TWO CONCEPTS FOR RAISING ACCELERATION GRADIENTS BY USING MULTI-MODED CAVITY STRUCTURES#

S.V. Kuzikov[1,2], S.Yu. Kazakov[1,3], J.L. Hirshfield[1,4], M.E. Plotkin[2],

A.A. Vikharev[2], V.P. Yakovlev[1,5]

[1]*Omega-P, Inc., New Haven, CT, USA*

[2]*Institute of Applied Physics, Nizhny Novgorod, Russia*
[3]*KEK, Tsukuba, Japan*
[4]*Yale University, New Haven, CT, USA*
[5]*Fermi National Accelerator Laboratory, Batavia, IL, USA*

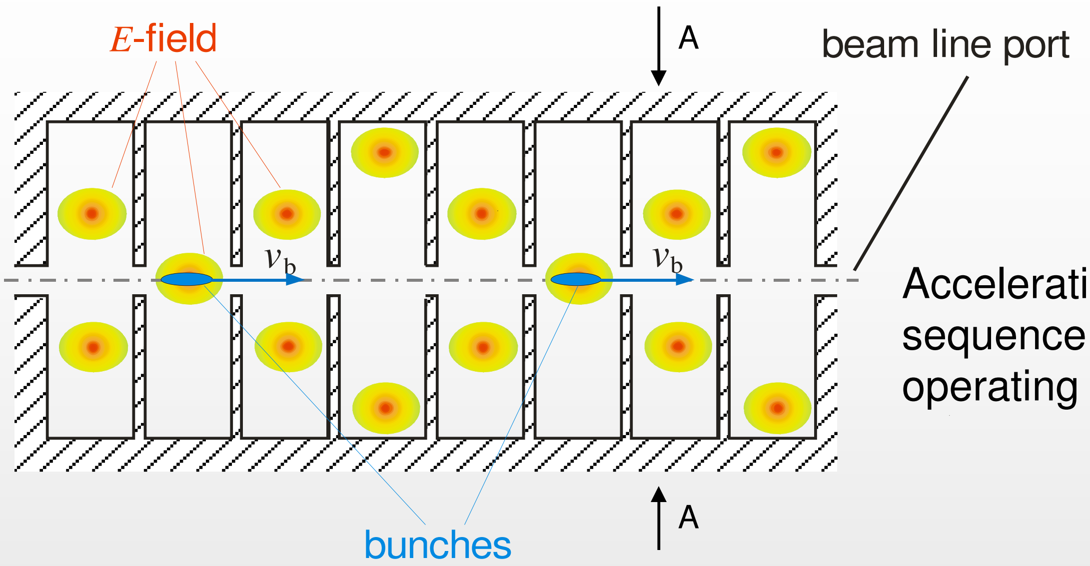
Work sponsored by in part by US Department of Energy, Office of High Energy Physics (2009).

OUTLINE OF TALK

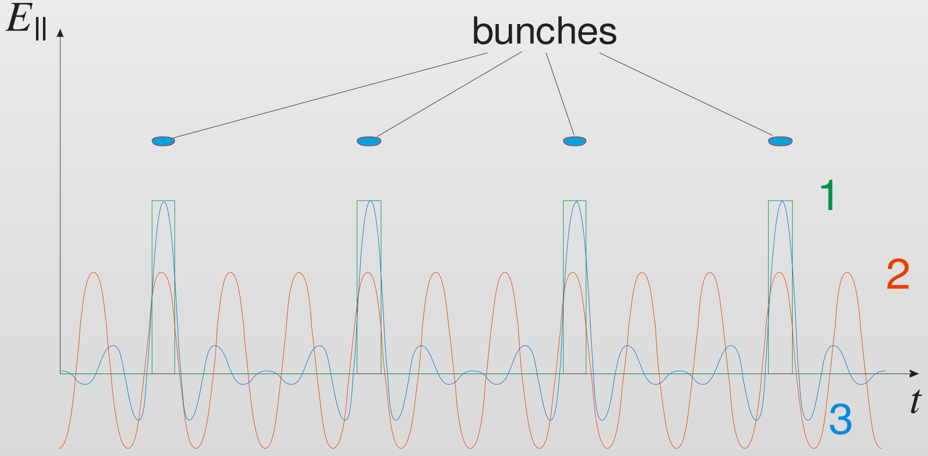
1. Previously,* we suggested a concept aimed at raising RF breakdown thresholds by reducing the exposure time of surfaces to high *E* and *H* fields, through the use of multi-mode cavity excitation.
2. A second related idea aims at the same objective by using a two-mode, two-frequency axisymmetric, but longitudinally asymmetric cavity.
3. Experimental tests of both ideas may be possible using CTF-3 beam facilities.
4. Methodology and possible time-schedule are suggested.
5. Complementary experiments may also be possible using two klystrons as the RF sources (S-band/C-band or C-band/X-band), rather than a drive beam.
6. Summary.

*Papers at AAC2006, AAC2008, PAC2009.

Principle of acceleration in a multi-frequency structure



Acceleration is shown of a moving periodic sequence of bunches in decoupled cavities, each operating in a superposition of harmonic modes.

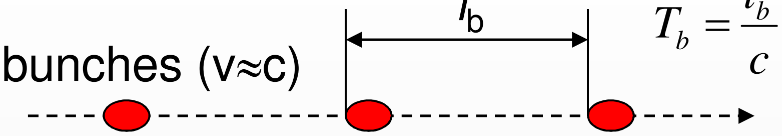


E-field in A-A cross-section

1 – ideal (desired) time-dependence of the field.
2 – time-dependence of the field in an ordinary single-frequency structure.
3 – time-dependence of the field in a multi-frequency structure (with finite number of modes).

This solution is periodic in time (period is that of the lowest mode).
Therefore, the spectrum of eigenmodes of each cavity has to be equidistant.

bunches (v≈c)



$$T_b = \frac{l_b}{c}$$

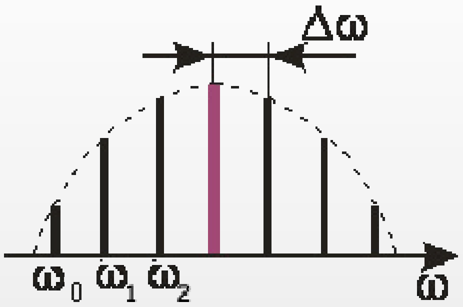
$$\vec{E}(\vec{r},t) = \sum_n a_n \cdot \vec{F}_n(\vec{r}) \cdot \exp(i\omega_n t),$$

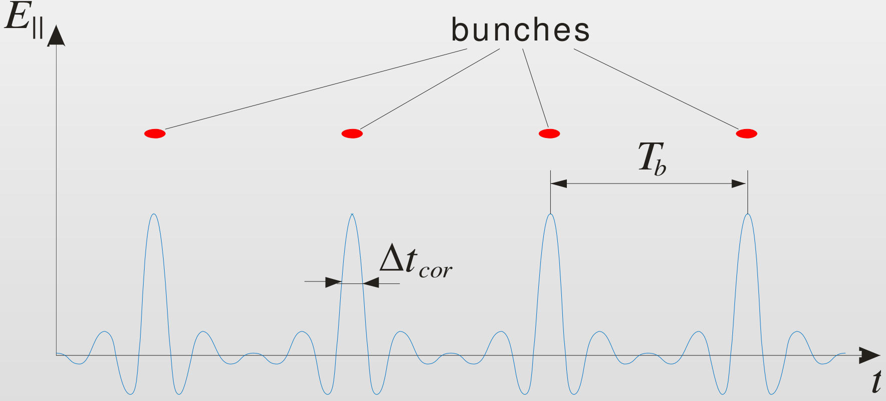
$\omega_n = \omega_0 + n \cdot \Delta\omega,$ where *n=0,1,2,…*

$$\vec{E}(\vec{r},t) = \exp(i\omega_0 t) \sum_n a_n \cdot \vec{F}_n(\vec{r}) \cdot \exp(i \cdot n\Delta\omega \cdot t),$$

$$\vec{E}(\vec{r},t+T_b) = \vec{E}(\vec{r},t),$$

Here $\omega_0/\Delta\omega = p/q$, where *p* and *q* are arbitrary integers.





When operating with a finite number of modes, the single peak duration is defined by the time during which the phases of the lowest- and highest-frequency modes differ by π, i.e.,

$$\Delta t_{cor} \approx \frac{\pi}{\omega_N - \omega_0}$$

Raising breakdown thresholds

W. Wuensch et al (2008) suggested to consider the initial stage of RF breakdown, in

ulated that a

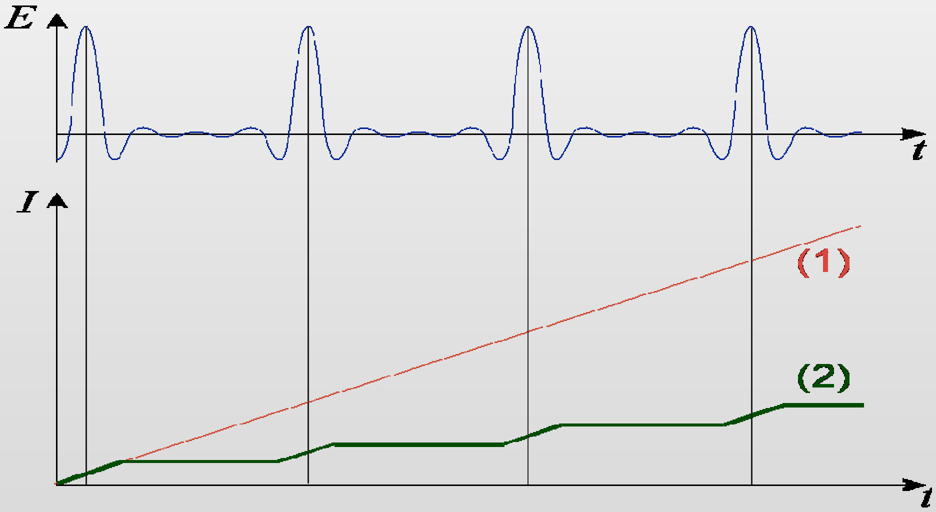
by emission

There are additional criteria proposed:

1. Modified Poynting vector (W. Wuensch et al)
2. Pulse heating and the stored energy (V.Dolgashev et al)

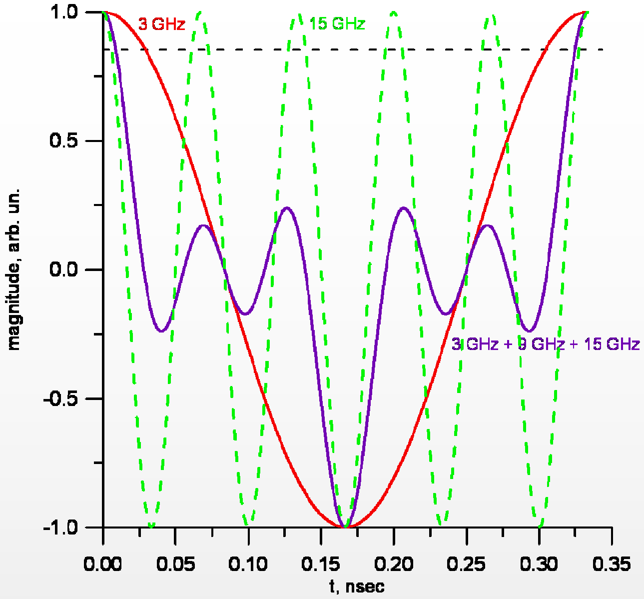
$$\Delta T(t) = B \cdot \int_0^t \frac{E^3(t') \cdot \exp(-\gamma / E(t'))}{\sqrt{t - t'}} dt',$$

This leads to a scaling law connecting the *E* field magnitude and pulse duration which was confirmed experimentally, namely $E_{thr}^6 \cdot t = const \equiv I.$



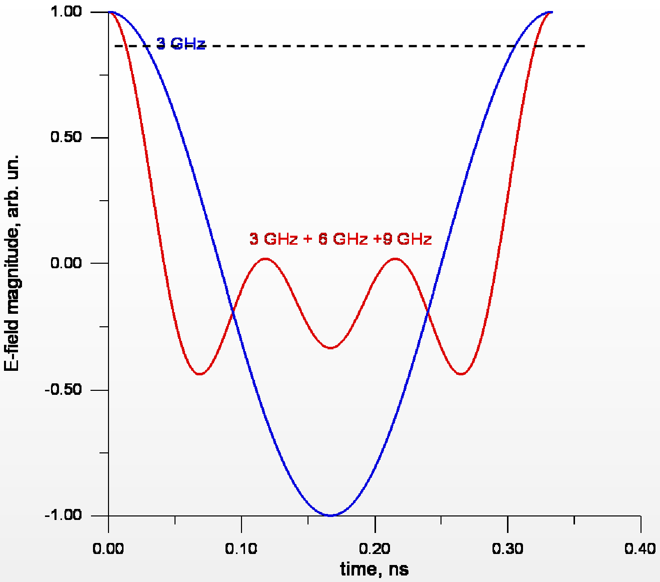
E(*t*) and *I*(*t*) dependencies for single- (1) and multi-frequency (2) structures

One may question how this scaling law might be modified if the exposure times to intense RF fields are shortened within each RF cycle, i.e. into the psec range.



Fields versus time for single 3 GHz cavity, for 15 GHz cavity, and for **3+9+15 GHz** multi-mode cavity.

In this case one may expect a raise in breakdown threshold by a factor **~$5^{1/6}$ = 1.3.**



Fields versus time for a single-mode 3 GHz cavity, and for **3+6+9 GHz** multi-mode cavity.

In this case one may expect similar raise of breakdown threshold by a factor of **~$(2*(9-3)/3)^{1/6}$ = 1.26.**

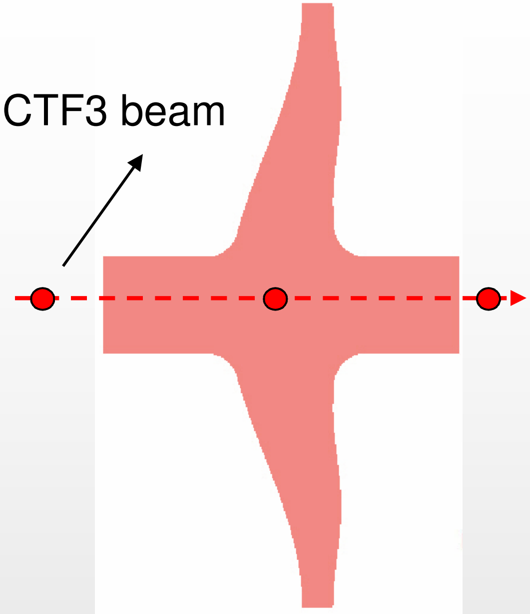
However, there is to date no experimental proof that the initiation of breakdown can be inhibited by reducing the <u>micro-pulse</u> width of RF fields, as contrasted with the customary role assumed for the <u>macro-pulse</u> width. An objective of our proposed experiments is to test that postulate.

Possible experiments with cavities powered by CTF3 beam

- We propose to build three cavities to be excited identically (by means of the same e-beam).
We would like to compare probabilities of breakdown in these three cases: 1-, 2-, and 3-mode cavities.

- The experiment conditions should provide the same *E*-field level in each cavity, in order to deal only with effect of the different exposure time.

- If our postulate is valid, the 3-mode cavity will be the most breakdown proof among the three.

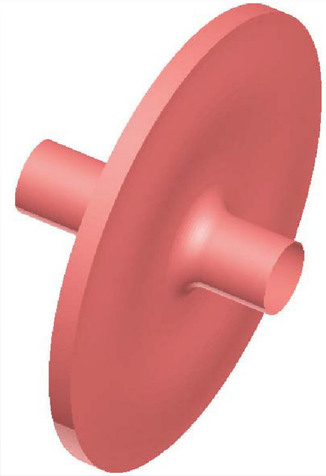


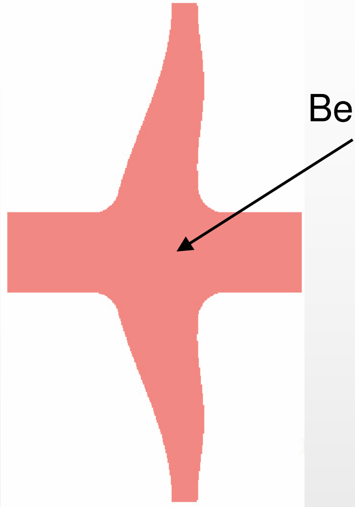
These experiments are aimed at investigating the fundamental basis of RF breakdown theory.

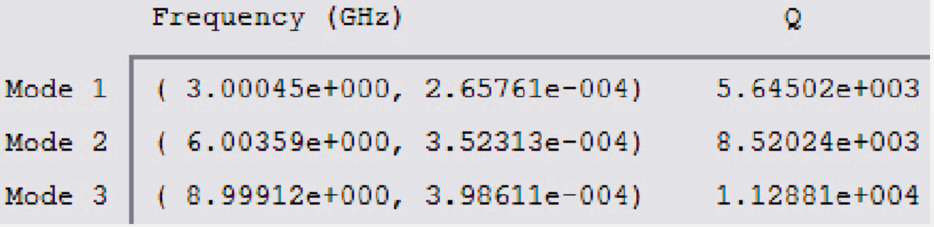
- We plan to investigate dependencies of the breakdown threshold on the temporal and spatial cyclic exposures of cavity surfaces to *E*- and *H*-fields.
- Investigations have already been made by others of breakdown dependencies on the field magnitude and macro-pulse duration, but not the shape of RF pulse.
- If a rise of breakdown threshold through reduction in the micro-pulse width can be proven, it could open a new means for accelerating particles with a higher gradient than through use of single-mode excitation.

Three-mode axisymmetric cavity with modes at 3, 6, and 9 GHz

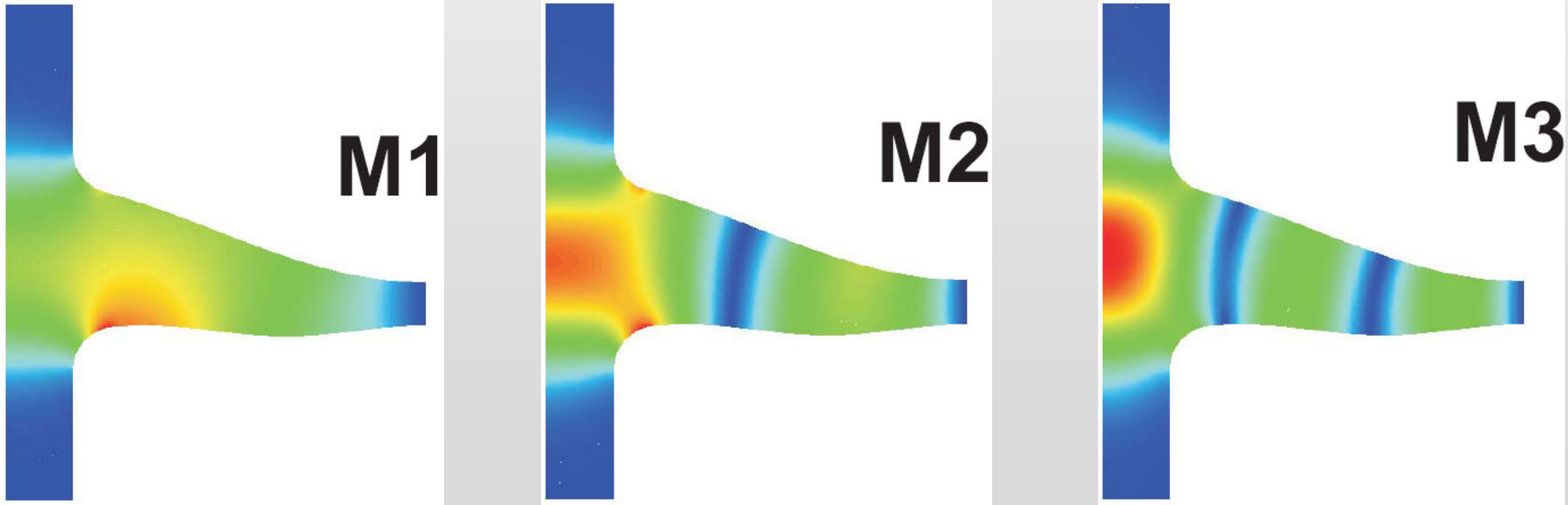
The first design issue is to obtain an equidistant mode spectrum. This has been solved by specific cavity shape (each mode is tuned by its own sine-like wall profile.







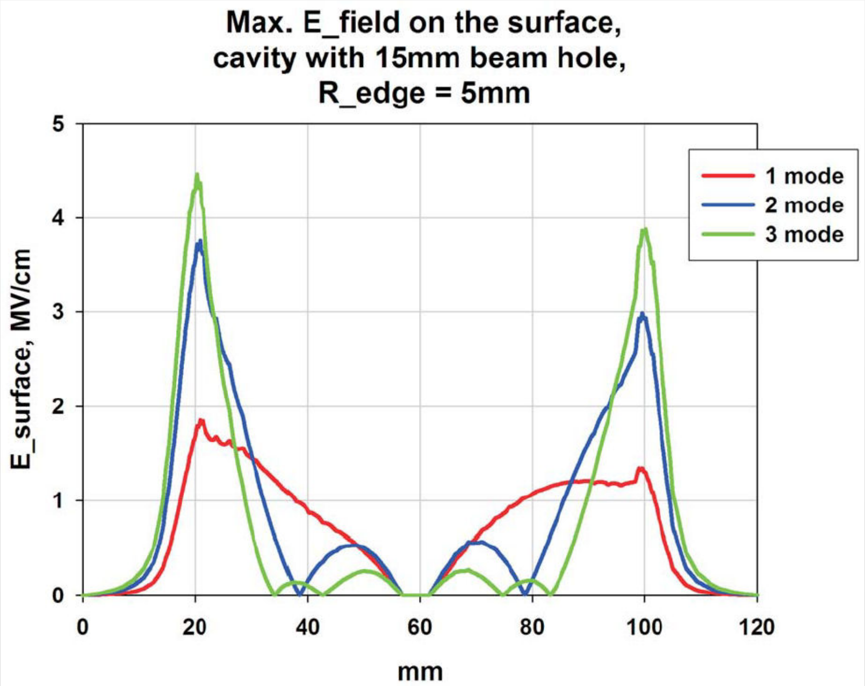
	Frequency (GHz)	Q
Mode 1	(3.00045e+000, 2.65761e-004)	5.64502e+003
Mode 2	(6.00359e+000, 3.52313e-004)	8.52024e+003
Mode 3	(8.99912e+000, 3.98611e-004)	1.12881e+004

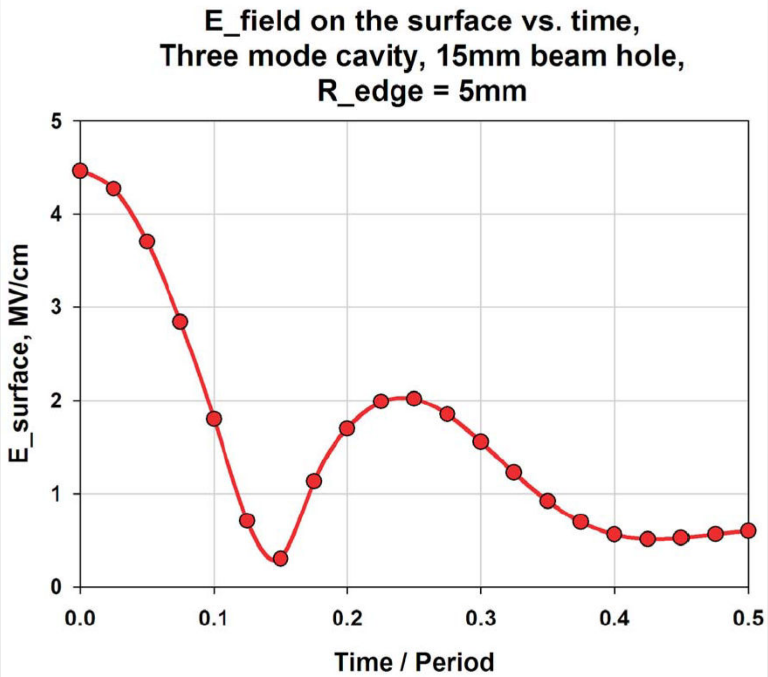


E-fields of eigenmodes

CTF3 beam parameters assumed in obtaining numerical results

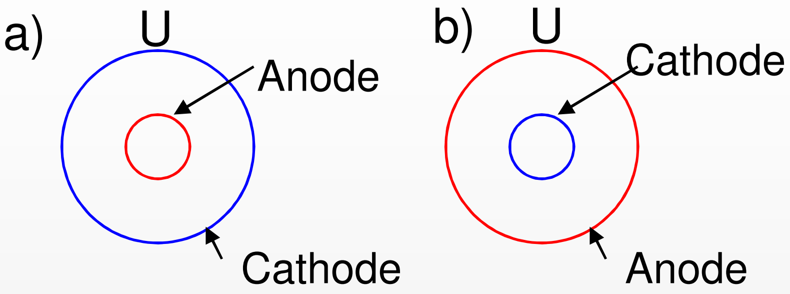
Electron energy, MeV	120
Bunch charge, nC	2.33
Bunch diameter, mm	23
Bunch length, mm	2
Bunch frequency, GHz	3
Train length, μs	0.693
Repetition rate, Hz	1



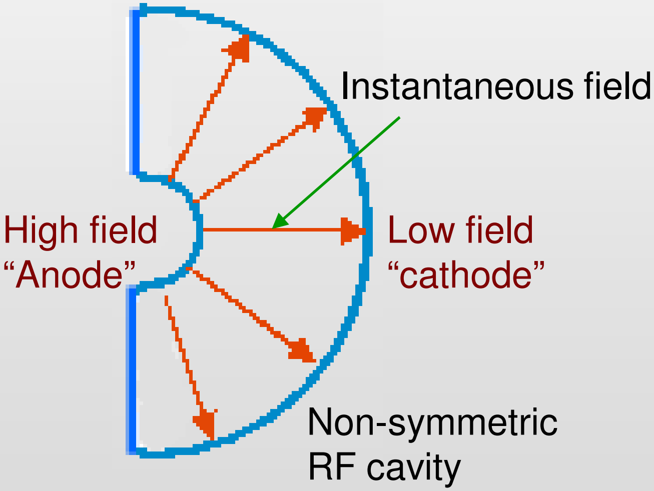


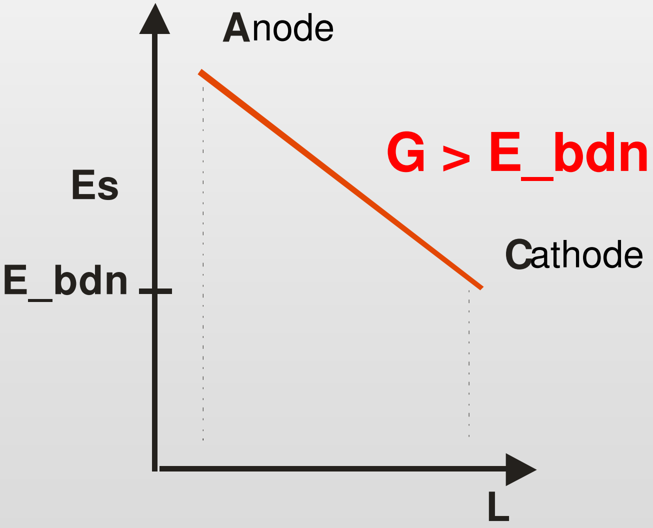
The maximum Poynting vector value in three mode cavity is S_C=0.45 W/μm^2.

2nd concept: Raising breakdown threshold by using an asymmetric cavity



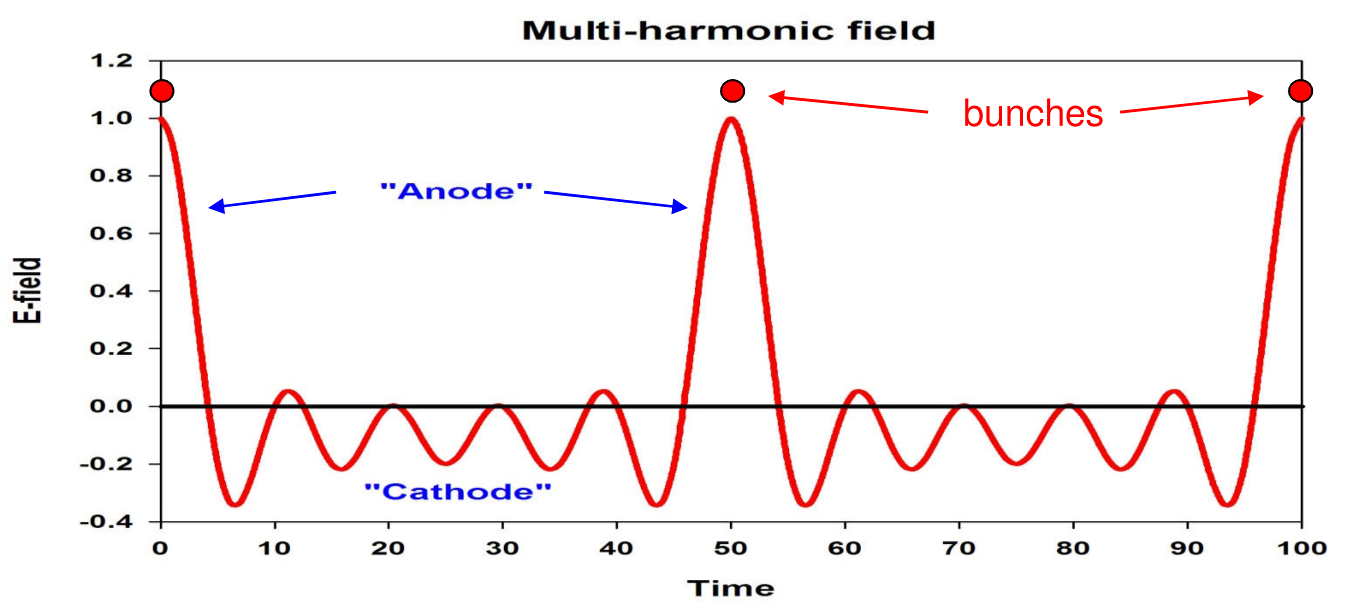
It is known for DC vacuum breakdown that, even when the voltage is the same, in case (a) breakdown threshold is higher than in case (b)! Cathode is more vulnerable.

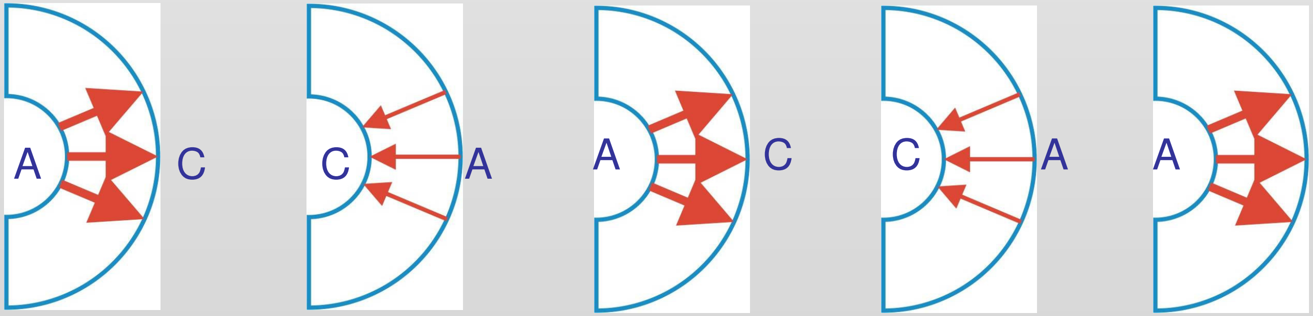




With RF fields, electron emission does not occur if the E-field pushes electrons in towards a wall. In a single mode cavity this doesn't help, since fields oscillate symmetrically between +maximum and –maximum. "Cathode" and "Anode" exchange roles each half period. In a multi-mode cavity, the situation may be quite different!

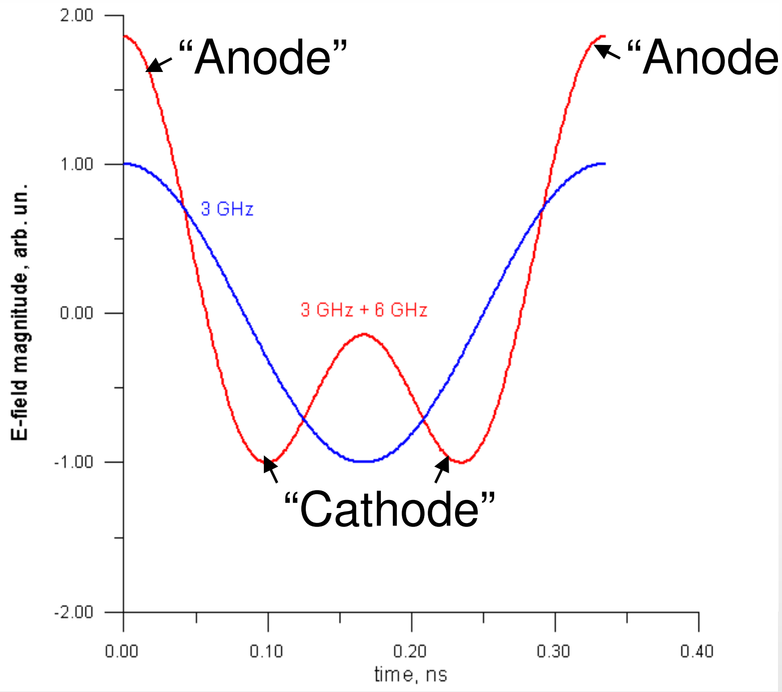
A multi-mode cavity without longitudinal symmetry allows unequal “anode” and “cathode” fields at metal surfaces, and can have an “anode” field higher than the “cathode” field. If it is correct that breakdown is determined only by the cathode field, it may be that a non-symmetric cavity will have a higher ratio of accelerating gradient to surface breakdown field, and will thus provide an increased acceleration gradient.



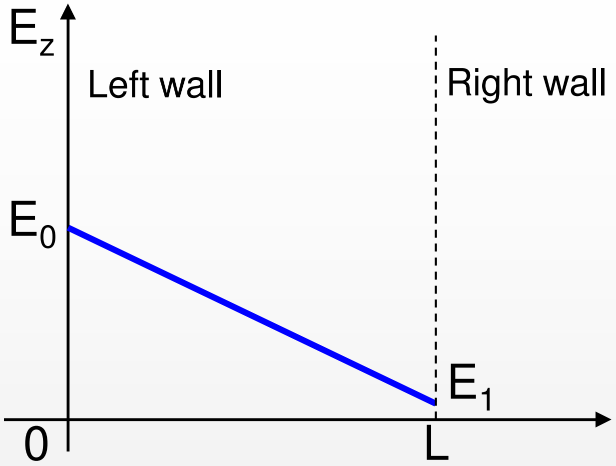


In the RF cavity “anode” and “cathode” change places with frequency *f*.

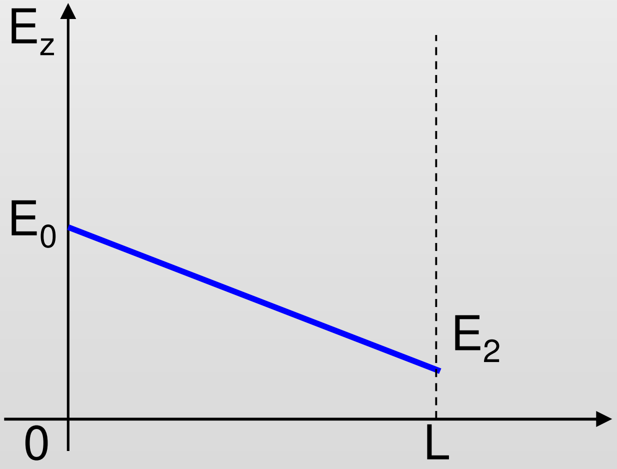
We consider a cavity having two axisymmetric modes at frequencies *f* and 2*f*.



Field on the left wall

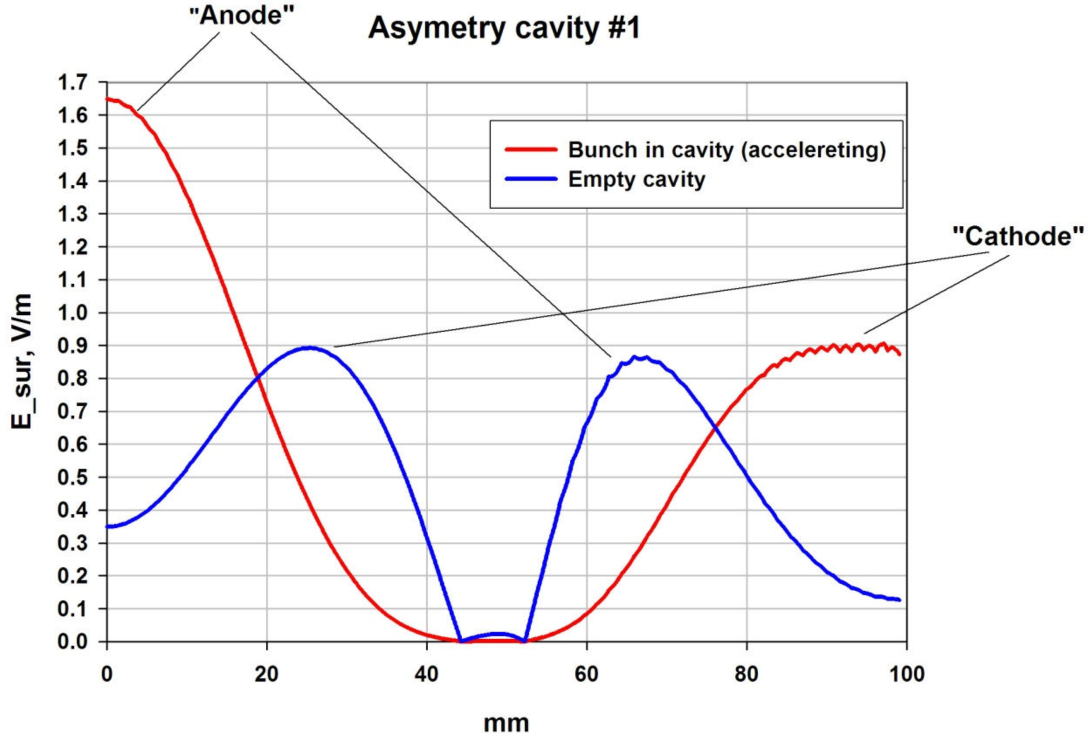


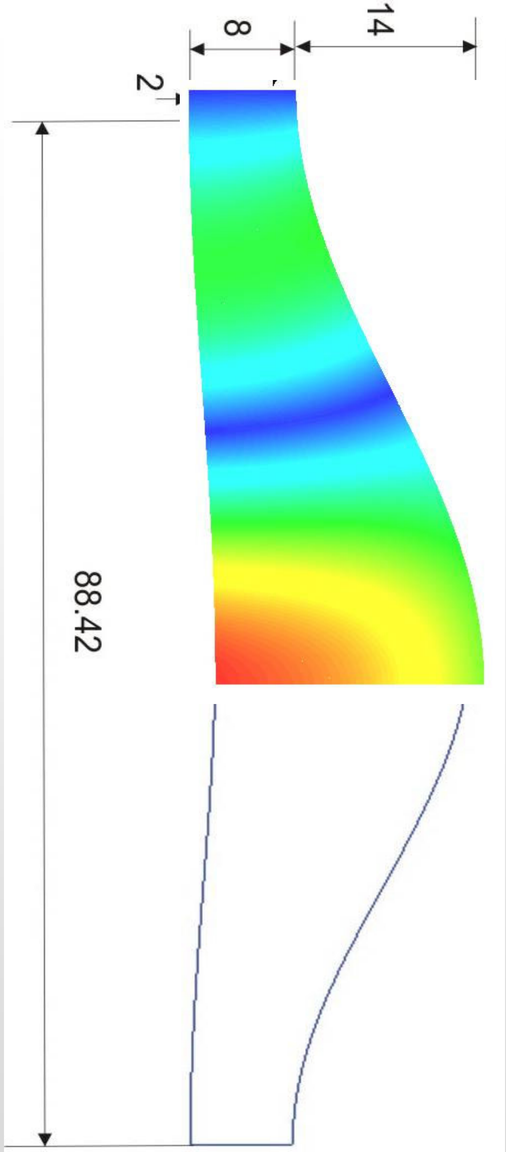
Longitudinal field distribution of the first asymmetric mode at frequency f



Longitudinal field distribution of the second asymmetric mode at frequency 2f

The field on the left wall has maximum about +2E$_0$.
But +2E$_0$ is actually "anode" field.
"Cathode" field on the left wall is -E$_0$.
The field on the right wall has maximum E$_1$+E$_2$ <E$_0$ (assumed to be less than breakdown threshold) due to asymmetry.



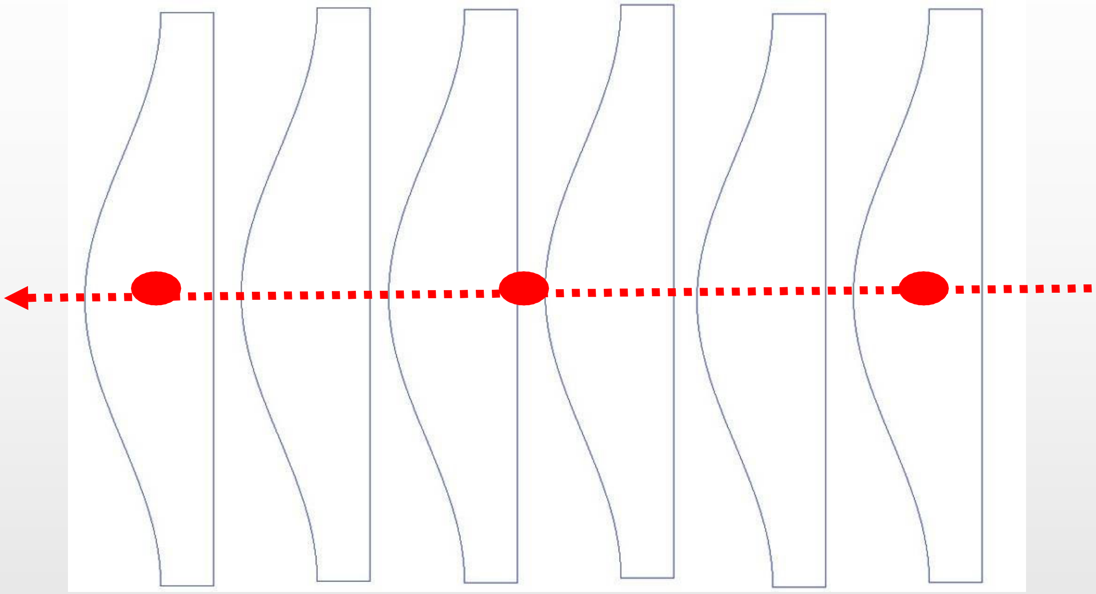


Optimal combination (amplitudes):
$A_f = 1$, $A_{2f} = 0.65$

$a_2 = G / E\_cth = 1.25$

Improvement in this ratio is $a_2 / a_f = 1.25 / 0.93 = 1.33$, suggesting a 33% increase in gradient without an increase in the "cathode" field, by use of a two-mode cavity.

If this concept can be proven, a future accelerating structure could have the following shape:

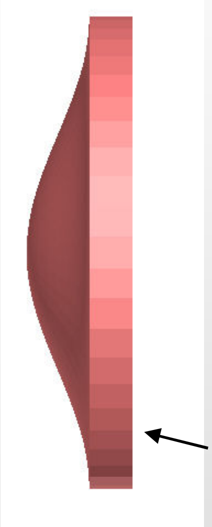


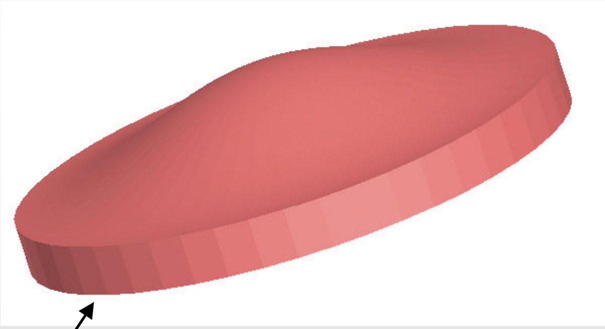
Conclusion:

By adding a relatively small amplitude (0.35-0.5) of second harmonic, it may be possible to increase accelerating gradient by about one-third without an increase in breakdown probability.

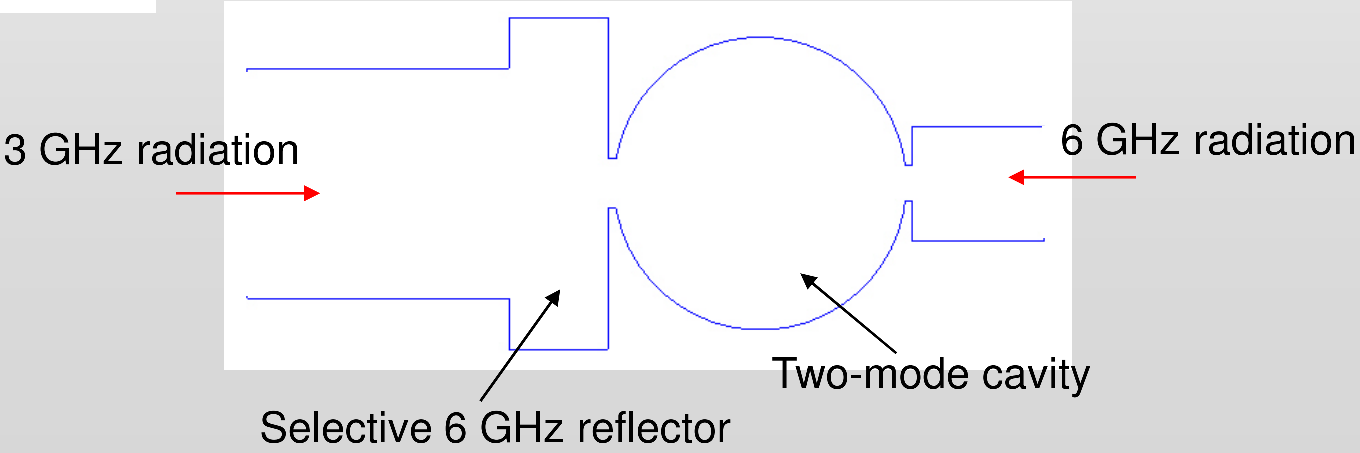
Use of two klystrons to power two-mode cavity, instead of drive beam

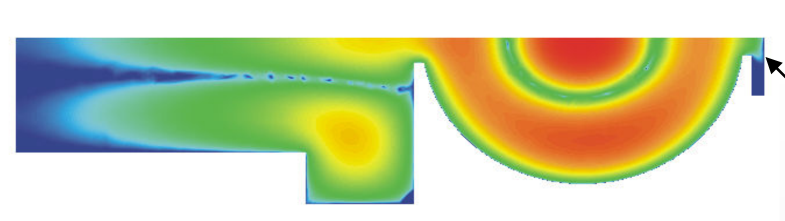
An alternative experiment scheme is to power a multi-mode cavity using independent coherent RF sources. This scheme provides greater flexibility then does use of a drive beam, since one would be able to vary powers and phases, and to compare single-mode regime with multi-mode regime in the same cavity. .
A key question is how to provide effective isolation between klystrons.





$f_1 = 3$ GHz, $Q_0 = 7\times10^3$,
$f_2 = 6$ GHz, $Q_0 = 11\times10^3$.

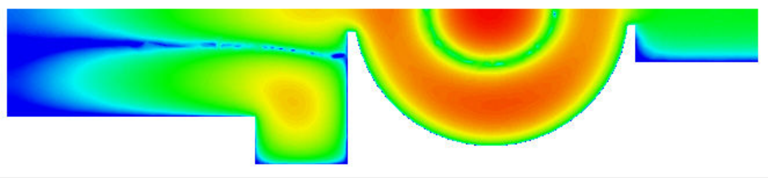




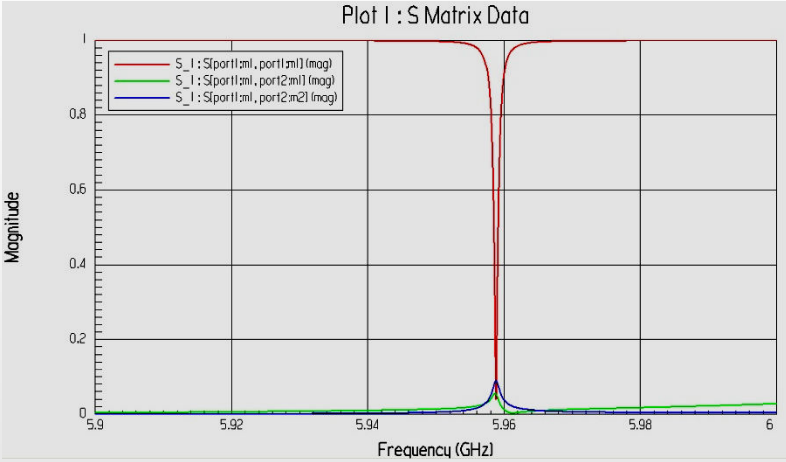
No hole

F_2=6 GHz, $Q_{diffr}=7.8\times10^5$

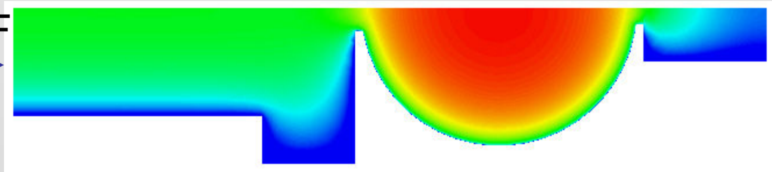
RF



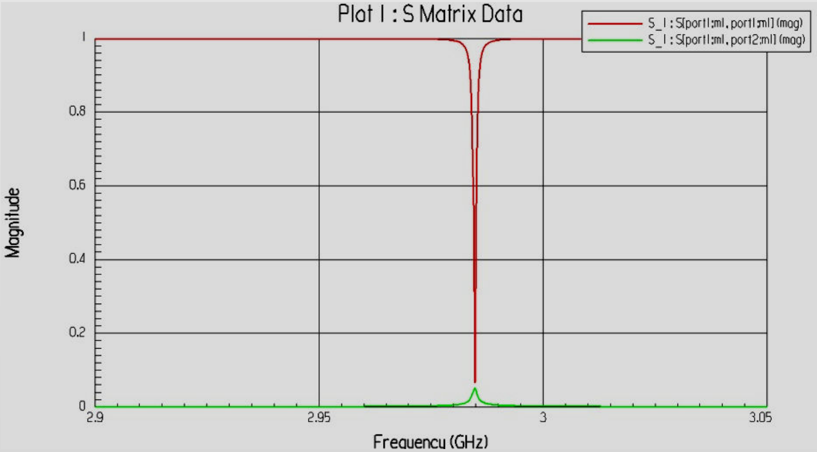
F_2=6 GHz,
$Q_{load}\approx Q_0$



RF



F_1=3 GHz, $Q_{load}=6.2\times10^3$
$Q_{load}\approx Q_0$



Summary

1. We propose experiments with multi-mode cavities aimed at raising the RF breakdown threshold, as a step towards understanding the fundamental nature of RF breakdown.

2. Two kinds of test cavities have been discussed, namely
   - axisymmetric cavities powered by a drive beam like CTF3, and
   - axisymmetric cavity having longitudinally asymmetric modes, powered either by a drive beam, or by independent RF sources.

3. Methodology involves comparison of breakdown probabilities in 1-, 2-, and 3-mode cavities having the same *E*-field levels, and visual observation of breakdown within the cavities.

4. Start of experiments could be towards the end of 2010 to the beginning of 2011.