SUPERCONDUCTING SPOKE CAVITIES

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Abstract

Superconducting (SC) TEM-class spoke cavities have been an area of active research during the past decade with application to cw and pulsed ion linacs required for proposed facilities world-wide. Single- and multi-spoke geometries have been developed for use with ions over the full mass range and for ion velocities $0.15 < v/c < 0.8$. Spoke cavities have generally been designed for 4 K operation, however, recent spoke-cavity results in 2 K operation, which rely on new and evolving cavity processing techniques such as clean assembly and hydrogen degassing, show very low rf losses even for high accelerating fields (corresponding to E_{PEAK}~30 MV/m) required in operations. Results indicate that higher voltage gains per cavity with reduced heat loads are possible at T=2 K. An overview of recent spoke cavity activities at several laboratories is presented.

INTRODUCTION

An obvious advantage of superconducting (SC) rf cavities compared to traditional room temperature structures is the very low rf losses, typically of the order of 10 Watts per active meter of accelerating structure. For continuous (cw) cavity operation and relatively light beam loading the total required electrical power, even considering cryogenic refrigeration, is of the order 100 times less for SC than for room temperature structures.

Even in pulsed operation or in applications with heavy beam loading superconducting structures may offer critical advantages. The relatively large bore diameter, typically 4-7 cm, yields a large transverse acceptance while the possibility of low operating frequency, ~350 MHz for spoke geometries, results in a large longitudinal acceptance. A large acceptance is desirable for high power hadron linacs where beam losses must be typically ≤1 Watt/meter. In addition, SC cavities are short (~1 m) and independently operated so that the linac array may be retuned if one or more cavities become inoperable. This high degree of fault tolerance is critical for applications requiring extreme reliability such as for the accelerator driven transmutation of nuclear waste (ADS). Finally, SC linacs offer the flexibility of operations such as multi-charge state and multi-ion acceleration which is simply not possible with any other available technology.

CAVITIES

SC ion linacs for relatively low energies ~10 MeV/u (v/c~0.1) and SC electron linacs for high energies up to several GeV (v/c~1.0) have operated for decades, however, only in the past fifteen years have applications requiring intermediate velocity cavities received detailed study. Applications include both cw and pulsed hadron linacs required, for example, for the production of rare isotopes, the production of intense spallated neutrons for nuclear waste transmutation (Accelerator Driven Systems or ADS) and pulsed proton drivers for fundamental physics studies.

The two SC hadron linac technologies developed for these applications are the spoke-loaded and the elliptical-cell cavities [1]. Spoke cavities tested to date are designed for particle velocities $0.15<\beta<0.75$ while demonstrated elliptical-cell cavities are for $0.5<\beta<1.0$. Spoke cavities operate in the fundamental TEM-mode, have a typical transverse dimension of $\lambda/2=c/f$ or about 0.5 m at a frequency of ~350 MHz. Elliptical cavities operate in a $TM_{010\pi}$ mode, have a typical transverse dimension of λ, which also turns out to be ~0.5m but at a higher frequency of 700-800 MHz. An example of a 1m long three-spoke loaded cavity developed for the Rare Isotope Accelerator [2] driver linac is shown in Figure 1. An array of 32 SC elliptical cell cavities also for β=0.6 along with another 50 elliptical cavities for β=0.8 are in operation at the Spallation Neutron Source [3].

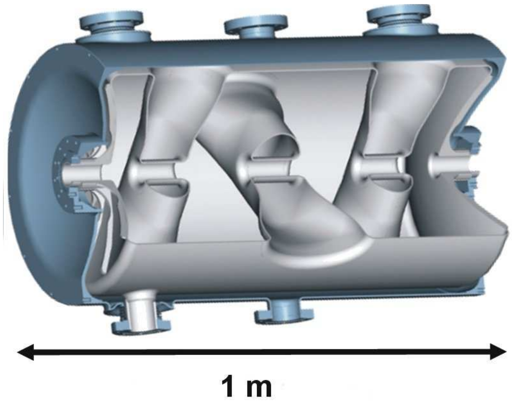

Figure 1: A SC 345 MHz β=0.63 3-spoke cavity built and tested for the Rare Isotope Accelerator driver linac.

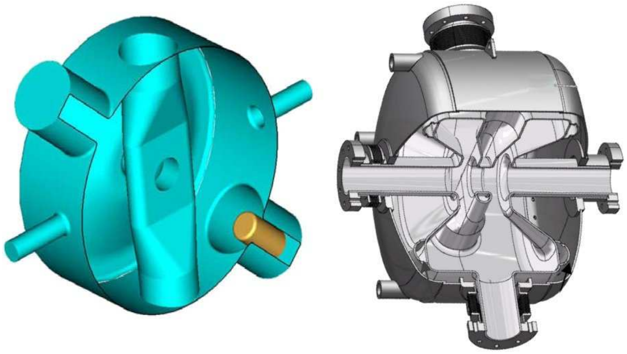

Figure 2: A 350 MHz β=0.175 single-spoke cavity from LANL (left) and a 352 MHz β=0.15 single-spoke cavity from IPN-Orsay (right).

Figure 3: Single-spoke cavities developed for SDI (top-left), EURISOL (top-right), AAA (bottom-left) and XADS (bottom-right).

Single-spoke cavities developed for several high-current and/or high-beam power applications are shown in Figures 2. and 3. The world's first SC spoke cavity was an 850 MHz, $\beta=0.28$ resonator developed in the early 1990's as part of work on Neutral Particle Beams [4] for weapons. In the mid-1990's a pair of single-spoke resonators for RIA (not shown) with $f_0=350$ MHz and $\beta=0.29$ and 0.4 were built, tested and then later reprocessed using clean room techniques to achieve accelerating gradients of more than 10 MV/m. Other recently developed high-performance single-spoke cavities include a $\beta=0.15$ 352 MHz cavity developed by IPN-Orsay for EURISOL [5], a pair of $\beta=0.175$ 350 MHz cavities developed at LANL for AAA [6] and a $\beta=0.35$ 352 MHz cavity from IPN-Orsay for XADS.

Multi-spoke cavities (shown in Figure 4.) have mostly been developed at Argonne for application to RIA [7] and operate at $f_0=345$ MHz with peak velocities $\beta=0.40$, 0.50 and 0.63. New multi-spoke cavities are under development at FZJ (Juelich) and Fermilab.

Figure 4: Multi-spoke cavities developed for RIA (top-left and bottom) and for HIPPI (top-right).

APPLICATIONS

SC linacs are well suited for cw operation. See *e.g.* Figure 5. The proposed cw Rare Isotope Accelerator (RIA) SC linacs require a total operating power of ≤ 13 MW (including refrigeration) as compared to ~500 MW required for a comparable room temperature linacs. In addition, SC cavities for RIA (300 total/185 spoke) provide the only available means of generating high-power (400 kW baseline) uranium beams needed for this next generation radioactive beams facility. Until much higher uranium beam currents, limited to ~3 particle μA in today's state-of-the-art ECR sources, multi-charge state acceleration is required and possible only with large transverse and longitudinal acceptance achieved with SC cavities and, particularly, with SC spoke cavities. At the same time, the broad cavity velocity acceptance and independently adjustable cavity phase permits retuning of the linac for lighter ions such as protons with energies up to 1 GeV.

High-power pulsed linacs also require large acceptance to minimize beam loss. The proposed pulsed 8 GeV SC proton driver linac for a High Intensity Neutrino Source (HINS) [8,9] uses existing SC cavity designs taken from development for the ILC and RIA. The baseline linac design is superconducting down to energies as low as 10 MeV/u, making use of the high real estate gradients (2-3 MV/m) achieved recently using clean room techniques. The low- and mid-beta SC linac sections use single-, and triple-spoke resonators operating at 325 MHz, the fourth subharmonic of 1300 MHz and also the frequency of existing klystrons developed for JPARC. In this section spoke cavities accelerate protons from 10 MeV up to 410 MeV. The remaining high-energy section of the SC linac uses 1300 MHz 8-cell $\beta=0.8$ and 9-cell $\beta=1.0$ TESLA cavities together with cryomodules and RF subsystems developed for the International Linear Collider.

Applications	Particle type	# Spoke Cavities (total SC cavities)	Duty Factor
RIA, EURISOL	Proton Heavy-Ion	90-185 (~200-400)	CW
XADS, AAA	Proton	100 (190)	
HINS (Proton Driver at FNAL)		90 (420)	Pulsed ~1%

Figure 5: Applications proposing to use SC spoke cavities.

FABRICATION & PROCESSING

Fabrication

Recently fabricated SC spoke cavities have been designed using modern 3D simulation codes such as MAFIA, Microwave Studio, and ProEngineer/ANSYS.

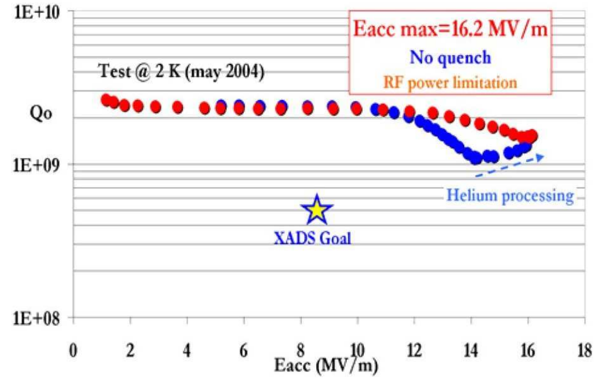

Figure 6: Q-curve test results for a 352 MHz β=0.35 single-spoke cavity developed at IPN-Orsay.

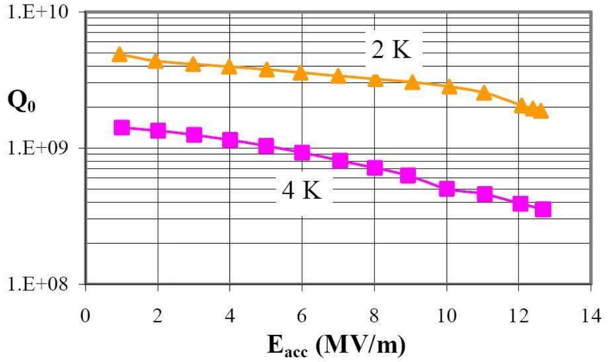

Figure 7: Q-curve test results for a 350 MHz β=0.175 single-spoke cavity developed at LANL.

Niobium parts are die formed from high RRR (high purity) 3 mm thick niobium sheet using hydroforming or deep-drawing techniques and then welded together under vacuum using an electron beam. This straightforward and highly flexible fabrication process is suited to producing large quantities of nearly any desired geometry. Cavities intended for linac operations are housed inside an integral helium jacket constructed from either stainless steel or titanium. Gravity fed liquid helium cools essentially the entire niobium surface including the spokes and the outer cylindrical housing.

Clean Processing

A major advance in SC cavity performance was achieved in the early 1990’s at laboratories such as KEK, DESY and JLab with the introduction of clean processing and handling techniques. These techniques were adapted at Argonne [10] and elsewhere for use with spoke cavities and other TEM-class cavities.

Chemical processing at most facilities has generally used mixtures of concentrated hydrofluoric, nitric and phosphoric acids referred to as buffered chemical polish (BCP) to remove ~150 microns of niobium from the cavity rf surface after fabrication. Alternatively, electropolishing (EP) based on concentrated hydrofluoric and sulfuric acid has been used at Argonne for decades and continues to be used for most chemical processing at ANL.

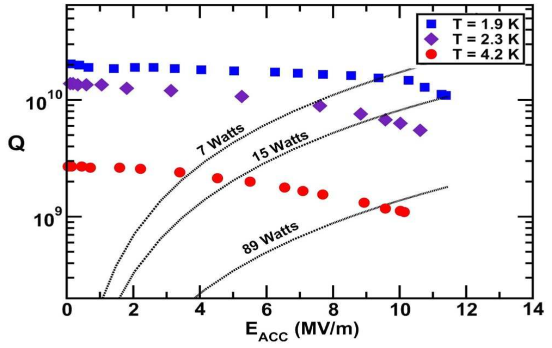

Figure 8: Q-curve test results (colored symbols) and lines of constant rf power for a 345 MHz β=0.63 triple-spoke cavity developed at ANL. At T=2 K, 7 Watts input power gives and energy gain of 7 MV/cavity.

High-pressure water rinsing using filtered deionized water in a (class 100) clean area for at least one hour is standard and required practice for achieving accelerating gradients ≥10 MV/m. Similarly, final assembly of the cavity together with the coupler and the vacuum pumping hardware must also be properly performed in a (class 10-100) clean area. Maintaining cleanliness in long-term linac operations is an area on continued interest.

CAVITY PERFORMANCE

Single-spoke resonators

High-performance single-spoke SC cavities have been recently developed and operated at three laboratories, ANL, IPN-Orsay, and LANL. New single-spoke cavities for HINS at FNAL are planned for the near future. Fabrication and processing techniques are mostly similar, except, as discussed, for the chemical processing. Significantly, all cavities have had good rf performance beginning with the initial cold test. Some examples are presented.

Figure 6. shows test results for a 352 MHz β=0.35 single-spoke cavity developed by IPN-Orsay for application to the accelerator transmutation of waste (EUROTRANS). Machining and welding operations were performed in industry by Cerca, BCP chemical processing at CEA-Saclay and final cold tests at INP-Orsay. The cavity achieved a peak accelerating gradient of E_{ACC}=16.2 MV in 2 K operation, the highest spoke cavity gradient achieved to date.

A pair of 350 MHz β=0.175 single-spoke cavities, also with application to nuclear waste transformation, was purchased by LANL from ZANON. BCP processing and cold tests were performed at LANL. Test results for one of the cavities are shown in Figure 7. Both cavities substantially exceeded the design gradient of E_{ACC}=7.5 MV/m by nearly a factor of two, leaving substantial operating margin for the required extreme high-reliability operation. Note that both cavities were tested at helium temperatures of 2 K and 4 K. However, there would be no substantial difference in terms of refrigerator wall-plug power since the factor 3-4 decrease in rf losses is offset by a 3-4 increase in refrigeration costs at 2 K. For waste transmutation applications total power required will be ~hundreds of kW/cavity due to beam loading.

Triple-spoke resonators

ANL has developed at set of 5 SC cavities for RIA including three 345 MHz SC multi-spoke cavities for velocities $0.35<\beta<0.75$ as part of the RIA driver linac baseline at ANL. A similar three-spoke cavity but with a reduced frequency of 325 MHz and a further optimized EM design, are part of the baseline design for the HINS proton driver at Fermilab.

Test results for the ANL $\beta=0.63$ triple-spoke cavity are shown in Figure 8. Using standard 4 Kelvin operation, 89 Watts of input rf power are required to achieve an accelerating gradient of 9.4 MV/m, corresponding to a peak electric field at the cavity rf surface of 27.5 MV/m. This field level reflects the use of state-of-the-art processing techniques for cavities in this range of velocity.

More recently, in order to remove hydrogen, which is introduced into the niobium during fabrication and which is known to decrease cavity performance, the $\beta=0.63$ triple-spoke cavity was degassed in a high-vacuum furnace for 10 hours at 600 ^{o}C. A light (5 μm) surface etch and high-pressure rinse were performed before retesting. Subsequent performance for T=4 K was almost unchanged, whereas, rf losses at 2 K were reduced by ~5x. At T=2 K only 7 Watts of rf power were required for 9.4 MV/m operation. Given, the ratio of helium refrigerator efficiencies for these temperatures, $\varepsilon_{4.2K}/\varepsilon_{2K} \approx 3.5$, operation at 2 K must be considered. Additional baking and 2 K testing of other spoke cavities is planned.

MICROPHONICS

The spoke cavity geometry, composed essentially of a cylindrical outer housing with spokes intersecting and supported at both ends has good intrinsic mechanical stability [11]. An example of a measured microphonics spectrum for a $\beta=0.5$ 3-spoke cavity for RIA is shown in Figure 9. Even at a high field, E_{ACC}=9.7 MV/m, no large peaks are observed above ~10 Hz. For reference a dashed line corresponding to 0.3^{o} phase error, the maximum tolerable value for RIA, is included. Low frequency vibrations below about 10 Hz are due to helium bath pressure fluctuations and will be compensated for using tuners based piezoelectric and magnetostrictive transducers which are well along in development.

CONCLUSION

Superconducting spoke cavities for most of the full velocity range required for proton and heavy-ion linacs have been developed. These cavities have large acceptance, low rf losses, good mechanical properties, operate at high accelerating gradients and represent the technology of choice for many of today's intermediate velocity hadron linac applications.

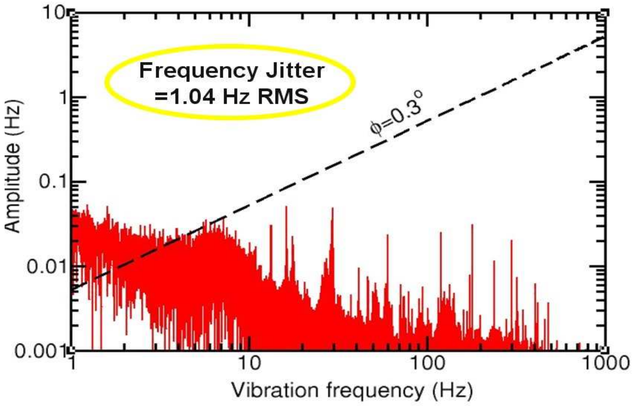

Figure 9: Microphonics spectrum of the ANL $\beta=0.5$ SC 3-spoke cavity operating at T=4.2 K and E_{ACC}=9.7 MV/m.

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