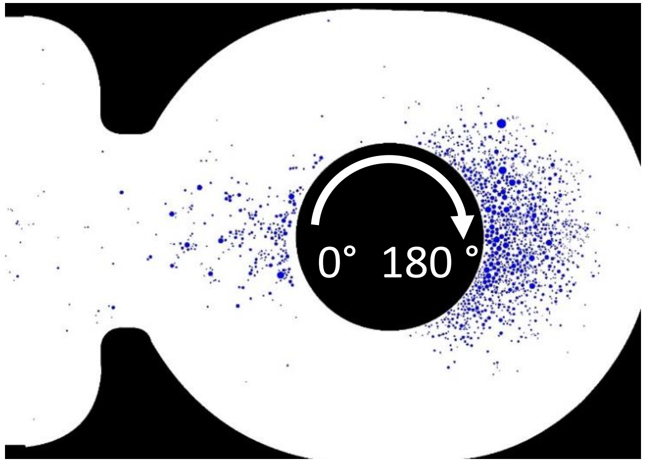


Antennas placed in rings around each iris.

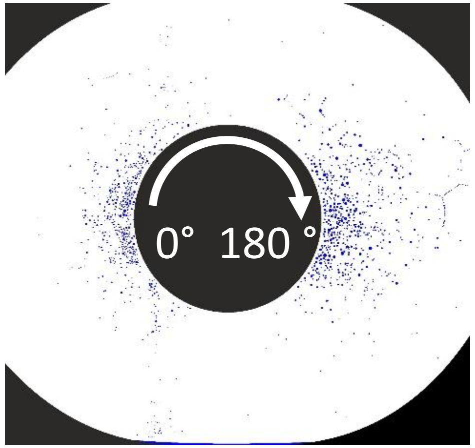


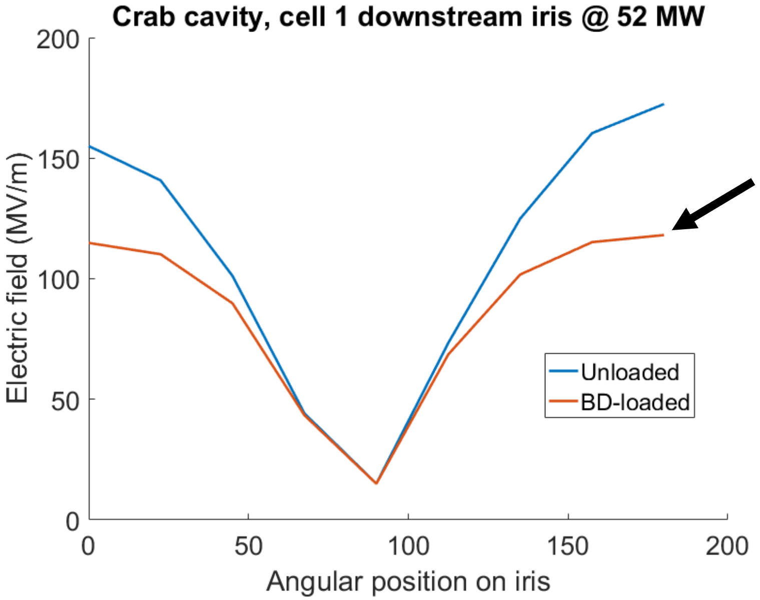
Application to the CLIC Crab Cavity

Cell 1

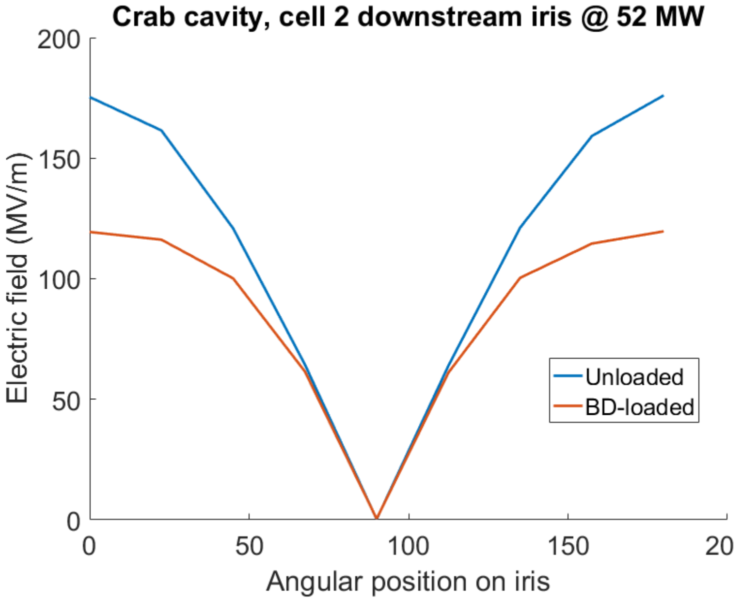


Cell 2



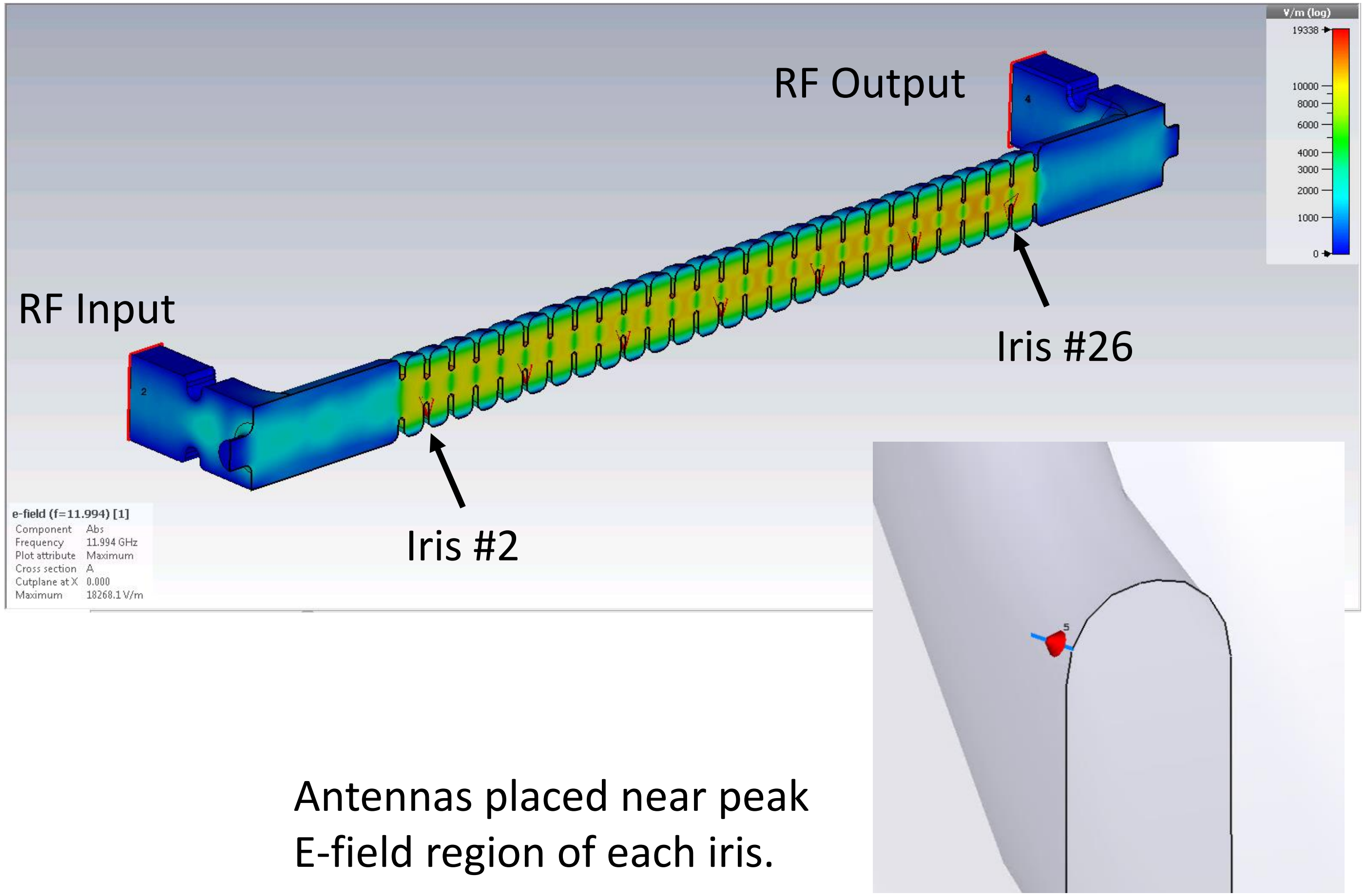


Peak value of 118 MV/m



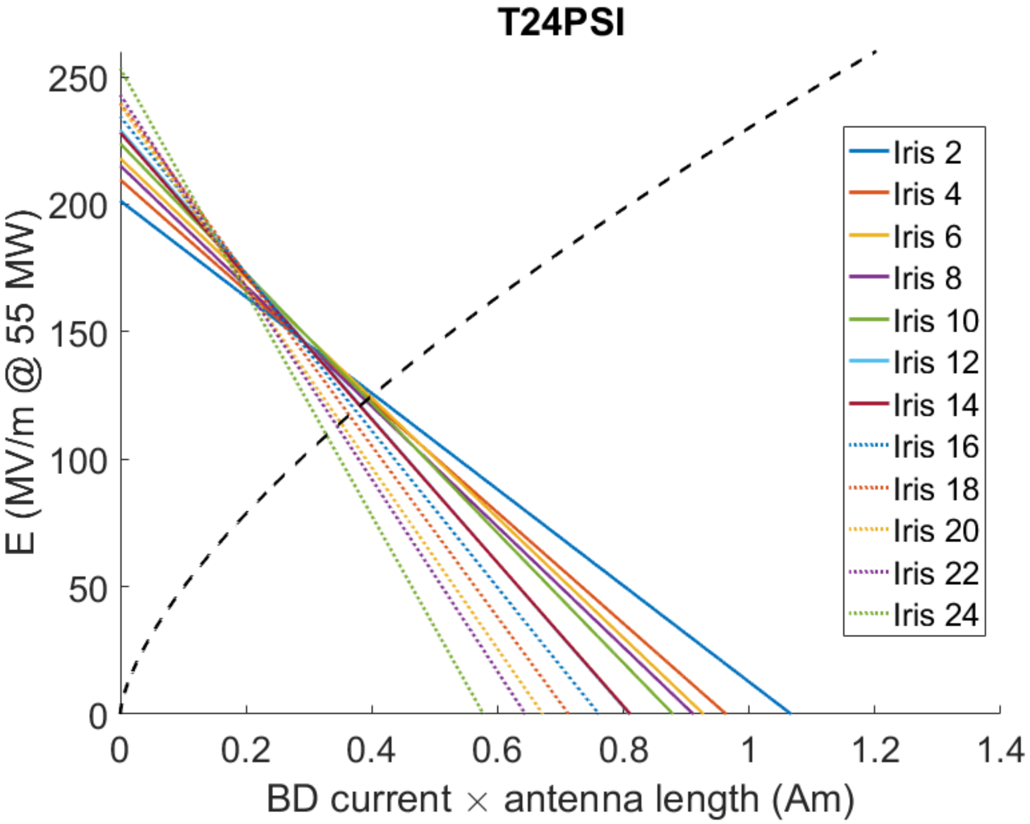
Application to T24 Structures

T24 PSI structure, E field complex magnitude

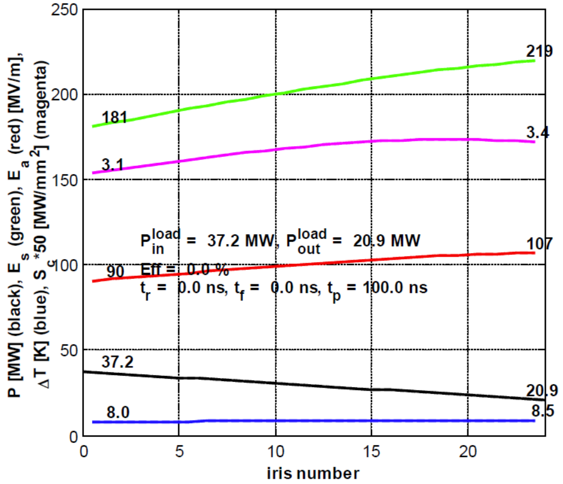


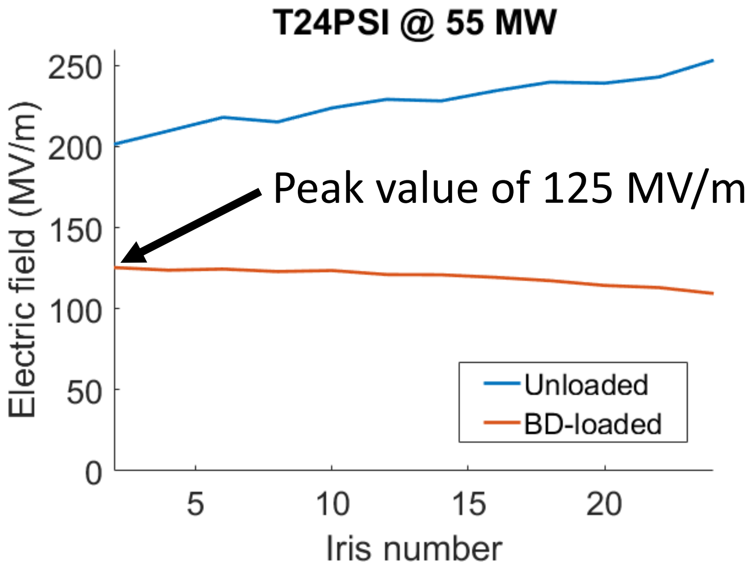
e-field (f=11.994) [1]
Component Abs
Frequency 11.994 GHz
Plot attribute Maximum
Cross section A
Cutplane at X 0.000
Maximum 18268.1 V/m

Antennas placed near peak E-field region of each iris.



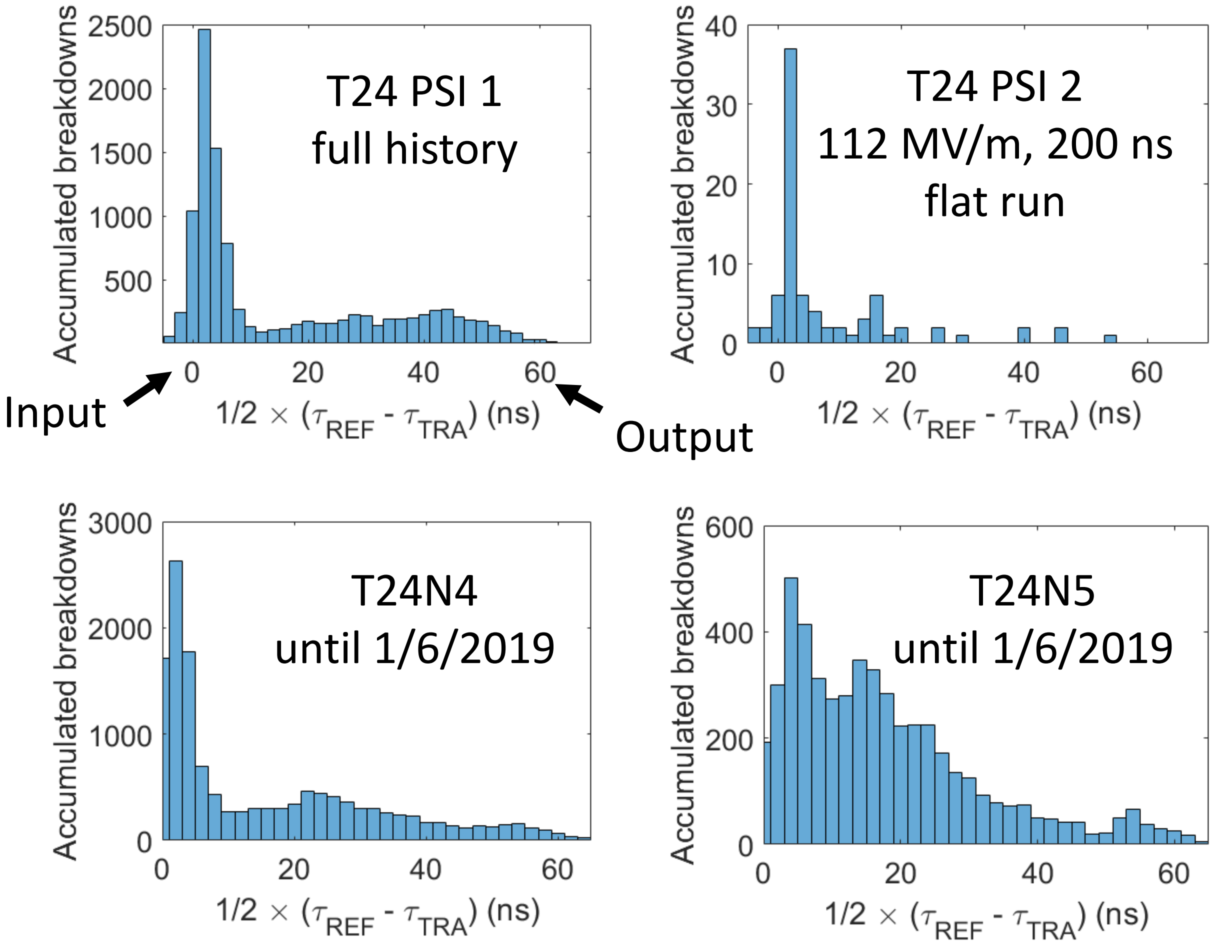
Application to T24 Structures




T24PSI @ 55 MW

Peak value of 125 MV/m

Breakdown locations in T24 structures:


T24 PSI 1
full history

T24 PSI 2
112 MV/m, 200 ns
flat run

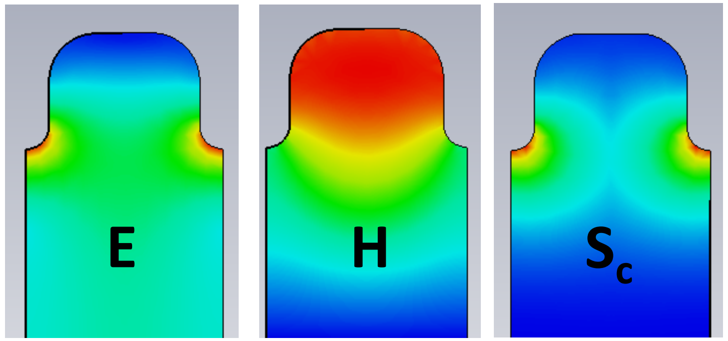
T24N4
until 1/6/2019

T24N5
until 1/6/2019

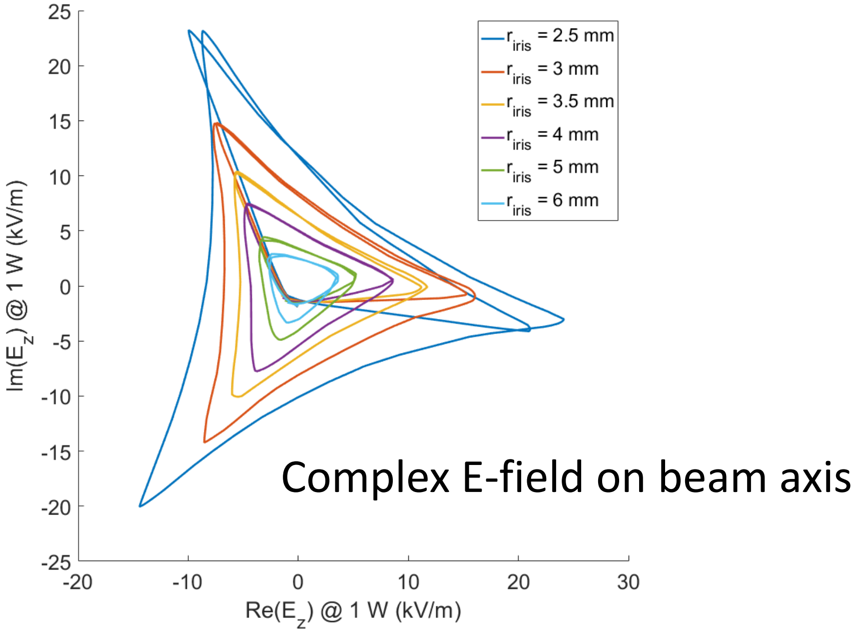
Aperture Scan

Simulated a series of accelerating cells with the following properties:

- 120° phase advance
- 2 mm iris thickness
- 2 mm corner rounding
- 8.33 mm periodicity (for β = 1)
- Iris radius scanned from 2.5 mm to 6 mm
- Tuned to 12 GHz by varying cell diameter
- Structures of 3 regular cells + 2 matching cells fed with TM01 via circular waveguide.



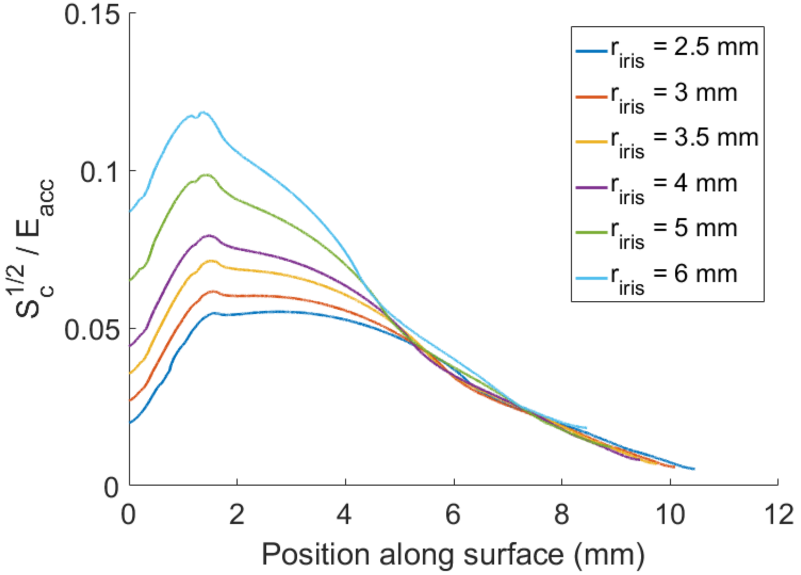
Eigenmode field distributions



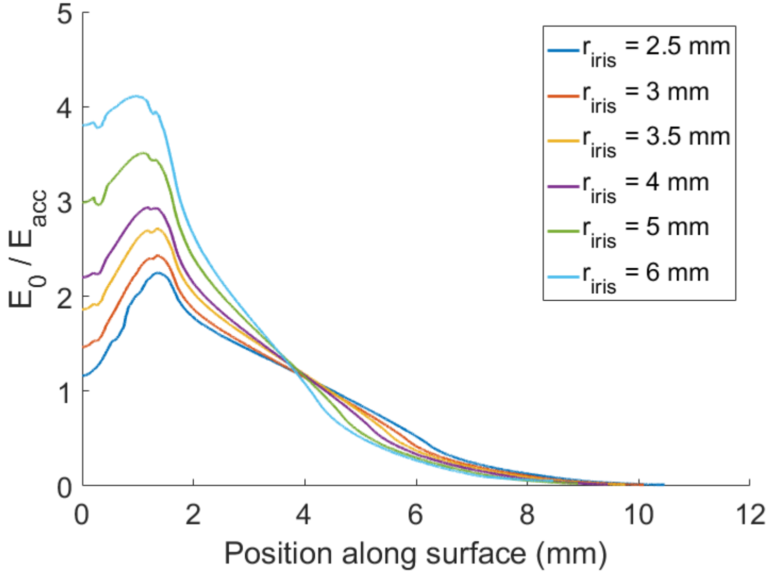
Complex E-field on beam axis

Aperture Scan – Breakdown Location

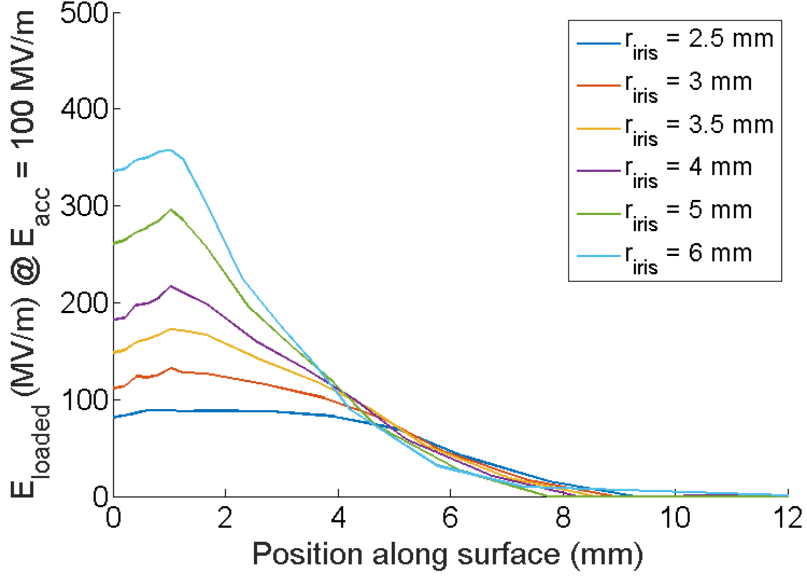
Sc distribution:



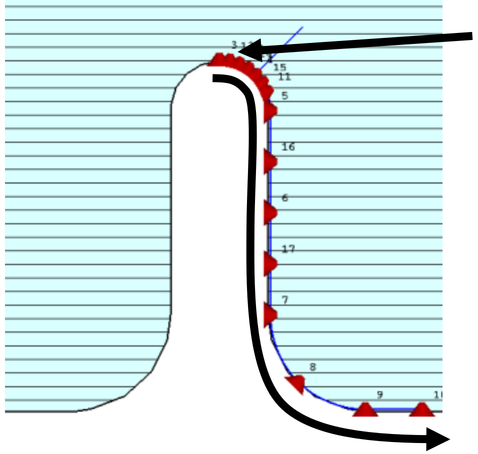
Unloaded E-field distribution:



BD-loaded E-field distribution:

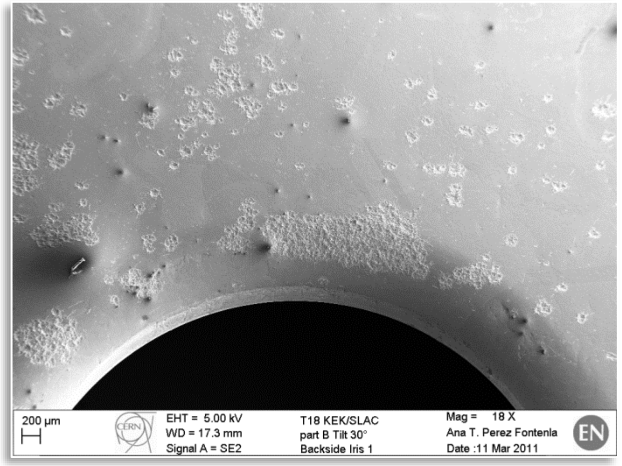


Antennas placed along surface of centre cell:



0 position is apex

Sample fields in this direction

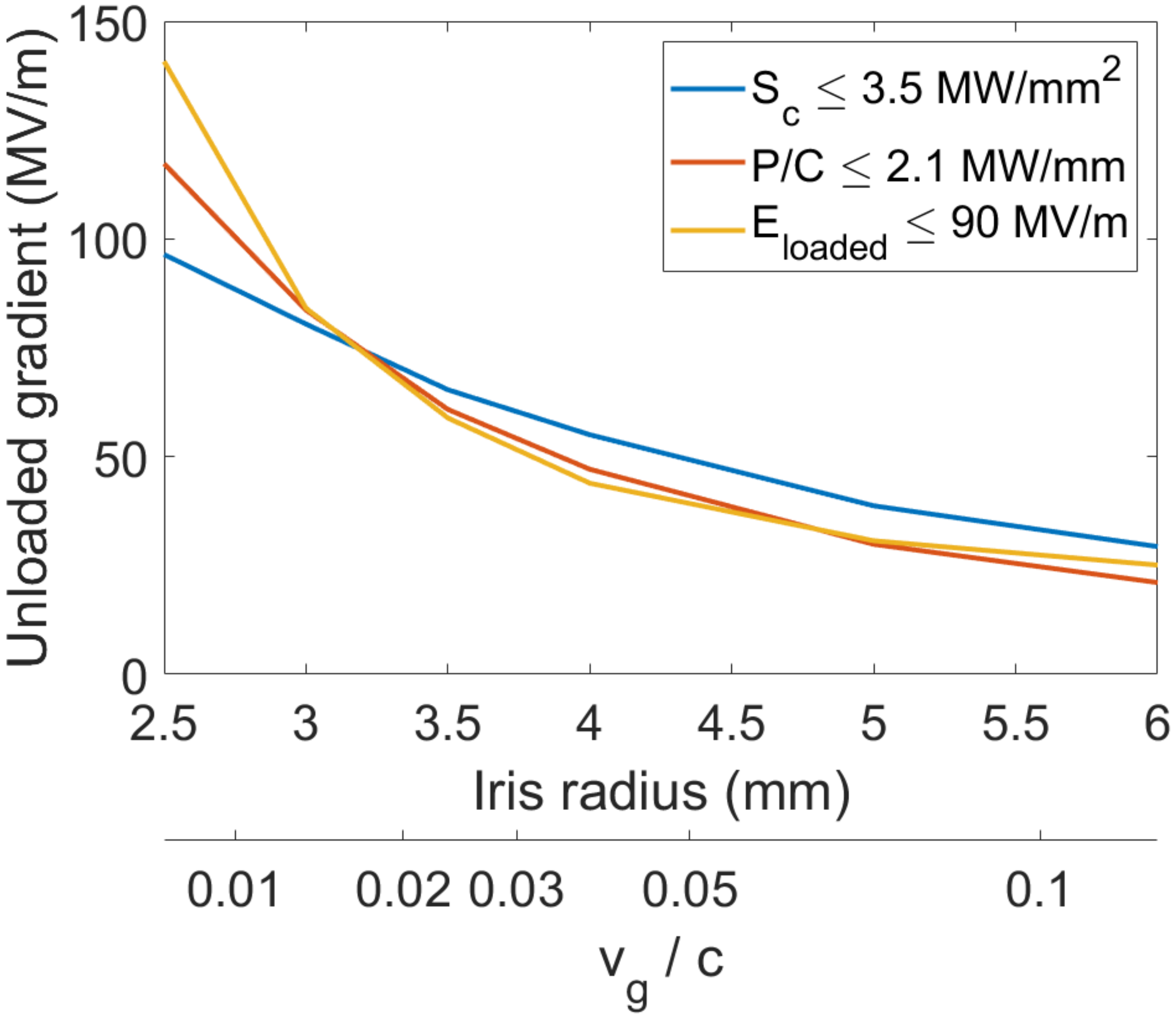


Structure post-mortem: A. P. Fontenla

Aperture Scan – Maximum Gradient

Maximum gradient for each aperture size using different limiting quantities.

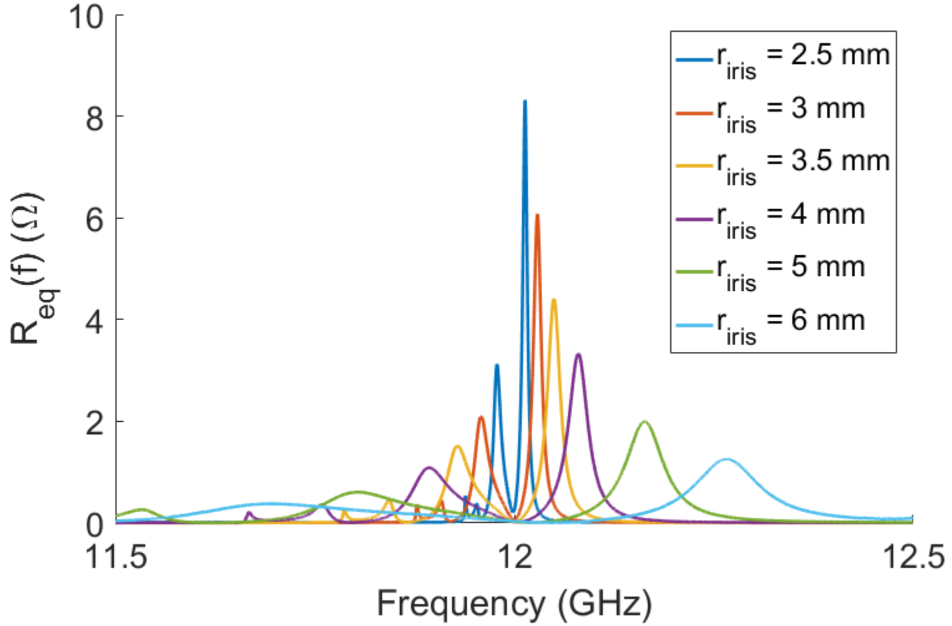
- P/C implies infinite gradient for $v_g = 0$.
- Loaded field model implies high but finite gradient (since some power flow still exists)
- P/C and S_c give satisfactory results for typical CLIC structures.
- Including stored energy & transients is in progress.

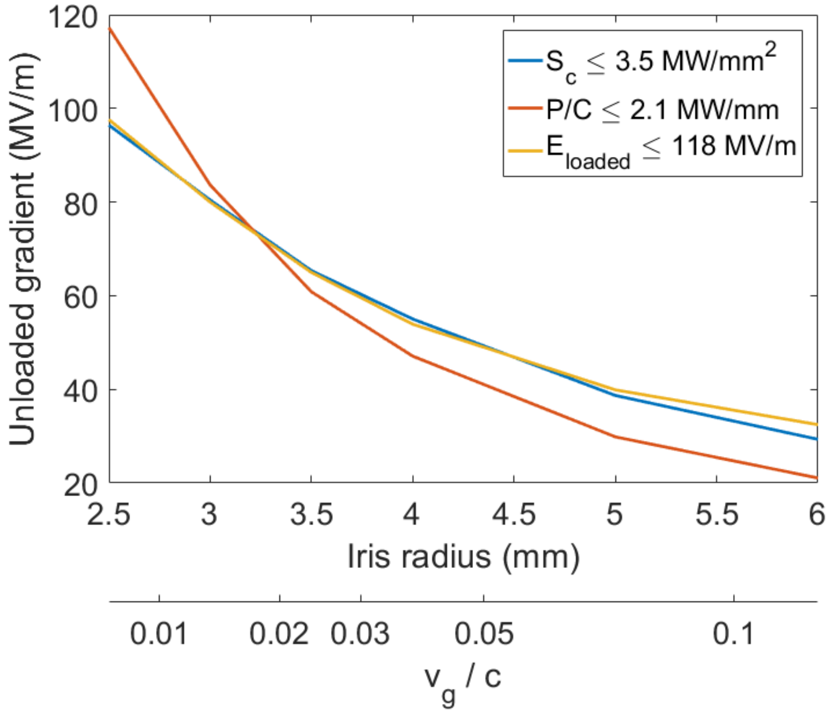


Including Transient Effects

NEW

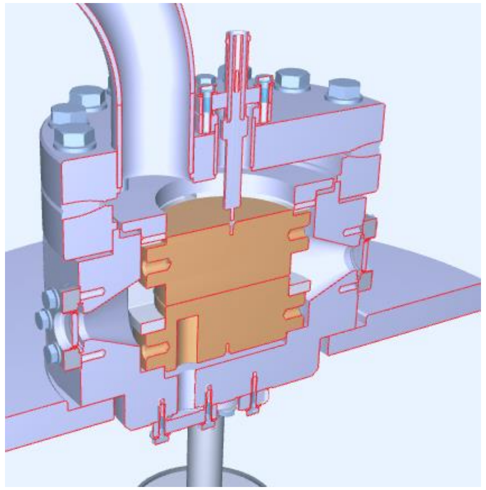
- $R_{bd}(f_0)$ implies a steady-state condition at RF frequency f_0.
- Promising results using $\int_{-\infty}^{\infty} R_{bd}(f)^2 df$ as the slope instead.
  - Can be physically interpreted as the total energy delivered to the breakdown for a delta function spike of current.
- Work in progress to verify consistency with old results.



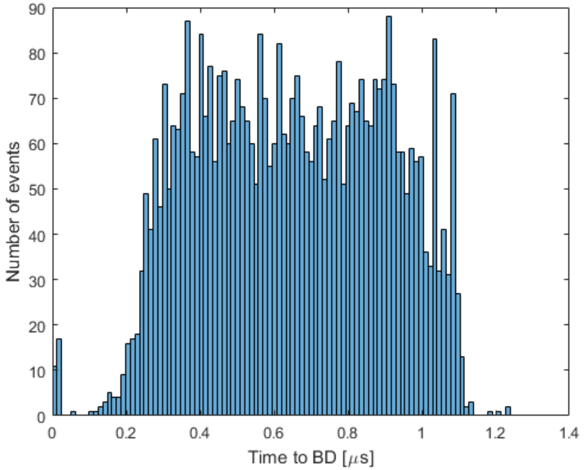


S_c for DC Breakdowns

- DC systems: copper electrodes under pulsed high voltage.
- No power flow except when charging or discharging.
- According to S_c model breakdowns should only occur on the rising and falling edges of the pulse. ($S_c = 0$ at $f = 0$)
- Experiments show roughly constant breakdown probability throughout the pulse duration.



Distribution of BDR vs. time within HV pulse:

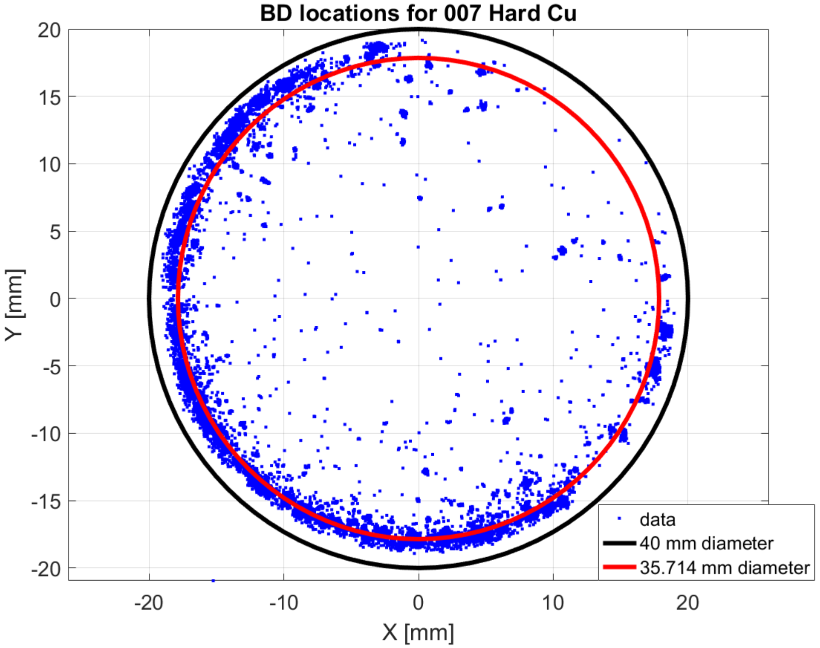


BD time histogram: I. Profatilova

Breakdown Positions in the DC Systems

Breakdowns near edge despite optimisation for low peak field. No consistent azimuthal dependence for small electrodes.

4 islands of breakdowns observed in large electrodes, corresponding to 4 windows in vacuum chamber.



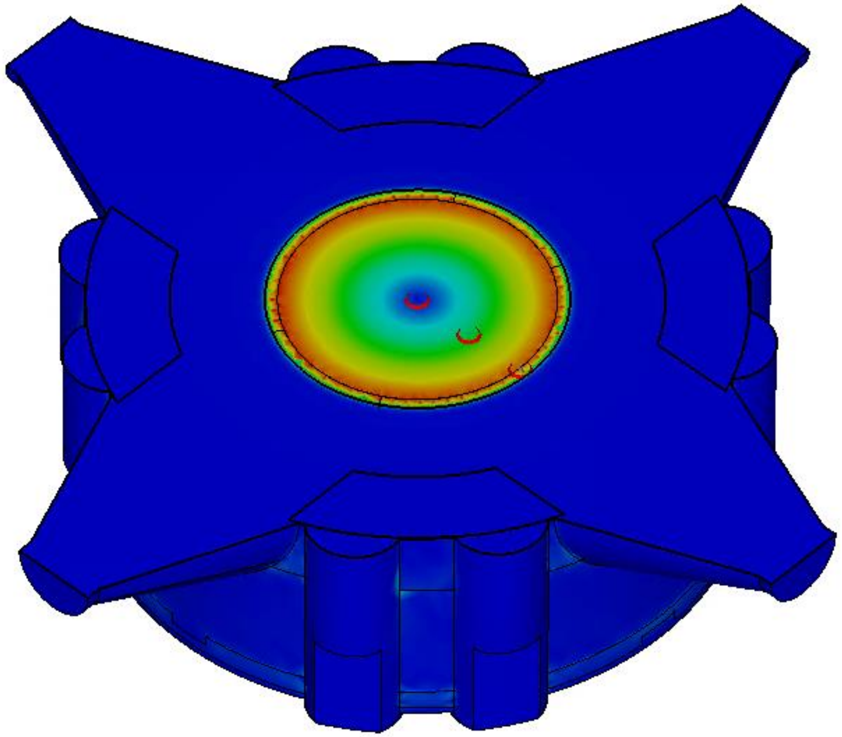
Hard Cu electrode with optimised edges, CERN
I. Profatilova

CuAg electrode, CERN
E. R. Castro

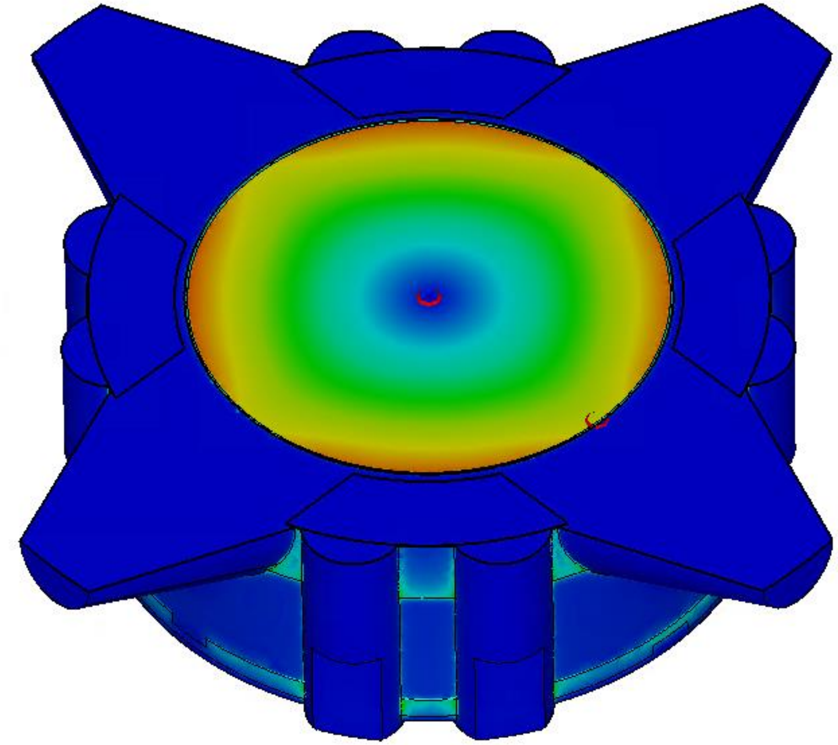
Soft Cu electrode, Helsinki
A. Saressalo

S_c in the DC Spark System

S_c at 100 MHz with 40 mm electrodes



S_c at 100 MHz with 60 mm electrodes



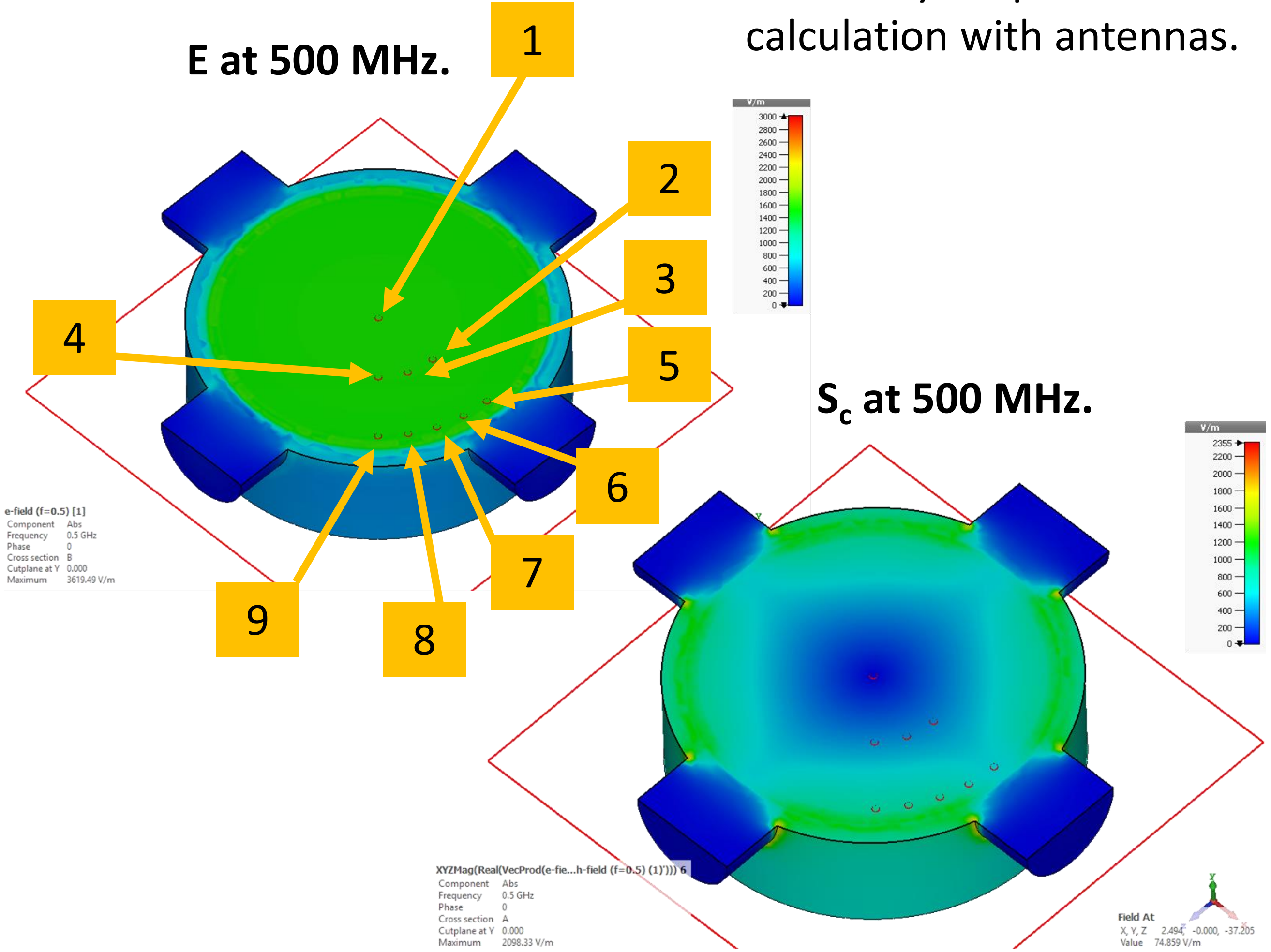
No justification for picking 100 MHz or any other frequency than 0, but spatial distribution matches experimental data! This suggests power flow is important.

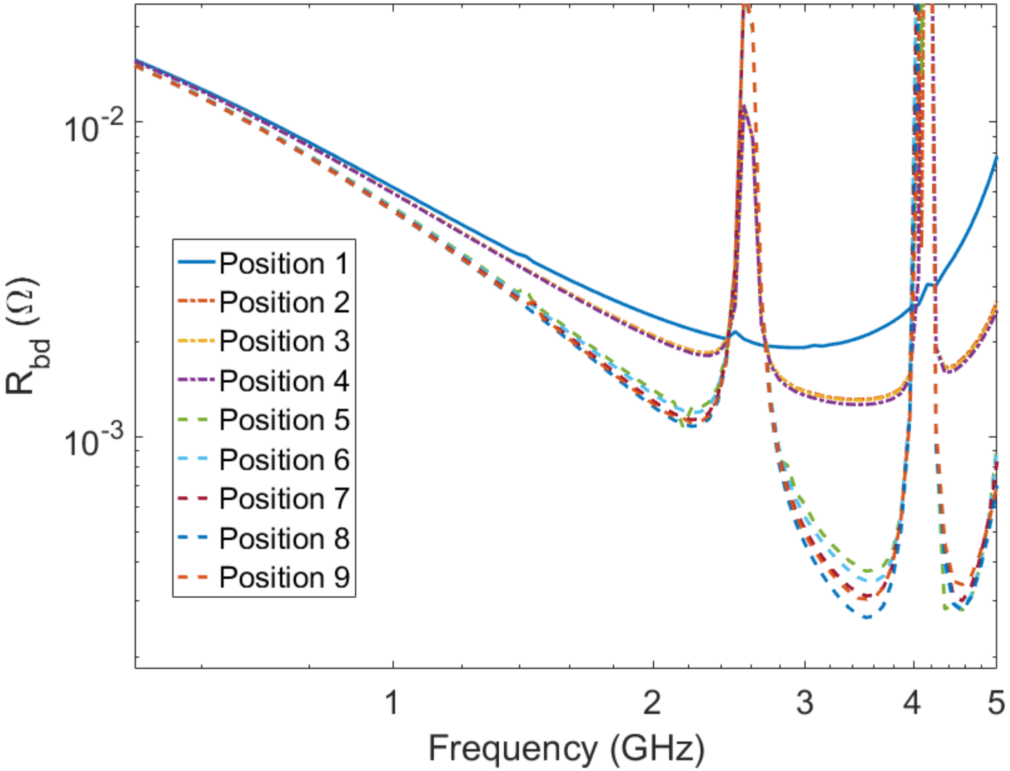
Impedance in a Simplified DC System

Geometry simplified for easier calculation with antennas.

E at 500 MHz.

S_c at 500 MHz.



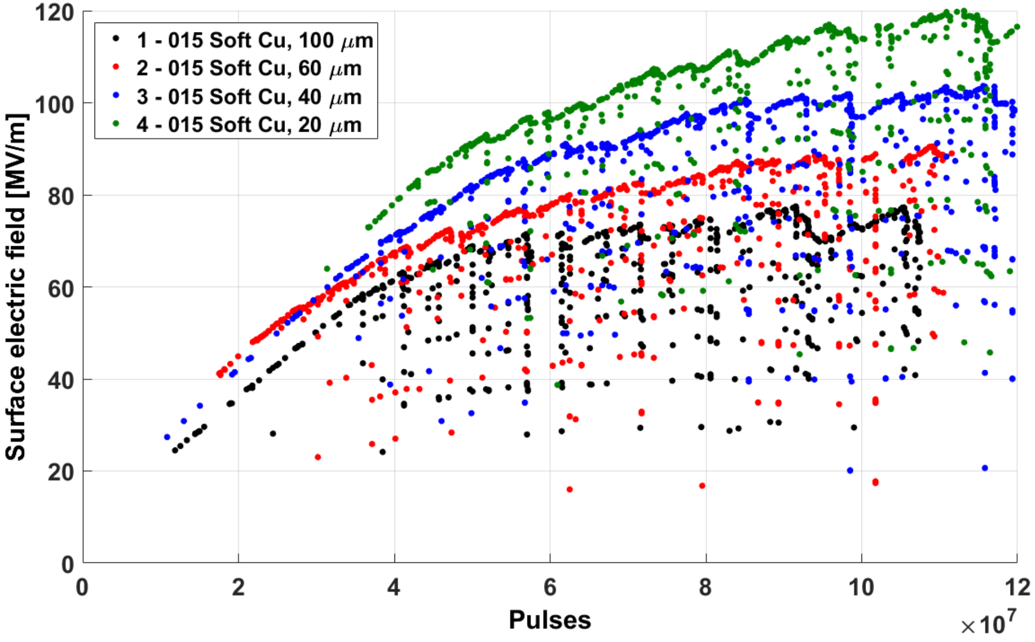


Qualitative agreement with Sc and experimental results. A broadband implementation is still in progress so no quantitative results for the DC case yet. Lower R_{bd} with fixed E = higher BDR.

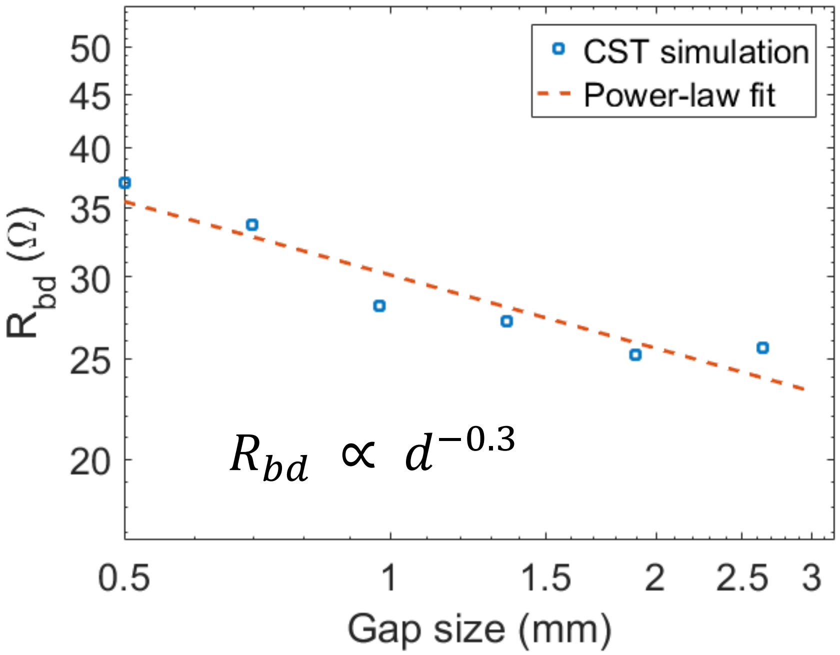
Gap size dependence

- Experimentally observed dependence of BDR on gap size.
- For a constant BDR, $V \propto d^{0.72}$.
- i.e. BDR is a function of $Ed^{0.28}$

Conditioning curves for various gap sizes



Simulation results for simplified DC system



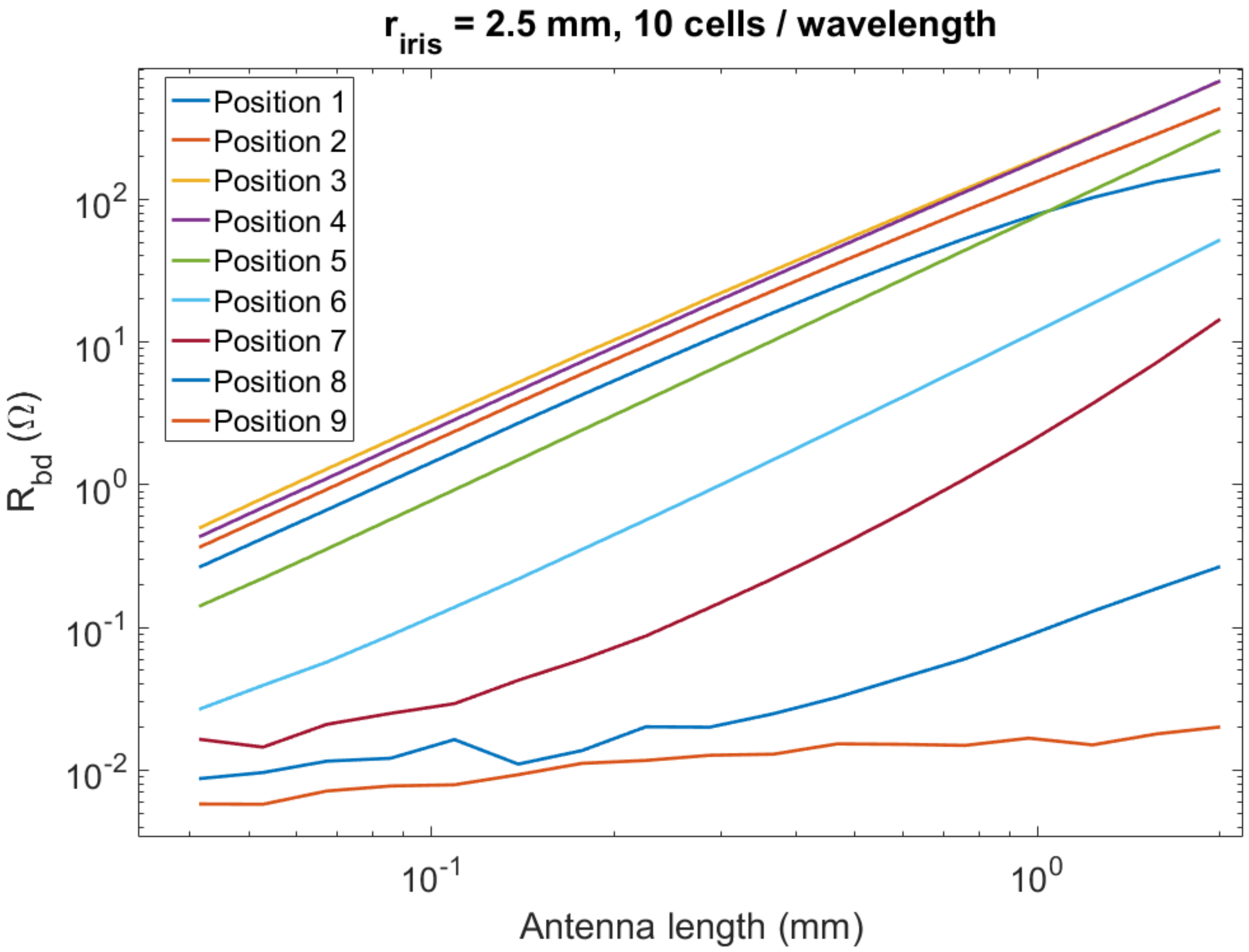
$R_{bd} \propto d^{-0.3}$

Summary

- New breakdown quantity proposed: breakdown-loaded E field.
- Follows E field distribution but limited by power.
- Makes distinction between unperturbed fields and fields under breakdown.
- Single-frequency model works well for TW structures.
- Working on describing transient (ie. broadband) phenomena.

Thank you!

Antenna Length Dependence



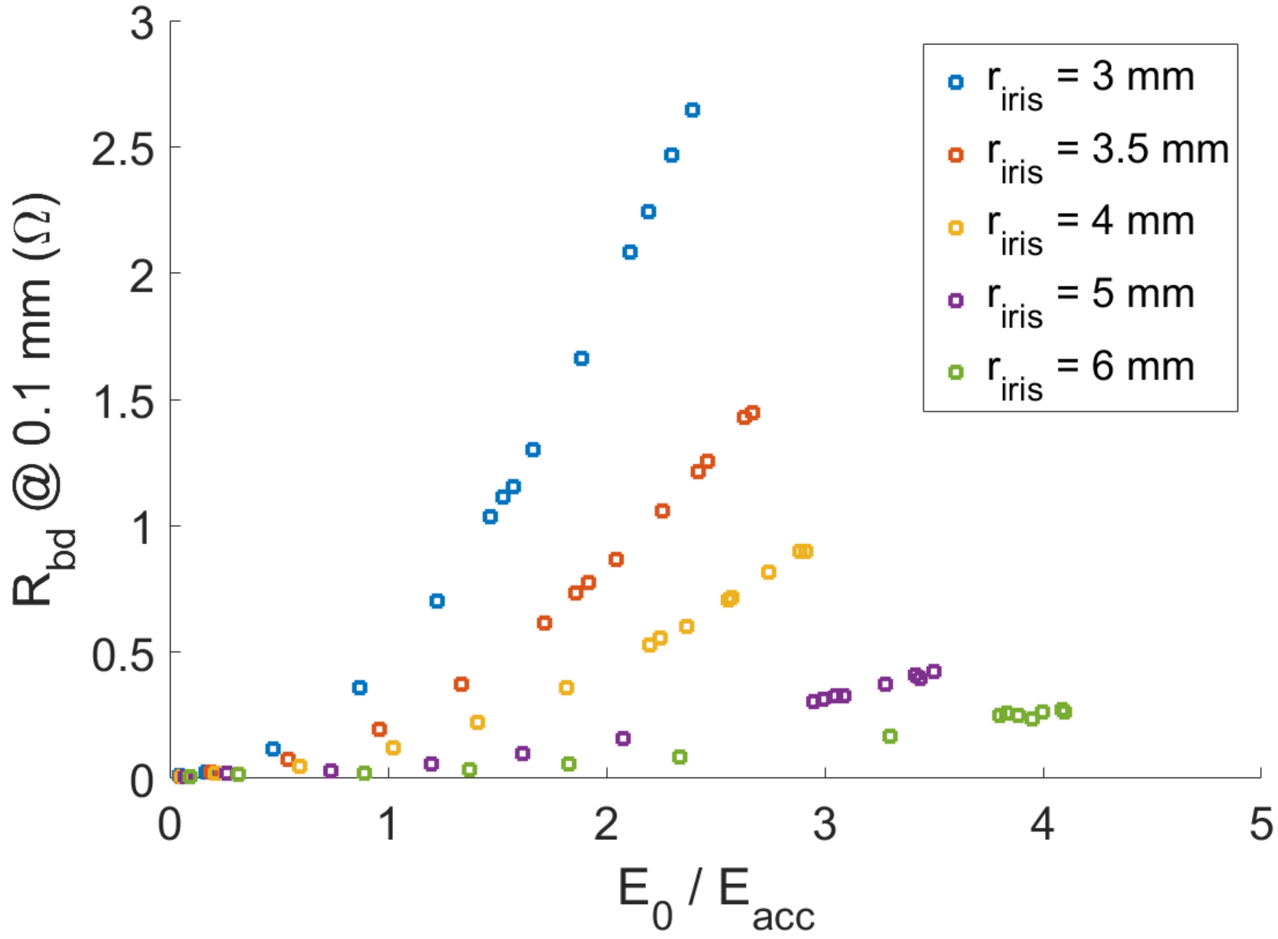
Observed dependence:

$$R_{bd} \propto l^2$$

Hertzian dipole in free space:

$$R_{rad} = \frac{\pi}{6} \zeta_0 \left(\frac{l}{\lambda}\right)^2$$

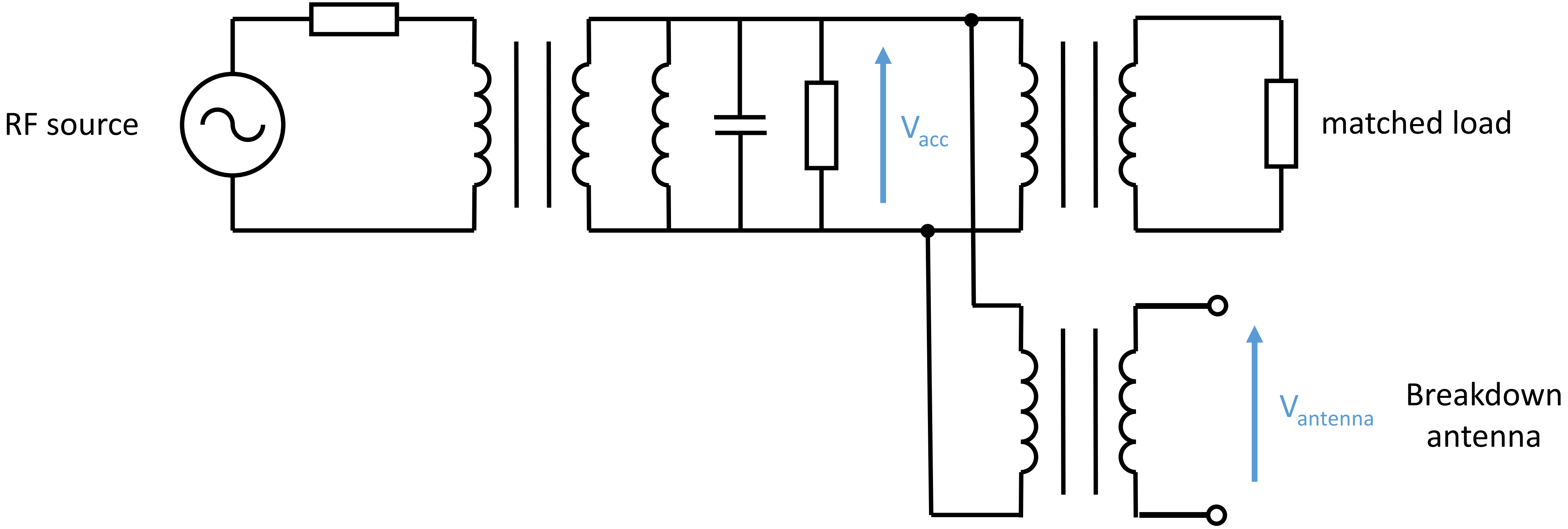
Dependence of R_{bd} on E Field



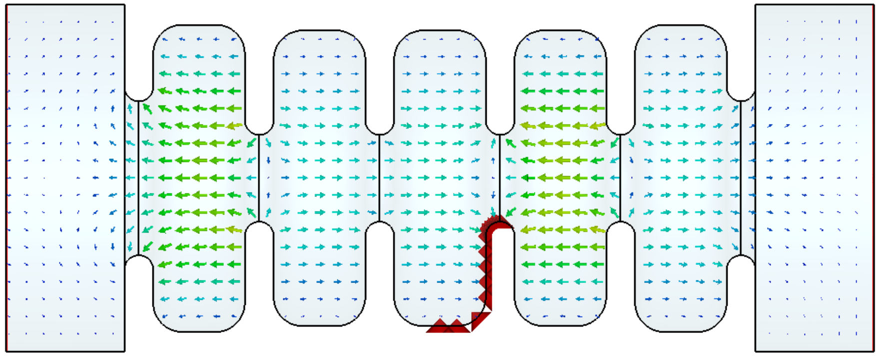
Within a given cell:

$$R_{bd} \propto E_{surf}{}^2$$

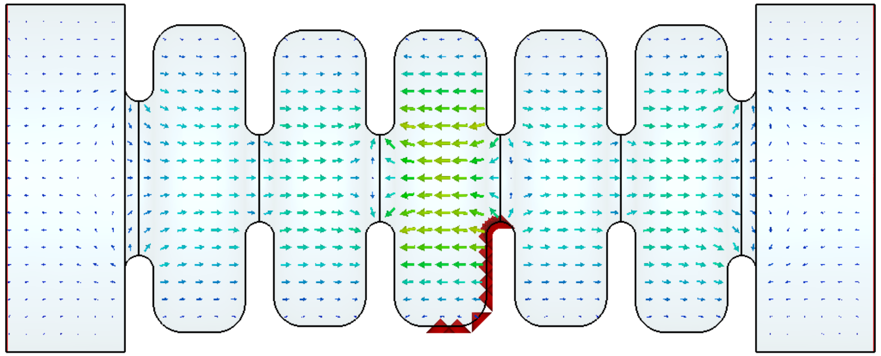
Circuit Model



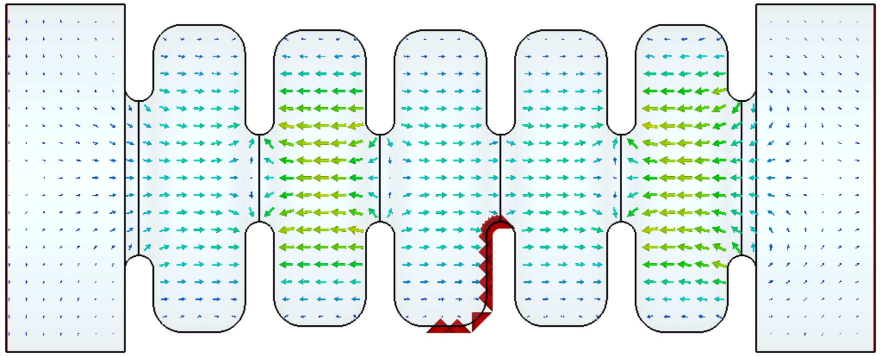
0°

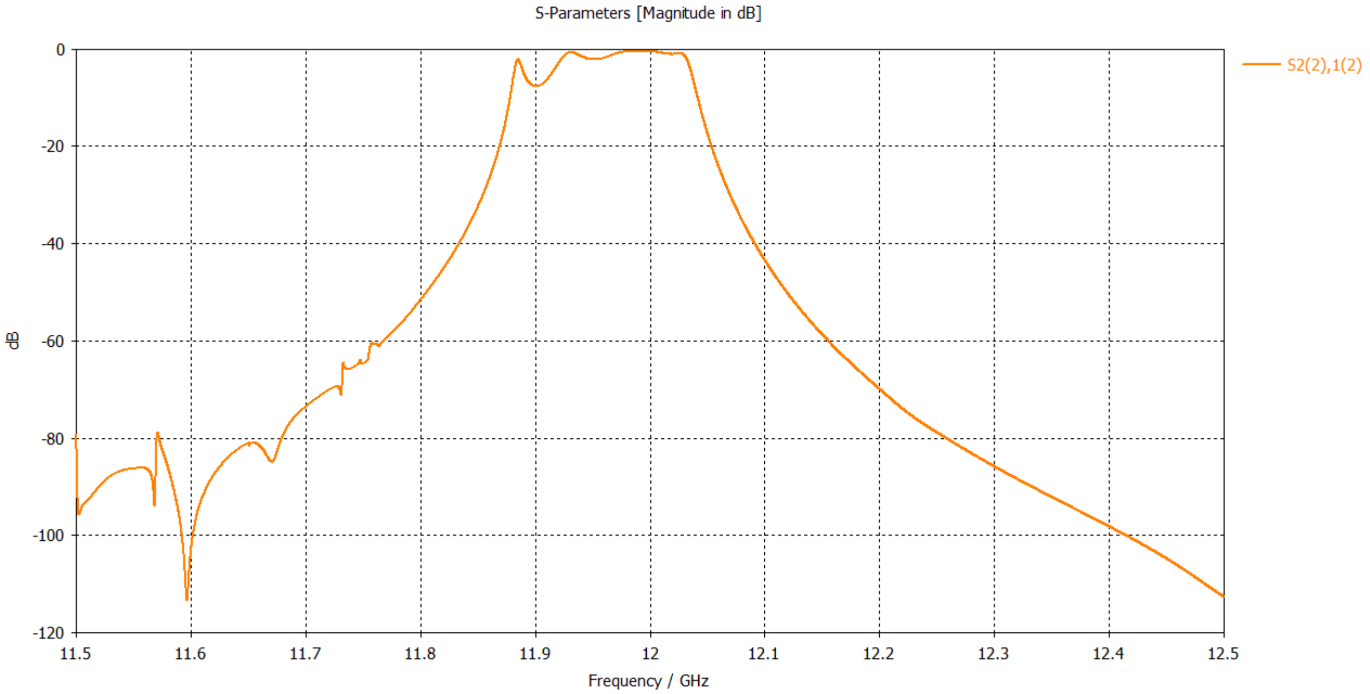


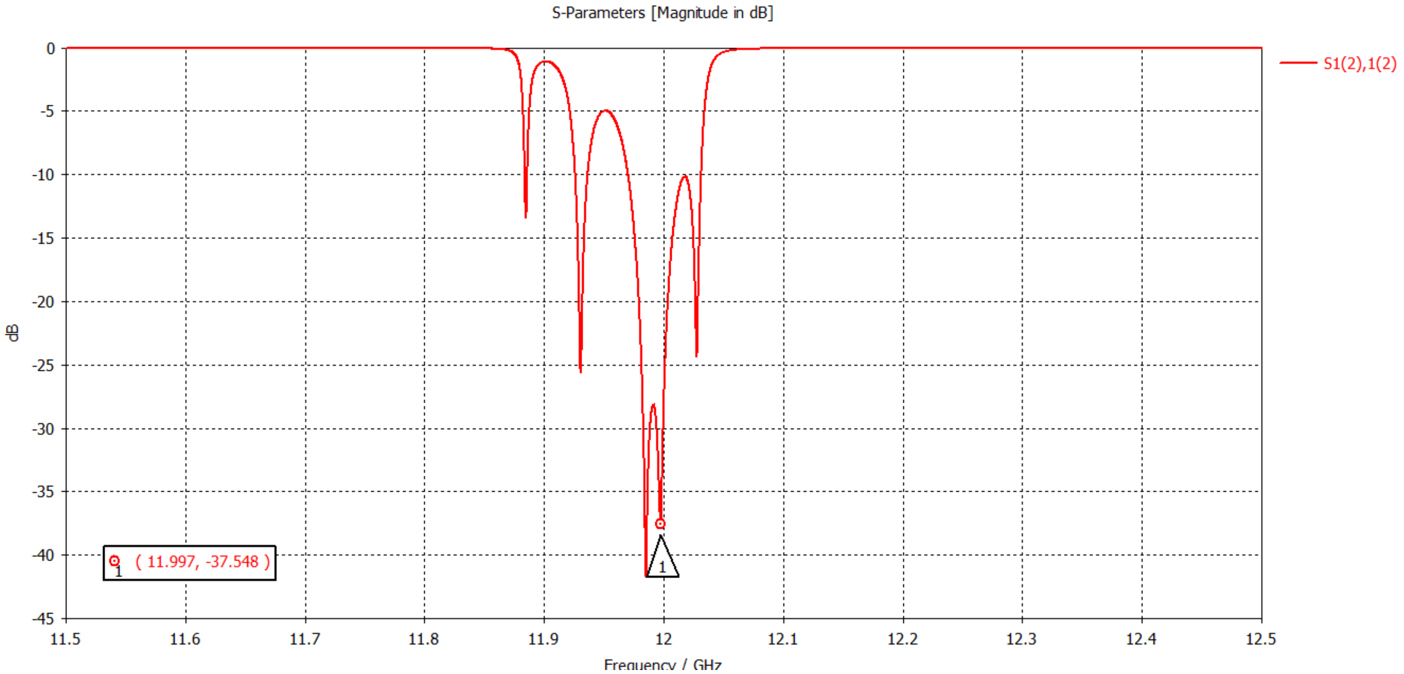
120°



240°




S-Parameters [Magnitude in dB]
S2(2),1(2)
dB
0
-20
-40
-60
-80
-100
-120
11.5
11.6
11.7
11.8
11.9
12
12.1
12.2
12.3
12.4
12.5
Frequency / GHz


S-Parameters [Magnitude in dB]
S1(2),1(2)
dB
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
11.5
11.6
11.7
11.8
11.9
12
12.1
12.2
12.3
12.4
12.5
Frequency / GHz
1
(11.997, -37.548)