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A preliminary study of the feasibility of using superconducting quarter-wave resonators for accelerating high intensity proton beams

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Abstract: The superconducting (SC) cavities currently used for the acceleration of protons at a low velocity range are based on half-wave resonators. Due to the rising demand on high current, the issue of beam loading and space-charge problems has arisen. Qualities of low cost and high accelerating efficiency are required for SC cavities, which are properly fitted by using SC quarter-wave resonators (QWR). We propose a concept of using QWRs with frequency 162.5 MHz to accelerate high current proton beams. The main factor limiting SC QWRs being applied to high current proton beams is vertical beam steering, which is dominantly caused by the magnetic field on axis. In this paper, we intend to analyze steering and eliminate it to verify the qualification of using QWRs to accelerate high intensity proton beams.

Key words: high intensity proton beam, superconducting quarter wave resonator, beam steering, correction

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1 Introduction

Low β (relativistic velocity, $\beta = v/c$) superconducting (SC) cavities, boosted by increasing interest in high intensity proton beam sources, have been developed worldwide [1]. With different geometries, frequencies, and gap numbers, a large number of resonators have been built for a variety of applications [2]. Cavities in TEM mode based on half-wave resonating, such as the spoke, HWR, and CH, are currently the major options for several design proposals [3–5]. Increasing beam current poses an issue of beam loading and space-charge problems, consequently, cavities with low cost and high accelerating efficiency are preferred.

A 10 mA/50 MeV superconducting proton linac as the demo of the Chinese Accelerator Driven System driver is designed and constructed [6]. Its injector part consists of a normal conducting radio frequency quadrupole with output energy 2.1 MeV and an SC linac enhancing beam energy up to 10 MeV. Two types of frequency, 162.5 MHz and 325 MHz, are chosen to ensure technical feasibility. The referred accelerating structures include CH cavities and HWRs with frequency 162.5 MHz, and 325 MHz spoke cavities. We propose a concept of using quarter-wave resonators (QWR) with frequency 162.5 MHz to accelerate the high current proton beam as another alternative to the injector linac since QWRs reveals better performances in fulfilling the aforementioned requirements than half-wave-type resonators.

2 Advantage and disadvantage

The frequency of 162.5 MHz is much higher than that of the SC QWRs for heavy ions, which are generally under 100 MHz. As a result, the cavity size is reduced a great deal, and the mechanical properties of the SC QWR are significantly improved. In case of the same designed β, a QWR provides a double sized effective accelerating length as spoke and HWR type cavities are mostly applied in frequencies above 300 MHz, while their cavity sizes are comparable. In terms of an HWR with identical frequency, it would

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require a larger sized cryomodule, which causes higher static and dynamic heat loss. Since an HWR needs twice the energy content for the same cavity voltage, it shows less efficiency on power utility. Lower fabrication cost is another essential point benefiting from reduced cavity size and also simple geometry, especially compared with a CH cavity. In addition, a QWR is capable of using a demountable end plate instead of electron beam welding, where the surface current density is sufficiently low. This unique characteristic for SC QWRs enables convenient access for post processing, and plays an important role in the improvement of quality factor.

The main factor limiting SC QWR to apply for high current proton beam is the beam steering caused by an up-down asymmetry with respect to the beam axis [7]. Along the beam axis, QWRs always have appreciable transverse field components, which induce beam steering, and can result in growth in the transverse emittance of the beam. For lighter ions and protons, beam steering can be more serious. Thus, correction of beam steering becomes a key step to realize the application of SC QWRs in high current proton beams. In the preliminary study phase, we will mainly use an analytic method combined with a numerical method to analyze the beam steering for a 162.5 MHz QWR, and present the corrected result by adopting the effective techniques usually applied in the ones for heavy ions [8].

3 Analytic derivation of beam steering in a QWR

The equation of motion for a proton beam being accelerated in a QWR presents as:

$$\frac{\mathrm{d}\vec{P}}{\mathrm{d}t}=e(\vec{E}+\vec{v}\times\vec{B}). \quad (1)$$

The solution is obtained by substituting all the related field components in three directions. In addition to the accelerating field, electrodynamics studies indicate the transverse field components along the beam axis, consisting of an electric field in the vertical direction parallel to the main resonator axis (E_y), and a magnetic field in the horizontal one (B_x). In the two gaps of the cavity, the electric field E_y distributes symmetrically with respect to the vertical axis y, while the magnetic one B_x is antisymmetric. These transverse fields deflect the beam in the vertical direction y, and the corresponding component of Eq. (1) will be focused. Using $\mathrm{d}t=\mathrm{d}z/(\beta c)$, the vertical momentum differentiation is determined:

$$\mathrm{d}P_y=\frac{e}{\beta c}[E_y(y,z)\cos(kz+\varphi_0)+\beta cB_x(z)\sin(kz+\varphi_0)]\mathrm{d}z, \quad (2)$$

where φ_0 is the synchronous particle phase, and $k=2\pi/(\beta\lambda)$, λ is the wavelength of the RF field. The magnetic field in the cavity is delayed 90° with respect to the electric one, therefore it is represented by a sinusoidal time-dependent function. The vertical electric field near the beam axis can be derived from Maxwell equations, and given by the formula:

$$E_y(y,z)=E_y(z)-\frac{1}{2}\frac{\delta E_z(z)}{\delta z}y. \quad (3)$$

It is presented as a superposition of the transverse component E_y and the RF defocus field. Within the beam aperture, the two parts are approximately uniform and axis-symmetrical, respectively. To express the beam steering explicitly, the momentum differentiation $\mathrm{d}P_y$ is replaced by a beam deflection angle $y'=P_y/P_z$ in the vertical plane. Combining with Eq. (3), and integrating (2) with respect to z, then we obtain:

$$\Delta y' = \frac{e}{m_p}\int_{-L/2}^{L/2}\frac{1}{\gamma\beta^2c^2}\left[\left(E_y(z)-\frac{1}{2}\frac{\delta E_z(z)}{\delta z}y\right)\right.$$
$$\left.\times\cos(kz+\varphi_0)+\beta cB_x(z)\sin(kz+\varphi_0)\right]\mathrm{d}z, \quad (4)$$

where $L=\beta_{\mathrm{G}}\lambda$, is the effective accelerating length of the cavity. β_{G} is the geometrical β of the cavity. It reveals that the beam steering strongly depends on RF field phase, amplitude, and beam velocity. Since transverse motion and longitudinal motion are coupled, the transverse electric field generally is canceled in the two gaps of the cavity, reversely, the magnetic one is added. Therefore, beam steering is substantially contributed by the magnetic field when the beam is on axis.

An obvious correction method for beam steering can be derived from Eq. (4): introducing the contribution of the RF defocus field to compensate the other two components. This method could be operated readily because it just requires a vertical displacement of the cavity. For a given offset y, the reduction factor varies with β but it is the same for any cavity gradient or synchronous phase. Another correction method, initially developed by ANL [9], based on the creation of the artificial E_y component is able to counteract the steering. It calls for adjusting E_y distribution along the beam axis, which is implemented by tilting the drift tube faces.

4 Calculation of beam steering

We extract all the field distributions along the beam axis from a 162.5 MHz QWR by using Microwave Studio, plotted in Fig. 1. For clarity, the amplitude of E_y is scaled by a factor of 10, and B_x is multiplied by light velocity c. The designed β_G is 0.085, which ensures the proton beam will obtain maximum energy gain at the two ends of the energy range 2.1–10 MeV. The detailed EM design and optimization are ignored in this paper. Applying the numerical method to the integration of Eq. (4), the beam steering was calculated in the concentrated velocity range from $0.067c$ to $0.145c$. As for the proton beam accelerated at high gradient, the velocity variation depending on the longitudinal position cannot be neglected, and had been taken into account during the numerical integration. Since very high gradient is not required by the applications of a low velocity proton beam, all the calculations were performed under the conditions of gradient 8 MV/m, as the worst case of steering, and synchronous phase $-30°$. Based on the first correction method, the beam steering is greatly reduced in a wide β range only by a vertical displacement of 0.9 mm (Fig. 2). As can be seen from the plots, for the β range greater than β_G, the electric part of beam steering is definitely weaker than the magnetic one, which is consistent with the previous prediction.

To apply the second correction method, a new E_y distribution can be created by modifying the tilting angles of the drift tube and beam port faces, as shown in Fig. 3. With the same conditions, integrating Eq. (4) again gives a consequence of steering. This processing would be iterative in order to obtain the best correction. The final result is shown in Fig. 4, the beam steering is largely eliminated. However, the determined tilting angles are small and require a high level of manufacturing accuracy, since the distribution of E_y is sensitive with respect to the angles' fluctuations.

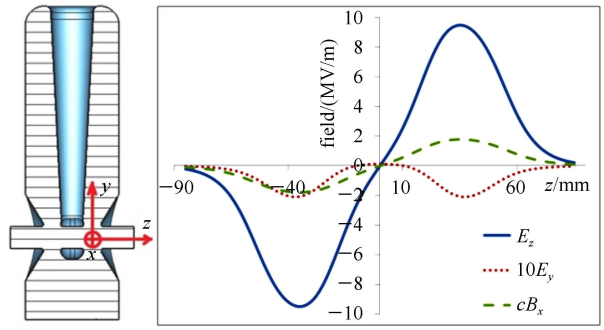

Fig. 1. Left: 162.5 MHz QWR, $\beta_G = 0.085$. Right: the field distribution along the axis. E_z (solid), $10E_y$(dot), cB_x(dash).

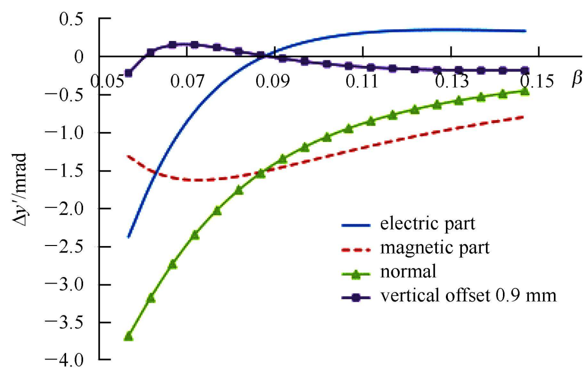

Fig. 2. The beam steering in 162.5 MHz QWR calculated by Eq. (4), normal (triangle), vertical offset 0.9 mm (rectangle), electric part (solid), magnetic part (dash).

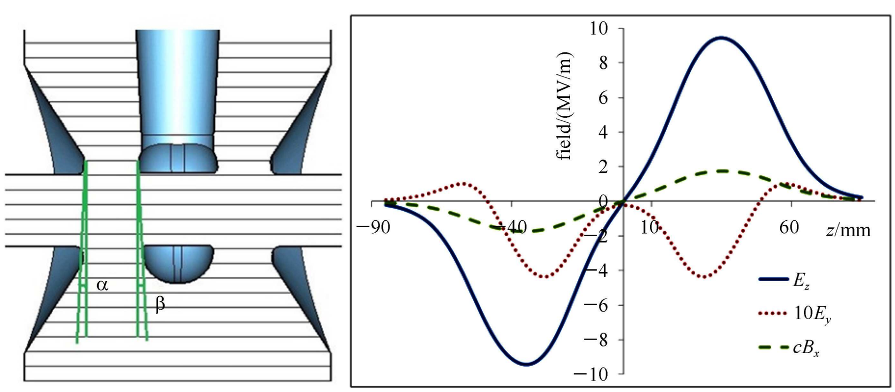

Fig. 3. Left: 162.5 MHz QWR with the modified shapes of the drift tube and beam ports, the tilting angle α=1°, β=3°. Right: the field distribution along the axis. E_z (solid), $10E_y$ (dot), cB_x (dash).

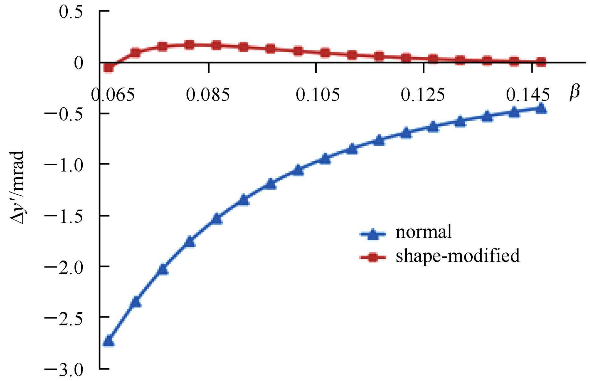

Fig. 4. The beam steering in 162.5 MHz QWR calculated by Eq. (4), normal (triangle), shape-modified (rectangle).

5 Conclusion

The numerical calculations for the QWR suggest that beam steering can be sufficiently reduced either by simply offsetting the cavity within 1 mm or shaping the face angles of the drift tube and beam port. Its ability of accelerating a high current proton beam is worth of expansion since a 162.5 MHz superconducting QWR presents a manifest merit to meet the requirements on cost and efficiency. For a specific linac consisting of couples of QWR, the offset of each cavity is determined by the beam velocity profile along the linac. Consequently, steering correction for each cavity can be optimized, and the previous method would present a better performance. This setup procedure is reasonable for a superconducting linear proton accelerator due to the simple fact that the whole beam velocity profile is definite. Although the value of cavity offset can be found from the analytic formula, in case of practical application, to pursue a more precise result, one should resort to those advanced tracking codes being capable of simulating beam motion in complex 3D electromagnetic fields. The latter method modifies the cavity shape so slightly that a high level of manufacturing accuracy is required. This makes the method hardly applicable in this particular QWR, while the previous one is practical and recommendable.

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