SUPERCONDUCTING 5-CELL CAVITY DESIGN AND COPPER PROTOTYPE CAVITY FOR AN ENERGY RECOVERY LINAC AT THE ADVANCED PHOTON SOURCE*

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Abstract

A 100-mA 5-cell cw superconducting cavity operating at 1.4 GHz has been designed for the proposed ERL upgrade project at the Advanced Photon Source. In order to achieve high current, the cavity shape was optimized and large end-cell beam pipes were adopted. The beam break-up (BBU) threshold of the cavity was estimated using the code TDBBU, which showed a high threshold for a 7-GeV energy recovery linac model. A copper prototype cavity was built using half-cell modules that were initially assembled by clamping the cells together. The rf parameters of the cavity and higher-order modes were measured and compared with the simulation results from Microwave Studio.

INTRODUCTION

In order to meet the needs of the upgrade of the Advanced Photon Source (APS) [1, 2], a 100-mA 5-cell cw superconducting cavity was designed and studied. An important issue for a high-current superconducting cavity is the beam break-up (BBU) threshold limit. In order to provide a high BBU threshold for the cavity, large end beampipes and low cell numbers were used. The cell shape was also optimized to give a low E_{pk}/E_{acc} and B_{pk}/E_{acc}. A copper prototype cavity was fabricated and measured using bead pulls and compared with simulation results.

BBU THRESHOLD

The expression of the BBU threshold for a single parasitic mode was given by [3, 4, 5]

$$I_{th} = -\frac{2c^2}{e\left(\frac{R}{Q}\right)_\lambda Q_\lambda \omega_\lambda} \frac{1}{T_{12}^* \sin \omega_\lambda t_r} \quad (1)$$

$$T_{12}^* = T_{12}\cos^2\theta_\lambda + \frac{T_{14}+T_{32}}{2}\sin 2\theta_\lambda + T_{34}\sin^2\theta_\lambda \quad (2)$$

where e is the elementary charge, λ is the mode number, $(R/Q)_\lambda$ is the ratio of shunt impedance and quality factor, Q_λ is the quality factor, θ_λ is the polarization angle from the x direction, t_r is the bunch return time, and the matrix T relates the transverse momentum to transverse displacement after one turn.

From Eq. (1) we see that the BBU threshold is inversely proportional to $(R/Q)_\lambda Q_\lambda$ and ω_λ. As a result, the BBU threshold may be improved by lowering either the $(R/Q)_\lambda Q_\lambda$ value or the cavity operating frequency. Since reducing the cavity frequency will increase the construction and operation cost as well as the risk of surface contamination, the BBU threshold was improved by decreasing the $(R/Q)_\lambda Q_\lambda$ value of the cavity.

CAVITY DESIGN

The cavity design is focused on lowering the $(R/Q)Q_e$ of the higher-order modes (HOMs) while maintaining the $(R/Q)Q_e$ of the accelerating mode (π mode), where Q_e is the external quality factor. A large iris was used to increase the coupling factor to greater than 3%, and large end beampipes were used to decrease the Q_e of the HOMs. The cell shape was optimized to lower the E_{pk}/E_{acc} and B_{pk}/E_{acc}. In order to keep the field flatness larger than 99%, the end half-cell was optimized separately. The end beampipe was designed to transition smoothly to the end half-cell to lower the Q_e of the HOMs. Although the R/Q was lowered by approximately 15 Ω for the operating mode, this structure reduced the Q_e of the HOMs significantly. Figure 1 shows the optimization parameters of the cell shape, and Figure 2 shows the cross-section of the cavity structure with the π-mode electric field in the cavity. The parameters of the final cavity are shown in Table 1.

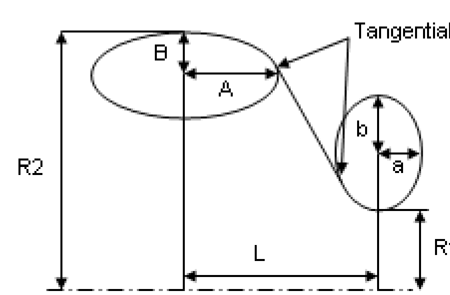

Figure 1: Cell shape optimization parameters.

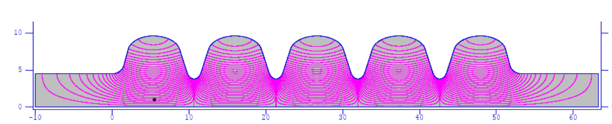

Figure 2: Optimized cavity shape and π-mode field contours calculated by Superfish.

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Table 1: Cavity parameters

Type	Elliptical
Frequency (MHz)	1407.7
Q_0	9.3×10^9
No. of cells	5
R_{Iris} (mm)	38
R_{pipe} (mm)	45
$R_{equator}$ (mm)	96.07
R/Q (Ω)	467
E_p/E_{acc}	2.62
B_p/E_{acc} (mT/(MV/m))	4.19
$Q_0 {*} R_s$ (Ω)	276
Loss factor (for σ_z=1mm) (V/pC)	5.6
Field flatness (%)	>99

HIGHER-ORDER MODES

The Q_e of the HOMs of the cavity were calculated by Microwave Studio (MWS) and compared with the 100-mA BBU limits for monopole, dipole and quadrupole modes [6].

For the monopole modes close to the 2N × 1407.7 MHz beam harmonics, assuming an upper power limit of 200 W per mode in a single cavity, the impedance limit is

$$\frac{R}{Q} Q < 2500\Omega\,, \tag{3}$$

Dipole modes:

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 1.4\times10^5 \frac{\Omega}{cm^2 GHz}\,, \tag{4}$$

Quadrupole modes:

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 4\times10^6 \frac{\Omega}{cm^4 GHz}\,, \tag{5}$$

where (R/Q) is the ratio of shunt impedance to quality factor using the circuit definition, Q is the quality factor, and *f* is the frequency of the HOM.

Monopole modes that are resonant with the beam harmonic frequency should be avoided as the beam power loss is extremely high. The simulation results show that there is no resonant monopole mode between 2815 ±34 MHz and between 5631 ±16 MHz, thus it satisfies the monopole limit. Comparing Figs. 3-5 with the BBU threshold limit for 100-mA current in Eqs. (4) and (5), the cavity can be seen to be capable of delivering 100-mA beam current.

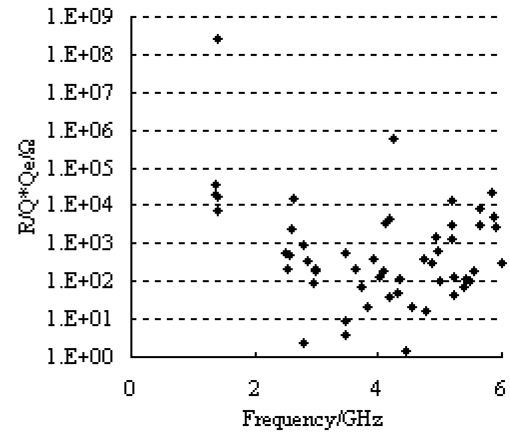

Figure 3: Monopole modes of the cavity.

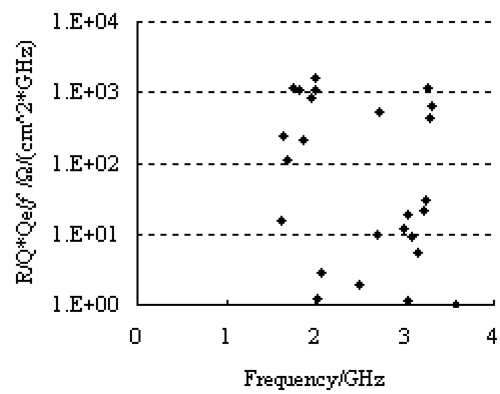

Figure 4: Dipole modes of the cavity.

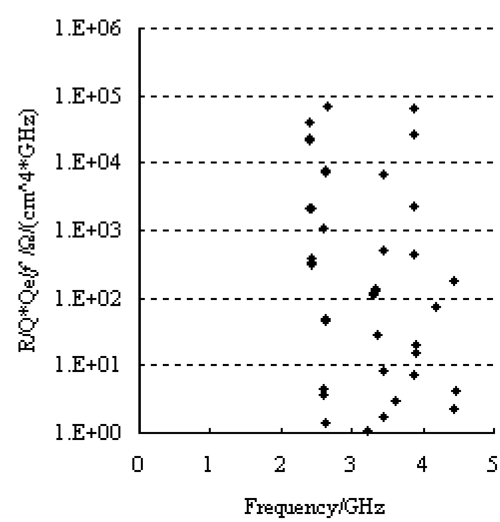

Figure 5: Quadrupole modes of the cavity.

BBU SIMULATION

The code TDBBU [7] developed at JLAB was used to calculate the BBU threshold of the cavity. The model consists of a 7-GeV one-pass ERL with an injection energy of 10 MeV and an accelerating gradient of 20 MV/m. Figure 6 shows the displacement of the bunch leaving the accelerator as a function of bunch number in both the x (horizontal) and y (vertical) directions. After about 50,000 electron bunches, the displacement of the bunch leaving the accelerator reaches a steady state. The convergence of the displacement shows that the beam current is below the BBU threshold.

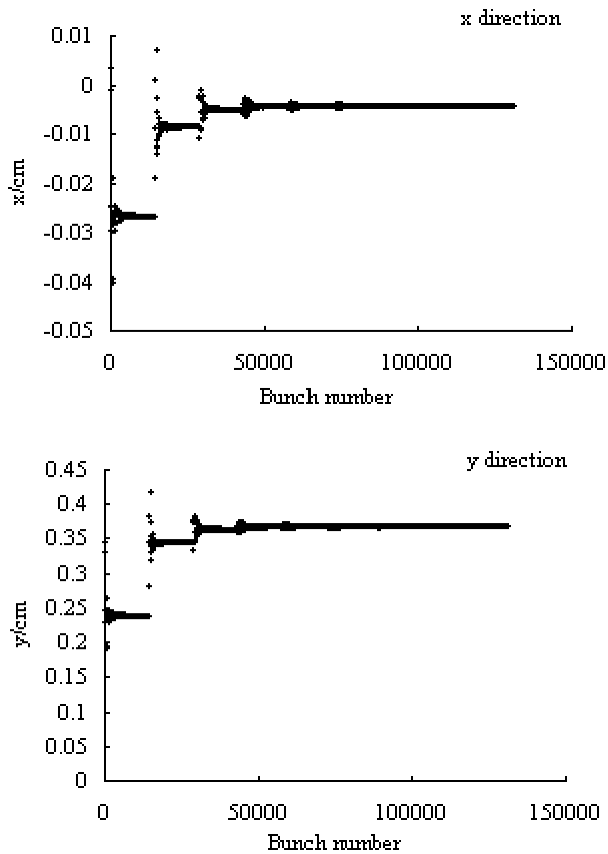

Figure 6: TDBBU simulation results for 100-mA accelerating beam current. The plots above show the displacement of the bunch leaving the accelerator as a function of bunch number.

COPPER PROTOTYPE CAVITY

A copper prototype cavity was built to verify the simulations of MWS. The copper cavity is shown in Figure 7. The cavity was bolted with 12 bolts between each mating surface for good electrical contact. Two orientation sticks were used to maintain alignment between cell halves. After tuning, 98.8% field flatness was measured by the bead pull method (see Figure 8). The measured dipole modes and the corresponding simulation results are shown in Table 2. Six major dipole modes were found and measured in the copper cavity and were in good agreement with the simulation results. The π-mode frequency error was found to be approximately 0.1 MHz for the copper prototype cavity. Figure 9 shows the field comparison of three major dipoles.

Figure 7: Copper prototype cavity.

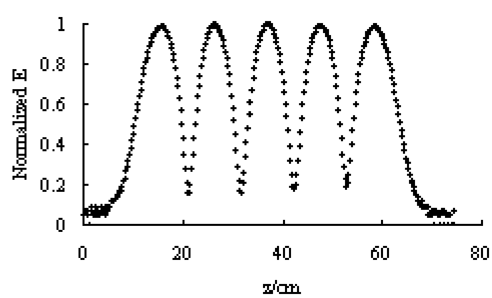

Figure 8: Field flatness of the π mode.

Table 2: Comparison of six major dipole modes

Major HOMs	Frequency (GHz) (Simulation / Copper cavity)
TE111	1.74273 / 1.7457
TM110	1.85807 / 1.8611
TM110	1.99041 / 1.9918
TE111	1.81258 / 1.8158
TE111	1.95653 / 1.9583
TM110	2.00725 / 2.0082

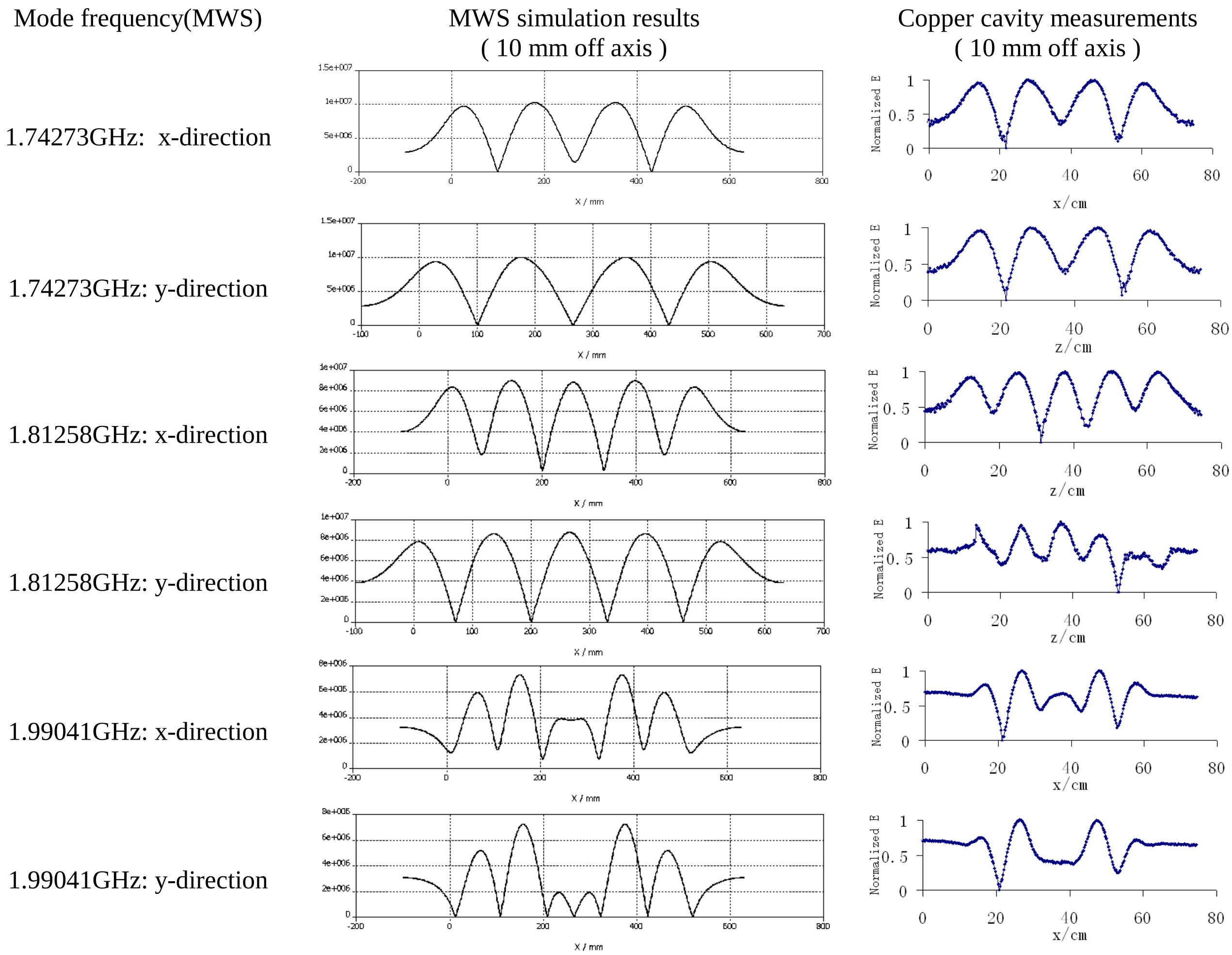

Figure 9: Comparison of dipole modes found in the copper cavity and the MWS simulation.

CONCLUSION

A 100-mA 5-cell superconducting cavity operating at 1.4 GHz was designed and studied for the proposed APS upgrade. The cavity was shown to have efficient damping of higher-order modes while maintaining a high R/Q for the operating π mode and a high geometry factor. The copper prototype cavity bead pull measurements were found to be in good agreement with simulation results both on field patterns and frequencies. The BBU threshold for this cavity was shown to be larger than 100 mA as predicted by the code TDBBU.

Although the cavity is designed for a 7-GeV ERL at the APS, it may be used in other ERLs of varying energies and frequencies.

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[7] TDBBU was written by G. Krafft.