CONCEPTS FOR RASING RF BREAKDOWN THRESHOLD BY USING MULTI-MODED CAVITIES#

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Work sponsored by in part by US Department of Energy, Office of High Energy Physics (2009-2010).

OUTLINE OF TALK

1. Criteria of RF breakdown triggering.
2. 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.
3. This concept can also be accompanied by "area" effect caused by reduction of the area occupied by high-field microwaves.
4. A second related idea named "anode-cathode" effect aims at the same objective by using a two-mode, two-frequency axisymmetric, but longitudinally asymmetric cavity.
5. Experimental tests of both ideas may be possible using CTF-3 beam facilities.
6. Methodology and possible time-schedule are suggested.
7. 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.
8. Summary.

*•"Asymmetric bimodal accelerator cavity for raising RF breakdown thresholds," by S.V. Kuzikov, S.Yu. Kazakov, Y. Jiang, and J.L. Hirshfield, ***Phys. Rev. Lett.*** 104, 214801 (2010).

•"High-gradient two-beam accelerator structure," by S.V. Kuzikov, S.Yu. Kazakov, Y. Jiang, and J. L. Hirshfield, ***Phys. Rev. Lett.*** Vol. 13, No.7, 071303 (2010).

And papers at IRMMW2007, AAC2008, EPAC2008, PAC2009, AAC2010.

Criteria of RF breakdown triggering

What do we know about RF breakdown by experiments with accelerating structures?
1. Breakdown *sharply* depends on electric field magnitude.
2. Breakdown threshold also depends on pulse duration.
3. It slightly depends on wall material and steady state temperature.

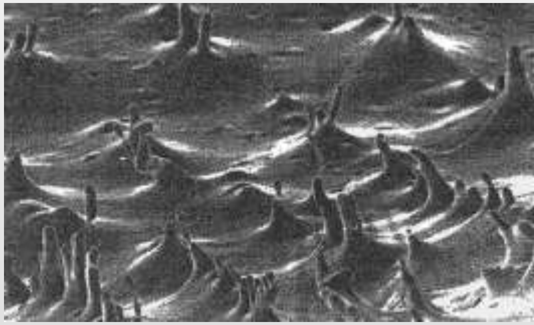
$E_{br} \approx 4$ MV/m, $\tau \approx 200$ ns

$$E_{thr}^{6} \cdot \tau = const$$

Modern breakdown theory is based on priority of *autoelectron emission*.

A breakdown can be separated at several stages:

- At the primary stage RF electric field produces electrons to tunnel from metal, this effect is described by the Fowler-Nordheim law.
- At the second stage the protrusions grow up, melted and evaporated.
- The freed molecules are ionized by oscillating electrons. The resulting plasma frequency grows up and approaches the field frequency.



Unfortunately, this theory does not explain experimentally proven facts:

1. *Breakdown threshold depends on magnetic RF field.*
2. *Standing wave accelerating structures have higher level of breakdown threshold in comparison with traveling wave structures.*

That is why, there are attempts to propose additional criteria:

1. Pulse heating $\Delta T<60$ K, and the stored energy $W<W_0$ (V.Dolgashev et al)

2. Modified Poynting vector (W. Wuensch et al)

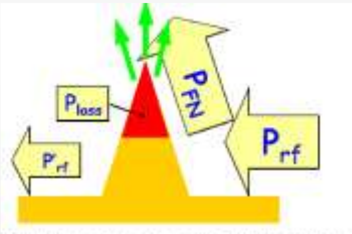


Figure 9. Schematic view of the power flow balance near the tip.

In the paper **A new local field quantity describing the high gradient limit of accelerating structures** by A. Grudiev, S. Calatroni, and W. Wuensch it is proposed to use a new criteria of field limit due to RF breakdown in a form of the modified Poynting vector which naturally includes also a magnetic field magnitude:

$$S_c = \left|\mathrm{Re}\,\vec{S}\right| + g_c \left|\mathrm{Im}\,\vec{S}\right|$$

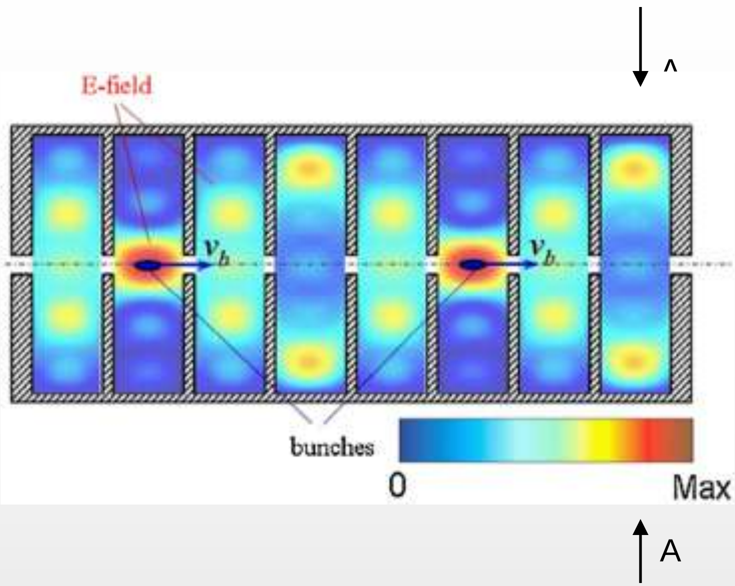
In particular, for majority of the accelerating structures S_c<5 W/μm² on structure surface at BDR<10^{-6} and 200 ns pulse length.

$$E_n = \sqrt{\left\langle E_n^2 \right\rangle} \cdot e^{i\varphi_E}, H_\tau = \sqrt{\left\langle H_\tau^2 \right\rangle} \cdot e^{i\varphi_H}, \vec{S} = \vec{E}_n \times \vec{H}_\tau \cdot e^{i\varphi_E + \varphi_H}$$

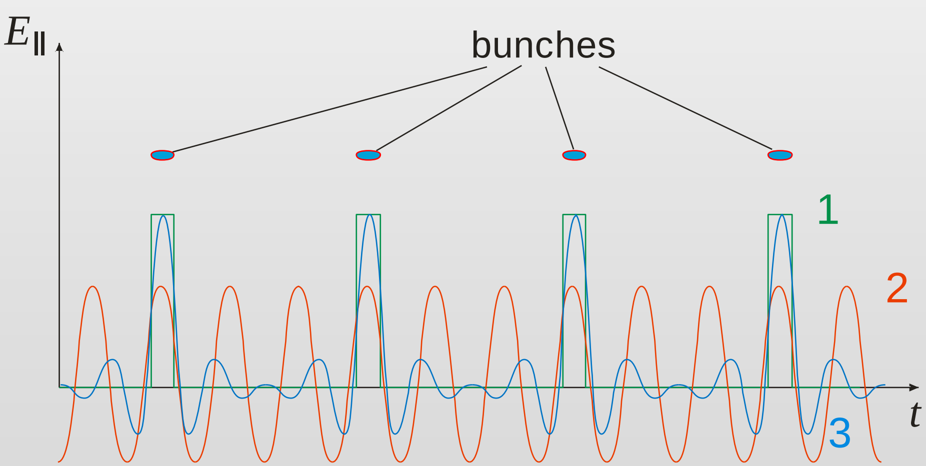
3. Field evaporation of nanoclusters (kind of ion field evaporation) (J. Norem et al)

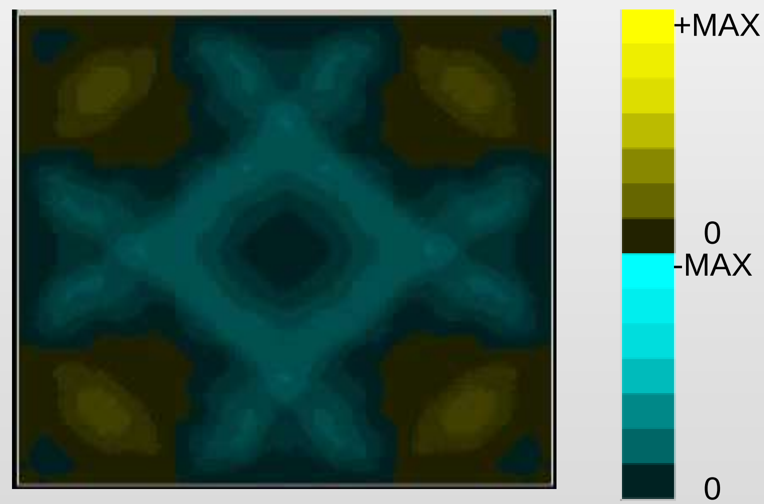
- G.Nusinovich (*Phys. Rev. AB,* 2009) suggests mechanism explaining role of magnetic field
- Influence of surface anisotropy is not seen in RF experiments (but regularly observed in DC experiments) (?)

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.

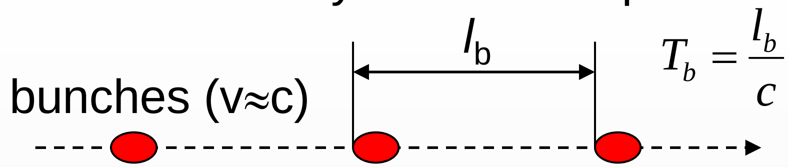




E-field in A-A cross-section

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.



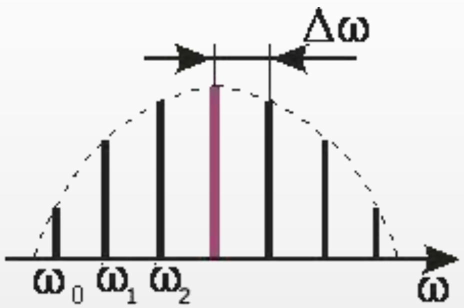
$$\vec{E}(\vec{r},t) = \sum_n a_n \cdot \vec{F}_n(\vec{r}) \cdot \exp(i\omega_n t),$$

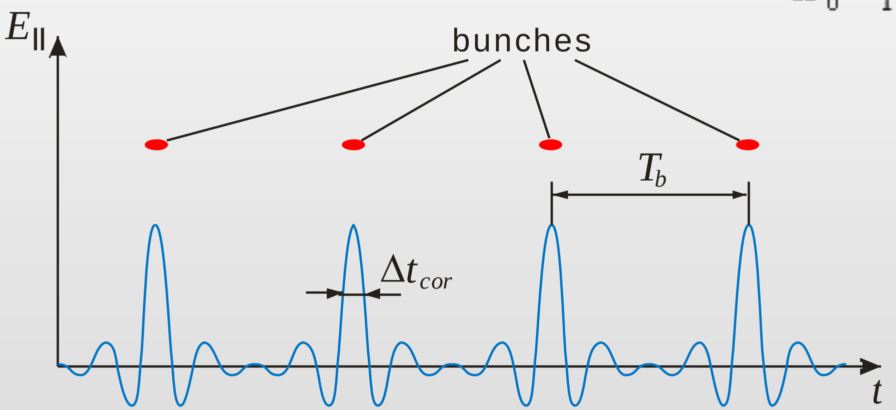
$\omega_n = \omega_0 + n \cdot \Delta\omega,$ where *n=0,1,2,…*

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

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

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

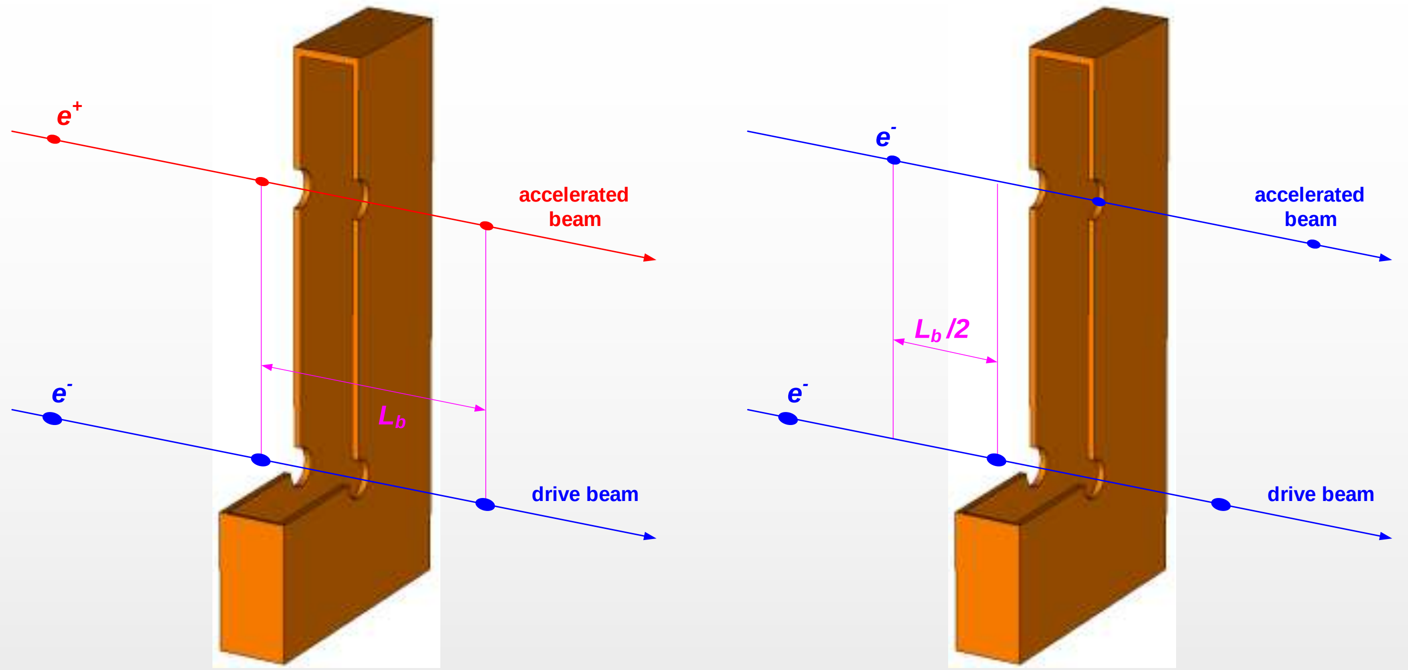


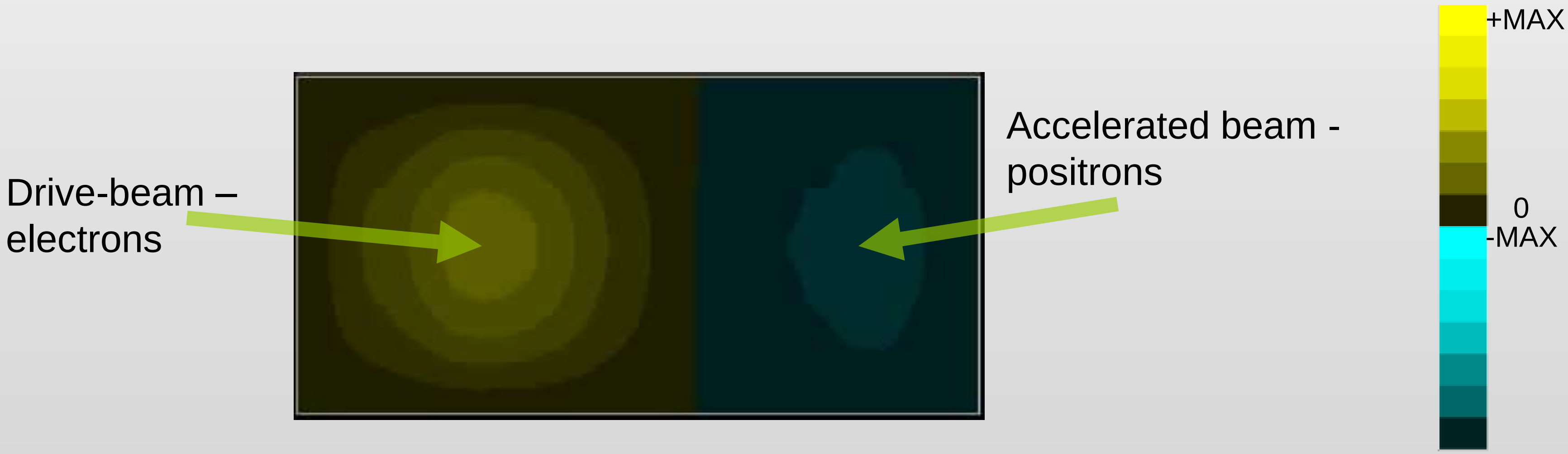


When operating with a finite number of modes, the single peak duration is defined by the time during which the phases of the lowest- and highest-frequency modes differ by π, i.e.,

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

Example of two-beam multi-mode accelerating structure with aspect ratio 1:2





Selective cavity detuning is used to provide a high transformer ratio (well above 2) with reasonable energy transfer efficiency.

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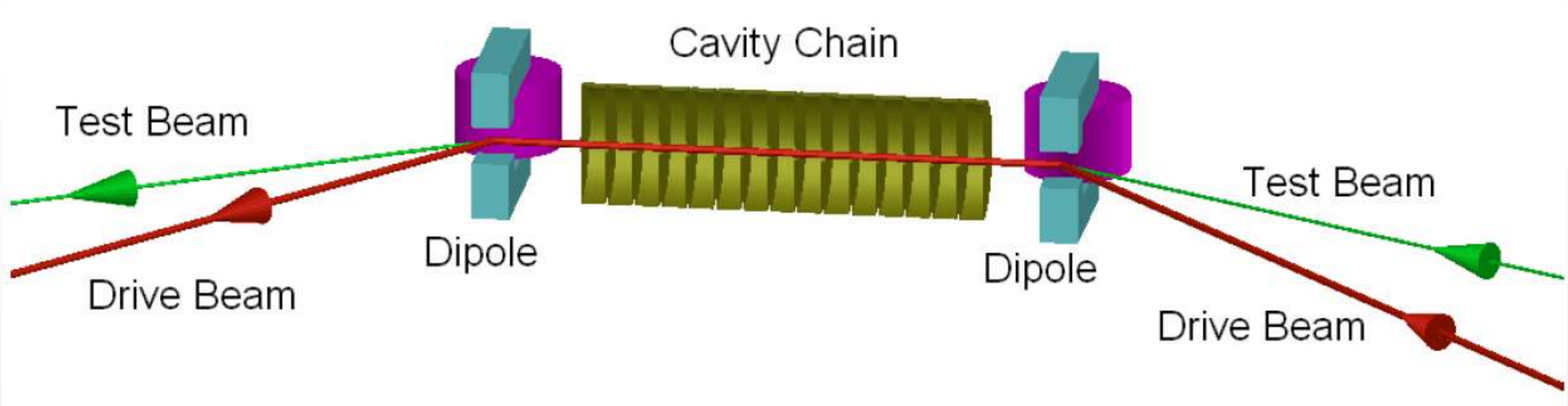
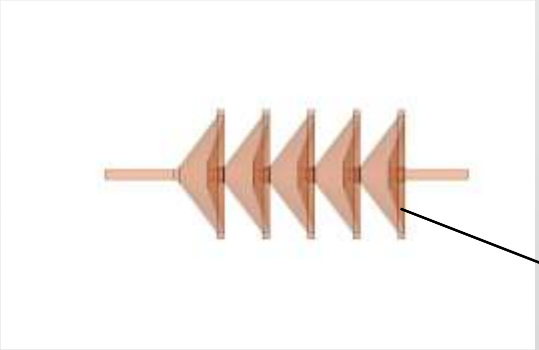
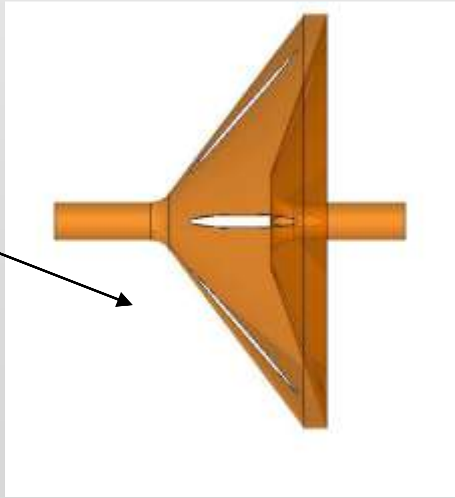
Detuned-Cavity Two-Beam Accelerator



A high-gradient two-beam accelerating structure is proposed

- high acceleration gradient for the room temperature accelerator, no cryogenic part, less estate cost
- no need for a microwave power distribution system along the accelerator
- no need for couplers and windows to introduce RF power into accelerator sections





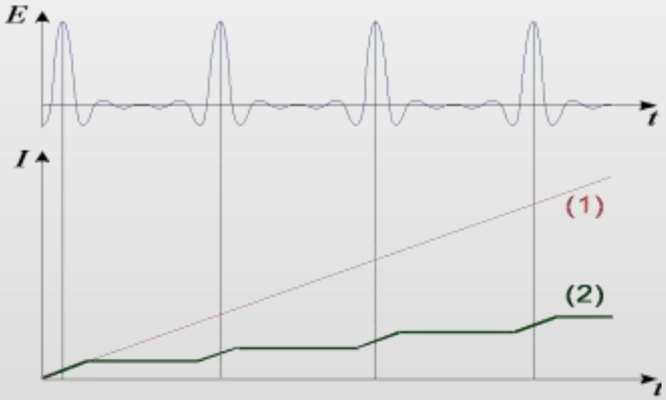
Conceptual design:
radial slots to damp undesired high order transverse modes.

Raising breakdown thresholds by reducing exposure time

W. Wuensch et al (2008) suggested to consider the initial stage of RF breakdown, in order to find a criterion governing breakdown ignition. It is postulated that a necessary condition for initiating breakdown is surface heating by emission currents up to a threshold temperature ΔT_{thr}.

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

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



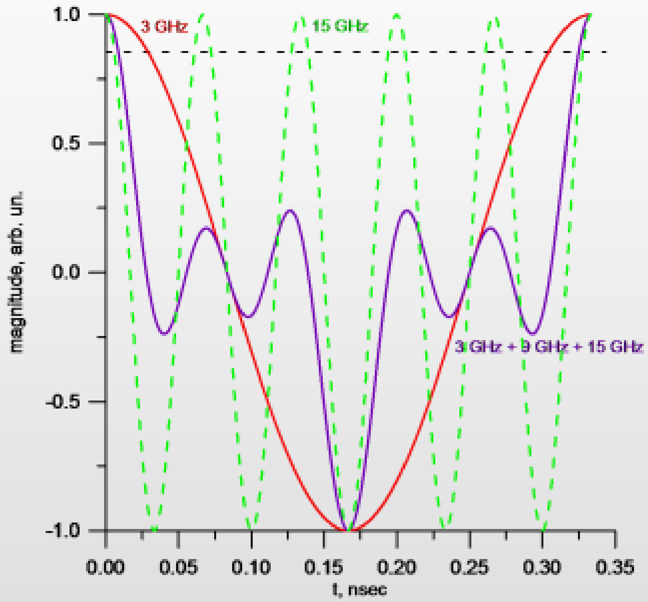
E(*t*) and *I*(*t*) dependencies for single- (1) and multi-frequency (2) structures

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.

A ratio of the exposure times for a single-mode structure and multi-mode accelerating structure:

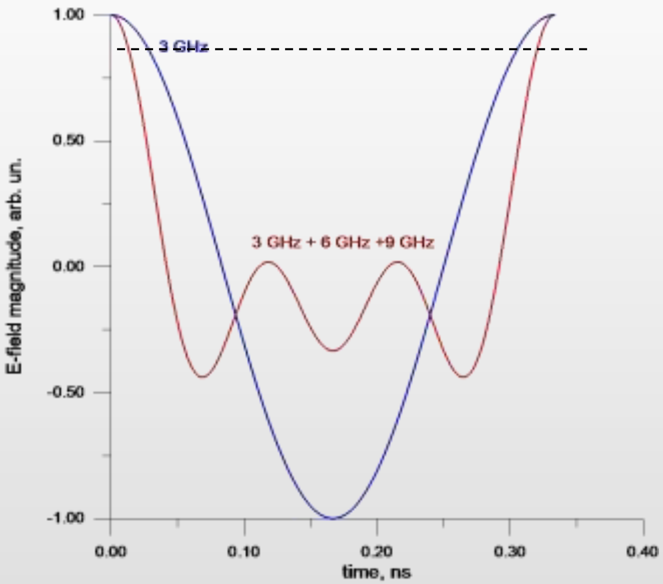
$$\Delta\tau_s / \Delta\tau_m = \sqrt{\sum_{n=0}^{n=N-1} (\omega_0 + n \cdot \Delta\omega)^2} \Big/ \omega_0 \cdot \sqrt{N},$$

where *N*- is a number of modes, ω_0 is a frequency of the lowest (fundamental) mode, $\Delta\omega$ is a frequency distance between modes, and *n* is a positive integer.



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 **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 **1.28**

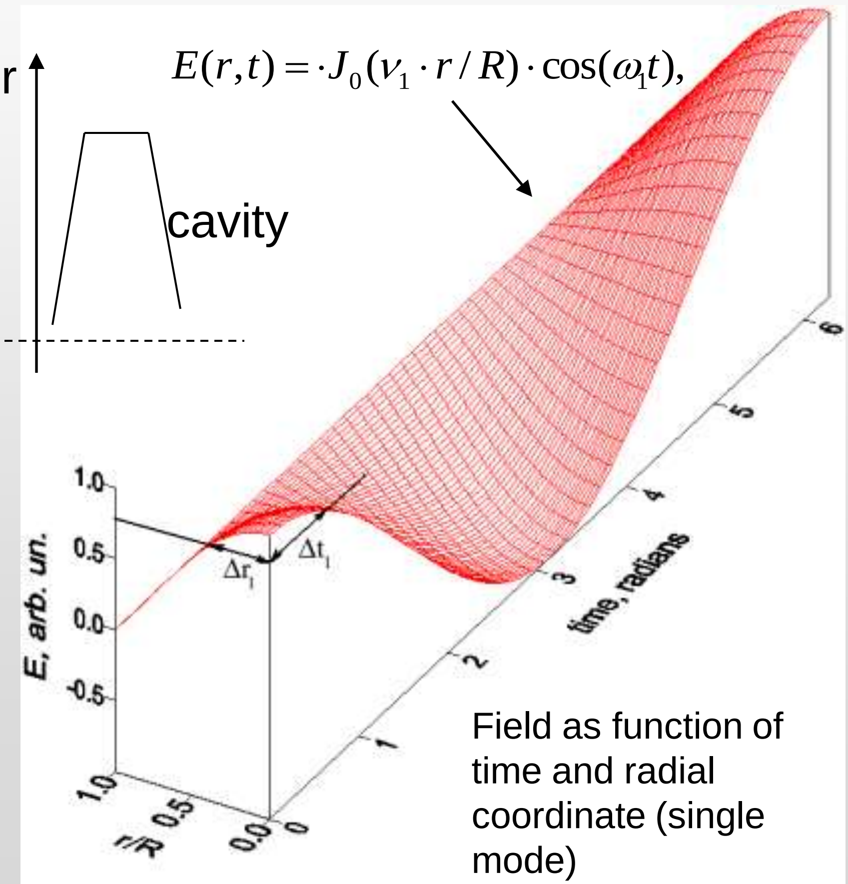
Area exposure reduction effect

Several modes in addition to reduction of exposure time form more narrow field peak on a wall than that peak in single-mode case.

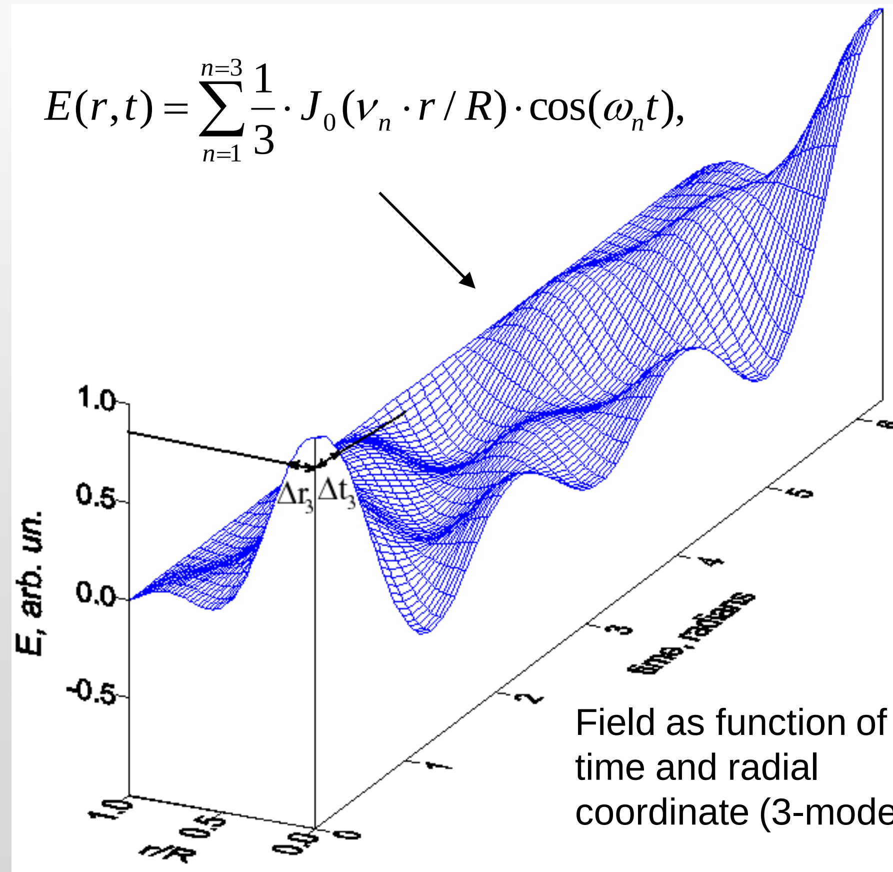
Breakdown probability *I* (or breakdown rate) depends on exposure time τ, electric field *E* and should also depend on number of initiation centers which is proportional to the area of the exposed cavity surface:

$$I \sim E^6 \cdot \tau \cdot S,$$

where *S* – is a area of that surface which is being exposed by high enough fields.



Field as function of time and radial coordinate (single mode)



Field as function of time and radial coordinate (3-modes)

We have $\Delta t_1 > \Delta t_3$ and $\Delta r_1 > \Delta r_3$ as well.

Numerical estimations

Probability of breakdown can be written as integral: $\widetilde{I} = 2\pi \int_{t_1}^{t_2} \int_{l_1(t)}^{l_2(t)} r \cdot dldt$

where the boundaries l_1(t), l_2(t) and t_1, t_2 are defined by the condition $|E| \geq 0.8 - 0.9 \cdot E_{\max}$

	$\widetilde{I}_1 / \widetilde{I}_N$	E^*/E
Two modes (N=2)	**9.06**	**1.44**
Three modes (N=3)	**24.5**	**1.70**

$\widetilde{I}_1 / \widetilde{I}_N$ - ratio of probabilities in multi-mode case and single-mode case

E^*/E - field enhancement factor in accordance with scaling law $E^6 \cdot \tau_1 \cdot S_1 = E^{*6} \cdot \tau_N \cdot S_N$ in order to keep the same breakdown probability.

What about alternative criteria?

1. Modified Poynting vector

In a three-mode cavity, if all modes have equal amplitudes, we have:

$$E(t) = E_0(\cos(\omega_1 t) + \cos(\omega_2 t) + \cos(\omega_3 t)) \qquad H(t) = H_0(\sin(\omega_1 t) + \sin(\omega_2 t) + \sin(\omega_3 t))$$

If we fix maximum of electric field at e-beam to be the same for the single mode case and for the three-mode case:

$$\langle E^2(t) \rangle = E_0^2(\langle \cos^2(\omega_1 t) \rangle + \langle \cos^2(\omega_2 t) \rangle + \langle \cos^2(\omega_3 t) \rangle)$$

because all cross-terms under averaging give zero.

$$S^{(3-\mathrm{mode})} \approx \frac{1}{3} S^{(1-\mathrm{mode})}$$

$$S^{(3-\mathrm{mode})} = i \cdot \mathrm{Im}\, S^{(3-\mathrm{mode})}$$

Conclusion: breakdown threshold is to be at least √N times higher in multi-mode case, where N - is a number of modes.

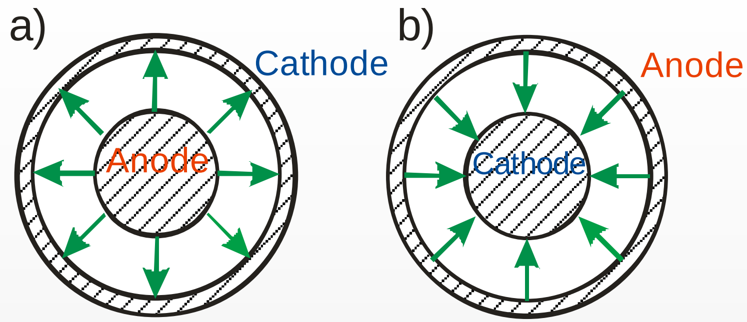
2. Stored energy

The stored energy is also N times less in comparison with single-mode case of the same acceleration.

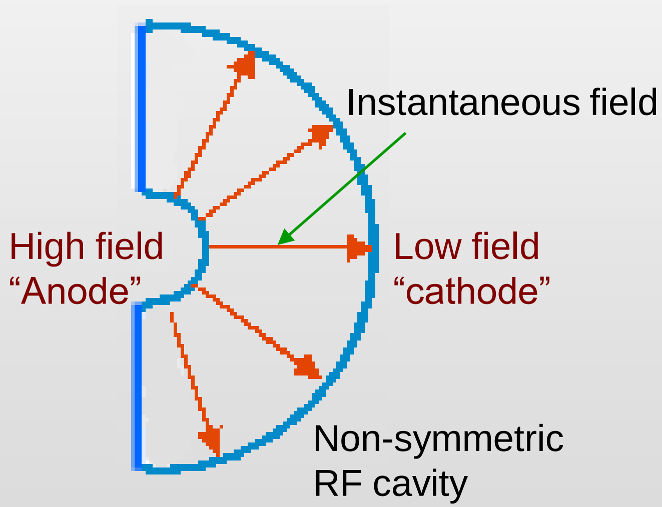
3. Nanocluster evaporation

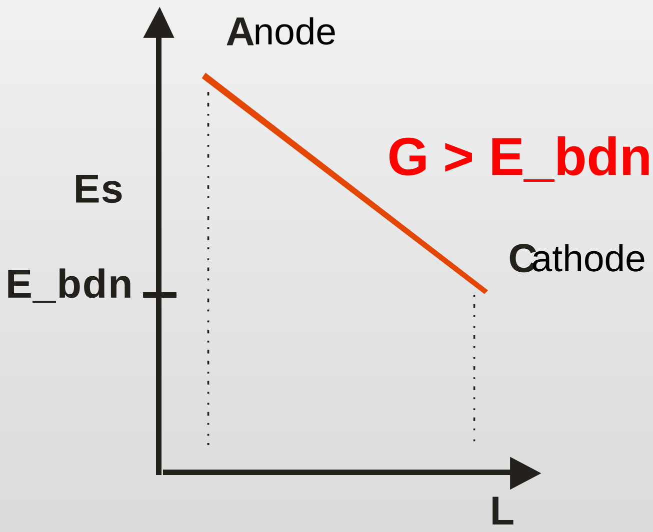
An “anode-cathode” effect could be used to test the validity of this criterion experimentally, and perhaps to increase acceleration gradient.

Raising breakdown threshold by using an asymmetric cavity (Anode – Cathode effect)



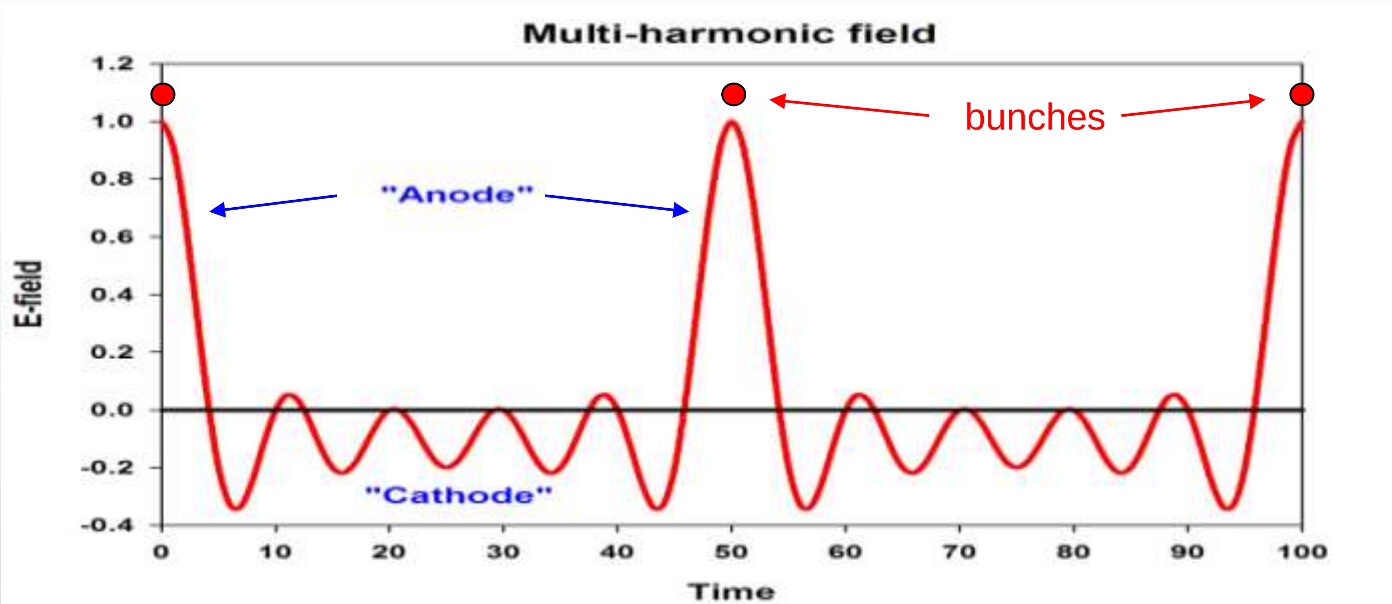
It is known for DC vacuum breakdown that, even when the voltage is the same, in case (a) breakdown threshold is higher than in case (b)! <u>Cathode is more vulnerable.</u>

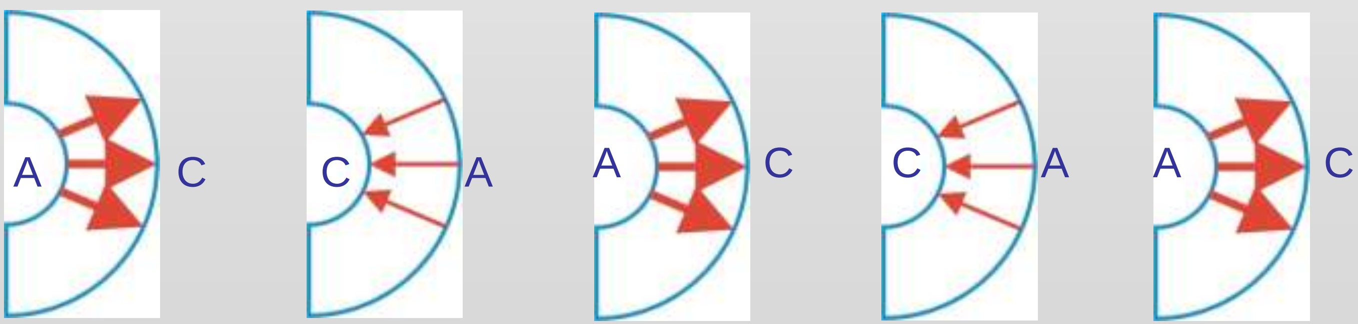




With RF fields, electron emission does not occur if the E-field pushes electrons in towards a wall. In a single mode cavity this doesn't help, since fields oscillate symmetrically between +maximum and –maximum. "Cathode" and "Anode" exchange roles each half period. In a multi-mode cavity, the situation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

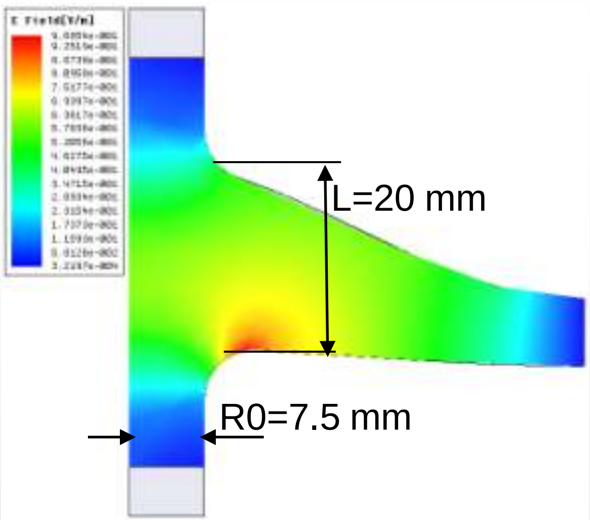
A multi-mode cavity without longitudinal symmetry allows unequal “anode” and “cathode” fields at metal surfaces, and can have an “anode” field higher than the “cathode” field. If it is correct that breakdown is determined only by the cathode field, it may be that a non-symmetric cavity will have a higher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

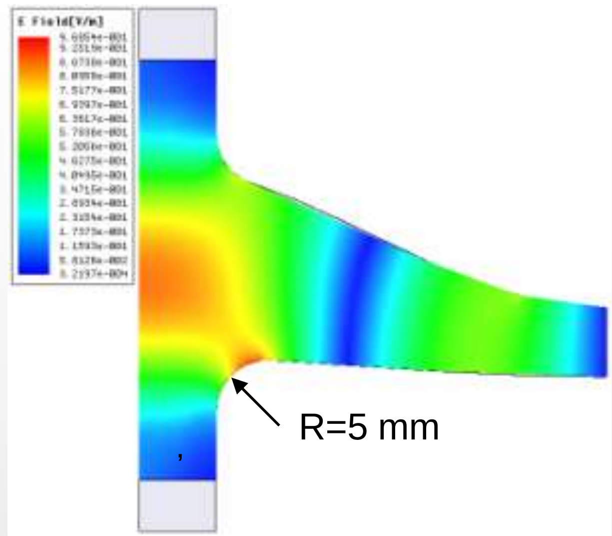




In the RF cavity “anode” and “cathode” change places with frequency *f*.

Influence of beam tunnel. Comparison of 3 GHz + 6 GHz multi-mode cavity with the single-mode pillbox of the same length and roundings at 3 GHz





3 GHz and 6 GHz modes of multi-mode cavity

$$E_1 = a_1 \cdot E_1^r(\vec{r})\exp(i\omega_1 t + \varphi_1)$$

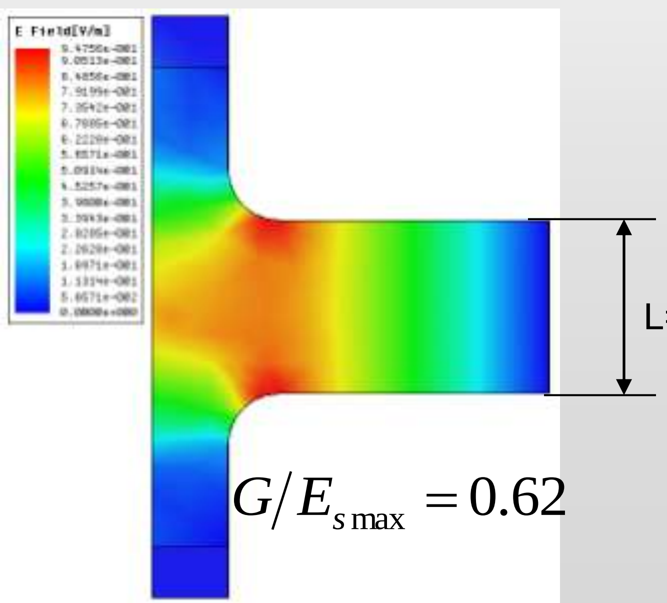
$$E_2 = a_2 \cdot E_2^r(\vec{r})\exp(i\omega_2 t + \varphi_2)$$

At the optimum we obtain:

$\varphi_1 = -0.68$ $\varphi_2 = -1.35$ $a_2/a_1 = 0.3$

$$G/E_{s\max} = 0.96$$

(*E*s max is a cathode field).



$$G/E_{s\max} = 0.62$$

3 GHz mode in pillbox

Conclusion: The gain in this case is

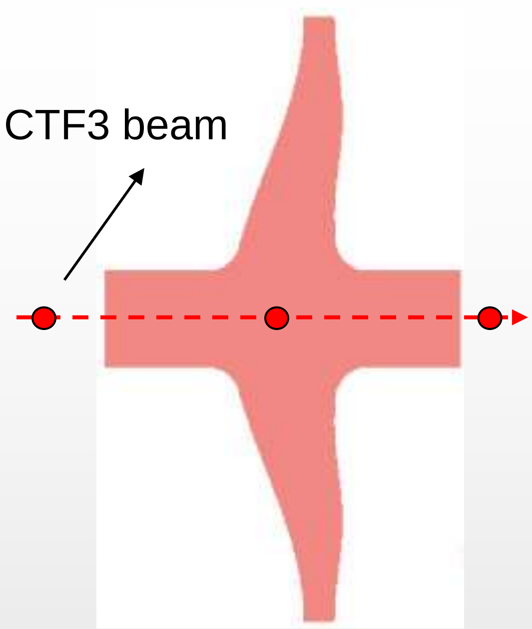
$$\frac{0.86}{0.62} = 1.55$$

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.

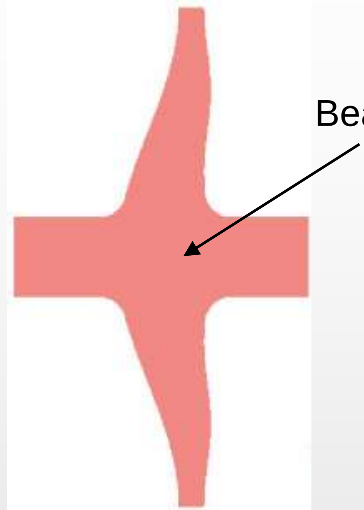


These experiments are aimed at investigating the fundamental basis of RF breakdown theory.

- We plan to investigate dependencies of the breakdown threshold on the <u>temporal and spatial </u>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 micro-shape.
- 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.

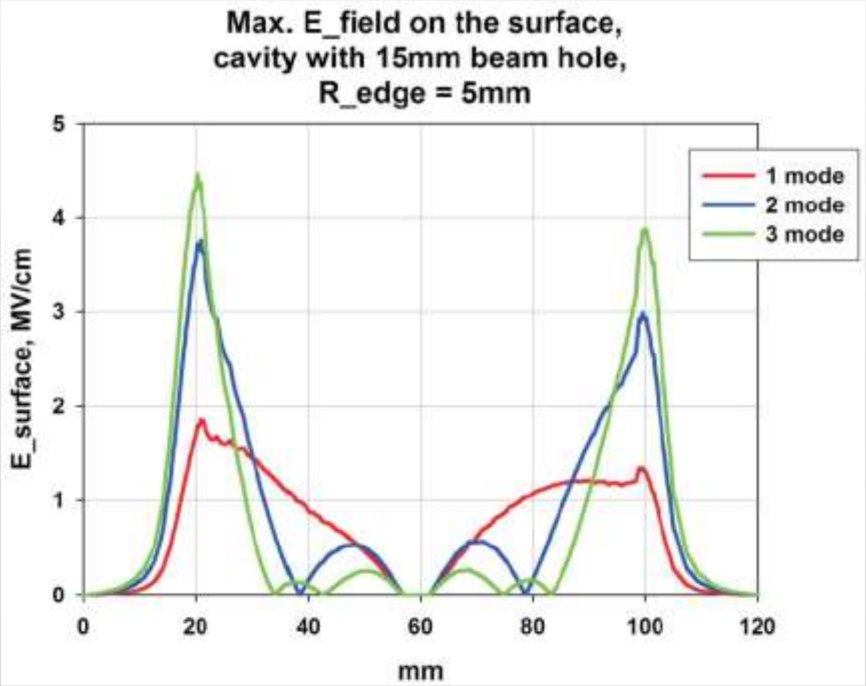


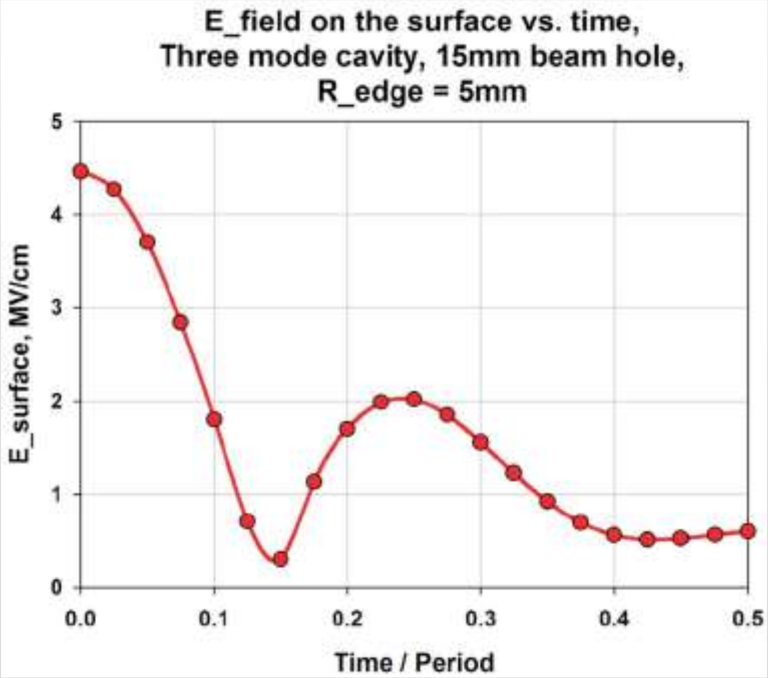
	Frequency (GHz)	Q
Mode 1	(3.00045e+000, 2.65761e-004)	5.64502e+003
Mode 2	(6.00359e+000, 3.52313e-004)	8.52024e+003
Mode 3	(8.99912e+000, 3.98611e-004)	1.12881e+004

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





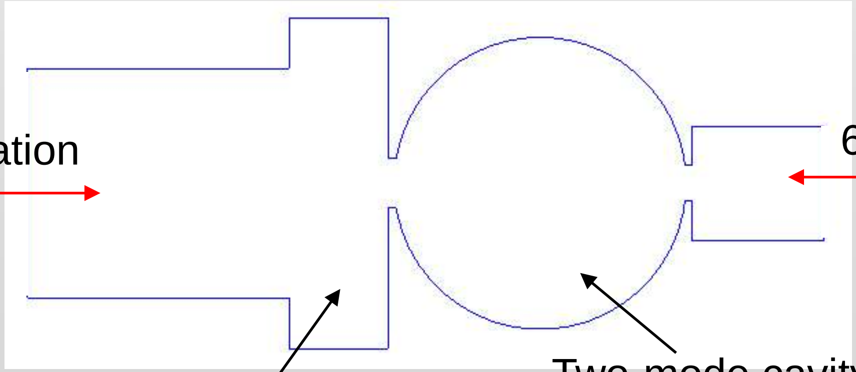
The maximum Poynting vector value in three mode cavity is S_C=0.45 W/μm^2.

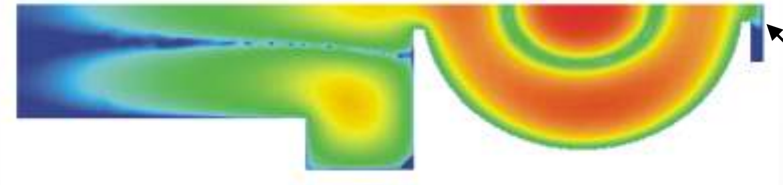
Use of two klystrons to power two-mode cavity, instead of drive beam

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.

Two-mode cavity

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

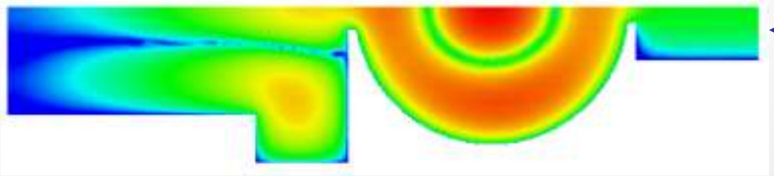




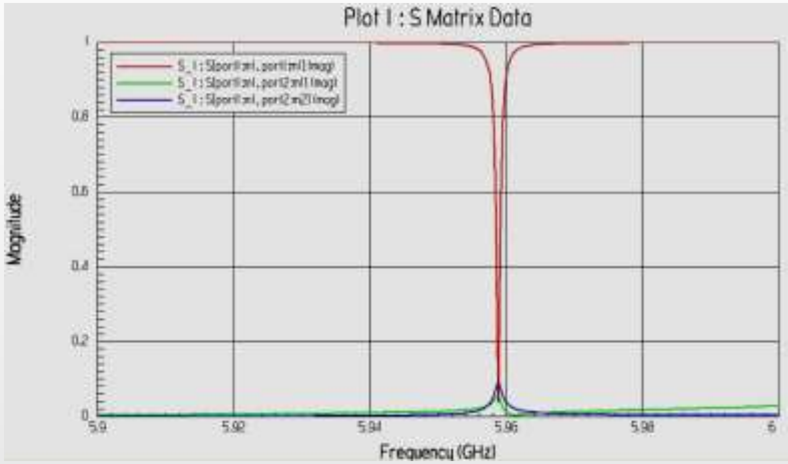
No hole

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

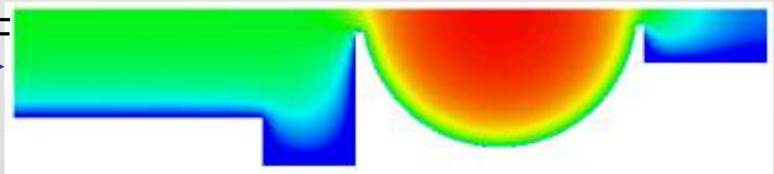
RF



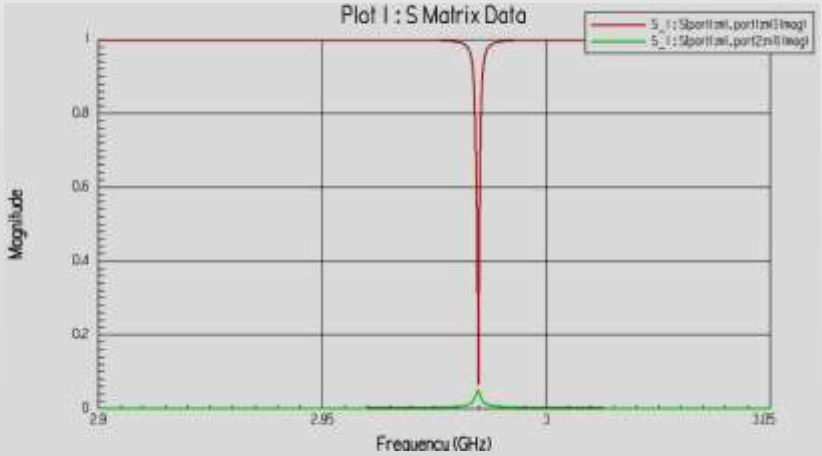
F_2=6 GHz,
$Q_{load}\approx Q_0$



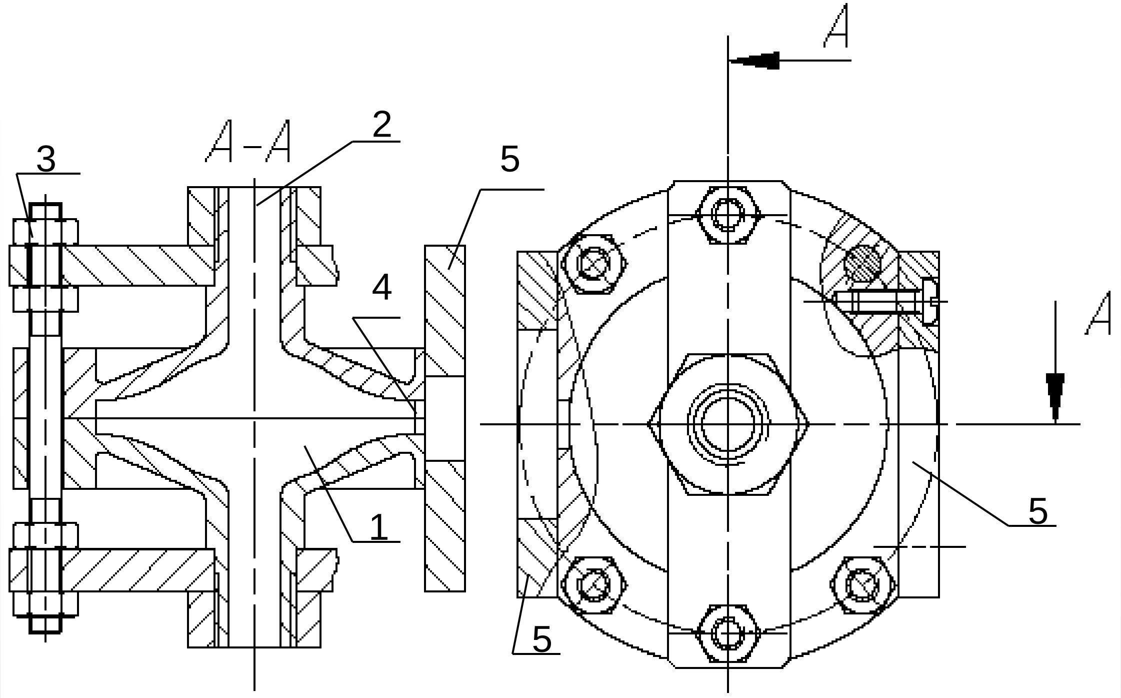
RF



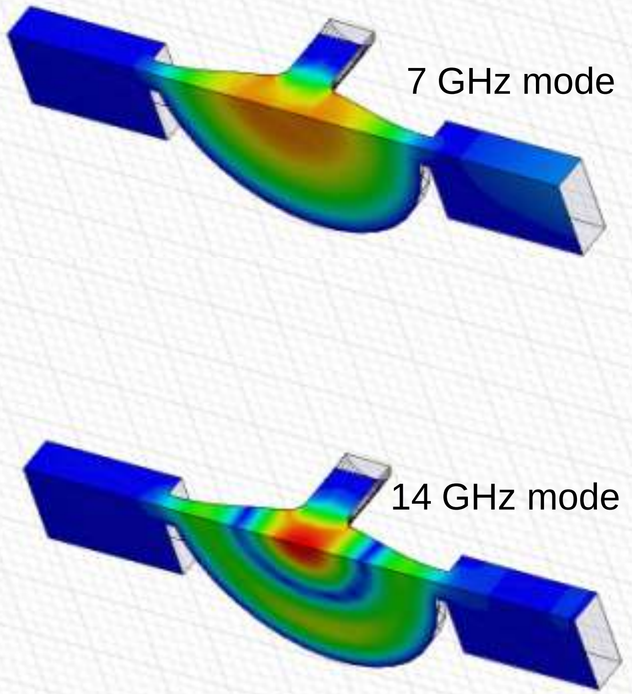
F_1=3 GHz, $Q_{load}=6.2\times10^3$
$Q_{load}\approx Q_0$

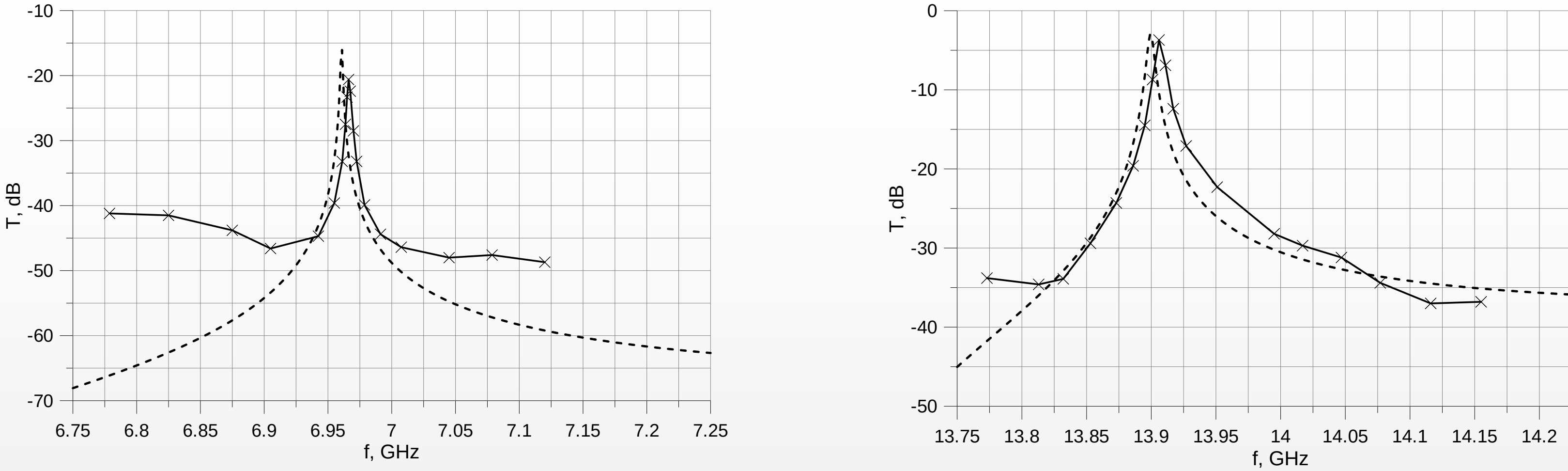


Low-power test of tunable two-mode (7 GHz + 14 GHz) cavity with flexible wall

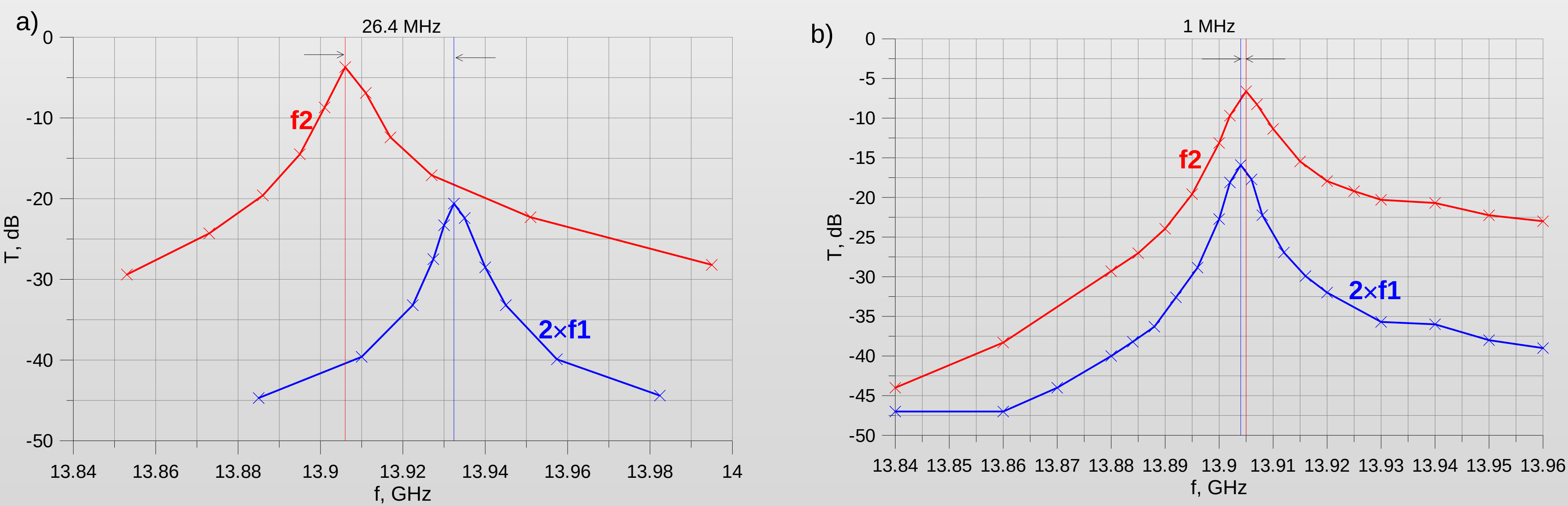


1 – cavity, 2 – beam tunnel, 3 – tuning screw, 4 – coupling holes, 5 – waveguide flanges.





Transmision characteristics before cavity deformation: solid curve – measurements, dashed - calculations.



Measured transmission Vs frequency: a – before cavity deformation, b – after cavity deformation.

What results do we expect to obtain in the end?

1. ***Optimistic case***

We prove that reduction of exposure time allows increasing breakdown threshold.

This proof opens a green light for all calculations based on the present breakdown theory. A raise of threshold would allow to invent new structures with higher gradient.

2. ***Pessimistic case***

We do not see difference between cavities (taking into account the accuracy of the experiment).

This requires to reconsider the breakdown theory!

3. ***The worst case***

We can not state neither (1) nor (2).

Such result could be because influence of so-called not taken into account factors:

1. Pulse heating
2. Multipactoring

Summary

1. We propose experiments with multi-mode cavities aimed at raising the RF breakdown threshold due to
   - reducing exposure time effect,
   - reducing high-field area effect,
   - anode-cathode effect,

   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 beginning of 2011.