STATUS AND TEST RESULTS OF HIGH CURRENT 5-CELL SRF CAVITIES DEVELOPED AT JLAB*

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Abstract

The development of a new compact CW cryomodule for use in future Energy Recovery Linacs (ERLs) and Free Electron Lasers (FELs) is underway at JLab with the objective of transporting beam current up to Ampere-levels [1]. Design goals include broadband cavity Higher Order Mode (HOM) damping, HOMs tuned to safe frequencies to minimize the power extracted from the beam, good real-estate gradient and cryogenic efficiency and consideration of cost and maintainability. Two 1497 MHz high current niobium five-cell cavities with waveguide end groups have been manufactured recently. We report on the latest results including high field tests in a vertical Dewar at 2K and a detailed assessment of the impedance budget for beam breakup (BBU) instability. The general cryomodule and cavity concept is described as well.

INTRODUCTION

Future high brightness, high energy and high current light sources for research and industry desire new CW cryomodules for superconducting RF (SRF) cavities with challenging technological objectives. These arise from demanding beam stability requirements at high beam currents with the need for superior HOM damping efficiency compared to existing designs to improve BBU thresholds by two or more orders of magnitude, moderate to high fundamental power couplers (FPCs), good cryogenic efficiency and comparably high accelerating fields in a compact layout. JLab is pursuing the conceptual design of such cryomodules for high power compact ERL-based FELs at low frequencies (< 1 GHz) and light sources at higher frequencies depending on the accelerating scheme (single- or multi-pass) and average beam current [1]. The design and concept followed is scalable to the frequency of choice. We have developed several cavities at 1497 MHz (CEBAF RF frequency) to make use of JLab's existing infrastructure for fabrication and testing of components. We also intend to address major technological issues by producing a cryomodule for a cavity pair to be installed in JLab's FEL injector as a first beam testbed. In this paper we present the latest status of our ongoing activities.

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CRYOMODULE CONCEPT

Figure 1 shows the principle cryomodule concept by means of the cavity pair module for JLab's FEL injector.

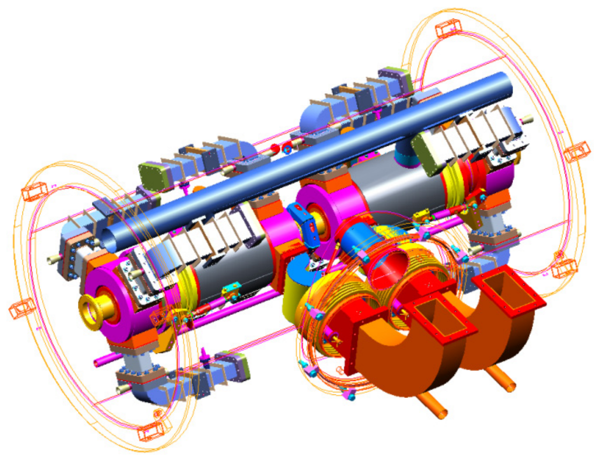

Figure 1: 3D CAD view inside a 1497 MHz high-current cavity pair cryomodule under development.

Each cavity is equipped with rectangular waveguide end groups for heavy HOM damping with a total of six waveguides. The cavities are housed in their own helium vessel so that the end groups are cooled as well. There are no helium-to-beam line vacuum flange joints. Utilizing a three-folded waveguide configuration employed in an SRF environment closely follows the efficient HOM-damping scheme of normal conducting storage ring cavities. One end group per side assures damping of HOMs even if they are tilted after fundamental mode tuning. The waveguides are spaced azimuthally symmetrically to capture modes of different polarizations and to avoid potential steering kicks. All waveguides incorporate cold to warm transitions with the HOM loads placed at ambient temperature. Five HOM waveguides per cavity are pointing outwards and are then turned by 90 degrees to provide a compact design. A rotation of the end groups with respect to each other prevents interference of the waveguides and creates room for a straight helium supply and two-phase return pipe. One waveguide per cavity will be used both as FPC and to extract HOM energy. It has a short waveguide section that is cut-off for the fundamental mode, the length of which determines the external quality factor, followed by a transition to a standard sized waveguide. It uses a high power RF window shielded from the beam by a "dogleg" transition to avoid line of sight to the ceramic. Dynamic losses in the warm section will be intercepted by a 50 K heat station. The cutoff of the HOM waveguides provides a natural filter to reject the fundamental mode, however, the evanescent fields in the waveguides are still significant. Hence superconducting extensions are used outside of the helium vessel to mitigate RF losses. One major concern is that the extensions must be kept superconducting by conduction cooling to the helium vessel or by additional external helium circuits.

RF TEST RESULTS

Initial considerations to optimize a high-current cavity aimed for a good cryogenic efficiency and a minimization of power extracted from the beam. The findings led to a rounded pillbox cell shape design with flat side walls resembling a "low loss" cell (high R/Q*G) [2]. It also provides strong coupling of HOMs to the end groups. By choosing five cells we have made a good compromise between HOM damping efficiency, mitigation of trapped modes and a compact design.

Various niobium prototype cavities with the new cell shape have been built earlier and successfully tested at high fields in a vertical Dewar at 2 K with no signs of multipacting [3]. Among those are two 1497 MHz single-cell cavities - one with a waveguide end group - and a bare 1497 MHz five-cell cavity. Based on the promising results two fine grain niobium five-cell cavities have been produced recently. These are fully equipped with two waveguide end groups as shown in Figure 2 and have been tuned for field flatness.

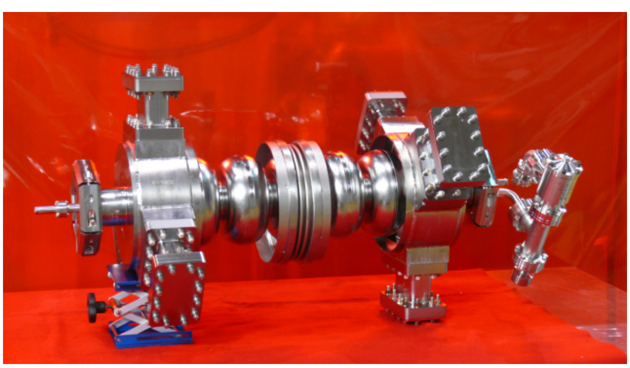

Figure 2: 1.5 GHz high-current cavity with two three-folded waveguides and blanked-off Nb extensions.

A series of vertical RF tests at 2 K have been performed to assess the limits of accelerating field (E_{acc}) and unloaded quality factor (Q_0) by exploring the feasibility of adequate cleaning, processing and assembly of the cavity, end groups and niobium extensions (4" long) as well as checking out potential multipacting barriers. Figure 3 summarizes the final vertical test results. Both cavities were tested with niobium blanked-off end groups using indium seals. No niobium extensions were assembled initially. Cavity #1 reached E_{acc} = 24.5 MV/m only limited by the available power (green triangles) and cavity #2 was quench limited at E_{acc} = 20.5 MV/m (blue diamonds). Both cavities are well suited for JLab's FEL injector, where only ~10 MV/m are required.

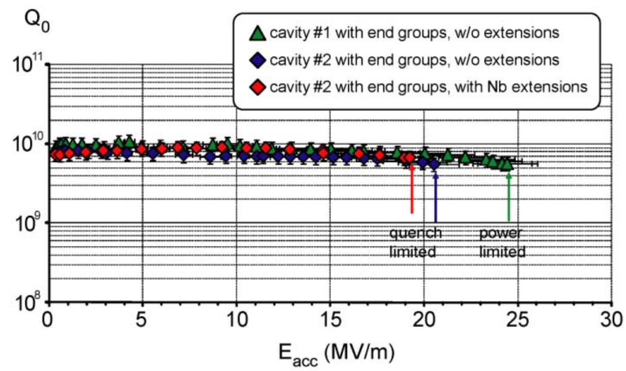

Figure 3: Q_0 vs. E_{acc} for two niobium 1.5 GHz five cell cavities with end groups measured at 2 K.

Cavity #2 was then disassembled to install the niobium extensions on each waveguide (two indium seals implemented per waveguide). After destroying a strong field emitter initially we could achieve similar Q_0-levels (red diamonds) as in the previous test. This indicates a sufficient decay of evanescent fields within the extensions not causing significantly more RF losses. However the quench limit was slightly reduced to E_{acc} = 19.2 MV/m. This could be the result of particulate contamination introduced during the second assembly step.

IMPEDANCE BUDGET AND BBU

The BBU instability is of major concern in high current accelerators and thus there is a demand for HOM damping schemes which exceed the performance of present cavities. A careful investigation of the broadband HOM damping efficiency becomes important. This has been confirmed recently in CEBAF's recirculating accelerator where strong BBU phenomena have been observed for the first time caused by a single inadvertently deformed cavity within a cryomodule installed in 2007 [4].

To assess the impedance budget of the high current 1497 MHz five-cell cavity design we have performed "bead pull" measurements on a full scale copper cavity for the most prominent modes and extensive 3D numerical calculations. For the latter we have used MAFIA in time domain, to compute the cavity broadband impedance from a Fourier Transform of the beam induced wake potential, and CST Microwave Studio (MWS) in frequency domain to deliver valuable information on the field profile and external quality factors (Q_{ext}) of individual modes. Both codes are able to calculate HOM impedances with absorbing boundary conditions at the waveguide and beam tube ends [5]. By utilizing a multi-beam excitation scheme in MAFIA [6] we have calculated monopole modes (excitation on axis) and different polarizations of dipole and quadrupole modes (excitation 1 cm off axis) to minimize mode overlaps particularly prevalent in well-damped multi-cell cavities. This helps to more rigorously identify radial field dependencies of HOMs - with some remaining crosstalk - and to evaluate dipole as well as quadrupole BBU scenarios. As summarized in Figure 4 the experimental and numerical findings are in good agreement. Here the HOM spectra (MAFIA) and individual impedances (MWS and measurements ($R/Q*Q_{ext}$)) are plotted up to 3GHz revealing impedances well below $10^6\ \Omega$ ($R = V_{eff}^2/(2P_{loss})$). With our setup the HOMs in the first dipole passband (TE_{111}) could not be measured accurately as these have been damped strongly yielding only a poor signal-to-noise ratio. Discrepancies between the different codes indicate that in MAFIA some modes, for instance quadrupole modes around 2.52 GHz, have not yet reached their peak impedance as the wake length has been limited to 672 m due to CPU time constraints. However, the most parasitic monopole and dipole modes are well resolved.

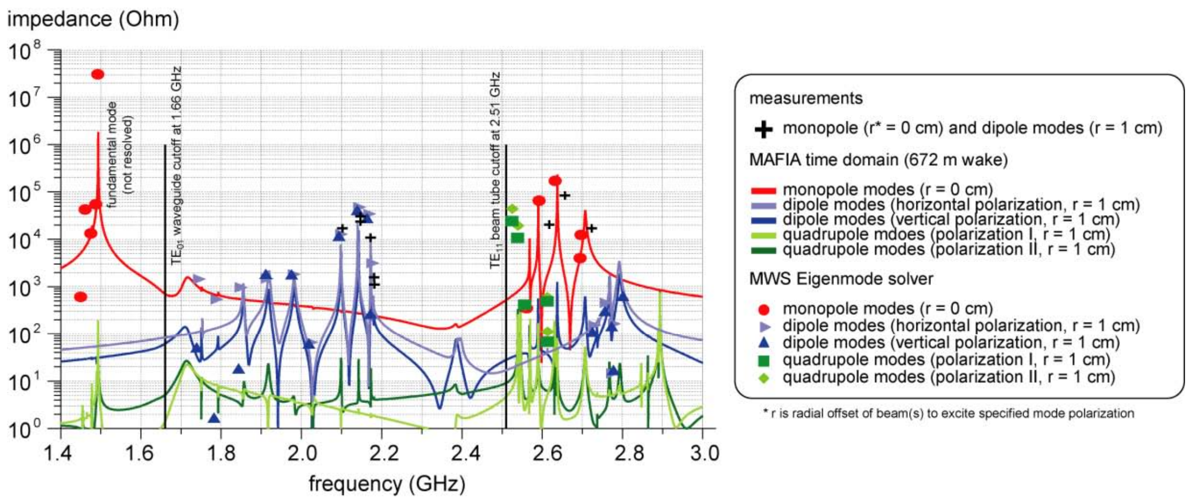

Figure 4: Comparison of simulated and measured HOM impedances (see text for further explanation).

To demonstrate the HOM damping efficiency of the high current cavity design BBU simulations have been performed using the GBBU code [7]. The lattice of the proposed Florida State University ERL-based FEL driver has been utilized for this purpose [8]. Here a bunch is injected at 10 MeV/c and accelerated to a maximum of 60 MeV/c assuming a 50 MeV cryomodule housing six cavities (E_{acc} = 16.7 MV/m). As beam deflecting dipole modes are the major cause of BBU instabilities we have taken into account the first two dipole passbands which contain the strongest HOM impedances. For a five cell cavity this amounts to ten horizontally and vertically polarized dipole modes respectively. A realistic spread of each mode frequency within ±5 MHz was generated uniformly among all six cavities prior to each simulation.

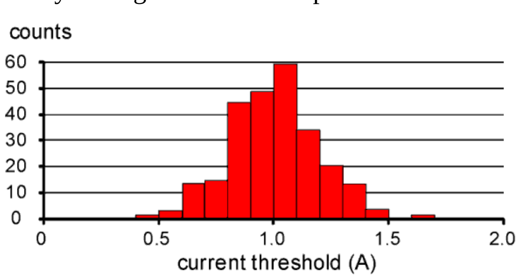

Figure 5: Histogram summarizing the results of 250 GBBU simulations with a mean BBU threshold of 0.95A.

Figure 5 displays the threshold current statistics of 250 GBBU simulations. The mean threshold current is about 1A, thereby providing confidence for our claim of an Ampere-class cryomodule.

CONCLUSION AND OUTLOOK

We have produced and tested two niobium 5-cell 1497 MHz cavities of optimized shape with waveguide end groups for high current applications. Both cavities have been tested at high fields in a vertical Dewar at 2K meeting our preliminary goal of E_{acc} = 16.7MV/m at $Q_0 = 8\times10^9$. More ambitious goals may be envisioned by considering further post processing of the cavities such as electro-polishing. The strong HOM damping efficiency of the cavity layout has been verified numerically and experimentally by assessing the impedance budget up to 3 GHz. Corresponding BBU simulations for a particular machine lattice shows that an Ampere of average beam current can be tolerated before the instability begins. The cavities produced are well suited for the cavity pair cryomodule (E_{acc} = 10 MV/m, 10 mA current) under design to be installed in JLab's FEL injector. With this cryomodule major technological issues can be addressed in a real beam testbed to prove the feasibility of a next generation of Ampere-class cryomodules.

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