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# APPLICATIONS OF SPOKE CAVITIES*

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## *Abstract*

The superconducting spoke cavity was introduced in the late 1980s in response to the need for superconducting structures in the mid-velocity range. Since then it has found application in many projects. Prototypes have been developed for a wide range of beam velocities. The characteristics and features of the spoke cavity are reviewed and some of their applications are presented.

## INTRODUCTION

Historically the development of superconducting cavities and accelerators has been divided into two main classes of applications. One was for accelerators for nuclear structure studies that required low-velocity ($\beta<0.2$), low-frequency (f~50-150 MHz) cavities. The other one was for high energy accelerators requiring velocity-of-light, high-frequency (f~0.5-1.5 GHz) cavities. In the late 1980s interest in high-current, mid- to high-energy proton accelerators led to the development of new superconducting cavity geometries. The first one was the coaxial half-wave cavity [1,2], which is also finding a wide range of applications. The other one is the spoke cavity [1,3], which has all the positive features of the coaxial half-wave, but also lends itself to multi-cell structures. At present spoke cavities have been developed and tested for $\beta$ from 1.75 to .62, and are also under development for $\beta$ up to 1.

While spoke cavities were mostly developed for 4.2K operation, recent development in fabrications and processing techniques (clean assembly, hydrogen degassing, etc) yields results such that 2K operation would be more economical for large machines, even taking into account the differences is refrigerator efficiency. Nevertheless, for small accelerators where 2K operation may not be practical, spoke cavities offer a viable 4.2K option.

## 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.

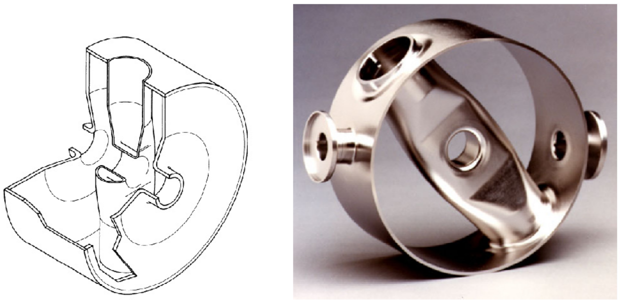

Figure 1: Single-spoke cavity [1, 3].

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.

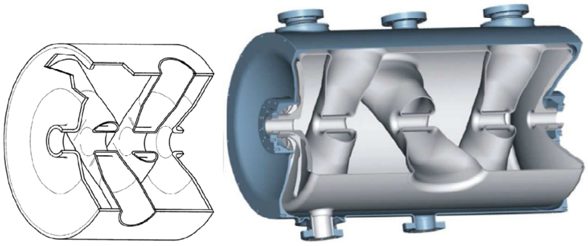

Figure 2: Double-spoke [1] and triple-spoke cavities [4].

Besides the mode geometry, the spoke (and also the coaxial half-wave) geometry differ from the other common "elliptical" TM geometry is several ways [5-8].

### *Size*

As shown in Fig. 3, for the same frequency, spoke cavities are substantially smaller than TM-class cavities. The transverse size of a spoke cavity is in the range 0.5-0.55 $\lambda$ while that of a TM cavity is about 0.95$\lambda$. 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 $\beta$, 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.

### *Cell-to-cell Coupling*

Unlike TM cavities where the cell-to-cell coupling occurs through the iris opening, a multi-spoke cavity is

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much more open and magnetic field lines couple all the cells as shown in Fig. 4.

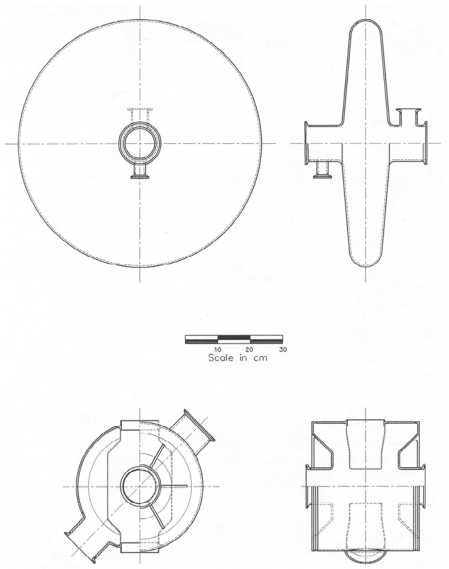

Figure 3: Relative size of 350 MHz, β=0.45 TM-type and spoke cavities [9].

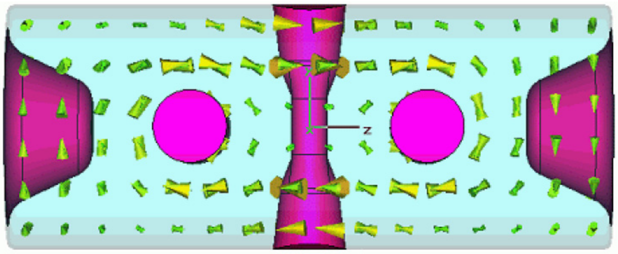

Figure 4: Magnetic field distribution in a triple-spoke cavity [10].

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 in 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 that there are no lower-order modes. This could simplify the damping and extraction of higher-order modes in high-current applications.

## *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. 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. 1, 2, and 3.

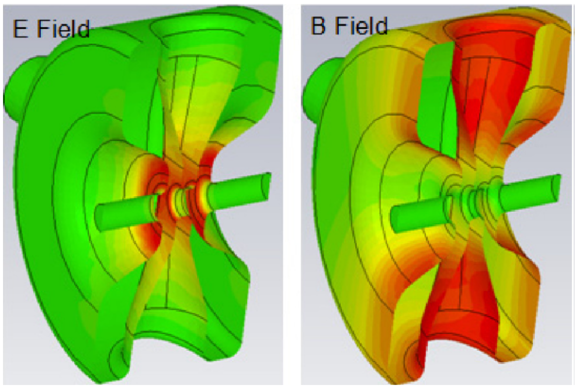

Figure 5: Distribution of surface electric and magnetic field in a single-spoke cavity [11].

It is also true that, for a given gradient defined by using the inside length of the cavity as a reference length, the peak surface fields will be higher in a spoke cavity compared to those in an elliptical cavity, at least in the high-β regime [5]. As mentioned above, in view of the fact that there is no need of using beamline length for location of the couplers in a spoke cavity, it is not clear that the surface fields would be significantly higher at a constant real estate gradient. Additionally, spoke cavities' intended use is mostly in relatively high-current and/or cw applications where the gradients would be modest.

## *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. This is illustrated in Fig. 6 showing the Lorentz transfer function of a 345 MHz, β=0.5 triple-spoke cavity [12-14].

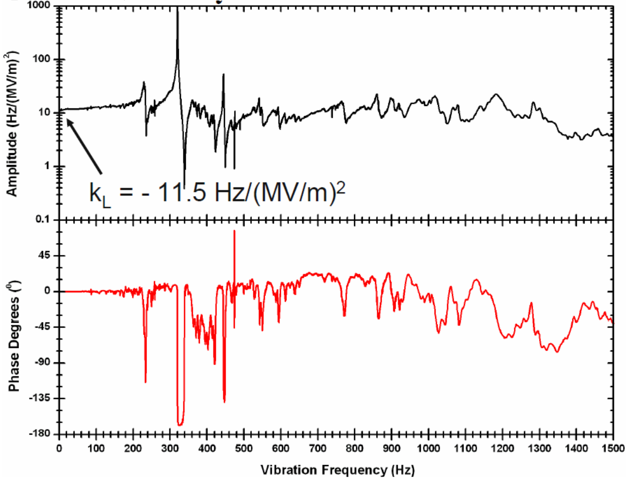

Figure 6: Lorentz transfer function of a 350 MHz, β=0.5 triple-spoke cavity [12-14].

## EXPERIMENTAL RESULTS

### *Achieved Gradients in Single-spoke Cavities*

To date many single-spoke cavities have been tested at 4.2 K and 2 K. Some significant results are shown in Figs. 7 and 8. Figure 7 is a Q-curve of a 352 MHz, β=0.35 developed at Orsay for the PDS/XADS and EURISOL projects. Surface fields of 49.5 MV/m and 134 mT were achieved [15]. Figure 8 is a Q-curve for a 325 MHz, β=0.22 single-spoke cavity [16] recently tested at Fermilab.

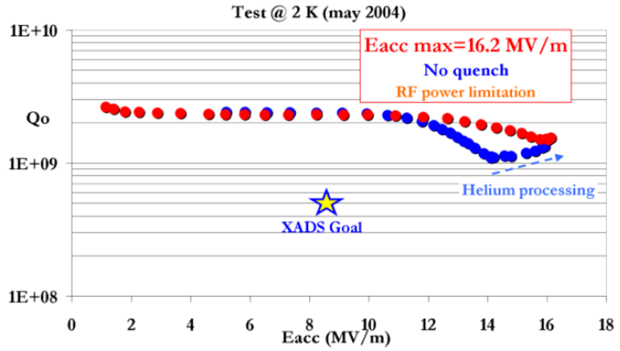

Figure 7: Q-curve of a 352 MHz, β=0.35 single-spoke cavity [15].

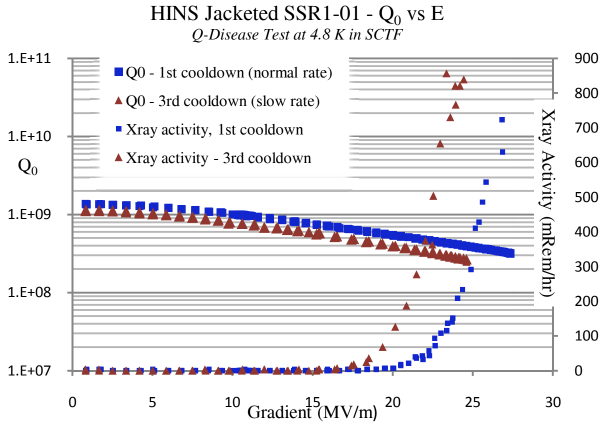

Figure 8: Q-curve of a 325 MHz, β=0.22 single-spoke cavity [16].

### *Achieved Gradients in Multi-spoke Cavities*

Figure 9 summarizes the experimental results achieved at ANL on two 345 MHz triple-spoke cavities, one for β=0.5 (open symbols) the other β=0.63 (closed symbols) at 4.2 K and 2 K [4, 17]. These results clearly show that flat Q-curves can be obtained at 2 K by careful hydrogen degassing of the niobium, and that, even at 345 MHz, 2 K operation would be more cryogenically efficient than 4.2 K operation. Interestingly, the degassing did not seem to eliminate the Q-slope at 4.2 K. This may indicate that, at least in this frequency range, the Q-slopes at 4.2 K and 2 K may have different physical origin which would require further investigation.

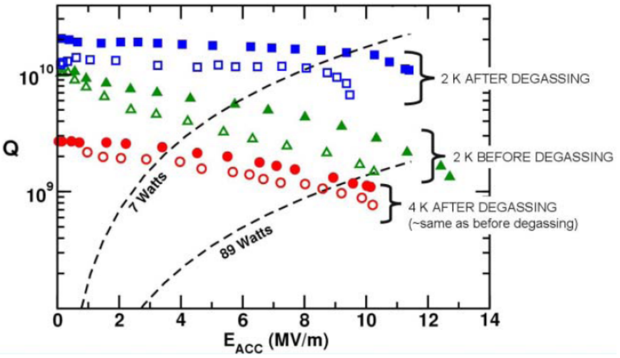

Figure 9: Q-curves for 345 MHz, β=0.5 (open symbols) and β=.63 (closed symbols) triple-spoke cavities [4,17].

### *Sensitivity to Magnetic Fields and Quenches*

Recent experiments at Fermilab have investigated the sensitivity of the performance of a single-spoke cavity to ambient magnetic field [16]. Q degradation at 4.7 K was becoming apparent if the cavity was cooled in an ambient magnetic field in excess of 200 mG. In another set of experiments, a magnetic field of 8-10 G was applied to a cavity which had been cooled in the absence of magnetic field. Repeated quenching of the cavity did not decrease the Q of the cavity at low and high rf field [16]. This is an indication that, while the spoke quenches, the outer conductor remains superconducting and provides shielding of the spoke and no magnetic field gets trapped when the spoke returns to the superconducting state.

### *Microphonics and Sensitivity to Helium Bath Pressure Fluctuations*

By carefully locating and designing stiffening ribs, deformation of the cavity under He bath pressure fluctuations in the high electric and magnetic field regions can have compensating effect and results in a very low sensitivity to these fluctuations of -0.5 Hz/torr [12].

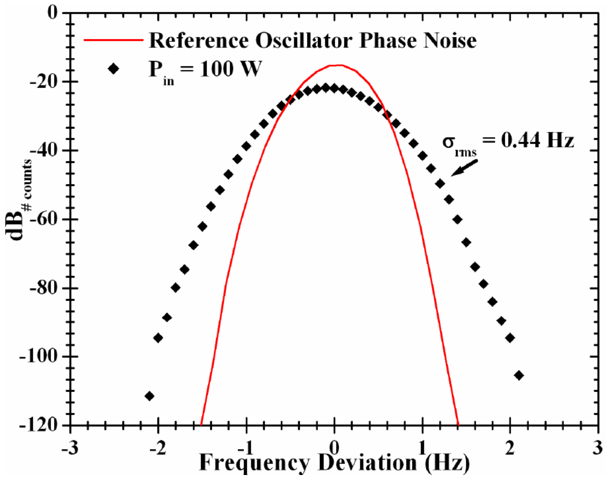

Figure 10: Measured probability density of the microphonics in a 345 MHz, β=0.5, triple-spoke cavity.

Extremely low levels of microphonics have been achieved in multi-spoke cavities. Figure 9 shows the probability density of the microphonics in a 345 MHz, β=0.5, triple-spoke cavity [12]. Even with a power dissipation of 100 W, the measured microphonics were gaussian over many orders of magnitude with an rms value of 0.44 Hz, barely higher than the noise of the reference synthesizer used in the measurements.

## SOME APPLICATIONS OF SPOKE CAVITIES

While no spoke cavity is already in use in operating accelerators, they are under consideration for a number of them.

EURISOL is the nest generation European ISOL facility for rare isotopes. Use of spoke cavities is planned in both the main driver and the secondary accelerator [18-20].

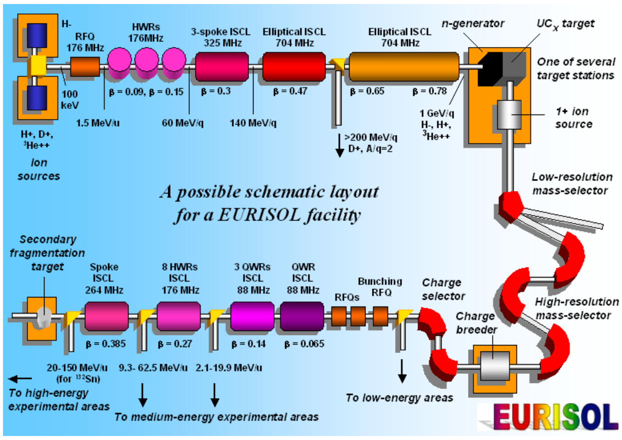

Figure 11: Concept of the EURISOL Facility.

The EUROTRANS project is an Accelerator Driven System for the transmutation of long-lived radioactive fission fragments and minor actinides produced in nuclear reactors. Its driver linac will produce a 600 MeV beam, of maximum current of 4 mA, but capable of accelerating 25 mA [21].

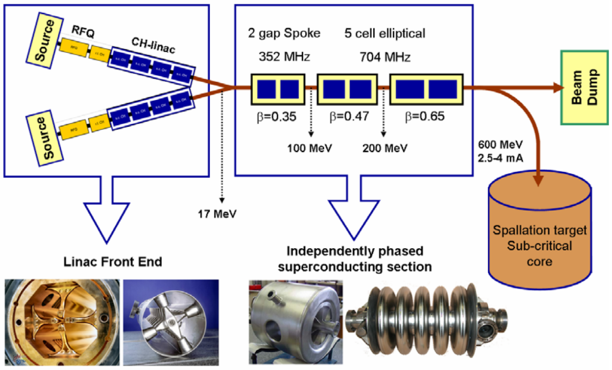

Figure 12: Concept for the EUROTRANS Project.

Figure 13: 352 MHz, β=0.15 and 0.35 single-spoke cavities developed for the EURISOL and EUROTRANS projects [15, 19, 20].

Project X at Fermilab is another proton linear accelerator which, up to 3 GeV, will be operated cw. The present concept, shown in Fig. 14 will use 3 types of single-spoke cavities operating at 325 MHz, of β=0.11, 0.22, and 0.41 [11]. An earlier concept included a triple-spoke section for β=0.6 [22].

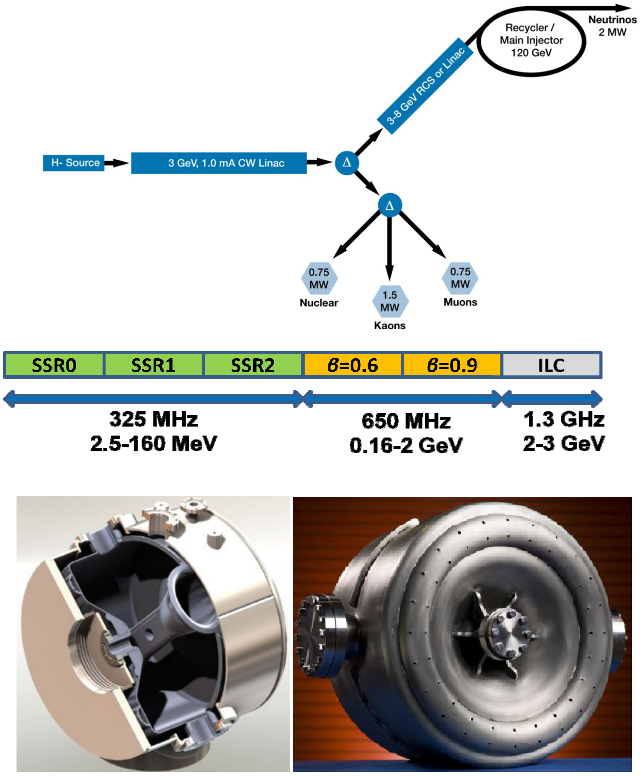

Figure 14: Present concept for Fermilab's Project X (upper), concept for the cw linac (middle), and prototype of the 325 MHz, β=0.22 single-spoke cavity.

The European Spallation Source (ESS) is a high-current proton linac to be built in Lund, Sweden. The linac, shown conceptually in Fig. 15, will deliver 5 MW of power to a target at 2.5 GeV with a nominal current of 50 mA. It is designed to include an upgrade to a power of 7.5 MW by increasing the current to 75 mA [23].

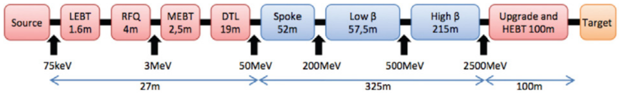

Figure 15: Concept for the ESS linac.

Spoke cavities are also under consideration for small electron accelerators where 2 K operation may not be practical. Because of their small size, spoke cavities can be designed to operate at frequencies where 4.2 K operation would be feasible, even in cw operation. Such a small machine, proposed by MIT, is shown in Fig.16 where a low emittance moderate current (~1 mA) would interact with a powerful laser and produce x-rays by reverse Compton scattering [24].

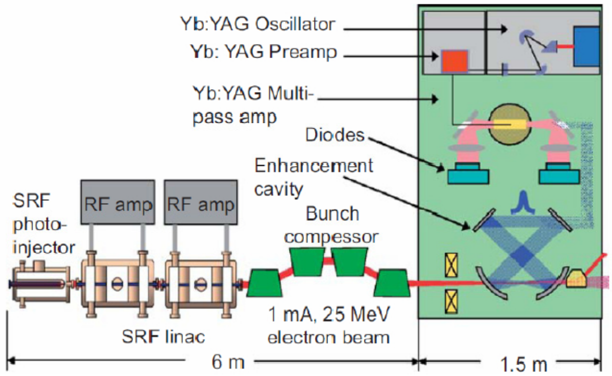

Figure 16: Layout of the MIT reverse Compton Source.

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