A RING-SHAPED CENTER CONDUCTOR GEOMETRY FOR A HALF-WAVE RESONATOR*

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Abstract

Half-wave resonators (HWR) are used and being proposed for the acceleration of high-intensity proton and heavy-ion beams in the $0.1 < \beta < 0.5$ velocity range. The highest performing half-wave resonator geometries use a center conductor with a race-track shaped cross section in the high-electric field region; a feature shared with spoke cavities which are also being proposed for the same velocity regime. We here propose a ring-shaped center conductor instead of the race-track shape. Preliminary studies show that the ring geometry has a similar peak surface electric field as the race-track one, and several other advantages. In particular, the ring-shaped geometry has: a lower peak surface magnetic field for a given accelerating voltage, a 36% higher shunt impedance for the same peak fields, and no quadrupole electric field asymmetry which was observed in the race-track geometry. For solenoid-based symmetric focusing, the quadrupole component may lead to unnecessary emittance growth which is not acceptable in high-intensity ion linacs. We will present a detailed comparison and a discussion of the two geometries.

INTRODUCTION

Half-wave resonators (HWR) are being used and designed for proton and heavy-ion linear accelerator projects around the world. Along with the quarter-wave resonator (QWR), the HWR structure was proposed for the acceleration of low-beta ion beams [1]. Several different designs were developed and tested over the years [2, 3], although few are operating in an actual accelerator [4]. The most common feature in these designs is an inner conductor coaxial to the outer conductor. We here propose to replace the race-track shaped central region of the inner conductor with a ring-shaped or a "donut"-like one. After listing the shortcomings of the original rate-track geometry, we present the new ring-shaped geometry and how it resolved all of these limitations.

SHORTCOMINS OF THE RACE-TRACK HWR GEOMETRY

During the design of a 162.5 MHz $\beta \sim 0.11$ HWR for the Project-X Injector Experiment PXIE [5], we encountered several difficulties with the chosen race-track shape of the center conductor. For each of these problems, we have developed and implemented the appropriate solution, we list in particular:

- An elliptical aperture to correct for the quadrupole electric field component due to the X-Y asymmetry of the race-track section of the center conductor.
- An intermediate transition from the race-track cross section to a round cross section to produce a uniform magnetic field distribution around the stem.

Quadrupole Electric Field Component

Due to the X-Y asymmetry of the race-track section of the center conductor, a quadrupole electric field component is produced, more details are given in [6]. This component is responsible of the X-Y beam asymmetry observed in the top plot of Figure 1. This figure was obtained by tracking an axial symmetric beam through 5 cavities to simulate the cumulative effect of the quadrupole field component on the beam. To solve this problem and preserve the beam symmetry, we had to use an elliptical aperture for the cavity. The bottom plot in Fig. 1 shows that a 9% (Y larger than X) asymmetry in the cavity aperture, compensates the quadrupole field component to produce a symmetric beam.

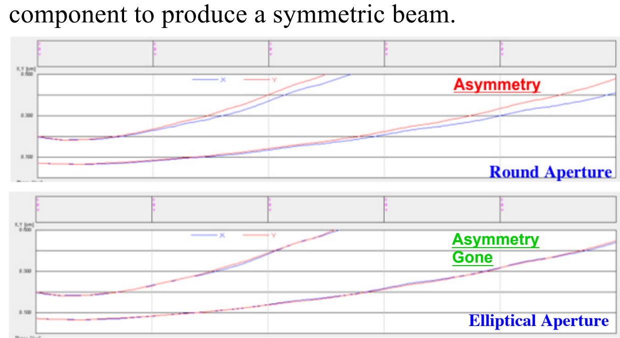

Figure 1: X(blue)-Y(red) rms and maximum beam size tracked over five race-track HWR cavities. The top plot is for a round aperture and the bottom is for 9% elliptical aperture.

Non Uniform Magnetic Field Around the Stem

Due to the loft transition from a race-track cross section in the central region of the center conductor to a round cross section at the top, there is no axial symmetry around the stem which leads to a non uniform magnetic field distribution. Furthermore, the location of the magnetic field enhancement corresponds to the location of the welds as the stem is made in two pieces welded on the narrow-curved sides as seen on the top plot of Fig. 2.

To address this issue, we introduced a short intermediate transition from the race-track cross section to

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a round cross section. Although it complicates the geometry in the central region, this solution produces a more uniform magnetic field around the stem as seen on the bottom plot of Fig. 2. By evenly distributing the magnetic field over the surface Bpk/Eacc is reduced.

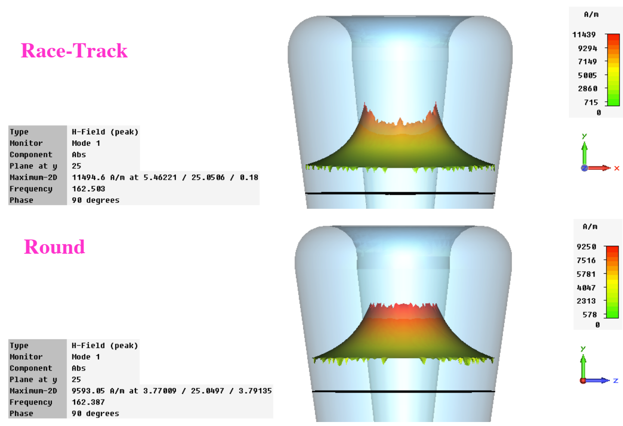

Figure 2: Magnetic field distribution around the stem for the original race-track loft (top) and after introducing the intermediate round loft (bottom). Notice the lower peak surface field achieved with the round center conductor geometry.

Reduced Shunt Impedance

Following the changes introduced to the race-track HWR geometry to compensate for the quadrupole electric field component and produce a uniform magnetic field distribution around the stem, we noticed that the shunt impedance (or the R/Q ratio) is reduced by about 10%. Table 1 compares the RF parameters of the final geometry to those of the original one. We clearly notice that the elliptical aperture didn't affect the peak electric field while the peak magnetic field is reduced by about 10% due mainly to the intermediate round loft in the stem. Here we clearly have a trade-off decision to make; the more complicated geometry with lower peak magnetic field versus the simpler geometry with higher shunt impedance. Instead of making this decision, we have chosen to study the option of completely replacing the race-track section by an axis symmetric ring. This option has the potential of solving all the limitations of the race-track geometry at once.

Table 1: Comparison of RF parameters between the original and final race-track HWR.

Parameter	Unit	Original value	Final value	Change
B_{opt}	-	0.11	0.11	-
L_{eff}	cm	20.3	20.3	-
E_{peak}/E_{acc}	-	4.6	4.6	0 %
B_{peak}/E_{acc}	mT/(MV/m)	6.3	5.7	-9 %
R/Q	Ω	219	199	-9 %
R_sQ	Ω	48	48	0 %

THE NEW RING-SHAPED HWR GEOMETRY

As shown in Fig. 3, we have replaced the original race-track section of the center conductor with a ring-shaped section. After re-optimizing the new HWR geometry we obtained the RF parameters of Table 2 where they are compared to those of the final race-track HWR.

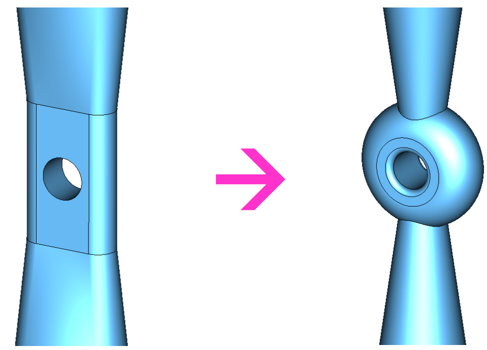

Figure 3: Replacing the race-track center conductor (left) by the ring-shaped center conductor (right).

Table 2: Comparison of RF parameters between the original race-track HWR and the new ring-shaped one.

Parameter	Unit	RT value	RS value	Change
B_{opt}	-	0.110	0.112	-
L_{eff}	cm	20.3	20.7	-
E_{peak}/E_{acc}	-	4.6	4.7	+2 %
B_{peak}/E_{acc}	mT/(MV/m)	5.7	5.0	-12 %
R/Q	Ω	199	272	+36 %
R_sQ	Ω	48	48	0 %

Table 2 clearly demonstrates that the ring-shaped geometry has significantly improved both the peak magnetic field and the R/Q ratio while preserving the peak electric field. In addition and because of the axial symmetry of the ring section, no elliptical aperture is needed, which makes the cavity manufacturing and alignment much easier. In this way, the ring-shaped geometry has resolved all of the shortcomings of the race-track one.

Higher Shunt Impedance

To explain the higher shunt impedance, we refer to Fig. 4 which shows the on-axis longitudinal electric field component for the same stored energy. The fact that the field is more peaked for the ring-shaped HWR makes the synchronous particle better synchronized with the field and more voltage is carried by the beam. More voltage for the same stored energy leads to a higher shunt impedance, as we recall the formula below:

$$R/Q = V^2/\omega U$$

where V is the voltage, ω is the angular frequency and U the stored energy.

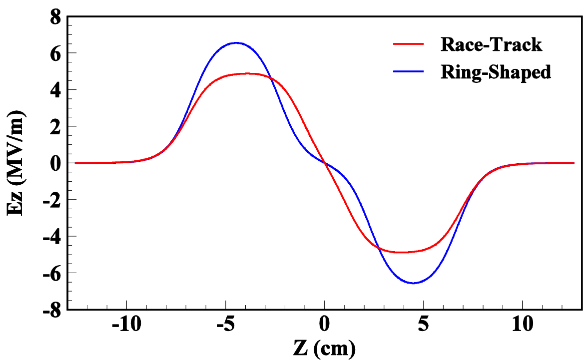

Figure 4: Longitudinal electric field on axis for the race-track and ring-shaped HWR geometries.

Round Aperture

As mentioned above, due to the axial symmetry of the central ring, we don't expect a quadrupole electric field component. Therefore, we keep the original round aperture. To check the effect on the beam, we simulated the same beam used in Fig. 1 through five consecutive ring-shaped HWR cavities. The result is shown in Fig. 5. The residual beam asymmetry, if any, is negligible and does not require a correction.

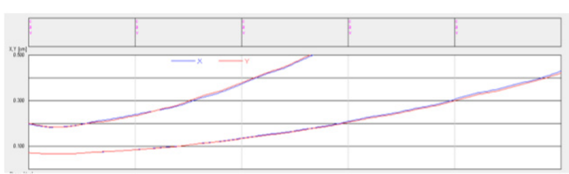

Figure 5: X-Y rms and maximum beam sizes tracked over five ring-shaped HWR cavities.

Field Distributions

In the ring-shaped HWR geometry, we don't need to introduce an intermediate round loft to produce a uniform magnetic field distribution around the stem. A round cross section is defined on top of the ring which is then directly lofted to the cavity top producing a naturally axial-symmetric stem. Figure 6 shows the electric and magnetic field distribution on the internal surface of the final ring-shaped HWR cavity.

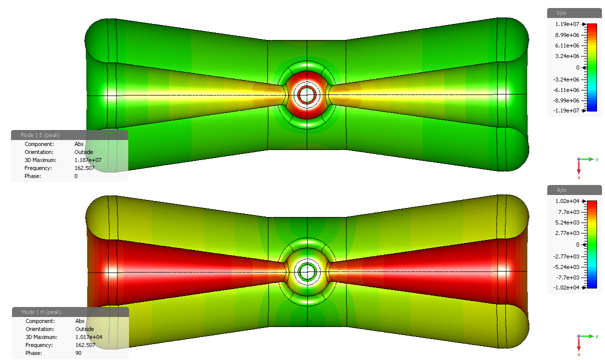

Figure 6: Electric (top) and magnetic (bottom) field distributions on the internal surface of the ring-shaped HWR cavity.

SUMMARY

The ring-shaped center conductor geometry for a HWR solves all the problems and limitations encountered in the race-track geometry. The advantages are:

- ✓ Significantly higher shunt impedance.
- ✓ Much lower peak magnetic field.
- ✓ No need for an intermediate round loft to produce a uniform magnetic field around the stems.
- ✓ No quadrupole electric field component and no need for an elliptical aperture.

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