

# CERAMIC ENHANCED ACCELERATING STRUCTURE (CEAS) OPTIMIZATION FOR IMPROVED SHUNT IMPEDANCE\*

B. Sims<sup>†</sup>, H. Xu, J. W. Lewellen, L. Duffy  
Los Alamos National Laboratory, Los Alamos, United States

## Abstract

We present a COMSOL Multiphysics®-based workflow, using the Optimization Module, to increase RF cavity shunt impedance ( $R_{sh}$ ) by systematically reshaping the nose cones. The cavity being optimized is utilizing the Ceramic Enhanced Accelerating Structure (CEAS) approach with a ceramic tube insert at the inner electric field zero of the TM020 mode, which increases the efficiency by reducing power dissipation. The CEAS concept, combined with the improved shunt impedance from nose cone optimization, yields a particularly efficient cavity. The cavity is parameterized with smooth geometric variables (nose tip radius, cone angle, gap, fillets). This optimization maximizes  $R_{sh}$  subject to frequency locking and engineering limits based on the cavity geometry. Eigen-frequency studies are used as the primary optimization tool producing a field map of the desired TM020 mode as well as the power dissipated on the walls and within the ceramic material. Post processing optimization computes  $R_{sh}$  and peak nose cone field from the electric field profile and losses. Single cell studies show higher  $R_{sh}$  without degrading cavity performance; optimal profiles provide moderating curvature to control local field enhancement.

## CERAMIC ENHANCED ACCELERATING CAVITIES

Ceramic Enhanced Accelerating Cavities are single-cell standing-wave accelerator structures using a typical copper accelerating cell design with a ceramic tube inserted parallel to the beam axis [1–3]. CEAS Cavities operate in a TM020 mode, creating a TM010-like field pattern in the paraxial region. In a typical metallic TM010 cavity, RF currents in the metal are the dominant cause of ohmic losses. This is alleviated in a CEAS cavity as the ceramic insert is an insulator which leads to minimized ohmic losses, dielectric losses are also low due to the loss tangent of the ceramic. The low source of losses in a CEAS cavity leads to higher efficiency than a conventional metallic accelerator cavity.

### Distributed Drive Cavities

The CEAS concept can utilize modern RF sources, such as a distributed RF drive, to remove the need for a fixed RF phase advance per cell. We modeled a distributed RF drive case, where each CEAS cell would be powered by its own solid-state amplifier [4] with independent phase and

power control. In Fig. 1, the CEAS cavity length ( $L_{cav} = 40.27$  mm) is not set by a constant phase advance; instead, it is chosen to maximize energy gain, i.e. beta-matching [5]. In addition, because the RF power to each cavity can also be controlled separately, the accelerator's output beam energy can be modified, which allows for many different operational modes.

### Optimizer Parameters

COMSOL was used for simulation and optimization [6] of a 5.1 GHz CEAS cavity nose cone geometry, shown in Fig. 1. The figure shows the 2D axially symmetric cross section of with labeled parameters. Dimensions in black were kept constant, while those in red were optimized. The COMSOL simulations used Trans-Tech D3500 ceramic. The design also uses the nose cone gap to beta match the transit time of an ultra-relativistic beam.

Table 1: Trans-Tech D3500 Material Properties

Material	$\epsilon_r$	$\tan(\delta)$
D3500	35.5	$1.06 \times 10^{-4}$

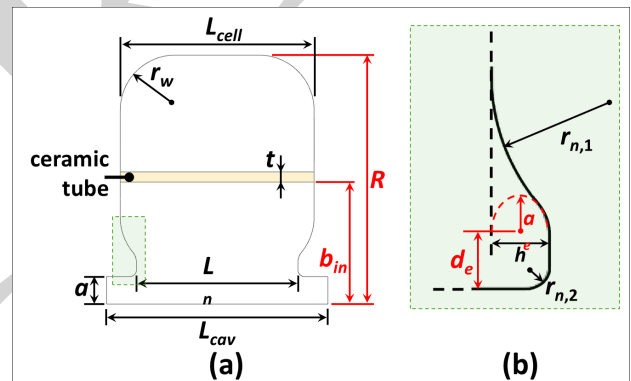


Figure 1: Optimizer parameters, black indicate fixed parameters, red indicates parameters being optimized.

## RESULTS

### Electric Fields

The COMSOL figure of merit (FOM) was defined as shown in Eq. 1.

$$\text{FOM} = \frac{R_{sh}}{\left(\frac{E_{pk}}{E_{acc}}\right)}. \quad (1)$$

$R_{sh}$  is the time-dependent shunt impedance,  $E_{pk}$  is the peak electric field inside the cavity, and  $E_{acc}$  is the accelerating gradient. This optimization target was chosen as it works to

\* Work supported by U.S. Department of Energy through the Laboratory Directed Research and Development program of Los Alamos National Laboratory, under project numbers 20210083ER and 20240136ER.

<sup>†</sup> sims@lanl.gov

maximize the shunt impedance of the cavity while also ensuring that the peak field in the cavity is reasonably minimized to mitigate risk of arcing. Specifically, the ratio between accelerating gradient and peak E-field was integrated in the FOM, as this is a common metric when designing cavities with strong reentrant designs that could present pronounced risk of arcing. A TM010-mode standard reentrant metallic cavity was also optimized using the same optimization and fixed parameters. The CST Eigenmode Solver was used to verify the time-dependent shunt impedance of the cavity. CST and COMSOL showed good agreement on all metric including, resonant frequency, shunt impedance, and unloaded quality factor. Figure 2 shows the optimized normalized electric field results for both the TM020 Ceramic cavity, (a), and the full metal TM010 cavity, (b).

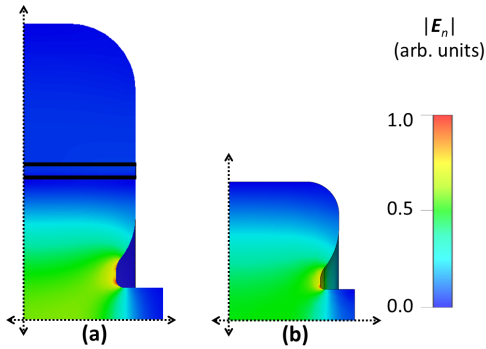


Figure 2: Cavity electric field magnitude distributions, (a) TM020 CEAS, (b) TM010 fully metallic.

Table 2: Comparing CEAS and metallic cavity results

	CEAS TM020	Metallic TM010
Resonant freq. [GHz]	5.098	5.098
Q factor	18 744.8	14 580
Shunt imp. [ $M\Omega$ ]	0.9359	2.497

### Ceramic Thickness and Shunt Impedance

During optimization we saw a strong dependence between the ceramic thickness and the resulting shunt impedance. We wanted to explore this correlation further so we studied different ceramic thicknesses, as seen in Fig. 3. Our reference point was the TM010 metallic cavity with a shunt impedance of  $2.5 M\Omega$ , the orange line on Fig. 3. The ceramic thickness was explored from 1 mm to 3 mm in 0.5 mm steps. We found that two cases showed improvement compared to the TM010 full metal cavity, 2 mm and 2.5 mm, with the best simulated case being at 2 mm with a 14% improvement compared to the TM010 cavity. Previous experiments done at LANL have shown that 2 mm ceramic tubes are practical and can

be used reliably. These results indicate that precisely machine custom thickness ceramics should be tested for further improvements.

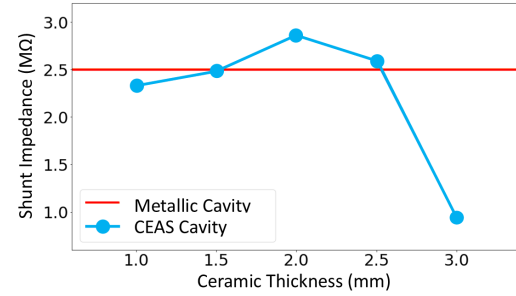


Figure 3: Shunt Impedance vs Ceramic Thickness.

## CONCLUSION

CEAS Cavities are a promising approach to cavity design where improving shunt impedance is a strong focus. The simulations and optimization done here illustrate the further improvements that can be gained over existing CEAS designs by optimizing the nose cone and ceramic thickness of the cavity. The need for precisely machined ceramics and refined nose cone geometry to take advantage of further shunt impedance improvement will require experimental confirmation in the future. Improved ceramic machining indicates the viability of designing and fabricating such precise inserts.

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