Employing High Epsilon Dielectric Materials for Enhancing Cu Accelerator Structure Efficiency and Mitigating Long-Range Wakefields

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Normal-conducting copper accelerator structures have been foundational building blocks for both high-gradient and high-average-power accelerators, across a variety of applications and particle species. While superconducting accelerator structures offer extremely high efficiency, they require complex refrigeration systems and precise resonance control, and are subject to detrimental phenomena such as quenching. Wakefield mitigation can be problematic in superconducting structures, and fundamental limits exist on achievable gradients. Finally, it can be more difficult to operate superconducting structures with quasi- or aperiodic bunch trains, making certain classes of applications more difficult. In summary, development of room-temperature accelerator structures gives access to highest gradients, operational flexibility, reduced wakefield effects and significantly reduced operational complexities.

RF-resonators operating at GHz frequencies, incorporating dielectrics, or fully fabricated with dielectrics[1] have been pursued for some time, offering the promise of greatly improved efficiency vs. copper structures, potentially much simpler fabrication [1,2], and reduced wakefields [3,4]. Unfortunately, effects such as field emission and multipacting have limited the achievable gradients of such structures when driven by external RF sources [5,6,7,8]. A commonality in structures exhibiting these limitations is the location of the dielectric: generally close to the beam, and generally subjected to the highest electric fields in the structure.

This observation suggests a path towards addressing these limitations while notably enhancing the shunt impedance of copper accelerator structures via the use of dielectric inserts. Specifically, modern high-ε dielectric materials, such as those developed for cell-tower resonators, offer the promise of increasing the shunt impedance of a pillbox speed-of-light cavity by approximately 50% compared to a TM_{010} "pillbox" cavity, while locating the dielectric in low-electric-field regions of the cavity. Proper placement of the insert allows significant reduction of wall current along the outer wall of a cavity resonating in a TM_{020}-like mode, preserving the accelerating field profile near the axis while reducing the overall wall losses. For high dielectric constants the power reduction can approach a factor of two, for the same on-axis field, even with non-zero dielectric losses, as shown in Fig. 1.

Our approach appears compatible, based on our initial simulation studies, with traditional efficiency improvement techniques such as adding nosecones, and geometry optimization in general, although the gains are not always as high as those calculated for pillbox cavities. This is unsurprising, since such methods also operate by modifying the cavity resonant mode. As one would predict from the above description, $\beta<1$ structures see less of an efficiency improvement compared to a speed-of-light structure.

In addition to reducing RF power consumption, we believe this approach also offers the ability to address long-range wakefields, of concern for high-brightness multibunch accelerators, as well as for high-average-current machines.

[1] Not to be confused with dielectric laser accelerators.

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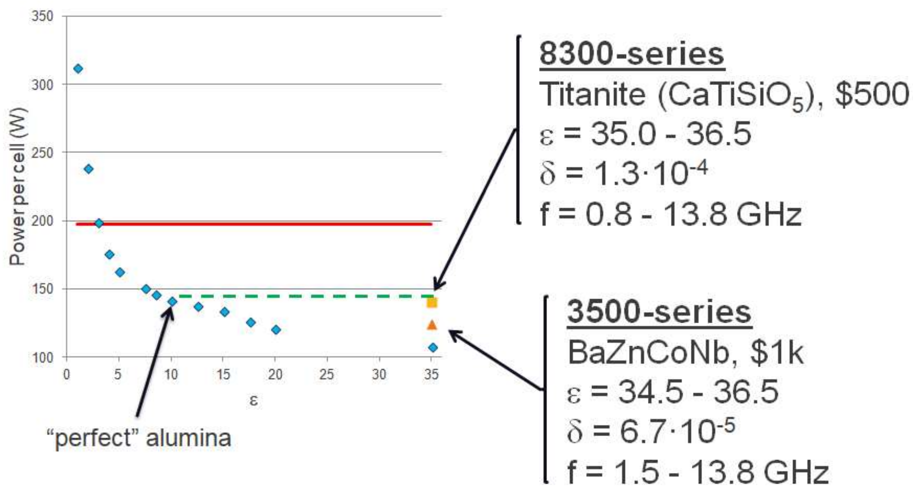

Figure 1: Calculated RF power required to obtain 1 MV/m average on-axis gradient in a C-band cavity, versus dielectric constant. Expected performance with two commercially available dielectrics from Skyworks (formerly Trans-Tech) are indicated. The red line is the "break-even" power versus a TM_{010}-mode cavity. The green dashed line is for "perfect" (lossless) alumina. Blue dots assume lossless dielectrics. Points for 8300- and 3500-series dielectrics include published loss tangents in the calculation.

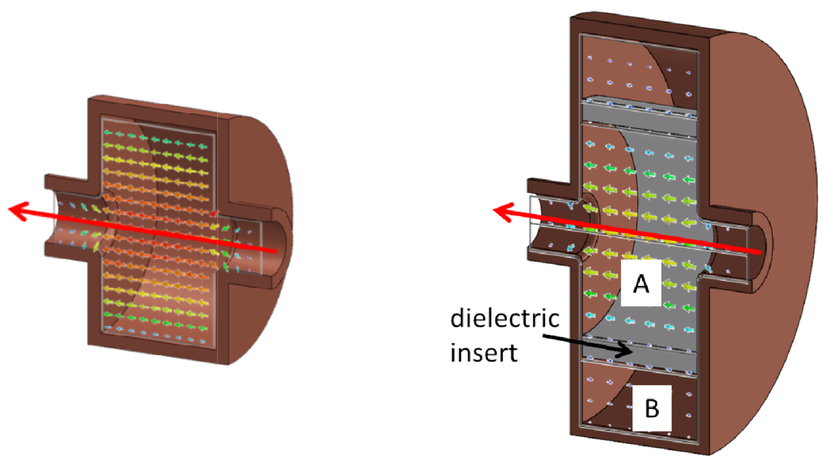

Figure 2: Comparison of conventional TM_{010}-mode cavity (left) and enhanced-efficiency TM_{020}-like mode cavity fields with dielectric insert (right). Large red arrow shows beam axis; small colored arrows show relative field amplitude and direction within a given cavity.

We propose development of this concept, with initial focus on single- and multi-cell resonators at C-band. We strive to demonstrate increased RF-efficiency, compatibility with cryo-cooled operation, and evaluation of intricacies in multi-cell resonators. Placement of the dielectric in low-field regions of the cavity should allow operation at higher gradients than previous dielectric-based structure designs. Study of triple-point junctions, where vacuum, dielectric and metal meet, and arcing is a known problem, will be emphasized. We note that the efficiency gains should be multiplicative with those obtained by cryogenic cooling, a topic of considerable recent interest, which modifies the surface resistance but not the mode pattern. The improvements to shunt impedance would be beneficial for high-gradient, high-brightness accelerators, but also for high-average-power machines such as those used to generate neutrino beams.

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