# STATUS OF LOW AND INTERMEDIATE VELOCITY SUPERCONDUCTING ACCELERATING STRUCTURES

K. W. Shepard, ANL, Argonne, IL 60439, USA

*Abstract*

Several types of reduced velocity (0.1 - 0.6c) superconducting accelerating structures are being developed for ion linacs to be used for spallation sources, exotic beam facilities, and other applications. This paper briefly reviews the characteristics and development status of some of the cavity types currently under development. Two different structure choices for the high-energy section of the proposed RIA driver linac are discussed.

## INTRODUCTION

Historically, superconducting RF development has divided into two major classes of resonant cavity [1]. One class is cavities based on various forms and combinations of right circular cylindrical cells operating in the TM010 mode, or TM-class cavities. These have been developed primarily for velocity-of-light, electron beams. The other class is based on various forms and combinations of linear element or transmission line operating in a TEM mode, or TEM-class cavities. The latter class is exemplified by the numerous types of quarter-wave-line cavities developed for heavy-ion linacs. TM cavities have generally been relatively high-frequency, ~ 1 GHz, and have operated at 2K. TEM cavities have generally been developed at low frequencies, ~ 100 MHz, for low velocities, < 0.2c, and have operated at 4K.

Over the past several years, the velocity range of both TM and TEM class structures has been expanded, as cavities have been developed for high-energy and high-intensity proton and ion linacs. This has been exemplified for the TM-class in the development of 805 MHz, elliptical-cell cavities for velocities as low as 0.62c for the SNS project [2]. As is discussed below, much current work is developing a variety of TEM-class cavities for particle velocities up to 0.62c, at frequencies of 175-352 MHz.

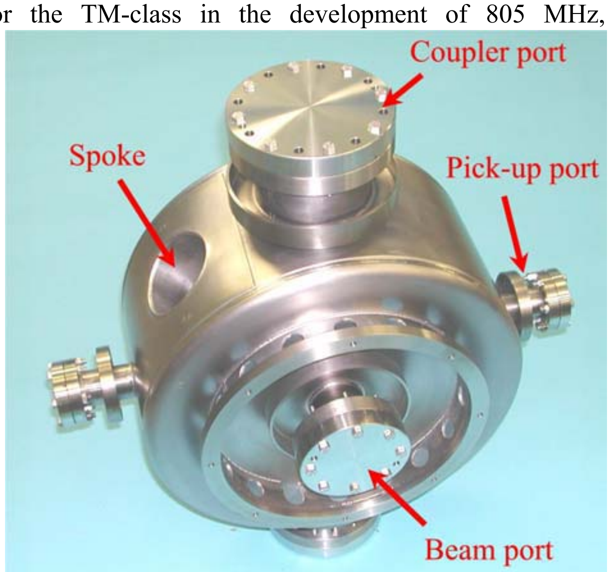


Figure 1: Los Alamos-built 350 MHz, β=0.175, single-spoke niobium cavity

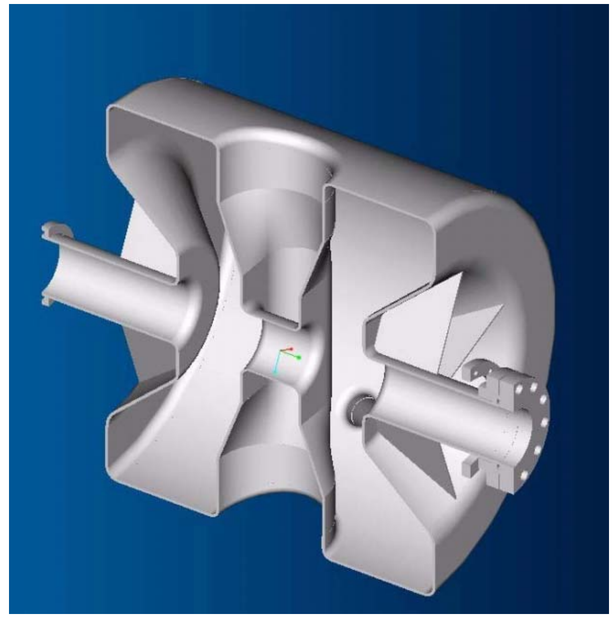

Figure 2: 352 MHz, β=0.35, single-spoke niobium cavity tested at IPN Orsay

These relatively high-velocity TEM-class cavities are based on two types of half-wave line structure, the coaxial half-wave line, which is similar to existing QWR structures, and spoke-loaded cavities, in which the transmission-line element is at right-angles to a cylindrical housing, a geometry similar to a spoke of a wheel. The spoke-loaded structure differs from the coaxial line in that it can be stacked into multi-cell combinations.

Several multiple-gap, low-velocity (<0.15c) half-wave TEM structures are being developed to provide relatively high-frequency structures to accept beam from high-intensity RFQ injectors systems.

Another thrust of recent development has been the application to TEM-class cavities of high-pressure-water rinse techniques, similar to those developed for TESLA and other TM cavities, to reduce surface particulates and increasing accelerating gradients.

In what follows, we will first summarize tests of recently completed prototype cavities, then list several cavities under development, but not yet tested, and finally, discuss application of TEM-class cavities to the high-energy section of the proposed RIA driver linac [3].

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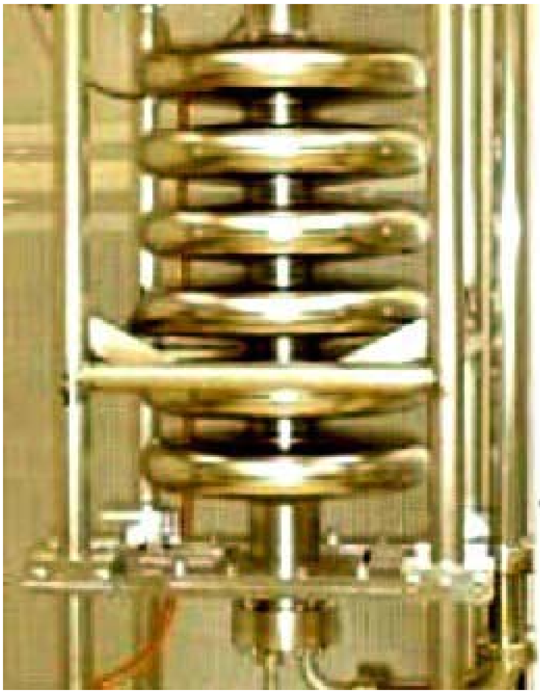

Figure 3: Prototype niobium six-cell elliptical-cell, 805 MHz, β=.47 cavity built by JLAB/MSU

## RECENTLY TESTED CAVITIES

### *Los Alamos*

At Los Alamos National Laboratory, two prototype single-spoke cavities designed to be injected with a high-intensity beam from the LEDA RFQ have been built and tested [4]. The 350 MHz, β=0.175 cavities, shown in Figure 1, have operated at 4K at peak surface electric fields as high as 37 MV/m.

### *IPN Orsay*

At the Institute for Nuclear Physics at Orsay, spoke cavities are being developed for high-power proton linacs to support two European projects, XADS and EURISOL. A single-spoke, 352 MHz, β=0.35 cavity, shown in Figure 2, has been built and tested [5] and has operated at 4K with peak surface electric fields as high as 37 MV/m.

### *MSU-NSCL*

At the National Cyclotron Laboratory at Michigan State University, a 322 MHz, β=0.29 coaxial half-wave cavity is being developed for the RIA driver linac [6]. A prototype has been built and tested and has operated at 4K with peak surface electric fields as high as 27 MV/m and at 2K as high as 33 MV/m.

### *JLAB/MSU*

In a collaborative effort between JLAB and the National Cyclotron Laboratory, a TM-class, six-cell elliptical-cell cavity is being developed for the RIA driver linac [7]. A prototype 805 MHz, β=0.47 cavity, shown in Figure 3, has been completed and operated at 2K at peak surface electric fields above 50 MV/m.

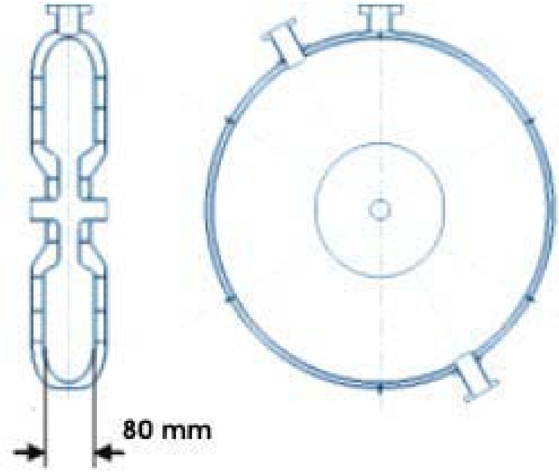


Figure 4: 352 MHz low-beta TM-class re-entrant cavity developed at INFN-Legnaro

### *INFN Legnaro*

At INFN Legnaro, a TM-class re-entrant cavity is being developed to provide a high-frequency, low-beta structure for injection with a high-intensity proton beam from a 352 MHz RFQ [8]. The single-gap cavity, shown in Figure 4, has very broad velocity acceptance and is useful for particle velocities as low as 0.1c. In tests to date the cavity has operated at 4K at peak surface electric fields as high as 26 MV/m, and can provide 600 kV of acceleration with 7.5 watts of rf input.

### *Argonne*

At Argonne National Laboratory a 345 MHz, two-spoke cavity is being developed for the RIA driver linac [9]. A prototype unit, shown in Figure 5, has been completed, and in initial tests at 4K has operated at peak surface electric fields as high as 40 MV/m. The prototype cavity can provide 3 MV of acceleration with 20 watts of rf input into 4K.

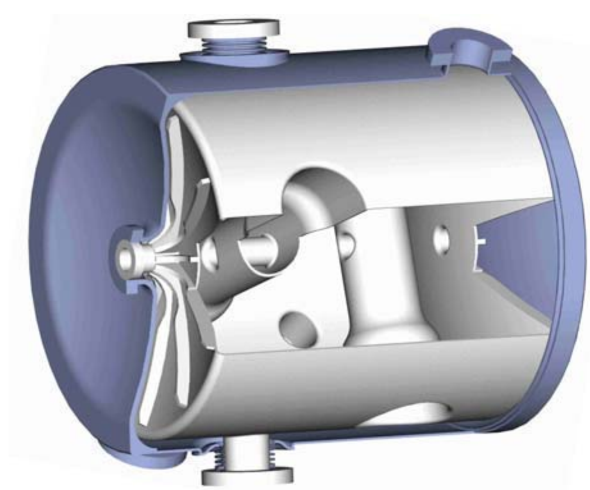

Figure 5: A 345 MHz, double-spoke, three-gap cavity for β=0.4. A niobium prototype has been built and tested at Argonne National Laboratory

Figure 6: A 352 MHz, four-gap ‘ladder resonator’ for β=0.12 is being developed at INFN-Legnaro

## UNDER DEVELOPMENT

Two different groups are developing low-velocity, multiple-gap structures to accelerate high-intensity beams from RFQ injectors. At INFN-Legnaro, a variant of the spoke structure, termed the “ladder resonator” is being developed [10]. A model of the 352 MHz, four-gap, β=0.12 structure is shown in Figure 6. At Frankfurt, a design for a 19-gap CH-structure has been developed, and a niobium prototype cavity is being constructed [11].

At Argonne National Laboratory, several types of cavity are being developed for use in the U.S RIA driver linac. Figure 7 shows two of these cavities [12]. One is a 115 MHz quarter-wave-line (QWR) structure for β=0.15, which has a drift tube shaped to correct rf magnetic dipole terms which cause beam steering in QWR structures. The other is a 172 MHz coaxial half-wave cavity for β=0.28. Niobium prototypes of both cavities are under construction with initial tests scheduled for late 2003.

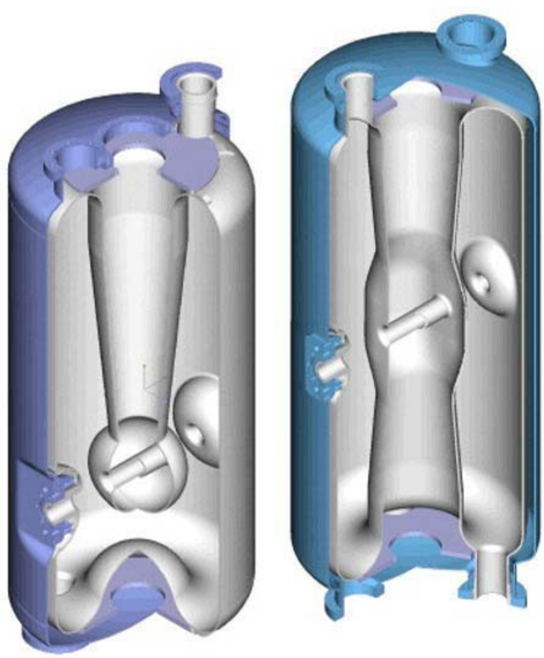

Figure 7: A 115 MHz, β=0.15 QWR cavity and a 172 MHz, β=0.27 coaxial half-wave cavity being prototyped at Argonne National Laboratory for the RIA driver linac.

## SPOKE-CAVITY BASED HIGH-ENERGY ION LINAC

At Argonne National Laboratory, designs for two superconducting niobium, 345 MHz, three-spoke-loaded cavities for the velocity range 0.4<β<0.75 have been developed [13]. Figure 8 shows a sectioned view of one of the two cavity types. The mechanical elements and overall design are similar to those of a recently tested 345 MHz two-spoke niobium cavity [9]. The cavities are being developed as an alternative to 805 MHz, elliptical-cell cavities in forming the high-energy section of the proposed RIA driver linac [3,13].

The RIA driver linac is required to operate cw, and to deliver at least 100 kW of uranium beam at an energy of 400 MeV/nucleon, and lighter ions at as high an energy as possible. For this application, TEM-class spoke-loaded structures offer a number of advantages with respect to TM elliptical-cell structures

For a given transverse diameter, elliptical-cell TM cavities operate at roughly twice the frequency of TEM spoke-loaded cavities. This simple fact has several important ramifications [1].

For multi-cell cavities, each cell is of length βλ/2 so that at lower frequency fewer cells are required, for a given overall length, which broadens the velocity acceptance of the structure. Conversely, for the same number of cells, a lower frequency cavity will be longer and produce more accelerating voltage than a higher frequency cavity, while maintaining the same velocity acceptance.

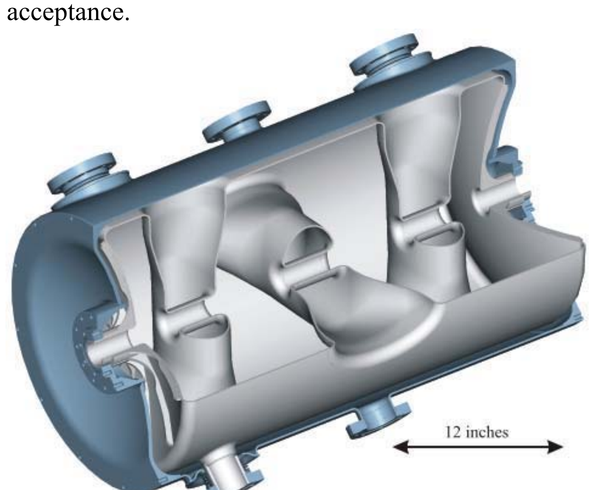


Figure 8: A 345 MHz, β=0.5 triple-spoke-loaded, four gap accelerating structure. A niobium prototype is under construction at Argonne National Laboratory.

Table 1: Electromagnetic parameters for the two triple-spoke cavities compared with two elliptical-cell six-cell cavities of similar $\beta_{GEOM}$ = v/c developed for the SNS linac and for the RIA driver linac [13].

| Cavity Type | Triple-Spoke | Elliptical Six-Cell | Triple-Spoke | Elliptical Six-Cell |
|---|---|---|---|---|
| $\beta_{GEOM}$ | 0.50 | 0.47 | 0.62 | 0.61 |
| Frequency | 345 MHz | 805 | 345 | 805 |
| Length | 65.2 cm | 52.55 | 80.87 | 68.2 |
| $G = Q{\bullet}R_S$ | 85.7 | 136.7 | 93.0 | 179.0 |
| R/Q | 494 | 160 | 520 | 279 |
| at an accelerating gradient of 1 MV/m: | | | | |
| $E_{PEAK}$ | 2.88 MV/m | 3.41 | 2.97 | 2.71 |
| $B_{PEAK}$ | 86.5 G | 69 | 88.6 | 57.2 |

Table 1 compares the electromagnetic parameters for two 805 MHz elliptical-cell and two 345 MHz spoke-loaded cavity geometries for the particle velocities $\beta_{GEOM}$ = 0.5 and 0.62. We note that a critical parameter, the peak surface electric field, is comparable for the two classes of structure, even for particle velocities above 0.5c. Also, note that the shunt impedance R/Q is appreciably higher for the spoke-loaded cavities.

Figure 9 compares the voltage gain as a function of particle velocity for the two types of cavity, assuming operation of all cavities at a peak surface electric field of 27.5 MV/m. Figure 9 shows the advantage of the lower frequency for the TEM-class spoke-loaded cavities in providing both broader velocity acceptance and higher voltage per cavity. For the RIA driver linac, this means the linac can be built not only with fewer types of cavity, but also with fewer cavities. Further, because of the broader velocity acceptance, the linac provides appreciably higher output energy for proton beams.

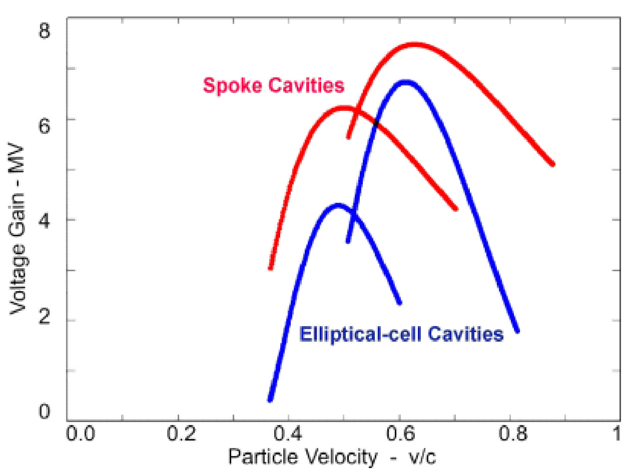


Figure 9: Velocity acceptance for two 345 MHz triple-spoke cavities compared with two 805 MHz elliptical 6-cell cavities, all operating at a peak surface electric field of 27.5 MV/m.

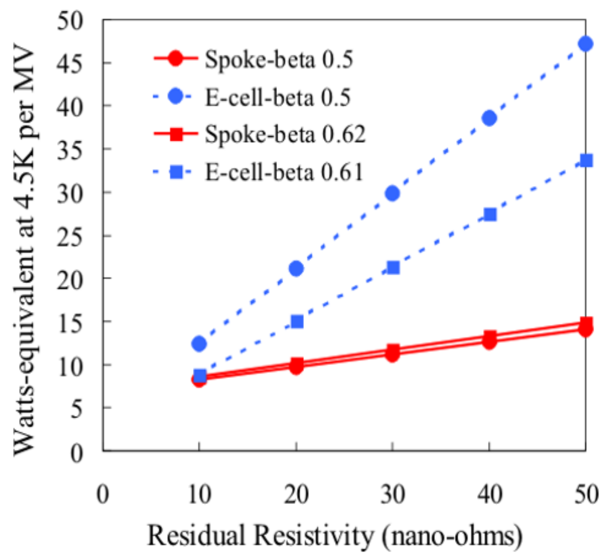


Figure 10: RF load into helium refrigeration as a function of cavity performance.

A major advantage of the lower frequency TEM structures is that the superconducting surface resistance is quadratic with frequency, so that using spoke loaded cavities will substantially reduce the rf losses and the refrigeration load, which is particularly important for cw operation. Also, at 345 MHz, the possibility of operation at 4K is opened, eliminating the need for sub-atmospheric cryrogenic system. Figure 10 compares the rf heat load required to maintain 1 MV of accelerating potential for the different cavities. In figure 10, all cavities are assumed to operate cw at a peak surface electric field of 27.5 MV/m. The spoke cavities are assumed to operate at 4.5K, and the elliptical-cell cavities at 2K. The 2K refrigeration system is assumed to operate at an efficiency such that 1 watt into 2K is equivalent to 4.5 watts at 4.5K.

Table 2: Summary of the parameters for the two design options for the high-energy section of the RIA driver linac (from reference [13])

| Parameter | Triple-spoke | Elliptical-cell |
|---|---|---|
| Frequency (MHz) | 345 | 805 |
| Peak E field (MV/m) | 27.5 | 27.5 |
| No. of cavity types | 2 | 3 |
| Total no. of cavities | 140 | 180 |
| Temperature (K) | 4.5 | 2.1 |
| Aperture (mm) | 40 | 80 |
| Synchronous phase | -25° | -30° |
| *Normalized Acceptance* | | |
| Trans. (π·mm·mrad) | 35 | 70 |
| Long. (π·keV/u-nsec) | 280 | 60 |

The heat load is plotted as a function of cavity performance or quality in terms of an effective residual resistance, ranging from excellent performance (10 nΩ) to poor (50 nΩ). Recent cavity design goals, prototype results, and production results range from 15 – 30 nΩ. For this range of performance, the triple spoke cavities would reduce the refrigeration load by roughly a factor of two relative to the elliptical-cell design option.

Table 2 compares several major parameters for the two design options for the RIA driver linac. We simply note that the use of TEM-class, spoke loaded cavities offer a number of advantages in terms of cost, simplicity, and performance for this particular application.

## CONCLUSIONS

The past several years have seen vigorous development of TEM-class low- and intermediate-velocity superconducting accelerating structures for a variety of applications. The development of half-wave loaded structures has greatly extended the velocity range covered by TEM-class cavities. The cross-over velocity at which elliptical-cell TM-class cavities become the structure of choice seems to be in the neighborhood of 0.5c, but requires detailed study for a given particular application because of the variety of choices of structure that are becoming available.

The use of new cleaning techniques has demonstrated a capability for substantially increasing the accelerating gradients at which TEM-class superconducting cavities are operated.

## ACKNOWLEDGEMENTS

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