PRELIMINARY CONCEPT FOR THE PROJECT X CW RADIO-FREQUENCY QUADRUPOLE (RFQ)*

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Abstract

Project X is a proposed multi-MW proton facility at Fermi National Accelerator Laboratory [1]. It is the key element for future accelerator complex development intended to support world-leading High Energy Physics (HEP) programs. The Project X front-end would consist of an H- ion source, a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ) accelerator, and a medium-energy beam transport (MEBT). To support current and future HEP experiments at Fermilab, a CW RFQ is required. One of the chosen RFQ designs has a resonant frequency of 325 MHz. A 162.5 MHz option is also being considered but is not presented here. The RFQ provides bunching of the 10 mA H- beam with acceleration from 30 keV to 2.5 MeV and wall power losses of less than 250 kW. Lawrence Berkeley National Laboratory (LBNL) is currently developing the early designs for various components in the Project X front-end [2]. The RFQ design concept and the preliminary thermal analyses are presented here.

INTRODUCTION

The Project X baseline RFQ design is 2.66 m long and will accelerate a 10 mA H- beam to 2.5 MeV, with a 64 kV vane-to-vane voltage (corresponding to a 1.55 Kilpatrick peak field). Most of the RF input power is dissipated on the cavity walls to establish the needed RF field with only about 17% of the total power transferred to the beam. Each of the two 1.33 m long RFQ modules will consist of four solid OFHC copper vanes that are modulated prior to being brazed together. A brazed copper structure has been chosen due to the high power, CW operation. A 304 stainless steel outer shell is to be bolted to the cavity by means of thread inserts in the copper. A series of 32 water-cooled pi-mode rods provides quadrupole mode stabilization, and a set of 48 evenly spaced fixed slug tuners is used for final frequency adjustment and local field perturbation correction.

The Project X RFQ design incorporates technology validated by recent RFQ's developed at LBNL, including for the Spallation Neutron Source (SNS) Front End [3] as well as a recent design completed for the Accelerator Driven Neutron Source (ADNS) [4]. The use of proven and reliable fabrication and assembly methods permits construction using readily available machinery incorporating previously proven techniques. The bolt-on, stainless steel outer stiffening plates provide the necessary structural rigidity as well as a means for reliably applying vacuum and RF sealing forces for the tuners, couplers, sensing loops and vacuum pumping manifolds. The outer shell also provides for a relatively simple method to interconnect the modules.

A preliminary 3-D CAD model of the RFQ conceptual design has been developed and is used here to present a description of the design characteristics. An overall view of a single RFQ module is shown in Fig. 1.

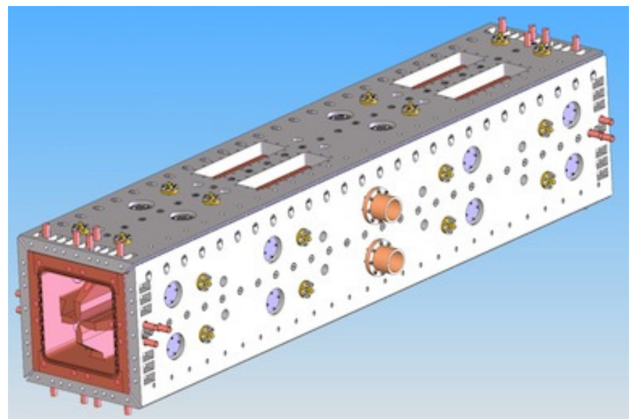

Figure 1: CAD model of a single RFQ module.

RFQ DESIGN DETAILS

Cavity Body

Each of the four vanes in a module are to be machined from a single piece of copper and will include simple cooling channels produced using an established gun boring technique. The RFQ vane tips are to be modulated by means of a fly cutter technique previously developed at LBNL using a commonly available programmable mill. Fiducial surfaces that also act as mating surfaces will be machined directly onto the vanes to provide high precision during both machining and assembly. Two vane geometries will be used (major and minor) with the opposing vanes being identical. Other features such as tuner ports, RF coupling ports, vane cut back cooling passages, cooling taps, vacuum pumping ports, pi-mode rod penetrations, sensing loop ports and tapped holes for the stainless steel backing plates are to be machined prior to finish machining of the cavity surfaces and vane tips. Note that all vacuum seals to the cavity for penetrations are recessed beyond the outer layer of stainless steel and are to be applied directly to the OFHC.

The finished vanes are to be brazed together along axially running joints. A zero-thickness brazing process will be used in order to maintain the tight vane tip-to-vane tip tolerance, which is dictated by the high dependence of cavity frequency on vane tip spacing. Wire braze alloy will be loaded into grooves in the joint surfaces such that the alloy spreads throughout the joint during the braze

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cycle by means of capillary action. This technique permits the RFQ modules to be assembled and the cavity frequency measured prior to the braze cycle to allow for dimensional adjustments, if necessary. A cross sectional view of the RFQ concept showing the cavity, outer shell, Pi-mode rods and RF couplers is provided in Fig. 2.

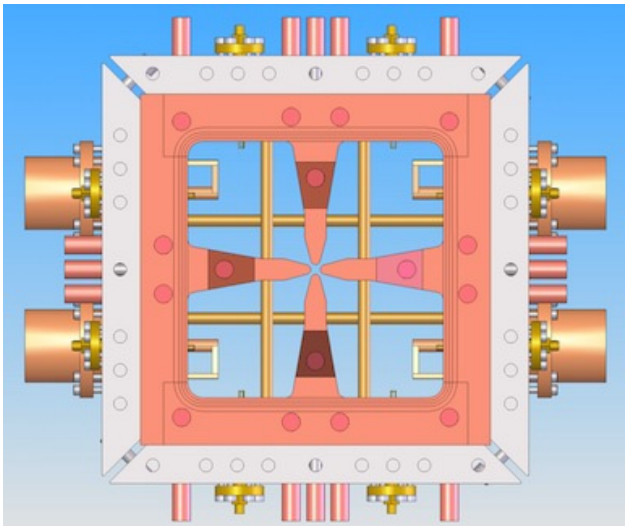

Figure 2: CAD model cross sectional view of the RFQ.

No special alignment fixtures or procedures will be required to connect the two RFQ modules together as the ends are designed to be self-aligning by means of embedded dowel pins. The bolted end connections are sufficiently strong and stiff such that the fully assembled RFQ can be lifted and handled as a single unit. This characteristic also allows the RFQ body to be supported using a simple kinematic (or 6-strut) system that will not impart any direct bending stresses on the assembled RFQ. A CAD image of the full RFQ is shown in Fig. 3.

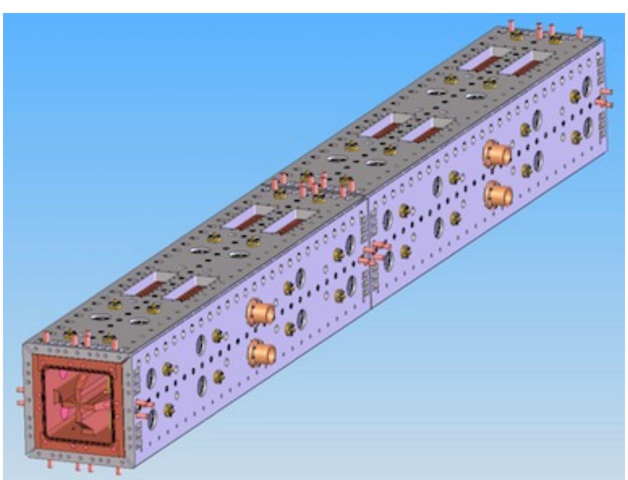

Figure 3: CAD model of the entire RFQ.

Cooling

A set of 12 cooling passages in the RFQ cavity walls are to be fed and controlled separately from the 4 channels embedded in the vanes. During operation, a combination of RF power dissipated in the cavity walls and heat removal through the cooling passages will cause the cavity to distort and shift in frequency. Continuous differential control of the cavity vane and wall water temperatures during operation provides a fine-tuning of the structure frequency during operation. Since the cavity frequency is very dependent on vane tip spacing, separate temperature control of the vane water provides up to four times the frequency range of a single control circuit.

The passages are to be gun drilled through the vanes with plug welds at the end penetrations. Each of the 12 mm diameter passages will carry approximately 8 gallons per minute of cooling water. At the beginning of the first module and at the end of the second module, there will be vane cutbacks for proper termination of the RF cavity. Dedicated cooling passages will be incorporated in order to accommodate the high local heat loads at the ends.

RF and Vacuum Seals

The module-to-module RF connection will be accomplished by means of a 3 mm wide, 250 µm high raised surface machined into the module ends around the periphery of the cavity. This sealing surface is to be backed up by a canted coil spring, which will absorb any RF that leaks past the primary seal. Outside of the canted spring is an O-ring, which provides the vacuum seal. The modules are to be connected together using a ‘flangeless’ joint design in which connecting bolts and barrel nuts are recessed into the outer layer of stainless steel. This technique was used successfully on the SNS RFQ, which used Glidcop for the outer structural layer.

The numerous penetrations into the RFQ cavities also require both RF and vacuum sealing. The vacuum, tuner, RF feed and sensing pick-up ports will have sealing surfaces that are recessed through the outer stainless steel in order to seal directly against the copper. The vacuum ports will consist of slotted holes penetrating the copper cavity walls. The slots will be designed to maximize gas conductance while preventing RF leakage into the pumps. O-rings will provide the vacuum sealing for these ports.

Cavity Tuning

Cavity tuning will be achieved with fixed slug tuners distributed along the length of the modules, similar to those used on the SNS RFQ. The preliminary design uses 24 tuners per RFQ module (1 per quadrant at 6 evenly distributed locations). The tuners are to be machined from solid slugs of copper.

Based on field measurements of the assembled RFQ (using a bead pull technique), each set of four tuners at a given axial location will be custom machined to predetermined lengths. Primary RF sealing will be accomplished by a step in the tuner OD that interfaces with the RFQ wall. Behind the step, an RF coil spring on the tuner OD will protect the O-ring, also located on the tuner OD. Load plates using setscrews will be held in place by a snap rings recessed in the stainless steel shell and will provide the necessary sealing load on the tuners.

Pi-mode Rods

A series of Pi-mode stabilizer rods (8 pairs per module) will be incorporated to provide RF mode stabilization (to minimize the dipole mode and maximize the quadrupole mode). The rods will pass through the vanes and provide a direct connection between opposing cavity walls. The rods will be brazed into the cavity walls at the same time that the four vanes are brazed together. The rods will be 6 mm diameter hollow copper tubes with active water-cooling. An exploded CAD image of a single RFQ module is provided in Fig. 4.

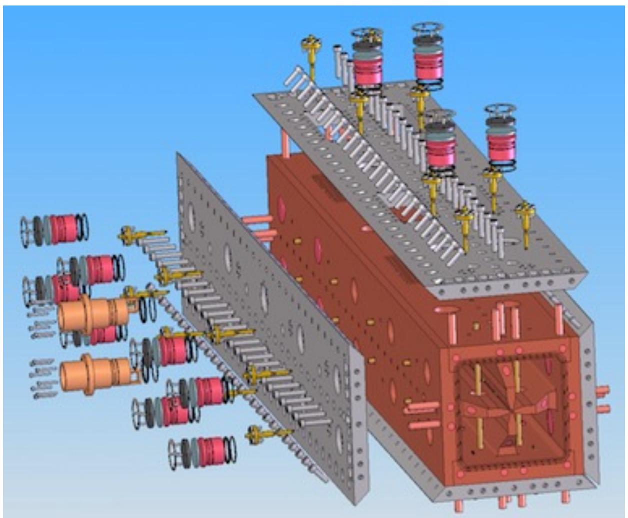

Figure 4: Exploded CAD model view of an RFQ module.

THERMAL ANALYSIS

A preliminary finite-element model of the RFQ has been developed using ANSYS®[5] to calculate the temperature distribution in the cavity vanes and walls for given RF heat loads and cooling water temperatures. The model consists of a one quadrant, 1 mm thick 3-D slice of the RFQ cross section. The surface nodes on either side of the slice are constrained to remain coplanar such that the longitudinal stresses will be accurately calculated while allowing for overall thermal growth in the z-direction. Using 2-D plane strain elements would over-constrain the model longitudinally and result in artificially high z-component compressive stresses. The thermal loads and constraints applied to the model include cavity wall heat flux from the RF, convective heat transfer on the cooling passage surfaces and symmetry boundary conditions.

With 18°C water in both the vane channels and the cavity walls, the resulting temperature profile ranges between 22 and 41°C at full RF gradient with an average linear power density of 516 W/cm (see Fig. 5). The maximum average power density on the outer wall is approximately 5 W/cm^2. Additional modeling to be carried out will include stress and displacement analyses, thermal analyses of the tuners and vane cutbacks, and prediction of the frequency shift of the RFQ cavity due to thermal loading.

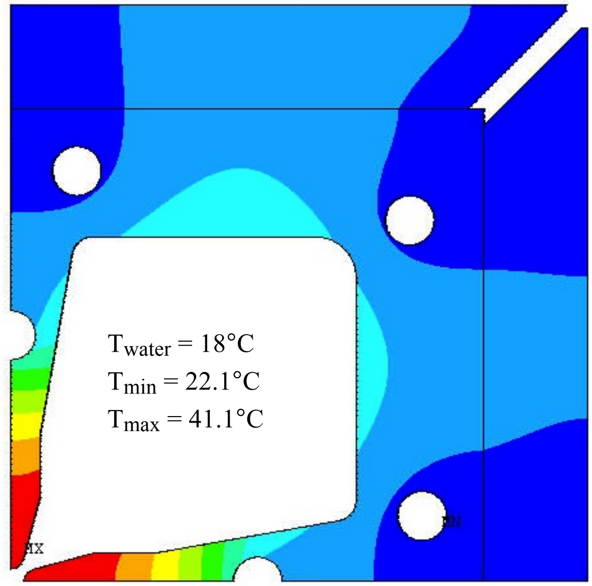

Figure 5: Temperature distribution in one RFQ quadrant.

The RFQ cooling scheme will use different water temperatures in the vane and wall passages. This differential cooling method will provide for tuning of the RFQ during operation by holding the wall water temperature constant and adjusting the vane water temperature up and down. The frequency of the 325 MHz RFQ can be shifted by an estimated -25 to -30 kHz for every 1°C rise in the vane cooling water temperature. For equal changes in the vane and wall water temperatures, the shift would only be approximately -6 kHz/°C. This sensitivity to vane water temperature will be used to fine-tune the RFQ frequency during operation.

SUMMARY

LBNL is currently developing the early design for the Project X front-end RFQ. The initial design concept and the preliminary thermal analysis were presented in this paper. The RFQ design will incorporate technology validated by recent RFQ's developed by LBNL. Future work will include refinement of the RFQ physics design, stress and displacement analyses, thermal analyses of the tuners and vane cutbacks, and calculation of the frequency shift of the RFQ cavity due to thermal loading.

REFERENCES

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