Investigation of Coupler Breakdown Thresholds for Plasma Processing of FRIB Quarter-Wave Resonators at Fundamental and Higher Order Modes

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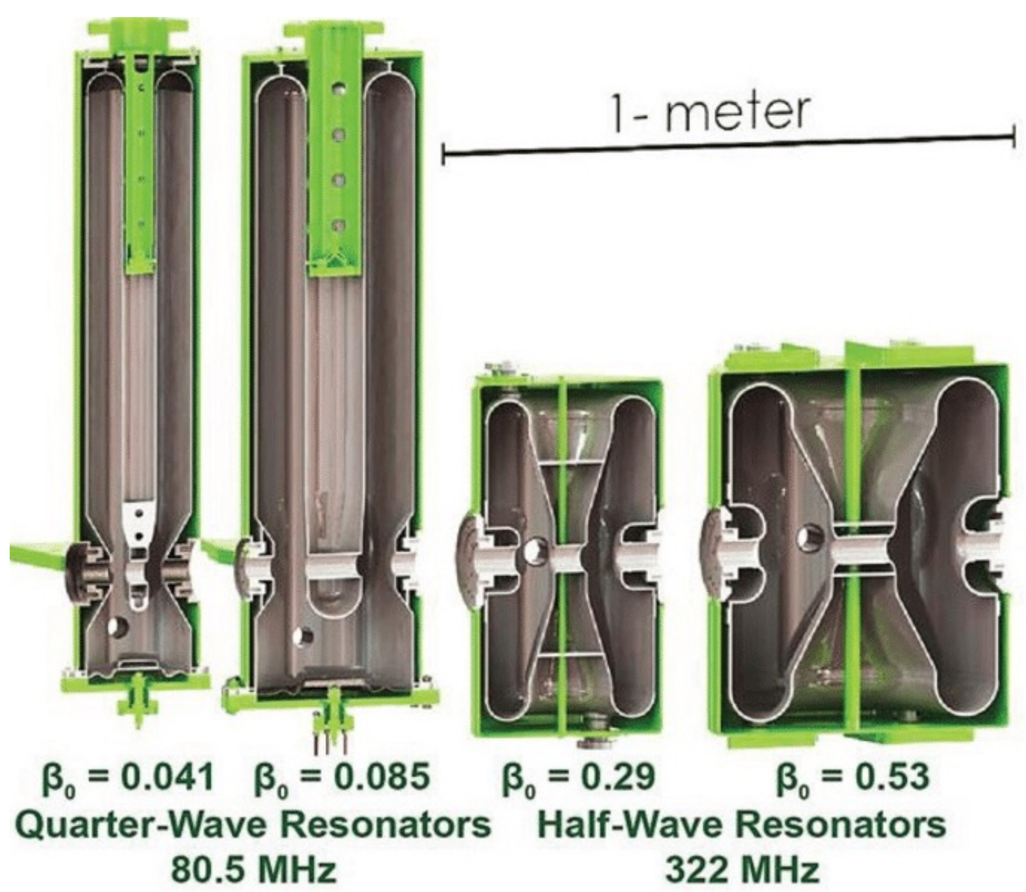
Overview

- FRIB is an accelerator facility supporting a heavy ion superconducting LINAC for nuclear physics research. ‘
- Both QWR and HWR are used to accelerate ions to ≥ 200 MeV per nucleon.
- Plasma processing is being developed to maintain long term performance of QWR and HWR.
- Plasma processing via chemical and physical processes can remove contaminants that cause field emission and multipacting.
- Plasma processing may be performed in-situ with the cryomodule which could prove advantageous over other surface treatments.



Fundamental and HOMs for Processing

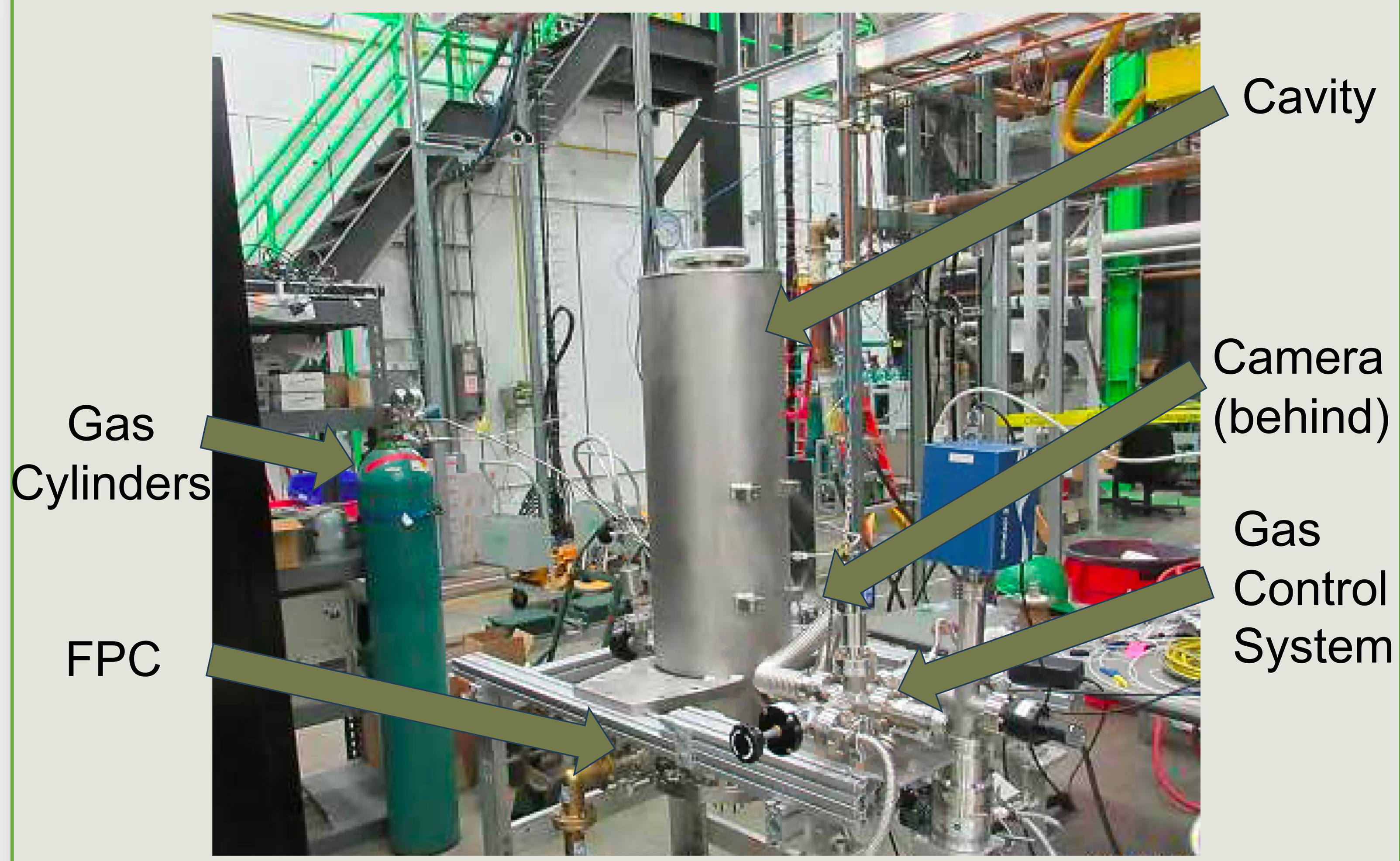
- FPC and cavity are poorly coupled at room temperature for fundamental mode; $Q_0 = 3 * 10^3, Q_{ext} = 10^6$.
- HOMs have less coupler mismatch and improve the ratio between cavity field and coupler field leading to improved power delivery to the cavity
- Modes used in FRIB β = 0.085 QWR for plasma ignition

Mode	Frequency [MHz]
TEM $\lambda/4$	80.120
TEM $3\lambda/4$	240.92
TEM $5\lambda/4$	402.24

Ignition of Fundamental Power Coupler

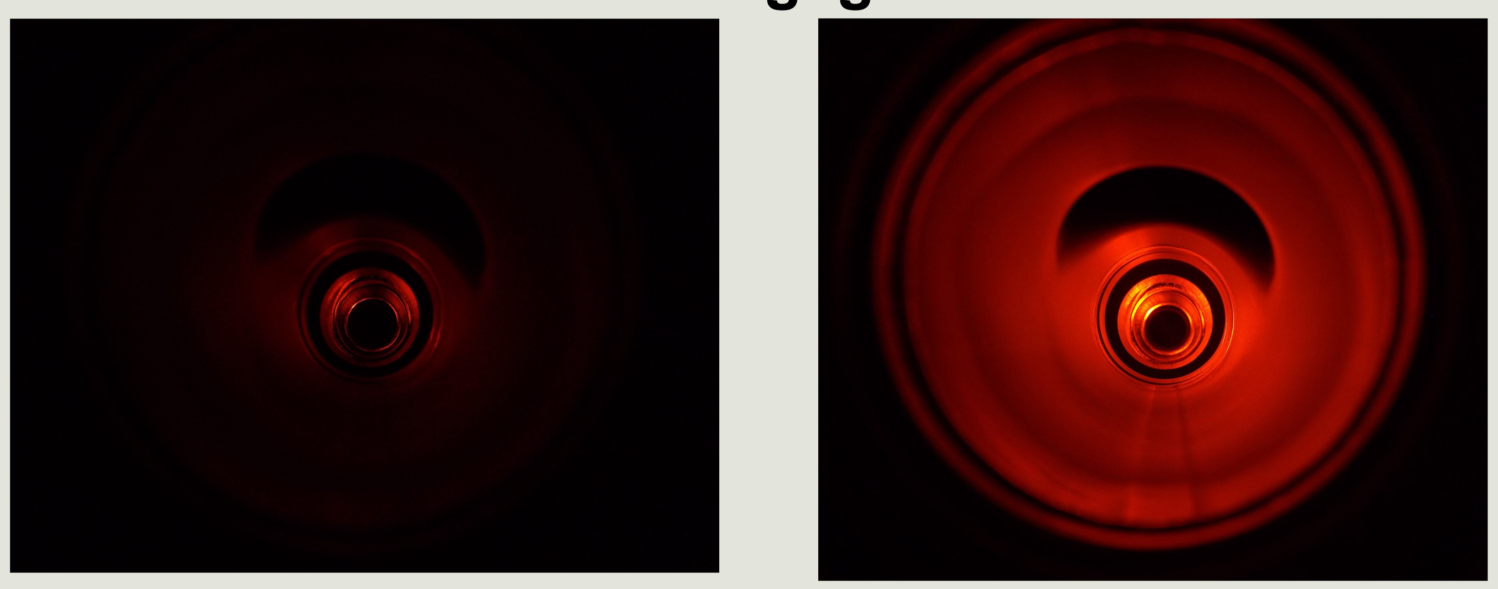
- FPC ignition must be avoided during plasma processing.
  - Copper may be sputtered into cavity.
  - FPC could be damaged due to intense plasma.
- Breakdown threshold must be understood for cavity and FPC to avoid FPC ignition.

Experimental Apparatus



Plasma Processing setup for β = 0.085 QWR

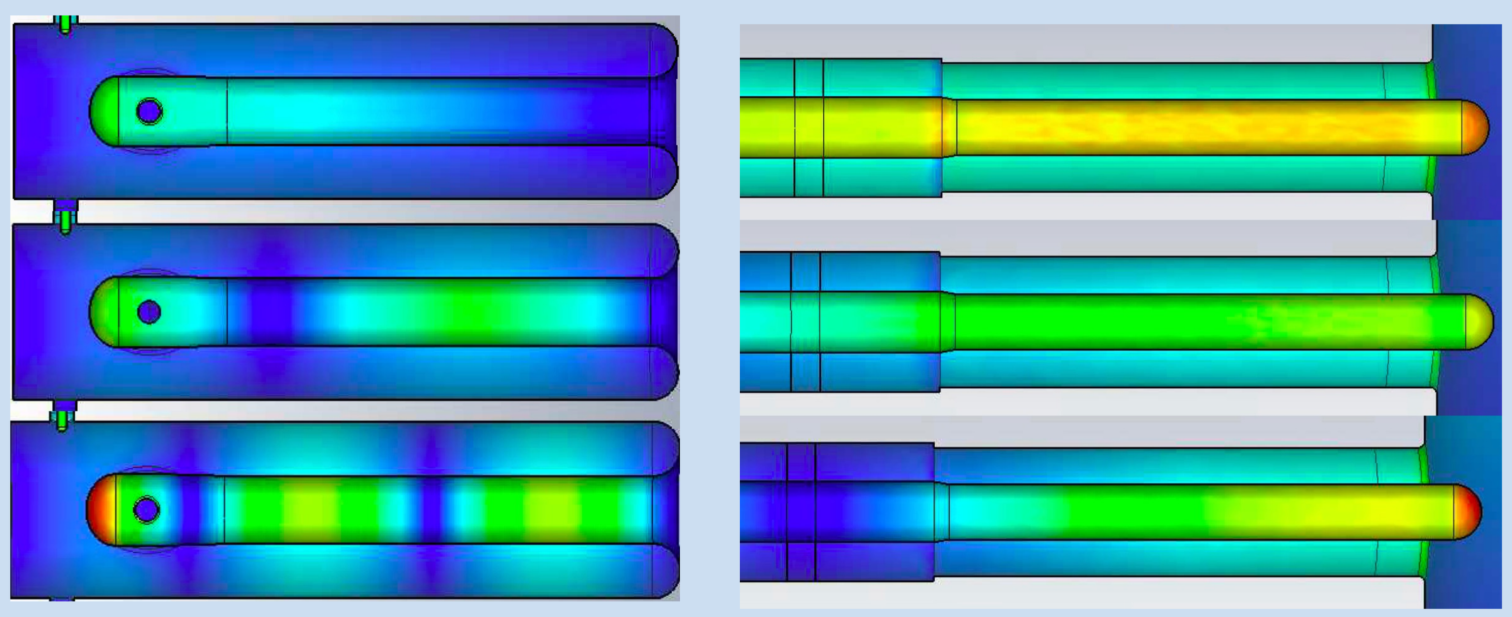
Observing Ignition



Neon & Oxygen Plasma

CST Simulations

- Cavity and FPC electric fields simulated using CST MWS
- Breakdown electric field characterized in different ways:
  - Global E_p: Peak surface electric field
  - Global E_{avg}: Highest average electric field
    - Found between beam port and inner conductor
  - Local E_p: Peak surface electric field along E_{avg}



Cavity **FPC antenna**

Theoretical Model

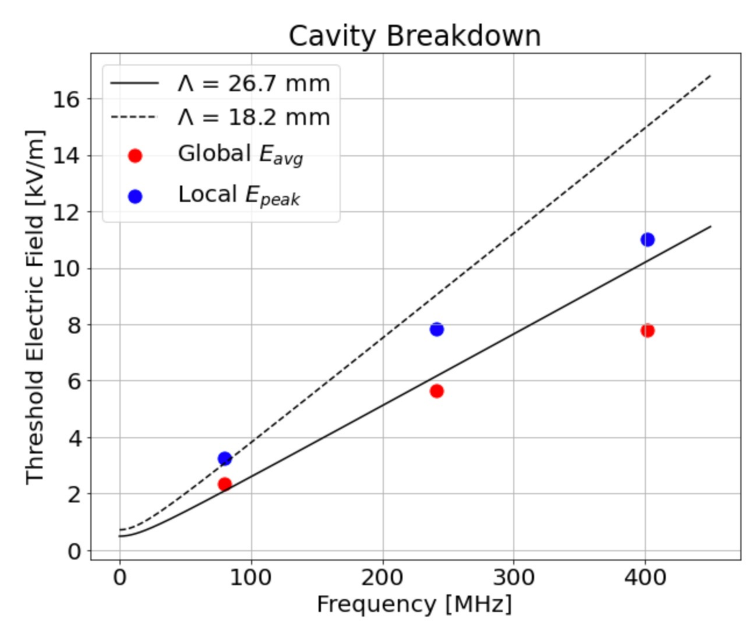
- A simplified model for breakdown was developed balancing ionization and diffusion of electrons [1].
- High frequency limit of model found to predict ignition threshold well for CEBAF cavity [2].
- The breakdown threshold is only determined by geometry of the volume, the gas characteristics, and driving frequency.
- Breakdown is described by:

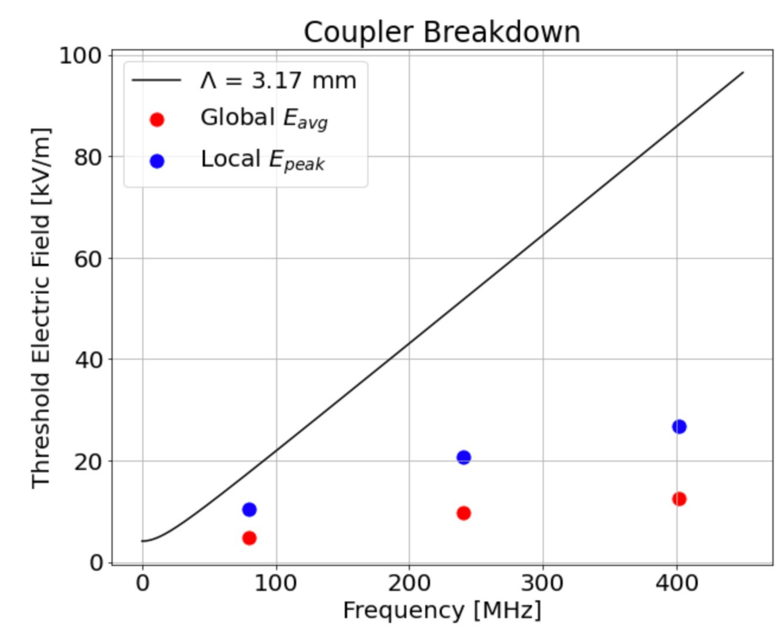
$$E_t{}^2 = \frac{l^2}{\Lambda^2}\frac{mu_i}{3e}\left(\nu_m{}^2 + \omega^2\right)$$

- Λ parameter is the “effective diffusion length” determined by the geometry.
- l, u_i, and ν_m are mean free path, ionization potential, and electron neutral collision frequency that are determine by the choice of gas species and pressure.

Threshold Predictions

- 2 models constructed for cavity geometry based on nominal dimensions and accelerating gap dimensions.
- Experimental measurements of stored energy and forward power at ignition are used to infer RF breakdown fields at ignition from CST MWS.
- Best characterization of breakdown comes from use of “Local E_p” for cavity volume.
- Diffusion model assumes $\Lambda > l$ which is **true** for cavity, but **untrue** for FPC.
- Different description of breakdown needed for FPC volume.
- A more rigorous treatment of the Λ parameter is required to better understand the theoretical breakdown limit.





Acknowledgments & Citations

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[1] S. C. Brown, *Introduction to Electrical Discharges in Gases*, Wiley, New York, 1966.

[2] S. Popovic et al., "Resonant-frequency discharge in a multi-cell radio frequency cavity," *J. Appl. Phys.* **116**, 173301 (2014).

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