DIELECTRIC CHARACTERIZATION OF BEAM LINE ABSORBER SAMPLES FOR NEXT-GENERATION HIGH INTENSITY ELECTRON BEAM SRF ACCELERATORS*

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Abstract

PERLE, under construction at IJCLab, is designed for high intensity electron beams of 5 MW peak power (20 mA, 250 MeV). Simulations of its SRF cryomodule predict more than 100 W of higher-order-mode (HOM) power per cavity induced by the short bunches, indicating that Beam Line Absorbers (BLAs) at 40 K may be required between cavities to dissipate the HOM power and protect the 2 K stage. However, the lack of complete properties of dielectric materials for candidate absorbers limits accurate BLA design. To address this, we are conducting dedicated studies of BLA materials at IJCLab. We measured the broadband dielectric properties of Kyocera SC1000 samples from BNL at room temperature using a setup at CERN developed for CLIC study and cross-validated the results with independent measurements from JLab. In parallel, we designed and simulated two cryogenic coaxial test stands, one operating up to 18 GHz and another extending coverage to 40 GHz. These warm measurements provide baseline data for upcoming cryogenic studies and validated input for the design of BLAs in next-generation accelerators such as the EIC at BNL, FCC-ee at CERN, and in particular PERLE at IJCLab.

INTRODUCTION

Kyocera SC1000 [1] has been primarily investigated for HOM absorbers in EIC and FCC-ee applications at warm, and here it also serves as a benchmark for cryogenic absorbers such as those required for PERLE [2] (see Fig. 1) and other ERLs or FEL facilities. Although dielectric measurements at cryogenic temperatures have been reported for various materials [3–5], only a limited number have been demonstrated to be compatible with cryogenic operation. In this work, we propose a systematic dielectric characterization approach for candidate absorber materials at cryogenic conditions using a coaxial-based setup, and in parallel, we perform simulations of BLA radio frequency (RF) absorption performance, enabling reliable prediction of their behaviour.

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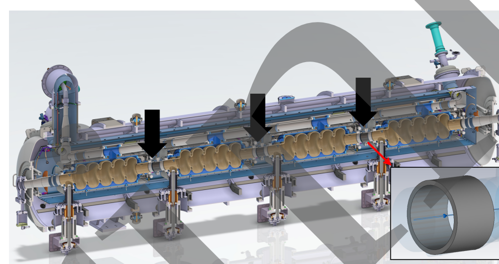

Figure 1: BLAs for the PERLE Cryomodule.

DIELECTRIC PROPERTIES OF MATERIALS

The RF absorption performance of BLAs is primarily determined by the dielectric properties of the material [6], which is described by the complex permittivity,

$$\varepsilon = \varepsilon' - j\varepsilon'', \tag{1}$$

where the real part ε' accounts for energy storage in the material and the imaginary part ε'' represents dielectric losses. Another relevant derived quantity is the loss tangent,

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} + \frac{\sigma}{\omega\varepsilon'}, \tag{2}$$

where ω is the angular frequency, and σ the electrical conductivity. Since most BLA candidate materials are ceramics, they behave as electrical insulators; therefore, the contribution of σ to the losses can be neglected [6–8]. However, low conductivity is not a strict requirement for BLA materials, as slightly conductive ceramics have also been used as HOM absorbers [3]. Ideally, candidate materials should exhibit a high loss tangent $\tan\delta > 0.3$ over a broad frequency range.

Another relevant parameter is the complex permeability,

$$\mu = \mu' - j\mu'', \tag{3}$$

which, for non-magnetic materials, can be treated as $\mu = \mu_0$. Nevertheless, it has been reported that under cryogenic conditions some materials may exhibit apparent magnetic losses, as observed in [5], although these effects were ultimately attributed to calibration artifacts.

Throughout this work, the relative quantities are used, such that $\varepsilon_r = \varepsilon/\varepsilon_0$ and $\mu_r = \mu/\mu_0$.

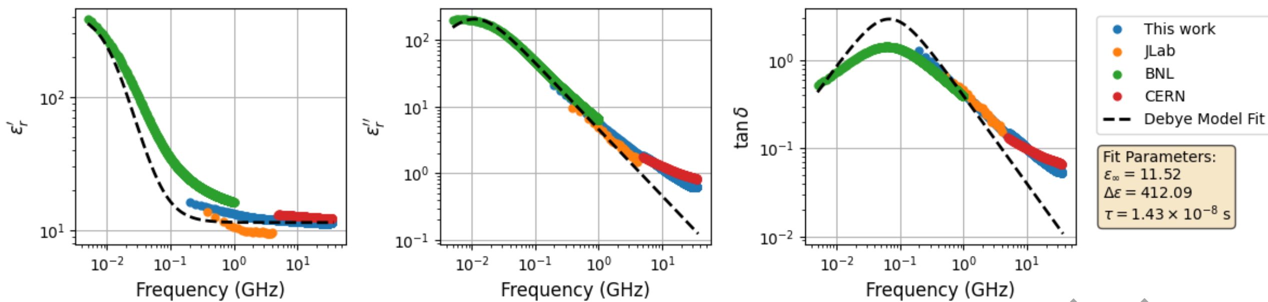

Figure 2: Dielectric properties of SC1000 measured by different institutions. (Left) Real part of the relative permittivity; (middle) imaginary part; (right) loss tangent.

SC1000 SAMPLES MEASUREMENTS

We characterized four SC1000 samples (100×100×8 mm), provided by Brookhaven National Laboratory (BNL) [9] for dielectric characterization, from 200 MHz to 35 GHz. The measurements were performed at CERN using a commercial device: SPEAG DAK-TL2 [10], a reflection-based setup equipped with a 1.85 mm coaxial connector, connected to a vector network analyzer (VNA). For each sample face, five independent measurements were performed. No significant variation between samples or between different faces of the same sample was observed, with variations remaining around 10%, contrary to previous reports for other sintered SiC materials [11, 12]. The dominant source of uncertainty was identified as the probe itself.

The averaged and smoothed results obtained for the four samples are shown in Fig. 2, together with measurements of SC1000 performed at Jefferson Lab (JLab), BNL, and CERN. The imaginary part of the permittivity, ε_r'', agrees better than the real part, ε_r', for the different measurements. These observations indicate a high level of consistency between measurements performed at different laboratories and confirm SC1000 as a reliable candidate material for HOM absorbers at room temperature. Moreover, a Debye model was fitted to the data, following the approach proposed for sintered SiC ceramics in [7]. The model is expressed as

$$\varepsilon_r(\omega) = \varepsilon_{r,\infty} + \frac{\varepsilon_{r,0} - \varepsilon_{r,\infty}}{1 + j\omega\tau}, \qquad (4)$$

and is capable of capturing the dielectric relaxation behavior of the imaginary part at low frequencies. The model provides a better fit for the real part of the permittivity at higher frequency. As a consequence, the loss tangent is overestimated below 1 GHz and underestimated above 1 GHz. This discrepancy between the model and the measured dielectric properties further supports the need for direct measurements.

COAXIAL BASED MEASUREMENT SETUP

Dielectric parameters of materials can be characterized using transmission lines. In such configurations a sample is placed in a coaxial airline, then an electromagnetic wave is injected at one port and the transmitted and reflected signals are measured at the output ports through the corresponding scattering parameters (S-parameters). From these quantities, ε_r and μ_r of the material can be extracted.

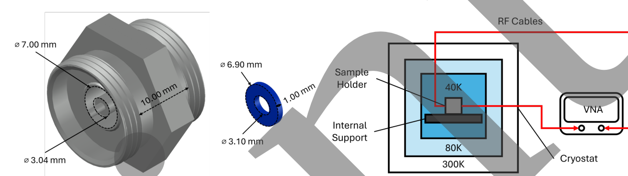

Figure 3: (Left) sample holder with sample under test; (right) simplified representation of the cryogenic setup.

We designed a coaxial sample holder to be placed in a cryostat inspired by the system used for the cryogenic testing of STL-150D at KEK [5]. Similar systems were independently implemented and extensively studied at CERN [13] and Cornell University [14]. The holder (see Fig. 3) consists of a 10 mm-long APC-7 coaxial airline and is capable of measuring dielectric parameters up to 18 GHz.

Retrieval Algorithm

To extract the permittivity and the permeability we implemented a retrieval algorithm based on the NRW method [15]. Due to its well-known mathematical instability at frequencies where the sample thickness corresponds to integer multiples of half the wavelength inside the material, the NIST iterative method [16] was also implemented to improve robustness. To account for the presence of air gaps between the sample and the inner and outer conductors, the following correction derived from the capacitance of a coaxial transmission line is applied:

$$\varepsilon_r = \frac{\ln(b_s/a_s)}{(\varepsilon_{r,\text{eff}})^{-1}\ln(b/a) - \ln(a_s/a) - \ln(b/b_s)}, \qquad (5)$$

where ε_r is the actual complex permittivity of the sample under test; $\varepsilon_{r,\text{eff}}$ is the effective extracted permittivity; a and b are the inner and outer radii of the coaxial line; and a_s and b_s are the corresponding inner and outer radii of the sample.

Simulation

Electromagnetic simulations of the proposed setup were performed using CST Studio Suite with the Frequency Domain Solver. Figure 4 shows ε_r of SC1000 obtained after processing the simulated S_{11} and S_{21} parameters. These results validate the proposed measurement setup and support proceeding with the fabrication of the sample holder and the procurement of candidate materials.

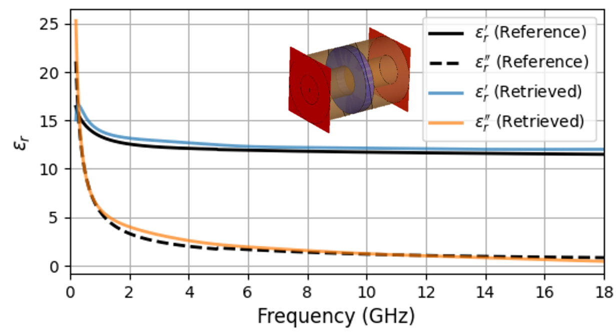

Figure 4: Retrieved dielectric permittivity for SC1000 from simulated S-parameters.

Table 1: Candidate Materials

Company	Material
Sienna Tech	STL150D-14KL/11/HTC
Kyocera	SC1000
Maruwa	AlN+SiC Composite
CoorsTek	SC30/35
EMC	CeSiC

Candidate Materials

Several candidate materials have been proposed, including sintered SiC/AlN and CMC ceramics. A non extensive list of the considered materials for further study is presented in Table 1. Among them, only STL150D14KL and CeSiC have been demonstrated to be compatible with cryogenic operation [3, 5, 17].

ABSORPTION CAPABILITY OF BLAS

To evaluate the absorption capability of a BLA, it can be simulated in a beam pipe section with ports defined at both ends, where a given mode is excited at one of the ports. The ports are defined as matched waveguide ports. Using the *S*-parameters of the resulting two-port system, the power absorption ratio $P_A(f)$ can be computed at each frequency point of the simulation sweep as

$$P_A(f) = 1 - \sum_m |S_{11}^{(m)}(f)|^2 - \sum_n |S_{21}^{(n)}(f)|^2, \qquad (6)$$

where the sums account for power reflected and transmitted into all propagating modes.

Considering a hollow cylinder with inner radius $R_{i,\mathrm{BLA}} = 65$ mm, length $l_{\mathrm{BLA}} = 100$ mm, and thickness $t_{\mathrm{BLA}} = 10$ mm, the absorption performance of a BLA made of SC1000 was evaluated for the TE_{11} and TM_{01} modes excited at one of the ports, modes typically linked with dipole and monopole HOMs. At each port, 60 propagating modes were considered. Figure 5 shows the resulting power absorption ratio up to 16 GHz, corresponding to the standard deviation of the Gaussian beam spectrum of PERLE in the frequency domain ($\sigma_f = 16$ GHz). The proposed geometry exhibits a broadband absorption in the studied range, with an average absorption of 20.27% for TE_{11} and 36.09% for

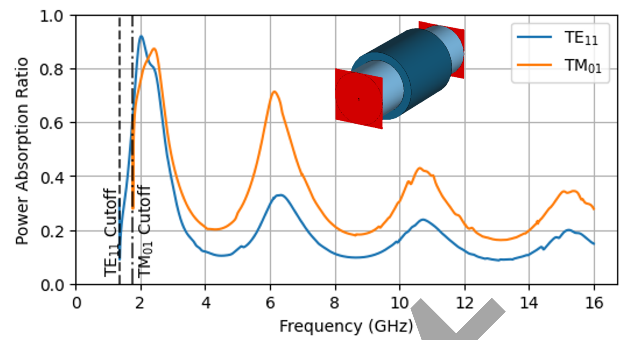

Figure 5: Power Absorption Ratio of a BLA made of SC1000 for TE11 and TM01 modes excited at Port 1.

TM_{01}. These results demonstrate that SC1000 provides effective broadband attenuation of the dominant propagating HOM modes, making it a suitable candidate for warm BLA and provide a benchmark for assessing its compatibility with cryogenic operation, which remains to be investigated.

CONCLUSION AND OUTLOOK

SC1000 was characterized from 200 MHz to 35 GHz, and the results are consistent with previous measurements reported by other institutions. These measurements were used to benchmark the proposed coaxial-based measurement setup, whose simulations demonstrate stable and reliable extraction of the material permittivity. Based on these results, we can proceed with the procurement of the setup. In parallel, the measured dielectric data were used to simulate the RF absorption performance of a BLA made of SC1000, confirming its suitability for warm operation and providing a reference for its expected cryogenic performance. Further simulations of the BLA behavior will be carried out, including the evaluation of fundamental mode losses and wakefield simulations to quantify the absorption of propagating HOMs. This methodology provides a consistent framework for evaluating and comparing candidate materials for cryogenic HOM absorber applications in PERLE and future accelerator facilities.

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