MINIMIZING TRANSVERSE-FIELD EFFECTS IN SUPERCONDUCTING QUARTER-WAVE CAVITIES*

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Abstract

Superconducting (SC) cavities presently used for acceleration of ions in the velocity range from 0.01c to 0.3c are based frequently on quarter-wave resonators (QWR). Numerous types of QWR cavities over a frequency range from 50 to 240 MHz have been built or are proposed for a variety of applications. Recent studies have revealed an important drawback of the QWR: the presence of beam steering fields in the aperture [1]. We have shown that this effect can be eliminated by appropriate shaping of the drift tubes [2]. There is, however, another problem in QWR drift-tube design caused by quadrupole terms in the transverse Lorentz force which can cause appreciable emittance growth when the linac lattice includes transverse focusing by SC solenoids. Solenoidal focussing provides a compact lattice and maximizes transverse acceptance while maintaining low longitudinal emittance. We discuss the design of QWR cavity geometries which eliminate both the dipole and higher order components in the equations of motion in the transverse planes, while keeping the ratio of surface-to-accelerating field low. The resulting QWR designs minimize emittance growth, which is critical in some applications.

1 STEERING IN DRIFT-TUBE CAVITIES

There are at present several projects (see, for example, [3-8]) in which quarter-wave and half-wave SC resonators will be used for acceleration. These resonators can provide high accelerating gradients, 5-7 MV/m, and are considered cost-effective for the construction of new accelerators, including low duty cycle machines.

We have developed a three-dimensional ray-tracing code for detailed beam dynamics studies to obtain better understanding of beam quality and design criteria for SC linacs [2]. Numerical studies of the three-dimensional rf electromagnetic field in the beam-cavity interaction area indicate appreciable steering components, both electric and magnetic, especially in higher-frequency QWR resonators. Beam steering is induced by dipole components of the field and is a strong function of rf phase, which couples the longitudinal and transverse motion. This coupling can result in growth in the transverse emittance of the beam which can become appreciable for beams of large longitudinal emittance. Also, steering effects will be most pronounced for light ions. Such emittance growth can not be compensated by static fields and can be a particularly serious problem in applications for high-intensity light-ion beams.

We found that the steering can be largely compensated by two different methods [2]. Simply offsetting the cavity beam-axis by 1-2 mm can often provide adequate compensation. In this method, the available range of steering is limited by the reduction of useful aperture. Offsetting can be effectively applied for low-intensity heavy-ion accelerators dealing with q/A<1/3 in velocity range ~0.01c-0.15c. This method will be used, for example, in the ISAC-II project [4]. More generally, steering can be largely eliminated over the entire useful velocity range by shaping the drift-tube and cavity-wall faces adjacent to the beam axis to provide appropriate corrective vertical electric field components. This method is being applied in a 115 MHz QWR resonator being developed for the RIA driver linac (see Fig. 1). In some cases steering is sufficiently small that the QWR can be used without any correction. For example, a plan for the pre-stripper section of the RIA driver linac calls for thirty uncorrected 57.5 MHz QWR cavities (see Fig. 2). Due to the low frequency, the steering component of the magnetic field is strongly suppressed. Even for a beam of protons there is no appreciable emittance growth because the longitudinal emittance of the beams in the RIA linac is small [9] and the beam center displacement remains less than 2 mm along this section of the linac. Beam center displacement for heavier ions is much less than for protons.

Figure 1 shows the 172.5 MHz β_G=0.252 HWR being developed for the RIA driver linac. Beam steering effects vanish in half-wave resonant cavities (HWR), since there are no dipole fields on the beam axis. In some projects (see, for example, ref. [6]) an HWR is proposed for lower velocities $\beta_G \approx 0.12$ to accept and accelerate light ions directly after the RFQ.

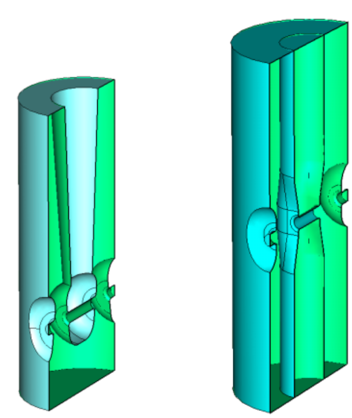

Figure 1: 115 MHz QWR (the left picture) and 172.5 MHz HWR (the right picture) of the RIA Driver linac.

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2 ASYMMETRIC DEFLECTIONS

Early SC resonator designs for accelerating heavy-ions included large diameter drift tubes to provide axial symmetry of the electric field in the beam aperture [10,11]. Some recent QWR designs have eliminated the drift tube, perforating the cylindrical central stems [7] as shown in the right-hand side in Fig. 2. The reduced cylindrical- symmetry around the beam axis introduces an appreciable quadrupole component of transverse rf field. We can define, for a given particle velocity and phase, an electromagnetic (EM) central axis of the QWR as an axis parallel to an axis centered on the physical beam aperture, but displaced vertically just enough to eliminate the steering due to the dipole components of the rf fields. Detailed analysis shows that the transverse effect of electric field in the accelerating gap can be represented as a sum of axially symmetric and quadrupole lenses. If particle is sent along the EM central axis, the transverse Lorentz force is zero for the defining input velocity and synchronous phase. To characterise the quadrupole component of the rf field, the deflecting angle of a proton at the design velocity and synchronous phase, but offset from the EM central axis by 1mm, was numerically calculated. The difference $\Delta\left(x_0' - y_0'\right)$ of the deflecting angles in horizontal and vertical planes is a measure of field asymmetry and is plotted in Fig. 3 as a function of the particle input velocity for 3 types of SC resonators. For the QWR with large drift tubes (Type 1 in Fig. 1) the

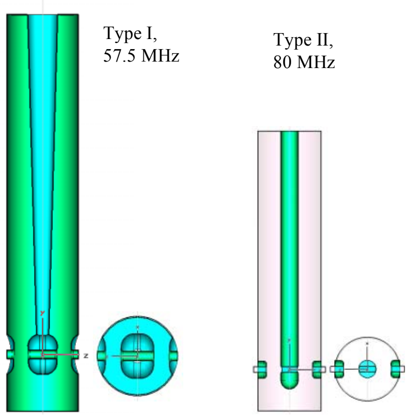

Figure 2. Two types of QWRs.

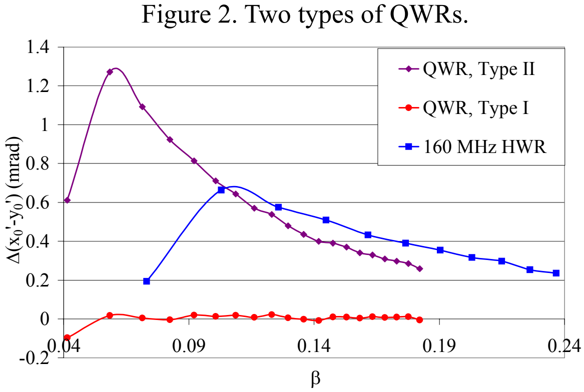

Figure 3: Difference of particle deflection angles in transverse directions as a function of particle velocity.

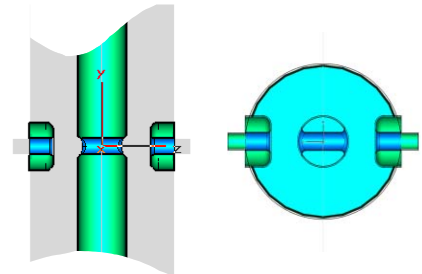

Figure 4: 160 MHz half-wave resonator.

parameter $\Delta\left(x_0' - y_0'\right)$ is negligibly small, which indicates that the rf field is axially symmetric with respect to the electrical center.

For HWR cavities, the transverse electrical center coincides with the physical aperture center. Fig. 3 also shows the parameter $\Delta\left(x_0' - y_0'\right)$ calculated for the HWR with a cylindrical stem shown in Fig. 4. The cylindrical stem introduces an appreciable quadrupole component of the defocusing electric field in the aperture.

3 BEAM DYNAMICS SIMULATIONS

Using SC solenoids for transverse beam focusing together with SC resonators offers several advantages. The solenoids can be placed close to the cavities inside the cryostats and a short focusing period can be achieved. A lattice with solenoidal focusing is compact, and maximizes both transverse and longitudinal acceptance.

Solenoids, however, rotate the beam, and beam quality can significantly suffer if solenoids are used with rf cavities which do not provide axially symmetric fields. Emittance growth in a solenoid channel can occur due to the strong coupling of horizontal and vertical motions.

We have carried out a series of numerical simulations of proton beams in order to study the emittance growth in five types of accelerating-focusing lattices listed in Table 1. The lattices simulated are similar to those presented in ref. [6,8,9], but differ in some minor details. Some results related to the ISAC-II project were reported in ref. [4].

In the first four types, the focusing period consists of one focusing element and two SC cavities. The length of the focusing period is constant along the linac for each type of lattice. The last type in Table 1 is the lattice of the proposed RIA driver linac [9], which consists of three cavities per focusing element and includes an inter-cryostat space. For all structures the transverse phase advance and required focusing fields have been calculated both by applying first-order matrix formalism and with the code TRACE [12]. The transverse phase advance was kept at 60° along the linac.

Results of the numerical studies of beam dynamics are shown in Figures 5, 6, and 7. Figure 5 compares the two QWR cavity lattices listed in Table 1, and shows the emittance envelope containing 99.9% of the particles along the linac for the two cases. As is seen, the quadrupole components of the defocusing field in QWR

Table 1: Linac lattices

Type	f, MHz	β_G	N_R	W_{in} MeV	W_{out} MeV	F[1]	Ref
QWR	57.5	0.062	32	0.8	20.5	S[2]	[9]
QWR	80	0.062	32	0.8	18.5	S	[8]
HWR	160	0.115	32	2.5	30	S	[6]
HWR	160	0.115	32	2.5	30	D[3]	[6]
HWR	172.5	0.252	88	10	107	S	[9]

[1] F denotes focusing type,[2] S denotes solenoid,
[3] D denotes doublet.

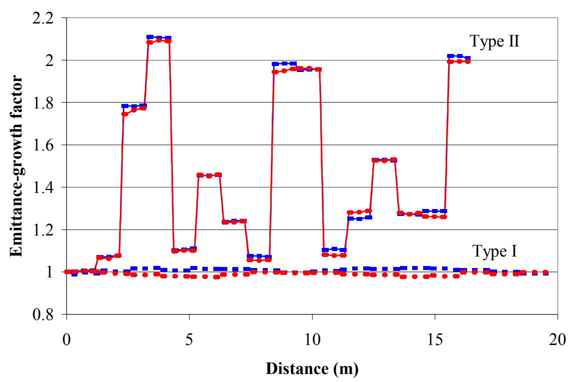

Figure 5: The 99.9% horizontal (squares) and vertical (dots) emittance growth along the linac for two types of QWRs.

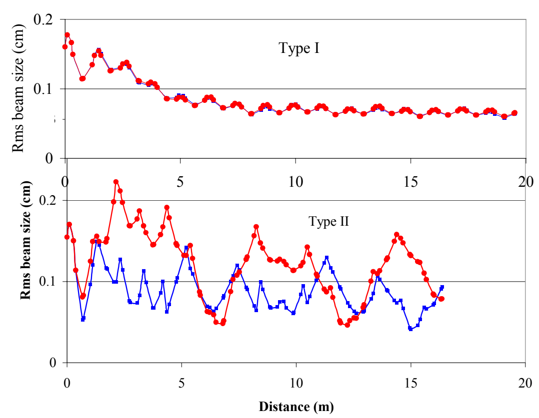

Figure 6: Horizontal (squares) and vertical (dots) rms beam size the linac for two types of QWRs.

cavities of type II (in Fig. 2) produce large emittance growth when used in a solenoidal focusing channel. Note that Type I QWR cavities produce no appreciable emittance growth. The axially-symmetric drift tubes of this type of cavity provide a higher degree of axial symmetry in the electric field in the beam aperture.

HWR cavities formed of simple cylinders also exhibit emittance growth due to electric field asymmetries. We have numerically simulated the dynamics of proton beams in the energy range 2.5-30 MeV for the 3rd and 4th lattices listed in Table 1. As is shown in Fig. 7, the cylindrical HWR produces appreciable emittance growth in both the solenoid-focusing and also the quadrupole focussing lattice. In the quadrupole focusing lattice (Lattice 4 in Table 1) the quadrupole component of the defocusing field produces a strong mismatch in the vertical beam envelope resulting in a 30% emittance growth, occurring mostly in that section where the velocity is less than $\beta_G c$ (see Fig. 7).

A HWR with a central cylinder flattened in the beam region (as shown in Fig. 1) has been proposed for the the medium-β section of the RIA driver linac [3]. The flattening of the central stem provides a symmetric electric field in the beam regions. Simulations of proton beams using the 5th lattice of Table 1 indicates less than 2% growth of the emittance over the 60 meter length.

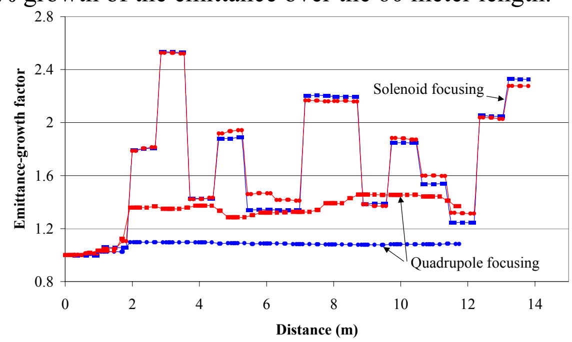

Figure 7: The 99.9% horizontal (squares) and vertical (dots) emittance growth along the linac with 160 MHz HWR.

4 CONCLUSION

Rf field properties of several geometries of QWR and HWR SC cavities and the impact of field asymmetries on beam quality have been studied by computer simulations of beam dynamics in realistic three-dimensional electro-magnetic fields. Beam parameters have been analysed for several typical examples of accelerating-focusing lattice. We find that beam steering due to the dipole component of the rf field and emittance growth due to the quadrupole field component in the aperture can be largely avoided by appropriate design of the SC resonators.

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