Prototype SSR2 Jacketed Cavity Preliminary Design Review and Niobium Procurement Readiness Review
- Report -

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Document Approval

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Revision History

Revision	Date Release	Originator: Role:	Description of Change
-	19 Mar 2019	L. Ristori, M. Kelly, A. Facco Reviewers	Initial Release
A	As in TC	M. Parise	PRR Nb recommendations have been addressed
B	As in TC	D. Passarelli	All recommendations have been responded

Revision control is managed via Fermilab Teamcenter Workflows.

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1. Introduction to revision A

In this revision, only the recommendations regarding the Niobium PRR have been addressed. The recommendations related to the cavity (part 2 in para. 7) will be addressed prior to the jacketed cavity FDR (Final Design Review).

2. Introduction

The PIP-II project at Fermilab, is building a superconducting Linac to fuel the next generation of intensity frontier experiments. Capitalizing on advances in superconducting radio-frequency (SRF) technology, five families of superconducting cavities will accelerate H^- ions to 800 MeV for injection into the Booster. Upgrades to the existing Booster, Main Injector, and Recycler Rings will enable them to operate at a 20 Hz repetition rate and will provide a 1.2 MW proton beam for the Long Baseline Neutrino Facility. The superconducting Linac currently has a set of frequencies (162.5 MHz, 325 MHz, 650 MHz) and energy range (2.1 MeV to 800 MeV). The relativistic β for the H^- ions goes from 0.07 to 0.854 over this energy range. Taking into consideration the number of cavities, acceleration efficiencies, cavity types and performance with an eye to costs, the design choices of a half wave resonator (HWR), two types of single spoke resonators (SSR1, SSR2), and two types of elliptical cavities (HB650, LB650) is made.
The current PIP-II beam optics design requires that each SSR2 cryomodule [1] contains five identical cavities (C) and three focusing solenoids (S) in the following order: S–C–C–S–C–C–S–C (beam direction) [2]. All the seven SSR2 cryomodules shall be capable to operate in the pulsed (20 Hz, 1% duty factor) and continuous wave (CW) regimes. In both regimes cryomodule shall support peak currents of 10 mA chopped with arbitrary patterns to yield an average beam current of 2 mA.

PIP-II requires a significant design coordination and integration oversight. As part of the oversight strategy, a design review plan specific to PIP-II has been developed [3]. The primary goal of the Project design reviews is to increase the likelihood of success by identifying potential or actual design problems as early as possible to minimize the cost, schedule, and performance impact. In this case, the review comprises of the Preliminary Design Review for the prototype SSR2 cavity (bare and jacketed) and the Niobium Procurement Readiness Review to fabricate those prototype cavities.

- Preliminary Design Reviews (PDRs) are technical and programmatic reviews intended to assure the design approach meets the technical requirements. Detailed designs are not expected, but preliminary design (~30-50% design maturity) and analyses are required to demonstrate compliance with requirements.
- Procurement (or Production) Readiness Reviews (PRRs) are held prior to the start of manufacturing and testing of major sub-system assemblies. PRRs are largely technical reviews, but include assessment of the planned cost, schedule, and personnel needs to complete the manufacturing processes that are covered.

3. Review Agenda

Location:	APS-TD, ICB - Hermitage meeting room or Zoom: https://fnal.zoom.us/j/591428030
Date:	3 April 2019
Time:	06:30 AM – 1:00 PM (CST)
Indico Site:	https://indico.fnal.gov/event/20275/
Participants:	

L. Ristori	FNAL, APS-TD	Role: Reviewer, Chair
M. Kelly	ANL	Role: Reviewer
A. Facco	MSU/INFN	Role: Reviewer
G. Wu	FNAL, APS-TD	Role: System Manager, Attendee
D. Passarelli	FNAL, APS-TD	Role: Coordinator, Presenter
P. Berrutti	FNAL, APS-TD	Role: Presenter
I. Gonin	FNAL, APS-TD	Role: Presenter
G. Romanov	FNAL, APS-TD	Role: Presenter
M. Parise	FNAL, APS-TD	Role: Presenter
F. Ruiu	FNAL, APS-TD	Role: Presenter
V. Yakovlev	FNAL, APS-TD	Role: Attendee
T. Nicol	FNAL, APS-TD	Role: Attendee
T. Khabiboulline	FNAL, APS-TD	Role: Attendee
M. Martinello	FNAL, APS-TD	Role: Attendee
Y. Pischalnikov	FNAL, APS-TD	Role: Attendee
N. Solyak	FNAL, APS-TD	Role: Attendee
S. Kazakov	FNAL, APS-TD	Role: Attendee
D. Longuevergne	IPNO – France	Role: Presenter
P. Duchesne	IPNO – France	Role: Attendee
D. Reynet	IPNO – France	Role: Attendee
S. Krishnagopal	BARC - India	Role: TBD
P. Jain	BARC - India	Role: TBD

4. Review Charge Statement

The review committee is charged to evaluate the prototype SSR2 jacketed cavity at preliminary design stage by responding to the following questions using the "PIP-II Review Report Template":

1) Technical Scope
   a) Are all design specifications, requirements, and performance approved and released?
      Yes for FRS and TRS. The committee was presented two requirement documents (cryomodule and cavity-coupler-tuner) which have been approved by project management and are in teamcenter.
   b) Is the RF design mature and technically sound to satisfy design specifications?
      Yes, the presented RF design version 3.1.0 satisfies the RF design specifications.

   c) Is the mechanical design likely to meet structural and multiphysics performance expectations?
      Yes for structural safety. For the most stringent loading condition at RT, preliminary structural/safety analyses performed in accordance with the FNAL safety manual, give a resulting MAWP=2.76 bar for the jacketed cavity. This exceeds the requirement of 2.05 bar.

      Provisional yes for endwall stiffness. The end wall stiffness combined with the frequency sensitivity means that the existing SSR1 slow tuner would be marginal in terms of providing sufficient force. Given the present SSR2 mechanical design, the SSR2 slow tuner will require some development beyond what has been achieved with the SSR1 tuner.
      Yes for Multiphysics. The expected LFD performance in operating conditions is estimated to be -3.65 Hz/(MV/m)^2 with ~10% margin with respect to the TRS (TRS <4.0 Hz/(MV/m)^2). Df/dp is calculated to be 0.8 Hz/mbar (TRS <25 Hz/mbar) in operating conditions and appears relatively insensitive to variations of tuner connection stiffness. Although this very low calculated value is the result of a fine design adjustment which cannot be realistically reproduced in real life, the expected df/dP extrapolated from results in similar structures is anyhow well within specifications. Finally, it is noted that the beam ports are longer in the SSR2 than in the SSR1. The committee has a recommendation for a further multiphysics analysis related to this.

   d) Have all the major interfaces been identified and accounted into the design?
      Yes for the most part. Mechanical models have some of the detailed interfaces to other hardware. There are not yet detailed design drawings or interface documents covering the cavity interfaces. The interface with the SSR2 coupler is being studied with the intent of using the same coupler as for the SSR1. A better definition of RF coupling/bandwidth specifications taking into account unavoidable calibration errors in real life is advisable.
      According to a 3D rendering, the dressed SSR2 appears to fit into the FNAL spoke test cryostat in its operational orientation. It is not clear that the installation process will be possible, due to the interference of certain parts during the insertion operations.
2) Design Management
   a) Is the design team organized and staffed to successfully complete the project?
      Yes, for the most part. Based on the quality and quantity of information presented at this review, the team has the necessary skills to accomplish the goals. Conflict for personnel resources was not extensively discussed and the reviewers cannot make a firm statement on whether or not the activities are adequately staffed to meet the presented schedule.
   b) Have all the major risks been identified and managed? Not yet. Risks associated with the SSR2 design and fabrication were not presented in a systematic or explicit way, such as in a slide or two. Several risks were mentioned at various points in the presentations.
      Nevertheless, the committee believes that the risks associated with the niobium procurement for prototype cavities are small.

c) Are procurements appropriately planned?
Provisional Yes for niobium procurement. There has been considerable and appropriate planning for the niobium procurement. We do make two related recommendations below (see 1.a and 1.b).

d) Is the development of associated drawing packages sufficiently mature for preliminary design stage?
Yes for niobium procurement. Part layouts for niobium cavity subcomponents as they will be cut and fabricated from as purchased niobium sheets and tubes were presented in detail. These, along with the mechanical design, are sufficiently advanced to launch procurement of the niobium for the prototype cavities.
Drawing packages for the cavity parts do not exist, however, the cavity mechanical model is well advanced and should be considered at least 30-50 percent complete by any reasonable metric.

3) Schedule

a) Is the schedule reasonable to achieve the planned scope? This is a reasonableness assessment by technical experts, not a detailed schedule review.
Yes. The scheduling is reasonable from a technical standpoint. Prototyping of cavities will be pursued in parallel by 3 different teams worldwide (France, India, USA). Parts of the schedule may be ambitious, particularly if many intermediate tests on bare cavities are performed, or if project personnel have competing work.

4) ES&H and QA/QC

a) Are all related ES&H aspects being properly addressed?
Yes, for this stage of the project. The design of SSR2 cavities is performed in accordance with Fermilab FESHM Chapter 5031.6 on Dressed SRF Cavity Pressure Safety. Preliminary analyses were presented showing that the cavity can be rated at room temperature at an MAWP of ~2.7 bar (above the requirements).
Although the committee was told that a FMEA and a Risk Assessment were performed for the SSR2 cavity, these documents were not presented at the review.

b) Are appropriate QA and QC steps being implemented?
Yes, for this stage of the project. Although, a Quality Assurance plan document was not presented at this review, the SSR2 team plans to utilize FNAL Vector system to define and document all QC and acceptance activities, including discrepancy reports.

5) Miscellaneous

a) Have lessons learned from SSR1 experience been addressed?
Yes, in large part. Conclusions on MP optimizations for SSR2 draw mostly on experience from SSR1 testing as a reference point for estimated hours necessary to process MP. Beam pipes are extended beyond the helium jacket end walls to avoid turbulent flow in cleanroom observed in SSR1 assembly tests with fogger and laser. Additionally, lessons learned by CNRS/IN2P3 with the ESS double-spoke effort are relevant for the design and overall fabrication/qualification strategy of SSR2. The collaboration should continue to draw from that experience.

b) Are there any other issues that have been identified that need to be addressed?
No additional major issues were identified by the committee. However, please see the comments.

6) Overall Readiness

a) Is the design sufficiently mature to allow Preliminary Design Review approval?
Yes. The design of the SSR2 cavity appears to be more than 30-50% complete in terms of the detail of the mechanical and EM models. The EM design is finalized, the structural design is mostly complete. The interfaces details, including drawings with dimensions and tolerances and interface documents will be necessary in the near future to ensure successful integration of the cavity with the other cryomodule systems.

b) Is the design sufficiently mature to proceed with Niobium material procurement for prototype cavities?

Yes, for the prototype cavities.

5. Findings

General, factual observations about material presented which require no response.

- One prototype cryomodule for SSR2 (SSR2-0) is planned prior to launching production cryomodules (SSR2-1 to 7). The cryomodule contains 5 cavities and 3 solenoids.
- 8 prototype cavities will be built for the prototype cryomodule (FNAL 2x, India 2x, France 4x). All niobium will be procured by FNAL.
- The delivery of SSR2 cryomodules will be a collaboration between Fermilab, IPNO and BARC.
- SSR2 work is being done in parallel with the SSR1 prototype cryomodule
- One prototype SSR2 cryomodule will be built before the seven production modules.
- International partners are engaged in the design activities during the prototype phase
- 5 cavities are required for the prototype cryomodule. Eight cavities are planned (2 FNAL, 2 BARC, 4 IPNO)
- Niobium procurement for 8 cavities should start as soon as possible after this review to maintain the project on schedule
- Cavity orders should be placed at the beginning of CY2020 at the different vendors.
- A total of ~ 2 years is assumed across partners, for bare cavity fabrication, testing, jacketing and testing again.
- FNAL cavities (and possibly BARC) will be tested at the bare stage prior to jacketing. Cavities from France will be tested only after jacketing.
- The present plan is to have CW operation, but maintain all capabilities needed for possible pulsed operation
- Several iterations of the EM design have been performed in large part to reduce the intrinsic susceptibility to multipacting
- The proposed EM design v3.1.0 already includes certain fabrication assumptions, for example the desire to have a cylindrical portion on the main body to facilitate trim-tuning operations.
- The SSR2 niobium has been parted out in detail with forming, machining and welding in mind
- Unlike SSR1 cavities which are fabricated in type A and B with bellows on opposite sides, SSR2 jacketed cavities are planned to be fabricated all as mechanically identical.
- The minimum material thickness necessary for structural and functional purposes is found to be 3.75mm. It is assumed that ~1mm of material is “lost” by forming and chemical processing. The raw sheet material is specified with a thickness tolerance of 4.7-5.0 mm to offset this reduction.
- The helium vessel will be manufactured from Titanium. All cavity flanges will be manufactured using Titanium grade 5. All other Titanium parts will be manufactured in Titanium grade 2. Nb-Ti alloy will not be used to join Nb to Titanium components. This approach is deemed acceptable if enough material (8mm) is left between the weld and the RF surface.

6. Comments

Observations with value judgments, or "soft" recommendations that require action by the design/engineering team, but where a formal written response is not requirement.

- **The committee commends the excellent quantity and quality of work that was performed and presented on the design and overall development strategy for the prototype SSR2 cavity.**
- **The committee believes that the design maturity for the SSR2 cavity is sufficiently advanced for the current stage of the project. The project is on track for a final design review of the cavity later in 2019 and to launch prototype cavity fabrication thereafter.**

- The committee advises that the TRS explain the reasons for the choice of the main cavity requirements such as energy gain per cavity and quality factor.
- The EM design of the cavity (v 3.1) is mature with detailed studies complete on field performance and multipacting. The designers have given considerable thought to minimizing multipacting by design.
- The field performance requirements are moderately aggressive (*e.g.* up to 80 mT Bpeak). Their full achievement might require longer R&D and testing time than planned. To reduce the schedule risk it may be helpful to consider at this early stage the total voltage required per cryomodule and feed this back into the acceptance criteria for individual cavities which will always have a scatter in performance (see also recommendation).
- Fixed couplers do not allow adjustment after installation. The full 3dB RF bandwidth of the cavity was specified to 64 Hz. Previous experience in TEM cavities have shown that final coupling factor after installation and cooldown may be found scattered by up to 20% around the design value. It is not clear if the 64Hz value leads to critical coupling under maximum specified beam loading. If so, a realistic error interval on the bandwidth - so on the coupling factor - should be specified to prevent the possibility of finding cavities under-coupled in operation. If this is not acceptable, the use of adjustable couplers - which allow changing the coupling factor after installation without breaking the cavity vacuum - might be considered.
- IPNO mechanical and EM simulation predictions consider the effect of real variations in Nb thickness and do well in understanding the effects on Lorentz detuning and, to a lesser extent, df/dP. In any case, the effect of df/dP should not be a problem with 2K operation.
- The relatively long SSR2 beam ports are conduction cooled and a thermal analysis has not yet been done (see recommendation).
- The present ~9 months schedule for processing and testing of the 8 prototype cavities may be difficult, particularly if many of the tests are performed on unjacketed cavities and are then repeated on the jacketed cavities.

- The reasons for HOMs studies were not particularly well explained or complete. These might be a non-issue for PIP-II.
- The presentation covering transverse momentum kicks in the SSR2 may have issues with improper units. This should be discussed by the collaboration and fixed if necessary.
- The choice of a 45 degree orientation for the coupler and the opposing port increases the risk of cavity contamination during clean-room assembly and venting. This non-optimal choice is intentionally maintained from the SSR1 design for practical reasons.
- Vendors should be consulted before assessing the Nb sheet size to be purchased in order to minimize costs (see recommendations).
- Tooling at cavity vendors - e.g. development of suitable stamping dies and procedures - may take longer than forecast by vendors themselves, and this should be taken into account as a schedule risk.
- The presenters indicated that there is sufficient vendor expertise in niobium-to-titanium welding that this technique does not pose a major technical risk. This technique is supported by the committee, provided that there is enough development effort at the vendor.

7. Recommendations

Items that require formal action and closure in writing prior to receiving approval to move into the next phase of the project, or items that require formal action and closure in writing prior the next review.

1. Before launching the procurement for the raw Niobium for the prototype cavities:
   a. Confirm as soon as possible that the planned niobium sheet dimensions can, in fact, be supplied and meet the requirements, some of which are more difficult to achieve for larger sheets. Adjust the sizes accordingly, if necessary.

      i. *Niobium sheet dimensions have been changed to 1000x1000x4.7 mm after we had an informative discussion with Niobium suppliers. The Niobium suppliers can deliver the Niobium in the quantities and dimensions (as specified in ED0010071) along with the required technical material specifications (as specified in ED0009878).*

   b. Consider splitting the physical niobium material specifications from the other procurement specifications to facilitate future procurements or, for example, minor changes is quantity or dimensions of niobium materials.

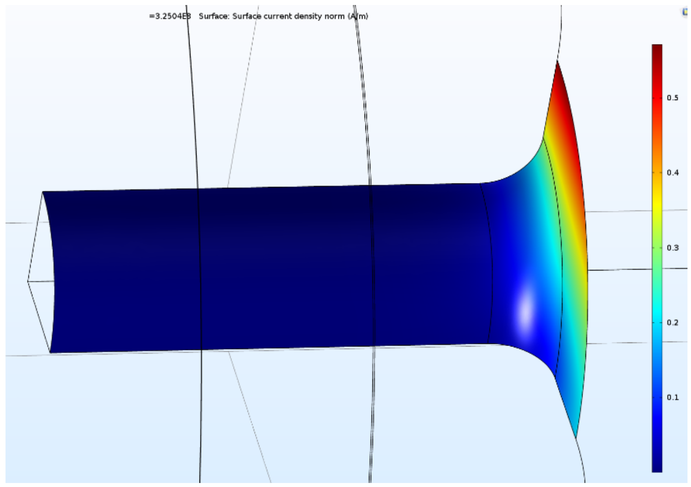
      i. *Procurement specification and technical specification have been split. Documents are in Teamcenter:*
      ED0009878 rev.- Raw Niobium technical specification for PIP-II SSR2 cavities
      ED0010071 rev.- Raw Niobium procurement specification for the prototype SSR2 cavities

2. Before the Final Design Review of the cavity:
   a. Consider revising the cavity performance acceptance criteria taking into account the average installed accelerating gradient and Q0 as required for the complete cryomodule.

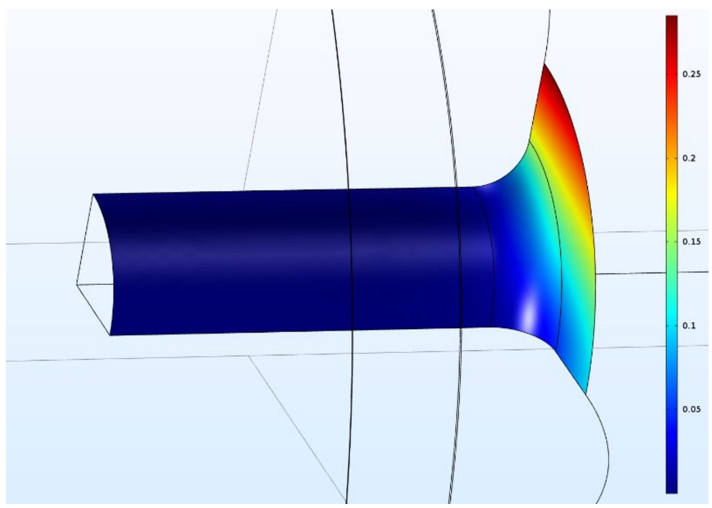
      i. The cavity gradient and quality factor for all PIP-II cryomodules were studied and reviewed. The total energy gain and cryoplant capacity are specified in PIP-II Global Requirement Document (ED0001222) and Cryogenic Heat Load PRD (ED0008200). Cavity nominal operation gradients and quality factors are summarized in SRF Cavity Parameters PRD (ED0010221). Acceptance criteria takes into account operational margin and potential performance degradation from cavity acceptance test to linac. For SSR2 cavities, nominal linac gradient is 11.47 MV/m and Q0 of 8.2e9. A jacketed cavity acceptance criteria before string assembly is 12.6 MV/m and Q0 of 9e9 in average. Cavities are typically accepted as a group for string assembly with average performance meeting acceptance criteria.

b. Analyze and document the effect of the substantially increased length of the cavity beam ports (compared to SSR1), particularly from the point of view of thermal stability.

   i. *RF dissipation in the beam tubes is negligible: both Magnetic field and Current are very low, one can look at the values from simulation.*

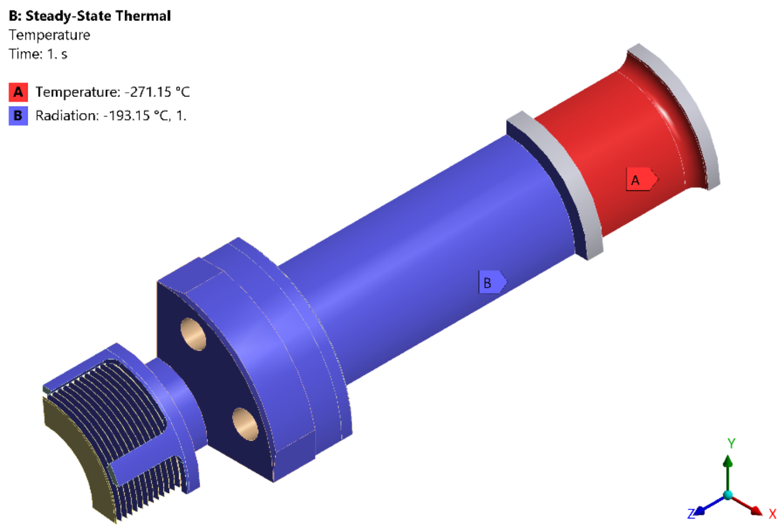


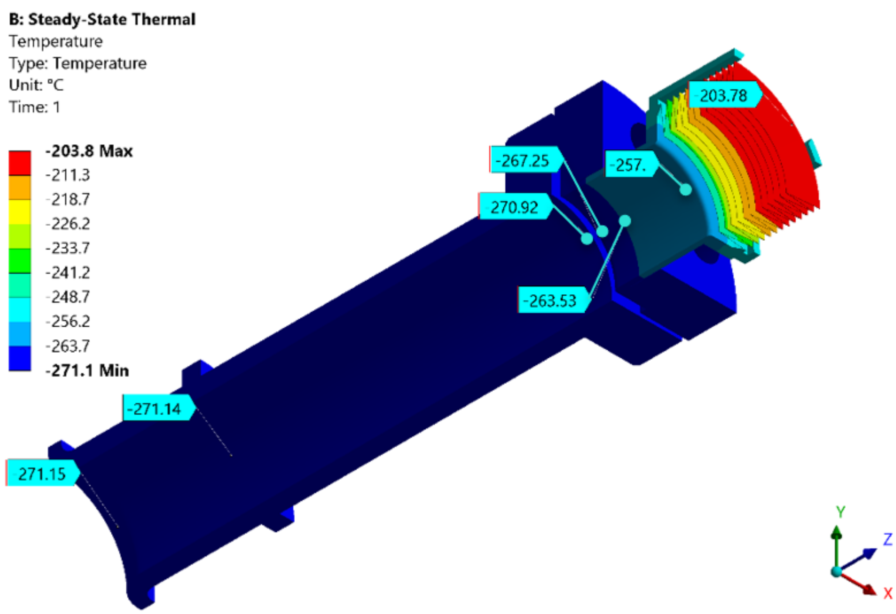
Surface current is negligible in the beam tubes: the EM field decays within the beam pipe blend.



Magnetic field (H) level is also negligible in SR2 beam tubes.
As a result the contribution to the cavity G factor of the beam pipes is insignificant being the surface integral of H^2 in the full cavity approx. 1.45E6 times bigger than the tubes portion of the cavity.
Given all these consideration one can conclude RF heating of the beam tubes can be neglected, there it does not impose any limitations to the RF performance of SSR2 cavities.

   ii. *Given the prior considerations it is not necessary for the beam tube to be superconducting starting right after the blend radius. However, even if the beam* *tube will be completely exposed to radiation from 80K shielding (worst case scenario), the maximum temperature will not exceed 3.2K. It is below the critical Niobium temperature of 9.2K.*





c. Study carefully the installation and integration aspects of a jacketed SSR2 cavity into the FNAL spoke test cryostat.

   i. The total area of the transverse cavity envelope was reduced to facilitate the installation of SSR2 cavities at FNAL spoke test cryostat. The position of the right-

angle valve was changed from the side port to the beam pipe port (ring side). Details will be presented at the Final Design Review.

d. Resolve and document a slow tuner plan that ensures that the tuner can impart sufficient force for the full planned (200 kHz) tuning range.

   i. *The coarse frequency range specified in the Technical Requirements is below the 200 kHz reported above. However, details about tuner design and requirements will be detailed in the Final Design Review of the tuner.*