STATUS OF SUPERCONDUCTING SPOKE CAVITY DEVELOPMENT

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Abstract

Superconducting (SC) TEM-class spoke cavities are required for proposed cw and pulsed ion linac applications world-wide. Several laboratories and institutions have demonstrated high field performance (Epeak>30 MV/m) in single- and multi-spoke geometries for use with ions over the full mass range and for velocities 0.15 < v/c < 0.8. Recent results show spoke cavities, previously designed for 4 Kelvin operation, now operate with better efficiency at 2 Kelvin, resulting in large part from performance gains due to techniques such as clean assembly and hydrogen degassing. Low Rf losses even for high accelerating fields (corresponding to Epeak~30 MV/m) required in operations have been achieved. The status of recent spoke cavity activities at several laboratories is presented.

INTRODUCTION

In the mid-1990's it was recognized that new ion driver linacs for rare isotope beams production required new accelerating cavities for the intermediate velocity region [1-3]. Drift-tube cavities at low-β and elliptical cell structures for beta near 1 had operated for years; however, suitable cavities for most of the full velocity region, 0.15 < v/c < 0.8, did not exist. Today, with 4 Kelvin spoke cavity field performance with accelerating gradients ~10 MV/m now well established, proposed new facilities based on spoke cavities will depend critically on additional gains in superconducting cavity performance realized in just the last couple of years. In particular, recent advances in spoke-cavities operating at 2 Kelvin (rather than 4 Kelvin) likely offer most cost effective technical solution for proposed cw ion linacs. In addition, substantial further performance increases in the overall SC linac accelerating gradient by as much as 30% and commensurate cost reductions are still possible if fully optimized electromagnetic (EM) designs under development at several laboratories, but not hitherto demonstrated, are developed.

APPLICATIONS

R&D on SC TEM-class spoke cavities in this decade has resulted in great progress and has led to many new proposed facilities worldwide. Applications span cw and pulsed ion linacs for production of rare isotopes, intense neutrino beam studies, and nuclear waste transformation facilities. Required field performance has been demonstrated in several spoke geometries including single-, double- and triple-spoke cavities mostly near 350 MHz and intended for use with ions from protons to uranium over nearly the full velocity range, 0.1 < v/c < 0.8.

The next generation of rare isotope beams facilities based on SC spoke cavities is being developed in the U.S. and Europe. AEBL [4] (Advanced Exotic Beam Laboratory), proposed at Argonne National Laboratory, uses 134 double- and triple-spoke cavities at 345 MHz (207 SC cavities total) to simultaneously accelerate five charge states of uranium to 200 MeV/u. A schematic is shown in Figure 1. Multi-spoke cavities for AEBL are the same designs that have been demonstrated previously for RIA [5]. Alternatively, the Isotope Science Facility (ISF) proposed by Michigan State University uses another class of λ/2 accelerating structure, the two-gap co-axial half-wave cavity. For ISF, 297 half-wave resonators (481 total cavities) at 322 MHz are used to produce 200 MeV/u uranium beams.

Eurisol, the European next generation ISOL facility also for rare isotope science proposes to use roughly 22 triple-spoke cavities at 352 MHz [6] in the medium-β section of a multi-kilowatt proton and light-ion driver linac. Another 154 spoke cavities for the Eurisol heavy-ion post-accelerator have also been proposed as shown in Figure 2.

Applications for the accelerator driven system (ADS) for nuclear waste transmutation or for tritium production also propose the use SC spoke cavities. In these applications extreme reliability is paramount and proposed accelerators rely on the high degree of fault tolerance which may be possible using an array of relatively short

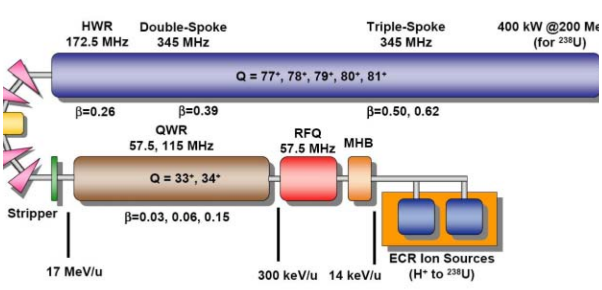

Figure 1: A driver linac for a proposed U.S. rare isotope beams facility using 134 SC multi-spoke cavities.

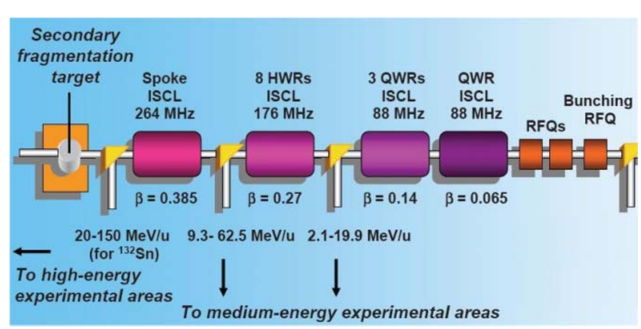

Figure 2: Proposed 150 MeV/u post accelerator for Eurisol using 154 SC spoke cavities.

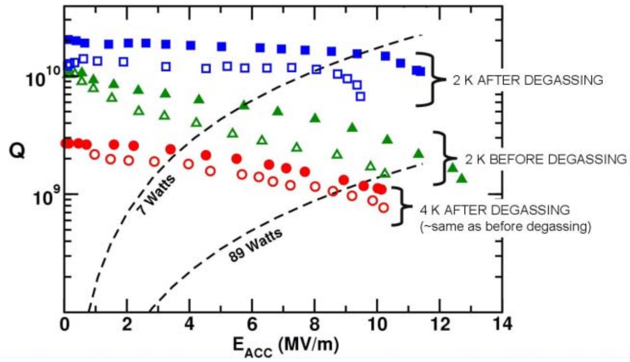

Figure 3: β=0.5 spoke cavity (open symbols) and β=0.62 spoke cavity (filled symbols) showing improvement in 2 K performance after hydrogen degassing. 4 K operation was little changed. Dashed line – rf power for β=0.62 cavity.

independently tunable accelerating structures. In Europe, spoke cavity development for ADS [7] is being pursued under the framework of Experimental Accelerator Driven Systems (XADS). In the U.S. a pair of spoke cavities for ADS was developed under the U.S. Department of Energy Advanced Accelerator Applications program [8].

Project-X, proposed by Fermilab, is another class of application proposing to use spoke cavities. Here, roughly 90 SC spoke cavities for the front end of an 8 GeV pulsed proton driver [9], coupled with the FNAL main injector, would be used to produce high-intensity neutrino beams. Two new β=0.22 325 MHz single-spoke cavities [10] for Project-X prototyped in collaboration with Zanon (Italy) and Roark (U.S.) are nearly complete.

DEVELOPMENT

2 Kelvin Operation

An important recent experimental development has been the very low surface resistances of <10 nΩ achieved in a pair of spoke cavities operating at 2 Kelvin. Spoke cavities built to date were all initially intended for 4 Kelvin operation. However, results shown in Figure 3 for triple-spoke cavities with β=0.5 and β=0.62 [11,12] before and after hydrogen degassing at 600°C show rf losses substantially reduced for 2 Kelvin operation. Performance at 4 Kelvin was relatively unchanged and, with the 2 K improvements, would require ~10X the rf power as with 2 K operation.

Low temperature 2 K operation is new for TEM cavities and will broadly affect the SC linac design including in the areas of cryoplant and cryomodule, cavity surface processing, rf power requirements and microphonics.

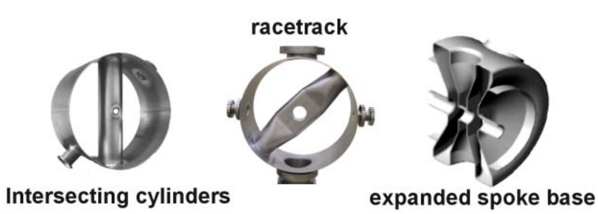

Figure 4: A simple spoke cavity based on intersecting cylinders (left). A "racetrack" design (middle) to minimize E_{PEAK} and an optimized spoke (right) to minimize B_{PEAK}.

However, these recent data as shown in Figure 3 indicate that major savings with 2 K operation are likely in both refrigerator capital and operating costs (even with refrigerator efficiency ratio $\varepsilon_{4.2K}/\varepsilon_{2K} \sim 3.6$ to 1).

EM Design

TEM cavity field performance due specifically to optimized shapes designed using modern 3D simulation codes such as MAFIA and Microwave Studio have greatly contributed to increased performance. Significant further improvements of 30% or more from EM optimization, particularly for the performance limiting peak magnetic field, are possible.

A spoke cavity in its simplest form may be formed from three intersecting cylinders: a cylindrical housing, a spoke, and a beam tube together with a pair of disc shaped end walls (See Figure 4).

However, it was clear since the fabrication of the first SC spoke cavity that the peak surface electric field, related directly to the expected onset of field emission, could be minimized by using a flattened racetrack shape near the beam tube in order to produce a relatively uniform electric field around the spoke circumference [2].

In the last few years, and particularly with the successes in reducing cavity field emission using high pressure water rinsing and cleanroom assembly, it became clear that magnetic field was often the performance limiting physical quantity for spoke cavities. Design work has been performed to reduce the magnetic field by increasing the spoke diameter at the base and using a re-entrant end wall as shown in Figure 5.

Recently, all of these techniques were combined for a β=0.62 triple-spoke resonator designed at Fermilab [13]. In addition to expanding the base of the spokes, elliptical sections are used (Figure 5 - A2&B2, a2&b2) to further

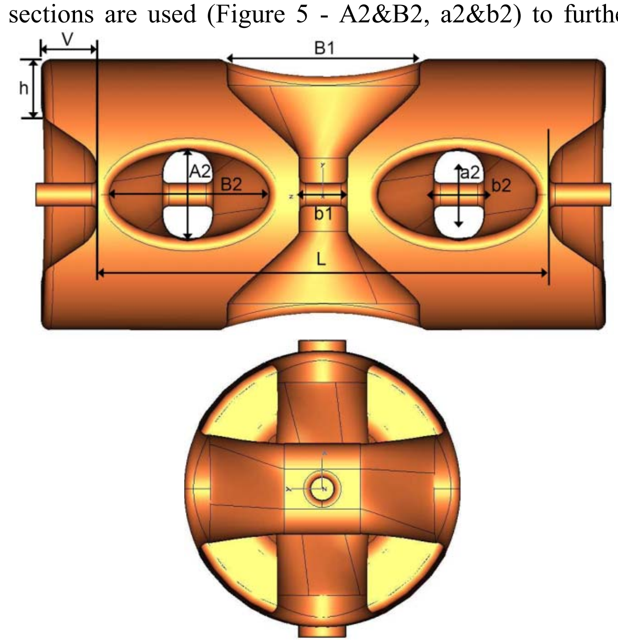

Figure 5: Preliminary EM design for an optimized triple spoke cavity at 345 MHz for β=0.54. The critical ratio B_{PEAK}/E_{ACC}=6.66 mT/MV/m or about a 30% improvement over existing structures. See also reference [13].

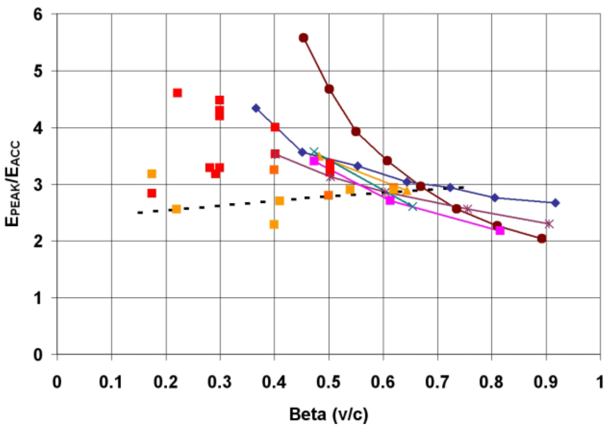

Figure 6: Peak surface electric fields. Solid squares – spoke cavities. Solid lines – elliptical cell cavities. Reference[14]

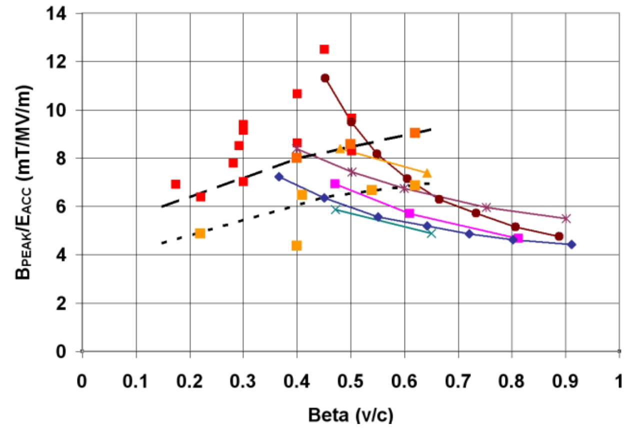

Figure 7: Peak magnetic electric fields. Solid squares – spoke cavities. Solid lines – elliptical cell cavities. Reference[14]

reduce the surface magnetic fields. These techniques have also been applied at Argonne in preliminary EM designs for triple spoke cavities at β=0.41 and β=0.54. An example for a β=0.54 cavity is shown in Figure 5.

Peak surface electric and magnetic fields for a range of intermediate velocity SC cavities are shown in Figures 6 and 7 respectively [14]. Solid lines are for elliptical cell cavities, while individual points are for spoke cavities. The dashed line roughly indicates the best values that may be achieved using the parametric design from Figure 5. In this case E_{PEAK} trends upward slightly with increasing beta going from E_{PEAK}/E_{ACC}=2.5 at β=0.15 up to about E_{PEAK}/E_{ACC}=3.0 at β=0.6.

Peak surface magnetic fields have been improved substantially in the latest designs. The long-dashed line in Figure 7 shows the peak surface fields for cavities built and tested to date. The short dashed line indicates the 25-30% improvement possible with the latest designs. Peak magnetic fields for spoke cavities also appear to increase relatively more quickly with increasing beta than do electric fields and are higher than in elliptical cell cavities above β~0.6.

CAVITY PERFORMANCE

Clean room processing

SC Spoke cavity performance has benefited from the same clean room processing and handling techniques developed in the early 1990's at laboratories such as KEK, DESY and JLab. These techniques were adapted at Argonne [15] and elsewhere for use with spoke cavities and other TEM-class cavities.

High-pressure rinsing with ultra-pure deionized water for several hours is standard practice with spoke cavities; however, effective spoke cavity rinsing requires explicit consideration during the design phase. Elliptical cell cavities generally provide easy access to the entire cavity surface and good drainage from just the two beam ports. However, spoke cavities (see *e.g.* Figure 5), and TEM-class cavities generally, require additional access ports for surface cleaning and chemistry. Single-spoke cavities at ANL, LANL, and IPN Orsay using two radial coupling ports and triple-spoke cavities at ANL using three radial coupling ports have been rinsed, assembled clean and

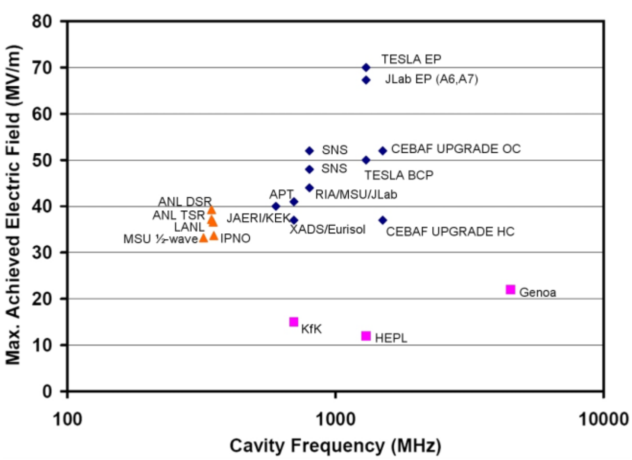

Figure 8: Best values for surface electric fields in SC cavities. Triangles – Spoke (λ/2) cavities. Diamonds – E-cell cavities using clean techniques. Squares – before clean techniques. Reference[16]

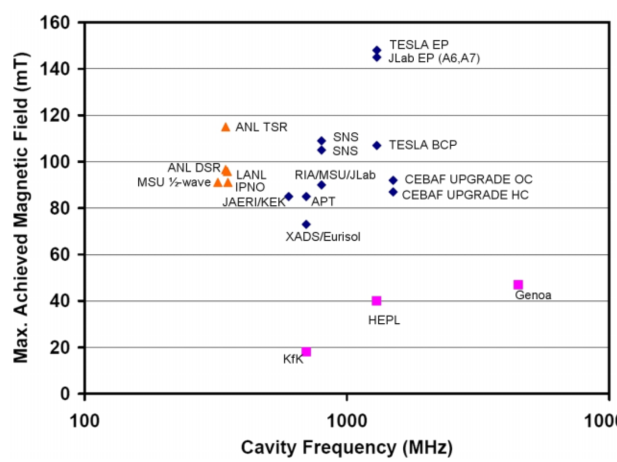

Figure 9: Best values for surface magnetic fields in SC cavities. Triangles – Spoke (λ/2) cavities. Diamonds – E-cell cavities using clean techniques. Squares – before clean techniques. Reference[16]

tested at relatively high fields with low field emission.

Best Results

To date about a dozen SC spoke cavities have been built and tested worldwide with all but one or two using high RRR niobium sheet, modern fabrication techniques, high-pressure water cleaning and some clean room assembly. Figures 8 and 9 show the best achieved electric and magnetic fields on the cavity surface for a variety of spoke- and elliptical cell (E-cell) cavities. Note that these are best results and cavities in operations generally run at somewhat lower fields than indicated here.

A comparison of maximum electric fields for spoke and E-cell cavities shows that spoke cavities presently operate at somewhat lower fields. Conventional wisdom is that this is due to the more complicated geometries and more difficult cleaning. In fact, the data do not support this. In most cases limiting performance in spoke cavities has been due to thermal-magnetic quench with little or no accompanying field emission.

Peak surface magnetic fields for spoke cavities are near ~100 mT and compare favorably with most E-cell cavity results. The clustering of spoke cavities with thermal-magnetic quench near 100 mT is also observed for other TEM-class cavities such as quarter- and half-wave cavities. This may indicate a systematic cause due to cavity materials, fabrication or processing. However, a vigorous R&D effort based on much better cold test diagnostics is required to address the underlying cause of quench in TEM cavities.

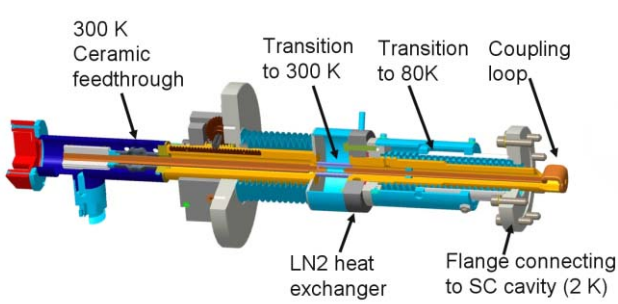

Figure 10: A CW fully variable inductive coupler for 109 – 345 MHz from ANL.

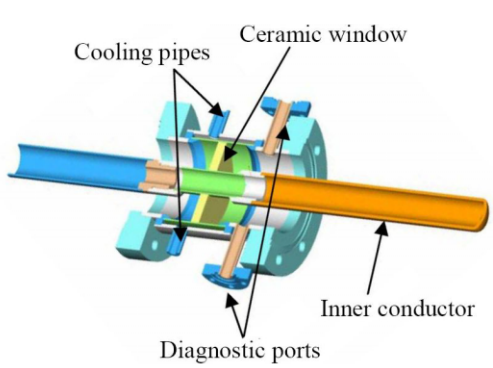

Figure 11: A CW 20 kW fixed capacitive coupler for 352 MHz from IPN Orsay.

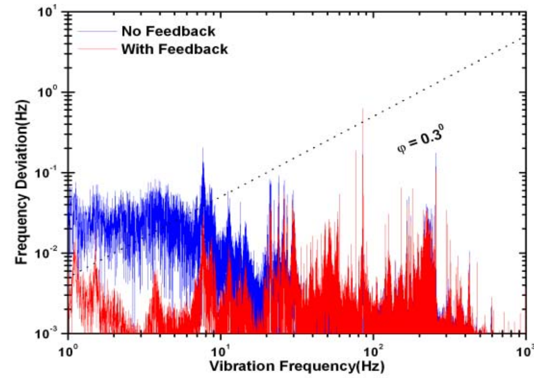

Figure 12: Microphonic damping in a β=0.5 triple-spoke using a radially mounted piezo tuner.

COUPLERS, TUNERS

Spoke cavities for the next generation of rare isotope beams facilities in the U.S. and Europe will require cw rf power couplers for frequencies of ~350 MHz with beam loading of ~10 kW per cavity and a total forward power of ~20 kW. Prototype couplers have been fabricated but not yet tested at these power levels

An inductive variable cw rf coupler [17] shown in Figure 10. has been developed and tested at ANL with spoke- and other TEM-class cavities for AEBL (see Figure 1). The design has functioned well at modest power levels in numerous cold tests at 4 Kelvin at frequencies from 109 to 345 MHz. In these tests the maximum available RF power was only a few kW, but thermometric measurements showed that RF losses in a formed SS bellows to be appreciably larger than tolerable for 20 kW cw operation at 2 Kelvin needed for AEBL.

At IPN a fixed position 20 kW capacitive coupler [18] shown in Figure 11. is being fabricated and will be tested with the IPN β=0.15 352 MHz spoke cavity.

FAST TUNERS

The spoke cavity geometry is intrinsically mechanically rigid and has been shown to have good microphonic properties [19,20]. However, for moderate beam loading as in proposed rare isotope beams facilities, a fast tuner is likely to be needed. An example of the use of a piezoelectric fast tuner for a β=0.5 3-spoke cavity for AEBL is shown in Figure 12. For reference a dashed line corresponding to 0.3° phase error, the maximum tolerable value for AEBL, is included. Low frequency vibrations below about 10 Hz are due to pressure fluctuations in the helium bath and have been compensated for (data in red) using small mechanical transducers mounted radially on the cavity outer housing. Both piezoelectric and magnetostrictive tuners have been tested and appear suitable.

CONCLUSION

Superconducting spoke cavities for the full velocity range required for proton and heavy-ion linacs have been developed and should represent the technology of choice for most cw intermediate velocity ion linac applications. Low temperature 2 K operation, which is new for spoke cavities, may offer additional large savings in both refrigerator capital and operating costs. Application specific tuners and couplers are being developed and initial test results are promising. Generally SC spoke cavity technology is well developed and likely to appear in the next generation of ion linacs.

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