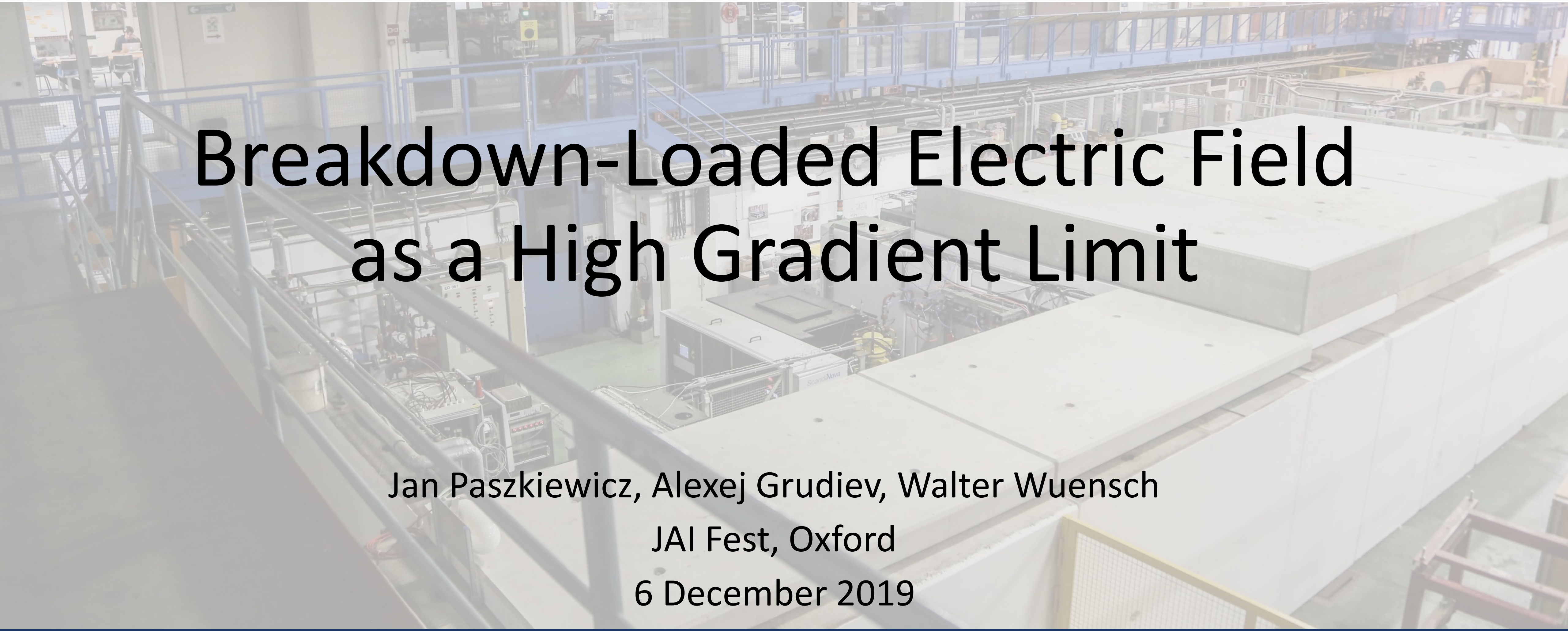
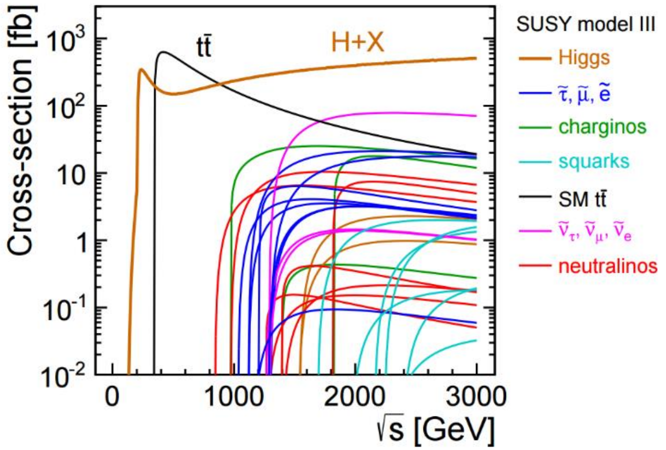


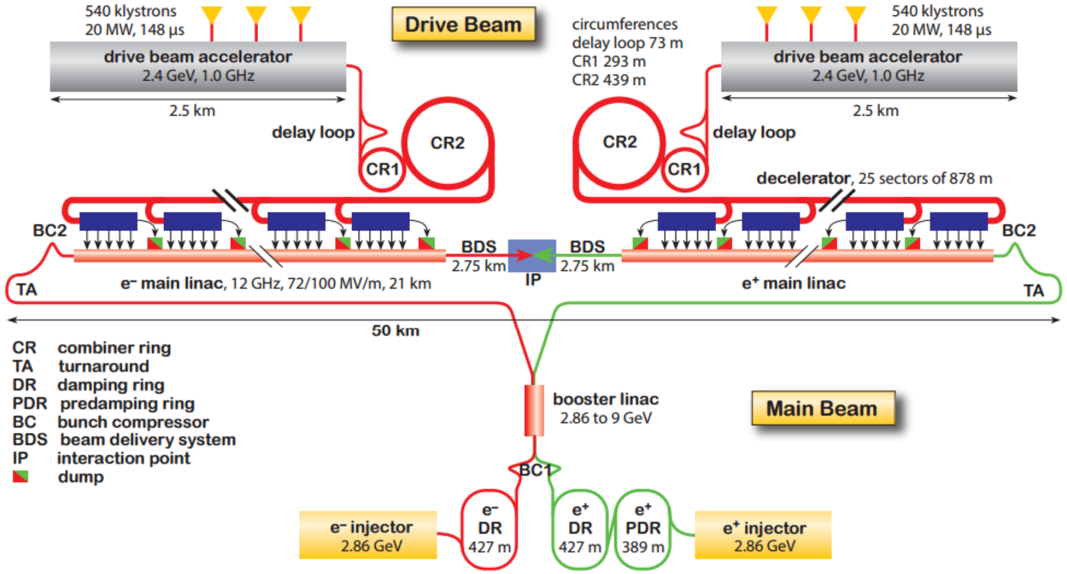
Breakdown-Loaded Electric Field as a High Gradient Limit

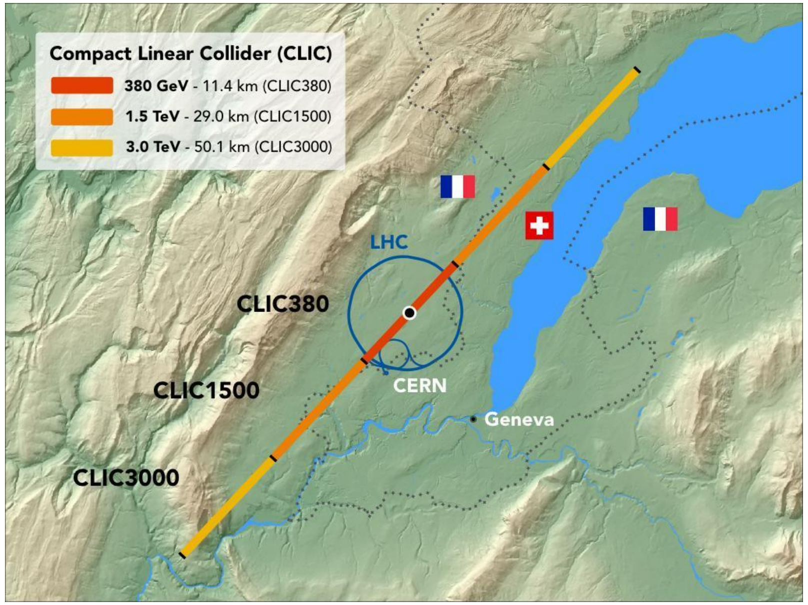
Jan Paszkiewicz, Alexej Grudiev, Walter Wuensch
JAI Fest, Oxford
6 December 2019

Compact Linear Collider

- Linear e^+e^- collider for precision particle physics measurements.
- Staged implementation up to 3 TeV.
- Linear due to synchrotron losses.
- 100 MV/m accelerating gradient for high energy with reasonable machine length.

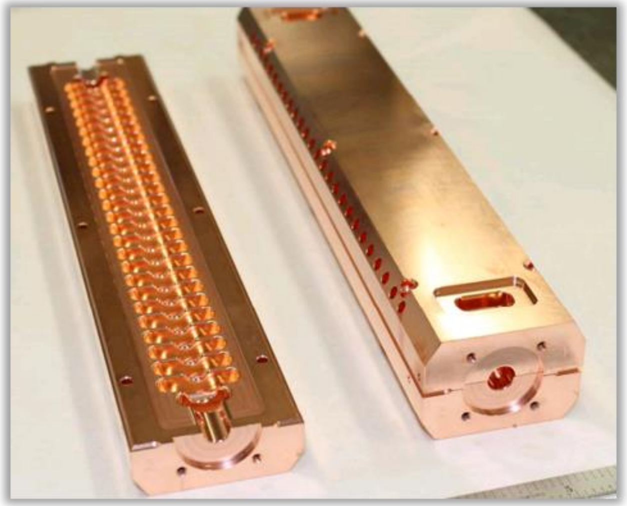


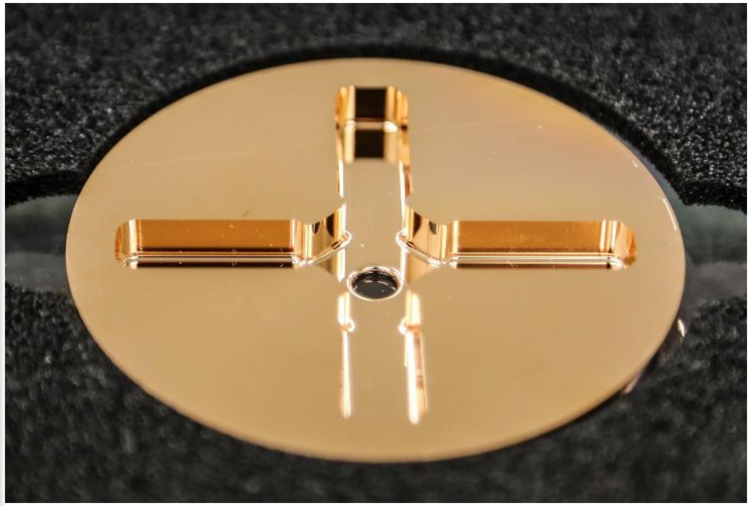


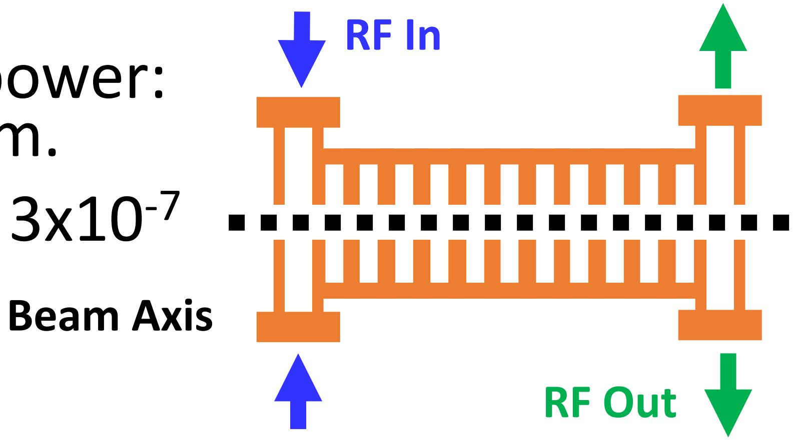


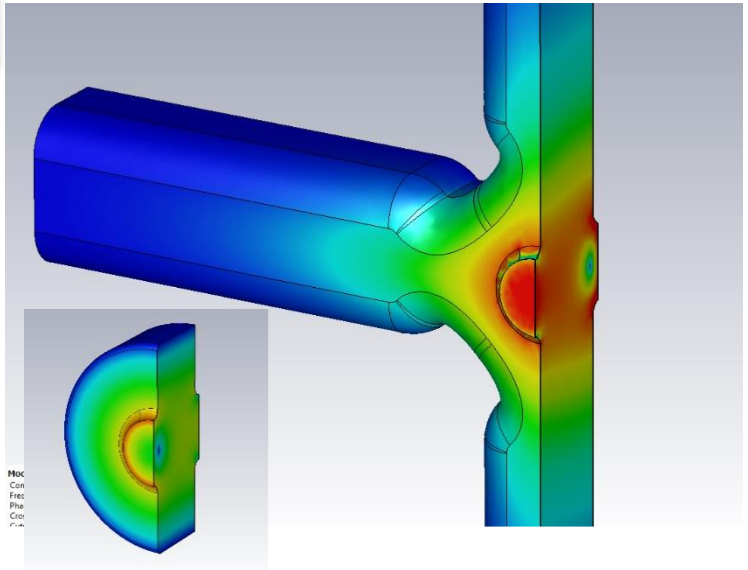
RF Accelerating Structures for CLIC

- 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.



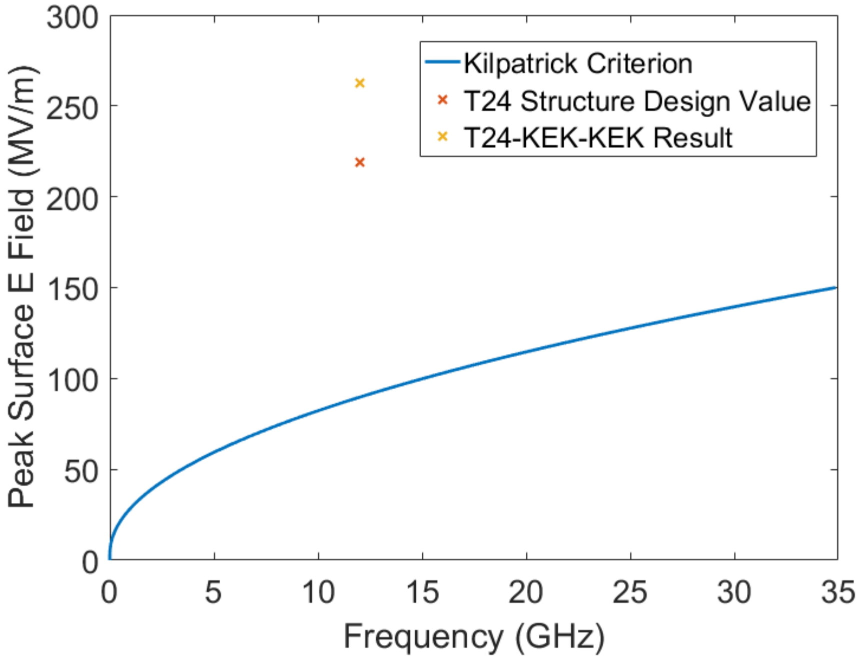




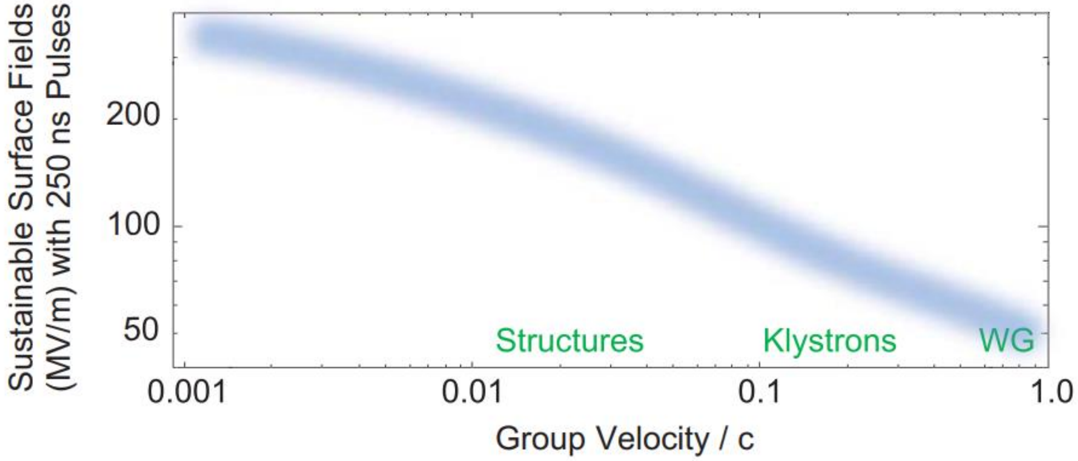


High-Gradient Limits: Electric Field

- Kilpatrick’s criterion: ‘classic’ quantity defining maximum surface E field.
- Different structure designs can reach different peak accelerating gradients and surface fields.
- It appears that breakdown is not just a function of E field. Dependence on H field, group velocity, power flow, and total voltage have all been observed.



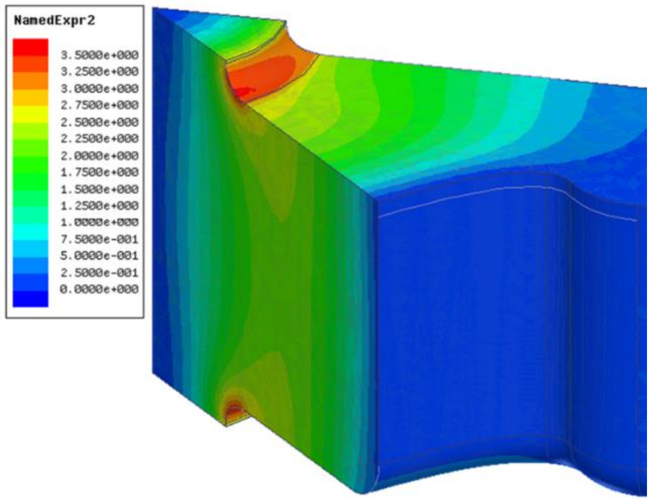
Dependence of peak E field with group velocity (C. Adolphsen)



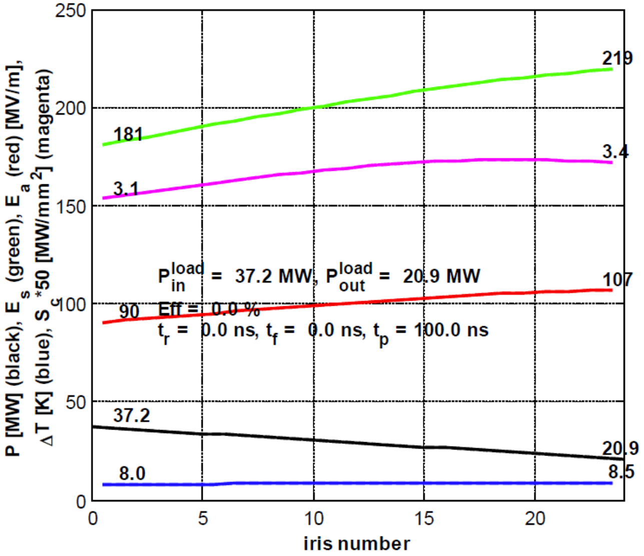
High-Gradient Limits: Power Flow

- Experimental data from CERN, SLAC and KEK suggests ultimate limit depends on power flow, not E field.
  - Global power flow: input RF power divided by aperture circumference
  - Local power flow: modified Poynting vector, S_c – used to optimise geometries

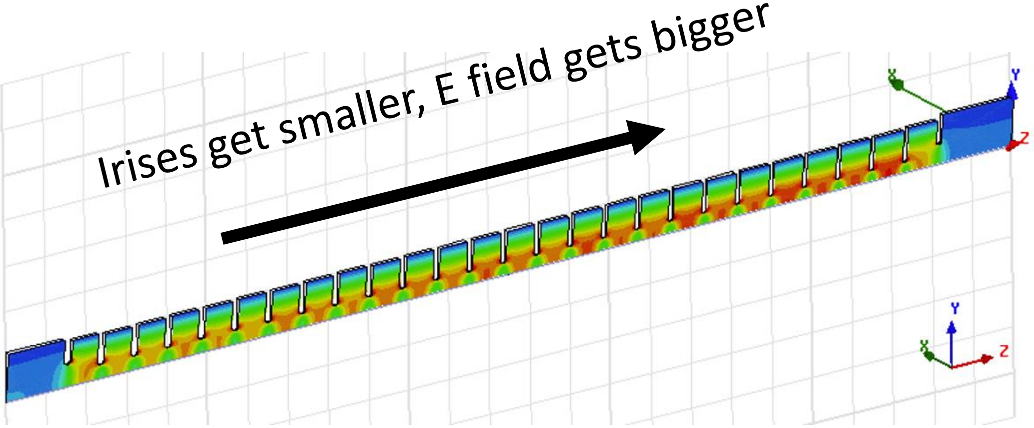
Example of surface S_c calculation in 1/8th of a damped cell:



Example of structure tapering profile:



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

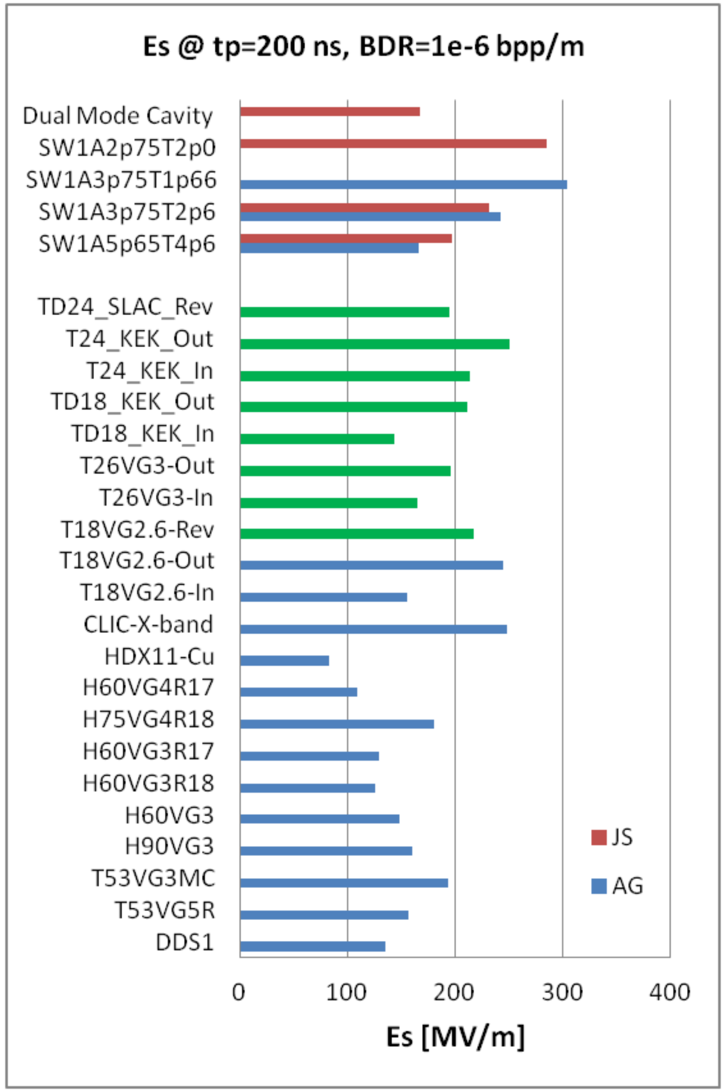


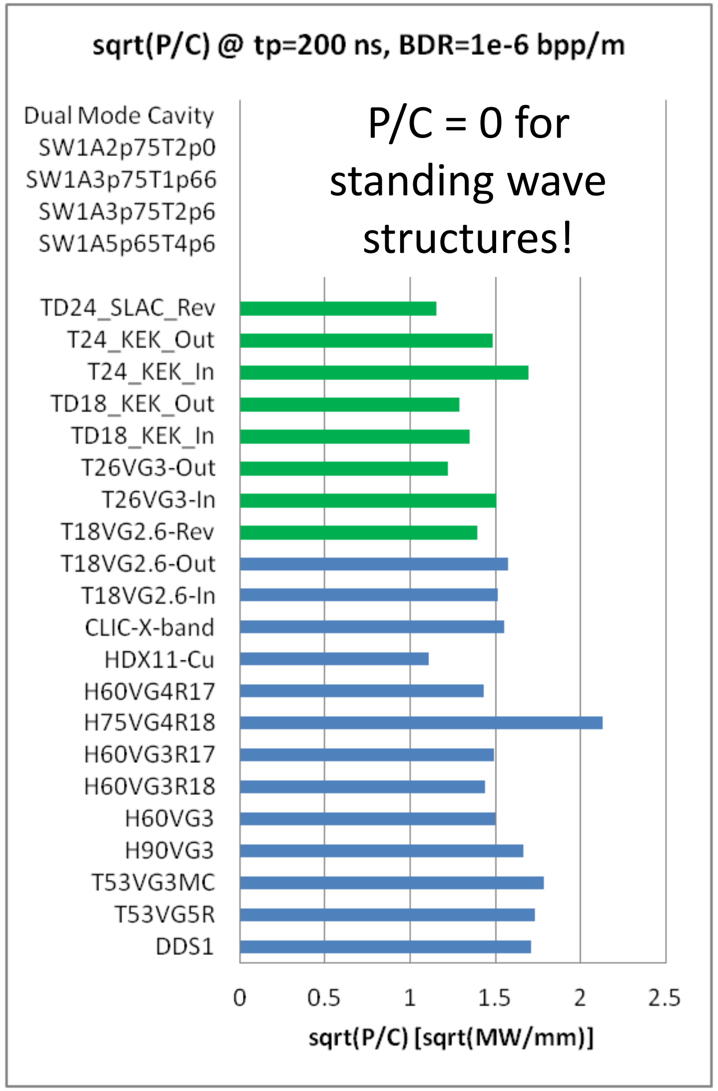
Irises get smaller, E field gets bigger

High-Gradient Limits: Power vs. E Field

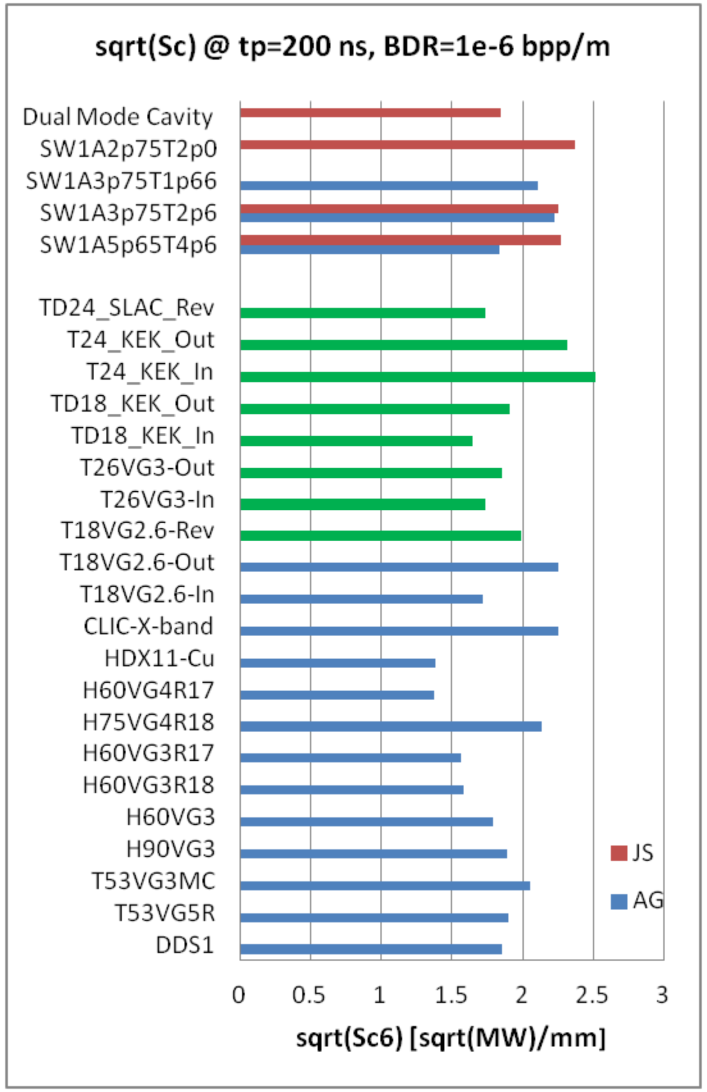
Standing wave

Traveling wave


Es @ tp=200 ns, BDR=1e-6 bpp/m


sqrt(P/C) @ tp=200 ns, BDR=1e-6 bpp/m

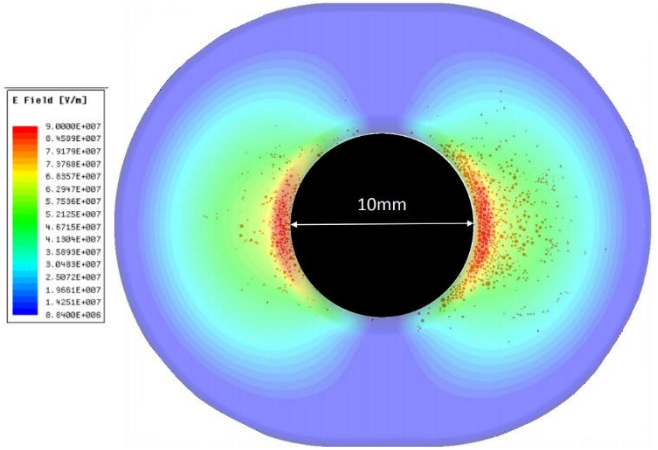
P/C = 0 for standing wave structures!


sqrt(Sc) @ tp=200 ns, BDR=1e-6 bpp/m

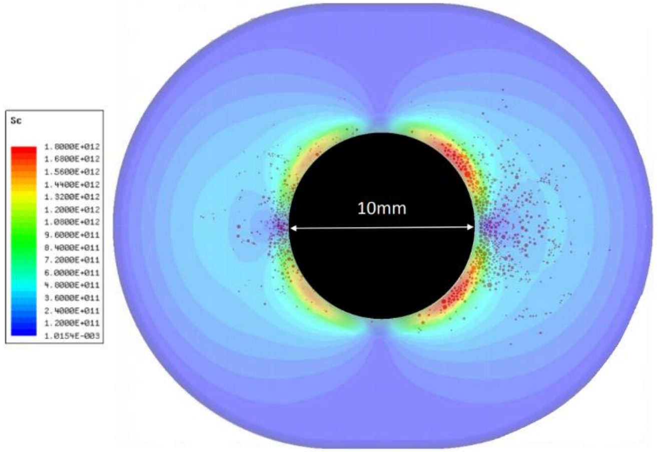
Plots from W. Wuensch’s slides for LCS

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?



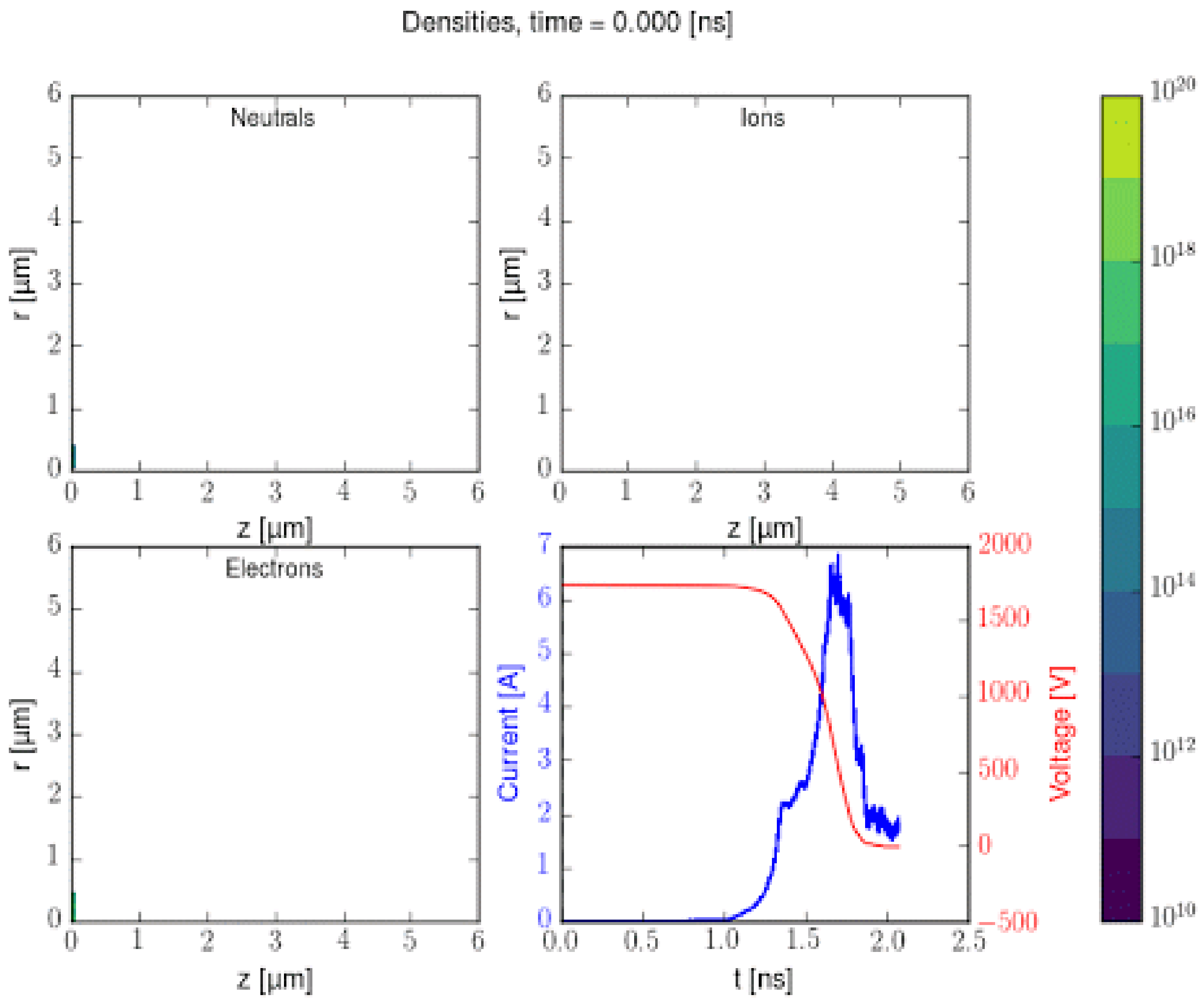
Breakdown locations vs. E field



Breakdown locations vs. Sc

Evolution of a Breakdown

- PIC simulations of breakdowns show that:
- Breakdown is a runaway process involving heating of an emission site and plasma formation.
- Takes a short but finite time to develop.
- A large number of charge particles is produced in the process – accelerating these particles requires a large influx of power.
- If power flow is insufficient, the field will decrease.
- Note that breakdowns are typically very small: ~10s of nm initially and ~50 um craters



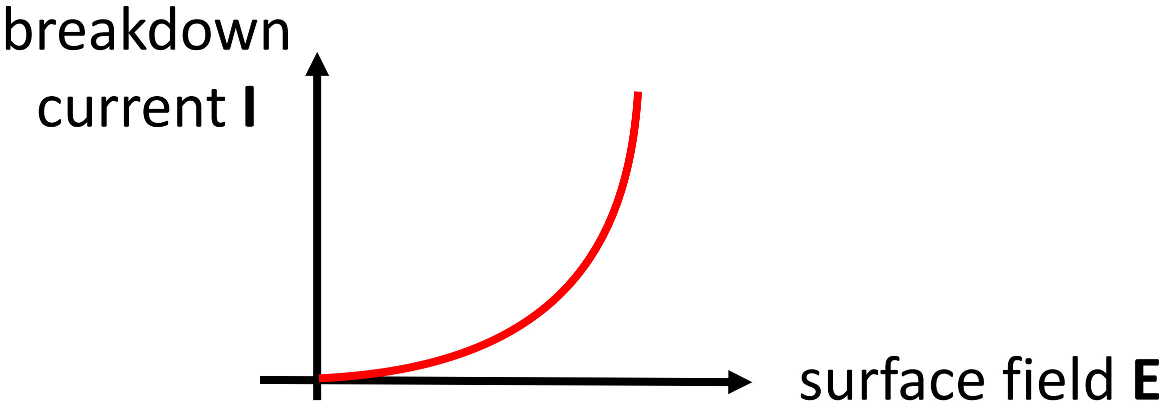
H. Timko et. al., Contrib. Plasma. Phys. 4, 229 (2015).
Animation by K. Sjobaek

Hypothesis

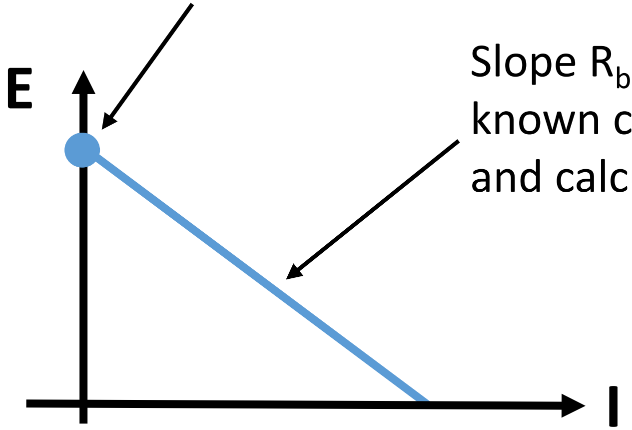
- Ultimate BD limit is a function of available power, like with S_c.
- Nascent breakdown extracts power from RF by acceleration of charged particles (electrons). Interaction through E field only.
- Emitted current is a function of surface E field.
- Local surface E field decreases under BD loading. (In 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)



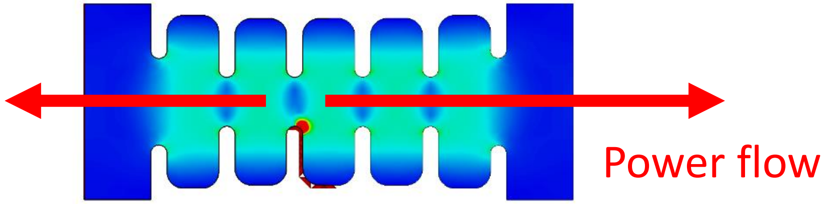
For every point in the structure, calculate a dependence of local field on antenna current:



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:

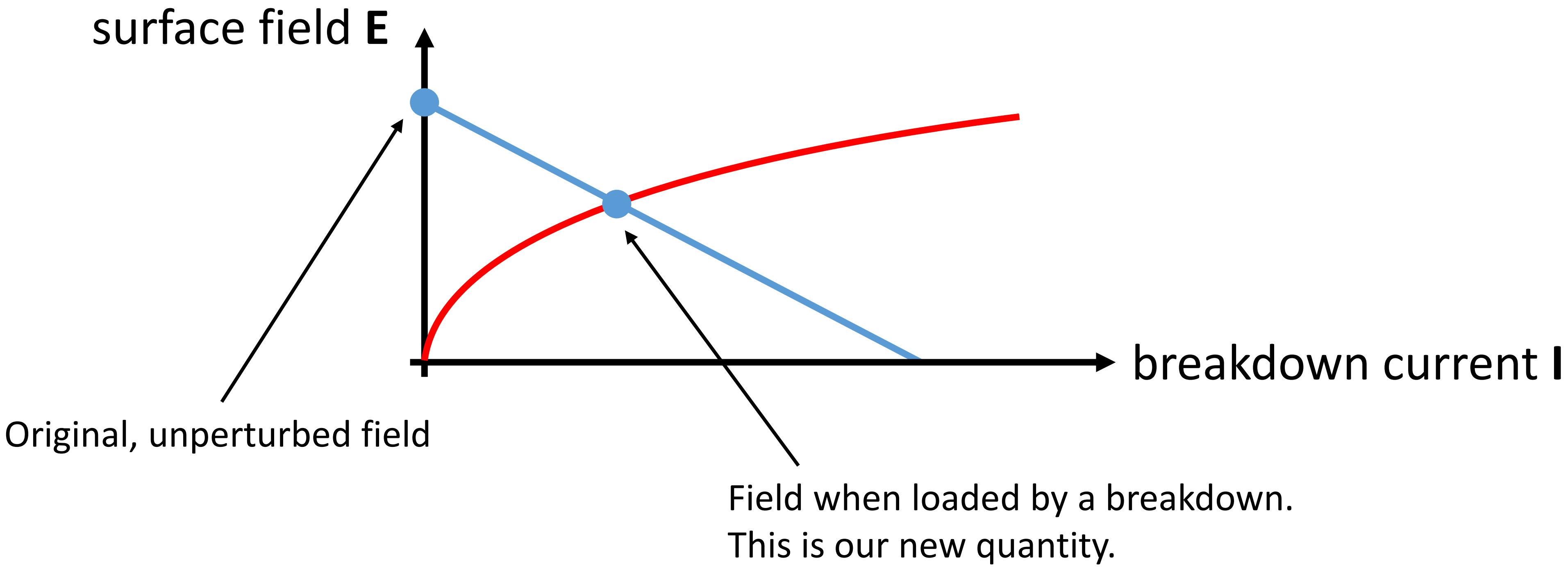


Define breakdown impedance as:

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

Outline of Procedure

Combine the two plots to find the equilibrium solution:

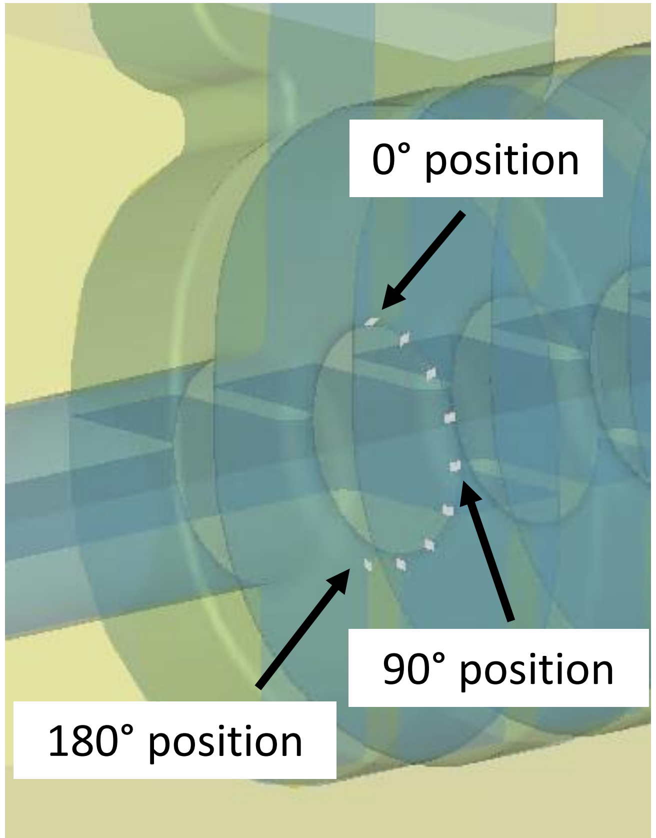


Original, unperturbed field

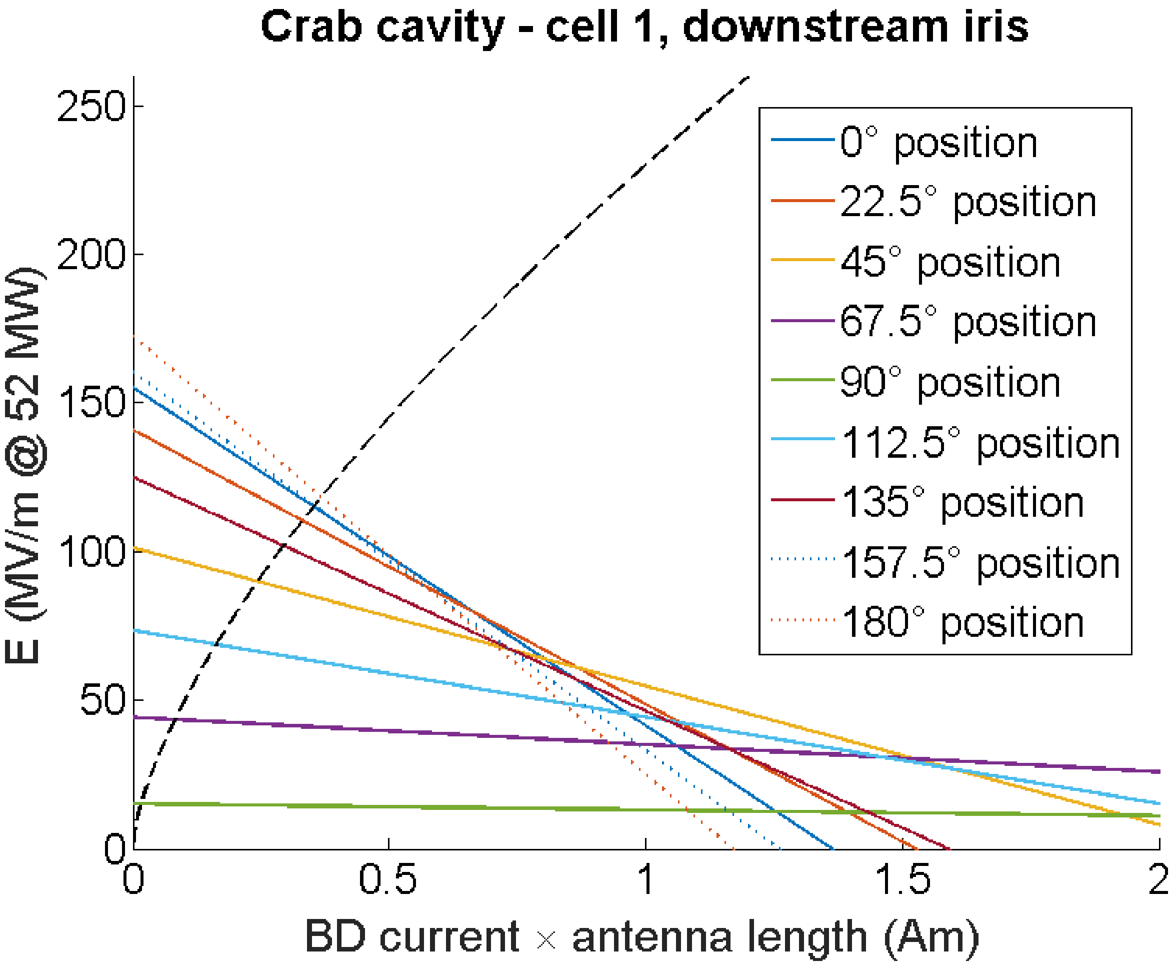
Field when loaded by a breakdown.
This is our new quantity.

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

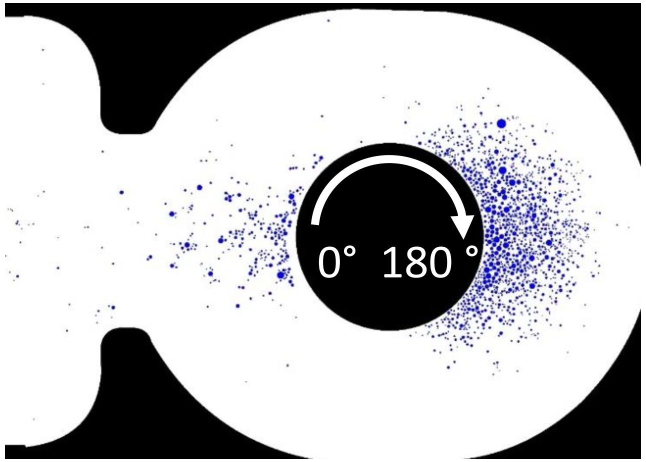


Antennas placed in rings around each iris.

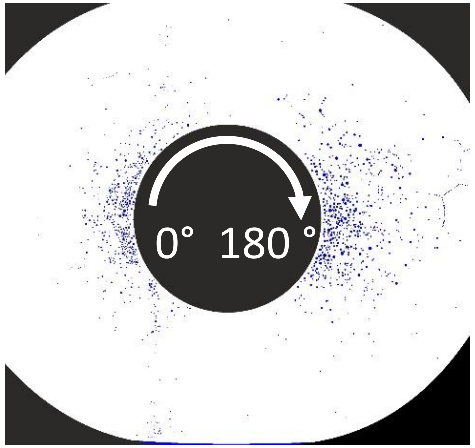


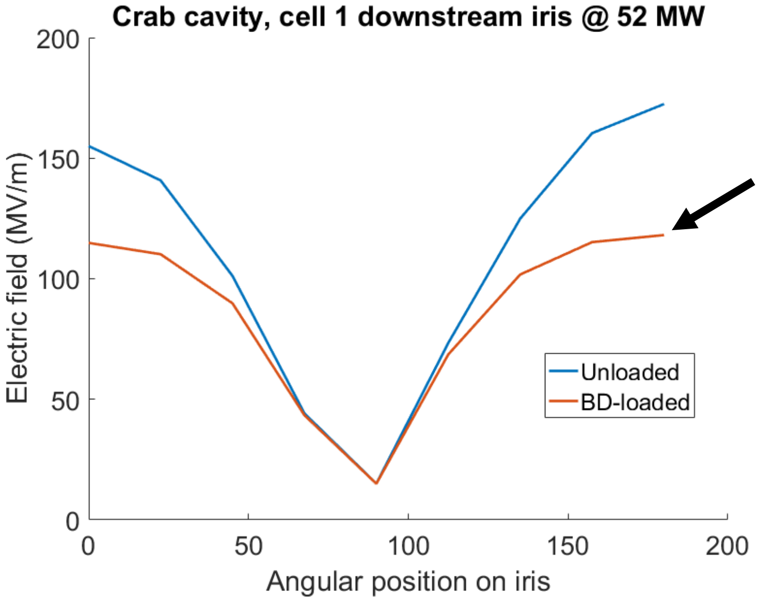
Application to the CLIC Crab Cavity

Cell 1

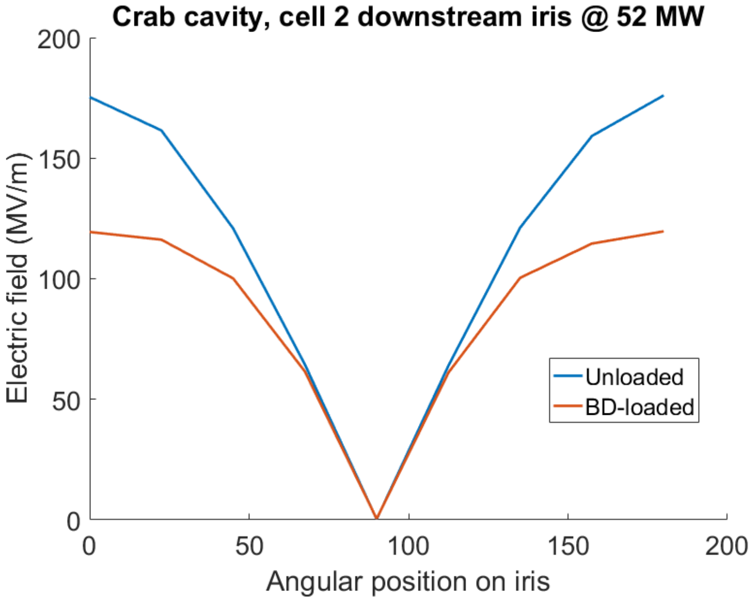


Cell 2



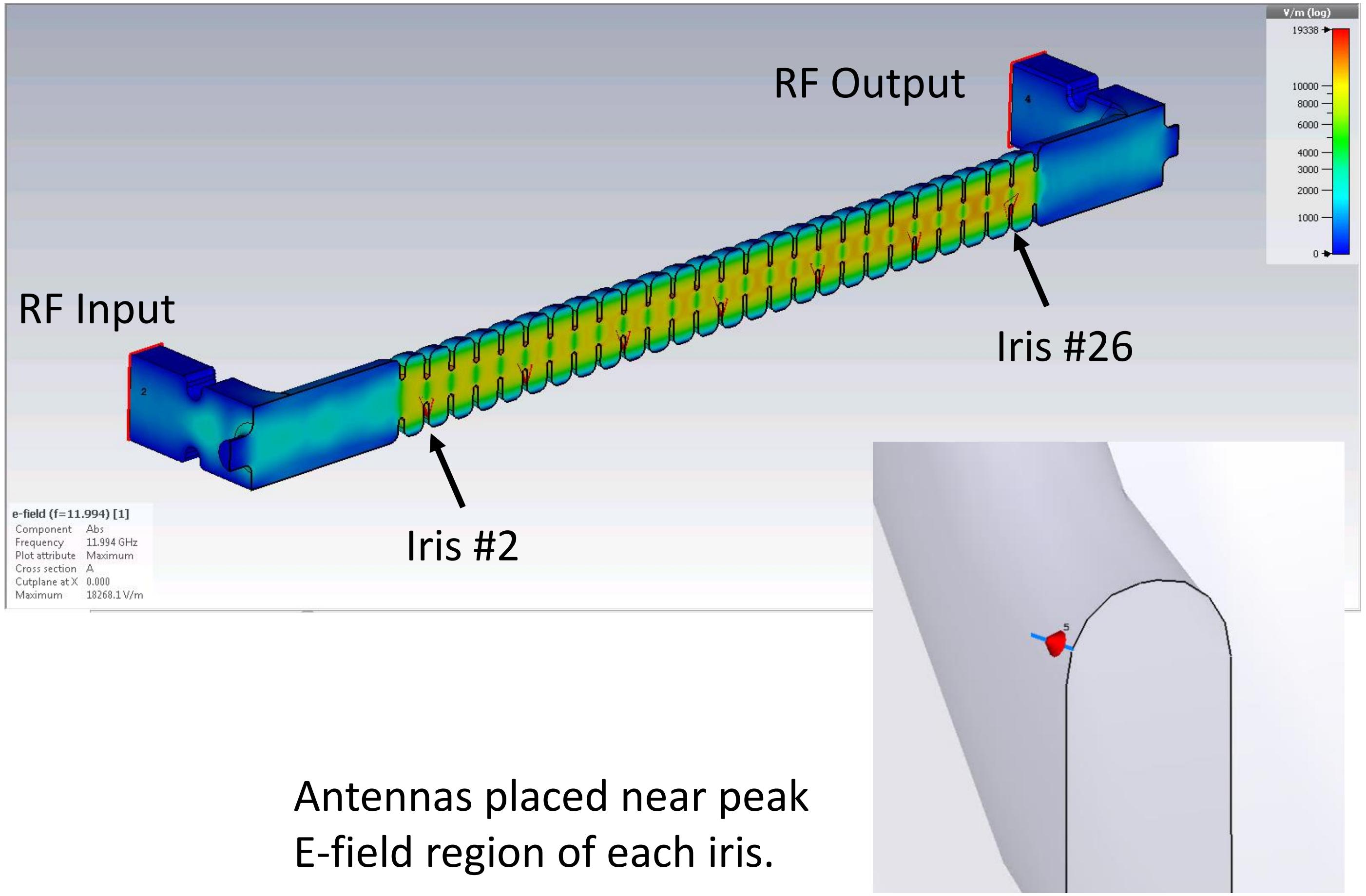


Peak value of 118 MV/m

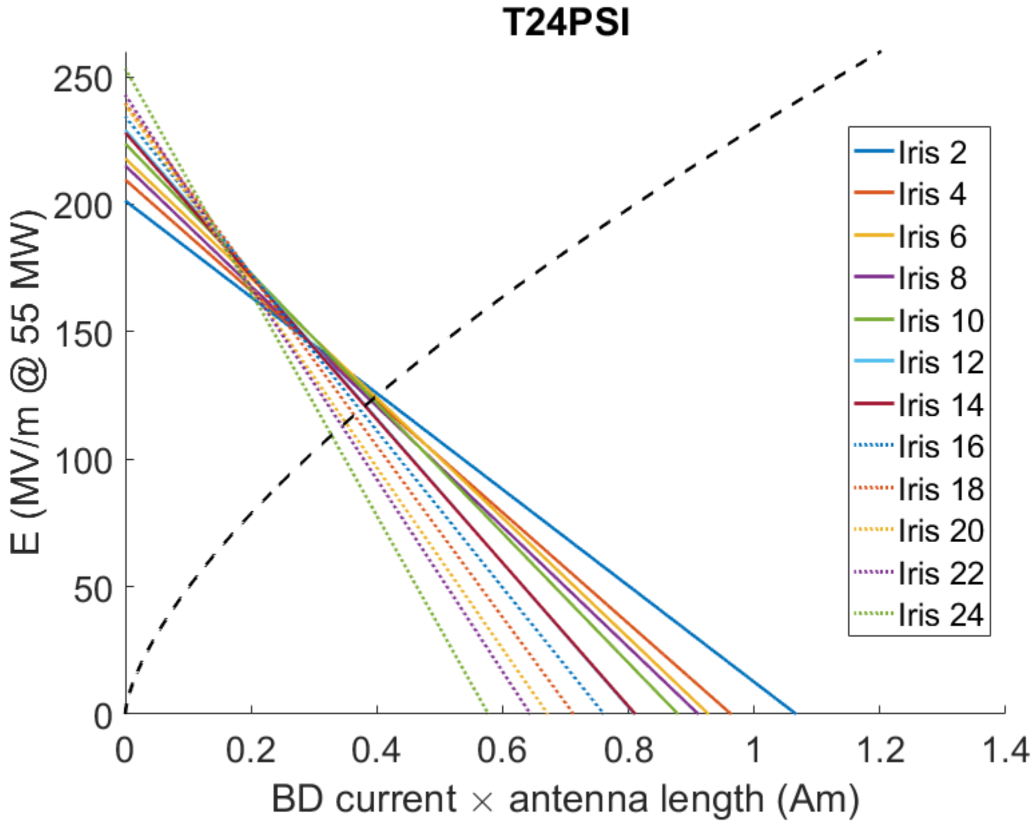


Application to T24 Structures

T24 PSI structure, E field complex magnitude

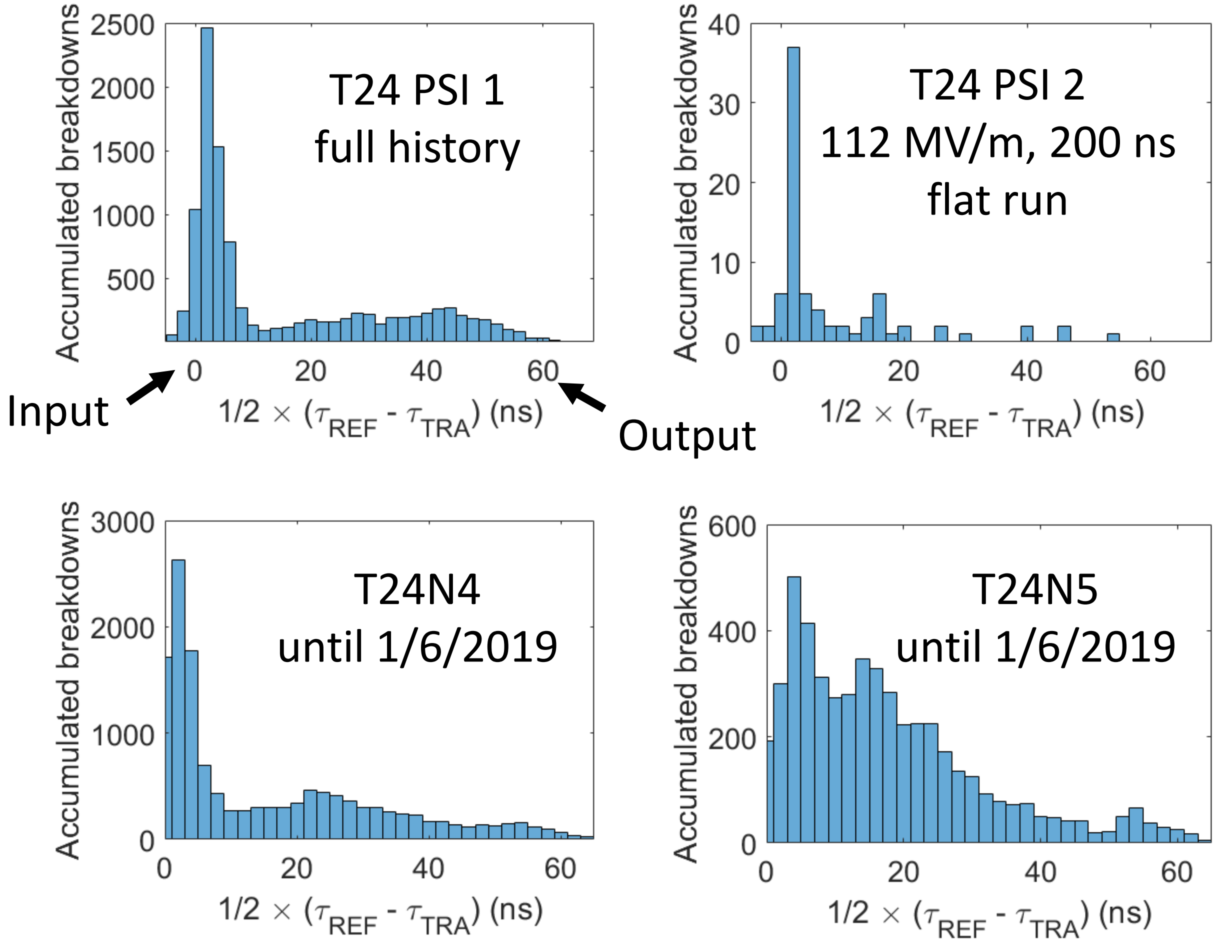


Antennas placed near peak E-field region of each iris.



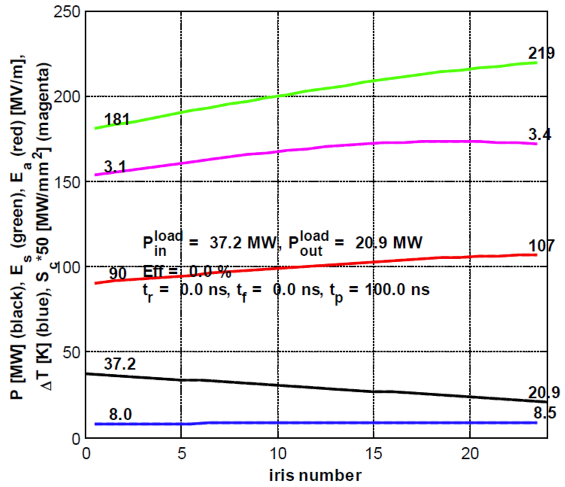
Application to T24 Structures

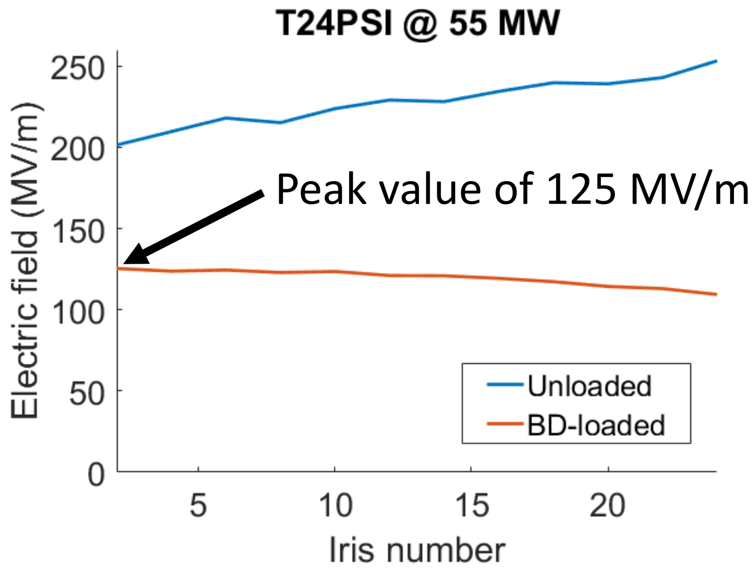
Breakdown locations in T24 structures:



Input

Output

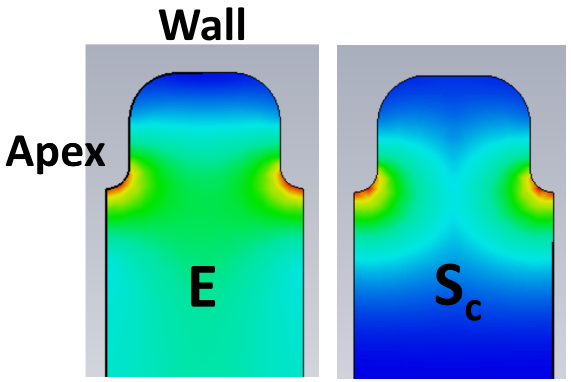


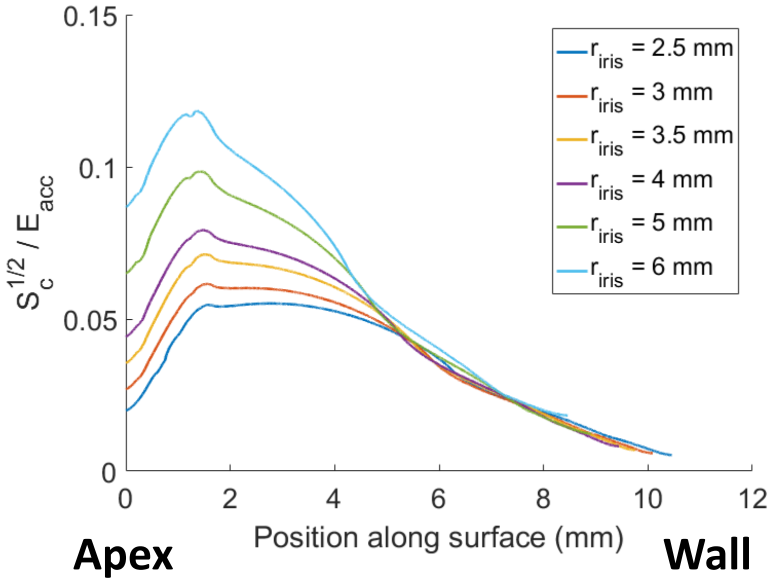


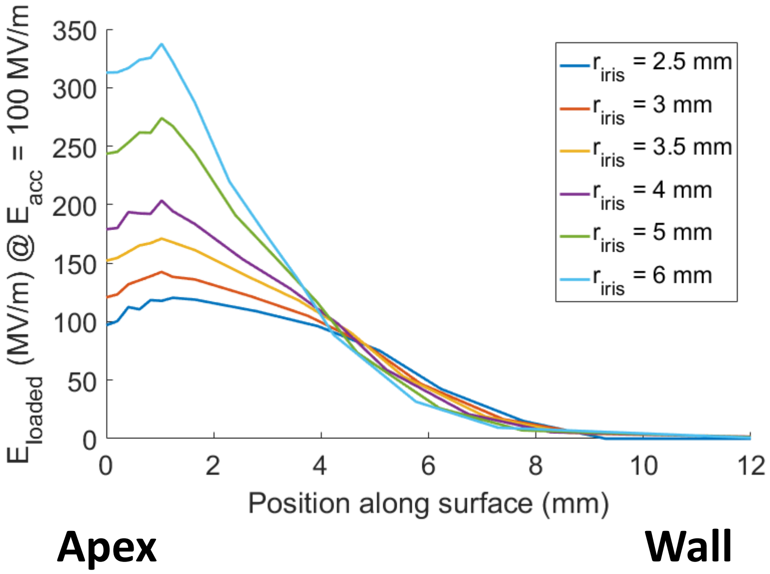
Peak value of 125 MV/m

Consistency with S_c in TM_{010} cells

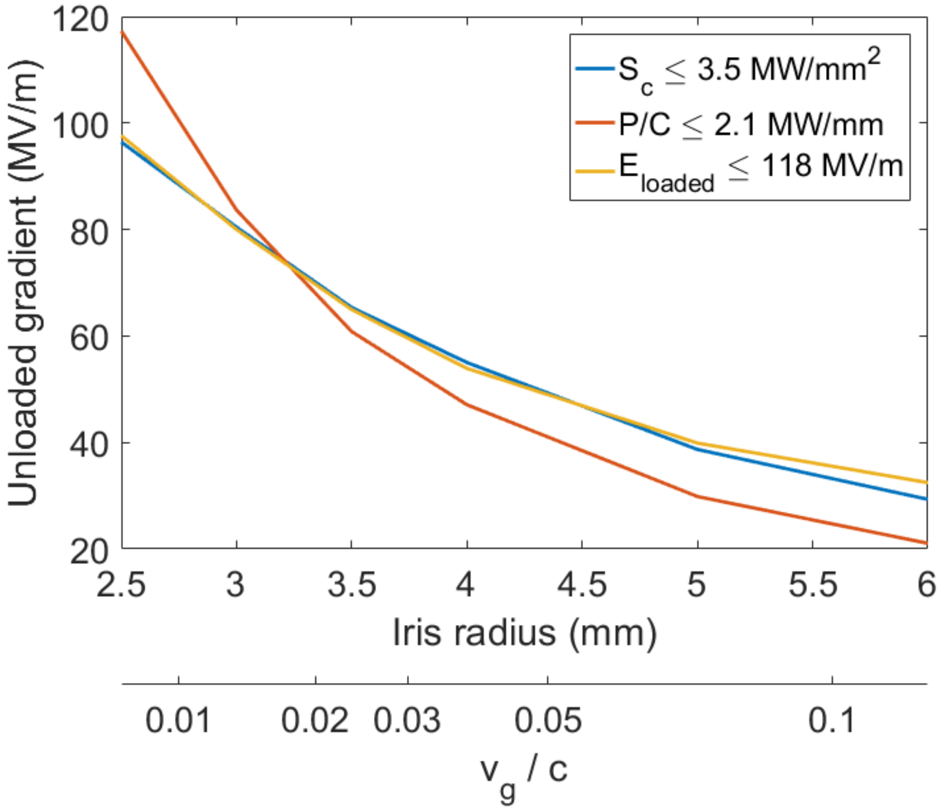
Locations of breakdowns within cells:







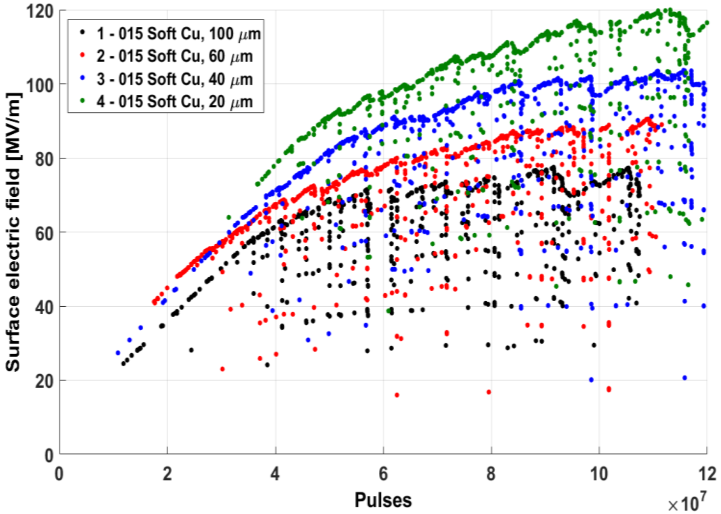
Prediction of maximum gradient:



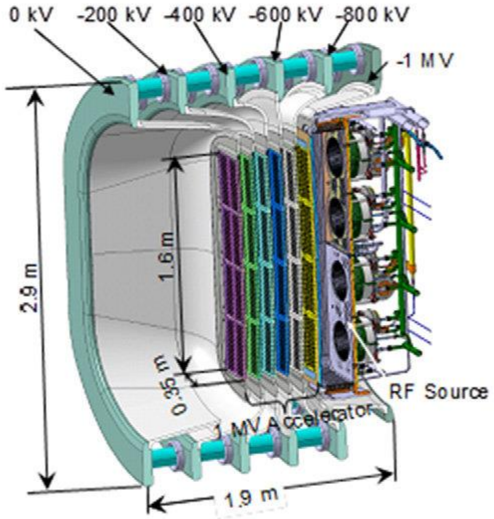
‘Voltage Effect’

- Some experiments show that maximum achievable E field depends on total voltage, i.e. gap size.
- DC Spark System at CERN showed constant BDR for constant $E \times d^{0.28}$
- Neutral beam injector for ITER with 1 MV DC voltage incorporates intermediate voltage shields to achieve higher fields by exploiting this effect.
- The loaded electric field model shows this effect and provides an alternative explanation.

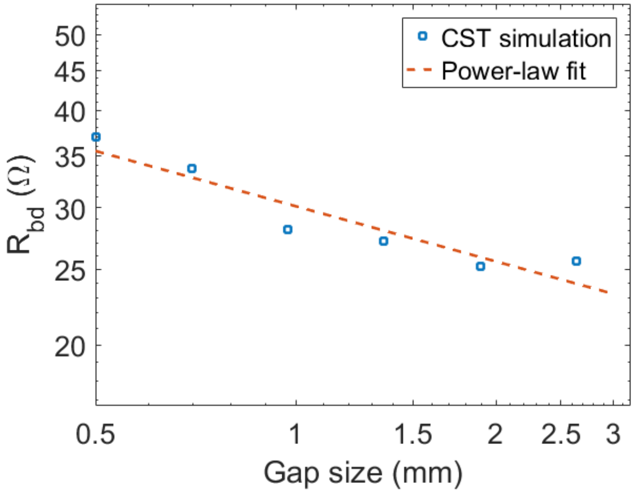
Conditioning curves for various gap sizes in the DC system at CERN



MITICA beam source for ITER



Breakdown impedance calculations for simplified DC system



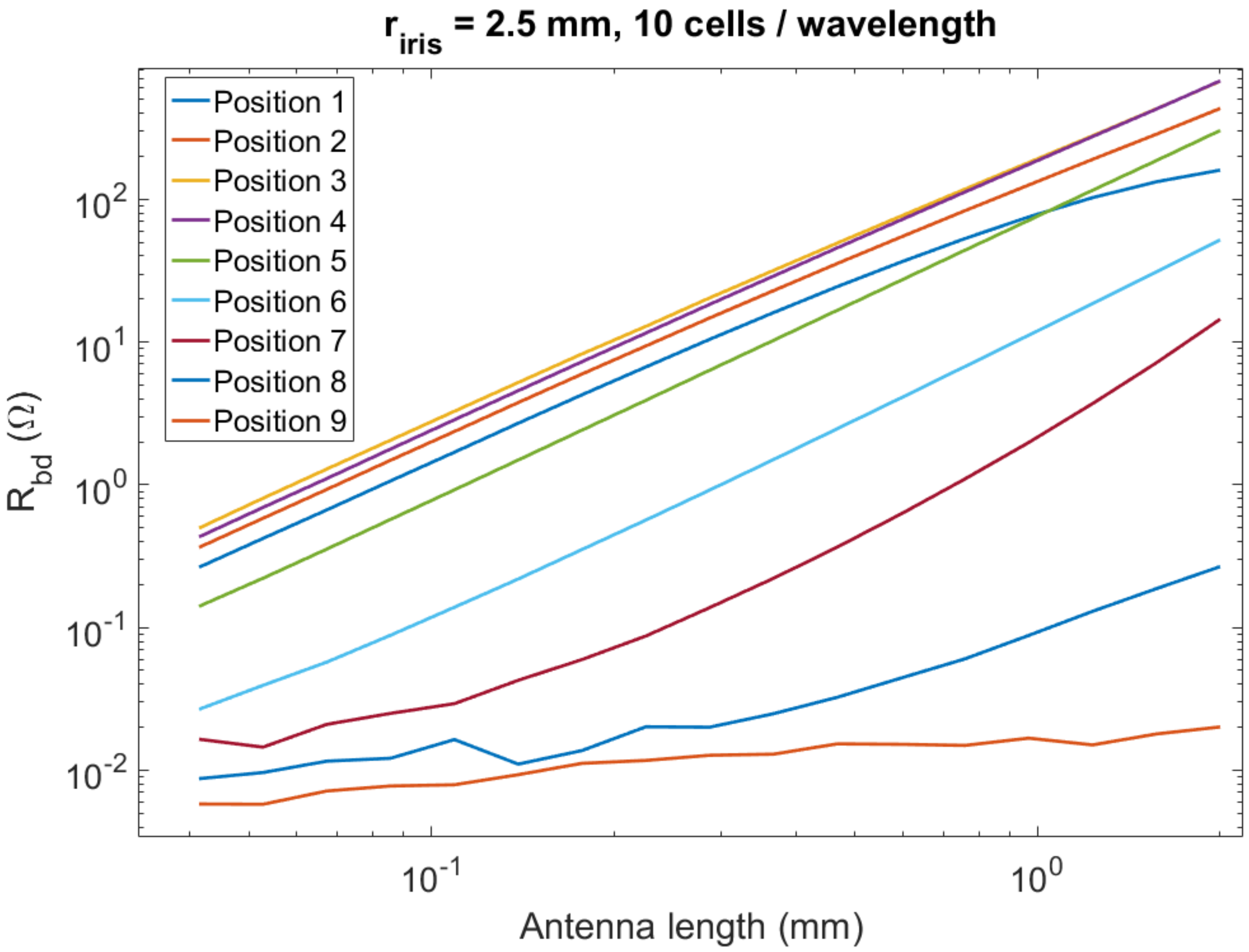
CERN DC system results: I. Profatilova
MITICA diagram: V. Toigo et. al.

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.
- Works well for RF structures:
  - Correct distribution of breakdown locations.
  - Consistency with Sc of limiting gradient.
- Other advantages:
  - Resolves issue of no power flow in DC experiments and predicts voltage dependence.
  - Has square root dependence on frequency in RF.

Thank you!

Antenna Length Dependence



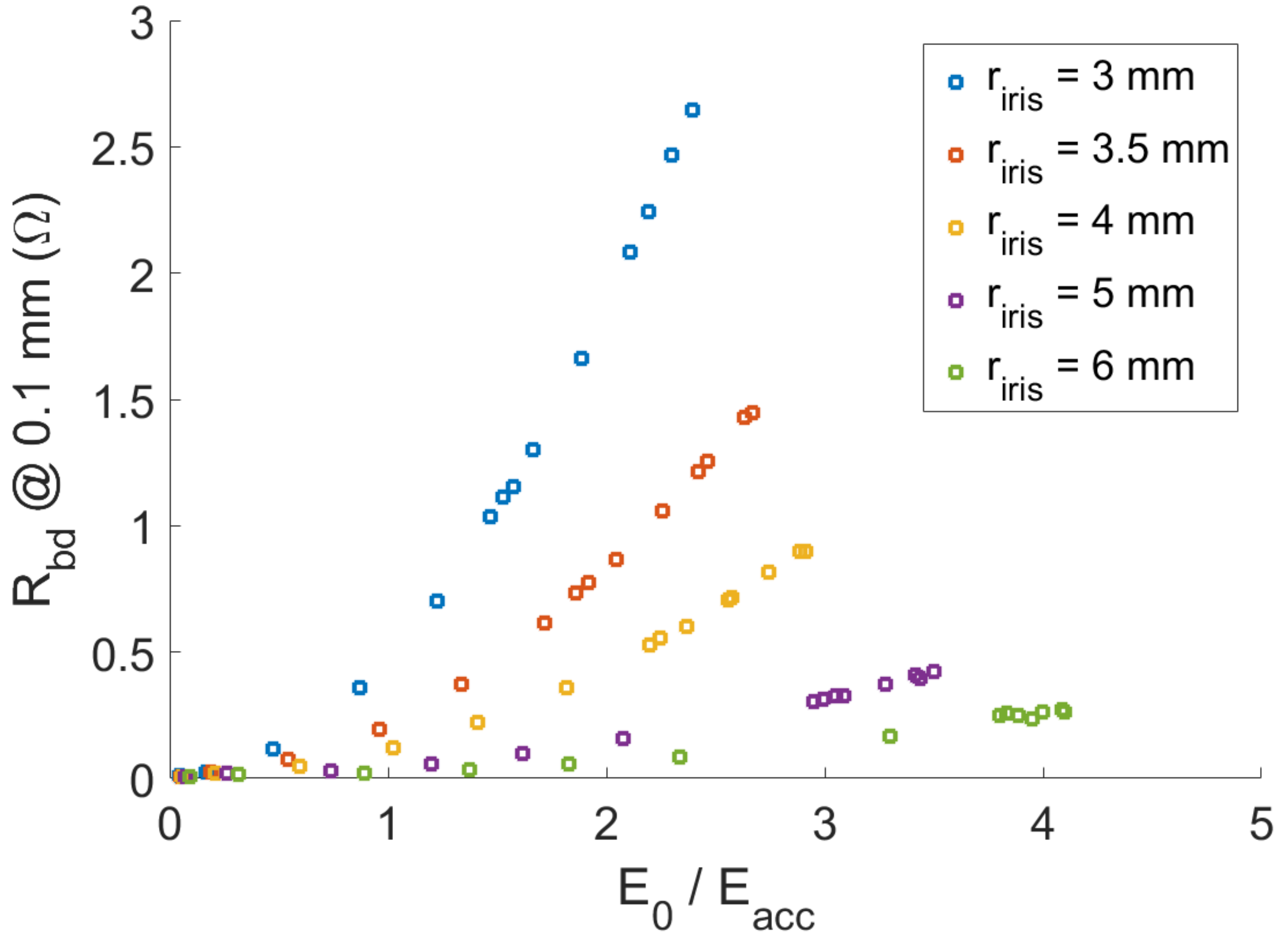
Observed dependence:

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

Hertzian dipole in free space:

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

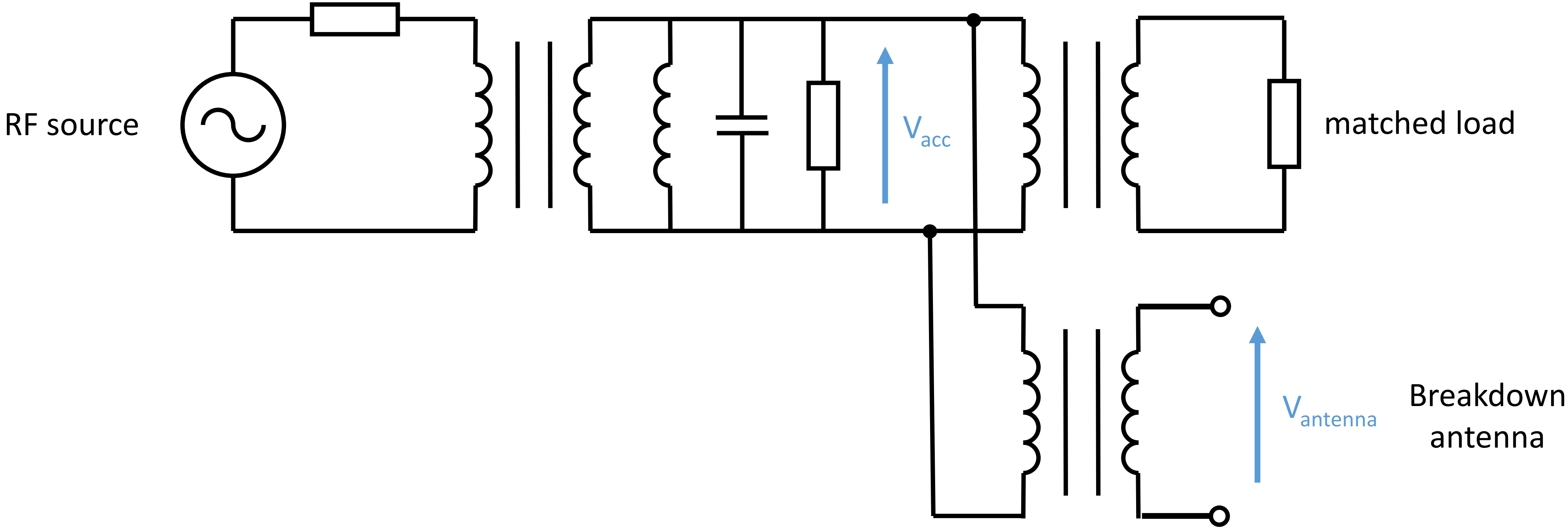
Dependence of R_{bd} on E Field



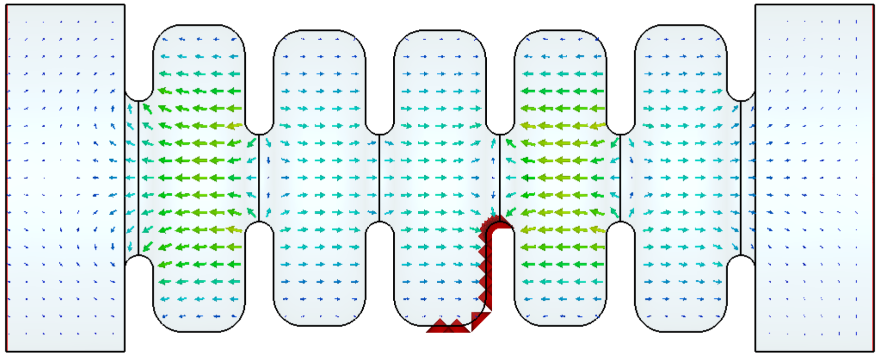
Within a given cell:

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

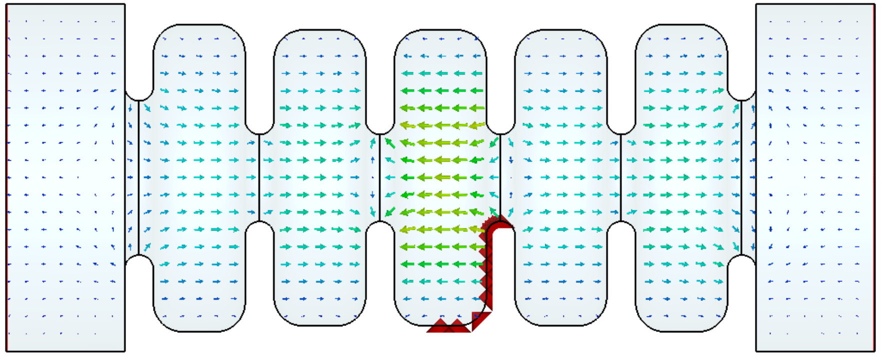
Circuit Model



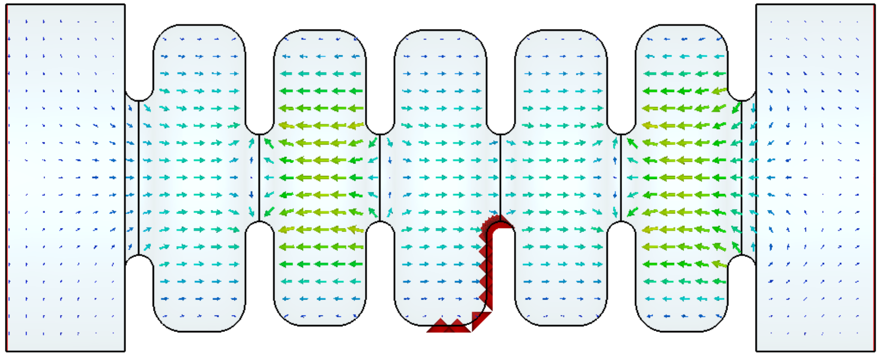
0°

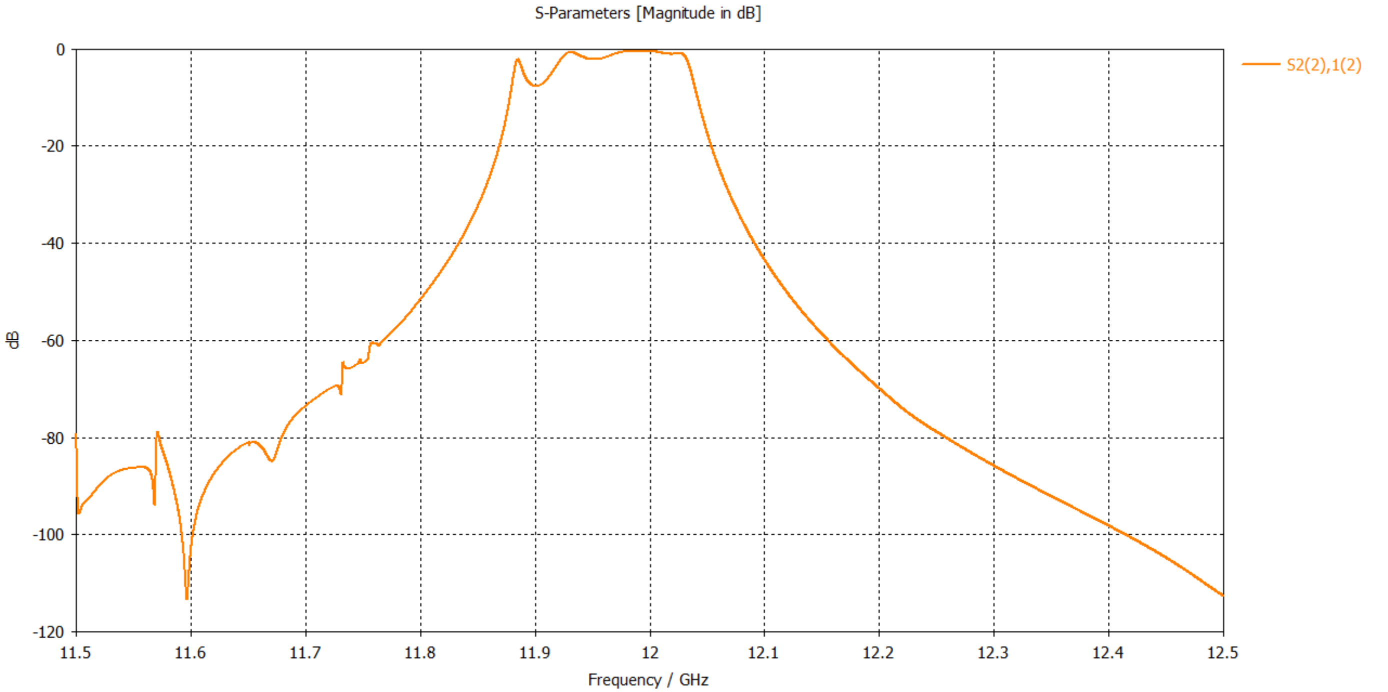


120°



240°




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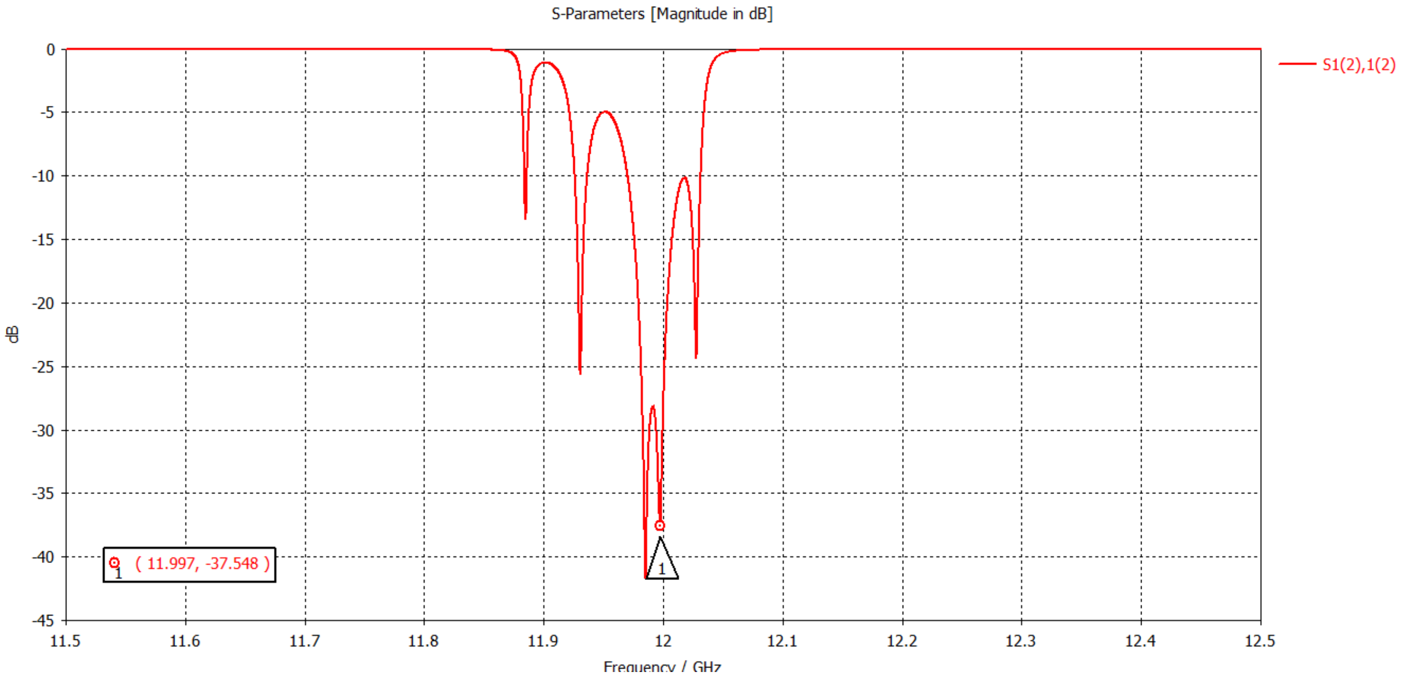
12
12.1
12.2
12.3
12.4
12.5
Frequency / GHz


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