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Modeling, Fabrication, and Optimization of Niobium Cavities: Phase III Second Quarterly Report

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Modeling, Fabrication, and Optimization of Niobium Cavities –Phase III
Second Quarterly Report

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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 third phase concludes the experimental a fluid flow study and optimization study. The first quarter and second quarter of phase three also begins the experimental set-up of secondary emission studies from niobium in superconducting mode. This study is to be completed by the end of the third year.

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.

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 impact can lead to the generation of one or more secondary electrons that in turn act as primary electrons. In turn, these electrons may 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). Consequently, RF power is absorbed. It becomes increasingly difficult to increase the RF energy in the cavity as the power supplied to the cavity is increased. 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. In addition, 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.

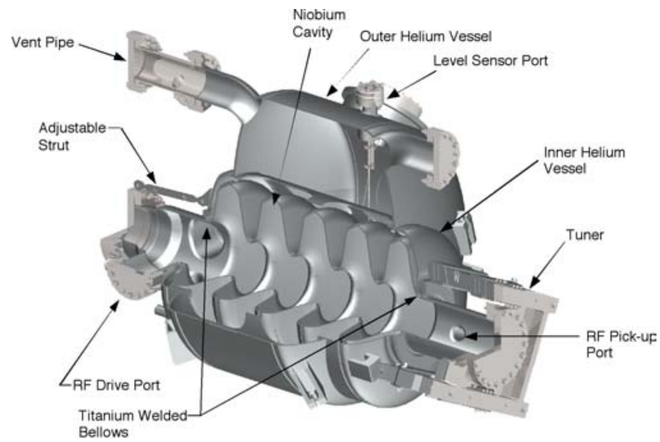

Figure 1. Schematic Diagram of Niobium Cavities (Executive Summary: Development and Performance of Medium-Beta Superconducting Cavities (LANL))

While models have been suggested for minimizing multipacting [2], a 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 III:

1. Multipacting Studies: Multipacting studies have been replaced by secondary electron emission studies. Due to the uncertainty nature of the multipacting code, loss of the undergraduate student spearheading the operation of the code (she graduated), and the inability to reproduce the author's (of the code) studies and other studies over the past couple of years, the focus on the multipacting code has been shifted to a Monte Carlo Back Scattering and Secondary Electron Scattering code developed by Dr. David Joy (ORNL and University of Tennessee Knoxville). The Monte Carlo code (source code provided) has direct relevance to the experiments to be performed. The code uses heuristic models making exclusive use of Monte Carlo method (e.g., determines: step size, type of scattering event, impact parameter, change in energy and momentum, etc.) in tracking electrons through the collision cascade. Given the primary electron energy and incident trajectory onto a bulk medium, information on the number of electrons leaving the surface along with their energy and angle of trajectory are computed, processed, and recorded. The type of scattering event is tracked in the medium. The code as supplied to us characterizes a number of bulk mediums including niobium. Currently, we have modified the source code to take into consideration a contamination layer over the surface of the bulk. Based on a most probable mean free path, the code chooses between an elastic and an inelastic scattering event. The elastic scattering cross section mechanism is modeled after a screened Rutherford potential (screened Coulomb collision cross-section). The inelastic scattering event is based on a Bethe stopping power (Joy's version). The layer and bulk mediums may be described using a single or multiple element species. The total cross-section for the multi-element species (e.g., water) is determined by averaging the atomic number and atomic weight of atoms composing molecule and then use this average to determine the total cross-section and stopping power. Although crude, it should allow for realistic scattering estimates. The code is being benchmarked against others' experiments for accuracy. The important feature of the code is its fast run time (30,000 particle run in a couple of minutes), its ability to handle any incident particle trajectory, and, with the aid of Field Precision's particle tracking code, the experimental observables are numerically computed.

Figure 2 shows the graphic user interface displayed with results. For the run shown, a 10 Angstrom surface layer of water is placed over a bulk medium of niobium. The particle trajectory window pictured in Fig. 1 is a result of an ensemble of 100 1keV electrons impinging with normal incidence to the medium. The red lines correspond to the secondary electrons that are generated and the blue lines correspond to the back-scattered electrons. A histogram plot of the number of particles scattered out of the material medium is also displayed based on particle energy. The red and blue colored lines respectively correspond to the secondary electrons and back-scattered electrons.

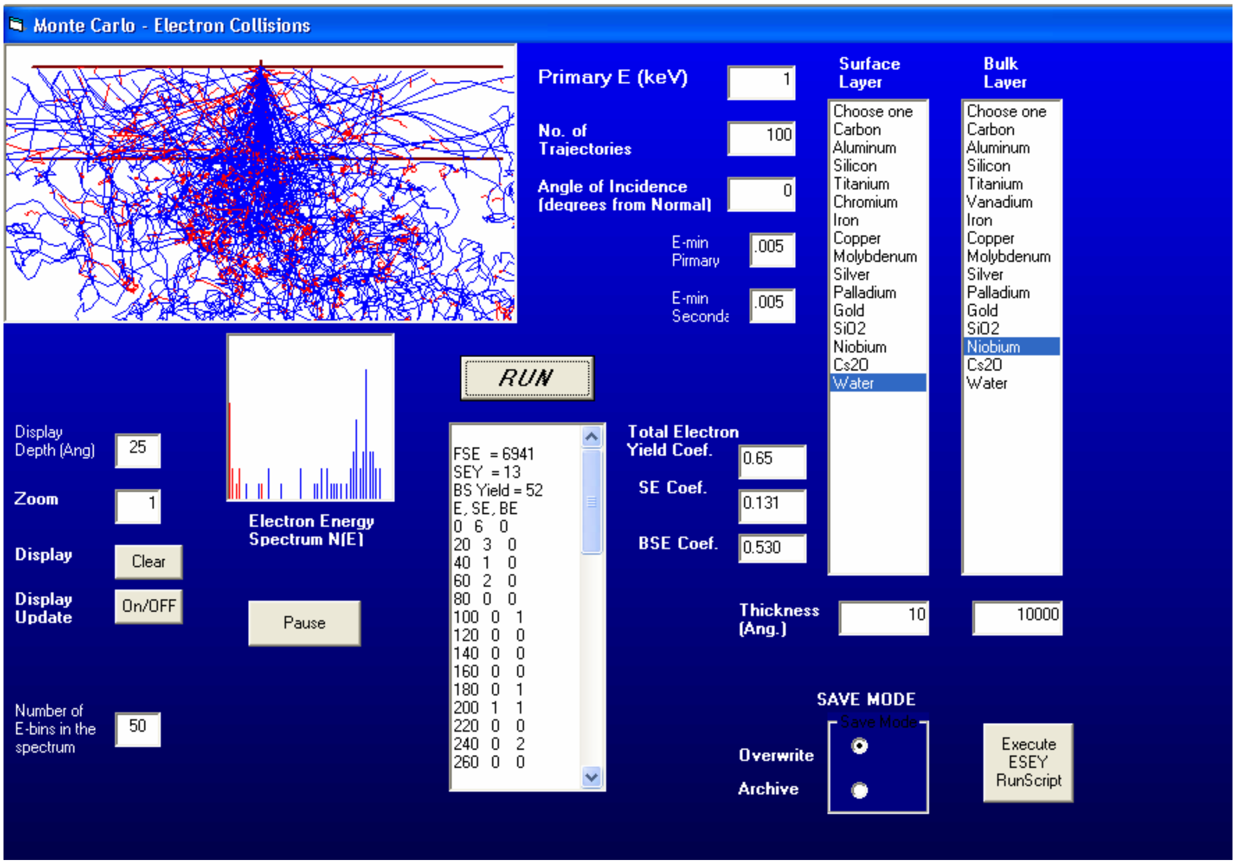

Fig. 2. The graphical users interface for a Monte Carlo Back Scattering and Secondary Electron Scattering code.

2. Experimental Set-up for the SEE from a Niobium Test Piece. Near the end of phase II, an existing vacuum chamber was modified for SEE studies. Through various donations, a cryogenic pump with controller was obtained. An electron gun, heat tape, and a residual gas analyzer (RGA) were received. To save about $55,000 or more, the insides of an old cryogenic pump has been converted to a cryostat. The "cryostat" was tested by the manufacturer and will reach superconducting temperatures for niobium (~8 ^{o}K). Sensor studies were conducted. These activities were reported in past quarterly reports and the final report during phase II. Funding was obtained through phase III of the research to set-up and run secondary electron emission studies of niobium in the superconducting state.

During the first quarter of phase III, sensor studies were completed. With the aid of a grid, field and geometry requirements for a position sensitive MCP/RAE electron sensor, electron gun specifications, sample size and cryostat geometry, optimal locations and potentials were obtained to detect single secondary electrons emitted from a niobium sample with various energies and trajectories. The first quarterly report illustrated optimal geometries based on simulation.

Except for two ports, all remaining ports in the existing vacuum chamber point off the central axis of the cylindrical chamber. This has made mechanical engineering designs of some of the external components very difficult. Further, electrical isolation from the chamber wall becomes an issue. A new, smaller, spherical chamber was purchased with six ports. The overall benefits of the new chamber outweighed using the existing chamber. In the end, money was saved by relaxing the design of other components to be attached to the chamber's ports. Compatibility of multiple vendors' products on the system as a whole was carefully designed with the aid of Transfer Engineering. Figure 3 provides a detailed mechanical drawing of an electron gun, electron sensor, x,y,z manipulator, and cryostat all mounted on the spherical six port cross vacuum chamber. This drawing shows relative positioning of all elements, taking into consideration space tolerances, which are consistent with single particle tracking studies provided in the first quarterly report of phase III. Other components such as the RGA cryogenic pump, sensors, and etc. are not shown in this drawing. Care was taken in the design to mitigate human inaccuracies in alignment by adding a special inverted bellows with longitudinal positioning flange and rotatable axis stage on the cryostat. The bellows with positioning flange allows for some added z positioning. With an appropriately designed sample, the azimuthal motion will allow for a number of different primary electron trajectories to be tested without the need to warm the cryostat, reposition the piece under test with the manipulator, and then cool the cryostat. At the end of this process, an ultra high vacuum is to be obtained (~ 10^{-8} to 10^{-9} Torr). Without the rotatable axis, it may take up to two or more days to obtain a single data point. Repeatability of experiment will always be questioned using this approach. Figure 4 illustrates the special shape of the niobium piece under test allowing up to four discrete angles to be examined. Further, a number of tests on virgin niobium surface can be performed at each discrete angle by slightly changing the angular position of the piece relative to the beam. LANL has already shipped us a chunk of niobium that will be machined at Transfer Engineering. The machined test pieces will then be shipped back to LANL to be conditioned and cleaned. Partially assembled equipment should be arriving near the end of the third quarter.

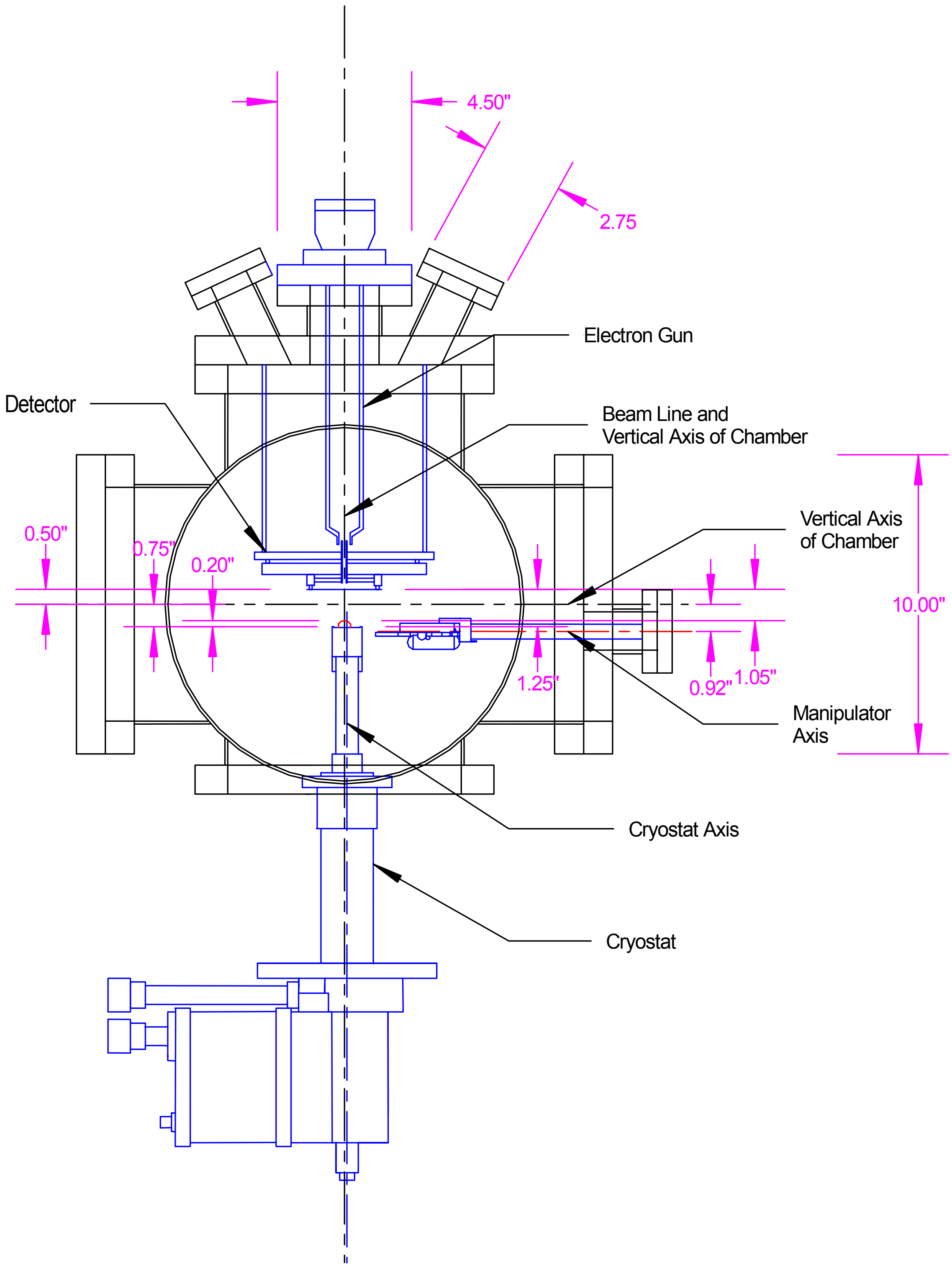

Fig. 3. Side view of a mechanical drawing showing the alignment of a cryostat with sample, a manipulator, an electron gun, and a detector connected on a spherical vacuum chamber.

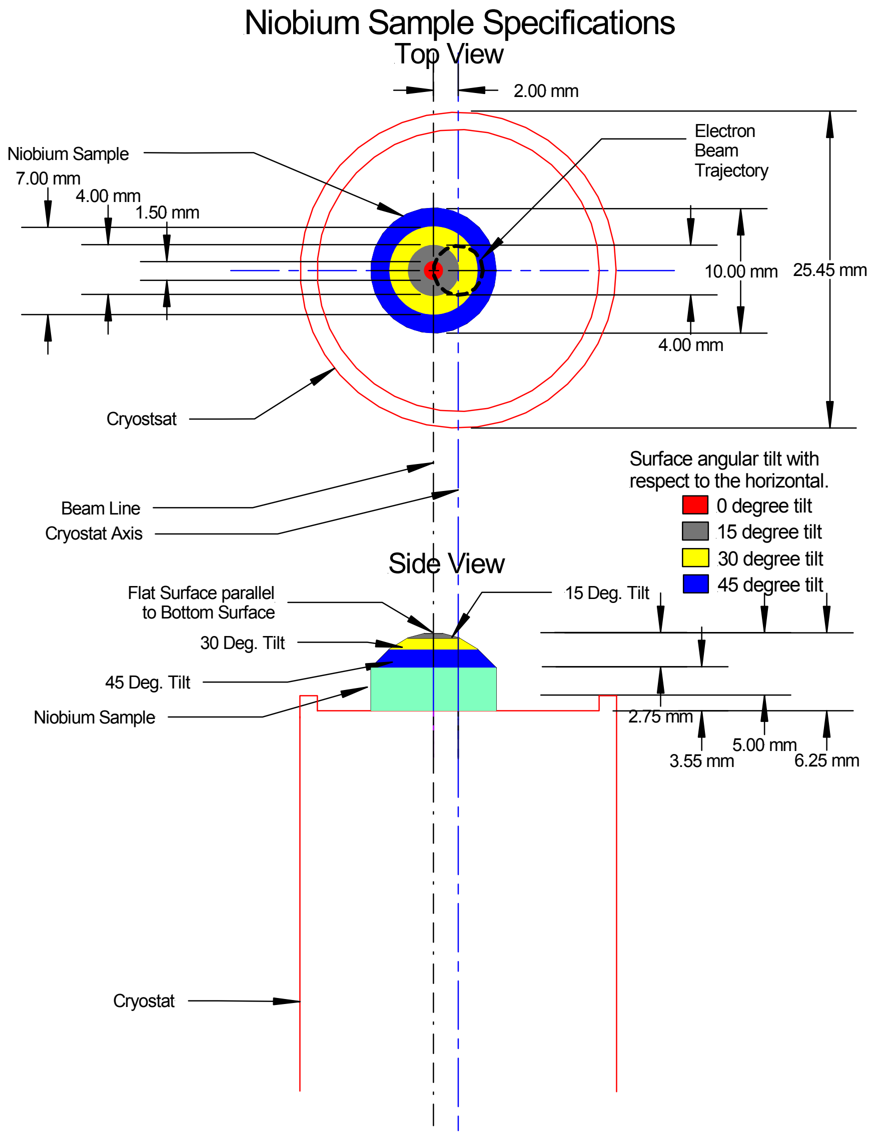

Fig. 4. Specially designed sample on cryostat mounted on rotatable axis stage (not shown). The cryostat axis is off center of the axis of the electron beam. The top view maps out the position of the electron beam (dashed black line) on the sample under test.

3. Experimental Visualization of the Verification of the Etching Process: The effort has been completed leading to a master thesis. All results have been reported in the first quarter report of phase III. The master thesis is to be defended in the third quarter.

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*