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

A. Perez Ruiz[†,1,2,3], A. Miyazaki[1,2], P. Martinez Reviriego[4], S. Gorgi Zadeh[4],
N. Catalan-Lasheras[4], A. Grudiev[4], A. Iziquel[3]
[1]Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[2]On behalf of the PERLE collaboration
[3]Accelerators & Cryogenic Systems, Orsay, France
[4]CERN, Geneva, Switzerland

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.

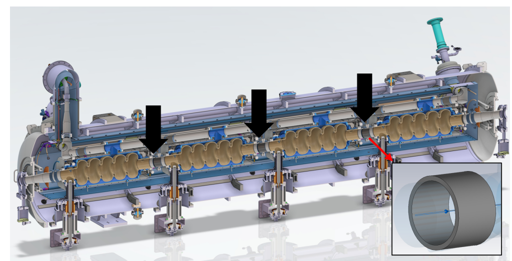

Figure 1: BLAs for the PERLE Cryomodule.

DIELECTRIC PROPERTIES OF MATERIALS

The RF absorption performance of BLAs is primarily determined by the dielectric properties of the material [6], which are 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 is 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 approximated as $\mu = \mu_0$. Nevertheless, it has been reported that some materials may exhibit apparent magnetic losses under cryogenic conditions, as observed in [5], although these effects were ultimately attributed to calibration artifacts.

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

* Work supported by funding from European Union's program EU HORIZON-INFRA-2023-TECH-01-01 under GA n°101131435.
† axel.perez-ruiz@ijclab.in2p3.fr

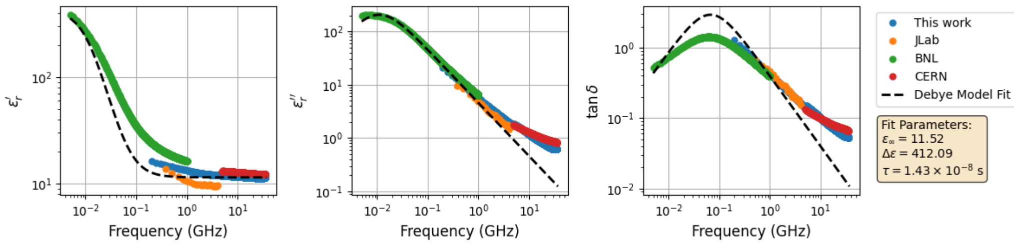

Figure 2: Dielectric properties of SC1000 measured by different institutions. (Left) Real part of the relative permittivity; (middle) imaginary part; (right) loss tangent.

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). All measurements reported in this work were performed at room temperature. 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 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'', shows better agreement than the real part, ε_r'. Small differences between production lots may lead to variations in density, porosity, and grain structure, affecting the effective permittivity and dielectric losses. Additional discrepancies may arise from calibration uncertainties and differences in measurement techniques. Overall, the measurements show good agreement between laboratories, confirming SC1000 as a reliable candidate material for room-temperature HOM absorbers.

Moreover, a Debye model was fitted to the data, following the approach proposed for sintered SiC ceramics in [7]. The model assumes a single dielectric relaxation mechanism 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. However, sintered SiC ceramics exhibit more complex dielectric behavior associated with their microstructure, porosity, and multiple polarization mechanisms over a broad frequency range. 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.

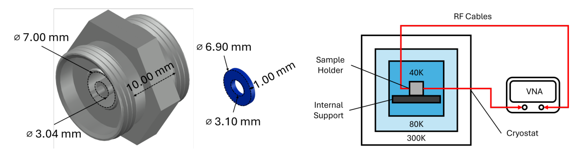

Figure 3: (Left) sample holder with sample under test; (right) simplified representation of the cryogenic setup.

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), whose main dimensions are indicated in the figure, 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:

$$\varepsilon_r = \frac{\ln(b_s/a_s)}{(\varepsilon_{r,\text{eff}})^{-1}\ln(b/a) - \ln(a_s/a) - \ln(b/b_s)}, \qquad (4)$$

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 sample holder were performed using CST Studio Suite with the Frequency Domain Solver. The CST model consists of a simplified coaxial airline geometry that preserves the critical

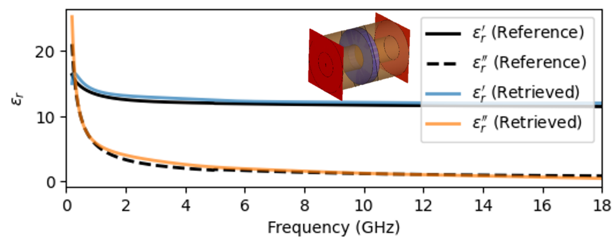

Figure 4: Retrieved dielectric permittivity for SC1000 from simulated S-parameters compared to reference values.

Table 1: Candidate Materials

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

dimensions of both the sample holder and the sample shown in Fig. 3 while omitting non-essential mechanical details. The dielectric properties of the sample used in the simulations were imported from the measurements shown in Fig. 2. Fig. 4 shows ε_r of SC1000 obtained after processing the simulated S_{11} and S_{21} parameters. The "Reference" curve corresponds to the previously measured dielectric properties of SC1000 shown in Fig. 2. These results validate the proposed measurement setup and support proceeding with the fabrication of the sample holder and the procurement of candidate materials.

Candidate Materials

Several candidate materials have been proposed, including sintered SiC/AlN and CMC ceramics. A non-exhaustive list of the considered materials for further study is presented in Table 1. Among them, only STL150D14KL, SC35 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

$$P_A(f) = 1 - \sum_m |S_{11}^{(m)}(f)|^2 - \sum_n |S_{21}^{(n)}(f)|^2, \tag{5}$$

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

Considering the CST model shown in Fig. 5, consisting of a hollow cylinder with inner radius $R_{i,\mathrm{BLA}} = 65\,\mathrm{mm}$, length $l_{\mathrm{BLA}} = 100\,\mathrm{mm}$, and thickness $t_{\mathrm{BLA}} = 10\,\mathrm{mm}$, the room-temperature absorption performance of a BLA made of

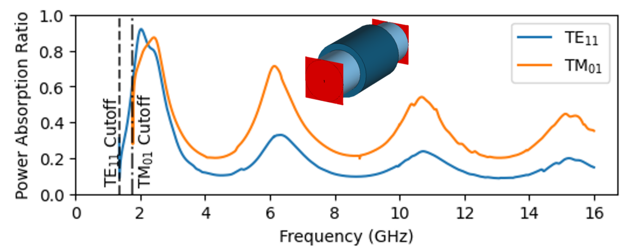

Figure 5: Power Absorption Ratio of a BLA made of SC1000 for TE_{11} and TM_{01} modes excited at Port 1.

SC1000 was evaluated for the TE_{11} and TM_{01} modes excited at one port, representing dipole and monopole HOMs. At each port, 60 propagating modes were considered. Fig. 5 shows the power absorption ratio up to 16 GHz, corresponding to the standard deviation of the PERLE beam spectrum ($\sigma_f = 16\,\mathrm{GHz}$). The proposed geometry exhibits broadband single-pass absorption, with average values of 20.27% for TE_{11} and 36.48% for TM_{01}, indicating effective attenuation of propagating HOMs over a broad frequency range. These values characterize the broadband RF absorption of the proposed geometry at room temperature but are not, by themselves, a measure of compliance with the PERLE HOM damping requirements, which require cryogenic dielectric characterization and dedicated wakefield simulations.

CONCLUSION AND OUTLOOK

SC1000 was characterized from 200 MHz to 35 GHz at room temperature, and the results are consistent with previous measurements reported by other institutions. These measurements provide a validated room-temperature baseline and 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, the setup can now be fabricated for future cryogenic measurements. In parallel, the measured dielectric data were used to simulate the RF absorption performance of a BLA made of SC1000, demonstrating broadband absorption of the dominant propagating modes and providing a reference for the absorber design. Future work will extend the dielectric characterization to the PERLE operating temperature (40 K), together with further BLA simulations, including the evaluation of fundamental mode losses and wakefield simulations to quantify the absorption of propagating HOMs and assess compatibility with the HOM damping requirements of PERLE. This methodology provides a consistent framework for evaluating and comparing candidate materials for cryogenic HOM absorber applications in PERLE and future accelerator facilities.

ACKNOWLEDGEMENTS

We would like to thank Wencan Xu and Silvia Verdu Andres from BNL for providing us with the SC1000 samples; Jiquan Guo and Patricia Duchesne for the fruitful discussions; and Lin Guo for providing us with the low frequency data of SC1000 measured in BNL.

REFERENCES

[1] *Silicon carbide (SiC/SSiC)*, Kyocera, 2023. https://www.kyocera-fineceramics.de/en/materials/silicon-carbide

[2] C. Barbagallo, "Design and optimization of higher order mode couplers for the superconducting cavities of the PERLE energy recovery linac", Ph.D. thesis, Université Paris-Saclay, Orsay, France, 2024.

[3] P. Kolb *et al.*, "Cold tests of HOM absorber material for the ARIEL eLINAC at TRIUMF", *Nucl. Instrum. Methods Phys. Res. A*, vol. 734, pp. 60–64, 2014. doi:10.1016/j.nima.2013.05.031

[4] R. Eichhorn *et al.*, "Cornell's HOM beamline absorbers", paper WEPWO059, pp. 2441–2443, Sep. 2013.

[5] T. Ota *et al.*, "Development of HOM dampers for superconducting cavities", in *Proc. PASJ'16*, Aug. 2016, paper MOP022, pp. 377–379.

[6] D. M. Pozar, *Microwave engineering*. Hoboken, NJ: Wiley, 2005.

[7] Y. Takeuchi *et al.*, "RF dielectric properties of SiC ceramics and their application to design of HOM absorbers", pp. 1195–1197, May 2005. doi:10.1109/PAC.2005.1590705

[8] W. D. C. Jr. and D. G. Rethwisch, *Materials science and engineering: an introduction*. Hoboken, NJ: Wiley, 2018.

[9] W. Xu *et al.*, "High-power test results for a cylindrical-shell silicon carbide higher-order-mode damper", *Phys. Rev. Accel. Beams*, vol. 27, p. 031601, 2024. doi:10.1103/PhysRevAccelBeams.27.031601

[10] *DAK. Dielectric Assessment Kit V 3.0: DAK-TL2 Hardware Setup*, Schmid & Partner Engineering AG, Mar. 2024. https://www.auden.com.tw/wp-content/uploads/2025/03/DAK-Professional-Handbook-March2024.pdf

[11] P. Martinez-Reviriego *et al.*, "HOM SiC loads for CLIC X-band structures: Design and measurements", *Nucl. Instrum. Methods Phys. Res. A*, vol. 1082, p. 171076, 2026. doi:10.1016/j.nima.2025.171076

[12] J. Guo, "HOM damping for the EIC ESR SRF cryomodule", presented at the International Workshop on Higher Order Modes in Superconducting Cavities, DESY, Hamburg, Germany, Oct. 2025, unpublished. https://indico.desy.de/event/47723/contributions/193785/

[13] G. De Michele, "Wakefield simulations and measurements for the CLIC RF accelerating structure", Ph.D. thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 2014.

[14] V. Shemelin and N. Valles, "Improved accuracy of measurements of complex permittivity and permeability using transmission lines", *Nucl. Instrum. Methods Phys. Res. A*, vol. 767, pp. 385–396, 2014. doi:10.1016/j.nima.2014.07.047

[15] E. J. Rothwell *et al.*, "Analysis of the Nicolson-Ross-Weir method for characterizing the electromagnetic properties of engineered materials", *Prog. Electromagn. Res.*, vol. 157, pp. 31–47, 2016. doi:10.2528/PIER16071706

[16] *Measurement of dielectric material properties*, SIGLENT Technologies, 2024. https://www.siglenteu.com/application-note/measurement-of-dielectric-material-properties/

[17] A. Saini, "Reviews of higher order modes effects in LCLS-II superconducting linac", presented at the ICFA Mini Workshop on High Order Modes in Superconducting Cavities, Warnemünde, Germany, Aug. 2016, unpublished. https://indico.global/event/6511/contributions/52775/