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SUPERCONDUCTING SPOKE CAVITIES FOR ELECTRONS AND HIGH-VELOCITY PROTON LINACS*

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Abstract

Over the last two decades, spoke resonators have been developed for the medium-velocity range of many proton and ion machines. These structures are now being considered and developed for electron linacs and high velocity proton linacs. The status of these developments and the properties of high-velocities spoke cavities are presented.

FEATURES OF THE SPOKE CAVITY

The spoke cavity, shown in Fig. 1, is a variant of the coaxial half-wave geometry. In its fundamental mode of operation, the spoke sustains a TEM mode where the length of the spoke is approximately half the wavelength. The current (and magnetic field) is large where the spoke meets the outer conductor, and the voltage (and electric field) is large in the middle of the spoke.

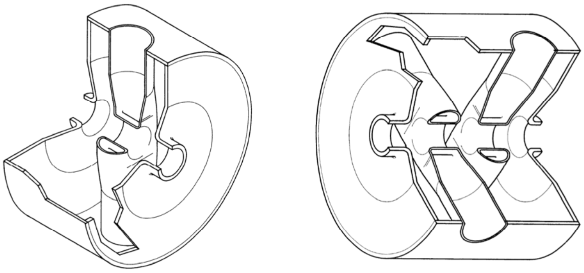

Figure 1: Single-spoke and double-spoke cavity [1].

In multi-spoke cavities, shown in Fig. 2, each spoke operates 180^0 out of phase with the nearest ones and is usually perpendicularly oriented with respect to them.

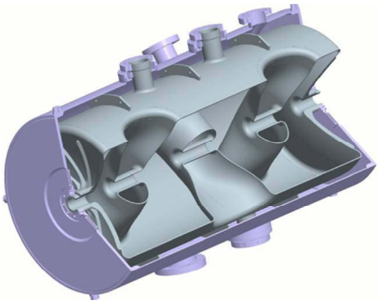

Figure 2: triple-spoke cavity [2].

The spoke cavity was initially developed for the mid-velocity range because of a number of attractive features [3, 4].

Size

For the same frequency and in the medium-velocity region, spoke cavities are smaller than TM-class cavities. The transverse size of a spoke cavity is in the range 0.5-0.55 λ while that of a TM cavity is about 0.95λ. As a result accelerators can be designed for low frequency where 4.2K operation is practical, while maintaining cavities of a reasonable size. At half the frequency of a TM cavity of the same β, a multi-spoke cavity of the same length would have half the number of cells. Therefore its velocity acceptance is broader and the cavity is useful over a wider range of velocities. Lower frequency would also result in a higher longitudinal acceptance, which might be beneficial in high current applications.

As will be shown later, the size difference is not as dramatic with spoke cavity designs that maximize the shunt impedance and minimize the surface fields. These optimizations lead to geometries of the spoke themselves which deviate substantially from cylinders; as a consequence, in order to maintain the frequency, the spokes have to be longer and the diameter of the cavity larger.

Cell-to-cell Coupling

Unlike TM cavities where the cell-to-cell coupling occurs through the iris opening, a multi-spoke cavity is much more open and magnetic field lines couple all the cells. The cell-to-cell coupling is much higher in multi-spoke cavities than in multi-cell TM cavities and they are much more robust with respect to manufacturing inaccuracies. Tuning to achieve field profile balance is probably unnecessary while it is an important and necessary step for TM cavities.

The strong cell-to-cell coupling, together with the fact that multi-spoke cavities have only a relatively small number of spokes, implies that the accelerating mode will be well separated from the nearest mode. In addition, unlike multi-cell TM cavities, the fundamental accelerating mode in multi-spoke cavities is the lowest frequency mode, and there are no lower-order modes. This was known to be true in the medium-velocity regime and it has been confirmed in all the high-velocity spoke cavities designed to-date.

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Surface Fields and Energy Content

In a spoke cavity, the electromagnetic fields are concentrated around the spoke and decay rapidly moving away from it. In contrast, in a TM cavity, a much larger volume is uniformly filled with electromagnetic energy. Thus, spoke cavities tend to have a small energy content and high shunt impedance.

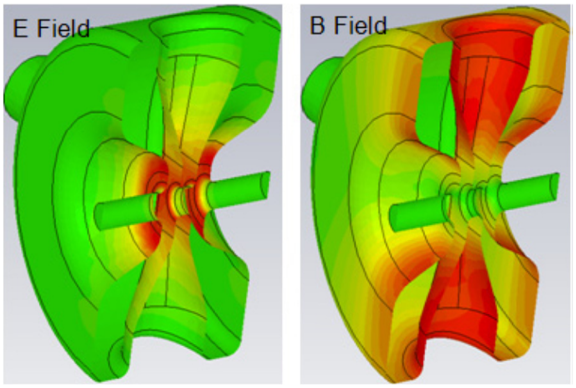

Figure 3: Distribution of surface electric and magnetic field in a single-spoke cavity [5].

This also means that the power couplers (both fundamental and for higher-order mode extraction if needed) can be located on the outer conductor instead of on the beamline as shown in Figs. 2, and 3. The impact of this aspect on the use of the beam line is illustrated in Fig. 4. [6]

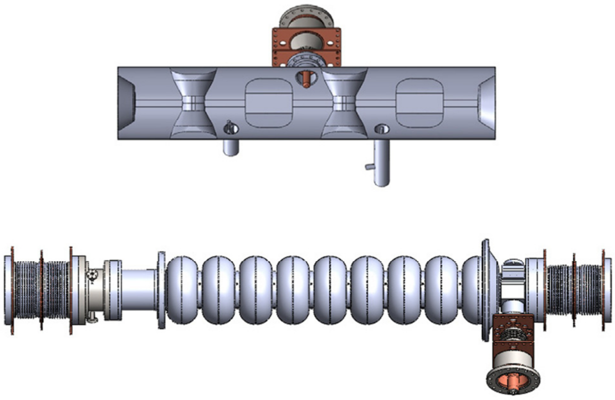

Figure 4: Relative location of couplers in spoke and TM-type cavities [6]

Electromechanical Properties

Unlike multi-cell TM cavities, spoke cavities have only a few mechanical modes that couple to the electromagnetic field, and they are at relatively high frequency. Spoke cavities can also be designed with very sensitivity to helium pressure fluctuations (~0.5 Hz/torr) by compensating the electric and magnetic effects instead of stiffening and have shown very low levels of microphonics (<1 Hz rms) [7-9].

POTENTIAL APPLICATIONS OF HIGH-VELOCITY SPOKE CAVITIES

One type of accelerator where high-velocity spoke cavities may find an application is in small, low-energy (a few 10's of MeV) electron accelerators where 2K refrigeration is not available or affordable. One example is the type of x-ray source based on Inverse Compton Scattering first proposed by MIT [10] and shown in Fig. 5. This concept for the accelerator is now being developed at Jefferson Lab. Minimization of 4K cryogenic losses implies low frequency, modest gradients, and high shunt impedance which are the characteristics of spoke cavities.

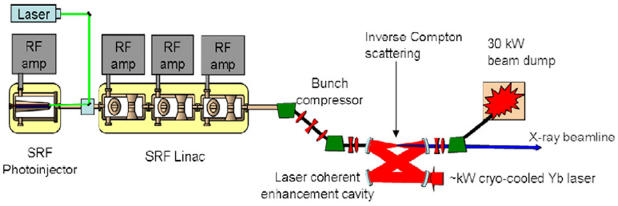

Figure 5: Concept layout for an Inverse Compton Source

In Japan there is a proposal for a non-destructive assay system of nuclear materials (uranium, plutonium, and minor actinides) in spent fuel using nuclear resonance fluorescence [6, 11]. An energy-recovering linac would be combined with a laser to produce high-brightness, monochromatic x/γ-rays via inverse Compton scattering. To be practical the ERL needs to be compact but still be able to deal with the high current and the instabilities due to the high-order modes. The rationale for considering spoke cavities in this application is that, since the fundamental and high-order mode couplers can be located radially instead of on the beamline, the cavities can be located closer to each other, increasing the "real estate" gradient. A schematic view of this ERL is shown in Fig. 6.

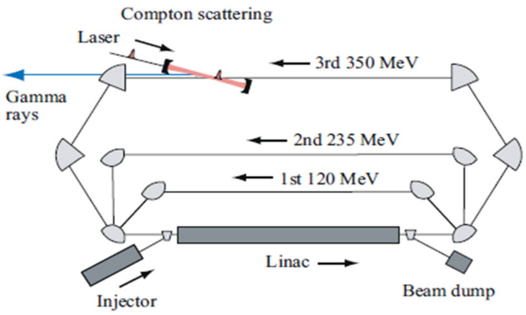

Figure 6: Schematic view of ERL for non-destructive assay of nuclear materials [6, 11]

Another potential application is in GeV-scale proton accelerators such as spallation sources. The use of spoke cavities would result in an accelerator with constant frequency from a few MeV to a few GeV, avoiding frequency transitions which can be the source of beam loss, and standardizing in equipment, in particular rf sources [12].

Finally, spoke cavities could also be considered in GeV-scale cw electron accelerators with low repetition bunch frequency, such as light sources. In this case, cryogenic losses would be an important consideration and, because of the low bunch frequency, there is no need to use high rf frequency. Spoke cavities could offer a low-frequency alternative while maintaining a reasonable size.

DESIGN OPTIMIZATION AND PROPERTIES OF HIGH-VELOCITY SPOKE CAVITIES

Spoke cavities have many more "degrees of freedom" that TM-type cavities and the parameter space to be explored is much larger [3]. This can lead to different strategies in their design.

KEK employed a multi-objective optimization procedure with a genetic algorithm for the design of 650 MHz, β=1 multi-spoke cavities for an ERL-based linac for non-destructive assay of nuclear materials [6]. The three objective were: the minimization of E_p/E_{acc}, B_p/E_{acc}, and $1/(R/Q)$. The results are shown in Fig. 7. This technique is quite powerful, rapid, and, if the objective, carefully chosen, can lead to excellent results. Its limitation is that the trade-offs are not always apparent.

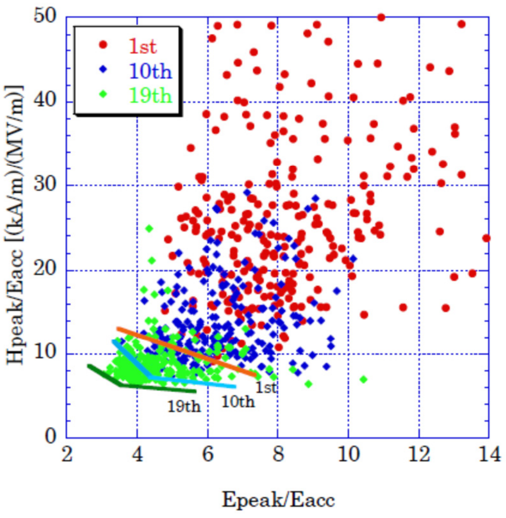

Figure 7: Distribution and Pareto front lines of E_p/E_{acc} and B_p/E_{acc} at successive generations [6].

ODU opted for a more systematic approach where each parameter was modified independently (keeping the frequency and beta constant) in order to assess its impact on the cavity properties [13-16]. This approach was probably slower but led to a good understanding of the importance of each design parameter and how it affects the final design, as well as providing a good basis for the design choices and the trade-offs involved. A number of single- double-, and triple-spoke cavities have been designed this way for a number of applications: GeV-scale proton linacs, small compact electron accelerators for inverse-Compton Scattering light sources, and larger electron accelerators for FELs or light sources. The design frequencies were 325 MHz, 352 MHz, 500 MHz, and 700 MHz; and the βs were 0.82 and 1.

Jefferson Lab has focused on 352 MHz, β=1, double-spoke cavities for a small light source [17].

In the end, as could be expected, all designs look fairly similar. The differences can be attributed to the different application and goals. Some designs had the goal of minimizing the peak surface fields (which in itself means deciding whether to minimize E_p/E_{acc} or B_p/E_{acc}), maximizing the shunt impedance, or a combination of both.

Spoke Shape

Since the highest surface electric and magnetic fields are located on the spoke –close to the beam line for the electric field and close to the outer cylinder for the magnetic field, (see Fig. 3) – the properties of the cavity will depend strongly on the geometry of the spoke and significant design effort is directed toward the shape of the spoke.

The simplest shape is that of a straight cylinder with a possible flattening in the beam line region (see Fig. 1). For multi-spoke cavities, the peak surface magnetic field can be significantly reduced by a non-circular cross-section near the outer conductor. The first attempt in that direction was by elongating the spoke parallel to the beam line, which resulted in a lower peak surface magnetic field [18]. It turns out, however, that even lower surface fields could be obtained by elongating the spoke cross-section perpendicularly to the beam line; the circular cross-section being the one with the highest surface magnetic field. This is illustrated in Fig. 8. The maximum peak surface magnetic field is for a near-circular cross-section at the spoke base. As the spoke is elongated longitudinally, the peak surface magnetic field first decreases and goes through a minimum. If instead the spoke is elongated transversally, the peak surface magnetic field decreases even further [13, 14, 16]. Transversally elongated spokes also lead to higher shunt impedance.

The peak surface magnetic field can be reduced even further by increasing the cross-section near the outer cylinder, further deviating from a straight cylinder. This can also be used to control the ratio of the peak surface magnetic field and peak surface electric field. For cavities designed to operate at 4.2 K, a ratio of B_p/E_p ~1.8

mT/(MV/m) would be a realistic goal given the state of the SRF technology; for cavities operating at 2 K, a ratio of ~2.2 mT/(MV/m) would be more appropriate. These numbers are of course very dependent on the state of the art and could evolve, and have evolved, in time. The resulting shape, shown in Fig. 9, yields low surface fields and a high shunt impedance; it has however the disadvantage of increasing the outer diameter of the cavity in order to maintain a constant frequency, thus reducing somewhat one of the main attraction of the spoke geometry. Nevertheless, even with these extreme spoke shapes, the spoke cavity is about 75% the transverse size of a TM cavity of the same frequency.

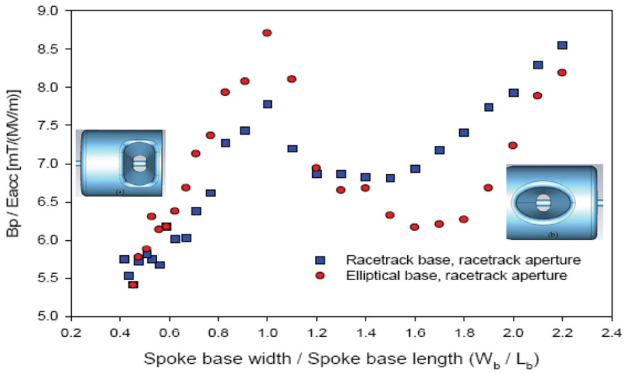

Figure 8: Peak surface magnetic field as a function of the shape of the base of the spoke. The field is maximum for a near-cylindrical spoke.

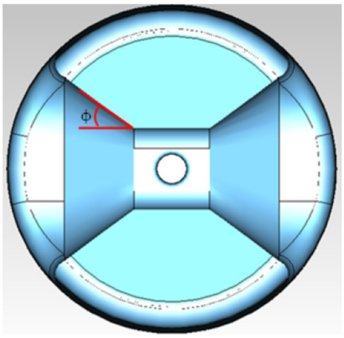

Figure 9: Typical spoke shape for low surface fields and high shunt impedance.

Similarly, the shape of the spoke near the beam line affects the peak surface magnetic field, with cross-sections elongated transversally reducing the peak surface magnetic field.

Higher-order modes

It was known that, in the low and medium-β regime, spoke cavities did not have any lower-order mode and that the first higher-order mode was will separated from the fundamental. That was cited as one of the attractive features of spoke cavities. Extensive simulations have confirmed that it is also the case for β~1 spoke cavities [19]. This is illustrated in Fig. 10 which shows the *R/Q* for a 325 MHz, β=0.82 double-spoke cavity.

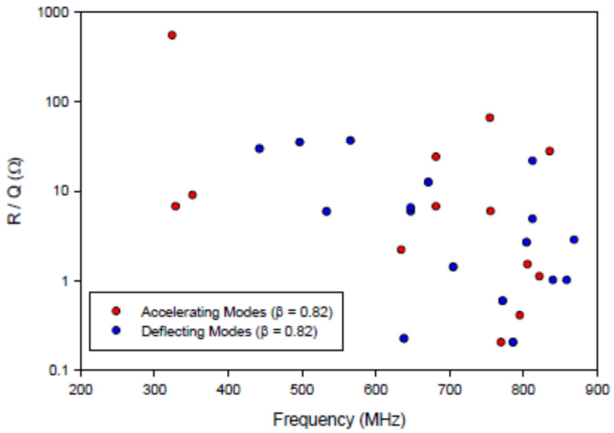

Figure 10: *R/Q* for particles of optimal velocity in a 325 MHz, β=0.82, double-spoke cavity.

Multipoles

Spoke cavities lack the circular cylindrical symmetry and therefore the electromagnetic fields of the fundamental accelerating field will have multipole components besides the accelerating monopole [20]. In some applications, the multipole components will need to be reduced and limited. One strategy would be to have a ring-shaped geometry near the beamline as was recently suggested for the half-wave geometry [21]. In such geometry, shown in Fig. 11, the quadrupole component was reduced by more than a factor of [20].

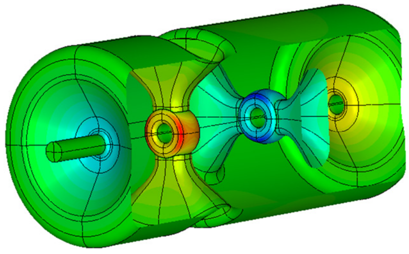

Figure 11: Double-spoke cavity with ring-shaped spoke near the beam line in order to reduce the multipole components.

Multipacting

As is always the case for new geometries for superconducting cavities, the presence of multipacting is a concern. As more and more complex and powerful simulation tools are developed extensive simulations can be made, but no definitive answer can be found until a cryogenic test on a real cavity. Such extensive simulations have been done both at Jefferson Lab [17] and ODU [22, 23] with similar results. Multipacting resonances occur at low field with high impact energy. The resonances that are found at expected operating fields have low impact energy.

The only data point that exists at present is a preliminary test of a 700 MHz, β=1, double-spoke cavity.

Multipacting levels were found at low field but were processed away [24].

Hardware

The only high-velocity spoke cavities in existence to-date are a 500 MHz and a 700 MHz, both double-spoke and β=1 [25]. They were designed by ODU and manufactured by Niowave Inc. Testing of the 700 MHz cavity is under way.

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