Summary of the April 12, 2012, PXIE RFQ Review at LBL

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Findings

The LBNL staff demonstrated that they have invested considerable effort into the beam dynamics, electromagnetic, and mechanical design of the RFQ to meet the requirements provided by Fermilab.

The RFQ design for Fermilab is very similar to that of the RFQ that the same LBL group is designing for IMP (Lanzhou, China).

A comparison parameter list of the two RFQs follows:

RFQ Parameter List

	PXIE	IMP	
Input energy	30	35	keV
Output energy	2.1	2.1	MeV
Frequency	162.5	162.5	MHz
DC Current	5-15	5-20	mA
Vane-vane voltage	60	65	kV
Vane Length	444.6	416.2	cm
RF Power	100	110	kW
Beam Power	10.5	21	kW
Duty Factor	100	100	percent
Transverse emittance	<0.15		mm-mrad, rms, norm.
Longitudinal emittance	<1.0		keV-nsec

Notable design features of the RFQ include:

- Four-vane style design with pi-mode stabilizers
- Four longitudinal segments, each ~1.1m long
- A large number of fixed slug tuners
- Brazed, all-copper (100% OFE copper) construction of each segment
- Bolted steel plates for longitudinal joining of segments
- Two RF drive loops to supply combined total power of ~ <100kW

RF simulations of the RFQ structure to validate the design have been comprehensive. The exact mechanical dimensions of the RFQ resonator are defined and based on CST MWS simulations. These have included the tuners, pi-mode stabilizing rods, and RFQ ends. There is significant tuning range provided by tuners to account for possible error in the frequency simulation using CST MWS. There are plans yet for a full 3-D simulation including the vane modulations.

The beam dynamics designs of both RFQs (IMP and Fermilab) are complete. The RFQ beam dynamics design meets the functional specifications, but it does not incorporate any requirements to limit beam halo. The RFQ beam dynamics design uses only beam rms parameters. The RFQ accelerated beam density distribution in the longitudinal phase space shows substantial halo formation as is seen in V. Lebedev's presentation at the Collaboration Meeting (p.16). The particle distribution deviates from the Gaussian distribution significantly below 10^{-2} level. The beam dynamics simulations were performed using PARMTEQ code, which is a standard tool for RFQ design simulations. All beam dynamics simulations were performed with 10^5 particles. However, simulations with more particles may be needed. The beam matching between the LEBT and RFQ was not presented.

A significant number of error and sensitivity simulations/analyses have been performed.

Multipactoring simulations have been done for much of the RFQ structure and no problem is evident for the areas simulated. Simulations of some areas that might be susceptible to multipactoring were not presented, e.g. where the pi-mode stabilizer rods pass through a hole in the vane. The review presentations indicated awareness that multipactoring effects in the input power couplers and tuners must yet be considered.

The mechanical interfaces at both the upstream and downstream ends of the RFQ are yet to be specified and agreed to by Fermilab and LBNL.

Mechanical design of the RFQ is at an advanced preliminary design stage. A complete 3-D CAD mechanical model is nearly complete and fabrication drawings can be started in the near future.

The LBNL design team is familiar with "Lessons Learned" from problems with other RFQs and indicates that those lessons have been considered in the design of the Fermilab RFQ to avoid similar issues.

The RF power input coupler design is still an open issue.

Three presentations were made on the mechanical design and modeling of the RFQ. The following points were mentioned in the presentations and during Q&A: Inserts will be used for threads of copper body; O-rings will be baked and without grease; cutting fluids will be specified to be compatible with UHV cleaning; pi-rods will be under low stress compression with sufficient cooling so that buckling is not a concern; a convective heat transfer coefficient of 18,000 watt/m^2K was used in their thermal analysis; a stainless steel collar will be used to join the modules together and a raised lip is designed to ensure the electrical connection between them; second brazing was also mentioned as method of braze repair, in case of vacuum leakage.

LBNL team will perform the following engineering analyses soon: vacuum system analysis; tuner RF/heating analysis; and stress analysis with final support points configured.

LBNL has designed about eight RFQs and has actually built five, including the RFQs in regular operation for the mainstream SNS and BNL programs. However, they have no prior experience with RFQs required to operate at 100% duty cycle.

The design includes 80 fixed slug tuners, 32 pi-mode stabilizer rods, and 48 field sensing loops as well as four (up to eight) vacuum pumping ports.

Water-to-vacuum braze joints are avoided in the design. It is a good decision to use the gun drilled channels for water cooling, plugging them by e-beam welding, and then having just one step brazing for the whole structure.

Separate cooling circuits for the vane tips and for the main body are envisioned for fine operational frequency tuning control.

Fabrication tests for brazing, vane profile fly-cutting, and a full length vane are planned.

A presentation was made describing advanced thermal and stress modeling of the RFQ.

Issues – water manifold, outside water connections for pi-mode cooling, RF probe rotation marking, water pressure (minimum required and maximum allowable) and flow specification, nominal water temperature specification, nothing was presented on end-wall heating. It is not clear who is responsible for providing vacuum pumps and water pump/chiller system(s).

Comments

The beam dynamics design was performed with the main focus to control the rms emittance and to provide high acceleration efficiency (>99.8%). This approach is not sufficient for an injector to a high energy, high-power accelerator. In the past, there have been RFQ designs with a reduced level of beam halo to which a single Gaussian distribution in the longitudinal phase plane can be fitted. Forming a low-halo longitudinal emittance requires removing the most remote particles inside the RFQ by appropriate choice of design parameters. This design procedure can result in lower acceleration efficiency, but helps to form a halo-free longitudinal distribution. This approach has not been applied for the design of the PXIE RFQ.

Once the realistic 3D model of the RFQ is available in the CST MWS or EMS, it is useful to do the following:

a) Compare the accelerating fields along the RFQ obtained from the 2-term (or 8-term) potential distribution of the PARMTEQ code and 3D fields from CST MWS and EMS
b) Compare the bunch center phase obtained in full 3D TRACK simulations with respect to the design reference phase along the RFQ. Deviation of the bunch center phase from the design phase is an indicator of beam halo forming in the longitudinal phase space. Such a deviation can take place if the RFQ vane modulations have been designed with some degree of simplification of the 3D fields.

The RFQ requires a strongly convergent beam to be created by the LEBT. Such a beam can be formed by making a large beam size in the solenoid which is usually accompanied with emittance growth. A study of the beam dynamics in the LEBT should be included in the RFQ design.

It is not clear who is responsible to provide the vacuum pumps and water pump/chiller system(s). These will likely be desirable for various testing purposes soon after the RFQ is assembled.

Plans and location for final assembly, tuning, and pre-power testing were not presented. These efforts will require space and equipment that should be identified well in advance of the need. Handling of the RFQ, transportation plans, and assembly plans, should be thought out soon so that any special considerations are incorporated into the final design and analyses.

It is necessary to demonstrate the integrity of module joint under operational conditions. The joint must supply sufficient compression in order to provide an excellent electrical contact; on the other hand, the raised lip must not be overstressed either by preload of connection bolts or by dynamic loads during handling.

The potential virtue leak of brazing joints (trapped volume, volume with very limit vent, or volume created during brazing) may require a revisit of the design, especially important when immersive cleaning will follow the final machining of the ends, because the cleaning solution in those voids will be hardly rinsed out and leaves traces for potential corrosion late.

The necessary passage for leak check shall also be considered in all places where vacuum seals exist, such as brazing seals, O-ring seals.

Second brazing as braze repair need be detailed soon, since it may affect the design of brazing joint geometry.

The convective thermal coefficient of 18,000 watt/m2K is a bit aggressive. Thermal analysis of the worst case scenario may also be advisable. Water system specifications such as minimum flow rate requirement, and maximum allowable pressure and flow rate, must also be established to ensure RFQ's desired performance.

Using vertical brazing for the ~1.2 m tall sections needs careful planning and tests prior to final execution.

Designs of the RF and vacuum seals around the slug tuners need to be checked carefully. RF heating of the slug tuners with deeper penetrations should be checked. Simulation of the nominal 20 mm penetration case was presented but deeper penetration cases (for 30 mm - 40 cm) may need to be checked for confirmation.

Recommendations

Fermilab should include tested external water circuit manifolds among the deliverables.

Fermilab should specify the types of water circuit connections to be used external to the RFQ.

Fermilab should specify the upstream and downstream mechanical/vacuum interfaces to the RFQ as soon as possible.

Regardless of who in the end provides the water pump/chiller system(s), LBNL should specify to Fermilab as soon as possible the design operating water temperature, required water flows, required minimum differential pressures, maximum allowable working pressure, and maximum allowable test pressure.

LBNL should soon begin producing quality control plans and risk identification and recovery plans for 'high risk' manufacturing and assembly operations, e.g. how to minimize risk due to failed brazing operation, how to avoid damaging large copper fabrications during handling, how to ship heavy precision fabrications to and from vendors and ultimately from LBNL to Fermilab.

Using two coaxial couplers is a good plan. The locations of the couplers need to be farther away from the ion source side on the RFQ structure to reduce contamination of the windows during operation.

Pump-out grooves may be needed around the Viton vacuum seals for more dependable vacuum system during operation.

In this design review, LBNL staff provided well prepared and sufficient information on their design of the 162.5 MHz RFQ structure. Designs for the beam dynamics, RF, and mechanical construction were shown convincingly. It is recommended to have one or two more design reviews to complete QA plans for parts and subassemblies, manufacturing schedule, and drawings. The next design review(s) would also include any updates in the simulations and any design changes.

Answers to the charge questions:

Does the design meet the functional requirements?

Despite a specific question from one review committee member as to what are the specific functional requirements for the Fermilab RFQ, no concise description of these requirements was presented to the review committee beyond the accelerator physics parameter list. The LBNL design does appear to meet the RFQ general functional requirements as they are understood by the review committee. No requirements specific to halo characteristics of the output beam appear to exist. The requirements of the particle distribution in the longitudinal phase space are not well defined also.

Is the current RF design adequately verified and cross-checked?

The RF design of the RFQ has been performed using a variety of standard codes for this purpose. Where cross-checks between ANSYS and MicroWave Studio were presented, the results appeared to be in close agreement. Cross checking of the RFQ beam dynamics design is not yet complete.

What engineering calculations have been performed and how have they been reviewed and approved?

Considerable mechanical and thermal modeling of the RFQ has been performed. How these calculations are reviewed and approved was not presented. The design team has much experience with RFQs, although they do not have specific experience with RFQs that operate at 100% duty cycle. More engineering analysis was proposed and the team will perform them soon.

Has manufacturing and assembly error analysis been performed? Is it adequately reflected in the RFQ design choices?

Yes, manufacturing and assembly error analyses have been performed, although the final mechanical machining and assembly tolerances are yet to be specified. The RFQ design choices appear to offer adequate insensitivity to errors of reasonable anticipated magnitude. This design is primarily based on the experience gained with the SNS RFQ. The proposed PXIE RFQ's transverse dimensions are larger by factor of 2.5. The fact that PXIE RFQ parts are much heavier than the SNS RFQ parts was discussed. Elaboration of manufacturing and assembly error analysis for large structures were not presented. There is an issue of precise fabrication of large parts with adequate accuracy. Of particular concern is a possible displacement of vane positions during the assembly of modules and a kink of the modules. These types of errors can affect beam quality.

What is the plan for Quality Assurance/Quality Control?

A specific QA/QC plan was not presented although each talk included allusions to care that needs to/would be taken to assure delivery of a quality product. It was stated that there is the intent to create a written plan. The inspection plans of parts and subassemblies prior to assembling will need to be prepared and presented at the final design review.

Given the history of previous RFQ issues, how has this RFQ design taken those issues into account and guarded against repeating problems that have been encountered?

At this stage, the LBNL team seems fully aware of problems encountered with other RFQs and has addressed them in their design wherever possible. They have avoided 'two-layer' walls that are candidates for problems experienced in the SNS RFQ and they have avoided direct water-to-vacuum braze joints and connections. Having gun drilled cooling channels is challenging but will deliver better performing RF structures when it is complete. Scrupulous attention to every phase of manufacturing, assembly, and testing will nevertheless be required to avoid repeating problems experienced with other RFQs. We would question using PISLs in the CW RFQ for the following reasons:

- PISLs have not been used in any CW RFQs before.
- The PISL was invented at KEK for the J-PARC project. As is well known, the J-PARC RFQ has shown significant issues with discharges and breakdowns. Therefore J-PARC has built a new RFQ without PISLs.
- Historically, PISLs were proposed to reduce the sensitivity of accelerating fields to manufacturing errors. 20-30 years ago manufacturing errors were a real issue. Nowadays, the accuracy of machining is excellent and the resonator structures can be built per design specifications. For example, this was recently demonstrated by the J-PARC team in the design and construction of a new 324 MHz RFQ: frequencies of dipole and higher modes were exactly as predicted. Therefore there was no need to tune dipole mode frequencies using the end plate tuners (fingers).
- Using PISLs in the PXIE RFQ complicates the design, increases the cost and may impact on the operational reliability.

Are the plans for and results of prototyping/fabrication test sufficient? Do they address key technical issues?

Yes, there are plans for brazing, vane profile fly-cutting, and prototype full-length vane fabrication tests. However, plans for tests and inspections of the assembled RFQ structure will need to be prepared and presented at the final design review. The main issue in fabrication is the brazing of the large heavy copper modules. Therefore, it may be reasonable to build the first segment as a prototype. If it is successful, it can be used as first module in the final RFQ resonator. If some issues remain and must be corrected, a new revised version of the first segment can be built. Of particular concern is finding a vendor for the brazing of a module longer than 40". The most experienced and popular vendor in construction of RF resonators, California Brazing, can accommodate only 40"-long structures for vertical brazing.

Are we ready to release procurements for long lead items (such as the copper)?
We do not see any long-term procurement items. We heard that the lead time for copper from one supplier is not extremely long, just five weeks. Therefore our recommendation is to start procurement after the review of the final design.

Is the design effort on track to initiate the RFQ fabrication in Oct 2012?
Yes, it would appear to be so, provided effort continues at the present pace. However, some additional RF and thermal simulations and designs for the vacuum and cooling, and supporting structure will have to be completed by then. Additionally, complete package of drawings and a production schedule will have to be ready by that time. We did not hear specific schedule plans and/or impediments from the LBNL team. The design team should consider comments and recommendations of this Committee and perhaps an additional Review is required to approve the final design and start fabrication.