A HYBRID DIELECTRIC AND IRIS LOADED PERIODIC ACCELERATING STRUCTURE

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Abstract

One disadvantage of conventional iris-loaded accelerating structures is the high ratio of the peak surface electric field to the peak axial electric field useful for accelerating a beam. Typically this ratio $E_s/E_a \geq 2$. The high surface electric field relative to the accelerating gradient may prove to be a limitation for realizing technologies for very high gradient accelerators. In this paper, we present a scheme that uses a hybrid dielectric and iris loaded periodic structure to reduce E_s/E_a to near unity, while the shunt impedance per unit length r and the quality factor Q compare favorably with conventional metallic structures. The analysis based on MAFIA simulations of such structures shows that we can lower the peak surface electric field close to the accelerating gradient while maintaining high acceleration efficiency as measured by r/Q. Numerical examples of X-band hybrid accelerating structures are given.

1 INTRODUCTION

One of the major challenges confronting future high energy linear accelerators is the development of high gradient accelerating structures. The most commonly studied structure is a conventional iris-loaded copper structure representing an evolution from those used at SLAC/SLC to the proposed NLC [1, 2]. However, in all the iris-loaded structures, the peak surface electric field E_s can be an important constraint in such high-energy accelerating structure design because it is in general found to be a factor of 2 larger than the axial acceleration field E_a [1, 2]. Because the peak surface electric field causes breakdown of the structure, it represents a direct limitation on the maximum acceleration gradient that can be obtained. If the peak surface electric field exceeds the breakdown limit at the operating frequency, it can cause damage to the irises through arcing and detune the structure. Thus the high ratio of E_s to E_a limits the achievable accelerating gradient, assuming the availability of high power RF sources is not a constraint here. In this paper, we propose a hybrid dielectric and iris loaded acceleration structure that has lower ratio of E_s to E_a, and comparable shunt impedance per unit length r and r/Q with a conventional iris-loaded accelerating structure. Using this device, E_s/E_a can be reduced to about 1, while maintaining reasonably good acceleration efficiency as measured by r and r/Q. The upper limit of the accelerating gradient can be increased, depending on the dielectric breakdown properties at high fields.

The use of uniform dielectric-lined circular waveguides as accelerating structures has been discussed in many previous studies [3, 4]. One distinct advantage is that the axial accelerating electric field is the maximum field in this class of structure. The acceleration mode used here is the TM_{01}. The group velocity is typically less than 10 percent of the speed of light. Such small group velocities can be obtained by the use of high dielectric constant ceramics, which however have the drawback of an enhanced peak surface magnetic field, which results in more power dissipation on the wall. The result is that the quality factor Q of a dielectric-lined waveguides is degraded compared to an iris-loaded structure with the same group velocity.

Based on these observations we might consider a hybrid dielectric and iris loaded structure in order to produce a device which balances high Q and reduced surface fields. This device is shown in Figure 1. Calculations of the properties of a hybrid traveling wave acceleration structure at 11.4 GHz as a function of iris size and permittivity of the loading dielectric are performed. We show that it is indeed possible to significantly reduce the ratio of the peak surface electric field to the accelerating field gradient without diminishing to any great extent the shunt impedance per unit length r and r/Q.

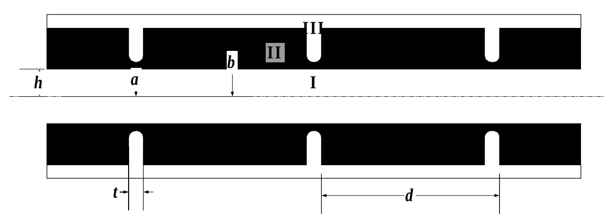

Figure 1: Schematic drawing of a hybrid dielectric-iris-loaded accelerating structure. In the figure, region I is vacuum; region II is ceramic with dielectric constant ε; region III is copper. a is the iris radius, b is the outer radius, and h is the beam hole radius. t is the thickness of the iris, and d is the length of one cell. In this paper, we use a to denote the iris radius for both hybrid dielectric-iris-loaded structures and pure iris-loaded structures.

2 NUMERICAL METHOD

One way to study traveling wave structures is to use a numerical code such as MAFIA [5]. This code provides accurate fields and other electromagnetic properties of a standing wave structure. Loew et al. [6] showed that by using RF properties of standing-wave structures, one could obtain RF properties of the corresponding traveling-wave structures.

Using MAFIA, one can calculate resonant frequencies, stored energies and power dissipation of resonant modes in an array of cavities. The standing wave field components output by the code can be analyzed to obtain the traveling wave components.

If two traveling waves of the proper phase can add up to a standing wave, there must conversely be two appropriately phased standing waves that add up to a traveling wave. This is the principle behind Loew's method.

3 NUMERICAL RESULTS

In this paper, we specialize our investigation to consider only the $2\pi/3$ mode of the propagated wave, whose wavelength λ is equal to the total length of 3 cells when the phase velocity is the speed of light as required for the acceleration of ultra-relativistic particles. First, we calculated a resonator with 3 cells using MAFIA. The field solutions and mesh coordinates were output to ASCII data files. A post-processing program was written to extract the field solutions and mesh information of the standing wave solution, and then carry out the conversion from standing-wave solutions to traveling-wave solutions using Loew's method.

Figures 2 and 3 show the MAFIA simulation results for the electric field pattern of the $2\pi/3$ mode in a pure iris-loaded structure and a hybrid dielectric-iris-loaded structure, respectively. Because of the axial symmetry, only the upper half part of the longitudinal cross-section is plotted.

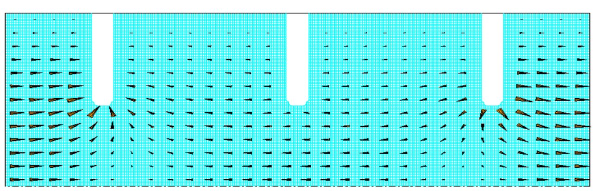

Figure 2: Electric field pattern of the $2\pi/3$ mode in an iris-loaded accelerating structure. The iris radius a = 5.6 mm, the iris thickness t = 1.0 mm, and outer radius b = 11.1254 mm. Here E_s/E_a = 2.4.

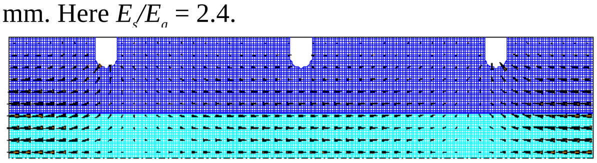

Figure 3: Electric field pattern of $2\pi/3$ mode in a hybrid dielectric-iris-loaded accelerating structure. The ε = 6, a = 4.0 mm, b = 5.361 mm, and the beam hole radius h = 2.0 mm. E_s/E_a = 1.01.

The corresponding traveling wave parameters of Figure 2 structure were calculated and given below in Table 1. In a pure iris-loaded structure, the group velocity of the TM_{01} wave and shunt impedance per unit length are determined by the radius of the irises a. Meanwhile, the outer radius of the cylinder has to be adjusted to maintain the phase velocity of the TM_{01} wave synchronized with the beam velocity c. Thus the iris radius is the governing geometric parameter for the RF properties of a pure iris-loaded accelerating structure. For the structure with iris radius a = 5.6 mm, resulting in a group velocity of 0.088c. The shunt impedance per unit length r is 75 MΩ/m, and the quality factor Q is 7251.

Table 1: RF Properties of an 11.4 GHz Pure Iris-loaded Structure

E_s/E_a	r (MΩ/m)	Q	r/Q (Ω/m)	v_g (c)
2.4	75.6	7251	10343	0.088

The contour plot and surface plot of the distribution of electric field amplitude are shown in Figure 4. We can easily identify that the peak surface electric field occurs at the edge of the iris, and E_s/E_a is about 2.4.

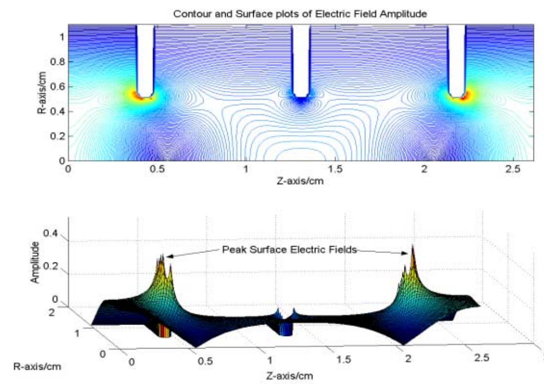

Figure 4: The contour plot and corresponding surface plot show the distribution of electric field amplitudes in a pure iris-loaded traveling-wave structure shown in Figure 2. We observe that the strongest electric field occurs at the edge of the iris. In this case, E_s/E_a is about 2.4.

Unlike pure iris-loaded structure, the group velocity and shunt impedance per unit length r of acceleration TM_{01} mode in a hybrid dielectric-iris-loaded structure is not only the function of beam hole radius, but also iris radius and dielectric constant. For a given group velocity, the outer radius of the cylinder is determined to synchronize the phase velocity with the beam velocity.

To illustrate our point, we have chosen dielectric constant ε_r = 6 for our example. In order to have a fair comparison for all the parameters studied here, we have chosen the group velocity to be nearly the same as in the pure iris loaded case. Table 2 gives RF properties of a hybrid structure. The ratio E_s/E_a = 1.01 is obtained. For a beam hole radius = 2 mm and adjusting the other parameters accordingly, we obtain r = 66MΩ/m, slightly lower than that of the pure iris-loaded structure listed in Table 1. Meanwhile, the quality factor Q = 4899 is about 30% lower than the pure iris loaded case due to the increased surface magnetic fields. However, the acceleration efficiency measured by r/Q is also improved by 30% and $E_s/E_a \approx 1$. Fig. 5 shows the contour plot and surface plot of electric field distribution in the hybrid structure given in Table 2. It shows that the peak surface electric field is reduced to the same magnitude as the peak axial electric field. Therefore, hybrid dielectric-iris-loaded structures reduce the peak surface electric field with comparable r/Q to iris-loaded structures. However, one should notice that the contact between the irises and the dielectric must be as close as possible. One might expect that if there is a large gap existing between a metallic iris and dielectric resulting from fabrication, and then the electric fields on the irises could be enhanced. From qualitative analysis, the surface electric field at the iris will go up, as the gap increases. Detail study of this effect should be investigated in the future, and also other engineering issues should be addressed.

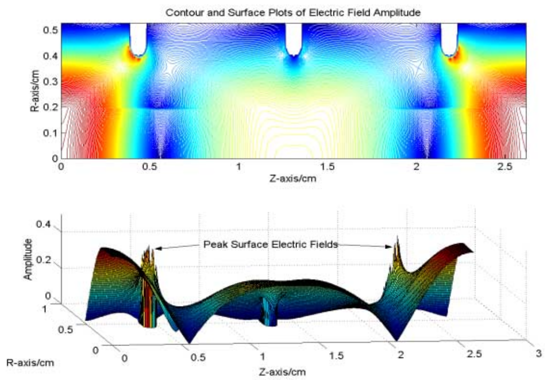

Figure 5: Contour and surface plots showing the distribution of electric field amplitude in a hybrid dielectric-iris-loaded traveling-wave structure shown in Figure 3. We can see the strongest electric field on the iris surface is about the same as the axial electric field in this case: Es/Ea is about 1.01.

Table 2: RF Properties of an 11.4 GHz Hybrid Dielectric-Iris-loaded Periodic Structure

E_s/E_a	*r* (MΩ/m)	*Q*	*r/Q* (Ω/m)	v_g (*c*)
1.01	66.8	4899	13635	0.087

Although we could lower the E_s/E_a by introducing dielectric loading into the structure, we have to encounter another unknown problem: dielectric breakdown under high frequency RF fields. The dielectric breakdown limit becomes the constraint of the maximum achievable accelerating gradient instead of the surface breakdown limit of copper in pure iris-loaded structures. Dielectric breakdown at various frequencies has been studied in wakefield acceleration experiments [7], and showed no sign of breakdown up to 20 MV/m at 15 GHz. Besides dielectric breakdown limit, other mostly unknown factors, such as Joule heating and vacuum properties of dielectric loaded structures under high RF power, should also be weighed in to evaluate this type of hybrid dielectric-iris-loaded structure. With a recently proposed experiment [8], breakdown phenomena can be explored at 50 - 70 MV/m field strengths, approaching the NLC desired gradient. Moreover, Joule heating and vacuum properties will also be investigated. If dielectrics can maintain these field gradients, then the scheme we analyzed in the paper would provide an alternate approach that lowers the peak field on the iris by more than a factor of two. This may be an important factor for realizing accelerating structures for very high gradient accelerators.

4 CONCLUSION

The analysis of hybrid dielectric-loaded periodic accelerating structures shows that the peak surface electric field can be reduced to levels comparable to the axial accelerating field gradient. However, this scheme also reduces the acceleration efficiency measures such as r and *Q*, although *r/Q* can be comparable to conventional iris-loaded structures. Although the numerical examples of X-band structures are only presented here, we expect that this scheme of reducing ratio of E_s to E_a in a conventional iris-loaded structure at any frequency band can be used by employing partially loaded dielectrics. The fundamental issues about using dielectric loaded structure for particle acceleration, such as dielectric breakdown, Joule heating and vacuum properties, determine if hybrid dielectric-iris-loaded periodic structures can be the alternatives for future linear collider acceleration structures. The experimental investigations on these issues are underway, and the advancement in material science also makes this class of structure very promising.

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