A COMPARISION OF SUPERCONDUCTING RF STRUCTURES OPTIMIZED FOR β = 0.285*

Z.A. Conway#, R.L. Fischer, M.P. Kelly, A.A. Kolomiets,
B. Mustapha, and P.N. Ostroumov, ANL, Argonne, IL 60439, U.S.A.

Abstract

Recent advances in low-beta superconducting RF technology have enabled the proposal and construction of ever-increasing-intensity ion accelerators, e.g. The Facility for Rare Isotope Beams (FRIB) at Michigan State University and Project-X at Fermilab. Superconducting TEM-class structures are required for these accelerators and beam quality preservation and cost efficiency are of the highest importance. This paper presents a comparison of the superconducting TEM-class cavities available for the acceleration of ions in the energy range of 16 to 55 MeV/u in order to guide their selection in future ion accelerator projects.

INTRODUCTION

At this time, two types of accelerator resonators may be seriously considered for the continuous-wave acceleration of heavy-ions from 16 to 55 MeV/u. These are superconducting halfwave and single-spoke resonators. We have chosen several resonator design parameters based upon the requirements of the FRIB driver accelerator at Michigan State University [1], the project which is the focus of this work. These parameters are: 1) beam port diameter = 4 cm, 2) accelerating eigenmode frequency = 322 MHz and 3) operating temperature = 2 K.

In the first part of this paper we describe the current electromagnetic and mechanical design of the halfwave and single-spoke resonators. We then discuss the different cryomodule requirements for each resonator type. Finally, we conclude with remarks comparing the processing of these resonators and recommend that halfwave resonators be used in this velocity range.

CAVITY PROPERTIES

Electromagnetic Design

The electromagnetic design of the halfwave and single-spoke resonators are being optimized to reach record high accelerating voltages, ≥2.5 MV per cavity, when processed with techniques developed for low-beta cavities in ANL's state-of-the-art surface processing facility [2].

The RF performance parameters which we focus our modelling efforts on are based upon the work of [3, 4] and are investigated by varying the cavity geometries both by inspection and parametric searches. The current results are given in table 1 with the CST Microwave Studio Models used for these calculations shown in figure 1. Operating at 2.5 MV both resonator's peak electric fields will be less than 40 MV/m and peak magnetic fields will be less than 660 Gauss. These field levels were recently exceeded at ANL by 50% [2] and represent a low-risk expectation of performance. The higher field levels achieved would reduce the number of resonators saving time and money for the accelerator in which they are used.

Table 1: Cavity RF Properties

	Halfwave	Single-Spoke
Frequency	322 MHz	322 MHz
β_{opt}	0.285	0.285
l_{eff}	26.6 cm	26.6 cm
$G = QR_s$	99 Ω	97 Ω
R/Q	200 Ω	235 Ω
E_{pk}/E_{acc}	4.2	3.8
B_{pk}/E_{acc}	70 G/(MV/m)	63.5 G/(MV/m)
U_0/E_{acc}^2	0.175 J/(MV/m)^2	0.149 J/(MV/m)^2

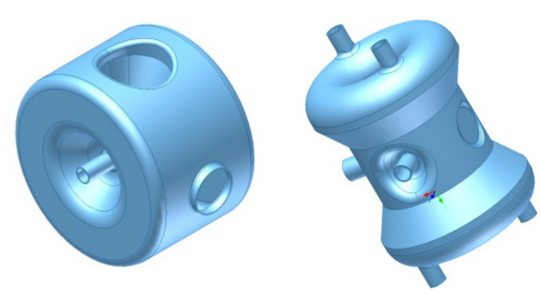

Figure 1: The electromagnetic model of the single-spoke and halfwave resonators. The single-spoke is 15" along the beam axis and 21" in diameter. The halfwave is 11.75" along the beam axis and 25" top to bottom.

Mechanical Design

The accelerating eigenmode RF field is strongly correlated with the mechanical design of the resonator. The RF field in accelerator resonators must be operated with stable amplitude and phase locked to the heavy-ion beam bunches. Mechanical vibrations which couple to the accelerating eigenmode disrupt the synchronization between the resonator RF field and the beam bunches. The level of RF power required to maintain the synchronization is determined by: 1) the strength of the coupling between the cavity accelerating eigenmode and externally driven mechanical vibrations, and 2) the

*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357and WFO 85Y64 Supported by Michigan State University
#zconway@anl.gov

operating characteristics of the cavity slow and fast mechanical tuning systems.

We minimize the coupling between the resonator RF field and external forces by designing the cavity mechanical structure such that the total RF eigenfrequency shift due to changes in the external pressure ($\Delta f/\Delta p$) is small. This technique is described elsewhere and has been successfully incorporated in the design of a spoke resonator and a quarter-wave resonator [2,5,6]. With appropriate gusseting we expect to reduce these sensitivities to low levels; for example the halfwave cavity simulated with ANSYS is -1.0 kHz/atm. Similar cavities have been characterized in the presence of microphonics and we can extrapolate the worst case scenario for the dynamic cavity RF frequency variations from these results to be less than 10 Hz peak to peak in operation. Fast mechanical tuners have already been prototyped for both classes of cavities which are able to tune the accelerating eigenmode frequency by ±100 Hz with bandwidth of > 25 Hz, well beyond the expected requirements for operation at 2 K. For example, figure 2 shows the fast-tuner transfer function with the prototype piezo-fast tuner [7] coupled to a 172 MHz halfwave resonator.

The fast tuner is decoupled from the slow tuner to separate the mechanically compliant slow tuner from the rigid fast tuner. This separates their functions yielding more predictable behaviour improving accelerator reliability and reducing risk. The slow tuner design builds upon the successful ATLAS energy upgrade cryomodule's design [8]. The halfwave cavity RF frequency response to the slow tuner, modelled with ANSYS, is given in figure 3; for comparison the single-spoke resonator slow tuner designed by FNAL can provide a similar tuning range [9].

CRYOMODULE

The cryomodule design for both resonators is based upon ANL's successful box cryomodule design [8]. Both the cryomodule for the halfwave and the cryomodule for the single-spoke resonators use the same spacing between

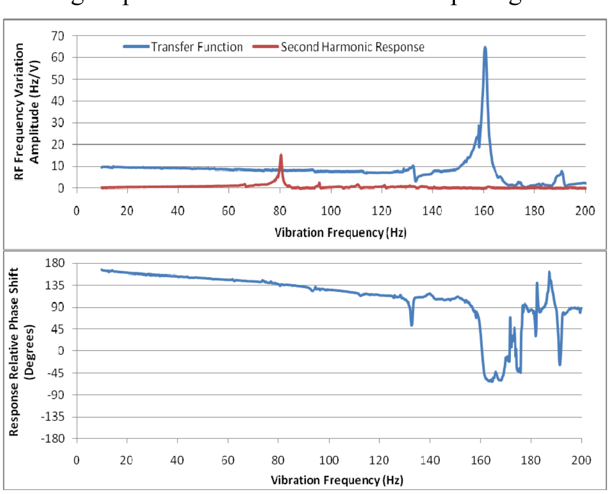

Figure 2: The piezo fast tuner transfer function amplitude (top) and relative phase shift (bottom).

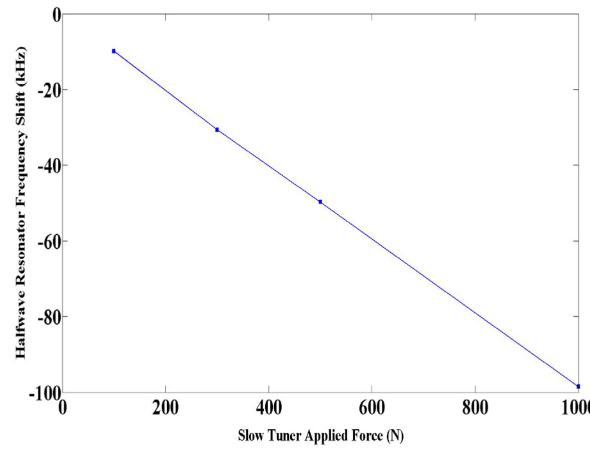

Figure 3: The simulated response of the halfwave resonator slow tuner at several applied force levels. The simulations were run with ANSYS.

Table 2: Accelerator Layout Summary

	Halfwave @ 2.5 MV/resonator	**Single-Spoke @ 2.5 MV/resonator**
# of Cryo	8	8
# of Res/Cryo	7	7
# of Resonators	56	56
Cryo Length (m)	4.2	4.6
Section Length (m)	36.5	40.1
Energy In (MeV/u)	16.3	16.3
Energy Out (MeV/u)	55.6	56.0

the beam line components.

The halfwave and single-spoke cryomodules differ due to: 1) the available space between resonators for clean string assembly and 2) the different dimensions of the resonators. Both of the cryomodules have identical numbers of tuners, couplers, transmitted power probes, etc. These items all have almost identical operating characteristics and do not pose a clear demonstrable difference between the two resonator types.

The halfwave resonator's tapered outer conductor increases the distributed capacitance and decreases the distributed inductance between the center and outer conductors; for a fixed voltage this increases the peak surface fields relative to straight-cylinder coaxial halfwave and single-spoke resonator geometries. In spite of this, the net real-estate gradient is increased due to the higher packing fraction of components along the accelerator beam line. The halfwave resonators can be positioned such that when the large diameter ends are positioned close together enough room between the beam ports remains for the clean assembly of the beam line string. Single-spoke resonator beam ports, which are

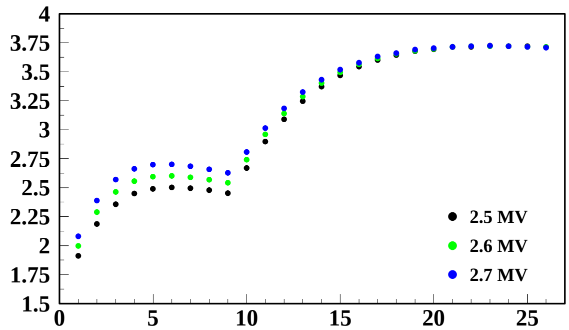

Figure 4: The average cavity voltage per cryomodule. The horizontal axis is cryomodule # and the vertical axis is the average cavity voltage gain.

flush with the resonator housing, limit how close the resonators can be positioned to adjacent beam line components.

Simulations performed with ANL's TRACK [10] beam dynamics software using realistic cryomodule layouts and resonator field distributions were used to determine the number of resonators required for operation. Table 2 shows the resonator and cryomodule counts with relevant simulation parameters/results. Notice, that the halfwave resonators with improved packing along the beam line reduce the overall length of the accelerator section by 3.6 m, saving money and space in cramped accelerator installations. Figure 4 shows the voltage gain per cavity calculated by TRACK. The simulations included both the $\beta = 0.285$ and the high energy $\beta = 0.54$ accelerator sections to accurately model the resonator/cryomodule requirements and the transition between resonator types. The original design called for 31 cryomodules (13 $\beta = 0.285$ and 18 $\beta = 0.54$) occupying 163.4 m along the accelerator. By optimizing the resonator geometry, cryomodule layout, and component lattice we have reduced the required number of cryomodules to 28 (9 $\beta = 0.285$ and 17 $\beta = 0.54$) reducing the length of the accelerator to 146.7 m, saving 16.7 m of beam line real estate.

CLOSING COMMENTS

Resonator Polishing

ANL has recently commissioned a new horizontal electropolish system capable of polishing low-beta resonators after final welding and machining. Final processing of complete resonators improves the chances for state-of-the-art performance, which was recently demonstrated for low-beta resonators at ANL [2]. The mechanics of electropolishing low-beta resonators where the center conductor and outer conductor are coaxial is very similar to the highly optimized procedure for polishing elliptical cell cavities for the ILC. This is the case for the halfwave resonator. The single-spoke resonator has the TEM-loading element located at 90^0 to the outer conductor axis of symmetry. The mechanics of electropolishing this class of resonator is not optimized and represents a higher risk for the accelerator. For example, one option to electropolish spoke resonators is to add ports to the end walls of the resonators. This increases the fabrication cost of the resonator by 4 additional ports and locates the aluminium cathodes perpendicular to the spokes. This option has not been extensively studied and further research and development is necessary [11].

Resonator Selection

We have briefly reviewed our investigation of two options to accelerate continuous-wave ion-beams from 16 to 55 MeV/u: a halfwave and a single-spoke resonator. Both options are viable in this energy range. However, the halfwave resonators exhibit several features which make them more attractive than the single-spoke resonators.

1) They have a higher packing fraction along the accelerator beam line which yields a shorter accelerator.
2) The risk of electropolishing complete cavities and producing state-of-the-art performance levels is much less.

For these reasons, halfwave resonators appear to be superior in this ion-beam velocity range. There is one major step left in our analysis and that is to compare the cost of fabrication of the different resonators and cryomodules. This work is only preliminary but favors the halfwave cavities. Future results from this investigation will be reported on once they are available.

ACKNOWLEDGEMENTS

We would like to thank Scott Gerbick, Joel Fuerst, Mark Kedzie and Ken Shepard for many helpful discussions regarding this work. We would also like to thank Jim Grudzinski for ANSYS modelling support.

REFERENCES

[1] R.C. York et al, SRF'09, Berlin, Germany 2009, FROAAU02, Pg. 888 (2009); www.jacow.org
[2] M.P. Kelly et al, PAC'11, New York, New York (2011), TUP046, these proceedings.
[3] B. Mustapha and P.N. Ostroumov, LINAC'10, Tsukuba, Japan (2010), To Be Published.
[4] Private communication, I. Gonin (FNAL)
[5] Z.A. Conway, Ph.D. Dissertation (2007).
[6] T. Schultheiss et al, PAC'11, New York, New York (2011), these proceedings.
[7] M.P. Kelly et al, LINAC'10, Tsukuba, Japan (2010), THP057, to be published.
[8] J.D. Fuerst, SRF'09, Berlin, Germany (2009), MOOCAU04, Pg. 52; www.jacow.org
[9] Y. Pischalnikov et al, SRF'09, Berlin, Germany (2009), THPPO043, Pg. 675; www.jacow.org
[10] http://www.phy.anl.gov/atlas/TRACK/
[11] Private communication, J.R. Delayen (ODU).