PROGRESS ON THE HIGH-CURRENT 704 MHZ SUPERCONDUCTING RF CAVITY AT BNL *

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Abstract

The 704 MHz high current superconducting cavity has been designed with consideration of both performance of fundamental mode and damping of higher order modes. A copper prototype cavity was fabricated by AES and delivered to BNL. RF measurements were carried out on this prototype cavity, including fundamental pass-band and HOM spectrum measurements, HOM studies using bead-pull setup, prototyping of antenna-type HOM couplers. The measurements show that the cavity has very good damping for the higher-order modes, which was one of the main goals for the high current cavity design. 3D cavity models were simulated with Omega3P code developed by SLAC to compare with the measurements. The paper describes the cavity design, RF measurement setups and results for the copper prototype. The progress with the niobium cavity fabrication will also be described.

INTRODUCTION

The Collider-Accelerator Department at BNL and the Physics and Astronomy Department at Stony Brook University are actively working on accelerator projects based on a superconducting RF (SRF) cavity for high-current linacs. At Stony Brook the motivation is the development of very high current, CW proton accelerating cavities for the intensity frontier, and BNL is pursuing R&D towards the electron-ion collider (eRHIC) [1] and coherent electron cooling [2]. The requirements of the high current, high brightness and high charge linac structures led to the design of a 704 MHz 5-cell cavity with strong HOM damping capability. Additional benefit of the new design is, its higher real-estate accelerating gradient, which is very important for long linacs.

To reach the critical HOM damping requirements of high current Energy Recovery Linac (ERL), the 704 MHz high-current superconducting cavity has been designed with consideration of both performance of the fundamental mode firstly, and the damping of dipole higher order modes (HOMs), which are mainly to reduce the $(R/Q)_d\, Q_{ext}$ values, is also immersed into the cavity design process. A copper prototype of the BNL3 cavity was fabricated by Advance Energy Systems, Inc. (AES) [3]. Several measurements were carried out on this prototype to check HOM propagation. This paper describes the cavity design and RF measurement of the copper prototype cavity.

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BNL3 CAVITY DESIGN

Nb Cavity Design

The new 5-cell cavity, BNL3 cavity [4], was designed with consideration of the fundamental mode performance, resulting in *R/Q* increase of about 20% compared to the previously designed BNL1 cavity for the R&D ERL at BNL [5], which has very long, large diameter beam tubes connected to room-temperature higher-order-mode dampers. The BNL3 cavity still employs the concept of using a large beam tube to propagate all HOMs but its end cells have irises that improve the confinement of the fundamental mode inside the structure. Three antenna HOM couplers, separated azimuthally by 120º, are located at each beam tube of the cavity. The HOM coupler groups at two ends of the cavity are rotated by 60º relative to each other. Through avoiding the room-temperature ferrite damper on the beam pipe, the real-estate gradient of BNL3 cavity has improved by about 50% as compared with the BNL1 cavity. To reduce the cross-talk between neighboring cavities, tapered sections to a reduced diameter beam pipe are added on both sides of the cavity. Figure 1 (top) shows the configuration of the BNL3 cavity with HOM couplers. The field profile of the fundamental mode by Superfish [6] is shown in Figure 1 (bottom).

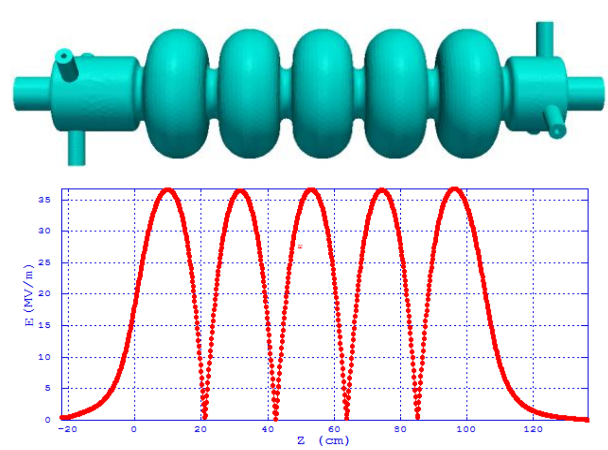

Figure 1: BNL3 cavity configuration with HOM couplers (top) and fundamental mode field profile (bottom).

One must take into account the beam break up (BBU) instability when designing cavities for high current energy recovery linacs. The BBU threshold beam current depends mainly on the strength of dipole HOMs. It is clear from BBU formula [7] that a small $(R/Q)_d\ Q_{ext}$ can increase the threshold current. The $(R/Q)_d$'s have been calculated with the 3D code Omega3P [8] for the whole cavity model. The BNL3 cavity was designed for the high current ERL machine, eRHIC, which is a 50-mA, 6-pass ERL and BBU is an important limit on the maximum shunt impedance of the HOMs, which together with the *R/Q* values determines the minimum required *Q* factors. Figure 2 shows the estimated worst-case impedance limit as red line (R_{sh_th}) set by the BBU for the maximum M_{12} value of the six arcs for 5 GeV eRHIC, which is 250.458 m. It also shows *R/Q* values in the frequency range from 800 to 2000 MHz (blue diamonds) and the simulated transverse impedances with waveguide boundary replacing tapers - $(R/Q)Q_{ext\_bp}$ (black squares) and for 6 probes on the cavity - $(R/Q)Q_{ext\_coax}$ (green triangles). Comparing the simulated impedances with the worst-case limit, we can conclude that (i) with proper alignment, the probe-type couplers can reach the waveguide-type HOM damping capability; (ii) the designed cavity's HOM impedance is well below the BBU limit.

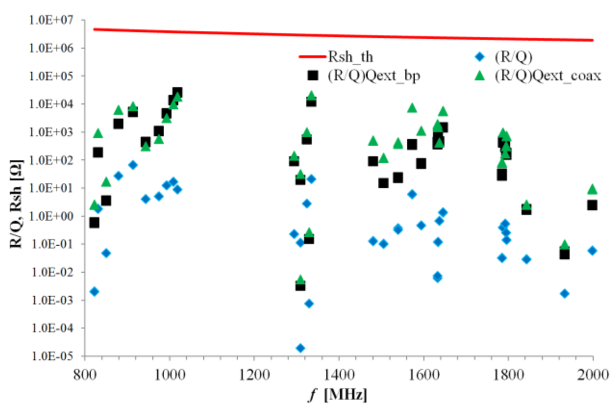

Figure 2: Simulated *R/Q* values (blue diamonds), transverse shunt impedance values without taper (black squares), transverse shunt impedance values with 6 probes (green triangles) and estimated worst-case BBU limit (red line).

Copper Prototype Cavity Design

There are two main benefits for making a copper prototype cavity prior to a niobium cavity. First of all, it will verify the RF performance, such as field flatness check, study of the HOM damping; secondly, the experience with tooling and making copper prototype cavity make fabrication of Nb cavity easier. To study the HOM propagating performance and HOM coupler's damping capability, we designed the prototype copper cavity with detachable endgroups. As it is shown in Figure 3, the copper prototype includes 5-cell cavity body, FPC side endgroup (left) and pick-up side endgroup (right). Using this copper prototype, we tuned the field flatness and study the HOM damping capability, which will be addressed in the following sections.

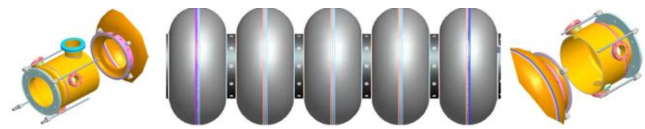

Figure 3: Prototype copper cavity (middle) and detachable endgroups (left and right).

ROOM TEMPERATURE TEST

Field Flatness

Because of the large cell-to-cell coupling, the initial field flatness was already 90% and it only took 3 passes to complete the tuning. The final field profile is shown in Figure 4. After tuning, the spread was ±1.2%, the tilt of the field was -1.0% and the mean field was 98.5%. The target frequency for the niobium cavity at room temperature has been set to 703.28 MHz, which was established with consideration of frequency changes due to cool-down to cryogenic temperature, material removal by the Buffered Chemical Polish (BCP), evacuation, pressure of liquid helium and so on. However, the exact frequency match is not required for the copper prototype and AES tuned the cavity to 703.16 MHz, which is close enough to the target. The same tooling and tuning technique will be used on the niobium cavity.

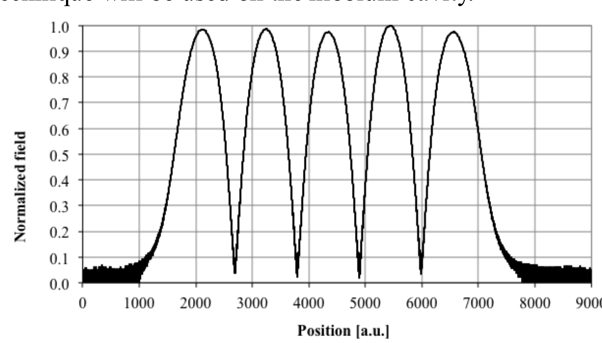

Figure 4: Field flatness tuning at AES.

RF Measurement on the Copper Prototype

To efficiently suppress a higher order mode we need the following: (1) propagate the HOM out of the cavity (no HOM trapped in the cells) to the location of HOM coupler or damper; (2) couple the HOM out through a HOM coupler, such as beam-pipe coupler, antenna coupler or loop coupler; (3) dissipate the HOM power in an absorber or load. Hence the first measurement was to check propagation properties of the higher order modes by measuring the external *Q* with open beam pipe ends. This measurement setup with different boundary conditions on the beam pipe is shown in Figure 5. The cavity has two short pieces of beam tubes, one with the

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fundamental power coupler (FPC) port, the other one with the pickup port, mounted on opposite sides.

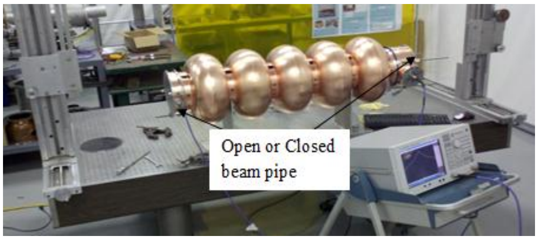

Figure 5: Measurement setup of BNL3 cavity with open beam pipe ends.

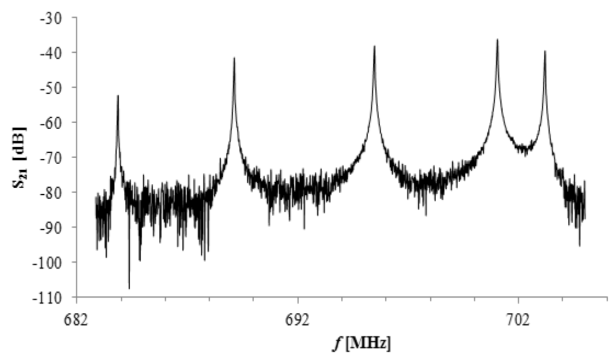

Figure 6: The fundamental passband of the prototype copper cavity with open beam pipe.

Figure 6 shows the fundamental passband of the cavity with open beam pipes. The simulated *Q*'s and frequencies agree well with measurement. However, the frequencies differ on the 100 kHz scale, because the cells in the model were ideal shape rather than the copper cells.

The HOM spectrum measurement from 0.8 to 2 GHz was shown in Figure 7. With detailed mode-by-mode measurement, it turned out that the dipole modes propagate into the beam tube very well. Only four *Q*-values could be measured by -3 dB bandwidth method and the highest external Q was found to be only 2878 at 1021.03 MHz, a mode whose R/Q is relatively small, 4.98 Ohm. The results also show that quadrupole modes propagated very well.

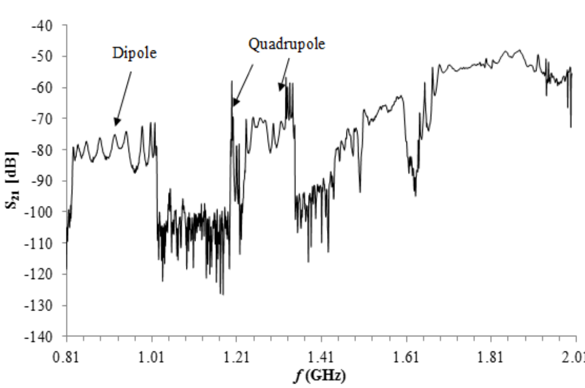

Figure 7: HOM spectrum of the prototype cavity with open beam pipe.

It is interesting to compare the open beam pipe and a close beam pipe because it will show clearly how good is the damping with open beam pipe, meaning how close is the "open" beam-pipe to a "perfect" absorber attached at the end of the pipe. Figure 8 compares of the S_{21} measurements for open and closed conditions. This measurement verifies the excellent propagating properties of the BNL3 cavity through the dramatic reduction of the loaded *Q* values in the open beam pipe case.

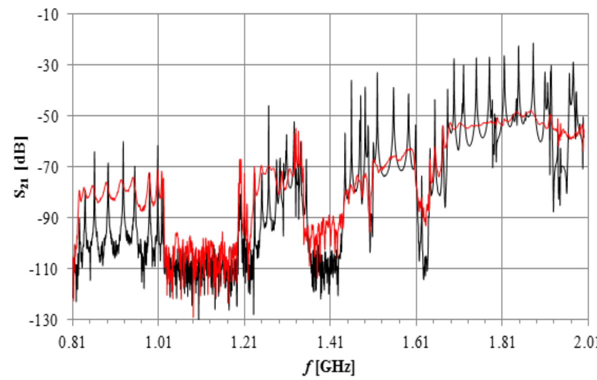

Figure 8: Comparison of the S21 spectra for closed (black) and open (red) beam pipes.

CONCLUSION

The BNL3 cavity was designed for high current SRF linac applications. The design addressed the fundamental mode optimization as done in a conventional cavity design as well as the higher-order-mode damping, which is important for high beam currents. A copper prototype was fabricated and tuned at AES to the final field flatness of 98.5%. The measurement of the HOM spectrum up to 2 GHz of the BNL3 cavity has been carried out. The measurement results show that the HOMs has excellent propagation properties. We conclude that the HOMs can be damped well given a proper HOM coupler configuration. The Nb cavity is under fabricating at AES and will be delivered to BNL this summer.

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