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Improved accuracy of measurements of complex permittivity and permeability using transmission lines

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ABSTRACT

Strong damping of Higher-Order-Modes (HOMs) excited by the beam in accelerating cavities is a necessary condition for achievement of high currents and low emittances in storage rings, electron-positron colliders, and high average power Energy Recovery Linacs (ERLs). Characterization of the electromagnetic properties of lossy ceramics and ferrites used in HOM loads is therefore an essential part of constructing these accelerators. Here we show how to improve these measurements beyond the state of the art. In the past, significant discrepancies have been typical between measured properties for different batches of the same material. Here we show that these can be explained not only by technological deviations in the material production but also by errors in the dimensions of the measured samples. We identify the main source of errors and show how to improve the accuracy of measuring the electromagnetic parameters of absorbing materials.

1. Introduction

In high-current accelerators using superconducting cavities, the fields excited by the beam in the higher-order modes (HOMs) of the cavity have to be kept small to avoid degradation of the beam quality and excessive power dissipation at cryogenic temperatures [1]. Due to the small wall losses of superconducting cavities, HOMs having no other source of damping linger for a long time. The HOM fields induced in the cavity by one bunch of a particles act on the particles in subsequent bunches and can cause the beam to become unstable. To avoid beam instabilities and cryogenic losses from HOMs, they can be damped by adding HOM couplers to the structure which damp HOMs in RF-absorbing materials.

These HOM loads became a substantial part of the accelerator. For example, the Cornell Energy Recovery Linac [2] will have 448 HOM loads. Suppression of the beam-breakup instability [3] in the ERL can be achieved only with a strong damping of cavity HOMs and careful handling of the beam-induced HOM power.

Importance of the HOM problem for the accelerator community led to several specialized HOM workshops with a separate session on the absorbing materials (CEBAF – 1993, Cornell – 2010, Daresbury – 2012, Fermilab – 2014).

In the following we show three examples of HOM loads that have been developed in our laboratory at Cornell. Other important examples are the HOM loads at KEK [5], those at CEBAF [6], and those at the European XFEL [7]. The RF design of the Cornell ERL HOM load was adopted from CESR's HOM load but major changes were implemented since that time (Fig. 1) because of the following reasons.

(1) To minimize the packing fraction, the ERL absorbers are operated at a temperature about 80 K.

(2) Shorter bunches, high current, and necessity of low emittance require damping HOMs over a large frequency range. This is why 3 different absorber materials were used for the ERL injector, so that the dangerous modes of any frequency face high absorption at least at one of them.

(3) Experiments with a beam showed that absorbers in the injector have an insufficient electric conductivity at the cryogenic temperatures and can be charged by the beam leading to the beam distortions. In search of a better design, an RF absorber as a single cylinder brazed into a tungsten-heat sink was adopted for the main ERL linac. New materials for the cylinder based on SiC or AlN with embedded carbon nanotubes or graphite are in advanced development and full scale samples are in hand.

2. Measurement of electromagnetic properties of absorbers

Electromagnetic properties of absorbing materials should be accurately determined to allow an adequate design of a higher-order-mode damping load.

Laboratory measurements of the dielectric permittivity ε and the magnetic permeability μ of potential HOM load materials are performed by inserting samples into a coaxial line or a rectangular waveguide as illustrated in Fig. 2.

The sample geometry is a cylinder with a hole (washer) for a coaxial line measurement and a rectangular plate for measurements

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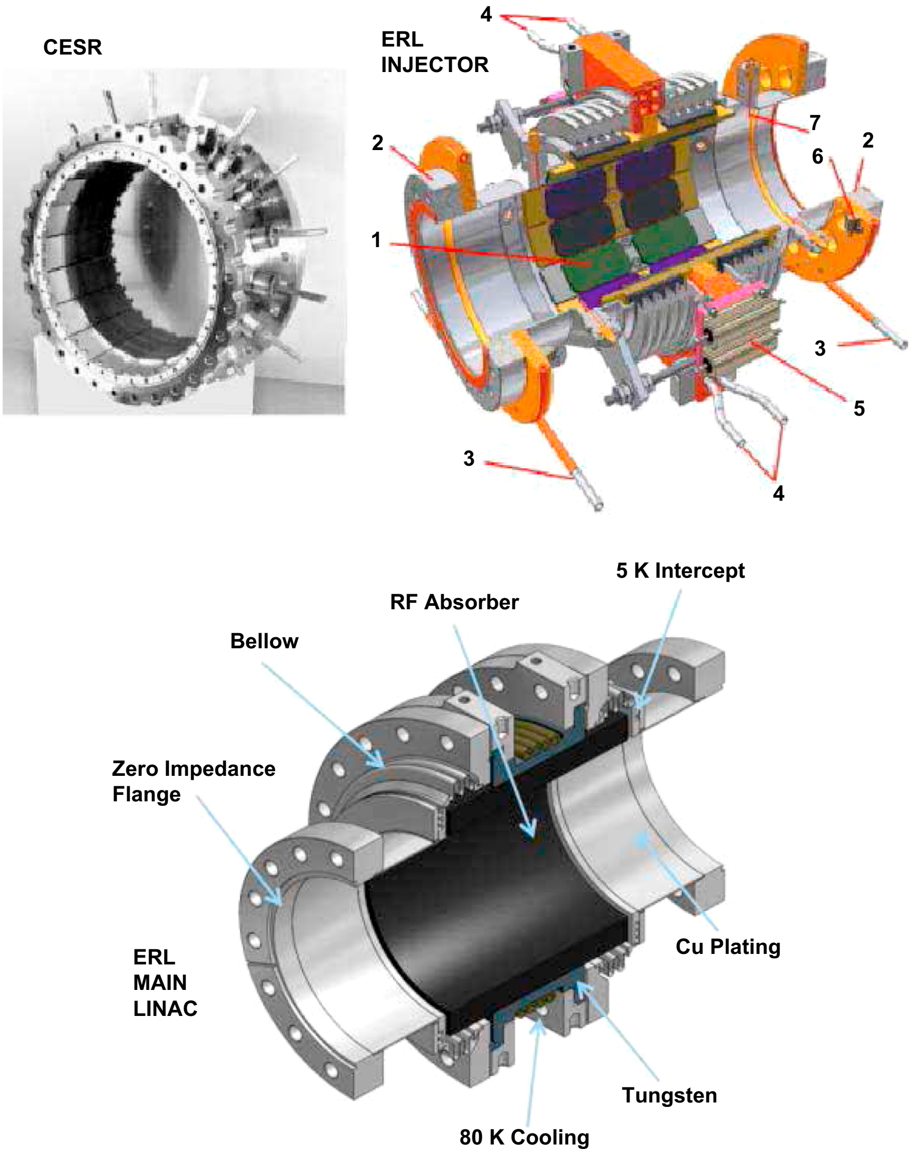

Fig. 1. CESR and ERL injector and main linac HOM loads. 1 – absorber plates, 2 – flange to cavity, 3–5 K He cooling loop, 4–80 K cooling loop, 5–80 K heater, 6–5 K heater, and 7 – HOM pickup.

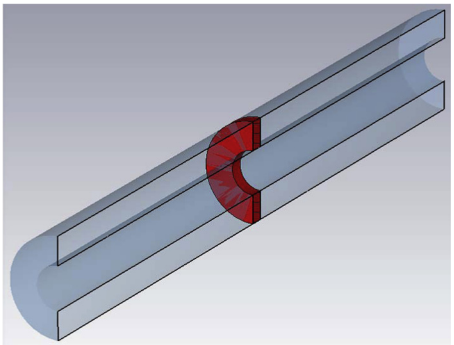

Fig. 2. Cross-section of a coaxial line with a sample.

with waveguides. Dielectrics and ferrites were measured at room and cryogenic temperatures at frequencies up to 40 GHz [4]. A sample was characterized via the *S*-parameters of the tested insertion device which is a holder with a sample inside, and from these two complex parameters, S_{11} and S_{21}, two other complex parameters, ε and μ, were found.

As it was pointed out at the HOM 2010 workshop [8], previous measurements of dielectric permittivity of possible HOM materials were inaccurate and future material characterization requires careful theoretical and experimental treatment. The situation with accuracy of measurements did not change, as the results of the next workshop on HOMs in superconducting cavities (HOMSC12) have shown [9]. Data for the samples made of the same material in different frequency ranges and with different transmission lines was discontinuous at the boundaries of the frequency ranges.

Careful study showed that even small gaps – which are unavoidable and arise from machining variation – between the metal surfaces of the coaxial line or waveguide and the surface of the measured sample lead to large errors in the values of ε. The strong field concentration near the inner conductor of the coaxial line results in especially large errors as discussed in [10]. Errors in μ are not so significant but can also be accounted for magnetic materials if the values of gaps are known.

Development of the theory for dielectric sample measurements within waveguides in the presence of gaps was found in the works of Baker-Jarvis [11] who summarized the earlier works in which the influence of gaps was analyzed [12–15].