SUPERCONDUCTING RESONATOR AND CRYOMODULE PRODUCTION FOR ION LINACS AT MICHIGAN STATE UNIVERSITY

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Abstract

Superconducting quarter-wave resonators, half-wave resonators, and cryomodules are being prototyped and fabricated at Michigan State University (MSU) for two ion linac projects. The 3 MeV per nucleon reaccelerator project (ReA3) is under construction as an upgrade to MSU's nuclear physics research program. ReA3 requires 15 production resonators, housed in three cryostats, with commissioning to begin in 2010. In parallel, MSU is engaged in a future laboratory upgrade, the Facility for Rare Isotope Beams (FRIB). FRIB requires a 200 MeV per nucleon driver linac, which includes 344 resonators (four different betas) housed in 52 cryomodules. FRIB development work is underway, with the prototyping of a FRIB cryomodule planned for early 2011. In addition, the acquisition strategy for FRIB resonators and cryomodules is being finalized, and the technology transfer program is being initiated. The status of the resonator and cryomodule production effort will be presented in this paper, including an overview of the acquisition strategy for FRIB.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is an approved ~550M$ project funded by a cooperative agreement between Michigan State University (MSU) and The US Department of Energy (DOE) for advancement in the study of rare isotopes. The driver linac for the FRIB project is an 200 MeV/u superconducting linac with final beam power reaching 400 kW. There are four types of resonators used; two quarter-wave resonators (80.5 MHz, Beta= 0.041 & 0.085) [1,2] and two half-wave resonators (322 MHZ, Beta= 0.29 and 0.53) [3]. The resonators are house in rectangular, top loaded cryomodule with internally built focusing solenoids. FRIB R&D has started with a focus on prototyping the beta=0.53 resonators in both vertical and horizontal configurations.

In addition, a superconducting reaccelerator (ReA3) is being constructed as an upgrade to the existing experimental program of the National Superconducting Cyclotron Laboratory (NSCL) at MSU. The NSCL facility produces a primary beam that is fragmented, producing a secondary beam of exotic ions. The reaccelerating linac will be used to accelerate the secondary ion beam to a final energy of up to 3 MeV/u. The first two cryomodules have been fabricated and installed. The first is a bunching cryomodule constructed with one accelerating resonator and two focusing solenoids. The second is an accelerating cryomodule housing 6 resonators and three solenoids. A third cryomodule is currently under construction housing 8 resonators and 3 solenoids. All three cryomodules use quarter-wave resonators of two different betas (0.041 and 0.085) and are the same designs used in the FRIB linac.

RESONATOR DESIGN

The driver linac will use superconducting quarter-wave (λ/4) and half-wave (λ/2) resonators to accelerate beams from β~0.025 (0.3 MeV/u) to β~0.53 (≥ 200 MeV/u). Various alternative designs and optimization strategies were considered. A linac based on 80.5 MHz λ/4 resonators and 322 MHz λ/2 resonators was found to be the most attractive solution. To minimize R&D and technical risk, the driver linac has a minimum number of resonator types and uses passive control of microphonics via a mechanical damper in the inner conductor of the λ/4 resonators. Four resonator types can efficiently cover the necessary velocity range. Each resonator type is a two-gap structure characterized in terms of its optimum β (β_{opt}), the fractional particle velocity (*v/c*) for which it provides the maximum acceleration. The resonators are shown schematically in Fig 1.

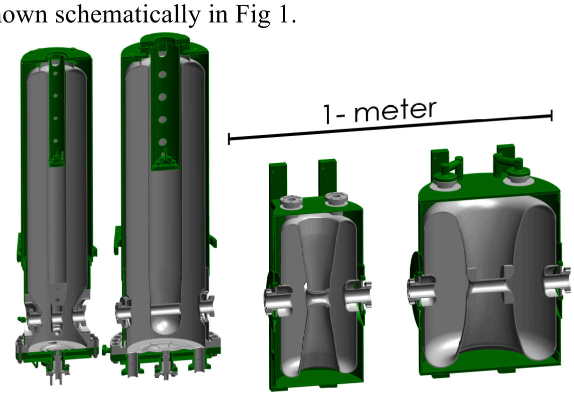

Figure 1: Four resonators used in the FRIB linac, two quarter-wave resonators (beta= 0.041 & 0.085) and two half-resonators (beta= 0.29 & 0.53).

CRYOMODULE DESIGN

The cryomodule design for the FRIB driver linac is based on a top plate loaded assembly design [4]. There is a total of 52 cryomodules in the driver linac made up seven cryomodule types. There are four cryomodules that make up the majority of the linac, each utilizing one of the four types of superconducting resonators and 9 T solenoids for beam focusing (a total of 47 cryomodules). Three additional cryomodule designs will be used for beam matching in the stripping section and second bend (a total of five cryomodules). The ReA3 cryomodules use the same cryomodule design as the FRIB linac. An example of a FRIB cryomodule configuration is shown in Fig. 2.

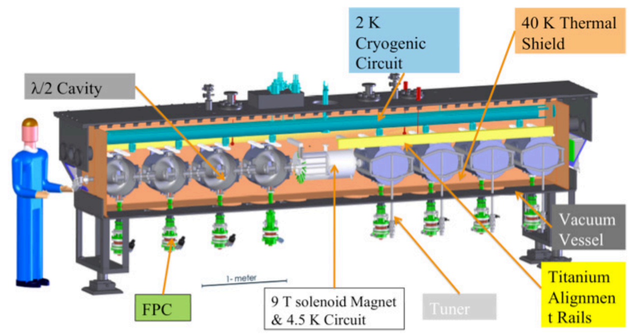

Figure 2: FRIB half-wave resonator cryomodule housing eight 322 MHz, Beta=0.53 resonators and one 9 Tesla solenoid.

The cryomodules have a cold-mass consisting of the accelerating resonators with their rf power couplers and beam focusing solenoids. These are assembled in a cleanroom to a rail structure made from titanium, to match thermal expansion, and the beamline space is hermetically sealed for removal of the cleanroom. Once outside the cleanroom, the resonators and solenoid(s) are aligned to a theoretical beam axis. The cold-mass assembly is then suspended from the cryomodule top plate using 4 Nitronic 60 rods links. The links will later be used to adjust the position of the cold-mass, after cool down, to the beam axis. After the cold-mass is suspended, assembly continues with the installation of tuners, magnetic shields, thermal shields, cryogenic distribution, diagnostics, and alignment fiducials. The top plate assembly is then lowered into a vacuum vessel. The cryomodules that contain quarter-wave resonators operate the resonators and focusing elements at 4.5 K. The half-wave versions operate at 2 K and 4.5 K for resonators and solenoids, respectively.

The ReA3 cryomodules use the same design with the exception of the thermal shield design. The FRIB cryomodules utilize a 38 K helium gas cooled thermal shield. The ReA3 cryomodules are not in a subterranean space and will utilize liquid nitrogen.

FRIB ACQUISITION STRATEGY

Resonators

There are a total of 344 resonators needed for the FRIB driver linac: 16 β_{opt}=0.041 λ/4, 98 β_{opt}=0.085 λ/4, 82 β_{opt}=0.285 λ/2, and 148 β_{opt}=0.53 λ/2. These numbers include both resonators required for acceleration and resonators required for phase matching at the location of the charge-stripper. The ReA3 cryomodules will use the same β_{opt} = 0.041 and 0.085 λ/4 resonators designs.

The 344 resonators required for the FRIB project will be fabricated by commercial vendors. Production rates will require ≥ 12 resonators fabricated per month for 36 months, which includes an initial 6-month start up period. The present experience suggests multiple vendors will be needed to meet production goals. Efforts shall be made to qualify multiple resonator vendors during FRIB R&D, technology transfer, and ReA3 activities. A step-wise approach will be used. Resonators vendors will first produce subassemblies as a pre-qualifying step. Having the resonators delivered as subassemblies provides an opportunity to inspect components against dimensional tolerances and surface imperfections, which is difficult in a fully assembled resonator. After the subassemblies are inspected, the final resonator welds are completed and the resonator is jacketed with the helium vessel. During FRIB production, resonator vendors will fabricate "build to print" jacketed resonators with a specification given for the final resonator frequency. The current production plan also views the initial bulk chemical etch as a fabrication step that is completed by the vendors. The SRF resonators form a "damage layer" of material during fabrication that can degrade resonator performance. To remove this layer and other possible surface contaminates, ~150 µm of material is etched from the internal surfaces of the resonator. The final frequency is a critical specification in the resonator fabrication and needs to be closely documented during stages of fabrication. All fabrication steps will have an influence on the frequency and care must be given to follow and track frequency shifts during fabrication.

Resonator Certification

All fabricated resonators are required to be certified before cold-mass assembly. Certification is granted with a vertical test of a processed resonator that meets the designed FRIB parameters (i.e. Q, gradient, vacuum integrity). Resonator processing will consist of the following steps: degreasing with detergent solution, low pressure ultrapure water rinse, removal of niobium damage layer with 1:1:2 Buffered Chemical Polish, low pressure ultrapure water rinse and high pressure ultrapure water rinse.

Resonators will be received from vendors with the first bulk chemistry completed. Upon receipt from the vendor, the resonators will be inspected using room temperature measurements, such as frequency, field flatness, and dimensional tolerances. Resonators meeting specifications will be fiducialed and precleaned to remove the bulk of the oils, grease, and particulate prior to entry into the cleanroom environment. Once in the cleanroom, the resonator is put through a series of cleaning steps, including degreasing and ultra-sonic cleaning with ultra-pure water and allowed to dry in the cleanroom. The resonators are then assembled with chemistry flanges and moved into the etching cabinet for leak checking. Prior to etching, etch rate measurements are preformed to establish the etch rate at the time of etching. The etch rate is an important parameter because the final resonator frequency is set by the final etch and must be within the tuning range of the resonator's tuner mechanics. The final etch is designed to be a light etch, only removing 30-50 μm. After etching the resonators are rinsed and transported to the high-pressure rinse station. The high-pressure rinse system provides the final cleaning of the resonators before assembly. High-pressure rinse time is based on surface area, but typically is about 2 hours per resonator.

Resonators are dried in the cleanroom for at least 24 hours to allow the majority of the water vapour to leave the internal surfaces. The resonator is then assembled onto a vertical test insert, leak checked, and dressed with rf connections and diagnostics. The certification test is completed by placing the insert into a vertical test Dewar, cooled to operating temperature, and tested. If the resonator meets the design specifications, it is deemed certified and prepared for transportation to the cold-mass assembly. The vertical insert is placed back into the cleanroom and the resonator vacuum in bleed back to atmospheric pressure with a filtered laminar flow of dry nitrogen.

An additional firing step is being investigated as a measure to reduce the hydrogen contained in the resonator's material, mitigating the risk of "Q-disease" during initial cryomodule cool down and operation. This step would be added to the resonator processing prior to the final chemical etch.

Resonator processing for FRIB is scheduled to span about 33 months, with 4 months of start-up and 29 months of production. To support the FRIB cryomodule production rate, the resonators must be processed at a rate of > 3 certified resonators per week.

Cryomodules

FRIB production for the driver linac will require the fabrication of 52 cryomodules over approximately three years. To meet the proposed FRIB schedule, cryomodule production will produce two certified units per month. This will be accomplished with two parallel assembly lines, each assembling one cryomodule per month. The production schedule will require cold-mass assemblies to be supplied at a rate of two per month, accomplished with a single assembly line. Cold-mass assemblies will be supplied under vacuum, system checked, and with individual elements aligned. Cryomodules will be constructed and installed in sequence of increasing energy (beta). Cryomodule final assembly will span 33 months with an initial 18 months for subassembly inventory.

CURRENT ACTIVITES

FRIB funding has started with activities focused on R&D issues and beginning phases of technology transfer. The FRIB R&D and technology transfer program will include an effort focused on the fabrication, Dewar testing, and cryomodule testing for the β=0.53 half-wave resonator. The plan encompasses a total production of 29 resonators and 3 cryomodules. The first cryomodule will be a prototype configuration, using only two resonators and one 9 Tesla solenoid. The prototype will be used to study resonator-to-resonator cross-talk, magnetic shielding requirements, and the cryogenic distribution system (having both 2 and 4.5 K circuits). The prototype will be followed with the production of two first article cryomodules of the FRIB design, housing 8 resonators and one 9 T solenoid. This plan will provide statistical information on resonator performance both in vertical and horizontal configurations. Technology transfer will also be a focus of this work, building a list of certified industrial vendors for resonator fabrication, solenoid fabrication, cryomodule subassembly fabrication (i.e. thermal and magnetic shields), and cryomodule assembly.

The ReA3 project is also ongoing with the commissioning of the first two cryomodules, as shown in Fig. 3, and the fabrication of two additional cryomodules. As with the ongoing FRIB R&D, industrial vendors will be used for most of the procurement of resonator and cryomodule components for the ReA3 project.

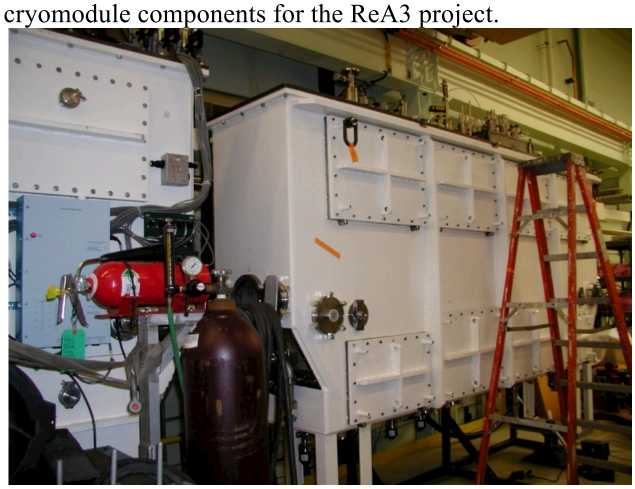

Figure 3: First two cryomodules installed and under testing in the ReA3 linac.

ACKNOWLEDGEMENTS

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