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

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Abstract

Multi-mode accelerating structures aimed at increasing accelerating gradient are described. Such structures operating in several resonant, equidistantly-spaced, axisymmetric, TM-like eigenmodes allow reduction of exposure time to surface fields, reduction of high-field areas and reduction of those fields which are responsible for electron emission. These effects are planned for use in studying the physics of RF breakdown phenomenon with the goal of designing new high-gradient accelerating structures.

ACCELERATION IN A STRUCTURE OF MULTI-FREQUENCY CAVITIES

Because rf breakdown is a strong limiting factor towards increase acceleration gradient, one needs first of all to prevent the initiation of breakdown. To follow this aim, let us consider a particle beam to be accelerated as a periodic sequence of tight bunches that move along a straight path with a velocity close to the speed of light. High accelerating fields need exist only during the narrow time intervals when test bunches traverse the cavities that comprise the accelerator structure. During time intervals between bunches, fields in each cavity should preferably be as small as possible. In each cavity, fields localized in space should periodically move between the structure axis when a bunch to be accelerated arrives, and at other times to move away from the axis and generally weaken (Fig. 1a) [1]. This principle automatically requires that cavity should contain equidistant spectrum of modes. The ideal electric field seen by bunches along the structure is sketched in Fig. 1b (curve 1—in green), in comparison with field behaviour in a single-frequency structure (curve 2—in red). In the case of a limited number of modes the resulted field would look like that in curve 3—in blue. It is widely accepted that thresholds increase for rf breakdown and thermal fatigue, as one decreases the exposure time to intense rf. It is thus natural to anticipate that a cavity in which the peak fields are present only during transit of the bunches - rather than during a substantial fraction of the interbunch period - should be capable of sustaining higher peak. An acceleration structure based on these main principles can be built either as a sequence of rectangular copper cavities driven in two-beam scheme [2-3], or as a sequence of axisymmetric cavities operated with alternating drive and accelerated bunches [4, 6].

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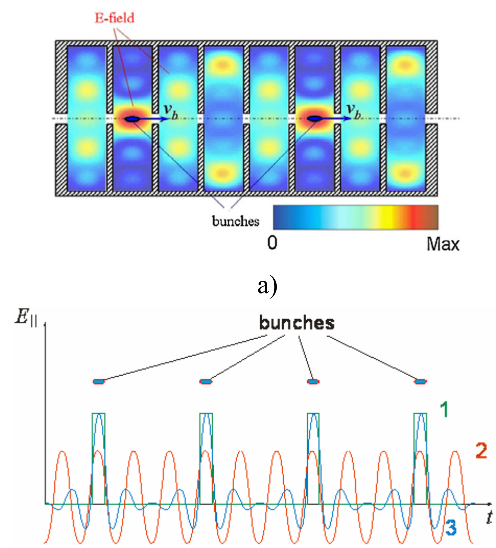


Figure 1: Principles of acceleration of moving periodic bunches in multi-mode structure. a - accelerating structure scheme, b - time dependence of fields: in ideal multi-mode structure (curve 1 in green), in single-frequency structures (curve 2 in red), in a multi-mode structure operating in a limited number of modes (curve 3 in blue).

CRITERIA OF RF BREAKDOWN TRIGGERING

RF breakdown is a complicated, multi-stage phenomenon, which can be viewed as a continuous sequence of several stages. A modern theory is based on priority of electron field emission, describing how RF electric field produces electrons to tunnel from metal, surface heating causes growth of the protrusions and surface material evaporation [7-8]. Experimental data obtained for many accelerating structures show that the breakdown probability I is dependent on electric field threshold E and also on exposure time τ by the scaling law [8]:

$$I \sim E^6 \cdot \tau. \qquad (1)$$

Second, new experimental results obtained recently show that breakdown probability may depend by the rf magnetic field, i.e. by the surface temperature rise [9-10]. The model underlying (1) does not explain why magnetic field plays a role. That stimulates attempts to develop a breakdown theory and to modify the scaling law (1). In particular, a so-called modified Poynting vector [8], pulse heating temperature rise, and the stored rf energy in an accelerating structure are considered to formulate criteria of breakdown initiation [8-9]. The mentioned criteria are based on squared field values: E^2, H^2, or $E\times H$. In a multi-mode structure in comparison with a single mode structure of the same acceleration gradient (accelerating field is constituted only by phase synchronous modes) all these values are by factor N smaller, where N is the number of modes; i.e. breakdown threshold is higher in multi-mode case. An absolutely alternative criterion is based principally on nanoclusters evaporation, rather than electron field emission [10]. From this point the disscissing in this paper “anode-cathode” effect could be used to test the validity of this criterion experimentally, and perhaps to increase acceleration gradient.

EFFECTS TO INCREASE ACCELERATING GRADIENT

The initial idea to apply multi-mode cavities was based on *exposure time reduction effect*. Further studies of multi-mode structures resulted in understanding that there are at least two complementary effects: *high-field area reduction* and so-called *“anode-cathode” effect*.

In order to compare the exposure time in a multi-mode accelerating cavity with that in a single-mode accelerating cavity we analysed time dependencies of fields in both mentioned cases [6]. As a result we obtained a ratio of the exposure time for the multi-mode structure and single mode accelerating structure:

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

where N- is a number of modes, ω_0 is the frequency of the lowest (fundamental) mode, $\Delta\omega$ is a frequency distance between modes, and n is a positive integer. In (2) it was also assumed that in a multi-mode cavity and in a single mode cavity we have the same field maximum. In concordance with the scaling law (1) we see that we can increase the accelerating field in comparison with the single-mode structure by a factor $E^*/E = \sqrt[6]{\Delta\tau_s/\Delta\tau_m}$ without increasing of the breakdown probability. In the two-mode case with modes at ω_0 and $3\omega_0$ we find E^*/E=1.14, while in the three-mode case (ω_0, $3\omega_0$ and $5\omega_0$) we find E^*/E=1.23.

Modern theory considers initiation of rf breakdown as a random process. That is why the frequently used and experimentally-proven scaling law (1) should also depend upon the number of initiation centres, which is proportional to the area of cavity surface exposed to high fields. In the modified form we should just multiply probability of the breakdown I in (1) by S, where S is an area which is being exposed to high enough fields. As seen in Fig. 1a in multi-mode case the effective exposed area is much less than in single-mode case. Results of rigorous numerical analysis are that the ratio of the breakdown probabilities for the three-mode case and the single mode case is about 1/25 [6]. This provides the field enhancement factor E^*/E=1.70 calculated in accordance with the modified scaling law.

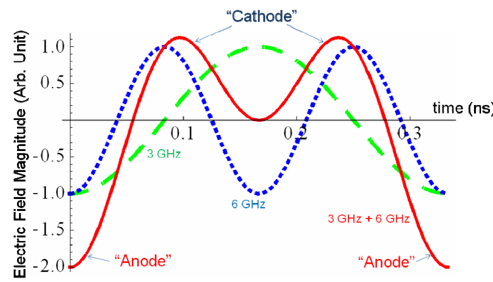


Figure 2: Time-dependence for a composite field (red-solid) excited at 3 (green-dashed) and 6 GHz (blue-dotted) with equal amplitudes and zero phase difference. Negative anode-like fields have twice the magnitude of positive cathode-like fields.

In an arbitrary single mode cavity, the rf field oscillates symmetrically between positive and negative maxima. In a multi-mode cavity, the situation could be strongly asymmetrical. As shown in Fig. 2, two harmonically related modes (at 3 GHz and 6 GHz, for example) excited in a cavity are able to produce a cathode-like field which is almost two times smaller than the maximum anode-like field. This property of a multi-mode cavity might be used to increase acceleration gradient. Since cathode phenomena such as electron emission and positive ion sputtering probably initiate breakdown, a cavity like in that in Fig. 3 with modes having non-equal fields on the left and on the right walls might be able to increase accelerating gradient. In this cavity the field on the right wall has maximum $+2E_0$. This value $+2E_0$ is actually an anode-like field, the cathode-like field on the right wall is approximately two times less i.e. $-E_0$, where E_0 is a breakdown threshold value in this case. The field on the left wall at all times has its maximum to be less than E_0 due to the assumed asymmetrical field structures of the eigenmodes. The cavity shown in Fig. 3 was investigated in detail in [5-6], where the calculated ratio of acceleration gradient to maximum surface field is by a factor of 1.55 higher in the designed multi-mode cavity than in a single mode pillbox cavity.

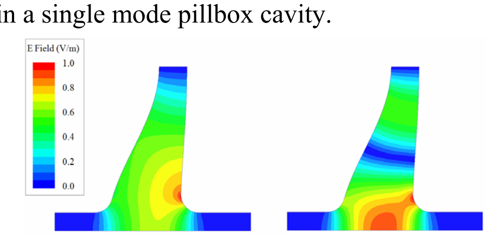


Figure 3: Electric field maps for the 3.0 GHz TM_{010} (left) and 6.0 GHz TM_{020} (right) modes.

POSSIBLE EXPERIMENTS WITH MULTI-MODE ACCELERATING STRUCTURES

Methodology of experiments naturally assumes comparison of breakdown probabilities in 1-, 2-and 3-mode cavities having the same surface *E*-fields. Two kinds of tests can be discussed, namely cavities powered by a drive beam like CTF3, and cavities powered by more than one phase-locked RF sources.

Preliminary calculations for CTF3 based experiment were carried out for three axisymmetric cavities: 3 GHz (single mode); 3 and 6 GHz (two-mode); 3, 6, and 9 GHz (three-mode). The first design issue, to obtain an equidistant mode spectrum, has been solved by a specific cavity shape. Field maps for the three mode cavity are shown in Fig. 4. In the two-mode cavity the highest mode is detuned, in single-mode cavity both higher modes are out of the resonant excitation condition. Calculations show that the CTF3 bunch parameters allow easily to excite several modes simultaneously and to achieve *E*-field level ~1 MV/cm in each cavity. Plan of the experiment assumes that surface fields in each cavity should be equal to one another. Roughly it is reached by cavity shape design. In order to provide fine tuning of fields, the bunch current could be varied.

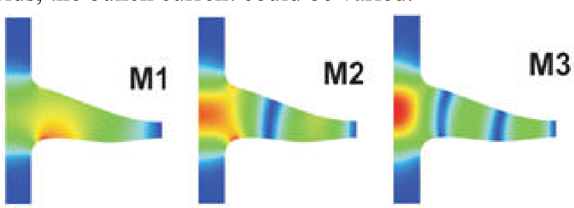
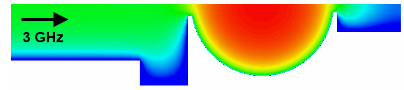
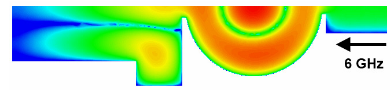


Figure 4: Modes of three-mode cavity: M1 – 3 GHz, M2 – 6 GHz, M3 – 9 GHz.

Experiments with several phase-locked high-power RF sources are attractive due to a possibility to easily vary amplitudes and phases of different modes. Such experiments are ideally acceptable to test anode-cathode effect, where two modes only are enough in order to demonstrate the expected essential increase of acceleration gradient. An asymmetric cavity concept and possible experimental scheme have been already described in [5]. The proposed bimodal cavity has two (3 GHz- and 6 GHz) coupling waveguides. This design (Fig. 5) provides that higher frequency radiation is not leaking through and being transmitted back towards the lower frequency source. A coupling design to accomplish this property uses a high-frequency choke. Loading *Q*-factor ($Q \approx 6 \times 10^3$) is two times less than coupling *Q*-factor for both modes, in order to avoid undesirable reflection. Experimental goals could include obtaining a theoretically-predicted 55% increase of acceleration gradient in comparison with conventional pillbox cavity. It seems also very important that due to a flexibility of this experiment we could (by changing phases of RF sources) to test regimes where either the cathode-like field reaches its absolute maximum or where anode-like field is highest. This should allow an experimental answer to the critical question: Do cathode or anode phenomena have a leading role in RF breakdown?



a)



b)

Figure 5: Power coupling into multi-mode cavity from waveguide at the left side at 3 GHz (a) and at right side at 6 GHz (b).

SUMMARY

We have described several means for increasing accelerating gradients in structures consisted of multi-mode cavities; namely time exposure reduction effect, high field area reduction effect, and anode-cathode effect. We have also proposed experiments with the axisymmetric multi-mode cavities, in order to prove the main principles of multi-mode acceleration and to study a nature of rf breakdown.

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