HIGH-VELOCITY SPOKE CAVITIES

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Abstract

There are several current and recent projects which explore the feasibility of spoke-loaded cavities operating in the high-velocity region. Spoke cavities have a large number of geometric parameters which often influence multiple rf properties. Fabricating, handling, and processing these cavities presents some unique challenges, not unlike other TEM-class structures. This paper will summarize the current efforts toward the design, fabrication, and testing of spoke cavities with optimum beta greater than 0.8.

INTRODUCTION

The original motivation for spoke cavity development was for medium energy, high current protons and ions [1]. And indeed, over the past several decades, proton and heavy-ion beams have become extremely important tools used in scientific research. Over the past 25 years, many groups around the world have made great progress developing spoke cavities to meet this demand. This progress has resulted in more and more spoke cavities being fabricated and tested [2–7]. Eventually, TEM- and TM-class cavity designs were overlapping in the $\beta_0 = v/c = 0.6$ region [2, 8]. With the advantages that spoke cavities can offer, there has been recent interest in the design and development of these structures for the high-velocity region. One such such example is shown in Fig. 1.

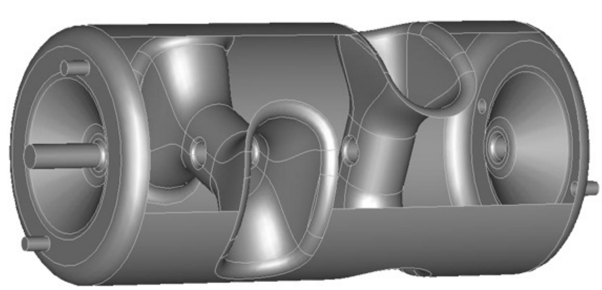

Figure 1: 325 MHz, $\beta_0 = 1$ double-spoke cavity.

FEATURES OF HIGH-VELOCITY SPOKE CAVITIES

Spoke cavities offer a number of attractive features which have been well documented elsewhere [9]. Here, the focus will be on how these features translate to spoke cavities designed for $\beta_0 > 0.8$.

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Size

In the fundamental mode, spoke cavities support a TEM mode along the spoke. For a uniformly shaped spoke, this results in the diameter being roughly half the rf wavelength. While this is true at low β_0 and for simple spoke geometries (i.e. uniformly cylindrical), optimized high-β_0 geometries result in this factor of 1/2 being increased, bringing the diameter closer to their TM-class counterparts. Nonetheless, since the BCS surface resistance is proportional to the square of the rf frequency, accelerators can be designed to operate at lower frequencies (and have fewer elements with different fundamental frequencies) where 4 K operation is practical while maintaining cavities of a reasonable size. Furthermore, at half the frequency of a TM cavity of the same β_0, a multi-spoke cavity of the same length would have half the number of cells. This results in a larger velocity acceptance causing the cavity to be useful over a wider range of velocities. Lower frequency would also lead to a higher longitudinal acceptance, which could prove beneficial in high-current applications. Figure 2 shows examples of the velocity acceptance for a single-spoke (2 cell) cavity, a double-spoke (3 cell) cavity, and a 5 cell elliptical cavity.

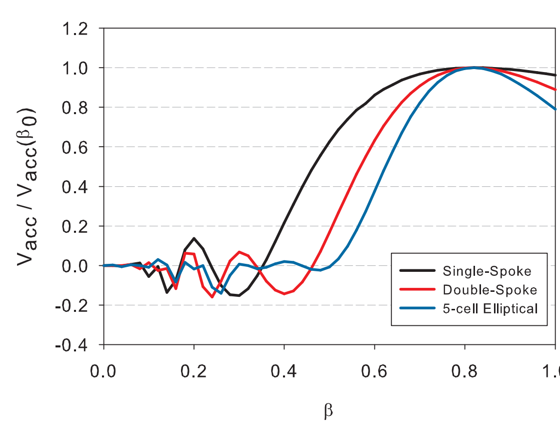

Figure 2: Accelerating voltage as a function of β normalized to the voltage at β_0 for 2 and 3 cell spoke cavities and a 5 cell elliptical cavity.

Cell-to-Cell Coupling

In spoke cavities, the magnetic field encircles the spoke(s) and couples one cell to the next. The result is a strong cell-to-cell coupling, especially in simple geometries. Tuning to achieve field flatness is therefore less important than in a cavity where the cells are coupled through the beam aperture via the electric field.

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Regardless of design velocity, the fundamental mode in a spoke cavity is the lowest frequency mode, which allows for a simpler damping and extraction of higher-order modes. In addition, the strong cell-to-cell coupling together with the small number of spokes implies that the accelerating mode will be well separated from the nearest mode.

One consequence of the optimized geometries presented here, with the elongated spoke base, is that the cell-to-cell coupling is reduced. As a result, there is some need for field flatness tuning which can be accomplished during the trim tuning, prior to the final cavity welding [11]. Figure 3 is an example of how the cell-to-cell coupling k decreases as the transverse dimension of the spoke base increase, and stays relatively the same as the base dimensions of a longitudinally oriented spoke increase. This is an important point that should be emphasized. A longitudinal spoke base orientation allows for a much larger mode separation and slightly smaller diameter, which is why, for some applications, they may be preferable to the transverse geometries presented here [12].

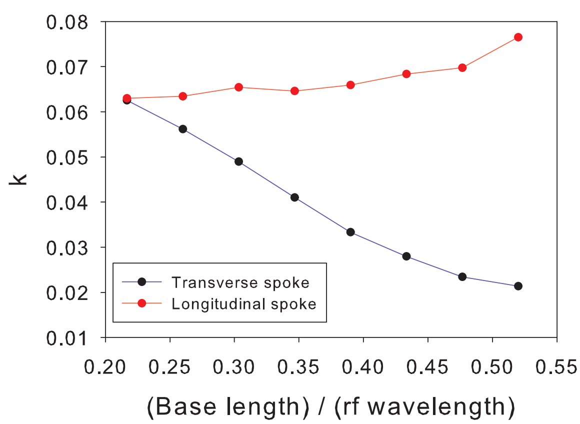

Figure 3: Coupling k between cells of an optimized $\beta_0 = 0.82$, 325 MHz double-spoke cavity. The left-most point is common to both curves since it represents a cylindrical spoke base.

HIGH-VELOCITY APPLICATIONS

While medium-velocity spoke cavities have been proposed for a number of high energy proton and ion applications, it is worth noting that the most recent activities toward the high-velocity region are primarily for small electron machines.

Current state-of-the-art linacs in operation around the world are designed for large facilities. The design choices made are vastly different than for a compact, relatively low-cost cw source of electrons. In an industrial or research university setting, a small electron accelerator operating at 2 K is unlikely to be practical. For this reason, low-frequency spoke cavities are being investigated for applications such as compact light sources [13–16] and a non-destructive assay system of nuclear materials in spent fuel using nuclear resonance fluorescence [17, 18]. An example of the layout for an inverse Compton light sources is shown in Fig. 4 [14].

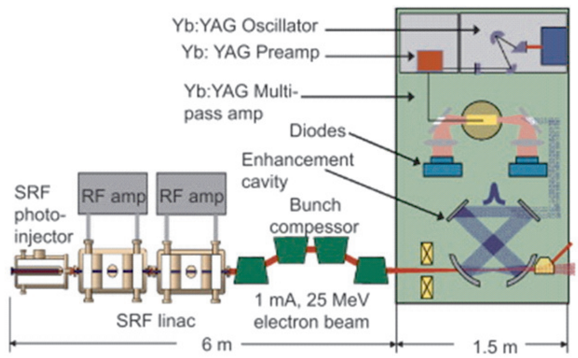

Figure 4: Conceptual layout of an inverse Compton source.

For high energy protons/ions, the velocity acceptance shown in Fig. 2 (for the double-spoke cavity) would result in a 96% efficiency for protons with energies ranging from 460 MeV to 1.5 GeV. While this particular application is not being pursued as aggressively as compact light sources, it is worth pointing out that this velocity range could prove useful in ADS applications, for example.

ELECTROMAGNETIC OPTIMIZATION

The primary goals of electromagnetic optimization are to reduce the peak surface electric and magnetic fields while increasing the shunt impedance. The basic geometry of a spoke cavity consists of an outer conductor, usually either cylindrical or rectangular, with one or more "spokes," which are conductors that run radially, through the longitudinal symmetry axis. The optimization, therefore, involves many degrees of freedom and a large parameter space to be explored [9].

Of the high-velocity spoke cavities designed, there have been two main optimization techniques used; one is a standard approach which investigates the effect each design parameter has on the peak surface fields, shunt impedance, energy content, etc. [12], the other involves combining a simulation code with a multi-objective genetic algorithm [18]. Both approaches result in similar optimized rf properties, shown in Table 1. In both cases, the reference length used to define E_{acc} is $3/2\beta_0\lambda$ and $E_{acc} = 1$ MV/m. The conceptual model a single-spoke version of the cavity designed at [18] is also shown in Fig. 5.

MULTIPACTING

Multipacting is common in TEM-class cavities, and high-velocity spoke cavities are no different. Prior to finalizing a new design, it is desirable to perform simulations in order to determine if the effect can be reduced. These simulations can help guide the geometric design in such a way as to reduce certain multipacting events. We now have

Table 1: RF Properties of two 325 MHz, β_0 = 1 Double-Spoke Cavities

Parameter	Individual Parameter	Multi-Objective Optimization
E_p/E_{acc}	3.7	3.7
B_p/E_{acc} [mT/(MV/m)]	7.1	7.5
R/Q [Ω]	737	691

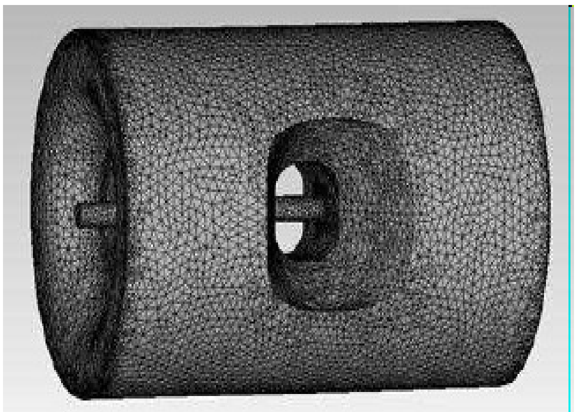

Figure 5: 325 MHz, β_0 = 1 single-spoke cavity.

powerful enough tools to do this, even for complex 3D geometries [19, 20]. Several such simulations have now been performed on high-velocity spoke cavities [21–23]. The results are similar and predict that high energy multipactors are likely to survive at low accelerating gradient while any possible multipacting activity at operating gradients would likely be of low impact energy. Another interesting observation obtained from simulation is shown in Fig. 6. What this illustrates is that the multipacting occurring at certain gradient intervals (i.e. < 3 MV/m, 3-6 MV/m, and > 6 MV/m for this geometry), is only present in specific locations on the cavity. We see that the multipacting activity below 3 MV/m (with high impact energy) happens on the outer conductor over the accelerating gaps. As the gradient is increased to between 3 and 6 MV/m, the activity shifts to low impact energy with resonant locations only in the spoke base rounding radii. Finally, as the gradient is increased to the highest levels, the only surviving resonant trajectories are in the rounding radius where the end cap meets the outer conductor. This is an important result because it suggests that perhaps the most detrimental multipacting, which would be at high gradient, can be affected by changing these rounding radii. In fact, this has been shown to be the case [11, 21].

A few of these cavities have now been fabricated and tested, allowing us to compare experimental data to simulation results [24, 25], which will be discussed in a later section.

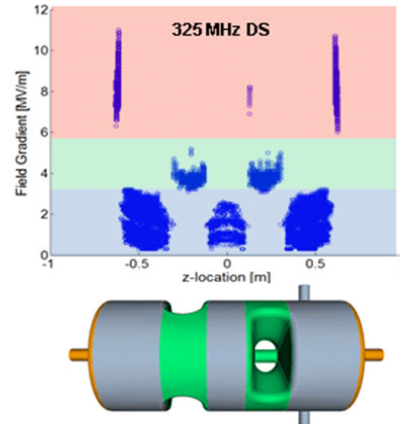

Figure 6: Multipacting simulations for a 325 MHz, β_0 = 1 double-spoke cavity. Multipacting activity is shown for increasing accelerating gradient in terms of the longitudinal position along the cavity.

CAVITY FABRICATION AND PROCESSING

A list of the high-velocity spoke cavities that have been fabricated, to date, is given in Table 2. Two 500 MHz double-spoke cavities have been fabricated (one at Jefferson Lab [26]), while the rest were fabricated at Niowave Inc. [27].

Table 2: Fabricated High-Velocity Spoke Cavities

Frequency [MHz]	# of Spokes	β_0
700	2	1
350	2	1
500*	2	1
325	1	0.82

*One fabricated at Jefferson Lab and one at Niowave Inc.

The techniques used for fabrication were not unlike those used for rotationally symmetric cavities; high purity niobium sheets were used to die form or deep draw the parts which can then be electron beam welded together.

The processing for each of these cavities were very similar:

- 120-150 μm bulk BCP
- 600 °C, 10 hours hydrogen degassing
- 10-30 μm light BCP etch
- HPR
- Cleanroom assembly
- 120 °C, 24-48 hour bake

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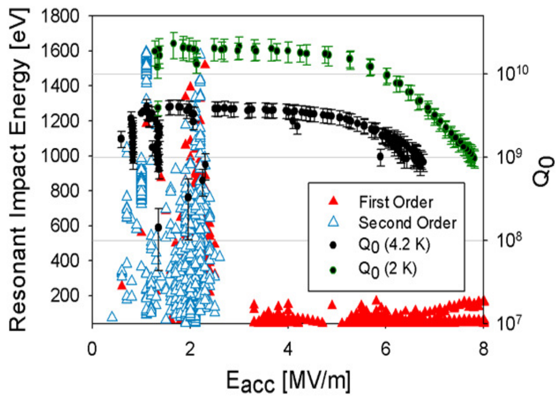

Figure 7: 325 MHz single-spoke cavity initial test results showing simulated multipacting events.

These are standard techniques and if there is any additional complication, it is introduced by the size of these cavities. This can limit the available facilities where some of this work can be done [24, 26], however, with the proper planning and fixturing, there is not a significant difference with fabricating/processing these cavities as compared to other TEM-class cavities.

CAVITY PERFORMANCE

The cryogenic testing of one 500 MHz double-spoke and the 325 MHz single-spoke were carried out at Jefferson Lab which houses the Vertical Test Area (VTA). The 700 MHz and 350 MHz double-spoke cavities were tested at Niowave's high-power test facility. In all of these cavities, multipacting was encountered in roughly the gradient range predicted by simulation and was relatively easy to overcome. An example of how the simulation compares to the test results is shown in Fig. 7. From the simulation, we would expect to encounter multipacing up to a gradient of 2-2.5 MV/m, which is very close to what our test results showed.

All cavities were tested at 4 K, and the two tested at Jefferson Lab were also tested at 2 K. Table 3 shows the results of all the 4 K tests.

Table 3: 4 K High-Velocity Spoke Cavity Performance

Frequency [MHz]	500	325	700	350*
$V_{acc}[MV]$	2.7	9.1	3.2	8.7
E_{acc}[MV/m]	4.5	12	5.0	6.8
E_p[MV/m]	16.7	43.2	22	34
B_p [mT]	34	72	39	55

*Pulsed operation

The 500 MHz, $\beta_0 = 1$ double-spoke cavity tested at Jefferson Lab had a high Q_0 and a residual resistance < 10 nΩ. Unfortunately, the performance was limited by a self-sustaining pulsing quench (with decay time of several msec), which is characteristic of thermal breakdown. The Niowave cavities did not experience any hard quenches.

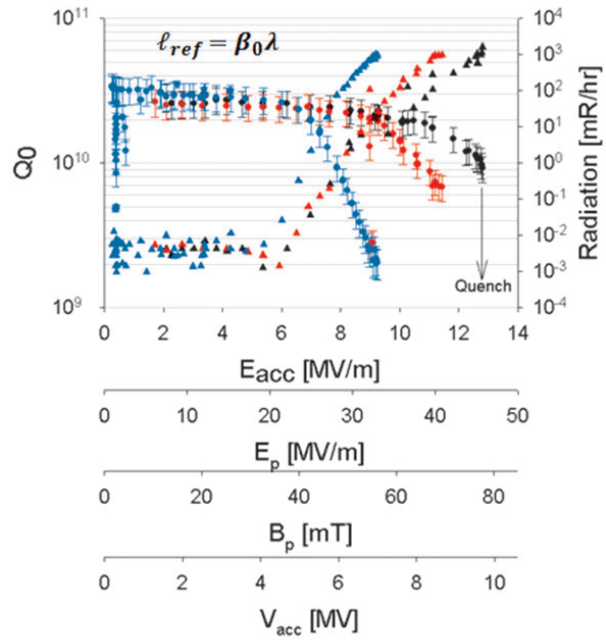

Figure 8: 325 MHz single-spoke 2 K tests after successive helium processing. The triangles are radiation levels and the closed circles are Q_0 values.

Field emission initially limited the single-spoke cavity performance. Helium processing was employed and significantly improved the performance, as is shown in Fig. 8 where the achievable gradient increased by roughly 30%.

Given the rf properties of this cavity, the accelerating gradient of ≈ 13 MV/m translates into a peak surface electric field of 45 MV/m, peak surface magnetic field of 77 mT, and giving an accelerating voltage of 9.7 MV.

CONCLUSION

Simulation, fabrication, and processing tools and techniques have advanced greatly over the past several decades, which allows for the reliable manufacturing of simple and complicated geometries alike. The experience gained fabricating and processing other TEM-class cavities provides a solid foundation which was used for this work.

These are the first high-velocity superconducting spoke cavities fabricated and tested, to date. Both the ODU/JLab $\beta_0 = 1$ and 0.82 cavities reached a high Q_0 and were found to have a low residual resistance. The single-spoke cavity quenched at ≈ 13 MV/m, while the double-spoke cavity experienced thermal breakdown. This limitation is not fundamental to the design. The cavities tested at Niowave Inc did not experience hard quenches and have yet to reach their full potential. Multipacting was encountered, at levels predicted by simulation, but was easily processed in all the cavities presented here.

The advantages spoke cavities offer are somewhat lessened in high-velocity spoke cavities optimized for low peak surface fields and high shunt impedance. Namely the transverse size increases and the separation between the fundamental and nearest modes decreases. However those advantages are still present, and can be quite significant depending on the application.

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