DEVELOPMENT OF A SUPERCONDUCTING 500 MHZ MULTI-SPOKE CAVITY FOR ELECTRON LINACS *

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Abstract

Multi-spoke cavities are well-known options for acceleration of heavy and light ions. A recently developed multi-spoke cavity for β=1 presents an attractive opportunity to use this cavity type for electron accelerators. One of the main attractive features of this cavity type is its compactness for relatively low frequency. A simplified design at 500 MHz allowed building of a multi-spoke cavity and cryomodule in a 2-year time frame with confidence and development of effective manufacturing techniques. It also constitutes an important step in proving the usefulness of this kind of cavity design for new applications in the electron machines. Niowave is now in a position to build on the success of this cavity to help advance the design of superconducting electron accelerators. Accelerating voltage of more then 6.7 MV in a single cavity at 4.2 K is expected with peak electric field of less then 22 MV/m, and peak magnetic field of less then 80 mT. The paper discusses the fabrication challenges of the complete cavity and the cryomodule, as well as room temperature and cryogenic test results.

INTRODUCTION

Superconducting radio frequency (SRF) accelerating cavities are being successfully used for acceleration of electron beams worldwide. The use of superconducting structures helps maximize the accelerating gradient, which is a highly desirable trait for applications involving linear accelerators. Application of today's multi-spoke accelerating structures in future SRF electron linacs will allow a further reduction in the accelerators overall size without compromising its performance. Compact accelerators utilizing SRF cavities can be successfully used in a broad range of applications from x-rays machines for cancer therapy and sterilization, to tuneable x-ray and gamma sources, to high energy electron accelerators.

The presented work completes the manufacturing of the proposed cavity and cryomodule at Niowave, Inc [1]. Niowave, Inc. is a high-tech research and manufacturing company that specializes in superconducting particle accelerators and their components.

The cavity is designed to operate at 500 MHz and is capable of differential accelerating of electrons by 6.7 MeV in a single unit with electric and magnetic surface fields no more then 22 MV/m and 80 mT respectively. The cryogenic system is designed to operate at 4.2 K with dynamic load of less then 50 W with negligible beam load. This cryogenic load can be significantly reduced by operating in a pulsed mode or by reducing the overall accelerating voltage.

ELECTROMAGNETIC DESIGN

This project at Niowave develops a relatively low frequency SRF electron accelerating structure, using a multi-spoke resonator geometry that has applications in nearly all medium and high energy electron accelerators.

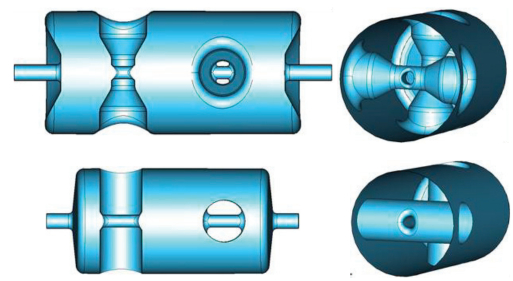

Figure 1: Two compared design options of the multi-spoke SRF cavity geometry.

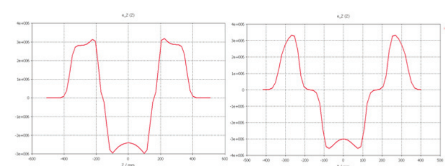

Figure 2: Longitudinal accelerating electric field profile for two compared designs: basic on the left, and advanced on the right.

The cavity geometry was designed at ODU and finalized after taking into account the manufacturing process preferences between Niowave and ODU. Two options of cavity geometry comparison used in the design stage are shown in Figure 1. The on-axis accelerating field profiles are shown in Figure 2. And the original design RF parameters are summarized in Table 1. The field levels shown in the table are very conservative with respect to the state of the art SRF cavities made from bulk niobium.

The development of superconducting half-wave or spoke accelerating structures began in the early 1990s at Argonne National Laboratory (ANL) [2]. Since then many programs have pursued the use of spokes for the acceleration of heavy-ions with velocities typically in the range of $0.2 < v/c < 0.8$ [3]. The spoke structure makes coupling several cavities together into a multi-spoke cavity inherently straightforward.

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Multi-spoke cavities for heavy ion linacs are currently being pursued by ANL, Frankfurt and Jüelich [4-6].

The use of multi-spokes for acceleration of electrons near speed of light has not been pursued to date, due to the strong performance of TM_{010} elliptical multi-cell structures. While these cavities can generate high gradients and have excellent performance, the multi-spoke cavity offers potential advantages [7,8], such as: smaller transverse cross section; stronger cell-to-cell coupling; stronger mode separation; mechanically more stable; fundamental couplers, HOM couplers and tuners are in active cavity regions

Multi-spoke cavities do have some disadvantages that may be offset by the advantages, including higher peak electric and magnetic fields for a given accelerating gradient (Ep/Ea and Bp/Ea) and higher cryogenic load (lower (R/Q)G).

Table 1: Advanced and Basic Design Options Parameters

Parameter	Advanced	Basic	Units
“0” mode frequency	499.8	499.9	MHz
“0” mode wave length	599.6	599.6	mm
β_0	1.0	1.0	
Cavity Geometry			
Length	818.4	633.2	mm
Radius	194.7	174.4	Mm
Iris-to-iris distance	718.4	633.2	Mm
End cup depth	-50.0	15.0	Mm
Aperture diameter	50.0	50.0	Mm
Spoke Geometry			
Aperture diameter	40.0	40.0	mm
Separation	319.3	341.8	mm
Inner diameter	74.9	140.0	mm
Outer diameter	150.0	140.0	mm
Cavity RF Properties			
Accelerating voltage	6.3	4.0	MV
E_{acc} at length λ	10.5	6.7	MV/m
E_{peak}	29.4	21.4	MV/m
B_{peak}	79.8	79.1	mT
R/Q	576.6	438.9	Ω
$G=R_s \cdot Q$	147.8	106.9	Ω
P_{loss}	59.7	44.1	W

MECHANICAL DESIGN

Important milestones in the fabrication of the multi-spoke cavity and cryomodule for electron accelerators were the niobium cavity fabrication by electron-beam welding, the welding of the stainless steel helium vessel, and the chemical processing and high-pressure rinsing of the inner cavity surface – all, except the EBW, done in house at Niowave. After this processing the rest of the four-piece cryomodule was assembled over about two months period.

The basic multi-spoke cavity design was chosen for the benefit of simplicity of manufacturing, and as a platform for development the manufacturing techniques and methods. The mechanical drawing of the proposed cavity is shown in Figure 3. The complete cryomodule design with the simplified geometry option is shown in Figure 4, with the niobium cavity and helium vessel surrounded by the liquid nitrogen thermal shield and magnetic shield (mu metal)..

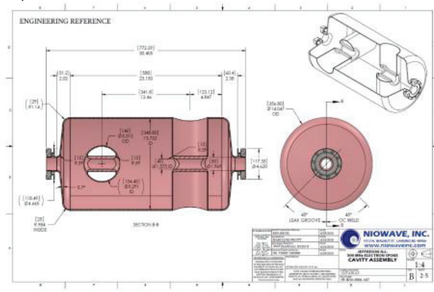

Figure 3: Mechanical design of the multi-spoke cavity.

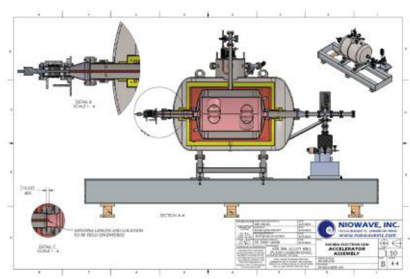

Figure 4: Mechanical design of the whole cryomodule assembly ready for the crytest.

RF MEASUREMENTS

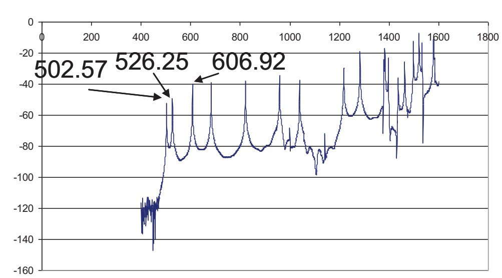

Figure 5: Eigenmode frequency spectrum from the room temperature measurements using network analyser.

As part of the final mechanical tuning of the cavity at the last stage of the manufacturing, room temperature measurements of the eigenmode frequency spectrum were conducted using the network analyser. Figure 5 shows the resulting eigenmode frequency spectrum from these measuremens.

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Additional set of measurements were done using the bead-pull technique for verification of the symmetry of the field distribution for the operating mode and for the nearest higher order modes (HOMs). The results of the bead-pull measurements together with the simulated electric field distributions in the mulkti-spoke cavity are shown in Figure 6.

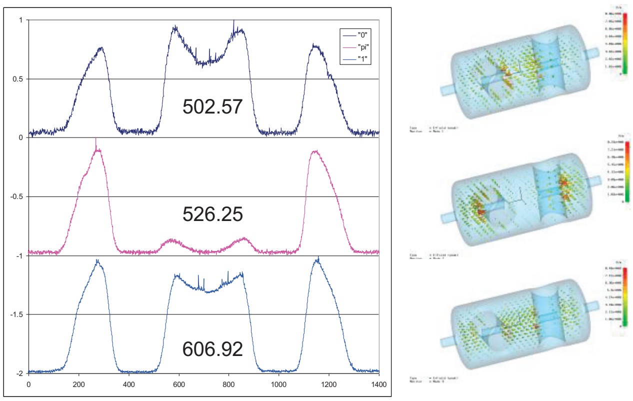

Figure 6: Bead-pull measurements for the fundamental and 2 higher order modes at room temperature.

Figure 7: Eigenmode spectrum measurements of the multi-spoke cavity in the full cryomodule assembly at room temperature.

The eigenmode frequency spectrum measurements at room temperature were repeated after the final cryomodule assembly in the setup shown in Figure 7.

The cavity presently is in the cryomodule and ready for final cryotesting.

IMPROVED DESING FOR 700 MHZ

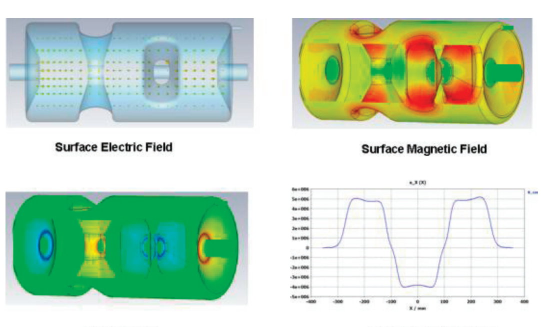

Figure 9: Longitudinal accelerating electric field profile for two compared designs.

As a direct result of the presented work, the next improved design of the multi-spoke cavity was done in the collaboration between ODU and Niowave. The new cavity is designed to operate at frequency of 700 MHz, and temperature of 4.2 K, with possible development of 2 K operation in the future. Some of the electromagnetic simulation results are presented in Figure 9. The design effective voltage in this cavity is ~6.4 MV with peak electric field less then 45 MV/m, and peak magnetic field less then 80 mT.

CONCLUSION

The most significant accomplishment of this work is the successful development of a new application for the compact type of the superconducting RF cavity. The transverse size of the cavity is significantly reduced when using the spoke geometry compared to the traditional elliptical accelerating structures. This project demonstrated that such a cavity can be successfully designed and built.

The next significant accomplishment is the continued emergence of the US industrial capability to build complete cryomodules with superconducting cavities that are ready to be used in existing and perspective projects. This capability had previously only existed inside the national laboratories. With the cryomodule testing capability moving to industry, many opportunities open up for commercial applications of the efficient SRF technology.

ACKNOWLEDGMENT

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