U.S. Muon Accelerator Program
Internal Review Report

Revision Date: May 11, 2015

Introduction

A review was held April 30-May 1, 2015 at Lawrence Berkeley National Laboratory (LBNL) to evaluate:

1. The readiness of the Muon Ionization Cooling Experiment (MICE) RF Module engineering design for fabrication;
2. The robustness of the vacuum system design and, in particular, to consider:
   a. The ability to maintain a sufficiently low pressure in the RF cavity to ensure reasonable operation;
   b. The ability of the vacuum system design to prevent damage to the Be windows on the cavity due to excessive differential pressure across the window;

In addition, to the above primary evaluation items, the review panel was also requested to comment on:

1. The preliminary plans for RF Module assembly at LBNL, deployment to Rutherford Appleton Laboratory (RAL) and operational testing at RAL;
2. The RF system interface specifications for MICE.

A copy of the full review charge is appended at the end of this document.

MICE RF Module Engineering Design Readiness

Findings

The RF Module Engineering drawings were provided to the committee and reviewed. In general, the design of the module and all of the individual components required is in a very advanced state. This benefits from the prototyping work that was carried out with the Single Cavity Test System (SCTS) as it was assembled and operated at the MuCool Test Area (MTA) at Fermilab. The operational experience that was obtained with the SCTS serves as critical guidance for finalizing key elements of the RF Module engineering design.

Comments

With a plan under development to commission the RF Modules at RAL, before they are placed in the cooling channel, it must be verified that all necessary ports for offline pumping and operation of a standalone vacuum system are present in the design. Also, a port with sufficient bore to serve as a backup pumping location should be included. These items should be documented before the drawings are released for fabrication.

The RF module vacuum vessel design is very nearly ready to proceed to procurement. Only the above vacuum port issues and a short set of mounting stand interface issues need clarification before the procurement process can move forward.

Preliminary specifications for the surface quality of the vacuum vessel were presented, which were based on ultra-high vacuum (UHV) preparation standards. In general, these UHV procedures for processing and assembly should be adhered to in order to keep the rough vacuum as good as possible.

With the re-baselining of MICE for the demonstration of ionization cooling, higher accelerating gradients required in the cavities has led to the plan to utilize SF_6 gas in the RF waveguides. The suitability of the RF windows in the coupler assemblies should be documented and the impact of a broken window described.

An updated coupler design was presented that included modifications for blocking the hole that coupled the inner and outer vacuum volumes as well as to improve support and adjustment ability for the coupler. A modification of the coupler loop was also presented which would lessen the rotation sensitivity when adjusting the coupler.

An updated tuner actuator design was presented. Initial characterization tests were described. The design appears to be more robust than the original prototype design against vacuum leaks. It also addresses mating issues that were identified in the original prototype design.

Recommendations

The committee provided the following recommendations with respect to the RF Module engineering design:

1. The present design includes a group of ports located at the top of the module. These ports should be replaced by a single large-diameter port (6-8 inches in bore) with sufficient length to facilitate instrumentation installation. This port can serve as an extra pumping port in the event of poorer than anticipated vacuum system performance.
2. A viewport should be included on each vacuum vessel cover plate to allow direct visual inspection of the Be windows. This will allow their integrity to be verified during preparation and after shipping. The committee noted that low power RF testing would also provide a clear indicator of the state of the windows.
3. The connection between the vacuum vessel and the stand should be modified to allow increased access to the vacuum flange bolt holes. This will be particularly important in the constrained environment during installation into the cooling channel.
4. A specification for the interface between the RF Module stand and the rolling platform (to be provided at RAL) must be provided as part of the engineering drawing package. This should include a specification of the adjustment mechanism and range.
5. A structural analysis should be provided for the module under:
    a. Vacuum load,
    b. Lifting load,
    c. Quench load.
6. Center of gravity and lift points should be called out in the drawing package.
7. Support of the coupler arms must occur in multiple configurations: standalone testing, shipping and when the module is placed in the cooling channel surrounded by the partial return yoke. The support configuration in each of these scenarios should be included in the drawing package along with the procedures for reconfiguration between them.
8. The present design of the coupler loop should be maintained since this represents a modification to an element that has already been validated in magnetic field. While the change is likely to be beneficial and would not be expected to cause any new operational problems, there is insufficient time in the schedule to test this change to the RF design. Thus the potential gains do not outweigh the potential risks.
9. Prior to procurement, the final module design should be integrated with the overall MICE cooling channel model to confirm that all mechanical interfaces are satisfied.

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MICE Vacuum System Design

Findings

A plan for partially segregated vacuum volumes consisting of the MICE cooling channel rough vacuum and a higher quality internal vacuum for the RF cavity was described. The particular challenge associated with this segregation is the danger posed to the Beryllium windows on the cavity irises if:

1. A differential pressure at the ~1 PSI level were to develop between the two volumes during any part of the pump-down or venting process;
2. A catastrophic failure to one of the vacuum systems resulting in a rapid inrush of air, which could:
    a. Create a differential pressure sufficient for window damage or failure;
    b. Create an air-hammer effect resulting in window damage or failure;
    c. Create sufficient turbulence in the vacuum volume to damage the window.

Possibilities for utilizing either burst disks or pop-off valves within the vacuum system to protect the Be windows were presented.

Comments

Based on the analyses presented at the review, there was a general consensus that the vacuum system design will not be capable of absolutely ensuring the survivability of the thin Be windows on the RF cavities in the event of certain catastrophic failure scenarios. The Be windows are most at risk in the viscous flow regime. No commercially available products appear to be available that would both provide relief at the small differential pressures required and also provide a sufficiently large choked flow to protect the windows (Note: if a device/configuration were to be identified, which potentially offers sufficient choked flow rate, that device should be thoroughly tested in the configuration required in the cooling channel vacuum system). Thus the focus should turn to whether the windows can be protected against the most likely failure scenarios. Thus, models should be developed for a realistic worst case venting that accounts for impulse/momentum effects and pressure differential on the windows. Sudden valve openings and shearing of small diameter (< 1-1/2) fittings would seem reasonable conditions to look at.

When the above analyses and predicted safety limits are in hand, the MICE team should move as quickly as possible to begin discussions on the safety issues and limitations with the RAL Health & Safety group to ensure that the necessary procedures and documentation are in place to allow operation of the MICE cooling demonstration in the MICE Hall.

Vacuum calculations assuming hydrogen were presented. The vacuum calculations should be done assuming nitrogen (water?) properties instead of hydrogen. The gas composition will be >50% water initially in both cavity and shell. Over time gas composition is expected to be roughly 40% water, 40% hydrogen, and 20% nitrogen/carbon monoxide. The calculations should assume a specific outgassing rate of 1×10^{-9}torr-liter/s-cm^2 or higher.

Recommendations

The committee provided the following recommendations:

1. A schematic, with all required ports and instrumentation locations labeled, should be prepared (and attached to the engineering design) to show the operational configuration of the RF module in its:
    a. Configuration as part of the MICE cooling channel:
        i. This should specify all interface points with the MICE vacuum system;
        ii. This should note where instrumentation and pumps will be operating in magnetic field.
    b. Offline testing configuration.
2. Based on the analyses presented at the review, a formal specification for the maximum allowable differential pressure across the Be windows should be developed and presented to the committee for review as soon as possible.
3. A full procedures and specifications document should be provided that describes the operational procedures for the system including:
    a. Initial pumpdown, including maximum pumpdown rate assuming a fixed conductance (value to be established) through the bypass line between the vessel and cavity vacuums;
    b. Transition to high speed pumping;
    c. Venting, including a maximum venting rate assuming a fixed conductance (value to be established) through the bypass line between the vessel and cavity vacuums;
    d. Safety interlocks;
4. An assessment should be made of the likely failure modes for the vacuum system components and a plan for corrective and maintenance actions should be provided.
5. A specification of the required vacuum instrumentation, including instrumentation operating in the magnetic field region (where possible, hardware which was validated during spectrometer solenoid and/or focus coil testing should be utilized in magnetic field), should be provided.
6. The failure scenarios for a Be window should be described for both offline and online operation of the module:
    a. Containment issues should be described;
    b. Diagnostic procedures should be documented;
    c. Proposed recovery procedures should be described;
    d. As soon as a draft document is ready, the RAL team should begin discussions with the RAL Health & Safety group to confirm that all procedures will be acceptable to the laboratory or that suitable modifications to those procedures can be implemented.
7. Given the potential risks to the RF Module Be windows, the MICE Hall vacuum roughing system for the cooling channel and RF modules should be isolated from all other roughing applications in the MICE Hall.
8. A fixed minimum conductance (arbitrarily proposed to be in the 3-10 L/s range) should be maintained in the bypass line between the cavity and outer vessel to protect against small fluctuations in the molecular flow regime and to provide pumping for non-gettable pumped gasses. A variable flow valve can be used in operations to increase the conductance above this minimum level. Figure 1 shows a potential system configuration for the bypass line.
9. Roughing pumps should be sized (or throttled) so that their pumping speed cannot exceed the maximum pressure differential, as specified based on recommendation #2 of this section, across the Be windows given the minimum conductance available through the bypass line.

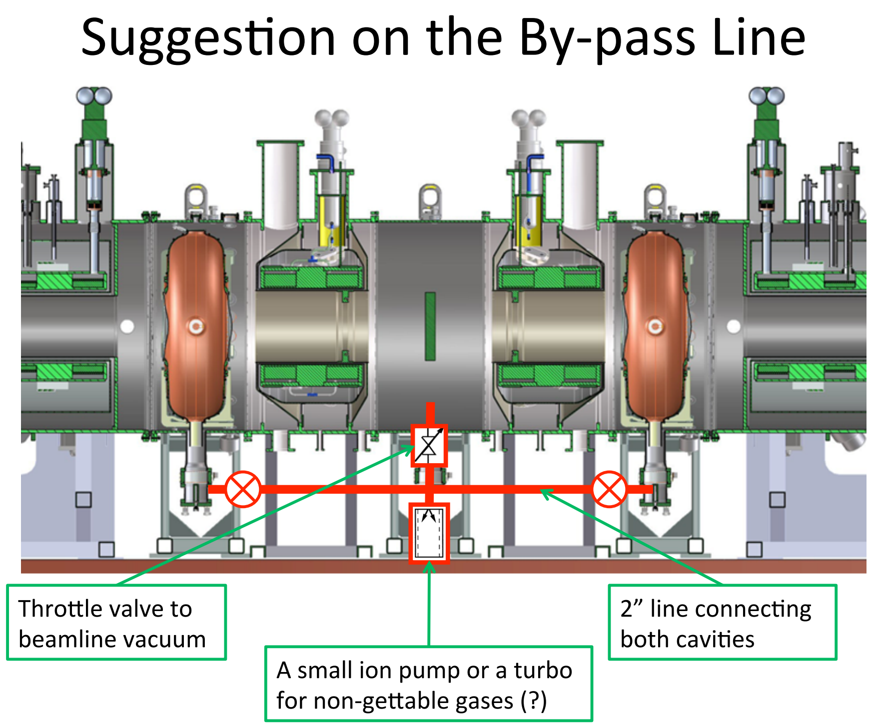

Figure 1 The bypass line configuration shown requires only a single throttling valve and small pump for non-gettable gases. An alternative configuration might involve a dual setup, where the throttling valve and small pump attached to a spare port on each RF Module.

MICE RF Module Assembly, Preparation and Delivery

Findings

A preliminary discussion of the RF Module assembly, preparation and delivery procedures was undertaken to verify the assumptions being made and to identify any critical issues needing further evaluation. It is presumed that detailed procedures for each of these steps will be reviewed at a later date (a follow-on review targeted for the August 2015 timescale).

Comments

Since the final RF Module design is very closely based on the existing SCTS design, the assembly and preparation procedures will closely follow those developed for the SCTS at Fermilab’s MTA. Thus the primary focus at this point in time was to identify assembly and preparation steps that may require modification as well as any new constraints that may apply.

Several issues were identified during assembly of the SCTS, which offered particular challenges. In particular, difficulties were encountered in bending and connecting the water cooling lines from the cavities to the outside of the module.

Another issue that developed out of the experience at the MTA was that bakeout of the cavity and vessel was extremely difficult. It was noted that the vacuum recovery of the module after a full venting to reconfigure for B-field operations showed a similar time history and final performance as the original pumpdown with baking. Thus, it was proposed to skip the bakeout step during LBNL assembly of the RF module unless it was shown to be absolutely required. Nevertheless, given concerns that exist about the quality of the vacuum in the MICE channel, in particular for water migration into the cavity vacuum volume, the committee felt that it would be wise to evaluate a hot-water in-situ bakeout option. It was noted that APS has been using 130C hot water as their standard in-situ bakeout for years. John Hoyt (hoytman@aps.anl.gov) of APS was identified as a good contact person for further information in this regard.

Precise fiducialization of the cavity to the external vessel will be required to achieve the physics goals of the experiment.

Recommendations

The committee provided the following recommendations:

1. As soon as possible, and before vessel procurement, prepare a draft module assembly plan so that all interferences and procedures can be reviewed. If design changes are indicated, these should be submitted to the committee for individual review.
2. In order to test the vacuum system and bypass line performance, dry pump-downs and ventings with dummy plates replacing Be windows should be carried out. If pressure relief valves of any sort are employed as part of the bypass, their performance should be evaluated at this stage.
3. Given the complexities and schedule requirements for the assembly and checkout process at LBNL, the team that will be designated to work on this project should be identified as soon as possible (certainly by August) and preliminary arrangements put in place to guarantee their availability when needed for assembly work. In addition, the team leader should be identified immediately and be kept in the loop for all remaining design and fabrication work.
4. A set of guidelines and training should be prepared for anyone who will be involved in assembly at LBNL (especially the technicians who would be doing the bulk of the assembly work).
5. The LBNL and Fermilab teams should review the reusability of tooling used in SCTS assembly for the final assembly process. A detailed list of required assembly tooling should be prepared and all existing hardware transferred to LBNL. Designs for any new tooling should be finalized as soon as possible and procured.
6. Preparation of the water cooling lines for installation of the cavity into the vacuum vessel is challenging. All lines should be pre-bent, with an inserted sleeve in the ID to prevent collapse, to allow safe installation of the cavity. All lines should then be leak-checked before installation.
7. It should be determined as soon as possible whether there will be any issues with shipping Be windows via commercial air transport.
8. Supporting elements of the design are not fully called out. For instance, actuator manifolds and controls are required. Instrumentation, such as field probes, light sensors, thermal sensors on the cavity body and cooling lines, etc., are required during assembly. The project must identify the plan and responsible parties for all supporting components as soon as possible. The interface requirements must also be specified.
9. A cavity measurement plan during module assembly should be prepared to enable proper fiducialization of the cavities with respect to the MICE cooling channel coordinate system.

MICE RF Module Integration Requirements

Operation of the RF Module in the MICE Cooling Channel requires a set of mechanical, vacuum, thermal and RF interfaces to be defined. Failure to adequately define these interfaces will jeopardize the MICE collaboration's ability to successfully execute the demonstration of muon ionization cooling. Thus, these issues require further attention prior to fabrication and delivery of the final hardware.

Comments

All interface elements for the RF Module need to be fully documented and copies provided to the MICE team at RAL. This includes interfaces for the actuators, the couplers, the cavity and coupler cooling loops, the vacuum system and any necessary instrumentation.

Particular issues have been identified which must be included in the MICE Hall installation plan. For instance, clean room capabilities are required during installation of the RF modules into the MICE cooling channel. They will also be required in the event that any access to the interior of the module is necessary or when couplers may require adjustment. It's very easy to undo all of the efforts in keeping the cavity and vessel clean in one misstep. Any contamination left in (or introduced into) the cavity can cause problems with RF performance, associated delays and ultimately failure to carry out the final step of the experiment. Keeping the cavity interior clean during installation is critical and requires close attention to the integration plan at RAL. This is not easy due to the additional restrictions imposed by Be window safety considerations.

It will be necessary to model both the thermal and tuning loops of the cavities in conjunction with the Low Level RF (LLRF) design. Cavity frequency is very sensitive to temperature (~3.5 kHz/deg C) and the cavity water system must have the necessary monitory and control capability.

A set of system states were presented for the RF system, which did not include a TRIP state. The TRIP state will be required for system operation.

Recommendations

The committee provided the following recommendations:

1. RAL should immediately take steps to define and acquire portable clean room capability for the MICE Hall. At the same time procedures for clean handling of the RF modules in the MICE Hall should be developed.
2. The US team should provide a detailed specification of the actuator operational requirements to the MICE Hall team as soon as possible. This should include:
    a. Operating pressure;
    b. Maximum flow rate;
    c. Control system interface requirements and any constraints on the hardware proximity to the modules;
    d. An estimate of gas supply requirements for a given operating duration;
    e. Preferred operating gas.
3. Incorporate external water system instrumentation and interface with thermocouples on the cavity bodies to monitor the status and balance between the two RF cavities.

Appendix A. Charge for the Review

U.S. Muon Accelerator Program
Memorandum

From: Mark Palmer, MAP Director, Fermilab

To: Derun Li, MAP Laboratory Manager, LBNL
Soren Prestemon, Division Deputy, ATAP Division, LBNL

Subject: Engineering Design Review of MICE RF Module

April 21, 2015

Dear Derun and Soren,

This memorandum is to identify key issues for evaluation at the Engineering Design Review of the MICE RF Module to be held April 30-May 1, 2015. This review represents the final opportunity to obtain input on the MICE RF Module Engineering Design prior to entering the procurement phase for two units of this critical piece of hardware. A prior review focused on the vacuum system issues associated with obtaining a sufficiently good quality vacuum. We need to cover the two primary topics in detail to ensure that we are ready to proceed: the RF Module Engineering Design and the Vacuum System Requirements. In addition to these primary issues, we also want to set aside some time to discuss: 1) the assembly, preliminary testing and shipping plans; and 2) interface issues (including instrumentation requirements) to the RF control system being designed principally by Daresbury Laboratory and Strathclyde University. Thus we have asked Colin Whyte (Strathclyde) to provide a brief overview that will be the basis of further discussion.

The MICE 201 MHz RF module has several unique features:

- The RF cavity is a closed pillbox design where the beam traverses thin Be windows that cover the irises;
- The RF system is intended for operation in Tesla-class magnetic fields; and
- The RF cavity utilizes a clean electropolished surface to improve its breakdown performance.

The two primary topics to be addressed at the review are:

I. A review of the readiness of the RF Module Engineering Design for component fabrication and, where further prototyping work may be required, to define the timeline for completing the necessary steps. Items that should be explicitly addressed include:
    1. Readiness of vacuum vessel design for fabrication –
        a. Identify any remaining issues or questions with respect to the design;
        b. Evaluate the adequacy of the specified complement of ports presently specified for the vessel;

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c. Review the planned surface preparation specifications for the vessel;
d. Review the acceptance requirements for the vessel.

2. Readiness of the RF cavity tuner actuators for fabrication –
   a. Summarize the status of and results from the prototype test program;
   b. Summarize any tests that are remaining;
   c. Identify any remaining design issues or issues that have arisen in the test program;
   d. Specify the procedures for dealing with actuator failures during operation.
3. Readiness of the RF coupler for fabrication –
   a. Summarize all recent vacuum and mechanical modifications and any test results that are available;
   b. Comment on the robustness of the present design for shipping.
4. Readiness of the cavity bodies and windows for RF module assembly –
   a. Summarize the results of the recent cavity selection and electropolishing process;
   b. Review the acceptance requirements for each cavity body;
   c. Summarize the results of the Be window selection process.

II. A review of the vacuum system requirements of the RF module when it is installed in the MICE Cooling Channel. Items that should be explicitly addressed include:

1. The expected conductance between the interior of each cavity and the cooling channel vacuum in the present engineering design.
2. The anticipated vacuum pressure attainable in the cavity given the pumping design, the connection to the cooling channel assuming a base pressure of 1-3×10^{-6} Torr in the cooling channel (note that these numbers are slightly worse than the assumptions used in January) and using the observed MTA cavity gas pressure and composition.
3. The maximum differential pressure that can be sustained by the Be windows
   a. Specify the methods used to develop the differential pressure rating;
   b. Identify any tests or calculations that may be required before deployment of the module in order to confirm the ratings;
   c. Specify the vacuum system procedures and interlocks required to protect the Be windows.
4. The procedures required to:
   a. Evacuate the system safely while maintaining acceptable differential pressure across the Be windows;
   b. Bring the system back to atmosphere safely while maintaining acceptable differential pressure across the Be windows;
   c. Protect the system in case of a catastrophic failure to the external vacuum system in the MICE cooling channel;
   d. Protect the system in case of a catastrophic failure to the internal cavity vacuum system;

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5. Identify any specification, operational, or interlocking requirements that may be required for the main MICE vacuum system in order to accommodate the RF module.

In addition, to the two primary issues for this review, we also propose to discuss the RF Module assembly process at LBNL. The key assumptions presently in our plan for this process are:

1. The modules and all components will arrive at LBNL early in FY16 and all acceptance checks and preliminary preparations will take place there;
2. Assembly of the two RF modules will take place at LBNL starting at the beginning of calendar 2016 and utilizing an enhanced clean room based on that available for RFQ work, but with greater filter coverage to improve the overall air quality;
3. The LBNL assembly and testing team will be augmented by members of the SCTS assembly team (FNAL and IIT members) to expedite the assembly process at LBNL;
4. A vacuum bakeout and subsequent low power RF tests will all be carried out before each RF module is shipped to RAL;
5. The RF Modules will ship to RAL as complete units (including Be windows and mounted RF couplers) under a dry N_2 atmosphere so that they can be mated directly to the RF systems in the MICE Hall for operational testing prior to being installed in the cooling channel;
6. The RF Modules will be shipped sequentially to RAL as they become ready.
7. The overall schedule aims for the final module to arrive in the UK by early June 2016.
8. A suitable set of inspection and acceptance procedures for the modules at RAL must be defined.

It will be important to discuss the validity of all of these assumptions at the review and to review the overall assembly schedule.

Finally, another secondary topic will be to review the RF interface specifications at RAL. An overview of the present status of the RF system plan by Colin Whyte will initiate this topic. We plan to initiate a more detailed review of these issues later in the summer.

Please let me know if there are items missing from this memo that you believe require explicit discussion at the review.

cc: Steve Virostek, LBNL
Alan Bross, FNAL

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