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HIGH GRADIENT TESTING OF THE FIVE-CELL SUPERCONDUCTING RF MODULE WITH A PBG COUPLER CELL*

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Abstract

We report results of high-gradient testing of the first 5-cell superconducting radio frequency (SRF) module with a photonic band gap cell (PBG).

Higher order mode (HOM) damping is vital for preserving the quality of high-current electron beams in novel SRF accelerators. Because HOMs are not confined by the PBG array, they can be effectively damped in order to raise the current threshold for beam instabilities. The PBG design increases the real-estate gradient of the linac because both HOM damping and the fundamental power coupling can be done through the PBG cell instead of via the beam pipe at the ends of the cavity. A superconducting multi-cell cavity with a PBG damping cell is therefore an attractive option for high-current linacs.

The first-ever SRF multi-cell cavity incorporating a PBG cell was designed a LANL and built at Niowave Inc. The cavity was tuned to a desired gradient profile and underwent surface treatment at Niowave. A vertical test (VTS) was then performed at LANL, demonstrating an abnormally low cavity quality factor in the accelerating mode of 1.6×10^6. Future tests are proposed to determine the source of the losses and resolve the problem.

Figure 1: 2.1 GHz 5-cell module with a PBG center cell, made from bulk niobium.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are the natural choice for future generations of high energy linacs, especially for high-duty-factor machines where the heat produced in the accelerating structure cannot be effectively extracted [1]. Going to higher frequencies in SRF cavities is desirable in some applications for various reasons. First, it allows us to lower cost and increase achievable luminosity of an electron beam. Second, it is necessary for harmonic cavities operating at multiples of accelerator frequency. However, higher-order-mode (HOM) wakefields excited by a beam scale as the frequency cubed and can easily destroy the beam in a high-frequency machine. One high-current linac of relatively high frequency is the proposed SRF harmonic linac for eRHIC [2], which would be used to undo nonlinear distortion of the beam's longitudinal phase space induced by the main linac waveform.

Photonic band gap (PBG) cavities are of interest to the particle accelerator community because they have reduced higher-order modes that can degrade beam quality [3,4]. Unlike a room temperature PBG cell, the superconducting cell must be closed in the transverse plane and utilizes waveguide couplers to extract the HOMs (Fig. 1). Waveguide couplers are commonly used as an HOM suppression mechanism but are usually attached to the beam pipe (see, for example, [5]). In contrast, low field at the periphery of the PBG cell allows us to attach the waveguide couplers directly to the outside wall of the cell. This is beneficial to HOM damping and increases real estate gradient by saving space on the beampipes [6].

One of the three waveguides is also utilized as a fundamental power coupler (FPC). This particular 5-cell module was originally designed for the LANL Navy FEL beamline with high beam current (100 mA), and therefore requires a strongly coupled FPC, which is achieved by removing one of the PBG rods. Accelerating properties of the module are similar to that of a design with 5 elliptical "low loss" cells [7].

Previous superconducting tests of single PBG cells have achieved high gradients and high quality factors [8]. However, building a 5-cell module involved new challenges such

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as ensuring that the peak surface magnetic fields in all cells are equal. For that reason fabrication and tuning techniques were first tested with a copper prototype of the 5-cell module which was also used to measure HOM damping properties [7]. After successful fabrication and tuning, a Nb cavity was made for high gradient testing.

FABRICATION AND TUNING

The cavity was fabricated by Niowave, Inc. from a combination of fine-grain niobium sheets and machined ingot parts, joined by electron-beam welding. Two halves of the PBG cell were stamped and then fitted and joined with the PBG array rods. All 5 cells were welded together in a few steps with tuning between them in order to account for the effect of weld shrinkage on field flatness.

Tuning was done by trimming halves of each elliptical cell at the equator. Gradient profile after the final weld was within 5% of the design and no additional tuning was required. Nevertheless, the elliptical cells were squeezed a little in longitudinal direction to even-out the profile. Final gradient profile is shown on Fig. 2.

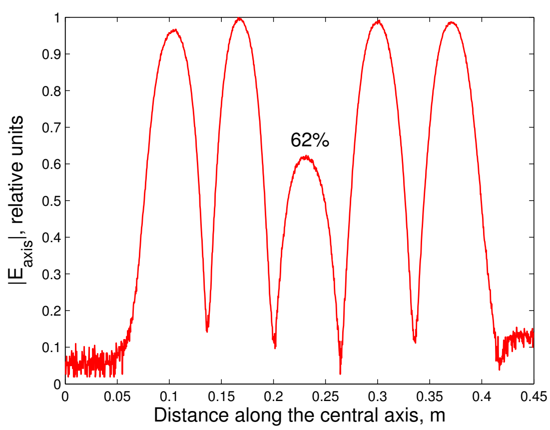

Figure 2: Gradient profile of the tuned cavity obtained from bead-pull measurements. The field in the center cell is intentionally lowered to ensure equal surface magnetic field in every cell.

The cavity quality factor measured at room temperature (Q_{300K} = 7300) corresponded to Nb bulk conductivity $\sigma = 6.3 \times 10^6\ \Omega^{-1} m^{-1}$ which is in good agreement with theory.

For a high-gradient test it was not necessary to tune the cavity to exactly 2.100 GHz, therefore the center (PBG) cell was not tuned. Nevertheless, the resulting frequency of the cavity in operation was within 0.5% of the design frequency (2.1062 GHz in liquid Helium). In a multi-cavity linac where all the structures must be tuned to the same frequency, a few different mechanisms of tuning have been proposed, including pushing on the inside of the PBG rods. A cavity tuner which stresses and compresses the full cavity to tune the frequency of the structure will affect the field flatness because the elliptical cells will tune much more easily than the center PBG cell. Likely such a scheme would allow sufficient tuning to synchronize a multi-cavity linac with very little cost in terms of field flatness, however. Prototype tuning and simulations of this effect are planned.

After welding, the cavity was chemically treated using 1:1:2 buffered chemical polish (BCP) solution of HF, HNO_3, and H_3PO_4 to etch 150 μm of the inner niobium surface, and high-pressure rinsed with ultrapure water, both at Niowave.

The FPC and the two HOM waveguide couplers were covered with Nb RRR≥300 plates to provide an RF seal. The plates were clamped between the cavity flanges and stainless steel covers. Aluminum hexagonal gaskets (Diamond) were placed between the waveguide flanges and the stainless steel covers to provide a vacuum seal (Fig. 3).

HIGH GRADIENT TESTS

At Los Alamos, the cavity was assembled with a pickup probe and an adjustable drive probe (Fig. 3) in a class 100 clean room. Both probes were hollow aluminum rods designed to match the 50 Ω impedance of coaxial lines. The pickup probe was designed to provide external quality factor $Q_e = 6 \times 10^{11}$, and the drive probe to provide Q_e in a range $2 \times 10^7 < Q_e < 10^{10}$. Adjustability was provided by a bellow that could be squeezed or extended to change Q_e (Fig. 3). A macor support plate was used to prevent the long drive probe from tilting relative to the axis.

A 200W TWT amplifier was used to feed RF power through the drive probe. A phase lock loop was used to lock the generated RF frequency to the cavity resonant frequency.

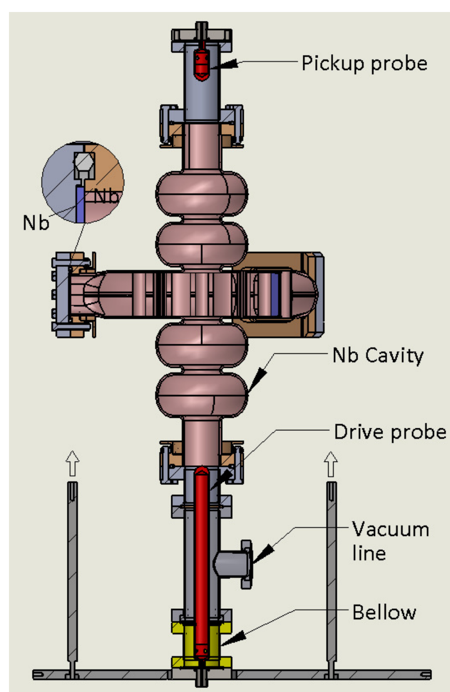

Figure 3: Cross section of the 5-cell module with the pickup assembly and the drive assembly.

The cavity was baked at 120 °C for 2 days. It was then pumped down to 5×10^{-8} Torr before putting it in liquid

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Helium. The cavity was then quickly covered with Helium to prevent hydrides from forming on the surface (Q-disease). A magnetic field compensating coil was used to compensate for the Earth's magnetic field.

A network analyzer was used to find all but one spatial variations of the monopole mode: π, $4\pi/5$, $3\pi/5$, $2\pi/5$ modes. Frequencies of the modes were confirmed with HFSS simulations. The $\pi/5$ mode was not excited by the probe because of it has small fields in the end cells.

It was found that even when the drive probe was all the way in (strongest coupling), all 4 modes were very under-coupled. The coupling to the cavity did not change even after going from a helium bath temperature of 4 K (atmospheric pressure) to 2 K. This indicates that the mode has a very low unloaded quality factor Q_0 dominated by non-superconducting losses.

Longer drive and pickup probes were made for coupling to the low-Q modes (simulated Q_e^{min} of the drive probe is 1.1×10^5). The RF surface was inspected but no defects were seen. The cavity was reassembled, high pressure rinsed and baked again. The experiment was then repeated at a helium bath temperature of 4 K.

With the new probes, the accelerating mode was still undercoupled which means that Q_e of the drive probe was higher than the simulations predicted. However, now we could use the phase lock loop to estimate Q_0 from pulse decay time: $Q_{0\,\pi} = 1.6 \times 10^6$. It was not possible to feed significant power into the cavity to reach high accelerating fields, so only the anomalous low-field Q value is shown in (Fig. 4). Using the same technique, Q_0 for the $3\pi/5$ mode was found to be even lower: $Q_{0\,3\pi/5} = 9.3 \times 10^5$.

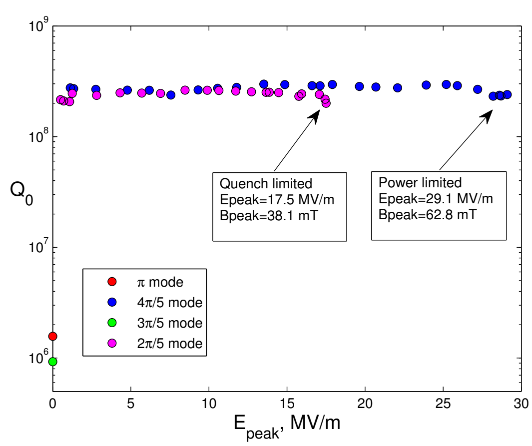

Figure 4: Cavity quality factor for different modes as a function of peak surface electric field at 4K. The drive probe was adjusted to provide near critical coupling to the modes $2\pi/5$ and $4\pi/5$, or max achievable coupling for modes π and $3\pi/5$.

The other two modes showed much higher Q factors, although still lower than expected: $Q_{0\,2\pi/5} = 2.2 \times 10^8$, $Q_{0\,4\pi/5} = 2.7 \times 10^8$. For each of the two modes, we were able to adjust the drive probe to be near critically coupled ($\beta \approx 1$) . We were able to feed up to 135W of power into the cavity and measured Q_0 vs E_{peak} (Fig. 4), where E_{peak} is the surface electric field used to compare the relative field levels of modes with very different shunt impedance values.

Maximum achievable field in the $2\pi/5$ mode was limited by quench-like behavior with rapid change from near zero to 100% reflected power and back. The quench showed no improvement after a few minutes of feeding the power. For the $4\pi/5$ mode, several similar quenches were processed and we eventually reached the limit of maximum available RF power. At surface field of about 29 MV/m, rapid increase in X-rays was observed indicating field emission, but was quickly processed. No consistent multipacting barriers were encountered.

Note that both $2\pi/5$ and $4\pi/5$ modes have small fields in the PBG cell, while both π and $3\pi/5$ modes have significant fields in the PBG cell. This indicates that the PBG cell is the source of the non-superconducting losses that limit Q factors of the π and the $3\pi/5$ modes.

CONCLUSIONS

The first SRF multi-cell accelerating cavity with a PBG coupling cell was fabricated and tuned to the desired gradient profile. The cavity has been tested at cryogenic temperatures, and it has been shown that the accelerating mode has an unusually low Q factor, inconsistent with the predicted BCS losses. There is strong evidence that the problem is in the PBG cell. It may be caused by either insufficient surface treatment that left foreign metal on the inner surface, or losses in the FPC and the HOM couplers. Losses in the waveguides could potentially be explained by poor RF seal that is formed by Nb plates clamped to the waveguide flanges. Other experiments with strongly coupled FPC (such as [9]) involved indium gaskets to provide both RF and vacuum seals.

Redesign of the waveguide covers is currently under development, using different gaskets to lower the losses or a field-cancelling structure to mitigate currents across the mechanical joint. Additional cavity processing steps (etching and high-pressure rinsing) may also be required as preparation for future tests.

ACKNOWLEDGEMENTS

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