Experimental Investigation of RF Breakdown in a Short-pulse X-band Cavity

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Outline

- Introduction: high-gradient acceleration with short RF pulses
- Numerical dark current studies of short-pulse RF breakdown
- Breakdown testing design of an X-band cavity in the short-pulse regime
- Preliminary experimental results
- Conclusion and plans

RF breakdown: motivation and observable signatures

Motivation

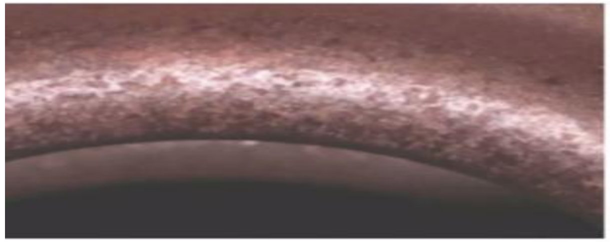
- High accelerating gradients enable compact linear accelerators.
- Breakdown limits the maximum sustainable accelerating gradient.
- Breakdown behavior depends on the RF pulse length.

During RF breakdown

The cavity field collapses or distorts, and input RF energy is reflected, redistributed, or absorbed.

Observable signatures

- Reflected RF changes
- Transmission/probe signal distortion
- Dark-current and optical bursts
- Vacuum response and possible surface damage



Breakdown-induced surface pitting in copper

KEY QUESTION: **How does RF breakdown initiate and evolve when an accelerating cavity is driven by short RF pulses (a few ns for X-band)?**

Mitigating the breakdown barrier with short RF pulses

- Empirical law and pioneering experiments suggested the benefits of using short RF pulses.
- Short-pulse regime is largely unexplored although there were pioneering experimental demonstrations.
- This work: directly examine the RF breakdown behaviors in an X-band cavity driven by RF pulses of a few ns long.

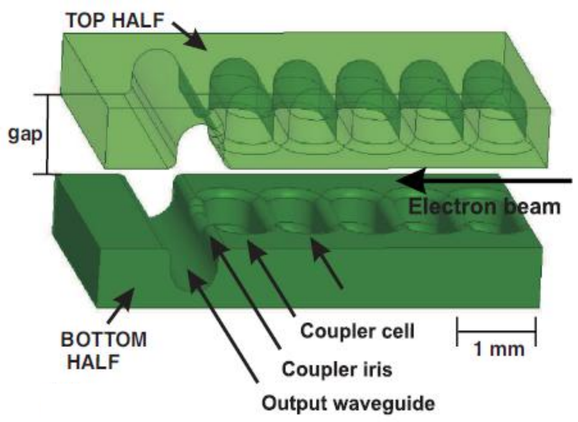
Empirical pulse-length trend

$$\mathrm{BDR} \propto E_a^{30}\, t_p^{5}$$

Breakdown rate depends very strongly on field and RF pulse duration.

A. Grudiev et al., *PRSTAB* **12**, 102001 (2009)

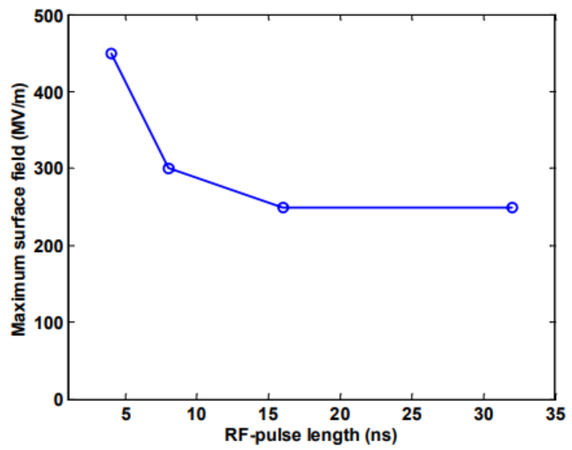
Beam-driven mm-wave structures



Approximately 300 MV/m fields in these mm-wave structures with a O(ns) pulse length.

M. Dal Forno et al., *PRAB* **19**, 011301 (2016)

High-power pulse-length tests



@CTFII, 30 GHz

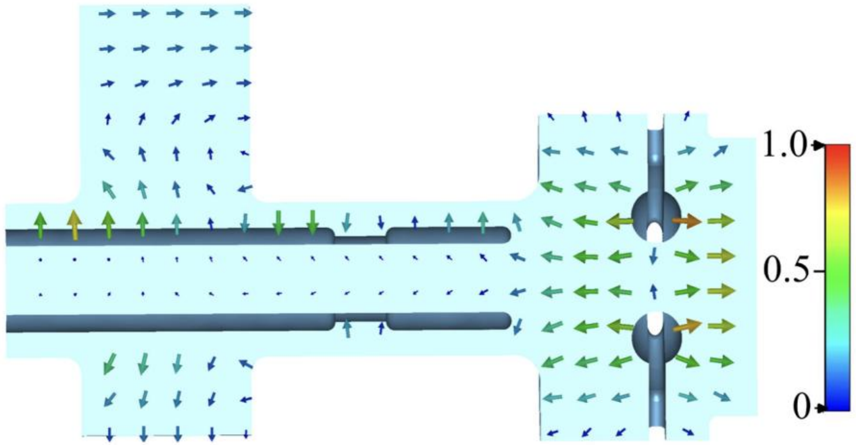
Shorter pulses supported higher surface fields.

W. Wuensch et al., Proc. PAC 2003, ROAA011

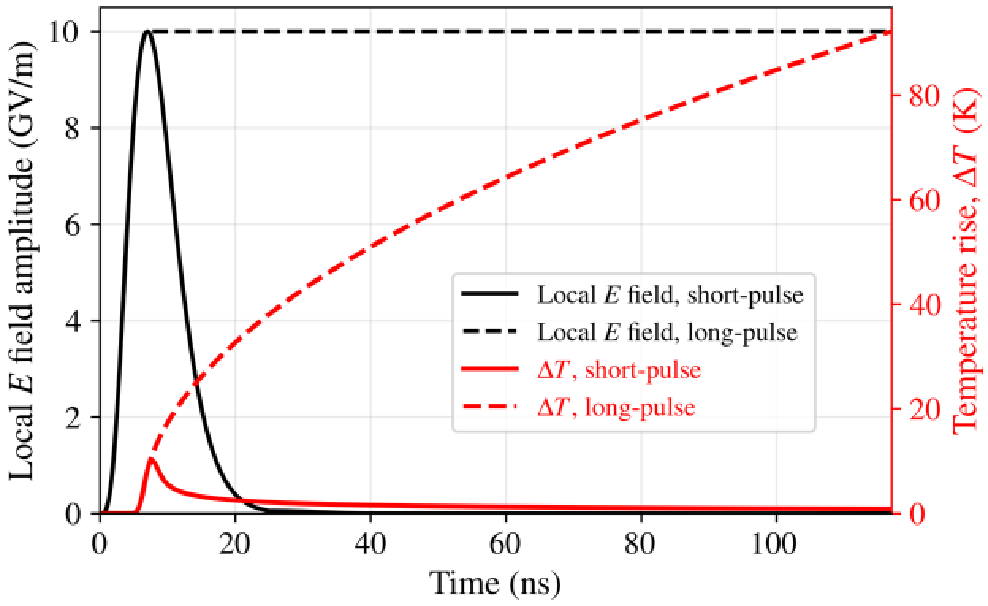
Numerical studies of dark current in an X-band short-pulse photogun cavity

- We performed analytical and numerical studies of dark current dynamics in short-pulse cavities, using the X-band gun cavity [see W. H. Tan *et al.*, 25, 083402 (2022) as an example
- We studied a few physics processes related to RF breakdown: field emission (this slide), multipacting, and electron cloud formation.

- **Short-pulse operation can enable high local fields by limiting field-emission-induced surface heating.**



Electric field pattern in the X-band photogun cavity

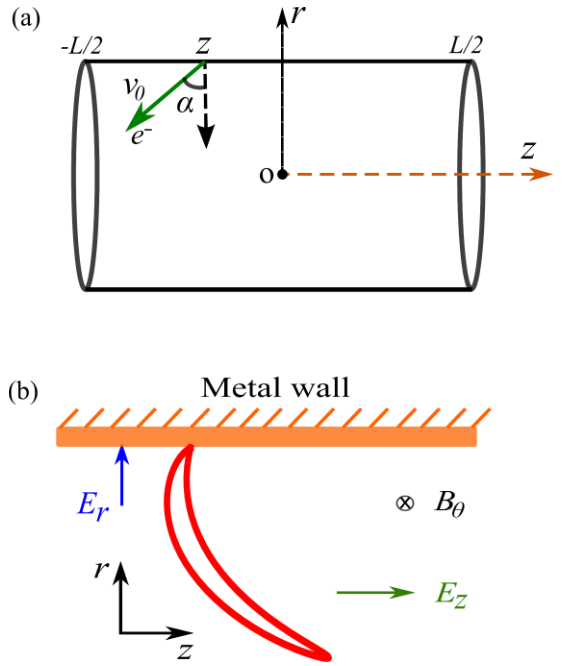


Same peak local field: the few-ns pulse produces a much smaller temperature rise than the long-pulse case.

G. Rijal *et al.*, PRAB **28**, 111301 (2025)

Analytical modeling of multipactor

- Analytical model was developed to describe multipacting resonance conditions and benchmarked with CST simulations.
- Radial variation of field components is incorporated to calculate trajectories.



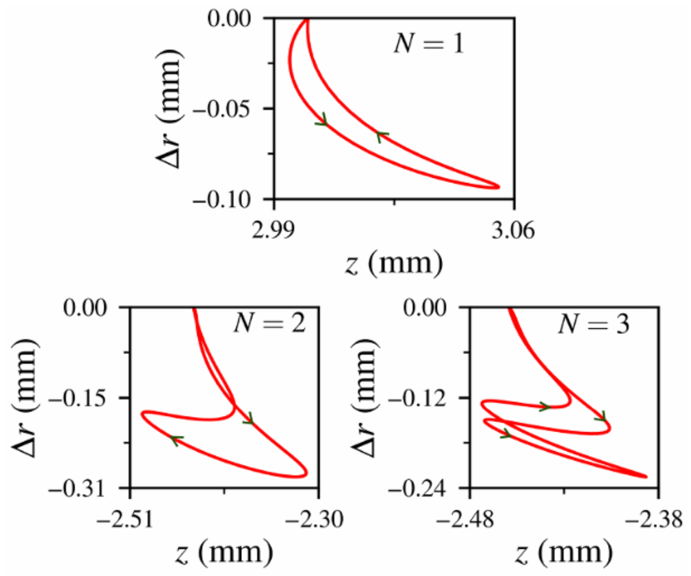


Fig: Sample resonance trajectories

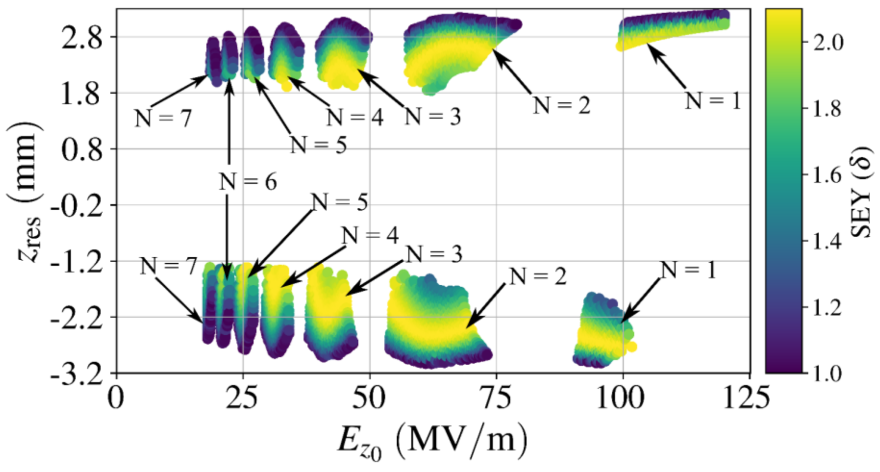
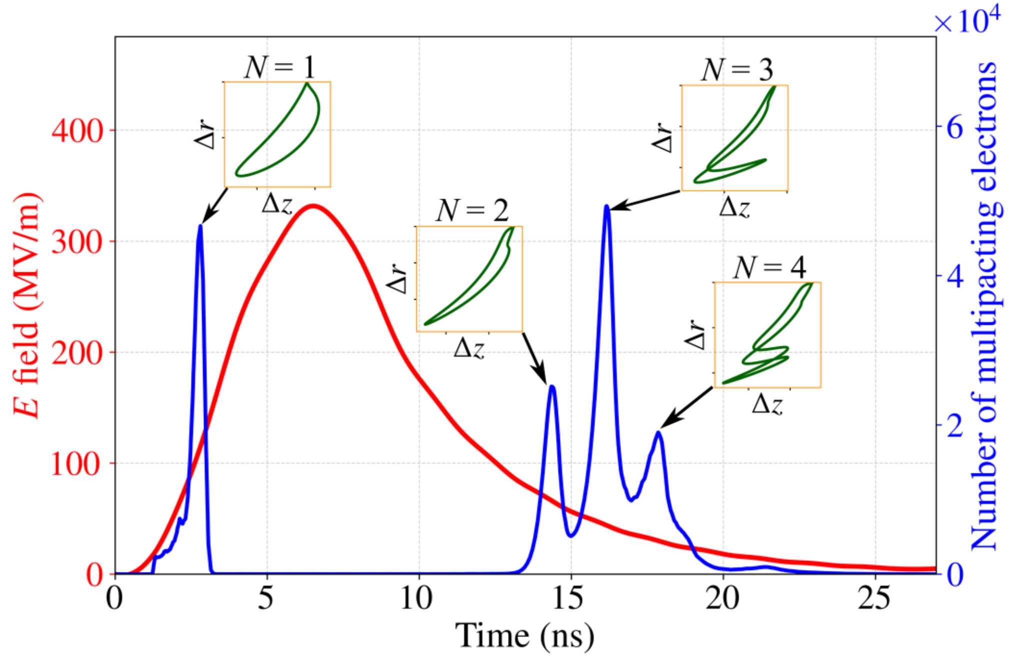


Fig: Resonance susceptibility plot

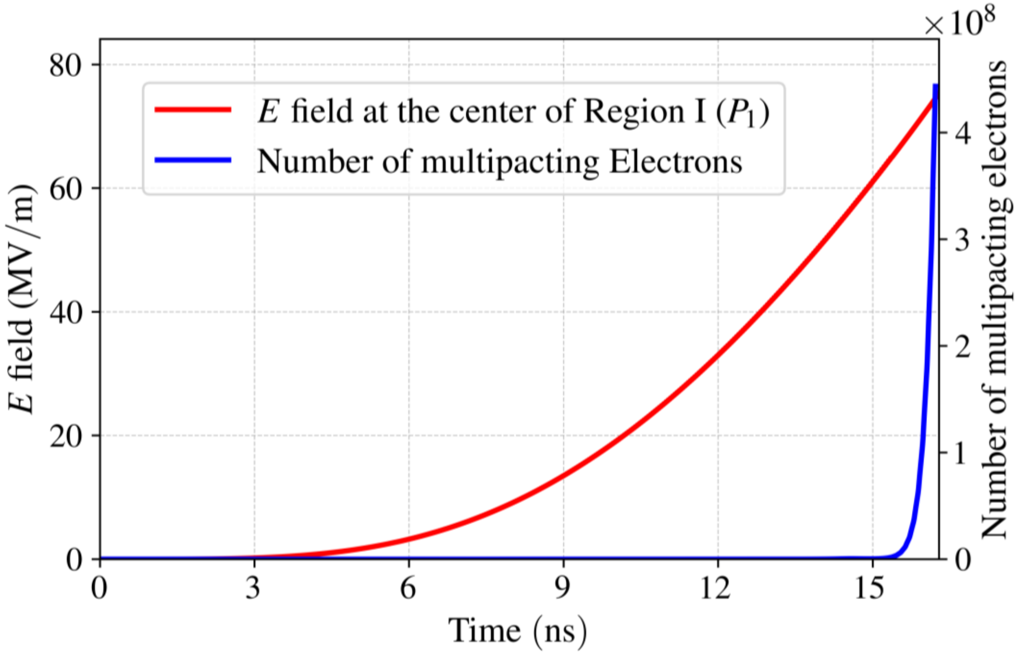
Numerical studies of dark current in an X-band short-pulse photogun cavity

- Short RF pulses can suppress dark-current buildup by limiting the available multiplication time.

Short-pulse case: resonance crossed quickly



Longer-pulse case: resonance persists



Key takeaway: Multipacting growth depends not only on field value, but also on how long the RF field remains near a resonant condition. Short pulses interrupt the multiplication process.

Plasma growth can modify the RF response

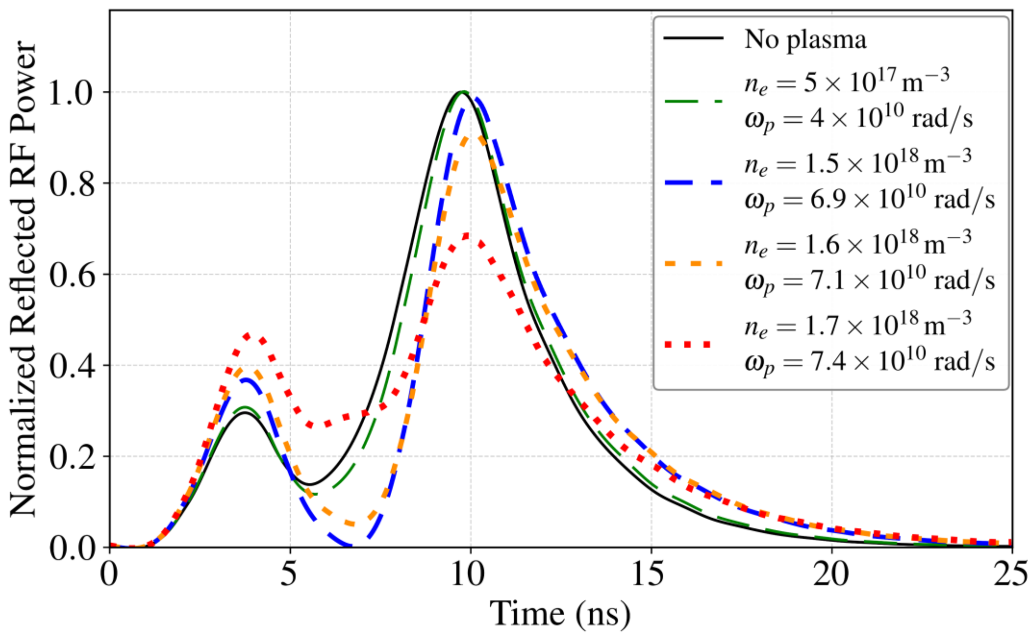


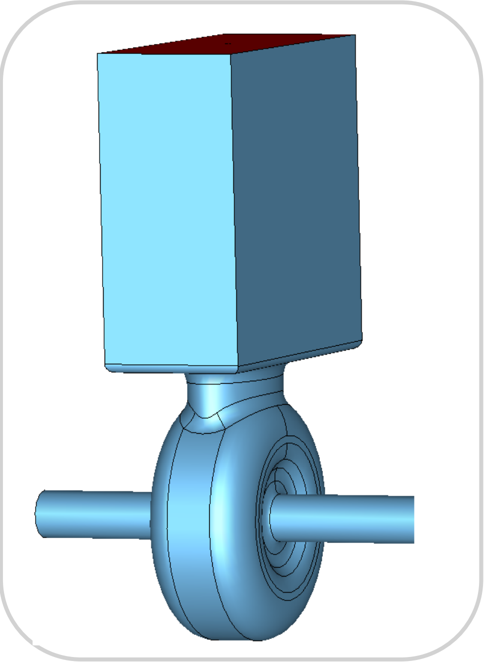
Fig: Reflected RF response for different plasma electron density.

- We studied the impact of dark-current electrons to the RF signals by simulating uniform effective dielectric layers.
- Plasma growth perturbs the cavity response and can absorb RF energy.
- The reflected RF waveform changes even for the same input pulse

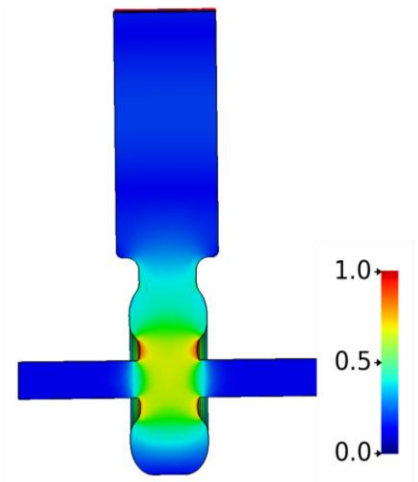
Experimental motivation: Investigate the correlation between RF response, dark-current emission, and optical signatures during short-pulse breakdown

The short-pulse X-band test cavity

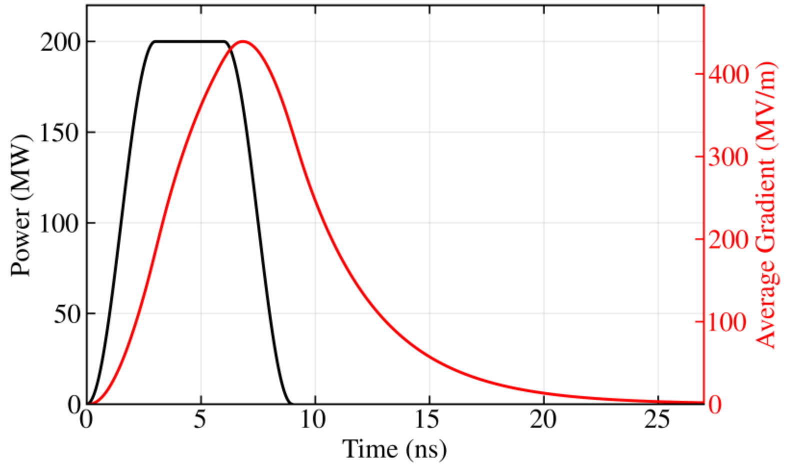
A dedicated single-cell platform for RF-breakdown studies



Parameter	Value
Beam aperture radius, a	1.76 mm
Loaded quality factor, Q_L	≈130
Shunt impedance, r_s	148 MΩ/m
Accelerating gradient, E_{acc}	$34\sqrt{P_{peak}\text{ (MW)}}$ MV/m
E_p/E_0T	1.65
H_pZ_0/E_0T	1.25
cavity fill time, τ	6.86 ns



E field – 11.7 GHz



Design objectives

- Optimize geometry to attain high field gradient while minimizing peak surface fields
- Use a simple single-cell geometry to study breakdown
- Measure the cavity response through independent RF, particle, and optical diagnostics

Dedicated breakdown test design

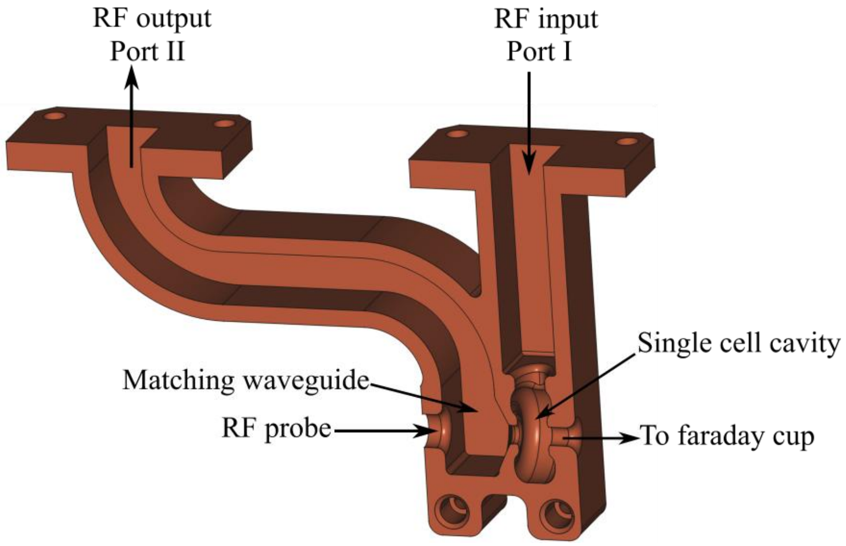


Fig: CAD model of structure

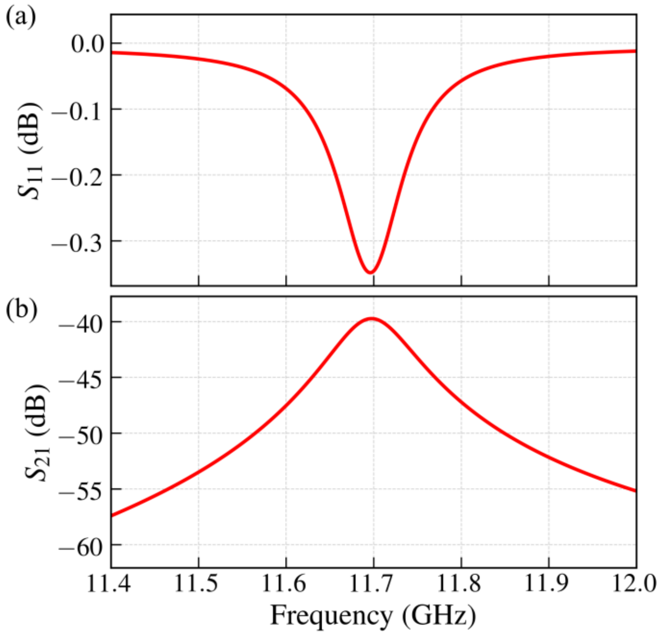


Fig: Reflection and transmission response

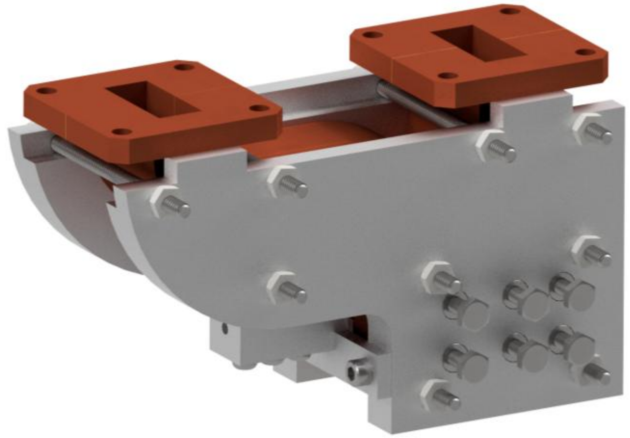


Fig: Test structure #1 Clamped structure

Test structure #2 brazed structure (test planned for early 2027)

- Weakly coupled waveguide for transmitted RF measurement
- Pickup probe for leakage-field measurement
- Faraday cup for dark-current measurement

Fabrication and assembly

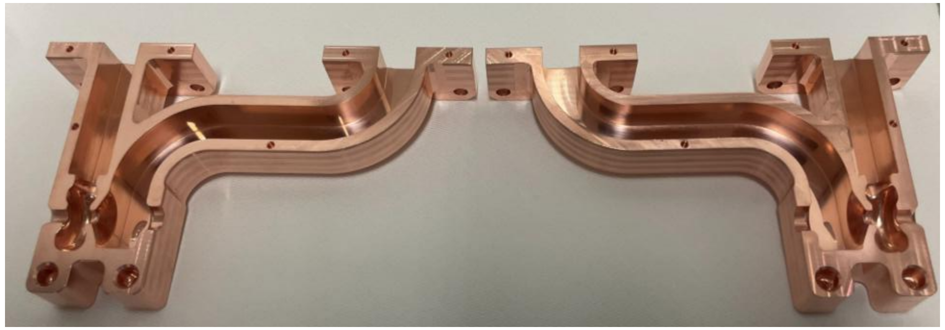


Fig :Two mirror halves of structure

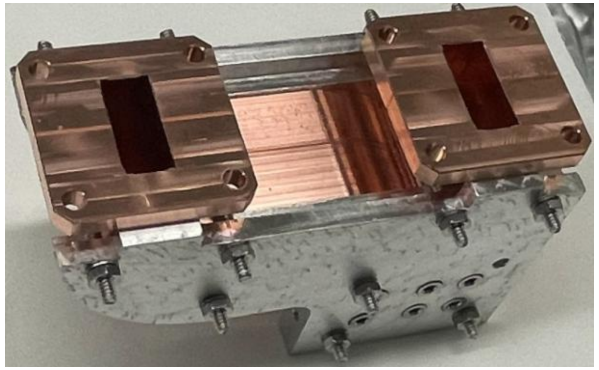
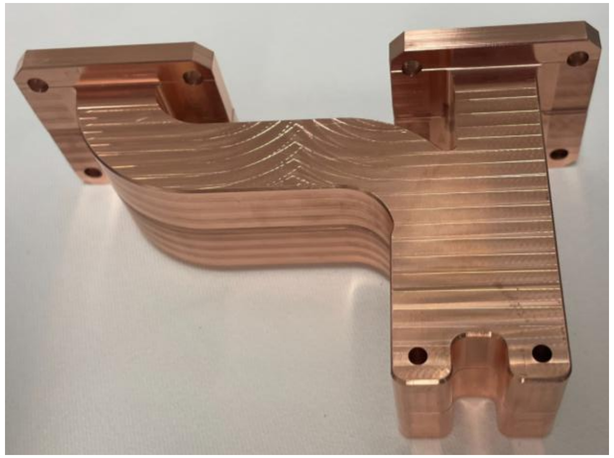


Fig :Two halves clamped together



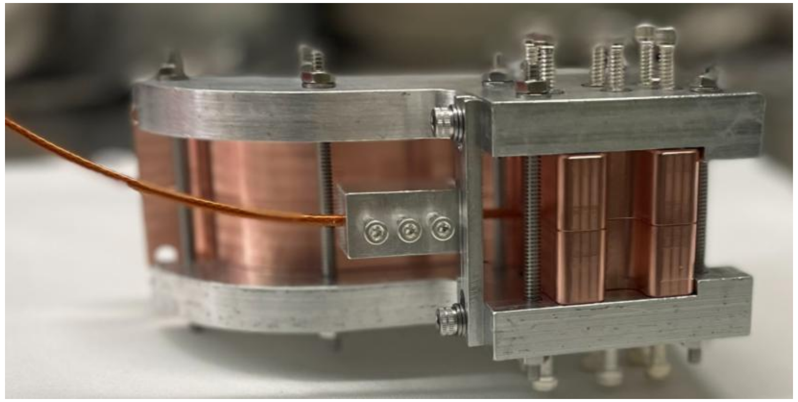


Fig :Bottom view of structure with probe inserted

Vacuum Installation- CAD model

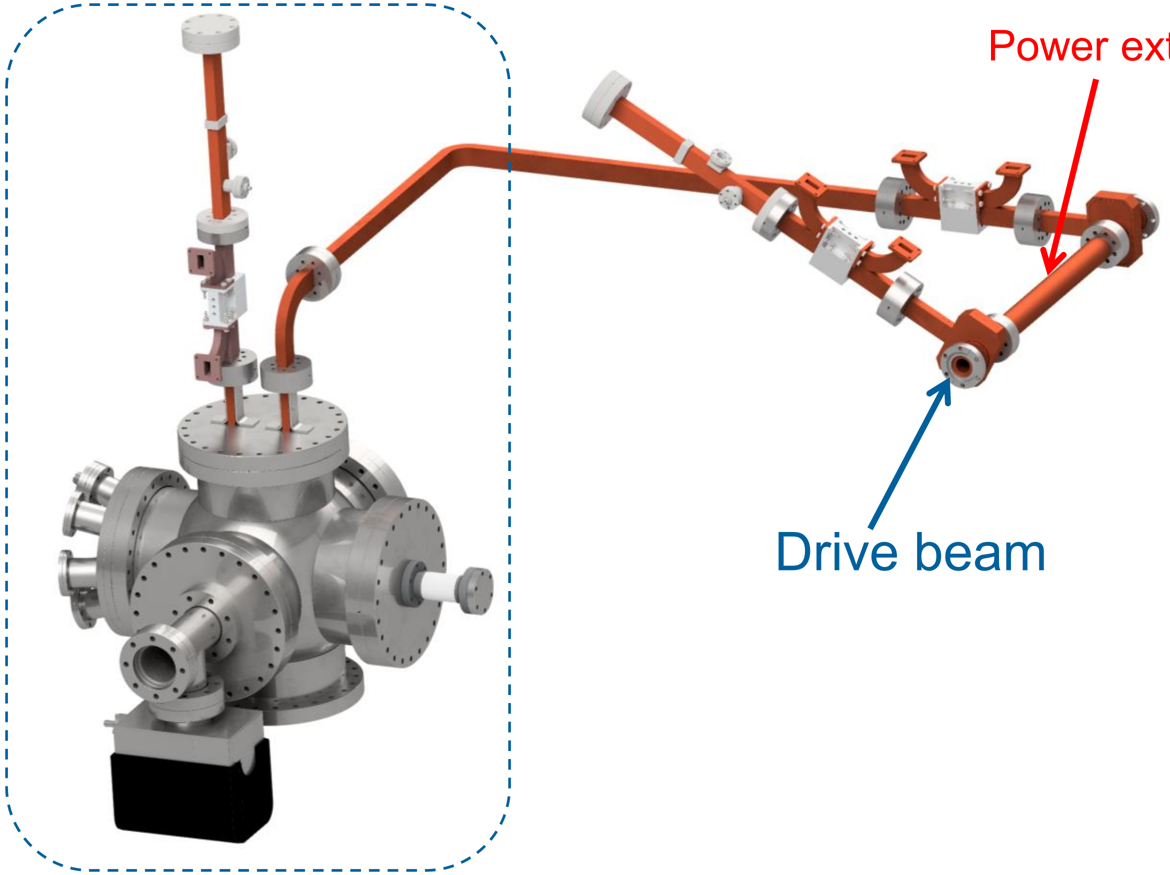


Fig: Vacuum chamber

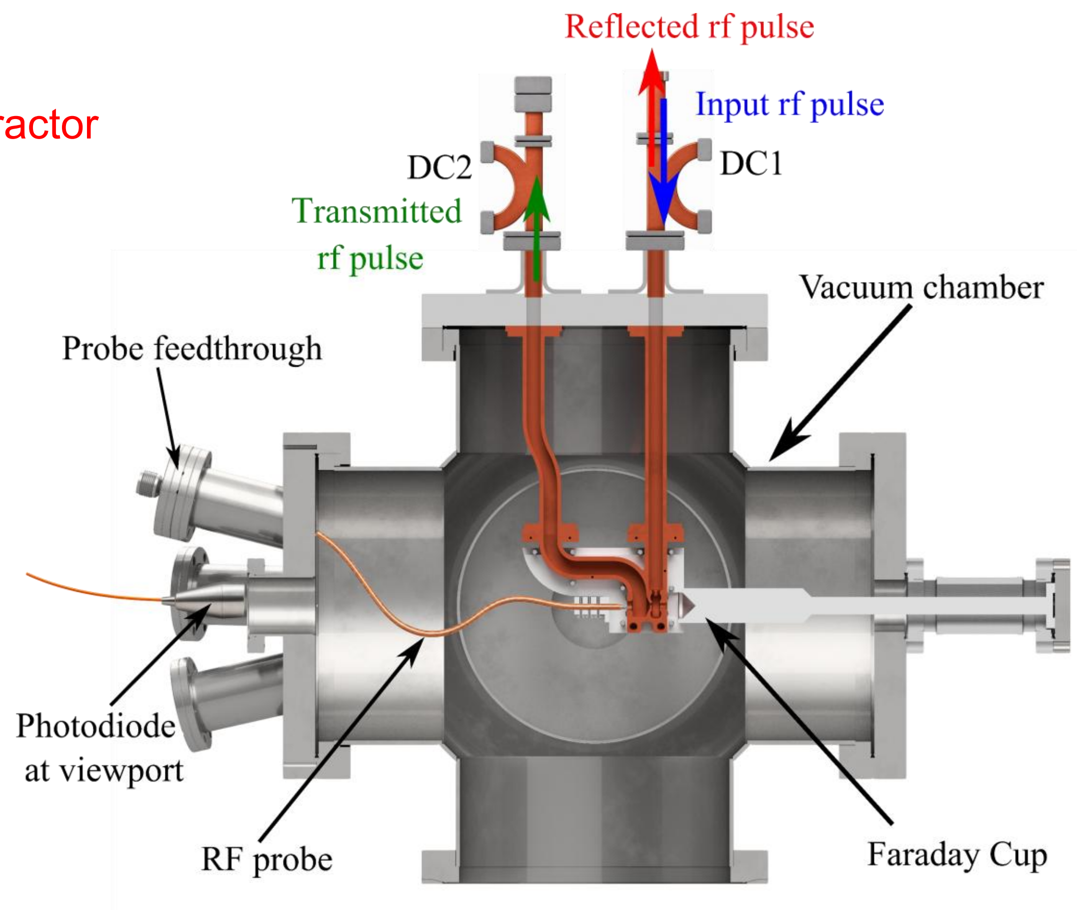


Fig: Installation schematics

Structure installation and experimental setup

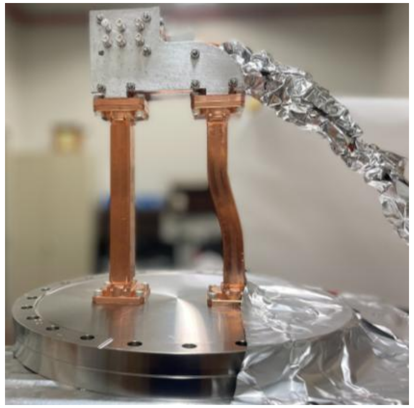


Fig: Clamped structure assembled to waveguide with flange from HP test chamber

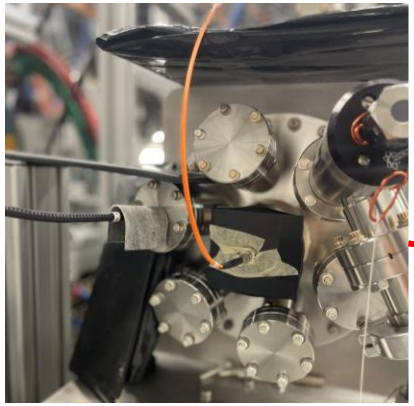


Fig: side view multiport flange Probe and photodiode connected

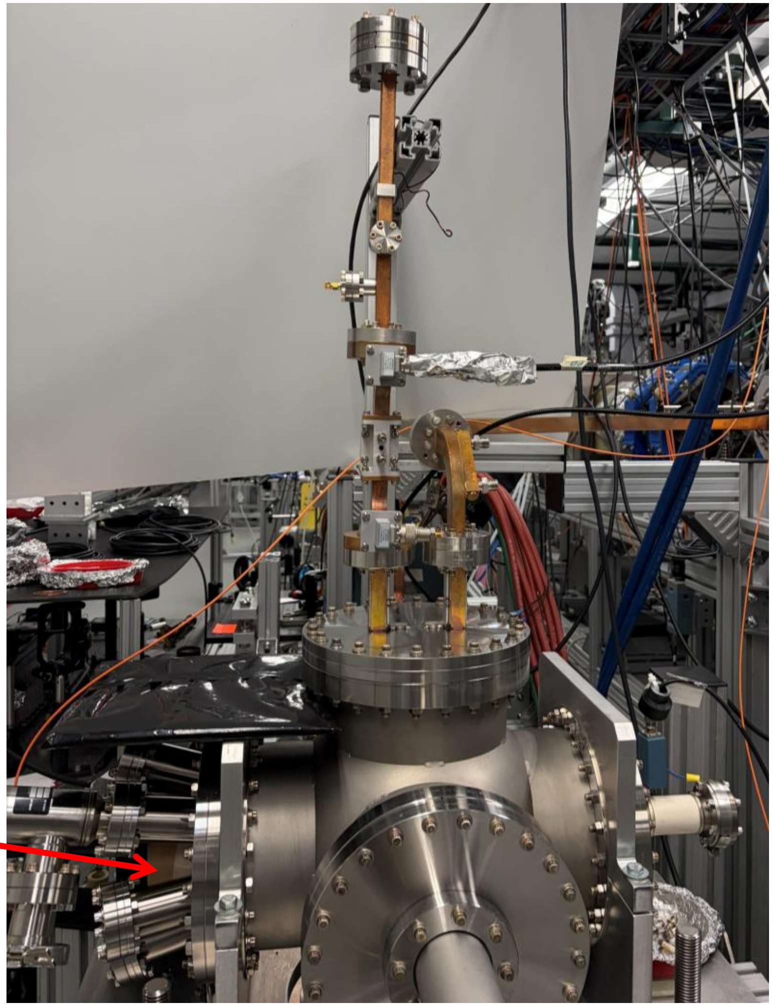


Fig: Vacuum chamber, structure installed

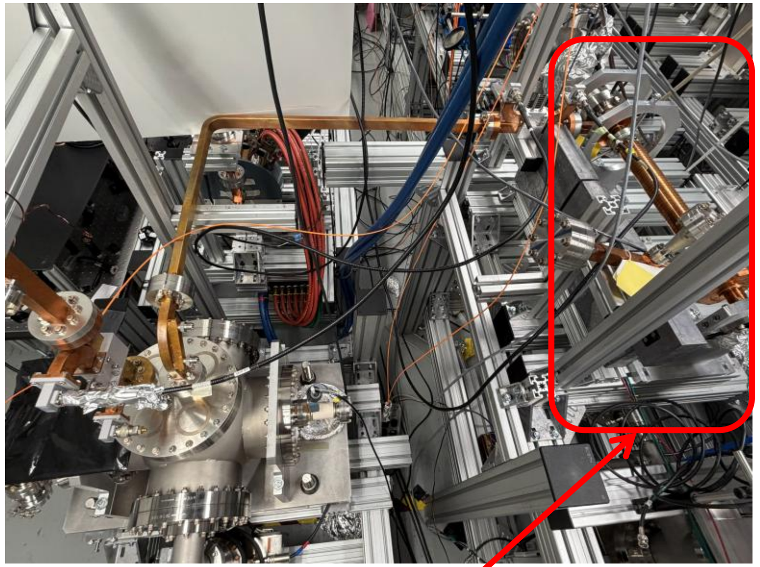
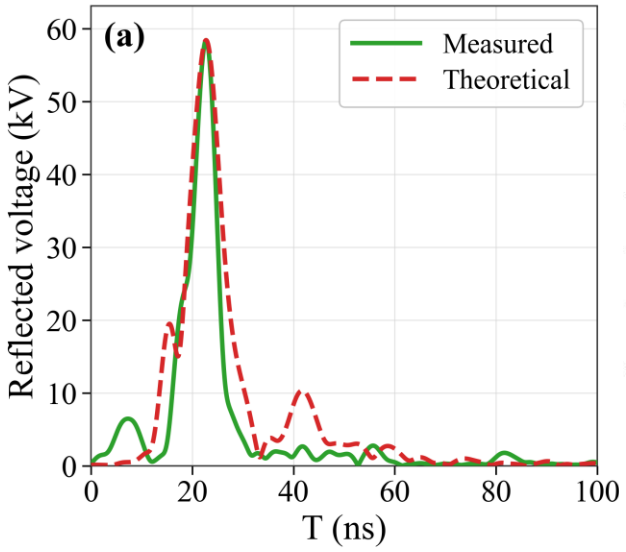
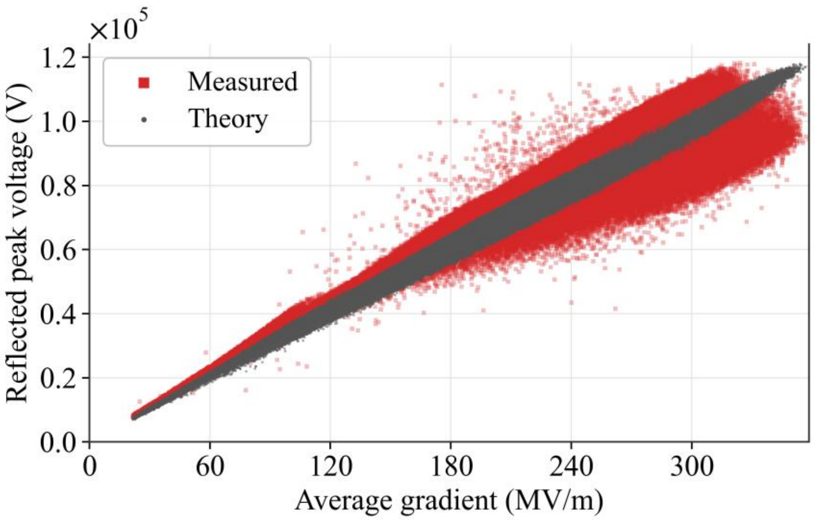


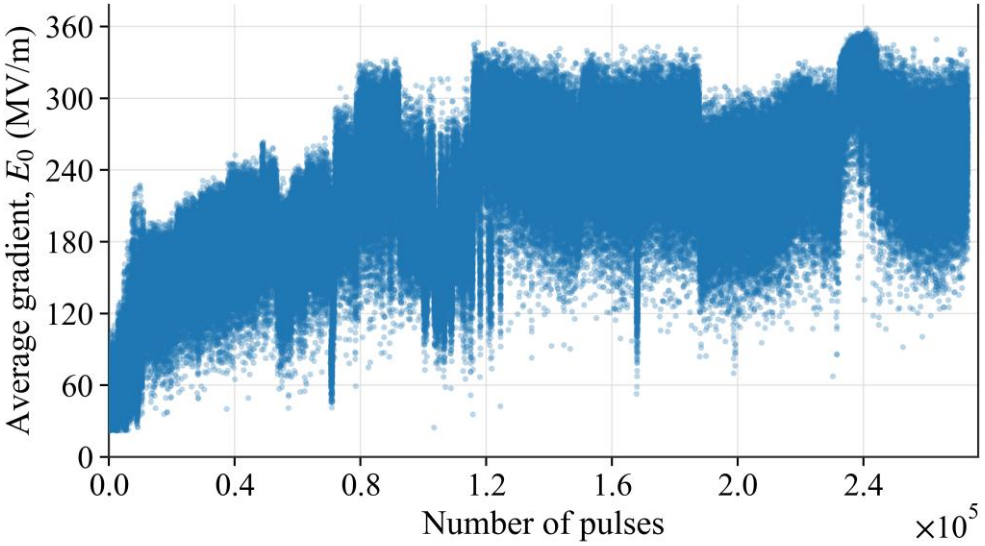
Fig: Top view- PETS and waveguide system connected to structure under test

Preliminary high-power testing results

- Data collected over 3 days in June 2026; analysis ongoing
- Forward waveform defines the RF drive entering the structure; reflected and transmitted waveforms capture how the structure responds during each shot.
- Theoretical RF signals calculated for each shot using the measured S-parameters and the measured input RF signal for each shot
  - Theory agrees very well with measurements
  - Gradient is calculated from measured forward power using simulation-based scaling.

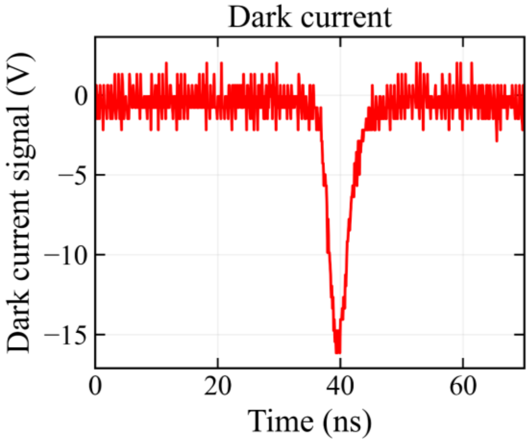


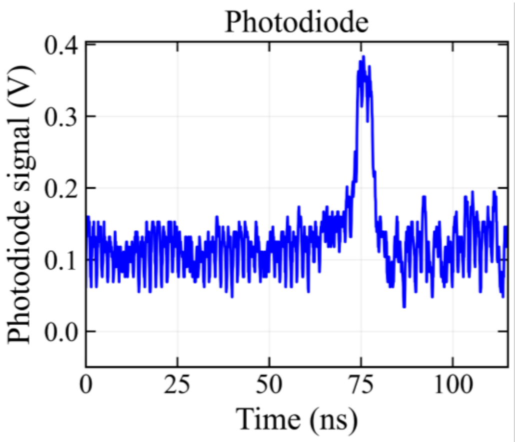


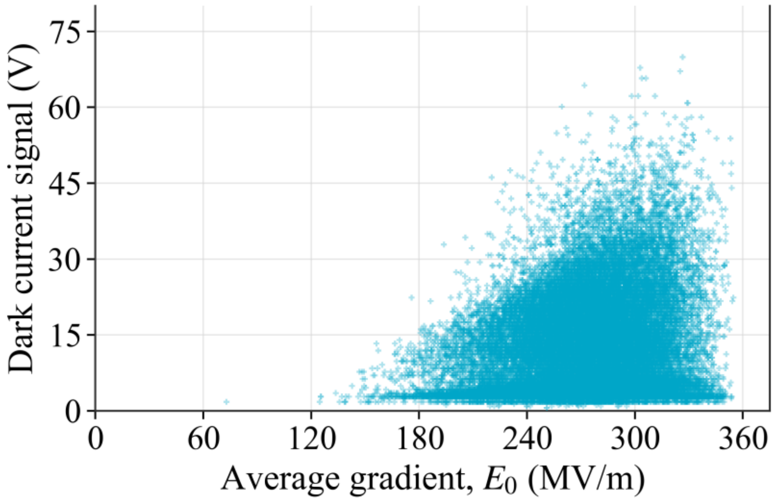


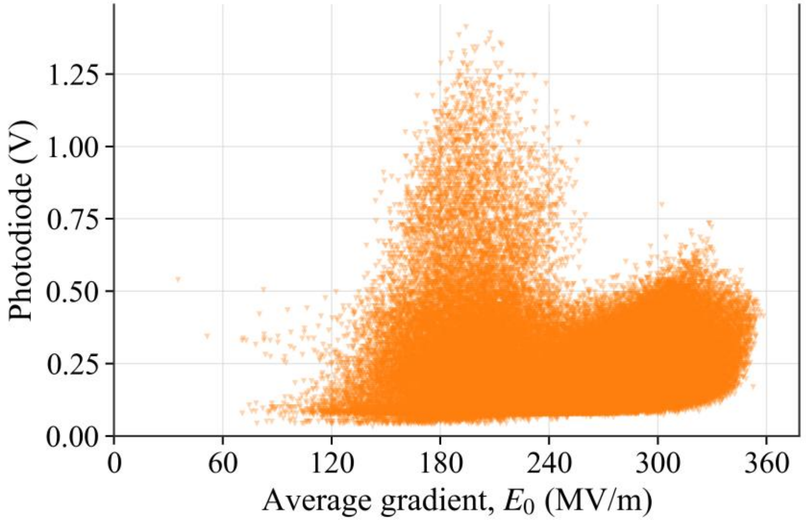
Preliminary high-power testing results (2)

- Breakdown diagnostics data collected: dark current, photodiode signal; see signature traces below
- Conditioning observed; higher gradient expected with more data taking planned this year





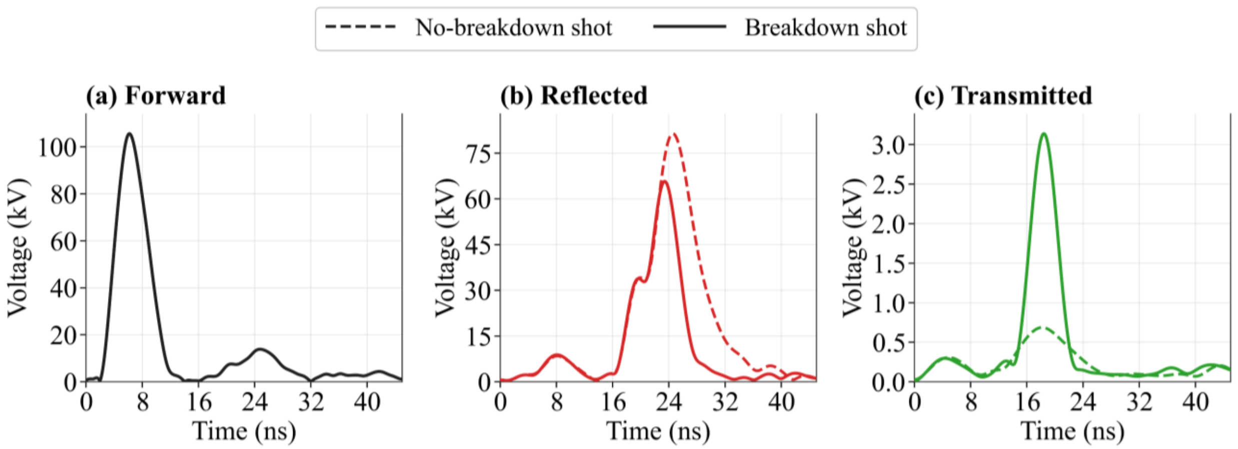


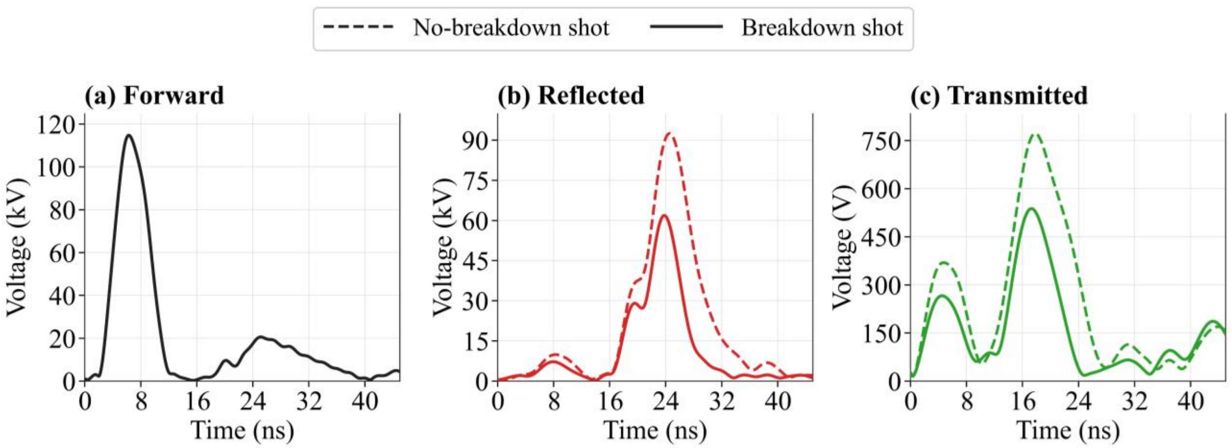


Representative RF characteristics during candidate breakdown events

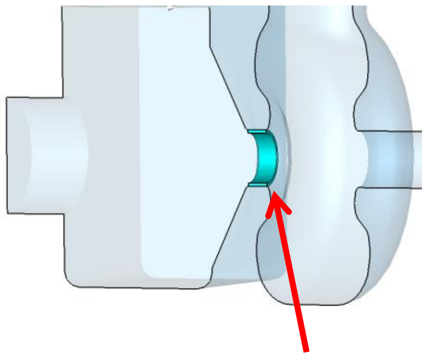
Selected events exhibit changes in the reflected and transmitted signals relative to matched non-breakdown shots

Dashed traces: non-breakdown reference signals
Solid traces: breakdown signals





- Candidate events exhibit different RF waveform changes relative to same forward peak power reference shots
- Possibly related to dark current; see one hypothesis for the increase of transmitted power simulated in CST
- Further data analysis ongoing



Thin layer with effective dielectric constant

Summary and future work

- ✓ A dedicated single-cell X-band cavity and diagnostic system have been developed for short-pulse RF-breakdown studies.
- ✓ The experiment provides systematic measurements of RF power, cavity response, dark current, and optical emission.
- ✓ Initial data analysis show correlated changes in reflected, transmitted, probe, dark-current, and photodiode signals in the short-pulse regime.
- ✓ Further data analysis and comparative numerical simulations ongoing to better understand the RF breakdown behavior and the cavity operation limit in the short-pulse regime.

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