A FAMILY OF L-BAND SRF CAVITIES FOR HIGH POWER PROTON DRIVER APPLICATIONS*

R.A. Rimmer, F. Marhauser, JLab, Newport News, VA 23606, U.S.A

Abstract

Recent global interest in high duty factor or CW superconducting linacs highlights the need for robust and reliable SRF structures capable of delivering high average RF power to the beam with moderate HOM damping, low interception of halo and good efficiency. Potential applications include proton or H- drivers for spallation neutron sources, neutrino physics, waste transmutation, subcritical reactors, and high-intensity, high-energy physics experiments. We describe a family of SRF cavities with a range of Betas capable of transporting beam currents in excess of 10 mA CW with large irises for minimal interception of halo and HOM and power couplers capable of supporting high average power operation. Goals include an efficient cell shape, high packing factor for efficient real-estate gradient and strong HOM damping to ensure stable beam operation. Designs are being developed for low-frequency (e.g. 650-975 MHz), but can easily be scaled to high-frequency (e.g. 1.3-1.5 GHz), depending on the application. We present the results of conceptual design studies, simulations and prototype measurements.

INTRODUCTION

SRF has become the technology of choice for high power, high duty factor or CW linacs for many applications. An efficient cavity shape and high packing factor (ratio of active length to tunnel length) in cryomodules helps to minimize total project capital and operating costs. For high current applications HOM damping and high beam break-up (BBU) threshold are critical. A large bore through the structure to minimize halo interception and potential activation is important for hands-on maintenance. To cover the high energy section of a large machine requires several different beta values from about 0.6 (possibly as low as 0.5) to as high as 1 for very high energy machines. JLab has recently developed a high-current cavity for electron machines ($\beta = 1$) [1], with a cell shape optimized to tune longitudinal HOMs away from harmonics of the beam and thereby minimize extracted HOM power, and with good HOM damping for high BBU threshold. This concept has been scaled to lower beta values for this study, see Fig. 1. 805 MHz has been used for this exercise, to simplify comparison with the JLab-produced SNS linac cavities, but the designs are easily scalable to any desired frequency. Prototypes of the original $\beta = 1$ version have been successfully tested to high gradients with reasonable Q factors [2].

* Notice: Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

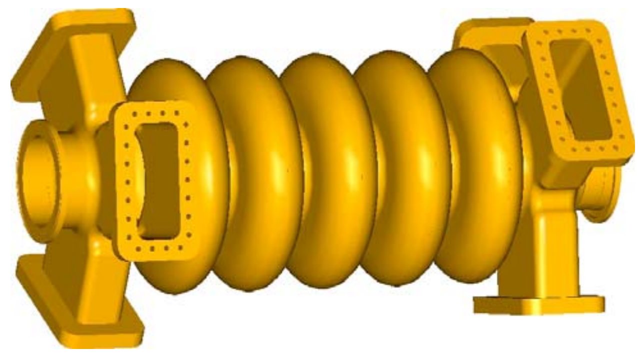

Figure 1: Cavity with rounded high-current β=0.85 cells, waveguide HOM dampers and fundamental power coupler.

CAVITY CONCEPT

The cavity shape is a compromise between efficiency (shunt impedance), aperture and HOM spectrum. For high-current driver applications the halo and beam stability issues are foremost, so we have adopted a relatively large beam iris with no insertions (couplers or HOM dampers) to intrude into the opening. This is achieved using waveguide fundamental power coupler (FPC) and HOM dampers. The cell shape is chosen to tune the longitudinal HOMs away from harmonics of the RF and thereby minimize HOM power extraction. This results in a relatively rounded cell profile, that is also reasonably efficient. The HOMs are also strongly damped for stability. The waveguide HOM dampers are tightly coupled to the end cell and exit radially to minimize the loss of beam line space. Waveguide loads can be anchored at room temperature for high currents or possibly at intermediate temperatures (e.g. attached to the cryomodule shield flow), if the HOM power is more modest.

Modular Family

For overall cost optimization, it is helpful to utilize modular construction for all components. Using the same FPC and HOM configuration for all members of the family helps to reduce costs and simplify fabrication. The cryomodule and ancillary components can be adaptable to different cavity lengths. For simplicity in this study we have stayed with 5-cell cavities, however if HOM damping is adequate it is possible to add more cells to the lower beta cavities while keeping the overall length constant. This would yield a family with 5 cells for $\beta = 1$, 6 cells with $\beta = 0.83$ and 7 cells with $\beta = 0.71$. The active length would be the same in all cases and all coupler, tuner and cryomodule parts would be interchangeable.

Cell Shape

As discussed above, the β = 1 cell shape is optimized primarily in terms of the HOM spectrum and beam clearance. The aperture is comparatively large (r = 0.175*λ) and the iris radius is sufficiently rounded, see Fig. 2, to limit electric field enhancement to a reasonable value. For the β = 1 cavity the outer part of the cavity is shaped to tune the HOMs to safe frequencies. This also results in a relatively "low-loss" type shape with modest peak magnetic field. It also enables all the cells for a given β value to be made from a single die set to reduce costs. The end cells have the same wall profile as the center cells but are tuned shorter to achieve field flatness. The length change is quite significant (6% at β = 0.81, 8% at β = 0.65) but this also has the advantage of raising the shunt impedance slightly compared to tuning by making the end cells with a different profile but the same length. One refinement for the lower beta versions of the cells is that the equator region of the cavity contains a short straight section. This facilitates the end cell tuning while maintaining a smooth transition at the equator joint. A summary of the parameters for the various shapes is listed in Table 1. The dominant trend is due to the larger aperture. For a survey of other commonly used cell shapes see [3]. Prototypes of the 5-cell β=1 cavity have been tested at JLab at 1.5 GHz, as well as a single-cell at 750 MHz, Fig. 3, [2].

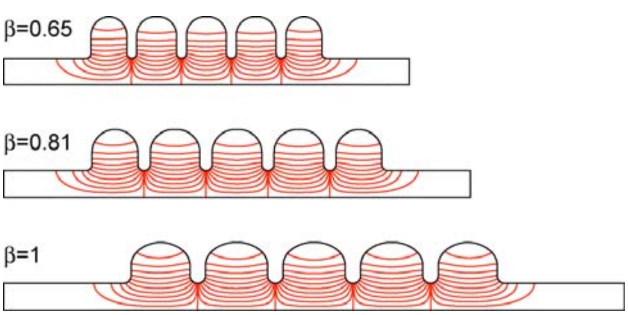

Figure 2: Cavity profiles and fields from Superfish.

Multipacting

With any new cell shape there is always a possibility of introducing an unexpected multipacting barrier. The new family of shapes has been analyzed with Fishpact [4] as part of the design process to lower the electron impact energy for any resonant multipacting condition within the expected operating gradient. The impact energy is therefore lower than or comparable to similar designs for both the center and the shorter end cell profiles. Impact energy plots for the three designs plus SNS are shown in Fig. 3, in which a secondary electron yield for a typical Nb surface has been assumed. Impact energies for the shortened end cells have also been investigated for the new designs. These are usually higher than in the center cells due to the reduced dimensions at the equator region. The single cell β=1 prototype at 750 MHz (center-cell profile) tested successfully to 25 MV/m and showed no sign of multipacting (Fig. 4).

Table 1: Comparison of Different Cell Shapes

	β	R/ $(Q\,\beta^2)$ Ω/cell*	E_{pk}/E_{acc}	B_{pk}/E_{acc}	G (Ω)	Iris r/λ	K_{cc} (%)
SNS	0.81	122.7	2.19	4.72	260	0.131	1.52
SNS	0.61	125.0	2.71	5.81	179	0.115	1.53
HC	1	104.2	2.45	4.14	276	0.175	3.17
HC	0.81	93.3	3.14	4.99	237	0.175	4.48
HC	0.65	73.5	4.28	6.43	201	0.175	6.09

* mid-cell profile, $R=V^2/P$

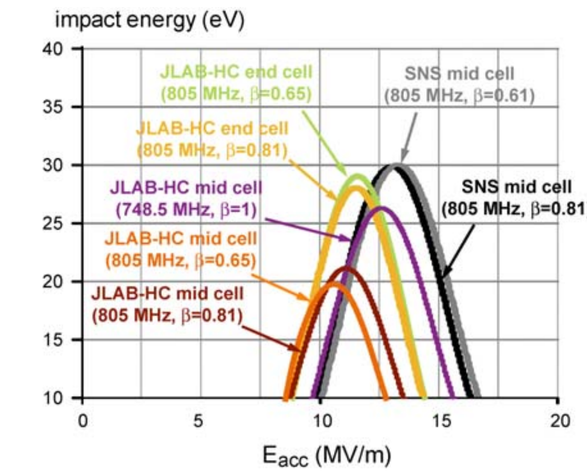

Figure 3: Electron impact energy on stable resonant trajectories calculated by Fishpact.

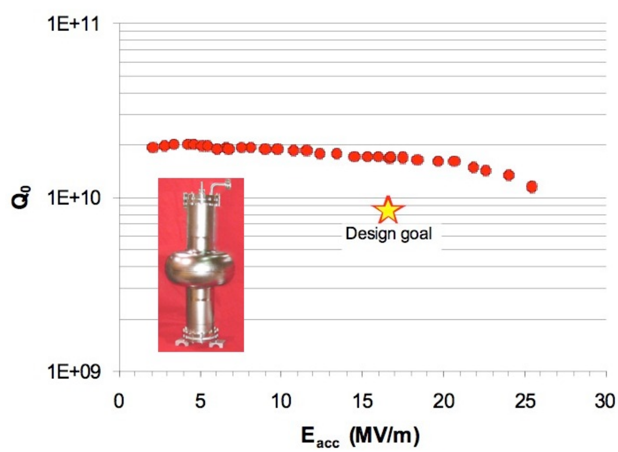

Figure 4: Test result of single cell 750 MHz β=1 cavity after BCP processing.

HOM Damping

Waveguide HOM dampers offer a good combination of strong coupling, high power handling capability, maximum use of active length and natural rejection of the fundamental mode. The symmetric orientation of the waveguide end groups on the cavity allows the capture of any orientation of dipole modes and all monopole modes, even if the field profile is tilted after tuning, and presents no dipole kick to the beam. The waveguide end groups at opposite ends of the cavity may be offset in azimuth to allow high-order multipoles to be captured and to allow a straight run for the helium header and fill lines along the module. Figure 5 shows the broad-band monopole spectrum for the high-current cavity β=0.65 calculated by MAFIA. Figure 6 shows the dipole spectrum. Vertical lines show harmonics of the RF frequency which are safely between dangerous HOMs. All impedances are fully resolved by applying the impedance spectrum extrapolation method described in [6].

Cryomodule

The overall layout is based on the JLab space-frame design but modified to accommodate the waveguide dampers. Operating voltage will depend on the application and processing. For standard chemical processing an average performance of 16.7 MV/m is assumed, which is similar to that achieved on average in vertical tests of the SNS cavities. Use of electro-polishing for final cavity processing might allow this to be raised further. Each cavity will have its own helium vessel with actively cooled end groups. There are no helium-to-beam-line vacuum flanged joints. HOM power is taken out to ambient temperature by waveguide dampers with gas or water-cooled HOM loads.

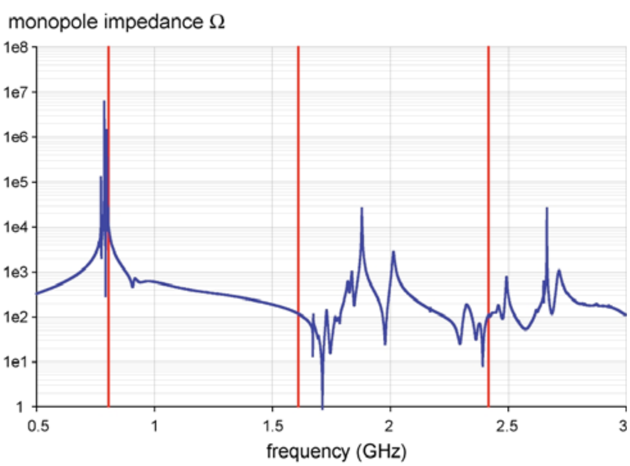

Figure 5: High-current β=0.65 cavity monopole spectrum.

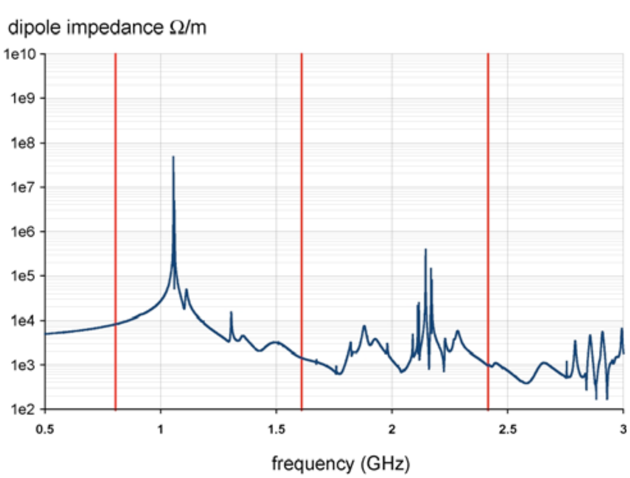

Figure 6: High-current β=0.65 cavity dipole spectrum.

Window and Fundamental Power Coupler

For a high-current machine the beam power required could be substantial. For each 1m of active length at 20 MV/m the fundamental power coupler would be required to supply 200 kW at 10 mA. This is well within the capability of existing coupler designs such as the PEP-II type waveguide window [7]. Dynamic losses in the warm section will be intercepted at the shield temperature but losses between that point and the cavity will contribute to the 2K heat load. Trace cooling of the FPC could be employed and the location of the shield heat station will be determined to minimize the total operating load.

CONCLUSIONS

We have developed a family of cavities to cover the medium to high-energy end of SRF linacs for high average power proton drivers. Preliminary analysis shows they have good HOM damping, reasonable peak surface fields and efficiency, low probability of multipacting, and a high module packing factor. These designs can easily be scaled to any desired frequency. Modular construction should allow for efficiency and commonality of components and subassemblies between different family members. Concepts for a cryomodule layout and ancillary components could be closely based on existing designs and production methods in use at JLab. Tasks remaining to be done include more detailed HOM analysis, thermal modeling, microphonic analysis of the structure and detailed design and prototyping of all main components. Funding permitting, prototypes of the low beta cavities will be fabricated and tested at JLab.

ACKNOWLEDGEMENTS

We would like to thank Jim Henry for timely and accurate assistance with solid modeling and Genfa Wu for help running Fishpact.

REFERENCES

[1] R.A. Rimmer et. al., "The JLab Ampere-Class Cryomodule Conceptual Design", Proc. EPAC06, Edinburgh, 2006.
[2] P. Kneisel et. al., "Preliminary Results From Prototype Niobium Cavities For The JLab Ampere-Class FEL", Proc. PAC07, Albuquerque, NM, 2007.
[3] H. Wang et. al., "Elliptical Cavity Shape Optimization for Acceleration and HOM Damping," Proc. PAC05, Knoxville, TN, 2005.
[4] G. Wu, http://www.jlab.org/~genfa/fishpact/
[5] R. Rimmer, H. Wang, G. Wu, "Strongly HOM-Damped Multi-Cell RF Cavities for High-Current Applications", Proc. SRF03, Luebeck, Germany, 2003.
[6] F, Marhauser et. al. ,"Enhanced Method for Cavity Impedance Calculations", these proceedings.
[7] R.A. Rimmer et. al., "A High-Power L-Band RF Window," Proc. PAC01, Chicago, 2001.