3-19-2003

Modeling, Fabrication, and Optimization of Niobium Cavities Phase II: Third Quarterly Report

Robert A. Schill Jr.
University of Nevada, Las Vegas, robert.schill@unlv.edu

Mohamed Trabia
University of Nevada, Las Vegas, mbt@me.unlv.edu

Revised 3/19/03
Final Version

Modeling, Fabrication, and Optimization of Niobium Cavities –Phase II
Third Quarterly Report

Principal Investigators (PI):

Robert A. Schill, Jr.
Department of Electrical & Computer Engineering, UNLV
4505 Maryland Parkway, Las Vegas, NV 89154-4026
Phone: (702) 895-1526
Email: schill@ee.unlv.edu

Mohamed B. Trabia
Department of Mechanical Engineering, UNLV
4505 Maryland Parkway, Las Vegas, NV 89154-4027
Phone: (702) 895-0957
Email: mbt@me.unlv.edu

Investigator:

William Culbreth
Department of Mechanical Engineering, UNLV
4505 Maryland Parkway, Las Vegas, NV 89154-4027
Phone: (702) 895-3426
Email: culbreti@nscee.edu

Current Students:

S. Subramanian (Graduate Student)
Anoop George (Graduate Student)
Myong Holl (Undergraduate Student)

Collaborators (DOE):

Dr. Tsuyoshi Tajima, Team Leader
Accelerator Physics & Engineering
LANSCE-1
Los Alamos National Laboratory
MS H817
Los Alamos, NM 87545
Phone: (505) 667-6559
Email: tajima@lanl.gov

AAA Research Area: Accelerators / Transmuter

Abstract

Niobium cavities are important parts of the integrated NC/SC high-power linacs. Over the years, researchers in several countries have tested various cavity shapes. They concluded that elliptically shaped cells are the most appropriate shape for superconducting cavities. The need for very clean surfaces lead to the use of a buffered chemical polishing produce for surface cleaning to get good performance of the cavities. The second phase has resulted in an experimental setup of a fluid flow experiment with experimentation to be completed in the third year. Other experimental activities include the evaluation of a vacuum system and various vacuum equipment purchases and modifications. An optimization code for a five cell niobium cavity based on resonant frequency and mode number was developed.

Introduction

The nuclear industry provides a significant percentage of the world, including the United States, with electricity. Nuclear power plants produce thousands of tons of spent fuel. Some of this spent fuel can be radioactive for thousands of years. The US DOE is currently exploring the possibility of creating a permanent storage site at Yucca Mountain, Nevada for nuclear spent fuel. Accelerator Transmutation of Waste is one complementary approach to deal with spent nuclear fuel. In this approach, a particle accelerator produces protons that react with a heavy metal target to produce neutrons. These neutrons are used to transmute long-lived radioactive isotopes into shorter-lived isotopes that are easier to be handled. A major component of the system is a linear accelerator (linac) that can accelerate a 100-mA beam of protons up to 1 GeV [1]. Los Alamos National Laboratory (LANL) is an active participant in developing a superconducting rf (SCRF) high-current linear accelerator. SCRF has three major components: niobium cavities, power couplers, and cryomodules. This effort mainly deals with niobium cavities.

Niobium cavities have several advantages including small power dissipation compared to normal conducting copper cavities. These cavities are usually made of multiple elliptical cells. Refer to Figure 1. They are formed from sheet metal using various techniques such as deep drawing or spinning. The cells then are welded using electron-beams. Multi-cell units are usually tuned by stretching or squeezing them. Niobium cavities need very clean surfaces, which can be achieved by chemical polishing and high pressure rinsing with ultra-pure water.

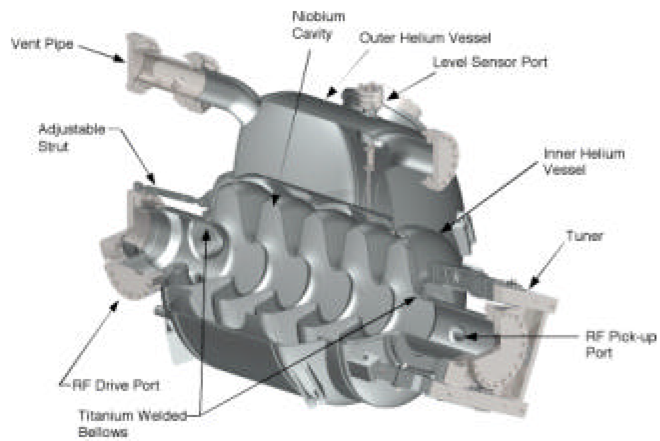


Figure 1. Schematic Diagram of Niobium Cavities (Executive Summary: Development and Performance of Medium-Beta Superconducting Cavities (LANL))

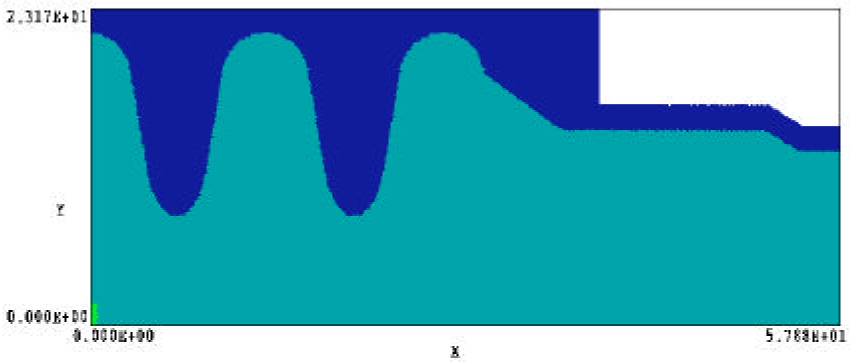
Under operation very high electromagnetic fields are present in these cavities. Besides the intended acceleration of a particle beam, these fields can also accelerate electrons emitted from the niobium surfaces. An electron emitted from the surface of the cavity wall is guided and accelerated by these RF-fields until it impacts on the cavity surface again. This re-impact can lead to the generation of one or more secondary electrons that in turn act as primary electrons that possibly might generate more electrons in a localized region. The number of secondary electrons is determined by the impact energy of the electron and by the secondary emission coefficient of the cavity material. If secondary electrons are created in phase with the RF-fields, and the impact is localized, a rapidly rising multiplication of electrons will occur. This localized resonant process is known as *multipacting* (multiple impacting). As a consequence, RF power is absorbed and it becomes impossible to increase the cavity fields by raising the incident power. The electron collisions with the structure walls lead to a temperature rise and eventually to a breakdown of the superconductivity. As a result, the Q_0 (quality factor) of the cavity is significantly reduced at the multipacting thresholds. Also, structural damage of the surface can occur. A good cavity design should be able to eliminate, or at least minimize multipacting. The factors that affect multipacting include: shape, surface finish, and coating.

While models have been suggested for minimizing multipacting [2], practical means of manufacturing the cavity walls to obtain optimal designs are still an issue. Attempting to improve the performance of multiple niobium cavities may be a daunting task because of the computational load associated with the evaluation of a particular design and the large number of variables and constraints involved. We propose approaching this task in a systematic way using principles of nonlinear programming. The consequence of this effort will allow the Superconducting RF Engineering Development and Demonstration group at LANL and the faculty at UNLV to target potential cavity cell configurations that improve upon existing designs.

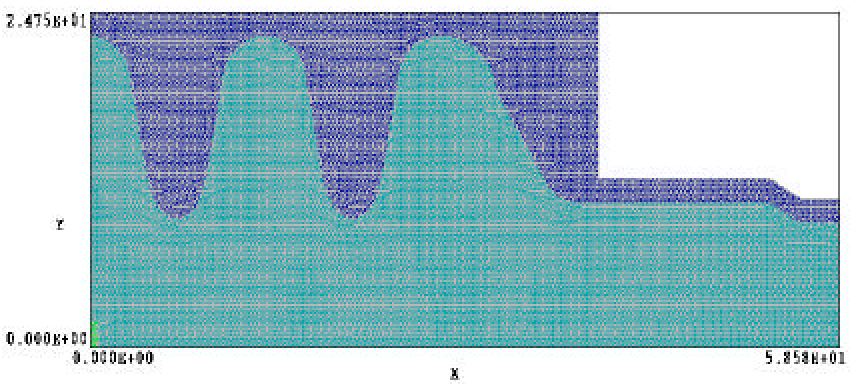
Summary of Achievements of Phase II:

1. <u>Optimization of the shape of the cavity to produce the desired resonant frequency and mode of operation</u>: This is a unique study with no precedent in the available literature. We have created a framework for interacting with two dimensional field codes

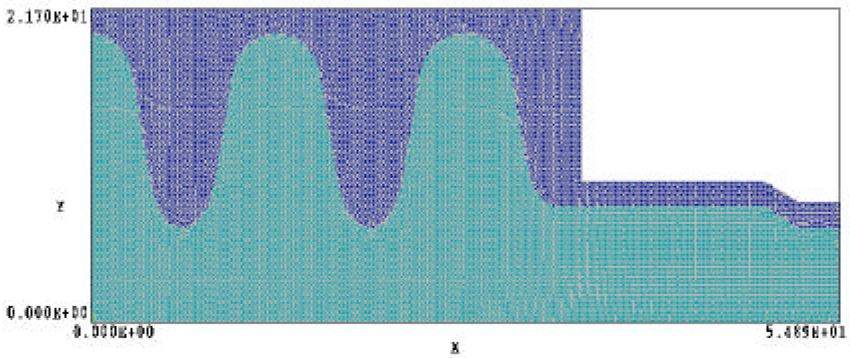
developed by Field Precision Inc. and an optimization program within a MATLAB environment. Figure 2a illustrates the outcome of a seed geometry, Fig. 2b, as the optimization routine hones in on the target frequency (700 MHz) and mode (pi mode). It is to be noted that the optimization process was stopped after a few days of iteration. At the time the code was terminated, the resonant frequency was approaching the target 700 MHz frequency but the pi mode was not found. It is observed that as the end cavities and the end pipes terminating the five cell geometry approach the same radius, both the target resonant frequency and the pi mode constraint will be found but for a three cavity geometry system as compared to the five cavity system. This implies that the optimization code is properly converging but it is converging to a geometry that is not of interest. The cavity geometry currently being employed at the LANL is illustrated in Fig. 2c. The end cells of the seed geometry (Fig. 2b) differ significantly from the existing geometry (Fig. 2c). The optimization process is being further constrained so to converge on a more desirable solution.



(a) Five-cell niobium cavity approaching an optimized geometry



(b) Five-cell niobium cavity seed geometry



(c) Five-cell niobium cavity original beta 64 LANL cavity geometry
Figure 2

2. <u>Assessment of a vacuum chamber and assembly to be used for SEE from niobium test piece.</u> An existing vacuum chamber has been modified for SEE studies. Through various donations, a cryogenic pump with controller was obtained. The vacuum chamber has been tested by an independent company to determine its capability to hold ultra low vacuum. It has been determined that pressures to 10^{-9} Torr should be possible. An electron gun, heat tape, and a RGA are on order. To save about $55,000 or more, the insides of an old cryogenic pump is being used as a cryostat. The "cryostat" was tested by the manufacturer and will reach superconducting temperatures for niobium (~8 ^{o}K). Quotes for a manipulator and load-lock chamber have been obtained. Figure 3 shows the existing cavity with pumps and blanks.

Figure 3. Vacuum Chamber, Cryogenic Pump, and Cryostat to be used for SEE Tests.

3. <u>Assessment of current etching techniques presently used in LANL</u>: The current method uses a baffle to direct the etching fluid toward the surface of the cavity. Refer to Figure 4. Finite element analysis shows that the baffle partially succeeded in achieving its purpose as can be seen in Figure 5. The flow is however restricted to the right half of the cavity with very limited circulation in the left half, which results in more etching of the iris region compared to that of the equator regions. These results confirm the observations of [3]. The current design also experiences flow circulation behind the baffles in the second through fifth cavity cells. There is a significant increase in velocity at the outlet.

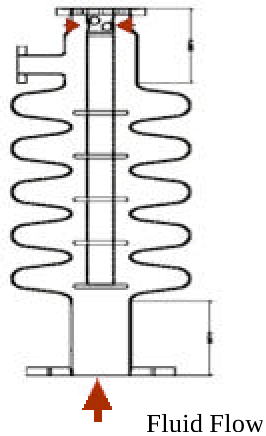


Figure 4. Current Etching Configuration of Niobium Cavities

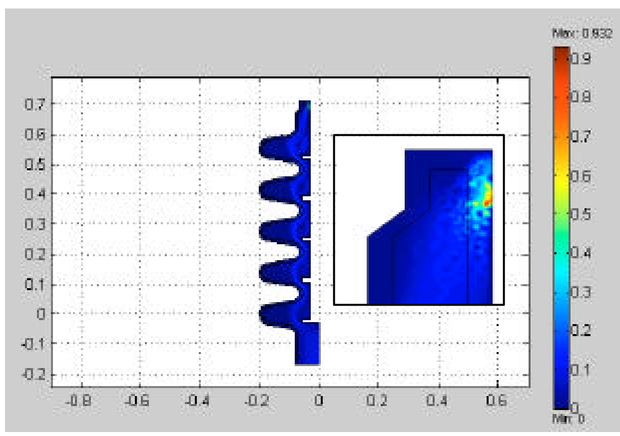


Figure 5. Velocity Field for the Current Baffle Design (inset: zoomed–in view of the flow at the exit)

4. Optimization of the Baffle Design: An alternative design is proposed and modeled. The proposed baffle design is also modified so that it can be extended inside the cells of the cavity. The exit flow is now parallel to flow inlet, Figure 6. Results show that flow circulation is eliminated. The flow is now closer to the surface of the cavity. We used optimization techniques to improve this design. [16]

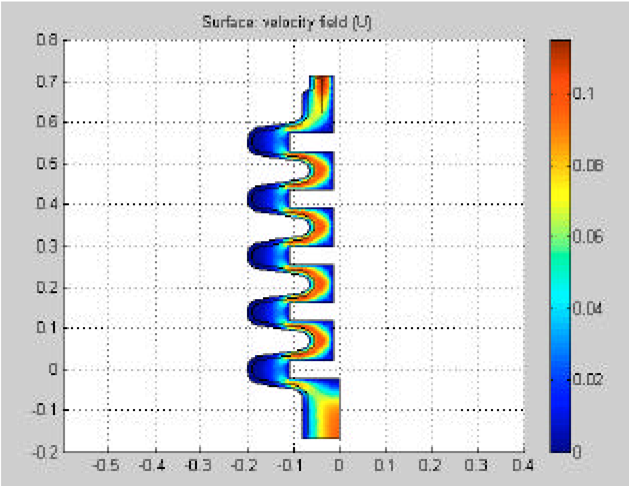


Figure 6. Velocity Field for the Optimized Modified Baffle Design

5. <u>Experimental Visualization of the Verification of the Etching Process</u>: LANL has loaned us a transparent cavity for use in flow visualization, Figure 7. A transparent plexiglass box was manufactured to enclose the cavity. Pump and piping system were also modeled, Figure 8. A complete setup including a computer-controlled x-y traverse and digital camera was assembled, Figure 9. We are currently testing the setup.

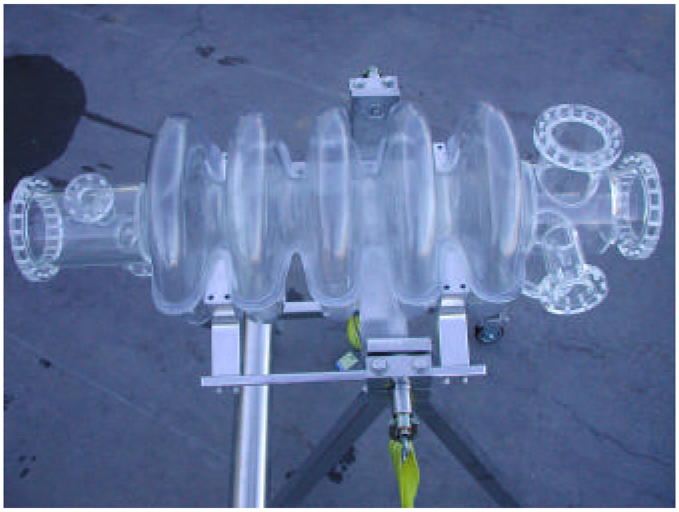


Figure 7. Photo of the LANL Transparent Cavity

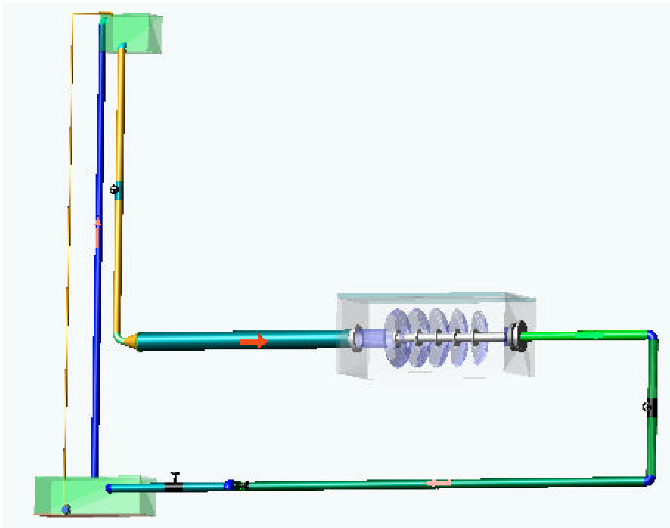


Figure 8. A Model of the Experimental Setup

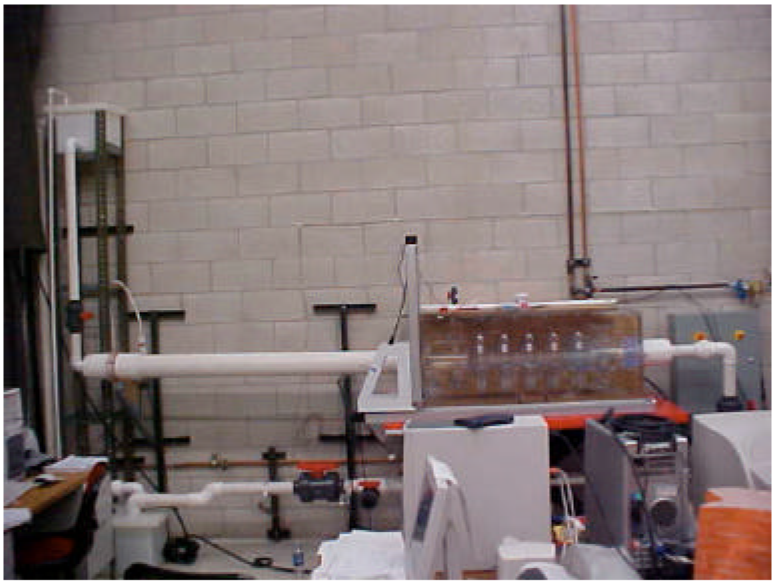


Figure 9. A Model of the Experimental Setup

6. These research activities are disseminated through:
   - One paper that was presented in the International Congress on Advanced Nuclear Power Plants (ICAPP), Hollywood, Florida, June 2002. The title of the paper is, "Modeling and Optimization of the Chemical Etching Process in Niobium Cavities."
   - Discussions with LANL personnel, especially Dr. Tsuyoshi Tajima.
   - Abstract accepted at the American Nuclear Society, Accelerator Applications Division, AccApp'03,"Accelerator Applications in a Nuclear Renaissance", San Diego, California – June 1-5, 2003. Abstract entitled: Optimization of a Five Cell Niobium Cavity. [Abstract No. 79389]

References

[1] "A Roadmap for Developing Accelerator Transmuting of Waste (ATW) Technology," DOE/RW-0519, October 1999.

[2] Hasan Padamsee, Jens Knobloch, and Tom Hays, **RF Superconductivity for Accelerators**, Wiley Interscience Publication, John Wiley, N.Y. 1998.

[3] *B. Aune et al., "The Superconducting TESLA Cavities," http://documents.cern.ch/archive/electronic/physics/0003/0003011.pdf*

[4] P. Kneisel et al., Nuclear Instrumentation Methods Physical Resources, **188** (1981) p. 669.

[5] Q. Shu et al., "Highest performance of TESLA 9-cell superconducting RF cavities by overcoming quenches in superfluid Lhe," IEEE Transactions on Applied Superconductivity v 7, n 2, p 371-374, 1997.

[6] P. Kneisel, "High gradient superconducting niobium cavities a review of the present status," IEEE Transactions on Applied Superconductivity v 9, n 2, p 1023-1029, 1999.

[7] U. Kelin and D. Proch in *Proceedings of the Conference of Future Possibilities for Electron Accelerators*, Charlottesville, pp. N1-17 (1979).

[8] R. Calder et al., *Nuclear Instrumentation Methods Physics Res. B, Beam Interaction Matter. At.*, ***13**:631 (1986).*

[9] R.E. Kirby and F.K. King, "Secondary Electron Emission Yields from PEP-II Accelerator Materials," SLAC-PUB-8212, October 2000.

[10] P.A. Tipler, Foundations of Modern Physics, Worth, 1969, p. 128.

[11] S. Humpheries, and D. Rees, *"Electron Multipactor Code for High-Power RF Devices," Proceedings of PAC 97, Vancouver, Canada.*

[12] Field Precision Finite Element Software for Magnetic and Electric Field Analysis, http://www.fieldp.com/.

[13] Trabia, M. and X. Lu, "A Fuzzy Adaptive Simplex Search Optimization Algorithm," ASME Journal of Mechanical Design, June 2001, pp. 216-225.

[14] Mekhilef, M., and M. Trabia, "Successive Twinkling Simplex Search Optimization Algorithms," ASME 27th Design Automation Conference, Pittsburgh, Pennsylvania, September 2001.

[15] Ceylan, Z., and M. Trabia, "Optimization of the Closure-Weld Region of Cylindrical Containers for Long-Term Corrosion Resistance," ASME 27th Design Automation Conference, Pittsburgh, Pennsylvania, September 2001.

[16] S. Subramanian, Q. Xue, M. Trabia, Y. Chen, and R. Schill, "Modeling and Optimization of the Chemical Etching Process in Niobium Cavities," International Congress on Advanced Nuclear Power Plants (ICAPP), Hollywood, Florida, June 2002.