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Preliminary study of a niobium quarter-wave prototype cavity for a heavy-ion superconducting linac

ZHANG Cong(张聪)[1,2;1)] ZHAO Hong-Wei(赵红卫)[1] HE Yuan(何源)[1]
XU Zhe(许哲)[1] ZHANG Zhou-Li(张周礼)[1,2] SUN Lie-Peng(孙列鹏)[1,2]
MEI Li-Rong(梅立荣)[1,2] CONG Yan(丛严)[1,2]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract Superconducting quarter-wave resonators, due to their compactness and their convenient shape for tuning and coupling, are very attractive for low-β beam acceleration. In this paper, two types of cavities with different geometry have been numerically simulated: the first type with larger capacitive load in the beam line and the second type of lollipop-shape for 100 MHz, β=0.06 beams; then the relative electromagnetic parameters and geometric sizes have been compared. It is found that the second type, whose structural design is optimized with the conical stem and shaping drift-tube, can support the better accelerating performance. At the end of the paper, some structural deformation effects on frequency shifts and appropriate solutions have been discussed.

Key words quarter-wave resonator, superconductivity, numerical simulation, electromagnetic field, frequency shift, linear accelerator

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1 Introduction

Superconducting linear accelerators in the energy range from 5 MeV up to about 200 MeV are being widely studied at many laboratories for the acceleration of protons and heavy ions. The primary features of using short, independently phased superconducting cavities, rather than large, normal-conducting DTLs, are the high accelerating gradient, the high ability and the feasibility of accelerating particles with different q/A in the same linac. Different geometries, like spoke, half-wave, quarter-wave resonator (QWR) and reentrant, have been put forward for beam velocities up to β=0.5, where multi-cell type superconducting cavities start to achieve good efficiency [1, 2].

Simplicity, accessibility and low fabrication cost could make QWRs preferable in comparison with other geometries. The superconducting cavities currently used for the acceleration of ions in the velocity range from 0.01c to 0.3c are based frequently on QWR. Numerous types of QWR cavities over a frequency range from 50 to 240 MHz have been built or proposed for a variety of applications.

Currently, the heavy ion research facility in Lanzhou (HIRFL) needs further development, and a high intensity superconducting linac, delivering heavy ions with energy of 14–15 MeV/u (~1 mA), is proposed. Most of the acceleration is provided by 100 MHz QWRs breaking into two beta sections. As for the low beta section, the radio frequency (RF) design of the prototype cavity is presented below.

2 Resonant cavity design

2.1 General approach

The design begins with a 100 MHz, single-drift-tube QWR cavity optimized for particle velocity $\beta = v/c$=0.06. According to the beam dynamics calculation, 12 such structures will suffice to cover the span of velocity for the low beta section.

2.2 Design and numerical simulation

The RF calculations were performed using com-

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1) E-mail: afeng.cong@gmail.com

puter simulation technology (CST) Microwave Studio version 2009, and starting from a simple QWR shape with a straight stem, flat top (shorted side), cylindrical drift tubes, the RF profile has been optimized in order to improve the accelerating performance. Based on the design experience of the existing low-velocity heavy ion superconducting accelerating devices at various laboratories of the world, the geometry of QWR at a close frequency and β has been referenced. Two types of cavity geometry can be chosen: the first one is the larger-capacitive-load type which is adopted in the 100 MHz, β=0.08 QWR of the New Delhi booster linac [3]; the second one is the lollipop-shape type employed in the 88 MHz, β=0.07 QWR of the first SRF linac section of SPIRAL 2 [4]. In what follows, the two types of cavity geometry have been discussed and compared. We hope to figure out one cavity shape which can establish the minimum surface electromagnetic field in order to provide the unit accelerating gradient, because a high surface electromagnetic field exceeding the critical electromagnetic field of the superconductor will cause the superconductor to turn into a normal-conducting state.

Figure 1 and Fig. 2 show the geometry and field distribution along the beam axis of the two types of cavities. Both geometry types of cavities have some features. As for the first type, the large capacitive loading in the high-voltage end shortens the cavity by nearly 120 mm, and this is done to reduce the size of the resonant cavity and to improve the mechanical stability, which decreases rapidly with the increasing length of the coaxial line. As for the second type, the $E_{\rm pk}/E_{\rm acc}$ ratio is reduced by the optimization of the drift tube dimensions and $B_{\rm pk}/E_{\rm acc}$ by a careful choice of the shape of the stem. In this paper, the definition of the accelerating gradient, $E_{\rm acc}=V_{\rm acc}/(\beta\lambda)$, is used, where

$$V_{\rm acc}=\left|\int E_z(z)\mathrm{e}^{\mathrm{i}\omega z/\beta c}\mathrm{d}z\right|,$$

in order to have a shape independent definition for the accelerating field [5]. $E_{\rm pk}$ is the maximum surface electric field and $B_{\rm pk}$ is the maximum surface magnetic field.

With the purpose of studying the optimization of

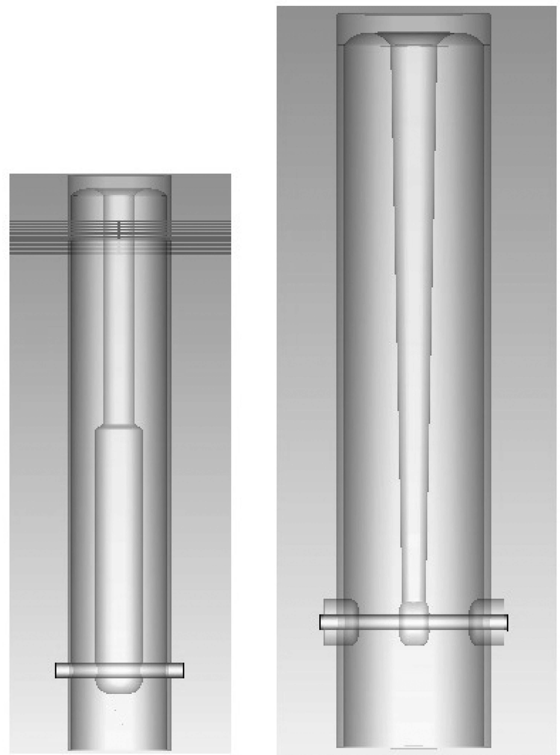

Fig. 1. The CST Microwave Studio Model (version 2009). The cutaway views of the larger-load type (left) and the lollipop-shape type (right).

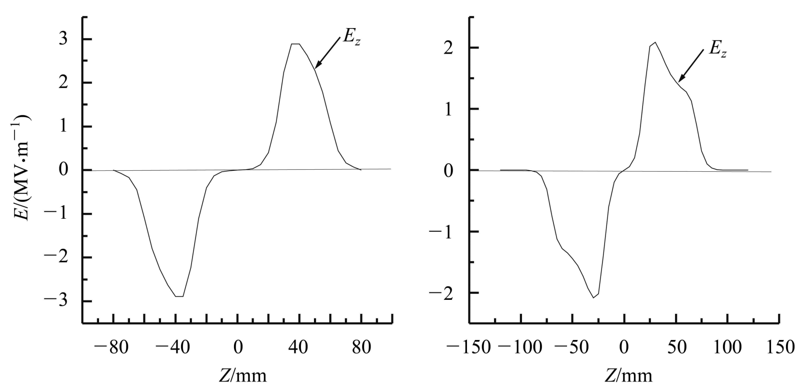

Fig. 2. Z component electric field distribution along the beam axis at the accelerating field of 1 MV/m. The origin of the coordinate is at the center of the resonator drift tube (the left for Type 1 cavity and the right for Type 2 cavity).

the two types of cavities exclusively, the accelerating component E_z distribution along the beam axis and the maximum surface fields are normalized to the accelerating gradient.

From Fig. 2, we can see that a in order to provide a per unit accelerating field, the Type 1 cavity has to create higher electric field along the beam axis, which will lower its tolerance for high accelerating field because of the upper limit of the electric field for superconducting cavity.

The electromagnetic field calculations (see Figs. 3 and 4) show that the maximum surface fields are located around the inner conductor: the magnetic field near the upper stem and the electric field in the beam axis vicinity. Apparently, in the second type of geometry, the way of enlarging the curvature radius of the drift tube and choosing carefully the stem conical part radii helps to obtain the lowest peak fields, and the final geometry gives peak fields over accelerating gradient ratios of $E_{\mathrm{pk}}/E_{\mathrm{acc}} \approx 6$ and $B_{\mathrm{pk}}/E_{\mathrm{acc}} \approx 9$ mT·m/MV, which are much smaller than those values of the first type (see Table 1).

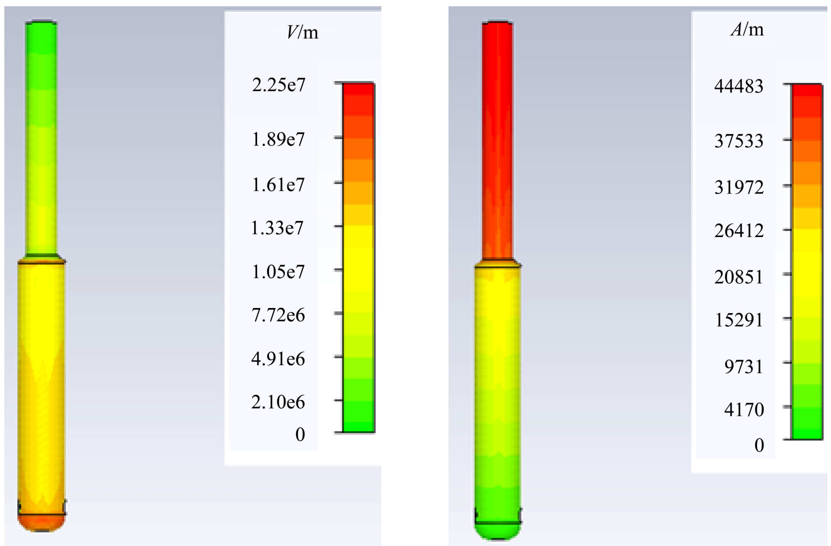

Fig. 3. (color online.) Electric (left) and magnetic (right) surface fields of the Type 1 cavity on the inner conductor, at the accelerating field of 3.01 MV/m, therefore the normalized peak surface electric field is 7.48 MV/m and the normalized peak surface magnetic field is 18.56 mT (the relation expression $H_{\mathrm{p}} = B_{\mathrm{p}}/\mu_0$ is used, where μ_0 is the magnetic permeability of vacuum with the value of $4\pi \times 10^{-7}$ T·m·A^{-1}, the same below).

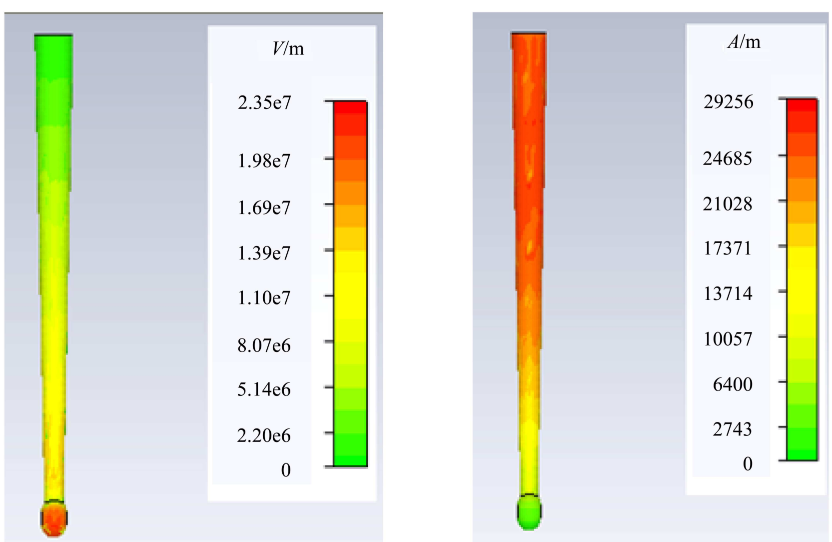

Fig. 4. (color online.) Electric (left) and magnetic (right) surface fields of the Type 2 cavity on the inner conductor, at the accelerating field of 4.15 MV/m, therefore the normalized peak surface electric field is 5.66 MV/m and the normalized peak surface magnetic field is 8.85 mT.

Table 1. EM parameters (from CST Microwave Studio 2009).

parameters	larger capacitive load	lollipop shape
frequency/MHz	100	100
β	0.06	0.06
beam aperture/mm	20	20
gap length/mm	30	50
drift length/mm	60	40
outer diameter of cavity/mm	120	180
length of inner conductor/mm	625	770
$(R_s/Q^*)/\Omega$	234	442
E_{pk}/E_{acc}	7.48	5.66
$(B_{pk}/E_{acc})/(\mathrm{mT{\cdot}m{\cdot}MV^{-1}})$	18.56	8.85

$*R_s/Q$ is the characteristic impedance, which is independent of the material properties and the cavity size and just dependent on the cavity geometry.

3 Effect of the structural deformation on frequency

The Type 1 cavity, comparatively, has smaller accelerating gaps and thus has severer issues of structural deformation with control of microphonics and the helium bath pressure fluctuation; but, the Type 2 cavity has no more severe with them due to its longer accelerating gaps and larger diameter.

Structural deformations, mainly at the top and the beam port of the cavity, as a result of microphonic vibrations and helium bath pressure fluctuation, will lead to frequency shifts of the resonators. Take the Type 2 cavity, for example, to study this problem, with the slight variations of the curvature radius of the rounded shape at the top and with the displacements of the beam tubes, the changes in frequency are plotted in Fig. 5.

In Fig. 5, the frequency varies from 99.66 MHz to 100.26 MHz (variation range is 600 kHz) with the changing of curvature radius r from 30.6 mm to 34 mm (displacement of ± 5 mm of the short plate); and it varies from 100.13 MHz to 99.80 MHz (variation range is about 330 kHz) with the displacement of ± 5 mm of the beam tube. It can be seen that the tiny deformations of the short plate (whose sensitivity is 60 kHz/mm) is more sensitive in the problem of frequency shifts than that of the beam tube (whose sensitivity is 33 kHz/mm).

A conservative external Q-quality value of 3×10^6 is chosen to estimate the overcoupling cavity band-

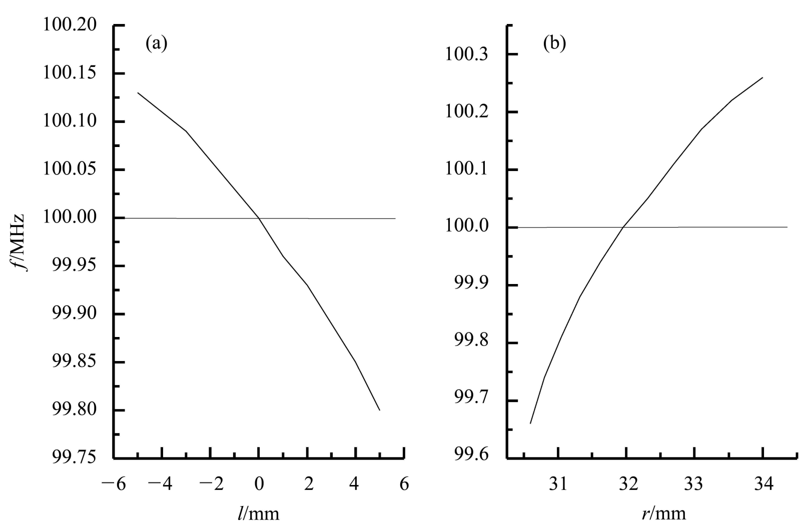

Fig. 5. The frequency variation with the displacement l^* of the beam tube (a) and with the curvature radius r of the rounded shape (b). * The negative values of l means that the two beam tubes move towards the center of the cavity; conversely, the positive values of l means that they move oppositely.

width using the relation expression

$$\Delta f=\frac{f_0}{Q_{\rm ext}},$$

therefore the cavity can just detune over a bandwidth of +/−16 Hz with the maintainence of amplitude and phase.

Therefore, at the same time of utilization of mechanical tuning, appropriate stiffening methods must be applied, especially around the rounded shape of the top, with the aim of minimizing frequency shifts caused by pressure fluctuations and microphonics, such as the welding of the Nb ring to the top and of Nb buttresses to the beam port region of the cavity.

4 Conclusions

We have studied 2 different geometries of the QWR with frequency of 100 MHz and β=0.06 respectively, for applications of low velocity section in heavy ion accelerators, with particular attention paid to minimizing the peak surface fields and consideration of structural deformations. We can see that the second type of geometry is more satisfactory with these lower values of $E_{\rm pk}/E_{\rm acc}$ and $B_{\rm pk}/E_{\rm acc}$, so it means that the Type 2 design can undertake a higher accelerating gradient, and an accelerating field of 7 MV/m leads to $E_{\rm pk}\approx$40 MV/m, $B_{\rm pk}\approx$62 mT, which should be achieved without too much effort by using the well-tried methods developed in the last fifteen years (high pressure rinsing, high purity niobium, clean conditions...). Moreover, the second type of geometry is more effective than the first one because the characteristic impedance $R_{\rm s}/Q$ of the second type is higher (Table 1). Thirdly, in the light of the issues of microphonics and helium bath pressure fluctuation, the Type 2 cavity with the larger accelerating gaps will be more competitive compared to the Type 1 cavity. To be more specific, the influence of structural deformation on frequency has been studied briefly on the Type 2 cavity. Despite the smaller size and the simpler structure of the Type 1 cavity, its accelerating performance cannot compete with that of the Type 2 structure.

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