DEVELOPMENT OF SUPERCONDUCTING INTERMEDIATE-VELOCITY CAVITIES FOR THE U. S. RIA PROJECT*

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Abstract

The U. S. RIA project includes a 1.4 GV heavy-ion driver linac that requires superconducting accelerating structures for a range of ion velocities $0.02 < \beta = v/c < 0.7$. A number of intermediate velocity niobium cavities are being developed for this and for related applications. This paper summarizes recent development for RIA of half-wave class TEM structures, both coaxial and spoke type, and foreshortened 6-cell elliptical-cell cavities. Two design options for the high-energy section of the driver linac are compared, one being the baseline design of 6-cell elliptical-cell cavities operating at 2K, another using triple-spoke cavities operating at 4.2K.

INTRODUCTION

A principal element of the proposed U. S. Rare Isotope Facility (RIA) will be a superconducting (SC), 1.4 GeV ion linac [1] capable of accelerating ions of any stable isotope from hydrogen to uranium, and delivering several hundred kW of cw beam onto production targets at 400MeV/nucleon or more.

The rf power requirements of cw operation are a strong incentive to make the entire linac superconducting, and for the past 5 – 6 years several types of intermediate velocity cavities have been and continue to be developed for this application. A baseline design has been established that utilizes the two types of 805 MHz six-cell foreshortened elliptical-cell cavity developed for the high-energy section of the driver linac for the U. S. SNS project [2]. An additional β=0.5 elliptical-cell cavity type and several types of half-wave loaded structure are being developed to cover the remaining intermediate-velocity section of the driver. Figure 1 shows schematically nine types of SC of the RIA baseline design, which cover the required velocity range $0.02 < \beta < 0.7$.

The first three cavity types, for the velocity range $\beta < 0.12$, are versions of already-developed SC QWR and interdigital cavities in use for many years in existing heavy-ion accelerators [3], and will not be further discussed here.

In what follows, we survey the current status of intermediate-velocity cavity development and compare the properties of elliptical-cell and spoke loaded cavities for the high-energy section of the RIA driver.

RECENT PROTOTYPE TESTS

Elliptical-cell cavities

Cavity types 8 and 9 in Figure 1 are the two types (β= 0.61 and 0.81) of 805 MHz elliptical-cell cavity which were developed at JLAB and which are being produced for the U. S. SNS project [4]. Measured performance for

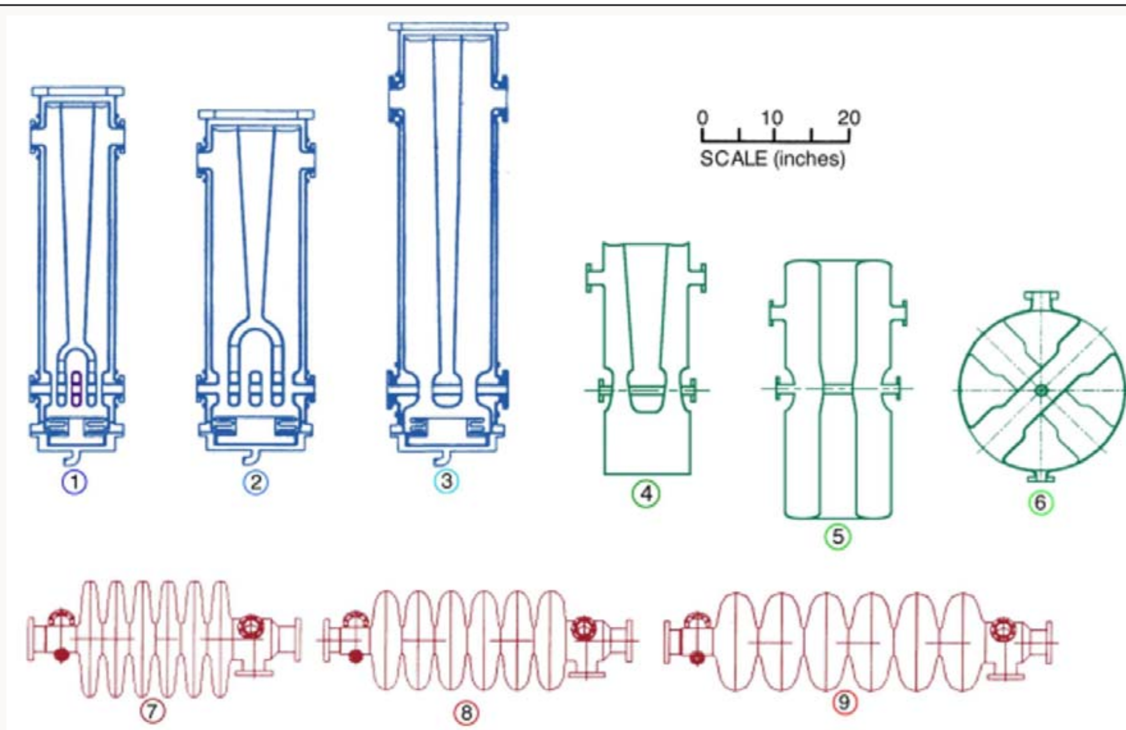

Figure 1: Schematic section views (roughly to scale) for nine types of SC accelerating structure ranging in frequency from 57.5 MHz to 805 MHz and in velocity from 0.02 to 0.81c.

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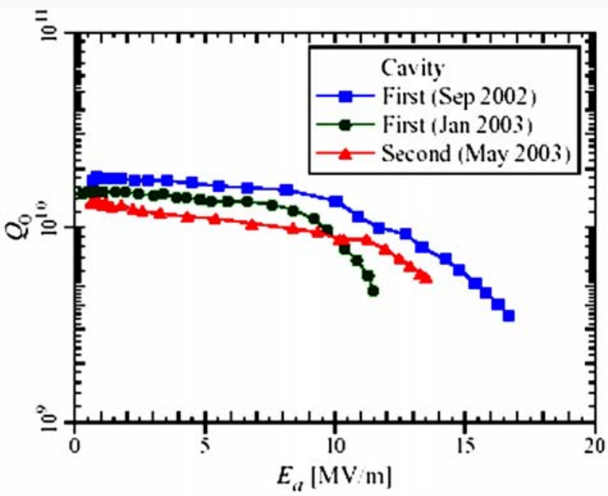

Figure 2: Performance at 2K of two 805 MHz, β .47 six-cell elliptical cell cavities developed [x]

the cavities so far produced has been reported elsewhere [5]. Some sixteen of the β=0.61 units have exceeded the performance goals for the SNS linac, which will operate in a pulsed mode with 6% duty factor. Performance goals have not yet been established for the RIA driver, but cw operation will greatly increase the refrigeration load, and reducing the rf loss in the 805 MHz cavities below the levels so far achieved in production for the SNS project should remain an R&D goal for the RIA project.

Cavity type 7 in Fig. 1, a β=0.47 six-cell elliptical-cell cavity, is being specifically developed for RIA by a JLAB/MSU collaboration. Test results on two prototype β 0.47 six-cell cavities, shown in Figure 2, were reported earlier this year [6] and indicate that performance comparable to that of the β=0.61 and 0.81 cavities developed for SNS has been achieved.

TM-class, half-wave and spoke cavities

The RIA baseline design calls for TEM-type [7], either half-wave or quarter-wave loaded cavities for velocities β < 0.4. All cavities operate at multiples of the bunch frequency, (805/14)or 57.5 MHz. The cavity types 1-3 of Fig. 1 operate at 57.5 MHz and differ little from existing niobium cavities presently used in SC ion linacs.

Cavity type 4 is a 115 MHz QWR cavity also similar to existing SC cavities except for design of the drift-tube, which has been shaped to minimize beam steering[8], a potential cause of emittance growth in the multiple-charge-state beams required of the RIA driver linac.

Half-wave cavities

Cavity type 5, being developed at ANL, is a 172.5 MHz coaxial half-wave cavity with geometric β=0.26. Figure 3 shows a sectioned view of the cavity, together with niobium elements of a prototype, construction of which is nearing completion [9].

A 322 MHz coaxial half-wave cavity is being developed at Michigan State University, where an alternate design for the RIA driver, bunched at 805/10


Figure 3: 172 MHz coaxial half-wave cavity for velocities β = 0.2 – 0.3. The cut-away view shows the niobium cavity within a stainless-steel helium jacket. On the right are niobium elements prior to the closure welds.

MHz, is being evaluated. A prototype has been tested, yielding the performance shown in Figure 4[10]. The performance at 2K is excellent. At 4.3K, however, the chemically-polished prototype exhibits a large Q-slope, a technical issue that needs to be resolved not only for this cavity, but for all the low-frequency cavities for RIA to achieve economic cw operation at 4K.

Spoke cavities

Spoke-loaded cavities have been developed at ANL for several applications, including the RIA driver[11]. Other groups have also reported [12]operation of single-spoke cavities at surface electric fields above 40 MV/m after cleaning with high-pressure water rinse(HPR).

Figure 5A shows niobium elements of a prototype two-spoke cavity (cavity type 6 of Fig. 1), being developed at ANL for the RIA driver linac[13]. The 345 MHz cavity has a geometric β= 0.4 and an active length of 38 cm.

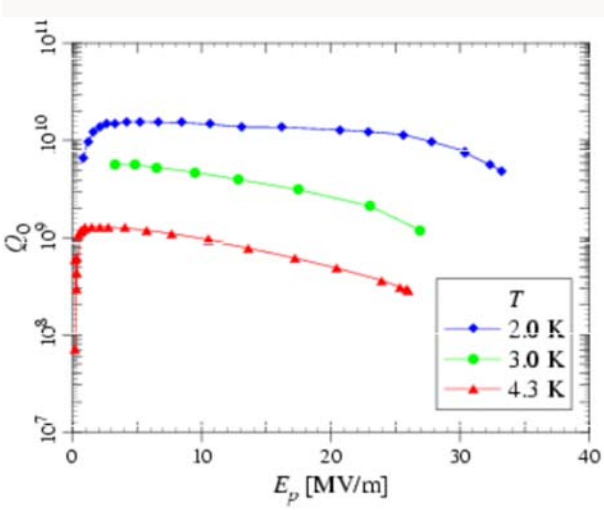

Figure 4: Performance of a prototype 322 MHz coaxial half-wave cavity being developed at MSU.

Figure 5A: Niobium elements of the 345 MHz double-spoke cavity prior to closure welds.

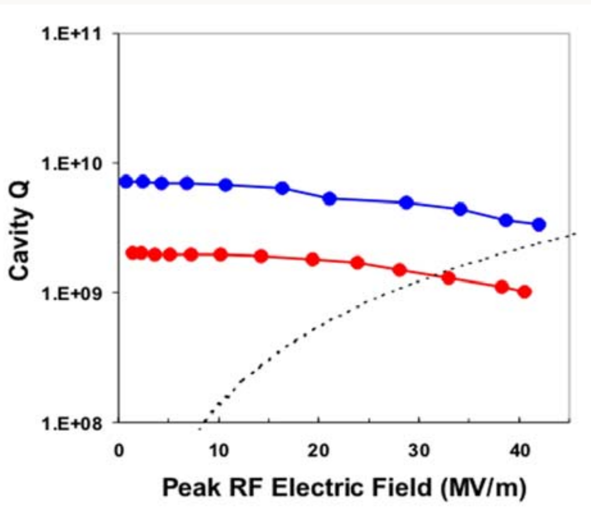

Figure 5B: Cavity Q as a function of E_{peak} at 4.2 K (the lower, red curve), and at 2K (the upper blue curve). The dashed line is a 20 watt RF load-line which is the RF load to helium at $E_{PEAK} \approx$ 31 MV/m, corresponding to an accelerating gradient E_{ACC} = 9 MV/m.

Figure 5B shows the performance obtained with this cavity [14]. The niobium surface was prepared by heavy electropolishing prior to the closure welds, and a very light buffered chemical polish (BCP) after welding. Using this technique produces a much smoother surface on a microscopic scale than can be achieved using only BCP. As a result, the performance at 4.2K shows very little Q-slope, and the cavity could be economically operated at 4.2K. As shown in Fig. 5B, at 4.2K with 20 watts RF input, the prototype cavity provides some 3.5 MV of accelerating potential. The mechanical stability of the double-spoke cavity is excellent. Microphonic-induced phase noise was found to be approximately 5 Hz peak-peak at 4.2K while operating at high field levels [15]. This measurement shows that RF loss-induced bubbling in the liquid helium does not cause unacceptable levels of microphonics.

4K OPTION FOR THE RIA DRIVER LINAC

The excellent performance obtained with the prototype double-spoke cavity opens the possibility of using spoke-loaded cavities for the high energy section of the driver linac, in place of the higher-frequency elliptical-cell cavities of the present baseline design [16]. As is discussed below, lower frequency operation can provide a number of benefits.

The transverse dimension of spoke cavities is of the order of 0.9 λ while for elliptical-cell structures it is of the order of 0.5 λ, where λ is the free-space wavelength of the accelerating mode. Thus, at the same frequency, spoke cavities have about half the transverse size of elliptical-cell structures. Alternatively, at the same transverse size, they will operate at about half the frequency. Since the BCS surface resistance of super-conductors is quadratic with frequency, spoke cavities operating at lower frequency will require less refrigeration and have the potential to operate at higher temperatures. Additionally, at half the frequency, a TEM structure will have half the number of cells of a TM cavity of the same length; and thereby will offer a broader velocity acceptance or better efficiency in accelerating particles over a range of velocities. Operating at lower frequency is also advantageous from a beam physics perspective, because of the increased longitudinal acceptance.

Designs for two SC niobium, 345 MHz, three-spoke-loaded cavities for the velocity range $0.4<\beta<0.75$ have been developed. Figure 6 shows a sectioned view of one of the two cavity types. The mechanical elements and overall design are similar to those of the above-described two-spoke niobium cavity.

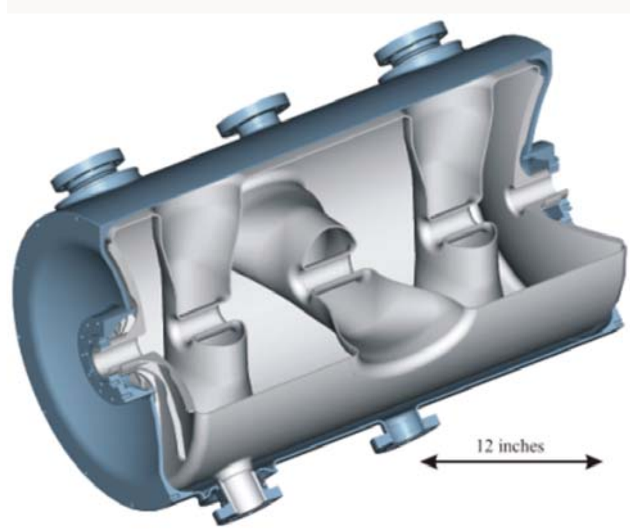

Figure 6: Cut-away sectioned view of a 345 MHz triple-spoke loaded cavity for geometric β=0.5. The inner, niobium cavity shell is shown nested in an integral stainless-steel helium container.

Table 1: Electromagnetic parameters for the two triple-spoke cavities compared with two elliptical-cell 6-cell cavities of similar geometric β.

Cavity Type	3 Spoke	6 Cell	3 Spoke	6 Cell
Beta Geometric	0.50	0.47	0.62	0.61
Frequency (MHz)	345	805	345	805
Length (cm)	65	53	81	68
G	86	137	93	179
R/Q	494	160	520	279
at an accelerating gradient of 1 MV/m:				
RF Energy (mJ)	397	341	580	330
peak E-field (MV/m)	2.9	3.4	3.0	2.7
peak B-field (G)	87	69	89	57

Table 1 details and compares the electromagnetic properties of the two 345 MHz triple-spoke cavities and the two six-cell cavities of the same geometric beta. We note that the triple-spoke cavities, particularly at β=0.5, exhibit appreciably higher shunt impedance.

Figure 7 compares the velocity acceptance, i.e. the voltage gain per cavity as a function of particle velocity, of the triple-spoke and elliptical cell cavities. The accelerating field level is determined by setting the peak surface electric field at 27.5 MV/m for all the cavities, the feasibility of which is indicated by recent experimental results.

Note that, because of the lower frequency enabled by using a TEM structure, the triple-spoke geometry provides both a significantly broader velocity acceptance and also a higher voltage gain than the elliptical cell

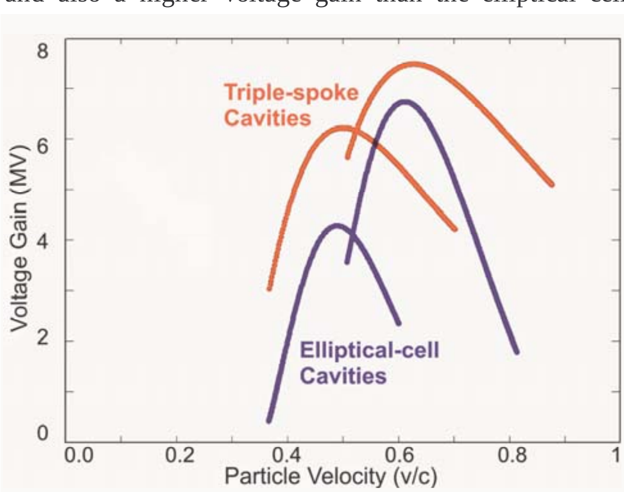

Figure 7: Voltage gain per cavity as a function of particle velocity for two 345 MHz triple-spoke cavities compared with two 805 MHz elliptical 6-cell cavities, all operating at a peak surface electric field of 27.5 MV/m.

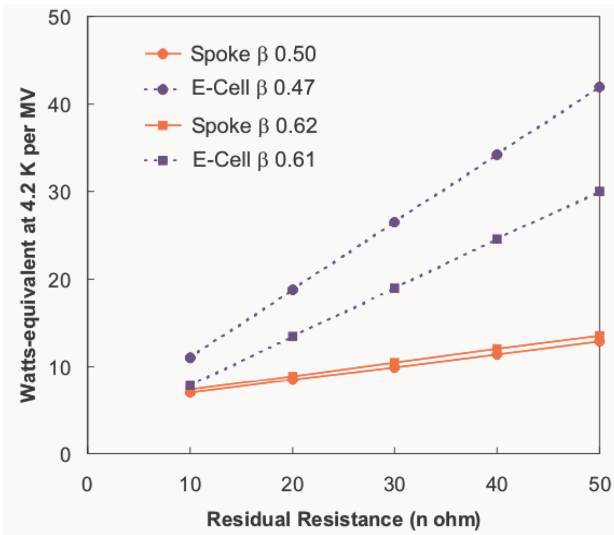

Figure 8: RF load into helium refrigeration as a function of cavity performance for operation at a peak surface electric field of 27.5 MV/m.

cavities. For the 345 MHz spoke-loaded cavities, at a given velocity the cell length is a factor of 2.33 longer than for the 805 MHz elliptical-cell cavities, which enables the spoke cavities to double the velocity acceptance while providing significantly more voltage. With two triple-spoke cavities we can span the required velocity range not only with fewer cavities, but also with fewer types of cavity.

The excellent shunt impedance of the spoke-loaded cavities, together with the relatively low operating frequency, enables us to design the linac not only to reduce the RF heat load but also to operate at 4.2K.

Figure 8 shows the RF heat load in watts per MV of accelerating potential for the 345 MHz triple-spoke cavities operating at 4.2K (solid lines). For comparison, we show the refrigeration load for the 805 MHz elliptical six-cell cavities operating at 2K (dashed lines). The heat load in Figure 8 is estimated assuming operation of all cavities at a peak surface electric field of 27.5 MV/m, as discussed above. The 2K system is assumed to achieve an efficiency such that a 1 watts into 2K is equivalent to 4 watts of heat load into 4.2K.

Note that for the spoke cavities, the reduced slope of heat load as a function of residual resistivity provides a larger design margin in terms of overall linac heat-load as contingent on a range of SC cavity performance.

The beam dynamics of the two design options has been detailed elsewhere: we simply note that a factor of two reduction in transverse acceptance by going to the spoke option is more than offset by the factor of 4.7 increase in longitudinal acceptance.

To summarize, spoke-loaded cavities can provide a number of advantages compared with the higher-frequency, elliptical-cell cavities that have been proposed for the RIA driver linac. In particular, by using TEM-class, spoke-loaded cavities described above we can:

- Reduce the required number of cavities by13%.
- Reduce by 2 the number of cavity types required.

- Increase the operating temperature from 2 to 4K
- Significantly reduce the refrigeration load.
- Increase the longitudinal acceptance by a factor of 4.7, decreasing the probability of beam loss
- Provide excellent mechanical stability, minimizing the difficulty of tuning and phase control.

For these reasons, construction of prototypes of the two triple-spoke cavity designs described above has been undertaken at ANL, with initial cold tests scheduled early in calendar year 2004.

CONCLUSIONS

Several types of intermediate-velocity cavities have been successfully prototyped since the last SRF workshop. In virtually all cases excellent performance has been obtained, and the feasibility of constructing a cw, high-intensity ion linac using superconducting accelerating structures for the full velocity range seems well established. Remaining development work for RIA can focus on optimizing available design options to maximize performance and reliability and to minimize costs.

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