Dielectric Assist Accelerating structures for compact linear accelerators of low energy particles in hadrontherapy treatments

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Abstract

Dielectric Assist Accelerating (DAA) structures based on **ultralow-loss ceramic** are being studied as an alternative to conventional disk-loaded copper cavities. This accelerating structure consists of dielectric disks with irises arranged periodically in metallic structures **working under the TM02−π mode**. Here, the numerical design of an **S-band DAA** structure for **low beta particles**, such as protons or carbon ions used for **hadrontherapy treatments**, is shown. **Four dielectrics** with different permittivity and loss tangent are studied as well as different particle velocities depending on the energy range. Through optimization, most of the RF power is stored in the vacuum space near the beam axis, leading to a significant reduction of power loss on the metallic walls. This allows to realize cavities with **extremely high quality factor over 100 000 and shunt impedance over 300 MΩ/m at room temperature**. During the numerical study, the design optimization has been improved by adjusting some of the cell parameters in order to both increase shunt impedance and reduce the peak electric field in certain locations of the cavity, which can lead to instabilities in its normal functioning.

Dielectric Assist Accelerating Structure

A DAA structure for low beta particles at low frequency (S-band) is studied for the first time in this work, as a solution for **compact linear accelerators of low energy and low beam current** such as medical accelerators for **hadrontherapy** treatments *[1]*.

The DAA structures *[2,3]* consist of axially symmetric dielectric cylinders with irises, periodically arranged in a metallic enclosure and operating in standing wave **TM02−π** achieving **extremely high quality factor Q_0 and shunt impedance Z_{eff}.**

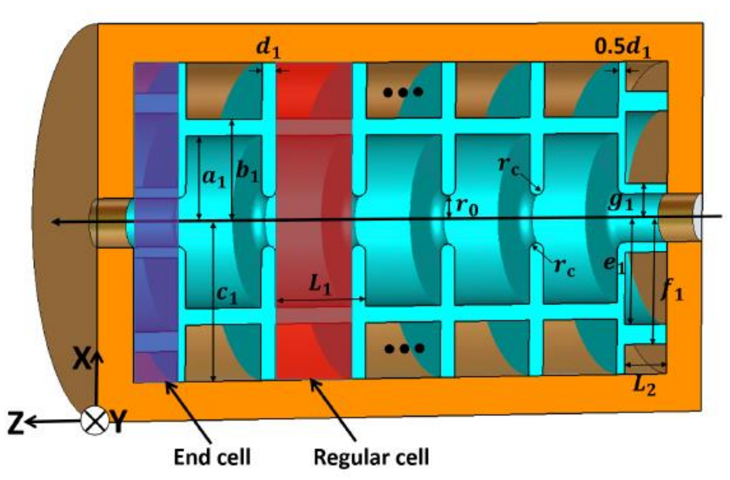

Figure 1. Conceptual Schematic of an S-band DAA structure.

Material	Acronym	ε_r	tan δ
CVD Diamond	Diamond	5.7	10^{-4}
MgO	D9	9.64	6×10^{-6}
$MgTiO_3$	D16	16.66	3.43×10^{-5}
$BaTiO_x$	D50	50.14	8×10^{-5}

Table 1. List of dielectrics.

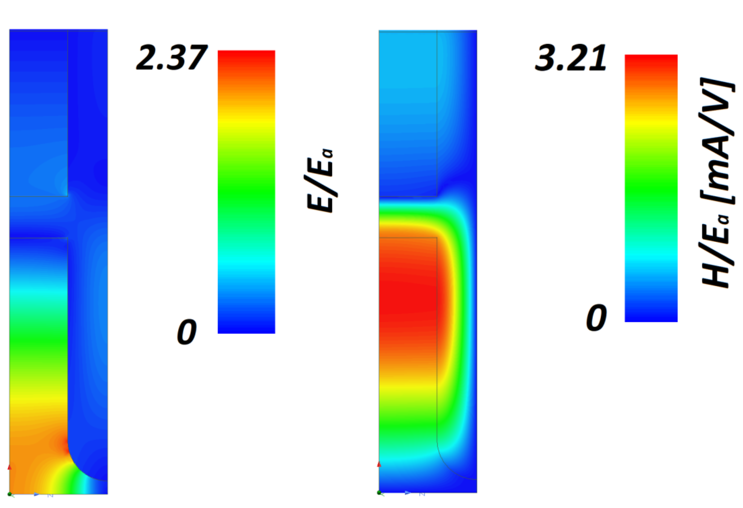

Figure 2. Electric and magnetic field profile for $TM_{02-\pi}$ *[4]*.

Geometry Optimization

Cavity performance is determined by a combination of a_1, b_1, c_1 **and** d_1 and $L_1 = \beta\lambda_0/2$. Optimization process is divided into steps:

1. Iris thickness is fixed: $d_1 = d_0 = \lambda_0/(4\sqrt{\epsilon_r})$.
2. Each set of (a_1, c_1) has a single value of b_1 for a given resonant frequency f_0.
3. Optimum (a_1, b_1, c_1) is found maximizing Q_0.
4. A scan in iris thickness is done: $d_1 = \xi \cdot d_0$ and steps 2,3 are repeated for each value of ξ.
5. Optimum (a_1, b_1, c_1, d_1) is found maximizing Z_{eff}.

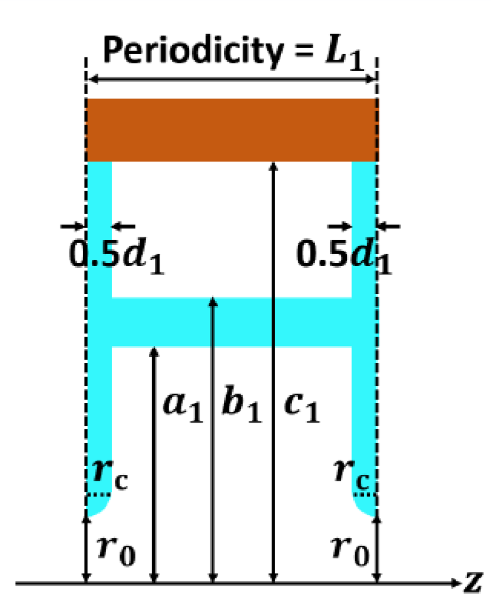

Figure 3. Regular cell geometry.

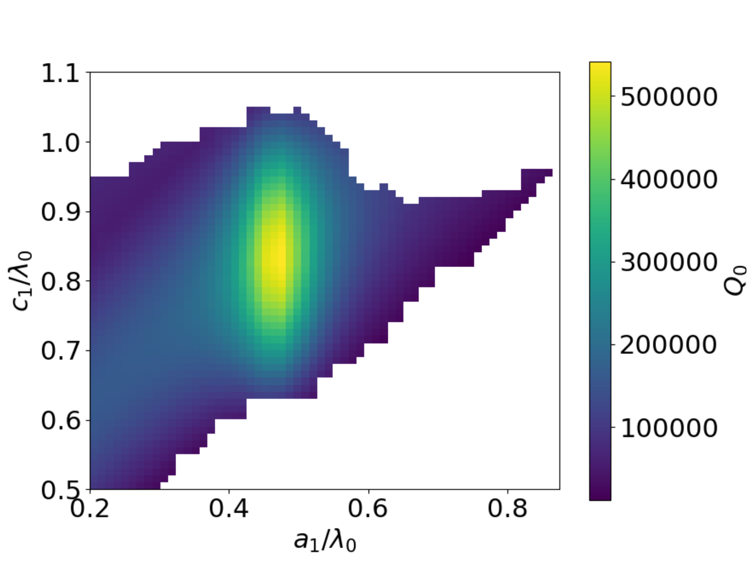

Figure 4. Optimization for (a_1, c_1) scan for a fixed d_1 for $MgTiO_3$ and $\beta = 0.6$.

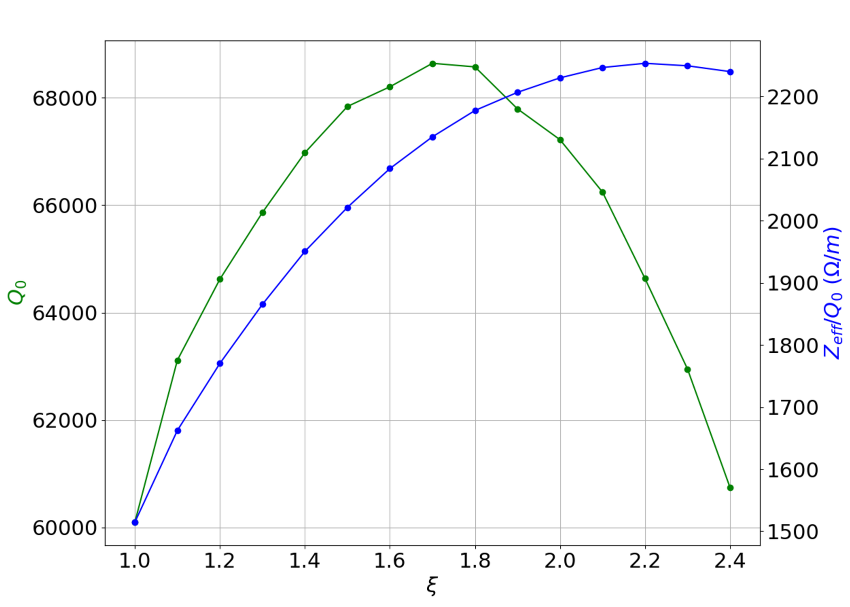

Figure 5. Optimum geometries for each value of d_1 for $MgTiO_3$ and $\beta = 0.6$.

Cavity performance

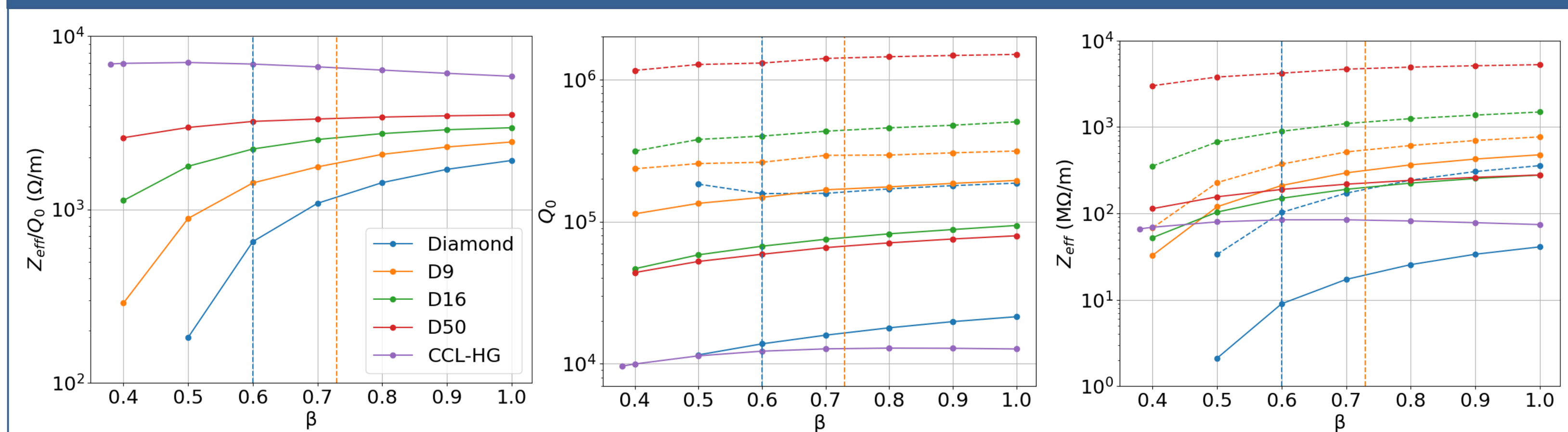

Figure 6. Regular cell performance for different particle velocity β and materials.

Particle velocities for hadrontherapy treatments vary between **0.37-0.6 for protons** and **0.43-0.73 for carbon ions** *[5]*.

RF Losses

Electromagnetic losses will be determined by:

- ***Surface copper losses:***

$$P_c = \frac{1}{2} R_s \int |\hat{\boldsymbol{n}} \times \boldsymbol{H}|^2 dS$$

- ***Volumetric dielectric losses:***

$$P_d = \frac{1}{2} \omega \epsilon_0 \epsilon_r \tan\delta \int |\boldsymbol{E}|^2 d\tau$$

Under **TM02−π metallic losses are highly suppressed**. Thus, DAA regular cell **performance will be determined by tan $\boldsymbol{\delta}$**, which depends strongly on the **manufacturing process of the ceramic.**

In addition, **Amorphous Carbon (a-C)** and **Diamond Like Carbon (DLC) coatings** were studied at CERN for Secondary Electron Yield (SEY) reduction to **avoid multipactor discharges** *[6]*. The surface losses will have an impact on the electromagnetic performance of the cavity.

- ***Surface coating losses:***

$$P_s = \frac{1}{2R} \int |\hat{\boldsymbol{n}} \times \boldsymbol{E}|^2 dS$$

only **high resistance materials** or **very thin coatings** can be used to suppress multipactor.

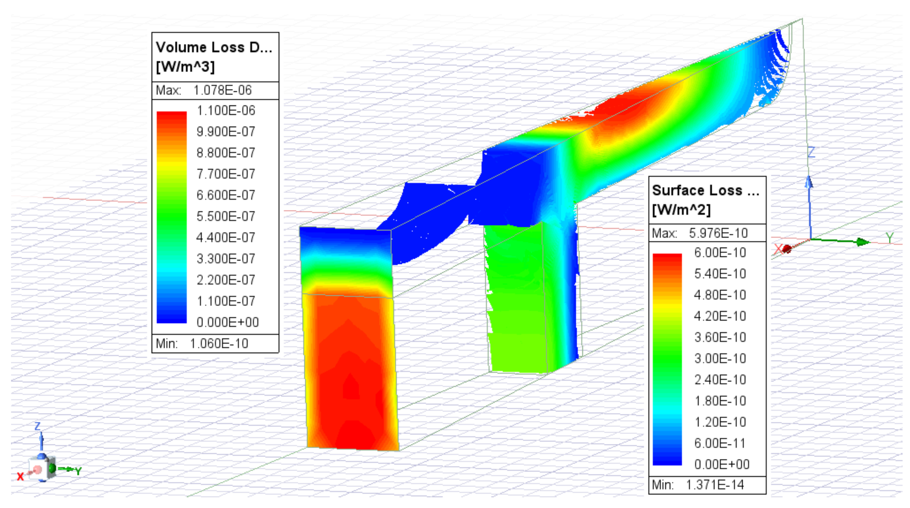

Figure 7. Electromagnetic losses distribution *[4]*.

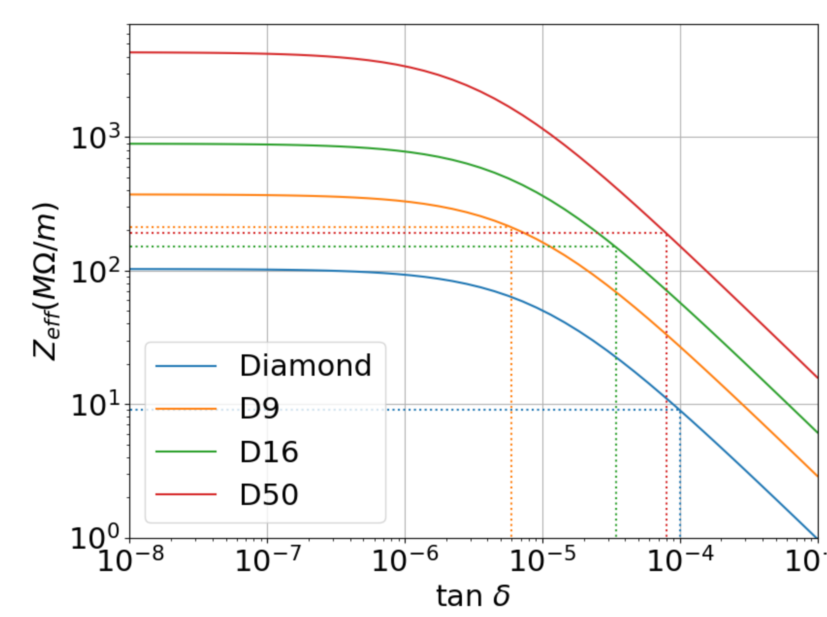

Figure 8. Z_{eff} for different tan δ.

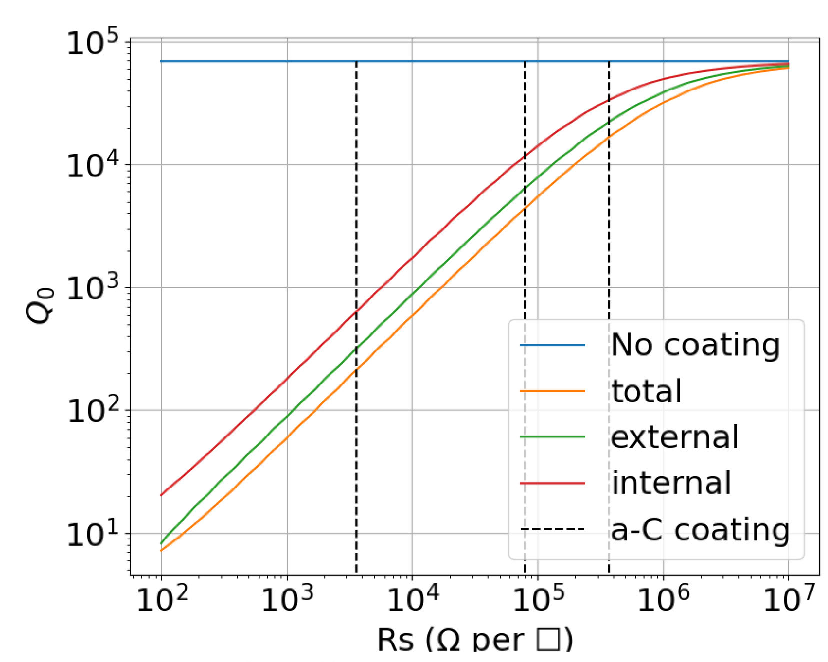

Figure 9. $\boldsymbol{Q_0}$ for different coatings scenarios and sheet resistance.

Conclusion

DAA structures for low beta particles have been studied for the first time, proving the potential to improve the performance of current room-temperature copper cavities. Efficiency increases for higher particle velocity and electrical permittivity. However, due to the high energy density inside the dielectric, **cavity performance will be limited by dielectric losses**, therefore reaching low dielectric loss tangent is a fundamental key in the fabrication of real ceramics.

Iris thickness plays a fundamental role in cell optimization by increasing accelerating voltage and reducing electric energy density inside the ceramic, decreasing dielectric losses. As a consequence, materials with higher loss tangent have thicker optimum irises than ideal geometries.

Finally, numerical simulations showed that low resistance coatings are unacceptable from an electromagnetic point of view, which imply that **only high resistance materials or very thin coatings can be used to suppress multipactor.**

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