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Design and study of a high-current 5-cell superconducting rf cavity*

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Abstract The Advanced Photon Source (APS) at Argonne National Laboratory is considering the development of a superconducting linac-based fourth-generation hard X-ray source to meet future scientific needs of the hard X-ray user community. This work specifically focuses on the design of an optimized 5-cell superconducting radio-frequency structure well suited for a high-energy, high-beam-current energy recovery linac. The cavity design parameters are based on the APS storage ring nominal 7 GeV and 100 mA beam operation. A high-current 5-cell cw superconducting cavity operating at 1.4 GHz has been designed. In order to achieve a high current, the accelerating cavity shape has been optimized and large end-cell beam pipes have been adopted. The beam break-up threshold of the cavity has been estimated using the code TDBBU, which predicts a high threshold beam current for a 7 GeV energy recovery linac model. A copper prototype cavity has been fabricated that uses half-cell modules, initially assembled by clamping the cells together.

Key words high current, superconducting cavity, higher order modes

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1 Introduction

As part of a proposed upgrade project for a future 7 GeV energy recover linac (ERL) at the Advanced Photon Source [1, 2], a high-current superconducting cavity was designed and studied [3]. The cavity was designed for 100 mA accelerating beam for continuous wave (cw) operation. A copper prototype cavity has been fabricated and measured using bead pull methods.

2 Cavity design

In order to support a 100 mA beam in the 7 GeV ERL, the superconducting cavity was designed to meet the following objectives: (1) less than 200 W power loss from each parasitic monopole mode in order not to exceed the power handling limit of the dampers; (2) greater than 100 mA Beam Break-up (BBU) threshold of dipole and quadrupole modes; (3) no parasitic monopole modes near the beam resonant frequency ($2N\times1407.7$ MHz); (4) elimination of detrimental trapped modes in the cavity; (5) coupling factor greater than 3%; and (6) low ratios of $E_{\rm pk}/E_{\rm acc}$ and $B_{\rm pk}/E_{\rm acc}$.

Proven methods have been used to achieve these objectives [4–6]. The end beam pipes were enlarged in order to decrease the external quality factor, $Q_{\rm e}$, increase the losses of selected higher order modes (HOMs), and transitions between the beam pipes and end-cells were smoothed to avoid trapped modes.

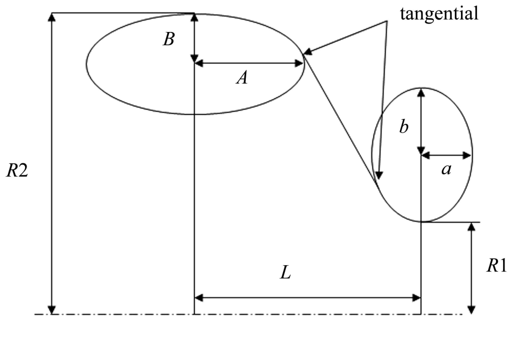

Fig. 1. Optimization parameters of the half-cell.

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Other approaches were to use only 5-cells, design a large iris radius to increase the coupling factor, and finally, cavity shape optimization.

The shape of the cavity was optimized by the high-frequency electromagnetic code Microwave Studio (MWS). Cavity optimization parameters are shown in Fig. 1. The end-cell shape varies slightly from the center cell to achieve a field flatness better than 99% for the accelerating π-mode. Design parameters of the cavity are listed in Table 1.

Table 1. 5-cell superconducting cavity parameters.

type	elliptical
operating frequency/MHz	1407.7
Q_0	9.3×10^9
No. of cell	5
$R/Q/\Omega$	467
$E_{\mathrm{pk}}/E_{\mathrm{acc}}$	2.62
$B_{\mathrm{pk}}/E_{\mathrm{acc}}/(\mathrm{mT}/(\mathrm{MV/m}))$	4.19
$Q_0\times R_{\mathrm{s}}/\Omega$	276
loss factor (for σ_z=1 mm)/(V/pC)	5.6
field flatness (%)	>99

3 Higher order modes

In order to maintain stable beam operation for a 100 mA electron beam in the cavity, the stability limits for monopole, dipole and quadrupole modes must be satisfied [6].

For the monopole modes close to the $2N\times1407.7$ MHz beam harmonics, assuming an upper power limit of 200 W per mode in one cavity, the impedance limit is:

$$\left(\frac{R}{Q}\right)Q<2500\ \Omega. \tag{1}$$

For the dipole modes:

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

For the quadrupole modes:

$$\left(\frac{R}{Q}\right)\frac{Q}{f}<4\times10^6\ \frac{\Omega}{\mathrm{cm^4GHz}}. \tag{3}$$

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

The higher order modes of the cavity including monopole, dipole, and quadrupole were simulated by MWS. The simulation results show that there is no resonant monopole mode between (2815±34) MHz and between (5631±16) MHz (see Fig. 2.), thus it satisfies the monopole limit. The dipole and quadrupole modes impedances satisfy the 100 mA BBU limit as shown in Fig. 3 and Fig. 4.

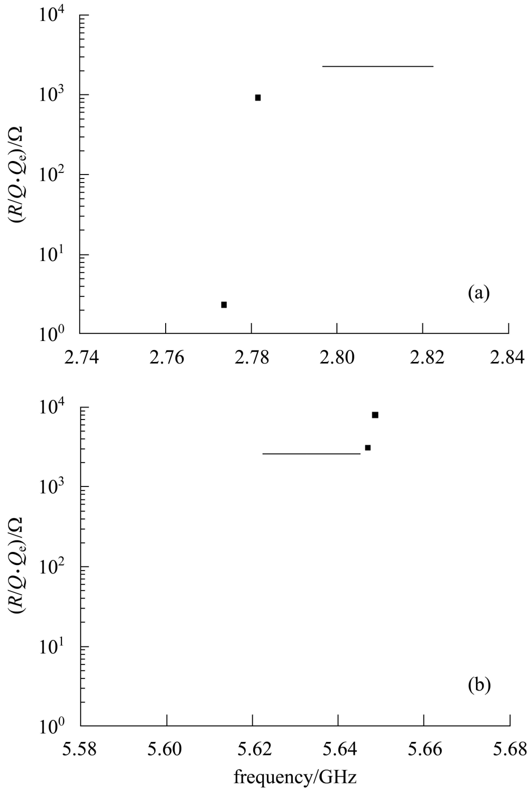

Fig. 2. Monopole modes of the 5-cell superconducting cavity. (a) no monopole mode between (2815±34) MHz; (b) no monopole mode between (5631±16) MHz. The dark line is the 200 W power limit for monopole close to 2.814 GHz and 5.628 GHz.

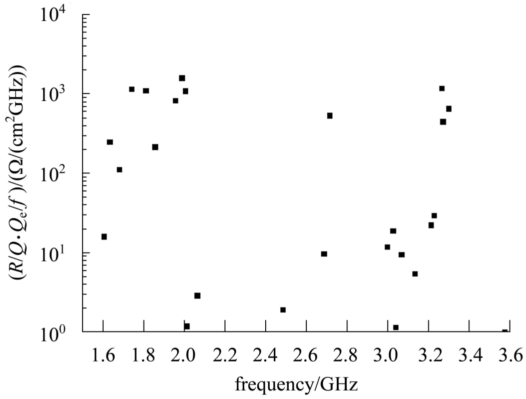

Fig. 3. Dipole modes of the 5-cell superconducting cavity.

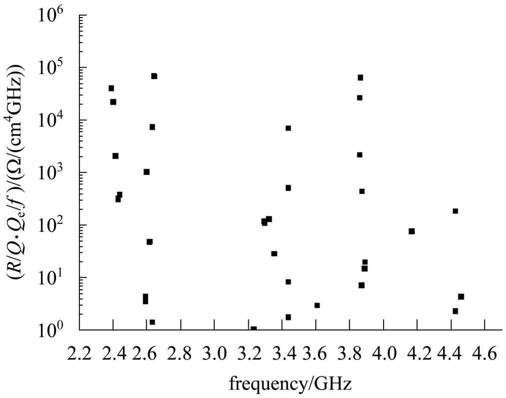

Fig. 4. Quadrupole modes of the 5-cell superconducting cavity.

The BBU threshold of the cavity was also calculated using the code TDBBU [7]. Simulation result using the optimized 5-cell cavity parameters indicates that the proposed APS 7 GeV single-pass ERL can accommodate 200 mA of accelerating beam.

4 Copper prototype cavity

A copper prototype cavity based on the superconducting cavity design was fabricated and measured to verify simulation results. The copper cavity was composed of half-cell modules and initially assembled by clamping the cells together. The cavity was bolted with 24 bolts between each contact surface for good electrical connection. Two orientation sticks were used to maintain alignment between cell halves. After tuning, the field distribution was measured by the bead pull method, its flatness is 98.8%. (see Fig. 5.). The measured dipole modes were in good agreement with the simulation results. The π mode frequency error was approximately 0.1 MHz for the copper prototype cavity. Table 2 shows the comparison of the copper cavity measurement and the simulation results. Six major dipole modes were found and measured in the copper cavity and were in good agreement with the simulation results.

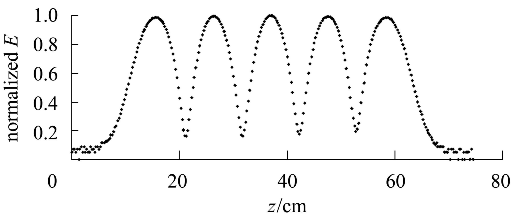

Fig. 5. π mode field pattern of the 5-cell superconducting cavity.

Table 2. Comparison of six major dipole modes of the cavity.

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

5 Conclusion

A 5-cell superconducting cavity has been designed with heavily damped HOMs and a large BBU threshold, the cavity can support up to a 200 mA accelerating beam operation for a 7 GeV single-pass ERL currently under consideration at the Advanced Photon Source. A copper prototype cavity has been fabricated and the initial measurement results show good agreement between experiment values and simulation results.

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