THE FABRICATION AND INITIAL TESTING OF THE SNS RFQ[*]

A. Ratti, R. DiGennaro, R. A. Gough, M. Hoff, R. Keller, K. Kennedy,
R. MacGill, J. W. Staples, S. Virostek, R. Yourd
E. O. Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The Lawrence Berkeley National Laboratory (LBNL) is designing and building the 2.5 MeV front end injector for the Spallation Neutron Source (SNS) [1,2]. This injector comprises an H⁻ ion source, a low energy beam transport line (LEBT), a radio-frequency quadrupole (RFQ) and a beam transport line designed to provide fast chopping of the beam. The RFQ is designed to accelerate the H⁻ beam from the energy of 65 keV to 2.5 MeV, while bunching it at 402.5 MHz. This high duty factor (6%) structure is made of a combination of Glidcop® and OFE copper and is fully brazed. The RFQ is built in 4 modules, each approximately one meter long. This paper covers the mechanical fabrication details of the modules, three of which have been completed. While the modules are coming out of production, they are conditioned and tested to full power. This paper will also describe the results of the beam tests on the first module, including capture efficiency and transmission.

1 INTRODUCTION AND SYSTEM DESCRIPTION

Under the funding of the US DoE, the SNS Project has formed a collaboration of six US National Laboratories, each responsible for part of the complex. The Lawrence Berkeley National Laboratory (LBNL) is responsible for the design and construction of the Front End, an H⁻ injector aimed at delivering 38 mA at 2.5 MeV of beam current. The facility is designed to operate with 1 ms pulses at a 60 Hz repetition rate, for a beam duty factor of 6%.

The Front End consists of an Ion Source, an electrostatic LEBT, an RFQ and a Medium Energy Beam Transport line (MEBT). The RFQ accelerates the beam from 65 keV to 2.5 MeV.

The RFQ is 3.7 meters long, approximately 5 free-space wavelengths at 402.5 MHz [3,4]. No longitudinal stabilization is used, but very strong transverse stabilization is included through the use of pi-mode stabilizers, six pairs in each module [5]. This significantly relaxes the geometric tolerances, and reduces the tuning procedure to providing a flat longitudinal field distribution at the correct frequency. Accordingly, each module has 20 fixed tuners, with a sensitivity of 4.5 MHz/cm.

Each module is a brazement of four quadrants, each quadrant a sandwich of a Glidcop® exoskeleton and OFHC cavity interior. The brazing process alters the geometry of the cavity, and therefore its frequency. Tests with models showed that the frequency is lowered by less than 0.5 MHz, which has been confirmed in the actual modules. This frequency shift was taken into account in the initial geometry, and remaining deviations could be compensated for with the large range provided by the slug tuners [6].

While coarse tuning is accomplished with the use of the fixed tuners, the cavity is kept at resonance during operation by varying the relative temperature of the cooling water on the vanes in relation to that of the cavity walls. RF power is magnetically coupled into the cavity by the use of eight drive loops, two per module.

The detailed design of the RFQ and its components, from the physics design, to the computer modeling and fabrication processes have been described and presented at previous conferences [7,8].

The RFQ comprises four 93-cm-long modules, joined in precise alignment. The first and last modules contain vane cutback regions to properly terminate the cavity and provide a flat longitudinal field profile. As the modules are completed, they are conditioned individually to full RF gradient with temporary cutback cells, added as appropriate, to each module [9].
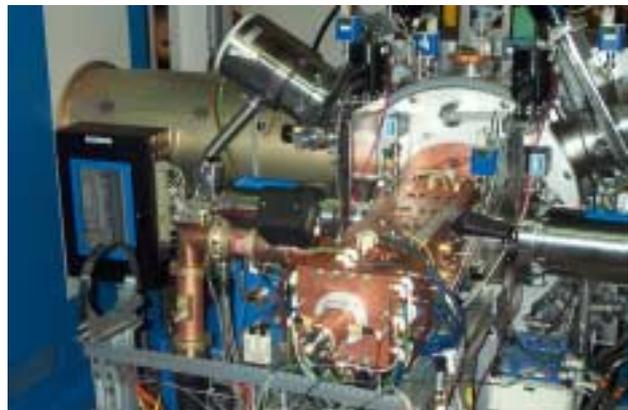

Figure 1 – The first module of the RFQ during beam tests.

2 ELECTRICAL MEASUREMENTS

Prior to final module brazing, as well as after completion, the field flatness and azimuthal symmetry are measured using the bead perturbation technique. The azimuthal field symmetry was consistently uniform to better than 1%, about the limit of the technique, and a longitudinal field flatness of 1% in each module is easy to achieve with all tuners moved in concert. When more modules are added, the sensitivity of the longitudinal field distribution to geometric errors will increase, and a code has been written which will aid in adjusting individual tuners to produce the required 1% longitudinal field flatness. The unloaded electrical Q of the first module, after RF conditioning, is about 75% of the pure-copper Q_0.

Among the electrical measurements, the tuning range and frequency sensitivity were measured. The fixed tuners provide a range of ±3 MHz around their reference point (tuner penetrating into the cavity by 8 mm) and the dual water cooling system can shift the cavity frequency by more than 500 kHz with a temperature change in the normal operating range of the chillers.

3 FABRICATION DETAILS AND PROGRESS

As fabrication of the RFQ has progressed, several design improvements have been incorporated. In the design adopted the cooling passages are created by milling the appropriate grooves into the rear surface of the copper vanes. A 25 mm thick Glidcop AL-15 plate was brazed to the back of the vanes to cover the passages and to increase the structural integrity of the modules. For Module 1, the Glidcop was brazed directly to the vane using two sheets of 2 mil thick 50/50 gold/copper foil. The 15 psi clamping load during brazing was provided by means of a stainless steel vacuum bag.

In order to improve the reliability and reduce the cost of the braze, a somewhat different method was developed for Modules 2, 3 and 4. Since achieving a water tight braze between Glidcop and copper over a large area has proven difficult, a 50 µm (20 mil) thick copper shim has been inserted between the Glidcop outer plate and the copper vane in the modified procedure. The copper-to-copper side of the shim provides a reliable water seal while the copper-to-Glidcop side becomes essentially a structural braze. Two layers of braze foil are used on the cooling passage side of the shim, and one layer is used between the shim and the Glidcop.

A relatively inexpensive method was developed to apply a positive clamping load on the parts during brazing. The vanes are sandwiched between two 40 mm thick graphite slabs. A series of approximately 32 molybdenum threaded rods are used to tie the graphite

plates together. Prior to brazing, there is little pre-load in the tie rods. As the parts are heated, the copper vane expands more than the rods which creates a compressive load on the braze. To prevent the force from becoming excessive and possibly breaking either the graphite or the tie rods, a thick copper washer is placed under each of the stainless steel nuts which hold the rods. The nuts have a conical shape on one side which sinks into the soft copper washers as the parts are heated. This method provides an estimated 20 to 30 psi of pressure on the parts during brazing. Upon cooling, the parts contract and the load on the moly rods is released. Figure 3 shows a vane in the clamping fixture prior to brazing. All 12 vane quadrants required for Modules 2, 3 and 4 have been successfully brazed using this method.

Figure 2 – RFQ clamping arrangement for GlidCop® to copper braze.

After completing the brazes, the vanes are machined to the required final dimensions. In order to meet the cavity frequency requirements, the vane tip machining must be accurate to within ±0.001". This is achieved by first performing a high precision grinding operation on the mating surfaces of the 4 vanes of a given module. These ground surfaces are then used as a reference for the set up of the horizontal mill which machines the vane tip modulations using a form cutter. A series of detailed CMM measurements verifies the accuracy of these machining operations. After brazing the 4 vanes together, the final verification of the dimensions is the frequency check. All three of the modules completed to date have been well within the frequency error band which is determined by the range of the RFQ slug tuners.

When the finish machining of a module is complete, a set of 4 tooling balls are mounted on the top surfaces. A coordinate measuring machine is used to fiducialize the modules with respect to the interior cavity features. Upon joining the 4 modules together, the RFQ becomes a rigid structure which does not allow the modules to be individually aligned. A steel tube support structure, using a 6 strut kinematic mounting system, has been designed and fabricated to hold and allow positioning of the complete RFQ.

4 BEAM TESTS

After RF power conditioning, the first module has also been tested with beam, and the transmission vs. operating gradient compared to simulations. Figure 3 shows the measured transmission vs. measured field level of an initial 30 mA H- beam matched into the RFQ and then into a Faraday cup immediately following the RFQ. These data are compared to the simulated transmission, with energy tails included. The input beam for the simulation was generated from the measured H- emittance at the RFQ match point. The two curves are in excellent agreement.
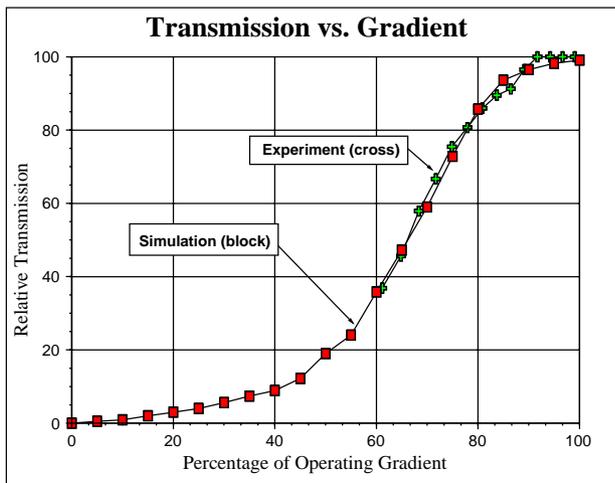

Transmission vs. Gradient

Figure 3 – Comparison of measured and calculated beam transmission as a function of cavity gradient.

The first two RFQ modules have been conditioned to full RF gradient in less than 20 hours each, with reconditioning times on the order of 2 hours even after long periods of being at atmospheric pressure. Each module will have two RF drive loops, although for the initial operation only one was used, establishing that the RF windows can handle twice their nominal peak power level.

The beam is chopped with a 68% duty factor square wave at about a 1 MHz rate to provide a gap in the beam circulating in the storage ring for extraction. The chopping is accomplished in two steps: a slow (<50 nsec rise/fall) step in the LEBT using an electrostatic deflector incorporated in the last einzel lens, and a fast one (<10 nsec rise/fall) in the 2.5 MeV MEBT using a traveling-wave chopper to be provided by LANL.

Beam chopping was also tested during the beam experiments with the first module. The first tests of the LEBT chopper were immediately successful, showing a 25 nsec rise/falltime and an on-off beam current ratio better than 100 (the limit of our monitoring).

5 STATUS AND PLANNING

The production of the RFQ is well underway: the fabrication of three of the four modules has been completed and the fourth module will be finished later this summer. The conditioning of the first two modules to full power and high duty factor (3%) has been completed and work is underway to condition the third module at this time. Once the fourth module is completed, tested and conditioned to full power later this summer, the four RFQ modules will be joined. After RF power conditioning, the first beam tests are to begin in early fall 2001.

A series of beam tests on the completed SNS Front End will occur at LBNL prior to shipping the system to ORNL for installation in 2002.

6 ACKNOWLEDGMENTS

7 REFERENCES

[1] R. Keller, et al., "Progress with the SNS Front End systems, these proceedings.

[2] R. Keller, et al., "Status of the SNS Front-End Systems", Proceedings of the European Particle Accelerator Conference, Vienna, Austria, June 2000, 1657-9.

[3] A. Ratti, et al., "The design of a high current, high duty factor RFQ for the SNS", Proceedings of the European Particle Accelerator Conference, Vienna, Austria, June 2000, 495-7.

[4] A. Ratti, et al., "Conceptual Design of the SNS RFQ", Proceedings of the XIX International Linac Conference, Chicago, IL, August 1998, 276-8.

[5] A. Ueno, et al., "Beam Test of the Pre-Injector and the 3-MeV H- RFQ with a New Field Stabilizer PISL", Proceedings of the XVIII International Linac Conference, Geneva, CH, August 1996.

[6] S. Virostek, et al., "Analysis of the thermally induced frequency shift for the Spallation Neutron Source RFQ", Proceedings of the XX International Linac Conference, Monterrey, CA USA, August 2000, 908-11.

[7] A. Ratti, et al., "Prototype Models for the SNS RFQ", Proceedings of the XIX International Linac Conference, Chicago, IL, August 1998, 600-3.

[8] A. Ratti, et al., "The SNS RFQ Prototype Module", Proceedings of the 1999 Particle Accelerator Conference, New York, NY, April 1999, 884-886.

[9] A. Ratti, et al. "Fabrication and Testing of the First Module of the SNS RFQ", Proceedings of the XX International Linac Conference, Monterrey, CA USA, August 2000, 911-3.

[10] D. Schrage, et. al., "CW RFQ Fabrication and Engineering, Proceedings of the XIX International Linac Conference, Chicago, IL, August 1998, 679-83.