MULTI-MODE CAVITY DESIGN TO RAISE BREAKDOWN THRESHOLD*

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Abstract

A multi-mode cavity design for a two-beam accelerator aimed to achieve an accelerating gradient exceeding 150 MeV/m is reported. The cavity has nearly square cross-section which allows excitation of several equidistantly-spaced eigenmodes by a bunched drive beam in such a way that the RF fields reach peak values only during time intervals that can be much shorter than for excitation of a single mode, thus exposing the cavity surfaces to strong fields for shorter times. This feature is expected to raise the breakdown and pulse heating thresholds. In order to measure an increase in breakdown threshold surface electric field due to this reduction of exposure time during each RF period, a high-power experiment is planned. Preliminary calculations show that such a study in which comparison of breakdown statistics would be made of a conventional single-mode cavity with a multi-mode cavity can in principle be carried out using the drive beam of the CTF-3 test stand at CERN.

MULTI-MODE ACCELERATING STRUCTURE AND EXPERIMENT TO RAISE BREAKDOWN THRESHOLD

A two-beam accelerating structure proposed in refs. 1-4 aims to sustain an acceleration gradient >150 MeV/m for a next generation e^+e^- linear collider. Fig. 1 shows a sketch of one cavity in such a structure.

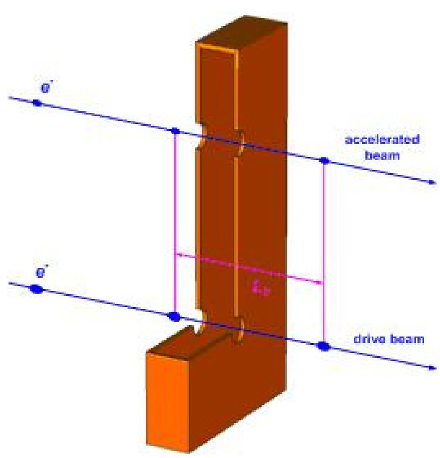

Figure 1: Layout of one cavity in the two-beam accelerating structure.

The structure is based on a periodic system of multi-mode cavities. Each cavity is excited in several equidistantly-spaced eigenmodes by the drive beam in such a way that the RF fields reach peak values only during the short time intervals when an accelerating bunch is resident in the cavities, thus exposing the cavity surfaces to strong fields for only a small fraction of each fundamental RF period. This feature is expected to raise the breakdown and pulse heating thresholds if one postulates the relationship between breakdown threshold surface electric field strength E_s and exposure time τ to be of the form:

$$E_s^p \cdot \tau = const, \qquad (1)$$

where $p > 1$.

The scaling law Eq. (1) was studied in many theoretical works as well as in experiments, where τ is assumed to be the RF macropulse length, i.e. much greater than an RF period. However, the suggested exposure reduction in a new multi-mode structure takes place for time intervals that are less than the basic RF period. This is illustrated in Fig. 2, where 3 and 15 GHz time dependencies are plotted in comparison with time dependence for a superposition of 3, 9, and 15 GHz. The figure shows that the superposition of harmonically related frequencies should be expected to have a higher breakdown threshold than the individual cases, in view of the Fowler-Nordheim breakdown threshold criterion [5-6].

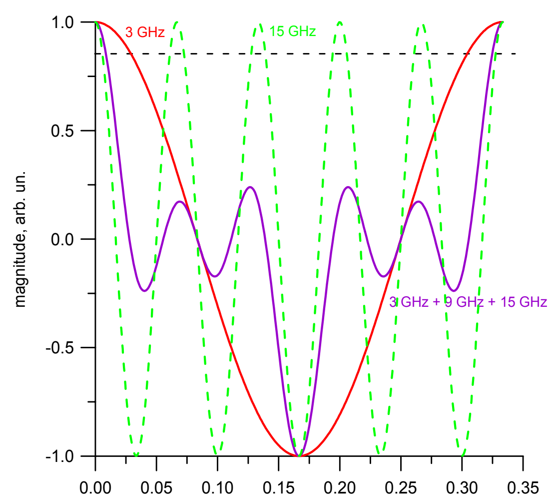

Figure 2: Field dependence on time for single 3 GHz cavity, for 15 GHz cavity, and for multi-mode cavity.

Nevertheless, experimental proof of the validity of the scaling law Eq. (1) for this case is needed. Thus, direct experimental comparison is proposed to accumulate breakdown statistics for three nearly square cross-section cavities operating in TM_{0nn} modes at: (*a*) 3 GHz, $n = 1$ only; (*b*) 3 and 9 GHz, $n = 1$ and 3 only; and (*c*) 3, 9, and 15 GHz, $n = 1$, 3, and 5 only.

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PRELIMINARY CALCULATIONS

Preliminary calculations were carried out for a smooth cavity prototype with axial length l_z = 10 mm and diameter of circular beam hole 5 mm, shown in Fig. 3.

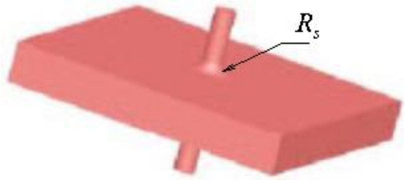

Figure 3: Layout of cavity prototype.

Individual parameters of each mode and multi-mode superpositions used for field calculations in the presence of electron bunches are shown in Tables 1 and 2. Here, μ is the transit-time reduction factor and E_s/G is the ratio of peak surface field to acceleration gradient, or overvoltage.

Table 1: Individual Parameters of Modes

	TM_{110}	TM_{330}	TM_{550}
f, GHz	3	9	15
Q-factor	6460	11220	14400
Rs, Ohms	3.1×10^5	1.8×10^5	3.9×10^5
$\rho = R_s/Q$, Ohms	48.0	16.0	27.1
μ	0.971	0.757	0.434
μR_s, Ohms	3.0×10^5	1.4×10^5	1.7×10^5
$\mu^2 R_s$, Ohms	2.9×10^5	1.0×10^5	0.74×10^5
E_s/G	1.9	2.2	3.0

Table 2: Collective Mode Parameters

	TM_{110}	TM_{110}+TM_{330}	TM_{110}+TM_{330}+TM_{550}
Rs, Ohms	3.1×10^5	4.9×10^5	8.8×10^5
μR_s, Ohms	3.0×10^5	4.4×10^5	6.1×10^5
$\mu^2 R_s$, Ohms	2.9×10^5	3.9×10^5	4.6×10^5
E_s/G	1.86	1.89	2.0

The operating modes of the cavity are shown in Fig. 4.

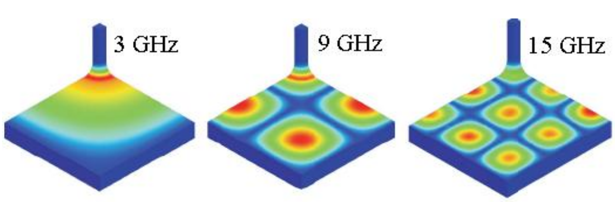

Figure 4: Modes of the cavity prototype. One-eighth of each example is shown.

Calculations have been carried out to determine the (normal) electric field along the cavity inner surface caused by passage a 3 GHz train of 1-nC charge bunches. After a transient period during which the finite cavity-Q fields build up to steady state, the surface field is evaluated. The surface field is highest when all modes participate, reaching about 340 MV/m at its maximum for beam parameters corresponding to CTF-3, namely I = 3.5 A, and τ = 1.5 µsec. This value occurs on the curvature of the fillet with radius R_s = 3 mm between the beam tunnel and the planar cavity wall. For the 3.0 GHz mode alone, the maximum surface field is about 200 MV/m. These surface field values can clearly be changed by altering the beam tunnel radius R_s.

Note that field structures of the modes are very close to those that exist in ideal square cavities. Nevertheless, calculations show that there are small frequency shifts caused by the beam apertures. These shifts spoil the equidistance spacing of the modes. Thus compensation of this undesirable effect by adjustment of geometrical parameters is necessary.

CAVITY DESIGN

The goal of the precise design is to configure three different cavities in which breakdown statistics can be compared. The first cavity would be tuned so that its resonance frequency for the TM_{110} mode equals the bunch frequency, but higher harmonics would be detuned from multiples thereof. The second cavity would be tuned so that its resonance frequencies for the TM_{110} and TM_{330} modes equal the bunch frequency and its third harmonic, but higher harmonics would be detuned from higher multiples. Finally, the third cavity would be tuned so that its resonance frequencies for the TM_{110}, TM_{330}, and TM_{550} modes would be tuned at the bunch frequency, and at its third and fifth harmonics. Preliminary exploration has shown that this goal can be met by judicious local smooth deformations in the cavity walls, with the deformations positioned to affect one particular mode more than others. An alternative means for achieving selective detuning is by use of absorbing elements in carefully positioned peripheral stubs. In simulations for this we used for the absorbers vacuum ceramics with ε = 14 and tanδ = 0.014.

Cavity#1

The design is shown in Fig. 5. The peripheral stubs are cut off for the lowest 3 GHz mode and open at higher frequencies. This is why Q-factors of both higher modes, listed in Table 3, are strongly lowered. There is also some detuning listed in the Table, which is negligible only for the 3 GHz mode. The field structure of the lowest mode is not perturbed in comparison with the TM_{110} mode in the cavity prototype, as shown in Fig. 6.

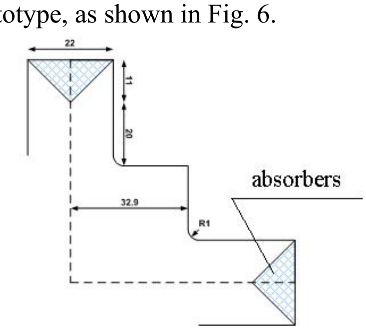

Figure 5: Scheme of the modified cavity with suppression of modes other than the TM_{110}.

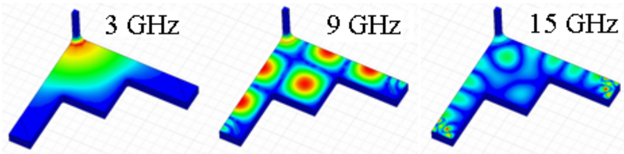

Figure 6: Modes of the cavity #1.

Table 3: Parameters of Modes in Cavity #1

Mode	Frequency, GHz	*Q*-factor
TM_{110}	3.00	5450
TM_{330}	9.64	570
TM_{550}	15.13	80

Cavity #2

The design scheme is similar to that shown in Fig. 5. In this case side stubs with absorbing ceramics have reduced widths in order that only the TM_{550} mode can penetrate into the stubs. This provides strong reduction of the TM_{550} *Q*-factor, as shown in Table 4. The field structures of the main modes in the cavity #2 are shown in Fig. 7.

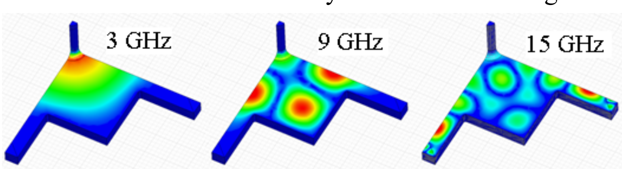

Figure 7: Modes of the Cavity #2.

Table 4: Parameters of Modes in the Cavity #2

Mode	Frequency, GHz	*Q*-factor
TM_{110}	3.02	6110
TM_{330}	8.98	10450
TM_{550}	14.85	330

Cavity #3

The design scheme of cavity #3 is shown in Fig. 8. Here steps of cavity shape compensate for the frequency shifts arising from beam apertures in the centre of the cavity. The field structures, frequencies and *Q*-factors of the main modes coincide closely with the corresponding parameters of modes in the cavity prototype. Table 5 lists parameters for cavity #3.

Table 5: Parameters of Modes in Cavity #3

Mode	Frequency, GHz	*Q*-factor
TM_{110}	3.00	6220
TM_{330}	9.02	11090
TM_{550}	15.00	14480

CONCLUSION

In order to investigate possible raising of breakdown thresholds, single, two-, and three-mode square shaped cavities to be excited by the same 3-GHz drive beam were analyzed. It was shown that selective absorbing and detuning/tuning of one or two of the higher-order modes

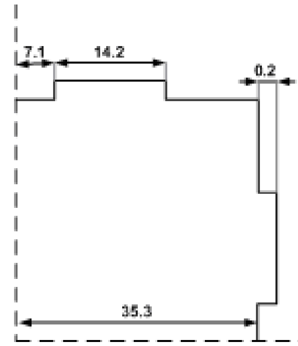

Figure 8: Scheme of the modified three-mode cavity.

can be achieved, so as to allow cavities to be built with three possible degrees of harmonic mode superposition; namely fundamental, fundamental plus third harmonic, and fundamental plus third plus fifth harmonics. This analysis points the way towards experiments comparing breakdown statistics for the three types of cavities that could be carried out using CTF-3 beam facilities at CERN, with the aim of validating (or not) the notion that it is the instantaneous exposure time to peak RF fields, and not the cumulative (macropulse) time, that governs breakdown rates.

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