L-band (1.3 GHz) 5-Cell SW Cavity High Power Test Results

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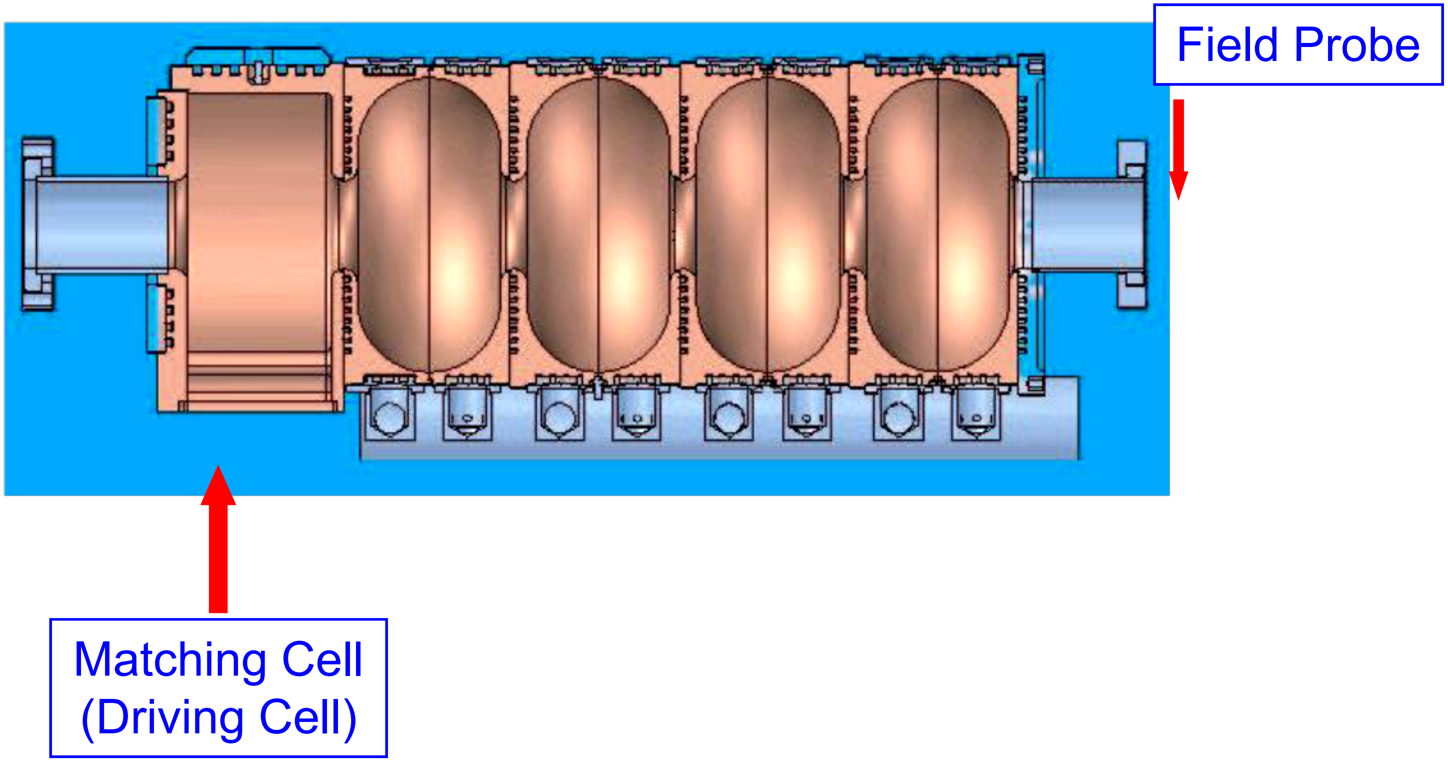
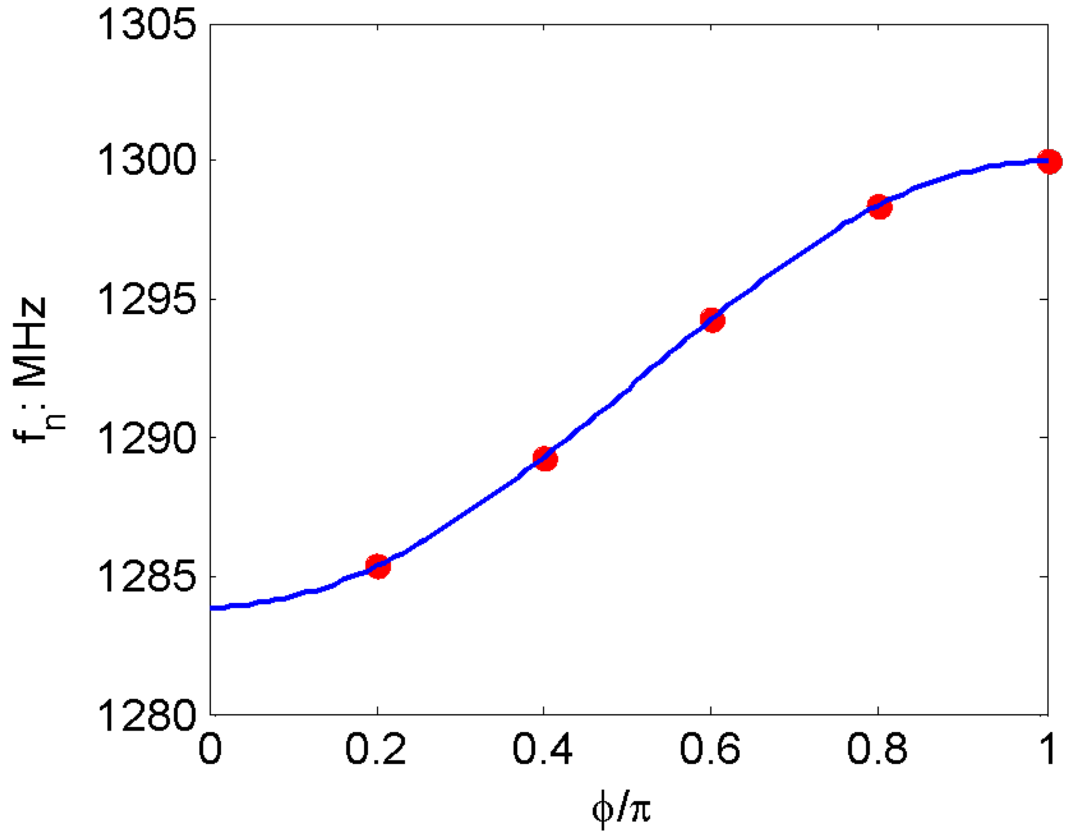
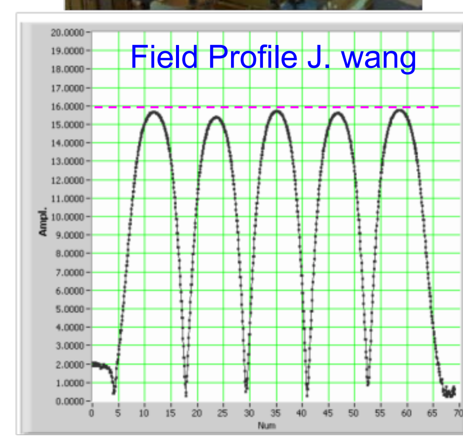
L-band 5-Cell SW Cavity Introduction

A half-length (5-cell) prototype, SW cavity was built at SLAC to verify that the ILC-required gradient (15 MV/m in 1.0 ms pulses) can be achieved stably and without significant detuning from the RF heat load (4 kW per cell).



L-band 5-Cell SW Cavity Introduction





$$f_\pi = 1.3\text{GHz},\ Q_0 = 29000,\ \ \tau = 1.8\mu\text{s},\ \beta_e = 1,\ k = 0.013$$

Gradient = 7.4 MV/m for 1 MW input rf power (verified in a beam test)

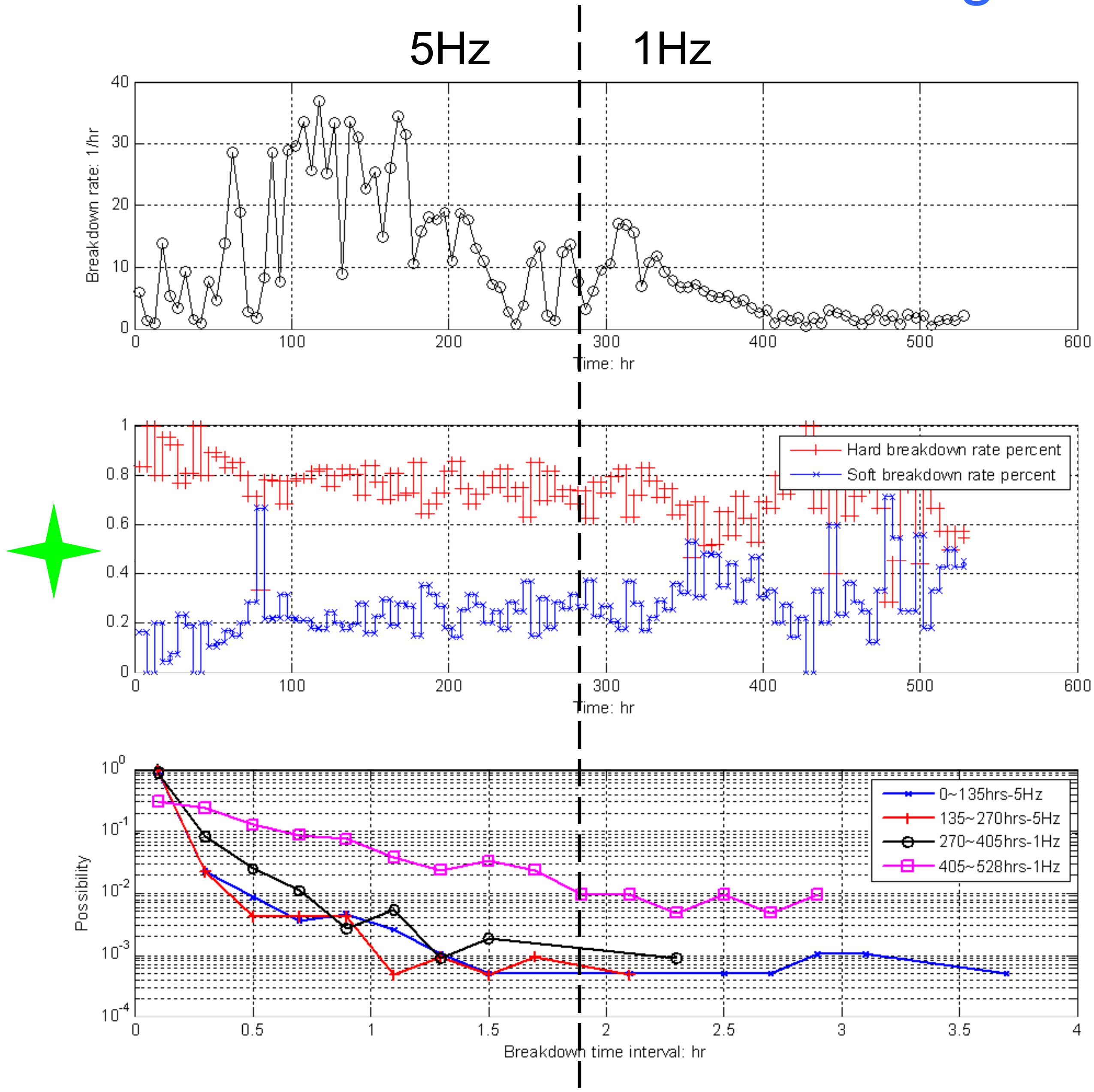
RF Conditioning Statistics Until Jan-4-2008

Pulse Width: us	Conditioning Time: hrs	
100	160	5Hz repeating frequency
200	20	
400	70	
1000	280	1Hz repeating frequency
Total	530 (~5.5e6 pulses)	

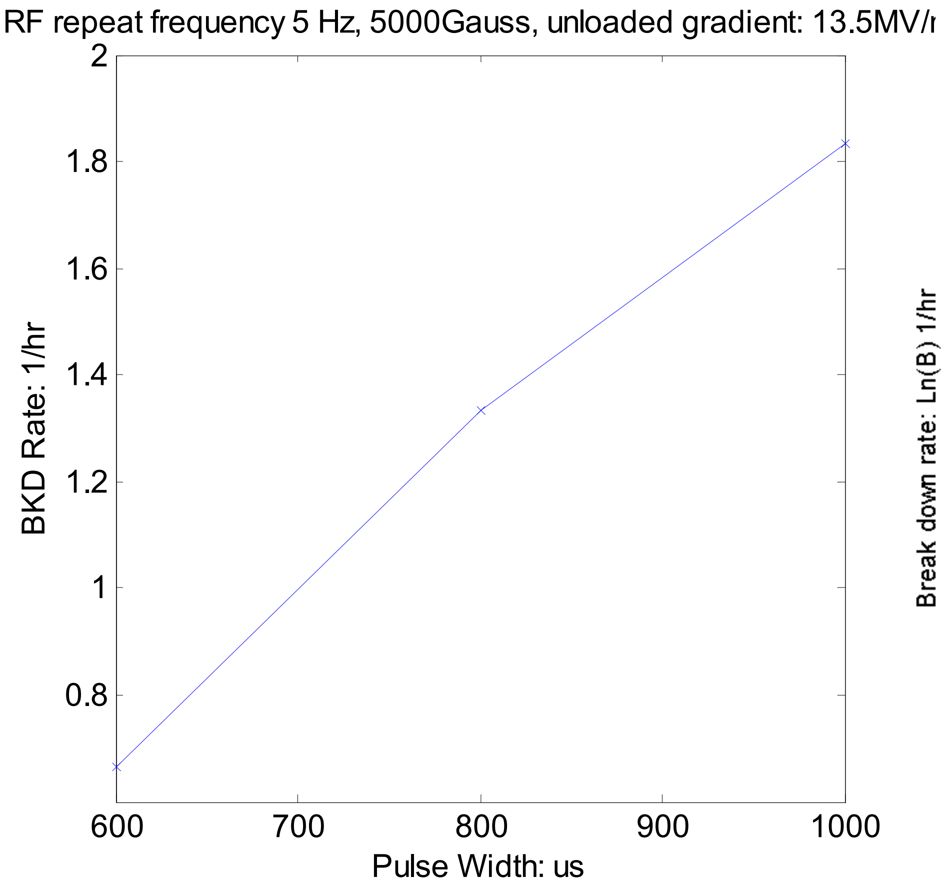
~Max unloaded Acc. Gradient: 15MV/m

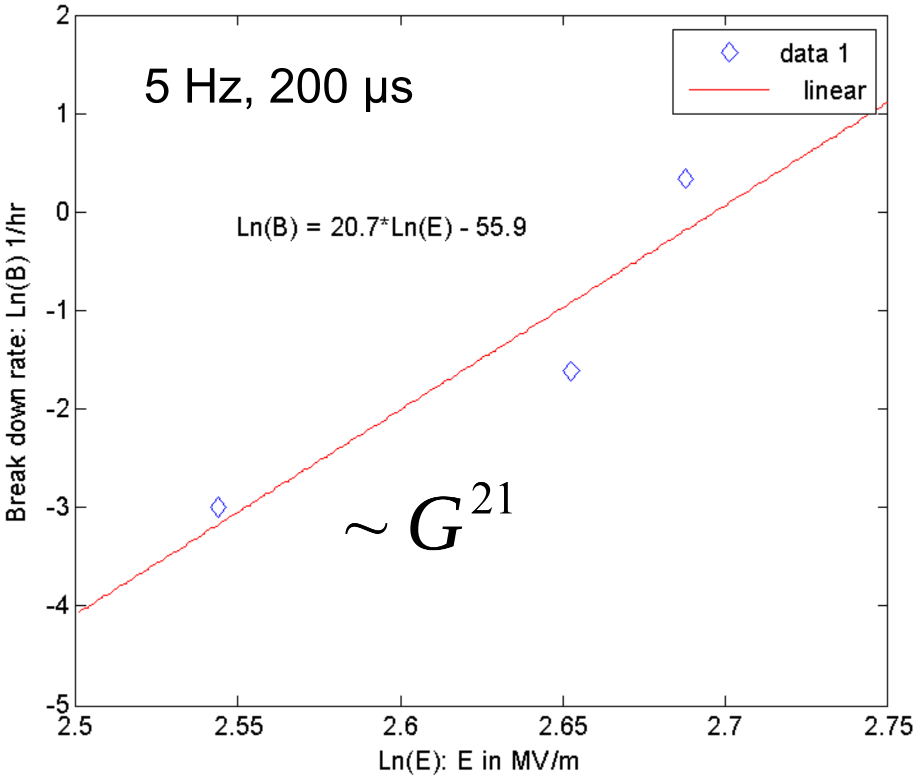
~6167 Breakdown Events (1233 per cell)

BKD Characteristics with RF conditioning Time

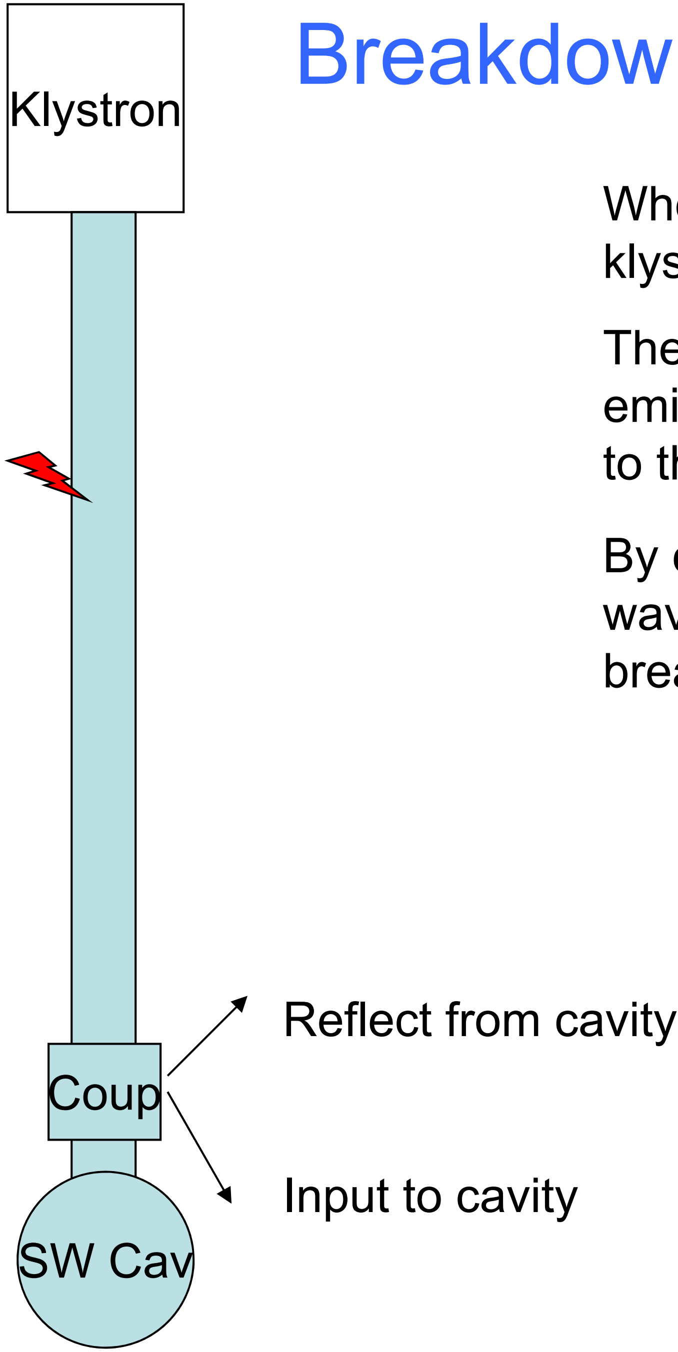


Breakdown Rate Pulse Width And Gradient Dependence





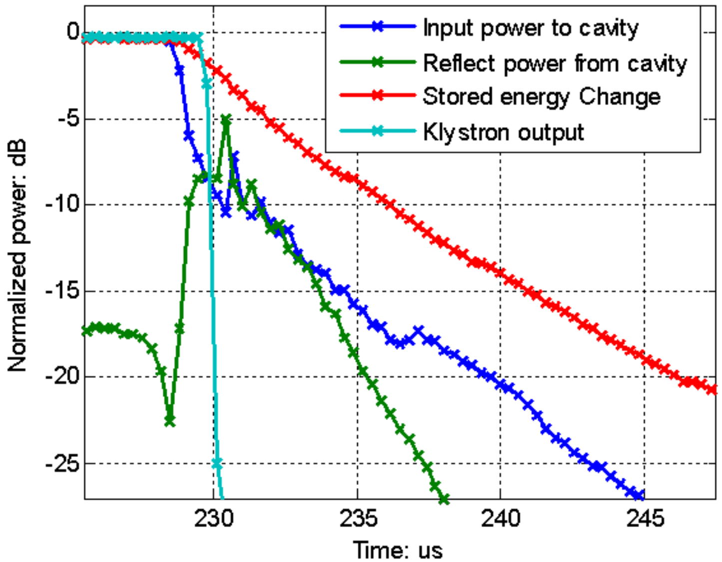
Breakdown in the Input Waveguide



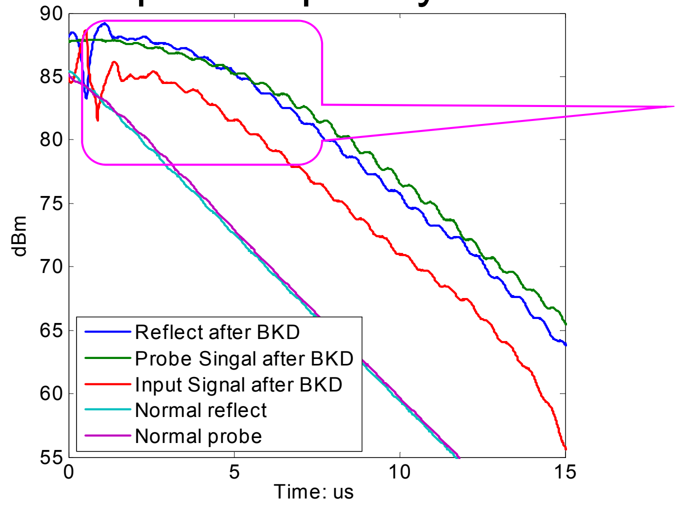
When breakdown occurs in the waveguide the klystron rf is shut off in few us.

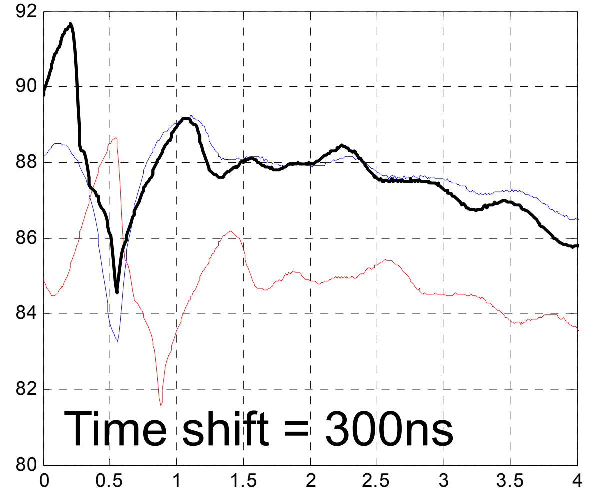
The cavity still sees input power, which is just the emitted power from cavity that is reflected back to the cavity by the waveguide breakdown

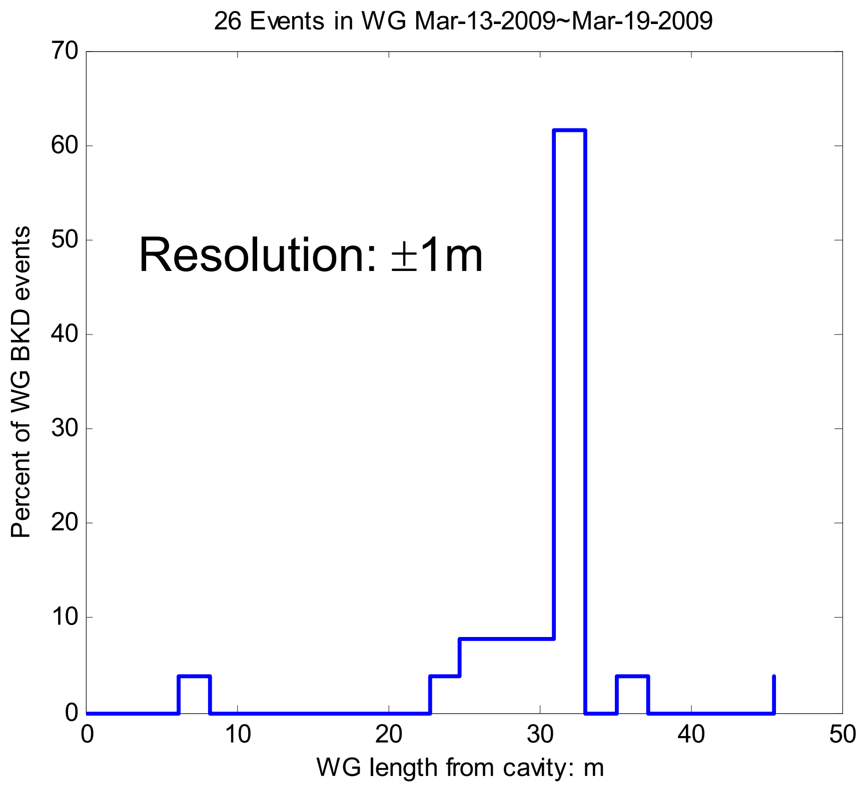
By comparing reflected and input power waveform timing, one can determine the breakdown position



Sample Frequency: 100MHz

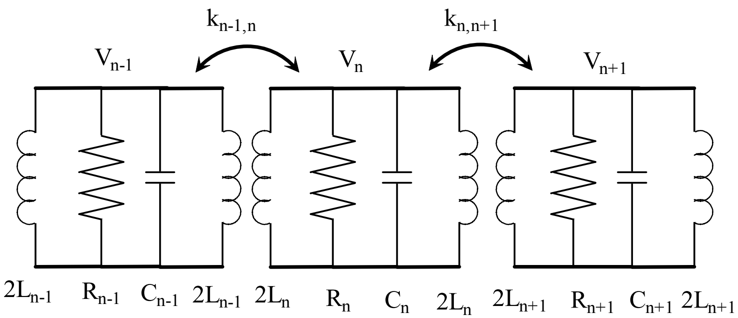






Cavity Coupled Resonator Equation

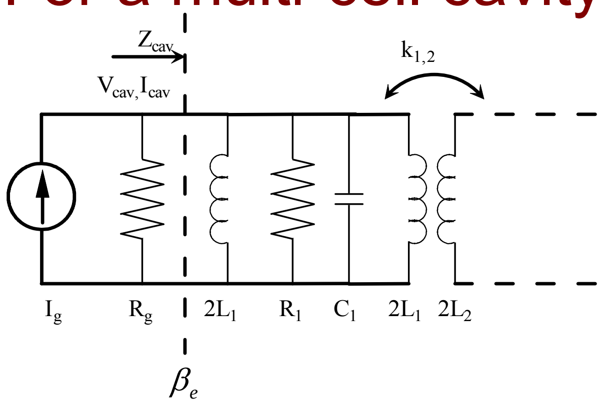
Coupled resonator equation for middle cells:



(a)

$$\frac{d^2\hat{v}_n}{\omega_n^2 dt^2}+\frac{1}{\omega_n Q_n}\frac{d\hat{v}_n}{dt}+\left(\frac{1}{1-k_{n-1,n}^2}+\frac{1}{1-k_{n,n+1}^2}\right)\frac{\hat{v}_n}{2}=$$
$$\frac{1}{2}\left[\frac{k_{n-1,n}}{1-k_{n-1,n}^2}\sqrt{\frac{(R/Q)_n\,\omega_{n-1}}{(R/Q)_{n-1}\,\omega_n}}\hat{v}_{n-1}+\frac{k_{n+1,n}}{1-k_{n+1,n}^2}\sqrt{\frac{(R/Q)_n\,\omega_{n+1}}{(R/Q)_{n+1}\,\omega_n}}\hat{v}_{n+1}\right]$$

For a multi-cell cavity coupling from one end:



(b)

$$\frac{d^2\hat{v}_1}{\omega_1^2 dt^2}+\frac{1}{\omega_1 Q_1}\frac{d\hat{v}_1}{dt}+\left(1+\frac{1}{1-k_{1,2}^2}\right)\frac{\hat{v}_1}{2}=$$
$$\frac{k_{1,2}}{2\left(1-k_{1,2}^2\right)}\sqrt{\frac{(R/Q)_1\,\omega_2}{(R/Q)_2\,\omega_1}}\hat{v}_2+\frac{d}{\omega_1 dt}\left(\hat{I}_g-\frac{\hat{v}_1}{\hat{R}_g}\right)$$

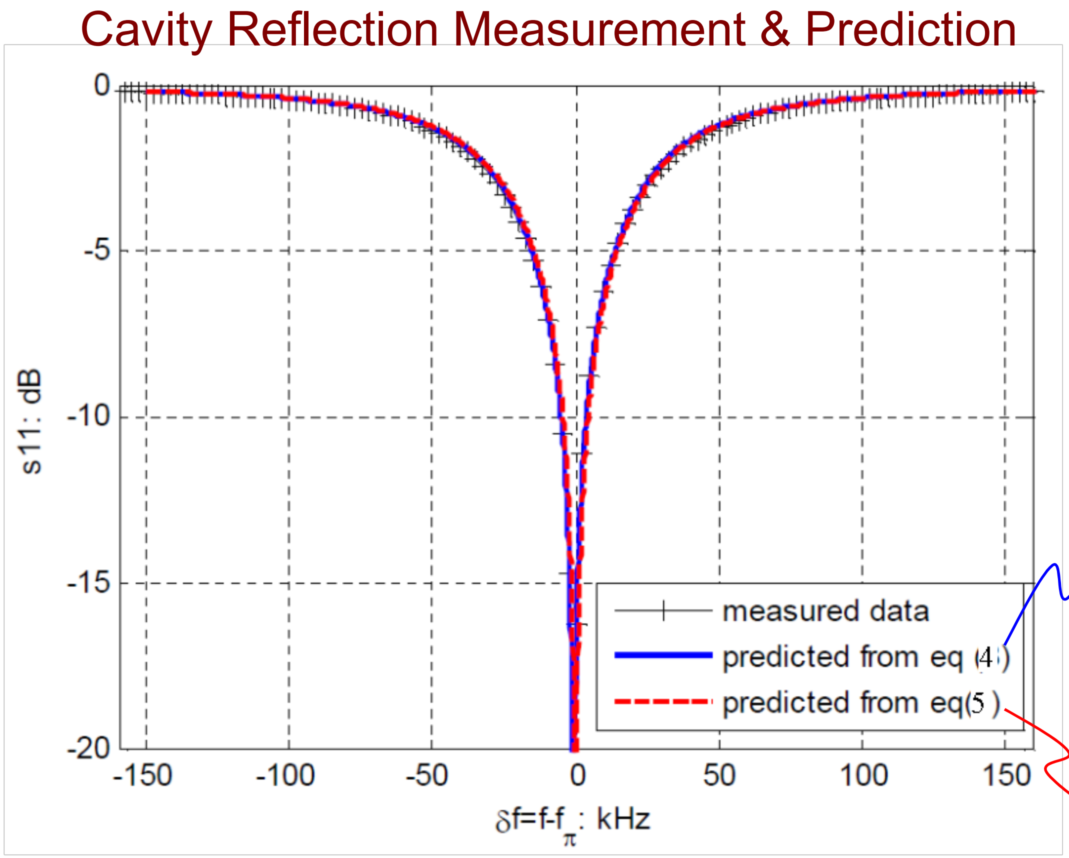
With β_e, generator resistor R_g could be expressed as

$$R_g=\frac{R}{\beta_e}\frac{V_1^2(\phi_q)}{\sum_{n=1}^{N}V_n^2(\phi_q)}$$

$V_n(\phi_q)$ (n=1…N) is n-th the cell voltage in q-th mode

Cavity Static and Transient Study

- Static Response



Circuit model

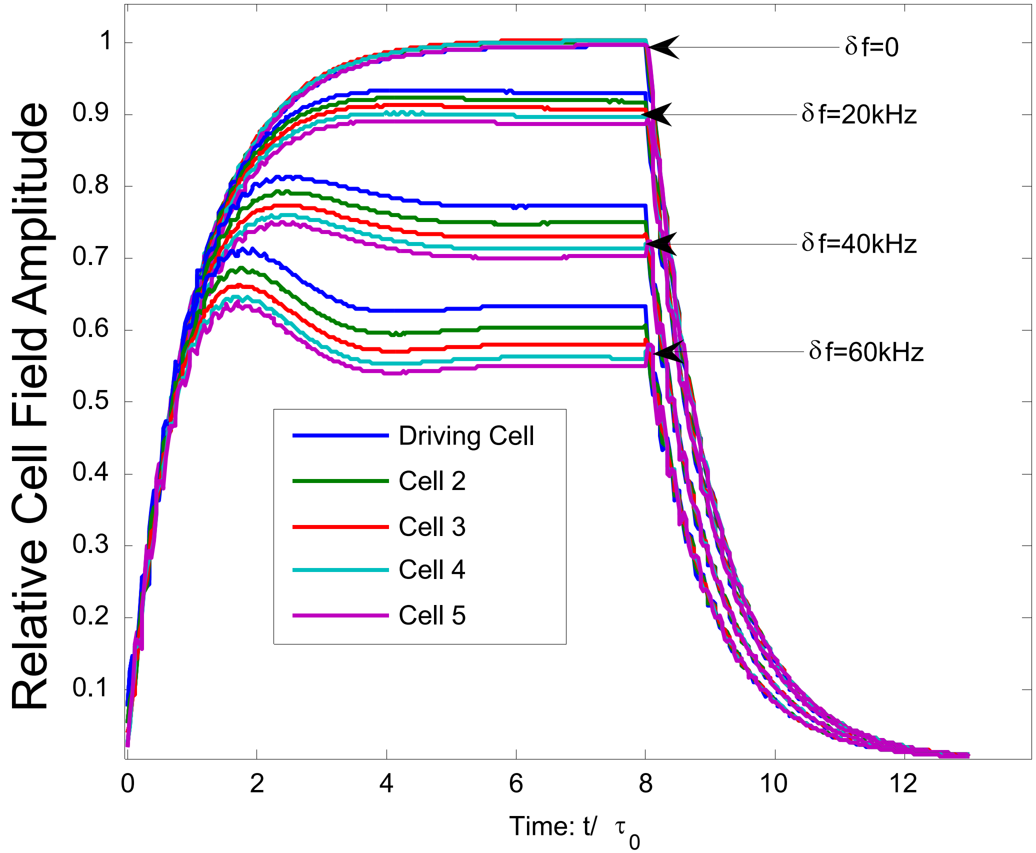
$$\Gamma = \frac{Z_{cav} - R_g}{Z_{cav} + R_g} = \frac{\beta_e \cdot Z_{cav} - R_q}{\beta_e \cdot Z_{cav} + R_q}$$

$$\Gamma(\Delta\omega) = \frac{1 - \beta_e - 2i\tau_0\Delta\omega}{1 + \beta_e - 2i\tau_0\Delta\omega}$$

The circuit model matches the static characteristics of the cavity!

Cavity Static and Transient Study

- Transient Response



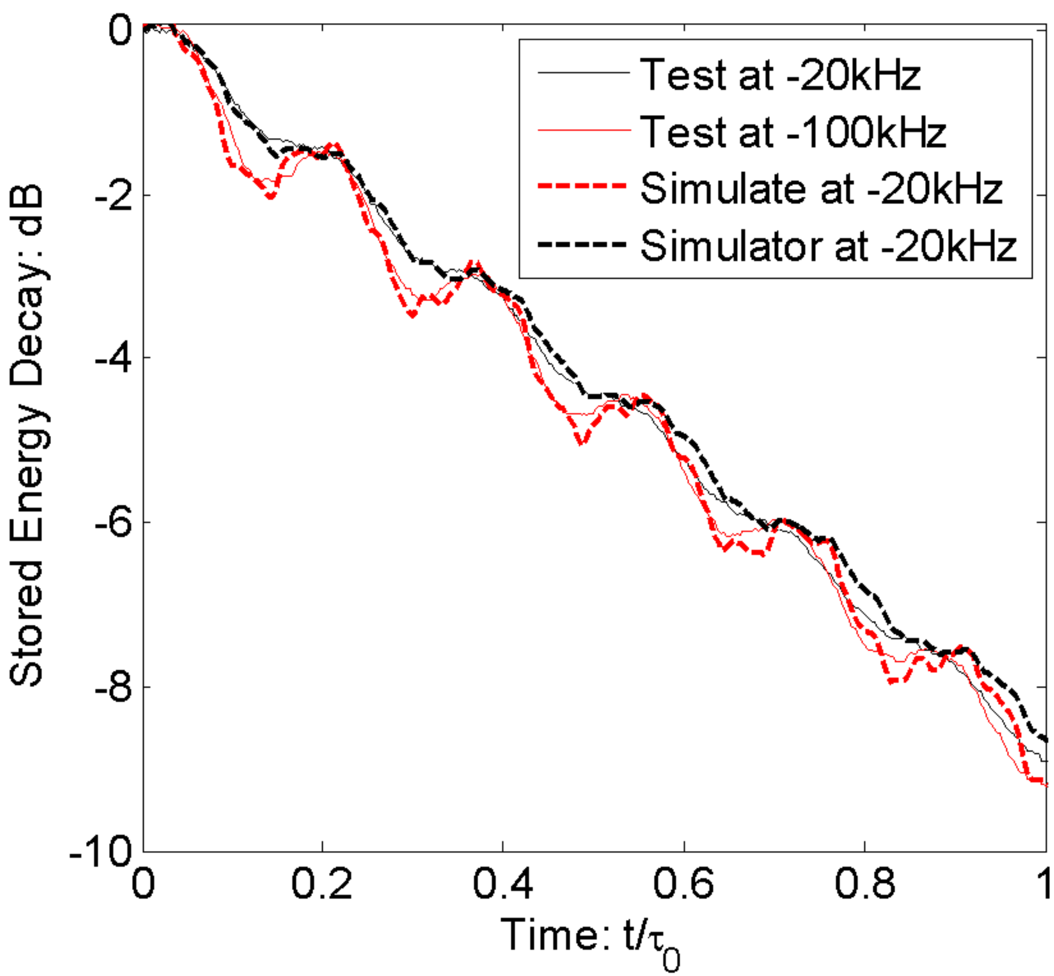
If the drive frequency differs from the nominal frequency, other cavity modes will be excited when the drive power is turned off

Simulated field amplitudes in the cavity cells for different drive frequencies but the same input power.

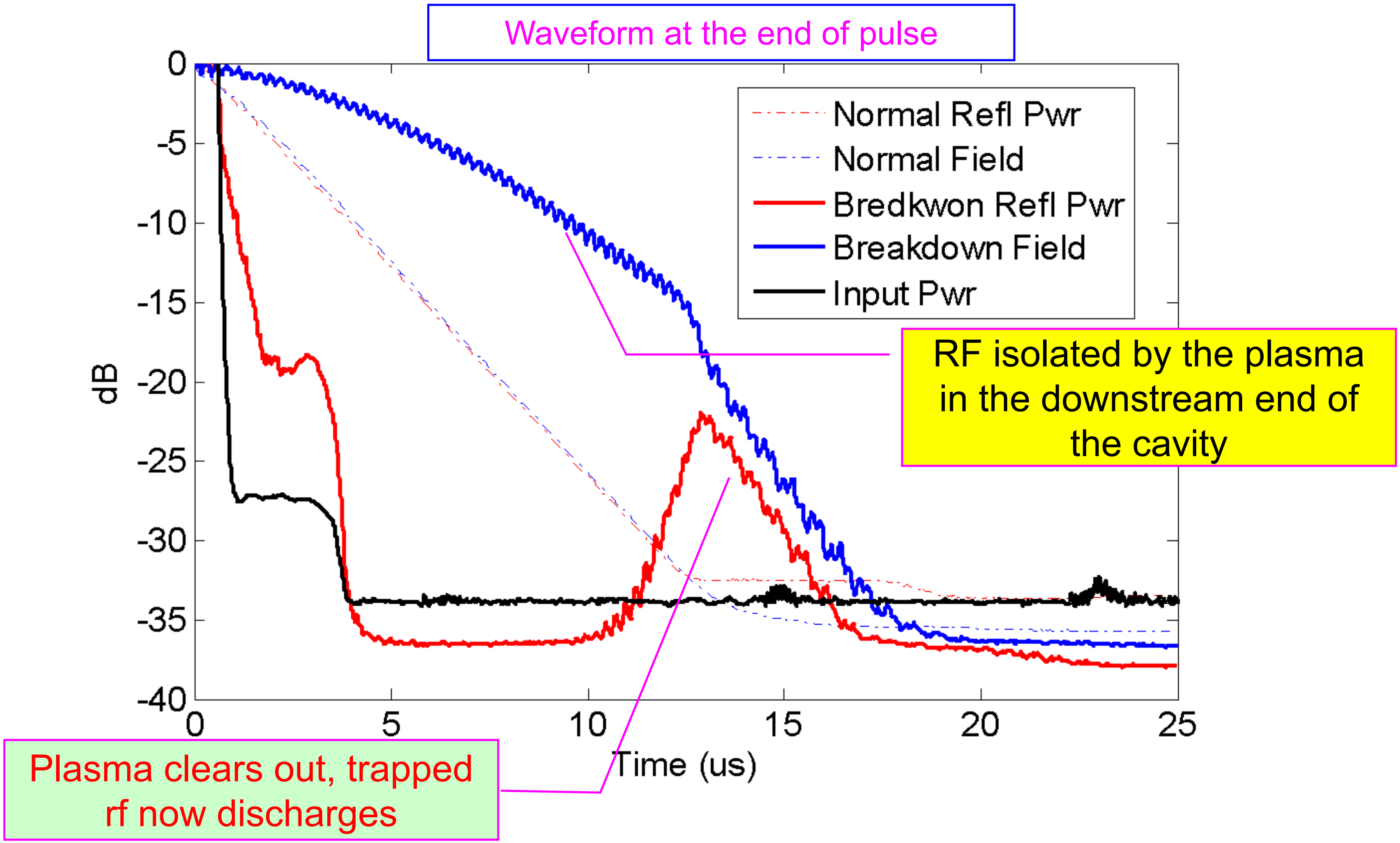
Cavity Static and Transient Study

- Transient Response

Mode beating after rf power turned off

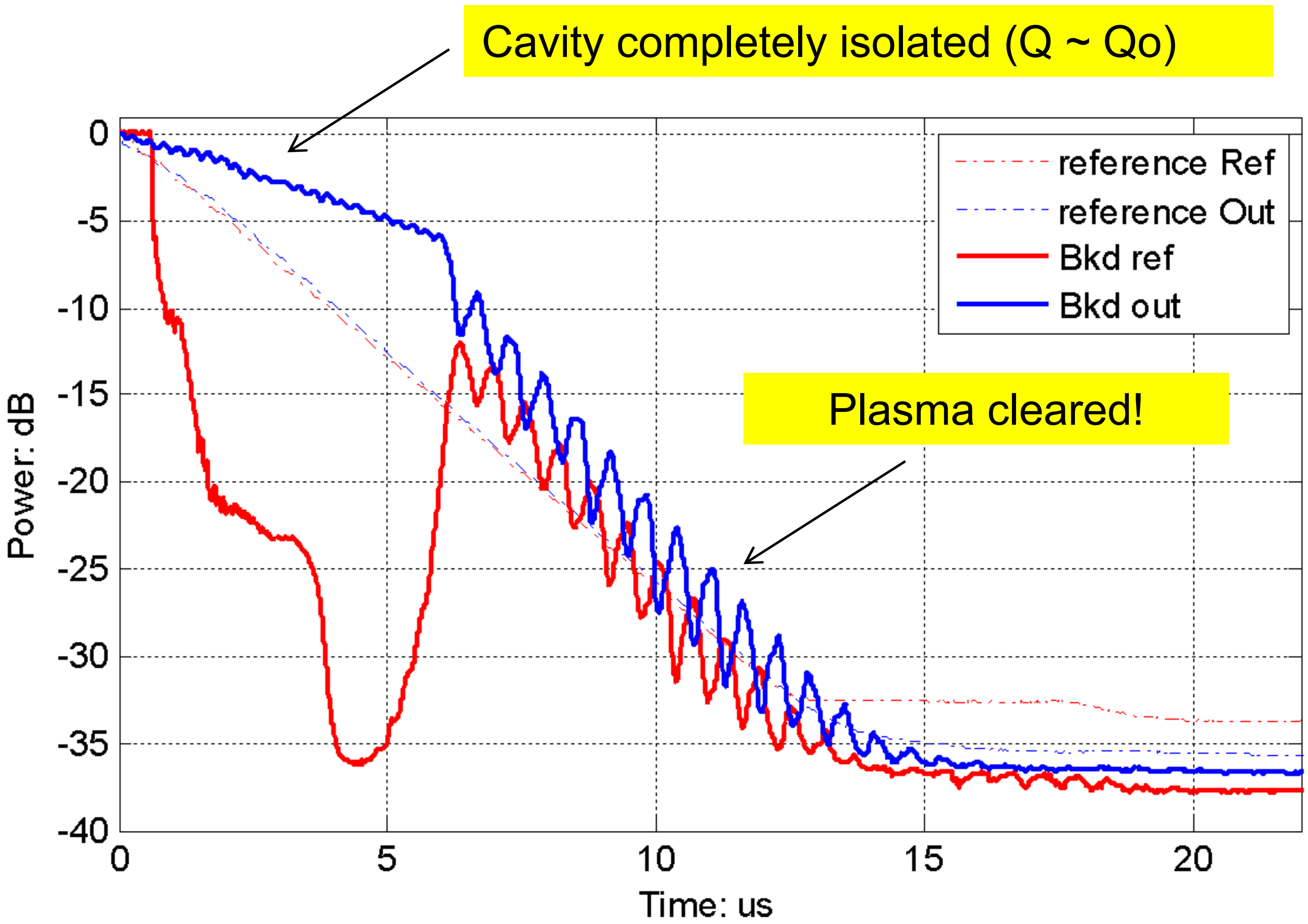


Cavity Breakdown Localization β = 1

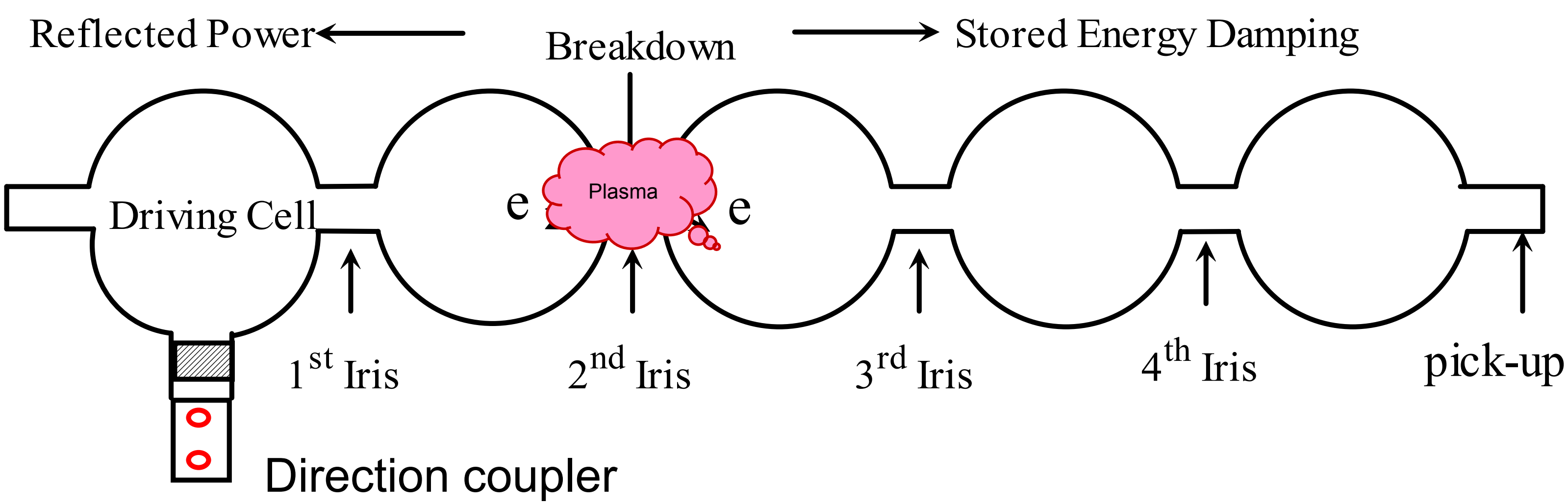


Typical Breakdown waveforms from the 5cell cavity, sampled at 100MHz.

Typical Breakdown Waveform



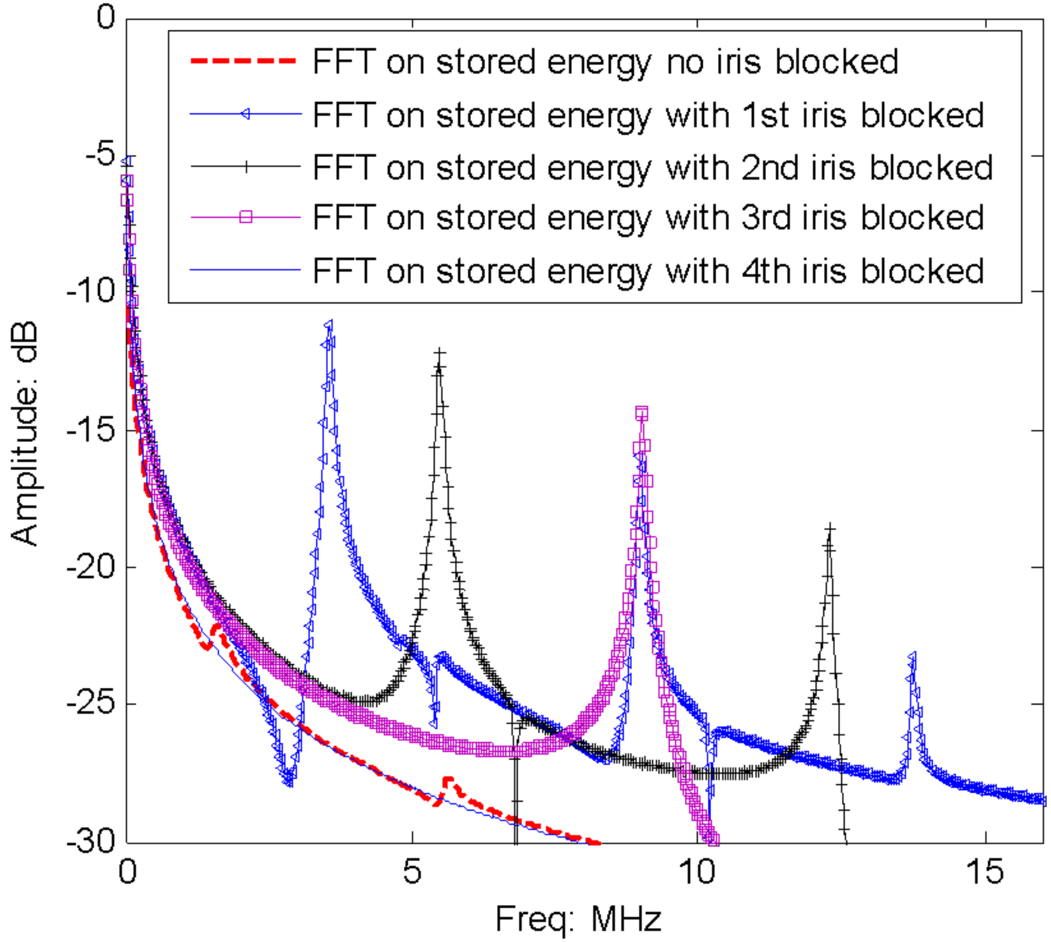
Cavity Breakdown Localization



- The plasma block the coupling. Cavity isolated to two parts.
- Both parts will see the natural modes beating after rf shutoff

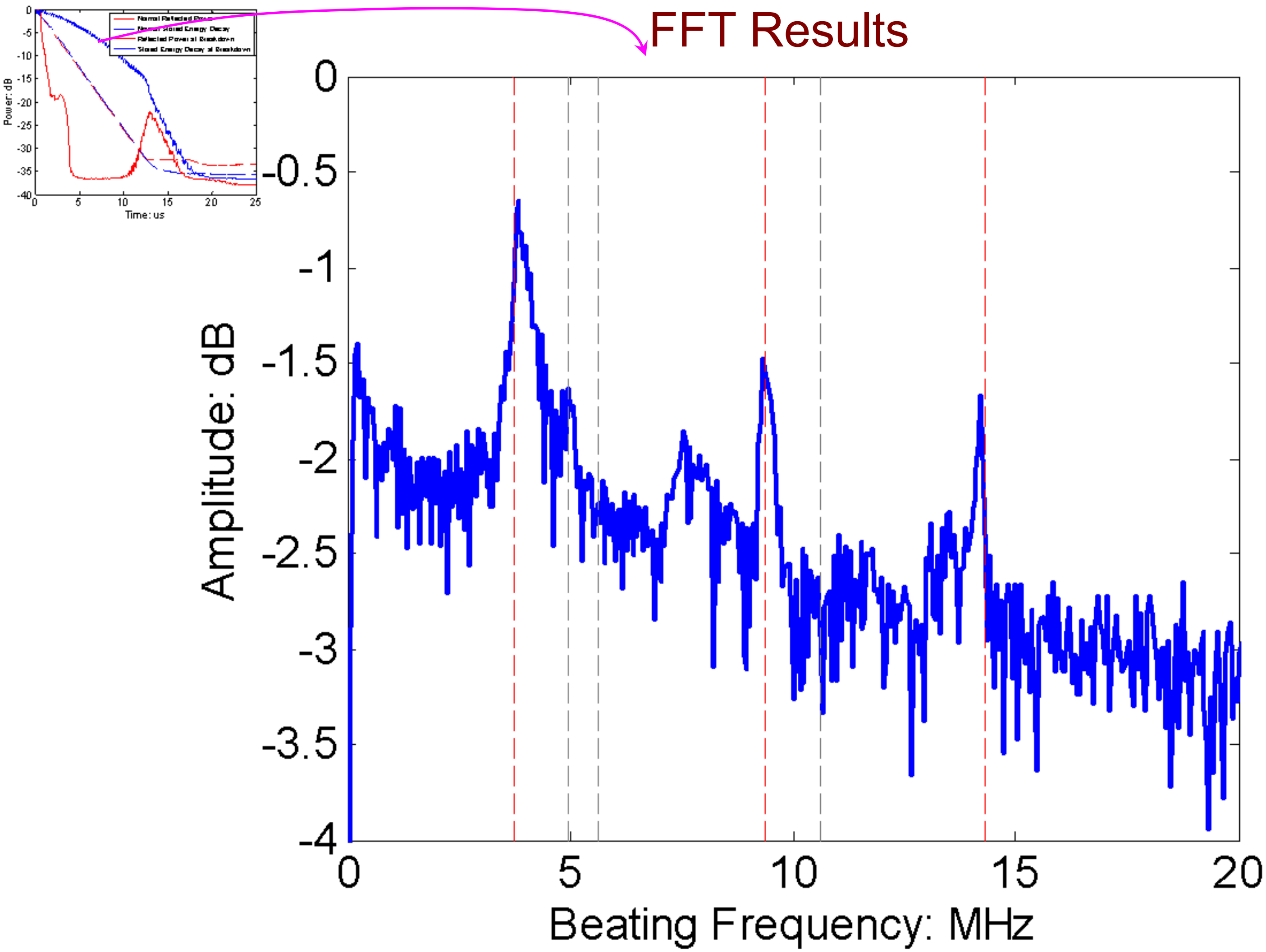
Cavity Breakdown Localization

Assume zero coupling at different irises and compute the FFT of the simulated field decay.



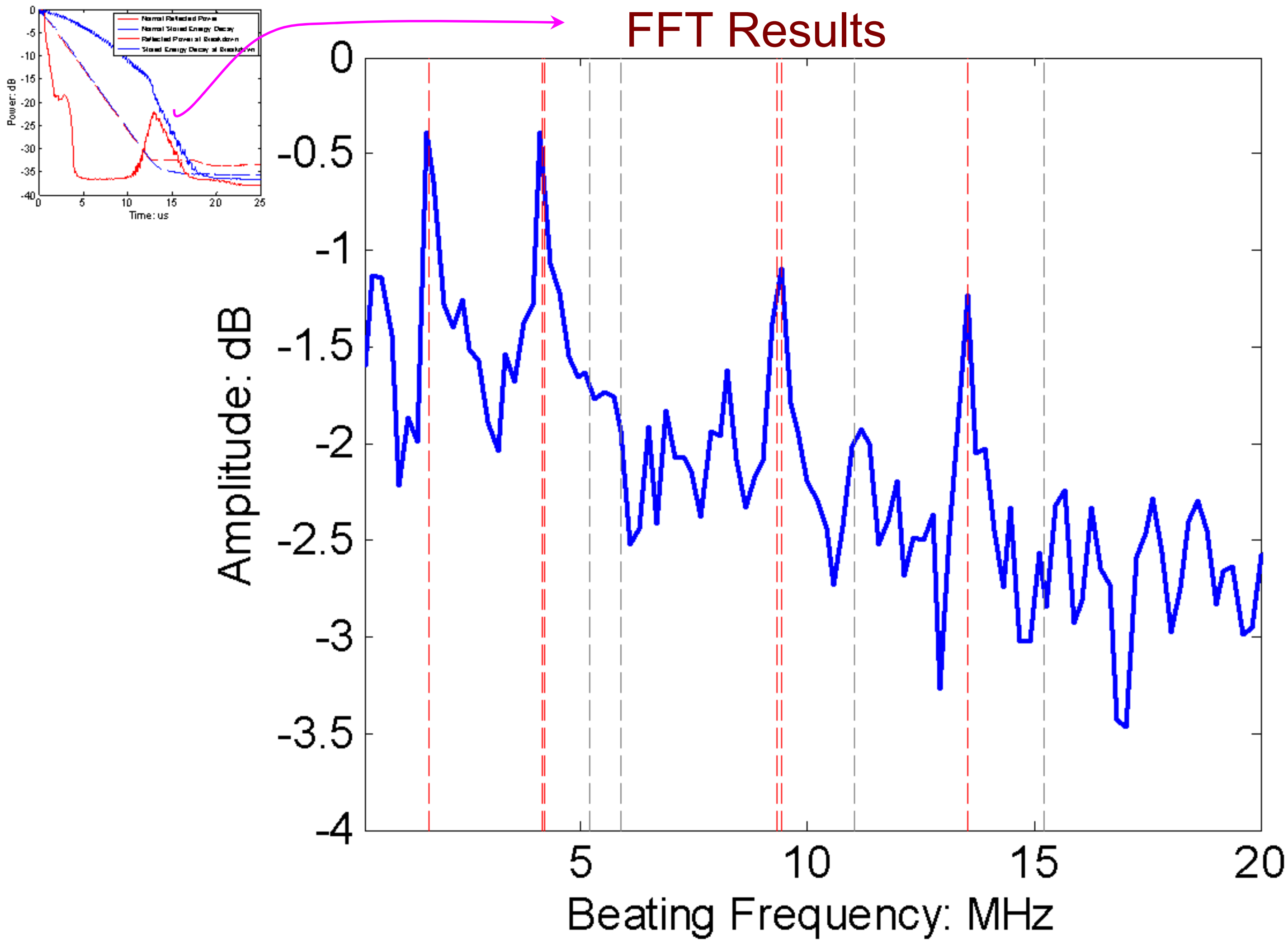
The distinct mode beating spectra differentiate the breakdown locations

Cavity Breakdown Localization



The dashed lines are the expected mode beating frequencies with the 1st iris blocked

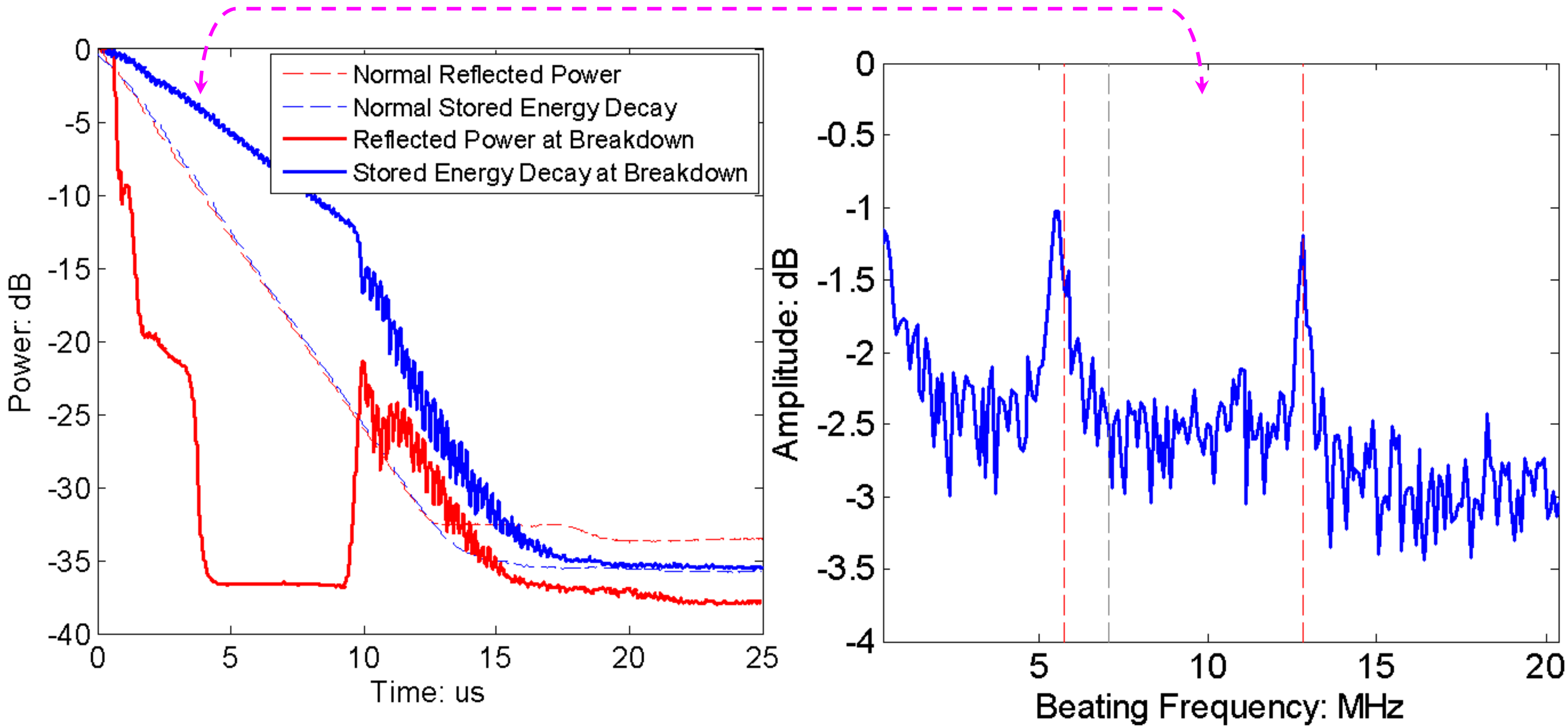
Cavity Breakdown Localization



The dashed lines are expected mode beating frequencies without breakdown

Cavity Breakdown Localization

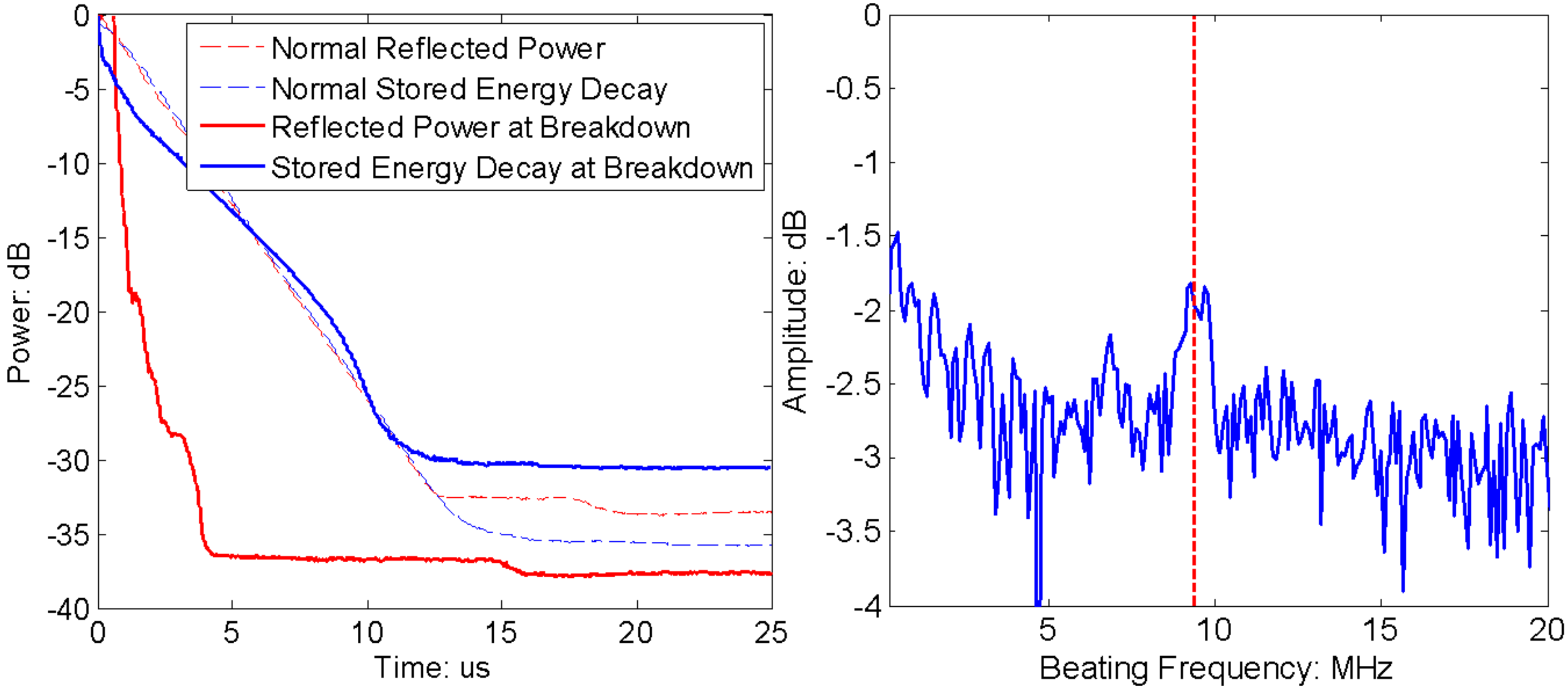
Example of Breakdown at 2nd iris.



The dashed lines are the expected mode beating frequencies with the 2nd iris blocked

Cavity Breakdown Localization

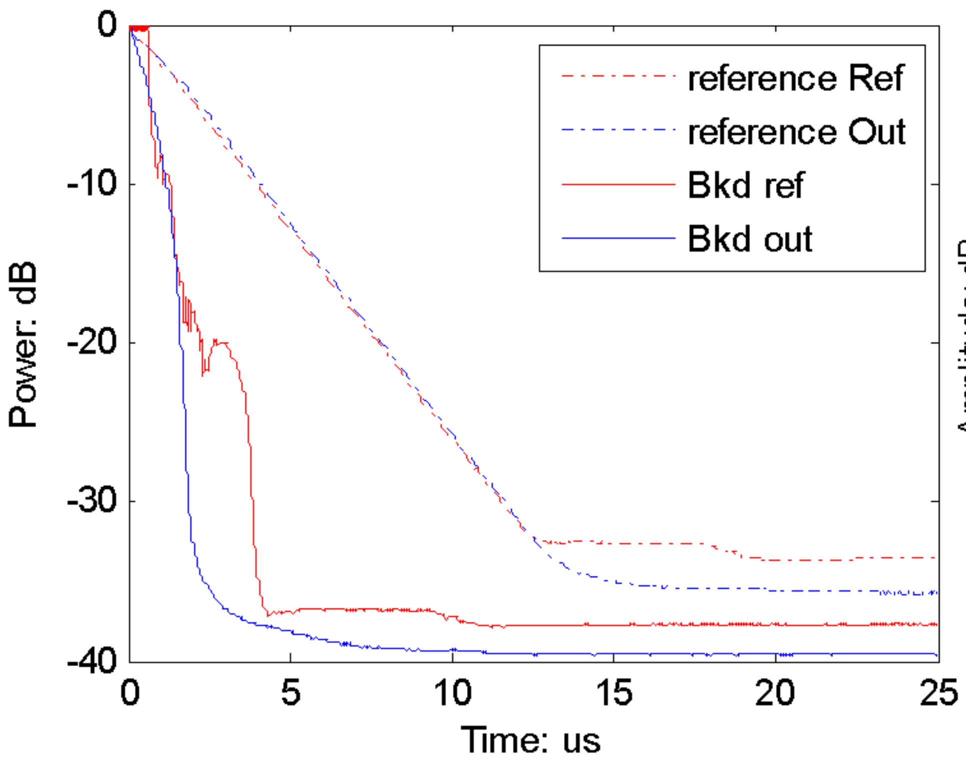
Example of Breakdown at 3rd iris.

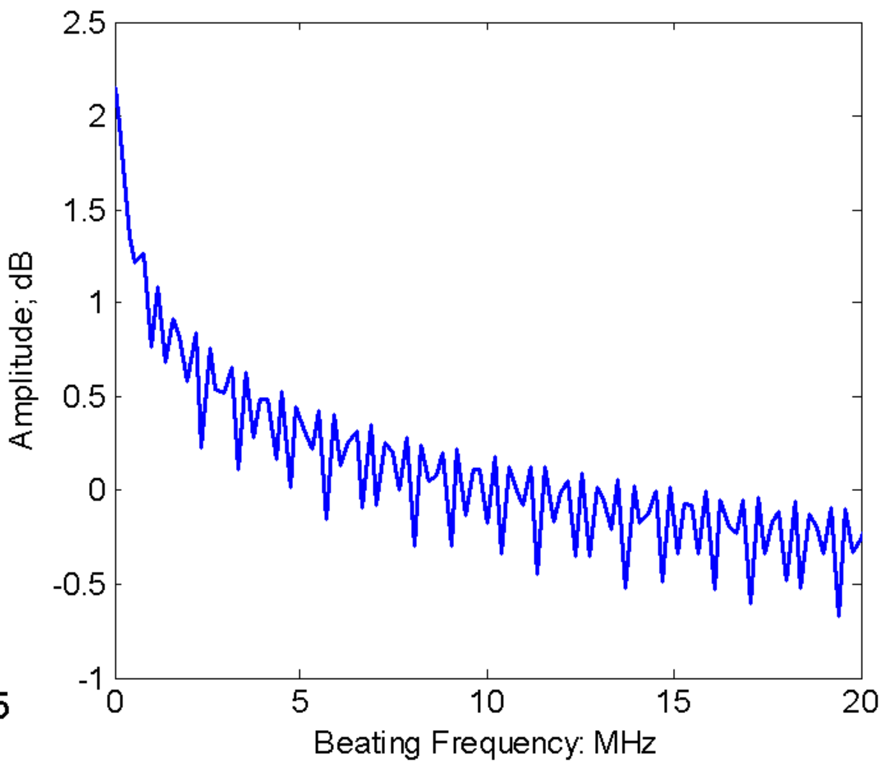


The dashed lines are the expected mode beating frequencies with the 3rd iris blocked

Cavity Breakdown Localization

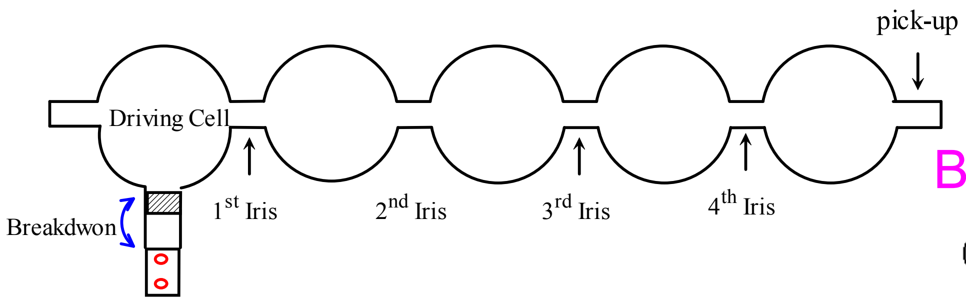
Example of Breakdown at 4th iris.



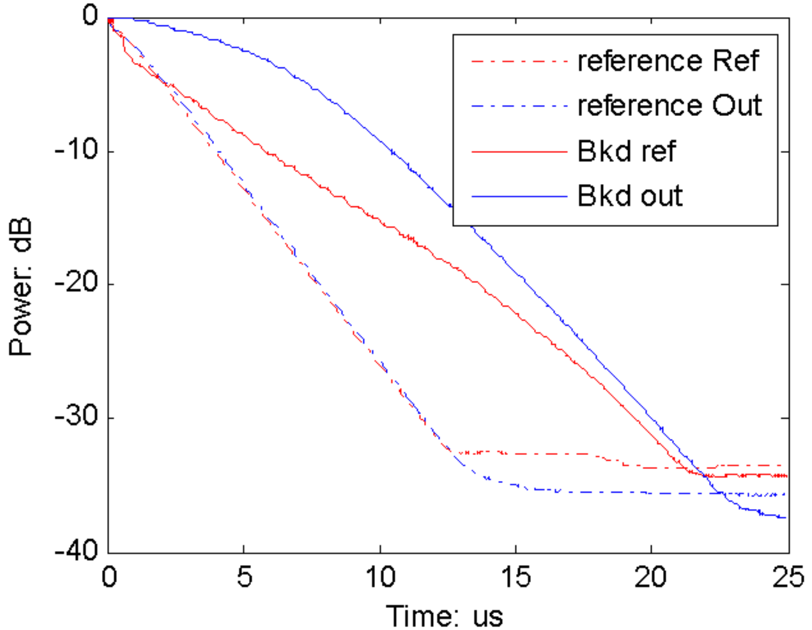


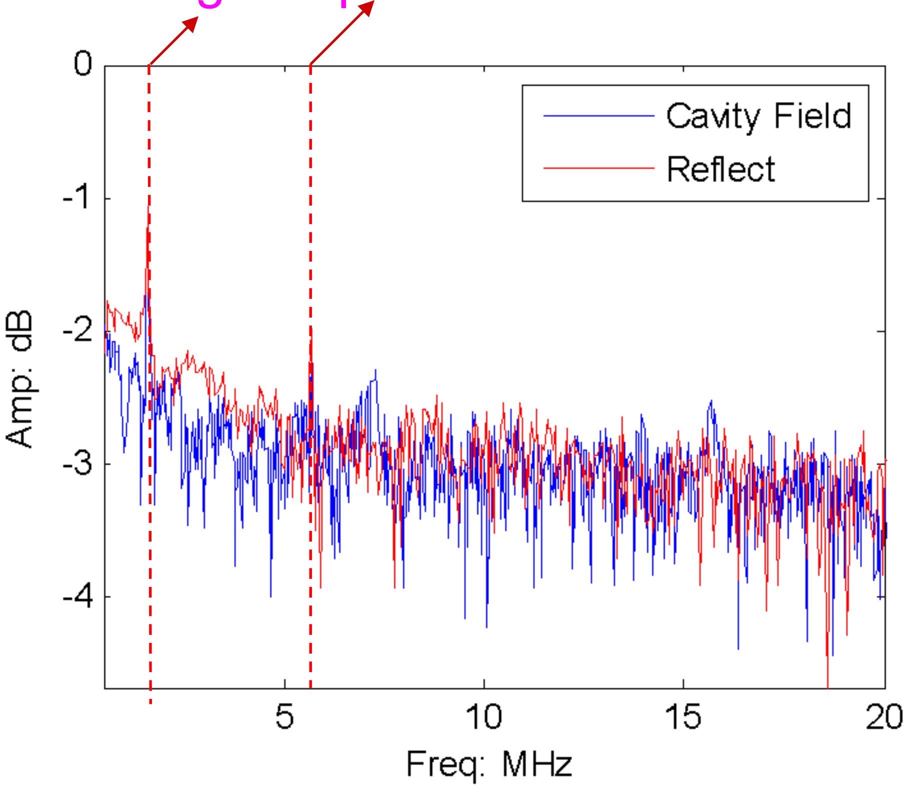
No Beating in the Stored Energy Decay !

Cavity Breakdown Localization



Beating Freq. from 5 cell natural modes.



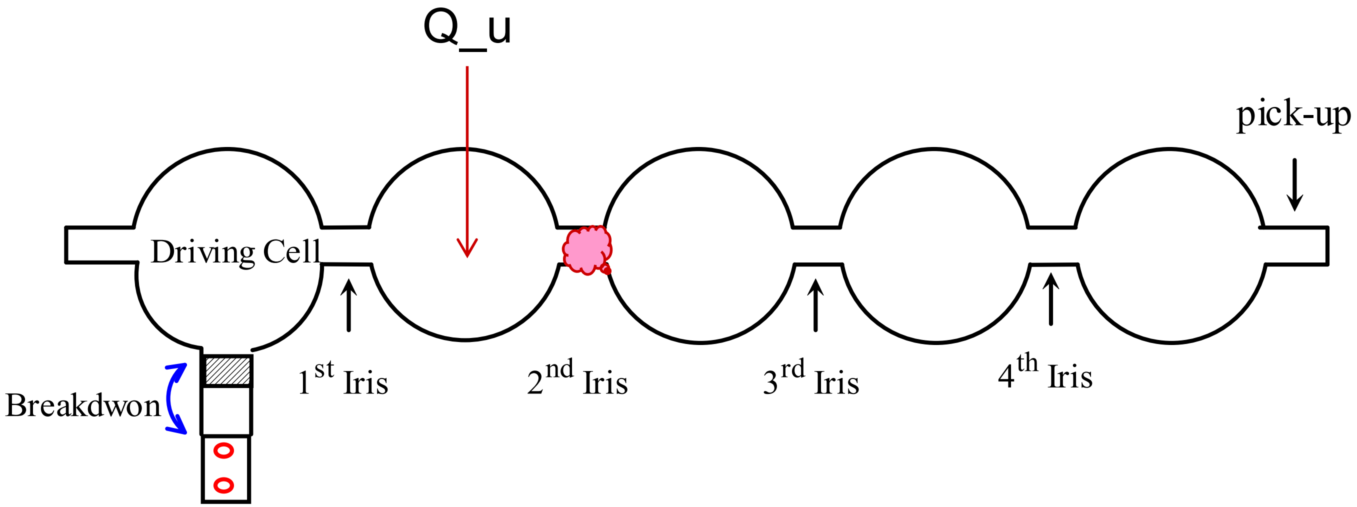


Breakdown between the directional coupler and cavity !

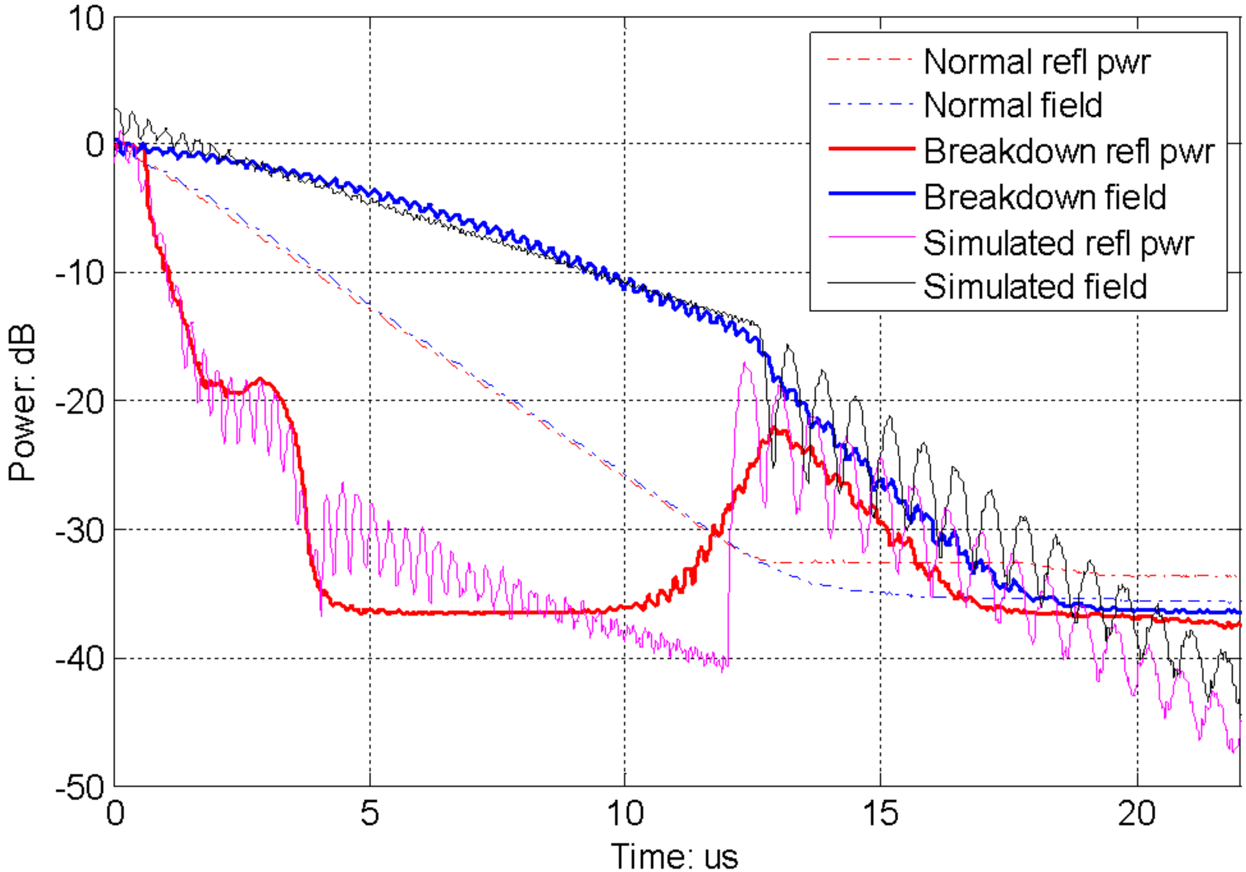
More Complex Cavity Breakdown Simulation

When first did the above analysis, the simulations with k = 0 for the breakdown iris did not match well the fast decay of the rf energy in the upstream, non-isolated part of the cavity.

Have recently modified the model, letting k of the breakdown iris and Qo of the upstream cell to vary to try to better match this behavior and that of the isolated part.

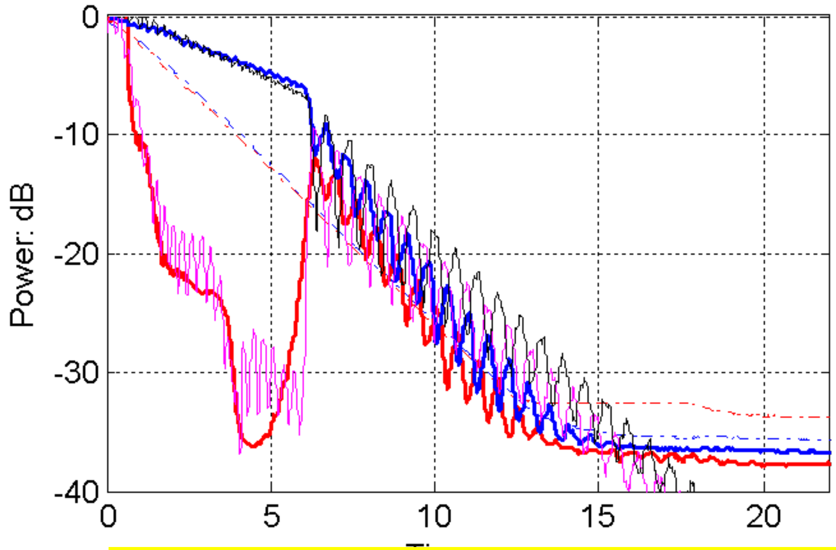


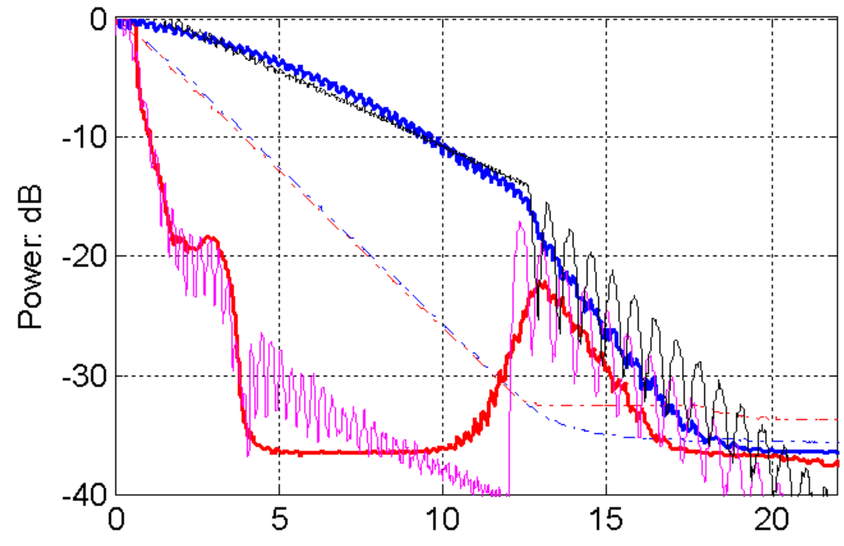
Cavity Breakdown Simulation – Iris 1 Breakdown



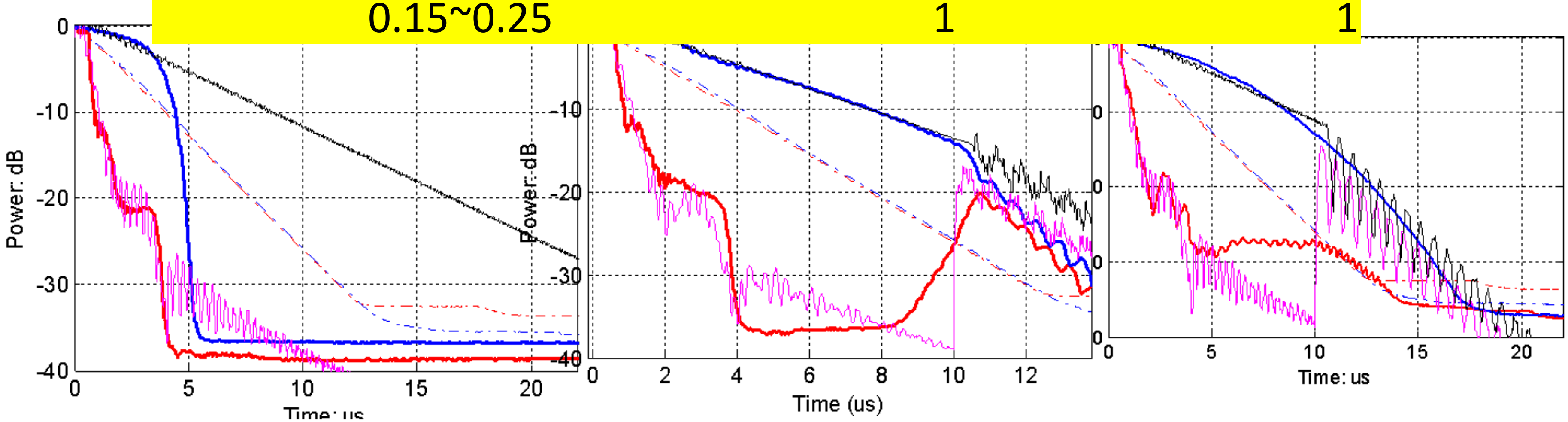
k_bkd/k_nor	Q_d_nor/Q_d_bkd	Q_u_nor/Q_u_bkd
0.2	1	4

Cavity Breakdown Simulation – Iris 1 Breakdown

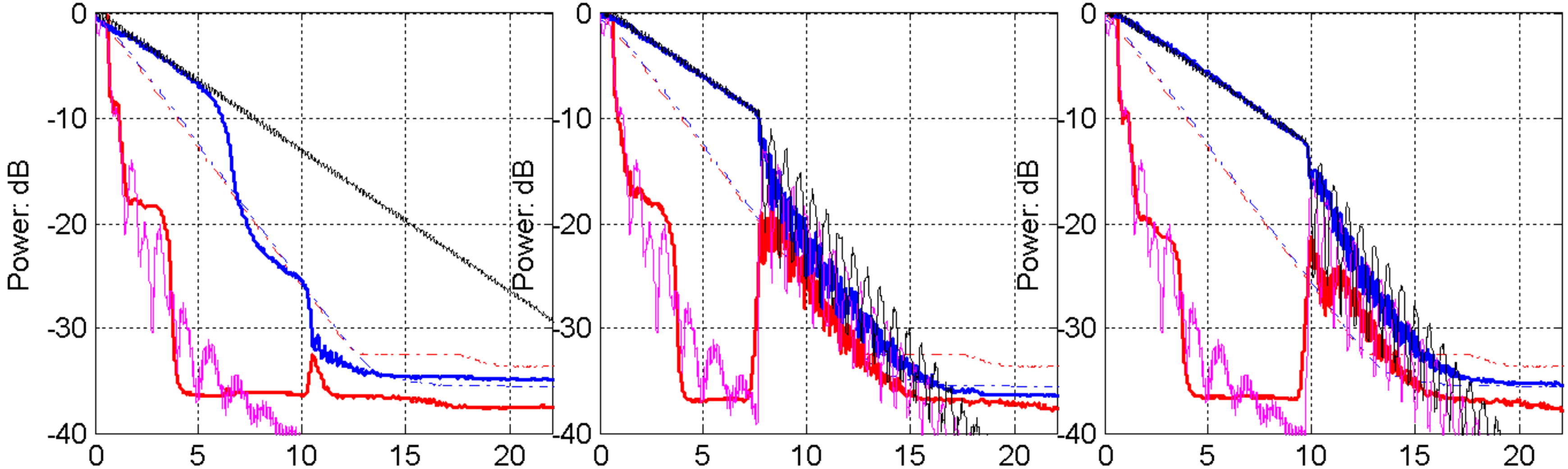




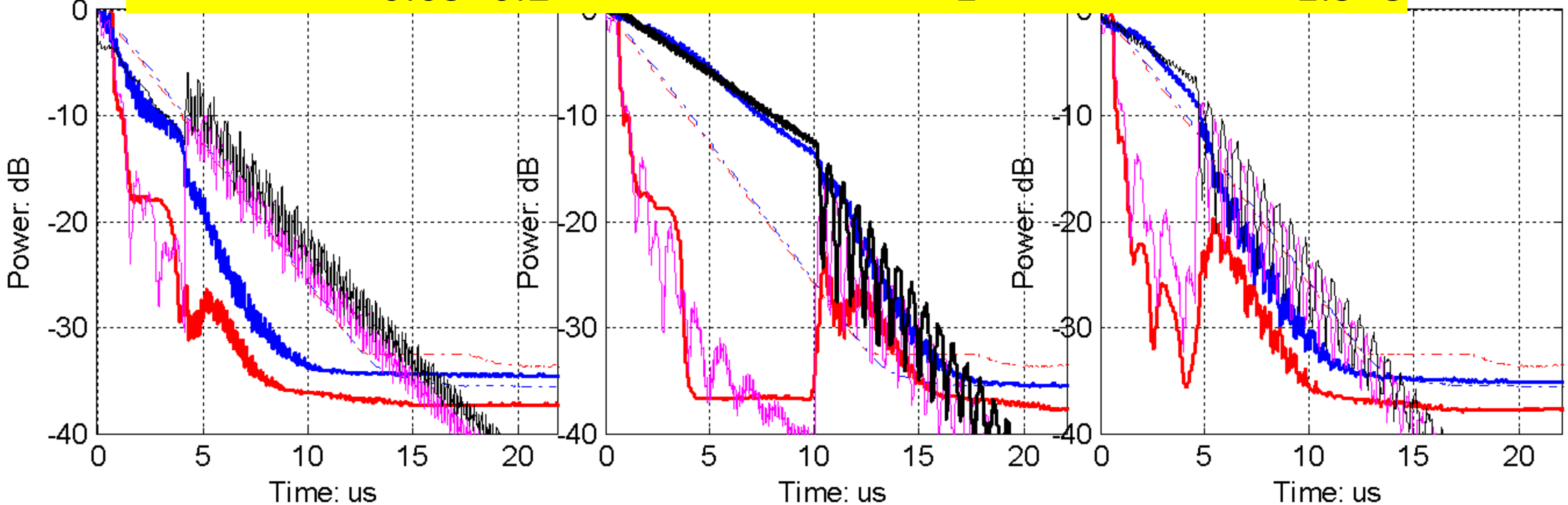
k_bkd/k_nor	Q_d_nor/Q_d_bkd	Q_u_nor/Q_u_bkd
0.15~0.25	1	1



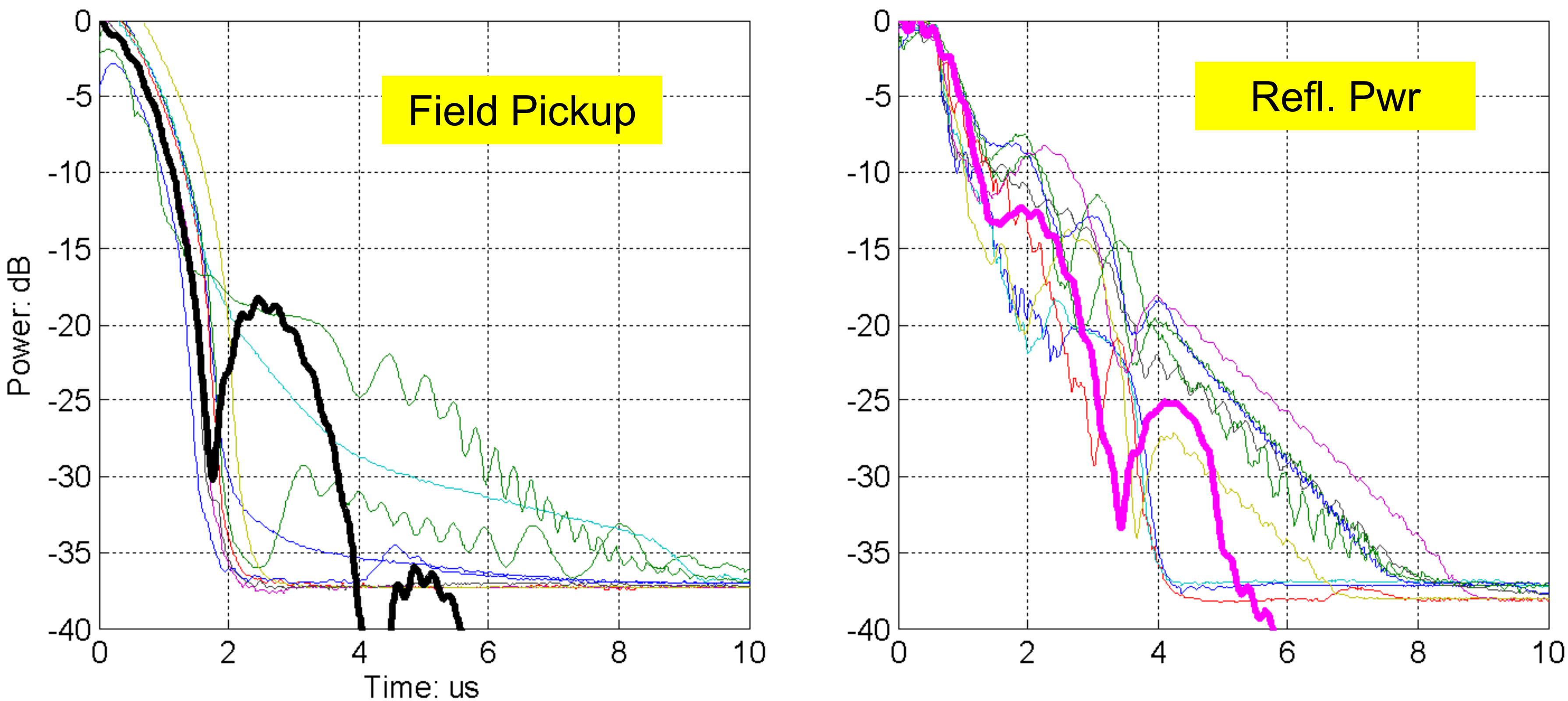
Cavity Breakdown Simulation – Iris 2 Breakdown



k_bkd/k_nor	Q_d_nor/Q_d_bkd	Q_u_nor/Q_u_bkd
0.05~0.2	1	1.5~8



Cavity Breakdown Simulation – Iris 4 Breakdown



k_bkd/k_nor	Q_d_nor/Q_d_bkd	Q_u_nor/Q_u_bkd
0.1	1	25

Summary: L-band 5-cell SW Cavity

1. Breakdown locations can be determined from the FFT signature of the decay fields
2. By varying the breakdown iris coupling and the upstream cell Q in the cavity circuit model, can match reasonably well the decay field patterns (through the simulations show more pronounced mode beating).
3. Why does the breakdown plasma stay for so long (many us) after the drive rf is shut-off and not cause large rf losses ?